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TEST OF STEPWISE ELECTRON BUNCH REPLACEMENT IN eRHIC USING AN ELECTRON LENS IN RHIC*

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Abstract

The electron-ion collider eRHIC requires frequent electron bunch replacements to maintain both high luminosity and high polarization in arbitrary spin patterns. If the bunch can be replaced in several steps, the requirements for both the electron gun and the electron accelerator are greatly reduced due to the lower bunch charge. However, a stepwise replacement of electron bunches will give rise to transient effects from the beam-beam interaction that will lead to emittance growth. Such a scheme was tested using one of the RHIC electron lenses with a multiple step increase of the electron current. The test provides an order-of-magnitude estimate of the effect in the absence of any further mitigating measures.

INTRODUCTION

eRHIC [1] is a proposed Electron-Ion Collider [2] based on RHIC [3] with requirements [2]: (i) highly polarized (~70%) electron and nucleon beams; (ii) ion beams from deuteron to the heaviest nuclei (uranium or lead); (iii) variable center of mass energies from ~20 to ~100 GeV, upgradable to ~140 GeV; (iv) high luminosity of $\sim 10^{33-34}$ cm^{-2}s^{-1}, and (v) the possibility of having more than one interaction region. We report on a test in support of achieving requirements (i) and (iv). eRHIC parameters relevant for the discussion are shown in Table 1, for e-p collisions at the highest center of mass energy (COM) energy E, and the highest luminosity. The synchrotron radiation power is limited to 10 MW in all modes to limit power consumption.

For high polarization in arbitrary spin patterns, electron bunches with the desired spin orientation (↑ or ↓) are injected at collision energy into the storage ring. Only one orientation is stable. Bunches with the unstable orientation will depolarize and then build up polarization in the stable direction due to the Sokolov-Ternov (ST) effect [4], with a characteristic time of 0.5 h at the highest energy (Table 1).

It is therefore planned to replace the electron bunches in the storage ring frequently to maintain both high polarization and high luminosity. The injectors are designed for a replacement every second, and each of the few hundred bunches (Table 1) are stored for a few minutes only. An eRHIC electron bunch has an intensity $\leq 30\times10^{10}$ (50 nC). We consider a scheme with a 5-step replacement, which would reduce the bunch intensity in the injector to $\leq 6\times10^{10}$ (10 nC).

If the electron bunch in the storage ring is not replaced in a single turn with a new bunch of closely matched intensity

Table 1: Selected eRHIC p-e Parameters (V5.1) for the Highest Center of Mass (COM) Energy E and the Highest Initial Luminosity $\mathcal{L}$ without Hadron Cooling [1]

Quantity	Unit	Max COM E p	Max COM E e	max $\mathcal{L}$ p	max $\mathcal{L}$ e
Energy E	GeV	275	18	275	10
Bunch intensity N_b	10^{10}	13.6	6.3	10.5	30
No of bunches k_b	...	330		660	
Neam current	A	0.56	0.26	0.87	2.48
RMS emitt. $\varepsilon_{x,y}$	μm	5.9/1.8	775/115	4.1/2.5	391/95
RMS bunch length σ_s	cm	7	1.7	7	1.9
IP $\beta_{x,y}$	cm	90/4.3	83/8.0	90/5.9	63/10.4
Beam-beam $\xi_{x,y}$	0.001	2/1	70/57	15/5	100/83
Luminosity factor	...	0.83		0.85	
Luminosity	10^{33}cm^{-2}s^{-1}	0.67		4.39	
IBS growth time†	h	10.4		9.2	
Damping time†	ms		12		70
ST (de)pol. time	h		0.52		9.86

† transverse

and emittance, there is a transitory beam-beam effect resulting in additional emittance growth. We were interested in experimentally determining the magnitude of this effect in the absence of any additional mitigation measures.

EMITTANCE GROWTH MEASUREMENT

We use the RHIC proton beam at 255 GeV, available during Run-17 [10], and the RHIC electron lens [5–9] in the Yellow ring to simulate the transitory beam-beam effects on the proton beam emittances. Figure 1 shows the time structure of the average proton beam current (constant), and the electron beam current of the lens. Every 6 min the electron beam is reduced to zero, and increased in 5 steps, spaced 100 ms apart, back to full current. The rise time from one step to the next is less than 6 μs (1/2 turn). This allows for the electron current to change while no proton bunches are passing through the lens. In the test all proton bunches were filled into the first half of the circumference.

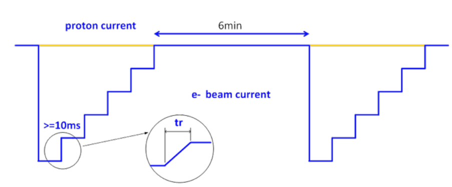

Figure 1: Proton and electron lens beam currents time structure (horizontal axis not to scale).

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Table 2 summarizes the proton and electron beam parameters. The main solenoid field of the electron lens is 6 T. The maximum beam-beam parameter created by the electron lens is about half the value of the high-luminosity case (Table 1). The proton and electron beam sizes were not fully matched, and the electron beam was larger by about 50%. This reduces the nonlinear effects compared to fully matched beam sizes at the same beam-beam parameter.

The proton bunches were all distributed in the first half of the turn. This allowed for the electron beam changes between proton bunch passages. After alignment the electron beam is colliding head-on with the proton beam – a good simulation of the eRHIC replacement scheme, in which longitudinal stacking of the incoming electron bunches is envisioned.

Table 2: Main Beam Parameters for the Experiment

Quantity	Unit	Proton beam	Electron beam
Energy	eV	255 G	5 k
Bunch intensity	10^{11}	1.7	–
No of bunches	...	$31^{\dagger}$	–
Beam current	mA	66	625
RMS emittance ε, initial	μm	2.0	–
RMS bunch length σ_s	m	0.43	–
$\beta_{x,y}$ at lens	m	6.5	–
RMS beam size in lens	μm	220	340
Beam-beam param. $\xi_{x,y}$	0.001	$7^{\star}$	–

† All in the first half of the turn.

* Created by the electron lens.

Figure 2 shows the Blue and Yellow emittances as measured by the IPMs, and the Yellow electron beam current for the experiment. The Blue and Yellow proton beams were not colliding, making the Blue a reference for Yellow. During the alignment of the electron beam to the proton beam at low electron beam current (50 mA) both Yellow emittances increased by almost 50%, likely due to a transitory beam-beam effect. A total of 23 bunch replacements were simulated.

The horizontal and vertical emittances ε of both rings, as measured by the IPMs, were fitted to straight lines,

$$\varepsilon(t) = \varepsilon_0 + \varepsilon_1 t, \qquad (1)$$

with the fit results for ε_1 presented in Table 3. The emittance growth rate ε_1 should scale approximately linearly with the bunch replacement rate, but not necessarily linearly with the beam-beam parameter.

SIMULATION

In weak-strong simulation studies [11] each newly injected electron bunch is represented by a rigid 3-dimensional Gaussian with an initial $8\sigma_\delta$ energy offset. This rigid bunch oscillates in the longitudinal phase space with a synchrotron tune Q_s, and is damped with the decrement Δ. The simulation parameters for this model are listed in Table 4.

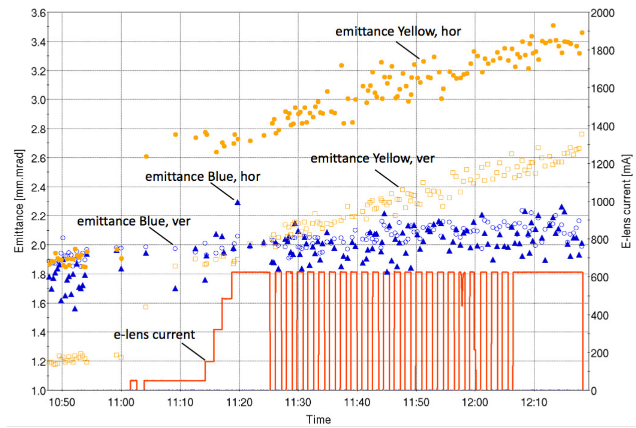

Figure 2: Blue and Yellow rms emittances as measured by the IPMs (left scale), and electron lens current (right scale). The detailed time function of the electron lens current is shown in Figure 1.

Table 3: Emittance growth rates ε_1 (Eq. (1)) measured and from eRHIC simulation, and calculated for optical mismatch filamentation and IBS for the max $\mathcal{L}$ mode in Table 1

Case	Emittance growth rate ε_1 Horizontal μm h^{-1}	Vertical μm h^{-1}
RHIC e-lens experiment $(\xi_x, \xi_y) = (7, 7) \times 10^{-3}$		
Blue measured, without e-lens	0.152	0.208
Yellow measured, with e-lens	0.706	0.698
p-beam, measured (diff. of above)	**0.553**	**0.490**
From filamentation, calculated	0.011	0.011
From IBS, calculated	0.057	0.057
eRHIC simulation $(\xi_x, \xi_y) = (15, 3) \times 10^{-3}$		
Proton beam, simulation	**0.164**	**0.032**
From filamentation, calculated	0.048	0.003
From IBS, calculated	0.457	0.272

At each bunch replacement the circulating electron bunch is removed, and protons are tracked for 7,800 turns (0.1 s). In the otherwise linear ring a weak beam-beam lens with $(\xi_x, \xi_y) = (10, 2) \times 10^{-5}$ provides filamentation during that time. Every 78,000 turns (1 s) an additional electron bunch with a charge of 10 nC is injected off-energy, until the desired total bunch intensity of 50 nC is reached. Figure 3 shows the evolution of the horizontal and vertical un-normalized proton beam emittances over the course of 100 bunch replacements. The obtained growth rates are almost identical to the ones resulting from on-energy accumulation, where no coherent synchrotron oscillations of the newly injected electron bunches occur. Strong-strong simulations are planned to study possible additional effects. The calculated emittance growth rate ε_1 for a time between storage ring bunch replacements of 6 min is also shown in Table 3.

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Table 4: Main Beam Parameters for the Simulation

Quantity	Unit	Proton beam	Electron beam
Beam-beam param. $\xi_{x,y}$	0.001	15/3	
Tunes $Q_{x,y}$	...	0.310/0.315	
RMS momentum spread σ_δ	...		1×10^{-3}
RMS bunch length σ_z	mm		10
Synchrotron tune Q_s	...		1×10^{-2}
Damping decrement Δ	...		5×10^{-4}

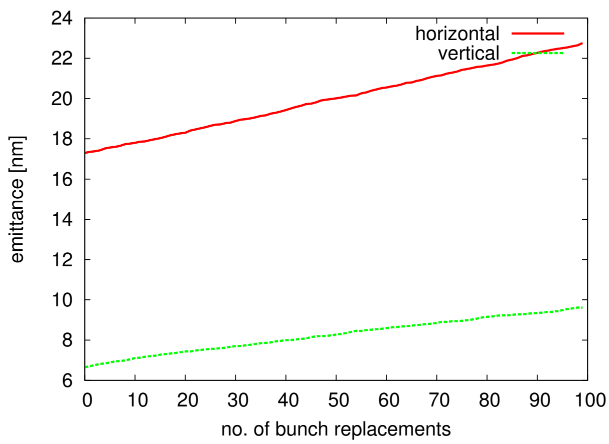

Figure 3: Simulated proton beam emittance evolution with stepwise electron bunch replacements.

DISCUSSION

Two mechanisms can lead to proton beam emittance growth. First, the change in the beam-beam strength creates an optical mismatch resulting in filamentation. This effect has been calculated, but only considers the electron lens as a linear element and disregards resonance effects. Second, the change of the tune and tune distribution affects the single particle dynamics. This effect needs to be simulated.

To calculate the emittance growth from optical mismatch filamentation we note that the beam-beam lens has the quadrupole strength $(Kl) = (4\pi/\beta_0)\xi_0$, where β_0 is the lattice function and subscripts "0" denotes values before modification due to the beam-beam lens. The change in the lattice functions $(\Delta\beta, \Delta\alpha)$ at the interaction point are [12,13]

$$\Delta\beta = \beta_0^2/\sqrt{1 + 4\pi\xi_0 \cot(2\pi Q_0) - 4\pi^2\xi_0^2}, \quad (2)$$
$$\Delta\alpha = 2\pi\xi_0\alpha_0 \cot(2\pi Q_0), \quad (3)$$

and, after decoherence, the change in the emittance is [14]

$$\frac{\Delta\varepsilon}{\varepsilon_0} = \frac{1}{2}\frac{(\Delta\beta/\beta_0)^2 + (\Delta\alpha - \alpha_0(\Delta\beta/\beta_0))^2}{1 + (\Delta\beta/\beta_0)} \quad (4)$$

In Table 3 the calculated emittance growth rate from filamentation is shown for both the e-lens experiment and the simulation. This effect accounts only for a small fraction of the observed emittance growth rate in both cases. The emittance growth rate from filamentation becomes negligible for a fractional tune of 0.25 or 0.75.

For the max COM E mode (Table 1) the beam-beam parameter ξ is reduced by a factor of 5 compared to the experiment. For small ξ it is possible to scan the ion tunes, and better working points may be found. In the experiment there was not enough time for this. For e-A operation and the same charge per ion bunch the beam-beam parameter is reduced by a factor 2.5 compared to e-p operation.

For the max $\mathcal{L}$ mode (Table 1), the Sokolov-Ternov (ST) depolarization time is much longer than in the max COM E mode, and the bunch replacement rate can be reduced by an order of magnitude. However, the beam-beam parameter will be a factor 2 larger than in the experiment, and there isna less room for tune changes. In this mode mitigation measures may be required. Beam cooling is foreseen eventually for all EIC versions [15]. Alternatively, a fast electron lens could be employed that makes up for the missing beam-beam strength while the electron bunch is being stepwise replaced.

Due to the large (22 mrad) full crossing angle in eRHIC crabbing is necessary. During accumulation in the longitudinal plane newly injected bunches perform coherent synchrotron oscillations with large amplitudes of several sigma until damped down by synchrotron radiation. With the crossing angle the longitudinal offsets translate into transverse offsets, which may result in additional ion beam emittance growth. These effects need to be studied numerically.

SUMMARY

In an experiment we measured the emittance growth rate of proton bunches, experiencing the repeated stepwise replacement of a colliding electron beam. For the experiment we used one of the RHIC electron lenses, and changed the current every 6 min to zero and stepped it back up in 5 steps 100 ms apart. The measured growth rate is approximately the same as the calculated IBS growth rate in eRHIC (Tables 1 and 3), which is also multiple times larger than the simulated growth rate with eRHIC parameters. IBS will therefore dominate the transverse emittance growth in eRHIC even with stepwise replacement of the electron bunches.

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REFERENCES

[1] C. Montag et al., “eRHIC design status”, presented at IPAC’18, Vancouver, Canada, 2018, paper TUYGBD3, this conference.

[2] A. Accardi et al., “Electron Ion Collider - The next QCD frontier”, Eur. Phys. J A, pp. 52-268, 2016.

[3] M. Harrison, T. Ludlam, S. Ozaki, “RHIC project overview”, Nucl. Instrum. Meth. A 499, pp. 235-244, 2003.

[4] A.A. Sokolov and I.M. Ternov, “Polarization and spin effects in the theory of synchrotron radiation”, Akad. Nauk. SSSR (Russian) 153, 1052-1053, 1963 [Sov. Phys. Dokl., 8, 1203, 1964].

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPMF006

[5] Y. Luo et al., “Six-dimensional weak-strong simulation of head-on beam-beam compensation in the Relativistic Heavy Ion Collider”, Phys. Rev. ST Accel. Beams 15, 051004, 2012.

[6] W. Fischer et al., “Operational head-on beam-beam compensation with electron lenses in the Relativistic Heavy Ion Collider”, Phys. Rev. Lett. 115, 264801, 2015.

[7] P. Thieberger et al., “High energy Coulomb-scattered electrons for relativistic particle beam diagnostics”, Phys. Rev. Accel. Beams 19, 041002, 2016.

[8] X. Gu et al., “Electron lenses for head-on beam-beam compensation in RHIC”, Phys. Rev. Accel. Beams 20, 023501, 2017.

[9] W. Fischer et al., “Compensation of head-on beam-beam induced resonance driving terms and tune spread in the Relativistic Heavy Ion Collider”, Phys. Rev. Accel. Beams 20, 091001, 2017.

[10] V.H. Ranjbar et al., “RHIC polarized proton operation for 2017”, in *Proc. IPAC’17*, pp. 2188-2190.

[11] C. Montag, ICFA Mini-Workshop on Beam-Beam Effects in Circular Colliders, LBNL, 2018.

[12] K. Hirata, "Beam-beam effects ...", in Handbook of Accelerator Physics and Engineering, World Scientific, p. 135, 1999.

[13] D. Rice, "Error sources and effects", in Handbook of Accelerator Physics and Engineering, World Scientific, p. 264, 1999.

[14] M. Syphers, "Emittance dilution ...", in Handbook of Accelerator Physics and Engineering, World Scientific, p. 276, 1999.

[15] Y. Zhang, "Overview of US EIC project and its cooling programs", in *Proc. COOL’17*, 2017.