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ELECTRON BEAM REQUIREMENTS FOR COHERENT ELECTRON COOLING FEL SYSTEM*

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Abstract

The proof of coherent electron cooling (CeC) principle experiment is currently on-going and due to the limitations of the 5-cell SRF accelerating LINAC, the final achievable energy of the electron beam is 15 MeV, i.e. 68% of its originally designed value, 22 MeV [1]. Consequently, all evaluations and simulation results need to be revisited for the reduced beam energy. This work focuses on the requirements of the electron beam quality in order to achieve the desired amplification from the FEL amplifier of our CeC system.

FEL AMPLIFIER OF THE PROOF OF CEC PRINCIPLE EXPERIMENT

As shown in Fig. 1, the FEL amplifier of the CeC system consists of three helical undulators. Illustrated in Fig. 2, the length of each undulator is about 2.49 meters. The separations between any two adjacent undulators are 42.25 cm where phase shifters are installed to match the phase of electrons with that of the radiation [2]. The undulator period is 4 cm and for the current set-up, the undulator field on axis is 0.134 T, which correspond to an undulator parameter of $a_w = 0.5$. The originally designed gain in the bunching factor is 100, requiring peak current about 100 A for 22-MeV electron beam with normalized RMS emittance smaller than 5 mm.mrad and RMS energy spread within 0.1%.

During RHIC run 17, the CeC system is commissioned and it is found that the cavity voltage of the 5-cell SRF LINAC is limited to 13.5 MeV and hence the maximal achievable energy of the electron beam is 15 MeV. Apart from all necessary modifications of the diagnostic system, the cooling process needs to be re-visited and here we present our preliminary studies of the requirements on the electron beam qualities for achieving the desired gain from the FEL amplifier.

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TOOLS AND SIMPLIFICATIONS

Since the FEL amplifier consists of three undulators with no quadruples in between, the beta functions vary along the amplifier section. Figure 3 (orange) shows the designed beta functions, which give minimal variation of the electron beam size along the amplifier.

We use Genesis 1.3 to investigate what are the requirements on electron beam quality to achieve the bunching gain about 100 [3]. For a preliminary estimate, we simplify the FEL amplifier as a single undulator of 7.5-m long with the undulator period of 4 cm and undulator parameter of 0.5.

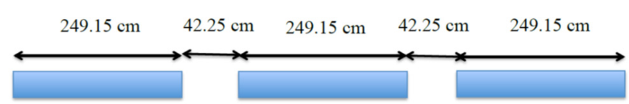

Figure 2: Illustration of the FEL amplifier of the CeC experiment.

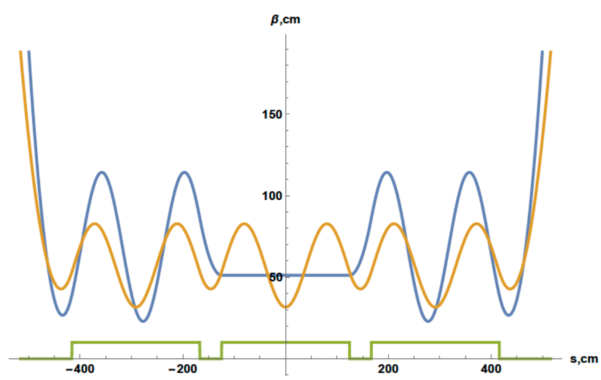

Figure 3: Variation of beta function along the FEL amplifier. Orange: the designed beta function of the amplifier, which gives minimal variation of electron beam size. Blue: one of the un-optimized lattice designs where the beta function is matched at the middle undulator but the overall variation of beam size is large.

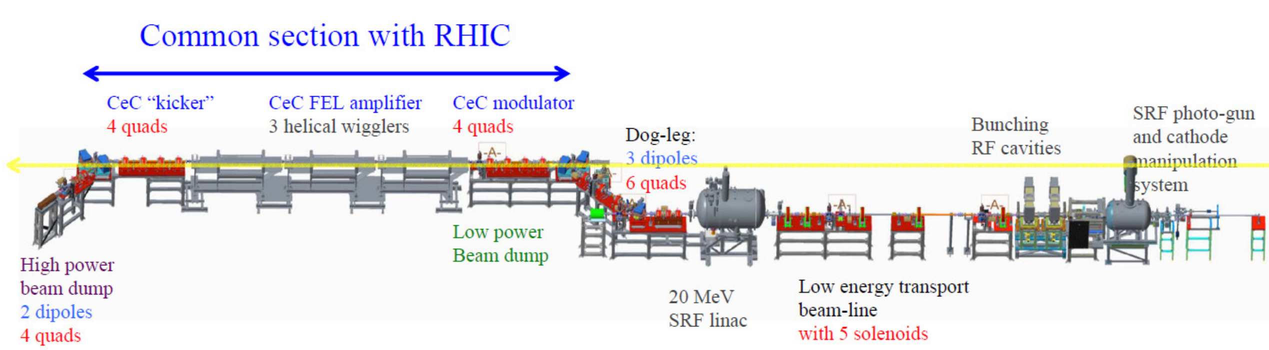

Figure 1: Layout of the proof of CeC principle experiment at RHIC IP2.

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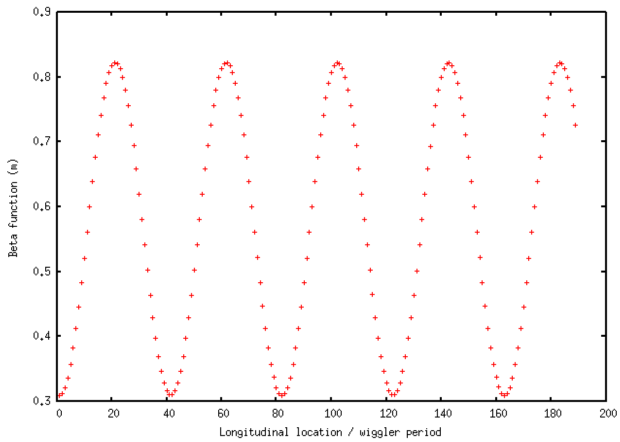

Figure 4: Beta function as calculated from the beam size variation obtained from Genesis simulation. The simulation is for a 7.5-m long undulator with 4 cm of undulator period. The initial electron beam size is chosen such that the beta function variation is similar to that of Fig. 3.

For each Genesis simulation, the initial electron beam size is chosen such that the variation or the beam size is similar to that of the designed lattice shown in Fig. 3 (orange). As shown in Fig. 4, the beta function calculated from the beam size variation in the simulation varies from 0.3 meters to 0.8 meters, successfully mimicking that of the Fig. 3 design.

To obtain the wave-packet created by density modulation of a single ion, we mostly run Genesis with quiet start and putting the expected initial bunching factor, i.e. 1e-6, into one slice of the electron beam. To ensure the FEL works in the linear region, we run separate simulations with shot noise on and check whether the exponential growth of the bunching factor reaches saturation.

SIMULATION RESULTS

In order to investigate how the peak current influences the FEL gain, we start the simulation with uniform current distribution. Figure 5 shows the profile of the wave-packet induced by an initial modulation located at zero. The amplitude of the initial bunching factor is 1e-6, as what expected from the CeC modulation of a single ion. As the longitudinal velocity of the electrons are slower than that of the ion inside the undulator, the ion slips forward with respect to the initial modulation. At the exit of the undulator, the slippage is given by:

$$\Delta L = N_u \lambda_0 \frac{a_w^2}{1+a_w^2} .$$

where N_u is the length of the undulator divided by undulator period, λ_0 is the optical wavelength, and a_w is the undulator period. For $N_u = 188$ and $a_w = 0.5$, the ion slips 37 optical wavelengths with respect to the location of the initial modulation.

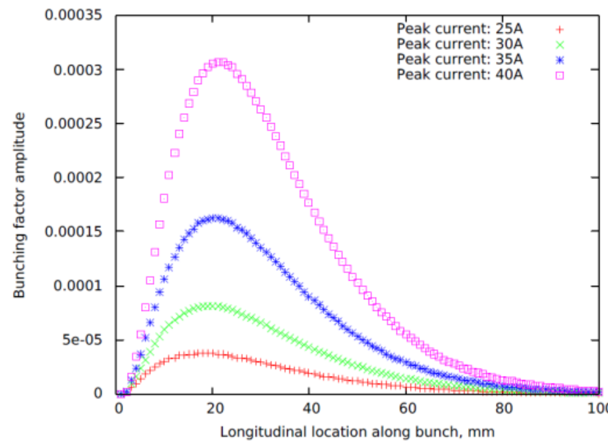

Figure 5: Amplitude of bunching factors along the wave-packet at the exit of the FEL amplifier. The initial modulation is at origin with amplitude of 1e-6. The electron beam has uniform longitudinal profile with various peak current as shown in the plot. The normalized RMS emittance is 5 mm.mrad and the RMS energy spread is 0.1%.

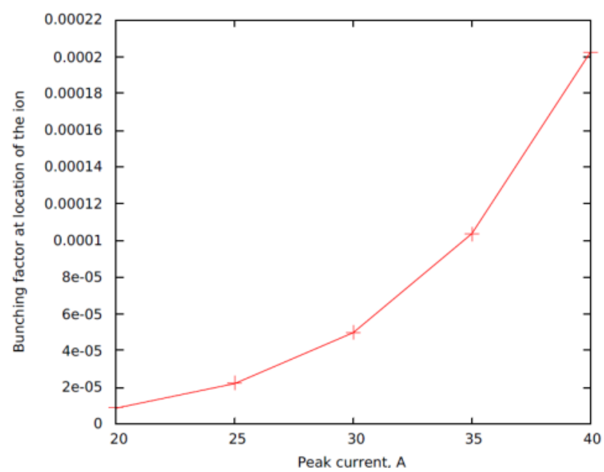

Figure 6: Amplified bunching factor at the location of the ion for various electron beam peak current.

Figure 6 shows how the amplified bunching factor at the location of the ion varies with the peak current of the electron beam. Simulations show that to achieve the desired gain of 100, the required peak current is 35 A. In order to check at what limit of peak current, the FEL saturates from shot noise, we run Genesis with shot noise turned on. Figure 7 shows that for peak current up to 40 A, the maximal bunching factor grows exponentially and the FEL works in the linear region. For peak current above 45 A, the variation of maximal bunching factor starts to deviate from exponentially growing, indicating the onsite of saturation.

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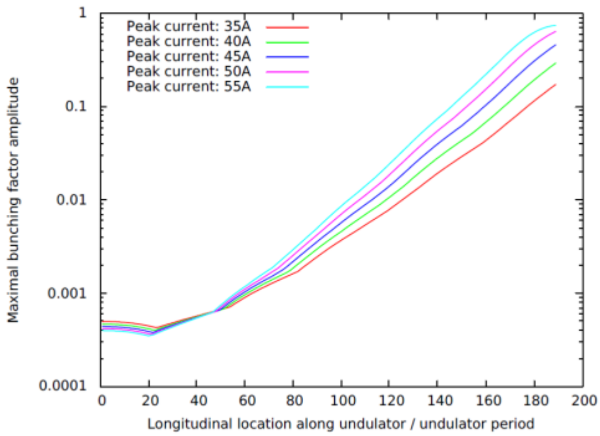

Figure 7: Growth of the maximal bunching factor along the undulator for various electron beam peak current.

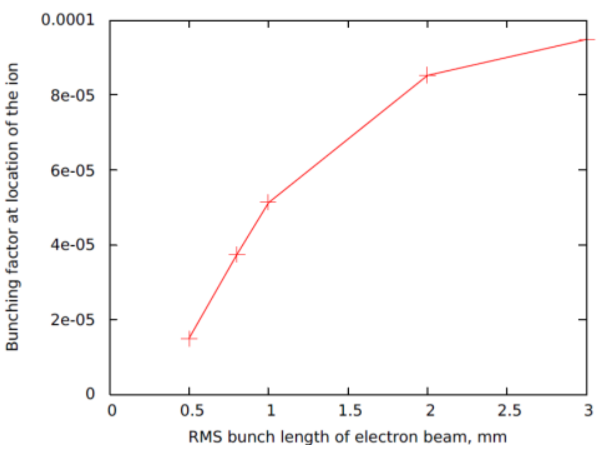

Figure 8: The amplitude of the amplified bunching factor at the location of the ion for various electron RMS bunch length. The peak current is 35 A and the longitudinal profile of the electron beam is Gaussian. The RMS normalized emittance is 5 mm.mrad and the RMS energy spread is 0.1%.

As the FEL instability relies on the coherent interaction of the radiation and the electrons, the electron bunch should be long enough to sustain such interaction. In order to investigate the influence of electron bunch length, we then run Genesis with Gaussian profile with various RMS bunch length. As shown in Fig. 8, the FEL amplification reduces by more than 20% once the RMS bunch length is longer than 2 mm.

The FEL amplification is also affected by the emittance of the electron beam. As shown in Fig. 9, the emittance should be kept under 6 mm.mrad to avoid substantial reduction (more than 30%) in FEL gain.

As expected, the most significant influences of FEL gain come from the energy spread. Figure 10 shows that the FEL gain reduces by a factor of two as the energy spread increases from 0.1% to 0.15%. Consequently, the RMS energy spread should not be larger than 0.1%.

SUMMARY

By running Genesis with a simplified model for the FEL amplifier of the CeC experiment, we obtained various requirements on the electron beam quality in order to achieve a gain of 100. To avoid reduction of gain by more than 30%, the electron beam peak current should be around 35 A with the RMS bunch length longer than 2 mm. The normalized RMS emittance should be smaller than 6 mm.mrad and the relative RMS energy spread should be within 0.1%.

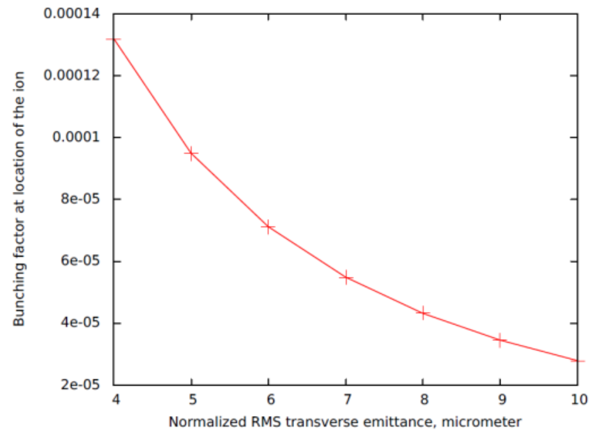

Figure 9: The amplitude of the amplified bunching factor at the location of the ion for various electron RMS emittance. The peak current is 35 A and the longitudinal profile of the electron beam is Gaussian with RMS bunch length of 3 mm. The RMS energy spread is 0.1%.

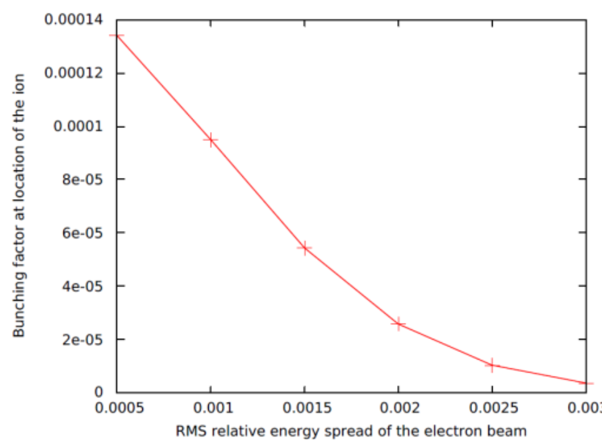

Figure 10: The amplitude of the amplified bunching factor at the location of the ion for various electron RMS energy spread. The peak current is 35 A, the RMS bunch length is 3 mm and the RMS normalized emittance is 5 mm.mrad.

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[1] V. Litvinenko *et al.*, "Commission of FEL-based coherent electron cooling system", presented at FEL'17, MOP041.

[2] Y. Jing *et al.*, "Simulation of phase shifters between FEL amplifiers in coherent electron cooling", presented at FEL'17, TUP072.

[3] S. Reiche, "Introduction on Genesis 1.3", available at: http://genesis.web.psi.ch/download/documentation/genesis_talk.pdf, 2002.