RF SYSTEM REQUIREMENTS FOR JLAB'S MEIC COLLIDER RING *

S. Wang#, R. Li, R. Rimmer, H. Wang, Y. Zhang
Jefferson Lab, 12000 Jefferson Ave. Newport News, VA 23606, USA

Abstract

The Medium-energy Electron Ion Collider (MEIC), proposed by Jefferson Lab, consists of a series of accelerators [1]. At the top energy are the electron and ion collider rings. For the ion ring, it accelerates five long ion bunches to colliding energy and rebunches ions into a train of very short bunches before colliding. A set of low frequency RF system is needed for the long ion bunch energy ramping. Another set of high frequency RF cavities is needed to rebunch ions. For the electron ring, superconducting RF (SRF) cavities are needed to compensate the synchrotron radiation energy loss. The impedance of the SRF cavities must be low enough to keep the high current electron beam stable. The preliminary design requirements of these RF cavities are presented.

INTRODUCTION

In the first stage of MEIC, ions will be injected from a pre-booster into the collider ion ring, and electrons will be injected from CEBAF into the collider electron ring. Both rings have same figure-8 shape, almost the same size, but vertically separated, as shown in Fig. 1. The Pre-booster holds a 0.22 ms long bunch. The proton bunch is extracted and transferred to the ion collider ring by a bunch-to-bucket transfer method. The ion collider ring will operate with harmonic number 5 (equal to the ratio of circumferences of the ion collider ring and the pre-booster), and hence five such transfers will be performed. In the ion collider ring, protons will be accelerated from 3 GeV to up to 25 GeV. Ion current will be up to 0.5 A. Then the long bunches will be transformed into thousands of short bunches (σ_s = 2 cm) through a debunching/rebunching process for final colliding. Electrons are injected from CEBAF at desired energy, from 3 GeV to 12 GeV. A stored electron beam of up to 3 A average current will be accumulated by stacking the CEBAF linac beam current. The compensation for the high synchrotron radiation energy loss of the 12 GeV electron beam requires a number of SRF cavities. The more SRF cavities, the larger total cavity impedance will be present, which may be harmful for stable operation of the high current electron beam. We have to design a very low impedance SRF cavity, which is a major challenge for the MEIC RF system, most likely combined with a bunch-by-bunch feedback system to fulfil the stability requirement in the electron ring.

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purpose.
# wang@jlab.org

RF CAVITIES FOR ELECTRON RING

The electron ring will use normal conducting magnets (with a maximum dipole field less than 1.7 T) and will store an electron beam varying between 3 and 12 GeV. Beam current should be up to 3 A for energy up to 6 GeV; however, the current will be lower for higher electron energies such that the total synchrotron radiation power shall be less than 10 MW. The maximum linear density of SR power in the vacuum chamber should not exceed 20 kW/m. For dipole bending radius of 57.94 m in lattice design, the synchrotron radiation energy loss parameters are shown in Table 1, from which the required SRF cavity gradient can be derived. The RMS bunch length shall be 0.75 cm.

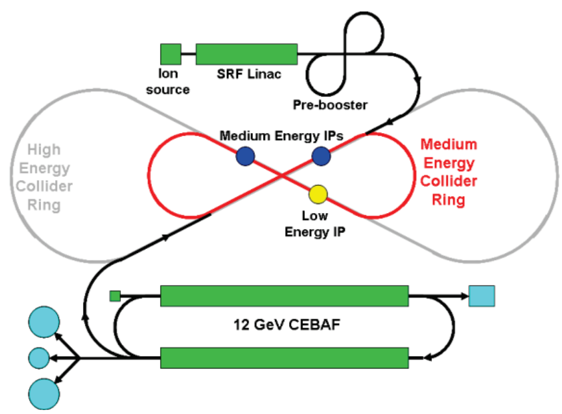

Figure 1: Layout of MEIC.

Table 1: Synchrotron Radiation Energy Loss

Energy (GeV)	5	7.5	12
Current (A)	3	1.5	0.23
SR power per ring (MW)	3.82	9.71	9.71
SR power linear density (kW/m)	7.87	20.0	20.0
Energy Loss per turn (MeV)	1.27	6.45	42.27

The frequency of the RF system in the electron ring has to be consistent with that of CEBAF to accommodate the bunch train from CEBAF. Because of the impedance requirement and in order to ease R&D and hardware cost, we choose the frequency to be 748.5 MHz, half of CEBAF frequency. Delivering the required RF power at 1.5 GHz would be much more expensive.

Other constraints for SRF design are, energy spread 7×10^{-4}, bunch length 0.75 cm, momentum compaction

ISBN 978-3-95450-122-9

factor 5.6×10^{-4}, harmonic number 3372. The RF peak voltage and phase can be derived from the bunch length and energy compensation requirements. The phase, in turn, combined with cavity shunt impedance, gap voltage and beam current gives the cavity coupling factor β. Then forward power from RF source can be determined. We limit the forward power to be less than 500 kW per cavity because of the coupler capability, and this determines the number of cavities. The single cell cavity design was chosen to minimize the number of higher order modes that can interact with the beam. Table 2 gives the preliminary RF parameters for the SRF cavity in the electron collider ring.

Table 2: Preliminary RF Parameters for SRF Cavity in Electron Collider Ring

Design Parameters	Units	12 GeV	5 GeV
frequency	MHz	748.5	748.5
number of cell		1	1
$R/Q = V_{eff}^2/(\omega^*U)$	Ohm	89	89
geometry factor G	Ohm	270.0	270.0
R/Q*G	Ohm	24030	24030
active length	m	0.2	0.2
operating temperature	K	2.1	2.1
Q0		1.29×10^{10}	1.29×10^{10}
shunt impedance ($R=U_{eff}^2/P$)	MΩ	1.15×10^{6}	1.15×10^{6}
input power	kW	485.4	191.1
P_{cavity} (surface losses)	kW	0.002	0.000008
P_{beam} (beam loading)	kW	485.4	191.1
average beam current	A	0.23	3
minimum gap voltage required	MV	2.1	0.14
accelerating gradient	MV/m	10.7	0.68
Q_{ext} (matched)		1.05×10^{5}	1.07×10^{3}
coupling factor β		1.2×10^{5}	1.2×10^{7}
total radiated power	MW	9.71	3.82
energy loss per turn	MeV	42.27	1.27
beam energy	GeV	12	5
rf effective accelerating voltage	MV	42.27	1.27
synchronous phase, 0 is on crest	deg	7.7	61.9
rf peak voltage required	MV	42.652	2.703
number of cavities needed		20	20

The MEIC electron beam is designed in a parameter regime (energy, current, and bunch frequency) in which e^+-e^- colliders of B-factories have been operated successfully for many years. It is expected that collective effects should be very similar in these two types of electron rings and therefore manageable in MEIC. Narrowband impedance in a storage ring, typically from the higher order modes of RF cavities, can induce coupled bunch instabilities—the wakefields generated by a bunch ring long enough to interact with the following bunches. Superconducting cavities exacerbate the problem, since natural cavity Q are high; HOM damping is critical. The large number of bunches require the reduction of the HOM Qs of the accelerating cavities and limit their allowable number in order to reduce the growth rate of multibunch instabilities. The threshold impedance spectrum for the excitation of multibunch instabilities can be obtained by equating the radiation damping time with the respective multibunch instability rise time. The limiting impedance is the longitudinal impedance when electron beam is at low energy, i.e., low radiation damping.

$$Z_{||,\ \mathrm{thresh}} = \frac{2E_0Q_s}{N_{cavity}f_{HOM}I_b\alpha\tau_s} \quad (1)$$

Where, E_0 is beam energy, Q_s is the synchrotron tune, N_{cavity} is cavity number, f_{HOM} is frequency, I_b is the beam current, α is the momentum compaction factor, τ_s is the longitudinal synchrotron damping time, 18.5 ms is used. Figure 2 shows the longitudinal impedance threshold as a function of frequency (without feedback).

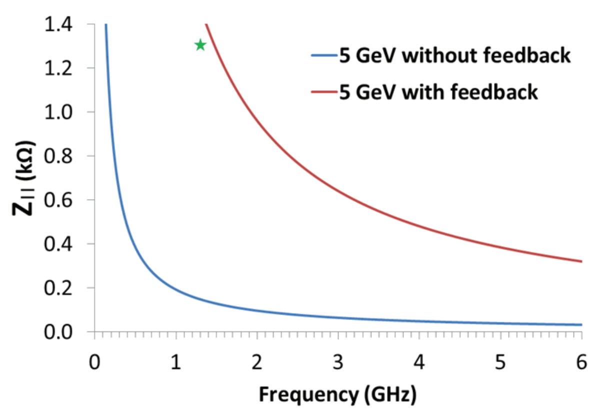

Figure 2: The longitudinal impedance threshold with and without feedback system for electron ring cavities. The green star indicates the impedance of the TM_{011} mode.

For a typical SRF cavity operating at 750 MHz the most dangerous higher order mode is the TM_{011} mode near 1.3 GHz. The corresponding impedance threshold is only 0.15 kΩ, according to Figure 2, which will require very strong damping. An SRF cavity concept with on-cell dampers is under the process of evaluation. Even this has ~1.3 kΩ impedance for TM_{011} mode calculated with CST and ACE3P [2]. With two, or even three on-cell damper, the impedance could be lower. The art of feedback systems has been well developed for B-factories, where amperes of current are stored. Since the bunch repetition frequency of MEIC is only somewhat higher than today's

B-factories, the technology for these feedback systems has been well proven. With the help of such a feedback system, a factor of 10 can be obtained [3], and we can get low enough impedance for the SRF cavity. Figure 3 shows the SRF cavity with one on-cell damper.

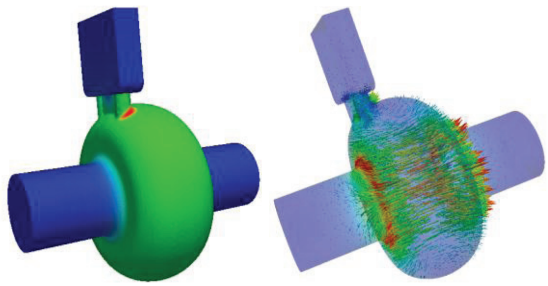

Figure 3: SRF cavity concept with one on-cell damper, TM_{010}. Left, surface magnetic field, right, electric field.

RF CAVITIES FOR ION RING

There will be two sets of RF systems in the ion ring. One can utilize LEIR-type FINEMET cavities to accelerate five bunches of ions to top energy at frequency around 1.1 MHz [4]. The other will use a 748.5 MHz RF cavity to rebunch ions into thousands of short bunches. The stored beam currents are up to 0.5 A for protons. The dual systems are needed because the revolution frequency varies during the energy ramping, see Table 3, favouring a low frequency system, but many short bunches are needed for colliding.

Table 3: RF Frequency Variation, Harmonic Number is 5

Ion species	Injection energy	Frequency (injection)	Top energy	Frequency (colliding)
p^+	3 GeV	1.078 MHz	25 GeV	1.110 MHz
$^{208}Pb^{82+}$	1.2 GeV/u	0.998 MHz	10 GeV/u	1.106 MHz

At such a low frequency, most of the variable frequency RF systems use inductance-loaded co-axial cavities. FINEMET can be used for the inductance to reduce the cavity length. The RF voltage required is determined by the ramping rate.

Once ions are accelerated to the top energy, the low frequency RF system will be turned off, and the ions left to circulate in the ring and form a longitudinally uniform distribution. Then the high frequency RF will be turned on to rebunch the ions into short bunches. Related ion ring parameters are shown in Table 4. The required RF voltage for bunching can be derived from Equation 2 to be 0.1 MV. This modest voltage can be provided by a single normal conducting cavity.

$$V_{RF} = \frac{2\pi c^2 \eta E}{\omega_{rev}^2 \sigma_b^2 H e \sin\phi_s}\left(\frac{\delta E}{E}\right)^2 \quad (2)$$

Where, η is the phase slip factor, -2×10^{-4}, RF phase ϕ_s is 90 degrees since there is no acceleration or synchrotron radiation losses to compensate.

Table 4: Parameters of Ion Ring High Frequency RF system

	Energy	Energy spread	Bunch length	Revolution frequency	H
p^+	10-25 GeV	3×10^{-4}	2 cm	0.222 MHz	3372

The multi-bunch coupled instability threshold in the ion ring at top energy depends on the Landau damping,

$$R_{sh} < \frac{|\eta|E}{eI_0}\left(\frac{\Delta p}{p}\right)^2 \frac{\Delta\omega_s}{\omega_s} F \frac{f_r}{f_0} \min\{J^{-2}{}_m(\pi\tau f_r)\} \quad (3)$$

With synchrotron frequency of 4.5×10^{-2}, the longitudinal impedance threshold can be calculated as shown in Figure 4. The proton energy is from 10 to 25 GeV. HOM damping of the RF cavity is still required but it is less severe than the electron ring. A scaled B-factory type cavity would be sufficient[5].

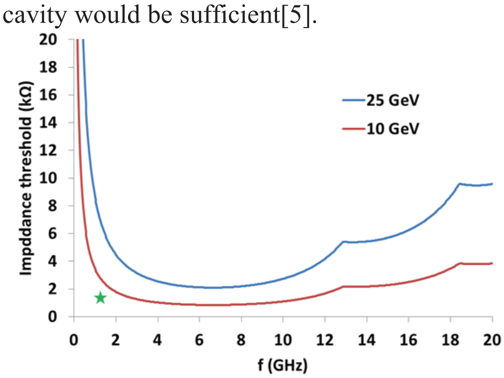

Figure 4: Impedance threshold for ion ring, the green star indicates the cavity's impedance is below threshold.

CONCLUSION

For the first stage of MEIC, the major challenge of the RF system is the high frequency, high power but low impedance SRF cavity for the electron ring. Although it is achievable according to our analysis, careful design efforts are needed.

ACKNOWLEDGMENT

The authors would like to thank Zenghai Li, Ng Cho and Lilin Xiao of SLAC for help with ACE3P calculations.

REFERENCES

[1] Y. Zhang et al., "Status of MEIC Design Studies," MOPWO082, these proceedings
[2] Kwok Ko, et. al., "Adv.ances in Parallel Electromagnetic Codes for Accelerator Science and Development," LINAC10, Tsukuba, Japan, 2010.
[3] H. Schwarz, R. Rimmer, "RF System Design for the PEP-II B Factory", EPAC94, London, UK, 1994.
[4] R. Garoby, et al, "THE LEIR RF SYSTEM", PAC'05, Knoxville, May 2005, p. 1619 (2005); http://www.jacow.org
[5] R. Rimmer, et al, "An RF Cavity for the B-Factory", PAC91, San Francisco, US, 1991.