SUBPICOSECOND, ULTRA-BRIGHT ELECTRON INJECTOR*

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We have designed and are building a subpicosecond electron injector. The injector is based on an 8 MeV photoinjector, used previously at Los Alamos in the APEX experiment. The nominal design includes magnetically compressing a 20 ps long, 3 nC bunch to a FWHM bunch length of 2/3 ps (peak current in excess of 3 kA) using a four dipole chicane buncher. The geometrical averaged transverse normalized transverse emittance after compression is about 15 π mm mrad.

I. INTRODUCTION

The prospect of advanced accelerator applications such as linear colliders [1,2] and short-wavelength free-electron lasers [3,4] has motivated research into developing shorter and shorter electron bunches with high brightness. The current state-of-the art bunch compression is from 10 ps to 0.6 ps at 37 MeV with 0.15 nC, with a transverse normalized emittance of about 25 π mm mrad [5]. Also of note is the compression reported using an alpha-magnet and rf gun [6], which has reported bunch lengths as low as 0.1 ps, but with charges on the order of 0.05 nC. These combinations of charge, bunch length, and emittance are not sufficient to meet the requirements for the advanced accelerator applications.

In order to further extend compression technology, we have designed and are currently commissioning an 8-MeV linac which has a predicted compression capability down to 0.7 ps for charges up to 3 nC, with a final transverse normalized emittance of about 15 π mm mrad. This machine, the Subpicosecond, High-brightness Accelerator Facility, is the first linac designed specifically for performing compression experiments, and includes diagnostic features required for picosecond-type bunches.

This linac will be used for measuring noninertial emittance-growth mechanisms, which may exist in magnetic compression systems [7]. This will require development of a new emittance measurement technique using beam-position monitors [8]. In addition, this linac will be used to drive an extreme ultraviolet (EUV) source, using the anomalous energy loss of a short electron bunch in a plasma due to the induced wakefield [9,10]. This type of source is considered as an option for next-generation lithography.

In this paper we will first discuss the physics motivation for this experiment, including the noninertial emittance growth mechanisms and the EUV radiation mechanism. In the following section we will describe the design of the linac, and in particular the four-dipole chicane compressor. Next we will provide simulation results describing the linac's predicted performance. In the final section we will discuss the status of the machine and future plans.

II. PHYSICS MOTIVATION

If an electron beam is not accelerating, it is easy to show that both the transverse and longitudinal space-charge forces scale inversely with the square of the relativistic mass factor. Because of this fact, designs for advanced accelerators which include bunch compression have the bunch compression occurring when the beam is at a relatively high energy (often greater than a GeV). However, it has been recently shown that this scaling for the space-charge forces does not hold for beams being bent in a dipole field [7]. Direct calculation of the longitudinal field from a moderate length line of charge that is bending yields

$$E_\theta = E_s\left(1/\gamma^2 - \beta^2 x/R\right) \qquad (1)$$

where E_s would be the electric field in the direction of the bunch's motion if the motion was straight, x is the transverse displacement from the line (in the bend plane) and R is the bend radius. Integrating over a uniform transverse bunch density, this field leads to an rms normalized emittance growth of

$$\Delta\varepsilon_n \approx \frac{1}{2}\alpha^2 \frac{I}{I_A}\ln\left(\frac{b}{a}\right)\frac{a^2}{\delta} \qquad (2)$$

where α is the bend angle, I is the peak bunch current, I_A is about 17 kA, a is the beam radius, b is the beampipe radius, and δ is the bunch length. This expression can be in turn integrated through a bunch compressor, resulting in this prediction for the emittance growth:

$$\Delta\varepsilon_n \approx \frac{1}{2}\alpha^2 \frac{I_o}{I_A}\ln\left(\frac{b}{a}\right)\frac{a^2}{\delta}\left(\ln\left(\frac{I_o}{I_p}\right)+\frac{I_p}{I_o}-1\right) \quad , \qquad (3)$$

where I_o is the uncompressed peak current and I_p is the compressed peak current. This emittance growth can be quite large - for example it is about 200 π mm mrad for a 1-nC, 1-mm-radius bunch compressed to 1 ps in a 1-radian bend. If the bunch length is sufficiently short, however, this emittance growth will not occur because of causality. This emittance growth mechanism can impact advanced accelerator designs significantly, and an experimental study of this effect needs to be made.

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* Work supported by the Los Alamos Laboratory Directed Research and Development program and by a Los Alamos CRADA with Grumman, CRADA number LA93C10102, under the auspices of the US Department of Energy.

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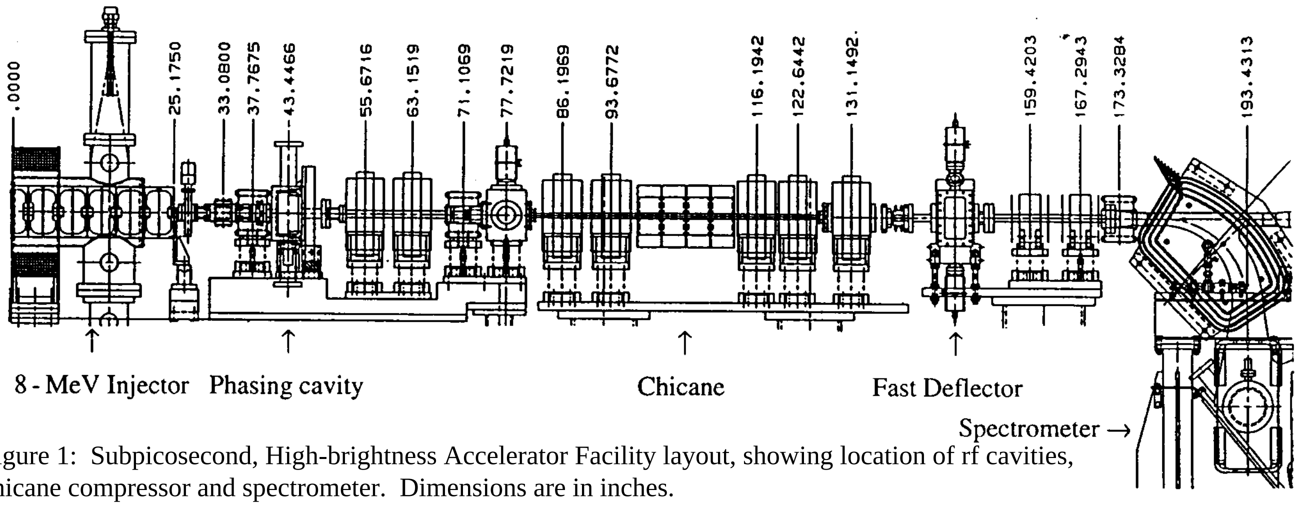

Figure 1: Subpicosecond, High-brightness Accelerator Facility layout, showing location of rf cavities, chicane compressor and spectrometer. Dimensions are in inches.

The EUV source is based on a wakefield generation in a plasma by a picosecond electron bunch. The plasma is generated by classical collisional ionization as a series of electron bunches pass through a gas target. If the electron density exceeds a critical value of about $1.6(10^{15}) / \tau^2$ cm^{-3}, where τ is the bunch FWHM is picoseconds, the wakefield in the plasma generates a large collective plasma wave. Detailed particle-in-cell simulations of the interaction indicate that an 8-MeV, 0.65 ps electron bunch will be fully decelerated after only 3 mm [10]. This plasma wave heats the background plasma electrons to about 30 eV, which then de-excite by line radiation. By optimizing the gas density, efficient (>0.1%) conversion of electron beam power to radiated power near 13 nm is possible [10].

III. LINAC DESIGN

The Subpicosecond, High-brightness Accelerator Facility, shown in Figure 1, is based on an 8-MeV photoinjector tank previously used at Los Alamos as the first acceleration tank of the 40-MeV APEX machine [11,12]. This injector will produce a low emittance (~5 π mm mrad), 10-20 ps electron bunch with a peak current of 200-300 A. The main components of the new linac are: (1) the APEX 8-MeV injector, (2) a 1-MeV phasing cavity which can modify the initial beam energy-phase correlation, (3) a four-dipole chicane for bunching, (4) a "fast-deflector" cavity which transversely spreads out the beam for time-resolved diagnostics [13], and (5) a spectrometer. All rf structures operate at 1.3 GHz.

The chicane (dipoles and beam-box) are shown in Figure 2. The first and last dipole deflect the beam upwards (in the figure) and the middle two dipoles defect the beam downwards. As a result the beam trajectory is curved. Particles with higher energy are bent less and have a shorter path length within the dipoles while particles with lower energy are bent more and have a longer path length [14]. By adjusting the phasing cavity so the particles at the front of the bunch have a lower energy than the particles at the end of the bunch, the bunch can be compressed. The beam box is wide at the center of the chicane where the dispersion is greatest. Thus the dipoles can be gradually turned on from zero field to the condition of maximum compression, with full beam transmission for all cases. The dipoles are H-magnets to minimize the fringe fields. The k_1 value for the fringe fields between the central magnets is 0.045, the k_1 value for the fringe fields between the dipoles of opposite polarity is 0.12, and the k_1 value for the end fringe fields is 0.22.

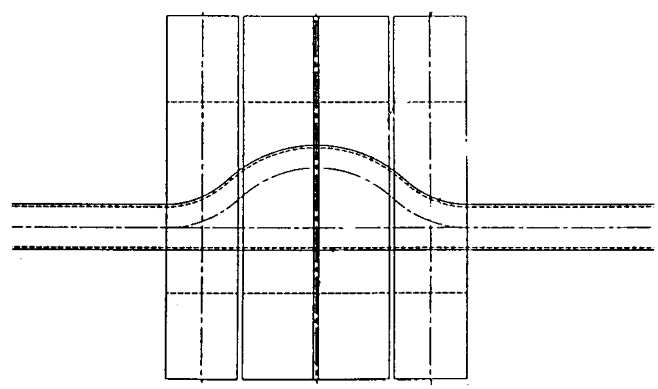

Figure 2: Top view of chicane design showing dipoles and curved beam box. The beam box maintains at least a 3:1 ratio of horizontal width to vertical width throughout.

The fast deflector, developed for the Los Alamos free-electron laser program, has a TM $_{110}$ mode operating at the same frequency as the injector and phasing cavity. The magnetic field is vertical as the bunch passes through it. If the phase of the cavity is adjusted so the field is zero when the center of the bunch is at the center of the cavity, the bunch center will not be transversely deflected. However, the front of the bunch will be deflected sideways, and the rear of the bunch will be deflected in the opposite direction. The bunch will be spread out horizontally in time, in a manner similar to the light in a streak camera. Subsequently, the spectrometer will deflect the beam vertically; the image of the beam on the screen in the spectrometer will show the phase of the particles transversely and the energy of the particles in the direction of the beam line. Thus the combination of the fast deflector and the spectrometer will provide a direct measurement of the beam's longitudinal phase space. With the distances shown in Figure 1, we predict a displacement of

1 cm on the spectrometer screen per ps, or a time resolution of at least 0.25 ps.

IV. PREDICTED PERFORMANCE

We have used the particle-pushing code PARMELA [15] to predict the performance of the Subpicosecond, High-brightness Accelerator Facility. It should be noted that PARMELA does not include the energy-independent space-charge forces described in section II, but does include all other known emittance growth mechanisms.

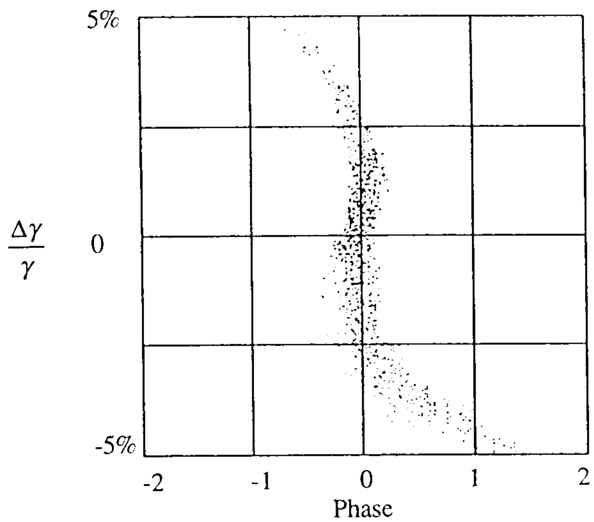

Figure 3: Longitudinal phase space of the bunch after chicane. Horizontal units are in degrees of phase at 1.3 GHz.

In Figure 3 we see the longitudinal phase space of the bunch just after the chicane. The optimum bunching occurs for a maximum bend of 39 degrees within the chicane, with an energy spread of about +/- 2.5%, and leads to a bunch length FWHM of 0.65 ps. Unfortunately, at this low beam energy, the bunch length grows quickly. Simulations indicate that the bunch length roughly doubles (to about 1.2 ps) after only 75 cm and is about 2 ps after 100 cm.

V. CURRENT STATUS AND FUTURE PLANS

The machine has been constructed and is being commissioned. Compression studies have begun in anticipation of the EUV generation experiment.

Particle-in-cell calculations of the energy loss mechanism in the plasma for the EUV experiment show that accelerating gradients are produced by the plasma wave on the order of 5 GV/m. Future plans include passing a witness bunch through this plasma to fully diagnose the fields present and to demonstrate this acceleration mechanism at these gradients. The generation of a witness bunch with an arbitrary timing separation between it and the main bunch is simplified by the fact that the machine uses a photoinjector. The dense plasma will also pinch the electron beam to a small equilibrium radius. Calculations show that the equilibrium radius is about 10 μm. It should be noted that many advanced accelerator concepts operate at high frequency, and which need a picosecond-type injector. For example, at 17 GHz, 1 ps is about 6 degrees of phase. Thus, we are also proposing to used this machine as an injector for a 100 MeV linac using the inverse axial-free-electron laser acceleration mechanism [16], operating at 17 GHz.

VI. REFERENCES

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