A DESIGN FOR 10 GeV, HIGH PEAK-CURRENT, TIGHTLY FOCUSED ELECTRON BEAMS AT FACET-II*

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Abstract

FACET-II will be a new test facility, starting construction in 2018 within the main SLAC Linac. Its purpose is to build on the decades-long experience developed conducting accelerator R&D at SLAC in the areas of advanced acceleration and coherent radiation techniques with high-energy electron and positron beams. The design consists of a 135-MeV high-brightness photo-injector constructed in an off-axis injection line in Sector 10 of the SLAC Linac, two new 4-bend chicane bunch compressors installed in Sectors 11 and 14, with a third compression stage provided by the existing FACET "W Chicane" in Sector 20. We develop a design to deliver peak currents more than 160 kA to the Sector 20 interaction region at 10 GeV, with 10 µm-rad emittances at 2 nC bunch charge and 1.4 % rms energy spread. The Sector 20 bunch compressor is re-designed for maximum peak current throughput and minimal emittance degradation via CSR, and the FACET-II compression scheme is optimized. We present 6D start-end beam tracking simulations using Lucretia including ISR, CSR, wakefields and space charge effects.

FACET-II OVERVIEW

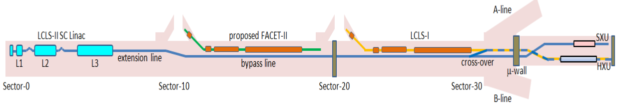

Figure 1: Location of FACET-II in SLAC Linac.

The FACET-II accelerator complex is to be installed in the central 1 km of the main SLAC Linac, between Sectors 10 and 20 as depicted in the schematic in Fig. 1 (located between LCLS-II and existing LCLS accelerators).

In this paper, we first describe the baseline design of the FACET-II accelerator and explore its capabilities through tracking simulations. More details of the baseline design of the FACET-II facility can be found in the FACET-II technical design report [1].

Finally, we discuss a potential upgrade involving a refit of the bunch compressor in Sector 20. This would allow for substantially increased peak current delivery to the Sector 20 experimental area.

BASELINE DESIGN

Design Overview

To achieve the scientific goals of the experimental program at FACET-II, a high peak-current bunch with small transverse emittance at the end of the Linac ($\gamma\varepsilon<20$ µm-rad) and 20 µm rms bunch length at the experimental region in Sector 20 is required. FACET-II will operate with electron bunches at a design energy of 10 GeV. The most challenging parameters for the design of the bunch compression scheme are given by the plasma wakefield acceleration (PWFA) experiments which benefit from peak currents more than 10 kA. The RF photocathode electron gun and injection system is like that used in LCLS. Our injector can produce up to 5 nC, with bunch lengths in the range 2-10 ps, with corresponding peak currents of up to 300 A and transverse emittances of <5µm-rad.

From the injector, 135 MeV electrons undergo three stages of bunch compression: the first two stages in Linac Sectors 11 and 14 and the final compression stage in Sector 20. Acceleration and energy chirp required by the bunch compression are provided by the existing s-band Linac inherited from SLC. The Linac is split into 3 main sections referenced as “L1”, “L2” and “L3”, with new bunch compressor 4-bend chicanes installed between these sections as depicted in Fig. 2.

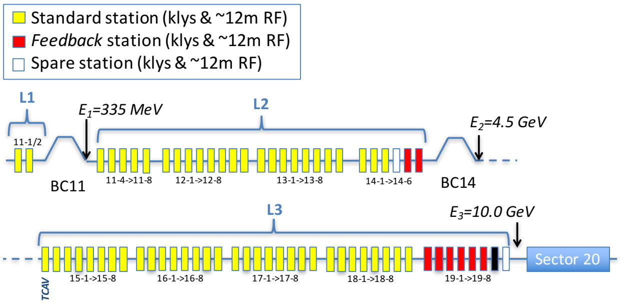

Figure 2: Configuration of Linac and bunch compressors in the main SLAC Linac.

The capabilities of FACET-II vary in a non-trivial way depending on the choice of initial charge from the RF gun. The baseline design is described below, where Fig. 3 depicts a range of compression configurations available for a 2 nC bunch from the gun.

The bunch compression is accomplished by a series of magnetic chicanes arranged and located such that nonlinearities in the compression and acceleration process (longitudinal wakefields, RF curvature, and second order momentum compaction) are all approximately compensated. The goal for the Linac design is to achieve the final bunch length requirements while minimizing sensitivities to RF phase and amplitude variations and to bunch charge variations.

The electron energy at the first compressor is 335 MeV. This choice avoids space charge effects, while the bunch compression is still early enough in the Linac to ease the effects of transverse wakefields. In the first compressor (BC11), the electron bunch length is reduced from 0.85 mm to 468 µm (rms).

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The second compressor (BC14, in Sector 14) compresses the electron beam down to a 96 µm rms bunch length. The energy of the second compressor, 4.5 GeV, is chosen as a balance between the conflicting requirements of emittance dilution due to synchrotron radiation, and the need to minimize energy spread when including the final compression stage in sector 20. The design of the compressors is also affected by the need to reduce CSR effects, which are most pronounced for short bunches. The most significant effect of CSR is to generate a time-dependent energy variation along the bunch. Designs utilizing relatively weak chicanes and larger initial correlated energy spreads for the various compression stages help control the effect CSR has on transverse emittance dilution. The largest single source of emittance dilution is within the Sector 20 bunch compressor. The need to keep the peak current as low as possible (~< 3 kA) at the entrance to Sector 20 whilst still compressing to <20 µm bunch lengths drives the overall compression scheme design.

A summary of the design beam parameters, verified by particle tracking codes (see below), is presented in Table 1 below.

Table 1: Key electron beam parameters for FACET-II. Required and Design beam parameters are shown, also typical operating range capabilities.

Parameter	Sym	Unit	Req	Des	Range
Final energy	E_f	GeV	10.0	10.0	4.0 – 13.5
Bunch charge	Q_0	nC	2	2	0.7 – 5
Pulse rep. rate	f_{rep}	Hz	1	30	1 - 30
N bunches per RF pulse	N_b	-	1	1	1 - 2
Emittance into Sector 20	$\gamma\varepsilon_{x,y}$	µm-rad	<20	4.4,3.2	3-6
Final rms Spot size	$\sigma_{x,y}$	µm	<20	18,12	6-20
Final peak current	I_{pk}	kA	>10	72	10-130
Final rms bunch length	σ_z	µm	<20	1.8	1.5 - 20
Final rms energy spread	$\sigma E/E$	%	-	1.4	0.4 – 1.6

Particle Tracking

6D tracking simulations have been made to model the beam transport through the FACET-II complex, including the non-linear compression and final beam focus process. The simulations include the effects of longitudinal wakefields in the 1 km linac as well as incoherent and coherent synchrotron radiation effects in the various bending magnets. Longitudinal space charge effects are also simulated. Simulations are performed using the tracking code Lucretia [2]. Simulations have also been made which calculate emittance dilution in the Linac due to transverse wakefields and anomalous momentum dispersion, each of which arises from a variety of considered error sources such as component misalignment and magnetic field errors. Diagnostics, correction techniques, and feedback systems have also been incorporated into the design.

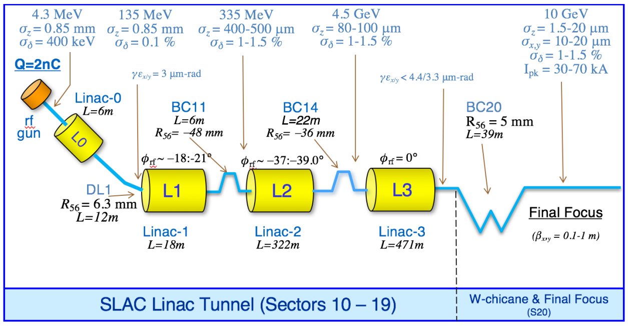

Figure 3: Schematic representation of the FACET-II electron beamlines showing key beam parameters throughout, as obtained from particle tracking simulations.

Results from particle tracking simulations are summarized in Figs. 3-5 below. The evolution of the longitudinal phase space can be seen in Fig. 4. Note the compression configuration of the Sector 20 chicane is opposite to the BC11 and BC14 chicanes (+ve R_{56}). This allows us to take advantage of the additional chirp imparted to the beam in the L3 Linac. As can be seen from the final tracked bunch distributions shown in Fig. 5, the proposed design delivers the required beam parameters. Large tails are present in the final beam due to the necessarily high energy spread and non-linear compression terms. Mostly, experiments care about the core of the beam however, and the tails can also be trimmed using collimators in the BC11, BC14 and BC20 bunch compression chicanes.

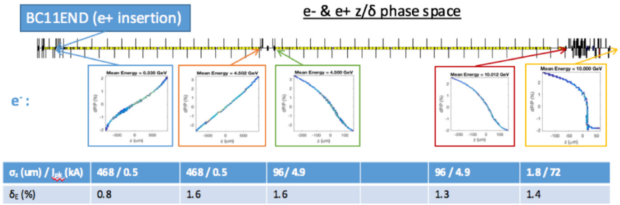

Figure 4: Longitudinal phase space of tracked particles throughout FACET-II bunch compression system.

Monte Carlo Error Analysis

Table 2: Beam parameters at the entrance to Sector 20 and at the Sector 20 experimental waist interaction point (IP) including spread from simulated error sources.

Parameter	Design Req.	Simulation
ε_x (µm-rad) [S19]	<20	4.4 +/- 0.5
ε_y (µm-rad) [S19]	<20	3.3 +/- 0.1
σ_z (µm) [IP]	<20	3.1 +/- 1.5
I_{pk} (kA) [IP]	>10	64 +/- 16

The sensitivity of the beamline complex to various jitter sources was studied. A Monte Carlo simulation was performed using 100 random error seeds including the following effects: Initial charge, position and timing jitter; phase and amplitude jitter in klystrons driving accelerating structures in L1-L3; magnet vibration. Magnitude of errors were derived from experience operating FACET and LCLS. The mean and rms range of beam parameters calculated are presented in Table 2.

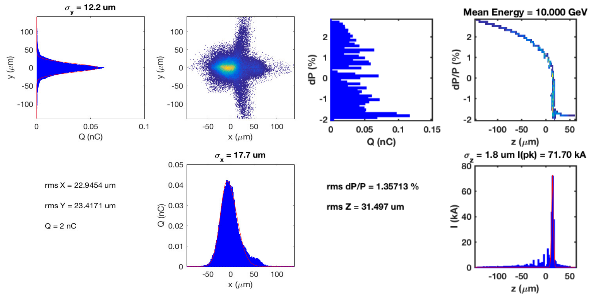

Figure 5: Transverse (left) and longitudinal (right) phase space of tracked particle beam at Sector 20 final focus waist.

SECTOR 20 UPGRADE OPTION

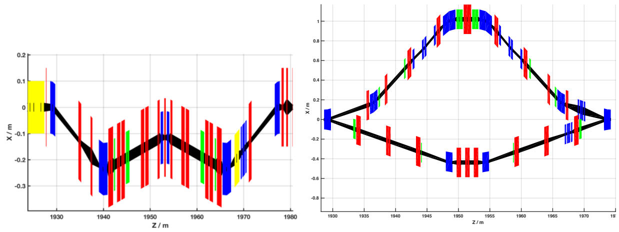

Figure 6 (a): Existing BC20E electron compression chicane (left). (b) Redesigned BC20 (right). Quadrupole magnets are shown in red, bends are blue, sextupoles are green, RF structures shown in Yellow. The redesigned optics includes an additional chicane arm to simultaneously transport positrons.

When compressing the electron bunch length <20μm, the final bunch compression system in Sector 20 becomes a limiting factor for beam quality due to emittance growth through CSR. We summarize here a simplified design for BC20E (Fig. 6b) which demonstrates greatly improved emittance preservation at high bunch compression in particle tracking simulations. To allow for the option of simultaneous delivery of electrons and positrons to the Sector 20 interaction region, a positron arm (BC20P) is also included in the re-designed optics but not discussed further here.

The optics re-design for BC20E needs to meet multiple requirements:

Pass a high peak current beam (>100 kA) or act as the final compression stage in generating a high peak current beam. The compression factor (R_{56}) should be tuneable in the range [0,+5] mm.

Minimize transverse emittance growth due to CSR at high peak compression ($\Delta\varepsilon < 5$ μm-rad).

Correct for chromaticity and second-order dispersion due to compression chicane and final focus magnets.

A "double dogleg" arrangement was chosen for BC20E as shown in Fig. 7. This configuration uses fewer bending magnets compared with the previous design and avoids over-compression in the center of the chicane. This improves CSR emittance degradation when transporting a high peak-current electron beam. The trade-off is reduced R_{56} tuneability (0:+5 mm vs. -10:+10 mm), however this is considered an acceptable range for all planned FACET-II experiments. Low betatron function amplitudes are maintained in the chicane (∼<100m) which was found to be important during FACET operations to minimize beam loss and aid in delivering stable and reproducible low-emittance beams to the interaction region. Two pairs of sextupole magnets are included for chromaticity and second-order dispersion compensation. A collimator is included downstream of the first quadrupole magnet for bunch shaping and 2-bunch "notch beam" configurations as used at FACET. A wiggler is included upstream of the final quadrupole in conjunction with a YAG screen for use as an energy spectrum monitor, again as used in FACET.

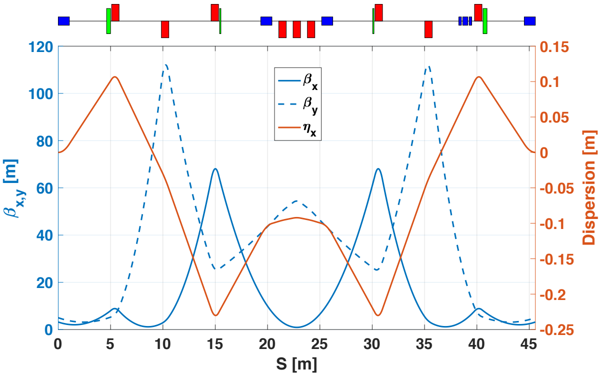

Figure 7: Lattice functions for re-designed Sector 20 electron bunch compression system.

A start-to-end 6D particle tracking simulation exists for the baseline design of FACET-II. The Sector 20 optics were replaced with the new design and the peak compression optimized using the phase of the L2 acceleration section. The longitudinal and transverse tracked phase spaces at the interaction point are shown in Fig. 8. The tracking simulation includes all physics effects described earlier. With these new optics, a peak compression of 176 kA was achieved with a final transverse emittance of 7 μm-rad. This should be compared with a maximum peak current of 76 kA and transverse emittance of 13 μm-rad for the baseline Sector 20 design (each with an initial transverse emittance of 3 μm-rad from the injector).

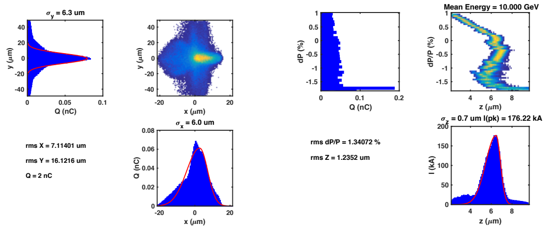

Figure 8: Longitudinal (left) and transverse (right) tracked particle distributions at the IP for Sector 20 redesign.

REFERENCES

[1] FACET-II Technical Design Report, SLAC-R-1072
[2] http://www.slac.stanford.edu/accel/ilc/codes/Lucretia/