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DIAGNOSTICS CHALLENGES FOR FACET-II*

C. Clarke†, S.Z. Green, C. Hast, M.J. Hogan, N. Lipkowitz, G. White,
V. Yakimenko, G. Yocky, SLAC National Accelerator Laboratory, CA 94025, USA

Abstract

FACET-II is a prospective user facility at SLAC National Accelerator Laboratory. The facility will focus on high energy, high brightness beams and their interaction with plasma and lasers. The accelerator is designed for high energy density electron beams with peak currents of approximately 50 kA (potentially 100 kA) that are focused down to below 10x10 micron transverse spot size at an energy of 10 GeV. Subsequent phases of the facility will provide positron beams above 10 kA peak current to the experiment station. Experiments will require well characterised beams however the high peak current of the electron beam can lead to material failure in wirescanners, optical transition radiation screens and other instruments critical for measurement or delivery. The radiation environment and space constraints also put additional pressure on diagnostic design.

INTRODUCTION

FACET (Facility for Advanced Accelerator Experimental Tests), a User Facility that delivers uniquely high powered multi-GeV electron and positron beams to its experimental program, completes its operations in 2016. FACET-II is a proposed upgrade to FACET currently at the conceptual design stage (Fig. 1). Its primary purpose is to support the development of advanced high-gradient techniques for acceleration (e.g. plasma wakefield acceleration [1,2] (PWFA) and dielectric wakefield acceleration [3] (DWA)). The high power beams, particularly in combination with the facility's multi-terawatt laser system [4], are also in demand by groups developing diagnostics in extreme regimes and studying materials, for example by using terahertz (THz) radiation in THz pump-laser probe experiments.

FACET-II will deliver improved electron beam quality due to advances in technology predominantly the radio frequency (RF) photocathode gun and injection system. It is expected that there will be a factor five longitudinal peak current improvement over FACET and a factor three improvement in transverse area. Though beam energy is 10 GeV (half that of FACET), the tighter bunches will produce much higher peak currents and associated electromagnetic fields (Table 1).

Note that the beam parameters are not independent and configurations are developed for experiments with an understanding for what parameters are most critical and what can be compromised on. Delivering both electrons and positrons adds additional constraint as the two systems are tied together in a shared linac and changing parameters of one may affect the other. Anticipated starting beam parameters are given in

Table 1: Ranges for FACET-II Beam Parameters Considering Design Limits for Electrons and Positrons Delivered to the Experimental Area. Note that the Start-up Beam Configuration will be Relaxed Parameters Shown in Table 2.

Parameter	Electrons	Positrons
Energy [GeV]	4.0-13.7	4.0-13.7
RMS Energy Spread [%]	0.4-1.8	0.5-1.5
Charge per pulse [nC]	0.7-5.0	0.6-2
Bunch Length σ_z	1-20	7-11
Beam size transverse σ_x [μm]	6-20	10-25
Beam size vertical σ_y [μm]	6-10	7-10
Peak Current [kA]	10-100	12-15
Repetition Rate [Hz]	1-30	1-5
Average beam power [kW]	0.1-4.2	0.005-0.14

Table 2 and are a more relaxed set of beam parameters that can satisfy the requirements for early experiments.

FACET-II Challenges

The FACET-II injector, linac, chicane and final focus performance has been studied through the 6D particle tracking codes *Impact-T* [5] and *Lucretia* [6] which includes longitudinal and transverse wakefields, coherent synchrotron radiation (CSR), incoherent synchrotron radiation (ISR) and third order optics (e.g. chromatic effects). Dynamic errors from sources of jitter were studied (the dominant sources are phase jitter in the first stage of the linac, timing jitter on the laser used for the injector and position jitter of the laser).

At FACET-II, we expect many of the first experiments to be studies of PWFA with the requirement on the beam parameters that peak current for both the electron bunch and the positron bunch is greater than 10 kA. For this beam configuration, the tracking studies with errors from jitter sources showed that some shots may have a peak current of 80 kA though the average is 30 kA. It cannot be prevented that we achieve sporadic shots of high peak current which can damage intercepting material in a single shot.

The configuration for PWFA does not lead to the highest peak current FACET-II can deliver. Figure 2 shows the variation of peak current and bunch length with electron bunch charge which is controlled through collimation of high and low energy parts of the beam in the bunch compressor chicanes. When the configuration is optimised for high peak currents, peak currents in excess of 100 kA can be achieved.

These extreme beams present challenges for diagnostics just as they create opportunities for experiments.

* This work performed under DOE Contract DE-AC02-76SF00515.
† cclarke@slac.stanford.edu

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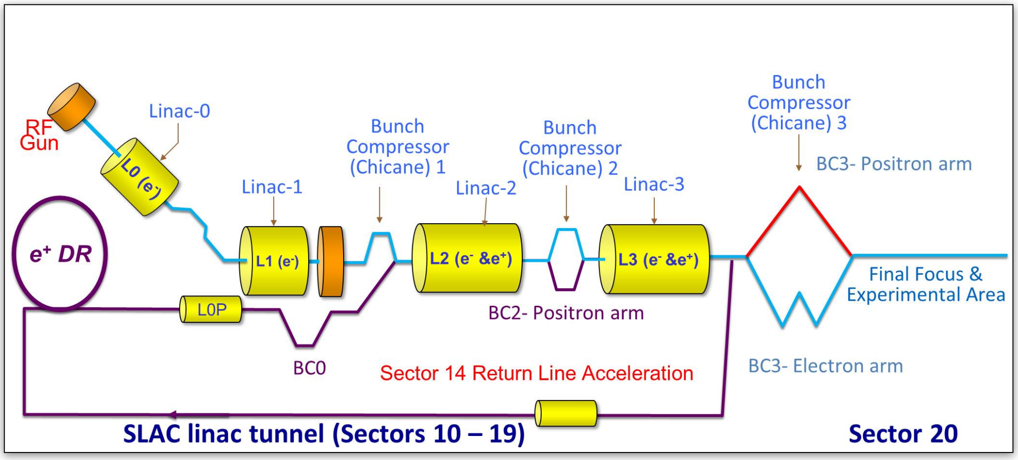

Figure 1: Overview of FACET-II. Electron and positron beams are delivered to the experimental area after multiple compression stages resulting in high peak current beams at the point of delivery.

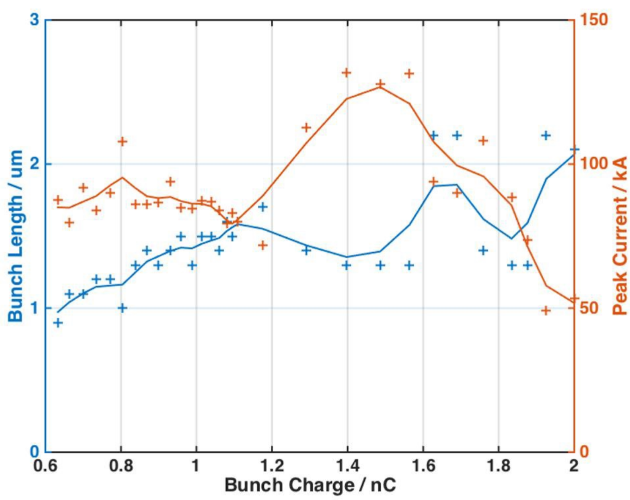

Figure 2: Charge is controlled with collimators in the bunch compressors (magnetic chicanes) that selectively collimate high and low energy offset tails of the beam from an initial charge of 2 nC from the RF photocathode gun. This affects the bunch length as shown. Maximum peak current occurs around 1.5 nC for electrons.

EXPERIENCE FROM FACET

FACET's experimental area is situated after three bunch compression stages and a final focus resulting in beams 20 μm r.m.s both transversely and longitudinally. Peak current is typically above 10 kA. Diagnostics in the experimental area change regularly depending on the experiments installed and many are built or otherwise provided by the experiment teams.

Optical Transition Radiation Profile Screens

Profile monitors based on optical transition radiation (OTR) were installed in the experimental area. Thin (1 μm) titanium foils were used to minimise emittance growth such that the profile screens upstream of experiments could be inserted during data-taking, giving shot-by-shot measurements of the transverse beam size entering the experiment.

During beam operation, these titanium foils broke. A single shot, when the beam was high enough density, was sufficient to make the entire screen unusable as the thin screen tore from a single hole.

This led to a redesign of the foil holder to allow several screens to be installed at once and driven in with a stepper motor vacuum feed-through. This allows the operator to move on to a fresh screen once one is damaged.

For screens installed at or close to the beam waist, thicker targets (500 μm) were installed which would not tear after a single spot of damage. If the thicker targets accrued a damage-spot, the target could be moved a few hundred microns to a fresh area. Figure 3 shows a 500 μm thick titanium disk that has been damaged in several places by the electron beam at FACET. Figure 4 shows a magnified image of one of the holes formed by multiple beam shots. When the beam is high enough density to cause damage, it can cause damage in a single shot.

FACET experience has shown limited success in using OTR screens for beam size tuning at the beam waist. However, they been used very effectively away from the beam waist. Screens are placed upstream and downstream of the beam focus to image transverse tails that appear at different phases. At these locations, the beam size is larger and the screens are not damaged.

Wirescanners

Beam size tuning at FACET most commonly relies upon wirescanners. The FACET optics can be set to move the waist of the beam to various locations in the experimenter area. Beam tuning usually occurs with the beam waist set to a wirescanner location. After beam tuning, the waist is shifted to the experiment "interaction point" (IP).

The wire scanners installed at FACET use 60 μm thick tungsten wires with gold coating to enable them to be sol-

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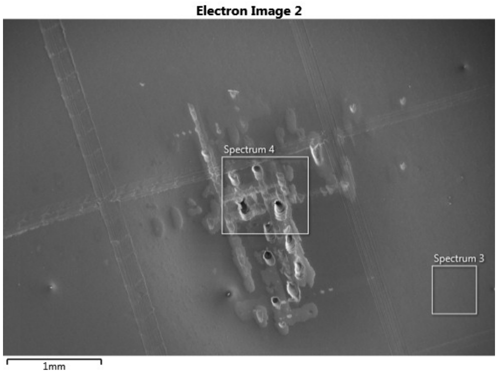

Figure 3: Titanium target with multiple regions of damage caused by multiple shots of the FACET electron beam.

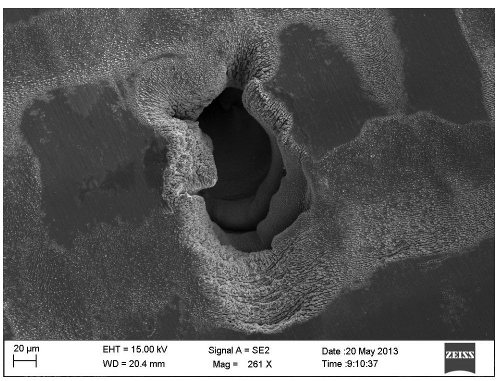

Figure 4: Magnification of a hole caused by the FACET electron beam. Material is 500 μm titanium.

dered. A particular wirescanner was installed close to the PWFA IP. After three months of beam operations, the wires were inspected. The gold had melted but the tungsten showed no signs of damage (Fig. 5). At FACET's beam parameters, wirescanners with tungsten wires were usually a reliable diagnostic for beam size but did break due to the beam on a couple of occasions.

Figure 5: Gold coating melted off wires used at IP for 20 by 20 beams.

Development by Experiment Teams

Other beam diagnostics have been implemented or developed by user groups to complement the basic tools for operators to deliver. Many diagnostics when developed by one team are subsequently used by other teams or the accelerator operators to deliver beam parameters that match specific needs for an experiment.

These additional diagnostics include electro-optic sampling for measuring the timing between laser and electron beam developed by the E-210 Trojan Horse experiment [7] team. Their experiment requires a laser pulse 250 fs in advance of the electron beam and their developed diagnostic allows them to adjust the timing of the laser appropriately and record the delay on a shot by shot basis.

Diagnostics to understand the beam-plasma interaction for PWFA experiments included a Cherenkov light-based profile monitor [8] and a KODAK LANEX (efficient rare-earth phosphor) screen to use in combination with a magnetic spectrometer to measure the energies of the "spent" wakefield-driving bunch and the plasma-wakefield-accelerated trailing bunch. LANEX screens were also used to image the x-rays which inform on the beam dynamics within the plasma. Thin metal sheets of various materials were used to convert the x-rays and provide information on the x-ray energy. An x-ray spectrometer consisting of bricks of alumina and x-ray sensitive diodes was tested in FACET but the backgrounds were high and the data hard to interpret leading to the preference to use screens.

Bunch profile diagnostic development based on reconstructing the profile from the Smith Purcell radiation [9] has also taken place as has measuring the properties of coherent transition radiation [10] and extrapolating electron bunch properties.

Any system that introduces materials to the beam path suffers some degree of beam damage and needs to be extracted from the beam path when not critical and needs a regular replacement schedule. In particular, this includes the LANEX screen which needed replacement after a few days of use.

Mechanisms for Material Failure

The damage to the foils and wires in FACET is primarily due to heating of the material from Ohmic losses. Contributions from electromagnetic showers are small in comparison and the average beam power is low due to the low repetition rate (1-10 Hz).

The impinging beam has strong electromagnetic fields that induce currents in the material. Calculations [11] solving for the induced currents indicated that with the optimally tuned FACET beam (20 μm for σ_x, σ_y and σ_z with 3.2 nC bunch charge), we were close to the critical conditions for failure of tungsten wires and titanium screens due to melting. This matches our operational experience. Usually once beam conditions were already sufficient for experiment delivery, they were not tuned further.

Failure of material will certainly occur if the material temperature rises above the melting point of the material. Typically, flaws in the material mean that failure occurs earlier. FACET experience saw this in particular for the 1 μm foils which were deposited thin films and not rolled material. Also, initially ductile materials could become brittle and eventually fracture due to repeated and excessive temperature increases below the melting point. This meant

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that material failure occasionally happened without the beam density being unusually high.

FACET-II EXPECTATIONS

FACET-II diagnostics at the point of delivery will initially be based on FACET diagnostics. Initial beam parameters are not expected to be pushing to the highest peak currents but instead will be ~10 kA, similar to FACET (Table 2). Experiments that require consistently higher beam currents will be scheduled for later in the operation when experience and development of new diagnostics is more mature.

Table 2: Objective performance for FACET-II upon first operation.

Parameter	Electrons	Positrons
Energy [GeV]	10	10
Charge per pulse Q [nC]	2	1
Bunch Length σ_z	20	20
Normalised emittance [μm]	10	20

Estimates for Damage

The temperature increase from Ohmic losses go as $(\frac{Q}{\sigma_z})^2$ [12]. FACET-II is capable of both higher charge and shorter bunch lengths than FACET (the two parameters are coupled as shown in Fig. 2) and therefore material damage through heating by image currents is a high concern.

Through analytical calculation of induced image charges, the temperature increase due to Ohmic losses can be estimated. Assuming the optimal design parameters for the electron beam for the expected linac and compressor set up to deliver >10 kA electron and positron beams to the experimental area simultaneously, the temperature increase when the beam impinges upon tungsten wires is estimated by Equation 24 in analysis by Lin and Whittum [12]. This assumes round Gaussian bunches for simplicity and leads to the approximate result that the temperature rise in the wire is above 2 million degrees Celsius.

It is clear from both analytic calculation and FACET operational experience that the materials are already being used at their limits. Any increase in peak current for FACET-II is at the expense of using diagnostics at the beam waist. Intercepting materials should be positioned in locations where the beam size is over 200μm to avoid Ohmic heating about the melting point of tungsten.

Wirescanners at FACET-II

Following from the OTR strategy of installing many targets at once, our planned wire scanner design for FACET-II includes many wires. A prototype card was wired and is shown in Fig. 6. Although this would not permit measurement of the high peak current beams at the waist, this will mitigate against the case were the beam configuration has nominally more relaxed parameters with dynamic errors producing errant high peak charge shots. Software will be used to "park" the beam as the card is being moved to go from wire-to-wire (as opposed to during wirescan measurements) to prevent all the wires from being broken if beam density is high enough. This is the initial plan for resuming beam operations with nominal delivered beam parameters close to FACET, sufficient for a great deal of the early experiments planned.

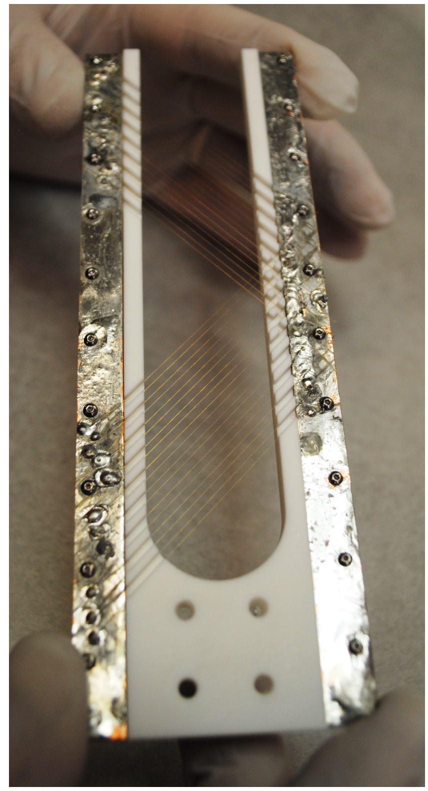

Figure 6: New wire card with multiple wires.

Multiple wirescanners can be used to interpolate the minimum beam size. A constraint on this is the limited beam line space available to be shared between delivery diagnostics and experimental apparatus. Compact wire scanners with integrated bellows that only need 4 inches of beam line have been designed for this area.

OTRs at FACET-II

The ladder design of multiple targets will continue to be used. Tungsten targets can be used and have already been effective for OTR in FACET. Normally, the screens are not used at the beam waist and will continue to be installed upstream and downstream of experiments.

Measuring Shorter Bunch Lengths

FACET uses a transverse deflecting cavity (TCAV) as its primary diagnostic for setting up the linac bunch compression correctly and adjusting collimators to deliver two bunches with parameters suitable for the wakefield experiments.

The TCAV has seen great success at FACET due to its operational simplicity. The existing X-band TCAV is in the

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electron arm of the final bunch compression chicane (BC3 in Fig. 1). FACET-II plans to install a second TCAV in the positron arm of BC3 (the positron arm does not currently exist and will be installed for FACET-II) for setting up the bunch compression for positron delivery.

The resolution of an X-band TCAV is predicted to be 7 μm [13]. LCLS have measured bunch lengths as small as 1.5 μm with an S-band TCAV [14]. We expect to study the technology choice for FACET-II and the theoretical resolution limits further.

Measuring Two Beams

FACET-II will deliver two bunches to the experiments. Uniquely in the world, there will be a two bunch delivery configuration that will be one electron bunch and one positron bunch. In this configuration, positrons will be accelerated in the same linac as the electrons and compressed in reversely polarised chicanes (Fig. 1). Peak to peak separation for electron and positron bunches for PWFA are of the order 200 μm. FACET-II's design includes adjustment of the bunch separation.

Techniques for resolving the two bunches and measuring their separation were evaluated [13]. Two techniques were implemented for FACET (where the two bunches are created by collimation of a portion of a stretched electron bunch): the X-band TCAV and electro-optic sampling (EOS).

EOS was an effort by the E-210 Trojan Horse experiment team, an example of the close relationship between facility and user development of diagnostics. This single-shot, non-invasive diagnostic is still being developed and is planned to continue through FACET-II.

No concerns have been identified yet with operating EOS in FACET-II. Higher electric fields will permit the electro-optic crystal to be placed further from the beam. Experience at FACET shows that the electro-optic crystal surface can be damaged by a single direct hit from the electron beam but is still functional.

The TCAV could also be used to measure bunch to bunch separation. However, to streak both beams simultaneously to tune on the bunch separation would require a TCAV downstream of the separate electron and positron chicanes. Magnet density is high in this region as it is the final focus but finding a location in the shared beamline will be investigated. Downstream of the experimental area, apertures need to be large as there are many particles deflected due to the beam-plasma interaction that could damage a structure.

CONCLUSION

FACET-II will be a facility that will deliver high-density beams of electrons and positrons, ideal for creating exotic states of matter and researching advanced accelerator technologies such as PWFA and DWA. However, to take advantage of the capability of >100 kA peak current beams, diagnostics need to be designed for this regime. Typical operations are expected to start with peak currents close to those of FACET (10-20 kA) where we have operational experience and overcome concerns by building in redundancy.

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REFERENCES

[1] M. Litos et al., "High-Efficiency Acceleration of an Electron Beam in a Plasma Wakefield Accelerator", Nature, vol.515 7525 (2014).

[2] S. Corde et al., "Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield", Nature, vol.524 7566 (2015).

[3] B. O'Shea et al, "Demonstration of Gigavolt-per-meter Accelerating Gradients using Cylindrical Dielectric-lined Waveguides", Proc. of IPAC, Dresden, Germany, TUOBB02 (2014).

[4] S.Z. Green et al., "Laser ionized preformed plasma at FACET", Plasma Physics and Controlled Fusion, vol.56 084011 (2014).

[5] J. Quiang, S. Lidia, R. D. Ryne and C. Limborg-Deprey, "Three-dimensional quasistatic model for high brightness beam dynamics simulation" Phys. Rev. ST Accel. Beams 9, 044204 (2006).

[6] `http://www.slac.stanford.edu/accel/ilc/codes/Lucretia/`

[7] B. Hidding et al, "Ultracold Electron Bunch Generation via Plasma Photocathode Emission and Acceleration in a Beam-Driven Plasma Blowout" Phys. Rev. Lett. 108, 3, 035001 (2012).

[8] E. Adli et al, "Cherenkov light-based beam profiling for ultrarelativistic electron beams" Nucl. Instrum. Methods Phys. Res., Sect. A, 783, 35-42 (2015).

[9] H. Andrews et al, "Reconstruction of the time profile of 20.35 GeV, subpicosecond long electron bunches by means of Coherent Smith-Purcell radiation" Phys. Rev. ST Accel. Beams 17, 5, 052802 (2014).

[10] Z. Wu et al, "Intense terahertz pulses from SLAC electron beams using coherent transition radiation" Rev. Sci. Instrum. 84, 022701 (2013).

[11] G. Stupakov, "Melting thin foils by incident relativistic electron bunch," SLAC-PUB-15729 (2013).

[12] X. E. Lin and D. H. Whittum, "Image Current Heating on a Metal Surface" Phys. Rev. ST Accel. Beams 3, 101001 (2000).

[13] M. D. Litos et al, "Evaluation of Temporal Diagnostic Techniques for Two-Bunch FACET Beam," Conf. Proc. C 110328, 568 (2011).

[14] H. Loos, "LCLS accelerator operation and measurement of electron beam parameters relevant for the x-ray beam," SLAC-PUB-15422 (2013).

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