PREINJECTOR DESIGN UPDATE FOR THE EIC[*]

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Abstract

To mitigate beam instabilities associated with low magnetic fields, the Rapid Cycling Synchrotron (RCS) for EIC has been redesigned to operate with a higher injection energy of 750 MeV, accepting only one bunch at a time and accelerating it immediately to collision energy. As a result, the electron preinjector must also be updated to supply an appropriately matched beam. In the latest concept, the extraction energy has been increased to meet the new RCS requirement, and a dedicated Beam Accumulator Ring (BAR) has been added to provide the required bunch merging. To maintain comparable cost while meeting performance goals, the preinjector design adopts Wien filters for spin rotation, an L-band capture linac to preserve polarization, a reduced bunch charge that eliminates the need for a stretch section, and a high-gradient S-band linac. This paper presents the updated EIC preinjector concept together with supporting design studies and simulation results.

INTRODUCTION

The EIC injector requires a polarized electron bunch at 750 MeV for single-bunch injection into the RCS. The new BAR takes over the bunch-merging function upstream of the ring. Compared with the earlier high-charge concept, this relaxes the preinjector bunch-charge requirement, removes the need for RF-based bunch merging in the preinjector, and allows the design to be optimized for robustness and spin preservation [1]. In the present study, the nominal preinjector bunch charge is 1.2 nC, with operation over about 1 nC to 1.7 nC; this keeps margin above the 1 nC requirement while significantly reducing wakefield and beam-loss risk relative to the previous multi-nC concept. Polarized-source R&D and related cathode development supporting this updated operating point were reported in Refs. [2, 3].

The choice of the main linac is now largely cost-driven. Once the BAR is included, a mature S-band solution becomes attractive because the required charge is modest, the achievable gradient is high, and the hardware can be procured from existing vendors. The spin constraint, however, remains stringent. The polarized source delivers longitudinal spin, whereas the transfer line and ring require vertical spin. The front-end accelerator design is therefore organized around one central rule: after the low-energy spin-rotation section, the beam spin direction should remain vertical throughout the preinjector.

Table 1: Updated preinjector requirements and representative design values.

Parameter	Required	Designed
Bunch charge [nC]	1.0	1.7 (up to 2.0)
RMS energy spread [%]	< 0.45	0.30
Polarization [%]	> 85	85
Norm. emit. [mm mrad]	< 95	80/50 (x/y)
Energy [MeV]	750	750
Spin direction	Vertical	Vertical
Rep. rate [Hz]	30	30 (20 also possible)

SPIN CONSIDERATIONS IN THE PREINJECTOR

Spin transport is one of the main design drivers of the preinjector design. From the Thomas–BMT equation,

$$\begin{aligned} \frac{d\vec{P}}{dt} &= \vec{\Omega}_0 \times \vec{P}, \\ \vec{\Omega}_0 &= -\frac{Ze}{m\gamma}\Bigg[(1+G\gamma)\vec{B}_\perp + (1+G)\vec{B}_\parallel \\ &\qquad + \left(G\gamma + \frac{\gamma}{1+\gamma}\right)\frac{\vec{E}\times\vec{v}}{c^2}\Bigg], \end{aligned} \tag{1}$$

Keeping the required spin orientation through a long solenoidal capture channel becomes difficult once the solenoidal field overlaps the accelerating field, because the beam energy increases continuously inside the RF structure. For an ideal solenoidal section, the condition for zero net spin rotation can be written approximately as

$$\int_S \frac{B_\parallel}{\gamma}\, ds = 0. \tag{2}$$

However, in an accelerating RF structure with strong space-charge effects, both γ and the effective overlap between the longitudinal magnetic field and the RF fields vary continuously along the beam path and from one tuning state to another [4]. In a conventional S-band front end, the taper cavity and the first accelerating section are often embedded in a solenoidal channel to control the beam size in the small aperture. For polarized operation, this is unattractive: the same solenoidal field that provides transverse matching also generates spin rotation, and the zero-net-rotation condition is therefore difficult to maintain during tuning and commissioning because small changes in RF phase, amplitude, launch phase, or solenoid settings alter the energy profile and hence the cancellation of the integrated spin precession.

Another possible approach is to allow the spin direction to deviate from vertical in the linac and then use a solenoid to restore the required orientation between the linac exit and

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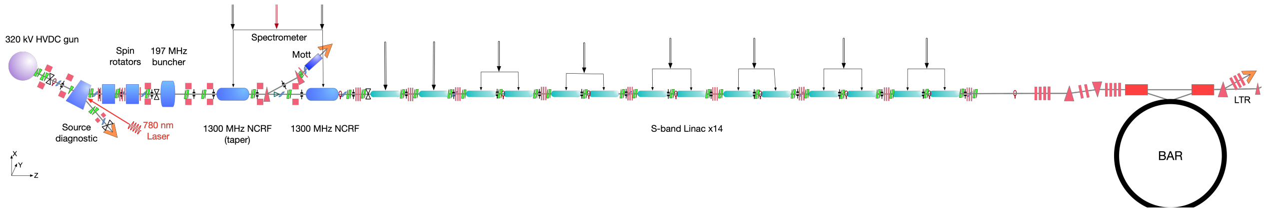

Figure 1: Updated EIC preinjector layout. The front end combines a 320 kV polarized HVDC gun, source diagnostics, two Wien filters, a 197 MHz buncher, and two 1.3 GHz capture cavities before injection into the S-band linac, BAR, and the RCS transfer line.

injection into the BAR. However, this would require a spin diagnostic such as Möller polarimetry at the end of the linac at 750 MeV. At the low average current available during tuning, the detection rate would be too low for efficient optimization, leading to long commissioning times and large measurement uncertainty.

The updated design therefore moves the dedicated spin rotation to low energy, ahead of the capture linac, using two Wien filters. Each Wien filter provides a 45° rotation, so the beam exits the double-Wien section with vertical spin before entering the L-band capture cavities. The beam energy in this region is about 300 keV to 320 keV, which keeps the spin-rotation section compact while maintaining flexibility for future adjustment of the linac energy range. A focusing element is placed between the two Wien filters so that the transport remains nearly achromatic. Both conventional triplet focusing and a permanent-magnet-solenoid option have been evaluated; in both cases the spin impact is negligible, so the final choice can be made on engineering grounds.

Instead of relying on a long solenoidal channel through the first S-band structures, the beam is first accelerated in L-band taper and capture cavities to above 10 MeV. At that point, the space-charge force is sufficiently reduced that injection into the S-band linac can be done without superimposing a strong matching solenoid on the accelerating structures. Figure 1 shows the resulting preinjector layout.

BEAM DYNAMICS TRACKING

All beam-dynamics studies presented here use the nominal 1.7 nC bunch, which provides operating margin above the 1 nC requirement. The low-energy section was modeled with GPT including space charge, wake effects, and spin tracking, while downstream transport through the linac was tracked with PARMELA. The beam envelope remains well controlled through the gun, the capture section, and the S-band linac. The main beam parameters along the line are summarized in Fig. 2. At the linac exit, the beam reaches 750 MeV with normalized emittances of about 80 mm mrad and 50 mm mrad in x/y and an rms bunch length of about 0.92 mm. The same lattice can operate over the 1 nC to 1.7 nC range without changing the overall architecture.

The main linac is operated off crest to suppress the wake-driven correlated energy spread while still meeting the final-energy target. The peak current at the linac exit is about 450 A, and the rms energy spread is 0.23 %, which is comfortably within the requirement of Table 1. After removing the small longitudinal tail used for downstream matching studies, the retained beam fraction is about 99.7 %.

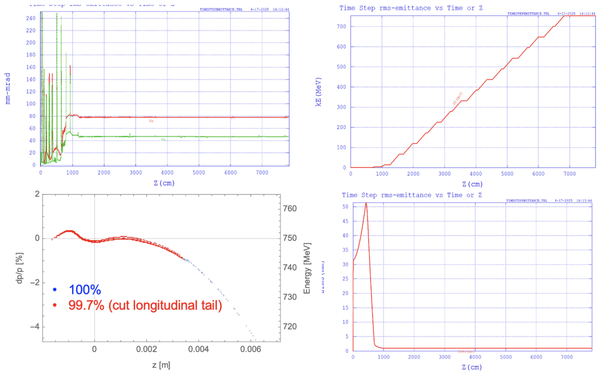

Figure 2: Evolution of the main beam parameters along the updated preinjector for the nominal 1.7 nC bunch: normalized emittance (top left), bunch longitudinal phase space (bottom left), beam energy (top right), and rms bunch length (bottom right).

The end-to-end error study was simplified to focus on the main conclusion. Eighty random seeds were tracked, including RF phase and amplitude jitter, magnet power-supply ripple, structure and quadrupole misalignment, BPM error, and laser timing and pulse-energy jitter. A 200 µm S-band alignment budget was assumed. Under these errors, the output variations remain modest: the rms energy varies by about 1 MeV, the rms energy spread by about 0.03 %, the arrival-time jitter is about 0.8 ps, and the orbit jitter is about 100 µm. These results meet the BAR and RCS injection requirements.

PREINJECTOR RF SYSTEM

After spin rotation to the vertical direction, the bunching and capture system starts with a 197 MHz buncher. This is followed by a modified 1.3 GHz taper cavity that matches the rapidly increasing beam velocity. The accelerating gradient is about 5 MV/m, bringing the beam from roughly 320 keV to 3.8 MeV. A downstream standard 1.3 GHz 7-cell AWA/APEX capture cavity then raises the energy to about 14 MeV at approximately 10 MV/m. The dual-coupler design avoids a strong transverse RF kick, which is important for preserving emittance in the capture section. Thermal studies and operating experience indicate that 30 Hz operation is feasible for the capture cavities [5]. Figure 3 shows the electromagnetic designs of the L-band taper and capture cavities.

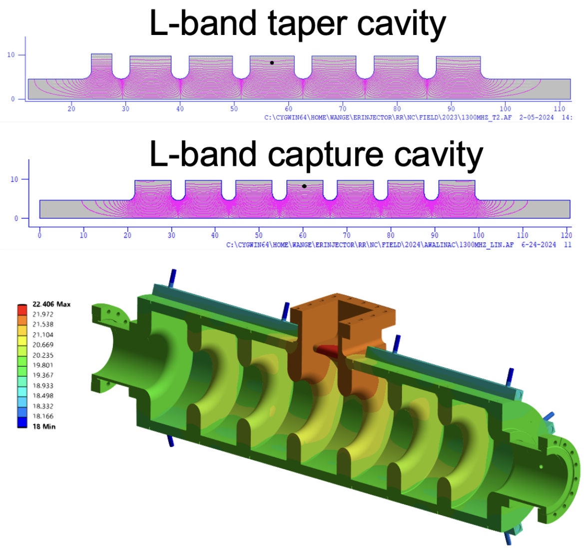

Figure 3: Electromagnetic designs of the L-band RF structures: taper cavity (top), capture cavity (middle), and thermal analysis of the capture-cavity assembly with coupler for 30 Hz operation (bottom).

For the main accelerator, the design uses fourteen 3 m S-band structures. The linac will be operated at 17.5 MV/m. If one klystron fails, twelve structures remain available with a gradient of 20.3 MV/m. The reserved linac space can accommodate at least sixteen structures. The 750 MeV EIC linac lies between a compact injector linac and a large XFEL-class facility, and therefore allows several viable RF configurations. The selected solution uses independent RF control for the first two S-band structures to preserve flexibility for longitudinal matching and RF focusing control, while the remaining sections are powered by 50 MW klystrons followed by SLED systems, with the compressed power split to feed two 3 m S-band structures per station. This configuration provides a practical compromise among cost, redundancy, and operational margin.

SPIN-RELEVANT COMPONENTS

The polarized HVDC gun commissioned during the EIC R&D program achieved bunch charges above 11 nC at 320 keV, while superlattice photocathode development demonstrated polarization at the 85% level [2]. The double-Wien system is one of the most important new subsystems in the present preinjector concept because it rotates the spin from longitudinal to vertical before the beam enters the RF section. This Wien-filter system must rotate a 1 nC to 2 nC bunch at 320 keV, which is beyond the current state of the art. Therefore, an R&D program is underway to develop this system, as presented in Ref. [3].

Since the Wien filter is used at the front end, a polarimeter is needed to measure both spin direction and polarization during tuning. A dedicated spin-diagnostic beamline is included to confirm the spin orientation and polarization before injection into the main linac. The diagnostic line is located at about 3.5 MeV to 4 MeV, where the beam energy is high enough for practical transport and the bunch chirp from the gun has been largely removed. This beam energy is similar to that used in the CEBAF high-energy Mott polarimeter [6]. In addition to polarization measurement, the line also provides beam-energy and energy-spread diagnostics. Figure 4 shows the layout of the spin-diagnostic beamline.

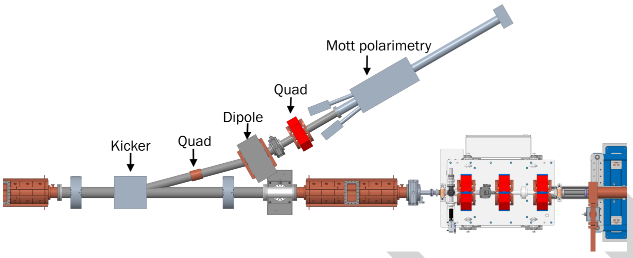

Figure 4: Spin-diagnostic beamline near 4 MeV, including the kicker, quadrupoles, analysis dipole, and Mott polarimeter branch used for polarization and energy diagnostics.

To continuously monitor spin-polarization changes, one bunch can be extracted periodically for diagnostics during commissioning. The kicker bends the selected bunch by about 15° to avoid interference with the main beamline, and a downstream dipole provides additional dispersion for energy-spread measurement. This arrangement supports efficient front-end commissioning without interrupting the primary beam path.

CONCLUSION

An updated EIC polarized preinjector design has been developed for the revised EIC injector. The design emphasizes spin preservation and practical cost control: low-energy Wien filters provide the required spin rotation, the L-band front end captures and accelerates the beam before it enters the main linac, and the S-band section provides the final energy gain. By separating the low-energy spin-rotation function from the main RF acceleration, the updated layout allows a vertically polarized bunch to be transported through the entire preinjector without significant spin distortion.

For the nominal 1.7 nC bunch, the design reaches 750 MeV with 0.23 % rms energy spread, about 80 mm mrad and 50 mm mrad normalized emittance, and acceptable sensitivity to realistic RF, alignment, and laser jitter. These results support continued engineering development of the spin rotator, RF front end, diagnostics, and linac systems.

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