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Discovery Science

Electron Bunch Trains for Advanced Accelerator, Radiation Source, and Imaging Applications

High brightness beams (HBBs) are essential for particle colliders, radiation sources such as free electron lasers (FELs), and advanced accelerator concepts. Particle colliders probe the fundamental constituents of matter and their forces, as well as the characteristics of the universe at the smallest and largest scales. Ultra-short pulses of x-ray radiation produced by FELs are used to study chemical reactions in biological material such as cells DNA, to understand the formation of complex new materials, and to diagnose high-density plasmas, such as warm dense matter and nuclear explosions. Advanced accelerators aim at developing a new acceleration technology, using for example plasmas and dielectric structures to make particle accelerators affordable for hospitals and small research laboratories at universities and in industry. This new technology could also have a strong impact on the size and cost of a future high-energy linear collider.

Brightness is a measure of the beam density in phase (position-momentum) space. HBBs have very low emittance, and therefore, can be focused to a small volume and retain short scale density modulations, thereby allowing for the emission of coherent radiation at extremely short wavelengths (Angstroms). The state of the art source of HBBs is the radio-frequency photo-injector gun. For example, sub-micron normalized emittances have been obtained both at the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF) and at the SLAC National Accelerator Laboratory Linac Coherent light Source (LCLS).

High brightness beams are created at the ATF and we explore the possibility of producing trains of HBBs and their application. We also develop the diagnostics needed to characterize these beams. We have recently demonstrated that trains of HBBs can be produced from a single long HBB using a masking method [P. Muggli et al., Phys. Rev. Lett. 101, 054801 (2008)]. With this method the characteristics of the bunch train can be tailored for particular applications through the design of the mask and the characteristics of the beam at the mask location. The number of bunches in the train can be
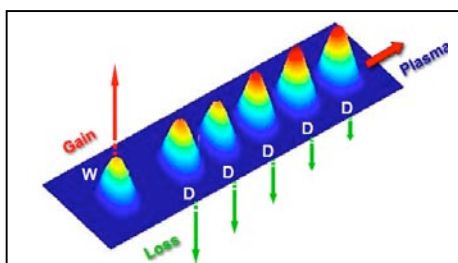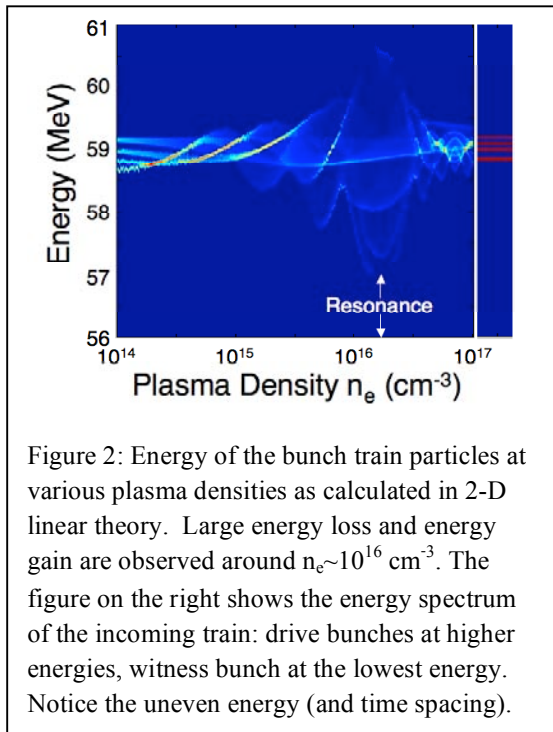

Figure 1: An experimental picture of the bunch train produced using the masking technique for PWFA applications. The five equidistant drive (D) bunches are followed by the witness bunch (W).

selected (N=1-10 in our case) by using a variable width slit in conjunction with the mask. The spacing between the bunches, as well as their length are determined by the mask dimensions. The mask pattern needs not to be periodic. So that trains of drive bunches followed by a witness bunch can be produced, e.g., for advanced accelerator applications (see Fig. 1). The bunch current is given by the incoming current and the amount of magnetic compression. We describe here the bunch train and its potential application to the plasma wakefield accelerator (PWFA), a femtosecond multi-frame x-ray camera, the study of coherent synchrotron radiation (CSR) in magnetic bends, and the generation of THz radiation.

Plasma Wakefield Accelerator

In the PWFA, the relativistic electron bunch travels in neutral plasma and drives a relativistic plasma wave or wake. The wakefield has a large longitudinal electric field that can be used to accelerate particles at a rate (1-100 GeV/m) orders of magnitude larger than in conventional rf accelerators (<200 MeV/m). In order to produce a high quality accelerated beam, a drive-witness bunch train is needed. The drive bunch

Figure 2: Energy of the bunch train particles at various plasma densities as calculated in 2-D linear theory. Large energy loss and energy gain are observed around $n_e \sim 10^{16}$ cm^{-3}. The figure on the right shows the energy spectrum of the incoming train: drive bunches at higher energies, witness bunch at the lowest energy. Notice the uneven energy (and time spacing).

loses energy to the plasma wake and is discarded at the end of the accelerator. The witness bunch extracts the energy from the wake. Its incoming emittance is preserved in the blow-out regime, and its energy spread remains small thanks to beam loading. To produce multi-GV/m wakefield amplitudes both bunches must be short (<100 μm) and separated by ~100 μm to fit within one wavelength of the relativistic wake in a plasma with typical density in the 10^{16}-10^{17} cm^{-3}. In a future PWFA-based linear collider, two independent linacs will produce the two bunches that will then be made colinear with the appropriate spacing at the plasma entrance. However, in order to test the two-bunch PWFA these two bunches will be produced using the masking method we demonstrated. This method will be implemented at the SLAC FACET [M.J. Hogan, private communication] currently under construction. The ATF experiments therefore serve as a beam physics test bed for the SLAC FACET project.

In addition to being a test bed for high-energy experiments at FACET, trains of drive bunches can also be used to resonantly excite plasma wakes to large amplitudes and increase the transformer ratio. Maximizing the transformer ratio maximizes the energy transfer efficiency from the drive to the witness bunch. The transformer ratio is the ratio of the peak decelerating field behind the drive bunch(es) and the peak decelerating inside the drive bunch(es). This ratio cannot exceed two for a single symmetric drive bunch, but can reach 2N for a train of N drive bunches with proper spacing and charge. In the experiments we have already performed at ATF we have demonstrated the resonant excitation of wakefields with N=3 (see Fig. 2). We have also observed much of the PWFA physics with a single long bunch and a train of bunches. Further experiments will lead to systematic quantitative measurements. We also have produced a train with a witness bunch (separation of

one and a half times the drive bunches separation). Acceleration has also been observed in the experiments, however we have not yet clearly demonstrated the origin of the accelerated particles.

Femtosecond Multi-frame X-ray Camera

Figure 3: schematic of a multi-frame x-ray camera. (Courtesy of I Pogorelsky, BNL).
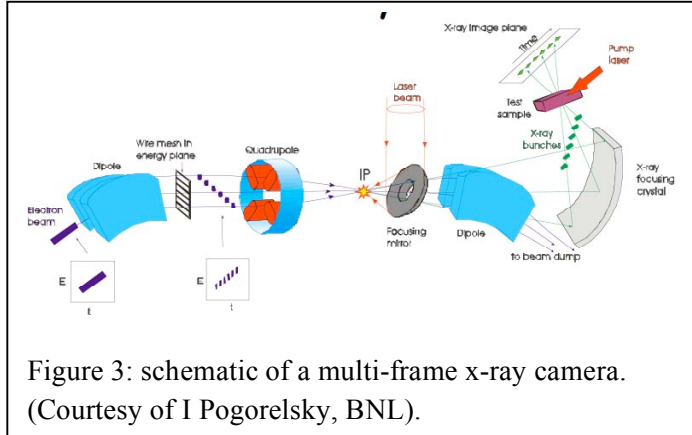
Inverse Compton Scattering (ICS) is a well-know method to produce short and intense pulses of x-ray by colliding a laser pulse with a HBB. In the case of a long incident laser pulse counter-propagating with the electron beam, the x-ray pulse has the same temporal structure as the electron bunch since the ICS emitted photons and the beam travel at approximately the same velocity. Therefore scattering off of the bunch ATF train with sub-picosecond separation produces a train of sub-picosecond x-ray pulses. The masking method produces a bunch train in which different bunches have a different energy. With the beam line arranged to have zero magnetic dispersion at the beam focal point, where it collides with the laser pulse, but with the derivative of the dispersion non zero, the bunches cross the axis with angles proportional to their energy. The scattered photons, from the various bunches, also follow the same angles. The x-ray pulses can be re-focused onto a sample while preserving their angular and time sequence. After traversing the sample, the x-rays can be captured on a single or multiple CCD cameras to effectively produce an N frames "movie" of the sample evolution (see Fig. 3). Currently the minimum bunch and x-ray pulse separation achievable at ATF is ~500 fs. However, with the addition of an x-band third harmonic cavity after the linac, phase space rotation is expected to allow for ~100 fs separation to be obtained through magnetic compression. This new sub-picosecond multi-frame x-ray camera will be a very valuable tool to study time sequences of ultra-fast phenomena in a single shot.

Coherent Synchrotron Radiation Suppression Studies
Energy recovery linacs (ERLs) greatly enhance the wall plug efficiency of linacs used for applications that weakly perturb the beam such as FELs and beam cooling systems. For example, collisions between ions or polarized protons with the polarized electron beam produced by an ERL envisaged at the BNL relativistic heavy ion collider (RHIC) greatly extends it capabilities. As a staging approach towards full-energy eRHIC, a medium energy electron-ion collider (MeRHIC) was recently proposed [MeRHIC: V.N. Litvinenko et al., EIC Workshop (LBNL, 11-13 December, 2008)]. Studies show that, in this case, short electron bunches are advantageous to simplify the ERL design. However, these bunches also have large peak currents (>300 A), and coherent synchrotron radiation (CSR) emission in the magnetic bends becomes an issue if not carefully controlled, and leads to significant energy spread and loss. Long-wavelength part of the synchrotron radiation can be strongly suppressed by the presence of the conducting surfaces of the vacuum chamber. This long wavelength cut-off value depends on the radius of the curvature of the orbit as well as the beam pipe transverse dimension. It follows that shielding can suppress energy loss due to coherent radiation. However, some dedicated experiments on CSR shielding did not

observe the expected shielding effect [H. Braun et al., Proceedings of PAC01 (Chicago, 2001)]. In addition, the effect of shielding on energy spread increase due to CSR is more involved and requires further investigation. The effect of CSR was observed on the bunch train produced at the ATF. CSR effects become important when tuning the linac for large bunch contrast. We are therefore building a variable height beam pipe to install in the last bending magnet of the bunch train beam line. We will also monitor the CSR energy emitted using a LHe cooled bolometer. The flexibility and the simplicity of the bunch train formation process will allow for a systematic study of the CSR suppression. This study will provide useful information for the eRHIC ERL, and will potentially save precious time and money in the ERL design and construction.

Dielectric Loaded Accelerator and THz Radiation Generation

The dielectric loaded accelerator (DLA) is a promising possible advanced technology for a future linear collider because it can sustain GeV/m accelerating gradients [M. C. Thompson et al., Phys. Rev. Lett. 100, 214801 (2008)] and works equally well for electrons and positrons. It is also a compact source of high power THz radiation [A.M. Cook et al., Phys. Rev. Lett. 103, 095003 (2009)]. The bunch trains produced for the PWFA are also ideal for DLA experiments and the DLA can be designed to operate at THz frequencies. The radiation power level is expected to be comparable to that obtained with Cherenkov FELs, but the DLA structure is much shorter than the gain length of CFELs. Short pulses of THz radiation have many applications including national security, detection of complex chemical and biological agents, treatment of surface cancers, etc. The electron bunch emits radiation through coherent Cherenkov generation at a frequency determined by the dielectric tube transverse dimensions. The fundamental mode (TM_{01}) has a large longitudinal electric field appropriate for the acceleration of a witness bunch at the proper location in the train.

Conclusions

In conclusion, the trains of high brightness electron bunches produced at the ATF are a very useful tool that serves as a test bed for bunch train generation at the SLAC FACET, resonant excitation of wakefield and acceleration of a witness bunch, generation of x-ray pulses for sub-picosecond multi-frame x-ray camera, studies of suppression of coherent synchrotron radiation in energy recovery linacs, and particle acceleration and THz generation in dielectric loaded accelerators. Each of these applications will potentially contribute to advances in high-energy particle physics, material sciences, medicine and other fields of research, thereby furthering the impact of accelerator physics on modern science and technology.