ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST026

INFLUENCES OF THE ENERGY JITTER TO THE PERFORMANCE OF THE COHERENT ELECTRON COOLING*

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Abstract

The bandwidth of a coherent electron cooling (CeC) system is typically two to three orders of magnitude higher than the traditional RF based stochastic cooling system, which make it possible to cool the ion bunches with high energy and high intensity. However, for such broad bandwidth, jitters in the energy of the cooling electron bunches present a serious challenge to the performance of the cooling system. In this work, we present simulation studies about the influences of the energy jitter to a CeC system with parameters relevant to the on-going CeC experiment at RHIC.

INTRODUCTION

As one of the candidates for cooling high energy proton beam with high intensity in a collider, the principle of CeC has not been demonstrated experimentally. To test its feasibility, the CeC experiment at RHIC has been developed with the goal of cooling of Au^{+79} ions with electrons at the energy of $\gamma = 28.5$ [1]. During the CeC experiment in RHIC run 21, it had been measured that the RMS pulse-to-pule jitter in the energy of the electron bunches was in the level of 0.1%, which was significantly larger than the slice energy spread of the electron bunch, i.e. 0.02% (RMS). It was suspected that such an energy jitter was responsible for the absence of the expected cooling from the CeC.

In this work, we investigate how the CeC rate is affected by the level of energy jitter in the electrons' energy through numerical simulations. Firstly, we validate the simulation code by benchmarking it with the analytical results for an infinitely long electron bunch. Then we simulated the evolution of the ion bunch profile in the presence of the CeC with realistic electron bunch for various level of energy jitter in the electron bunches.

REDUCTION OF LOCAL COOLING RATE DUE TO ENERGY JITTER

During the cooling process of the PCA based CeC, each ion creates an electron density perturbation in the modulator, which is then amplified in the PCA and generates an electric field in the kicker section to cool the ion. Figure 1 (red triangles) shows the cooling electric field in the kicker section as predicted by 3D simulation for the CeC experiment at RHIC. The arrival time of the ion with respect to the cooling field depends on the energy of the electrons and the ions. In the presence of an energy jitter in the electron bunches, the arrival time of the ions with respect to the cooling field that they generate varies from turn to turn, which leads to a reduction of the cooling rate.

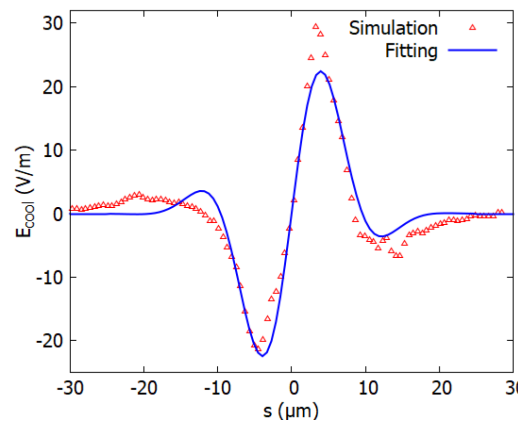

Figure 1: Cooling field initiated by an ion in the electrons of the CeC experiment at RHIC. The red triangles are data from the 3D simulations with code SPACE and the blue solid curve is the fitting from Eq. (1).

To simplify the analytical derivation and long-term cooling simulation, we fit the cooling field with the following expression (see the blue curve in Fig. 1) [2]:

$$E_{fit}(z) = E_A \exp\left(-\frac{z^2}{2\sigma_c^2}\right)\sin(k_0 z), \quad (1)$$

with $\sigma_c = 6.475\mu m$, $E_A = 28.1V/m$ and $k_0 = 3.28\times10^5 m^{-1}$. We assume that the energy jitter of the electron bunches has Gaussian distribution, i.e.

$$f(\delta_e) = \frac{1}{\sqrt{2\pi}\delta_{jit}}\exp\left(-\frac{\delta_e^2}{2\delta_{jit}^2}\right), \quad (2)$$

where $f(\delta_e)$ is the probability function to find the electron bunch has energy of $E_0 + \delta_e E_0$, E_0 is the designed energy of the electrons, and δ_{jit} is the R.M.S. spread of the energy jitter. In the presence of the energy jitter of the electron bunches, the effective energy kick received by an ion for cooling should be averaged over the distribution function of the energy jitter, i.e.

$$\langle\delta\gamma\rangle = Zel_k \int_{-\infty}^{\infty} f(\delta_e) E_{fit}(\Delta z)\, d\delta_e, \quad (3)$$

where $\Delta z = R_{56}(\delta_e - \delta_h)$ is the longitudinal location of the ion with respect to the cooling electric field, l_k is the length of the kicker section, R_{56} is the longitudinal dispersion from the modulator to the kicker and δ_h is the relative

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
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energy deviation of the ion. Inserting Eq. (1) and Eq. (2) into Eq. (3) yields [3]

$$\langle \delta\gamma \rangle = -Zel_k E_A \exp\left(-\frac{z_h^2}{2\tilde{\sigma}_c^2}\right)\sin\left(\tilde{k} z_h\right)\cdot R_{jit} \tag{4}$$

where we defined the following parameters

$$R_{jit} \equiv \eta^{-1}\exp\left(-\frac{k^2\sigma_{jit}^2}{2\eta^2}\right), \tag{5}$$

$\sigma_{jit} \equiv R_{56}\delta_{jit}$, $\eta = \sqrt{1+\left(\sigma_{jit}/\sigma_c\right)^2}$, $\tilde{k} \equiv k\eta^{-2}$, $\tilde{\sigma}_c \equiv \sigma_c \eta$, and $z_h \equiv R_{56}\delta_h$. Eq. (4) shows that the energy jitter results in an overall reduction of the energy kick for cooling by a factor of R_{jit}. In addition, the wavelength, $\lambda = 2\pi/k$, and the coherent length, σ_c, of the effective cooling field are also increased due to the energy jitter.

BENCHMARKING SIMULATION WITH ANALYTICAL RESULTS

We have developed a numerical tracking code to simulate the evolution of the ion bunch in the presence of the CeC [4, 5]. Energy jitter of the electrons has been added to the simulation and to validate the simulation, we benchmarked the simulation results with that from the analytical prediction for an ion bunch with small energy spread such that the sinusoidal function in Eq. (4) can be linearized. In this case, Eq. (4) becomes

$$\langle \delta\gamma \rangle = -Zel_k E_A k z_h \cdot \eta^{-3}\exp\left(-\frac{k^2\sigma_{jit}^2}{2\eta^2}\right). \tag{6}$$

Since the cooling time is inversely proportional to $\langle \delta\gamma \rangle$, we obtain

$$\tau_{cool}\left(\delta_{jit}\right) = \tau_{cool}\left(0\right)\left(1+R_{56}^2\delta_{jit}^2/\sigma_c^2\right)^{3/2} \times\exp\left(\frac{1}{2}\frac{k^2 R_{56}^2\delta_{jit}^2}{1+R_{56}^2\delta_{jit}^2/\sigma_c^2}\right). \tag{7}$$

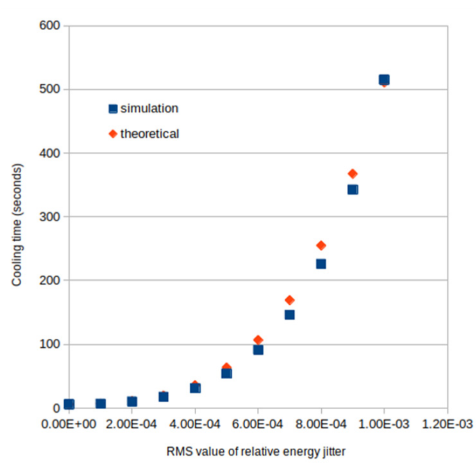

Figure 2: Increase of the cooling time with the R.M.S. amplitude of the bunch-by-bunch energy jitter in the electron beam. The blue squares are data from simulation and the orange diamonds are the analytical results calculated from Eq. (7).

Simulations have been performed for an ion bunch with R.M.S. energy spread of $\sigma_E/E = 6\times10^{-5}$, $R_{56} = 1.2cm$ and for a cooling electron bunch that is long enough to cover the whole ion bunch. As shown in Fig. 2, the cooling time from particle tracking agrees reasonably well with what predicted by Eq. (7), indicating that the tracking code is valid at least in the regime of small energy spread of the ion bunch.

SIMULATION RESULTS FOR THE CEC EXPERIMENT

To investigate the tolerable level of the bunch-by-bunch energy jitter in the electron beam for the CeC experiment, we have carried out simulations for the beam parameters listed in Table 1 and Table 2. These parameters are based on the measurements during the CeC run 21. Both the energy spread and the emittance in Table 1 are the values for the central portion of the electron bunch, i.e., $\pm 7.5\ ps$ around the location with the maximal peak current. With these parameters, the cooling field is what shown in Fig. 1.

Table 1: Parameters of the Electron Bunch

Energy, γ	28.5
Peak current, A	75
Full bunch length, ps	15
Energy spread R.M.S.	2×10^{-4}
Norm. emittance, R.M.S., mm.mrad	1.5

Table 2: Parameters of the Ion Bunch

Energy, γ	28.5
Bunch intensity	8.4×10^{8}
Bunch length, R.M.S., ns	3.5
Energy spread R.M.S.	1.2×10^{-3}
Longi. emittance, R.M.S., eV.s/u	0.36
Norm. emittance, R.M.S., mm.mrad	2.5
β^* at cooling section, m	5
RF voltage (28 MHz cavities), KV	400

Figure 3 shows the profiles of the ion bunch after 40 minutes of cooling with various levels of the bunch-by-bunch energy jitters in the electron beam. Since the electron bunch is shorter than the ion bunch by more than two orders of magnitude, the cooling mostly affects the ions with small synchrotron oscillation amplitude, which leads to the development of a narrow peak towards the centre of the ion bunch. The red solid curve in Fig. 3 shows the profile of the 'witness' bunch which is not overlapping with the electron bunch. Over the period of 40 minutes, the peak current of the 'witness' bunch decreases by 10% due to the intra-beam scattering (IBS) while the peak current of the ion bunch overlapping with the electron bunch increases by 45% if there is no energy jitter in the electron bunch train (blue curve in Fig. 3). In the presence of an energy jitter with the R.M.S. level of 0.02% (green curve in Fig. 3), the peak current of the ion bunch increases by 22% as the

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results of the cooling, indicating a factor of two reduction in the efficiency of the cooling. Cooling with an electron beam with R.M.S. energy jitter greater than 0.04% will essentially diminish the effects from cooling as suggested by the results shown in Fig. 3 (magenta, orange, and cyan curves). Based on these results, we conclude that the R.M.S. bunch-by-bunch energy jitter in the electron bunch train should stay below 0.02% to avoid drastic reduction to the cooling efficiency.

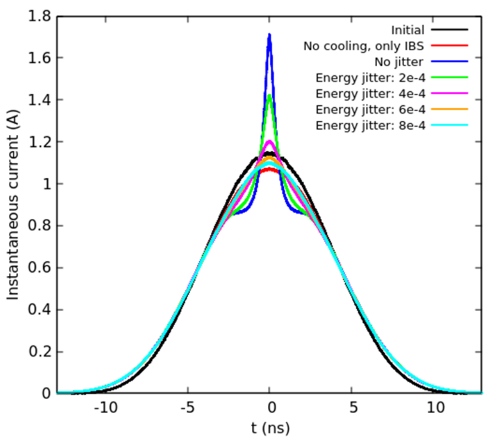

Figure 3: The longitudinal profile of the ion bunch as predicted by the simulation. The abscissa is the location along the ion bunch and the ordinate is the instantaneous current. The black curve is the initial profile of the ion bunch at t=0 and all other curves are the profile at $t = 40$ minutes. The red curve is the profile of a 'witness' bunch which is not overlapping with the electrons, and the blue, green, magenta, orange and cyan curves are the profiles of the ion bunch which is cooled by an electron beam with R.M.S. energy jitter of 0, 0.02%, 0.04%, 0.06% and 0.08% respectively.

SUMMARY AND DISCUSSION

In a CeC system, the longitudinal shifts of the cooling field at the kicker section with respect to the ion that creates the field in the modulator can reduces the cooling efficiency of the system. Such shifts can be caused by the bunch-by-bunch energy jitter in the electron beam. Our studies focus on how much such energy jitter can affect the cooling performance and what is the tolerable energy jitter for the on-going CeC experiment. There are other adverse effects associated with the energy jitter as well, such as the stability of the orbit, the envelop and the energy spread, which have been neglected by this study but should be addressed in the future.

For the parameters shown in Table 1 and Table 2, we found that the tolerable R.M.S. energy jitter is 0.02%. However, these parameters are not optimal for demonstrating cooling and for the coming runs, an ion bunch with less bunch intensity, i.e., 2e8 ions per bunch, and smaller longitudinal emittance, will be used. We plan to update these studies for the new set of beam parameters.

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