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STATUS AND FIRST RESULTS FROM FACET-II TOWARDS THE DEMONSTRATION OF PLASMA WAKEFIELD ACCELERATION, COHERENT RADIATION GENERATION, AND PROBING STRONG-FIELD QED*

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Abstract

FACET-II is a National User Facility at SLAC National Accelerator Laboratory with the goal to develop advanced acceleration and coherent radiation techniques using a 10 GeV electron beam of unprecedented beam intensity with >100 kA peak current and <10 μm spot size, a 10 TW experimental laser system, and a variety of solid, gas and plasma targets. A diverse experimental program will investigate beam-driven plasma wakefield acceleration (PWFA), injection, and control with the aim of demonstrating efficient multi-GeV/m PWFA while preserving emittance and narrow energy spread. Complimentary research programs into the application of machine learning for accelerator diagnostics and control, novel techniques for the generation of intense coherent radiation, and probing strong-field quantum electrodynamics also make use of the facility's unique beam intensity and laser capabilities. The first year of beam delivery to experiments has focused on user assisted commissioning of beam delivery and experimental systems, including a novel EOS BPM with 10 fs bunch length and 5 μm transverse resolution. This contribution will describe the status of the facility, experimental systems, and novel diagnostics, in addition to reviewing the first scientific developments from User programs including initial progress towards beam-driven PWFA.

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INTRODUCTION

The upgraded FACET-II accelerator provides uniquely high intensity, multi-GeV electron beams for the study of advanced acceleration and coherent radiation techniques. FACET-II uses the same experimental area as FACET, which ran from 2012-2016, with the addition of a new photocathode injector capable of producing single or double bunches with few μm emittance, a set of three bunch compressors capable of producing >100 kA beams, and a rebuilt final focus and experimental area to expand experimental capabilities [1, 2]. The design is compatible with a future upgrade to regain positron capabilities and allow for the simultaneous delivery of accelerated electron and positron bunches.

Delivery to users started in 2022 for user assisted commissioning of beam delivery and experimental systems. The key performance parameters of 2 nC, 10 GeV, and <20 μm emittance have been met, with regular delivery to users of beams with transverse spot sizes down to ~20×20 μm^2, and bunch lengths of ~20 μm in 2022. Further development will push the beam parameters to unprecedented intensity with spot sizes at the interaction point of <5 μm and bunch lengths down to 1 μm, reaching peak currents of >100 kA, and single and double bunch configurations as outlined in Table 1.

The unique beam properties made possible by the upgraded FACET-II facility allow for a wide spanning experimental program through the development of ultra-high brightness electron beams and their interaction with lasers, plasma, and solids. Strong collaboration between the various user programs has been necessary to allow for the execution

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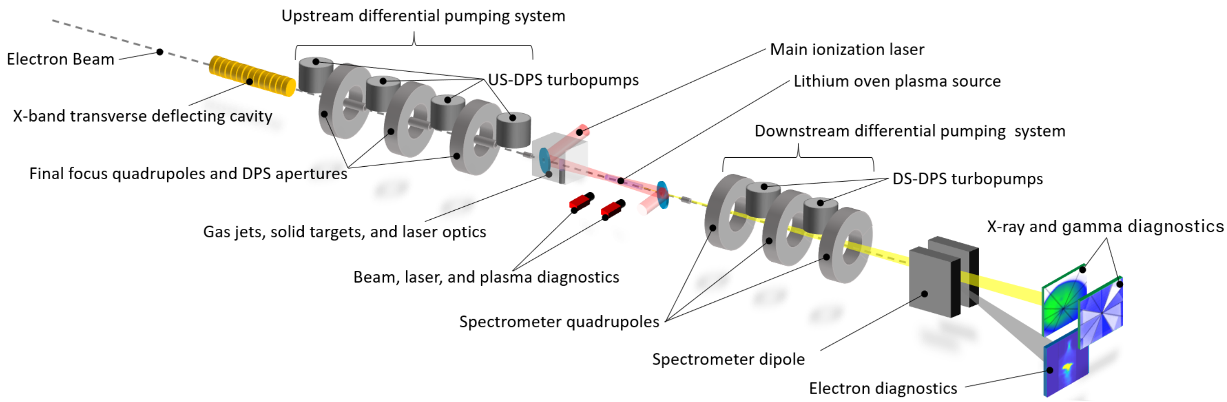

Figure 1: The FACET-II experimental area beamline showing the electron, laser, plasma, and diagnostics infrastructure.

Table 1: The currently achieved and design FACET-II electron beam parameters at the interaction point.

Beam Parameter	Current	Design range
Beam energy (GeV)	10	4 – 13.5
Charge per bunch (nC)	0.5 – 2	0.5 – 3
Repetition rate (Hz)	1 – 30	
Norm. emittance (μm)	~ 20	3 – 6
Spot size at IP (μm)	20	5 – 20
Min bunch length (μm)	20	1 – 100
Max peak current (kA)		10 – 200
Bunch configuration	Single	Single/Double

of multiple user programs simultaneously without major hardware reconfiguration between.

Experimental Area

After acceleration and compression through the ~1 km FACET-II linac, the beam is delivered to the experimental area, depicted in Fig. 1. A final focusing system consisting of two quadrupole triplets provides the final shaping and transverse control of the beam prior to the interaction point (IP). This is followed by a spectrometer beamline for characterizing the electron beams, as well as photons and positrons. An X-band transverse deflecting cavity (XTCAV) provides logitudinal diagnostics with ~1 μm/3 fs resolution.

The IP area contains a multipurpose vacuum chamber that contains gas jets, solid targets, and opto-mechanics to focus and maneuver the ionization and probe laser beams and the lithium plasma oven for beam-driven PWFA studies. The lithium oven produces a 40 cm long plasma with nominal density of 4×10^{16} cm^{-3} using 5 Torr helium buffer gas to contain the lithium vapour, while an alternate parallel beampipe can be filled with H_2, He, or Ar gas for the production of long plasmas of up to 5 Torr pressure. Gas jets deliver mm to cm-scale high density jets of H_2 or He, or a mixture of gasses up to 1200 psi pressure. A differential pumping system (DPS) installed on either side of the IP contains the experimental gases used for plasma studies without the use of solid windows in the beam path. The DPS consists of a series of turbopumps separated by conductance limiting apertures between them along the beamline. The beamline pressure is reduced by several orders of magnitude at each DPS stage, from up to 5 Torr at the IP, down to nTorr pressure a few meters upstream at the location of the XTCAV.

The IP area is serviced by a 10 TW, 800 nm Ti:sapphire laser that is split into a main high power line for plasma ionization and electron-laser collisions, and probe laser lines including EOS-BPM, shawdowgraphy probe, lithium oven plasma probe, and a transverse ionizer for ionizing the gas jets. A deformable mirror provides closed-loop wavefront optimization in the laser room and open-loop optimization in the tunnel to optimize spot size and intensity.

The EOS-BPM is a non-invasive tool for measuring both transverse and longitudinal beam positions on a shot-by-shot basis. This system has an ultimate timing resolution of 10 fs, and transverse resolution of <5 μm [3]. This system has been commissioned in single-crystal mode for longitudinal measurements, and the second crystal has been installed for EOS-BPM commissioning in the next experimental run.

FIRST RESULTS

Beam-Driven Plasma Wakefield Acceleration

A key goal of the FACET-II facility is to demonstrate the beam parameters required by a future linear collider in a single stage of beam-driven PWFA [4]. The first step is to demonstrate energy depletion from a single-bunch drive beam into a wake. Initial PWFA studies were performed by passing the beam through several meters of helium and hydrogen gas to investigate beam ionization, and for commissioning of the electron spectrometer and betatron diagnostics [5]. Beam ionization of the gas has been observed by viewing the plasma recombination light and the electron spectrum on the spectrometer diagnostics screens. Fig. 2(a) shows energy loss by the single bunch passing through a 3 m H_2 plasma, with electrons decelerated to down to <2 GeV. By configuring the spectrometer to view high energy electrons, a small amount of charge from the tail of the bunch can be seen to be accelerated by multi-GeV in Fig. 2(b).

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Further studies will investigate the dynamics of this beam-ionization, as the beam intensity at the measured beam properties were not expected to be sufficient for field ionization on its own. This indicates a high intensity substructure exists on the beam, such as microbunching as has been observed in the LCLS accelerator, and mitigated by the use of a laser heater [6]. FACET-II will begin commissioning a similar laser heater when it comes back online in 2023.

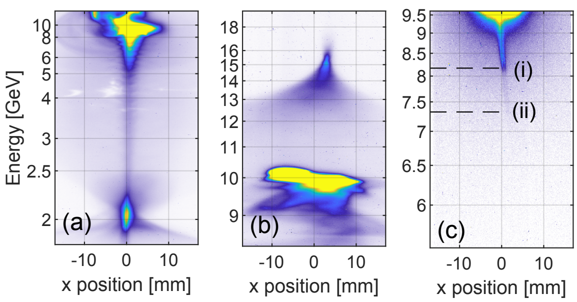

Figure 2: Images acquired on the electron spectrometer. Plots (a) and (b) show the energy lost and gained by an incoming 10 GeV beam by PWFA in m-scale H_2 gas plasma. Plot (c) shows non-linear Compton scattering in beam-laser collisions with (*i*) first and (*ii*) second harmonics visible.

Generation of Intense Coherent Radiation

The high beam intensity from FACET-II opens a new regime for generating intense gamma radiation through interactions with dense plasmas. One such experiment is investigating relativistic kinetic plasma instabilities in high density gas jets with plasma densities of 10^{18-20}cm^{-3}, and solids targets with density 10^{23-24}cm^{-3}. Initial studies focused on commissioning the experimental setup, including gas jet operation with the DPS, laser ionization and timing, development of a shadowgraphy probe for visualizing the plasma formation, and beam-based characterization of laser-generated plasma.

A second experiment aims to demonstrate the near-field coherent transition radiation (NF-CTR) self focusing effect. This occurs when short, high intensity bunches pass through a metallic foil and the induced fields can focus the electron beam to solid-densities (~10^{23} cm^{-3}) and generate an intense beam of coherent γ-rays [7]. Damage threshold studies have been undertaken to understand thermal effects on foils, and electron diagnostics commissioned to search for the NF-CTR effect. Next steps include improving the beam properties to drive stronger CTR fields, and the single foil has been replaced with a multi-foil stack to enhance the effect.

Machine Learning for Accelerator Applications

The extreme intensity beams provided by FACET-II are driving the need for the development of novel diagnostics that are non-intercepting and machine learning (ML) tools to provide both non-invasive diagnostics and ML based accelerator tuning [8]. An edge radiation based diagnostic is under development which images the interference pattern from synchrotron radiation emitted in adjacent bend magnets. The beam divergence, emittance, and energy spread can be continuously extracted from non-invasive, single-shot images at bend locations along the linac using ML tools. Hardware is currently implemented in the injector dog-leg and first bunch compressor bends, with a first demonstration of the single shot emittance diagnostic achieved.

ML tools for accelerator control are being developed using a combination of model-dependant and model-independent tuning approaches. Initial studies on injector emittance optimization and a Bayesian optimization of sextupole tuning to achieve smaller spot sizes at the IP have been carried out. Further development of these tools will allow for more predictable and stable beam delivery with improved performance, while also broadening the array of beam configurations available.

Probing Strong-field Quantum Electrodynamics

The facility's combination of electron and laser capabilities provides the opportunity to probe the strong-field regime of QED where the QED critical field is exceeded. By colliding the relativistic electron beam with high-intensity laser pulses with $a_0 = 1 - 10$, the laser intensity in the rest frame of the electron beam is boosted to ~ 10^{29} Watt/cm^2 allowing for precision measurements of the fundamental strong field QED processes in the perturbative and non-perturbative regimes [9–12]. Initial progress has focused on optimizing the spatial and temporal overlap between the electron and laser beams, and using the deformable mirror to optimize laser spot size. A clear indication of non-linear Compton scattering has been observed on the electron spectrometer, shown in Fig. 2(c). With the current parameters, the quantum parameter χ ~ 0.1, which is already within the quantum regime. Continued improvements to both the electron and laser parameters, as well as diagnostics will transition from probing the perturbative to non-perturbative regimes.

CONCLUSION

The first beam delivery to Users of the FACET-II National User Facility in 2022 allowed for development of experimental hardware and diagnostics commissioning. The first plasma interactions were generated in both high density gas jets and long H_2 and He plasmas. Electron and photon spectrometer diagnostics have been commissioned to cover a broad range of user needs, and novel virtual diagnostics and ML tools are being developed. Additionally, the first Compton interactions have been observed in the direction of probing strong field QED. Further development of both electron and laser beam properties will continue to advance the facility's capability for critical research in advanced acceleration techniques, ultra-high brightness beams, novel radiation sources, and more.

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