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THE DESIGN OF A HIGH CHARGE POLARIZED PREINJECTOR FOR THE ELECTRON-ION COLLIDER

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Abstract

The design of the Electron Ion Collider (EIC) electron pre-injector to generate a 4 x 7 nC bunch pattern to meet the requirements for injection into the Rapid Cycling Synchrotron (RCS) has been designed. The major challenges are the generation and transport of the high charge polarized electron beam, while achieving small energy spread. The pre-injector design includes the polarized electron source, bunching section, traveling wave plate (TWP) LINAC, zig-zag phase space manipulation and a spin rotator. In this proceeding, we discuss the RF frequency selection, and achieving energy spread as low as 0.25% by longitudinal phase space manipulation. We also report the results of beam dynamics simulation.

EIC PREINJECTOR INTRODUCTION

The EIC pre-injector should produce 85% polarized electron beam with 8 bunches in a repetition frequency of 1 Hz with up to 7 nC of charge. The polarized electron beam will be generated from a high voltage (HV) DC gun with a strained superlattice GaAs(SL-GaAs) photocathode. A pre-buncher with ballistic compression will be used to compress the bunch length to 10 ps. The TWP LINAC will use standard 2.856 GHz S-band normal conducting TWP to boost the beam energy up to 400 MeV. Then, a longitudinal matching section will be placed between the LINAC and the spin rotator to assure beam stability in the RCS. The longitudinal matching section includes a zig-zag section for rotating the beam in longitudinal phase space and a de-chirp cavity to minimize the energy spread. The electron beam spin orientation is longitudinal from the cathode. A dipole solenoid spin rotator will be placed before injecting into the RCS [1]. Two Mott polarimeters will be used, one at the photocathode cathode preparation system and another at the gun beam diagnostic beam line. Table 1 shows the beam requirements at the exit of the pre-injector. The photocathode operational lifetime is expected to be on the order of weeks. Figure 1 shows a schematic of the 400 MeV pre-injector.

Table 1: EIC Pre-injector Beam Requirements

Parameter	Value
Charge [nC]	7
Energy [MeV]	400
Normalized emittance [mm-mrad]	< 40
Bunch length [ps]	40
dp/p [%]	0.25
polarization [%]	85

POLARIZED ELECTRON SOURCE

The Stanford Linear Collider (SLC) polarized gun achieved up to 16 nC bunch charge in the 1990's, however, it operated at lower voltage and using a more complex cathode exchange system as desired for the EIC. Instead, we have developed an inverted HV load lock DC gun, based upon the polarized gun operating at TJNAF [2]. We redesigned the electrode, anode and high voltage feedthrough to reliably generate the high charge polarized beam at a design voltage of 350 kV.

Using an inverted HV load lock has multiple advantages: to reduce the outgassing surface, to eliminate line of sight field emission from feedthrough to ceramic, to store photocathodes for rapid replacement, and to eliminate photocathode activation from within the HV chamber.

The gun provides a total of 8 bunches at a repetition rate of 1 Hz. Compared to the SLC gun operating at an average current 2.4 μA with photocathode lifetime of 4 days, the gun for the EIC should have an operational lifetime of several weeks. A cathode load lock system is used to permit the exchange of the photocathode within an hour. To mitigate field emission from the cathode and ensure a long operational photocathode lifetime the maximum cathode gradient is limited to 4 MV/m.

The peak current as the function of gap voltage can be estimated using the 2D Child law:

$$j_{2D} = j_{1D}\left(1+\frac{d}{4r}\right),\qquad j_{1D} = 2.33\times10^{-6}\ V^{3/2}/d^2, \tag{1}$$

where V is the voltage across the DC gap of width d, and r is the laser spot size radius. The gap distance is determined by the maximum gradient on the cathode electrode. To achieve 7 nC bunch charge with 3 A peak current, the bunch length is set to be 1.5 ns. The current density is less than 7 A/cm^2, the surface charge limit threshold observed in the SLC experiment.

As part of the EIC R&D effort we have designed, fabricated and are now commissioning this high voltage polarized gun [3]. It is in routinely operating at 300 kV and generating bunches of 7-10 nC. Figure 2 shows a plot of the charge generated from a bulk GaAs photocathode using the R&D gun.

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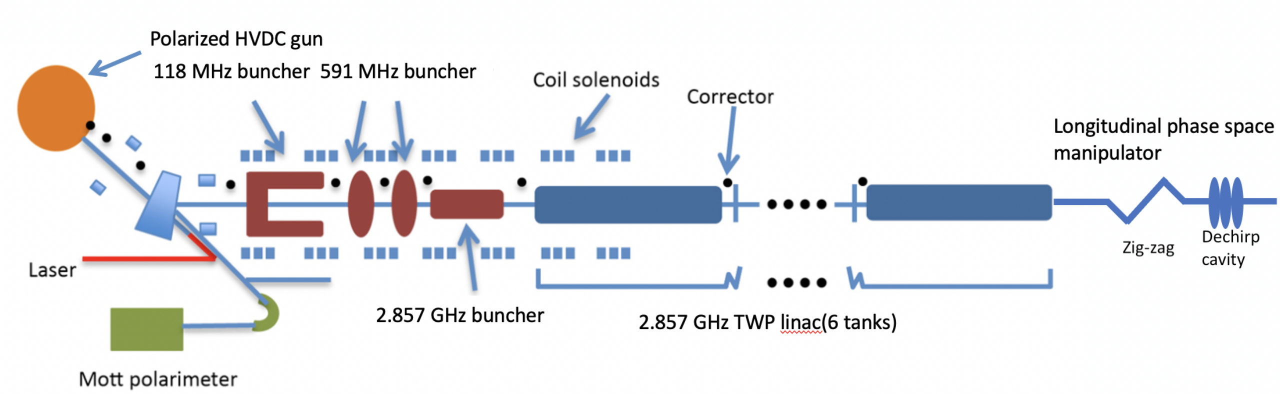

Figure 1: A schematic of the 400 MeV preinjector.

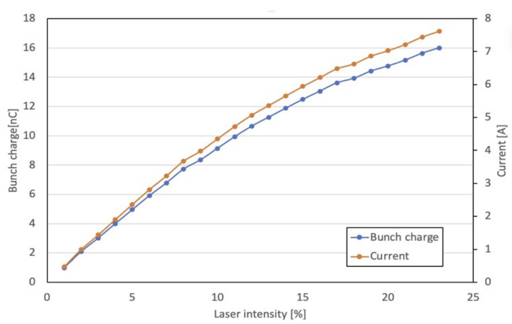

Figure 2: Gun bunch charge and peak current as a function of laser intensity.

Table 2: RF Cavity Frequencies in the Pre-injector

Cavity	Frequency [MHz]
Main LINAC	2856
Fundamental buncher	118.23
5th harmonic buncher	591.15
Taped buncher	2856
Dechirp cavity	1182.3
Bunch gap in one LINAC RF pulse	2436 [ns]

PREINJECTOR BEAM DYNAMICS

The preinjector provides 2×7 nC bunches within 2.5 μs, which is typically the pulse length for an S-band LINAC. The LINAC will operate at 100 Hz to provide four pairs of bunches, with 10 ms spacing between pairs. A total of 8 bunches (4 pairs) will be provided at a repetition rate of 1 Hz. The frequencies of the various RF cavities in pre-injector are listed in Table 2. All cavity frequencies are harmonics of 1.23 MHz, which is $1/80^{th}$ of the beam repetition frequency in the Electron Storage Ring (ESR). The initial transverse bunch radius is 8 mm at the cathode, providing sufficient area to generate the 7 nC bunch charge. Although the gun is designed to operate at 350 kV, a voltage of 300 kV is sufficient to meet the beam requirements. Photocathode ion back-bombardment is not expected to be a significant issue due to the low average current required, so the laser spot will be centered on the photocathode. A circularly-polarized laser beam will illuminate the photocathode perpendicularly. The electron will be deflected 12° using a dipole magnet or can be sent to a diagnostic beam line to measure the beam polarization. The dipole magnet faces are wedged by about 3° to provide the equal focusing for both transverse directions. Two solenoids are placed between the gun and the dipole and another solenoid is placed after the dipole to focus the bunch into the RF bunching section. A solenoid channel surrounds the bunching section and half of the first LINAC section to maintain a small beam envelope. Once the bunches are compressed to less than 5 ps, they continue through 6 tanks of 2.856 GHz LINAC, boosting the bunch energy to 400 MeV. To ensure injected bunch stability in the RCS, a zig-zag bunch stretching section is placed after the LINAC to increase the bunch length to 40 ps, and to reduce the energy spread to 0.25% using a 1182.3 MHz de-chirp cavity.

The code Parmela (version 3.38) was used to design and simulate the pre-injector beam dynamics. The initial bunch parameters from the cathode are listed in Table 3. A genetic optimization and multi-objective parabola optimization were used to optimize these parameters. Figure 3 shows the bunch parameters such as RMS emittance and bunch size. The bunch energy spread in the preinjector is dominated by the LINAC RF curvature. Table 4 summarizes the simulation results for 7 nC bunches at the exit of the LINAC.

Table 3: Initial Bunch Parameters From the Cathode

Parameter	Nominal
Bunch charge [nC]	7
Bunch length [ns]	1
Bunch radius [mm]	8
RMS thermal emittance [mm-mrad/mm]	0.2
Gun voltage [kV]	280-350

To achieve longitudinal microwave stability, the RCS requires the injected bunch to have a longitudinal emittance less $\sigma_t \sigma_E = 4 \times 10^{-5}$ eV-s , less than 0.3% rms dp/p and bunch length of 40 ps.

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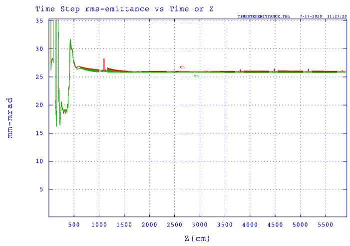
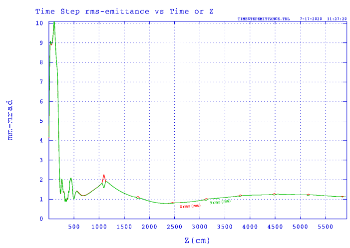


(a) RMS normalized transverse emittance



(b) RMS beamsize

Figure 3: The emittance and beam size along the preinjector beamline with bunch charge of 7 nC.

Table 4: Bunch Parameters at the Exit of the 400 MeV LINAC

Parameter	**Nominal**
Bunch charge [nC]	7
Bunch length [ps]	4.7
RMS normalized emittance [mm-mrad]	26
RMS beam size [mm]	0.9
Energy spread dp/p	5.6×10^{-3}

The longitudinal emittance at the LINAC exit is 1.2×10^{-5} eV-s. By rotation in longitudinal phase space, we can first increase the bunch length to 40 ps and the de-chirping cavity can then reduce the energy spread to 0.25%. The longitudinal matching section is designed that a bunch stretching r_{56} will provide the required bunch stretching, utilizing the intrinsic energy spread in the bunches, followed by a de-chirping cavity to reduce the energy spread to the required value. The longitudinal phase space is shown in Fig. 4. The zig-zag includes four dipole magnets with bending angles of 22° and a 3 m drift in between the 1^{st} and 2^{nd} as well as the 3^{rd} and 4^{th} dipoles. The zig-zag stretches the bunch length to 40 ps. Five quads are used to define the r_{56} of the zig-zag. A de-chirping cavity is needed to reduce the energy spread. A lower frequency cavity is preferred to achieve minimum dp/p, however, a higher frequency cavity will de-chirp the beam more efficiency and cost less. We evaluated multiple frequencies (591,1182, 1773 MHz) and chose 1182 MHz as the best solution to achieve the required energy spread. Figure 5 shows the de-chirping cavity voltage as the function of the bunch length. The minimum rms energy spread achieved is 0.18%. By tuning the de-chirping

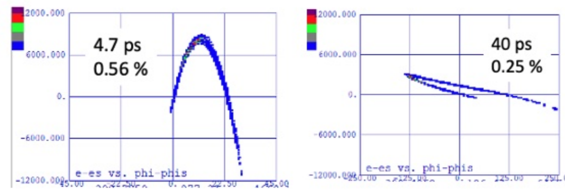


Figure 4: The longitudinal of phase space at exit of LINAC and exit of dechirp cavity. The RMS bunch length and RMS energy spread have been shown in the each plot, respectively.

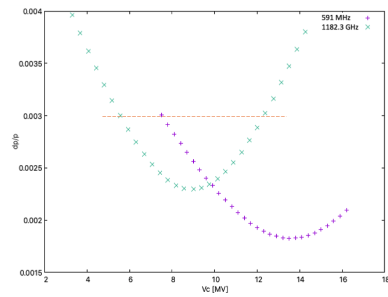


Figure 5: The energy spread as the function of dechirping cavity gap voltage. 591 MHz and 1182 MHz dechirping frequency are compared.

cavity, the rms energy spread can be controlled to 0.25% with a gap voltage 9 MV.

CONCLUSION

We designed a 400 MeV polarized pre-injector for EIC. It should provide 7 nC, 30 mm-mrad and 0.25% dp/p electron beam to RCS for further acceleration. The polarized electron source HV DC gun R&D is on-going. We have generated 10 nC bunches at 300 keV.

ACKNOWLEDGMENT

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