FACET EMITTANCE GROWTH*

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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. The FACET beamline consists of a chicane and final focus system to compress the 23 GeV, 3.2 nC electron bunches to $\sim$20 μm long and $\sim$10 μm wide. Simulations of the FACET beamline indicate the short-duration and large, 1.5% rms energy spread beams may suffer a factor of four emittance growth from a combination of chromaticity, incoherent synchrotron radiation (ISR), and coherent synchrotron radiation (CSR). Emittance growth is directly correlated to head erosion in plasma wakefield acceleration and is a limiting factor in single stage performance. Studies of the geometric, CSR, and ISR components are presented. Numerical calculation of the rms emittance can be overwhelmed by long tails in the simulated phase space distributions; more useful definitions of emittance are given. A complete simulation of the beamline is presented as well, which agrees with design specifications.

INTRODUCTION

FACET Design

The Facility for Advanced Accelerator and Experimental Tests (FACET) is a new facility being constructed in sector 20 of the SLAC linac. One of the immediate applications of FACET will be plasma wakefield acceleration (PWFA) in a two bunch drive-witness configuration which is expected to increase witness bunch energy by a factor of two or greater. The beamline is composed of a chicane and final focus system which will compress 23 GeV, 3.2 nC electron bunches to $\sim$20 μm long and $\sim$10 μm wide [1].

Table 1: Typical Simulation Parameters for the FACET Beamline

Simulated FACET Parameters	
Final Energy	23.3 GeV
Charge per bunch	3.24 nC
Transverse spot size (IP)	10 μm
RMS Energy Spread	1.5%
Sec. 20 Entrance Norm. ϵ_x	90.0 mm-mrad
Sec. 20 Entrance Norm. ϵ_y	4.09 mm-mrad

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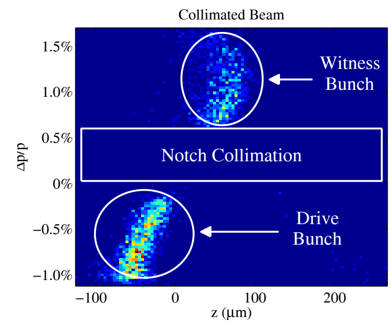

Figure 1: Longitudinal phase space at the IP, 10 mm R_{56}, with momentum tail and notch collimation. Drive bunch (z std. dev. 23 μm) is at left with lower energy, the witness bunch (z std. dev. 18 μm) at right with higher energy. Bunch separation is 120 μm, with a charge ratio of 1.6.

Emittance Growth

Preserving transverse emittance of the beam is desirable. Transverse beam emittance has been shown to be directly correlated to head erosion in PWFA [2]. In the drive-witness bunch PWFA configuration, the drive bunch both ionizes the plasma and creates the wakefield. It takes a finite time to create the ion column which focuses the majority of the bunch. The unfocused head diverges and the ionization front moves backwards, reducing coupling to the witness bunch [3].

In order to manage transverse emittance at the interaction point (IP), geometric and radiative contributions to emittance growth must be understood. Geometric emittance growth occurs due to the large energy spread of the beam. It is difficult to compensate for the large 1.5% energy spread which results in incorrect focusing in quadrupoles. Incoherent synchrotron radiation (ISR) and coherent synchrotron radiation (CSR) also contribute to emittance growth throughout the beamline. These radiative processes, caused by high beam current in bends, can cause significant phase space filamentation and thus emittance growth [4]. Nominal longitudinal compression with an R_{56} of 4 mm results in a maximally compressed bunch at the IP, while PWFA calls for over-compression with R_{56} of 10 mm; both cases can cause significant current in bends. In addition, the integrated momentum compaction over the entire chicane is large, which contributes to emittance growth [4].

Core Emittance Definition

Simulations of the FACET beam show long tails in transverse phase space (Fig. 2). While the tail densities are too

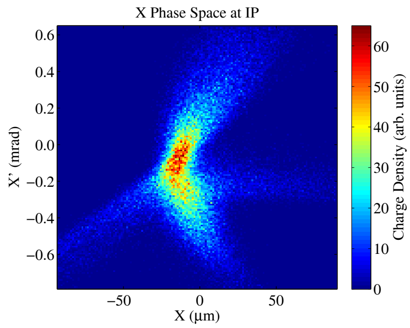

Figure 2: Tails in x phase space at the IP (not including notch collimation). Note the elliptical core of the beam.

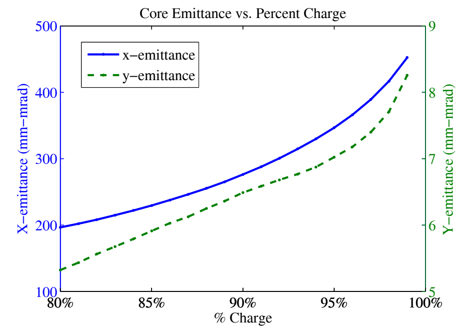

Figure 3: The large growth at higher percentage indicates inclusion of halo particles. 95% beam charge represents the core emittance without this large growth.

low to contribute to the plasma wake, they can significantly affect the numerically-calculated transverse emittance. It is necessary to introduce a four-dimensional transverse emittance measurement of the core of the beam. The 4-D emittance must be physically measurable, as it will be one of the parameters used to commission the beam.

In order to treat each transverse plane democratically, the definition of the 2-D rms emittance can be extended to four dimensions, assuming no correlation between the x and y planes:

$$\begin{aligned}\epsilon^2_{\mathrm{rms,4D}} &\equiv (\sigma_x^2\sigma_{x'}^2 - \sigma_{xx'}^2)(\sigma_y^2\sigma_{y'}^2 - \sigma_{yy'}^2) \\ &= \epsilon_x^2\epsilon_y^2 \end{aligned} \tag{1}$$

which corresponds to an ellipsoid with a contour of:

$$\begin{aligned}K =&\frac{1}{\epsilon_x}\left(\gamma_x x^2 + 2\alpha_x x x' + \beta_x x'^2\right) \\ &+ \frac{1}{\epsilon_y}\left(\gamma_y y^2 + 2\alpha_y y y' + \beta_x y'^2\right)\end{aligned} \tag{2}$$

The factors $\beta_{x/y}$, $\alpha_{x/y}$, and $\gamma_{x/y} = (1 + \alpha_{x/y}^2)/\beta_{x/y}$ are the Courant-Snyder parameters of the beamline as propagated from the north damping ring through the linac, while $\epsilon_{x/y}$ accounts for the emittance.

Although it is possible to fit the 4-D ellipse to the beam in phase space, it is unnecessary and can be misleading as the first-order transport is the best description of the beam core.

The core emittance can then be defined by the typical rms emittance of 95% of the charge that lies within a 4-D ellipsoid of the shape given by equation 2. The percentage is arbitrary (see Fig. 3); however, removing 5% of the beam charge which corresponds primarily to its halo should not affect the plasma simulation significantly.

EXPERIMENTAL SETUP

FACET Beamline

The FACET beamline includes a damping ring which feeds 3.2 nC bunches into the linac via an arc which compresses the bunch. Accelerating structures are used to increase bunch energy and shape longitudinal phase space. Prior to sector 20, RF introduces a correlation in longitudinal phase space, while R_{56} from the sector 10 chicane, further compresses the bunch. The 6-bend W-chicane in sector 20 compresses the bunch to give the desired momentum-time correlation at the IP. A collimator is placed after the first bend of the chicane. At this location, dispersion causes momentum to be well correlated in the x plane. Collimation separates the bunch into two bunches of differing momentum (Fig. 1). The W-chicane over-compresses the longitudinal phase space to separate the two bunches in time, resulting in a drive and witness bunch. Final focus optics match the beam into the experimental area. The design allows for significant flexibility in the form of overall compression of the beam, currently from an R_{56} of 2 mm representing under-compression, to the over-compressed case of 10 mm [5]. (See Fig. 4.)

In order to make a clearer experimental measurement of PWFA, it is desirable to create a witness bunch with greater energy than its drive bunch. In an energy spectrometer measurement, the drive and witness bunch will then separate from each other instead of moving together. Adjusting the beamline chicane to an R_{56} of 10 mm results in an over-compressed case, exchanging the drive bunch with the witness bunch. The drive bunch is adjusted to have more charge than the witness bunch in order to access nonlinear plasma dynamics, which include benefits such as emittance blowup reduction, increased oscillation wavelength, and greater tolerance on driving bunch density [6].

Simulation

Elegant [7], a 6-D particle tracking and simulation code, is used to simulate the beamline from the north damping ring to the interaction point. At the moment, due to historical reasons, there is slight residual dispersion of 12.7 mm at the model transition from the arc to the linac, which is removed with an artificial first-order matrix transform. Collimation in the W-chicane can be simulated with Matlab or shower [8], a wrapper for EGS4 [9].

In order to determine the respective emittance contributions of the beam energy spread, ISR, and CSR, each effect is activated within the simulation individually.

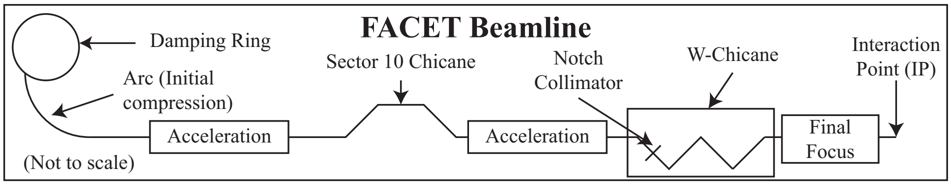

Figure 4: The FACET beamline, from damping ring to interaction point.

SIMULATION RESULTS

Simulated x-y core emittances are 314 mm-mrad and 6.92 mm-mrad. Collimation at this R_{56} yields bunch separation of $\sim$120 μm, bunch length σ_z from a bi-modal Gaussian fit of 23 μm for the drive bunch and 18 μm for the witness bunch, and driver-to-witness charge ratio of $\sim$1.6 in the 10 mm R_{56} case. An R_{56} of 4 mm has corresponding core emittances of 263 mm-mrad and 15.4 mm-mrad. (Table 2.) Simulated quadrupole scans show similar measurements for both cases, supporting the 4-D 95% method of understanding emittance. The 95% emittance calculations are significantly lower and show that a large contribution to the emittance is in the form of tails in the distribution.

CONCLUSIONS

Emittance growth in FACET is mostly due to bunch energy spread. A complete simulation including the plasma wakefield [10] will allow for optimization to reduce head erosion. Over-compression in the final chicane can create two distinct bunches appropriately separated and with good charge ratios, and allow for simpler energy measurements. A pre-ionized plasma [10] with a drive and witness bunch could reduce dependence on low emittance and will be examined.

This full beamline simulation will now allow the study of several effects revolving around the stability of the beamline. Sensitivity to RF jitter and amplitude can be examined, as well as magnet strength and misalignments can also be studied to determine how precisely tuned the beamline will need to be. A complete simulation will be useful to the simulation of a transverse deflecting cavity used to measure the time structure of bunches [11]. The detail retained by a full simulation can show in more detail the resolution of the deflecting cavity.

Including plasma simulation at the IP will enable beamline optimization for PWFA. Two-bunch PWFA can be simulated in detail, giving further insight into dynamics involving bunch separation, emittance, and charge ratio. Simulation of a ramped bunch profile shows promise in achieving transformer ratios larger than 2 [12] and can be studied more completely when included with plasma simulation.

Table 2: Emittances given are normalized and corrected for dispersion. 95% emittances are calculated as defined.

Emittance at IP for 10-mm R_{56} (mm-mrad)				
Effects	$\epsilon_{x,nc}$	$\epsilon_{x,nc}$, 95%	$\epsilon_{y,nc}$	$\epsilon_{y,nc}$, 95%
$\Delta p/p$=0, no sext.	93.0	85.0	4.11	3.43
Geometric	423	281	10.5	6.86
Geom, ISR,	450	307	10.5	6.87
Geom, ISR and CSR	464	314	10.4	6.92
Emittance at IP for 4-mm R_{56} (mm-mrad)				
Effects	$\epsilon_{x,nc}$	$\epsilon_{x,nc}$, 95%	$\epsilon_{y,nc}$	$\epsilon_{y,nc}$, 95%
$\Delta p/p$=0, no sext.	95.5	87.3	4.13	3.44
Geometric	335	244	26.9	15.5
Geom, ISR	352	264	26.9	15.3
Geom, ISR, and CSR	348	263	26.9	15.4

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