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DISCLAIMER

COLLECTIVE EFFECTS IN THE RHIC-II ELECTRON COOLER *

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Abstract

Electron cooling at RHIC-II upgrade imposes strict requirements on the quality of the electron beam at the cooling section. Beam current dependent effects such as the space charge, wake fields, CSR in bending magnets, trapped ions, etc., will tend to spoil the beam quality and decrease the cooling efficiency. In this paper, we estimate the defocusing effect of the space charge at the cooling section and describe our plan to compensate the defocusing space charge force by focusing solenoids. We also estimate the energy and emittance growth cased by wake fields. Finally, we discuss ion trapping in the electron cooler and consider different techniques to minimize the effect of ion trapping.

INTRODUCTION

RHIC II is an upgrade for RHIC aimed at a tenfold increase of Au-Au luminosity. High energy electron cooling is planned as a part of the upgrade to counteract Intra-Beam Scattering (IBS). The base-line design of the RHIC-II electron cooler employs an SRF energy recovery linac (ERL) as a driver accelerator. The ERL will deliver the electron beam with a beam current of 50 mA, an energy of 54 MeV, a bunch charge of 5 nC, and an r.m.s. emittance of 4 μm or smaller. The bunch repetition rate will be the same as that of RHIC, 9.4 MHz. The high brightness, high intensity beam will be generated by a CW SRF photogun.

RHIC-II electron cooling imposes strict requirements on the beam quality [1]. The required angular and energy spreads of the electron beam should not be larger than 10^{-5} and $5 \cdot 10^{-4}$ respectively. These numbers are r.m.s values calculated relatively to the average ion beam trajectory and energy.

In the ERL, collective effects can be separated into two groups: instabilities that can limit the maximum beam current and effects that tend to dilute the beam quality reducing cooling efficiency. The former group includes transverse cumulative and multi-pass beam breakup (BBU) instabilities. The latter group includes the space charge effect, wake fields, CSR in bending magnets, trapped ions, and e-cloud. In this paper, we estimate an impact of collective effects on the beam dynamics in the electron cooler and describe mitigation techniques if they are required.

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SPACE CHARGE EFFECT AT THE COOLING SECTION

The space charge force tends to increase the angular spread in the electron beam. The r.m.s. beam envelope equation with the space charge is given by

$$\sigma'' + K\sigma = \frac{\epsilon^2}{\sigma^3} + \frac{I}{2I_A\gamma^3\beta^3\sigma} \qquad (1)$$

where K is the external focusing, ϵ is the beam emittance, I is the peak current, I_A is the Alfven current, equal to 14 kA for electrons, and $\gamma\beta$ are relativistic factors. For designed nominal e-cooler parameters, $I = 60$ A, $(\gamma\beta) = 107$, ϵ_n=$4 \cdot 10^{-6}$ m, $\sigma = 4.3 \cdot 10^{-3}$ m, the space charge term is a factor of 25 larger than the emittance term in the cooling section of the e-cooler. Therefore, the beam dynamics in the cooling section is dominated by the space charge. The effect of the space charge on the beam angular spread in the cooling section was simulated by PARMELA [2]. If no external focusing was applied, the angular spread grew up by approximately a factor of 4 to $3 \cdot 10^{-5}$ μm.

To compensate the angular spread growth, we plan to install 20cm-long solenoids with a maximum field of 240 G. The solenoids will be grouped in pairs with opposite polarity. Such pairs of solenoids will be installed every 11 meters of the cooling section. Figure 1 shows the angular spread of an ideal uniformly charged cylindrical distribution simulated by PARMELA with the solenoidal focusing and without. With the solenoidal focusing, the r.m.s. angular spread at the end of the cooling section is smaller than the required 10^{-5}.

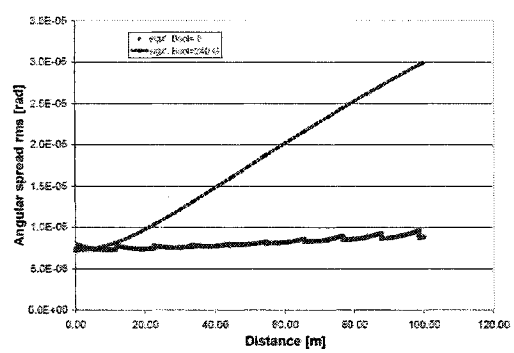

Figure 1: Evolution of the angular spread of an ideal uniformly charged cylindrical distribution in the cooling section, simulated by PARMELA, with the solenoidal focusing (red curve) and without (blue curve).

MULTI-PASS BEAM BREAKUP INSTABILITY

The current two-loop design of the electron cooler ERL utilizes two SRF cavities. Because the number of cavities is small, the cumulative (single-pass) BBU presents no danger in the ERL.

Transverse multi-pass BBU can present an insurmountable problem for operations of a multi-pass machine even with a single cavity. The design of the 5-cell SC BNL cavity [3] was optimized to reduce the quality factor of HOMs and push BBU threshold beyond the ampere level. Both numerical simulations using the code MAFIA [4] and preliminary measurements with the copper model show that ferrite absorbers situated next the five cell cavity set the quality factor of dipole HOMs to the range of $10^2 - 10^4$.

Multi-pass BBU in the e-cooler ERL was simulated using codes GBBU [5] and TDBBU [6]. The Q and R/Q values of dipole HOMs were simulated by MAFIA. To study the dependence of the BBU threshold on ERL parameters the recirculation time, the recirculation matrix, and HOM frequencies were varied within a "reasonable" range. In most of these simulations, the BBU threshold was between 2.5 and 5 Amps. The minimum threshold current observed in these studies was 1.5 A which is still well above nominally required 50 mA.

SHORT-RANGE WAKE FIELDS

Interaction of the beam electromagnetic field with beam surroundings induces high-frequency, short-range wake fields causing beam quality degradation. These effects include beam interaction with accelerating cavities, the resistive wake, interaction with bellows and other nonuniformities of the vacuum chamber.

Interaction of the electron beam with the 5-cell SC BNL cavity was simulated by R. Calaga [3] using the code MAFIA. In his dissertation, Calaga has calculated the loss-factor $k_{\|}$ and the kick factor $k_{\perp}$ equal respectively to

$$k_{\|} = 1.12 \text{ V/pC} \text{ and } k_{\perp} = 3.28 \text{ V/pC/m}. \qquad (2)$$

Assuming that the average energy loss and the average deflection angle are approximately equal to the induced energy spread and the angular spread respectively, we used (2) to estimate the energy spread and the angular spreads for the e-cooler. Table 1 summarizes the result of this calculation. Note that the angular spread produced by the SRF cavities has to be added quadratically to the beam angular spread at the location of cavities, which is approximately equal to $2 \cdot 10^{-4}$.

Another effect that can potentially diminish the beam quality is the resisitve wake, which arises from interaction of the bunch electromagnetic field with the resistive vacuum pipe. Using formalism developed in [7], we calculated the energy and angular spreads produced by the resistive wake. Table 1 contains the result of these calculations. Based on this result, we can conclude that the resistive wake will not have a substantial impact on the electron beam quality and can be neglected.

Additionally, interaction of the beam with vacuum pipe bellows was simulated using ABCI [8]. It was assumed that each set of bellows had six convolutions and that each convolution had an area of 0.35 cm^2. The simulated angular and energy spreads, shown in Table 1, indicate that interaction with bellows will not have a significant impact on the electron beam if the number of sets of bellows is smaller than a few tens.

Table 1: Impact of Short Range Wake Field Effects on the beam quality. The angular spread was calculated for 1 mm displacement. The angular spread produced by SRF cavities and bellows has to be added quadratically to the beam angular spread at the location of cavities and bellows, approximately equal to $2 \cdot 10^{-4}$.

	Energy Spread	Angular spread
SRF Cavities	$4 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
Resistive Wake	$5 \cdot 10^{-5}$	$5 \cdot 10^{-7}$
Bellows	10^{-5}	10^{-7}

CSR AND IMAGE CHARGES

CSR

Calculation of the CSR effect on the beam energy spread have to include shielding by the vacuum pipe. The effectiveness of shielding is described by the parameter

$$x_{th} = \frac{2\pi^3 R \sigma_{es}^2}{3h^3}, \qquad (3)$$

where σ_{es} is the r.m.s. bunch length, h is the gap of the vacuum chamber in dipole magnets, and R is the bending radius of magnets.

If x_{th} is smaller than unity, shielding is negligible. If x_{th} is larger than $4\pi^2$, the coherent radiation is almost completely suppressed. In the range $1 < x_{th} < 4\pi^2$, SCR is reduced by the factor $F_r = x_{th}^{-1/3} \exp(-x_{th})$. For the electron cooler with R=0.5 m and h=0.03 m, equation (3) yields approximately 38. This means that CSR in the e-cooler ERL will be almost completely suppressed by shielding.

Deflection of the beam centroid by image charges

If the beam is offset from the vacuum chamber axis, redistributed image charges on the vacuum chamber impose a coherent force on the beam proportional to the beam offset. To calculate the force produced by images it is convenient to separate the beam current onto DC and AC components. The AC component includes all integer harmonics of the bunch repetition rate except the zeroth harmonic. For a cylindrical pipe, the AC and DC parts of the image force are

$$F^{AC} = \frac{2e^2 N_e x}{\gamma^2 b^2 l_b} \text{ and } F^{DC} = \frac{2e^2 N_e x}{b^2 l_b}\eta, \qquad (4)$$

where e is the elementary charge, N_e is the number of electrons in a bunch, b is the beam pipe radius, l_b is the bunch length, x is the displacement from the vacuum chamber axis, and η is the beam duty factor. The corresponding growth lengths for (4) are respectively:

$$L_{AC} = 550\,\text{m} \text{ and } L_{DC} = 160\,\text{m}. \qquad (5)$$

Assuming an initial beam displacement of 1 mm, these forces cause the beam centroid to gain a deflection angle at the end of the 100 m long cooling section equal to $3 \cdot 10^{-7}$ and $4 \cdot 10^{-6}$ respectively. Note that these numbers are overestimated because the presented calculation did not include the focusing effect of the solenoids at the cooling section.

ION TRAPPING AND E-CLOUD

Ion trapping

Ion trapping in the ERL and beam transfer lines can reduce the beam quality. According to the standard matrix stability analysis [1], ions of all chemical elements can be trapped in the CW electron beam. The accumulation time of H_2 in the beam will be approximately equal to 30 sec at a pressure of 10^{-10} Torr. Although accurate assessment of the impact of trapped ions on the beam quality is difficult, operational experience accumulated worldwide shows that trapped ions can distort the linear machine optics, create strong nonlinearities, and enhance beam losses.

To clear trapped ions from the beam we plan to use electrostatic clearing electrodes. The field of these electrodes draws trapped ions out of the electron beam when ions reach the area where the electrodes are situated. The equilibrium neutralization degree of the electron beam with clearing electrodes will be equal to the ratio of the ion lifetime to the accumulation time. Assuming that the ion liftime is no longer than the distance between electrodes (5 m) divided by the thermal velocity of ions (1.8 km/sec), we obtain the equilibrium neutralization degree of the order of $5 \cdot 10^{-4}$, which is sufficiently small not to produce any observable effect on the beam quality.

Additionally to clearing electrodes we can use clearing gaps in the beam. Analytical estimates presented in [1] show that the length of clearing gaps should be of the order of a few microseconds and the time interval between clearing gaps should not exceed a few hundred milliseconds. Because of the large time interval between clearing gaps the beam intensity can be "slowly" ramped down and up in a few milliseconds to avoid RF transition effects.

e-cloud

The charge of cooled RHIC ion bunches exceeds the charge of electron bunches by a factor of a few. This prevents ion trapping in the cooling section but opens the door to the electron cloud effect, which was observed in warm sections of RHIC. According to measurements done at RHIC the linear charge density of the electron cloud, if not suppressed, is of the order of 1 nC/m with an r.m.s. transverse size of the cloud distribution of the order of 2 cm. These e-cloud parameters yield the characteristic growth length equal to 70 m and the coherent angle at the end of the 100 m long cooling section equal to $1.4 \cdot 10^{-4}$, which is much larger than the specification on the angular spread in the cooling section.

Calculations show that the e-cloud charge density has to be lowered by a factor of 20 to lower the deflection angle below $5 \cdot 10^{-6}$. NEG coating of the vacuum pipe proved to reduce the e-cloud density by more than an order of magnitude. We also expect additional e-cloud suppression by the field of the undulator wrapped on the vacuum chamber of the cooling section. After the e-cloud will be suppressed by NEG coating, the linear part of the residual angular spread growth can be compensated by the focusing solenoids designed to compensate the beam space charge at the cooling section. Additional suppression of the effective secondary emission coefficient can be achieved by modifying the vacuum pipe surface if this is necessary. The operational experience with the electron cloud at RHIC and simple estimates show that the aforementioned methods and tools will allow us to keep the electron cloud under control. However, considering the potential seriousness of this problem we plan to continue detailed studies of the effect.

SUMMARY

The analysis presented in this paper shows that collective effects in the RHIC-II e-cooler do not present a showstopper for the e-cooling project. Such effects as the space charge in the cooling section, ion trapping, and e-cloud require accurate evaluation of their impact on the beam dynamics and careful development of mitigation techniques to minimize that impact.

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