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Design of the Source Development Lab Bunch Compressor

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Abstract

The accelerator at the Source Development Lab at BNL consists of a 1.6 cell RF photocathode electron gun followed by a 230 MeV SLAC-type linac that includes a magnetic chicane bunch compressor. The nominal specifications call for a 10 ps FWHM bunch of 2nC charge to be compressed in time by a factor of 25 at an energy of 85 MeV. The design of the compressor magnets and the beam dynamics from the gun through the magnetic chicane are described.

1 INTRODUCTION

Next generation light sources and linear colliders will operate with electron beams that occupy very small 6D phase space volumes. The Source Development Lab (SDL) is designed to take advantage of the latest methods for producing these high brightness beams, including the use of short-pulse lasers to tailor electron beam pulse shapes produced by RF photocathode guns, the latest generation BNL-type photocathode, and magnetic pulse compression to squeeze the beam longitudinally to a very short bunch length and high peak current. At the NSLS the primary use for this beam will be the production of short wavelength light through the FEL interaction and by Thomson scattering of an infrared laser. Our FEL uses the NISUS wiggler [1] as part of a high-gain amplifier which can be operated in several configurations which provide tunable radiation at wavelengths from 1μm to below 100 nm. In combination with the gun laser, Thomson scattering from the linac beam can provide tunable x-rays from 100 to 300 keV.

This paper briefly reviews the accelerator, then focuses on the design of the magnetic bunch compressor and the beam dynamics through the compressor.

2 ACCELERATOR COMPONENTS

The electron source [2] is a radio-frequency photocathode developed by a collaboration from BNL, SLAC, and UCLA. It consists of a 1.6 cell RF structure driven at 2856 MHz. The maximum gradient is 140 MV/m, yielding an exit energy of approximately 8 MeV.

To produce electrons in the RF gun, the photocathode is illuminated with 266 nm light generated by frequency tripling the fundamental from a Ti:Sapphire laser. Up to 0.4 mJ of UV light is available with a tunable pulse length ranging from 60 fs to 20 ps which should be more than sufficient to produce several nancoulombs of charge from a copper cathode. A square transverse intensity profile with a 65 degree wavefront tilt is used to match the beam onto the RF photocathode. The square intensity profile is optimal for emittance correction. The wide bandwidth of the Ti:Sapp laser allows for longitudinal pulse shaping so that nonlinear emittance correction may be investigated.

The linac currently consists of four SLAC-type constant-gradient linac tanks operating at 2856 MHz, with provision for installation of a fifth section. The first two linac tanks are used to accelerate the beam to approximately 84 MeV, where it enters the magnetic chicane. The final two linac tanks following the chicane accelerate the beam to a maximum energy of 230 MeV.

3 CHICANE DESIGN

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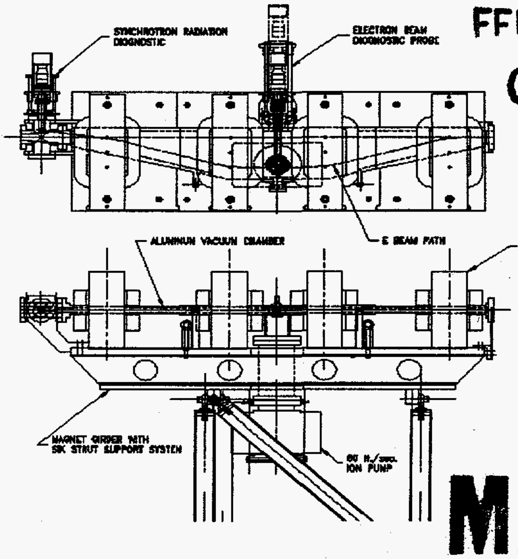

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Figure 1: Magnetic chicane.

The SDL bunch compressor is made up of three major components: the dipole mangets, the vacuum vessel system with the beam diagnostics, and the mechanical support system. The 4 dipoles are fabricated from solid blocks of 1008 low carbon steel. Steel dowel pins at the magnet midplane accurately locate the yoke blocks. Each magnet uses eight air-cooled pancake coils of 16 turns. Current density is held to less than $1.5\mathrm{A/mm}^2$ to avoid thermal distortion. The coils also extend away from the iron to allow natural convection cooling. The field strength is 4.5 kG, magnetic length is 19 cm, and the gap is 3 cm. The magnetic design was optimized with the three dimensional code TOSCA.

The aluminum vacuum chamber is machined in halves and seam-welded at its periphery. Two CCD cameras are used as electron beam and synchrotron radiation diagnostics. The electron beam probe is injected through the center

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of the vacuum chamber. It has a YAG crystal[3] and mirror to observe beam shape. It also has 3 slots 0.3, 0.6, and 1.0 mm wide, respectively, so that slice emittance may be studied. The slots may also be used to select a fixed energy bandwidth for transmission to the wiggler. The local emittance and local energy spread are key determinants of single-pass FEL performance. The probe may be moved to any tranverse position in the chamber by a stepper motor. The maximum displacement of the beam is 14 cm at 84 MeV. The compressor may be operated at any value from zero field to full strength. The synchrotron radiation monitor is used to observe emission as the beam passes through the final bend magnets. A variable position mirror is needed to accommodate potential magnet repositioning. The CCD mount is also moveable to accomodate variations in the direction of radiation emission.

A six strut system was selected to support the magnet girder. The struts simplify survey and alignment and take the place of a separate stand. The struts are bolted to a steel ground plate which is bolted and grouted to the floor.

Drift distances are 38 cm between outer magnets and 25 cm between the central magnets. For a given compressor length it is desirable to maximize these outer drifts (from magnets 1 to 2, and 3 to 4) in order to minimize the emission of coherent synchrotron radiation (CSR). The separated magnet configuration also reduces coupling between adjacent magnets. The outer magnets may be placed in either of two positions; the normal operating position is shown in Figure 1, the other position has them placed adjacent to the inner magnets. The latter position generates a greater portion of the path-length difference in the bends, and will be used to investigate the effects of coherent synchrotron emission on beam emittance and energy distribution.

4 BUNCH COMPRESSION DYNAMICS

There are several methods of producing short electron bunches, but they are not all applicable to the high charge ($\geq$ 1 nC) regime. The electron bunch length immediately adjacent to the cathode surface is approximately equal to the input laser pulse length. It is possible to produce short bunches in the RF gun through two mechanisms. The Ti:Sapp laser can produce 100 fs pulses directly, or a longer laser pulse may be timed at an advanced RF phase so that velocity bunching [4] occurs in the first 1/2 cell of the gun. Both of these methods are applicable to small beam charges ($\ll$ 1 nC) only. At higher charges the low energy and high charge density in the gun cause both bunch-lengthening and emittance growth due to space charge forces. This paper describes bunch compression via magnetic rotation at higher energies, where space charge forces are small.

The bunch compression, ΔL, due to energy spread is

$$\Delta L = R_{56}\,\frac{\Delta E}{E} + T_{566}\left(\frac{\Delta E}{E}\right)^2 \qquad (1)$$

where $R_{56} = \int ds\, \eta/\rho$, η is the dispersion, ρ is the bending radius inside the compressor magnets, $\Delta E/E$ is the correlated spread in beam energy produced by running the bunch off-crest in the linac, and T_{566} is the appropriate second order matrix element. For the chicane configuration with four equal-length magnets, the dominant R_{56} term can be written [5]

$$R_{56} = 2\theta^2(L_{dft} + \frac{2}{3}L_{mag}) \qquad (2)$$

where θ is the bend angle in each magnet, L_{dft} is the drift distance between magnets, and L_{mag} is the length of each magnet. The drift distance from magnet two to three does not affect the compression, and may be made larger or smaller to accomodate diagnostics or beamline length constraints. Equation 2 shows that the drifts contribute more to ΔL than do the bends. For a fixed chicane length, CSR will be reduced by maximizing the drifts.

Nonlinear components of the longitudinal bunch distribution are produced by curvature of the RF waveform and longitudinal wakefields generated in the linac. These nonlinearites may be partially corrected [6] by the T_{566} element of the magnetic field. For our design $T_{566} = -7.4$ cm and $\Delta E/E = 1\%$ yielding a second order path length difference of just 7.4μm, too little to correct aberrations in the distribution. Investigations are underway to study longitudinal pulse shaping to balance the curvature due to wakefields and RF.

Conservation of the longitudinal emittance requires that the uncorrelated energy spread of the bunch grow in inverse proportion to the bunch length reduction. The maximum energy spread that the FEL will tolerate sets a limit on the amount of compression that may be achieved. The input beam to the compressor is expected to have an uncorrelated RMS energy spread of .04% and a FWHM bunch length of 10 ps. The FEL and scattering experiments will tolerate approximately 1% energy spread at the compressor (0.4% at the wiggler), hence we may compress the beam by a factor of 25 for a compressed FWHM of a few hundred femtoseconds. Figures 2 and 3 show the results of a PARMELA simulation of 2 nC of charge represented by 1000 macro particles. The peak current after compression is 10 kA in a bunch length of 200 fs FWHM. The actual performance will depend on the details of the bunch distribution and wakefields generated.

Short, high current bunches generate significant coherent synchrotron radiation (CSR) at wavelengths near the bunch length and longer. The CSR power generated by N particles bending through an angle θ is [7]

$$P[\text{watts}] = 2.42 \times 10^{-20}\frac{N^2}{\rho^{2/3}[\text{m}]\,\sigma^{4/3}[\text{m}]}\frac{\theta}{2\pi} \qquad (3)$$

where ρ is the the bending radius and σ is the RMS bunch length. The SDL chicane parameters are $\rho = 1.25$ m, $\theta = 0.25$, and $\sigma = 50\mu$m. This yields an output power of 65 kW. The CSR is emitted predominantly in the final bend of the chicane. The total emitted CSR energy is 0.4 mJ near 60μm wavelength. We plan to detect the CSR spectrum for use as a bunch length diagnostic. The total beam power is

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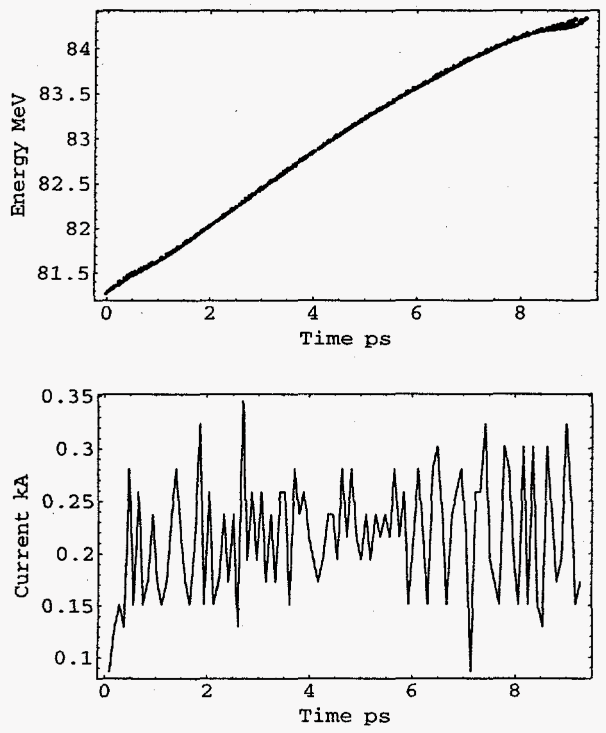

Figure 2: PARMELA simulation of energy-chirped beam entering chicane.

$P_{beam} = IV = 8.4 \times 10^{10}$W. Thus the energy loss due to CSR is $4 \times 10^{-4}/0.17 = 0.2\%$, a modest increase over the 1% induced energy spread.

Emittance dilution is of course anticipated to accompany the compression process, and calculation of its magnitude represents an active area of research[8]. The SDL accelerator with its compressor should provide an experimental platform for measuring these effects. Emittance growth is minimized by bringing the beam to a tight focus (increasing its divergence angle) in the final chicane bend. There is a quadrupole triplet installed just upstream of the chicane for this purpose.

5 SUMMARY

The design of the SDL electron bunch compressor has been described including its structure, magnetic properties and the electron beam dynamics. It is currently under construction. This compressor is expected to compress a 10 ps FWHM, 2 nC into 200 fs FWHM bunch length. This yields a peak current of 10 kA.

6 ACKNOWLEDGEMENTS

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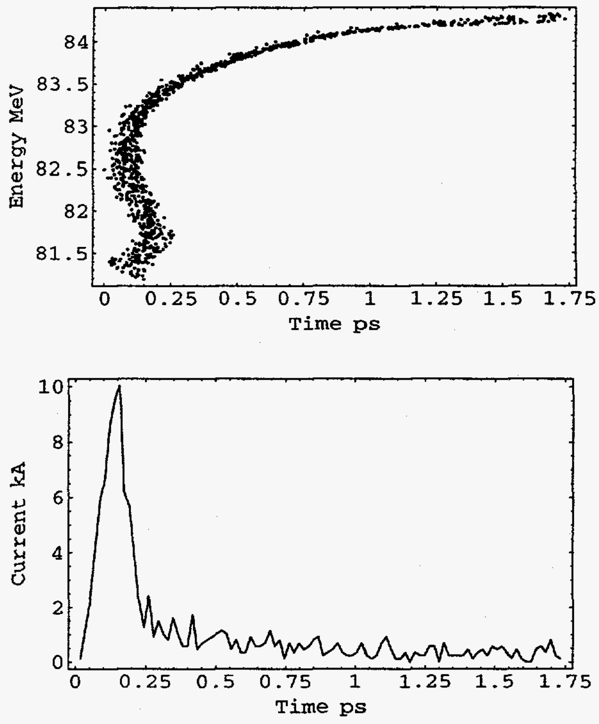

Figure 3: PARMELA simulation of compressed bunch exiting chicane.

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