FACET-II: ACCELERATOR RESEARCH WITH BEAMS OF EXTREME INTENSITIES*

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Abstract

The FACET National User Facility used part of SLAC's two-mile-long linear accelerator to generate high-density beams of electrons and positrons. These beams are so intense, they are ideal for creating exotic states of matter and researching advanced accelerator technologies. Scientists from all over the world have come to FACET to do experiments. In five years of its experimental program, FACET delivered consistently high impact results towards developing technologies for future linear colliders [1]. High-efficiency acceleration of an electron beam with small energy spread in a plasma wakefield was demonstrated [2]. A new regime of acceleration of positrons in a self-loaded PWFA was discovered [3]. The positron PWFA program at FACET allowed for the first time demonstration of acceleration in linear regime, quasi-non linear regime and acceleration in a hollow plasma channel [4]. The Trojan Horse [5] experiment was able to capture and accelerate laser-triggered charge through Plasma Wakefield Acceleration for the first time as part of emittance preservation studies. Two modes were demonstrated: a high charge mode which was less demanding of laser-to-beam synchronization and a low charge mode which relied on sub-30fs synchronization but had the potential to generate beams with two to three orders of magnitude lower emittances than what is available from conventional photo injectors.

In April 2016, FACET operations came to an end to make way for the second phase of SLAC's x-ray laser, the LCLS-II, which will use part of the tunnel occupied by FACET. With this transition, the world's only multi-GeV facility for advanced accelerator research has ceased operation. FACET-II is a new test facility to develop advanced acceleration and coherent radiation techniques with high-energy electron and positron beams. It is the only facility in the world with high energy positron beams and it offers an opportunity to build on the decades-long experience developed conducting advanced accelerator R&D at SLAC. FACET-II represents a major upgrade over current FACET capabilities and the breadth of the potential research program makes it truly unique. No other test facility has attracted such broad interest across so many branches of the Office of Science.

FACET-II: SCIENTIFIC OBJECTIVES

The FACET-II science program has 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 enables a broad class of coherent radiation and beam/matter interaction science at field strengths and energy densities not available anywhere else. A broad experimental program has been mapped out based on extensive input from the user community, in particularly from a series of FACET-II Science Opportunity Workshops held at SLAC October 12-16, 2015*. We will continue to 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. The nominal parameters for FACET-II Phase 1 are driven by the needs of the wakefield accelerator programs. FACET-II will continue to explore the physics of plasma wakefield acceleration in regimes relevant to future collider and X-ray free electron laser applications. Specifically, experiments will operate with accelerating gradients in excess of 10 GeV/m – orders of magnitude larger than conventional accelerators. To attain these large gradients requires plasma densities on the order of 10^{17} e-/cm^3. To effectively drive large amplitude wakefields in the plasma requires the beam dimensions (radially and longitudinally) to be of the order of the plasma collisionless skin depth, or 17µm in this case. Large amplitude wakes are achieved when the electron bunch has sufficient charge to reach peak currents on the order of the Alfven current (17kA). Recent experiments at FACET have demonstrated that the positron parameters to be delivered in Phase 2, similar to those for electrons, can access regimes applicable to plasma afterburner applications. A future upgrade will deliver both electron and positron bunches to the plasma in close succession and allow studies relevant to collider designs with positron acceleration in the wakefield produced by an electron bunch. The one kilometer-long linac will produce a nominal energy of 10GeV that ensures the required yield from the positron target and enables stable operation with these highly compressed electron and positron bunches.

* FACET-II Science Opportunities Workshops SummaryReport, Mar 29, 2016, https://www.internal.slac.stanford.edu/scidoc/docMeta.aspx?slacPubNumber=SLAC-R-1063

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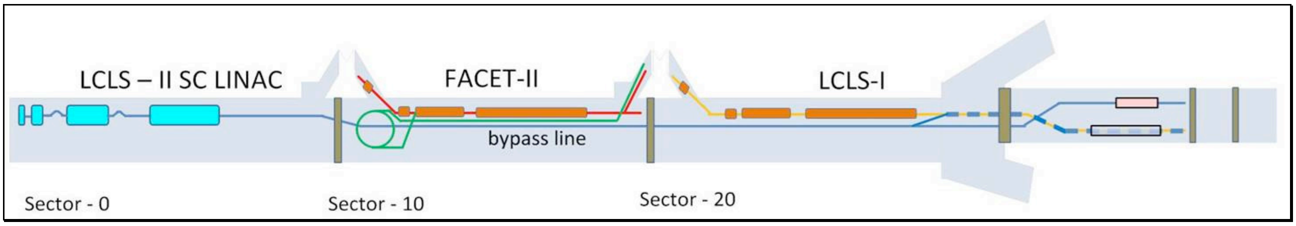

Figure 1: Schematic layout of FACET-II in the middle third of the SLAC linac, downstream of LCLS-II and upstream of LCLS-I.

Other parts of the PWFA program such as the Trojan Horse experiments benefit from the highest peak currents and can accept lower charge. The FACET-II beamline has the flexibility to produce electron peak currents in excess of 50 kA by increasing the compression and collimating the energy tails in the bunch compressors. In this configuration, the bunch charge at the IP is reduced to about 0.7 nC. At the other end of the parameter range, the Compton experiments would prefer the highest possible charge in a small transverse size, but do not require the shortest bunch. For these experiments FACET-II can deliver 5 nC with a beam size on the order of 10 µm.

The FACET-II scientific program will make orders of magnitude advances in three primary areas: accelerating gradient, beam quality and photon flux. Wakefield acceleration—whether in plasma or in dielectric waveguides—is a cornerstone of the program, building on a more than twenty-year history of performing groundbreaking work in GeV-scale beam-driven wakefield acceleration at SLAC. A major goal of FACET-II is to utilize gradients 1,000 times higher than current technology in a meter scale prototype plasma accelerator. The existence of such ultra-high gradients also makes it possible to trap particles and produce a beam with 1,000 times the brightness currently achievable. The combination of uniquely high energy, high density beams and the short pulse, high power FACET laser enables the generation of very high flux photon beams. In principle, 100-1000 times higher gamma flux from 10 MeV to 5 GeV and 10,000 times higher total gamma flux up to 5 GeV should be deliverable.

By offering pulse charge from pC to a nC, emittance from nm to microns, electrons and positrons, single and double bunches, tailored current profiles of up to nearly 100kA and energy up to 10GeV, FACET-II provides experimental capabilities unparalleled anywhere in the world. By leveraging the additional infrastructure afforded by SLAC's laser group, the FACET laser systems provide multi-terawatt peak powers with state of the art synchronization approaching 10fs. These capabilities will draw in additional experimental programs that exploit these capabilities to their fullest, generating orders of magnitude improvements in electron and photon beam brightness. The initial vision for the FACET-II science programs is described in this section, but this will certainly evolve to reflect the most pressing science issues of the time as guided by the Program Advisory Committee.

FACET-II: DESIGN OVERVIEW

The most demanding design parameters for FACET-II are set by the requirements of the plasma wakefield experimental program. To drive the plasma wakefield requires a high peak current, in excess of 10kA. The transverse beam quality required by the wakefield and other experimental programs is a normalized transverse emittance <20 µm-rad in both planes delivered to the Sector 20 region. The beam energy is 10 GeV, set by the Linac length available and the repetition rate is up to 30 Hz.

The FACET-II project is scheduled to be constructed in two major stages: 1) a new photoinjector at Sector 10 and two bunch compressors in the Linac will restore operation with electrons; 2) a new positron damping ring located in the Sector 10 tunnel with injection and extraction lines will restore operation with positrons. A third stage planned as a future upgrade will construct a new final chicane in Sector 20 to provide for simultaneous delivery of positrons and electrons to the experimental area. A schematic of the layout of FACET-II in the linac is shown in Figure 1.

For stage one, FACET-II will complete the original LCLS-II installation of the photoinjector and its auxiliary systems at Linac Sector 10. This will include installation of a gun and injector beamline in the Linac housing and power sources and control electronics in the gallery. These systems will connect the new injector at Sector 10 with the Linac, where the beam can then be accelerated and transported to the existing FACET experimental area in Sector 20. Two bunch compressor chicanes will be installed in Sector 11 and Sector 14 to provide the first two of three stages of bunch compression needed to produce the required high energy density beams in Sector 20. The third stage of compression is in Sector 20. A shield wall, similar to the existing one in Sector 20, will be constructed in Sector 10 to separate the LCLS-II and FACET-II accelerator areas.

In stage two for positron operation, FACET-II will reuse the existing positron target at Sector 19. A new small damping ring, which fits inside of the accelerator tunnel, will be installed at Sector 10. In addition to the beamlines in the tunnel, there will be power sources and control electronics in the gallery. Two new beamlines in Sector 10 will bring the positrons from the existing Positron Return Line into the new Damping Ring and from the Damping Ring back into the main linac at the last magnet of the Sector 11 bunch compressor. The Sector 14 bunch compressor will also need a second arm for simultaneous electron and positron operation.

As a future upgrade for the simultaneous delivery of positrons and electrons to the user area, a second arm of the final chicane will be installed in Sector 20. This beamline in the tunnel will be connected to power supplies and control electronics in the gallery.

Electron Injector

In order to achieve the scientific goals of the experimental program at FACET-II, a high electron peak current with small transverse core beam size at the experimental IP waist, ~<20µm, and a small longitudinal emittance are required. FACET-II will operate with an electron energy up to 10 GeV. The most challenging parameters are for the plasma wakefield acceleration (PWFA) experiments which require peak currents in excess of 10 kA. The RF photocathode gun and injection system is similar to that used in LCLS. This injector is capable of producing a charge of up to 5 nC in a bunch length of <10 ps, corresponding to peak currents of >120 A with transverse emittances less than 5 µm. This implies a required compression ratio in excess of 100 to achieve the desired beam characteristics at the IP waist in Sector 20. Acceleration and compression is done in the 2nd kilometer of the SLAC linac in 3 compression stages. A schematic of the electron injector, linac and bunch compressors is shown in Figure 2

The capabilities of FACET-II vary in a non-trivial way depending on the choice of the initial charge from the RF gun. The baseline design is for a 2 nC electron bunch charge from the electron gun, or a 1 nC positron bunch, generated from a 4 nC electron bunch striking the existing positron production target in Sector 19, returned and damped from a new positron damping ring [REF ### SLAC-R-1067, title: FACET-II Conceptual Design Report]. To demonstrate design flexibility and characterize the extremes of the possible parameter space, a second configuration option is considered corresponding to a 5 nC pulse from the electron gun.

Bunch Compressors and Linac

Both electrons and positrons undergo three stages of bunch compression, the first two stages in Linac Sectors 11 and 14 and the final compression stage in Sector 20. For positron operation, positrons produced in sector 19 are returned to the beginning of the Linac in a ceiling-mounted transfer line, their energy boosted to 335 MeV, and injected into a damping ring in Sector 10. The initial stage of positron compression takes place in the transfer line from the damping ring before injection into the main linac in the final bend of BC11 (in Sector 11).

The bunch compression is accomplished by a series of magnetic chicanes arranged and located such that nonlinearities in the compression and acceleration process (longitudinal wakefields, RF curvature, and second order momentum compaction) are all tolerable. The goal for the Linac design is to a) achieve design peak current requirements for both positron and electron bunches, b) deliver the correct longitudinal profile into the final BC20 compression stage and c) minimize sensitivities to RF phase and amplitude variations and also to bunch charge variations. The electron energy at the first compressor is 335 MeV. This choice avoids space charge effects, while the bunch compression is still early enough in the linac to ease the effects of transverse wakefields. This energy choice is also compatible with the desired energy for

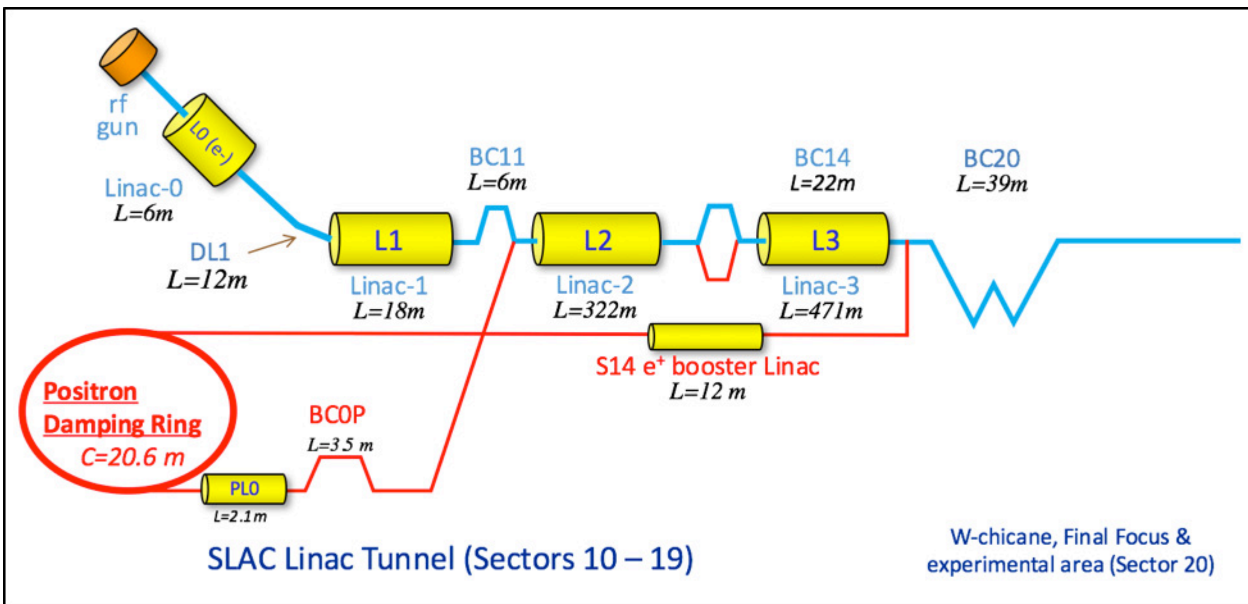

Figure 2: Schematic showing injector, linac, bunch compressors, and experimental area for stage one in blue and stage two in red of the FACET-II project.

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damping ring operation for positrons. In the first compressor (BC11), the electron bunch length is reduced from 0.85 mm to 470 µm (rms). For operation with positrons, the positron beam is injected into the linac at the final BC11 bend. The bunch length of the positrons, upon extraction from the damping ring, is 3.9 mm (rms). To match well into the linac compression scheme, an additional bunch compressor (2.1m S-band RF section and 4-bend chicane) is included in the damping ring-to-linac beamline section. The positron bunch length is compressed to 276 µm (rms) before being injected into the shared linac through a horizontal dogleg section.

Positron System

The positrons are produced by sending an electron bunch onto the existing positron target and capture section in Sector 19. The positron bunch is transported back to Sector 11 in the existing Positron Return Line. A new beamline that starts in Sector 11 takes the positrons from the Return Line and injects them into a new Damping Ring in the Sector 10 Linac tunnel. The energy of the beam from the positron production system is 210 MeV, while the desired Damping Ring energy is 335 MeV, so 125 MeV of energy must be provided by S-band accelerating structures located in Sector 14. The accelerating structures replace a section of the existing return line. A schematic of the positron systems for stage two of the FACET-II project is shown in Figure 2.

The positron beam into the damping ring has a large transverse emittance that must be reduced by three orders of magnitude in a few milliseconds. Because the damping ring is located in the existing Linac tunnel, the diameter of the ring must be smaller than 3 meters. This constraint dictates a compact design with minimal gaps between the magnets in the arcs. The large injected beam size also dictates that the acceptance of the ring be large enough to accommodate on-axis injection. The proposed design incorporates many aspects of recent developments for diffraction-limited light sources. The beam energy is chosen to be 335 MeV which is as high as possible given the space constraints and reasonable choices of magnet technology.

Given the compact dimensions, the magnet design for the damping ring arcs is particularly challenging. As proposed, the three dipole magnets in each arc cell are wound on a single block of steel and are shaped to additionally provide quadrupole and sextupole field components. The additional arc quadrupoles have a very compact and innovative design, also incorporating sextupole field components. Designs for these magnets are described in the FACET-II Technical Design Report. The straight sections contain both the injection and extraction and the RF cavities. Vacuum requirements are not particularly challenging because of the single bunch operation.

A second new positron beamline in Sector 10 takes the beam from the damping ring extraction point, performs a 1st stage of bunch compression and injects it into the last dipole magnet of the 1st electron bunch compressor (BC11) in Sector 11. All of the components of the injection and extraction lines are conventional. Once the positrons are injected into the Linac, they are accelerated to 10 GeV in the second and third Linac sections. The second stage of bunch compression is performed in a second arm of the bunch compressor in Sector 14 (BC14) and the 3rd stage in the chicane in Sector 20. They are focused to a transverse size of <20 microns at the FACET Interaction Point and dumped at the end of Sector 20.

Future Upgrades

To support the full breadth of the experimental program planned for FACET-II, several additions or upgrades will be required to expand future capabilities. One such upgrade is the 2nd chicane in Sector 20, the sailboat chicane.

The Plasma Wakefield Acceleration experimental program will eventually desire a higher current electron bunch than provided in the baseline configuration. As one possible implementation, we have designed the linac and bunch compression to be compatible with a 1nC/5nC configuration of the positron /electron beams respectively. The 1nC/5nC configuration has a large imbalance in the wakefield loading in the linac between electron and positron bunches as well as CSR effects. This configuration would require installation of new 2nd or 4th harmonic (C- or X-band) acceleration sections in the Linac for energy equalization.

To achieve the highest possible peak currents in Sector 20 (>100 kA) would require the addition of two subsystems: 1) a 4th harmonic "linearizing" x-band RF structure in L1; 2) a "laser-heater" system in the electron injector to spoil the longitudinal phase space and control CSR emittance dilution. Both of these systems were successfully utilized during LCLS operations and could be used to aid operations at FACET-II but are not necessary for the baseline parameters initially required by the FACET-II user community.

Other upgrades considered are: 1) installation of a witness injector to provide an independent bunch to sample the plasma wakefields. This allows complete freedom to tailor the drive bunch shape for maximum transfer efficiency. 2) installation of a differential pumping system to isolate the vacuum in the experimental region from the Linac vacuum. This provides flexibility with the plasma chamber experiments and avoids the need for beryllium windows. 3) installation of a Compton source for a variety of proposed experiments. 4) operation of Compton sources in the Sector 20 chicanes to form a photon-photon collider in the final bend of BC20.

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