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BEAM DIAGNOSTIC CHALLENGES FOR FACET-II[*]

S. Z. Green[†], M. J. Hogan, N. Lipkowitz, B. O'Shea, G. White, V. Yakimenko, G. Yocky
SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Abstract

FACET-II, the Facility for Advanced Accelerator Experimental Tests II, is a new accelerator R&D test facility to be constructed at SLAC. It will provide high-energy, high-density electron and positron beams to advance the development of beam driven plasma wakefield acceleration and support a broad range of experiments. The FACET-II beams are expected to have 10 GeV energy, contain 2 nC of charge, have a transverse normalized emittance of 7 microns, be compressed to about 1 micron long and focused to about 6 micron wide at the interaction point. The nominal peak current is 20 kA and is expected to fluctuate up to 200 kA. Most experiments desire complete knowledge of the incoming beam parameters on a pulse-to-pulse basis. However, the extreme beam densities and strong fields of the beam current will destroy any diagnostics intercepting the beam in a single shot and impose unique challenges for beam diagnostics. Moreover, non-intercepting diagnostics are desirable to provide feedback for machine setup and characterization. We need to look beyond conventional diagnostics to seek new solutions for measurements of the high charge, small beam size, short bunch length, and low emittance.

INTRODUCTION

FACET-II, the Facility for Advanced Accelerator Experimental Tests II, is a new accelerator research and development test facility to be constructed at SLAC National Accelerator Laboratory. It's an upgrade of the FACET User Facility that delivered 20 GeV electron and positron beams for experimental programs from April 2012 to April 2016. Experiments at FACET produced high impact results on efficient acceleration of electrons and positrons in plasma. Highlights of these results include mono-energetic electron acceleration, high efficiency electron acceleration [1] and the first high-gradient positron plasma wakefield acceleration (PWFA) [2].

In April 2016, the Linac Coherent Light Source-II (LCLS-II) began construction for the second phase of SLAC's x-ray laser in the first kilometer (Sectors 0 to 10) of the SLAC Linac that previously housed the first half of the FACET accelerator. This represented an opportunity to rebuild and upgrade FACET. FACET-II will occupy the second kilometer of the SLAC Linac from Sectors 10 to 20 and use existing experimental infrastructure in Sector 20 (S20). A schematic layout of FACET-II relative to LCLS and LCLS-II is shown in Fig. 1. FACET-II will operate as a national user facility with experimental programs between 2019 and 2026.

FACET-II will continue to support advanced accelerator PWFA experiments. PWFA research priorities at FACET-II include emittance preservation with efficient acceleration, high brightness beam generation and characterization, positron acceleration, and staging studies. High-gradient high-efficiency acceleration was demonstrated at FACET and will be used to benchmark FACET-II. Full pump depletion of the drive beam and preservation of emittance at the micron level are planned as the first high impact experiments. Emittance preservation at the 10's of nm level is necessary for collider applications. Ultra-high brightness plasma injectors may lead to first applications of PWFA technology and allow the study of emittance preservation at this level. The delivery of positron beams to FACET-II will enable the only positron capability in the world for PWFA research. The emphasis will be to develop techniques for positron acceleration in PWFA stages. An independent witness injector will be added to FACET-II at a later stage as an Accelerator Improvement Project (AIP) to enable studies of high transformer ratio and staging challenges such as timing and alignment.

FACET-II ACCELERATOR

The goal of FACET-II is not only to restore beam capabilities for experimental programs but also to provide beams with greatly improved quality. A schematic of the FACET-II electron and positron systems is shown in Fig. 2. The FACET-II accelerator begins with the radio frequency (RF) photocathode gun and injection system at Sector 10 (S10) that enable delivery of low emittance beams. The 4.3 MeV electron beam goes through the first accelerating section L0 and reaches 134 MeV when injected into the linac for further acceleration through L1, L2, and L3 in Sectors 11–19. Three compression stages BC11, BC14 and BC20 are required to achieve the desired bunch length for compressed electron beams to be delivered to the experimental area in Sector 20 (S20). The design of the injector complex up to BC11 is based on the LCLS S20 injector.

Beam Dynamics

The FACET-II beams were modeled and tested with the 6D particle tracking models *IMPACT-T* [3] and *Lucretia* [4]. Simulation of the injector uses *IMPACT-T* which includes three dimensional space charge effect and is the simulation tool used for LCLS and LCLS-II. The rest of the FACET-II beam dynamics modeling was performed with *Lucretia* for tracking that includes effects of incoherent synchrotron radiation (ISR), coherent synchrotron radiation (CSR), longitudinal and transverse wakefields in structures, and longitudinal space charge. This Matlab-based toolbox was benchmarked against other tracking engines in the context of Linear Col-

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[†] selina@slac.stanford.edu

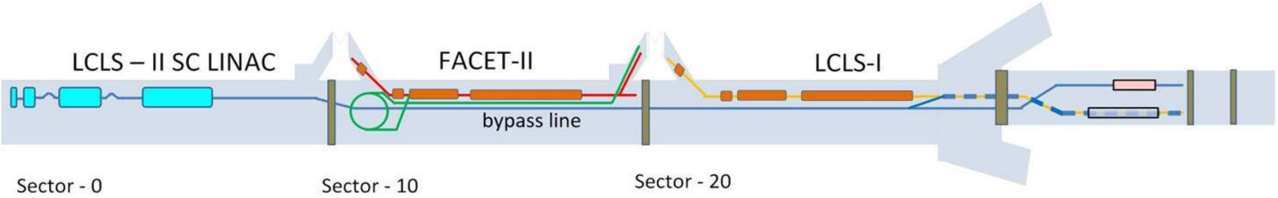

Figure 1: A schematic layout of FACET-II.

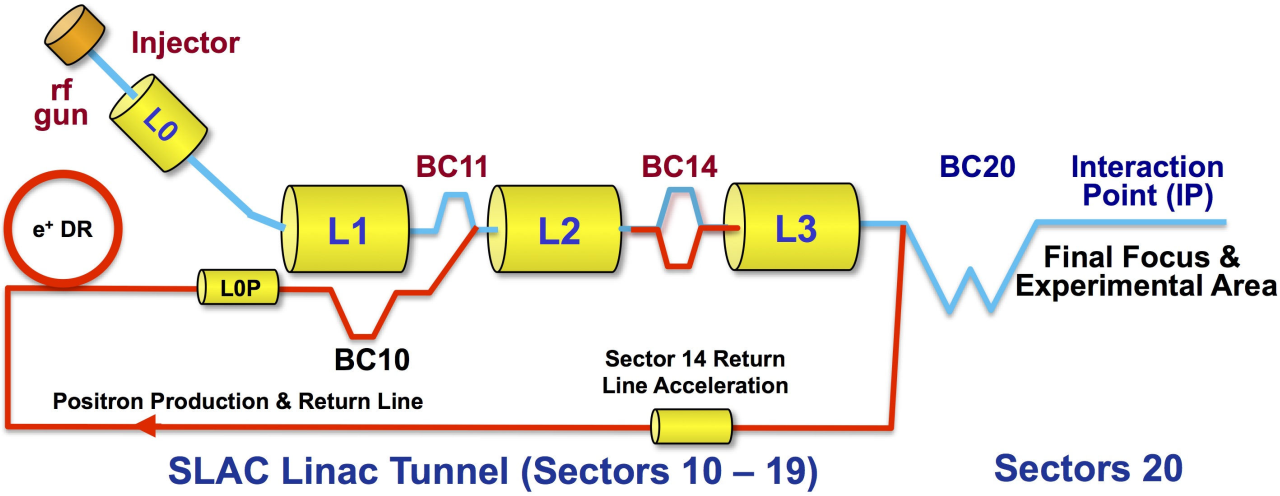

Figure 2: A schematic of the FACET-II electron and positron systems showing the injector, linac, bunch compressors, damping ring, and experimental area.

lider design and FACET. The FACET-II beams were designed and optimized based on these simulation studies to achieve the goals of the experimental programs.

The FACET-II nominal electron beam parameters and their operational ranges are shown in Table 1. Since the diagnostics for electrons and positrons are essentially the same and electrons in FACET-II have more extreme values, only the electron beam parameters are listed. The beam energy of 10 GeV is set by the linac length available for acceleration. The rest of the parameters are mainly driven by the need of the PWFA programs as they have the most demanding requirements and is a priority for the user program. With an upgrade of the BC20 optics, the peak current can reach up to 200 kA.

Table 1: FACET-II Electron Beam Design Parameters and Their Operational Ranges

Parameter	Baseline Design	Range
Final Energy [GeV]	10.0	4.0–13.5
Charge per pulse [nC]	2	0.7–5
Repetition Rate [Hz]	30	1–30
Normalized transverse emittance at S19 $\gamma\epsilon_{x,y}$ [µm–rad]	4.4, 3.2	3–6
Spot Size at IP $\sigma_{x,y}$ [µm]	18, 12	6–20
Min. bunch length σ_z (rms) [µm]	1.8	1.5–20
Max. peak current I_{pk} [kA]	72	10–130
Min. energy spread (rms) [%]	1.4	0.4–1.6
Max. ave. e^- beam power [kW] (10 GeV, 5 nC, 30 Hz)	1.5	0.1–4.2

ACCELERATOR DIAGNOSTICS

Beam diagnostics are essential to the operation of the accelerator as they provide controls, monitoring and tuning as well as optimization of the beam for experiments. Non-intercepting diagnostics are needed to provide feedback to the machine. FACET-II will re-use existing FACET electron beam diagnostics where possible or will adapt existing designs used at LCLS and FACET. The most useful LCLS injector diagnostics are reproduced for the FACET-II injector to provide to the linac a beam of known charge, arrival time, bunch length and distribution, energy, energy spread and distribution, as well as projected and sliced transverse emittance. Other critical diagnostics are located in or after the Bunch Compressors for longitudinal phase space and transverse profile diagnostics. In particular, at each bunch compressor, there will be Transverse RF Deflecting Cavities (TCAV) and a relative Bunch Length Monitor, a YAG screen for measuring energy spread, a wire scanner for transverse beam size and emittance measurement, as well as Beam Position Monitors.

Beam Position and Charge Monitors

Beam Position Monitors (BPMs) are the primary diagnostic for monitoring, feedback and tuning. They will be installed in every focusing magnet and key dispersive locations throughout the linac.

Resonant toroid current transformers with calibration winding are used in Toroids to measure the beam charge. Toroids in FACET-II monitor total beam charge at boundaries of functional areas. In particular, a toroid will be in place upstream and downstream of each bunch compressor. Matlab and python scripts regulate beam parameters at individual key locations for energy and orbit stabilization feedback.

Longitudinal Profile Diagnostics

A transverse deflecting cavity (TCAV) operating in conjunction with a profile monitor or wire scanner downstream can be used to measure bunch length and distribution. It is self-calibrating since the RF frequency is well known, however it is invasive to the beam and the same pulse cannot be used for downstream experiments. Relative Bunch Length Monitors (BLEN) such as coherent edge radiation monitor and wall gap monitor are non-destructive and provide pulse-by-pulse bunch length monitoring, but require calibration from a TCAV. A wall gap monitor with ceramic gap and diode will be used as a relative bunch length monitor in the injector system since the frequency is smaller than 300 GHz and peak current is lower than 300 A. A simple ceramic gap radiates into waveguide-coupled diodes (30 GHz to 60 GHz) for bunch length of 0.5 mm to 5 mm before injection into the linac. In BC11 and BC14, a coherent edge radiation monitor consisting of a mirror and pyrometer will be used since frequency will become greater than 300 GHz and peak current will be higher than 300 A. This type of pyroelectric bunch length monitor provides a relative bunch length diagnostic and works well for finding and maintaining peak compression.

Transverse Profile Diagnostics

Profile monitors are the most efficient and intuitive transverse diagnostics available. The Profile Monitors based on Optical Transition Radiation (OTR) are useful for imaging high energy and focused beams with the advantage of being able to see the entire beam profile. However, coherent effects influencing the beam profile have been observed in LCLS [5] due to microbunched structures at optical wavelengths. Strong Coherent Optical Transition Radiation (COTR) is a problem for compressed bunches and is expected at FACET-II for OTR Profile Monitors. The strong COTR from compressed bunches will saturate the OTR screens. Therefore, the wire scanners after BC11 will be used instead of OTR profile monitor for focused beams. There are ways to mitigate this COTR effect, such as screen tilt and fast camera gating, but these approaches have not yet been tested. Since wire scanners have more straightforward calibration in comparison to OTRs, they remain a reliable way to measure beam size for the linac. Wirescanners installed after each bunch compressor can also provide multi-profile emittance measurements to ensure emittance preservation across the linac-Bunch Compressor system.

EXPERIMENTAL DIAGNOSTICS

FACET-II will inherit and improve FACET's diagnostics at the experimental area in S20. Diagnostics that are available to use in place or to be improved upon will be described first, and then concepts for novel beam diagnostics to meet the challenges presented at FACET-II will be discussed.

Energy Spectrum

One of the most useful devices proven for both experiments and beam tuning is the so-called SYAG Profile Monitor in S20. A chicane in a plane of large horizontal dispersion deflects the beam vertically. X-rays from the resulting stripe of synchrotron radiation are intercepted by an off axis scintillator crystal made of Cerium doped Yttrium Aluminum Garnet (Ce:YAG). The X-ray intensity is proportional to the beam intensity giving a measurement of the beam energy spectrum and thus the energy spread can be measured on a shot-to-shot basis without being invasive to the beam.

Longitudinal Profile Diagnostics

Three different methods (TCAV, THz Michelson Interferometer, and Electro-Optic Sampling) of measuring the longitudinal beam profile were tested at FACET. The X-band TCAV provides a resolution of about 10 µm for bunch length measurement in a single shot, but it is destructive to the beam and the measurements are subject to chromatic distortions in the transport optics. The THz Michelson Interferometer, measurements require a scan of many shots and thus represents and average measurement with a resolution of about 5 µm. The Electro-Optic Sampling (EOS) system provides a measurement with resolution of 10 µm in a single shot. The EOS is subject to distortion from laser fluctuations and is challenging to set up. The last two methods are both non-destructive to the beam. The EOS studies performed at FACET were able to measure two-bunch separation of 122 µm with 10 µm resolution that can be improved further [6]. The EOS method appears to be the best of the three available options for longitudinal diagnostics. Nevertheless, FACET-II needs better resolution for the sub-micron beam and there were numerous improvements identified to increase resolution with the EOS as well as to optimize the system for more robust signals.

Another possibility for longitudinal beam profile diagnostics is the Attoscope scheme [7] that was tested at the Brookhaven National Laboratory Accelerator Test Facility early this year with results qualitatively supportive of simulations [8]. This diagnostic method could be developed and evaluated further to test at FACET-II.

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Transverse Profile Diagnostics

The OTR foils and wires used in profile monitors located near the FACET IP were very susceptible to damage from the high peak current (10 kA) beam at focus. FACET-II will maintain both OTR profile monitors and wire scanners in the experimental area. The use of multi-screen OTR ladders and multi-wire fork wire scanners [9] away from beam waist will help to mitigate damage.

Emittance Measurements

One of the main goals for FACET-II is to demonstrate emittance preservation with low emittance PWFA beams. Therefore, reliable low-emittance measurement techniques are required.

Emittance measurement with a quad scan in a dispersed region can be studied and improved further for FACET-II emittance preservation [6] with normalized emittance down to a few micrometers.

Diagnostics for Extreme Beams

The FACET-II beams will be compressed to about 1 micron long and focused to about 6 micron wide at the interaction point (IP) for experiments in S20. The peak current will be up to 200 kA with emittance of 7 micron–rad. The surface temperature rise by image currents due to single bunch heating [10] is proportional to $(\frac{Q}{\sigma_z})^2\frac{f^2(\sigma_y/\sigma_x)}{\sigma_x\sigma_y}$. Based on calculations and experience from FACET, the extreme beam densities and strong field of the beam current at FACET-II will destroy any diagnostics intercepting the beam in a single shot and thus impose unique challenges of beam diagnostics. Conventional diagnostics such as those used for operation of the machine as mentioned in the previous section cannot be used in the IP area if any material from the device intercepts the beam. Moreover, most experiments desire complete knowledge of the incoming beam parameters on a pulse-to-pulse basis. Therefore, the key is to develop diagnostics that are non-invasive and provide single-shot measurements. Some of the experimental diagnostics challenges were explored and discussed [6,9] based on experience from FACET. The unprecedented beams at FACET-II provide exciting diagnostic challenges for the accelerator community. A few concepts for novel beam diagnostics are discussed next.

Edge Radiation Interference Interference of dipole edge radiation [11] can be used to monitor for beam divergence as illustrated in the setup in Fig. 3. The visibility of the fringe resulting from the interference depends on beam divergence and emittance. Therefore, the emittance of the electron or positron beams can be determined by the intensity distribution of the edge radiation in this interference scheme that results in fringes of the light intensity. This method was tested with a beam of 60 MeV with emittance of ~1 µm at the Brookhaven National Laboratory Accelerator Test Facility. The edge radiation interferometry is a possibility for measuring low emittance beams and requires further study and development for beams with similar parameters as FACET-II.

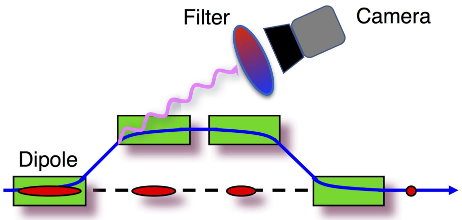

Figure 3: A potential setup for edge radiation from two dipoles.

Betatron Radiation Betatron radiation was emitted by electrons oscillating around the propagation axis due to the constant focusing force in the ion cavity of beam-driven plasma accelerators as illustrated in Fig. 4. There was a proposal [12] to set up a betatron radiation double differential spectrum (DDS) at FACET-II to recover the beam emittance. A bent crystal disperses the betatron radiation where the line-width of the radiation is proportional to the beam emittance. The rms line-width gives emittance through spread in K red-shifts, assuming Gaussian betatron amplitude distributions. This method requires detectors for photons with energy in the keV and MeV range further downstream of the plasma accelerator.

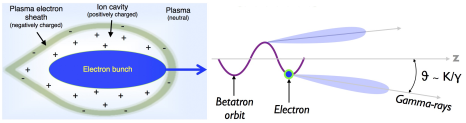

Figure 4: Illustration of betatron radiation from a beam-driven plasma accelerator.

Quadrant EOS The PWFA program at FACET-II will use two closely spaced bunches for experiments. This can be both electron or positron bunches, or a positron witness bunch after an electron drive beam, separated by about 150 µm. Traditional BPMs cannot resolve two beams within this short distance. To study positron witness acceleration in an electron wake as one of the PWFA experiments, the use of quadrant Electro-Optic Sampling (EOS) to measure the position of two beams in space and time will be pursued. This method takes a probe laser from the existing high power 800 nm Ti:Sa laser system that FACET-II inherits from FACET for laser ionized preformed plasma experiments [13]. The Coulomb field from the electron or positron bunch induces birefringence in the EO crystal(s) which could be a single crystal with a hole for beams to pass through or four crystals surrounding the electron/positron beams arranged in a quadrant pattern as shown in Fig. 5. A short, wide laser pulse intersecting the crystal receives polarization rotation. The e-beam profile decoded from polarization pattern is imprinted on the laser [14]. Cameras can be set up to image the EO crystal and be analyzed to provide transverse position that is correlated with time. This type of setup will give both temporal and spatial information for the beams where phase shift occurs depending on where the beam offset is. The spectrally encoded EOS with imaging spectrometer enables non-destructive measurement of r-t beam correlations [15]. The goal is to measure correlations along the ~1 ps long bunch pairs. If testing is successful, this quadrant EOS method will be able to provide powerful single-shot longitudinal and transverse diagnostics.

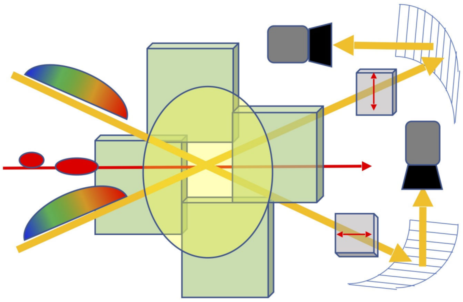

Figure 5: A setup for quadrant EOS with imaging spectrometer.

Bunch Length Monitor in a Gas Cell A gas cell setup could be used to measure bunches of about 3 fs to 30 fs long. Figure 6 is a conceptual illustration of a setup with a gas cell. A laser light resonantly pumps gas to reach an excited state. Its relaxation to intermediate state is triggered by the beam field. The emission rate from intermediate to ground state depends on the temporal spectrum of the beam field. The temperature of the gas affects what wavelength will trigger the transition to the intermediate and relaxed state. Therefore, one can detect gas transitions to characterize pulse length [16].

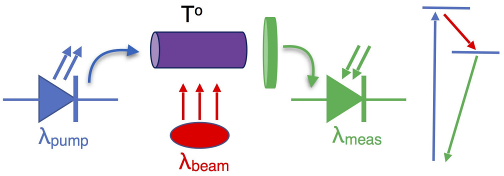

Figure 6: A bunch length monitor with gas cell.

CONCLUSION

FACET-II will deliver high-quality, high-density beams of electrons and positrons for advanced accelerator research. Diagnostics for operation of the injector and accelerator are well developed and based on proven designs at LCLS and FACET. The much higher-intensity electron beams from the photocathode gun pose greater challenges. FACET-II will need even more robust diagnostics when operating with very high peak currents. Conventional diagnostics are unable to measure the small beam size, short bunch length, and low emittance to meet the experimental needs in the IP area. Therefore, new diagnostic methods need to be developed in conjunction with the User Community. Operating as a national user facility, FACET-II welcomes users to submit proposals to develop and test novel diagnostics at the FACET-II beamline. Successful development and implementation of non-invasive, single-shot diagnostics will enable the next generation of experiments to access new regimes with FACET-II's unique capabilities.

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