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UPDATES ON COLLECTIVE EFFECTS ESTIMATIONS FOR JLEIC*

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Abstract

JLEIC is the high luminosity and high polarization electron-ion collider (EIC) currently under design at Jefferson Lab. Its luminosity performance relies sensibly on the beam stability under high-intensity electron and ion beam operation. The impedance budget analysis and the estimations of beam instabilities are currently underway. In this paper, we present the update status of estimations for these collective instabilities, and identify areas or parameter regimes where special attentions for instability mitigations are required.

INTRODUCTION

An electron-ion collider (EIC), with a high center-of-mass energy (30~140 GeV), high luminosity (10^{33}~10^{34} $cm^{-2}s^{-1}$) and high polarization (~70% for the electron and light ion beams), is identified [1] as the next exploring machine for studying the nuclear structures and interactions. JLEIC is the Jefferson Lab proposed EIC that features figure-8 collider rings for polarization manipulation (especially for deuterons). It's luminosity concept [2] is based on those in the modern lepton colliders, with low beam emittances, short bunches in conjunction with low β^* at IP, high bunch repetition rate, and a 50 mrad angle of crab crossing to alleviate parasitic beam-beam effects. The low emittance and short bunches for the ion ring is made possible by a sophisticated electron cooling system [3], including DC cooling in the ion booster and at injection energy for the ion ring, and the high-energy bunched cooling [4] at the collision energy.

The JLEIC baseline parameters [5] are conceived following the unique luminosity concepts of the design, which further determine the behaviour of collective instabilities in the collider rings [6]. For example, the small emittance of the ion beam requires relatively low charge per bunch and consequently high repetition rate for the luminosity performance. This implies less significant single-bunch instabilities; yet it poses strong requirements on the bunch-to-bunch feedback systems to mitigate the longitudinal and transverse coupled bunch instabilities. In this paper, we discuss the current status of the JLEIC impedance studies, summarize the single and coupled bunch instability estimations, and present preliminary account of the two-stream instabilities, i.e., electron cloud effect in the ion ring and the ion effects in the electron ring.

STATUS OF IMPEDANCE ESTIMATION

The single and coupled bunch instabilities are respectively driven by the interaction of the beam current with the machine broadband and narrowband impedances. The estimation of the broadband impedance budget requires engineer drawings of the vacuum chamber. Yet for JLEIC presently the machine engineering design had just begun, and no details are available except for the elements count for most of the impedance-generating components in both rings (see Table 1). With the lacking of the actual component designs, at this stage, we can only use the impedance budgets of existing machines, such as PEPII or RHIC, as references. One reason for using PEPII for reference is that there is consideration for the JLEIC e-ring to adopt the PEPII HER vacuum components, such as BPMs and RF cavities. Another reason is that the bunch length $(\sigma_z \approx 1\ \text{cm})$ for JLEIC is comparable to that in PEPII, given that the effective impedances are bunch-length dependent. With the PEPII impedance budget [7] and the JLEIC component counts in Table 1, and assuming these components are identical with those used in the PEPII HER, we get $L \approx 99.2$ nH, $|Z_\parallel/n| \approx 0.09\ \Omega$ and $|Z_\perp| \approx 0.03\ \text{M}\Omega/\text{m}$. If components in SUPERKEKB [8] are used as reference, the JLEIC e-ring impedance estimation becomes $L \approx 28.6$ nH, $|Z_\parallel/n| \approx 0.02\ \Omega$ and $|Z_\perp| \approx 6.5\ \text{k}\Omega/\text{m}$, with the note that the smaller bunch length $(\sigma_z \approx 0.5\ \text{cm})$ for SUPERKEKB than that in JLEIC may cause underestimation of the effective impedance.

Table 1: Impedance-Generating Components in JLEIC

Elements	e-Ring	ion-Ring
Flanges (pairs)	1215	234
BPMs	405	214
Vacuum ports	480	92
Bellows	480	559
Vacuum valves	23	14
Tapers	6	6
Collimators	16	16
DIP screen slots	470x10^3	-
Crab cavities	2	8
RF/SRF cavities	32	40
RF/SRF bellows	0	60
RF/SRF Valves	68	24

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For the JLEIC ion ring, the short ion bunch ($\sigma_z \approx 1$ cm) is made possible only with strong bunched electron cooling [4], which is unprecedented for ion beams in existing ion rings. Since a shorter bunch often implies lower effective broadband impedance than that for a longer bunch, here we use the vacuum components in RHIC [9] as an over-estimation of the broadband impedance: $\left|Z_{\parallel}/n\right| \approx 0.71\ \Omega$ and $\left|Z_{\perp}\right| \approx 0.2\ \mathrm{M\Omega/m}$.

The element counts in Table 1 do not yet include components such as collimators, feedback kickers, and clearing electrodes. In addition, some special components unique to the JLEIC design, such as the crab cavities and IR chamber, require detailed impedance modelling and cannot use reference of impedances from the existing machines.

INSTABILITY ESTIMATIONS

The single and coupled bunch instabilities in JLEIC were estimated earlier [6], for the electron beams at the collision energies of 3, 5, and 10 GeV and for the proton beam at 100 GeV. It shows that for the single bunch instability, the electron beams at 3 and 5 GeV are vulnerable to the longitudinal microwave instability, and mitigation methods to increase Landau damping, such as using damping wigglers or harmonic cavities, are required. The longitudinal and transverse coupled bunch instabilities for the electron beams (at all collision energies) are manageable, because the growth times for the electron beams are longer than or comparable to the damping time of the state-of-art fast feedback systems. However, for the proton beam at 100 GeV, with harmonic *h=3460*, the current low-cost RF cavity design would require several tens of feedback kickers unless a more efficient HOM damping scheme for the RF cavities is employed. A study of the joint effects of the HOMs from the accelerating/focusing RF cavities and crab cavities [10] is currently underway.

ELECTRON CLOUD IN THE ION RING

In an ion ring, the ionization of residual gas and the beam-loss induced surface emission provide the source for the primary electrons, while the electron cloud build-up comes mainly from the secondary electron production [11]. Unlike the trailing-edge effect of electron cloud for long ion bunches in conventional ion rings, here the high rep rate and short bunches of the ion beam in JLEIC renders the electron cloud build-up process similar to those in positron rings of modern lepton colliders. For the proton beam at E_p =100 GeV, the electron cloud density rapidly rises up and then saturates at around the neutralization density of

$$\rho_{sat} = \frac{N_b}{\pi b^2 L_{sep}} = 2\times 10^{12}\ \mathrm{m}^{-3}\ ,$$

with the number of protons per bunch $N_b = 0.98\times 10^{10}$, the average pipe radius $b = 4.86$ cm, and the bunch separation L_{sep} =0.63 m. Such saturation behaviour is modelled in Ref. [12] for a similar set of parameters. The electron-cloud induced single-bunch transverse mode coupling instability (TMCI) threshold can be estimated using two-particle model [13]

$$\rho_{th} = \frac{2\gamma Q_s}{\pi r_p C\langle\beta_y\rangle} = 1.7\times 10^{13}\ \mathrm{m}^{-3}$$

for the synchrotron tune Q_s=0.053, ring circumference C= 2154 m, and $\langle\beta_y\rangle = 64$ m. With $\rho_{sat} < \rho_{th}$, the bunch is stable from the electron-cloud induced strong head-tail instability. The electron-cloud induced coupled-bunch instability for the JLEIC ion beam is yet to be assessed.

ION EFFECTS IN THE ELECTRON RING

The ionization scattering of the electron beam with residual gas molecules in the vacuum chamber can cause ion trapping in the electron ring. The trapped ions can cause many undesirable effects for the stability of the electron beam, such as emittance growth, halo formation, and coherent coupled bunch instabilities. For symmetric bunch pattern, the critical ion mass for the ions to be trapped is given by [14]

$$A_{x,y}^{trap} = \frac{r_p N_b L_{sep}}{2\sigma_{x,y}(\sigma_x+\sigma_y)}.$$

For JLEIC electron ring, with L_{sep} the bunch separation distance, $N_b = 3.7\times 10^{10}$, the critical ion masses in Table 1 indicate that all ion molecules ($A \geq 2$) will be trapped for even bunch fill.

Table 1: Critical Ion Mass for Trapped Ion

E [GeV]	3	5	10
L_{sep} [m]	0.63	0.63	2.52
σ_x[mm]	0.15	0.26	22.2
σ_y[mm]	0.07	0.12	0.51
A_x^{trap}	0.5	0.2	0.24
A_y^{trap}	1.1	0.4	0.4

Bunch clearing gaps in electron rings are often used to clear the ions so as to prevent them from accumulating turn after turn. For a single gap, with h the harmonic number and n the number of bunches in the train, the stability criteria for the ion motion is [15]

$$\left|\mathrm{Tr}\,(\mathrm{M}_{x,y})\right| \leq 2$$

for

$$M_{x,y} = \left[\begin{pmatrix} 1 & L_{sep} \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -k_{x,y} & 1 \end{pmatrix}\right]^n \begin{pmatrix} 1 & L_{sep} \\ 0 & 1 \end{pmatrix}^{h-n},$$

which is the one-period transport matrix of the ion particle phase-space vector, with

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$$k_{x,y} = \frac{2N_b r_p}{A\sigma_{x,y}(\sigma_x + \sigma_y)} .$$

For the JLEIC electron ring, the A vs. n for the x-motion (y-motion) is displayed in Fig. 1 (Fig. 2), where dots are marked when the stability (or ion trapping) condition is satisfied. These results show that almost all ions are trapped as n approaches h, and a gap of a few percent of the ring circumference will help clear up the ions.

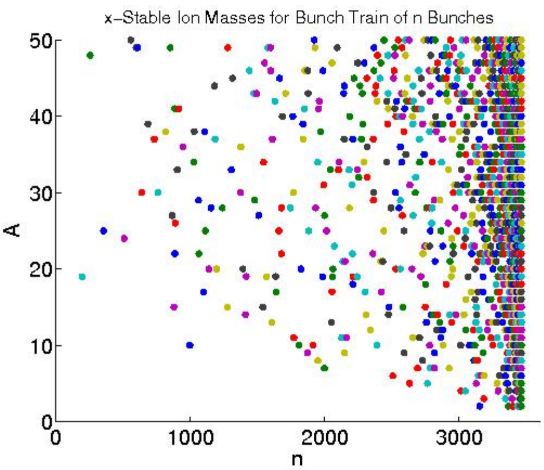

Figure 1: Ion stability in the A vs. n plot for the x-motion.

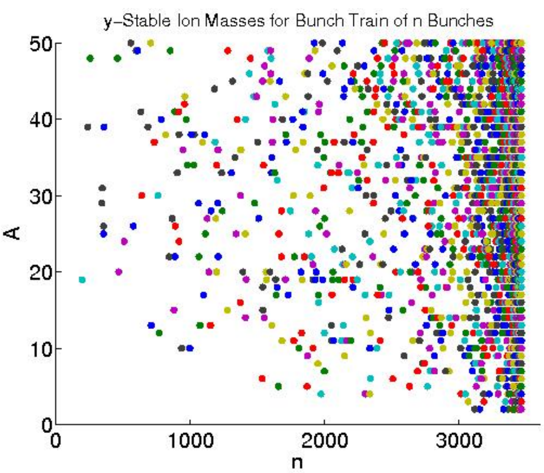

Figure 2: Ion stability in the A vs. n plot for the y-motion.

With the ions being cleared after each turn by a clearing gap or gaps (under multi-train operation), there is still the fast beam-ion instability (FBII) [16] that could cause coupled transverse dipole motion of the electron bunches, with the dipole amplitude increases in time and along the bunch train. Under the assumptions that (1) the force between the ion and electron beam is linear to their dipole offsets and (2) constant frequency for all ion oscillations, the FBII is characterized by the growth time

$$y_b(t) \propto \left(t/\tau_g\right)^{-1/4} e^{\sqrt{t/\tau_g}}$$

$$\tau_g^{-1}[s^{-1}] = 5p[Torr]\frac{N_b^{3/2} n_b^2 r_e r_p^{1/2} L_{sep}^{1/2} c}{\gamma \sigma_y^{3/2} (\sigma_x + \sigma_y)^{3/2} A^{1/2} \omega_\beta} .$$

For realistic beams, one needs to include the Landau damping effect of the ion oscillation frequency spread. Then the dipole amplitude growth is characterized by the e-folding time [17, 18]

$$y_b \propto e^{t/\tau_e}, \quad \tau_e^{-1} \approx \tau_g^{-1} \frac{c}{4\sqrt{2\pi} L_{sep} n_b a_{bt} f_i}$$

for f_i being the coherent ion oscillation frequency, and a_{bt} the ion frequency variation. For JLEIC electron ring, τ_g and τ_e are shown in Table 2 (for a_{bt} =0.5). For E_e=10 GeV, the growth time is comparable to that of the PEPII HER beam. However, for E_e=3-5 GeV, the growth time is orders of magnitude faster and is consequently a serious concern for the electron beam stability. Possible mitigation methods include using chromaticity to Landau damp the FBII, or using multiple bunch trains to reduce the growth amplitude. Comprehensive numerical modelling of FBII will be performed, along with its joint effect with beam-beam induced tune spread and coupled bunch beam-beam instability in the case of gear change scenario [19].

Table 2: Growth Time of FBII for JLEIC e-Ring

E_e [GeV]	3	5	10
τ_c [μs]	0.01	0.11	13.9
τ_e [ms]	0.02	0.1	3.2

CONCLUSIONS

In this paper, we present the status of our initial back-of-envelope estimations for JLEIC beam stability at the collision scenarios. As the engineering design progresses and when more details of impedance spectrum are available for the JLEIC collider rings, a more in-depth modeling will be conducted for the impedance-induced single and coupled bunch instabilities, including the chromaticity and uneven bunch filling effects on the coupled bunch instabilities. The HOMs from both the accelerating/focusing RF cavities and the crab cavities are to be considered. We also need to model the electron-cloud buildup and its effect on the ion beam stability, as well as the effects of chromaticity and multiple bunch train on the mitigation of fast beam-ion instability for the electron beam.

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