Outline

* Focussing & Spontaneous Radiation
  – Overview
  – State of knowledge
  – Future possibilities, limitations, discussion

* Acceleration
  – Overview
  – Gradient
  – Bunches
  – Afterburners
    • e.g. LCLS doubler for 0.25nm (50keV)
  – Higher transformer ratios
  – Stages

* Summary/Discussion
* Two-beam, co-linear, plasma-based accelerator
* Plasma wave/wake excited by relativistic particle bunch
* Deceleration, acceleration, focusing by plasma
* Accelerating field/gradient scales as $n_e^{1/2}$
* Typical: $n_e \approx 10^{17}$ cm$^{-3}$, $\lambda_p \approx 100$ µm, $G > MT/m$, $E > 10$ GV/m
* High-gradient, high-efficiency energy transformer
* “Blow-out” regime when $n_b/n_p >> 1$
SLAC/UCLA/USC Experiments @ FFTB
Studied all aspects of beam-plasma interaction


Nature 411, 43 (3 May 2001)


Betatron X–ray emission in E–157

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E-157 @ SLAC

Ionizing Laser Pulse (193 nm)

Li Plasma

\( n_e \approx 2 \cdot 10^{14} \text{ cm}^{-3} \)

\( L \approx 1.4 \text{ m} \)

Optical Transition Radiators

Bending Magnet

Cerenkov Radiator

Dump

\( \int C \, dt \)

Streak Camera (1ps resolution)

X-Ray Diagnostic

Patrick Muggli, EPAC-SLAC, 11/09/00
BEAM ENVELOPE/TAIL

Particle/Envelope equation:

$$\frac{\partial^2 \sigma}{\partial^2 z} + K^2 \sigma = \left\{ \begin{array}{ll} 0 & \text{for a single particle or tail} \\ \frac{\varepsilon^2}{\sigma^3} & \text{for a beam of emittance } \varepsilon \end{array} \right.$$ 

in an ion channel of focusing strength

$$K = \frac{\omega_{pe}}{\sqrt{2\gamma c}} = \frac{1}{\beta^2}$$

- Particles/tail oscillate
- Envelope executes betatron oscillations
- Tail aligned with the beam’s head at envelope minima
- Tail flipped at envelope maxima
- Tail oscillates at half the betatron frequency
Unmatched Beam

Plasma Focusing Force > Beam “Emittance Force”

\[ \beta_{\text{beam}} > \beta_{\text{plasma}} \]

- Multiple betatron oscillation of the beam envelope in the plasma

Patrick Muggli, EPAC-SLAC, 11/09/00
BEAM TAIL OSCILLATIONS

Measured from Beam Position Monitor \(\approx 3.8\) m after the plasma

- Tail oscillation follows envelope betatron oscillation \((1/2 \beta\text{-tron period})\)
- Consistent with no amplification of the tail over \(L \approx 1.4\) m and up to \(n_e \approx 5 \times 10^{14} \text{ cm}^{-3}\)

Spot Size @ DS OTR
\((\approx 1\) m from plasma exit\)

Beam Centroid @ BPM6130
\((\approx 4\) m from plasma exit\)

\[ K*L \propto n_e^{1/2} \]

\[ \sigma_{0 \text{ uv Pellicle}} = 43 \mu m \]

\[ \varepsilon_N = 9 \times 10^{-5} \text{ (m rad)} \]

\[ \beta_0 = 1.15 \text{ m} \]

Patrick Muggli, EPAC-SLAC, 11/09/00
Dynamic (Time Dependent) Focusing

- The beam (head) creates its own channel
- Different z-slices of the beam experience different focusing field amplitudes and undergo a different number of betatron oscillations

2-D PIC Simulation

3-D PIC Simulation, $L=1.4\text{m}$
\[ \omega_{\text{x-ray}} \equiv 2 \gamma^2 \omega_\beta \propto \sqrt{n_e} \]

\[ \lambda_{\text{x-ray}} \approx 1\text{Å}, \text{ or } E_{\text{x-ray}} \approx 10 \text{ keV} \]

\[ (n_e = 1.5 \times 10^{14} \text{ cm}^{-3}) \]

\[ \# \text{ photons} \propto n_e^2 \]
Rough Analysis on 6.4 KeV photon numbers

Beam energy $\gamma \approx 60000$, $k_\beta L \approx \pi$, $\sigma = 15 \ \mu\text{m}$, $N=2\times10^{10}$

The total $\beta$-radiation energy satisfies

$$\frac{\Delta \varepsilon}{\varepsilon} = \frac{1}{3} \gamma \cdot r_e \cdot k_\beta^2 \cdot K^2 \cdot L$$

and is about $130\times10^{10}$ eV.

It is distributed in a broad spectrum with a bandwidth $\frac{\Delta \omega}{\omega_0} \approx 1$

The bandwidth of Bragg scattering of the above spectrum depends on the inserting angle of x-ray and receiving angle of the detector, and is about $\delta \omega/\omega_0 \approx 0.02$. We estimate there are $2\times10^6$

6.4KeV(+-130eV) photons out of the $\beta$-radiation.

The x-ray detector receives $4\times10^4$ photons. The attenuation of xray is mainly due to the low transmission of 6.4 KeV photon through a 20- $\mu\text{m}$ Ti material. By accounting of 4% transmission and some loss due to air attenuation, they agree reasonably well.
Summary

• We show evidence of spontaneous x-ray emission due to e- β motion. Incoherent scattering shows the radiation power varies with the square of the plasma density.
• We quantify x-ray signals by Bragg scattering 6.4 KeV photon energy at the 2nd pinch. Photon numbers received by the detector agree reasonably well with the theoretical estimation.
• X ray fluorescence provides information of beam position and x-ray emission energy at low frequency.
A) Schematic of the experimental setup

Figure 1: Schematic of experimental setup. Insert shows a Xybion photo of the image plane.
Conclusions

1) We have measured positron spectra for 5-30 MeV for a variety of densities and conditions.

2) We have demonstrated that we can match the spectra with theory.

3) Yield vs. Density curve showed the difficulty of this experiment. Small changes in incoming beam parameters lead to large changes in signal.

4) A yield vs. waist plot was created showing a correlation with beam size and a reduction toward the beam matching condition.

5) Positron yield has been obtained for 3 different oven lengths and showed a correlation to the magnitude of the plasma wake.

6) A thin target positron source driven by betatron X-rays emitted in a plasma has been demonstrated
High Gradient Acceleration

* Motivation is applications requiring high energy (gradient)
* e.g. Largest cost driver for a linear collider is the acceleration
  – ILC geometric gradient is ~20 MV/m ➞ 50km for 1 TeV
* Size of facility is costly ➞ higher acceleration gradients
  – High gradient acceleration requires high peak power and structures that can sustain high fields
    • Beams and lasers can be generated with high peak power
    • Dielectrics and plasmas can withstand high fields
* Many paths towards high gradient acceleration
  – RF source driven microwave structures
  – Beam-driven microwave structures ➞ ~100 MeV/m
  – Laser-driven dielectric structures ➞ ~1 GeV/m
  – Beam-driven dielectric structures
  – Laser-driven plasmas ➞ ~10 GeV/m
  – Beam-driven plasmas
* Acceleration gradients of ~50 GV/m (3000 x SLAC)
  - Doubled energy of 45 GeV beam in 1 meter plasma
  - Record Energy Gain
  - Highest energy electrons ever produced at SLAC
  - Significant advance in demonstrating the potential of plasma accelerators

Next Step:
- 25 GeV stage
- Two Bunches, $6 \times 10^{16}$ e$^-$/cm$^3$
- FACET Project: 2km of SLAC Linac

A new facility to provide high-energy, high peak current \( e^- \) & \( e^+ \) beams for PWFA experiments

Scheduled for completion late 2010, first experiments early 2011

Beam Parameters Driven by Science Needs
Delivered to 100m area with three distinct functions:
1. Chicane for final stage of bunch compression
2. Final Focus for small spots at the IP
3. Experimental Area

Advantageous location:
- Preserves \( e^+ \) capability
- No bypass lines or interference with LCLS
- Linac setup virtually identical to SPPS/FFTB
Generate Two Bunches by Selectively Collimating During Bunch Compression Process

- **Energy**
- **Phase Space**
- **Temporal Profile**

Exploit Position-Time Correlation on e⁻ bunch to create separate drive and witness bunch

Modeled using similar analytic framework (CSR) as LCLS as well as tracking/shower codes

Disperse the beam in energy

\[ x \propto \frac{\Delta E}{E} \propto t \]

Adjust final compression

...selectively collimate

M. J. Hogan, FLS2010 Page 19
FACET Experiments will accelerate a discrete bunch of particles with narrow energy spread

* Double Energy of a 25GeV Beam in ~1m
* Drive beam to witness beam efficiency of ~30% with small dE/E

$L_p \sim 1$ m
* Afterburner for X-ray FELs (LCLS...)  
  – Use alternate pulse format from photo-injector or notch collimator to generate two bunches  
  – Double energy of one bunch with less than a meter of plasma, recall:  
    \[ \lambda_{\text{rad}} \approx \frac{1}{\gamma^2} \]  
    – FEL application will require small slice emittance & slice energy spread  
      • Emittance needs to be similar to effective radiation emittance \( \frac{\lambda_{\text{rad}}}{4\pi} \)  
      • dE/E needs to be less than the FEL Pierce Parameter (rho) \( \sim 10^{-4} \)  
  – Key length scale for the slice is set by the FEL cooperation length (slippage over a gain length) \( \sim 60\text{nm} \)  
* May allow for new designs with high transformer ratio PWFA and much shorter linac  
  – Initial studies of 1 to 5 GeV acceleration for FELs – see poster WE6RFP098 by Wei Lu
Projected Test Case 1 (High Charge)

- Run distance = 48 cm
- Transformer ratio = 0.99
- Witness $\sigma_E/E = 0.008 = 2.3 \times 10^{-4}$ per cooperation length

- $N_d = 1.04 \cdot 10^{10}$, $\sigma_{z,d} = 10 \mu m$
- $N_w = 2.1 \cdot 10^9$, $\sigma_{z,w} = 2 \mu m$
- Separation = 92 $\mu m$
- $n_p = 10^{17}$ cm$^{-3}$
- $E_0 = 13.5$ GeV
- $\sigma_{x,y} = 1.7 \mu m$
The projected case assumes the fields stay fixed.
The effect of head erosion was calculated.
The following figure shows the variation caused by head erosion over the propagation distance.
Projected Test Case 2 (Low charge)

- Run distance = 39 cm
- Transformer ratio = 0.97
- Witness $\sigma_E/E = 0.027 = 3.1 \times 10^{-4}$ per cooperation length

- $N_d = 8.32 \cdot 10^9$, $\sigma_{z,d} = 10 \, \mu m$
- $N_w = 4.2 \cdot 10^9$, $\sigma_{z,w} = 5 \, \mu m$
- Separation = 68 $\mu m$
- $n_p = 2 \cdot 10^{17} \, \text{cm}^{-3}$
- $E_0 = 13.5 \, \text{GeV}$
- $\sigma_{x,y} = 1.7 \, \mu m$
The projected case assumes the fields stay fixed.
The effect of head erosion was calculated.
The following figure shows the variation caused by head erosion over the propagation distance.
• Beam will develop uncorrelated energy spread due to betatron oscillations in the ion column.

• Relevant formula is:

$$\frac{\sigma_E}{E} = \frac{1}{3} \varepsilon_N R c \gamma_{beam} k_p^2$$

• Putting bounds on this by looking at the beam energy before and after doubling, we find that the maximal relative energy spread on the order of $2 \times 10^{-4}$.
SASE is pretty insensitive to longitudinal phase space, as long as the energy spread over cooperation length is less than rho. If I use your correlated energy spread $3 \times 10^{-4}$ over the cooperation length as the energy spread, emittance 2 um, and a peak current of 16 kA, I got 13 m gain length at 0.38 Angstrom (4 times shorter than 1.5 Angstrom) using Ming Xie's fitting formula, or about 255 m to reach saturation (assuming it takes about 20 Lg). Another effects at this high energy is quantum diffusion due to spontaneous undulator radiation, which tends to increase the slice energy spread and delay saturation.

The parameters you found looks quite encouraging but 0.38 A is damn short wavelength. Is the slice emittance the same as projected (2 um) in plasma accelerator?

Zhirong
Conclusions (so far...)

* Have identified suitable gaussian bunch profiles that will allow a PWFA to double a beam with LCLS energy in less than half a meter
* The uncorrelated energy spread induced by betatron motion in the plasma ion column is calculated to be less than rho
* The correlated energy spread resulting from the slope of the loaded plasma wake is linear along the bunch and on the order of the gain bandwidth over a cooperation length
* At very short wavelengths the slice emittance needs to be on the order of the radiation emittance (~ 0.3 mm-mrad) to minimize the gain length & eventual saturation length
* Future studies:
  – Investigate the feasibility of producing the identified bunch pairs with the LCLS injector
  – Investigate lower initial energy options for 1Å light using less SLAC linac
High Transformer Ratio PWFA for XFEL Applications

Wei Lu, Chengkun Huang and Warren B. Mori
• A high charge (5-10nC) low energy driver (1-3GeV) with an elongated current profile is used to drive a plasma wake in the blowout regime.

• An ultra-short high quality low charge beam (1nC) can be loaded into the wake at a proper phase and be accelerated to high energy (5-15GeV) in very short distance (10s of cms).

• The parameters needs to be optimized, such that high quality (0.1% energy spread and 1mm mrad emittance) and high efficiency (60-80%) can be simultaneously achieved.
• The fourth generation of light source (e.g., the LCLS in the U.S. and the XFEL in Europe) requires high energy electron drivers (16–20 GeV) of very high quality (nC of charge, 1 mm mrad of emittance, 0.1% of the energy spread, 100 fs in duration).

• We are exploring the possibility of using high transformer ratio PWFA to meet these challenging requirements. This may have the potential to reduce the size of the electron drivers by a factor of 5 or more, therefore making these light source more affordable.
PWFA with Transformer Ratio~5

- Higher efficiencies, brightness possible with non-gaussian bunch profiles
- Applications to colliders, X-FELs
Preserving brightness – investigate emittance growth from several sources

* **Hosing.** Experimental signature is exponentially growing transverse displacement of accelerated bunch. Will excite through deliberate r vs. z correlation on drive bunch.

* **Ion motion.** Potentially an issue when \( \frac{n_b}{n_p} \sim \frac{m_i}{m_e} \). Partially mitigated by using large emittance drive beam. FACET will attempt to quantify this for the first time by lowering the plasma density and measuring the emittance vs the ratio \( \frac{n_b}{n_p} \).

<table>
<thead>
<tr>
<th></th>
<th>Normalized Emittance [mm-mrad]</th>
<th>Sigma z [µm]</th>
<th>( n_p )</th>
<th>( \frac{n_b}{n_p} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFTB &lt; 2005</td>
<td>&gt;120 (x &amp; y)</td>
<td>700</td>
<td>( 10^{14} )</td>
<td>~10</td>
</tr>
<tr>
<td>FFTB &gt; 2005</td>
<td>50 x 10</td>
<td>&gt;12</td>
<td>( 10^{17} )</td>
<td>~10</td>
</tr>
<tr>
<td>FACET</td>
<td>30 or 50 x 10*</td>
<td>&gt;18</td>
<td>( 10^{14} - 10^{17} )</td>
<td>&lt;( 10^4 )</td>
</tr>
<tr>
<td>PWFA-LC</td>
<td>D = 100, M = 2 x 0.05</td>
<td>D = 30, W= 10</td>
<td>( 10^{17} )</td>
<td>100, ( 10^4 )</td>
</tr>
</tbody>
</table>

*Smaller emittance possible with upgrades*
Staged Approach Would Borrow from PWFA-LC ‘Warm’ Option

- TeV CM Energy
- 10’s MW Beam Power for Luminosity
- Positron Acceleration
- Conventional technology for particle generation & focusing

Lots of room or optimization:
- Drive linac energy (length, # and size of turnarounds, compression, CSR, synchrotron losses, cost)
- Number of stages
- Beam time structure for highest efficiency, energy spread, plasma uniformity

M. J. Hogan, FLS2010  Page 34
PWFA-LC ‘Cold’ Option

* Same DB Energy = 25 GeV
* Same DB Charge = 3e10
* Same Linac Bunch Charge and Total Bunches per second
* DB bunch spacing = 150 ns (split bunches between linacs)
* DB current = 32 mA
* DB gradient = 31.5 MV/m (ILC) so ~ 1km DB Linac
* Pulse structure: 4 ms pulses at 30 Hz (12% duty)
* Linac bunch spacing = 9 us
* Turn-Around spacing = 150 ns (Each Linac 1 km)
* DB Accelerator Cost < 500 M$
* Fits on SLAC Site?

DB = Drive Beam
Summary

* PWFA offers strong transverse & longitudinal forces that can be used to produce short wavelength radiation and accelerate particles at high gradient
* Using a plasma column to oscillate a discrete bunch of particles with preserved emittance and narrow energy spread is a possibility but has many challenges
  – Coupled with long. wake, hosing?
* Using a plasma as a single stage energy booster or afterburner appears possible
  – Tolerances to maintain dE/E per Lc
  – Must demonstrate that can use (and preserve) low emittance to keep Lg and Lsat reasonable
* Experiments at FACET will illuminate some of these issues
* Plasma as a means to an end (final energy) seems most likely path on 5-10 year time scale
* Need more focus to fill out Eric & Bruce’s table (rep rate etc)