Research Topics in Beam Physics Department

Introduction

The physics of particle beams has been a broad and vibrant research field encompassing the study of charged particle beams and their interactions. This includes the interaction of particles within the beam, the interaction of beams with the environment and external electromagnetic fields, the interaction of beams with other beams, and finally the interaction of particle beams with beams of electromagnetic radiation. Its foundation is based upon magnetic optics, nonlinear dynamics, and collective effects. Optics and nonlinear dynamics primarily control the quality of the beam while collective effects limit its intensity. The quality and intensity of the beam are two dominant aspects in measuring the performance of all accelerators; to achieve high brightness the beam must have high intensity and high quality. Research efforts in optics, nonlinear dynamics, and collective effects are vitally important for all future developments that use particle accelerators because all new accelerators push the required beam brightness to ever higher levels. This push is fundamental and a requirement to advance research in molecular biology and material and environmental sciences.

Historically, new discoveries in beam physics have led to transformative innovations in particle accelerators. For example, the theory of the Free Electron Laser (FEL) based on self-amplified spontaneous emission (SASE), development of bunch compression, and solenoid compensation for a space-charge dominated beam have provided the key ingredients for the success of the Linac Coherent Light Source (LCLS). The LCLS as a coherent X-ray source improves the peak brightness by ten orders of magnitude. Recently, a seeding scheme, based on a highly nonlinear manipulation of longitudinal phase space called Echo-Enabled Harmonic Generation (EEHG) has been proposed at SLAC. This could well be a transformational method leading to a substantial improvement in longitudinal coherence and synchronization. Since EEHG has the potential of generating extremely high harmonics, up to the 100th, it could become a foundation for second generation FEL facilities. In the sections below, we describe some of the critical subjects for the future of FELs.

1) Seeding schemes

The SASE free electron laser generates radiation with excellent coherence in the transverse direction. However, since it starts from the random shot noise in the beam; the longitudinal coherence length is typically much shorter than the bunch length. This means that the temporal structure of the radiation will randomly fluctuate from pulse to pulse, as different longitudinal modes are contributing to the overall pulse envelope. The total energy of the radiation will also vary between some limits.

Several ideas have been proposed to improve the longitudinal coherence of the SASE process. They are based on a technique which introduces an initial seed of electromagnetic field, or an initial beam current modulation, using a coherent laser beam. If the amplitude of the seed is considerably larger than the power of the noise, the FEL process will pick up and predominantly amplify the seed modulation. This will result in FEL output that has excellent coherent properties in both longitudinal and transverse directions. The seeding process results in much higher stability and reproducibility of the pulse shape of the FEL radiation and also benefits from the exact synchronization to the external seed laser pulse. Because of the obvious advantages of seeding, most of the future low-energy X-ray FEL facilities, planned or under construction, will implement seeding in one form or another.

Over the past few years several schemes have been proposed that accomplish this goal. It was demonstrated quite early at Brookhaven National Laboratory (BNL) that high gain harmonic generation (HGHG) can be used to initiate the spatial modulation of the electron bunch. The seed laser pulse can also be generated in the process of high-order harmonic generation (HHG), when a powerful pulse of an infrared laser radiation passes through a noble gas. This technique showed remarkable success and capability to generate seed radiation with a wavelength of about 10 nm.

Last year a new seeding technique called EEHG was proposed at SLAC. It can potentially generate very high harmonics much more efficiently than HGHG. A first proof-of-principle EEHG experiment has been carried out at the NLCTA facility at SLAC and the experimental results were published recently in PRL. The experimental study is complemented by extensive theoretical analysis by members of the Beam Physics department.

The self-seeding method is a promising scheme that does not require a seed laser. It makes use of special x-ray optics to spectrally filter the SASE light, which is then used to seed a fresh electron bunch to produce fully coherent x-ray pulses. The scheme is applicable to arbitrary wavelengths including the hard x-ray wavelength range. Variations of self-seeding such as the x-ray regenerative amplifier and x-ray FEL oscillator have been proposed and studied. Recently, the Beam Physics effort focused on a two-bunch self-seeding method that is especially suitable for applications to a high-energy machine such as the LCLS.

2) Coherent synchrotron radiation (CSR)

CSR in electron and positron machines introduces a universal source of impedance which may become a dominant contribution to the wakefield at high frequency. The importance of CSR in accelerator beam dynamics was realized many decades ago, however, relatively recently, with the advance of high-current, high-brightness beams, this topic became of critical importance in the design and operation of many accelerators.

Over many years, the Beam Physics department was at the forefront of theoretical and experimental research on CSR. In the mid nineties, R. Warnock and P. Morton wrote a number of pioneering papers where they developed an analytical method for calculating the CSR effect in a toroidal waveguide of rectangular cross section. Their method makes it easy to precisely evaluate the suppression of CSR due to the shielding effect of the conducting walls of a vacuum chamber.

It was later realized that the CSR effect, if unchecked, not only increases the radiated power of the beam, but can also drive beam instabilities and deteriorate the beam parameters. One of the first observations of such deleterious effects was carried out on a bunch compressor at the CLIC test facility by an international team that included Tor Raubenheimer from SLAC. A quantitative theory of the CSR driven instabilities was developed at SLAC in 2002 by S. Heifets and G. Stupakov. This theory was then confirmed by, and showed excellent agreement with, experiments at light sources at LBL and BESSY in Germany.

More recently, the Beam Physics effort has focused on developing computational algorithms and computer programs to simulate the microwave instability caused by CSR in rings.

It is worth emphasizing that the theoretical and numerical studies developed over many years are now being extensively benchmarked and verified in commissioning of the LCLS. The good agreement between the theory and experiment gives confidence that the CSR effects are well understood and points to directions for further progress. Currently, our study emphasizes the calculation in realistic vacuum chambers and possible mitigation methods. In our long-term plan, we will focus on the dynamics beyond the one-dimensional and longitudinal effect.

3) Microbunching instability

The microbunching instability was first observed in numerical simulations; CSR can also amplify shot noise in a beam during bunch compression. Based on an understanding of the underlying physical mechanism, theories of the microbunching instability in bunch compressors were developed in 2002 at SLAC and Argonne. The theoretical results (with corresponding computational tools developed in parallel) now constitute necessary elements of every bunch compressor design and optimization study for generation of high-current, low-emittance beams.

It was later realized that the more detrimental effects of the instability comes from the longituidinal space charge (LSC) field. A laser heater was invented to mitigate the LSC microbunching for the LCLS project at SLAC. The laser heater implemented at the LCLS was successful in suppressing the microbunching instability and enhancing the FEL performance. Its design has since been adopted worldwide for all short-wavelength FEL projects.

Although the microbunching instability is somewhat controlled for the LCLS SASE FEL, there remains a certain level of microbunching in the beam that generates coherent optical transition radiation (OTR) when the beam passes a thin foil. Typically, incoherent OTR from a thin foil is used to diagnose the beam profile. However, for a high-brightness electron beam such as at LCLS, coherent OTR from microbunching interferes with the use of OTR techniques for beam diagnostics and presents unique challenges to high-brightness beam diagnostics.

It is also expected that the microbunching instability may become more severe for future higher-brightness machines and for seeded FELs that demand much better control of the longitudinal phase space than SASE FELs. Thus, further theoretical and experimental studies of this instability will greatly reduce the risks of such machines.

4) Ultra-short electron beams

It is extremely important to make X-ray pulses so short that one can study the ultra-fast processes of the phase transition of material, of chemical interactions, and of biological processes. The SASE based FELs presently give us a pulse length from tens to hundreds of fs. To cover those processes at the atomic level requires orders of magnitude improvement to tens of attoseconds.

The time structure of the x-ray pulse is determined by several factors, mainly the electron bunch length and the FEL coherence length. In an XFEL the electron bunch length is typically much larger than the coherent length, which leads to a series of spikes in the x-ray pulse. Several methods to reduce the bunch length down to or below the 1-fs region have been proposed. One direct method is to reduce the electron bunch charge (low charge mode), hence to reduce the bunch length to get a short x-ray pulse. The other way is to keep the same electron bunch, but manipulate the electron bunch with a slotted foil or with ultra-short optical lasers. After this manipulation, only a small fraction of the electron bunch lases while the other parts are suppressed, so we can obtain a short x-ray pulse.

The low charge operating mode for an XFEL was first demonstrated at LCLS at 20 pC. Based on the electron beam measurements and start-to-end simulations, the expected FEL pulse fwhm length is about 2 fs. Simulations show that, for the hard x-ray at 1.5 Å, there are only a few spikes, and for the soft x-ray at 1.5 nm wavelength, there is only a single longitudinally coherent spike. Experimental measurements show reasonable radiation energy from the x-ray pulse, but the pulse length obtained in this low charge mode is unknown due to the resolution limit of the present diagnostics. Further studies to explore the low charge operating limitations including beam physics and practical issues are of great importance for the future design and upgrades of XFEL facilities.

5) Emittance exchange

Emittance exchange between longitudinal and transverse planes or between flat and round beams may play an important role in future synchrotron light sources. Many early theoretical concepts were developed at SLAC by M. Cornacchia and P. Emma, using a deflecting RF cavity. More recently D. Xiang has suggested using lasers. We have a number of ideas for testing these concepts in the onsite facilities.

Summary

The selected topics focus on the frontiers in developing the next-generation of light sources such as the seeded FEL with ultra-short pulse length, where CSR becomes the dominant limiting effect to the performance of the machine. Clearly, the results of such research will be applicable to many other accelerator facilities since we aim to improve the beam quality and to increase the beam intensity into a new regime.

Selected publications:

1) G. Stupakov, “Using the Beam-Echo Effect for Generation of Short-Wavelength Radiation,” Phys. Rev. Lett. 102 (2009) 074801.
2) D. Xiang and G. Stupakov, “Echo-enabled harmonic generation free electron laser,” Phys. Rev. ST Accle. Beams 12 (2009) 030702.
3) Y. Ding, et al., “Measurements and simulations of ultralow emittance and ultrashort electron beams in the linac coherent light source,” Phys. Rev. Lett. 102 (2009) 254801.

4) Y. Ding, et al., “Generation of attosecond x-ray pulses with a multicycle two-color enhanced self-amplified spontaneous emission scheme,” Phys. Rev. ST Accle. Beams 12 (2009) 060703.
5) D. Xiang, Z. Huang, G. Stupakov, “Generation of intense attosecond x-ray pulses using ultraviolet laser induced microbunching in electron beams,” Phys. Rev. ST Accle. Beams 12 (2009) 060701.
6) S. Heifets, G. Stupakov, “Coherent synchrotron radiation instability in a bunch compressor,” Phys. Rev. ST Accle. Beams 5 (2002) 064401.
7) Z. Huang, K-J. Kim, “Formulas for coherent synchrotron radiation microbunching in a bunch compressor chicane,” Phys. Rev. ST Accle. Beams 5 (2002) 074401.
8) K. Bane, et al., “Measurements and modeling of coherent synchrotron radiation and its impact on linac coherent light source electron beam,” Phys. Rev. ST Accle. Beams 12 (2009) 030704.
9) W.A. Barletta, et al., “Free electron lasers: Present status and future challenges,” Nucl. Instrum. Meth. A 618 (2010) 69.
10) Z. Huang, et al., “Measurements of the linac coherent light source laser heater and its impact on the x-ray free electron laser performance,” Phys. Rev. ST Accle. Beams 13 (2010) 020703.
11) G. Stupakov, I.A. Kotelnikov, “Calculation of CSR impedance using the mode expansion method,” Phys. Rev. ST Accle. Beams 12 (2009) 104401.
12) D. Xiang, “Laser assisted emittance exchange: downsizing the x-ray free electron laser,” Phys. Rev. ST Accle. Beams 13 (2010) 010701.
13) Y. Ding, Z. Huang, R. Ruth, “Two-bunch self-seeding for narrow-bandwidth hard x-ray free-electron lasers,” Phys. Rev. ST Accle. Beams 13 (2010) 060703.
14) D. Xiang, W. Wan, “Generating ultrashort coherent soft x-ray radiation in storage rings using angular modulated electron beams,” Phys. Rev. Lett. 104 (2010) 084803.
15) Z. Huang, K. Bane, Y. Ding, P. Emma, “A single-shot method for measuring femtosecond bunch length in linac-based free-electron lasers,” Phys. Rev. ST Accle. Beams 13 (2010) 092801.
16) D. Ratner, A. Chao, “Steady state microbunching,” to be published in PRL.
17) D. Xiang, et al., “Demonstration of the echo-enabled harmonic generation technique for short-wavelength seeded free electron lasers,” Phys. Rev. Lett. 105 (2010) 114801.