OPTIMIZATION STUDIES FOR THE ADVANCED PHOTOINJECTOR EXPERIMENT (APEX)*

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Abstract

The Advanced Photoinjector Experiment (APEX) seeks to validate the design of a proposed high-brightness, normal conducting RF photoinjector gun and bunching cavity feeding a superconducting RF linac to produce nC-scale electron bunches with sub-micron normalized emittances at MHz-scale repetition rates. The beamline design seeks to optimize the slice averaged 6D brightness of the beam prior to injection into a high gradient linac for further manipulation and delivery to an FEL undulator. Details of the proposed beamline layout and electron beam dynamics studies are presented.

INTRODUCTION

The Berkeley Light Source [1] has been proposed as a next generation, high-repetition rate VUV Free Electron Laser based on SASE, Enhanced SASE, and seeded, harmonic generation techniques. The front end of the electron beam driver is a high-repetition rate (~1MHz or higher), high-brightness photoinjector. This beam is then fed into a SCRF linac system for acceleration up to 1-2 GeV and injection into the FEL beamlines.

A very basic set of design parameters for the drive beam at the injector exit are known at this point. The slice averaged RMS normalized beam emittance must be lower than ~0.8mm-mrad, beam energy needs to be high enough to neglect space charge effects, the beam needs to carry ~60A peak current and ~500pC bunch charge. The bunch energy spread should be small enough to allow for seeded, harmonic generation but large enough to damp the severe longitudinal instabilities in linac and high energy bunch compressor systems. This puts the required energy spread between ~100eV and ~1.5keV.

Injector Components and Modeling

The photoinjector is designed around some novel and some recent standard elements. A novel 750keV VHF electron gun [2] has been designed recently to provide a high accelerating gradient ov the electron bunch length, CW operation, and ultra-high vacuum for engineered photocathodes. A ~1MHz drive laser provides for high repetition-rate bunch production as well as longitudinal and transverse pulse shaping. A 650MHz bunching cavity impresses a longitudinal velocity chirp on the beam which then compresses to produce the required peak current. Pre-booster, booster, and injector linac structures are used to provide acceleration to ~100MeV, transverse focusing, and to complete emittance compensation. Solenoid magnets are used for beam transport between rf structures. All simulations are performed using the azimuthally-symmetric ASTRA code [3].

The particle emission model is handled internally within ASTRA. A simple longitudinal flat-top model is used with a nominal 30ps (rms) duration. A hard-edged, spatially uniform transverse distribution is also used, with a nominal 2mm spot diameter. The transverse momentum distribution is Gaussian. The rms transverse normalized emittance assumes a slightly optimistic measure of 0.5mm-mrad/mm radius (rms). Hence, a 0.25mm-mrad emittance corresponds to a 0.5mm rms radius. The initial beam energy is 10eV with 25meV rms spread.

ISSUES IN BEAM EVOLUTION AND INJECTOR DESIGN

A schematic of the beamline is shown in Figure 1. The design of the beamline has been guided by two competing principles. The first is to provide complete emittance compensation and the second is to generate a useful longitudinally compressed bunch.

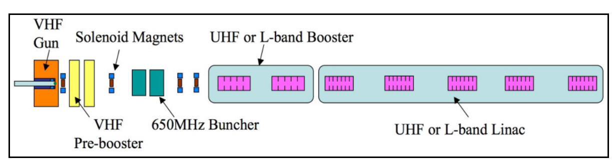

Figure 1. Schematic of APEX beamline.

Emittance growth in electron accelerators has many sources. The important ones for APEX include variations in focusing between longitudinal slices due to chromatic aberrations and varying transverse space charge forces, radial plasma oscillations in high current slices, and mismatch to transport channels. Emittance compensation is the well-established technique used to remove slice-by-slice variations in the transverse phase space that lead to increased normalized projected emittance over the entire bunch. For linear variations in slice current, it can be shown to be an exact compensation technique [4].

Longitudinal compression is necessary to balance the requirements of high peak current in the main linacs with producing high brightness beams from the

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photocathode and electron gun. Ballistic (velocity) bunching methods at low beam energy (< 1MeV) can be staged with a buncher cavity and a short drift length. However, this technique in its simplest form does not permit both longitudinal compression and preserving the uniform longitudinal current profile. Space charge blowout at the low energy creates tails in the distribution. Phasing the buncher cavity can sharpen or tweak the distribution, but not remove the tails. As a result, the longitudinal current profile becomes sharply peaked before the beam is accelerated further. The highly nonlinear variation in slice current then confounds the emittance compensation process.

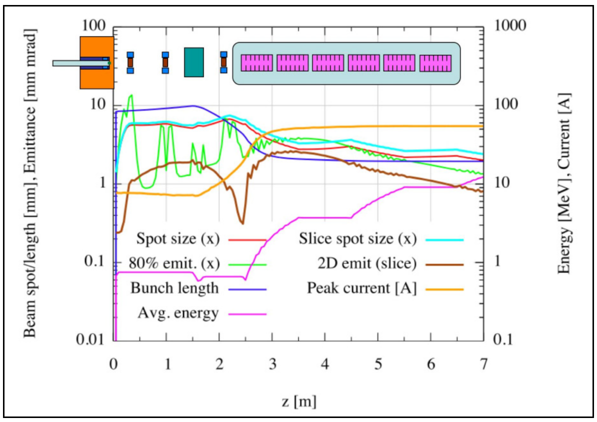

Figure 2. APEX injector front end and beam parameters. (Case 2)

Front End Matching and Beam Evolution

The front-end of the injector (in one case) and the evolution in beam parameters is shown in Figure 2. The beam exits the VHF gun, is focused by solenoid magnets into a 650MHz buncher cavity, drifts and longitudinally compresses until it reaches the entrance of the linac structure. The optimized design displays the emittance oscillations expected at low energy, while the peak beam current rises through bunch compression to its final value. The remainder of the injector is shown in Figure 3, where the beam reaches a final energy of ~81MeV.

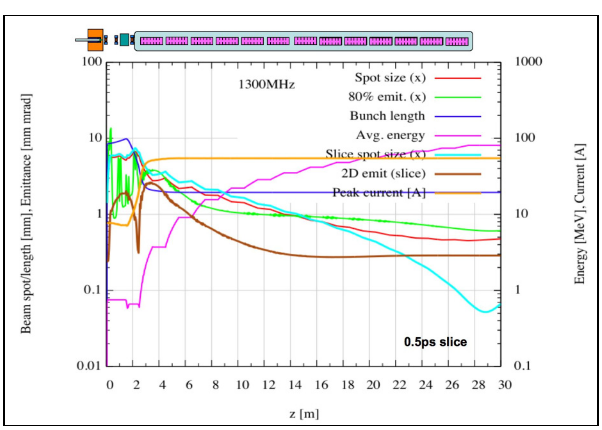

Figure 3. APEX injector beam parameters. (Case 2)

CASE STUDIES

The design presented so far represents a single, optimized point design. Five optimized point designs have been developed to study pathways for improving the final beam quality. Cases 1 and 2 are the nominal cases where the linac frequency is either 650MHz (Case 1) or 1300MHz (Case 2). Case 3 attempts to improve the longitudinal distribution by decreasing the laser pulse duration, increasing the laser spot size, adding additional acceleration between the gun and the buncher, adding an additional buncher cavity, and running the linac at very high gradients (25MV/m) without ramping. Case 4 expands on Case 3 by adding another pre-booster cavity, and then adding booster linacs before the main injector linac, which are run at high gradient. Case 5 slightly increases the laser pulse length from Cases 3-4, while substantially reducing the laser spot size on cathode. Case 5 also allows the linac gradients in the booster and injector linac sections to monotonically increase.

The slice current variation at the injector exit is shown in Figure 4. Of note is the small shift in position of the peak current slice in Cases 2 and 5. In all cases the peak current lies between 55A and 65A.

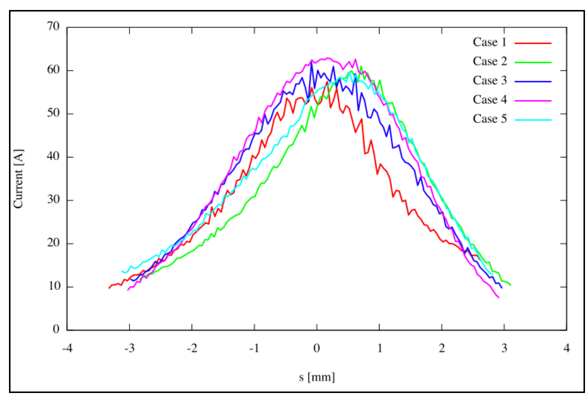

Figure 4. Slice current variation.

The variation in slice emittances for the five Cases shows more variation in Figure 5. In Case 2, the 1300MHz linac has a ramped gradient profile, while Case 5 has both a 650MHz booster and 1300MHz linac

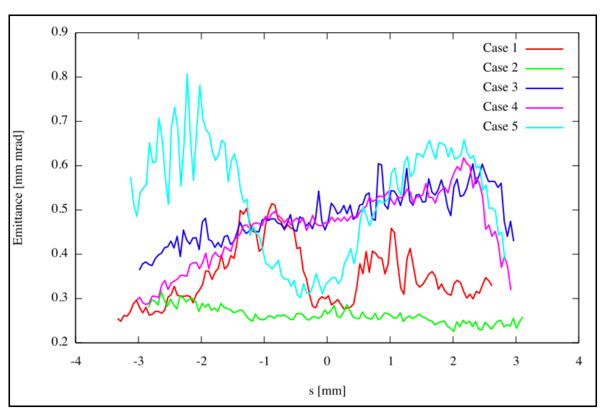

Figure 5. Slice emittance variation.

with ramped gradient profiles. Case 1 has a ramped 650MHz linac. Cases 3 and 4 have unramped, high-gradient linacs. Mismatch and overfocusing away from the current peak in the 650MHz boosters and linacs tends to drive those slices into wavebreaking and prematurely ending the emittance oscillation before complete emittance compensation can occur for all slices.

The variation in 4D slice brightness is shown in Figure 6. We define the 4D brightness as

$$B_{4D} = \frac{I_{slice}}{\varepsilon_{nx}\varepsilon_{ny}}. \quad (1)$$

The inverse-square dependence on the emittance readily shows itself for Cases 1, 2, and 5.

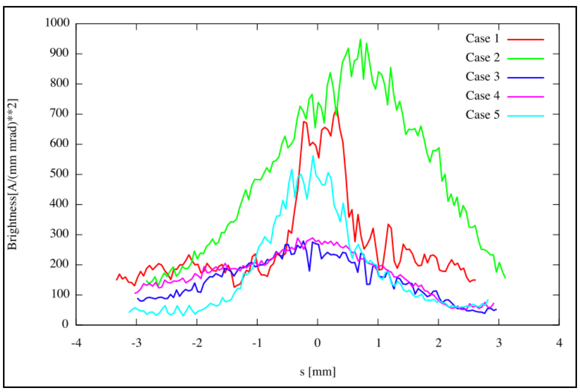

Figure 6. Slice 4D brightness variation.

The slice energy spread variation is shown in Figure 7, and is calculated after first removing the average slice energy.

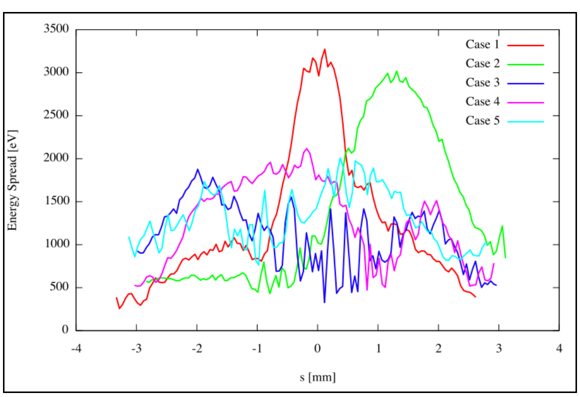

Figure 7. Slice energy spread variation.

The variation in slice 6D brightness is shown in Figure 8. We define the 6D brightness as

$$B_{6D} = \frac{I_{slice}}{\varepsilon_{nx}\varepsilon_{ny}\sigma_E}. \quad (2)$$

Here the combination of low slice emittance and low slice energy spread produce a dramatic variation between the 5 Cases.

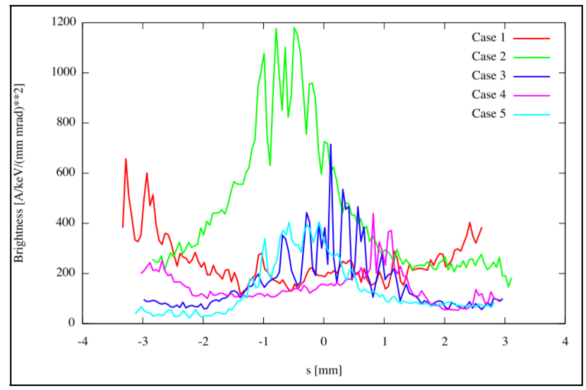

Figure 8. Slice 6D brightness variation.

CONCLUSIONS

A set of baseline injector designs have been presented to meet the initial system specifications. Emittance compensation techniques with difficult matching requirements still seem to work as expected. Wavebreaking and departure from quasi-laminar flow into the emittance-dominated regime occurs first for 'off-peak-current' slices. Proper focusing delays wavebreaking until later in the emittance oscillation cycle.

REFERENCES

[1] J. Corlett, *et. al.,* "A high repetition rate VUV-soft x-ray FEL concept", Proceedings of the 2007 Particle Accelerator Conference, Albuquerque.

[2] J. Staples, *et. al.,* "Design of a VHF-Band RF Photoinjector with Megahertz Repetition Rate", Proceedings of the 2007 Particle Accelerator Conference, Albuquerque.

[3] ASTRA code and executables may be found at www.desy.de/~mpyflo.

[4] L. Serafini, J.B. Rosenzweig, *Phys Rev. E* **55**, 7565 (1997).