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PLASMAS, DIELECTRICS AND THE ULTRAFAST: FIRST SCIENCE AND OPERATIONAL EXPERIENCE AT FACET*

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Abstract

FACET (Facility for Advanced Accelerator and Experimental Tests) is an accelerator R&D test facility that has been recently constructed at SLAC National Accelerator Laboratory. The facility provides 20 GeV, 3 nC electron beams, short (20 μm) bunches and small (20 μm wide) spot sizes, producing uniquely high power beams. FACET supports studies from many fields but in particular those of Plasma Wakefield Acceleration and Dielectric Wakefield Acceleration. FACET is also a source of THz radiation for material studies. We present the FACET design, initial operating experience and first science from the facility.

INTRODUCTION

Accelerators are our primary tool for discovering the fundamental laws to the universe. Each new frontier we probe requires a new, more powerful machine. Accelerators using conventional technologies are therefore increasing in size and cost. The future of this field will require new accelerating techniques that can reach the high energies required over shorter distances. New concepts for high gradient acceleration include utilizing the wakes in plasma and dielectric and metallic structures. FACET was built to provide a test bed for novel accelerating concepts with its high charge, highly compressed beams. As a test facility unlike any other, it has also attracted groups interested in beam diagnostic techniques and studies using terahertz radiation. In addition, the SLAC linac continues to offer opportunities to study conventional acceleration structures and accelerator physics.

FACET construction was completed in May 2011 and it became a United States Department of Energy User Facility for High Energy Physics in January 2012. FACET was commissioned and the first User Run took place over 12 weeks in 2012.

FACET has a five year program, operating four to five months every year through to 2016. Proposals are solicited every year and peer reviewed with the highest ranked experiments gaining beam time.

THE FACILITY

FACET delivers electron bunches to experiments with tightly focused transverse beam sizes and ultra-short bunch lengths. Positron bunches will be commissioned in 2013 for delivery to FACET experiments in 2014.

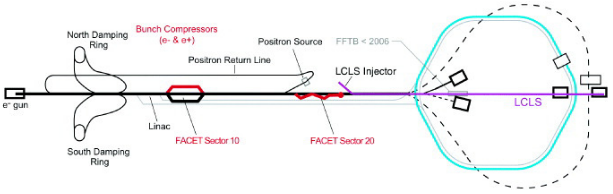

Figure 1: The SLAC linear accelerator and associated facilities. Two kilometers of s-band accelerating structures lead into FACET's final focus section. FACET's dump separates the first 20 sectors of the linac from the final 10 which are used by LCLS.

Multiple experiments share the same beam line and the waist of the beam is shifted according to the location of the experiment. The design parameters are given in Table 1 along with the best beam parameters that have been the achieved during the 2012 user run and typical parameters that were delivered regularly.

Linear Accelerator

FACET uses the first two-thirds of the SLAC linac to accelerate electrons up to 20 GeV (Fig. 1). An extraction kicker after the accelerating structures can direct the electrons to either the FACET experimental area and dump or into a positron target. Positrons are generated at the target and boosted to 200 MeV. They are then transported to the start of the linac and accelerated such that they enter the positron damping ring at 1.2 GeV. The positrons are then accelerated to an energy above 20 GeV using the same beamline as the electrons.

Bunch Compression

Three stages of bunch compression deliver the ultra-short bunches (with a design value of σ_z of 17 μm or 57 fs) to FACET experiments.

The first stage of compression occurs on injection from the damping ring to the linac. The bunches are compressed from 5.5 mm in the damping ring to 1.5 mm in the linac.

The next stage was built in 2002 for the Sub-Picosecond Pulse Source (SPPS) to compress electron bunches further to $\sim$50 μm. This is a magnetic chicane in Sector 10 of the linac. The positron arm of the chicane was built in March 2012 and is exactly symmetric to the electron chicane.

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Table 1: FACET beam design parameters compared to the best beam parameters and the typical beam parameters achieved during the FACET User run 2012 without significant beam tuning.

Parameter	**Design Goal**	**2012 Best**	**2012 Typical**
Energy [GeV]	23	20.35	20.35
RMS Energy Spread [%]	1.5	1.5	1.5
Charge [nC]	3	3.2	2.9
Bunch Length σ_z	<30	20	20
Beam size $\sigma_x \times \sigma_y$	<15×15	20×23	35×35
Repetition Rate [Hz]	30 Hz	1-10 Hz	1-10 Hz

The third and final compression occurs in another magnetic chicane 20 m upstream of the experimental area. This brings the length of the bunch to a σ_z of $\sim$17 μm. This chicane can be set to compress either electrons or positrons.

Final Focus

The optics in FACET are designed to deliver a small, round beam at the "Interaction Point" (IP). The longitudinal position of the IP can be changed using upstream quadrupoles. Therefore, a series of experiments that require small spot sizes at different locations along the beam line can be supported by changing the optics.

Notch Collimator and Jaw Collimator

The notch collimator was installed in March 2012 to selectively collimate the incoming electron or positron bunches, effectively producing two bunches [2]. In wakefield acceleration studies, these bunches are termed the drive and witness bunch. The two bunches are separated by $\sim$160 μm (from simulation), which is ideal for wakefield studies.

The notch collimator is a tantalum blade that can be inserted into the beam path in the middle of the last chicane. At this location, energy is strongly correlated with position in x so by removing a portion of the beam in x, two bunches separated in time are formed after the chicane. The separation can be changed as well as the amount of charge in each of the drive and witness bunch.

A significant change of the optics is necessary in the final chicane which nominally has a R_{56} setting of 5 mm but needs to be changed to 10 mm to over-compress the bunch. In 2012, we saw the successful production of two bunches separated in time. More work will follow in 2013 to characterize this chicane setting and the notch collimator.

A jaw collimator immediately downstream is able to shape the bunch, producing ramped-charge drive bunches.

Transverse Deflecting Cavity

An x-band transverse deflecting cavity (xTCAV) allows single-shot measurement of the longitudinal profile of the bunch. Located upstream of the experiments but downstream of the notch collimator, it deflects the bunches transversely according to the longitudinal position in the bunch. The deflected bunch is then intercepted by a downstream profile monitor screen providing an image of the temporal distribution of the bunch. The resolution is designed to be 10 μm.

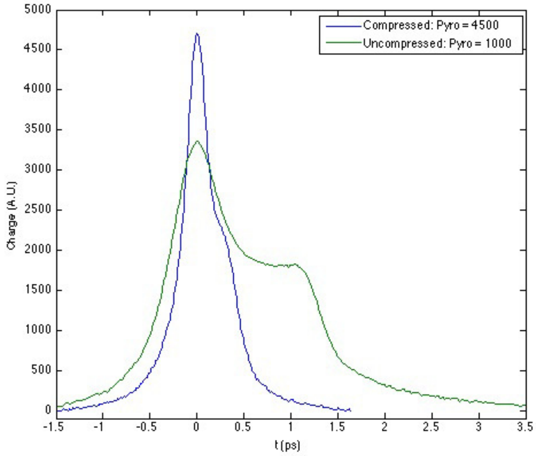

Figure 2: Preliminary results for longitudinal bunch profiles as measured by the xTCAV. Shown are two bunch profiles for the maximally compressed bunch (blue) and an uncompressed bunch (green).

Data were taken with the xTCAV in 2012. Studies are ongoing to understand the effects of the beamline optics and how to correct for intrinsic tilt. A variety of longitudinal profiles were observed from near-Gaussian bunches at maximum compression to two-peaked structures off-compression (Fig. 2).

Experimental Area

The main area for experiments at FACET is the "IP Area" (Fig. 3) immediately after the final focus system. The optics are designed to focus the beam in this area. 8 meters of optical breadboard support experiments and diagnostics.

Upstream of the IP Area, there is a 2.5 m optical table currently used for studies of the THz coherent transition radiation from the beam being intercepted by thin titanium foils.

The experiments are supported by diagnostics [3]. There are beam position monitors and toroids through the linac. Optical transition radiation (OTR) beam profile monitors and a wirescanner provide beam spot size information in the IP Area. Pyroelectric detectors measure coherent transition radiation (CTR) providing a monitor of the bunch length. Synchrotron x-rays from a wiggler magnet in the third-stage bunch compressor chicane are intercepted and imaged to measure the energy spread. As part of the support for acceleration studies, there is an energy spectrometer at the dump table that uses Cerenkov light emitted in a defined air gap.

INITIAL OPERATING EXPERIENCE

The SLAC linac was turned off in April 2008 after the final PEP-II run. The last third continued to be used for LCLS however, the first two-thirds of the linac were unused, aside from a short check, until June 2011. Bringing the linac back for FACET after this period of dormancy came accompanied by challenges with the expected hardware failures which were systematically dealt with; for the 2012 User run, accelerator hardware uptime was over 90%. There were also significant operational challenges related to the new operation of the linac for highly compressed beams, the strong chromatic correction to the FACET lattice and the demands of the experimental program.

Commissioning the electron beam for FACET

The electron beams at FACET were commissioned during two periods [1]. The first period comprised 12 weeks in the summer of 2011. There followed a downtime period to complete the upgrade of the sector 10 chicane to allow compression of positrons as well as electrons. This downtime period of nearly 6 months also permitted several upgrades and improvements to the beamline and diagnostics including bunch length monitors in sectors 2 and 18 and movers on two sextupoles in the sector 20 chicane plus realignment of portions of the linac. The second commissioning period was in spring 2012 and comprised 5 weeks. The downtime work was of considerable benefit to achieving the goal of "20x20x20" bunches in 2012.

Operating the linac as a User Facility

The experiments were scheduled for 12 weeks immediately following the 2012 commissioning period. The beam time in these 12 weeks was divided between the experiments, access days and machine development days.

FACET tunnel access days were scheduled and planned in advance due to the large amount of support required by SLAC staff to both do the scheduled work during the access and recover from the access. Recoveries from shutting down the linac for at least half a day often took an equivalent amount of time before beam could be delivered with close-to-ideal parameters in FACET.

The day after the access was scheduled for machine development and beam set-up for experiments. Continuous machine development was necessary to study the beam and study new optics or lattices. As a result of weekly study, beam parameters, stability and reliability at FACET steadily improved.

Experiments ran 24 hours a day and efforts were taken to schedule each experiment in long blocks of time to minimize the time spent changing the configuration of the optics from one experiment to another. This was challenging as it put a strain on personnel on both the experimenter and machine side. Configuration changes and beam tuning took considerable amounts of time making this a large burden on the accelerator physicists and operators but systematic procedures and experience led to improvements. Accesses by experimenters outside of the access days were detrimental to the beam quality and the target beam parameters were difficult to achieve following an access without considerable beam tuning.

An operational difficulty at FACET in 2012 involved the frequent failure of the OTR screens. This affected the ability to tune the beam's transverse size quickly as the only diagnostic capable of measuring it at the focus was the wirescanner which took minutes per measurement. The 1 μm thick titanium foils were destroyed by the high power electron beams at high bunch compression and small transverse spot-size. A 500 μm titanium disk was successfully used for beam spot-size tuning towards the end of the run and these thicker disks will be used throughout the IP Area in 2013.

There were also electronic hardware failures in the experimental areas from radiation damage. We estimate that the experimental area sees between 2 and 4 kilorad of dose each week depending on location, a tenth of the dose being from neutrons. Most electronics in FACET suffered from the radiation, in particular the cameras used for the diagnostics.

FIRST SCIENCE FROM EXPERIMENTAL PROGRAM

Two rounds of proposals for FACET have been peer-reviewed and awarded beam time. A third round of proposal review is scheduled for October 2012. In the first FACET user run, which lasted 12 weeks in 2012, six experiments had beam time and two test-beam studies.

Plasma Wakefield Acceleration

SLAC has a history of plasma wakefield acceleration (PWFA) with studies at the Final Focus Test Beam (FFTB) culminating in the acceleration of electrons from 42 GeV to 85 GeV in 85 cm [4]. The 2012 studies at FACET used field-ionized lithium and rubidium plasma. Plasma density was $10^{14} - 10^{17}\mathrm{e}^-/\mathrm{cm}^3$ and the length of the plasma column was 20-30 cm. The plasma was contained within cooled buffer-gas, helium in the case of lithium and argon in the case of rubidium.

Field-ionized plasma wakefield acceleration using lithium resulted in signs of a small amount of beam-plasma interaction and acceleration of 3-4 GeV. Changing to rubidium, which has a lower first ionization energy, led to significantly more beam-plasma interaction and more consistent results, less dependent on the quality of the beam

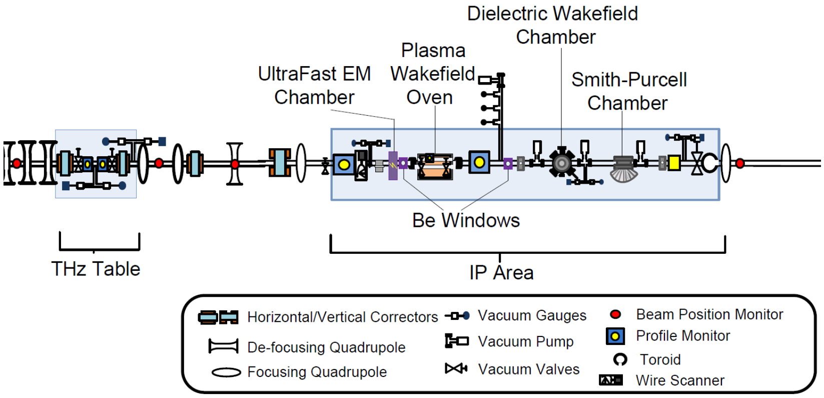

Figure 3: The IP Area includes two chambers that can be used to insert samples into or near the beam (UltraFast EM Chamber and Dielectric Wakefield Chamber). There is also an oven used in plasma acceleration studies plus experimental diagnostic devices such as the Smith-Purcell Chamber.

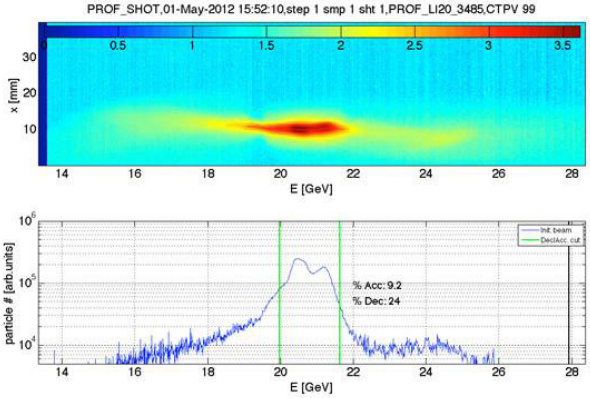

Figure 4: Image from cherenkov spectrometer from beam after passing through lithium vapor. Approximately a quarter of the bunch has interacted with the plasma and lost energy and just under 10% has gained energy.

(Fig. 4). It was estimated that between 10-20 GV/m acceleration gradients were seen. Dark current was produced from double-ionizing the rubidium and the also ionizing the argon buffer gas.

The next step is to put two bunches produced by the notch collimator through the rubidium vapor. A 10 TW laser will be installed for the next run as to get 20 GV/m gradients with the inevitable loss in charge density that comes from dividing the bunch into two, the vapor needs to be pre-ionized.

Head Erosion Study Head erosion is one of the limiting factors in PWFA. The head of the drive bunch becomes de-focused as the bunch traverses the plasma, lowering the charge density until it no longer ionizes the plasma therefore moving the ionization front further down the drive bunch with length of plasma traversed. Studies purposefully spoiling the emittance of the electron bunch at FACET using 50 μm gold foils demonstrated that the beam-plasma interaction could be slowly diminished and stopped altogether by increasing the emittance of the incoming bunch [5].

Betatron Radiation Diagnostic Hard X-rays and gamma rays are produced by the betatron oscillation of electrons in a beam-driven plasma wake. This betatron radiation was used as a diagnostic for beam matching into the plasma in 2012. Beam matching is critical for maximizing the energy extraction efficiency of a plasma accelerator stage. The detector was built immediately in front of the FACET dump. It comprised a 30 cm x35 cm phosphorescent screen which observed the transverse extent of the radiation and a sampling electromagnetic calorimeter with photodiodes for measuring the on-axis spectrum. To estimate the spectrum, the observed intensity patterns across the calorimeter are fit with a Gaussian-integrated synchrotron spectrum and compared to simulations [6].

Wakefield Acceleration in dielectric and metallic structures

Other concepts for accelerating structures involve wakefields in dielectric or metallic structures. These structures are also of considerable interest as THz sources.

Wakefield measurements in structures are common to facilities around the world but FACET offers high bunch charge and short bunch length which can drive multi-GV/m fields. This is where the longitudinal breakdown thresholds are for dielectric structures [7] so studies at FACET push the limits of the technology.

Dielectric structure studies at FACET in 2012 placed cylindrical structures of silica, diamond, alumina and sapphire and looked at the narrow-band, high-power coherent cherenkov radiation (CCR) produced to identify the modes being excited. Future plans include using slab-symmetric structures of diamond and silica and a Bragg-mirror structure.

Bunch length and profile measurement

Measuring bunch profiles of a few fs in a non-invasive and cost-effective manner is a challenge for future light-sources and accelerators. FACET provides a test-bed for bunch profile measurements in this regime.

In one experiment, coherent Smith-Purcell radiation is detected and used to reconstruct the temporal profile of the electron bunch [8]. Another experiment reconstructs temporal profiles from the power spectrum of the coherent transition radiation (CTR) from 1 μm titanium foils using a Michelson interferometer [9]. The results from these techniques are being bench marked against each other and also the measurement of the longitudinal bunch profile seen by the xTCAV.

THz studies

The short bunch length and high bunch charge at FACET makes it an excellent broadband THz source with high-peak field. When the beam passes through thin metal foils, transition radiation is produced with little degradation to the main electron beam so THz extraction is essentially parasitic to the other FACET experiments.

Calculations indicate that the CTR electric fields created are 0.6 V/Å or more when the beam's transverse size and length are optimized (20 μm) and the pulse contains 13 mJ making FACET potentially the brightest THz light source in the world [9]. Preliminary measurements with a large and flat beam (σ_x = 317 μm, σ_y = 36 μm) at 3 nC charge show 0.46 mJ of THz energy per pulse [10] as measured by a pyroelectric joulemeter. A knife-edge scan of the THz radiation at its focus measured σ_x = 1.36 mm and σ_y = 1.08 mm. The Michelson interferometer scan measured the length of the THz pulse as σ_z = 39 μm. The peak electric field of this THz pulse is 0.057 V/Å.

The THz radiation can be extracted, focused and delivered to experiments. A THz transport line has been designed to bring the THz radiation out of the accelerator tunnel to a local laser room to study materials in these intense fields and perform biological and chemical imaging.

Ultrafast processes in materials

Currently an experiment is taking advantage of the intense electromagnetic fields associated with the electron beam to probe domain switching in magnetic solids on the femtosecond timescale. This "Ultrafast Electromagnetic Switching" experiment inserts thin magnetic foils into the beam to be exposed to a single electron bunch. The exposed foils are removed from the beamline and analyzed with a spin-sensitive scanning electron microscope which can image the pattern of the magnetic domains. The resulting figure-eight pattern (Fig. 5) is from precessional switching [11]. The full characteristics of the pattern cannot be explained by the magnetic field alone; there is an effect where the electric field provides a torque, linear with the electric field strength.

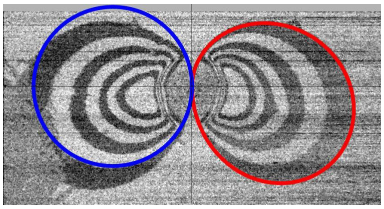

Figure 5: Image from a spin-sensitive SEM of a thin film of iron grown on a tungsten crystal after exposure from a single electron bunch. The full size of the image is ∼900 μm. The blue circle shows the hypothetical switching boundary when only the magnetic field effect is included. The red circle takes into account the torque on the magnetization induced by the electric field. The distorted lines near the center are due to reduced magnetization as the film is heated near Curie temperature by the electron bunch.

The materials have expanded from simple magnetic solids to magnetic films such are as used in spintronics applications for MRAM memory and also ferroelectrics and multiferroics. Signs of femtosecond scale switching of electric polarization were seen in samples of PZT in 2012.

FUTURE FOR FACET

FACET will operate for four to five months each year for the next four years. There will be periods of dedicated beam tuning prior to each user run to ensure good beam delivery to the users. In 2013, positron beams will be commissioned for delivery to FACET's experiments in 2014. A large upgrade to the facility next year will be the installation of a 10 TW laser for pre-ionisation of the plasma. This expands the plasma program at FACET beyond multi-GeV PWFA to Trojan Horse Plasma Wakefield Acceleration which can produce exceptionally low emittance electron beams and the study of the Self-Modulation of Long Lepton Bunches which paves the way towards PWFA with protons.

New proposals for experiments, whether a part of the wakefield acceleration program or a general beam physics or material science program, can be submitted throughout the year.

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