COHERENT SYNCHROTRON RADIATION EFFECTS IN THE ELECTRON COOLER FOR RHIC

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Abstract

The Coherent Synchrotron Radiation (CSR) could be a concern in many modern accelerator projects. In the proposed electron-cooling project for the Relativistic Heavy Ion Collider (RHIC), the electron cooler is designed to cool 100 GeV/nucleon bunched ion-beam using 55 MeV electrons. The electron bunch length will be on the order of cm, and the charge per bunch would be around 5 - 10 nC. We study the CSR effect in this paper.

INTRODUCTION

Because the synchrotron radiation damping mechanism is essentially absent for the heavy particles, electron cooling was proposed as the method to cool the particle beams in the storage ring of heavy particles [1, 2] based on the heat-energy transfer from the beam to an electron stream with lower temperature. Without additional perturbations, the electron cooling of ion beams stops when the ion beam and the cooling electron beam reach the equilibrium temperature. For a planed luminosity upgrade for the Relativistic Heavy Ion Collider (RHIC) operated by BNL, an important component is the electron cooling of the RHIC gold ion beams [3]. The luminosity increase for the RHIC II upgrade would be about 40, of which a factor of 10 is anticipated to come from the electron cooling, and the other 4 comes from beta function reduction at the interaction point and increasing (doubling) the number of bunches.

To cool the 100 Gev/u gold beam, the single bunch charge of the electron bunch has to be on the order of 10 nC. In one scenario, this charge is compressed to a rms bunch length of approximately 12 mm to be accelerated by a LINAC. Later the electrons will be debunched from 12 mm to about 50 mm before entering the cooling region. Since the electrons need be debunched, during the acceleration, the electron beam is chirped. The transport line then consists of three components [4]: a decompressor which will debunch the electrons; a rotation cavity which will reverse the chirp on the electron bunch; and finally a compressor which will bunch the electrons and safely transport the electrons back to the LINAC and then after energy recovery the electrons are dumped. The requirement on the electron beam quality directly affect the efficiency of cooling the gold beam, it is of great importance to make sure that the transport line will preserve the electron beam quality. Though the bunch length is relatively long, the single bunch charge is high, one question is whether the coherent synchrotron radiation (CSR) [5, 6] in the decompressor and compressor would be a concern. In this paper, we study the CSR effects.

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CONSIDERATION AND PARAMETERS

CSR is mostly a longitudinal effect, and due to the chromatic transfer function, the transverse phase space volume is also affected. For a transversely thin beam with a Gaussian distribution in the longitudinal density, the energy loss gradient along the bunch is equal to [5, 6]

$$\frac{d\mathcal{E}}{cdt} = \frac{2Ne^2}{\sqrt{2\pi}(3\rho^2\sigma_s^4)^{1/3}} F\left(\frac{s}{\sigma_s}\right), \tag{1}$$

with

$$F(\xi) = -\int_{-\infty}^{\xi} \frac{d\xi'}{(\xi-\xi')^{1/3}} \frac{d}{d\xi'} e^{-\xi'^2/2}, \tag{2}$$

where N is the bunch population, ρ is the bending radius, σ_s is the rms bunch lenth. Compared with the high brightness electron beam for the Linear Collider (LC) or the Free-Electron Laser (FEL), the bunch length here is longer, but the bunch charge is also higher, the scaling $d\mathcal{E}/(cdt) \propto N(\sigma_s)^{-4/3}$ tells us that CSR effects here in the e-cooler could be a concern as that in the LCs and the FELs. In the lattice design, each piece of magnet has a length of $L = 0.75$ m and the bending angle is $\theta = \pi/4$, hence the path length difference between the trajectory taken by the electron and that of the radiation is $\Delta L = L - 2L\sin(\pi/8)/(\pi/4) \approx 1.9$ cm. Normally, the vacuum chamber cut-off wavelength is on the order of a few millimeters and, we know the steady-state CSR impedance is applicable to wavelength down to the cut-off wavelength. Therefore, in our calculation, it would be fine, if we take the steady state CSR impedance. Of course, the free-space CSR impedance will overestimate the CSR effect and we will come back to this point in the following.

As the nominal set of parameters, the reference kinetic energy is 55 MeV, the emittance is on the order of 30 to 60 mm-mrad. In our calculation here, we set the initial rms bunch length to be $\sigma_{zi} = 12$ mm. Since we want to stretch it to a rms length of $\sigma_{zf} = 50$ mm at the e-cooler point, and the lattice provides a $R_{56} = -32.8$ m, we need chirp the electron beam so that the head will have higher energy, and the tail lower energy. The corresponding initial chirp we need is $\sigma_\delta^c = 1.16 \times 10^{-3}$. At the e-cooler point, we then

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need a cavity to reverse the chirp, so that the electrons in the head will have lower energy than the electrons in the tail would. Since at the e-cooler point, the rms bunch length is already 50 mm, a linearizer is probably a requirement. In our calculation, we implement a linearizer to correct the RF curvature. At the end of the compress arc, we also add a cavity to remove the residual correlated energy chirp. At the e-cooler, the intrinsic energy spread $\sigma_{\delta f}$ is on the order of 10^{-4} to ensure good cooling efficiency. If we assume that $\sigma_{\delta f} \approx 1.0 \times 10^{-4}$ and, there is no phase space volume degradation, we would require the initial intrinsic energy spread to be less than $\sigma_{\delta i} = \sigma_{\delta f}\sigma_{zf}/\sigma_{zi} \approx 4.17 \times 10^{-4}$.

PRELIMINARY RESULTS

We take the optic for the bunch deompression and compression arc from Ref. [4], with the beta-function and dispersion function shown in Fig. 1. Before we calculate

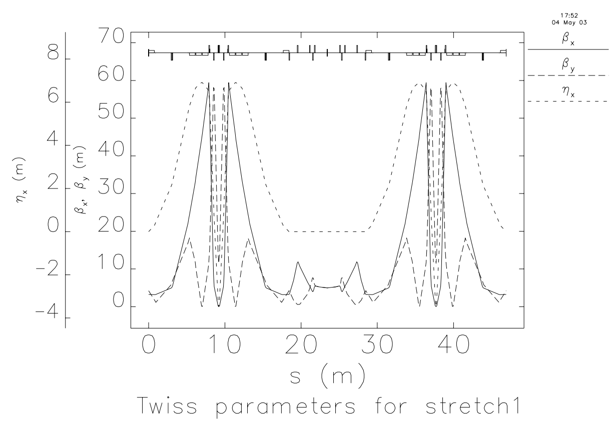

Figure 1: The β_x, β_y and η_x in the beam line.

the CSR effect, let us have a look at the electron beam paramters in such transport line. Shown in Fig. 2 is the evolution of the rms bunch length and the rms energy spread (including the chirp). In Fig. 2, $\sigma_5 = \sigma_z$ is the rms bunch length, and $\sigma_6 = \sigma_\delta$ is the rms energy spread. As we find, the electron bunch was initially 12 mm long, and it stretched to be 50 mm at the e-cooler, then it is compressed back to its original bunch length. In this special case, we take $\sigma_{\delta i} = 1.0 \times 10^{-4}$, and we chirp the bunch to have enough correlated energy spread for debunching. The correlated energy spread is recovered at the end of the beam line, and no longitudinal degradation.

After studying the beam line, in the following, we will focus on the beam quality at the e-cooler point, taking into account the degradation due to the CSR in the transport line. The requirements at the e-cooler point are that: $\sigma_{\delta f} \sim 10^{-4}$, $\sigma_{zf} \sim 50$ mm and the normalized emittance $\epsilon_{nf} < 60\,\pi$ mm-mrad. In Table 1, we set $\sigma_{zi} = 12$ mm, charge $Q = 10$ nC and, vary ϵ_{nxi} and $\sigma_{\delta i}$ to study the initial value dependency. In Fig. 3, we show a typical case for the evolution of the emittance growth and in Fig. 4 for

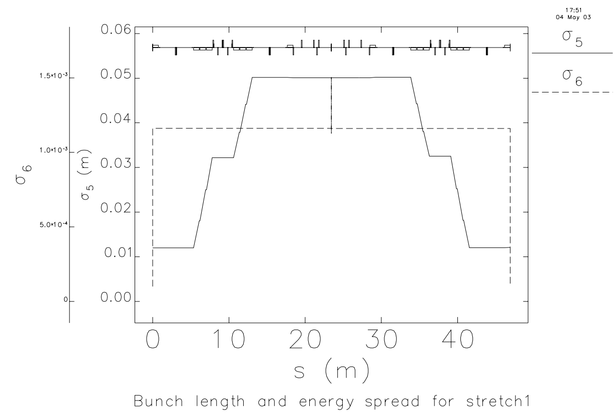

Figure 2: The evolution of the rms bunch length and the energy spread in the beam line.

Table 1: The units are the following: 10^{-4} for rms energy spread σ_δ; π mm-mrad for normalized emittance ϵ_n and mm for rms bunch length σ_{zf}.

$\sigma_{\delta i}$	$\epsilon_{n(x,y)i}$	ϵ_{nxf}	ϵ_{nyf}	$\sigma_{\delta f}$	σ_{zf}
1.0	10	23.6	12.6	2.09	56.6
	20	36.1	25.1	2.03	56.6
	30	48.6	37.7	2.00	56.6
	40	61.8	50.2	1.99	56.5
2.0	10	23.6	12.6	2.10	57.0
	20	37.0	25.2	2.07	57.0
	30	50.1	37.8	2.04	56.9
	40	63.2	50.4	2.03	56.8
3.0	10	25.2	12.7	2.15	57.4
	20	39.5	25.3	2.13	57.4
	30	53.0	38.0	2.12	57.3
	40	66.2	50.6	2.10	57.3

the rms bunch length and the energy spread. In Fig. 3 and Fig. 4, the initial $\sigma_{\delta i} = 2.0 \times 10^{-4}$ and $\epsilon_{n(x,y)i} = 40\ \pi$ mm-mrad.

The results show that the final bunch length and energy spread are almost independent of the initial energy spread or the emittance within the range we studied. The net amount of growth in the transverse emittance is also almost independent on the initial conditions. Within the range we studied, it seems to us that the CSR will cause some phase space degradation, but the degradation is not dramatic. Of course, compensation scheme on the lattice would be a plus.

OTHER POSSIBLE SCENARIO

Now, let us look at the other possible scenario, e.g. a L-band cavity. The initial electron rms bunch length is then about $\sigma_{zi} = 6$ mm, and the charge is around $Q = 5$ nC. Ac-

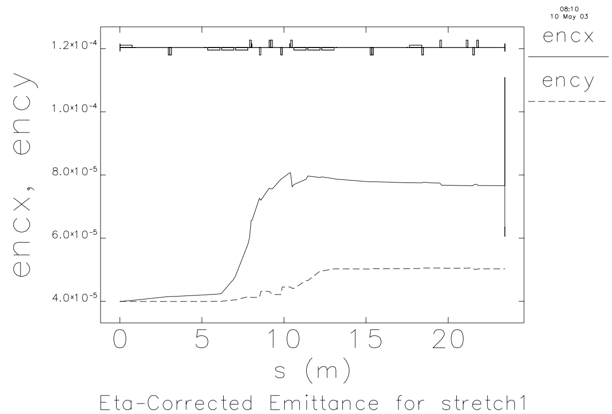

Figure 3: The evolution of the emittance $\epsilon_{n(x,y)}$ growth in the beam line.

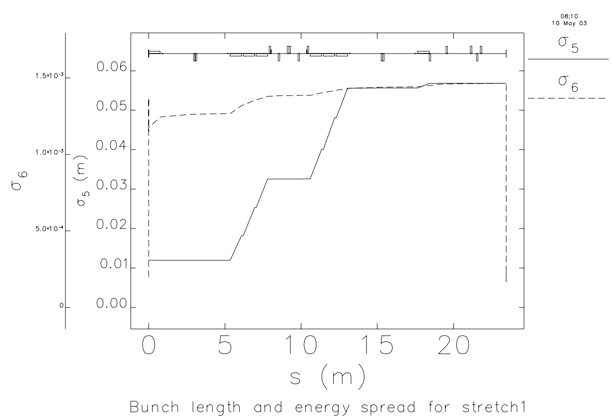

Figure 4: The evolution of the rms bunch length σ_5 and the energy spread σ_6 in the beam line.

cording to the scaling we just discussed, i.e., $d\mathcal{E}/(cdt) \approx N(\sigma_s)^{-4/3}$, then the situation would be similar to what we discussed above for the case of $\sigma_{zi} = 12$ mm, and $Q = 10$ nC.

To study a different case for future design reference, we set the initial bunch length $\sigma_{zi} = 3$ mm. Accordingly, the require energy chirp is $\sigma_\delta^c = 1.43 \times 10^{-3}$ to ensure that at the e-cooler point $\sigma_{zf} = 50$ mm. Assuming that there is no longitudinal phase space degradation, then if we want to ensure that at the e-cooler point, the final energy spread $\sigma_{\delta f} < 10^{-4}$, then the initial energy spread should be smaller than $\sigma_{\delta i} = \sigma_{\delta f}\sigma_{zf}/\sigma_{zi} \approx 1.67 \times 10^{-3}$.

The results are summarized in Table 2. We find similar fact that the amount of degradation is almost independent of the initial conditions. However, the net effect is larger as we expected, since in this extreme case, though the charge is only half, the bunch length is four times shorter. According to the scaling we discussed previously, i.e. $d\mathcal{E}/dt \propto N(\sigma_s)^{-4/3}$, we would expect larger net effect in this case based on the parameters we used. Of course, in real life the initial bunch length $\sigma_{zi} \approx 6$ mm, and the situation would be much better as what we studied for the case of $\sigma_{zi} = 12$ mm and $Q = 10$ nC.

Table 2: The units are the following: 10^{-4} for rms energy spread σ_δ; π mm-mrad for normalized emittance ϵ_n and mm for rms bunch length σ_{zf}.

$\sigma_{\delta i}$	$\epsilon_{n(x,y)i}$	ϵ_{nxf}	ϵ_{nyf}	$\sigma_{\delta f}$	σ_{zf}
1.0	10	51.2	14.5	1.10	65.0
	20	67.6	28.9	1.09	64.6
2.0	10	52.2	14.5	1.09	65.2
	20	67.8	28.9	1.08	64.9
3.0	10	53.5	14.5	1.09	65.6
	20	70.2	29.0	1.09	65.3

DISCUSSION

In this paper, we study the CSR effect for the proposed electron cooler for the RIHC II in BNL. The results presented in this paper are based on Borland's Elegant code [7]. We find that the CSR effect will bring some effect at the e-cooler point, but the effect is not dramatic. As we mentioned before, we adopted the free space CSR impedance and, we did not implement the shielding cut-off due to the vacuum chamber. Should we take this into account, the CSR effect would be even smaller. The results presented here are only the starting point for looking into this problem. Further study is needed.

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