BEAM DYNAMICS AND INSTABILITIES IN MEIC DESIGN*

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Abstract

In this paper, we report the first study of beam related instabilities in lepton ring of the proposed electron-ion collider beyond the 12 GeV upgrade of CEBAF at Jefferson lab. The design parameters are consistent with PEP-II. Present studies reveal that coupled bunch and two stream instabilities are important issues and we need feedback system.

INTRODUCTION

The Medium Energy Electron Ion Collider (MEIC) at Jefferson Lab has been envisioned as future high energy particle accelerator beyond the 12 GeV upgrade of CEBAF. The MEIC will consist of the existing polarized electron source complex with 12 GeV upgrade and a new ion complex with polarized and unpolarized light to medium ions. The conceptual layout is shown in Fig. 1 and the basic parameters in comparison with the similar machines are discussed in Table 1. The maximum permissible collision frequency at 1.5 GHz is dictated by the existing electron machine, allowing the relatively small charge per bunch and large crossing angle resulting in the increased beam stability and high luminosity. In this paper, we present the preliminary study of collective effects for e-ring.

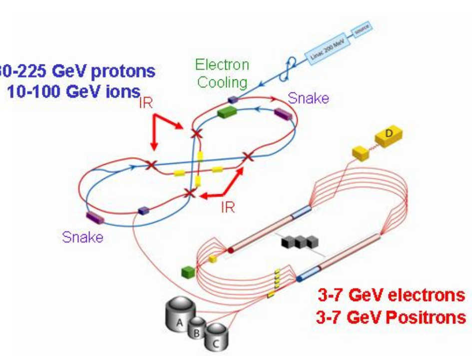

Figure 1: Conceptual Layout of MEIC at Jefferson Lab.

Table 1: Comparison of MEIC Design Parameters with Similar Machines

Parameters	MEIC	KEKB	PEPII
Beam energy E_b (GeV)	60/5	8/3.5	9/3.1
Collision freq (MHz)	748.5	509	238
Circumference (m)	1000	3016	2200
h (harmonic no.)	2500	5120	3492
K_B (# of bunches)	2500	5120	1658
Particle/bunch N_e (10^{10})	0.416/2.5	1.4/3.3	2.6/5.6
Bunch length σ_l (mm)	10/7.5	4/4	10/10
Total current I (A)	0.5/3	1.1/2.6	0.99/2.14
Rad. power P_{rad} (MW)	6	4/2.1	3.6/2.4
SR loss/turn (MeV)	2	3.5/0.81	3.58/1.14
RF voltage (MV)	9.0	10-20/5-10	18.5/5.9
Energy spread σ_E (10^{-4})	3/7.1	6.7/7.1	
Norm. hor. emit. ϵ_x^n (µm-rad)	0.35/54	123/281	390/850
Norm. vert. emit. ϵ_y^n (µm-rad)	0.07/11	2.5/5.6	15.8/33.5
Hor. beta-star β_x^* (cm)	10	33	50/37.5
Vert. beta-star β_y^* (cm)	2	1	2/1.5
Luminosity per IP (10^{33} cm^{-2} s^{-1})	5.6	10	3

IMPEDANCE BUDGET

A ring contains various elements and the net impedance is usually estimated by adding the impedance contributions of the individual components. Table 2 shows the impedance budget of MEIC e-ring based on the PEP-II design [1]. The size of MEIC e-ring is almost half of the PEP-II rings but the bunch length and the beam energy are comparable. In this calculation, we assume that the figure-8 shape of the MEIC e-ring does not affect the calculation. The impedance sum in Table 2 is 0.15 Ω, however, we assume the total impedance of 1 Ω to be more conservative.

Table 2: MEIC Impedance Budget

Component	# of items	Inductive Impedance (Ω)
Bellow	128	1.3×10^{-2}
Flange	1024	2.8×10^{-3}
Valve	10	1.0×10^{-2}
BPM	256	4.6×10^{-4}
Vacuum Port	256	9.0×10^{-5}
Taper	8	2.0×10^{-2}
DIP Screen		6.0×10^{-2}
IR injection crotch	2	2.2×10^{-2}
Feedback pickup/kicker	5	1.2×10^{-2}

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It is important to note that the loss factor of the inductive elements are significantly small [1].

SINGLE BUNCH INSTABILITY

The low Q broadband impedance in the storage ring excite wake fields that damp out rapidly before subsequent bunches arrive. Thus, they do not drive coupled bunch instabilities. They do, however, contribute to single bunch coherent effects, which limit the maximum achievable beam current in one bunch. The most pronounced longitudinal single bunch instability is the microwave instability. For a given longitudinal broadband impedance, microwave instability occurs when the peak beam current exceeds a certain threshold value $(I_p)_{\parallel}^{\mu wave}$ [2] which is given by

$$(I_p)_{\parallel}^{\mu wave} = \frac{2\pi|\eta|(E_T/e)(\beta\sigma_p)^2}{\left|Z_{\parallel}/n\right|_{BB}} \quad (1)$$

where $\left|Z_{\parallel}/n\right|_{BB}$ is the effective broadband impedance of the ring. For MEIC, σ_l = 7.5 mm of Gaussian bunch with average bunch current I_b = 1.2 mA results in the peak current of 64 A. Using (1) for MEIC parameters, stability requires $\left|Z_{\parallel}/n\right|_{BB} \leq 0.75\ \Omega$.

The corresponding transverse microwave instability (transverse fast blowup instability) – solely depends on the beam peak current for $\sigma_l > b$, however, it does also depend on the bunch length for $\sigma_l < b$. The peak threshold current is given by [2]

$$(I_p)_{\perp}^{FB} = \frac{4(E_T/e)\nu_s}{|Z_{\perp}|^{BB}\langle\beta_{\perp}\rangle R}\max\left(\frac{b}{\sigma_l}, \frac{\sigma_l}{b}\right)F' \quad (2)$$

where b is the radius of beam pipe, R is the radius of ring and $F' = \sqrt{2\pi}R$ for the Gaussian. Note that for transverse broadband impedance, we have used the relationship $|Z_{\perp}|_{BB} = \frac{2R}{b^2}|Z/n|_{BB}$ [2]. For MEIC, b = 30 mm, $(I_p)_{\perp}^{FB}$ = 850.5 A.

The transverse mode coupling instability is driven by the imaginary part of the broadband impedance and occurs when the average beam current and/or the Im($Z_{\perp}$) is high enough to shift the low order synchrotron modes of the bunch (typically a=0 and a=-1) sufficiently that their coherent frequencies merge and become degenerate. The threshold peak current scales as

$$(I_p)_{\perp}^{\rm mc} = \frac{4(E_T/e)\nu_s}{{\rm Im}(Z_{\perp})\langle\beta_{\perp}\rangle {\rm R}}\frac{4\sqrt{\pi}\beta}{3}F' \quad (3)$$

where F′ is the same factor as discussed above and $(I_p)_{\perp}^{\rm mc}$ = 523.2 A. For completeness, we have compared the impedance requirements for different comparable machines in Table 3.

COUPLED BUNCH INSTABILITY

The high-Q (narrow band) RF cavities in a storage ring have long-range ringing wake fields, which cause different bunches to interact leading to coupled bunch instability. In this preliminary calculation, we have used two 6-cell normal conducting RF cavities operating at 1.5 GHz because no data is available for 748.5 MHz. The longitudinal growth time of the dipole (a = 1) and the quadrupole (a = 2) modes predicted by ZAP [2] are shown in Table 4. It is important to note that these mode are undamped and hence we need feedback system. It is clear that the dipole modes can grow faster than the quadrupoles and hence they are unstable. The growth time of the modes corresponding to the transverse coupled bunch instability (TCBI) are illustrated in table 5. The dipole (a = 1) modes have short growth time and undamped, however, the quadrupole modes (a = 2) are damped.

Table 3: Comparison of Impedance Requirements

Parameters	MEIC	eRHIC	KEKB	PEPII
E_b (GeV)	5	5	3.5	3.1
Circumference (m)	1000	1278	3016	2200
h (harmonic no.)	2500	2040	5120	3492
K_B (# of bunches)	2500	120	5120	1658
N_e (10^{10})	2.5	10	3.3	5.91
σ_l (mm)	7.5	16.0	4.0	10
I_b (mA)	1.2	3.75	0.5	1.3
I (A)	3.0	0.45	2.6	2.14
V (MV)	9	5.0	5-10	6
ν_s	0.045	0.05	0.01-0.02	0.0371
α (10^{-3})	3	9.1	0.1-0.2	1.8
σ_p (10^{-4})	7	4.8	7.1	8
ϕ_s (deg)	13	9.2		13
$\|\frac{Z}{n}\|_{BB}$ (Ω)	0.75	0.5	0.012	0.15
$\|Z_T\|_{BB}\frac{\beta_{av}}{b}$ (GΩ/m)	4.7	1.3	0.6	1.0
Im$(Z_T)_{BB}\beta_{av}$ (MΩ)	70	42	4.7	20

Table 4: Growth Time of Longitudinal Modes

Mode	Growth Time
a = 1	τ_1 = 43 µs
	τ_2 = 44 µs
	τ_3 = 46 µs
a = 2	τ_1 = 411 µs
	τ_2 = 416 µs
	τ_3 = 442 µs

TWO STREAM INSTABILITIES

Fast Beam Ion Instability

The characteristic rise time of the fast beam ion instability according to the linear theory is described as [3]

$$\frac{1}{\tau} = \frac{4d_{gas}\sigma_{ion}\beta_y N_e^{3/2} n_b^2 r_e r_p^{1/2} L_{sep}^{1/2} c}{3\sqrt{3}\gamma\sigma_y^{3/2}(\sigma_x+\sigma_y)^{3/2}A^{1/2}} \quad (4)$$

Table 5: Growth Time of Transverse Modes

Mode	Growth Time
a = 1	τ_1 = 0.3 ms
	τ_2 = 0.6 ms
	τ_3 = 2.6 ms
a = 2	τ_1 = 13.5 ms
	τ_2 = 15.0 ms
	τ_3 = 83.0 ms

where $d_{\text{gas}} = p/(K_B T)$ is the density of the residual gas corresponding to the pressure p and temperature T; K_B is the Boltzmann constant. σ_{ion} is the ionization cross section, β_y is the average vertical beta function, n_b is the number of bunches, r_e and r_p are the classical radius of electron and proton respectively, L_{sep} is the bunch spacing, γ is the relativistic factor, $\sigma_{x,y}$ are the horizontal and vertical beam sizes respectively, A is the ion mass in unit of proton mass and c is the speed of light in free space. The growth time τ used in (4) gets modified by considering the effect of ion decoherence [4]. The ion coherent angular frequency ω_i is given by

$$\omega_i = \left(\frac{4 N_e r_p c^2}{3 A L_{sep} \sigma_y (\sigma_x + \sigma_y)} \right)^{1/2} \tag{5}$$

Taking into account of the ion coherent frequency spread, the linear theory gives the coupled bunch motion in the bunch train like $y \sim \exp(t/\tau_e)$, where the growth time τ_e is given by

$$\frac{1}{\tau_e} = \frac{1}{\tau} \frac{c}{2\sqrt{2} l_{train} (\Delta\omega_i)_{rms}} \tag{6}$$

where $(\Delta\omega_i)_{rms}$ is the rms spread of ion coherent angular frequency and the length of the bunch train $l_{train} = n_b L_{sep}$. The growth rate corresponding to different $(\Delta\omega_i)_{\text{rms}}$ are shown in Fig. 2.

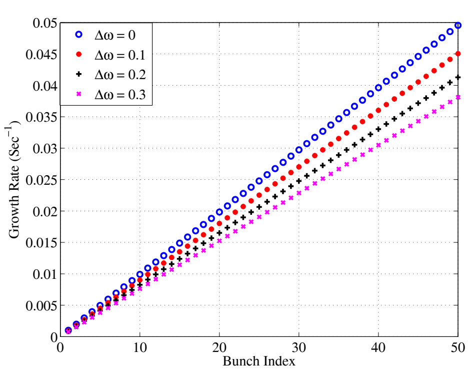

Figure 2: Growth rate versus bunch index corresponding to different frequency spread $(\Delta\omega_i)_{\text{rms}}$.

Electron Cloud Effects

Synchrotron radiation from the closely spaced positron bunches in MEIC can generate photoelectrons inside the vacuum chamber and cause secondary emission due to multipacting in the presence of beam's electric field. This phenomena can lead to fast build up of electron density, known as electron cloud effect – resulting into beam instability coupled to multi-bunches in addition to a single bunch. In this paper, we provide an estimate of the growth rate and the density threshold.

The rise time of the coupled bunch instability is approximately given by [5]

$$\tau_{e,CB} = \frac{\gamma \omega_\beta h_x h_y L_{sep}}{2 r_p N_e c^2} \tag{7}$$

where $\omega_\beta = \omega_0 \nu$ is the betatron angular frequency, ω_0 is the angular frequency of revolution, h_x and h_y are the chamber half aperture, r_p is the classical radius of the beam-particle. For MEIC of average beam aperture 30 mm and positron beam, $\tau_{e,CB} = 4.2\ \mu$s.

The single bunch instability driven by the electron cloud could be potentially strong because it can not easily be damped by a feedback system, which results into the strong head-tail or transverse mode-coupling instability (TMCI). The threshold value for the electron-cloud density is given by $\rho_{thr} = \frac{2\gamma\nu_s}{\pi r_e C \beta_y}$ [6] which evaluates to $5 \times 10^{12}\ \text{m}^{-3}$.

CONCLUSION

We have performed the beam instabilities calculations for the lepton ring of MEIC design studies at Jefferson lab. Impedance budget is comparable to the PEP-II design estimate. As expected, the single bunch instability is not a serious issue, however, we need feedback system for the coupled bunch instabilities. A preliminary estimates of the two stream instabilities have also been reported.

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