ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPGW111

START TO END SIMULATION ON BEAM DYNAMICS IN COHERENT ELECTRON COOLING ACCELERATOR*

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Abstract

A Coherent electron Cooling (CeC) has a potential of substantial reducing cooling time of the high-energy hadrons and hence to boost luminosity in high-intensity hadron-hadron and electron-hadron colliders. In a CeC system, a high quality electron beam is generated, propagated and optimized through a beam line which was carefully designed with consideration of space charge effect, wakefields and nonlinear dynamics such as coherent synchrotron radiation and chromatic aberration. In this paper, we present our study on the beam dynamics of such a beam line and compare the simulation result with what was measured in experiment.

INTRODUCTION

The CeC beamline (Figure 1) consists of low energy beam transport (where electron beam is prepared and accelerated to a total energy of 14.6 MeV), a dogleg section to transport the beam to a common section where the electron beam is co-propagating with the hadron beam. In the common section, the electron beam is picking up information from hadron beam in modulator section (consists of four quadrupoles for beam optics tuning). Then the information is amplified in the FEL section and reacts back to the hadron beam with proper phase adjustment to cool the hadron beam, i.e., to reduce the hadron beam's energy spread and phase space areas. The performance of the CEC is highly dependent on the electron beam's quality. Thus a self-consistent start to end (S2E) simulation of the accelerator section is crucial in determining the amplifier's (FEL) performance and in predicting the machine setups to characterize the cooling.

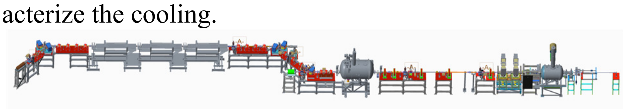

Figure 1: Engineering drawing of CeC beamline (electron beam travels from right to left).

INJECTOR-ACCELERATOR SECTION

There are three RF systems in the CeC's accelerator section – a quarter-wave SRF gun cavity (1.25 MeV, 113 MHz), two NC bunching cavities (250 keV, 500 MHz) and a 5-cell SRF linac (13.1 MeV, 704 MHz). All three RF systems are operated at harmonics of a global clock, 78 kHz – the RHIC's revolution frequency. In between cavities, 6 solenoids are used for electron beam's phase space manipulation and beam size control. More specifically, the solenoid in between gun cavity and bunchers is used to perform emittance compensation, i.e., provide optimal transverse focusing to minimize emittance growth from space charge effect of low energy electron beam. After the beam gains energy chirp from bunching cavities and experiences ballistic compression in long straight section (~ 10 m to linac), the beam current increases to ~ 50 – 100 amps thus space charge effect is stronger. We used 5 solenoids in this 10-m long drift to control emittance and beam size to match to optimal beam conditions at the entrance of the linac.

There are many different beam dynamics in the beam line that could potentially affect beam qualities severely, namely space charge, wakefields, shielding effect from vaccum chamber etc. Doing all beam dynamics in one simulation code is unimaginable. We chose IMPACT-T [1] to simulate beam's 6D phase space evolution along the beamline while used many other codes to calculate other effects, e.g., ECHO/ABCI for wakefields [2], SUPERFISH/CST/ACE3P for RF fields, etc. We benchmarked our calculated beam properties (like beam envelope, phase space distributions, energy evolutions) in IMPACT-T with many other well established beam dynamics codes e.g., GPT/PARMELA/ASTRA. Figure 2 shows a 3D simulation of our gun cavity in CST.

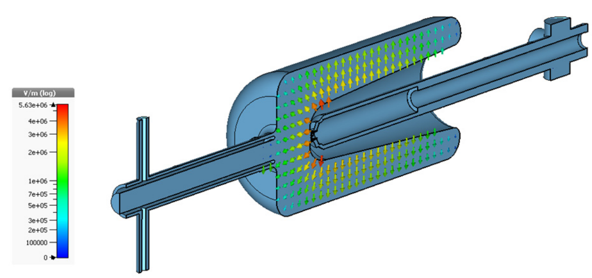

Figure 2: RF fields simulated in CST with cathode stalk inserted shows strong focusing at the cathode.

Our cathode stalked is recessed so that the initial RF field provides a strong transverse focusing to the beam. Figure 3 shows the on axis field for various cathode locations. The fields simulated from these codes were then imported into IMPACT-T to interact with electron beam. One important beam issue was the wakefields originated from busy sections along the beam line. One of which would be around our bunching cavities. Figure 4 shows the wakefields simulated by ECHO/ABCI in and around the buncher assembly which are the dominant contribution along the beamline.

* Work is supported by Brookhaven Science Associates, LLC under Contract No. DEAC0298-CH10886 with the U.S. Department of Energy, DOE NP office grant DEFOA-0000632, and NSF grant PHY-1415252.
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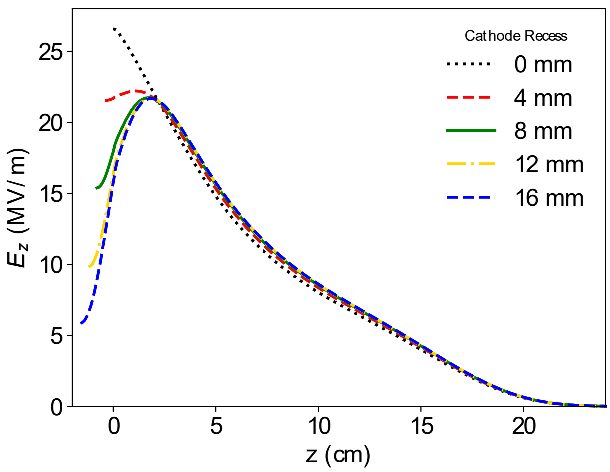

Figure 3. With adjustable cathode recess position, the proper focusing force can be selected to better suit beam dynamics in the gun.

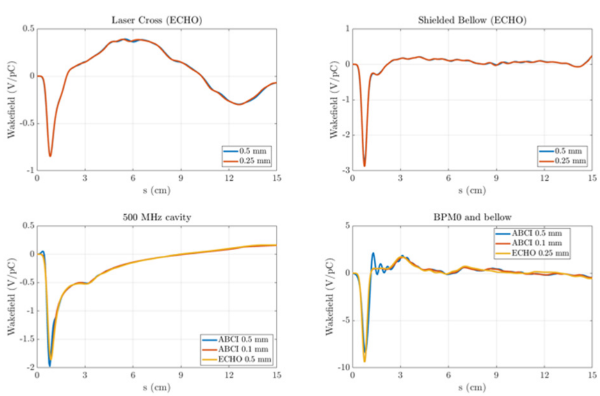

Figure 4. wakefields (around bunching cavities) simulated in ABCI and ECHO have decent agreement.

Optimization in IMPACT-T takes all beam line components as variables (magnets, cavities…). The optimization goals were to achieve high peak current for core part of the beam while keep the overall emittance low. Figure 5 shows the longitudinal phase space of electron beam at the end of linac (@ ~ 13 meters). For a beam with bunch charge 1 nC, the peak current of the beam exceeds 100 A and sliced energy spread (RMS) is lower than 2e-4.

The emittance evolution for such machine setting can be seen in Figure 6. At the end of the accelerator section, the projected emittance < 6 um with peak current > 100 A satisfies experimental requirements. We benchmarked our findings in IMPACT-T and others beam dynamics codes, such as GPT/ASTRA/PARMELA and developed an online app to show evolution of beam envelope, emittance, energy, bunch length, etc, as is shown in Figure 7. Such GUI can help us understand our beam qualities with current machine settings and greatly enhance our routine machine tuning with online modelling.

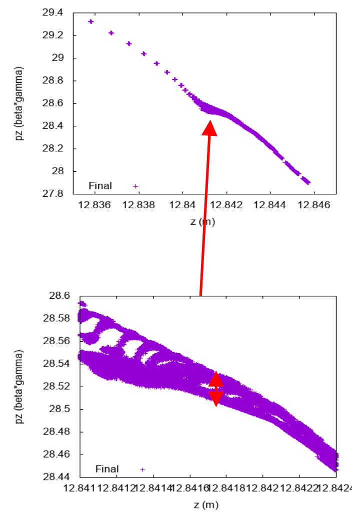

Figure 5. longitudinal phase space at the end of linac shows the beam has a core with peak current > 100 A and slice energy spread < 2e-4 with correlated energy chirp ~ 2e-4. The core consists of ~ 80% of the total charge of 1 nC.

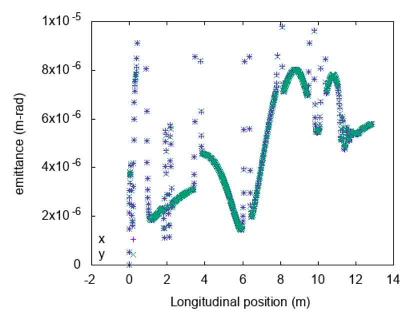

Figure 6. beam emittance at the end of beamline with optimized settings ~ 5.7 um, satisfies the experimental requirement.

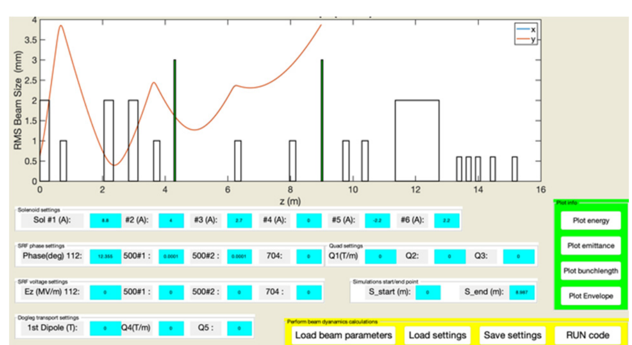

Figure 7. An online modelling of beam dynamics in accelerator section based on beam simulation for CeC experiment.

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DOGLEG AND FEL AMPLIFIER

After the linac, we used 8 quadrupoles (3 after linac, 1 in the middle of dogleg and 4 before the undulator) to match the beam optics from the exit of low energy beam transport (LEBT) to the entrance of FEL (2 quads in dogleg are fixed for dispersion matching). We used alternating quadrupole settings to minimize the beam size along the beam line. Figure 8 shows the optics function calculated in ELEGANT [3] using the particle distribution at the end of LEBT.

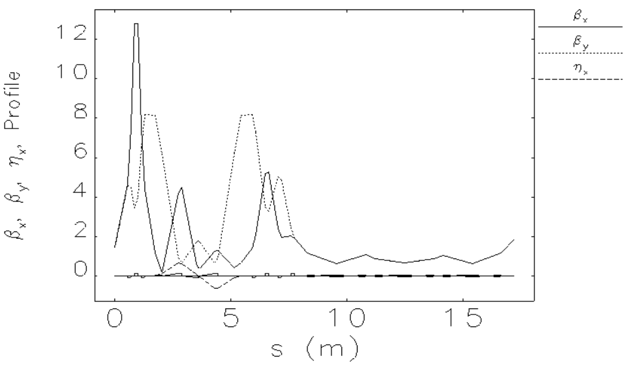

Figure 8. optics matching from the end of LEBT to and along the FEL section was done in ELEGANT using alternating quadrupoles.

We studied chromatic aberration and coherent synchrotron radiation in our ELEGANT simulation. Figure 9 shows when energy spread is large, chromatic aberration causes severe beam quality degradation.

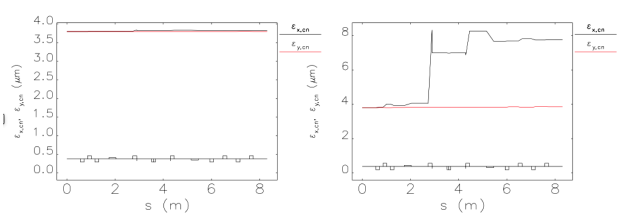

Figure 9. beam emittance can be blown up when the energy spread is large (~ 1%, right). The emittance growth in dogleg is minimal while energy spread is reasonably low (~ 0.1%, left).

The FEL simulation was performed in the well known GENESIS code, where we study and record the evolution of bunching factor for different longitudinal slices. To extract the growth of the imprint from ion-electron interaction with effect from shot noise (thus causing saturation), we simulate the electron beam in the undulator with and without an initial δ like signal and calculate the difference. Figure 10 shows a schematic drawing of how we perform such calculation using GENGESIS. Being the difference between two complex numbers, such a FEL response is a complex function, i.e., it is described both by the amplitude, and the phase.

$$b_1(z)=|b_1(z)|e^{i\theta_1(z)},\ b_2(z)=|b_2(z)|e^{i\theta_2(z)}$$

$$b_s(z)=|b_s(z)|e^{i\theta_s(z)}\equiv b_2(z)-b_1(z)$$

Electron slice with highest bunching factor is selected and its amplitude and phase are recorded along the FEL as shown in Figure. 11. The undulators end at about 7.5 m, and we want to operate the FEL in linear regime where it has predictable phase information, i.e., the variation of phase of the signal over different random noise is low. The bunching amplitude non-linear regime when SASE noise is close to saturation.

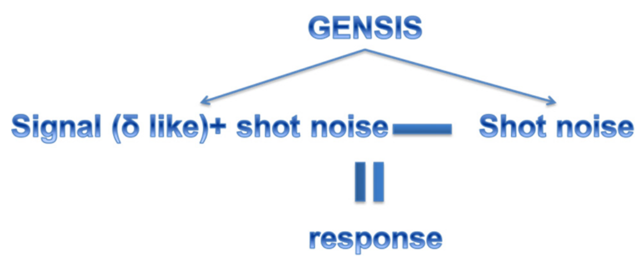

Figure 10. We calculate the gain (growth of bunching factor) of the imprint from ion beam on electron beam by taking the difference of bunching factor evolution (amplitude and phase) in GENESIS with and without signal.

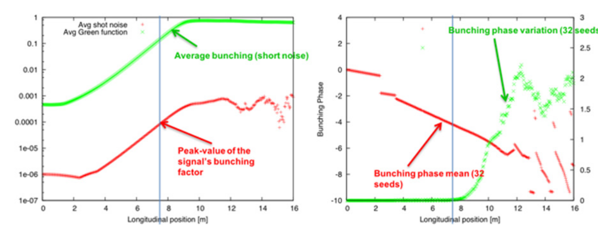

Figure 11. GENESIS simulated evolution of bunching factor of an imprint indicates we have plenty of gain for cooling (left). We operate our FEL in linear regime where phase variation due to shot noise stays low (right).

CONCLUSION

We performed S2E simulation in CeC beamline and studied various beam dynamics issues. The designed electron beam can satisfy experiment requirements

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