ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-TUP069

SIMULATING BEAM DYNAMICS IN COHERENT ELECTRON-COOLING ACCELERATOR WITH WARP

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Abstract

Coherent Electron Cooling (CeC) [1] is a novel cooling technique based on amplification of interaction between hadrons and electron by an FEL. If proven, this CeC could bring a revolution in hadron and electron-hadron colliders. A dedicated CeC proof-of-principle experiment is under way at RHIC collider (BNL) using a sophisticated SRF accelerator for generating and accelerating electron beam. This paper is dedicated to studies of beam dynamics in the CeC accelerator and specifically to emittance preservation in its ballistic compressions section. Two 500-MHz RF cavities are used for generating the necessary energy chirp leading in 1.56-MeV, 0.5-nsec-long electron bunched to compress them to 25-psec duration downstream. During the commissioning of the CeC accelerator we noticed that beam emittance can be strongly degraded when electron beam passes these 500 MHz RF cavities off-axis. We used a full 3D PIC code WARP to simulate effect of the off-axis beam propagation through these cavities.

INTRODUCTION

The CeC PoP experiment [2] is divided into two sections, the accelerator section and the cooling section (see Fig. 1). In the accelerator section, 1.05-MeV electron beam is first generated by a 113 MHz SRF gun. This electron beam is then "bunched" by two 500 MHz RF cavities and accelerated by a 704-MHz RF cavity to about 14.6 MeV. This acceleration provides the CeC electron beam with enough speed to match up with the RHIC's hadron beam. After passing through a dogleg, electron beam will enter the cooling section.

The first part of the cooling section is the modulator, where the electron – hadron interaction takes place, the CeC electron beam will carry the density imprints of the RHIC's hadron beam which will then be amplified by the FEL undulators. At the end of cooling section, the electron beam will be allowed to merge with RHIC's hadron beam and perform coherent electron cooling.

During the commissioning of CeC PoP machine, we allowed a 1.05-MeV electron off-axis electron beam to pass through two 500-MHz RF cavities. The cavities were aiming to provide an energy chip for compressing a 0.5-nsec electron beam to 25 psec downstream. While we varied the phase of these cavities, a correlation between the phase and transverse positions of the off-axis electron beam following the cavities was observed. The data of transverse position of the off-axis electron beam was recorded by a beam-center position monitor (bpm) about 2 meters after the second 500 MHz RF cavity. The phase of both cavities was changed linearly in time, while a sine-wave like pattern of bpm readings were shown (see Fig. 2). This whole event was simulated by using the full-3D PIC code WARP. In WARP, an electron beam with the same initial condition to the experiment was used. It passed through two 500 MHz RF cavities with multiple offset values in the y-direction. The control comparison was also performed by allowing the same electron beam to pass through the same cavities at the center of the cavities. Details are shown in the next section.

ANALYSIS

We first simulated the effect of a single 500 MHz RF cavity to an off-axis electron beam. The beam had the same initial condition as with that of the experiment. The phase of cavity was set into zero-crossing (The phase with no total kinetic energy gain for the beam, but energy chirp). This was the default setting for the experiment. During the simulation, we allowed both the off-axis beam and the centered beam (electron beam without offset to the cavity center) to pass through this RF cavity. Multiple beam profiles

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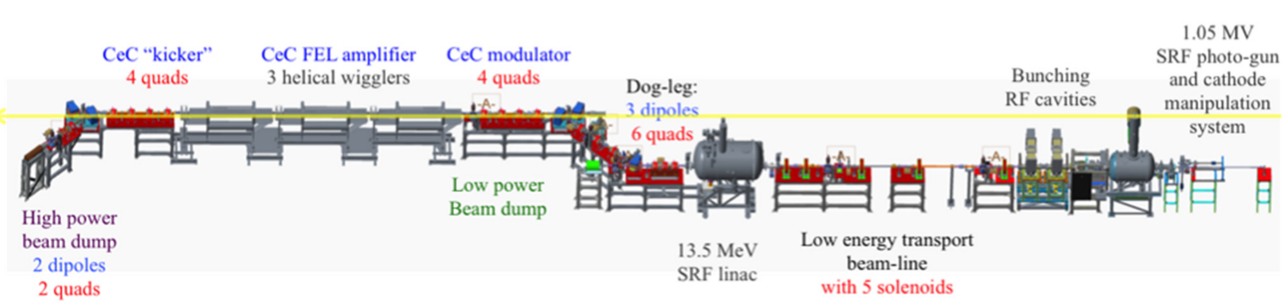

Figure 1: Schematic drawing of the CeC PoP Experiment machine. CeC electron beam travels from right to left.

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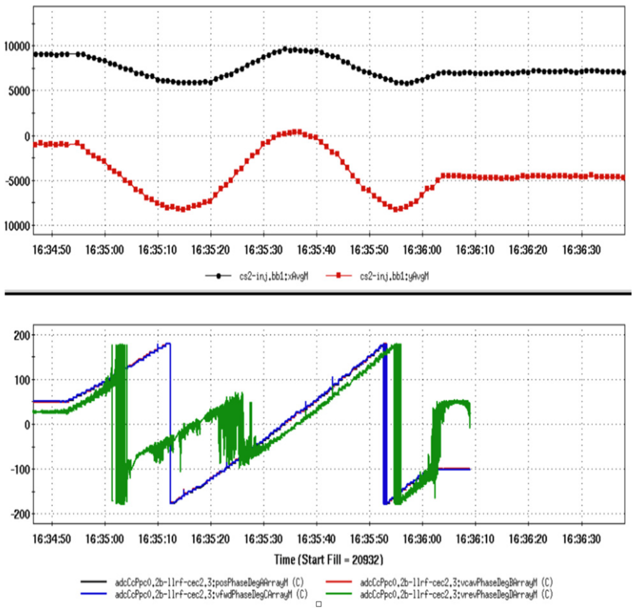

Figure 2: Experimental data of beam position monitor reading and 500-MHz cavity phase with off-axis electron beam.

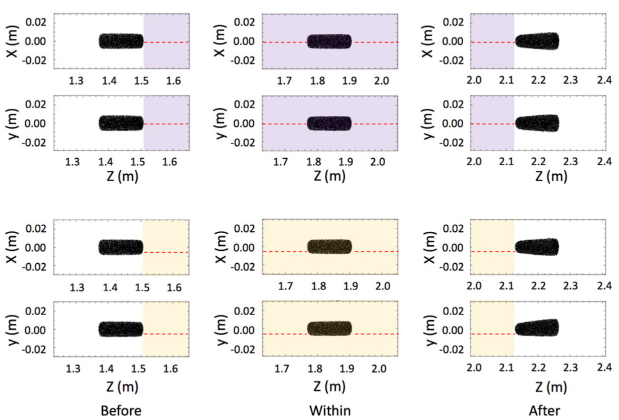

Figure 3: 2D beam profile comparison in (r,z) space. Purple and yellow region indicates the location of centered RF cavity and 5-mm +y off-axis RF cavity.

were recorded for both cases in the positions of before, inside, and after the RF cavity (see Figs. 3–6). Compared to the centered beam case (upper half of Figs. 3–5), an asymmetrical pattern was introduced to the off-axis beam after it passed through the RF cavity.

This pattern was in the same axis of the initial beam position offset relative to the cavity center, that being the y-axis (see Fig. 4). Also, this asymmetry in transverse phase space is affecting the beam center position significantly. Resulting a beam center position gain. However, the same effect had not been observed in the longitudinal direction (see Fig. 6). From this result, we can conclude that off-axis RF cavity dose create a transverse kick to the beam, in the same axis with the initial beam center position offset.

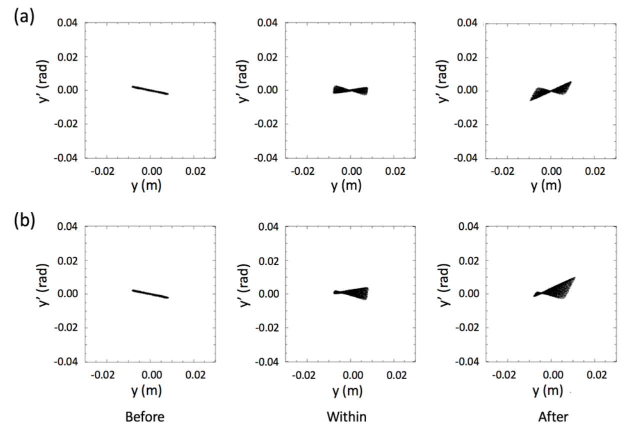

Figure. 4: Beam phase-space (y-y') comparison, starting with (a) a centered beam phase space, or (b) an off-axis beam phase space.

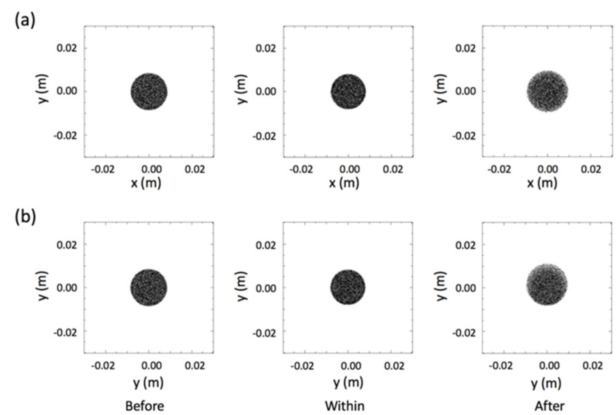

Figure 5: Two-dimensional (x-y) beam profile comparison, starting with (a) a centered beam profile, or (b) an off-axis beam profile.

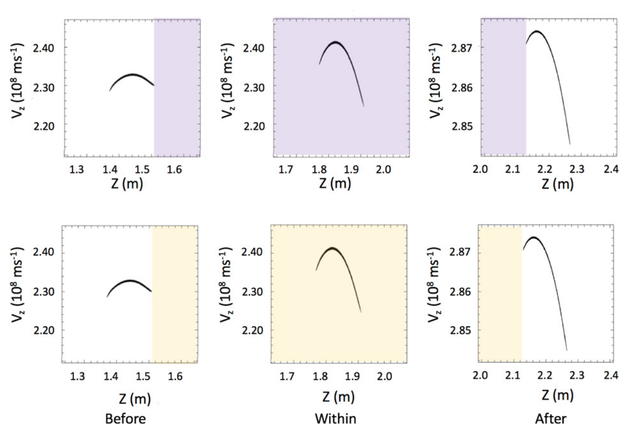

Figure 6: Longitudinal beam phase space (z-v_z) comparison. Purple and yellow region indicates the location of centered RF cavity and 5-mm +y direction off-axis RF cavity.

38th International Free Electron Laser Conference FEL2017, Santa Fe, NM, USA JACoW Publishing
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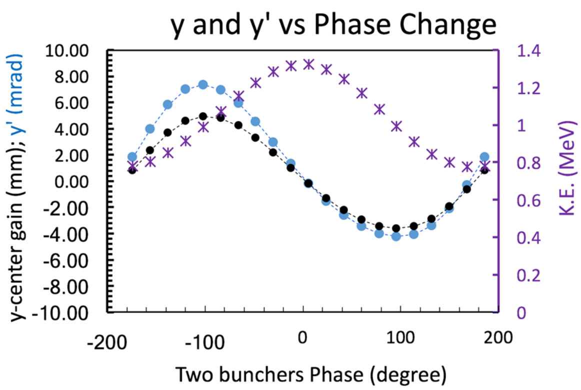

Figure 7: WARP simulation result on CeC electron beam passed through two 5-mm +y off-axis 500 MHz RF cavities.

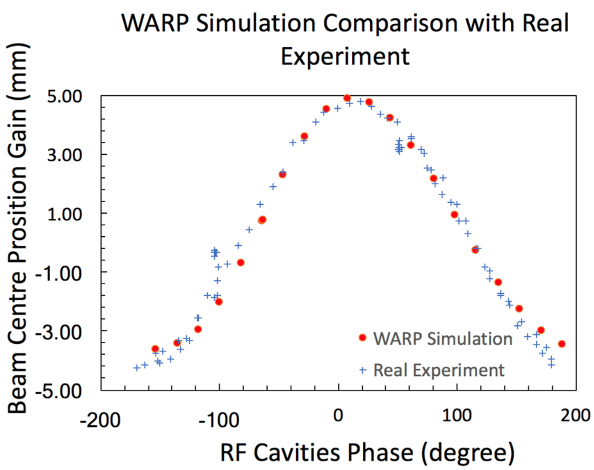

Figure 8: Comparison of WARP simulation with real experiment data of commissioning.

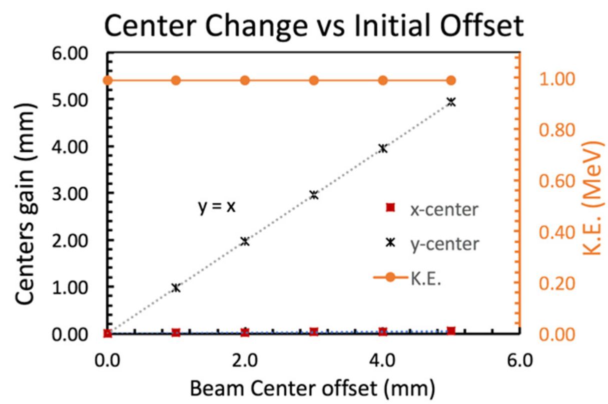

Figure 9: WARP Simulation result, showing final beam position offset for a given initial beam position offset.

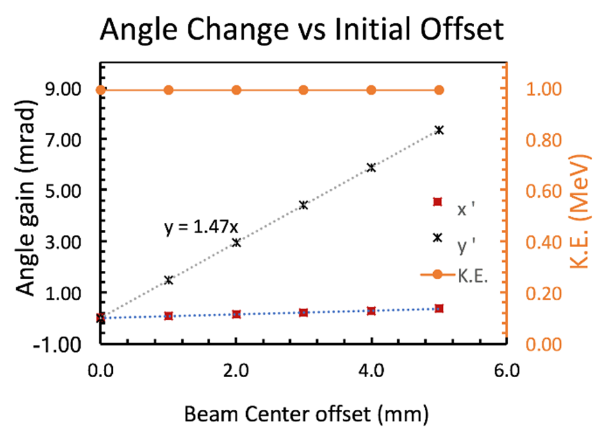

Figure 10: WARP Simulation result, showing final beam angle for a given initial beam position offset.

RESULTS

In the next simulation, the same off-axis electron beam was allowed to pass through two 500 MHz RF cavities, a recreation of the real experiment. The resulting beam center position gain was plotted against the RF phase change (see Fig. 7). Not only the beam center position gain, but also the final beam angle had a periodic oscillation while the RF cavities phase were changing. This result clearly indicates a similar sine-wave pattern as of that in (Fig. 1). However, it should be notice that the values of phase angle in (Fig. 7) is a dummy. Only the relative phase between data points carry meanings. After a constant shift in the phase data in (Fig. 7), we put on a comparison of WARP simulation (5 mm +y direction off-axis RF cavities) with the real experiment data (see Fig. 8).

The result shows a great agreement between WARP simulation and real experiment data. Beam center position after the RF cavities in WARP was drifting as expected in the experiment.

Moreover, according to the simulation, the drifting magnitude of both position and angle depend on the initial offset of the beam position, relative to the cavity's center (see Figs. 9 and 10). If we change the initial beam center position offset in a fixed RF phase, the final beam position and beam angle change linearly. Therefore, scanning RF phase of cavities will have no effect on the final beam center position and beam angle for an initially centered electron beam.

SUMMARY

In summary, WARP simulation on off-axis RF cavities had a great agreement with the real experiment during the CeC PoP machine commissioning. The final beam position and angle were modified along the same axis of the beam initial offset (between the initial beam center and the cavity center), by the phase of the RF cavities. At some phase angle, this offset can be canceled. While it can also be magnified in pluses or minus direction at certain phase angles. Resulting beam final center position and angle oscillate with the RF phase angle. Moreover, the magnitude of this oscillation depends linearly to the value of initial beam position offset. Larger the initial offset, larger the oscillation amplitude. There will be no oscillation for initial centered beam.

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In the future, we will use WARP to construct a full start to end simulation of CeC PoP machine. This not only can establish a new numerical model for the experiment, but also proof the capability of WARP simulation.

ACKNOWLEDGEMENT

Work is supported by Brookhaven Science Associates, LLC under Contract no. DEAC0298CH10886 with the U.S. Department of Energy, DOE NP office grant DE-FOA-0000632, and NFS grant PHY-1415252.

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