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CAPTURE, ACCELERATION AND BUNCHING RF SYSTEMS FOR THE MEIC BOOSTER AND STORAGE RINGS*

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Abstract

The Medium-energy Electron Ion Collider (MEIC), proposed by Jefferson Lab, consists of a series of accelerators. The electron collider ring accepts electrons from CEBAF at energies from 3 to 12 GeV. Protons and ions are delivered to a booster and captured in a long bunch before being ramped and transferred to the ion collider ring. The ion collider ring accelerates a small number of long ion bunches to colliding energy before they are re-bunched into a high frequency train of very short bunches for colliding. Two sets of low frequency RF systems are needed for the long ion bunch energy ramping in the booster and ion collider ring. Another two sets of high frequency RF cavities are needed for re-bunching in the ion collider ring and compensating synchrotron radiation energy loss in the electron collider ring. The requirements from energy ramping, ion beam bunching, electron beam energy compensation, collective effects, beam loading and feedback capability, RF power capability, etc. are presented. The preliminary designs of these RF systems are presented. Concepts for the baseline cavity and RF station configurations are described, as well as some options that may allow more flexible injection and acceleration schemes.

INTRODUCTION

For the ion accelerator complex, one major change from earlier design is that only one booster exists between the source-linac system and ion collider ring [1]. In this booster, ions are captured and form a single long bunch, accumulated to the required bunch charge, and then ramped, to 8 GeV(H^+)/3.2 GeV/u(lead ion) and cooled, before being transferred to the ion collider ring. In the ion collider ring, nine long bunches are formed before being ramped to collision energy. At collision energy, the long bunches are debunched and rebunched in to 476 MHz buckets before collision with the electron bunches.

For the electron collider ring, it accepts bunch trains from CEBAF. The RF system needs to provide synchrotron radiation energy compensation and bunch longitudinal formation at different collision energies with high enough beam current, and stable operation.

CAPTURE AND RAMPING RF CAVITIES IN BOOSTER AND ION COLLIDER RING

In the ion source-linac system, ion bunch trains are accelerated to 285 MeV (proton) or 114 MeV/u (lead ions) before being delivered to the booster. Like other rapid cycling synchrotrons, the micro bunches from the linac will be accumulated in the booster ring, captured by the potential well produced by the RF field. The 8 GeV booster ring is designed to utilize multi-turn injection with combined longitudinal and transverse painting and charge exchange mechanism.

At low energy, space charge effect is the most important effect that limits the maximum available total charge in each ramping cycle. That is why a long bunch is needed in the booster in order to lower the space charge density.

During the energy ramping process in both booster and collider rings the beta of ions varies so the RF frequency needs to be variable to keep up with the revolution frequency. So, we need choose the inductance-loaded RF cavities as the ramping cavities. Because the ramping rate is limited by the super-ferric bending magnets [2], the total gap voltage needed for ramping is not high, as shown in Table 1. We chose ferrite-loaded cavities for the design for the lower cost. In the design, we assumed a linear ramping process. Design data for the ramping cavities in booster and collider ring are shown in Table 2.

Table 1: Summary of Ramping Cavity Configuration

	Booster	Collider
Circumference (m)	238.88	2149.9
Harmonic Number	1	9
Gaps per Cavity	2	
Cavity Number	2	7
Cavity Length (m)	2.2	
Total Cavity Length (m)	4.4	15.4
Ferrite Toroid Inner Radius (m)	0.25	
Ferrite Toroid Outer Radius (m)	0.5	
Ferrite Stack Length (m)	1	
Maximum Gap Voltage (kV)	10	

Table 2: Summary of Ramping Cavity RF Parameters

	Booster		Collider	
	H^+	$^{208}Pb^{67+}$	H^+	$^{208}Pb^{67+}$
Energy(GeV/u)	0.285 ~ 8	0.114 ~ 3.2	8 ~ 100	3.2 ~ 40
RF Frequency (MHz)	0.817 ~1.274	0.571 ~ 1.22	1.248 ~1.255	1.223 ~ 1.25
Ramping Time (Sec)	0.404	0.57	12.0	12.2
Vgap (kV)	8.0	5.75	7.9	7.9
Beam Power (kW)	8.0	1.85	27.5	10.8

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Cavity Power Loss (kW)	41.2	41.2	23.6	23.6
Total RF Power (kW)	98.5	86.2	357.4	241
Syn. Phase (degree)	30			

BUNCHING RF CAVITIES IN ION COLLIDER RING

In the collider ring, after the nine long ion bunches are ramped to the desired collision energy (up to 100 GeV for H^+, 40 GeV/u for Lead ion), the RF voltages of the ramping cavities will be adiabatically turned off, ions will then fill all the circumference of the ring except the abort gap produced with a barrier bucket potential well. After the longitudinal density profile becomes uniform enough, one or two 476 MHz RF cavities adiabatically turn on voltage to start the pre-bunching process. The main bunching RF cavities are 952 MHz SRF cavities. The higher frequency means higher bunching efficiency. The choice of 952 MHz is also for future upgrade of 952 MHz collision rate after new 952 MHz SRF cavities replace all the 476 MHz PEP II cavities. At the starting operation stage, the bunch rate in ion collider ring needs to match the 476 MHz frequency in the electron ring, that is why we need a 476 MHz pre-bunching process in ion collider ring. The good news is that we don't need to produce a very short bunch ready for collision, just 476 MHz rep-rate is desired. So we can determine the bunch length requirement in pre-bunching process according to Equation 1.

$$V_{RF} = \frac{2\pi c^2 \eta E}{\omega_{rev}^2 \sigma_b^2 He}\left(\frac{\delta E}{E}\right)^2. \quad (1)$$

The harmonic number is 3416, revolution frequency is 0.139 MHz, energy spread is 2.0e-4, phase slip factor 6.327e-3. At 100 GeV, if one 476 MHz cavity is used for pre-bunching, a $\sigma_b = 85$ mm bunch can be formed with 120 kW forward power. During the pre-bunching process, the synchronous phase is zero, the bucket length has maximum value of 360 degree, 85 mm corresponds to ~ 49 degrees (at 476MHz). If two 476 MHz cavities are used, a $\sigma_b = 60$ mm or 34 degrees (at 476 MHz) bunch can be formed with 120 kW forward power for each cavity.

After the pre-bunching process, the 476 MHz cavities are turned off adiabatically and main bunching 952 MHz cavities are turned on adiabatically. Now in the 952 MHz bucket train, only every other bucket is filled. RF parameters for producing the required short bunches with 952 MHz SRF cavities are shown in Table 3 and 4.

Table 3: Summary of Ion Collider Ring Parameters

Revolution Frequency	0.139	MHz
RF Frequency	952.6	MHz
Harmonic Number	6832	
Mom. Comp. Factor	6.413e-3	
Bunch Length	12	mm
Cavity Active Length	0.157	m
Cavity Insertion Length	1.91	m
Temperature	4.2	K
Surface Resistance	353	nΩ
Geometry Factor	216.98	
R/Q	105.7	
Q_0	6.15e8	
Shunt Impedance	6.5e4	MΩ

Table 4: Summary of Ion Collider Ring Bunching Cavity RF Parameters

	Proton	Lead Ion	
Energy	100	40	GeV/u
Current	0.5		A
Circumference	2150		M
Energy Spread	2.0e-4	2.0e-4	
Phase Slip Factor	6.3e-3	5.9e-3	
V_{peak}	18.94	17.92	MV
Synchronous Phase	0.0		Degree
V_{gap}	1.18	1.19	MV
Gradient	7.52	7.59	MV/m
Synchrotron Tune	0.036	0.034	
Forward Power	46.9	109.8	kW
Cavity Power Loss	21.6	22.0	W
Coupling Beta	8.7e3	2.0e4	
δf	-21.3	-21.1	kHz
Q_{ext}	7.07e4	3.07e4	
Q_L	7.07e4	3.07e4	
Cavity Number	16	15	
Total RF Power	0.75	1.65	MW

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

$$R_{sh} < \frac{|\eta| E}{e I_0}\left(\frac{\Delta p}{p}\right)^2 \frac{\Delta\omega_s}{\omega_s} F \frac{f_r}{f_0} min\{J^{-2}{}_m(\pi\tau f_r)\} \quad (2)$$

The longitudinal impedance threshold can be calculated as shown in Fig. 1.

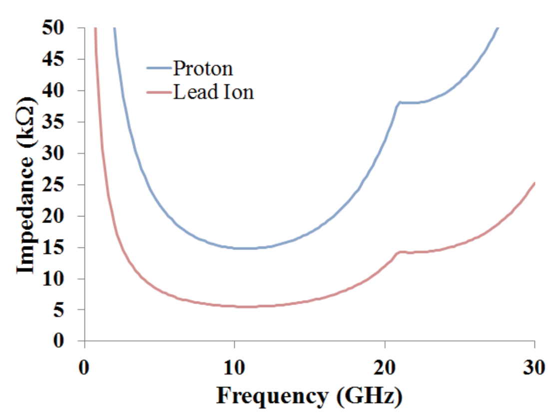

Figure 1: Impedance threshold for ion ring.

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A new single-cell HOM damped SRF cavity is designed as shown in Fig. 2 with SLAC's ACE3p code [3]. This design will be used for both the ion ring bunching process and future electron ring upgrade.

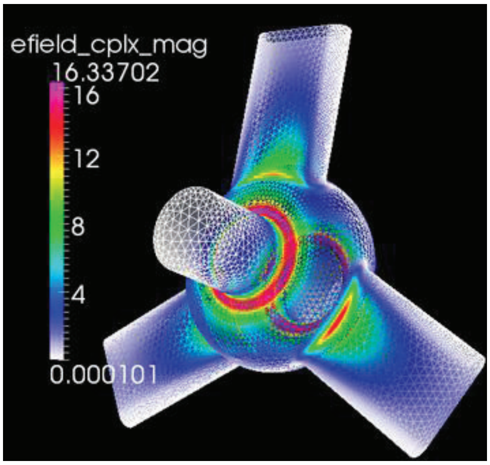

Figure 2: HOM damped cavity.

RF CAVITIES IN ELECTRON RING

In the current design, the electron ring will use the 476 MHz normal conducting RF cavities and klystrons from PEP II to lower cost. There are 34 RF cavities and 13 1.2-MW klystrons available.

The electron collider ring will store electron beam with energy varying between 3 and 10 GeV. The maximum beam current will be up to 3 A. In the high-energy end, the beam current is lower because of being constrained by synchrotron radiation power per ring (< 10 MW) or linear synchrotron radiation power (<10 kW/m). The RMS bunch length shall be 1.2 cm except at 10 GeV where the bunch length will be 1.6 cm because of limited RF power.

The RF peak voltage and phase can be derived from the bunch length and synchrotron radiation energy compensation requirements. The cavity coupling factor β = 3.6 is used to calculate the forward power. We limit the forward power to be less than 500 kW per cavity because of the coupler capability. The single cell cavity design was chosen to minimize the number of higher order modes that can interact with the beam. Table 5 and 6 give the preliminary RF parameters for the cavity in the electron collider ring.

Table 5: Summary of Electron Collider Ring Parameters

RF Frequency	476.3	MHz
Harmonic Number	3416	
Radius of Dipoles	110.452	m
Crossing Angle	81.7	Degree
β Function at Cavity	5	m
Momentum Comp. Factor	2.142e-3	
Bunch Length	12	mm
R/Q	218.8	
Q_0	32000	
Q_L	6.96e3	
Shunt Impedance	7	MΩ

Table 6: Summary of Electron Collider Ring Cavity RF Parameters

Energy	3	5	10	GeV
Current	3	3	0.71	A
Energy Spread	2.73e-4	4.55e-4	9.10e-4	
SR Power per Ring	0.34	2.56	10	MW
Energy Loss / Turn	0.11	0.88	14.12	MeV
Linear SR Power	0.340	2.625	9.911	kW/m
V_{peak}	0.73	3.44	20.56	MV
Syn. Phase	9.06	14.89	43.39	Degree
V_{gap}	0.73	0.34	0.79	MV
Gradient	2.3	1.1	2.5	MV/m
Syn. Tune	0.017	0.028	0.042	
Beam Power / Cavity	343.2	264.8	384.6	kW
Forward Power	438.6	497.8	492	kW
Cavity Power	75.4	16.9	89.3	kW
δf	-212.3	-466.0	-33.9	kHz
L. SR Damping Time	188.19	40.65	5.08	mS
T. SR Damping Time	376.38	81.30	10.16	mS
Active Cavity Number	1	10	26	

Narrowband impedance in a storage ring, typically from the higher order modes of RF cavities, can induce coupled bunch instabilities. The large number of bunches requires 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. So for operations at low energies, the cavity number is reduced to minimize the total impedance,

$$Z_{||,\ \text{thresh}} = \frac{2E_0 Q_s}{N_{cavity} f_{HOM} I_b \alpha \tau_s} \qquad (3)$$

Bunch by bunch feedback systems will be required for stable operation with 3 A at low energies.

SUMMARY

The 952 MHz SRF cavity is being developed to ensure both successful operation of initial stage and future electron ring upgrade. The Configuration of the 476 RF systems in MEIC needs careful design for operation at different energies with high enough current.

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REFERENCES

[1] F. Lin, et al, “Progress on the design of the polarized medium-energy electron ion collider at jlab”, this proceeding, IPAC 15, Richmond, USA.
[2] F.R. Huson et al., IEEE Trans. Nucl. Sci. NS-32, 3462 (1985).
[3] Kwok Ko, et. al., “Advances in Parallel Electromagnetic Codes for Accelerator Science and Development,” LINAC10, Tsukuba, Japan, 2010.