FACET-II*

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Abstract

FACET-II is a National User Facility at SLAC National Accelerator Laboratory providing 10 GeV electron beams with µm·rad normalised emittance and peak currents exceeding 100 kA. FACET-II operates as a National User Facility while engaging a broad User community to develop and execute experimental proposals that advance the development of plasma wakefield accelerators. FACET-II is currently commissioned and has started with first experiments. The special features of FACET-II will be shown and first results from the experiments.

INTRODUCTION

Though conventional technology can satisfy near-term needs, the practical limits to the size and cost restrict the energy reach of linear colliders. A revolution in acceleration technology is needed to realise a multi-TeV linear collider. Such a new technology needs to meet criteria: it needs to be high gradient, efficient and result in high luminosity at the collision point.

Plasma Wakefield Acceleration (PWFA) is a scheme initially proposed four decades ago [1, 2] for high (GV/m) gradient acceleration, 1,000 times the acceleration in a given distance compared to conventional RF technologies. Extremely large electric fields can be sustained in a plasma wave caused by an intense, charged particle bunch and used to accelerate a second (trailing) bunch of electrons to high energies.

Experimental beam test facilities are essential in the development of the scheme. There are few facilities with the high beam intensities required to study PWFA in the regime for future collider applications. SLAC National Accelerator Laboratory has supported three generations of facility for the study of PWFA [3]: Final Focus Test Beams (FFTB), FACET and the upgraded facility FACET-II.

Experiments at FACET (2011-2016) demonstrated 9 GeV acceleration in one metre with 30% efficiency and low energy spread [4]. The studies at FACET were limited by the relatively high emittance of the incoming electron beam which used a thermionic gun and damping ring to produce the electron bunches. The years between 2016 and 2020 were used to upgrade the facility, renamed FACET-II, with a new low emittance photo-cathode injector and new bunch compression scheme and final focus. The new facility allows these studies to continue with a focus on aspects of emittance preservation with a single 10 GeV acceleration stage.

FACET-II began commissioning in 2020. The first experiment run was in 2022. The goal of the initially invited experiments was to demonstrate the capabilities of the FACET-II facility and commission the experimental hardware. First science results from this initial run will inform the direction of more in-depth studies in the next FACET-II runs.

FACET-II National User Facility

The FACET-II accelerator provides uniquely high intensity beams. Science meetings were held over several years to develop a programme that could use these beams [5]. The programme encompasses not only GeV-level PWFA studies but also the development of ultra-high brightness electron beams from plasma-based injectors and high-intensity x-ray and gamma-ray sources plus the study of high-energy high-intensity electron beams and their interaction with lasers, plasmas and solids. Novel diagnostics to characterize the extreme beams are being developed combining beam-physics, machine learning (ML) and artificial intelligence (AI).

FACET-II operates as a Department of Energy National User Facility for High Energy Physics. Proposals are welcome from scientists all around the world and evaluated through a peer review process for beamtime at FACET-II [6]. Operating a broad science program draws expertise and the opportunity to collaborate with scientists in different fields, which benefits each of the individual science thrusts.

BEAM DELIVERY STATUS

Commissioning of the new FACET-II facility (Fig. 1) began in 2020. The single electron bunch configuration has been commissioned (Table 1) and will be further optimised. Future configurations include a two bunch configuration for PWFA demonstrations.

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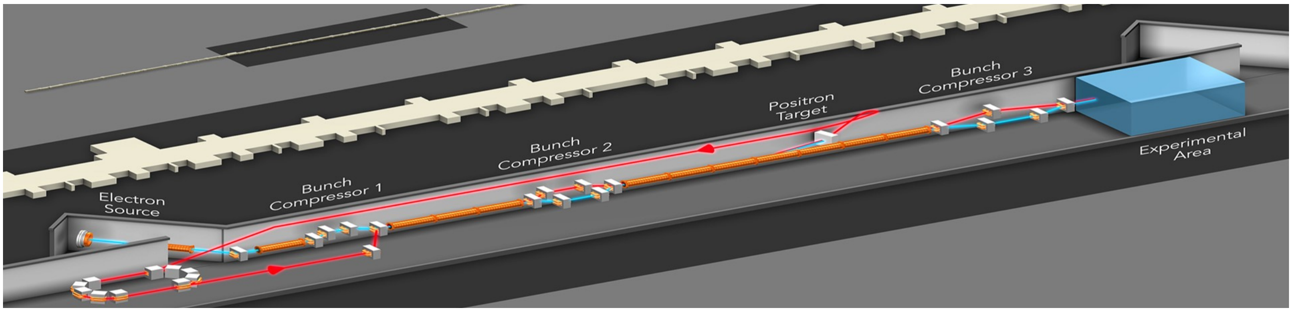

Figure 1: Layout of FACET-II. The facility is 1 km long comprising a photo-cathode injector, three accelerating sections, three bunch compression sections and a final section where experiments are staged. The current installation is compatible with a possible future upgrade to deliver positrons.

Table 1: FACET-II Current Beam Parameters and Design Objective Range

Parameter	**Nominal**	**Design Range**
Beam energy (GeV)	10	4.0–13.5
Repetition Rate (Hz)	10	1–30
Bunch charge (nC)	2	0.5–3
Bunch length (σ, µm)	20	1–100
Beam spot size (σ, µm)	30	5–200

First Science with Machine Learning and Virtual Diagnostics

The extremely intense beams at FACET-II lead to challenges as the compressed and focused beam cannot be characterised using intercepting diagnostics as they can be damaged by the beam in a single shot [7]. An early focus was therefore given to experiments developing Machine Learning (ML) enhanced virtual diagnostics and ML based tuning.

One such diagnostic uses edge radiation for emittance measurements. Edge radiation at a bend magnet in the dog-leg immediately after the injector was imaged on a camera. Machine learning was used to reduce noise and enhance the analysis (Fig 2). The next step is to deploy at downstream bunch compressor locations and implement real time analysis.

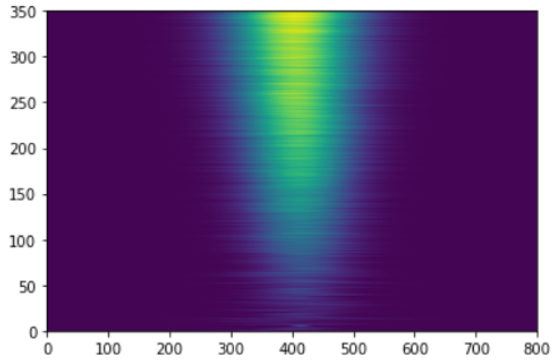

Figure 2: Edge radiation image acquired and filtered using a machine learning noise reduction technique.

In tandem with information from ML-enhanced diagnostics, ML is also expected to help achieve high quality beams with unprecedented parameters by enabling simultaneous adjustment of more variables across the machine than would be possible by hand. ML driven control is expected to streamline tuning, improve up-time, and lower burden on operations staff.

A combination of model-dependant and model-independent tuning approaches are being developed, and some are already being prepared for use in regular operation. Early ML control studies focused on injector emittance optimization, and similar techniques are now are being extended to downstream sections of the accelerator. For example, Bayesian optimization was recently used in sextupole optimisation within the final focus to achieve smaller spot sizes within the interaction area (Fig. 3).

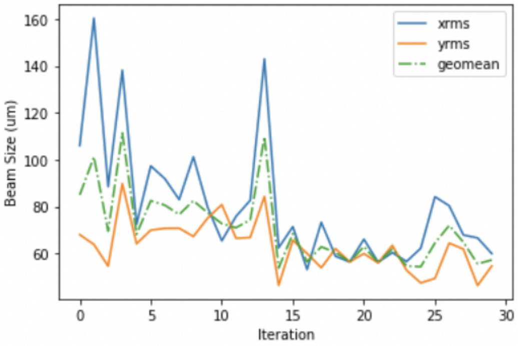

Figure 3: Machine learning applied to sextupole adjustments for beam size optimisation at a wire scanner in the interaction area.

SECTOR 20 OVERVIEW

The experimental area, labeled in Fig. 1, is comprised of the final focusing optics, beam characterization tools for before and after the interaction point of the beam, and the re-imaging quadrupoles and spectrometer dipole before the main beam dump (Fig. 4).

The Interaction Area

The interaction area includes a Ti:Sapph laser (typical parameters are in Table 2). There is a large vacuum chamber with opto-mechanics that are used to focus and manoeuvre the laser beam onto the electron beam trajectory. 20% of

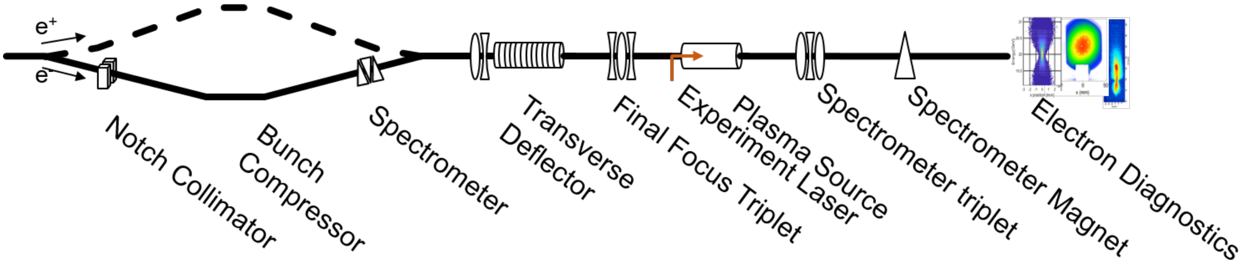

Figure 4: Layout of FACET-II. The facility is 1 km long. Compatible with a possible future upgrade to deliver positrons.

the main laser beam is picked off and sent to an independent compressor for the use of experiments and diagnostics with lower laser energy requirements.

The chamber also includes movers for the positioning of solid targets into the path of the electron beam and a gas jet that operates from below atmospheric pressures up to 1200 psi.

Downstream of the large vacuum chamber is a long beampipe that can be filled with gas for the production of a long plasma.

All this hardware is the result of years of collaboration between experiment groups, copious computer aided design and a combined effort from multiple institutions to install hardware that can service multiple experiments at once without reconfiguration beyond remote movement of actuators.

Table 2: FACET-II Sector 20 Laser Parameters. The laser is 800 nm Ti:Sapph [8]

Parameter	**Typical**	**Range**
Energy at target	220 mJ	10–320 mJ
Pulse duration	60 fs	60–500 fs

Electro-Optic Sampling Diagnostic

After the final stage of compression, the longitudinal profile can be measured with a transverse deflecting cavity (TCAV). When the two-bunch configuration is developed, this will be invaluable to measure the relative spacing and charge distribution. However, this is an invasive measurement and cannot be performed simultaneous with the experiment data collection.

Therefore, a non invasive diagnostic based on the electro-optic response of a GaP crystal to the passage of the electron beam is being developed which can provide information on the timing and longitudinal profile of the electron bunches without being invasive to downstream experiments.

This electro-optic sampling (EOS) device was commissioned and provided important insights for electron-laser beam timing with approximately 20 fs resolution. It was used to quantify the laser-ebeam timing jitter to the order of 50 fs and characterised a picosecond drift due to an issue with the RF lock between the injector laser and RF which is in the process of being repaired.

Next step is to install a second GaP crystal and use the diagnostic additionally as a beam position monitor.

Differential Pumping

The interaction area is required to contain gases at pressures of up to a few mbar and other equipment (such as motors) that are not compatible with the ultra-high vacuum requirements of the RF devices upstream, in particular the X-band TCAV located only 6 meters upstream. Vacuum tight 50 µm beryllium windows had been used in FACET to isolate the vacuum regions however the extreme beams of FACET-II create holes in intercepting materials, including the beryllium windows.

The differential pumping system consists of multiple 2000 L/s mag-lev turbopumps installed on either side of the interaction point, separated by conductance limiting apertures. There are four turbopumps installed on the beamline upstream of the interaction area and two turbopumps on the downstream side. Apertures will be installed in between stages of turbopumps in the final configuration of the system. This system will be capable of maintaining nTorr pressures at the location of TCAV with a static fill of 5 Torr helium gas in the plasma chamber at the IP.

The beryllium windows were installed for FACET-II's 2022 run and almost immediately sustained 100 µm holes from the beam intensity. The windows were left in place with beam-drilled holes and used in combination with the differential pumping system without the use of additional apertures to maintain adequate vacuum pressures on either side of the interaction region. This system was commissioned with up to 5 Torr helium gas or 2 Torr hydrogen gas in this state.

Gamma, Electron and Positron Diagnostics

After the interaction area, a magnetic spectrometer allows the beam to be deflected and imaged onto downstream screens according to the energy. The experiments at the interaction point have a common need to image the products of the interactions though the spectral range of interest and particle species may vary. The collaboration between experiments has lead to a large suite of downstream diagnostics covering a large energy range, detecting electrons, positrons and gammas [9].

The diagnostics were characterised as part of the 2022 experimental run using scattered beam through 1 mm aluminium.

FIRST SCIENCE USING EXTREME BEAMS IN INTERACTION AREA

PWFA Results in Helium and Hydrogen

Demonstration of a 10 GeV-gain PWFA stage with low emittance preservation and high efficiency will be done once the two-bunch mode of operation at FACET-II has been commissioned where a drive bunch and trailing bunch are optimised for beam-loading the plasma wake. With the currently commissioned single bunch at FACET-II, the initial goals for PWFA were to demonstrate depletion of energy in a single bunch indicating that the intense beam was suitable for driving a strong wake.

The initial first science of showing plasma formation and energy depletion of the drive beam to below 1 GeV was undertaken with helium during commissioning of the differential pumping system. During these tests, features of beam-plasma interactions were seen that require further investigation including signs of betatron oscillations and injected charge as shown in Fig. 5. Subsequent studies were performed with hydrogen which has a lower ionization energy. An approximately 2 metre long column of hydrogen plasma was produced. Trailing particles at the end of the electron bunch were detected to be accelerated to 13 GeV (Fig. 6). This demonstrates the FACET-II beam capabilities are there to ionize and drive a strong wake in both helium and hydrogen and to transfer a large portion of its energy into the wake.

Next steps will be to focus on preserving the quality of an accelerated beam by adding a second, trailing bunch.

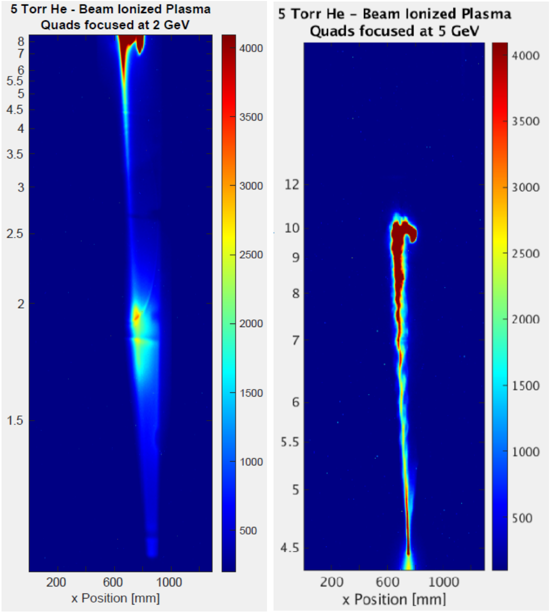

Figure 5: Initial plasma-beam interactions in 5 Torr helium. Interactions were seen that will be subject of future studies. Left: Possible injected charge from ambient plasma electrons accelerated up to 2 GeV. Right: Scalloping of beam due to betatron oscillations along the plasma.

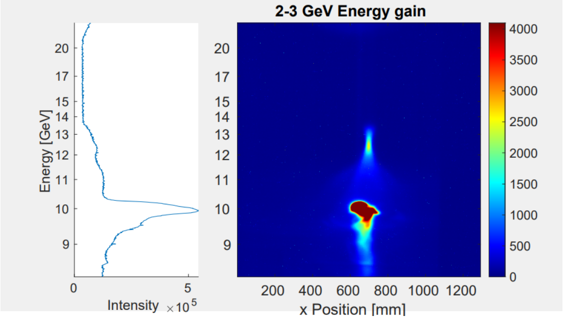

Figure 6: Electron energy gain from 10 GeV up to 13 GeV with 2 m-long hydrogen plasma

Plasma Lens Results

The goal of another experiment was to develop a hydrogen plasma lens [10]. A 2 cm long gas jet nozzle was pulsed with hydrogen gas at sub-atmospheric pressures within the integration chamber, positioned 2 mm away from the electron beam path. The hydrogen gas was pre-ionized by the main Ti:Sapph laser at 20 mJ, focused with an axilens. There were indications of beam focusing observed by viewing the beam size re-imaged in the spectrometer. The experiment demonstrates the working state of the gas-jet, laser-beam timing and alignment techniques plus downstream diagnostics.

The next stage of the program will be optimization followed by a broad investigation into the hydrogen lens as a focus assist for experiments that need sub µm, high density beams. The plasma lens could for example assist the hydrogen PWFA experiment by beam matching into the plasma. In PWFA, the transverse size of incoming beam needs to be correct such that the divergence due to the beam emittance is balanced by the attractive force due to ion focusing in the plasma. A mismatch causes betatron oscillations.

Beam Filamentation Results

The high beam and plasma densities at FACET-II provide the conditions for laboratory astrophysics experiments investigating relativistic electromagnetic plasma instabilities. The aim of these experiments is to demonstrate the filamentation of a highly relativistic charged particle beam in a high-density plasma, and measure the associated emission of a bright burst of gamma rays [11].

When increasing plasma density, one should observe a transition from blow-out to instability. Expected signatures include a sudden decrease of gamma-ray radiation. A first look at gamma diagnostics in the first FACET-II run indicates that a signal reduction at higher pressure might have been measured (Fig. 7) however more work needs to be done to prove an effect.

Strong Field QED Results

When exceeding the QED critical field $E_{crit} \sim 10^{16}$ V/cm, the vacuum becomes unstable to pair production and novel strong-field phenomena are expected to occur. This regime is referred to as the strong-field regime of QED. The equivalent laser intensities that are required to reach

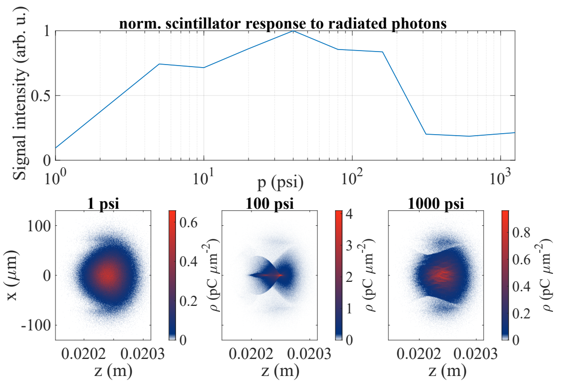

Figure 7: Scan of backing pressure to the hydrogen gas jet potentially showed a reduction in signal at gamma diagnostics at higher pressures.

this regime exceed 10^{29} W/cm^2 and cannot be achieved with existing or even currently envisioned laser systems. These extreme fields become however accessible when combining high-intensity laser pulses with ultra-relativistic electron beams due to the Lorentz boost. The E-320 collaboration aims to combine the FACET-II electron beam (10 – 13 GeV) with intense laser pulses ($a_0 \sim 1 - 10$) to access this regime of strong-field QED for the first time, and to perform precision measurements of the fundamental processes of pair production and photon emission from the perturbative to the non-perturbative regime.

The collaboration has worked with other experiment groups to improve the laser quality using a deformable mirror and focuses the main laser to micron-level spot size with an off-axis parabola. The laser and electron beam are overlapped both spatially and temporally with a YAG screen and using the timing from the EOS. Collisions between the photons and the electrons result in down-scattering through Compton scattering. In the current geometry, the spectrum of the down-scattered electrons is dominated by the first order (linear) process with a clear Compton edge at around 8 GeV (Fig. 8). The spectrum extends faintly to lower energies and indicates the emission of higher harmonics through non-linear Compton scattering.

Next measurements aim to increase the number of electrons that down-scatter through the non-linear process by improving the experimental conditions, e.g. by increasing the laser intensity and matching the size of the electron beam to the laser focus. Better signal levels and stable interaction parameters will enable systematic studies of the emission process at different laser intensities.

CONCLUSION

FACET-II's first user run in 2022 demonstrated the capabilities of the FACET-II facility and readiness of the experiment hardware and diagnostics for the scientific programme that lies ahead. Initial science results show that the FACET-II electron beam succeeds at field ionization and drives strong plasma wakes over metre-scale distances in hydrogen gas, enabling studies in future runs for single stage PWFA, injection and beam-plasma stability studies. In addition, the preliminary observations of a hydrogen lens, beam filamentation and non-linear Compton scattering will be followed up with optimization. Tools and virtual diagnostics using machine learning techniques show promise for future optimization and understanding of the FACET-II beam delivery, leading to improvement of the scientific output.

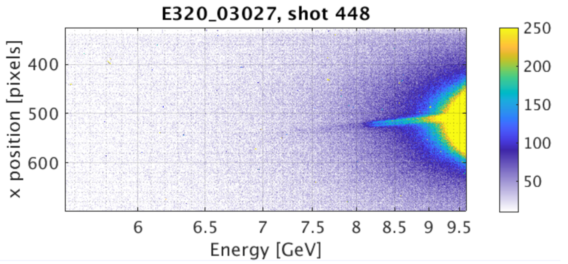

Figure 8: Electron energy loss from first and higher order Compton scattering (energy calibration preliminary). The main beam at 10 GeV is mostly out of the image. The scattered electrons can be seen down to approximately 7.5 GeV.

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