FACET-II
Facility for Accelerator Science and Experimental Test Beams-II
Located in the SLAC Linac at Sector 10

April 2, 2013
1 Executive Summary

The discovery of the Higgs boson, a subatomic particle responsible for endowing all other particles with mass, is one of the major discoveries of the last decade. To unlock the mysteries of the subatomic world, physicists use the world's most powerful microscopes – particle accelerators. The resolving power of these microscopes is proportional to the energy of the beams they produce. Since their inception nearly 80 years ago, the energy reach of accelerators has grown exponentially due to continued breakthroughs in accelerator physics and engineering. The highest energy beams in the world are currently at the 27km circumference Large Hadron Collider (LHC) in Europe. Although it is a monument to human engineering, scientists are approaching a practical limit to the size and cost of such collider facilities. Innovation is essential for continued progress.

Electrons can “surf” on waves of plasma – a hot gas of charged particles – gaining very high energies in very short distances. This approach, called plasma wakefield acceleration, has the potential to dramatically shrink the size and cost of particle accelerators. Research at the SLAC National Accelerator Laboratory has demonstrated that plasmas can provide 1,000 times the acceleration in a given distance compared with current technologies. Developing revolutionary and more efficient acceleration techniques that allow for an affordable high-energy collider is the focus of FACET, a national user facility at SLAC.

FACET uses part of SLAC’s two-mile-long linear accelerator to generate high-density beams of electrons and their antimatter counterparts, positrons. These beams are so intense, they are equivalent to focusing all the power of the sun onto a surface 10 meters square. This produces large electric and magnetic fields over a very short span of time – ideal for creating exotic states of matter and researching advanced accelerator technologies.

High-energy particle beams also provide unparalleled tools for studying the building blocks of life at the molecular level using powerful beams of x-rays. With the recent success of the world’s first x-ray laser, the Linac Coherent Light Source (LCLS) at SLAC, scientists can image the smallest structures with intense pulses lasting only a millionth of a billionth of a second – like an ultimate high speed camera. FACET also produces unprecedented intensities of terahertz or “sub-millimeter” electromagnetic radiation, which has many applications in material science, semiconductor research, chemical imaging and more.

Scientists from all over the world come to FACET to do experiments aimed at improving the power and efficiency of particle accelerators used in basic research, medicine, industry and other areas important to society. Experimental proposals are peer-reviewed by the SLAC Accelerator Research Experiment Committee (SAREC), which would also review FACET-II proposals. There has been extensive outreach to
the user community through three FACET User Meetings at SLAC, satellite FACET informational meetings at IPAC and other conferences, and direct involvement of the users in the FACET-II proposal.

In early 2016, the second phase of SLAC’s x-ray laser, the LCLS-II, will begin commissioning using part of the tunnel occupied by FACET, and the world’s only multi-GeV facility for advanced accelerator research will cease operation. FACET-II is a new test facility to provide DOE with the unique capability to develop advanced acceleration and coherent radiation techniques with high energy electron and positron beams. FACET-II is an opportunity to build on the decades-long experience developed conducting advanced accelerator R&D at the FFTB and FACET and re-deploy HEP infrastructure in continued service of its mission.

FACET-II will provide a major upgrade over current FACET capabilities and the breadth of the potential research program makes it truly unique. It will synergistically pursue accelerator science that is vital to the future of both advanced acceleration techniques for High Energy Physics, ultra-high brightness beams for Basic Energy Science, and novel radiation sources for a wide variety of applications. An international group of high energy physicists are interested in using it as a foundation for the world’s the first photon collider. Nuclear physicists have proposed using the unprecedentedly high intensity gamma beams to study the structure of nuclei and as a novel particle source for future colliders. No other test facility has attracted such broad interest across so many branches of the Office of Science.
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The frontier of any experimental science is defined by the capabilities of its instruments. Exploration of the universe at its finest scales requires probes of the shortest wavelengths—the highest energies—available. The observation and manipulation of microscopic systems on the time, distance, and energy scales on which chemistry occurs requires novel radiation sources of unprecedented brightness, flexibility, and speed. Significant innovations that extend the reach and capability of these instruments is the key to leading at these frontiers.

2 Experimental Program

We need to push the properties of accelerators beyond the present limits of performance and create innovative ways of applying accelerator technologies in order to advance science and further the goals of High Energy Physics and Basic Energy Science. Reaching well beyond the trillion-electron-volt (TeV) energy scale with an electron/positron collider will not be affordable without a marked improvement in accelerating gradient. Techniques developed to enable a TeV collider will also make GeV-scale light sources smaller and less expensive. Providing the luminosity required to support precision science will require significant gains in beam brightness and accelerator power efficiency. Such gains will improve the source quality and reduce the operating cost of light sources.

Developing the accelerator science necessary to make game-changing performance improvements requires significant experimentation and refinement. Such work requires a suitable test facility where machine changes can be made and significant beam time assigned to experiments without adversely impacting a scientific user community.

Decades of experience in advanced accelerator research have shown that some basic facility features are needed to support the work:

- A stable, well-diagnosed beam with broadly adjustable properties
- An extensive user-configurable beam area with a wealth of diagnostics
- An external diagnostic hutch where both electrical and optical signals can be gathered and processed
- A laser hutch, providing coherent radiation for excitation and diagnostics

Facilities at Argonne, Brookhaven, SLAC, UCLA and elsewhere cover the energy range below 1 GeV, but there is currently no planned national user beam facility above the 1 GeV range after FACET. Wakefield acceleration and coherent radiation generation are fundamentally collective effects that grow stronger with beam density and energy, and consequently the science and potential applications grow more compelling with beam energy and brightness. The wealth of attosecond-scale manipulation techniques being developed for the photon sciences (e.g. iSASE, ESASE, HGHG, and seeding) all become more robust at higher energies, where path length slippage and space charge effects can be mitigated.

An additional consideration for an advanced accelerator research facility is the pulse format. Many advanced accelerator experiments are inherently single-pulse (or
single drive-witness pair) experiments because the physical process is single pass (non-resonant), or because the experiment relies on single-shot diagnostics (such as cameras), or both. Short pulse trains of <10 bunches are useful to probe long-range wakefield effects, as are pulses with widely variable spacing (perhaps out to 100 ns).

The FACET-II science program will have three principle thrusts:

- High gradient acceleration techniques for the next e+/e- collider
- Radiation generation and enhancement techniques for photon science
- Physics of very high field interactions with materials

The high energy and high brightness characteristics of the FACET-II beam will enable a broad class of coherent radiation and beam/matter interaction science at field strengths and energy densities not available anywhere else. While an experimental program is defined below that focuses on key challenges for discovery science, we will also seek out new opportunities to apply the unique capabilities of FACET-II to solve problems in other scientific areas, drawing in university and industrial researchers in the process.

Wakefield acceleration—whether in plasma or in dielectric waveguides—will be a cornerstone of the program, building on a more than 20 year history of performing groundbreaking work in GeV-scale beam-driven wakefield acceleration at SLAC.

2.1 Plasma Wakefield Acceleration (PWFA) Program on FACET-II

2.1.1 Introduction

With the construction of the FACET-II facility, Plasma Wakefield Acceleration (PWFA) program will enter the third phase of R&D towards realizing a PWFA–based electron-positron (e⁺e⁻) collider at the energy frontier and as a driver of a Fifth Generation light source. The first phase of this research was carried out between 1998 and 2006 at the FFTB facility at SLAC. It conclusively demonstrated that a plasma can sustain ultra-high gradients over meter lengths to give energy gains of interest to high-energy physicists [1]. The on-going, second generation of PWFA research (for example, the E200 Collaboration experiment at FACET) is aimed at demonstrating that a PWFA can deliver beams that have a relatively small energy spread and a significant charge, as well as high gradient acceleration. PWFA experiments on FACET in 2015 will seek to demonstrate high gradient acceleration of positrons using plasma wakes [2]. These experiments are expected to continue until 2016 when FACET must make way for LCLS-II.

The proposed FACET-II facility opens new and significant opportunities to further the development of the PWFA concept. Compared to the current FACET facility where the maximum charge per bunch is about 3 nC, the FACET-II facility will provide bunches containing up to 6 nC of charge in a fully compressed bunch. These
high charge bunches will allow us to address important questions in the development of the PWFA concept. These are:

Can we use a low-energy but high-charge drive beam, such as that from FACET-II, to obtain a 25 GeV per stage energy gain with a very high efficiency of energy extraction from the drive (primary) beam to the trailing (secondary) beam? We call this the high transformer ratio problem.

Can we inject a witness bunch, produced by an independent accelerator, into the plasma with the required degree of spatial and temporal proximity to achieve the desired performance?

Can super-high brightness beams be generated using the PWFA scheme itself and accelerated without significant emittance growth to high energies?

What are the limits to the repetition rate of a single-stage PWFA module for stable operation and/or for staging of two PWFA modules.

Answering these important questions through experiments will be the main goals of the PWFA research program at FACET-II.

2.1.2 The High Transformer Ratio Problem

The E200 experiment currently underway at FACET relies on significant beam loading to flatten the accelerating field, [3] thereby ensuring that the particles in the trailing beam gain energy uniformly. This results in a narrow energy spread. Beam loading causes local damping of the wake such that the energy of the drive beam is efficiently transferred to the trailing beam via the wake. However beam loading leads to an effective reduction of the transformer ratio, [4] which is defined as $T = E^+ / E^-$, where $E^+$ and $E^-$ are the magnitudes of the accelerating and the decelerating fields, respectively.

In the linear regime of the PWFA, the unloaded wake produced by a symmetric beam has a transformer ratio of 2. In the blowout or the bubble regime shown in Figure 2-1, for particles in the tail of the one-bunch case (blue curve) $T$ is much greater than 1. When the wake is loaded by the trailing bunch, however, $T$ can be reduced to 1 or less (red and green curves) as shown in Figure 2-1b. This means that with the current 20 GeV FACET drive beam we expect the energy gain of electrons to be equal to or less than 20 GeV.
Figure 2-1: The wakes produced in plasma can have a dramatically different transformer ratio depending on the extent of the beam loading by the trailing bunch. (a) Shows the three pulse shapes used to produce the wakes and (b) shows the line out of the longitudinal electric field of the excited wake. The transformer ratio is the ratio of the peak decelerating (peak of the positive green curve) to the peak accelerating (peak of the spiky negative curves) field. (Courtesy Weiming An, UCLA)

Cost considerations of a future PWFA-based linear collider indicate that the primary beam should have a charge of several nC and a beam energy of several GeV. [5] This allows us to design a single PWFA stage with a beam-loaded transformer ratio of at least 3. This means that the drive linac for a future PWFA-based linear collider needs to deliver 5 or 10 GeV drive pulses with 4 or 8 nC of charge while adding 15 to 30 GeV per stage to the beam that is being accelerated. This concept requires about 20 stages to reach an energy of 1 TeV. We can accomplish this using one of two approaches.

In the first approach we break the assumption of a symmetric drive beam as shown in Figure 2-2(a). If, instead of using a temporally Gaussian current profile, we shape the beam so that it is bi-Gaussian with a longer rise and a sudden fall, then the unloaded transformer ratio can be increased to a value much greater than 2. As can be seen in Figure 2-2, if the drive beam has a linear rise over 100 μm followed by a sharp drop over 1 μm the fully loaded transformer ratio can be as high as 8. With a more gradual fall time, T becomes smaller but even for a 5-μm fall time, a T of 4 appears feasible. It is therefore possible that a 10 GeV drive beam could add up to 40 GeV per electron to the trailing beam.

There are of course many challenges to realizing such a result in practice. We need to understand how to precisely craft the drive beam pulse shape and how to produce such a high charge and transversely compact trailing beam and load it in the wake with sub-micron accuracy. We do not know whether the drive and trailing beams will be stable or if the beams will be susceptible to the hosing instability. [6] Answering these questions will be the prime goal of exploring this idea.
Figure 2-2: The idea behind generating high transformer ratio wakes using a shaped drive beam. (a) beams with the wake structure and (b) the on axis electric field showing a near uniform decelerating field and a highly nonlinear accelerating spike soon after the beam has entered the plasma. In this case T=8. Drive Beam Parameters: Q = 6 nC, σ_r = 5 μm, L_z = 100 μm, ε_N = 5 mm mrad, E = 10.0 GeV. Trailing Beam Parameters: Q = 0.288 nC, σ_r = 2 μm, σ_z = 1 μm, ε_N = 1.0 mm mrad, E = 100 MeV. Distance between two beams: 12.5 μm. Plasma Density n_p = 3.17 x 10^{18} cm^{-3}. The beams propagate in a pre-ionized plasma and k_p^{-1} = 3 μm. (Courtesy Weiming An, UCLA)

Although for linear wakes that are excited by symmetric bunches T is less than equal to 2 , it can be shown that in a certain regime [7] of the fully blown-out wake, T = k_p σ_z / Λ^{1/2} > 2. Here k_p, σ_z and Λ are wake wave number, rms bunch length and charge per unit length, respectively. Thus by appropriately optimizing the plasma density for a given charge and bunch length it is possible to achieve unloaded T >>2 and a loaded T of >2. The goal here would be to use the 10 GeV FACET-II beam to add 30 GeV per particle to the electrons in the trailing beam over a distance of less than a meter while extracting more than 90% of the drive beam’s energy. Figure 2-3 shows such a case where the loaded T is about 3. The FWHM energy spread of the trailing bunch is still a only few percent.

To load these wakes we need trailing beams to be much shorter than the drive beam and these must contain a significant amount of charge to flatten the wake so that the energy spread will be narrow. The current approach to getting such a drive beam/trailing beam structure is to collimate a portion of an appropriately chirped beam in the dispersive plane and then to partially recompress the beam. [2] In this process, however, a significant amount of original beam charge is lost and the drive beam/trailing beams are tens of μm long. These lower charge, longer bunches require a longer and lower density preformed plasma in the current E200 experiment.

However, FACET-II will be able to supply electron bunches that contain up to 6 nC of charge. This opens the possibility of producing a drive beam/trailing beam configuration with an adequate amount of peak current in each to self-ionize the gas. We will therefore be able to produce the wake with the drive pulse and beam-load the wake with the trailing pulse. An example of such a case is discussed in
detail in Ref. (2) and will in fact be the first experiment to do at FACET-II. The drive beam will have an rms bunch length of 30µm and contain 3x10^{10} electrons, while the trailing bunch will have a bunch length of 10 µm and contain 1x10^{10} electrons.

The separation between the two bunches will be 115 µm and both bunches will be focused to a spot size of 3.3 µm in a 1x10^{17} cm^{-3} Li vapor. In this case, the energy should double from 10 to 20 GeV in just 30 cm.

![Image](image_url)

**Figure 2-3:** Generation of fully loaded transformer ratio wakes of 3 using the FACET-II beam. (a) shows the beams and the wake and (b) shows the energy spectrum of the two beams after just 26 cm. Drive Beam Parameters: Q = 4 nC, σ_{r} = 5 µm, σ_{z} = 20 µm, ε_{N} = 5 mm mrad, E = 10.0 GeV. Trailing Beam Parameters: Q = 0.288 nC, σ_{r} = 2 µm, σ_{z} = 2 µm, ε_{N} = 1.0 mm mrad, E = 100 MeV. Distance between two beams: 93.5 µm. Plasma Density n_{p} = 2.0 x 10^{17} cm^{-3}. The beams propagate in a pre-ionized plasma. (Courtesy Weiming An, UCLA)

The higher transformer ratio experiments need trailing bunches on the order of 2 µm rms with sub 100 nanometer emittance and a significant amount of charge. It is not easy to achieve all these requirements with a few femtosecond jitter between the drive and the trailing beam. Fortunately, there are other possible methods for generating such a trailing beam in situ without any loss of charge in the drive beam that can be developed at FACET-II. Below we discuss two different methods that we would like to explore on FACET-II for generating suitable beams for injection into a PWFA that is operating in the high transformer ratio mode.

### 2.1.3 Generation of super-high brightness beams

#### 2.1.3.1 Density down-ramp injection using beam parameters at FACET-II

A sudden density transition from a high-to-low-density region will trap plasma electrons in the wake. [8] Even a relatively gradual density transition can trap electrons as the wavelength of the wake adiabatically increases. [9] We have examined this so-called down-ramp injection, via 3D particle-in-cell (PIC) code simulations, using the FACET-II beam driver with a charge of 5 nC, a transverse
emittance of $5 \times 5 \, \mu m$, an energy of $10 \, GeV$ and a spatial size of $10 \times 10 \times 10 \, \mu m$. Plasma density is varied from $2 \times 10^{18} \, cm^{-3}$ to $1.5 \times 10^{18} \, cm^{-3}$ with a down-ramp length of $115 \, \mu m$.

Figure 2-4(a) shows the wake excited in the down-ramp and the trapped beam in this wake. The density distribution shows that the injected particles have a “head” with a relatively larger emittance that forms a halo around a beam core with a smaller emittance. To eliminate the particles of the beam halo, we just take the 95% electrons into account. The emittance of the beam core is $\varepsilon_{n,0.95} \approx 70 \times 100 \, nm$ as shown in Figure 2-4(b). The beam charge, peak current and brightness are $580 \, pC$, $47 \, kA$ and $1.4 \times 10^{19} \, A/\text{rad}^2\text{m}^2$ respectively. The emittance of the beam head is much larger, i.e. $\varepsilon_{n,0.95}$ are $630 \times 590 \, nm$. The beam charge, peak current and brightness of the particles in the beam head are $610 \, pC$, $107 \, kA$ and $2.9 \times 10^{17} \, A/\text{rad}^2\text{m}^2$ respectively. Clearly for these parameters, there is a trade-off between current and brightness of the core and head.

![Figure 2-4](image)

**Figure 2-4**: Simulation results of density down ramp injection with a $5 \, nC, 10 \times 10 \times 10 \, \mu m$ beam driver. (a) electron density distribution (b) $x2-p2$ phase space of the beam core. The unit simulation length in this figure is 1 micron. (Courtesy Fei Li and Wei Lu Tsinghua University & UCLA)

The total emittance of the beam can be further reduced if the drive beam charge is lower. We next use a drive beam with spatial size $10 \times 10 \times 10 \, \mu m$, but with a lower charge of $1 \, nC$. The plasma density is varied from $2.9 \times 10^{17} \, cm^{-3}$ down to $2.2 \times 10^{17} \, cm^{-3}$ and the down ramp length is $260 \, \mu m$. The results of this simulation are shown in Figure 2-5. The emittance of the total beam is now $120 \times 120 \, nm$. The beam charge, peak current and brightness are $230 \, pC$, $27 \, kA$ and $3.8 \times 10^{18} \, A/\text{rad}^2\text{m}^2$, respectively. Thus there appears to be a trade-off between the drive beam charge and the trailing beam brightness that is counter-intuitive and calls for experimental investigation.

How will such an experiment be realized at FACET-II? The $5 \, nC$ beam used in the first simulation is capable of field-ionizing hydrogen gas, but a $1 \, nC$ beam will require a laser-ionized column of hydrogen. At the upstream end of a tube of hydrogen at the appropriate pressure we will place a thin gas cell containing higher
pressure gas with an approximately 200 micron entrance and exit holes to create the necessary density ramp. [10,11] Such cells have been successfully used in injector- accelerator experiments done with intense laser pulses. The beam trapping preferentially occurs in the down-ramp and the electrons are then accelerated in the accelerator portion of the wake excited in the approximately 30 cm long ionized gas column in the downstream tube. The attraction of this method is that it is simple and in principle jitter free. The emittance, energy and charge of the accelerated beam can be measured by changing the length of the tube and the scale-length of the density ramp. If this technique can be perfected it will give beam emittances that are smaller than those achieved by state-of-the art methods.

![Figure 2-5](image)

**Figure 2-5:** Simulation results of density down ramp injection with a 1.1 nC, $10 \times 10 \times 10$ μm beam driver. (a) electron density distribution (b) x2-p2 phase space of the total bunch. The unit simulation length in this figure is 1/3 micron. (Courtesy Fei Li and Wei Lu, Tsinghua University & UCLA)

### 2.1.3.2 Electron Injection by Transversely Colliding Laser Pulses

Generation of low emittance electron bunches will be tested at FACET using the so-called Trojan Horse scheme, [12] wherein a longitudinally co-propagating laser pulse ionizes and injects electrons inside an electron beam driven wake. At FACET-II we propose to test a variation of this scheme that has the potential to generate the highest brightness beams to-date. [13] We call this the transversely colliding laser injection method. Here ultra-bright electron bunches are produced using ionization injection triggered by two transversely colliding laser pulses inside a beam-driven wake. The relatively low intensity lasers are polarized along the wake axis and overlap with the wake for a very short time. The result is that the residual momentum of the ionized electrons in the transverse plane of the wake is much reduced and the injection is localized along the propagation axis of the wake. This minimizes both the initial “thermal” emittance and the emittance growth due to longitudinal phase mixing. This concept can be successfully tested through 3D particle-in-cell (PIC) simulations. In Figure 2-6 we show the injection process of helium electrons by two colliding laser pulses in a wake formed in a partially ionized He plasma by an electron beam. We show that ultra-short (~8fs) high-current (0.4kA) electron bunches with normalized emittance of 8 and 6 nm in the two planes and brightness greater than $1.7e19$ Amp rad$^{-2}$ m$^{-2}$ can be obtained for realistic parameters.
The transverse colliding pulse is inherently more complex than the density down ramp injection. We now have to deal with femtosecond synchronization of two laser ultra-short laser pulses that must overlap with one another within a micron inside the wake. In either scheme electrons will be accelerated to multi-GeV levels within roughly 10 centimeters. How will one measure the emittance of such a beam? Perhaps the most conclusive demonstration that the beam has a brightness exceeding $10^{19}$ Amp rad$^{-2}$ m$^{-2}$ will be to send this beam through a section of the LCLS undulator and measure SASE gain. This is currently being studied through integrated PIC and FEL simulations.

![Figure 2-6: Snapshots from PIC code simulations illustrating the transverse colliding pulse injection of helium electrons into the ion cavity. Snapshots (a) to (c) show the charge density distribution of driver beam, wake electrons and helium electrons at three different times (a) ~80fs before laser pulses collision (b) around laser pulses’ collision time (c) ~200fs after collision when the injected electrons become trapped in the wake. (Courtesy Fei Li and Wei Lu Tsinghua University & UCLA)](image)

### 2.1.4 Determining the repetition rate of a single module for stable operation and staging of two PWFA modules.

The repetition rate requirements of a future PWFA depend on the application. [14] For instance a PWFA-based X-FEL may operate at one kHz whereas a future linear collider may need to operate at 10 kHz with a CLIC-like drive bunch structure. Different drive beam train formats can be tested at FACET-II to see what ultimate repetition rates are acceptable. FACET-II will have high charge bunches compared to FACET which means that we can probably operate with field-ionized plasmas of noble gases which can be flowed and replenished in between shots. This could be tested at FACET-II.

The staging of two PWFA modules is a far more challenging problem. Any misalignment between the drive beam in the second stage and the accelerating beam from the first stage will lead to strong radiation loss and emittance growth. [15] This problem will have to be addressed at some point and engineering solutions will have to be developed.
2.1.5 Summary

The PWFA program on FACET-II will seek to demonstrate a high efficiency, high transformer ratio PWFA stage that gives a 20-30 GeV energy gain while generating an electron beam with high charge, low energy spread and low transverse emittance. While working towards this goal we will develop new beam injection and diagnostic techniques. We have considered two new injection schemes that allow for the full use of the FACET-II drive beam, as opposed to current experiments that require spoiling the FACET drive beam. One is to use the natural injection that occurs in a density down ramp and the other is to use active injection via counter-propagating laser pulses. Repetition-rate limitations have not yet been addressed in any plasma wakefield experiments. High-efficiency transfer of drive-beam energy to the trailing beam will likely be necessary for high luminosity colliders. Additionally, particle-beam-ionized plasmas can be rapidly replenished via laminar flow of fresh gas on a tens of kHz time scale. FACET-II possesses unique capabilities that will enable these studies.

2.2 Physics of positively charged drive beams for PD-PWFA

2.2.1 Motivation for CERN Experiments with Protons

LHC proton bunches are the only plasma wakefield drivers that carry enough energy to produce an ILC type electron or positron bunch in a one or few plasma stage. Existing laser pulses and electron particle beams do not carry enough energy. ILC bunches of 2x10^{10} particles at 1TeV carry about 2 kJ. For reference, an LHC bunch at 7TeV and with 10^{11} protons carries over 100kJ. Protons also have a large mass, can have a very high energy (~TeV/p^2) and are so “stiff” that bunches can propagate over many meters of plasma without significant transverse size change. Therefore, a large average accelerating gradient (1GeV/m or more) could be sustained over the entire acceleration length without suffering from the gradient dilution arising when staging is required [16]. Gradient dilution occurs because of the drift distance necessary between stages to seed the next drive bunch into the next plasma section and to capture and re-focus the witness bunch. It can vastly exceed the length of each stage and drastically decrease the average accelerating gradient.

Operating at lower peak gradient also means at lower plasma density since the maximum accelerating field increases with the square root of electron density (that is, \( E_{\text{max}} \approx n_e^{1/2} \)). This also means that the size of the accelerating structure or plasma density perturbation is larger, as both scale with the inverse square root of electron density (in 3D, \( \approx \lambda_{\text{pe}}^{3} \approx (n_e^{-1/2})^3 \)). This reduces the requirements in bunch longitudinal and transverse (focusing) compression (\( \sigma_r, \sigma_z < \lambda_{\text{pe}} \)) and in temporal and spatial alignment. Matching of the bunch transverse size to the weaker plasma focusing field (\( E_r \)), which scales with the plasma density is easier since the matched size also increases with decreasing density (\( \sigma_r \approx n_e^{1/4} \)). This is true even for very low emittance bunches.
2.2.2 PD-PWFA Physics experiments at SLAC with electron and positron bunches

Short proton bunches, on the order of 100 µm, are suitable for driving wakefields with large amplitude (1GV/m or more), but these are not currently available. Initial experiments will be performed around 2015 at CERN with longer bunches in the self-modulation instability regime. [17] These experiments use bunches of length $\sigma_z=12$cm with plasma wavelength $\lambda_{pe}=1.5$mm.

High energy (~20 GeV) positron bunches are much less “stiff” and can self-modulate in only a few cm whereas CERN SPS proton bunches (~450 GeV) need meters of plasma.

In addition, it is well known that plasmas respond very differently to negatively and positively charged particle bunches. This was clearly demonstrated in the PWFA experiment performed at the SLAC FFTB. [18,19,20] Even in the self-modulation regime, plasma behavior is quite different as soon as the nonlinear, high-gradient regime is reached, as was demonstrated in numerical simulations (see Figure 2-7). [21]

Figure 2-7: Electron (top) and positron (bottom) bunch density after propagation of 10 cm (left) and 1 m (right) plasma with a density of $2.3\times10^{17}$cm$^{-3}$. 

Figure 2-8: Plasma density perturbation driven by a short (σ=100 µm) and wide (σ=430 µm) proton bunch. The proton bunch density is indicated in red while the witness electron bunch to be accelerated is shown in black.

Short positron bunches can be produced at SLAC and are therefore the ideal candidate to test the concept of a PWFA stage driven by a, positively charged bunch shorter than the plasma period. In particular, the transverse evolution of the drive bunch along the plasma is a concern since there is no equivalent of the bubble regime that exists for negatively charged particle bunches. Simulations indicate that positively charged bunches need to be shaped like pancakes, in contrast to the pencil shape of electron bunches, in order to drive wakefields towards the blowout regime (see Figure 2-8). [22] In addition these simulations also indicate the real blowout is difficult to reach. This could lead to emittance growth of the accelerated witness bunch. The conditions appear to be much less favorable for positively charged bunches than for negatively charged bunches in the self-modulated PWFA regime (see Figure 2-7). Simulations clearly show that the loss of drive particles along the plasma is significantly larger with positively charged bunches. This leads to lower wakefield amplitudes and larger dephasing between the wakefield structure and the drive bunch and thus also with the accelerated bunch. The situation seems worse when approaching the nonlinear PWFA regime.

One to one comparisons between the case of an electron and a positron bunch could clearly show these differences and help in determining an optimum regime of operation with short, positively and negatively charged bunches. This difference will be evidenced by measuring the energy loss and gain by drive bunch particles, as well as by measuring the drive bunch self-modulation. In addition, the availability of a short, trailing electron bunch to witness the wakefields with a variable delay with respect to the drive bunch will be a great asset.

Simulation of the self-modulation PWFA regime is much more challenging than that of the short bunch PWFA regime and numerical codes have not been benchmarked against experimental results.

The availability both electron and positron bunches long and short would definitely give access to a number of PWFA regimes that have never been accessed before, which will drive new discoveries in PWFA physics. Existing plasma-based PWFA designs (see section 2.1) use electron beams to drive the wakefields. In order to create a next-generation electron/positron collider we need to be able to accelerate the positron bunch directly.

Therefore the availability of a witness bunch, whether electron or positron, with independently controllable parameters, would greatly enhance the relevance of the results to advanced accelerators. The actual acceleration of a witness bunch with a bunch length well below the plasma wavelength could be directly tested, both in the self-modulated and in the short bunch PWFA regime. In particular, we could test the acceleration of a positron bunch in the wakefields driven by an electron bunch. This is the favored scheme for the acceleration of a positron at high-gradient in a plasma. However, no clear parameter set that can produce a high quality positron bunch
exists. The availability of a facility to test this scheme would no doubt generate the new and original ideas needed.

The availability of an electron witness bunch produced by an RF photo-injector gun would allow for exquisite and independent control of the witness bunch parameters (charge, length, timing, and transverse size), a required condition for the demonstration of beam loading producing narrow final energy spread and for optimization of the energy transfer efficiency.

Results with a positron drive bunch would bring early and important results relevant to the longer-term plans with a proton bunches as a driver. Producing suitable, short proton bunches will require very significant efforts and maybe even the design of a dedicated circular machine. Therefore establishing the physics of this scheme with positron bunches will validate this ambitious and important scheme.

2.3 PWFA Based on High Brightness Photoinjector-derived Electron Beams

In this section, we summarize the new physics that is made possible by the introduction of very high brightness electron drivers in PWFA experiments. The scenarios presented take advantage of the improved compressibility of photoinjector beams, particularly at low charge, as well as superior focusability of low emittance systems. These attributes permit three new experimental initiatives in FACET-II: teravolt-per-meter plasma wakes with ultra-short beams; ion motion experiments (with associated implications for fusion physics); and exploration of the quasi-nonlinear regime of the PWFA. We now recount briefly the case for investigating each of these topics at FACET-II.

2.3.1 TV/m PWFA Using Femtosecond Beams

Scientists have recently proposed using low charge ($Q$), in the pC range, as a path to achieving GeV-class beams that may be compressed down to hundreds of attoseconds. [23] Further, these beams are predicted to have very low transverse emittance, and thus unprecedented brightness. This proposal [24] addresses two challenges in the x-ray SASE FEL. It breaches the fs frontier in x-ray pulse length, and should also allow single-spike x-ray SASE FEL. [25] Both features are critical for resolving properties of atomic and molecular systems at the spatial and temporal scales relevant to electronic motion. Low charge operation is therefore important for advancing both FEL capabilities and fundamental beam physics.

Recent experimental work at the SLAC Linear Coherent Light Source (LCLS) focused on generating compressed beams with short pulses. In initial tests, 20 pC beams were compressed to rms duration $\sigma_t \approx 2$ fs, while achieving transverse normalized emittances of $\epsilon_{n,x} = 0.14 \, \mu$m and $\epsilon_{n,y} = 0.4 \, \mu$m at an energy $U_b = 14$ GeV. This beam, having high peak current, $I\sim$8 kA, and low emittance is predicted to produce nm-wavelength FEL pulses in the single-spike regime. [26] We propose to use similar beams at FACET-II to generate an extremely high field PWFA.
Beams having short duration can produce coherent excitations with frequency components up to a cut-off of $\omega_m \sim \sigma_z^{-1}$. Further, in the context of PWFA, as with all Cerenkov-class interactions, the amplitude $E$ of the radiated field scales as $E \propto N_b \omega_m^2 \approx N_b / \sigma_z^2$, where $N_b$ is the number of particles in the beam. To maximize the wake amplitude, the maximum excitation frequency must equal the plasma frequency, $\omega_m = \omega_p$, giving the optimization condition $\omega_p \sigma_z \approx 1$. This scaling has been investigated experimentally, [27,28] theoretically and computationally, [29, 30] and its validity in application even in the nonlinear “blowout” regime [31] is well understood. PWFA operation in the blowout regime is desired, as the plasma electrons are all evacuated from the beam channel, producing acceleration dependent only on longitudinal position $\xi = z - v_b t$ in the beam channel, where $v_b \equiv c$ is the beam $z$-directed velocity. Further, the nominally uniform ion density makes focusing linearly dependent on radial position $r$ relative to the beam axis. Both of these attributes of the wake forces are deemed necessary for producing high quality beams with the phase space density demanded by advanced applications in high-energy physics and at x-ray FELs.

For the LCLS 20 pC beam scenario, $\omega_p \sigma_z \approx 1$ yields a plasma electron density $n_0 = \left[4\pi r_c (c\sigma_r)^2 \right]^{-1} \approx 7.8 \times 10^{19} \text{ cm}^{-3}$ corresponding to a gas density of several atm.

We can estimate whether this case accesses the blowout regime by evaluating the ratio of beam electrons to plasma electrons found within a volume of a cubic plasma skin-depth ($k_p^{-1} = c / \omega_p$), $\hat{Q} = N_b k_p^3 / n_0 = 4\pi k_p r_c N_b$. [29] In our case we have $\hat{Q} = 7.4$; a value exceeding unity indicates the blowout regime may be achieved. To access the blowout regime we must also focus the beam to a rms size $\sigma_x$ smaller than a skin-depth, $k_p \sigma_x \ll 1$. The self-consistent equilibrium beam size in the plasma arising from PWFA ion focusing is a function of the equilibrium $\beta$-function, $\beta_{eq} = \sqrt{2\gamma / k_p}$ as $\sigma_{x,eq} = \sqrt{\beta_{eq} \gamma / \pi}$. For our current parameters, $\beta_{eq} = 140 \mu m$ and $\sigma_{x,eq} = 45 \text{ nm}$, and thus $k_p \sigma_x = 0.075$. The beam density associated with this extremely bright beam in the dense plasma is $n_b = 6.5 \times 10^{31} \text{ cm}^{-3}$, giving $n_b / n_0 = 84$, a highly nonlinear blowout scenario. To gauge the strength of the plasma wakes in initial particle-in-cell (PIC) simulations we use a slightly initially mismatched injected beam, to $\sigma_z = 77 \text{ nm}$ ( $n_b / n_0 = 28$). These simulations were carried out using the 2D EM PIC code OOPIC, [32] with the predictions for the longitudinal plasma wake $E_z(r, \xi)$ shown in Figure 2-9. This simulation produces unprecedented large fields, in excess of 1.3 TV/m. This field amplitude is also remarkable in that it is enormous even by internal atomic physics standards. Indeed, the collective field such beams can readily ionized matter, thus allowing both plasma formation, and a unique probe of atomic physics in an extreme field limit. The size of $E_z$ is not surprising, however, in that the fields at the beam edge before the plasma entrance is estimated as $E_{r,\text{max}} = eN_b / 2(4\pi)^{1/2} \epsilon_0 \sigma_x \sigma_z = 1.5 \text{ TV/m}$; the maximum transverse field is roughly transformed to longitudinal field amplitude by the plasma response.
To produce the conditions for plasma creation and optimum plasma wake formation, we must implement an appropriate focusing scheme. Further, in order to consider implementing this experiment in a spatially-limited region such as FACET-II, we should make the focusing system as compact and easily implemented as possible. We may base the mini-β optics on an ultra-high field gradient system based on permanent magnet quadrupoles (PMQs), similar to that developed for previous UCLA experiments on inverse Compton scattering. [33] This system, tunable by repositioning of quadrupoles, can achieve quadrupole gradients of over 700 T/m and has the further advantage of evading restrictions on performance due to geometric and chromatic aberrations without requiring complex sextupole correction schemes. With the PMQs arranged in a modified triplet configuration, [33] ELEGANT simulations [34] indicate that we can focus the beam to $\sigma_z = 130$ nm. This size is well suited for injection into the plasma, with a final β function of 1.2 mm. While this beam size is not matched to the plasma focusing, it is small enough to ionize the gas, and enter into an adiabatic focus, as shown in Figure 2-10.

The bare (no plasma) beam is compelling, as this beam allows electric field levels possibly at high as 100 V/Å, into the range that accesses the barrier suppression ionization (BSI) regime [35] in a wide variety of atomic species. This implies that the field strength at FACET-II will make it easier to create the desired plasma using the electron beam. In previous experiments at FACET that employed over an order of magnitude smaller fields, plasma formation was attributed to tunneling ionization [36, 37, 32]. Accessing BSI is an exciting possibility—a highly focused, multi-kA beam in and of itself is new instrument for performing fundamental atomic physics investigations. We will be able to use the very intense beams at FACET-II to expand upon existing research programs, such as the ultra-fast magnetic switching studies currently active at FACET, and study phenomena that have thus far been inaccessible.
As a practical rather than fundamental concern, the self-consistent ionization of a high pressure gas by the beam fields must occur within hundreds of attoseconds to create the plasma within the appropriate time scale to allow the full amplitude plasma wakefields to develop. The UCLA PBPL team studied this computationally and theoretically and found it to be practical with the final focus discussed above. The method is straightforward using Li gas, and is possible even in hydrogen. [38]. It should be noted that with beams well below optical wavelengths in dimension, all signals from beam profile monitors are coherent, and coherent imaging techniques should be embraced.

2.3.2 Ion Motion in High Brightness Beam Drivers

The condition \( n_b > n_0 \) is a defining characteristic of the blowout regime. Indeed, as seen above, the density of the high brightness driving beam in a PWFA may exceed \( n_b \) by several orders of magnitude. Under these circumstances, the beam’s electric field can produce relativistic plasma electron motion. [39,40] Additionally, this electric field is high enough that the ions may move significantly during the beam passage. For the parameters given by S. Lee, et al.,[41] and quoted by Raubenheimer in his discussion of the implementation of a PWFA “afterburner” to boost the energy of a linear collider (LC) by at least a factor of two, [42] the ions can collapse towards the beam axis, causing a large, non-uniform ion density spike within the beam. This ion collapse has disastrous implications for preserving the transverse emittance of the accelerating beam, effectively negating the oft-claimed advantage of linear transport in the blowout regime. Thus the issue of ion motion is of critical importance in evaluating the viability of using the PWFA in a collider and other high brightness beam applications. [43]

The theoretical and computational analysis of the ion collapse problem has been performed at UCLA PBPL. [44] The phenomenon of ion collapse in the PWFA can be viewed in several useful ways. First, it is a form of wakefield, with as direct as possible coupling between the beam and its environment, in this case plasma.
electrons and ions that lie in the beam path. The fact that linear collider beams are of unprecedented density (similar to solid matter) means that they act as a high energy density driver of plasma motion. As such, the study of physical effects associated with plasma wakefields in such extreme scenarios represents an unprecedented opportunity in high field plasma physics. This frontier opens up a new application to an unrelated field, as the ions are simultaneously heated and confined by the application of the beam focusing fields. Thus, with appropriate choice of ionized species (i.e. deuterium and tritium), we may envision an alternate scenario for creating fusion-relevant plasma conditions.

Figure 2-11: Surface plot of ion density distribution, as simulated by OOPIC showing increase in \( n_i > 200 \) due to ion collapse (from Ref. 20)

To create the conditions for ion collapse at FACET-II, we concentrate on a large-charge scenario with the following beam parameters: \( Q = 3 \) nC, \( \varepsilon_{n,x} = 3 \) \( \mu \)m, with moderate compression to \( \sigma_z = 0.2 \) ps (\( \sigma_z = 60 \) \( \mu \)m). Using \( \omega_p \sigma_t \equiv 1 \) we have a relatively low plasma density, \( n_0 \equiv 8 \times 10^{15} \text{cm}^{-3} \), and a total phase advance for small amplitude ion oscillation in the beam’s potential well of

\[
\Delta \phi = \sqrt{\frac{Z_r n_b \sqrt{2 \pi \gamma}}{A \varepsilon_{n,x}}} = \sqrt{\frac{Z_r n_b}{A \varepsilon_{n,x}} (2 \pi \gamma)^{1/4}} \approx \frac{\pi}{2}.
\]

This phase advance indicates that the ions indeed focus inside of the driving beam. The first observable consequence of this ion collapse, which is illustrated in Figure 2-11, is that the transverse emittance of the trailing part of the drive beam increases dramatically.

Ion focusing not only may concentrate the ions, it may impart to them a large kinetic energy, thus providing temperatures similar to those in fusion plasmas. The maximum energy may be estimated from the potential at the beam’s edge to be

\[
q \Phi_{max} = \frac{Z_r n_i m_n c^2}{2 \sqrt{2 \pi \sigma_r \sigma_z}} r_{\text{beam edge}} \approx \frac{Z_r n_i m_n c^2}{2 \sqrt{2 \pi \sigma_z}}.
\]
For our parameters, this indicates that we may achieve energies near to 100 keV in a deuterium plasma, which is adequate for achieving D-T fusion. We may observe these particles in fusion events by allowing them to collide with a tritiated wall, for example, or by using an electrostatic energy analyzer. If we wish to confine the ions for a longer time ($\Delta \phi \gg 1$) we can utilize a higher density gas, with density on the order of TV/m. Then, by increasing $n_0$ by a factor of 10,000, the phase advance for ion oscillations is augmented by a factor of 100. In this case, the ion temperature achieved is expected to be nearly the same, in the range of 100 keV, as can be deduced from the expression for the potential given above.

### 2.3.3 The Quasi-Nonlinear Regime of the PWFA

The original form of PWFA proposed exciting wakefields through the use of relativistic electron bunches, which induce a small density perturbation in the plasma. Using the linearized equations of motion, continuity and Maxwell’s equations, one can readily discern the basic dynamics of PWFA in the linear regime. While the simple harmonic plasma response allows the wakefields to be driven resonantly, a small density perturbation implies that plasma electrons persist both within the volume of the driving bunch and in the beam (driving and accelerating) region. Consequently, the fields experienced by the beams are non-ideal in both the radial and longitudinal directions. In the blowout regime of PWFA, as noted above, a high intensity beam excites nonlinear plasma oscillations, having amplitude-dependent period, and thoroughly evacuates a bubble of its plasma electrons leaving behind only the ions, with associated (up to the onset of ion motion) excellent quality transverse and longitudinal fields. These distinct advantages, however, come at the expense of a nonlinear plasma response that does not permit, for example, the use of pulse trains in future linear colliders [27].

![Figure 2-12](image)

**Figure 2-12** (Left) Plasma electron spatial ($r,z$) response to a 4-beam pulse train with each beam having $Q^* = 0.11$, separated by $\sigma_r = 190 \mu m$, and (right) the associated longitudinal electric fields.

In order to envision large total charge acceleration needed for linear colliders, we must consider how to achieve blow-out while maintaining a resonant plasma
response. Such a regime is accessed with high brightness beams, by restricting pulse trains to a total charge where $\tilde{Q}<1$. With very low emittance beams, the beam density may permit blow-out conditions to be accessed even with low $\tilde{Q}$. This scenario is termed the quasi-nonlinear regime, and is the subject of large theoretical [45] and experimental [46] interest, with first experiments now commencing at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory. We show an example of quasi-nonlinear operation in Figure 2-12, in which a 4-pulse train with a periodicity equal to the linear plasma period resonantly excites a wave. This mode produces total plasma electron rarefaction in the region around the beam, similar to the blowout regime. In this case the normalized charge is 0.44, we have a constant plasma period of 190 µm and beam charge per pulse is 16 pC. This is indeed an experimental design regime of interest to FACET-II. We can apply pulse-train chopping techniques to a photoinjector-enabled FACET-II (see Section 3.3.3) to create these high brightness, low emittance, and relatively low charge beams. [47] The additional energy in the beam, and the ability to access shorter beam dimensions give FACET-II a large advantage over the present ATF configuration.

2.4 Trojan Horse Under dense Photocathode PWFA and follow-up applications

2.4.1 Introduction

Plasma acceleration at FACET aims for both maximized energy gain (e.g., in the E-200 experiment) as well as for dramatically increased beam quality, stability and tunability (E-210 experiment). These experiments and other advanced hybrid LWFA/PWFA strategies require a high-power laser system capable of ultra short, high-intensity pulses for preionization of the plasma, and highly controllable electron release in the wakefield to enable pump-probe measurements and many other applications.

At FACET, therefore, a ~10 TW, ~50 fs laser system is currently being installed. However, the synchronization obtainable at FACET at the interaction point between electron bunch and laser pulse will be several hundreds of femtoseconds, mainly because of the thermal cathode and the large compression factor of the electron bunch. Such a jitter is unacceptable for many advanced experiments.

Installing a photoinjector and a high-power laser system at FACET-II would improve the expected jitter between electron bunch and laser pulse to probably less than 50 fs. Many experiments would profit greatly from such a reduced jitter, and others would become feasible in the first place. The proposed system would have potentially much higher maximum beam density and connected radial fields, allowing for extended self-ionization studies and extended acceleration lengths.

2.4.2 Advantages of excellent synchronization between electron beam driver from photocathode and low-energy Ti:Sapphire laser beam (~100 µJ)

One experiment that would profit massively from improved synchronization would be E-210, “Trojan Horse Plasma Wakefield Acceleration”, whose name alludes to the ancient tale where the Greek soldiers are hidden in the horse's belly. This
experiment depends on the strongly localized release of electrons inside a beam-driven plasma blowout. This localized release is done by focusing a co-propagating laser pulse to an intensity slightly above the ionization threshold of an additional gaseous component (for example, helium in a lithium plasma oven or the second ionization level of rubidium in a rubidium oven). Therefore the electrons would be released only in the arbitrarily small focal region of the laser pulse. Since this laser pulse only needs a maximum density of the order of \(10^{14-15}\) W/cm\(^2\) in order to ionize this component, the electrons receive a very limited transverse kick by the transversely oscillating laser fields. At the same time, the electrons are accelerated in GV/m electric plasma fields in the forward direction, which results in transversally extremely cold electrons with minimized transverse emittance down to the unprecedented level of \(10^{-4}\) µm. This would constitute a breakthrough in plasma acceleration, for the first time providing electron bunches with much better beam quality when compared to state-of-the-art accelerators based on conventional technology.

The release position of electrons by the photoionization laser relative to the plasma wave determines the trapping point inside the plasma wave and therefore the electron witness bunch parameters after the acceleration. Therefore, the synchronization between the driver electron bunch and the release laser pulse should be as good as possible. It is expected that with a photoinjector and smaller compression factor the jitter between laser pulse and driver electron bunch will be much better at FACET-II as compared to FACET. At the same time, the duration of the witness electron bunch, and consequently the energy spread of the witness bunch electrons, is strongly dependent on the laser pulse duration. Therefore, the laser pulse should be as short as possible. Fortunately, the controlled release of electrons requires a laser pulse energy of only \(\sim 100\) µJ. At such energy levels, laser pulse compression to the sub-10-fs level (e.g., in a gas-filled hollow fiber via group velocity dispersion) is relatively easy.

### 2.4.3 Advantages of high-density electron beam driver from photocathode

In addition to laser pulse duration and synchronization, the characteristics of the driving electron beam are important for the Trojan horse scheme. At FACET, the electric self-fields of the electron bunch are barely high enough to self-ionize low-alkali metal vapor media such as rubidium and lithium. The parameters eventually obtainable at FACET-II at the interaction point (i.e. 6 nC, 10x10x20 µm beam size) allow the maximum radial self-fields of the driver bunch to approach an estimated 100 GV/m. Such unprecedented values would be enough to overcome not only the first ionization thresholds of alkali metal vapors (~5 eV), but also those of a variety of other gases such as hydrogen, nitrogen, oxygen, CO\(_2\), etc. Therefore, independent of the specific requirements for the Trojan horse scenario, self-ionization and other phenomena could be studied in an unprecedented parameter range. For the specific Trojan horse scenario, such large electric self-fields of the driver beam would allow for testing and optimizing the Trojan horse scheme in a fully gaseous environment at ambient conditions. For example, instead of having to use alkali metal vapors, we could use hydrogen as the beam-ionized, beam-driven plasma wave medium, and
helium as the gas to be released by the injection laser pulse. Working with species that are gaseous at ambient conditions would be highly beneficial from an engineering point of view, since the optical access is easy. The gas may be contained in a glass container at room temperature, whereas alkali metal ovens need a temperature of many hundreds of Kelvin, water cooling, and a buffer gas, which prohibits easy optical access. These studies are directly relevant to future scenarios where electron bunches from laser-wakefield accelerators would be used as driver electron beams, and a small split-off fraction of the main laser pulse would be used to release the electrons in the electron beam driven wakefield. Such future systems have the inherent advantage of synchronization to the femtosecond level.

2.4.4 Advantages in case of a Joule-class (>10 TW) Ti:Sapphire laser beam

A high-power (> 10 TW) laser system would further allow for preionization of the low-ionization threshold component. This would decouple the acceleration process from the ability of the driver bunch to self-ionize the plasma medium. We could preionize not only alkali metal vapors, which are hard to access due to the geometry of the plasma oven, but also media which are gaseous at ambient conditions. For example, we could preionize hydrogen with the preionization laser pulse, and ionize helium with the release laser pulse. The mixture of hydrogen and helium could be stored in a glass vessel, which allows for easy access by the laser pulses, and for probing and diagnostics. In this configuration, the preionization laser pulse would ionize the helium gas a few ps before the electron beam arrives, and the release laser pulse would hit and ionize the helium gas a couple of tens of fs after the electron beam. In this configuration, it would be possible to study the Trojan horse process when the electron beam density is much weaker than in the self-ionization case. Also, it is possible to extend the total acceleration length (and thus the energy gain) by having the electron beam self-ionize during the first part of acceleration, and then have the laser pulse take over ionization in the latter part of the acceleration, where the electron beam may drop below the self-ionization threshold due to head erosion, pulse scalloping and other effects.

A high-power laser pulse capable of driving a plasma wave by itself could further be used to boost the energy of the electron beam coming from the photocathode. Such an external injection and energy boost process would be most effective at lower electron energies (i.e., at a couple of hundreds of MeV instead of 10 GeV).

Further, a high-power laser pulse could be used for Thomson scattering. The ultralow emittance of the witness beam generated by the Trojan horse process would allow for extremely large beam brightness, which could be exploited in Thomson scattering schemes, where the high-power laser pulse would scatter with the electron witness beam.

2.4.5 Further scenarios and light source experiments

A currently discussed scenario for FACET-II is to ramp up the energy of the electron beam in several major radiofrequency-cavity based stages. The first would accelerate to 200 to 250 MeV, the second to 4 GeV, and the final to above 7 GeV and
possibly as high as 10 GeV. In any case, studies on Trojan horse acceleration could potentially be done after each of these stages, shown in Figure 2-13. Note that while in reality, the facility setup has to be strictly linear, in the figure the three stages are drawn next to each other to indicate that in principle we may be able to insert R&D sections after each stage.

A 200-250 MeV, high-density electron bunch would be sufficient to drive a plasma wave in a low-ionization threshold medium over a limited distance, and a low-energy laser pulse could then release electrons in that plasma wave. However, since the electron energy of 250 MeV is moderate, a 10 TW+ LWFA stage could be used to substantially boost this energy to the ~1 GeV level. Then, the boosted bunch could be used as a PWFA driver in the Trojan horse stage (see 250 MeV arm of Figure 2-13). Since such a bunch with relatively high charge would be produced to generate a Trojan horse witness electron bunch with much lower charge, this witness bunch may gain several GeV of energy. The witness bunch could then be used to power a cryogenic undulator, such as the one which is currently used at the NLCTA in order to directly make use of the expected excellent witness bunch’s emittance. [49] In turn, the output of the undulator could be used to definitively measure such unprecedented emittance. There may be space limitations after the first accelerator stage in the final version of the facility which would not allow us to implement a Trojan horse/LWFA booster/undulator stage. On the other hand, in case of limited funding to build FACET-II up to the 10 GeV level, we would still be able to do substantial R&D on Trojan horse E-210 follow-up experiments at 250 MeV.

**Figure 2-13:** Sketch of potential Trojan horse R&D at FACET-II

At around 4 GeV, there would be no need to implement an LWFA booster stage. We would directly be able to conduct E-210 follow-up R&D with a beam at this energy level. While it is not shown in the figure, this stage is also attractive for Thomson scattering with a high-power laser pulse.
Note that the figure, for reasons of simplicity, does not depict the preionization laser beam, which would be highly desirable to preionize PWFA stages.

At the highest driver beam energies of 10 GeV, potentially the electron energy and flux of the driver beam and the witness beam may already be too high to use an undulator for free-electron-laser x-ray generation due to potential material damage in the undulator. A Thomson scattering light source, however, could be realized here after the Trojan horse stage.

2.4.6 Summary

The combination of photoinjector gun and accelerator, synchronized with a Ti:Sapphire short-pulse laser beam (30 fs, ideally less) will be ideally suited to do extended research in the context of follow-up experiments to the E-210 Trojan Horse Underdense Photocathode Plasma Wakefield Acceleration experiments. Such research at FACET-II is highly promising, since the scheme may enable the production of electron beams with highest tunability and stability, bunch durations down to the sub-fs regime and normalized emittance down to $\epsilon_n \approx 10^{-4} \mu m$. One of the most intriguing applications of such a hybrid accelerator system would be to power a free-electron-laser, potentially allowing for a performance much better than at the LCLS.

The following requirements are Essential for such research: an electron beam driver generated by a photoinjector, an electron energy of > 200 MeV, a beam density after compression such that the electric self-fields exceed 10 GV/m, and a synchronized laser pulse at the 30 fs, 100 µJ level.

Other features are Highly Desirable. These include an electron energy up to 10 GeV, a beam density with self-fields up to 100 GV/m, and excellent synchronization between the electron driver beam and the laser pulse. This laser pulse would be used for preionization and/or for electron witness bunch production, and therefore should have the smallest possible pulse duration, at least for the low-energy µJ-level arm. It could also be used for laser wakefield acceleration to boost the incoming electron beam energy from the photo gun prior to Trojan horse stages, which would further connect the FACET-II to laser wakefield acceleration groups worldwide.

2.5 Dielectric Wakefield Acceleration at FACET-II

Recent studies at Argonne, Brookhaven and SLAC have focused on large amplitude wakefields driven in dielectric structures. The primary applications focus on high-gradient dielectric wakefield acceleration (DWA) with other applications in. beam energy chirp mitigation for future FEL application, and developing high-power, narrowband, tunable sources of THz radiation. Relevant, outstanding issues in DWA research include the determination of a working parameter space for this technology such as structure material and geometry optimization, effects of transverse modes and beam-break up, 1D- and 3D-periodic structures for enhanced mode confinement, and, ultimately, demonstration of high gain in acceleration through a passive dielectric lined structure.
The UCLA-led E-201 collaboration (2011-) at SLAC FACET is pursuing studies covering several of these key issues. The experimental program includes a careful parameter optimization of materials (e.g. SiO₂, sapphire, diamond, alumina) to explore and identify the limits and causes of dielectric breakdown at high fields. These materials exhibit low loss tangents in THz frequencies and can thus accommodate large fields before the onset of breakdown effects. We are studying other geometries such as 1D-periodic claddings (i.e. Bragg-like alternating dielectric materials) and fully 3D photonic-like structures for enhanced mode confinement and higher breakdown thresholds compared to purely metallic boundaries. Finally, we have developed advanced autocorrelation techniques to fully characterize the modal content of the structures using the emitted coherent Cherenkov radiation (CCR) as a diagnostic. The emitted CCR also has proven useful as a powerful, tunable THz source.

The E201 experimental program has a well-defined scope of goals to address issues in ultrahigh-gradient DWA studies today, but there are a number of open questions in the field that are not readily addressable given current electron beam limitations at FACET. These include the demonstration of high gain in acceleration, the investigation of shaped drive bunches for enhanced transformer ratios, and the exploration of beam breakup and acceleration in long structures. In order to begin to address these issues in detail, the current beam constraints, notably in beam emittance and lack of drive beam parameter flexibility, must be overcome.

The viability of a dielectric structure as a future driver for compact free-electron lasers (FEL) or colliders lies in the ability to demonstrate high-gradient DWA. The proposed parameter space of FACET-II allows such investigation of high-gradient fields. First, the ability to create a drive-witness beam pair with variable chirp and delay will allow the clear observation of acceleration. Second, the ability to shape the drive bunch (e.g. triangular ramp or multi-pulse) with a readily adaptable beam will allow the exploration of enhanced transformer ratios. Third, the photoinjector quality beam with low emittance and small spot sizes will permit the use of long structures. The effects of beam breakup due to transverse mode excitation in long structures can be investigated. Long structures also allow achieving higher energies in acceleration. Finally, the improved beam quality will permit the study of advanced 3D-photonic bandgap-like structures which have smaller beam gaps and tighter tolerances on input beams. The accelerating gradients benefit from the scalability of the wakefields with smaller dimensions of the beam. The fields are proportional to the beam charge divided by the wavelength squared, and the wavelength of the mode scales with beam dimensions. This will also allow the exploration of low emittance, low charge regimes where GV/m are more readily achieved. This exploration is also synergistic with laser-fed accelerator structures, which also demand low emittance, low charge drive beams.

### 2.5.1 Introduction to DWA

The DWA typically consists of a dielectric lined waveguide and a relativistic electron beam (drive beam) that generates a wakefield in the medium (Figure 2-14 shows a cylindrically symmetric configuration of a DWA structure). A trailing particle bunch
(witness beam) can sample the wakefield and gain or lose energy depending on its phase (or delay) relative to the drive beam. The peak accelerating gradient is determined by the bunch charge, bunch length, bunch size and properties of the dielectric lined waveguide, such as the dielectric constant, and waveguide dimensions (e.g. inner/outer radii).

![Figure 2-14: Conceptual schematic of a generic dielectric lined cylindrical waveguide.](image)

### 2.5.2 E-201 at SLAC FACET

One of the flagship experiments at the SLAC FACET facility is E-201, which aims at the direct testing of DWA structures. The main goals of the experiment are the characterization of the emitted CCR and the determination of achievable field gradients. The DWA samples (cylindrical, slab, and Bragg array) are mounted on a monolithic block incorporated on a remote control 5-axis precision stage (Figure 2-15, right). A gold coated off-axis parabolic mirror is mounted coaxially at 90° to collimate and extract the CCR to a Michelson interferometer with pyroelectric detectors (Figure 2-15, left). The mirror also has a 3mm hole to allow the electron beam to propagate to a beam dump for future energy modulation measurements. A high-magnification imaging system allows for the observation of the face plane of the structures for signs of damage due to breakdown (signified by a violent flash and subsequent reduced transmission of laser light through the structure). The FACET facility has nominal parameters of $E=28\text{GeV}$, $\sigma_z=20\mu\text{m}$, $\sigma_x = \sigma_y = 20\mu\text{m}$, and $Q=3\text{nC}$, which allows the excitation of fields in excess of 1 GV/m in the THz scale DWA structures.
Figure 2-15: The experimental chamber at FACET (left). Photograph of the sample holder mounting block (right).

Preliminary results, from the experimental runs in 2012, show signs of breakdown in certain structures. In Figure 2-16, an alignment laser illuminates the inner dielectric of the cylindrical structure before the beam passes (Figure 2-16a), then again after it passes (Figure 2-16b). The cladding is not intact after the beam passes, presumably due to the heating caused by the >GV/m fields produced in the dielectric. A photograph of the sample mounting block shows clear signs of vaporization (Figure 2-16c). The cylindrical structures were characterized as darkened and brittle after exposure to the beam and the high fields. In addition, the first CCR measurements showed a weak signal at the expected fundamental mode for the cylindrical structures. The studies will continue through the next experimental runs with additional efforts placed on drive beam preparation and improved signal-to-noise in the diagnostics.

![Figure 2-16: (a) In-vacuum image of a cylindrical DWA with a laser shining through the end. (b) Image of the structure after exposure to high-fields of the beam; the cladding is no longer intact and the laser light seeps out of the side of the structure. (c) Photograph of the various cylindrical DWA structures exposed at the experiment](image)

2.5.3 DWA studies at FACET-II

The FACET-II parameter space has the potential to expose DWA research to the low emittance drive beam regime, which enables wakefields above 1 GV/m in smaller structures. Here we present several possibilities opened up by the FACET-II studies.

2.5.3.1 Drive + Witness beam

The proposed photoinjector would improve the quality of the beam, allowing the further characterization of DWA structures and the ability to unambiguously observe acceleration using a drive-witness pair. Recent experiments in THz scale slab-symmetric structures at the BNL ATF show acceleration using a chirped beam but with very modest fields (<10MV/m). The fields scale with charge and emittance, which determines the structure’s dimensions and fundamental accelerating mode. With expected fields surpassing the GV/m range, FACET-II will allow the observation of near-GeV acceleration.

2.5.3.2 Long structures

The improved emittance due to the photoinjector would enhance the delivery of small spot size beams (<20µm) with low emittance and longer collimation, allowing the use of long structures. In the current FACET setup, the structures are limited to 2.5cm in length. This is mainly due to the beam beta functions for a given beam spot size, since the gap of the structures must be five to six times the rms spot size to
ensure full transport through the structure. At FACET-II, structures over ten times longer (e.g. 50cm) can be studied due to the improved emittance from the photoinjector. This allows the study of similar gap DWA structures with small beam sizes, yet much larger beta functions. Long structures are important for observing gain in acceleration and studies of beam breakup, and also will provide insight on the maximum length of the structures as it relates to multi-staged accelerating systems.

### 2.5.3.3 Beam breakup

One of the limiting issues with long DWA structures is the undesirable effect of beam breakup within the structure. The beam dynamics due to interaction with the higher order mode excitation leads to stability issues caused by off-axis or off-angle operation. Such operation can lead to coupling to transverse modes that have adverse effects, including emittance growth, increased energy spread, and head-tail instabilities (see Figure 2-17). Beam breakup effects resulting from parasitic wakefield excitation may limit the efficacy of DWA structures as next generation drivers. Therefore these issues must be studied in detail experimentally. The FACET-II photoinjector will allow unprecedented control of a high-energy beam to purposefully excite transverse modes and develop a fundamental understanding of suppression methods and the limits of the harmful behavior of beam breakup.

![Figure 2-17: Effects of beam breakup due to excitation of transverse modes.](image)

### 2.5.3.4 Shaped bunches

For Gaussian beams, the transformer ratio (TR), the ratio of accelerated field to decelerated field, is limited <2. The viability of a DWA as a future driver for advanced applications and light source lies in the ability to overcome this TR limitation. Studies have shown that triangular longitudinal profiles, or ramped beams, have the potential to demonstrate TR>2. In the FACET-II scenario, jaw collimators may be used to longitudinally shape the drive bunch while maintaining small transverse emittance. For example, in the current FACET scenario, structures of inner diameter (ID) 200µm, and a ramped bunch produce a TR of 1.5 for a 1nC beam. However, with reduced spot size, ID=30µm, the TR increase to >5 with the same ramp and charge (Figure 2-18). This is a dramatic improvement and a
necessary step to demonstrate the viability of the DWA as a future compact high-brightness driver.

![Ramped beam R>>2](image)

Figure 2-18: Concept of shaped drive beam (left) and witness beam acceleration with high transformer ratio (right).

### 2.5.3.5 Longitudinally periodic structures

With advances in nano- and micro-fabrication technology of dielectrics (e.g. ceramics and diamond) the development of 1D-periodic structures is feasible. In FACET, transversely periodic structures are being investigated for mode confinement and damage threshold measurements. However, with the introduction of multi-pulse beams, longitudinally periodic structures can be studied as well. By exploiting the position-time correlation and using a notch or rigid-mask collimator, FACET-II will be able to produce a multi-pulse drive beam.

The longitudinal DWA structures are analogous to “slow-wave” structures where the group velocity of the wakefield can be controlled by appropriate selection of dielectric constants and periodicity. One scenario under theoretical and numerical investigation is the “zero group velocity” structure, which is composed of quartz and diamond. Figure 2-19 shows the mode confinement of the structure and the field within the structure once the beam has left, where a near-standing wave is produced and confined to the structure.

![Rendering of periodic structure (a), mode confinement of structure (b) and field (c).](image)

Figure 2-19: Rendering of periodic structure (a), mode confinement of structure (b) and field (c).

### 2.5.3.6 Photonic structures

Motivated by the need to abandon the use of metals in the presence of high fields, we have looked at a few examples of simple beam-driven all-dielectric wakefield accelerators from the perspective of bandgap photonics in 1D. However, we also gain design advantages in the ability to manipulate the modes’ characteristics by
examining fully 3D photonic-like structures, such as the woodpile in Figure 2-20. Control and manipulation of properties — such as modal confinement, spatial harmonic content, phase velocity, and group velocity — are reasons why an all-dielectric beam-driven accelerator would be expected to benefit by borrowing from the field of optical bandgap photonics. The smaller beams and low charge operating regime afforded by FACET-II would allow further studies of these structures.

![Figure 2-20: Concept of the sapphire ($\varepsilon = 9.3$) woodpile (left) and simulated bandgap diagram (right).]

### 2.5.4 Conclusion

The proposed FACET-II parameter set opens up the possibilities for novel and exciting research into dielectric wakefield acceleration that is currently inaccessible due to constraints on drive beam generation and transport. These pertinent studies and demonstrations are necessary to ascertain the feasibility of the DWA as a next generation, compact accelerator for FEL and collider applications.

### 2.6 BIG: Beams of Intense Gamma-rays at FACET-II

#### 2.6.1 Introduction.

Richard Feynman once wrote:

> One very powerful way of experimentally investigating the strongly interacting particles (hadrons) is to look at them, to probe them with a known particle; in particular the photon (no other is known as well). This permits a much finer control of variables, and probably decreases the theoretical complexity of the interactions [50].

Indeed, $\gamma$-ray sources are intensely used in quantum chromodynamics (QCD) research to study structure of nuclei and nucleons. Controllable linear and circular polarization of the Compton back-scattering $\gamma$-ray sources opens the window of spin and parity observables in this research.

Polarized Compton back-scattering $\gamma$-ray sources, pioneered at ADONE and SLAC in the 1960s, [51] remain an important research and application tool. Presently there are four operational facilities covering $\gamma$-ray energy range from 1 MeV to 2.4 GeV.
The area of research is roughly split into low, medium and high energy ranges. Low energies, $E_\gamma = 1\text{--}15$ MeV, are well-suited to studying the resonant structure and states in nuclei below the giant dipole resonance. Nuclear resonant fluorescence (NRF) is the primary method for these studies. In addition, direct photon excitation and disintegration of nuclei gives access to a number important processes in astrophysics, such as $^{16}\text{O}(\gamma,\alpha)$. [52] Figure 2-21 indicates the richness of the nuclear structure.

![Figure 2-21: E1 dipole strength distribution in N = 82 isotones. (Courtesy of A. Tonchev, LLNL).](image)

Intermediate energies, $E_\gamma = 100\text{--}200$ MeV, are optimal for studying spontaneous breaking of QCD chiral symmetry. The main areas of interest are near threshold of pion photo-production, [53] measuring nucleon spin polarizabilities [54] and measuring the integrand of the Drell-Hearn-Gerasimov integral for the deuteron. [55].
Figure 2-22: The $\gamma + p \rightarrow \pi^0 + p$ reaction: (a) $Re(E_{\omega})$, the solid blue curves represent chiral perturbation theory (ChPT) calculations, and the dashed orange curves represent the unitary fit; (b) $Im(E_{\omega})$ [Courtesy of A.M. Bernstein, MIT].

High energies, $E_\gamma > 200$ MeV, are needed for studying the resonant structure and states in nucleons. The high energy reach of BIG opens the possibility of searching for light-quark + glue hybrid baryons and, probably, heavy-quark baryons. This research requires meson photo-production and direct access to gluons. These experiments are focused on a high precision extraction of pseudoscalar meson photo-production amplitudes. The most general analytic form of the cross section involves 16 spin-dependent observables, which can be reached using the flexibility of BIG in combination with a sophisticated detector. [56]. Potential discoveries include a hypothetical glue-ball [57].
In addition to QCD experiments, the BIG can be used for R&D in generating polarized lepton (positron and muon) beams for future linear lepton and linac-ting lepton-hadron colliders. Furthermore, it can act as a test-bed for a γ–γ collider. The time structure of BIG may allow us to create a textbook experiment – generating an electron-positron pair in vacuum by colliding two γ-ray beams.

All existing Compton back-scattering sources create γ-rays with a similar overall energy spectrum. The energy spread of γ-rays can be limited by geometrical collimation, with about 1.5% of the flux per 1% energy spread in the region near the top energy of the photons:

\[
E_{\gamma \max} = \frac{\hbar \omega \cdot \frac{1+\beta}{1-\beta + 2\hbar \omega / \gamma mc^2} \sim \frac{4\gamma^2 \hbar \omega}{1+4\gamma \hbar \omega / mc^2}}{1+4\gamma \hbar \omega / mc^2};
\]

\[
\gamma = 1/\sqrt{1-\beta^2}.
\]

Hence, the spectral (energy) density of the beam is determined by its total flux \( \dot{N}_\gamma \) and the maximum energy of the photons in the beam:
The $\gamma$-ray energy resolution can be obtained either by tagging the energy of scattered electrons or by collimating the beam. The tagging approach does not create high fluxes, since only one $\gamma$-ray per collision can be effectively used. Collimation does not impose such restrictions. The resolution obtained by collimation depends on the quality of the electron beam.

Table 2-1 compares main parameters of existing polarized Compton $\gamma$-ray sources. A number of bremsstrahlung $\gamma$-ray sources exist as well, but these are unpolarized and in a large background of low energy photons, and are therefore not suitable for QCD experiments.

Table 2-1: Main parameters of operational polarized Compton back-scattering $\gamma$-ray sources and the BIG.

<table>
<thead>
<tr>
<th>Name</th>
<th>ROKK Location</th>
<th>GRAAL Accelerator</th>
<th>LEPS Location</th>
<th>Hi\gammaS Accelerator</th>
<th>BIG Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Novosibirsk, Russia</td>
<td>Grenoble, France</td>
<td>Harima, Japan</td>
<td>Durham, NC, USA</td>
<td>Palo Alto, CA, USA</td>
</tr>
<tr>
<td>Accelerator</td>
<td>VEPP-4M</td>
<td>ESRF</td>
<td>SPRING-8</td>
<td>Duke SR</td>
<td>SLAC</td>
</tr>
<tr>
<td>e-beam, GeV</td>
<td>1.4 - 6</td>
<td>6</td>
<td>8</td>
<td>0.24 – 1.2</td>
<td>1.10</td>
</tr>
<tr>
<td>$\gamma$-beam, GeV</td>
<td>0.1-1.6</td>
<td>0.55-1.5</td>
<td>1.5-2.4</td>
<td>0.001-0.095</td>
<td>0.001-2 (5)</td>
</tr>
<tr>
<td>best $\gamma$-energy resolution, %</td>
<td>1-3</td>
<td>1.1</td>
<td>1.25</td>
<td>0.8-10</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Note: not all parameters in the table can be obtained simultaneously.

It is clear from Table 2-1 that the BIG is a superior source when compared with the other existing sources. It has a $\gamma$-ray energy span of more than three orders of magnitude, from MeV to GeV, about 10-fold better energy resolution than competing sources, and two to four orders of magnitude larger flux. BIG’s unprecedented intensities and unique time structure open unprecedented opportunities for its utilization in fundamental and applied research.

In addition to existing Compton back-scattering $\gamma$-ray sources, there are a number of recent proposals for new sources. Two of them are in the USA: one is proposed at LLNL [LLNL’s prop] and the other is the recently proposed ASTA facility at FNAL [59]. While both of these proposals promise to deliver very high fluxes of $\gamma$-rays, their energy reach and coverage do not match that of the BIG. The LLNL source, with its 200 MeV linac, will generate $\gamma$-rays with a maximum energy near 1MeV. The
ASTA facility, with its proposed 800 MeV SRF linac, would be capable of generating high intensity γ–ray beams with a maximum energy of 15 MeV.

Hence, a large number of ground breaking experiments requiring high flux, excellent energy resolution and detailed energy scans will become possible at BIG. In short, the BIG is the dream facility for polarized photo-production and photon scattering experiments.

2007 Nuclear Physics Long Range Plan “The Frontiers of Nuclear Science” Effective Field Theory clearly indicate importance of intense polarized γ–ray sources for frontier QCD research. It reads:

*Effective field theories provide a powerful framework for solving physical problems that are characterized by a natural separation of distance scales. They are particularly important tools in QCD, where the relevant degrees of freedom are quarks and gluons at short distances and hadrons and nuclei at longer distances. Indeed, at energies below the proton mass, the most notable features of QCD are the confinement of quarks and the spontaneous breaking of QCD’s chiral symmetry. Chiral perturbation theory is an effective field theory that incorporates both; when applied to mesons it is a mature theory. Perhaps the most striking advances in chiral effective field theory have come in its application to few-nucleon systems. This has yielded precise results for nucleon-nucleon forces and also produced consistent three-nucleon forces. This opens the way for precision analyses of electromagnetic reactions on light nuclei, e.g., the Compton scattering reactions on systems having two or three nucleons.*

The BIG would be perfectly suited for the research described above. Its energy range is ideal and its intensity is sufficient for the challenges presented by the experiments.

Another challenge where BIG may excel is studying the spontaneous breaking of chiral symmetry due to the finite quark masses. This study requires polarized photon energies between the thresholds of neutral and charged pion production (e.g. between the \( \pi^0 \) threshold of 144.7 MeV and the \( \pi^+ \) threshold of 151.4 MeV). As a result of the vanishing of the threshold amplitudes in the chiral limit, the experiments are difficult to perform because the cross sections are small. Furthermore, an energy scan with very narrow energy spread of the γ–ray (well below 1% FWHM) is needed to map this energy range. This is the reason why experts in the field call it “dream experiment” [60]. Existing and proposed polarized γ–ray sources either do not have energy reach (HIγS) or have very low flux: with GRAAL or LEPS it would take about 10,000 years to collect necessary statistics. The BIG’s intensity and energy resolution would allow us to perform this experiment in under one year.

The BIG’s energy reach and unprecedented intensity (~ 10,000-fold increase in the energy of interest) opens a window for studying critical details of chiral dynamics in meson photo-production. Excellent energy spread down to 0.1% FWHM in the BIG’s collimated γ–ray beam opens a new window into nuclear structure studies.
2.6.2 Nuclear Structure Studies: Nuclear Resonant Fluorescence (NRF), including pigmy resonances

Studies of nuclear structure, some of which also have an astrophysical context, would strongly benefit from the high intensity and high quality of γ-ray beams at the BIG source at FACET-II. The most important parameter in any NRF or photo-induced experiment is the number of photons per eV, or the flux energy density. This is dictated by the fact that the width of nuclear states below the neutron separation energy ranges from few meV to eV depending on the nucleus and structure involved. BIG’s tunability and flux energy-density exceed any operating sources by orders of magnitude, making it a perfect choice for this application. We anticipate that dozens of scientists from the U.S. and Europe will want to take advantage of BIG for research into nuclear structure.

Studies of nuclear structure are on the forefront of low energy nuclear physics and astrophysics. The neutrino flavor transformation in the star explosions determine charged- and neutral-current interactions of supernova neutrinos. Mapping the M1 strength distributions for isotopes ranging from 40Ar to isotopes of Mo have been proposed for neutral-current detectors. The stable isotopes of Mo are likely to be sensitive to both n_e and anti-n_e interactions [61].

The electric dipole (E1) response is a fundamental property of atomic nuclei. As with other collective multipole responses it is directly connected to the bulk properties of nuclei and nuclear matter. Recently, the E1 response (especially its low-lying part) has been shown [62, 63, 64] to provide a constraint on the isovector properties of nuclear matter, e.g., the symmetry energy, which are key ingredients in the description of exotic astrophysical objects like neutron stars. [65] Furthermore, the E1 response builds up the major part of the photo-absorption cross section and represents the dominant γ-ray strength function, an important quantity in determining reaction rates in different astrophysical scenarios. [66, 67] Photon induced reactions are an ideal tool to investigate the dipole strength below and above thresholds in a model independent way. However, data are so far available only for a few nuclei mainly at or close to the magic shell closures. Measurements of (γ,γ') reactions at BIG will extend these studies to a wider range of masses including highly deformed nuclei.
The nuclear dipole response covers a range of structural phenomena, as shown in Figure 2-24. Physics themes involving electric and magnetic dipole distributions, which can easily be separated making use of the polarization of the photon beams, range from the study of isospin purity of states, to the emergence and evolution of nuclear quadrupole and octupole collectivity, and the build-up of nucleon skins. The best-known dipole excitation is the giant dipole resonance (GDR), which is typically found at energies around 15 MeV, well above the neutron-separation threshold. On the low-energy tail of the GDR another structure has been identified in a small set of nuclei, as mentioned above. This enhancement of strength around or below the neutron-separation threshold, referred to as Pygmy dipole resonance (PDR), is typically interpreted as the effect of a neutron skin building up around a proton-neutron symmetric core. The lowest part of the electric dipole response, at few MeV excitation energy, is dominated by multi-phonon excitations involving the octupole degree of freedom. The latter requires a short bursts of \( \gamma \)-rays natural for BIG’s time structure. In either case, the enhanced, collective electric dipole strengths at low energies are a challenge to nuclear theory, since they can usually only occur due to particle-hole excitations across a major shell.

Figure 2-24: Schematic of the dipole response over a broad range of energies, up to 10's of MeV, and related structural phenomena.

- **GDR**: Giant Dipole Resonance: \( E_x \sim 10 - 20 \) MeV, B(E1) \( \sim \) 5 - 10 W.u.
- **SM**: Orbital “Scissors” mode: \( E_x \sim 3 \) MeV, B(M1) \( \sim 3 \mu_n^2 \)
- **QOC**: Two Phonon Excitation: \( E_x \sim 4 \) MeV, B(E1) \( \sim 10^{-3} \) W.u.
- **PDR**: Pygmy Dipole Resonance
Figure 2-25: Evolution of the GDR for all Sm isotopes calculated by the QRPA model [68]

Figure 2-25 depicts calculated GDR distributions for Sm isotopes across the onset of deformation. For spherical isotopes the resonance has a Lorentzian-type shape, whereas the GDR splits into two Lorentzians in deformed isotopes, corresponding to vibrations with respect to the two major axes. A similar behavior can be expected for the PDR, but has so far not been observed due to the lack of data in deformed regions. An additional complication is the disentanglements of PDR and GDR strengths, since - as indicated in Figure 2-25 - the PDR lies on the low-energy tail of the GDR.

Dipole excited states, particularly, the PDR, are at the intersection of nuclear structure and nuclear astrophysics. They are of interest to nuclear structure because they represent a weak collective mode that remains to be understood in a systematic way. The astrophysics context is clearer, since these states directly influence the rates for stellar photodisintegration reactions. Nuclear resonance fluorescence studies of the PDR show that we are missing significant (maybe most) of its excitation strength because cascades through lower-lying excited states have thus far escaped detection. Coincidence measurements, which will isolate cascades from the PDR, require the intensity and energy resolution of BIG. In addition, coincidences provide a unique way to excite other collective dipole structures, such as quadrupole-octupole coupled (QOC) states or the nuclear M1 scissors mode, and simultaneously observe their detailed decay behavior, which is the smoking gun of their nature. Such fingerprints are, for example, the one-phonon decays of QOC states corresponding to the annihilation of a quadrupole phonon, as depicted in Figure 2-26.
Background suppression is a very big problem for this kind of experiments. Very low background to signal ratio is one of the unique aspects of BIG. BIG’s geometry, e.g. a short chicane where γ-rays are generated, provides for bremsstrahlung-free environment. In addition, the time structure with short bursts of γ-rays creates an additional 30,000 fold suppression of the background to signal ratio, compared with near-CW storage ring sources, such as HγS. Finally, a 10-fold narrower energy spread in the γ-ray energies provides for removing the beam-related background. Hence, BIG would open opportunities to perform experiments which are currently impossible because of the signal to background ratio being low.

In contrast to existing facilities, the very high brilliance of the beam will allow to excite specific states and study their detailed decay behavior, even in regions of high level densities. High-resolution charged particle spectroscopy has been used to map out the fission barrier landscape of many of the light actinides. [69,70] As a result, a new picture of the triple-humped fission barrier was established with an unexpected, rather deep, third hyper-deformed minimum. New photo-fission experiments could significantly improve our present knowledge on the fission resonance structure and on the potential energy landscape of the actinides, which has very important astrophysical relevance as well: the fission barrier controls the fission losses at the end of the η-process path and also the population of long-lived uranium and thorium nuclei. The improved beam energy resolution of the BIG will allow for the search and study of narrow fission resonances near the barrier.

### 2.6.3 Nuclear Physics near pion threshold

Intense beams of medium energy polarized γ-rays are of great interest for a variety of QCD and nuclear physics experiments. Below we describe some of new physics which can be studied with the BIG.
2.6.3.1 Isospin Breaking Due to the Light Quark Masses

Chiral symmetry in QCD is both spontaneously [71] and explicitly broken due to the non-zero values of the light quark masses. Since the up and down quark masses differ by almost a factor of two, isospin symmetry is also violated. [72] Strong isospin violation is usually predicted when \((m_d - m_u)/\Lambda_{QCD} \approx 2\%\). However, there is one case where strong isospin breaking is predicted when \((m_d - m_u)/(m_d + m_u) \approx 25\%\). [73] The quantity of interest is \(a(\pi^0 p)\), the s-wave scattering length on the proton. [74]

Clearly this quantity cannot be directly measured since \(\pi^0\) beams cannot be constructed. Our present knowledge comes from data involving charged pions and constructing the isospin even s wave scattering length, \(a^+ = (a_{\pi^- p} + a_{\pi^+ p})/2\), measured from pionic hydrogen and deuterium, with the Coulomb contributions removed. [75, 76] If isospin symmetry holds, then \(a^+ = a(\pi^0 p)\). To test this it is essential to measure \(a(\pi^0 p)\). This is difficult since \(\pi^0\) beams cannot be made. However it can be measured as a final state interaction in the \(\gamma p \rightarrow \pi^0 p\) reaction with transversely polarized protons in the energy region between the \(\pi^0\) threshold of 144.7 MeV and the \(\pi^+\) threshold of 151.4 MeV. [77, 78] This experiment requires a beam of \(\sim 10^9\) photons/sec with \(\pm 1\%\) energy resolution. [79] This beam is possible with the proposed FACET-II facility at SLAC. The experiment requires a time structure in which each beam burst is divided into 1000 short beam bursts. It requires an \(a \approx 4\pi\) photon detector with good energy and time resolution to observe the \(\pi \rightarrow \gamma\gamma\) decay mode, a transverse polarized proton target (butanol) and state of the art electronics due to the low duty cycle. Even with this intense beam the experiment requires \(\sim 2000\) hours of running time to measure \(a(\pi^0 p)\) with a statistical accuracy of \(\pm 10^{-3}/m_{\pi}\), which is comparable with the present determination of \(a^+\). A comparison of \(a(\pi^0 p)\) and \(a^+\) will test the predicted violation of isospin symmetry. [80] This is an ambitious and difficult experiment to test a fundamental consequence of explicit chiral symmetry and isospin breaking due to the non-zero up and down quark masses first pointed out by Weinberg over half a century ago, and will test a firm confinement scale QCD prediction.

2.6.3.2 Measurements of the Drell-Hearn-Gerasimov Integrand for the Deuteron

We propose measuring the integrand of the Drell-Hearn-Gerasimov integral for the deuteron from as close as possible to the maximum photon energy of 160 MeV. S. B. Gerasimov [81] and, independently, S. D. Drell and A. C. Hearn [82] showed that, using reasonable assumptions,

\[
\int_\omega^\infty \frac{\sigma_{1/2} - \sigma_{3/2}}{\omega} d\omega = -4S\alpha\pi^2 \left( \frac{\kappa}{M} \right)^2
\]

where \(\sigma_{1/2}, \sigma_{3/2}\) are total inelastic cross section when the target nucleon spin and the incident photon helicity are anti-parallel (parallel), \(\omega_T\) is the threshold photon
energy for inelastic processes, \(M, \kappa\) are the mass and anomalous magnetic moment of the target, and \(S\) is the spin of the target. The equation above applies to protons, but Hosada and Yamamoto [83] and Gerasimov pointed out that these arguments could be applied equally well to the deuteron. That is, the deuteron could be treated as the object of the sum rule rather than simply as a source of neutrons. The resultant "GDH" sum rule is given by

\[
\int_{\omega_2}^{\infty} \frac{\sigma_{1/2}^d - \sigma_{3/2}^d}{\omega} d\omega = -4\alpha\pi^2 \left( \frac{\kappa_d}{m_d} \right)^2
\]

where \(\omega_2\) is the threshold not for pion production (≈145 MeV) but for photo-disintegration (≈2.2 MeV), and \(m_d\) and \(\kappa_d\) are the mass and anomalous magnetic moment of the deuteron, respectively. The sum rule values for the proton, neutron, and deuteron are given in Table 2-2.

Table 2-2: Sum rule values for particles

<table>
<thead>
<tr>
<th>Target</th>
<th>(\kappa)</th>
<th>(\int GDH, \mu b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>1.79</td>
<td>-204.0</td>
</tr>
<tr>
<td>n</td>
<td>-1.91</td>
<td>-232.0</td>
</tr>
<tr>
<td>d</td>
<td>-0.14</td>
<td>-0.6</td>
</tr>
</tbody>
</table>

The GDH integral for the deuteron can be separated into three terms:

\[
\int_{\omega_2}^{\infty} \frac{\sigma_{1/2}^d - \sigma_{3/2}^d}{\omega} d\omega = \int_{\omega_2}^{\omega_x} \frac{\sigma_{1/2}^d - \sigma_{3/2}^d}{\omega} d\omega + \int_{\omega_x}^{\omega_{\max}} \frac{\sigma_{1/2}^d - \sigma_{3/2}^d}{\omega} d\omega + \int_{\omega_{\max}}^{\infty} \frac{\sigma_{1/2}^d - \sigma_{3/2}^d}{\omega} d\omega = -0.6 \mu b
\]

The second term, which also can be measured at BIG, has been measured at Brookhaven’s Laser Electron Gamma Source and elsewhere. For the high photon energies relevant to the third (unmeasured) term we note that to the order of 0.1% the deuteron can be treated as the sum of a neutron plus a proton plus trivial corrections. The first term remains unknown. Currently there is no available source for such measurement, but BIG will be the perfect source to fill in this gap.

If the sum rule is valid then the sum of the unmeasured terms of the GDH integral for the neutron and proton must equal the unmeasured term of the deuteron. Adding these to the measured terms of the deuteron, the GDH integral should yield a value in agreement with the sum rule prediction.
If the GDH rule holds, then we can conclude that the sum rule is valid and calculating the "unmeasured" terms of the neutron and proton integrals will be a test of nucleon models. If no agreement is observed, then something is wrong with the sum rule. Perhaps the assumption of unsubtracted dispersion relations?

![Graph showing cross section difference](image)

**Figure 2-27:** The cross section difference entering the GDH Sum Rule integral. Note that the abscissa scale is logarithmic so the area under the curve is proportional to the contribution to the sum rule integral.

The Blowfish detector, [84] with its associated electronics and data acquisition system, is ready for use for these measurements. The measurements require a detailed energy scan, where both the energy reach, the energy resolution and the intensity of the BIG makes it uniquely suited for this important measurement.

The experiment will involve photon energy scans from 2 MeV to about 200 MeV. The helicity of the photons should be switchable. The difference in energy between charged and neutral pion threshold is about 4.5 MeV so the energy resolution should be less than 2%. The required flux is at least $10^7$ per MeV. BIG can achieve the required polarization, energy range, energy resolution and intensity. We expect to complete this experiment in about 2000 hours of beam-time.
2.6.3.3 Compton Scattering from a High Pressure Polarized $^3$He Target

Experimental and theoretical investigation of the nucleon structure has grown more intense in the last two decades, resulting in breakthroughs in both experiment and theory. Nucleon polarizabilities, describing the response of the nucleon in external electromagnetic fields, have attracted more attention. Significant efforts have been devoted in the last two decades to unpolarized Compton scattering measurements from the proton and deuteron to extract the nucleon electric and magnetic polarizabilities. However, very little is known about nucleon spin polarizabilities, which are fundamental quantities related to the structure of the nucleon. For a spin 1/2 target, there exist four independent spin polarizabilities. Due to the lack of free neutron targets in nature, our knowledge of the neutron polarizabilities is poor. A theoretical calculation shows that double-polarization asymmetries from circularly polarized photons Compton-scattering off a polarized $^3$He target elastically are expected to be sensitive to the neutron spin polarizabilities. [85]

We propose a double polarization Compton scattering experiment of circularly polarized photons from a polarized $^3$He target at the elastic kinematics. The experiment will be carried out with a photon energy of 120 MeV at a minimum photon flux of $5 \times 10^8$/sec. The polarized $^3$He target is a high pressure target based on the spin-exchange optical pumping technique, and the scattered photons can be detected by using a detection system such as the NaI Detector Array (HINDA). During the experiment, the double polarization asymmetry will be formed by flipping the target spin direction or the beam helicity. The proposed layout of the experiment using HINDA system is shown in Figure 2-28.

![Figure 2-28: The proposed experimental setup for Compton scattering using NaI Detector Array (HINDA) system](image-url)
Figure 2-29: The projected sensitivity to the neutron spin polarizability $\gamma_1$ from double polarization asymmetry measurement from a polarized $^3$He target as a function of photon scattering angle in the laboratory frame. The simulated results for Compton scattering (red points) are plotted along with theoretical calculations using different $\gamma_1$ values.

We propose a total beam time of 900 hours with 100% polarized photon beam and a 50% polarized $^3$He target with a target thickness of $1.1 \times 10^{22}$ atoms/cm$^2$ and have considered possible physics backgrounds and detection efficiency. The spin-dependent asymmetry difference can be formed from the simulated events, and compared with different neutron spin polarizabilities. For example, the projected sensitivity to the neutron spin polarizability $\gamma_1$ is shown in Figure 2-29.

2.6.3.4 Other opportunities

There is added interest in measurements of both single and double polarization observables in deuteron photodisintegration based on the discrepancy that Nath observed in the reaction $d(\gamma p)n$. [86] The break between theory and experiment occurs at just the energy at which measurements of other reactions suggest the existence of a narrow two-nucleon state/resonance, making the experiment especially compelling. The present indications must be treated very carefully since such a state, usually referred to as a dibaryon, has been sought for decades, and its existence has been announced and then refuted.

BIG can resolve this controversy. The $d(\gamma n)n$ measurements involve a secondary scattering of the emitted neutron, making the high flux of the BIG essential. If the Nath data are confirmed, then a program of follow-on measurements is anticipated. These will not only expand the energy range but also address the related polarization of the neutron in the orthogonal direction. In addition, measurements
of the reaction \( ^3\text{He} (\gamma n)(np) \) would be very interesting -the presence of a narrow two-nucleon resonance should show up in this reaction. While this specific possibility is very speculative, it has discovery potential and therefore is very exciting.

Another set of experiments that can be pioneered at BIG are the Bethe-Heitler processes. [87] For low-Z nuclei which, arguably, may be the most interesting, the question of flux is paramount, as the effect is small. The energy asymmetry in wide- and medium-angle electron/ positron pair production off protons (and other targets) is caused by the interference between the first- and second-order Born diagrams and the Compton scattering diagram. It directly probes aspects of quantum electrodynamics, as well as providing a direct measurement of the real part of the Compton amplitude. The two-photon Bethe- Heitler amplitude is closely related to the two-photon exchange amplitude in \( ep \rightarrow ep' \) which is believed to cause the breakdown of the Rosenbluth separation in electron scattering. [88, 89] It may be much easier to measure two photon exchange effects to high precision in \( \gamma p \rightarrow e^+ e^- p' \) than to measure the electron-positron asymmetry in \( e^\pm p \rightarrow e^\pm p' \) elastic scattering.

![Diagram](image)

**Figure 2-30:** A schematic top-view of the proposed experimental layout showing the photon beam, the horizontal target ladder, the pair spectrometer dipole, and the tracking packages (not to scale).

### 2.6.4 QCD with real photons: Nucleon structure

The spectra of baryon resonances have been a focus of experimental and theoretical studies, both for particles composed of the light u and d quarks, and those containing one or more of the heavy c and b quarks. In the energy region available at
BIG (from 300 MeV to 5 GeV) the nucleons exhibit many major and minor resonance states. There is increasing activity aimed at understanding the spectra of particles containing one or more s quarks, so-called hyperon physics. [90] At present the knowledge of the Ξ and Ω families is particularly limited with only a few states experimentally studied, and scant knowledge as to their properties. [91] The 5 GeV energy reach of the BIG allows us to search for light-quark + glue hybrid baryons as well as for heavy-quark baryons. Figure 2-31 shows some of the recent lattice QCD predictions, showing the bands of states with alternating parities and increasing energies. [92] Each state has a well-defined spin and generally a dominant flavor content. The number of non-hybrid states of each spin and flavor in the lowest-energy bands is in agreement with the expectations based on weakly broken SU(6)O(3) symmetry. These states correspond to the quantum numbers of the quark model.

![Figure 2-31: Lattice QCD predictions](image)

It would be very important to find some of these predicted states experimentally, but the experiments would be very complicated. To convincing extract such states we would need to measure almost all polarization observables. This would require a ~ 4π detector to analyze recoil polarization for some channel like $K\Lambda$ or $K\Xi^+$, and both linear and circular photons and one target polarization. [93] High flux γ-rays from the BIG and its fully controllable polarization are well suited for such studies. The extremely high intensity of the BIG, exceeding all existing Compton γ-ray sources by four orders of magnitude, is the key for making these experiments possible.

In addition, a precise measurements of $d\sigma/dt$ and the meson helicity in the ϕ photoproduction in the energy region of 2 to 3 GeV may reveal the existence of a 0 ++
glueball, whose contribution falls off rapidly at high energies because of a negative value for $\alpha(t=0)$. [94] Furthermore, the study of the strangeness quark content in nucleon - which is of great relevance for modern particle physics - can be extracted from the spin observables in $\phi$-photo-production. Also, photo-production of a $\Lambda$ in $\gamma p \rightarrow \Lambda K^+$ reactions is of great importance for a microscopic understanding of hypernuclei.

2.7 Gamma-gamma collider

Gamma-gamma colliders have recently attracted much interest because they would, thanks to s-channel production, probably provide the cheapest option to construct a dedicated Higgs factory. [95, 96] Such a project would require a recirculating linac and possibly energy recovery. The crucial issues for gamma-gamma Higgs factories are the realization of Compton collisions with high repetition rate, the intensity and properties of the Compton- backscattered photons, the stability and the efficiency of the Gamma-gamma Compton process.

A recent proposal for a Higgs factory gamma-gamma collider, called “SAPPHiRE” is based on a recirculating superconducting linac in possible synergy with the Large Hadron-Electron Collider [95]. Pertinent parameters are compiled in Table 2-3.

**Table 2-3:** Example parameters for SAPPHiRE.

<table>
<thead>
<tr>
<th>SAPPHiRE</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>total electric power</td>
<td>$P$</td>
<td>100 MW</td>
</tr>
<tr>
<td>e- beam energy</td>
<td>$E$</td>
<td>80 GeV</td>
</tr>
<tr>
<td>beam polarization</td>
<td>$P_e$</td>
<td>0.90</td>
</tr>
<tr>
<td>bunch population</td>
<td>$N_b$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>repetition rate</td>
<td>$f_{rep}$</td>
<td>200 kHz</td>
</tr>
<tr>
<td>bunch length</td>
<td>$\sigma_z$</td>
<td>30 $\mu$m</td>
</tr>
<tr>
<td>crossing angle</td>
<td>$\theta_c$</td>
<td>$\geq 20$ mrad</td>
</tr>
<tr>
<td>normalized horizontal emittance</td>
<td>$\gamma \varepsilon_x$</td>
<td>5 $\mu$m</td>
</tr>
<tr>
<td>normalized vertical emittance</td>
<td>$\gamma \varepsilon_y$</td>
<td>0.5 $\mu$m</td>
</tr>
<tr>
<td>horizontal IP beta function</td>
<td>$\beta_{x^*}$</td>
<td>5 mm</td>
</tr>
<tr>
<td>vertical IP beta function</td>
<td>$\beta_{y^*}$</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>horizontal rms IP spot size</td>
<td>$\sigma_{x^*}$</td>
<td>400 nm</td>
</tr>
<tr>
<td>vertical rms IP spot size</td>
<td>$\sigma_{y^*}$</td>
<td>18 nm</td>
</tr>
<tr>
<td>horizontal rms e- CP spot size</td>
<td>$\sigma_{x^{CP}}$</td>
<td>400 nm</td>
</tr>
</tbody>
</table>
Another recent proposal for a gamma-gamma Higgs factory, submitted to the European Strategy Group Open Symposium in Cracow, uses CLIC technology [96]. There had also been an earlier proposal and study for a gamma-gamma Higgs factory “CLICHE” based on CLIC-1 [97]. Yet another proposal has been presented during the ICFA Higgs Factory workshop 2012 at Fermilab [98].

Gamma-gamma Higgs factories realize collisions through Compton backscattering of laser (or FEL) photons off the high energy electron beams close to the interaction point. A Higgs factory has advantages compared to a positron-electron collision scheme, in that the electron beam energy required to produce a Higgs particle is lower (about 80 GeV instead of 120 GeV), and positrons are not required. Electron beam energies of 80 GeV and a high repetition rate are the basis of the Higgs gamma-gamma collider, and are within reach of present accelerator technology. At a beam energy of 80 GeV, the laser wavelength should be 300-400 nm. For efficient conversion the total energy of the Compton-scattering laser pulse should be a few joules, e.g., 1 TW peak power and 5 ps pulse length, implying 1 MW average power at 200-kHz repetition rate. Stacking laser pulses in a high-finesse optical cavity reduces the input laser power required by two orders of magnitude, to about 10 kW. An economic way to produce the required e- energy is by means of a SC recirculating linac [95]. Operating a recirculating linac with much higher electron current in energy-recovery mode would also, or further, decrease the needed laser power [99]. The Compton IR layout with integrated optical cavity and the production of the required photon beam using a laser or FEL need strong R&D, a large part of which could be studied at FACET-II.

FACET-II can perform several important tests for future gamma-gamma colliders. Specifically, FACET-II could study the realization of multiple collisions using a multi-mirror optical stacking cavity, and the associated laser systems. Two types of such cavities, built by LAL Orsay in France and U. Hiroshima in Japan are presently being
tested at the KEK-ATF2, but only with very low repetition rate. Studies of efficiency, tuning schemes, and the photon-beam parameters will be important steps towards a high-energy gamma-gamma collider.

In addition, low energy gamma-gamma collisions could directly be realized at FACET-II. A possible test involves generating electron-positron pairs using two gamma-ray beams colliding at a small angle, on the order of tens of mrad. This would be the first pair creation test using photons.

The maximum cross-section is at $E_{cm} \sim 1.4$ MeV $\sim 1$e-25 cm$^2$.

Therefore it is optimal to use a drive beam energy around 4GeV and generate 30MeV gammas using a CO$_2$ laser. In this case the C.M. energy, calculated as $E_{cm} = 2E_\gamma \sin \theta$, comes to $\sim 1.4$MeV. Generated positrons and electrons will have close to 30 MeV energy in the laboratory system with an energy spread of 1.4 MeV.

The trajectories of the generated particles are defined by the magnet field of the last dipole. This will allow for a very practical detection system that can detect about 30 events per minute.
Another option is to generate a gamma-ray beam and a VUV beam from two consecutive electron bunches. A focusing mirror can then reflect helium VUV photons and cause them to collide with the gamma-ray head-on. There is potential of higher luminosity in this mode of operation as well as reaching energies needed for generating muon pairs. Also this scheme of self-generated gamma-rays could be of interest for a future gamma-gamma Higgs factory. The gamma-ray and VUV could be generated by an undulator, or possibly by an FEL process.

2.8 High intensity Positron Source studies using Gamma beam generated with Compton Beam scattering

The SLC positron source was developed in the early 1980s and successfully supported the physics needs for decades of operations. It still holds the record for highest positron flux capability of the order \(4 \times 10^{12} \text{ e}^+ / \text{sec}\). Demands for newly proposed collider facilities exceed capabilities of the SLC type positron source by a few orders of magnitude. There are number of proposals aimed at addressing this issue, yet there is no demonstrated solution that provides a positron source that can meet the needs of ILC, CLIC, LHeC, eRHIC, and other projects [100, 101, 102, 103]. ILC needs a positron source capable of \(3 \times 10^{14} \text{ e}^+ / \text{sec}\), and luminosity of LeHC will be limited with a source below \(4 \times 10^{16} \text{ e}^+ / \text{sec}\) (see Table 2-4). The survival of the conversion target is ultimately the limiting factor. Use of novel targets (liquid metal jet target, crystal structure target, pellets) might be necessary to address the demand on the positron beam intensity for the next generation of colliders. The gamma beam capabilities at FACET-II will open unique opportunities to study and advance the ideas on novel positron sources. In this section, we will address the generation of the gamma beams that will be of interest for the testing of novel conversion targets [104].

Table 2-4: Positron production at the SLC source compared with the needs of future projects
<table>
<thead>
<tr>
<th></th>
<th>SLC</th>
<th>CLIC (3 TeV)</th>
<th>ILC (RDR)</th>
<th>LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>energy</strong></td>
<td>1.19 GeV</td>
<td>2.86 GeV</td>
<td>5 GeV</td>
<td>60 GeV</td>
</tr>
<tr>
<td><strong>e⁺/ bunch at IP</strong></td>
<td>40 x 10⁹</td>
<td>3.72 x 10⁹</td>
<td>20 x 10⁹</td>
<td>2 x 10⁹</td>
</tr>
<tr>
<td><strong>e⁺/ bunch before DR inj.</strong></td>
<td>50 x 10⁹</td>
<td>7.6 x 10⁹</td>
<td>30 x 10⁹</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>bunches / macropulse</strong></td>
<td>1</td>
<td>312</td>
<td>2625</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>macropulse rep. rate</strong></td>
<td>120</td>
<td>50</td>
<td>5</td>
<td>CW</td>
</tr>
<tr>
<td><strong>bunches / second</strong></td>
<td>120</td>
<td>15600</td>
<td>13125</td>
<td>20 x 10⁶</td>
</tr>
<tr>
<td><strong>e⁺ / second</strong></td>
<td>0.06 x 10¹⁴</td>
<td>1.1 x 10¹⁴</td>
<td>3.9 x 10¹⁴</td>
<td>400 x 10¹⁴</td>
</tr>
</tbody>
</table>

Experimental programs require one of two types of gamma beams: quasi-monoenergetic photons beams or beams with a large energy spread. Optimization of the laser and electron beam parameters to achieve a narrower energy spread (and higher polarization) with angular collimation often results in many orders of flux reduction. The positron generation experiment requires maximizing gamma beam flux, possibly along with a high polarization. The laser and electron beam intensity and their focusing are pushed to the practical limits in this case.

There are many factors to consider when selecting the optimal energy of the gamma beam for positron generation. The energy dependence of the Bethe-Heitler $e^- e^+$ pair creation process is shown in Figure 2-34.

![Figure 2-34: Energy dependence for the cross section of the Bethe-Heitler process $\gamma \rightarrow e^- e^+$ plotted as ratio of cross-sections at given energy to one at extremely high $E_\gamma : \sigma_\text{tot} / \sigma_\infty$. The dependence is plotted for hydrogen, titanium and tungsten targets.](image-url)
The energy dependence curve suggests that this process would benefit from a higher energy gamma beam. On the other hand, the longitudinal emittance of the captured beam is proportional to the energy of the generated positrons. The acceptance of the damping ring in practical designs thereby limits the energy of the gamma beam. Detailed optimization studies [100] concluded a soft optimum in the range of 30-100 MeV.

The expected efficiency of converting polarized $\gamma$-photons into captured positrons is between 0.2 and 2%, depending on the energy of the gamma beam [6]. Therefore, every positron requires, as precursors, more than fifty $\gamma$-photons assembled in the beam format (time pattern) of the $e^−-e^+$ collider beams. There are different proposals to accumulate this $\gamma$-flux for collider applications. A lower intensity yet more concentrated gamma beam is proposed for the conversion studies at FACET-II.

The integral efficiency of the $\gamma$-production in the collision can be estimated from
\[
\frac{N_\gamma}{N_e} = \frac{N_\varphi}{S} \sigma_c, \quad \text{where } N_\gamma, N_e, \text{ and } N_\varphi \text{ are the numbers of } \gamma\text{-rays, electrons, and laser photons, respectively, } S \text{ is the cross-sectional area of the interacting beams, } 
\sigma_c = \frac{8}{3} \pi r_e^2 = 6.652 \times 10^{-29} m^2 \text{ is the Compton scattering cross-section, and } 
\frac{e^2}{m c^2} = 2.818 \times 10^{-15} m \text{ is the classical electron radius. With 0.1 Joule of a CO}_2\text{-laser beam focused to its practical limit of 25-}$\mu$m rms radius, the efficiency is estimated as } N_\gamma/N_e=0.1. \text{ It is expected that electron beam will be focused to a size smaller than laser beam, at 7.4-GeV electron energy, for the generation of the 100 MeV gammas. A similar efficiency can be achieved in the case of a Ti: Sapphire laser beam of 1.0 Joule. With the Ti:Sapphire laser only a 2.1-GeV beam will be needed for the generation of 100 MeV gammas. The laser beam can be focused much more tightly in this case, but the interaction cross section will be dominated by the electron beam size at approximately the same } 25 \text{-}$\mu$m spot. \text{ It will become more challenging to design the IP optics for Ti:Sapphire laser beam due to the small divergence of this high energy laser. Generation of gamma beams with lower than 100MeV energy will be more efficient with a CO}_2\text{ laser beam. The advantages of CO}_2\text{ laser beam for this applications as well as its excellent match to the high-energy pulse linac at SLAC were discussed in more detail in [104]. }

To complete the optimization of the laser parameters, such as the peak power $P,$ pulse duration $\tau,$ and the energy per pulse $E,$ we note that to maintain the maximum efficiency of the laser and $e$-beam interactions, the laser focal spot should match the $e$-beam size, and its pulse length should be close to the Rayleigh length $Z_R = \frac{2\pi\sigma^2}{\lambda},$ where $\sigma$ is the laser beam radius at the focal plane. For a Gaussian beam of radius 25 $\mu$m, the Rayleigh $R_L=0.3$ mm, and the optimum pulse length of the CO$_2$ laser is $\sigma_{e} \approx 1$ ps.
The magnitude of the nonlinear Compton scattering is characterized by the normalized vector potential, \( a = \frac{e}{mc^2} \sqrt{\frac{(A_\mu A^\mu)}{A_\mu A^\mu}} \), where \( e \) is the charge of the electron, \( A_\mu \) is the four-vector potential of the laser, and \( mc^2 \) is the electron’s rest energy. The parameter \( a \), simply called “laser strength”, can be re-written more conveniently as a function of the laser’s wavelength \( \lambda \) in \( \mu m \), and intensity \( I \) in \( W/cm^2 \). In this form \( a = 0.60 \times 10^{-9} \lambda I^{1/2} \). The nonlinear Compton scattering approaches the linear process at \( a \geq 1 \), thereby putting an upper limit on the maximum laser intensity. The laser strength is not expected to exceed 0.3 for the proposed CO\(_2\) laser beam parameters.

Summarizing this discussion on optimizing the IP for the Compton \( \gamma \)-source, we propose the set of parameters compiled in Table 2-5.

### Table 2-5: CO\(_2\) laser- and e-beam parameters at the Compton IP.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser beam energy</td>
<td>( E_L )</td>
<td>0.1 J</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>( \lambda )</td>
<td>10.2 ( \mu m )</td>
</tr>
<tr>
<td>Rayleigh length</td>
<td>( R_L )</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Laser beam length</td>
<td>( \sigma_t )</td>
<td>1 ps</td>
</tr>
<tr>
<td>Normalized vector potential</td>
<td>( a_0 )</td>
<td>0.3</td>
</tr>
<tr>
<td>Electron beam size</td>
<td>( \sigma_e )</td>
<td>15-25 ( \mu m )</td>
</tr>
<tr>
<td>Electron beam energy</td>
<td>( E_e )</td>
<td>4-7.4 GeV</td>
</tr>
<tr>
<td>Gamma beam energy</td>
<td>( E_\gamma )</td>
<td>30-100 MeV</td>
</tr>
<tr>
<td>( \gamma )-ray production efficiency</td>
<td>( N_\gamma/N_e )</td>
<td>(~0.1)</td>
</tr>
</tbody>
</table>

A wide range of gamma beam energies, high peak intensities, and low divergence of the gamma beam (due to high energy and low geometrical emittance of the electron beam) make this source optimal for studying novel ideas for conversion targets.

Crystal and hybrid targets are examples of novel conversion targets. Either a gamma beam or the electron beam could be used to hit the test targets. Particles traversing at small angles along a single crystal axis experience the collective scattering force of many crystal atoms. The enormous fields inside the crystal can trap the particles along an axis or plane, a process called channeling. High-energy electrons are attracted by the positive nuclei and, therefore, can produce strongly enhanced coherent bremsstrahlung and pair production. These effects could be used in a positron production target. The target length can be shorter than for an amorphous material, which then yields a higher conversion coefficient and a lower emittance of
the positron beam. This makes single crystals very interesting for positron production targets.

### 2.9 BIG - gamma-ray source at FACET-II

The BIG, based on the electron beam and lasers at FACET-II, will be a very versatile, nearly mono-energetic gamma-ray source for nuclear physics experiments. The high quality of the incoming electron beam will allow it to act as a collimator, turning BIG into a nearly mono-energetic gamma-ray beam.

We will assume that energy of the beam in FACET-II can be tuned from 1 GeV to 10 GeV. In combination with two lasers operating at 800 nm and 10 μm, the BIG therefore has 1,000-fold tunability from about 2 MeV to 2 GeV. The high-energy reach can be increased to 5 GeV using the third harmonic of 800 nm laser, but with an accompanying 5-fold loss in the flux.

We will be able to switch lasers or select different harmonics to adjust gamma-ray energy in coarse steps, or change the electron beam energy to provide nearly continuous fine-tuning of the laser.

<table>
<thead>
<tr>
<th>Injectors</th>
<th>Beam</th>
<th>Energy [GeV]</th>
<th>(\varepsilon_{nx} \times \varepsilon_{ny}) [μm x μm]</th>
<th>(\sigma_{x} \times \sigma_{y}) [μm x μm]</th>
<th>(\sigma_{z} \times \Delta E/E) [μm x %]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermionic</td>
<td>3nC e⁻</td>
<td>10</td>
<td>30 x 3</td>
<td>20 x 20</td>
<td>40 x 1</td>
</tr>
<tr>
<td></td>
<td>1.5nC e⁺</td>
<td>10</td>
<td>30 x 3</td>
<td>20 x 20</td>
<td>40 x 1</td>
</tr>
<tr>
<td>Photoinjector</td>
<td>20pC e⁻</td>
<td>10</td>
<td>0.1 x 0.1</td>
<td>1 x 1</td>
<td>2 x 1</td>
</tr>
<tr>
<td></td>
<td>1nC e⁻</td>
<td>10</td>
<td>1 x 1</td>
<td>3 x 3</td>
<td>5 x 1</td>
</tr>
<tr>
<td></td>
<td>6nC e⁻</td>
<td>10</td>
<td>5 x 5</td>
<td>10 x 10</td>
<td>20 x 1</td>
</tr>
<tr>
<td></td>
<td>3nC e⁺</td>
<td>10</td>
<td>30 x 3</td>
<td>20 x 20</td>
<td>40 x 1</td>
</tr>
<tr>
<td>Witness photoinjector</td>
<td>0.1nC e⁻</td>
<td>0.1</td>
<td>1 x 1</td>
<td>50 x 50</td>
<td>20 x 0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lasers</th>
<th>Energy / Power [Joule / TW]</th>
<th>Rep rate [Hz]</th>
<th>(\tau) [fs]</th>
<th>(\lambda) [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti: Sapphire</td>
<td>1 / 30</td>
<td>10</td>
<td>30</td>
<td>0.8</td>
</tr>
<tr>
<td>CO₂ laser</td>
<td>0.1 / 0.1</td>
<td>120</td>
<td>1000</td>
<td>10.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gamma beams (Inverse Compton)</th>
<th>Energy [GeV]</th>
<th>Intensity</th>
<th>Rep rate [Hz]</th>
<th>(\sigma_{x} \times \sigma_{y}) [μm x μm]</th>
<th>(\sigma_{z}) [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti: Sapphire</td>
<td>1.8 GeV</td>
<td>10¹⁰</td>
<td>10</td>
<td>5 x 5</td>
<td>10</td>
</tr>
<tr>
<td>CO₂ laser</td>
<td>150 MeV</td>
<td>10¹⁰</td>
<td>120</td>
<td>5 x 5</td>
<td>10</td>
</tr>
</tbody>
</table>

The \(\gamma\)-ray beam energy range comfortably covers the energy ranges of interest for users of H\(\gamma\)S (TUNL, Duke University) and LEPS (Spring 8, Japan). Using two set of lasers (CO₂ and Ti: Sapphire) and electron beam energies from 1 GeV to 10 GeV,
FACET can generate gamma rays with continuously tunable energy from 2 MeV to 1.9 GeV. This three orders of magnitude tunability is indeed unprecedented.

FACET can create gamma rays with unprecedented intensity – from $10^{10}$ to $10^{11}$ gammas per second. This intensity, in combination with the high brightness of the electron beam, allows us to collimate the gamma ray to a nearly mono-energetic beam with energy spread as low as 0.1%.

There is, however, a tradeoff between energy spread comes and flux: For example, a gamma-ray beam with 1% rms energy spread would have typical flux of $10^8 - 10^9$ gammas per second, while increasing resolution to 0.1% will reduce the flux to $10^7 - 10^8$ gammas per second. Exact numbers depend on specific choice of the gamma-ray energy, as shown in Figure 2-35.

**Figure 2-35**: Normalized gamma-ray distribution as function of their energy for 10 GeV e-beam: top graph is for a CO$_2$ laser, bottom graph is for a Ti: Sapphire laser.
The polarization of the \( \gamma \)-rays can be controlled by that of the scattered laser beam, and can be linear (vertical or horizontal), circular (left or right) or elliptical. The degree of polarization depends on the gamma-ray energy: it is very close to 100% at low energies and is 97.7% for 1.9 GeV gamma rays.

Many experiments require a fine energy resolution, and an electron beam with very low emittance provides for such possibility. A simple geometrical collimation of the \( \gamma \)-ray beam can create a \( \gamma \)-ray energy spectra with FWHM below 0.1% (see Figure 2-36). Scanning the energy of the beam will allow us, for example, to de-convolve fine structure of the spin observable at the pion threshold.

![Energy Spectrum](image)

**Figure 2-36:** A narrow energy spectrum of BIG's collimated beam. Energy spectrum of 0.1% FWHM or better could be obtained at BIG.

Time structure of the gamma-ray bursts can be important for experiments. While pulsed structure with 100-120 Hz is a standard feature of BIG, the structure of each pulse can vary. The \( \gamma \)-rays can be delivered in one short picosecond duration burst, or can be distributed into as many as 1,000 ps bursts separated by 1 nanosecond.

### 2.10 Generating High-Brightness Muon Beams With High-Energy Gammas

Hadron colliders are impractical at very high energies because effective interaction energy scales with beam energy and luminosity must rise as energy squared. Further, the prevailing gluon-gluon background radiation makes it difficult to sort out events. Positron-electron colliders are constrained at TeV energies by bremsstrahlung radiation and also by cost because long linacs are required to avoid synchrotron radiation in the rings. A muon collider will have the same advantages in energy reach as a positron-electron collider, but without prohibitive beamstrahlung and synchrotron radiation.

High-brightness polarized muon (\( \mu^+\mu^- \)) beams are generated through gamma conversion into pairs in the nuclei field. The dominant effect in the interaction of the high-energy photons with the solid target will be the production of electron-
positron pairs. The low-phase space of the resulting muon beams adequately compensates for the small probability of generating a \( \mu^+\mu^- \) pair. The probability of a \( \mu^+\mu^- \) pair creation is suppressed approximately by a factor of \( \mu_0^2/\mu_0^2 \). However, FACET-II will be able to generate extremely powerful high-energy \( \gamma \) beams through Compton backscattering, making it possible to study high brightness muon beam production. Low intrinsic emittance from the direct production of the \( \mu^+\mu^- \) pairs makes this approach competitive with the currently considered production scheme, in which a high-power proton beam generates a pion shower, and the pions, in turn, decay into muons. Indirect muon production is orders-of-magnitude more efficient in terms of the number of the muons per incident beam power. Approximately 0.2% of the drive beam power is converted into the muon beams in case of proton drivers, and only 0.001% is converted with gamma drivers. The brightness of the resulting beam, however, is much lower with protons, so that very challenging and complicated cooling schemes must be incorporated into the system. Therefore, using protons to create neutrinos may not be as cost-effective as some researchers believe. [105]

The interaction of few-GeV gamma rays with the solid target is dominated by their conversion into electron-positron pairs. At these energies, Compton scattering of the photon from the atomic electron is considerably smaller. We will consider the ratio of the \( \gamma \rightarrow \mu^-\mu^+ \) to \( \gamma \rightarrow e^-e^+ \) cross sections. One can split the Bethe-Heitler total cross-section, describing pair creation, into two parts: an asymptotic region at very high energies of the photon cross sections \( \sigma_\infty \), and an energy dependent part at lower energy, \( \sigma(E_\gamma) = \sigma_{\text{tot}}/\sigma_\infty \) (Figure 2-34), that is in the range from 0 to 1. [87] It shows moderate advantage of the light nuclear targets at the lower energy range, and low efficiency for the gamma energies near the muon pair creation threshold.

![Figure 2-37: Energy dependence for the cross section of the Bethe-Heitler process \( \gamma \rightarrow \mu^+\mu^- \) plotted as \( \sigma_{\text{tot}}/\sigma_\infty \). The dependence is plotted for hydrogen, titanium and tungsten targets.](image)

The energy-independent part can be written in the following form [8]: \( \sigma_\infty = \left(\frac{\alpha}{\pi}\right) 4\alpha Z^2 r_c^2 \log(W_\infty) \) where \( \alpha \) is the fine structure constant, \( Z \) is the atom charge, \( r_c \) is a classical-particle’s radius, \( W_\infty \approx 136 \frac{m_e\mu}{m_e} \) for hydrogen, and \( W_\infty \approx \frac{119}{\alpha^2} \frac{m_e\mu}{m_e} \) for the rest of the nuclei. The total cross section rises linearly in \( \log(E_\gamma) \) with the slope
\[ W_M \approx \left( \frac{1}{4} \right) \frac{1}{1.49 \, m_{e\mu}} \] for hydrogen, and \[ W_M \approx \left( \frac{1}{4} \right) \frac{1}{1.54A^{0.27} \, m_{e\mu}} \] for the rest of the nuclei. Therefore, the total cross-section is \[ \sigma_{\text{tot}} \approx \left( \frac{28}{9} \right) \alpha Z^2 r^2 \log(1 + W_M E_\gamma). \]

This derivation is valid for well above the threshold photon energy for the muon pair creation and below its saturation energies, i.e. where \( W_M E_{\text{sat}} < W_{\text{mc}} \). The gamma beams generated with Ti:Sapphire laser beam at FACET-II are within this range.

Now, the probability that the photon will create a \( \mu^+\mu^- \) pair can be estimated as \[ \frac{\sigma_{\text{tot} \mu}}{\sigma_{\text{tot} e}} \approx \left( \frac{1}{4} \right) \frac{m_{e\mu}^2}{m_{\mu}^2} \] or between 0.2x10\(^{-5}\) and 0.5x10\(^{-5}\) (see Figure 2-38). Using the second or third harmonic of the Ti:Sapphire laser beam will result in a heaker energy gammas (at lower beam intensity) and will improve muons pair cross section as well it will lower emittances. Some electrons and positrons will be scattered and will regenerate gamma photons with sufficient energy for \( \mu^+\mu^- \) pair production. This or other sources of correction to the assessment were not considered since they are not expected to change the result by more than tens of percents.

![Figure 2-38: Probabilities of creating \( \mu^+\mu^- \) pairs as a function of the incident photon energy for hydrogen, titanium and tungsten targets are plotted.](image)

Approximately 50\% of the \( \mu^+ \) and \( \mu^- \) beams will be generated with energies ranging from \( E_\gamma/2 \) to \( E_\gamma \) when \( E_\gamma >> 4m_\mu c^2 \). The duration of the \( \mu^- \) beam will be similar to that of the \( \gamma \) beam, or drive electron-beam. The estimate of longitudinal emittance can be written in the form \[ \varepsilon_{N\|} \approx c \tau_e \frac{Y_{\mu max} - Y_{\mu min}}{4}, \] where \( Y_{\mu}, Y_{\mu min}, \) and \( Y_{\mu max} \) are the mean, the minimum, and the maximum values for the captured \( \mu^+ \) and \( \mu^- \) beams, and \( \tau_e \) is the duration of the electron bunch.

The generated muons have a divergence of \( 1/\gamma_\mu \) and muon beam size at the exit of the target with length \( L_{\text{target}} \) will be dominated by the muons divergence and can be estimated as \( \sigma_{\mu \text{min}} \approx \frac{L_{\text{target}}}{2\gamma_\mu} \). Therefore, the normalized transverse emittance can be assessed as \[ \varepsilon_{N\perp} \approx \frac{L_{\text{target}}}{2\gamma_\mu}. \] The longitudinal and transverse normalized emittances of
the $\mu^+\mu^-$ beams produced with a high-intensity 2 GeV $\gamma$ beam from the tungsten target which is one radiation length long are calculated as 150 and 50 $\mu$m, respectively. For comparison, it is estimated [105] that the longitudinal and transverse normalized emittances of the captured muon beam produced with proton beams are 20 cm and 18 mm, respectively. Approximately one million muons are expected to be captured per second in the 120 Hz mode with abovementioned emittances. Immersing the target into a focusing field, thereby limiting the muon beam's size expansion during the gamma ray-beam interaction, can further reduce transverse emittances. Utilizing crystal targets for pair creation will allow channeling of the created muons therefore will result in even colder beams.

Availability of the muon beams with very low transverse emittances is crucial for studies of novel muon beam cooling and acceleration techniques in the crystal lattices and nanostructures [106, 107] due to naturally low acceptance angles of such structures.

### 2.11 Laboratory Astrophysics at FACET

Ultrahigh-energy cosmic rays (UHECR) and photons have been observed, but their sources and production mechanisms in space are yet to be understood. Laboratory astrophysics experiments may contribute to the understanding of cosmic accelerators in two categories: 1) Calibration experiments for the testing and calibration of UHECR observational techniques, and 2) Dynamics experiments for the investigation of relativistic plasma dynamics to elucidate the underlying physics of cosmic acceleration.

Two calibration experiments have been carried out at the FFTB. The E-165 FLASH experiment helped shed light on the apparent discrepancies in the energy determinations of cosmic rays around $10^{19}$ eV with precision measurements of air fluorescence yield in an electromagnetic shower. [108] The T460 experiment demonstrated the principle of a novel detection technique for ultrahigh-energy cosmic neutrinos based on radio Cherenkov signals due to the Askaryan effect. [109]

In principle FACET can provide high-energy-density particle beams at $10^{16}$ J/m$^3$ for dynamics experiments, creating extreme relativistic plasmas in a regime relevant to cosmic acceleration studies and accessible in a terrestrial environment. A third category of lab-astro experiments involves using high intensity or high energy density particle and laser beams as a probe for fundamental physics. An example is the creation of Unruh radiation from a violently accelerated electron in a laser field due to interaction with quantum vacuum fluctuations, a process similar to Hawking radiation from the event horizon of a black hole. [110]

While the extreme astrophysical conditions can never be replicated in the laboratory, the challenge is to devise and perform lab-astro experiments that will uncover the physical principles involved that can be scaled up to understand these powerful astronomical sources. Relativistic particle outflows, commonly observed in astrophysical sources such as active galactic nuclei and gamma-ray bursts, are a key...
element in many models of cosmic acceleration. Their interaction with ambient plasmas is believed to give rise to particle acceleration producing the observed radiation spectrum. An understanding of their dynamics is thus crucial to the development of a theory of a cosmic accelerator. In particular, experiments seek to investigate how kinetic energy of the outflow is converted into plasma instabilities which in turn power particle acceleration and radiation.

A key difficulty is the need for overall charge-neutral beams (overlapping e+ and e-beams) to mimic astrophysical outflows. At FACET, relativistic electron-positron plasmas in the form of directed “jets” could be created by showering high-energy-density electron beams onto a solid target, analogous to the e+ e- pairs that come off the positron target. The dynamics of jet-plasma interaction can be investigated over a scale length of several collisionless skin-depths. In a collisionless plasma, the mean-free-path is long compared to the skin depth so the latter is the relevant scale. Laboratory results can be applied to astronomical collisionless plasmas and will provide important tests of simulations for magnetic filamentation, inductive, wakefield, and ponderomotive acceleration, synchrotron radiation spectra, jet-plasma instabilities, and jet propagation over long distances.

The 2001 Workshop on Laboratory Astrophysics [111], the 2003 Workshop on Quantum Aspects of Beam Physics [112], the 2003 Orion Workshop [113], and the 2006 SABER Workshop [114] all included presentations on lab astrophysics using particle beams. After the 2006 workshop, SLAC conducted a limited study of these beam-based lab-astro concepts. During the past decade, research teams around the world have instead developed astrophysics-relevant research utilizing high energy-density (HED) facilities such as intense lasers and z-pinch [115]. Research is underway in many areas, such as compressible hydrodynamic mixing, strong shock phenomena, radiation flow, radiative shocks and jets, complex opacities, equations of state, dust formation, super strong magnetic fields, and relativistic plasmas. We will not review these developments, so the reader is referred to the HEDLA Meetings, held every two years, for details. [116]

We list the presentations from the Lab-Astro, Orion and SABER workshops that are relevant to possible lab-astro experiments in Table 2-7 through 2-9. Online workshop proceedings include further details [111, 113, 114]. The Proceedings of the 2003 “Quantum Aspects of Beam Physics” workshop [112] cover many of the same lab-astro topics, so we do not review it here. The titles in the tables clearly indicate the preponderance of “dynamics” experiments, especially those involving charged beams, neutral beams, and lasers, in some cases with background magnetic fields superimposed to mimic astrophysical environments such as shocks, particle jets, gamma-ray bursts, supernovas, and neutron stars. Calibration experiments are the next most represented, and these can be related to dynamics experiments when code validation is required to connect simulations, laboratory results, and astrophysical observations. Beam parameters for most experiments are usually not discussed in detail, although for jet-plasma and laser-induced shock/instability experiments there is some specific information in the slide presentations. Broadly speaking, the lab-astro experiments that might use SLAC’s relativistic electron-
positron beams are often flexible with respect to beam energies, which simply change the time and length scales according to the Lorentz factor. The bunch densities are usually in the range $10^{14} - 10^{18}$ /cc, bunch lengths are in the range 10 - 1000 µm, bunch diameters are of order 10 to 100 µm, plasma lengths are about a meter, and background magnetic fields (usually solenoidal) vary from 1 to 104 Gauss depending on the experiment.

Table 2-7: Presentations related to possible experiments from 2001 Lab-Astro Workshop. [111]

<table>
<thead>
<tr>
<th>Presenter</th>
<th>Title</th>
<th>Experiment Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>David Cline</td>
<td>Primordial Black Hole Induced Plasma Instability Expt.</td>
<td>Dynamics</td>
</tr>
<tr>
<td>Pierre Sokolsky</td>
<td>High Energy Shower Expt. for UHECR</td>
<td>Calibration</td>
</tr>
<tr>
<td>Jasper Kirkby</td>
<td>CLOUD Cosmic Ray Expt. on Climate Variation</td>
<td>Calibration</td>
</tr>
<tr>
<td>Pisin Chen</td>
<td>Plasma Wakefield Acceleration Expt. for UHECR</td>
<td>Dynamics</td>
</tr>
<tr>
<td>K. Nakajima</td>
<td>Laser Driven Dirac Acceleration for UHECR Expt.</td>
<td>Dynamics</td>
</tr>
<tr>
<td>A. Odian</td>
<td>Non-Askaryan Effect Expt.</td>
<td>Calibration</td>
</tr>
<tr>
<td>S. Colgate</td>
<td>Magnetic Flux Transport and Acceleration Expt.</td>
<td>Dynamics</td>
</tr>
<tr>
<td>T. Kamae</td>
<td>Photon Collider for Cold e + e − Plasma Expt.</td>
<td>Dynamics</td>
</tr>
<tr>
<td>M. Begelman</td>
<td>X-Ray Iron Spectroscopy and Polarization Expt.</td>
<td>Calibration</td>
</tr>
<tr>
<td>Johnny Ng</td>
<td>Relativistic e + e − Plasma Expt.</td>
<td>Dynamics</td>
</tr>
<tr>
<td>T. Katsouleas</td>
<td>Beam-Plasma Interaction Induced Photon Burst Expt.</td>
<td>Dynamics</td>
</tr>
<tr>
<td>R. Blandford</td>
<td>Beam-Plasma Filamentation Instability Expt.</td>
<td>Dynamics</td>
</tr>
<tr>
<td>J. Scargle</td>
<td>Relativistic MHD Landau Damping Expt.</td>
<td>Dynamics</td>
</tr>
</tbody>
</table>

Table 2-8: Presentations related to possible experiments from Orion Workshop 2003. [113]

<table>
<thead>
<tr>
<th>Presenter</th>
<th>Title</th>
<th>Experiment Type</th>
</tr>
</thead>
<tbody>
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<tr>
<td>Presenter</td>
<td>Title</td>
<td>Experiment Type</td>
</tr>
<tr>
<td>------------------</td>
<td>----------------------------------------------------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Pierre Sokolsky</td>
<td>Laboratory Particle Astrophysics</td>
<td>Calibration</td>
</tr>
<tr>
<td>Robert Bingham</td>
<td>Fundamental Physics using Atomic Beams and Lasers</td>
<td>Fundamental Physics</td>
</tr>
<tr>
<td>David Saltzberg</td>
<td>Neutrino Astrophysics and the Askaryan Effect</td>
<td>Calibration</td>
</tr>
<tr>
<td>Kevin Reil</td>
<td>Alfven Wave Induced Wakefield Acceleration for UHECR</td>
<td>Dynamics</td>
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<tr>
<td>Richard Sydora</td>
<td>Nonlinear Alfven Wave Dynamics: Wave Steepening and Particle Acceleration</td>
<td>Dynamics</td>
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<tr>
<td>Johnny Ng</td>
<td>Cosmic Accelerators in the Laboratory</td>
<td>Dynamics</td>
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<tr>
<td>K. Nakajima</td>
<td>Intense e+e- Pair Beam Production in Superstrong Laser-Matter Interactions for LabAstro Experiments</td>
<td>Dynamics</td>
</tr>
<tr>
<td>A. Yashin</td>
<td>Wave-Packet Approach to Unruh Effect</td>
<td>Fundamental Physics</td>
</tr>
<tr>
<td>Richard Klein</td>
<td>Creation of a Neutron Star on a Petawatt Laser</td>
<td>Dynamics</td>
</tr>
<tr>
<td>A. Spitkovsky</td>
<td>Electrodynamics of Magnetized Rotators</td>
<td>Dynamics</td>
</tr>
<tr>
<td>Robert Bingham</td>
<td>Similarities between e and v Beams in Plasmas</td>
<td>Dynamics</td>
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<tr>
<td>R. Paul Drake</td>
<td>Connecting Laboratory Experiments with Astrophysical Phenomena</td>
<td>Dynamics</td>
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Table 2-9: Presentations related to possible experiments from SABER Workshop 2006. [114]
The characteristics of the FACET-II facility at SLAC will make it an ideal test-bed for measurements of crucial importance for the CLIC study. Consequently the CLIC study is preparing a formal proposal for the approval of the following experiments to be performed at FACET-II:

- Experimental verification of the performance of system identification, feedback and on-line alignment algorithms for the linear collider and final-focus
- Direct measurement of the long-range transverse wakefields of industrialized CLIC main-linac accelerating structures
- Direct measurement of the transverse wakefields of linear collider final focus collimator geometries

More details of the experiments are presented in the following sections.

### 2.12.1 Verification of on-line system-identification, feedback and tuning algorithms

The performance of future linear colliders will depend critically on beam-based alignment (BBA) and feedback systems. ILC and CLIC will routinely undergo dispersion-free steering (DFS) in the main linacs [117, 118]. In CLIC, an option for a parasitic on-line dispersion-free correction is being studied.

DFS is a beam-based alignment technique for steering the orbit and correcting the dispersion at the same time. The technique requires accelerating one or more test beams with different gradients to evaluate the dispersion. The steering is performed by minimizing the offset of the nominal beam in the beam position monitors (BPMs) and zeroing the difference between the test beam trajectories and the nominal trajectory. The experimental verification of the DFS algorithm is essential to prove its effectiveness and to prepare the commissioning of such machines.

Knowledge of the system model is crucial for developing effective beam-based algorithms. In the CLIC main linac for example, even small changes in the acceleration gradients, the phases, or the magnet strengths can significantly change
the the system model. A reliable knowledge of such a system response is very important. We propose using an adaptive system identification algorithm that measures the system response matrix dynamically and automatically [119]. We propose to test such system identification procedures and beam-based alignment algorithms for linear colliders at FACET-II. Figure 2-39 shows the results of some simulations.

The very small emittances in linear colliders require fast correction of static and dynamic imperfections, e.g. misalignment and ground motion, through beam-based alignment algorithms and feedback. The effectiveness of such algorithms is, however, limited by the knowledge of the matrix representing the response of the beam trajectory to the action of the correctors. FACET-II, with its km-long linac accelerating both electrons and positrons to a relatively high final energy, and with micro-metric emittances, will offer an ideal setup for testing beam-based alignment algorithms and the system identification algorithms. We believe that this experiment will be crucial to consolidate and perfect the procedures needed to commission and operate future linear colliders.

![Figure 2-39: Emittance growth in the first 2 km of SLC linac, after BBA correction. Left-hand plot shows the horizontal and vertical emittance for 1:1 corrected and DFS corrected machines. The right-hand plot shows the vertical emittance growth after DFS when the correction is computed using an imperfect model. Each curve is the average of 100 randomly misaligned machines.](image)

During the first half of 2012 we have been able to perform the experiment at FACET. During this time we have installed our software on the FACET servers and performed several tests of system identification and beam-based alignment. The system identification and beam-based alignment algorithms have proven to be extremely successful, especially when dealing with orbit correction. We believe we can improve these results and test more advanced techniques such as emittance tuning bumps or dispersion bumps.

System identification results are shown in Figure 2-40. The response matrices shown in the figure were obtained automatically in about two hours of operation with no need for any human intervention, using our dedicated software.
Figure 2-40: Result of the system identification algorithm during the run in June 2012. From top to bottom, left to right, the matrices $R_{xx}$, $R_{xy}$, $R_{yx}$, and $R_{yy}$.

Figure 2-41: Result of the orbit correction algorithm during the run in June 2012. From top to bottom: the horizontal orbit, the vertical orbit, and the absolute error.

Example of results of global orbit correction are shown in Figure 2-41. An initial orbit, exhibiting an oscillation as large as about 1 mm, was steered to read zero on the BPMs, within the jitter of the machine. The orbit correction we implemented performed in an efficient and robust manner. The orbit correction software
automatically performed the six iterations shown in figure in less than two minutes, with each iteration taking about 20 seconds.

2.12.2 Measurement of long-range transverse wakefields in industrialized accelerating structures

Manufacturing of the CLIC main linac accelerating structures will progress from the prototype phase to an industrial facility in a few years. Given the complexity of the manufacturing process, it will be crucial to suppress the long-range wakefields as effectively in the industrialized structure as in the test prototypes. Given the characteristics of its electron and positron beams, the FACET-II facility will provide a unique opportunity to measure wakefield suppression.

The CLIC baseline accelerating structure is composed of a tapered chain of 26 damped cells with a double-feed coupler for the input and the output power [120]. See Figure 2-42 for a picture of a prototype. The damping suppresses the wakefields in order to reduce them to an acceptable value and to preserve small emittances during the accelerating process. It is implemented by four rectangular waveguides coupled to the main accelerating cells. The waveguides are terminated by inserting pieces of lossy dielectric loads inside. We expect to have strong long-range wakefield suppression, about a factor 50 in 6 RF cycles (15 cm). This will allow us to minimize the coupling of two consecutive bunches of the CLIC train. The simulated transverse wakefield is shown in Figure 2-43.

Figure 2-42: High-power test structure. The overall length is 30 cm.
The x-band test structure setup will consist of six accelerating structures in a common vacuum tank. At this stage no power will be sent to the test structure and the double feed couplers will be terminated by the loads. The test structure will consist of clamped aluminum cells. We would need positrons to function as a driving bunch and electrons as a witness bunch to measure the kicks due to the drive bunch by varying the bunch separations in order to map wakefields.

We would like to measure the transverse wakefields of a fully-featured accelerating structure as a function of distance behind a driving bunch. The driving and the witness bunches must be separately positrons and electrons in order to separate trajectories and achieve sufficient resolution in the downstream beam position monitors (BPMs), which measure the deflecting angle. This angle is in inverse proportion to the energy of the witness bunch. The achievable resolution of the wakefield will depend on beam energy, driving bunch charge, beam offset and BPMs resolution. The absolute value of the wakefield can be increased by installing multiple structures. Bunch length should be ideally less than 1 mm in order to resolve the third dipole band which shows up a peak around 40 GHz in the real part of the impedance spectrum.

2.12.3 Measurement of collimator transverse wakefields

Another experiment to be performed at SLAC is the measurement of collimator wakefields. Collimator wakefields in the Beam Delivery System (BDS) of future linear colliders, such as the ILC and CLIC can be an important source of emittance growth and beam jitter amplification, consequently degrading the luminosity. For this reason it is vital to understand and measure such collimator wakefields both theoretically and experimentally. Single-bunch collimator wakefields have been measured in [121, 122, 123, 124] with the aim of benchmarking theory, numerical
calculations and experiments. Those studies revealed some discrepancies between the measurements and the theoretical models. Given the characteristics of such wakefields, a lower energy beam with short bunches is required. The perfect candidate for such measurements is the beam provided by the End Station Test Beam (ESTB) test facility at SLAC.

New measurements using ESTB at SLAC will help to understand the origin of the above-mentioned discrepancies. For a rigorous comparison between measurements, theoretical calculations and simulations, the precise measurement of the bunch length will be essential. We are especially interested in the regime of short bunches relevant for the CLIC studies. This experimental test uses several collimator prototypes with different materials and geometric design, with the system set up to provide bunches with longitudinal length as close as possible to the nominal CLIC bunch length. We will compare the measured wakefield kick factors with simulation and analytic calculation results.

2.13 FEL R&D or ‘A particle beam physics research program at the FACET-II’

2.13.1 Introduction

Particle beam physics is at the core of the development of new instruments for the exploration of the properties and organization of matter at the sub-atomic, atomic and molecular scale with increasing space-time resolution. High energy accelerators, are the instruments that allowed the development of the standard model of elementary particles, and are now opening the exploration of atomic and molecular science with the resolution of angstroms and femtoseconds.

A strong and robust program of research in the physics of particle beams and their interaction with lasers and plasmas is critical as we continue to expand the capabilities of particle accelerators, while reducing their cost and size. The program must have a theoretical/numerical simulations component and a strong experimental component to verify calculated expectations on a large scale. National laboratories such as SLAC have the facilities needed to carry out the research and are the natural medium for this activity. The program should also have a strong university component, essential for educating the new generation of scientists in this field. The university component can and should include some smaller "university scale" experiments as well. We can prove many concepts with experiments at existing, medium size, accelerator test facilities, such as the Accelerator test facility at Brookhaven National Laboratory or NLCTA at SLAC, using beam energies in the range of 50 to a few hundred MeV.

There is a large class of important, frontier experiments requiring electron beam energies larger than a few GeV. One such class of experiments is that of laser/plasma accelerators. Another class is the acceleration and manipulation of high brightness electron beams, including manipulation with lasers, used for synchrotron radiation sources and FELs, discussed in section 2.13.2.

In the following sections we describe several experiments. It is important to notice that while these frontier experiments may vary in their primary goal, the beam
physics, the required instrumentation and the theoretical/numerical tools have much in common. There is a strong synergy between these types of research and the facilities needed for experimental proof. The advances in laser/plasma accelerators, with the capability of producing accelerating fields of 1 GeV/m or larger, is an important step toward reducing the cost and size of hard x-rays FELs and advancing particle physics. The improved knowledge of how to transport high brightness beams while preserving their 6-dimensional phase space and measuring their characteristics will be extremely useful for advances in laser plasma accelerators and their applications.

In the last section we will outline a program with the goal of developing an x-ray FEL using a laser/plasma accelerator as a driver, that would definitely join the two primary types of the frontier research.

There are four lines of research to improve the performance of existing FELs and open the way to the next generation of these photon sources:

- Quality and control of the electron bunch - the lasing medium and the 6-dimensional phase space distribution;
- Quality and control of the FEL photon pulses, including transverse and longitudinal coherence, peak power, and spectral power density;
- Special features important for experiments using the photon pulses, are tunability, synchronization, polarization control, intensity stability, pulse duration, and multicolor FELs;
- Maximization of the energy transfer from the electrons to the photon pulse. Increasing the number of coherent photons generated per electron.

### 2.13.2 Electron beam - brightness for next-generation FELs

The FEL lasing, its gain length and many other characteristics depend strongly on the electron brightness and 6-dimensional phase space distribution. The phase space distribution is determined by the electron source, the acceleration and compression process, and a variety of collective effects, including coherent synchrotron radiation, wake fields in the linac, longitudinal space charge effects and more. The present state of the art is good enough to power a SASE FEL down to a few Ångstrom wavelengths. However, the peak current is limited by CSR effects, and the distribution is not ideal for the lasing process. A typical example of longitudinal distribution of the electron bunch at the LCLS undulator is shown in Figure 2-44.
The current and energy spread change along the bunch, thus changing the local gain length, a situation similar to that of a conventional atomic laser where the density and temperature of the lasing medium change along its length. The less than ideal current and energy profile limit the transverse and longitudinal photon pulse coherence, and the effectiveness of seeding, self-seeding or iSASE. It also reduces the peak power obtainable when tapering the undulator.

Improving the 6-dimensional phase space distribution and making it nearer to the ideal condition for driving an FEL is a difficult task, requiring the development of new methods to: compress the beam to achieve the high current needed to drive an FEL, better control and possibly take advantage of collective instabilities, shape the beam temporal profile, and optimize the electron current generated by the gun. Improved higher resolution diagnostics to characterize high brightness, very short (femtosecond duration) electron and photon pulses, as well as hundreds of femtoseconds long bunches needed for very small radiation line width, are also a challenge and in need of continuous development. It will also need the development of higher resolution phase space diagnostic instrumentation.

Examples of possible studies include, but are not limited to: shaping the temporal and special profile of the electron current from the gun to minimize linac wakefield effects, using velocity bunching in the injector to minimize downstream magnetic compression, introducing nonlinear elements in the bunch compressors. These experiments are time consuming and require the flexibility to modify critical components such as the electron gun, linac, compressor system, thus making it impossible to execute in a user facility FEL such as LCLS. Study and proof of techniques to reduce the RF jitter from the power sources is another crucial program as jitter in the RF amplitude and phase translates to electron beam energy jitter in the accelerator and a chirp in the photons.

### 2.13.3 SASE FELs and longitudinal coherence

Hard x-ray FELs now in operation operate in the SASE mode, the typical photon pulse line width is given by the FEL parameter, $\rho$, of about $10^{-3}$, and the temporal profile consists of spikes with length proportional to the cooperation length. Each spike has a transform limited line width, again on the order of $\rho$. Very short photon
pulses of a few femtosecond duration, consisting of a few spikes, have been obtained at LCLS at SLAC by two methods: 1) reducing the electron bunch charge and compressing its duration to a few femtosecond; 2) filtering the electrons through a foil to spoil their emittance except for those in a very short part of the bunch.

The generation of very short photon pulses is one line of development for soft and hard x-ray FELs. However, the small number of lasing electrons limits the number of photons in a pulse. For larger bunch charges and longer photon pulses with many spikes, the longitudinal coherence is well above the transform limit.

Much attention and work has been dedicated to improving the longitudinal coherence for long bunches and reducing the line width to values between $10^{-4}$ and $10^{-5}$. The methods proposed include seeding the electron beam with external lasers, and self-seeding. More recently an idea was proposed at SLAC to implement a corrugated pipe to induce strong longitudinal wakefields, which can be used to manipulate the chirp in the beam energy. [125] Calculations to prove this principle at lower energies and some experiments at about 60MeV to confirm the theory were conducted [126,127]. We need to conduct a full-scale demonstration using high brightness GeV beams with parameters similar to the beams at the entrance to the wiggler to validate the use of the technique on FEL accelerators. Another recent proposal, called the improved SASE (iSASE), is to insert electron delay lines between the undulator sections to discretely increase the photon/electron interaction instances within the bunch to increase the SASE gain. [128] This experiment also requires a full scale experimental facility. An R&D program should include experimental assessments of the most promising methods, explore the capabilities of each technique and characterize their technology requirements.

For the studies of these techniques, in particular the external laser seeding (which requires imprinting an external energy modulation on the electron beam, which then causes the beam to bunch further and using the higher harmonics of the initial bunching) it is important to have a beam of a few GeV energy, similar to that required for soft x-ray FELs and high brightness beams. The preservation of the bunching from the seeding point to the radiating undulator and the study of nonlinear effects in the harmonic generation are important and can only be realistically studied with a beam energy not too far from that of the beam energy required for the FEL.

2.13.4 Polarization control, multicolor FELs, synchronization and other special features

A GeV class test facility is needed with enough space dedicated to the undulator systems to test methods of varying and controlling the photon polarization, generating prescribed multicolor photon beams, and developing techniques to synchronize x-ray pulses with other laser pulses for pump-probe experiments down to the femtosecond level.
Multicolor pulses can be generated by using different undulators on the same electron beams or possibly with other techniques such as electron beam energy chirping by use of external lasers. The proposed facility will offer the unique opportunity to utilize the beam generated by a laser/plasma accelerator to drive an FEL, possibly using undulators with a transverse magnetic field gradient to compensate for large energy spread in the electron beam generated by plasma accelerators. If successful this opportunity for a novel way to drive the FEL would have an important impact on the design of future coherent photon sources, reducing the cost and size of these facilities and making them available on a wider scale.

2.13.5 Terawatt peak power FELs

Increasing the peak power and reducing the pulse duration of the x-ray pulse can have an important impact on single shot imaging experiments, making possible the imaging of a single molecules. This goal can be achieved using tapered undulator if the longitudinal coherence of the photon pulse is increased with respect to the SASE case, reducing the line width to $10^{-4}$ or better. The studies of the longitudinal coherence, and the related longitudinal phase space distribution are critical for this possibility.

An alternative to the tapered undulator approach is to use a high charge, long, energy chirped electron bunch to drive the FEL, generating a long photon pulse with a frequency chirp. The chirp could be of the order of 1% in energy and 2% in frequency. The photon pulse, initially in the few hundred femtosecond region, can then be compressed with a double grating system to a pulse length of about 10 fs, with a corresponding increase in peak power. The large frequency band can be useful in imaging, in particular to reduce the number of diffraction patterns needed for 3-dimensional sample reconstruction. The electron energy chirp can be further enhanced with specially designed vacuum pipe as wakefield generator, which can be tested on the FACET-II/ITF beamline as described in section 3.3.3.

2.13.6 Seeding Methods

We present several schemes for seeding that should be pursued. These schemes each have distinctive requirements and areas for concern, and may best be studied at dedicated test facilities. We also discuss issues can apply to any FEL scheme, seeded or otherwise, although some are more relevant or suited to certain design types than to others.

2.13.6.1 Self-seeding

Self-seeding is a straightforward extension to SASE FELs that can ideally yield coherent output, or at the minimum a significantly reduced bandwidth and thus increased spectral brilliance. Researchers at SLAC have demonstrated a self seeding scenario [129] At the beginning of 2012 the LCLS implemented hard x-ray self-seeding with a single diamond monochromator. This scheme is currently limited to
a pulse duration of the order of 10 fs. To produce x-rays with even narrower bandwidth, we can investigate different crystals and alternative self-seeding configurations, such as using two bunches.

For soft x-ray applications, R&D is focused on various monochromators that provide high resolving power, tunability, and small optical delay to reduce the electron chicane requirements. Soft x-ray self-seeding R&D efforts can be pursued at the LCLS as well. The main challenges are how to achieve tight synchronization, and how to improve the resolving power of the monochromator to yield a coherence length of 100s of fs (a bandwidth below 20 meV).

The Enhanced Self-Amplified Spontaneous Emission (ESASE) technique could resolve some of the synchronization issues by providing an alternative method to link the output to an external laser. It also provides an alternative method to changing the electron bunch length for controlling the pulse length and can be applied to generate short pulses, as described below. Cross-correlation between x-rays and experimental lasers is needed to provide the necessary time stamp.

R&D in this area has several goals. We need to improve soft x-ray monochromators by reducing bandwidth and increasing tunability, which implies R&D on optical systems. It is important to test optimal placement of monochromators, verify improved brilliance, and explore tapering. With ESASE, we can evaluate these techniques in combination and develop required laser cross-correlation technology. Most of these goals can be met at existing facilities or involve component R&D that do not need to be incorporated into a full FEL facility. However, since lower bandwidth monochromators will deliver less power to the second stage of the FEL, the minimum power levels required for coherent output need to be experimentally observed. This does require a full FEL facility, although the scaling for the required power can be verified without achieving 1 nm wavelength.

2.13.6.2 High Gain Harmonic Generation

High Gain Harmonic Generation (HGHG) is a standard harmonic generation scheme and has recently been successfully implemented in the FERMI FEL operation down to 20 nm radiation wavelength. The expected effective harmonic conversion factor for a single stage HGHG is about 10. In order to go to shorter wavelengths, the concept of the “fresh bunch” cascaded HGHG has been proposed. The scheme can be sensitive to beam timing jitters and various errors can be accumulated through the cascading process.

R&D should focus on demonstrating cascaded HGHG at higher harmonic radiation wavelengths. This research can be carried out in SDUV in SINAP, SDL in BNL and FERMI FEL in Trieste.

While the HGHG operates in the nonlinear regime and does not require much FEL gain, the power radiated by the electron bunch is critical for the scheme. Thus, there are constraints on minimum current and maximum emittance for this scheme to work. While it would be preferable to observe HGHG reaching 1 nm output, a
well-characterized FEL output one harmonic jump away from 1 nm, in the range of 5 to 10 nm, should be sufficient for R&D needs.

2.13.6.3 Echo Enabled Harmonic Generation

Echo Enabled Harmonic Generation (EEHG) is a novel beam manipulation concept using two seeded lasers, and is currently under intense study in several laboratories. The scheme has the potential to go directly to a higher harmonic number well beyond a factor of 10. However, going beyond a factor of 100 (to reach soft x-rays from UV laser) presents tough challenges due to physical effects such as intrabeam scattering and incoherent and coherent synchrotron radiation, as well as practical effects such as tolerance, jitter, and imperfection of laser and electron beams. R&D should focus on better understanding and modeling of these physical and practical effects. The strictest requirements are on the second seed laser with tolerances that depend on the ratio $\lambda_2/\lambda_{x\text{-ray}}$. Demonstrations of EEHG beyond a factor of 10 as well as reaching shorter wavelengths are critical, and are planned at NLCTA at SLAC, SDUV in SINAP, SDL at BNL and FLASH at DESY.

EEHG involves purely external manipulations of the electron beam, with radiated power during the seeding stage actually being a deleterious effect. The manipulations themselves are very complex and produce a delicate phase space structure, so it is crucial to demonstrate bunching at the 1 nm wavelength. While FEL radiation and gain are helpful indicators of success, they could in theory be replaced by accurate slice diagnostics of the beam.

2.13.6.4 HHG (at-wavelength and cascaded)

This direct seeding method uses a High Harmonic Generation (HHG) process in a noble gas to produce attosecond pulses with enough power at very short wavelengths to overcome incoherent shot noise. The broad bandwidth of HHG systems is not well matched to the FEL bandwidth, dropping the effective efficiency of the seeding process. Typical efficiencies for state-of-the-art systems are on the order of $10^{-6}$ and fall significantly lower below 10 nm wavelength. Several optical elements are necessary to transport and focus the HHG source to the undulator entrance, causing further losses. As a result, power requirements for the HHG driver are daunting. Combining an Extreme Ultraviolet High Harmonic Generation (EUV HHG) source with a single-stage HHG or EEHG in a hybrid approach may enable us to reach soft x-rays of nm wavelengths. R&D can be carried out at FLASH, SPARC and elsewhere.

Key R&D efforts include improving total efficiency from the HHG drive laser to FEL output and optimizing transport of HHG output radiation. We can either reduce HHG bandwidth at a given high harmonic, or explore filtering of the HHG source. It is important to test FEL output beam quality both at the selected HHG target wavelength and at an x-ray harmonic.

Even more so than in the HGHG scheme, radiation by the electron beam is a crucial aspect of HHG seeding. The seeding begins in the small-signal regime, requiring a large amount of FEL gain. Still, the FEL performance could be characterized in the 5
to 10 nm range and then extrapolated to a final harmonic jump to 1 nm. There might be some advantage in varying the tradeoff between bunch compression and energy spread in order to make the effect of HHG seeding on the beam more readily apparent.

### 2.13.6.5 FEL efficiency and high peak power

As electron beam power is a limiting factor, improving the efficiency of energy conversion from the electron beam to the radiation pulse is a major priority. This becomes especially important when applications require pulses of short duration with a large number of photons. Typical SASE FELs have an efficiency on the order of $10^{-3}$, which can be modestly increased through tapering. Simulations suggest seeded FELs can be tapered much more effectively with an order of magnitude improvement. After succeeding with the self-seeding experiment, LCLS can be the ideal place to carry out R&D with increased taper strength and additional undulators, potentially producing a TW-class FEL. High power may also allow one x-ray pulse to be split and delivered to several experimental stations, increasing the capacities of x-ray FELs.

### 2.13.6.6 Harmonics and short wavelength optimization

Nonlinear 3rd and 5th harmonics allow for radiation at significantly shorter wavelengths than what is practical at the fundamental resonant wavelength for a given electron beam energy. Typical measured power levels at LCLS and FLASH are 1% for the 3rd harmonic and 0.1% for the 5th harmonic, as a fraction of the fundamental power level. With a tapered undulator, simulations predict reaching a few percent of the power level in the fundamental on the 3rd harmonic under some conditions. This potential enhancement should be explored further. Harmonic afterburners that are not effective at the FEL gain can still produce enhanced radiation at short wavelengths if placed after the saturation when a subharmonic pulse has been reached.

### 2.13.6.7 Polarization control

Polarization control can be carried with an afterburner undulator, tuned to either the upstream wavelength or a harmonic, as described above. A pair of undulators in crossed geometry and a phase shifter in between is an alternative method, which may allow more rapid variation of polarization but with less control of stability. R&D can be carried out at FERMI@Elettra with APPLE undulators and is planned at LCLS with a DELTA undulator. *Probably should define APPLE and DELTA acronyms*

### 2.13.6.8 Pulse duration and bandwidth

Coherent pulses are desirable for many applications. Low-bandwidth pulses with transform-limited duration of hundreds of fs are also useful, but may require a post-FEL monochromator. In the opposite limit, attosecond pulses, especially synchronized as part of a pump-probe configuration, have many applications.
Various techniques have been proposed to reduce the x-ray pulse length below a femtosecond. The spoiler foil has been successfully tested. Other promising techniques include: compressing few-pC electron bunches; ESASE or ESASE-like bunch manipulation; and variants of EEHG and HHG using a few-cycled seed laser. Methods for pulse shaping and control are also important goals.

2.13.6.9 Beam quality and consistency

Jitter in the FEL output should be reduced as much as possible. In addition to designing for low jitter in timing, pulse energy, and wavelength, diagnostics for both electron beam and radiation fields and feedback control are important areas of R&D. Many applications require longitudinal and transverse coherence. While SASE typically offers ~80% transverse coherence, seeded beamlines may yield even better results. Laser-seeded FELs must contend with the multiplication of phase variations (e.g., frequency chirp) by the total harmonic jump.

2.13.6.10 Justification and priorities

A full scale test facility is needed to test the most promising schemes explored and developed and experimentally demonstrated at various laboratories. Such a full scale demonstration is important prior to implementing the novel schemes at user facilities.

For hard x-rays, self-seeding is likely the only viable approach for seeding. For soft x-rays, EEHG is the best risk-reward scheme, and should be aggressively pursued. Self-seeding is also a very viable option with possibly a modest loss in capabilities. R&D on hard and soft x-rays is already being pursued at LCLS and should be expanded upon. HHG seeding and other short-wavelength sources to a large part depend on external developments in the field; however, the criteria for a good laser for seeding an FEL are distinct from those for atomic physics research, and thus some guided HHG development is desirable, especially for trains of pulses with narrow bandwidth at a given harmonic. Also, HHG seeding with a single pulse is a good candidate for producing an attosecond pulse. Other ideas for generating attosecond pulses, such as using short electron bunches or variations on the EEHG scheme, are important to pursue as well. Work on an HGHG cascade is underway at FERMI@Elettra, and its requirements are essentially a subset of what is necessary for studying the EEHG scheme.

Improving the photon intensity is an important aspect to enhance the capabilities of a given FEL facility. The efforts will allow for more science to be done at a single FEL beam-line. A full FEL beamline with enough undulator to go past the conventional saturation point should be aggressive pursued for these studies. Optimization of FEL harmonics production can improve the photon energy reach and/or reduce the linac cost.

Polarization control requires a functioning FEL but does not require going to saturation, in fact it is expected not to work well at saturation. As improvements in undulator technology may solve this concern, this is a lower priority item. Again, it is less important to operate at 1 nm for these studies.
Synchronization, generating repeatable, high-quality electron beams, measuring sub-fs pulses accurately, and other diagnostics are important issues but do not require a functioning FEL to pursue. To study repeatability and uniformity of the electron beam, a priority item is to work with an at least 2 GeV and high beam quality electron beam which is compressed to the order of 1 kA current, and to use some combinations of laser heater, third harmonic cavity, and wakefield enhancement device in order to flatten the energy profile and damp small-scale instabilities. Other desirable R&D consists of studies of independent components which will be discussed in the section on diagnostics and control systems.

2.14 FACET-II THz Studies

The terahertz (THz) region of the electromagnetic spectrum represents a largely unexplored and untapped tool with respect to manipulating and controlling phases of matter using light. When we apply intense THz fields to samples we have the potential for conditioning or controlling matter, stimulating it with surgical precision, and exploring pathways to induce new phases not accessible via other means. An ultrashort single-cycle THz light pulse (see Figure 2-45) has a frequency that is resonant with the bonds that hold materials together (~1-20 THz) and is capable of biasing a material or device on time-scales of order 100 femtoseconds.

![Figure 2-45: THz electric field temporal profile](image)

The bonding strength of materials corresponds to energies of around 1 eV, with the spacing between atoms of a few Angstroms. The ratio of these numbers gives electric fields on the order of 0.1 - 1 V/Å (10-100 MV/cm), which sets the scale of fields that are required in order to exert a non-perturbative influence on the structure of solids all-optically. These fields correspond to electromagnetic energy
densities of 1 to 10 GPa, comparable to the pressures required to synthesize new phases of matter in diamond anvil cells.

There is a long history of using lasers and various nonlinear optical down-conversion techniques to generate single cycle THz light fields, and field strengths are now on the order of 1 MV/cm. While these approaches are being continuously improved, there is no clear pathway towards reaching the field strengths noted above in the frequency range of interest. [130] Accelerator-based sources, making use of the large electric and magnetic fields associated with a relativistic electron bunch, provide a means of reaching fields at the level of 1 V/Å. Indeed, at 0.35 nC bunch charges, experiments at using the SLAC linear accelerator have demonstrated peak fields of around 0.4 V/Å with higher fields possible. [131] Similar fields are possible at FACET now, with peak energies around 1 mJ. Recent experiments also using the SLAC linac have demonstrated that these fields can be used for switching of magnetic materials. [132, 133] Figure 2-46. shows a historical summary of the THz electric fields generated by both laser-based and accelerator-based sources.

Figure 2-46: Historical summary of peak THz electric field, comparing laser-based and accelerator-based sources.

The interaction of THz fields in this parameter space with matter is only just beginning to be explored. The science case is broad, with opportunities spanning atomic and molecular to condensed phase systems. We described a few examples in the sections that follow.

2.14.1 THz manipulation of atoms in the solid state:

Whereas many nonlinear THz-driven responses associated with electron motion in materials have been observed [134, 135, 136, 137, 138] over the last decade and
more, studies in which these fields are used to directly manipulate atomic positions are in their infancy. In parallel with the magnetic switching studies, the electric field of single cycle THz fields can be used to manipulate and unravel the coupled structural and electronic degrees of freedom and the complex phase transitions that underlie the emergence of ferroelectricity and multiferroicity, in which the ferroelectric polarization is encoded through atomic displacements within the unit cell. Through vibrational excitation and all-optical application of intense single-cycle fields, [139] these measurements will enable discovery of means for programming these materials with light and controlling the microscopic pathways that the atoms and electrons follow along their potential energy surfaces, which in turn determine their functional properties. In recent experiments at the LCLS, [140] we have shown how large amplitude modulations in the internal electric fields within ferroelectric PbTiO$_3$ nanolayers are reflected in atomic-scale motions within the unit cell, elucidating the first steps in the photovoltaic response of these materials. The THz fields generated by FACET-II may be used to directly reorient or switch the polarization, or induce specified electrical, electromechanical, or structural responses, effectively guiding these systems along well-defined atomic-scale trajectories. We will be able to couple these THz fields with absolutely synchronized probe pulses also generated by the FACET-II electron beam.

### 2.14.2 THz manipulation of electrons and spins

Relativistic electron beams at FACET-II represent a truly unique source of intense half cycle electric and magnetic field pulses that are the closest analog to an electric switch operating at THz speeds. They enable novel forms of controlling the behavior of electrons and spins in future devices relevant for information technology. While transition-metal oxide electronics based on electric field driven metal-to-insulator phase transitions is one of the most promising avenues towards energy efficient field-effect transistors, [141] switching the magnetization direction in ferromagnetic transition metals by electric fields alone, i.e. without dissipative electric currents, can be considered as the holy grail of energy efficient magnetic data storage. Both goals can be attacked using the unique x-ray and THz capabilities available at FACET-II.

Ongoing magnetic switching experiments at FACET demonstrate the feasibility of such an approach (Figure 2-47). The high-energy electron bunch traverses the magnetic sample with an in-plane easy axis, imprinting a figure-eight magnetic pattern that depends on the number of electrons in the bunch and the temporal length of the bunch. Before exposure to the beam the sample is uniformly magnetized in-plane. When using 140 fs long pulses a characteristic deviation from an ideal figure-eight pattern (observed for ps long pulses) occurs. This deviation is ascribed to the influence of the electric field as indicated by the simulation shown in the lower panel of the figure. Such experiments currently employ a post mortem analysis of the magnetic switching patterns.
Figure 2-47: Schematic of the magnetic switching experiment using an ultrashort electron bunch surrounded by a magnetic and electric field. [132]

The availability of femtosecond laser probe beams at FACET-II will open up radically new ways of probing transient electronic and magnetic states. It will enable us to study femtosecond electron dynamics in epitaxial transition metal oxide films undergoing an insulator-to-metal transition induced by THz electric-field pulses (~0.1GV/m). [142] Obtaining laser snapshots of the evolving electronic structure in a single-shot fashion is essential to the fundamental understanding of pure Mott-Hubbard-like switching of electrical conductivity without dissipative lattice transformation.

Current methods often require repetitive measurements near the damage threshold [142]. We need to go beyond that to understand the fundamental processes and develop new materials that can withstand the required electric fields. Such studies can also be extended to ferromagnetic metals, where even higher THz fields (>1GV/m) can alter the electronic structure significantly, [132] leading to novel forms of magnetization switching. Our final goal of such switching experiments will be to determine the coherence time of THz electronic excitations driven by the intense electrical field pulses. While electronic dephasing and lifetimes have been studied in detail for the optical frequency region less is known for low-energy excitations in the THz spectral range. The unique availability of electron-positron bunch pairs with variable temporal spacing at FACET-II would finally open up the possibility to study the influence of electronic coherence in the time domain. Only for a coherent electronic motion would the subsequent positron bunch restore the initial electronic and spin configuration.

2.14.3 THz radiation to trigger surface chemical reactions

Many processes relevant to society, such as catalysis in chemical and energy production, the fabrication of computer chips, weathering and corrosion, the behavior of biomaterials and the fate of contaminants in the environment, rely on surface chemical reactions. Catalytic reactions are driven thermally. These thermal excitations include phonons (substrate lattice vibration), frustrated vibrational motion of molecular adsorbates, and translational and rotational motion of
molecular adsorbates (Figure 2-48A). When the excitation of these vibrations mediates the nuclear motion along the reaction coordinate, chemical reactions cause bonds to either break or form.

FACET-II will provide opportunities to develop ways to stimulate chemical reactions on surfaces by triggering the motion of nuclei using THz radiation generated by an ultra short electron bunch. Assuming an electron pulse width of 100 fsec, broadband radiation will be obtained with a high frequency cut-off at 10 THz, which matches the frustrated vibrational motions of adsorbed species on the surface. Both the frequency of THz radiation and the strong, directional electric field are of major interest. The coherent and broadband character of THz radiation from FACET-II will generate a strong electric field, >1x10^9 V/m (or >0.1 V/Å). The quasi half-cycle pulse character of the radiation corresponds to a strong ultrashort half-cycle unipolar pulse. We envision using this strong electric field to excite frustrated vibrational motions collectively to drive a chemical reaction (Figure 2-48B). [143]

In addition to the field strengths and pulse shapes noted above, a key aspect of these studies involves generating synchronized optical or infrared probe pulses to probe the dynamics driven by the THz fields. These can be generated by a phase-locked laser or directly by the same transition radiation process that has been employed at FACET to generate coherent THz fields (Figure 2-49). Here the optical transition radiation can be separated by a dichroic mirror from the broadband THz fields and used as an absolutely synchronized probe pulse to record chemical dynamics.
Nonlinear optical probes, for example, allow for direct access to the structural symmetries of a crystal and can be used as powerful probe of the underlying atomic-scale dynamics. We have carried out preliminary studies along these lines using the LCLS electron beam with high fields and observed dynamic processes at these high fields not previously observed (Figure 2-49).

Figure 2-49: Schematic of coherent transition radiation process in which a femtosecond electron beam passes through a thin metallic foil in order to generate intense THz fields (left). First THz pump/optical probe studies of dynamics in GaAs in which pump and probe are simultaneously generated by the foil (right).

2.15 National-Security and Fundamental Topics with Intense Beams of Photons of Energy 5 MeV and Greater Produced by Inverse Compton Scattering

The DOE’s National Nuclear Security Agency (NNSA) of the United States has instructed the nation’s design laboratories to conduct full-system certification using a methodology called Science-based Stockpile Stewardship that is expressly absent any future full-scale test. In short, the Stewardship program must make the best scientific use of the cataloged data.

Were it possible, tests of nuclear weapons would include the confinement of the released energy (the yield) by a calorimeter, the temperature rise of which would provide a direct measure of the yield. Realistically, however, the yield is determined indirectly by a variety of other means. For example, the prompt yield is inferred from the output of gamma rays. [144, 145, 146] Radiochemical analyses of the atomic and isotopic constituents remaining in the aftermath of the explosion provide another, independent evaluation of the yield. Both methods of yield inference hinge on extant knowledge of instrument calibrations and photonuclear cross sections. Today, while the data may be stored and static, these methods remain active topics in search of better information on which to base their estimations.
Figure 2-50: Supernovas – the fiery death of massive stars where heavy-element nucleo-synthesis takes place – provide C, O and other elements of life.

Our proposal for national security missions entails the use of FACET-II for reducing uncertainty in models tangible to stockpile stewardship, for example, to improve our understanding of absolute energy output. Other topics relevant to national security and undertaken with a bright, quasi-monoenergetic source of gammas of ≥5 MeV in energy include predictive capability of material damage, fundamental nuclear physics, and radiography. More advanced, if ambitious, uses of FACET-II are also of interest to the NNSA. The generation of coherent gammas for the manipulation of nuclear transitions in analogy with the coherent excitation of electronic transitions is but one example. Below, we outline some of the research areas of interest as well as introduce topics for general consideration at FACET-II.

2.15.1 Calibration of United States Nuclear Test Gamma-Ray Detectors

This topic is of interest to science-based and predictive-capability Stockpile Stewardship programs at the LANL and LLNL. HFK detectors (high-frequency kinertium, the latter being a tungsten alloy) were used to measure gamma production from nuclear tests, and their data are archived. These detectors produced vital statistics that are recorded for significant events in United States Nuclear Test History, which ended in September 1992. Pulsed, spectrally-broad bremsstrahlung radiation produced at LINACS was used to calibrate the bandwidth response of HFK detectors. We remain far less certain, however, of the absolute energy calibration, or spectral response, of these detectors. To the extent that models carry uncertainties from this clouded aspect of archived data, a program in spectral calibration of HFK detectors becomes a matter of Stockpile Stewardship. For the calibration, we would chart the response of an HFK detector versus energy of an incident and reasonably monochromatic gamma beam. The gamma source at Duke University’s HIγS has the needed energy range but not enough flux. A gamma source at FACET-II, however, could deliver all the needed aspects of energy range, energy resolution, and flux.
2.15.2 Astrophysics and Stellar Nucleosynthesis

Nuclear reactions in stars take place at temperatures between $10^8$ and $10^9$ eV, but the corresponding reaction rates are rarely measured below 1 MeV in the laboratory. Most rates used in stellar models thus come from severe extrapolations of the experimental data into the astrophysical-temperature regime. We offer as an example the lively controversy [147, 148] about the laboratory cross sections for $^{12}\text{C} (\alpha, \gamma)^{16}\text{O}$ and consequences [149] of their theoretical extrapolation to the low energies at which the reaction effectively operates. As for the nomenclature of the reaction, the parenthetical $(\alpha, \gamma)$ and ordering of nuclei means that $^{12}\text{C}$ is the target bombarded by an alpha particle, which on collision produces a $\gamma$ and leaves $^{16}\text{O}$. The reaction affects the relative abundance of two atoms of which we are largely made, making it little wonder that the $^{12}\text{C} (\alpha, \gamma)^{16}\text{O}$ problem is of paramount importance in nuclear astrophysics. Moreover, the ratio C/O following helium burning (of which $^{12}\text{C} (\alpha, \gamma)^{16}\text{O}$ is a part) figures critically in the fate of massive stars, determining in some instances whether they collapse to black holes or neutron stars. The $^{12}\text{C} (\alpha, \gamma)^{16}\text{O}$ cross section also appears in burning models and perhaps forensics of nuclear weapons.

Weller et al. at HIγS indicate that $^{12}\text{C} (\alpha, \gamma)^{16}\text{O}$ cross sections are reported for energies no lower than 1.2 MeV and are in sufficient discord to make extrapolation to stellar-burning energies of 0.3 MeV treacherous. [148] The inverse reaction, $^{16}\text{O} (\gamma, \alpha)^{12}\text{C}$, however can be examined at HIγS and the cross section for $^{12}\text{C} (\alpha, \gamma)^{16}\text{O}$ obtained by detailed balance. Calculations by Weller et al. showed that the then present $5 \times 10^7 \gamma$/s flux of HIγS at $E \approx 10$ MeV in 2009 was sufficient to inspect $^{12}\text{C} (\alpha, \gamma)^{16}\text{O}$ at the equivalent energy of 1.5 MeV. An expected brightness upgrade for HIγS to $\sim 10^{11} \gamma$/s would push the equivalent energy far lower. Still greater fluxes, however, as might be produced at FACET-II, will be needed to measure the $^{12}\text{C} (\alpha, \gamma)^{16}\text{O}$ cross sections accurately at the equivalent (incident alpha) energies of 300 keV and lower as relevant to nucleosynthesis in red giants (cf. Fig. 6 of Fowler [147]). In topics as diverse as stellar evolution, the nucleosynthetic origins of life’s elements, and the outcome of silicon burning and the heavier elements that follow, much would be riding on such a foundational measurement.

Apart from $^{12}\text{C} (\alpha, \gamma)^{16}\text{O}$, there are numerous other reactions of importance in nucleosynthesis with still greater uncertainty. Weiss [150] lists ten $p$-capture processes (proton-capture nucleosynthesis, such as $^{27}\text{Al} (p, \gamma)^{28}\text{Si}$) for which the uncertainties at stellar temperatures range from factors of 2 to nearly 2000. Specific isotopes of Na, Mg, and Al figure in these processes and range widely in their calculated abundances, often turning an estimated metallicity of a star into a hazardous guess. As with the $^{12}\text{C} (\alpha, \gamma)^{16}\text{O}$ reaction, a FACET-II beam of high flux could interrogate nine of these $p$-capture processes at relevant stellar temperatures using the inverse reaction and detailed balance. Doubtless other nucleosynthetic processes are in need of similar clarifications.
2.15.3 Nucleon Compton Scattering and Tests of QCD

Experimental work on photo-disintegration of few-body nuclei at energies below the pion threshold (<145 MeV) probes the universal dynamics of nuclei (at low energies) and the effects specific to the nuclear force (at higher energies). With implications for the Gerasimov-Drell-Hearn Sum Rule, and their connections to quantum chromodynamics (QCD), such experiments are certain to stimulate collaborations between theorists and experimentalists, in particular toward understanding the way that QCD manifests itself in low-energy photon reactions. Weller et al. [148] capably motivates this area of research in the context of H1γS and conveys its excitement. We wish to call attention to the fact that H1γS is the only facility within the United States active in this nuclear-science subfield, while China, Japan, and Europe have either built new inverse-Compton gamma sources or are about to, for entry into this and other fields of photonuclear physics. It is crucial, we believe, for FACET-II to complement or exceed the capacity of H1γS in order for the U.S. to maintain an active international role in what appears to be the growing topical areas made possible by inverse-Compton gamma sources.

2.15.4 Polarizing and Probing the Quantum Vacuum

The vacuum is not inert. Since the beginnings of quantum electrodynamics in the mid 1930s, it has long been predicted that the vacuum in special circumstances can be a nonlinear medium through which photons interact. Strong electromagnetic fields, for example, can convert the vacuum into a birefringent and dichroic dielectric medium. Intense laser pulses available today provide high intensities of $10^{22}$–$10^{24}$ W/cm$^2$ and associated strong electric fields of $10^{12}$–$10^{13}$ V/cm but are insufficient by themselves for us to witness vacuum polarization. The combination of intense lasers, a gamma photon source, and nuclear physics at FACET-II, however, could reveal the long-sought prediction of QED of elastic photon-photon interactions within the vacuum. We imagine that lasers capable of producing peak pulsed intensities of $6\times10^{24}$ W/cm$^2$ will be available. Propagating against this laser pulse in vacuum will be a linearly-polarized gamma pulse of 10-MeV photons (generated by FACET-II). The net rotation of the beam that probes the vacuum polarization is proportional to the fluence of the intense laser pulse and the photon energy of the probe beam. The gamma energy of a probe beam can thus be a significant multiplier of rotation. Where the linear polarization of a visible-wavelength probe (~2 eV) would rotate ~50 nanoradians when propagating against a $6\times10^{24}$ W/cm$^2$ pulse in vacuo, the polarization of a 10-MeV beam rotates 0.25 rad (14 degrees). A probe-beam detector is necessary, and in this case involves a deuterium target. The known nuclear physics of the angular distribution of deuteron photodisintegration at 10 MeV can be used to deduce the polarization angle of the incident gammas. We offer this realizable experiment as but one example where extremes in energy and fields that exist in the separate disciplines of lasers and nuclear physics can be joined to bring about interesting and unique phenomena.
2.15.5 Diffraction, Imaging, and Coherent Excitation

Nuclear-resonant diffraction is not a new topic [151] but needs to re-examined for experimental use amid the coming generation of gamma sources produced by Compton laser-backscattering, as planned for FACET-II. Such sources of gammas are bright, quasi-monochromatic (energy resolution of ≤1%), polarized, and tunable across the giant dipole resonances (GDRs) held by isotopes from tritium through transuranics. In analogy with visible optics, the GDRs have real and imaginary indices of refraction that can influence a diffraction pattern depending on the detuning of the gamma energy from resonance. Thus, complementary to x-ray diffraction and its sensitivity to electron density, nuclear diffraction of gammas would presumably have a tunable sensitivity to atomic constituents and positions. The gammas of Compton laser-backscattering are also expected to exhibit a partial spatial coherence, presenting the opportunity to image the structures of non-crystalline materials. Coherent diffractive imaging is applicable to spatially-coherent sources and is used, for example, at DESY and the LCLS in connection with their programs in 2-D imaging (and 3-D reconstructions) of biological molecules illuminated by x-ray, FEL light. A program in imaging would take into account the issue of pair production within the examined material and the mitigation of this problem through the latest or foreseeable advances in gamma-beam imaging or geometries. The combination of today's high-intensity lasers with advanced high-current sources such as FACET-II can also be examined for ways to produce spatially- and temporally-coherent gammas, for entry into the topic of coherent-excitation of nuclear transitions.

3  FACET-II Accelerator Overview

The reuse of the first third of the SLAC linac to form the backbone of the FACET-II facility follows a tradition of successful redeployment of accelerator infrastructure at SLAC.

We determined the basic configuration for FACET-II through two separate studies of facility characteristics needed to support accelerator R&D for the High Energy Physics (HEP) and Photon Science programs.

On the HEP thrust, the FACET-II configuration evolved rapidly from prior advanced accelerator R&D experience at the Final Focus Test Beam and FACET facilities. Discussion with the community of experimentalists who used the FFTB and who currently use FACET informed the design, as did discussions with the SLAC Accelerator Research Experimental program Committee (SAREC). We then developed a staged approach to providing a cost-effective world-leading facility.

On the Photon Science thrust, multiple study groups have examined what accelerator science issues would have the greatest impact on photon science light sources. For more than a decade the recommendations have remained the same: a facility capable of supporting world-class photocathode, electron source, beam
compression, and emittance preservation studies at high energy. With the commissioning and operation of LCLS, the need has become clear for a facility compatible with attosecond-class laser-electron interaction experiments (e.g. seeding), forwarding-looking FEL experiments (e.g. ESASE), and ability to support penetrating studies of bunch compression methods and instabilities.

Over the course of the last two years, these two thrusts have been interwoven into the current FACET-II proposal. As both programs require well-diagnosed, high brightness high energy beams, the two programs are strongly synergistic and able to efficiently use a common facility.

FACET-II will be built upon the existing 10 GeV of accelerator in sectors 0-10, as well as the positron source and damping ring. A new rf gun electron source, bunch compressors, and diagnostics will be added to provide high brightness beams. An experimental region will be created by clearing a ~100m space in Sector 10, and PPS changes made to permit more independent operation from LCLS-II.

Over the course of operation, upgrades and enhancements to FACET-II will be identified by the experimenters and SLAC staff. With guidance from the community and from SAREC, these upgrades will be prioritized and executed as resources allow.

3.1 The FACET-II Facility

The FACET-II facility shown in Figure 3-1 and Figure 3-2 will have a core minimal facility consisting of a Dogleg and Final Focus in Linac Sector 10 for electron drive bunch studies, including studies of multi-bunches and plasma acceleration and instabilities. There are several independent additions which will extend the reach for accelerator science at FACET-II. First, the addition of positrons will enable positron drive bunch studies and positron plasma interactions. Second, a dedicated witness bunch injector will allow detailed emittance and low energy spread studies. And finally, the Integrated Test facility (IFT) injector will provide very low emittance drive bunches, a variety of multi-bunches, and tailored drive bunches for transformer ratio studies.

The FACET-II project will include a new experimental area at Sector 10 in the existing linac tunnel. It will replace and extend the functions of FACET, which will be dismantled as part of the LCLS-II construction project. FACET-II will be located upstream of the LCLS-II injector. At this point along the linac, the beam has an energy of 10 to 13 GeV and the emittance is very small. By installing a new focusing system at Sector 10, the beam can be focused and compressed in length to sizes appropriate for plasma wakefield accelerator research. Comparable power densities for positron beams will be provided with the addition of an upstream positron bunch compressor. A shielding wall at the end of Sector 10 will allow access to the upstream portion of the linac during LCLS-II operations.
A final focus system and an experimental area are being designed to fit in the existing linac tunnel in Sector 10. The new beam line equipment will start about 150 meters upstream of the entry point of the beam from the LCLS-II injector. Positrons would be made by using the PEP-II electron extraction system in Sector 10 and the PEP-II high energy bypass line to take the beam to Sector 19, where a short new beam line will connect the beam to the positron production source. The remaining positron production equipment, return line, and South Damping Ring would remain the same.

The Sector 10 final bunch compressor and final focus beam line will consist of a dogleg to compress the beam longitudinally and offset it from the linac axis, followed by an arrangement of quadrupoles to focus the beam to an interaction point near the middle of the sector. The dipole magnets for the dogleg and most of the quadrupole magnets for the focusing system will be salvaged from the FACET area and the SLC final focus system. The quadrupole magnets for the final doublet will be salvaged when FACET when it is decommissioned. Tracking programs that include second-order effect are being used to compute the FACET-II beam parameters summarized in Table 3-1 and Table 3-2.

**Table 3-1:** FACET-II Preliminary Beam Parameters
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Adjustable up to 13 GeV without compression; and up to about 10 GeV with full compression and maximum peak current.</td>
</tr>
<tr>
<td>Charge per pulse</td>
<td>2 to $3 \times 10^{10}$ (3 to 4.5 nC) $e^-$ or $e^+$ per pulse with full compression; $3.5 \times 10^{10}$ $e^-$ or $e^+$ per pulse without full compression.</td>
</tr>
<tr>
<td>Pulse length at IP ($\sigma_z$)</td>
<td>20 μm with 4 % fw momentum spread; 35 μm with 1.5 % fw momentum spread.</td>
</tr>
<tr>
<td>Spot size at IP ($\sigma_{x,y}$)</td>
<td>20-25 μm nominal</td>
</tr>
<tr>
<td>Momentum spread</td>
<td>4 % full width with full compression; (3% FWHM); &lt; 0.5 % full width without compression.</td>
</tr>
<tr>
<td>Momentum dispersion at IP ($\eta$ and $\eta'$)</td>
<td>0</td>
</tr>
<tr>
<td>Drift space available for experimental apparatus</td>
<td>2 m from last quadrupole to focal point; approximately 25 m from the focal point to the beam dump.</td>
</tr>
<tr>
<td>Transverse space available for experimental apparatus</td>
<td>3 x 3 m</td>
</tr>
</tbody>
</table>

**Table 3-2:** FACET Detailed Beam Options
The space available for experimental equipment in the linac housing is sufficient for the experimental program. The linac tunnel cross section is approximately 3 meters by 3 meters, while there is about 25 meters of longitudinal space between the last beam line quadrupole and the beam dump. The floor and beam line pitch downward at an angle of approximately 0.25 degrees. The experimental region is approximately 10 m below ground in the linac tunnel, where it is well shielded by earth and concrete so that the full beam power can be absorbed safely.

A new controlled entry point in the existing Sector 9 equipment shaft will provide users with convenient stairway access to this experimental region, enabling them to set up and work on experimental apparatus without interfering with LCLS operations. A user trailer will be located adjacent to the Klystron Gallery to support experiments in the linac tunnel.

### 3.1.1 General Technical Description of FACET-II

The following assumptions were used to guide the layout and functionality of FACET-II. The FACET experimental results will be used to indicate and specify FACET-II capabilities and science directions. The layout will maintain positron capability if technically and financially possible, with several options being explored. The layout will share e-source technology and bunch compressors with ITF where possible. There is a plan to synchronize R&D of FACET with FACET-II installation. Where possible, the facilities in Sectors 0-10 will be used to minimize the construction costs. Spare parts from FACET, PEP-II and SLC will be incorporated to minimize costs.
3.1.2 Layout

FACET-II will consist of a new beam focusing system, to be installed in Sector 10 of the linac housing to support experiments requiring tightly focused and compressed beams of electrons or positrons, and a bunch compressor in Sector 10, to be modified to compress positron bunches as well as electron bunches. The overall site layout for the accelerator complex at SLAC is shown schematically in Figure 3-1, with the modified areas highlighted.

3.1.3 Modes of Operation

The linac accelerator facility was upgraded in the 1980's to generate and accelerate beams of electrons and positrons for the SLC program at repetition rates up to 120 pulses per second. This facility has been in nearly continuous use, providing short, intense bunches of electrons and positrons for the PEP-II, FFTB, ESA, and LCLS programs.

The proposed Sector 10 focusing system will take full advantage of the linear accelerator facility and all these improvements. The mode of operation likely to be most reliable and economical will involve pulsing the linac at 30 times per second, with 15 pulses accelerating electrons to the production target, interleaved with 15 pulses per second of positrons delivered to the users. Faster pulse repetition rates are possible with the existing control and timing systems, up to a maximum of 120 pulses per second. This mode would create 120 pulses of positrons per second, accelerated on the same linac cycles as 120 pulses of electrons. For most applications, however, 10 to 30 pulses per second is likely to be the most cost effective mode.

The linac systems up to the Sector 10 experimental area will operate independently of any LCLS or LCLS-II activities. A shield wall similar to the one added in S20 for FACET, will be added in S10 (see Figure 3-3) and allow experimenters to enter the linac housing in this area while the LCLS and LCLS-II are operating.
3.1.4 Delivery of Positrons to Sector 10

FACET-II can be used to deliver either electrons or positrons to the proposed new experimental area in Sector 10. The production of positrons involves first accelerating an electron beam to Sector 9, extracting it, passing it along the bypass line, and where it is directed to a target to produce positrons. The positrons are then returned using existing hardware to the South Damping Ring (SDR), where they are stored until the next linac pulse.

The future pulse compression chicane, to be located in Sector 4, will be made symmetric, allowing both electrons and positrons to pass through.

Switching the Sector 10 system between electrons and positrons will require reversing the polarities of some of the magnets, a procedure likely to take about a day or two to complete. This will not be practical as a routine quick-switch operation; however, switching polarities can be done whenever the research program requires the opposite charge, and the work required to switch polarities can be done outside the linac housing without interfering with any other running accelerator program. With the magnet polarities reversed, a positron beam can be focused and delivered to experiments in Sector 10, and the beam parameters will be virtually identical to those that can be achieved with electrons.
3.1.5 Dedicated Witness Bunch Injector in FACET-II

A dedicated injector of low emittance, high charge, short e- bunches into a plasma wakefield accelerator to be the high quality accelerated bunches is an exciting possibility and is a first example of a staged accelerator. This witness bunch injector is described in Section 3.3.2.

3.1.6 ITF Injector

The ITF will make a very bright short bunch that could be used very effectively in FACET-II. The bunch length will be shorter and the horizontal emittance will be about 10 times smaller than from the damping ring. Both make for enhanced plasma acceleration. The ITF is described in Section 3.3.3.

3.2 FACET-II Technical Details

The FACET-II facility consists of a bunch compressor, a final focusing section, an experimental area, a beam dump, a shield wall, and above-ground facilities for users and data acquisition equipment. The experimental area lies in Sector 10 of the linac tunnel, upstream of the point where the LCLS injector joins the linac.

3.2.1 FACET-II Layout

Figure 3-4 shows an expanded view of the Sector 10 area at the SLAC site, including Error! Reference source not found. the paved areas on both sides of the Klystron Gallery and proposed locations for associated above-ground experimental counting house and Klystron Gallery electronics area. The position of the focal point in the linac tunnel below is also indicated for orientation.

![Diagram](image)

**Figure 3-4:** FACET-II region in the Klystron Gallery. The linac tunnel is approximately 25 feet underground below the Klystron Gallery and will be easily accessible through a new stairway to be installed in the Sector 9 equipment shaft. The large red rectangle indicates the location of a building to house experimenters. The smaller red rectangle indicates an area in the Klystron Gallery for an enclosed room to house experimental equipment that must be near the focal point but accessible when the beam is on.
Figure 3-5: Cutaway view of the underground linac tunnel in the Sector 10 FACET-II final focus region showing the proposed staircase at the upper left in Sector 9 and the LCLS injector vault in the lower right.

A cutaway drawing of the linac tunnel in this region is shown in Figure 3-5. A new entrance stairway is shown in the upper left corner of the figure, and the injector vault of the LCLS system is shown in the lower right. Personnel will walk about 210 feet down the linac tunnel from the bottom of the access stairs to the final focus area for the FACET-II beams.

Cross-sectional views of the linac housing upstream of the final focus and at the position of the FACET-II focal point are shown in Figure 3-6. The FACET-II beam is offset approximately 60 cm to the south of the nominal linac trajectory, placing it near the center of the tunnel. The existing light pipe is part of the linac alignment system and will be left in place for this purpose, although the accelerator and its associated support structure and waveguides will be removed in the area of the focal point. The figure also shows two quadrupole magnets on the overhead bypass lines used to transport beams of electrons and positrons to the former PEP-II.
Figure 3-6: Tunnel cross section upstream of the FACET-II final-focus region. The linac and its support structures are shown above the alignment light pipe and the e⁻ and e⁺ bypass lines that transport electrons and positrons to the PEP-II HER and LER rings.

The linac beam trajectory, the light pipe, and the electron and positron bypass lines to PEP-II are visible in Figure 3-7, a photograph taken in the linac housing near the proposed FACET-II focal point. Penetrations extending up to the Klystron Gallery above are located at twenty foot intervals along the tunnel, providing convenient access for pipes, conduits, and cables. Existing cable trays visible in the upper right corner of the photograph can accommodate additional cables if needed for experiments.
Figure 3-7: Sector 10 FACET-II region in the linac tunnel. The linac beam passes through the vacuum pipe directly above the large laser alignment pipe. The electron and positron transport lines (labeled bypass e- and e+) are visible overhead on either side of the row of light bulbs, and a convenient cable tray runs along the upper right.

3.2.2 Reduced Damping Ring Energy

We propose lowering the energy of the damping rings would be lowered, which would reduce the beam emittances and provide higher charge density in both electron and positron bunches. The bunch charges remain about the same. Calculations have shown that if the damping ring energies are lowered from 1.2 GeV to 0.9 GeV, a final bunch length of about 20 μm can be achieved and the horizontal beam size would be reduced by about a factor of three.
Horizontal emittance, energy spread, and bunch length SLC damping ring for $5 \times 10^{10}$, $2 \times 10^{10}$, $6 \times 10^9$ and zero current with new vacuum chamber and an RF voltage of 800 KV; beams were assumed to have a 10% emittance coupling.

Figure 3-8: FACET-II will reduce the damping ring energy from 1.2 to about 0.9 GeV to reduce the transverse beam emittance allow spot sizes to be generated in Sector 10 similar with FACET in Sector 20. (T. Raubenheimer and M. Woodley)

3.2.3 X-T CAVITY bunch length monitor

The bunch length monitor currently in Sector 20 uses x-band technology to illuminate details of the bunch longitudinal shape well below the 20 micron level. We will move this monitor to Sector 10 (see Figure 3-9) in order to use it with FACET-II. See Error! Reference source not found. This monitor has demonstrated that it can
3.2.4 FACET-II Beam Optics

The new FACET-II lattice will be installed in Sector 10, beginning after quadrupole QLI10-201. A schematic plan view of the magnet layout is shown in Figure 3-10, while Figure 3-6 provides a cross-sectional view of the linac tunnel with existing components and the new FACET-II beam line. The lattice consists of the dogleg section, the final focus (FF) section, and the experiment section with a beam dump. Four horizontal bend magnets in the dogleg section deflect the FACET beam 55.6 cm from the linac axis into a parallel beam line with the FF and experiment sections. The beam interaction point (IP) is located 2 meters downstream of the last FF quadrupole.

Figure 3-10: Horizontal layout of the FACET-II magnets in Sector 10, where quadrupoles are shown in blue, bends and wiggler in red, and sextupoles in green
The beta functions and dispersion are shown in Figure 3-11. The symmetric quadrupole arrangement in the dogleg section is designed to cancel the first-order dispersion generated in the four bends and to create the linear matrix transformation term $R_{56} = 4\ \text{mm}$ necessary for the final stage of the bunch length compression. Additionally, two sextupoles with opposite strengths cancel the second-order dispersion, as shown in Figure 3-12. The sextupoles also reduce the unwanted quadratic bunch-length term $T_{566}$ from 44 mm to 9.5 mm. A wiggler section consisting of three vertical chicane bends is included near the dogleg center to generate a pattern of synchrotron radiation suitable for measuring the beam energy without interfering with the primary program.

**Figure 3-11:** FACET-II beta functions and dispersion in linac Sector 10.

The final focus section consists of two quadrupole doublets which focus the beam to a small round spot at the IP with $B_x^* = 1.5\ \text{cm}$, $B_y^* = 15\ \text{cm}$, and zero dispersion. For a 10 GeV beam with normalized emittance of $\gamma\varepsilon_x = 50\ \mu\text{m}$ and $\gamma\varepsilon_y = 5\ \mu\text{m}$, the first-order IP beam size is $\sigma_x = \sigma_y = 20$ to $25\ \mu\text{m}$. The optical configuration in the experiment section consists of a quadrupole doublet located 6 meters after the IP, followed by a vertical bend magnet. The quadrupoles focus the extracted beam to a second focal point, and the bend magnet deflects the beam to the dump. The bunch length compression mechanism results in a large energy spread. This energy spread causes beam size growth due to energy-dependent focusing in the quadrupoles, dispersion in the bends, and second-order aberrations in the sextupoles. We used tracking simulations to compute the chromatic beam size growth at the IP as a function of a generic flat energy spread. If the sextupoles are turned off, then the horizontal size grows faster with increasing energy spread, due to the uncorrected second-order dispersion.
The bunch length is compressed in three steps, starting in the RTL transfer line from the damping ring to the linac, and followed by the compressor chicane in Sector 4, where $R_{56}$ is greater than zero. The final compression is achieved in the Sector 10 dogleg with the optimum value of $R_{56} = 4\, \text{mm}$ after tuning the RF phases in the linac cavities. The RF phase settings were optimized using the LiTrack simulation code. The longitudinal phase space at the IP for the shortest bunch with a Gaussian fit length has $\sigma_z = 20\, \mu\text{m}$.

### 3.2.5 Experimental Area

The space available for experimental equipment starts at a vacuum valve immediately following the last final focus quadrupole before the focal point. The nominal focal point will be 2 meters downstream of this quadrupole, and the beam dump will be another 23 meters downstream of this point. This drift distance will accommodate a wide variety of experimental arrangements to suit the needs of users and will include a magnetic dump line spectrometer for the outgoing beam. A cross-sectional view of this section of beam line is provided in Figure 3-13.

The Klystron Gallery above the Sector 10 tunnel will house the power supplies for the focusing magnets and the electronics for the instrumentation and control system. The Klystron Gallery also has space in this area for any experimental equipment that must be near to the focal point but be continuously accessible to the experimenters when the beam is on. Existing penetrations at twenty-foot intervals provide paths for direct connections between apparatus in the Klystron Gallery and apparatus in the tunnel directly below.
Figure 3-14 is a conceptual layout of an advanced acceleration experiment involving a plasma oven set up on an optical table at the focal point. With this table in place, an experimental apparatus can quickly be installed, aligned, and reconfigured as needed. Also shown are two magnets downstream of the focal point that will be used for measuring the energy of the outgoing beam and forming an image of the focal point at the second focus in the dump line. The optical table and plasma oven are shown in the tunnel cross section view in Figure 3-13.

Figure 3-13: Tunnel cross section at the position of the FACET-II final focus. For illustration of the size of the experimental area, a four-foot wide optical table is shown which serves as a mounting platform for a lithium oven, centered on the FACET-II beam position, for the plasma wakefield acceleration experiment.
3.2.6 Beam Dump

The beam dump will consist of an air-cooled beam dump module surrounded by steel shielding. It will be supported by a structure similar to the structure that supports the Sector 4 compressor magnets. Shielding around the dump will be constructed from a stack of steel plates clamped together using threaded rods. The
beam dump module will be copper, cooled through conduction to the surrounding steel. The system will include a burn-through monitor system designed to shut down the linac in the event of a dump failure. The dump will be designed to allow the addition of a water-cooling system if an experiment requires a particularly high average beam power.

3.2.7 Shielding Wall

A shielding wall will be constructed in the linac tunnel between the dump and the LCLS-II injector area. The wall will consist of two overlapping but separated sections with a passageway between the two areas. A personnel protection system (PPS) controlled gate will limit travel between the areas during LCLS operation. The walls will be constructed by stacking concrete shielding blocks in the tunnel, with special pieces to fit around the alignment light pipe and various cable penetrations. In addition, a movable shielding plug assembly will be incorporated into the laser alignment pipe below the linac support girder to allow for the use of this alignment system when needed. The plug assembly will be copied from a similar unit near the west end of the accelerator.

3.2.8 Stairwell in Sector 9

A new entrance door will be installed at the top of the Sector 9 stairway and equipped with standard PPS provisions to allow user access under controlled conditions. The new PPS features and stairway proposed for Sector 9 will be identical to the arrangement in Sectors 19 and 24. Personnel will walk about 210 feet down the linac tunnel from the foot of the access stairway to the FACET-II experimental area. With a stairway installed in the Sector 9 shaft, the nearest equipment shaft to the FACET-II experimental area will be in Sector 4. This shaft will remain available for lowering large or heavy objects into the linac tunnel. Equipment lowered into Sector 4 can be easily moved on carts to Sector 10, a distance of about 1900 feet. Moving equipment in this way is standard practice in the linac tunnel.

3.2.9 Positron Compressor Technical Description

A bunch compressor system will be installed in Sector 4 of the linac to compress positrons and electrons. We will use the bunch compressor currently in Sector 10, which will need to be partially removed for LCLS-II installation. The key components of the compressor system are four identical dipole magnets, which together form a magnetic chicane. Upstream of this chicane, the linac RF system is tuned to introduce a correlation between the momentum of the electrons and their longitudinal position within the bunch, such that the higher momentum electrons are shifted toward the trailing end of the bunch. As the bunch passes through the chicane, the electrons or positrons with lower momentum follow a longer path, allowing the higher momentum electrons to catch up, and resulting in a significantly shorter bunch. A schematic view is shown in Figure 3-16. Figure 3-17 shows a view of the bunch compressor in Sector 10, which will be moved into Sector 4 for use at FACET-II.
3.3 Upgrade Addition Opportunities

The beam parameters achievable with the FACET facility will be adequate to support the science programs outlined in Section 2 of this proposal. If the results from these programs lead in future directions with more stringent demands on the beams, then the basic facility could be extended with one or more hardware improvement projects or changes in operating parameters, depending on the specific requirements. Possible improvements include positron beams, a witness bunch injector, ITF injector and laser systems. The following sections provide detail on each feature.
3.3.1 Positron beams

Positrons add a new dimension to the FACET-II science program. The positron beam can be easily restored in the FACET-II and LCLS-II eras using the high energy bypass line of the former PEP-II. LCLS-II will use this bypass line downstream of Sector 20 and FACET-II. Two beam lines have to be rebuilt (see Figure 3-18). The extraction point of electrons for PEP-II was in Sector 10. We need to move this line upstream by 100 meters into Sector 9 and a reinstall a 100-meter bypass line extension, consisting of a pipe and two quadrupoles. These components are shown in Figure 3-19. The second task is to connect the bypass line in Sector 19 to the old transport line from the linac to the positron target. This line is new but is only about 25 meters long. Most of the magnetic components for this line exist, and we will be able to reuse the remaining positron system hardware.

![Figure 3-18: The bypass transport line has to be restored in two places to provide positrons to FACET-II.](image)

![Figure 3-19: Photograph of bypass line components: extraction pulser magnet on the right and insertion dipole on the left.](image)

3.3.2 Witness Bunch Injector

A witness bunch injector and 200 MeV accelerator and bunch compressor, based on the design developed for the LCLS or XTA project, can be installed in Sector 10 of the
linac to produce very short low-emittance electron bunches without the need for the damping ring. The witness bunches will be timed to be accelerated in the plasma by the drive bunch produced by the damping ring and accelerated by the linac. The location is shown in Figure 3-20.

**Witness injector**

![Diagram](image)

**Figure 3-20:** Location of a possible witness bunch injector for the final focus of FACET-II.

### 3.3.3 ITF injector or ‘Integrated Test Facility in FACET-II’

It is possible to replace the existing FACET electron injector and electron damping ring with a high brightness injector and bunch compression system that would provide not only the high-charge, low emittance electron bunches needed to drive plasma acceleration for the FACET-II R&D program, but also the high brightness, high peak current bunches for x-ray FEL R&D. The bunch length will be shorter and the horizontal emittance will be about 10 times smaller than from the damping ring, enhancing plasma acceleration. This injector, combined with additional modifications to the accelerator configuration in sectors beyond S1 will create an Integrated Test Facility (ITF) in FACET-II. The ITF will enable R&D in high energy bunch compression, seeding, high brightness beam transport, FEL undulators, timing/synchronization and diagnostic systems while remaining compatible with the FACET-II R&D program. We will retain a transport line from Sector 10 to the existing positron target in Sector 20, the positron return line, and the positron damping ring to support the FACET-II R&D program. The ITF will be designed to operate with multiple bunches to enable THz-pump, x-ray-probe experiments and studying multi-bunch generation of long term hot plasmas. The ITF in FACET-II will provide electron energies reaching the order of 10 GeV, creating a unique accelerator test facility in the world for conducting R&D for both soft and hard x-ray FELs at the FACET-II facility.

A simplified schematic of the ITF is shown in Figure 3-21, showing the four principal areas of the facility, L0 through L3. The 5 nC operation mode of ITF for FACET-II PWFA experiments has been calculated with the electron bunch properties shown in Figure 3-22 and Table 3-3. Significant reductions in the horizontal spot size and
bunch length are expected.

Figure 3-21: Simplified schematic of the Integrated Test Facility (ITF) in FACET-II indicating x-ray FEL studies that can be conducted at various locations.

Figure 3-22: Beam simulation of the ITF RF photo-gun producing 5-nC bunches needed by FACET-II with 10x lower transverse emittance and shorter bunch length.

Table 3-3: ITF photoinjector parameters for 5-nC operation for FACET-II.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>5 nc</td>
</tr>
<tr>
<td>Laser pulse length</td>
<td>8 ps FWHM in Gaussian</td>
</tr>
<tr>
<td>Laser diameter</td>
<td>3 mm in uniform</td>
</tr>
<tr>
<td>Laser launch phase</td>
<td>30° from zero-crossing</td>
</tr>
<tr>
<td>RF gradient on cathode</td>
<td>115 MV/m</td>
</tr>
<tr>
<td>Electron energy</td>
<td>135 MeV</td>
</tr>
<tr>
<td>RMS projected emittance</td>
<td>4.3 μm (95% particles)</td>
</tr>
</tbody>
</table>
The following sections describe each of the principal sections of the ITF in detail.

### 3.3.3.1 L0 - Injector

The ITF injector, located in Sector 0 (S0) of the linac tunnel, will be very similar in design to the LCLS-I and LCLS-II photoelectron injectors located in S20 and S10, respectively, except it is significantly simplified since it can be in line with the downstream linac. It will use the existing tunnel in S0 with a new beamline identical to that for the LCLS RF gun through LO linac structures. Principal components and beam parameters are shown in Figure 3-23 and Table 3-4. As mentioned earlier, gun simulations indicate that the injector could also be operated at high charge (5 nC) and moderate normalized emittance (5 μm) for high peak current FACET-II wakefield acceleration experiments where emittance is not as critical. High current performance will need to be verified by experiment.

![Figure 3-23: ITF photocathode injector (135 MeV) in area L0. Green = existing, minimal modifications. Blue = modified and / or moved existing hardware. Red = new hardware](image)

<table>
<thead>
<tr>
<th>Bunch charge</th>
<th>20 pC</th>
<th>250 pC</th>
<th>1 nC</th>
<th>5 nC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>135 MeV</td>
<td>135 MeV</td>
<td>135 MeV</td>
<td>135 MeV</td>
</tr>
<tr>
<td>Pulse length, FWHM</td>
<td>1.5 ps</td>
<td>5 ps</td>
<td>8 ps</td>
<td>12 ps</td>
</tr>
<tr>
<td>Emittance (μm RMS)</td>
<td>0.2</td>
<td>0.5</td>
<td>1.2</td>
<td>5</td>
</tr>
</tbody>
</table>
Principal components in L0 (see Figure 3-23) include:

**RF Photocathode Gun:** This will be a copy of the LCLS RF gun and solenoid system. RF power will come from a modulator located in sector 1-2.

**Laser System:** The laser for the photocathode gun used for the ITF FEL program will be similar to the LCLS laser, but it will operate at only 30 Hz. A second laser having higher pulse energy (2mJ) at 8-ns FWHM pulse length will be needed to produce 5-nC beams for FACET-II wakefield acceleration experiments. Both ITF and FACET-II lasers will be located in a new laser room with appropriate laser transport lines.

**Accelerator Structures:** The first accelerator (K02) will be replaced by a SLAC structure modified to have dual RF feeds similar to the LCLS L0-A structure. It will be installed further downstream from the existing structure and will be driven by the existing K02 RF. The existing K01 structure will be moved upstream and used for the second accelerator (L0-B).

**Laser Heater:** This will be a duplicate of the LCLS laser heater system.

**Diagnostics:** The emittance measurement station will use a quad scan and OTR, similar to the LCLS system. A 135-MeV spectrometer will be used to measure energy and energy spread. S-band cavity detectors will be used to measure the beam’s phase with respect to the RF drive voltage.

**Other:** The system will include new magnet and LLRF controls and new BPM processors.

Tunnel length requirements for major systems in L0 are given in Table 3-5.

<table>
<thead>
<tr>
<th>Sub-system</th>
<th>Tunnel Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCLS Injector length gun to OTR2</td>
<td>14 Meters</td>
</tr>
<tr>
<td>Spectrometer</td>
<td>3 Meters</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>17 Meters</strong></td>
</tr>
<tr>
<td>Available CID Sector 0 length to 1-1A structure</td>
<td>19 Meters</td>
</tr>
</tbody>
</table>

### 3.3.3.2 L1 - Bunch Compressor 1 (BC1) System

The first bunch compressor (BC1) in area L1 will be similar in design to the LCLS BC1 and is expected to have similar performance. CSR emittance growth is expected to limit the peak current to about 400 Amps. [152]
Figure 3-24: ITF L1 bunch compressor BC1 (250 MeV, <400 Amps).

Principal components are shown in Figure 3-24 and include:

**RF System:** The existing 1-1A to 1-1C structures and RF systems can be used. The 1-1A modulator klystron will be used to power all three structures. The beam in these structures will be off-crest, similar to the L1S system in LCLS. A new X-band structure (similar to LCLS L1-X) and klystron will be required as a linearizer. Modulator 1-1B will be modified to be used for this system.

**Bunch Compressor and Diagnostics:** This 250-MeV bunch compressor will be similar to the LCLS BC1 compressor. Stations K1-2 will be removed to allow room for the bunch compressor, S-band transverse deflecting cavity (TCAV), emittance station and spectrometer.

**Positron Chicane:** A double chicane at BC1 is required to introduce positrons into the linac without modifying the positron return line, so that the positrons follow the chicane on the other side of the electron beamline. In the case that we need to modify the positron return line to introduce the positrons a bit downstream, the BC1 can also serve as the electron chicane facilitating the introduction of positrons into the linac. Figure 3-24 shows both options.

**Transverse Cavity (TCAV):** A short S-band TCAV structure, similar to LCLS TCAV0 will be powered by the K1-1C RF system and will be used for bunch length measurement.

**Emittance Station:** A quadrupole scan and wire scanner detector will be used to make emittance measurements.
**Spectrometer:** A 250-MeV spectrometer will be used with the S-band TCAV for longitudinal phase space measurements.

**Other:** Magnets, low level RF (LLRF) controls and BPMs will be upgraded to be similar to LCLS.

Tunnel length requirements for major systems in L1 are given in Table 3-6.

**Table 3-6:** Approximate tunnel length requirements for L1 sub-systems.

<table>
<thead>
<tr>
<th>Sub-System</th>
<th>Tunnel Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1A to 1-1C structures</td>
<td>Not moved from original</td>
</tr>
<tr>
<td>LCLS X-band, BC1 and emittance measure</td>
<td>16 meters</td>
</tr>
<tr>
<td>TCAV1</td>
<td>1 meter</td>
</tr>
<tr>
<td>Spectrometer</td>
<td>5 meters</td>
</tr>
<tr>
<td>Total</td>
<td>22 meters</td>
</tr>
<tr>
<td>Available space with K1-2 and current electron</td>
<td>~ 20 meters</td>
</tr>
<tr>
<td>chicane removed</td>
<td></td>
</tr>
</tbody>
</table>

**3.3.3.3 L2 - LINAC Systems and Bunch Compressor 2 (BC2) Test Area**

Area L2 of the ITF will use high power RF systems in Linac sectors 1-3 and 2-2 through 4-4 with minimal modification. Accelerator structures will be removed from sector 4-5 through 52 to provide a 72-m long bunch compressor test area with a beam energy of up to 3.5 GeV.

**Figure 3-25:** ITF L2 bunch compressor BC2 test area (1 to 3.5 GeV).
Principal components are shown in Figure 3-25 and include:

**Linac System:** Existing linac structures, klystrons and modulators will be used to accelerate the 250-MeV beam from BC1 to energies as high as 3.5 GeV in the BC2 Test Area.

**BC2 Test Area:** A bunch compressor similar to the LCLS BC2 will be installed initially. Space is provided in the test area for new bunch compressor designs. These can be used in conjunction with the main bunch compressor or with the main compressor set to straight-through mode.

**X-band TCAV1:** The station 4-5 modulator will be modified to operate an X-band klystron for the X-band TCAV system. The X-band TCAV will be similar to the system designed for LCLS. Space is provided for multiple TCAVs and a SLED RF compression system if higher resolution is required.

**Spectrometer:** A 3.5-GeV spectrometer will be used with the X-band TCAV for longitudinal phase space measurements.

**Other Diagnostics:** A 4-wire emittance measurement using 40 meters of beamline space will be available. ITF operation at 20 pC will require that the Linac BPM processors be replaced with LCLS-style stripline processors. S-band cavity detectors will be used to measure the beam’s phase with respect to the RF drive voltage.

Tunnel length requirements for major systems in L2 are given in Table 3-7.

<table>
<thead>
<tr>
<th>Sub-System</th>
<th>Tunnel Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCLS BC2 or compressor test space</td>
<td>27 meters</td>
</tr>
<tr>
<td>TCAVX1</td>
<td>3 meters</td>
</tr>
<tr>
<td>Emittance measurement / TCAV drift / 2 RF stations</td>
<td>40 meters</td>
</tr>
<tr>
<td>Total length</td>
<td>70 meters</td>
</tr>
<tr>
<td>Available space</td>
<td>72 meters</td>
</tr>
</tbody>
</table>

**3.3.3.4 L3 - Experimental Test Area**

Area L3 of the ITF will use the existing RF systems in sectors 5-3 through 5-8 and remove RF structures from sectors 9 and 10 (upstream of LCLS-II) to provide a test area for high brightness, high energy beams, both for the FACET-II experimental program and for FEL R&D. Beam energies from 1 GeV to 10 GeV are available. The used beam will be sent to the existing BL 9-0 high power (60 kW) dump.
Figure 3-26: ITF L3 high energy test area.

Principal L3 components are shown in Figure 3-26 and include:

**Linac System:** Existing linac structures, klystrons and modulators in sectors 5-3 through sector 8 will be used to accelerate or decelerate beam from BC2 to energies ranging between ~1 and 10 GeV. RF structures will be removed from sectors 9 and 10 to create the experimental area.

**Experimental Area:** This will provide a 110 m x 3 m standard LINAC tunnel area in addition to a wider 10 m x 6 m test area. The downstream end of the experimental areas is located approximately 50 meters from the LCLS-II injector laser room, and may be able to share laser some facilities with LCLS II. Note that the ECHO-100 test is expected to require 33 meters of beam line.

**X-band TCAV2:** A high-energy X-band TCAV driven by the 9-1 modulator will be used for temporal measurements.

**Spectrometer:** The existing BL 9-0 25-degree tunnel will provide space for a 5-m dispersion high resolution spectrometer.

**Other diagnostics:** A 4-wire emittance measurement system, high-resolution BPMs for low charge beams and S-band cavity phase monitors will be provided.

**Positron production line:** A pick-off point for extracting electrons into a transport line headed to the S20 positron target will be located near the spectrometer dipole magnet.

**Shielding:** The BL 9-0 tunnel is shielded for high power beams. However, a new shielding wall is needed downstream of the spectrometer to enable access to FACET-II/ITF while LCLS-II is operating. This will be similar to the existing wall that isolates FACET from the LCLS-I and will be installed as part of the LCLS-II project. It is probably not practical to build a more massive shield wall that would enable access to LCLS-II while FACET-II/ITF is operating.
3.3.3.5 ITF Implementation

The four areas of the ITF are designed to be implemented in stages, providing functional facility operation at the end of each stage. The simplified implementation plan is as follows:

LO - Injector: Since the Injector is largely a reproduction of those used for LCLS-I and II, the estimated time to develop a detailed design is one year after project start. Installation and commissioning take place in the second year after start.

L1 – BC1: Detailed design is completed in the second year after project start. Construction and commissioning take place in the third year after start.

L2 – BC2: Detailed design is completed in the third year after project start. Construction and commissioning take place in the fourth year after start.

L3 - Experimental Area: Detailed design is completed in the fourth year after project start. Construction and commissioning take place in the fifth year after start.

Project completion: Project is completed at the end of the fifth year.

3.3.4 FACET Laser Systems

Two optical laser systems will be required for FACET-II. The first will be an ultrashort pulse Chirped Pulse Amplification (CPA) system based on laser pumped Ti:sapphire. This system will produce 1 J per pulse at 800 nm with a pulse width of 30-35 fs, thus providing 30 TW of peak power. Systems like this are currently commercially available, although at lower rep-rates. Operation at 120 Hz to match the Linac rep-rate will require a custom design. The second laser system will provide 100 mJ per pulse at 10.6 micron wavelength with a pulse width of 1 ps, and therefore a peak power of 0.1 TW. This system will be based on pressure and isotopically broadened CO2 and while it will be a custom laser, it will be based on commercial components as well as the design work done at Brookhaven Accelerator Test Facility (ATF).

3.3.4.1 Ultrashort pulse Ti:sapphire system:

As stated above, the goal for the ultrashort pulse Ti:sapphire system is to produce 1 J per pulse with pulse widths as short as 30 fs. CPA systems with these energy levels and pulse widths are commercially available and becoming fairly common at rep-rates of 10 Hz or less. The technically challenging aspect of this system is indicated in red in Figure 3-27. Reaching 1 J after compression requires roughly 1.5 J from the Multi-pass Amplifier (MPA). At 120 Hz, this corresponds to 180 W of average power, which is beyond the current state of the art for commercial systems.
This also means that the pump laser for the MPA must provide 6 to 7 J per pulse, or almost 1 kW of average pump power at 532 nm, which is currently beyond the state of the art, especially for a single 120 Hz laser. One solution to this pump laser problem is to temporally interleave multiple lower rep-rate pump lasers. For example, 5 Hz lasers that provide 7 J are commercially available. While multiplexing 24 beams into one amplifier crystal is an engineering challenge, this is exactly what was done for the Bella laser at LBNL – albeit at half the scale. Another advantage of this scheme is that the system could start out at a lower rep-rate and then be gradually upgraded over time.

This leaves the thermal management in the MPA of a Ti:sapphire crystal being pumped by 1 kW of power. Fortunately, Ti:sapphire has very good thermal properties, which get even better if the crystal is cooled to liquid nitrogen temperatures. While cryo-cooled Ti:sapphire is not commercially available at this energy level, SLAC has experience building cryo-cooled Ti:sapphire amplifiers and cryo-cooled Yb lasers have been demonstrated at >1 kW average power.

3.3.4.2 Short pulse CO$_2$ laser system:

The goal of the second laser system will be to provide 100 mJ per pulse at 10.6 μm wavelength with a pulse width of 1 ps, and therefore a peak power of 0.1 TW. This system will be based on an Optical Parametric Amplifier (OPA) pumped by the Ti:sapphire laser system that will generate tunable mid-IR pulses. The mid-IR Signal and Idler wavelengths will then be difference frequency mixed in a non-linear crystal. This will produce 30-100 μJ of 10.6 μm pulses with a pulse width of 100-200 fs. At this point the pulses can be further amplified in two stages. The first of stage uses a pressure amplifier that relies on multiple passes, either spatially multiplexed or regenerative, and would amplify the 100 μJ pulses to roughly 5 mJ. At that point the final isotopically broadened CO$_2$ amplifier can be double passed to get to the desired 100 mJ level. The 100-200 fs seed pulses from the OPA will over fill the spectral gain bandwidth, and therefore the final output pulses will be broadened to the 1 ps level.
3.3.4.3 Timing and synchronization

Since the Ti:sapphire oscillator effectively acts as the master clock for both the Ti:sapphire and CO₂ systems, we will need to synchronize this oscillator to the RF of the linac with a precision of <100 fs. Fortunately, this is exactly the same requirement as the timing requirements on the LCLS photo-gun drive laser. In this case, we have demonstrated synchronization of the oscillator to the linac low-level RF to as good as 30 fs. Unfortunately, the linac itself has 50-100 fs of jitter in the bunch arrival time relative to the RF. This means the total arrival time jitter will be on the order of 100 fs. In order to solve this problem, we have recently implemented a technique (x) that allows us to measure the arrival time of the laser relative to the x-rays or electrons to within 10 fs. This technique is based on splitting off a small portion of the laser beam, generating a broadband chirped pulse by self phase modulation, and then using this chirped pulse to probe the reflectivity change that occurs when the x-rays or electrons hit a thin foil such as SiN (see Figure 3-28). While this does not actually improve the synchronization, it allows the experimental data to be post-processed with 10 fs timing precision.

![spectra from 100 consecutive shots](image)

**Figure 3-28:** 100 subsequent spectra of the chirped probe pulse showing the change when the x-rays arrive

3.3.4.4 Harmonic generation

The Ti:sapphire system will be capable of generating harmonics of the 800 nm fundamental wavelength. With the 1J output of this system, a harmonic generation package such as the one shown in Figure 3-29 would provide as much as 400 mJ at 400 nm, 150 mJ at 266 nm, and as much as 10 mJ at 200nm. In all cases the pulse width will be in the 50-60 fs range.
3.4 Project Management and Schedule

3.4.1 Project Execution Plan

A Project Execution Plan (PEP) was developed several years ago for the construction phase of the FACET project at SLAC, including project schedule and budget. The PEP described how the estimates of the costs and their associated contingencies were calculated, and explained methods used to control the project and identify issues as they arose in order to ensure early corrective action. The PEP also included plans for safety, risk management, and formal procedures for system engineering, including change control. FACET-II will make a similar PEP.

Many of the components for the Sector 10 Final Focus, including magnets, vacuum equipment, diagnostic devices, electronics, and power supplies will be salvaged from the FACET, FFTB, PEP-II, and SLC facilities and will be reused directly or refurbished as needed. Other components will be acquired from outside vendors or fabricated in SLAC shops. New components to be constructed in SLAC shops will all be copies or simple extensions of proven designs from other SLAC facilities. For example, the new components for the positron compressor chicane will be similar to components that are now used to compress electrons.

3.4.2 Technology Driven Possible FACET-II Time Line

We give possible timeline for FACET-II and its additional extensions, which may vary depending on technology developments and engineering.

Design study & define experimental program  
FY2013-FY2014

PED engineering funding  
FY2014-FY2015
FACET-II construction start  FY2016
FACET D&D in Sector 20  FY2016 April
FACET-II mechanical installation start  FY2016
FACET-II construction complete  FY2018
FACET-II first beam  FY2018

3.4.3 A Staged Approach to the Evolution of the FACET-II Facility

The diverse research program planned at FACET-II naturally lends itself to a staged approach to construction. After each phase is completed and commissioned, FACET-II will be run to support a new set of experiments. The facility will continue to evolve through a multiyear lifecycle to provide an ever broader program. The order in which the various upgrades are implemented will be dictated by guidance from the scientific program committee, accelerator advisory committees and funding agencies. Below is one possible implementation scenario, although it is understood that the sequence may change with the scientific priorities of the national program.

The first phase would restore current FACET capabilities in a new facility compatible with operation of LCLS-II after 2016. This phase relocates the existing FACET chicanes and Final Focus upstream of LCLS-II. If implemented promptly, it will minimize the interruption to the user programs currently carried out at FACET by national and international collaborations and avoid a lengthy and costly restart. The details of this core facility are described in section 3.1. This phase should be completed by FY18, limiting the break in the program to 2 years.

Phase two would install a new photo-injector to provide a high brightness witness bunch for the high gradient acceleration experiments. It would be based on existing SLAC hardware at relatively modest cost. It could be installed in FY19. The witness bunch photo-injector is described in Section 3.3.2.

The next upgrade might be the installation of lasers to support high energy and intensity gamma ray programs on the time scale of FY20. There are three sub stages in the laser system: a 10Hz, Ti Sapphire system, a 10 micron CO2 based system at 120 Hz and finally an upgrade of the Ti:Sapphire laser to 120 Hz operation. The high rep-rate upgrade option is expected to be 75% of the laser system cost and will be reevaluated based on scientific priorities. The main drivers for this option are the multi-GeV gamma and polarized muon beam programs. The laser systems are described in Section 3.3.4.

Positrons are an essential element in the FACET-II science program. There are two stages to positron operation at FACET-II (see Section 3.3.1): first, to deliver positrons alone to the experimental area and second, to deliver both electron and positron beams simultaneously with a variable delay between the beams. The first stage could be realized in FY19 and the second in FY21.

The current electron source is based on a thermionic injector and damping ring. This could be upgraded with an LCLS style photo-injector system as described in the ITF (injector test facility) Section 3.3.3. This is the most expensive upgrade but
Fortunately most of the experimental programs can run with reduced performance before it is complete. The infrastructure to carry out research related to FELs would be completed in 2020.

The sequence outlined here is only one possibility. The construction of this multipurpose facility will likely be funded by multiple agencies and their priorities will determine the order of the various additions.

![Figure 3-30](image)

**Figure 3-30:** A staged evolution of the FACET-II facility is shown. The cost of individual phases in M$ is shown inside the boxes. The proposed chronological ordering shows the earliest items to the left.

<table>
<thead>
<tr>
<th>Table 3-8: Summary table describes the proposed experimental program dependence on available facility options. (<strong>RS:</strong> Option is <strong>Required to Start</strong>; <strong>RF:</strong> Option is <strong>Required to Finish</strong> -- program can be started before this option is realized; <strong>B</strong> denotes beneficial)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High gradient acceleration</strong></td>
</tr>
<tr>
<td>LC relevant stage demonstration</td>
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<tr>
<td>High transformer ratio challenge</td>
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<tr>
<td>PWFA with positively</td>
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<tr>
<td>Project Area</td>
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<td>------------------------------------------------------------------------------</td>
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<tr>
<td><strong>charged particles</strong></td>
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<tr>
<td>Ion motion in PWFA</td>
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<tr>
<td>Generation of super high brightness beams</td>
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<tr>
<td>Dielectric wake field acceleration</td>
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<tr>
<td><strong>ITF / FEL / General accelerator R&amp;D</strong></td>
</tr>
<tr>
<td>Long linac tuning/emittance preservation</td>
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<tr>
<td>Energy chirp compensation with short wakefield structures</td>
</tr>
<tr>
<td>High energy bunch compression and CSR mitigation</td>
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<tr>
<td>Attosecond electron bunch generation (single cycle optical/UV pulse)</td>
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<tr>
<td>Plasma based coherent radiation generation</td>
</tr>
<tr>
<td>High-brightness beam diagnostics: transverse profiles, ultra short bunch measurements</td>
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<tr>
<td>THz generation (with tapered undulator, corrugated pipe, grating compressors</td>
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<tr>
<td>Beam manipulations techniques (Echo, emittance exchange)</td>
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<tr>
<td><strong>BIG (Gamma source)</strong></td>
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<tr>
<td>High intensity positron source for ILC, ...</td>
</tr>
<tr>
<td>Studies for high brightness polarized muon source</td>
</tr>
<tr>
<td>Low energy QCD</td>
</tr>
</tbody>
</table>
3.4.4 FACET-II Operation

It is anticipated that FACET-II will operate about 4 to 5 months per year with the potential of extended runs if the science demand is strong and funding is available.
4 Comparison with other facilities

Some of the important features that distinguish different test facilities are the beam energy, brightness, power, charge, time structure, available particle species (electrons, positrons, ...), complimentary capabilities (lasers, cryogenic infrastructure, and the often underestimated institutional expertise in carrying out particular experimental programs.

High average beam power, whether due to high current and or high energy, is often not an advantage because it leads to experimental difficulties and corresponding higher cost. For this reason, most of the facilities available for accelerator R&D operate with low beam power.

The vast majority of experimental programs can and should be carried out at more flexible and easier to operate smaller facilities. Experimental programs at high power facilities need to be carefully selected to be those where the experimental program requires the beam energy or power and justifies the higher cost. Below we summarize the main experimental programs requiring multi-GeV energy at FACET-II:

High-gradient accelerator research:

For plasma wakefield-based linear collider designs, there is a trade-off between higher drive beam energy and a larger number of plasma stages, with an optimum for a drive beam in the range of 10-25 GeV. The energy reach of Facet-II is thus well suited for demonstration of both a single PWFA cell and the staging of multiple plasma cells. The performance of a single plasma stage can be maximized to produce larger energy gain and higher efficiency by precise shaping of the longitudinal profile of the drive beam. A major factor limiting the ability to precisely shape the longitudinal profile are wakefields in the drive beam accelerator. Yet a high peak-current is required to drive large amplitude wakefields in the plasma for rapid acceleration. Higher drive beam energy makes it easier to increase both the beam peak current and the sharpness of the longitudinal profile. These considerations lead to the choice of approximately 10GeV, 50J beam at 10-120 Hz. While these are challenging parameters, SLAC has two decades of operating a high current linac and the resulting operational issues are well understood.

Photo-produced positrons and muons for HEP:

A larger beam energy also gives a higher flux of Compton produced multi-GeV gammas for photo-production of polarized e-/e+ and μ-/μ+ pairs. The higher energy and commensurately higher gamma flux is necessary to efficiently study muon beam generation. In addition, the energy resolution of an optimized Compton source is determined by the geometrical emittance of the electron beam and therefore higher energy electrons will generate a gamma beam that is much more mono-chromatic.
High-brightness beams for FEL applications:

Hard X-ray SASE FELs require beam energies of approximately 10 GeV to reach short wavelengths of around 1 Angström. The FEL performance, however, is strongly related to the beam brightness. The planned FEL experiments at FACET-II address the issues of generating and preserving beam brightness from inception, through multiple stages of acceleration and compression up to the required final energy.

These programs are vital for the HEP mission and for other programs across the Office of Science and they would be enabled at FACET-II by the high-brightness multi-GeV beams that SLAC has delivered for decades.

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