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THE ACCELERATOR DESIGN PROGRESS FOR EIC STRONG HADRON COOLING

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Abstract

The Electron Ion Collider (EIC) will achieve a luminosity of 10^{34} cm^{-2}s^{-1} by incorporating strong hadron cooling to counteract hadron Intra-Beam Scattering, using a coherent electron cooling scheme. An accelerator will deliver the beams with key parameters, such as 1 nC bunch charge and 0.01 % energy spread. The paper presents design and beam dynamics simulation results, up to the cooling section. The challenges of the accelerator design, and the R&D topics being pursued are discussed.

INTRODUCTION

To maintain a luminosity of $L = 10^{34}$ cm^{-2}s^{-1} in EIC during long collision runs, it is desirable to cool the hadron beams to balance emittance growth due to intrabeam scattering (IBS), thereby allowing one to maintain the hadron beam quality for long collision runs (≥ 24 hours). The EIC high luminosity parameters were selected to have an IBS growth time of about 2 hours. The requirement for strong hadron cooling is to cool hadrons with energies/nucleon of 275 GeV, 100 GeV and 41 GeV. A novel method called Coherent electron Cooling (CeC) is selected as the baseline cooling method for EIC due to its high cooling rate on high energy protons [1]. The mechanism of CeC is similar as stochastic cooling, but uses electron beam instead of RF signal to increase the amplifier bandwidth.

Here, an electron beam with small energy spread and a smooth longitudinal density distribution co-propagates with the same velocity as hadron beam in a section called the modulator.

A fluctuation of proton density along the electron bunch imprints a correlated energy variation of the electrons along the bunch. After the modulator section, the electron beam is deflected off from the proton's beam line and passes through a dispersive chicane section where the energy modulation of the electrons is transformed into a density modulation . This micro-bunching can be amplified by space charge by inserting subsequent chicanes spaced by a quarter of the plasma oscillation wavelength of the electron beam. This section is called the "amplifier". Meanwhile, the proton beam passes through a dispersive section as well, transferring to correlated energy modulation. The pathlength of electrons and hadrons between modulator and kicker sections are exactly the same value with a high precision of better than 0.3 µm. After the amplification section, the electron beam and the proton beam are merged together in a section called the kicker where the micro-bunched electrons act on the protons and reduce the proton beams energy spread and emittance.

Table 1: EIC Strong Hadron Cooling Beam Requirements

Parameter	**100 GeV**	**275 GeV**
Charge [nC]	1	1
Peak Current [A]	8.5	17
Normalized emittance [mm-mrad]	3	3
Bunch length [mm]	14	7
slice rms dp/p	7×10^{-5}	5×10^{-5}
ebeam β at M / K [m]	20 / 10	100 / 8
e chicane 1,3 [cm]	-1.71	-0.68
e chicane 2 [cm]	4.62	1.52

Table 1 shows the optimal electron parameters in the cooling section [2]. Now, we are focusing on 275 GeV and 100 GeV cases. The set up to cool 41 GeV protons will be studied in the future. A slice energy spread less than 10^{-4} is very challenging. Figure 1 shows the cooling facility lay out.

COOLING ELECTRON ACCELERATOR OVERVIEW

The CW electron beam is generated by a 400 kV DC gun. The energy is then boosted up to 5.6 MeV in the injector. A dogleg with dual-solenoid merger brings beam into the LINAC that consists of eight fundamental frequency cavities together with three third harmonic cavities. The LINAC accelerates the electron beam up to 150 MeV with a small energy spread. A chicane and a dechirp cavity provide an extra knob to tune the bunch length to the desired value for different cooling energies. The electron beam is then transported to the 40 meters long modulator section and 100 meters of amplification section , which includes three R_{56} tuneable chicanes and quadruples triplets for strong focusing. Once the electron beam signal is sufficiently amplified, it merges into a 40 meters kicker section. A special magnet geometry known as a "BATES bend" brings the beam back to LINAC for the energy recovery [3].

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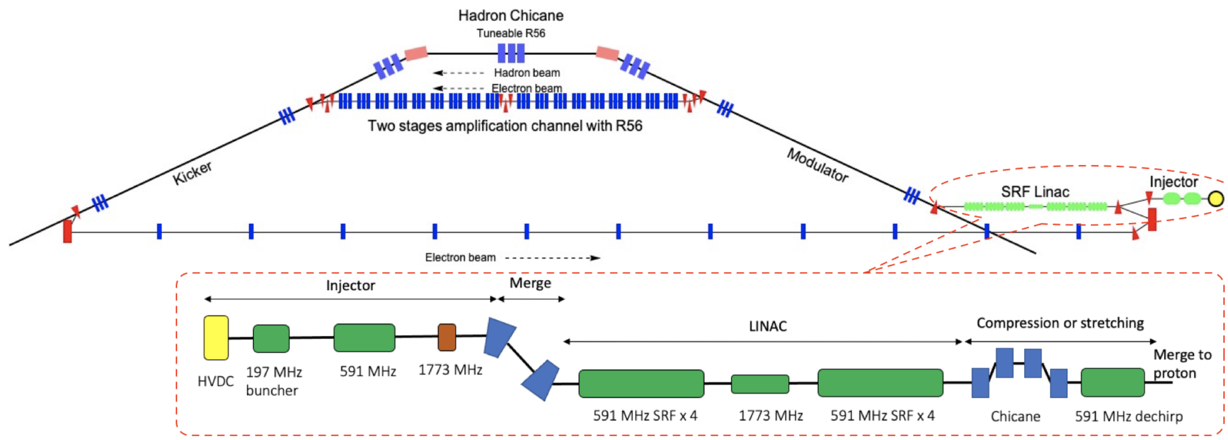

Figure 1: A schematic of strong hadron cooling accelerator and a schedumatic drawing of the gun to electron-proton merger.

Electron Source

A high voltage DC(HVDC) gun with a multi-alkali photocathode is the only realistic option to produce 100 mA of average current with 100 ps initial bunch length and a 1um-rad emittance. Taking into account the required continuous stable operation, a gap voltage of 400 kV appears to be sufficient and feasible. We choose 287 ps as the initial bunch length, so that we can achieve 1.1 mm-mrad emittance at 1 nC. The electron beam will be generated by a laser illuminating an alkali antimonide cathode, which approaches meeting the goals of high average current and acceptable lifetime. Methods of generating large grain or even single crystal K_2CsSb cathode materials are being explored to push the material quantum efficiency and the lifetime to their theoretical limit. The 100 mA, 1 nC electron source hasn't been full demonstrated to date. One of EIC R&D projects is developing a high current HVDC gun, aiming to generate 550 keV, 1 nC and 100 mA average current electron beam.

Injector

The injector includes a High Voltage DC electron source, a 197 MHz bunching section, a 591 MHz 1.6 cell SRF booster and a 1774 MHz (3rd harmonic cavity). The injector boosts the electron beam energy up to 5.6 MeV with an rms bunch length of 5.8-6.8 mm.

At the end of the injector, we use a merger dogleg with two-dipole and two solenoids to steer the beam into LINAC. The advantage of this merger is that it gives sufficient space for quadrupole matching section of the high energy return beam and it has a large longitudinal energy acceptance. We use chevron dipoles that have focusing in both directions. The two solenoids are tuned to keep dispersion zero after the merger. To merge high energy electrons with energies of 149.77 MeV, 54.46 MeV, or 22.33 MeV, we place a three-dipole chicane before the last merger dipole. The three energies' electron beams can be merged into the LINAC (see Fig. 2).

To inject the beam into the LINAC through the dogleg merger, the emittance of the beam from the injector has to be minimized. The 5.6 MeV injector using 591 MHz/1773 MHz

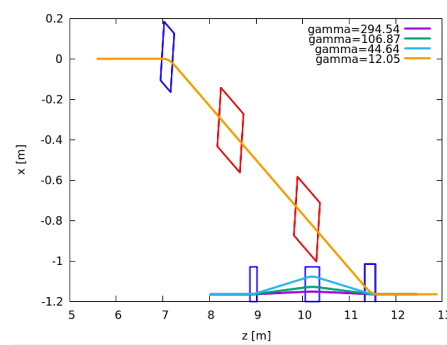

Figure 2: The lattice of the Dogleg merger with dual solenoid. It also shows three energies' trajectories merging into the LINAC.

injector can achieve a normalized transverse emittance about 2.1 mm-mrad. The beam energy at the exit of the 1st LINAC can achieve 25 MeV and the x/y emittance is frozen at 2.8/3.2 mm-mrad. The emittance increase compared to the injector is due to the energy variation caused by the longitudinal space charge in the merger.

LINAC

The LINAC consists of eight 5-cell 591 MHz SRF cavities and three 1774 MHz SRF cavities. The electron bunch is on crest to get maximum acceleration. Each 591 MHz cavity in its own cryomodule provides 20 MV accelerating gap voltage. In-between the cryomodules, there is a quadrupole to maintain the beam size. The 3rd harmonic, 1774 MHz SRF cavities with 10 MV gap voltage improve the bunch longitudinal linearity. At the exit of the last LINAC, we can get rms transverse emittance of 3.3 mm-mrad. The RMS dp/p is 8.6×10^{-5} and the slice dp/p is 5×10^{-5}. The accelerator's wake fields and the transverse quadrupoles kicks at the couplers will be included once we have a detailed SRF cavity design.

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Bunch Length Tuning

To cool the low-energy protons, the electron beam's energy must be reduced to match the velocity of the proton. The cooling simulation shows that reducing the peak current is an effective way to maintain a high cooling rate at low-energy cases [2]. However, limited by the 591 MHz LINAC, we cannot generate long bunches while attaining the required energy spread. By adding a longitudinal phase space manipulator after the LINAC, we will have an extra knob to tune the bunch length both ways. A chicane with R_{56} of 180 mm is inserted after the LINAC. With quadrupoles, the R_{56} range can be varied. To cool 100 GeV proton, the electron beam peak current can be reduced down to 8.5 A. To cool 275 GeV proton, the electron beam peak current can be varied between 17 A to 30 A.

From the gun to the merge point into IR2, all simulations were carried out using the 3D simulation tools GPT 3.4 including space charge effect and CSR. Table 2 shows the beam parameters before merging into proton beamline.

Table 2: Electron Beam Parameters before Merging into Proton Beamline

Parameters	**54.46 MeV**	**149.77 MeV**
$\varepsilon_{n\_x,y}$ [mm-mrad]	3.2 / 2.8	3.2 / 2.8
Bunch length [mm]	14	6.8 or 3.5
Peak current [A]	8.5	17 or 30
Slice dp/p	4×10^{-5}	$(5 \text{ or } 10) \times 10^{-5}$

COOLING SECTION

The hadron part of the cooling channel extends from the last dipole RHIC D6 to the corresponding dipole D5 at the end of the straight section. The entire cooling section includes the 40 m modulator and the 40 m kicker sections and provides 100 m space for electron amplification section. The orbit geometry ensures that electrons and hadrons have the same path length between the modulator and kicker. In the amplification section, the chicanes lengthen the electron path length by 25 mm. The hadrons continue after the modulator section on their trajectory before being bent by D5. Then it is in the direction of the straight section as well. Figure 3 shows the symmetric hadron lattice at IR2. The quadruples are used

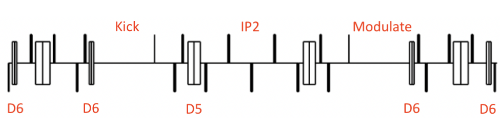

Figure 3: Hadron lattice at IR 2. The kicker and modulator sections are labeled.D5 and D6 are the superconducting dipole magnets.

to tune the beta and dispersion functions of modulator and kicker section to meet cooling requirements. The dispersion of ≃ 1-2 m at the modulator and kicker sections redistributes cooling from the longitudinal to the transverse plane. The amplification section consists of three chicanes to turn the energy modulation into a density modulation. The electron bunch longitudinal space charge will increase the beam energy spread and lengthen the bunch length when through the cooling section if their R_{56} is not zero. However, using the regular four dipoles chicane in the amplifier with the drift space will give negative R_{56} and cause the microbunch slippage. This slippage of the modulated micro-bunches will misalign with the same hadrons at the kicker section. One of the methods to solve this problem is reversing sign of R_{56} in one of chicanes in the amplification section and achieve a the total $R_{56} = 0$ [4]. To avoid anti-cooling, the chicane's $R_{56_1} \cdot R_{56_2} \cdot R_{56_3} > 0$, because the hadron chicane provides a positive R_{56}. Here the positive R_{56} means the high momentum particles move backward in the beam frame. We have designed chicanes with embedded quadrupoles. To generate positive R_{56}, the dispersion crosses the zero between the 1st and the 2nd dipoles, resulting in a shorter path length for the lower energy electrons. Figure 4 shows the dispersion and lattice layout of the chicane. It can cover the R_{56} range from 4.62 cm to -1.71 cm and meet the requirements shown in Table 1.

To shorten the plasma wavelength of the electron beam to

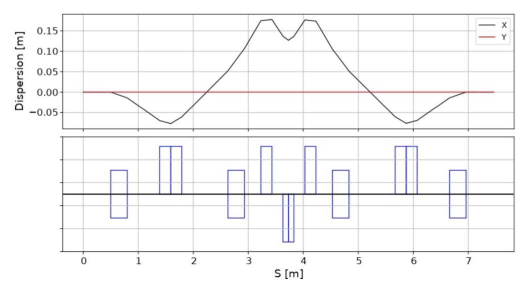

Figure 4: R_{56} tune-able chicanes at amplification section.

reduce the cooling section to a practical length, the electron beam needs to pass through a focusing section and maintain small beta through the entire microbunching section by a periodic quadrupole triplet spaced by 1.4 m between the triplets. The average beta function in the amplification section is 1.5 meters and gives total two stages amplification length of 100 m.

CONCLUSION

We designed an accelerator for EIC strong hadron cooler. It should provide the 1nC, 3 mm-mrad and $< 10^{-4} dp/p$ electron beam to the cooling section. We also developed a preliminary design for the cooler section lattice for both hadrons and electrons. 3D PIC simulation have been performed. The beam parameters meet the cooling requirements. The further study will focus on the beam noise and beam halo.

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