ESTIMATIONS OF COHERENT INSTABILITIES FOR JLEIC*

R. Li, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

Abstract

We present preliminary estimations of single and coupled bunch coherent instabilities for the electron and proton beams at collision energies for the JLEIC design. Further improvement of the estimations, as well as mitigation methods, are discussed.

INTRODUCTION

The required features of an electrion-ion collider (EIC) [1] include high collision luminosity (10^{33}~10^{34} cm^{-2}s^{-1}) for a wide range of both ion species and the center-of-mass energies, and high polarization (~70%) for the electrons and light ions. JLEIC is the Jefferson Lab EIC currently under active design [2]. It has the unique figure-8 shape for the collider rings for optimal control of the ion beam polarization. The luminosity concept for JLEIC is similar to those of lepton colliders [3], such as using short bunches in accordance with the small β^* at interaction point (IP), and using moderate bunch charge to alleviate single bunch collective effect in conjunction with high bunch repetition rate to enhance luminosity. Parasitic collision is alleviated by a 50-mrad angle of crab crossing. The short ion bunch with small emittance in the JLEIC design is unprecedented, and is achieved only via staged electron cooling, including the highly challenging strong electron cooling at collision energy.

The features and baseline parameters of JLEIC design determine the behaviour of collective effects in the collider complex. These collective effects need to be assessed for a wide range of beam energies and ion species, and also for the entire ion bunch formation process. Ideally, the wakefield-induced beam instabilities can be analytically and numerically studied once the machine impedance budget is available. However, developing impedance budget and performing instability estimations are an iterative and gradually refining process. Presently, JLEIC design is still at its early phase and the engineering design has just begun. At this stage, a preliminary estimation of impedance threshold for various coherent instabilities is necessary for the engineer design to make design choices so as to minimize machine impedance and ensure beam stability. In this paper, we present our initial estimations for single and coupled bunch instabilities using the recent JLEIC baseline design parameters. The estimated impedance threshold will be compared with the expected impedances for the JLEIC collider rings, as inferred from impedance budgets for some existing machines similar to the collider rings in the JLEIC complex.

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BASELINE PARAMETERS

The JLEIC baseline parameters for three different collision scenarios are presented in Ref. [4]. For the estimation of coherent instabilities, we use Table 1 for the electron ring parameters at collision energies of E_e = 3, 5, 10 GeV [5], and use Table 2 for the ion ring parame-ters at top collision energy E_p = 100 GeV [6].

Table 1: Parameters for the JLEIC Electron Ring (e-Ring)

E [GeV]	3	5	10
Num. of electrons/bunch		3.7x10^{10}	
Bunch number		3464	
Momentum compaction		1.09 x10^{-3}	
Average beta (x,y) [m]		11.95, 13.15	
Betatron tune (x,y)		52.7475, 52.768	
Momentum spread (x10^{-4})	2.78	4.55	9.28
Bunch length [cm]	1.2	1.2	1.4
ΔE [MeV/turn]	0.116	0.898	14.37
x-emittance [nm-rad]	2.0	5.55	22.2
y-emittance [nm-rad]	0.4	1.11	4.44
Trans. damping rate [s^{-1}]	2.67	12.35	98.83
Long. damping rate [s^{-1}]	5.33	24.71	197.65
RF voltage [MV]	0.41	2.02	17.87
Number of RF cavities	1	2	15

Table 2: Parameters for the JLEIC Ion Ring (p-Ring)

E [GeV]	100
Num. of protons per bunch	0.98x10^{10}
Bunch number	3464
Momentum compaction	6.22 x10^{-4}
Average beta (x,y) [m]	18.2, 18.9
Betatron tune (x,y)	24.22, 23.16
Momentum spread	3.0 x10^{-4}
Bunch length [cm]	1.2
Transv. emittance [nm-rad]	4.70, 0.94
RF Voltage [MV]	42.6
Number of cavities	34

Note that with the help of electron cooling, the proton beam at collision pertains similar features (see Table 2) as those for the low-energy electron beam in Table 1, in terms of the bunch length, energy spread and transverse emittances. The very short ion bunch in JLEIC means that unlike the approach in existing ion rings, here additional care is needed to account for (and minimize) the effective broadband impedance for the ion ring, as has been done in modern lepton colliders. Currently the bunch structure formation process for the ion beam, from injection to booster all the way to the final collision configuration in the collider ring, is still under development [7].

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SINGLE BUNCH INSTABILITY

Longitudinal Microwave Instability (LMWI)

With the Boussard approximation, the LMWI instability threshold is given by the Keil-Schnell criterion:

$$\left|Z_{\parallel}(n)/n\right|_{\text{eff}}^{\text{th}} \approx 2\pi|\eta|(E_e/e)\sigma_\delta^2/I_p \qquad (1)$$

For the JLEIC parameters in Table 1 and 2, the instability thresholds are listed in Table 3. It is interesting to note that unlike PEP-II LER, which is a separate ring and has a different dipole configuration from that in HER, here the JLEIC e-ring uses the same dipole configuration for a wide range of beam energies, with both dipole strength and energy spread from synchrotron radiation scale with beam energy. As a result, energy spread for beam at 3 GeV in the JLEIC e-ring is much smaller than that for the PEP-II LER beam, and thus the former is vulnerable to LMWI while the latter is not. This estimation indicates the necessity to employ suppression mechanisms against the microwave instability for the JLEIC e-ring at low energy. Such mechanisms include use of an alternative dipole configuration, damping wigglers, or a Landau cavity. For the ion ring, the machine impedance is expected to be much smaller than the threshold impedance, so the beam is safe from this instability.

Table 3: Threshold for Single Bunch Instability

	PEP-II (LER)	JLEIC e-Ring			JLEIC p-Ring
E (GeV)	3.1	3	5	10	100
I_p (A)	113	59.0	59.4	50.6	15.6
η (10^{-3})	1.31	1.09	1.09	1.09	6.22
σ_δ (10^{-4})	7.7	2.78	4.55	9.28	3.0
ν_s (10^{-2})	3.7	0.88	1.46	2.51	0.053
$\langle\beta_\perp\rangle$ (m)	20	13	13	13	18
$\left\|Z_{\parallel}/n\right\|_{\text{eff}}^{\text{ring}}$ (Ω)	~0.1	≤ 0.1 (expected)			≤ 0.5
$\left\|Z_{\parallel}/n\right\|_{\text{eff}}^{\text{th}}$ (Ω)	0.145	0.027	0.125	1.16	22.5
LMWI	stable	unstable	stable		Stable
$\left\|Z_{\perp}\right\|_{\text{eff}}^{\text{ring}}$ (MΩ/m)	0.5	≤ 0.5 (expected)			5
$\left\|Z_{\perp}\right\|_{\text{eff}}^{\text{th}}$ (MΩ/m)	1.2	0.81	2.25	9.0	449
TCMI	stable	stable			stable

Transverse Coupled-Mode Instability TCMI

The impedance threshold for the transverse mode coupling instability (TMCI) is estimated by

$$\left|Z_{\perp}(n)\right|_{\text{eff}}^{\text{th}} \approx F\,(E_e/e)\nu_s/\left(\langle\beta_\perp\rangle I_p\right), \qquad (2)$$

with F the bunch form factor. For Gaussian bunches, $F = 16\pi\sqrt{2}/3$, yielding threshold results as shown in Table 3 for both the JLEIC electron and proton beams at collision scenarios. In Table 3, the expected machine impedances are estimated from impedance budget of existing machines, such as PEP-II [3] or RHIC [8]. More accurate estimation will be available as the JLEIC engineer design progresses. For more complete studies of TMCI, we need to resort to eigenmode solver of Vlasov equation that also takes into account the bunch lengthening caused by potential-well distortion. In particular, the Christmas-tree-like equilibrium longitudinal charge distribution [9] for the proton bunch under strong electron cooling, with dense core and long tail, requires special care for its role in stability assessment.

COUPLED BUNCH INSTABILITY

Narrow-band impedances from RF cavities can cause longitudinal or transverse coupled-bunch instabilities (LCBI or TCBI). For the JLEIC electron ring, we expect to use PEP-II RF cavities, with the detailed parameters of HOM impedances listed in Table 1 and 2 of Ref. [10]. For the JLEIC ion ring, an initial RF cavity design has recently been developed, featuring 2-cell cavity with HOM damping. Detailed parameters for the HOM impedances for the new ion-ring RF cavity are shown in Table 4 and 5 [11]. In the following, we present estimations of the growth rate for the coupled-bunch instability using ZAP [12] under the assumption of even bunch filling pattern. This assumption gives an upper bound of the instability growth rate for general filling patterns. Since the growth rate is much faster than the natural damping rate, the design will rely on fast feedback systems (FBS) to control the instabilities. Consequently, we will assess the stability by comparing the instability growth time with the damping time of advanced bunch-by-bunch FBS, which can be in the range of millisecond.

Table 4: Longitudinal HOM Parameters (p-Ring)

f [MHz]	$R_s^{\parallel}$ [Ω]	Q
940.8	7.98e06	2.98e06
1771.9	2.25e04	5643.9
1814.0	1.00e05	5265.5
2894.8	3.33e04	9172.4
3079.4	2.23e02	2.65e04

With the JLEIC machine and beam parameters in Table 1 and 2, and the RF HOM parameters in Ref [10] for the electron ring and in Table 4 and 5 for the ion ring, the growth rates for coupled bunch instabilities are obtained by ZAP and shown in Table 6. Here in the TCBI calculations for the electron and the proton beams, a nonzero chromaticity of $\xi = 1$ and a finite betatron tune spread of 3×10^{-4} are assumed.

Table 5: Transverse HOM Parameters (p-Ring)

f [MHz]	$R_s^{\perp}$ [kΩ / m]	Q
792	42.0	115
1063	38.0	27
1133	1.82	54
1202	12.2	871
1327	76.7	611
1420	126.9	1138
1542	0.89	92
1595	1.39	145
1676	64.5	783
1749	2.31	1317

Table 6: Growth Time for the Coupled Bunch Instabilities in the JLEIC Design

	e-Ring			p-Ring
E (GeV)	3	5	10	100
$\tau^{\parallel}_{a=1}$ [ms]	6.1	8.5	16	2.2
$\tau^{\parallel}_{a=2}$ [ms]	118	163	199	12
$\tau^{\parallel}_{\mathrm{damp}}$ [ms]	187.	40.5	5.1	> 30 sec
$\tau^{\perp}_{a=0}$ [ms]	1.6	2.7	6.4	8.6
$\tau^{\perp}_{a=1}$ [ms]	25	39	58	132
$\tau^{\perp}_{\mathrm{damp}}$ [ms]	375	81	10.1	> 30 sec

In Table 6, $\tau^{\parallel}_{a=1}$ and $\tau^{\parallel}_{a=2}$ are the growth time for the longitudinal dipole and quadruple mode respectively, and $\tau^{\perp}_{a=0}$ and $\tau^{\perp}_{a=1}$ correspond to the growth time for the transverse rigid and dipole mode. $\tau^{\parallel}_{\mathrm{damp}}$ and $\tau^{\perp}_{\mathrm{damp}}$ for the e-ring each represents the natural longitudinal and transverse damping time due to synchrotron radiation, while $\tau^{\parallel}_{\mathrm{damp}}$ and $\tau^{\perp}_{\mathrm{damp}}$ for the p-ring are the damping times for the proton beam due to electron cooling [13]. Note that for the electron ring, the lowest energy of 3 GeV yields the fastest growth time of $\tau^{\parallel}_{a=1}$=6.1 ms for LCBI, and $\tau^{\perp}_{a=0}$=1.6 ms for TCBI, which are expected to be mitigated by advanced FBS as used in modern electron storage rings. The fast growth times of $\tau^{\parallel}_{a=1}$=2.2 ms and $\tau^{\perp}_{a=0}$=8.6 ms for the proton beam require the longitudinal and transverse FBS in the proton ring working as effectively as those in an electron ring. This, however, requires much stronger kicker strength than those found in modern proton-ring FBS, implying higher broadband impedance due to kicker cavities. Additional efforts are needed to further damp the HOM of the p-ring cavities and alleviate these excessive demands on kicker strength. The Landau damping effect on transverse coupled bunch instability, from either chromaticity or beam-beam tune shift spread, are subject of further studies.

CONCLUSIONS

Preliminary estimations of collective instabilities are performed for selected collision energies of the JLEIC collider rings. Our estimations show that for the current design, the low energy electron beam is vulnerable to the longitudinal single bunch instability. In addition, to mitigate the coupled bunch instabilities, both electron and proton beam require strong longitudinal and transverse fast bunch-by-bunch feedback systems as strong as those employed in PEP-II or modern storage-ring light sources. This present new challenges for the kicker strength for the proton ring, and require further investigation and optimization. The JLEIC instability estimations can be further improved as the engineering design progresses and impedance budget gets further developed.

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REFERENCES

[1] http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf
[2] G. Krafft (ed.) et al., "MEIC Design Summary", arXiv: 1504.07961, 29 Apr 2015.
[3] "PEP-II an Asymmetric B Factory", Conceptual Design Report, SLAC-418, 1993.
[4] Y. Zhang, "JLEIC Baseline Update and New Parame-ters", https://www.jlab.org/indico/event/210/ (2017).
[5] F. Lin, private communication (2017).
[6] V. Morozov, private communication (2017).
[7] R. Gamage and T. Satogata, pg. 2448, Proceedings of IPAC2016 (2016).
[8] S. Pegg and W. W. MacKay (editors), "Collective Instabilities in RHIC", RHIC/AP/36 (1994).
[9] A. Sidorin et al, THAP01, Proceedings of COOL 2007 (2007).
[10] R. Rimmer et al., PRST-AB 3, 102001 (2000).
[11] F. Marhauser, private communication (2017).
[12] M. Zisman, S. Chattopadhyay, J.J. Bisognano, "ZAP USER'S MANUAL" LBL-21270 (1986).
[13] H. Zhang, "Cooling Simulation Studies", https://www.jlab.org/indico/event/210/ (2017).

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