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EIC IMPEDANCE AND BEAM DYNAMICS*

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Abstract

A new high-luminosity Electron-Ion Collider (EIC) is being developed at BNL. Beam collisions occur at IP-6, involving two rings: the Electron Storage Ring (ESR) and the Hadron Storage Ring (HSR). The vacuum system of both rings is newly developed, and impedance optimization is progressing. Both rings ' beam-induced heating and thermal analysis are performed to manage and control thermal distribution. The study uses simulated single bunch wakefields to explore collective effects across the Rapid Cycling Synchrotron (RCS), ESR, and HSR. Discussions encompass impedance analysis, collective effects and beam interactions, and the impact of ion and electron clouds on beam dynamics.

INTRODUCTION

A new Electron Ion Collider (EIC) is under development at Brookhaven National Laboratory to provide high-intensity beams for collision experiments, including heavy ions and protons at 0.7 and 1 A, as well as electrons at 2.5 A [1]. Preliminary impedance budgets have been established for the ESR and HSR rings, while ongoing efforts are focused on determining the impedance budget for the RCS ring. These budgets are critical for conducting particle tracking simulations and monitoring changes in single-bunch stability in response to updates in the total wakefields. Single-bunch wakefield simulations are performed to obtain the pseudo-Green function for ESR and HSR with a 0.5 mm and 4 mm bunch length, respectively. To validate the results, three different electrodynamics codes, CST [2], GdfidL [3], and ECHO 3D [4], are applied. Beam-induced heating and thermal analysis are performed for the vacuum components of both the ESR and HSR rings using the 3D electromagnetic code CST. The analysis addresses the impact of beam-induced resistive wall (RW) losses and synchrotron radiation on ESR vacuum chamber components. As the vacuum design progresses, we estimate the power loss and conduct temperature analysis for various HSR components, including the cryo-cooled BPM-bellows assembly, injection stripline-based kicker, beam-screens, roman pot, polarimeters, and others. A recent update on the beam-induced heating and thermal analysis of several EIC components can be found in [5, 6].

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RCS

To accumulate a 28 nC charge in the RCS, slip stacking and off-momentum injection schemes are being considered to merge two 14 nC bunches (1.1 mA single-bunch current) at 3 GeV energy and further accelerate the beam to 5 GeV, 10 GeV, and 18 GeV. A copper-coated stainless steel chamber has a circular profile with a 17.8 mm internal radius. The main beam parameters before slip stacking are presented in Table 1 at 3 GeV. First, to estimate the instability thresholds, we used the analytical approximation for the Transverse Mode Coupling Instability (TMCI) at zero chromaticity [7], Eq. (1) and the Boussard criterion [8] with a constant of 9.4 substituted for $\sqrt{2\pi}$ in Eq. (2).

$$\frac{\Delta\nu_y}{\nu_s} = \frac{eI_{th}}{2E\nu_s\omega_0}\sum_j \beta_{yj}k_{yj} \cong 0.7 \tag{1}$$

$$I_{th,MWI} = 9.4\frac{E\nu_s^2}{e\alpha(ImZ/n)_0}(\omega_0\sigma_t)^3 \tag{2}$$

The resistive wall kick factor has been multiplied by a factor of 2 to compensate for the geometric impedance contribution. The instability thresholds presented in Table 1 are above the required single-bunch current.

Secondly, since the impedance budget calculations for the RCS are still in progress, the preliminary calculated vertical dipole wakefield for the Electron Storage Ring (ESR) is used

Table 1: Main RCS Parameters before Slip Stacking

Parameter	Units	Value
Energy, E_0	GeV	3
Circumference, C	m	3844.63
Momentum compaction, α_c		0.6×10^{-3}
Revolution period, T_0	μs	12.8
Energy loss, U_0	keV	30.5
Energy Spread, σ_δ		1.1e-3
RF System		
591 MHz (h=7584), V_{RF}	MV	0.8
RF bucket height,	%	0.6
Synchrotron tune, ν_s		0.014
Bunch length, σ_t, σ_s	ps, mm	98, 29
Damping time, σ_x, σ_τ	ms	2.4, 1.2
Average beta, $\beta_{x,y}$	m	19.5
Single bunch current, I_0	mA	1.1
MWI threshold		
$I_{th,MWI}$, Z/n=0.1 Ω	mA	10
TMCI threshold, I_{th}	mA	2.2

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as an approach to perform particle tracking simulation using the ELEGANT code [9]. The W_{yD} is presented in Fig. 1, where the green trace represents the contribution of the resistive wall (Cu), calculated analytically using the Bane and Sands approach [10], and the orange trace represents the contribution of the geometric wakefields, calculated using the GdfidL code. The blue trace shows the sum of both wakefields. The vertical kick factor obtained from the current wakefield for a 98 ps bunch length is k_{yD} = 408 V/pC/m and corresponding to I_{th} = 3.6 mA, which agrees well with the ELEGANT-predicted threshold obtained from simulations, as shown in Fig. 2. The slip stacking simulations, including the longitudinal wakefield, have been set up in the ELEGANT code by M. Borland [11]. Simulations with the vertical dipole wakefield and the updated parameters for the RCS are ongoing.

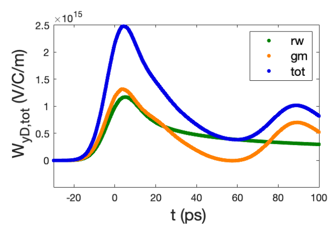

Figure 1: The vertical dipole wakefield simulated for ESR.

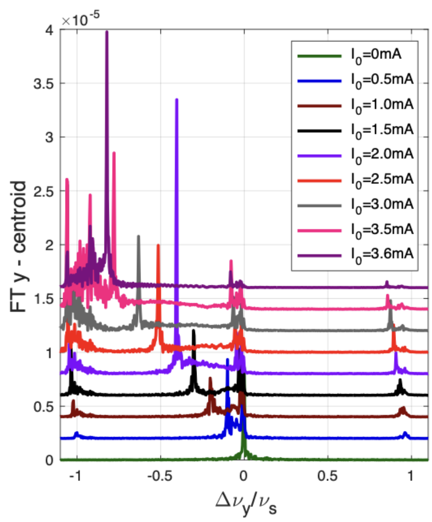

Figure 2: Vertical tune shift vs. single bunch current.

ESR

A comprehensive study of reversed phasing in the RF system of the ESR at the EIC has been performed [12–15]. The ESR of the EIC requires a high-power RF system to compensate losses due to synchrotron radiation and beam-induced wakefields. With the RF voltage of V_{RF} =12 MV at 5 GeV and V_{RF} =24 MV at 10 GeV, the required detuning frequency becomes so large that the beam can be Robinson unstable [7]. The concept of the reversed phasing RF system is considered a viable option for stable beam operation. It involves setting up two groups of cavities with the same RF cavity voltage but different synchronous phases. This concept has been well-studied, and experimental testing has been conducted with success. The RF system with reversed phasing was tested with a beam in the KEK B-Factory [16], and no issues were found during operation. Figure 3 illustrates the results of bunch length simulations by ELEGANT for the ESR RF system with reversed phasing at 5 GeV energy, utilizing 10 focusing and 7 defocusing cavities. The detune frequencies (±16.2 kHz) are much lower than the revolution frequency f_0 = 78.194 kHz. The total number of macroparticles used in ELEGANT is 5 k. The bunch length dependence exhibits a parabolic shape, with the bunches at the end of the train having a significantly larger length than those early in the train. The energy spread deviates slightly from the nominal value, but predominantly remains consistent from bunch to bunch. The present simulations have been performed with the RF system only, including the RF cavity impedance. Since the bunch length is varied along the train, it may affect the Robinson threshold with the presence of the beam-induced wakefields and impedances (leading to a tune shift).

Beam-ion instability, as predicted by [17], was anticipated to be a concern for the ESR, because any coherent motion of the electron beam would imprint onto ions in the HSR, potentially reducing luminosity and increasing detector backgrounds. The updated ESR vacuum system design, partly motivated by the necessity to suppress this instability, has expanded the use of NEG coating, resulting in a fivefold reduction in the expected residual ion pressure. Simulations using Elegant and other analyses conducted to date for the updated vacuum design indicate stability for colliding beams [14].

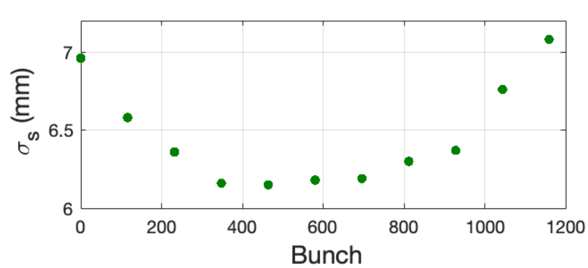

Figure 3: The bunch length σ_s dependence on the bunch number M_i, $\sigma_s(M_i)$.

HSR

Pseudo-Green function have been calculated for various HSR vacuum components, including the HSR screen with pumping slots, the polarimeter and the bellows with the pump ports. The geometric impedances are obtained by Fourier transformation of the Pseudo-Green function. While good agreements have been generally found among the results calculated by different codes, we have seen significant discrepancies when we calculate the wake potential for the HSR screen with pumping slots [18] . We have also found

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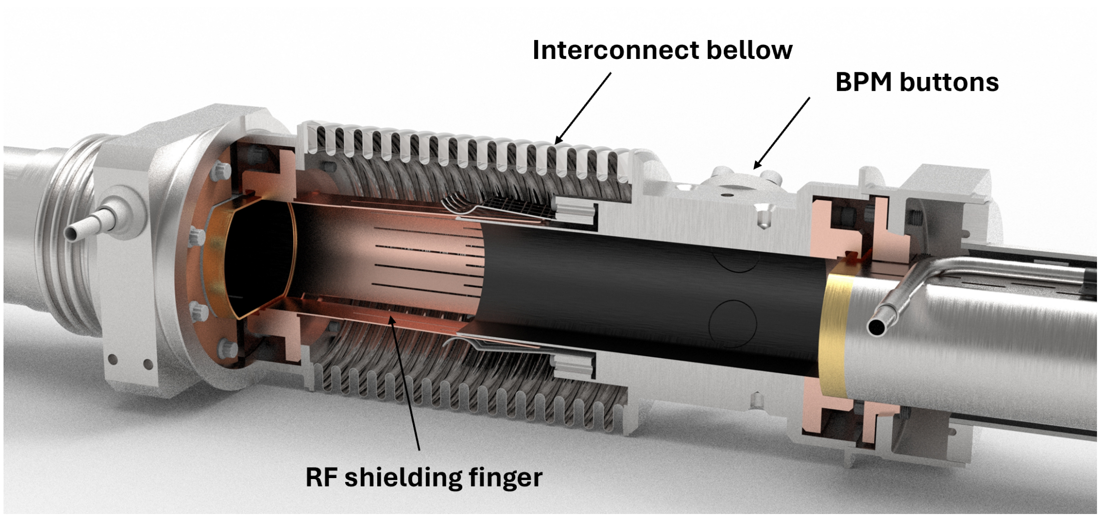

Figure 4: The HSR Interconnect section.

some convergence problems when calculating the transverse wake potential using ECHO3D, especially when the wake potential to be calculated is very small. The contributions to the resistive-wall impedance of the beam screen are summarized in Ref. [19]. Further efforts were put to understand the secondary electron yield (SEY) thresholds for electron cloud growth at different beamline locations like the snakes [20,21]. Ongoing simulation studies analyse the prospects of using octupoles to mitigate the electron cloud driven head-tail instability in the HSR and design a set of scrubbing beams. Beam studies in RHIC are scheduled to evaluate the dynamic aperture limitations to octupole operation.

A new interconnect module is being designed (Fig. 4) to bridge the beam screen across a magnet interconnect and allow for thermal contraction and magnet misalignment while offering low impedance. A new BPM button is included in the HSR interconnect module. Contributions of the cold bellows and BPM Button (blwbpm) to the total longitudinal wakefield are shown in Fig. 5 for comparison with other HSR vacuum components such as beam screen (beamscr), strip line kickers (sl), flange steps (step), warm RF shielded bellows (blw warm), 125 mm and 88 mm diameter RF shielded gate valves (gv) and abort ferrite-based kickers (ak).

BEAM-BEAM

The nonlinear beam-beam interaction induces tune spread and provides Landau damping to suppress transverse instabilities. Coherent beam-beam modes will lead to a reduction in this damping. This has been studied using the approximation that the transverse profiles of the interacting beams only vary in offset and not shape. The equations of motion for macro-particle j in beam 1 are given by:

$$\begin{aligned} \ddot{x}_j + Q_{x1}^2 x_j &= \alpha_1 \bar{x}_1 + F_x(x_j - \bar{x}_2, y_j - \bar{y}_2) \\ \ddot{y}_j + Q_{y1}^2 y_j &= F_y(x_j - \bar{x}_2, y_j - \bar{y}_2), \end{aligned} \tag{3}$$

where $\bar{x}_k$ is the x centroid of beam k and $F_x(x, y)$ is the horizontal force for the unperturbed beam. Figure 6 shows the growth rate calculated using simulations and using perturbation theory on the Vlasov equation. As is clear from the figure there can be significant regions of tune space that are unstable.

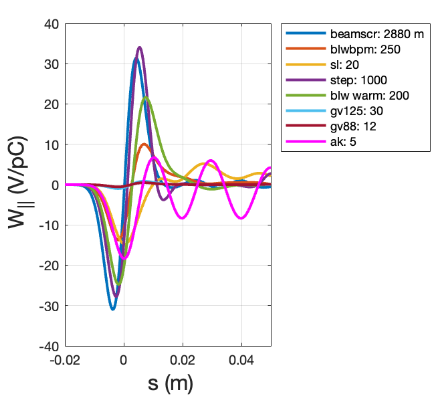

Figure 5: Longitudinal wakefields simulated for the HSR vacuum components with a 4 mm bunch length.

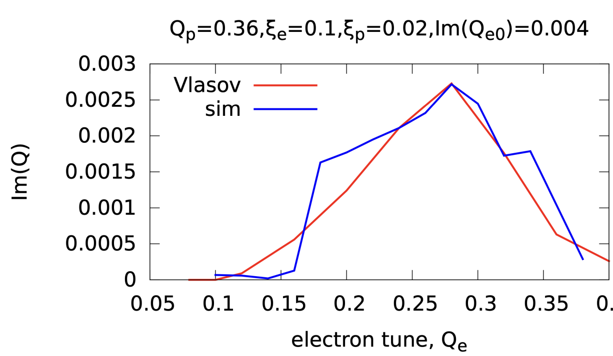

Figure 6: Instability growth rates for a proton tune of 0.36 and varying electron tune. The unperturbed phase space distribution was $1 - J_x - J_y$. The value of α_1 was 0.6 of the threshold value when the motion of beam 2 was set to zero; $\alpha_2 = 0$.

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