

BEAM DIAGNOSTICS FOR FACET*

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Abstract

FACET, the Facility for Advanced Accelerator and Experimental Tests, is a new facility being constructed in sector 20 of the SLAC linac primarily to study beam driven plasma wakefield acceleration beginning in summer 2011. The nominal FACET parameters are 23 GeV, 3 nC electron bunches compressed to about 20 μm long and focussed to about 10 μm wide. Characterization of the beam-plasma interaction requires complete knowledge of the incoming beam parameters on a pulse-to-pulse basis. FACET diagnostics include Beam Position Monitors, Toroidal current monitors, X-ray and Cerenkov based energy spectrometers, optical transition radiation (OTR) profile monitors and coherent transition radiation (CTR) bunch length measurement systems. The compliment of beam diagnostics and their expected performance are reviewed.

FACET BEAM

The Facility for Advanced Accelerator and Experimental Tests (FACET) will provide high-energy, high-peak-current, low-transverse-emittance electron and positron beams in the first 2 km of the SLAC linac (Figure 1). The main FACET beam parameters are listed in Table 1.

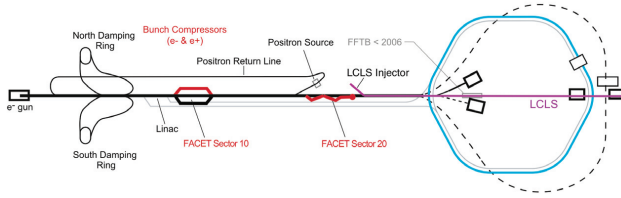


Figure 1: FACET schematic in the SLAC linac.

Table 1: FACET Beam Parameters

Energy	23 GeV
Charge	3 nC
Bunch Length σ_z	20 μm
Spot Size σ_r	10 μm
Peak Current	22 kA
Species	e^- & e^+

The newly constructed experimental area is located in sector 20 where the beam is focused to an interaction point (IP) for plasma wakefield acceleration (PWA) experiments, one of the major programs at FACET. A layout of the FACET beamline elements is shown in Figure 2.

We present the main diagnostics for measuring the position, charge, transverse and longitudinal beam properties for FACET.

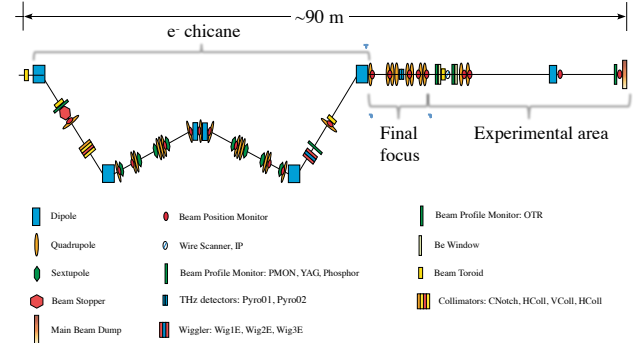


Figure 2: Beamline elements and diagnostics in sector 20 at FACET.

BEAM DIAGNOSTICS

Beam diagnostics techniques are being developed and implemented for FACET. We report on the system development and characterize the expected performance.

Beam Position Monitors

The beam position monitors (BPMs) are positioned (Figure 2) along the FACET beamline to provide high-resolution measurement of the beam trajectory. These are strip-line BPMs based on digital down conversion. The BPM data can be used to analyze and tune the accelerator. Operating requirements for the FACET BPMs are specified in Table 2.

Table 2: General Operating Requirements

Resolution for single pulse measurement	5 μm
Single pulse operation range	0.3-3 nC
Maximum drift	5 $\mu\text{m}/\text{hour}$
Maximum systematic position offset, including mechanical and electrical offsets	200 μm
Maximum non-linear position error at a beam position	20%
Minimum bit size	1 μm at 0.2 nC
Noise floor	5 μm rms
Repetition rate for single pulse	30 Hz

Toroidal Current Monitors

Toroids provide absolute measurements of the beam charge on a pulse-by-pulse basis. Four toroids (each has 8 turns) are being installed in sector 20. The beam charge will be measured to an accuracy of 2% for the charge range between 0.3-3.0 nC.

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Energy Spectrometers

The x-ray based energy spectrometer is non-invasive to the beam. Upstream of the plasma wakefield acceleration (PWFA) experiment, a vertical deflection of the electron beam creates x-ray synchrotron radiation in the bunch compressor chicane. More detailed description can be found in [1][2]. To detect the synchrotron x-rays, a $10 \times 10 \times 0.08$ mm³ scintillator crystal made of Cerium doped Yttrium Aluminum Garnet (YAG:Ce) is inserted at a 45° angle to the photon beam. The scintillating light is visible and can be imaged by a scientific CMOS (sCMOS) camera to produce an energy spectrum of the electron bunch. The pco.edge [3] sCMOS camera has a resolution of 2560×2160 pixels, each $6.5 \mu\text{m} \times 6.5 \mu\text{m}$ in size. The camera readout noise is less than 3 electrons at 50 frames per second in global shutter mode. The digitization is with 16 bits for 0.46 electrons per count. The energy resolution depends on the imaging system but is dominated by the beam size due to the beam focusing and emittance.

A Cerenkov light based energy spectrometer will be in place downstream from the plasma wakefield experiment to verify energy changes resulting from the plasma wake. An imaging magnetic spectrometer ensures that the beam profile in the dispersed plane is proportional to the beam energy and not deflections in the plasma. Cerenkov light from an air gap located at the image is captured by another sCMOS camera to reconstruct the beam distribution. The final energy resolution of the spectrometer depends on the dispersion and the separation between pixels for the camera. The FACET system will be similar to systems developed for the FFTB PWFA experiments [4][5].

Transition Radiation Monitors

Transition radiation is emitted as the ultra-short electron bunches pass through a one-micron thick titanium foil oriented at 45° relative to the beam. A silicon beam splitter transmits the coherent transition radiation (CTR) to a pyroelectric detector to measure the relative bunch length in the range of 10 to 100 μm , assuming Gaussian beams. The silicon splitter reflects the non-coherent optical transition radiation (OTR) to an sCMOS camera for measurement of the transverse beam profile.

Figure 3 shows a top view of the integrated system of the bunch length monitor (BLN) and the OTR profile monitor. The design of the pyroelectric detector for BLN is similar to that of LCLS [6] where a horn in front of the pyro element collects the terahertz radiation and enlarges the detector area, as well as provides RF shielding. Due to its wideband response, the pyro detector is sensitive to high frequencies and will be capable of measuring short bunches at FACET.

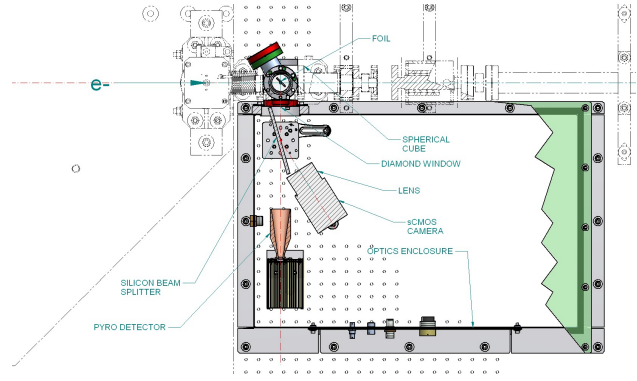


Figure 3: The integrated system of OTR profile monitor and bunch length monitor.

Nominal bunch distributions from an ELEGANT simulation of FACET beam are shown in Figure 4. A bunch length of 19 μm is obtained from a Gaussian fit to the particle distribution in Z.

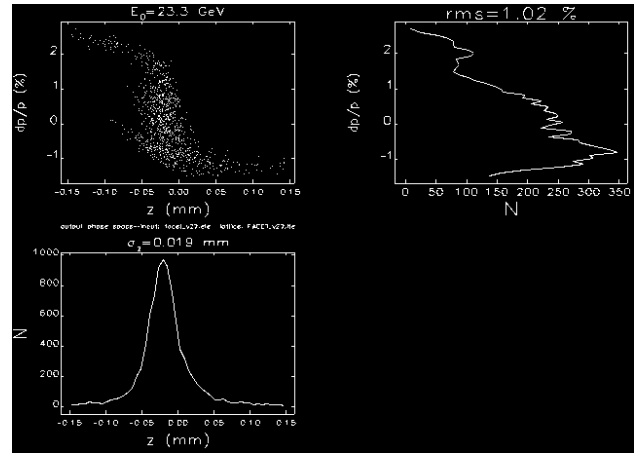


Figure 4: The simulated longitudinal phase space, energy spectrum and current profile at the location of BLN for the FACET beam.

The integrated system of BLN and OTR profile monitor will be installed upstream of the PWFA experiment located at the FACET IP to provide transverse and longitudinal measurements of the beam before entering the plasma.

Another OTR profile monitor is installed downstream of the plasma cell to measure the beam spot size after the beam-plasma interaction. Both of the upstream and downstream OTR profile monitors will use the pco.edge camera with a standard Nikon 105 mm AF Micro-Nikkor f/2.8D lens.

The OTR lens performance has been characterized using techniques similar to what is described in [7] taking into account effects from vacuum windows and color filters. Measurements are made by imaging a uniformly back-illuminated USAF1951 test target onto a CCD sensor with the Nikon lens. The CCD camera used for testing is a Photometrics CoolSNAP HQ2 with a resolution of 1392×1040 pixels and pixel size of 6.45

$\mu\text{m} \times 6.45 \mu\text{m}$. An image taken at f/11 is shown in Figure 5 with added texts to illustrate the group and element numbers in the pattern.

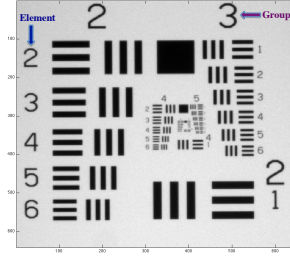


Figure 5: An image of the central part of the USAF1951 test pattern captured by a Nikkor 105mm f/2.8D lens at a magnification of 1:1 and an aperture of f/11.

The spatial frequency F represents the spacing of lines in the test pattern and can be calculated by $2 \times \text{Group} + (\text{Element} - 1)/6$ in unit of line pairs per mm (lp/mm). A rough and subjective estimate of the resolution can be established by identifying the smallest element in which an observer can distinguish all the line pairs in the test pattern. Nevertheless, resolution can be quantified. A contrast transfer function (CTF) is the black and white contrast at a particular spatial frequency, normalized to contrast at the lowest frequency. The CTF can be determined directly from a square wave test pattern such as the USAF1951 resolution target. However, the performance of a lens is typically referenced by a modulation transfer function (MTF) that can be obtained from a sine pattern. Alternatively, the MTF can also be derived [8] from the CTF:

$$MTF(F) = \frac{\pi}{4} \left[CTF(F) + \frac{CTF(3F)}{3} - \frac{CTF(5F)}{5} + \frac{CTF(7F)}{7} + \frac{CTF(11F)}{11} - \frac{CTF(13F)}{13} - \frac{CTF(15F)}{15} - \dots \right]$$

The latter method is used to calculate the MTF results presented in Figure 6. For example, for the case where no window and no filter were used, the 50% MTF frequency is about 17 lp/mm corresponding to $29.2 \mu\text{m}$ and the 10% MTF frequency is about 45 lp/mm or $11.1 \mu\text{m}$.

The resolution test compares the effect on resolution with the use of diamond or sapphire window, as well as red or blue filter. The diamond window is 1.2" in diameter and $250 \mu\text{m}$ thick while the sapphire window is ultraviolet grade with 0.94" view diameter and about 2.03 mm thick. The response curves suggest that sapphire provides better resolution than diamond.

The nominal beam size at the upstream OTR location is Gaussian with $\sigma_x = 550 \mu\text{m}$ and $\sigma_y = 55 \mu\text{m}$. Note that at large apertures, the MTF is limited by optical imperfections and limited by diffraction at small apertures. The aperture of f/11 appears to be optimal in our optical system. Using the formula given in [9], the maximum f-number to resolve a resolution of $55 \mu\text{m}$ beam is much larger than 11. Therefore, our optical

system provides sufficient resolution to resolve the OTR image of the beam.

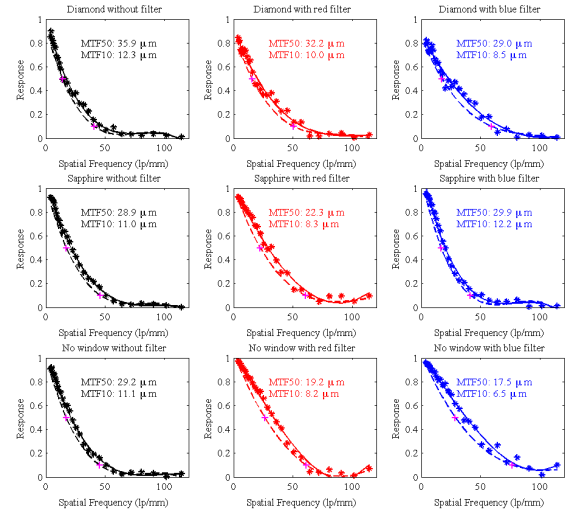


Figure 6: Resolution of the Nikkor 105mm f/2.8D lens at a magnification of 1:1 and an aperture of f/11. Solid lines are third order polynomial fits to the CTF data (*) and dashed lines are the MTF curves derived from CTF.

SUMMARY

Beam diagnostic measurements not only provide valuable insights to the running and tuning of the accelerator but also are crucial for the PWFA experiments in particular. Beam diagnostic devices are being set up at FACET and will be ready for beam commissioning in summer 2011.

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