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GENERATING SUPERGAUSSIAN DISTRIBUTION AND UNIFORM SLICED ENERGY SPREAD BUNCH FOR EIC STRONG HADRON COOLING*

E. Wang†, W. F. Bergan, Brookhaven National Laboratory, Upton, NY, USA
S. Benson, Thomas Jefferson National Accelerator Facility, Newport News, VA, USA
J. Qiang, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract

Strong Hadron Cooling (SHC), utilizing the coherent electron cooling scheme, has been extensively investigated for the Electron Ion Collider (EIC). Throughout our cooling optimization studies, we realized that a Super-Gaussian electron bunch offers enhanced performance in comparison to a Gaussian bunch. Our approach involves initiating the electron beam distribution in a double peak form, transitioning them into a Super-Gaussian distribution due to the longitudinal space charge. Subsequently, a chicane within the linac section compresses the bunch to meet the required bunch length. We tuned a third harmonic cavity amplitude to reduce the nonlinear term of the chicane. Moreover, given the low initial current leading to a small but non-uniform slice energy spread, we evaluated utilizing laser heating techniques to achieve a uniformly distributed slice energy spread. In this report, we discuss the concepts and simulation results.

INTRODUCTION

In the EIC conceptual design, Strong Hadron Cooling using Coherent electron Cooling (SHC-CeC) is employed to balance the hadron IBS and diffusion, thereby maintaining the emittance during collisions at 275 GeV and 100 GeV. [1, 2]. The injection energy of 25 GeV and collision energy of 41 GeV hadrons have to be cooled by a conventional electron cooler. We designed an Energy Recovery Linac (ERL) that could be used for both low-energy cooler and the SHC-CeC. Figure 1 shows the schematic layout of a hybrid ERL integrated SHC and low-energy cooler.

The concept of the gun to linac section was described in [3]: i) we use 197 MHz SRF cavities with 591 MHz harmonic cavities as the main booster cavity before the chicane. ii) With the chirp in the bunch, we compress the bunch length by a factor of 3 using chicane. iii) the electron beam goes through the series of 591 MHz superconducting Linac. iv) A laser heater after linac is used to get a uniform sliced energy spread. At the entrance to the chicane, the beam can be kicked out for the low-energy cooler. Once the initial injection of the hadron beam is achieved, it will be boosted to operate in collision mode. The electron beam passes through the 591 MHz cavities for the SHC-CeC.

SHC-CeC will amplify the density-modulated microbunch to produce a wakefield strong enough to kick the hadron particles in momentum space. The amplification process depends on the current. For uniform amplification of the microbunch, a constant current along the bunch is required, like a beer-can distribution. We can initially generate a beer-can distribution bunch, however, the longitudinal space charge reduces the current at the beam's edge, resulting in a Gaussian-like longitudinal distribution at the end of the injector. In this paper, we proposed a method using laser shaping, compression, and laser heating to produce a uniform current and uniform slice energy spread electron bunch for SHC-CeC.

METHODS

Generate Super-Gaussian Distribution Beam

The longitudinal space charge force can be expressed as

$$E_z \propto \frac{Z_0}{\beta\gamma^2} g \tag{1}$$

where g is geometry factor that is relevant to the beam distribution and beam pipe geometry. Z_0 is the vacuum impedance. At low energy, the longitudinal space charge is large due to small γ^2. Our method is to apply a dual-peaks initial distribution on the beam, by the longitudinal space charge, the dual-peaks will be smoothed out and evolve to a uniform-like Super-Gaussian distribution.

In a HVDC photogun, the cathode temporal response is much less than 1 ps while the bunch length is in 0.1-1 ns. Therefore, the initial longitudinal distribution of the beam can be assumed to be the same as the laser longitudinal distribution. We used micropulse stacking to generate an initial longitudinal distribution. For practical and stable operation, we use eight micropulses stacked together and independently control the amplitude of each pulse. Adjacent pulses are spaced 2 σ apart, and each micropulse with the same spin direction is spaced at least 4 σ apart to prevent interference.

A Super-Gaussian electron distribution at the end of the linac has the functional form:

$$f(z) = Ae^{-\{\frac{z^2}{2\sigma^2}\}^p} \tag{2}$$

$$A = \frac{p}{\sqrt{2}\sigma\Gamma(\frac{1}{2p})}\ , \tag{3}$$

where p can be used to evaluate the flatness and flat range of the longitudinal profile. Solving analytically a 3D space

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy
† wange@bnl.gov

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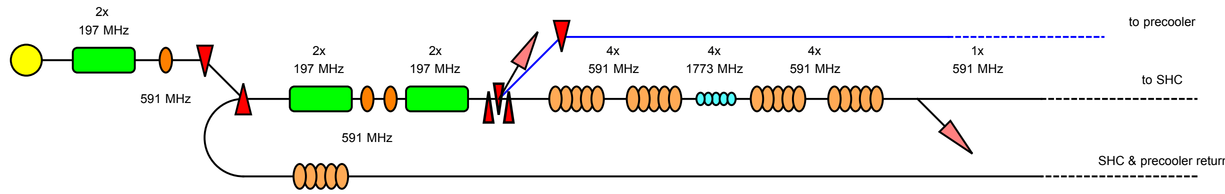


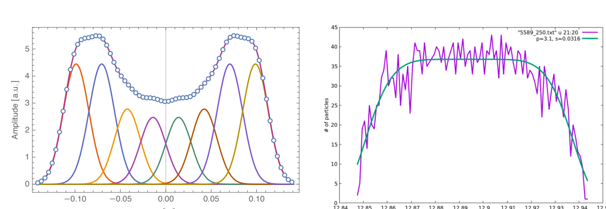
Figure 1: The schematic layout of the gun through the linac.

charge issue with an artificial beam distribution can be challenging. We use General Particle Tracking (GPT) to evaluate the distribution. The main changes in particle distribution will occur from the gun up to the chicane, where the beam energy is around 14 MeV.

As a result, our objective is to maximize the value of p in Eqn. 3 at the chicane entrance. The variables represent the amplitude of eight Gaussian micro-pulses. To streamline the process, we assume symmetry between the head and tail of the bunch, reducing the variables from eight to four. The initial RMS bunch length is a variable for optimization. In the case of a pencil-shaped bunch, a longer bunch length can decrease the space charge and result in a smaller transverse emittance, but it may also raise the energy spread due to RF curvature. Therefore, we aim for an RMS energy spread of less than 2×10^{-4}.

In the injector, the bunch is always at the RF crest to achieve the maximum accelerating voltage, and the RF voltage is also set to the maximum. The booster cavities between the merger and chicane were configured to generate a beam chirper, which will be further discussed in the next section. As the longitudinal space charge and transverse space charge are uncoupled, we can optimize them independently. All focusing elements, such as solenoid strength, are optimized to minimize transverse emittance after optimizing the longitudinal distribution. After optimization, the initial and final longitudinal laser distribution is shown in Figure 2.

At the entrance of the chicane, the beam longitudinal distribution can be fitted by the super Gaussian distribution with $p = 3.1$ and σ =0.03 m. The eight micro-Gaussian pulse sigma is 2 mm with relative amplitudes: 9, 9, 8, 5, 5, 8, 9, 9 respectively from the 1st to the 8th micropulse.
To minimize the transverse emittance and reduce halo, we utilize a 0.9 σ truncated Gaussian distribution which has a



(a) Optimized initial hollow distribution of beam from cathode.

(b) The GPT simulated longitudinal bunch distribution at the entrance of chicane

Figure 2: The laser initial distribution and the beam distribution at the end of injector.

nearly linear radial electric field. The achievable minimum emittance at the injector's end is 2.5 mm−mrad.

Impact of the Beam Compression

To achieve the necessary bunch length for different operation modes, we employ a chicane-type bunch compressor to achieve a 7-9 mm bunch length in RMS. Then, we can utilize a 591 MHz multi-cell SRF cavity for continuous beam acceleration. With the initial Super-Gaussian beam passing through the four-dipole chicane, a non-uniform distribution beam will be generated as a result of the nonlinear effect of the chicane:

$$z = z_0 + R_{56}\frac{\delta E}{E_0} + T_{566}\left(\frac{\delta E}{E_0}\right)^2 , \tag{4}$$

where R_{56} is chicane's longitudinal dispersion and T_{566} is the 2nd-order longitudinal dispersion.

To mitigate the nonlinearity of chicane-induced distribution changes, we utilize an upstream third harmonic cavity to produce correlated energy spread. A quadratic correlated energy spread can be written as

$$\frac{\delta E}{E_0} = a z_0 + b z_0^2 . \tag{5}$$

With Eqn. 4, we can get

$$z = (1 + aR_{56})z_0 + (bR_{56} + a^2 T_{566})z_0^2 . \tag{6}$$

When $aR_{56} + a^2 T_{566} = 0$, the final distribution will be the same to the initial distribution but with compression or stretching. The T_{566} of four dipoles chicane is $-(3/2)(R_{56}/\cos^2\theta_0)$ and R_{56} is $(2L/\cos\theta_0)(1-(1/\cos^2\theta_0))$.

The energy spread can be written as

$$\frac{\delta E}{E_0} = \frac{k(3eV_3\sin(\phi_1+\pi) - eV\sin(\phi_1))}{E_0} z_0 + \frac{k^2(-1/2eV\cos(\phi_1) - 9/2eV_3\sin(\phi_1+\pi))}{E_0} z_0^2 \tag{7}$$

where the first term is the compression factor determined by the required bunch length divided by the initial bunch length. The necessary energy gain from the RF cavity is

$$e(V_1\cos(\phi 1) + V_3\cos(\phi 1 + \pi)) = E_0 - E_1 \tag{8}$$

where E_1 is the initial energy and E_0 is the beam energy before getting into the chicane. We find that the ratio $V_3/V_1 \approx 1/6$. The electron bunch will be accelerated to

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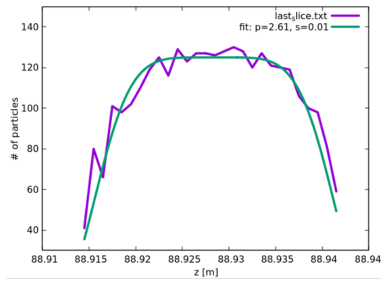
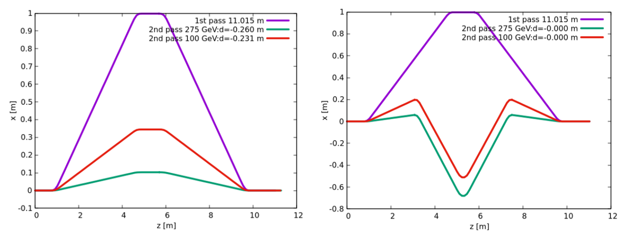


Figure 3: The current profile along the bunch at the end of linac.



(a) 1st pass bean and 2nd pass beam trajectory in a four dipole chicanes

(b) 1st pass bean and 2nd pass beam trajectory in a splitter.

Figure 4: Comparison of typical four dipole chicanes and splitters beam path with different beam energy.

150 MeV in the linacs with eight 5-cell 591 MHz cavities and four 1773 MHz third harmonic cavities. The beam is slightly off-crest to eliminate chirp. Lowering the voltage of the downstream 1773 MHz cavity can offset the correlated energy spread produced upstream. With this set up, at the end of linac, we get a Super-Gaussian distribution with p of 2.61 (as shown in Fig. 3). More precise optimization is taking on bmad using genetic optimizer [4].

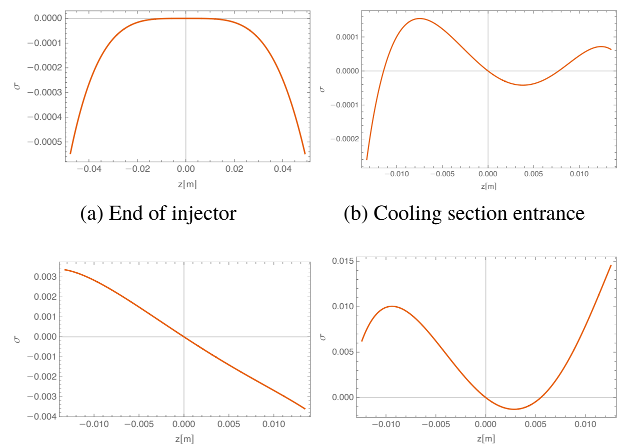
Chicane Design in the ERL Linac

Using the scheme described above, we need to install an $R_{56} = -0.47$ m chicane in the the ERL to regulate the bunch length [3]. However, two distinct energy beams will experience varied path lengths in the chicane (such as Fig. 4a), as depicted by

$$E\frac{c\Delta\phi}{2\pi f} = R_{56}\Delta E \ , \qquad (9)$$

where $\Delta\phi$ is the phase difference between the injection beam and recovery beam, and Eqn. 4a, resulting in decreased energy recovery efficiency and necessitating significantly more power from the RF couplers. In our chicane design, R_{56} is –0.47 meters and causes a path length difference of about 0.254 meters for the 14 MeV first pass beam and 135.7 MeV second pass beam. To achieve isochronous conditions for both high and low energy beams, we split the two return beams into separate paths, as illustrated in Figure 4b.

We developed a five-dipole splitter. The field of the middle three dipoles can be adjusted to accommodate various 2nd pass beam energies, allowing for the 2nd pass beam path length to match that of the 1st beam path. When switching the energy from 150 MeV to 51 MeV, the three dipoles need



(a) End of injector (b) Cooling section entrance

(c) Chirp at return (d) Beam dump enterance

Figure 5: The longitudinal phase space along the ERL.

to be shifted by approximately 20 cm. We placed quadrupoles between the first two and last two dipoles to achieve achromatism in the section. The maximum dispersion of the splitter section is –0.62 meters.

With double quadrupoles on each side of the chicane, the beam's normalized transverse emittance growth increased from 2.4 mm–mrad to 2.51 mm–mrad. At the end of the linac, the transverse emittance is well preserved. With a laser heater, the RMS sliced energy spread is around 0.055%.

Energy Recovery Match

Once the chicane is inserted into the linac section, there's a notable change in the bunch length before and after it. In ERL mode, the initial beam path undergoes compression via the chicane to yield a shorter bunch for experiments, as shown in Fig. 5.

The second beam path experiences a 180° delay in the 197 MHz RF cavity, however, resulting in a reverse chirp. Consequently, the elongated beam can not be injected into the 591 MHz linac. One possible solution involves reversing the R_{56} of the splitter. However, this necessitates additional space with strong focusing, and compromises beam quality. Alternatively, our approach entails integrating an RF cavity into the return loop and adjusting the R_{56} of "Bates bending" as the longitudinal matching segment. After matching the longitudinal phase space, 5 illustrates achieving a 1.7% peak-to-peak energy spread at the beam dump.

CONCLUSION

We've developed an SHC ERL section capable of producing nearly uniform current and energy spread beams for several energy modes. Additionally, we've developed a solution for integrating a chicane into the ERL. Simulation results demonstrate that the beam exiting the linac section satisfies the SHC requirements.

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