JLEIC SRF CAVITY RF DESIGN*

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Abstract

The initial design of a low higher order modes (HOM) impedance superconducting RF (SRF) cavity is presented in this paper. The design of this SRF cavity is for the proposed Jefferson Lab Electron Ion Collider (JLEIC). The electron ring of JLEIC will operate with electrons of 3 to 10 GeV energy. The ion ring of JLEIC will operate with protons of up to 100 GeV energy. The bunch lengths in both rings are ~12 mm (RMS). In order to maintain the short bunch length in the ion ring, SRF cavities are adopted to provide large enough gradient. In the first phase of JLEIC, the PEP II RF cavities will be reused in the electron ring to lower the initial cost. The frequency of the SRF cavities is chosen to be the second harmonic of PEP II cavities, 952.6 MHz. In the second phase of JLEIC, the same frequency SRF cavities may replace the normal conducting PEP II cavities to achieve higher luminosity at high energy. At low energies, the synchrotron radiation damping effect is quite weak, to avoid the coupled bunch instability caused by the intense closely-spaced electron bunches, low HOM impedance of the SRF cavities combined with longitudinal feedback system will be necessary.

INTRODUCTION

In order to achieve high luminosity in the electron ion collider, shorter bunches and higher beam current are needed. In the ion collider ring of JLEIC [1], after a series of acceleration, the last step of manipulation before colliding is bunching. Since there is no significant synchrotron radiation the ion bunches are located at the zero crossing of RF voltage. The resulting bunch length is inversely proportional to the RF cavity frequency and square root of RF voltage. So, higher frequency is preferred and 952.6 MHz was chosen as mentioned above. With this frequency, the required total RF peak voltage can be derived to be around 43 MV to obtain a bunch length of 12 mm, so SRF cavities are preferred for the ion collider ring.

In the electron ring of JLEIC, the synchrotron radiation power loss becomes more significant when beam energy is higher. CEBAF is used as injector for the electron collider ring. Initial energy at injection will be up to 10 GeV with an option to upgrade to 12 GeV in the future. The number of normal conducting PEP II RF cavities available won't be sufficient at this higher energy, so SRF cavities of the same type as used in ion ring may be added to the electron ring in the second phase of JLEIC. Eventually the PEP-II NC cavities may be phased out and replaced by 952.6 MHz SRF cavities, enabling a higher bunch rate in both collider rings.

In the electron collider ring the beam current at the high energy end will be limited by the RF power supply available, so the beam current at high energy end could be increased in the future by adding more klystrons if desired. At the low energy end, the synchrotron radiation damping effect becomes too weak to suppress the coupled bunch instability of the nominal 3 A beam current without proper HOM impedance control. Two strategies are used to ensure the beam stability: low HOM impedance cavities and bunch-to-bunch feedback systems.

LOW HOM IMPEDANCE CAVITY

In order to lower HOM impedance, it is proposed to use three on-cell dampers to extract HOM power, just as in the PEP-II RF cavity [2]. A one third model of the present concept with electric and magnetic field on surface is shown in Fig. 1. In ion ring application, the SRF cavity will see the max gradient, about 8 MV/m, the corresponding Bmax is 71 mT.

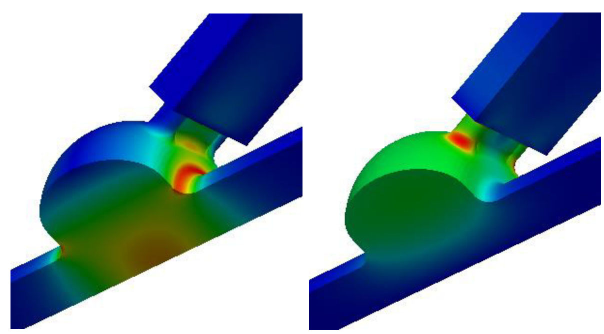

Figure 1: One-third model of the cavity. Left: electric field; right: magnetic field.

All three damper waveguides are located on one side of the cavity and symmetrically located around the central axis of the cavity. We compared two, three and four damper waveguides in different configurations; this is the one that gives lowest overall impedance.

The cut-off frequency of the damper waveguide is chosen to be half way between the fundamental mode and the lowest HOM, ~1 GHz. In this way HOMs can be extracted well without too much leakage of fundamental mode.

Good coupling between the damper waveguides and cavity is essential for the low impedance design, however too large of an opening may cause unacceptable field concentration around the aperture. A ridged waveguide iris with a dumbbell shaped cross-section is added be-

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tween the waveguide and the cavity to control the coupling, see Fig 2. The width of the waveguide neck is optimized to minimize the HOM impedance. The blend radius of the curved surface that connects the waveguide neck to the cavity is also enlarged to decrease the $\boldsymbol{B}_{\max}$ at the end of the waveguide neck, as indicated in the right graph in Fig. 1.

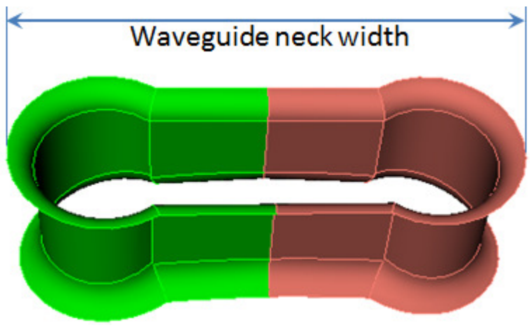

Figure 2: Dumbbell-shaped waveguide iris.

The damper waveguides are located on the elliptical section of the cavity surface. The openings of the damper waveguides on the cavity surface concentrate the cavity surface currents of the fundamental mode in the section between the damper waveguides. In HOMs the oscillating current near the damper waveguides excites fields in the damper waveguides and propagates the HOM energy outward. In order to get good coupling and facilitate fabrication, the damper waveguides are positioned to be normal to the cavity elliptical surface, as illustrated in Fig. 3.

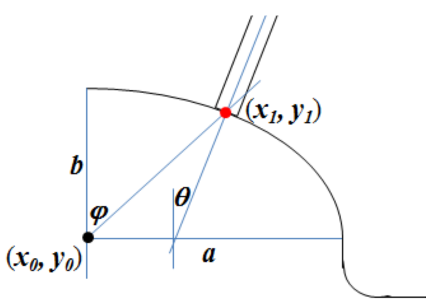

Figure 3: Position and direction of the damper waveguide.

The damper waveguides are designed to couple to the azimuthal magnetic field, they must be placed on the cavity wall such as to be close where the dangerous HOM fields are strong, but not be at a null point for any harmful mode. So, the waveguide-cavity angle $\boldsymbol{\varphi}$ in Fig. 3 is optimized to minimize the overall HOM impedance.

The RF simulation of the cavity is performed with SLAC's ACE3P [3]. Two codes of ACE3P are available for impedance calculation. Omega3P is used for frequency domain calculation and can be used to model a specific mode; T3P is used for time domain calculation and get the broad-band impedance spectra. By tuning the design of the cavity as mentioned above, the Qs of HOMs drop as HOM energy is more efficiently coupled out to the damper waveguide and the outward traveling wave inside the waveguide becomes stronger. When the Qs become quite low, we can only use the time domain code T3P to calculate the impedance, Omega3P can no longer find the right Eigen mode. Fig. 4 shows a typical Omega3P result of a TM_{011} mode. Both standing wave and inside the cavity and the traveling wave inside the waveguide can be seen.

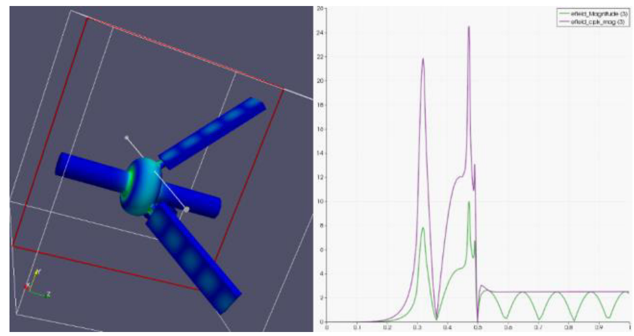

Figure 4: Omega3P results. Left: cavity model and the electric field on cavity and damper waveguide surface. Right: the electric field amplitude (purple) and the time varying electric fields of the standing wave (green) inside the cavity and the traveling wave inside the waveguide.

Figure 5 shows the longitudinal impedance spectrum deduced from T3P results. The red curve shows the coupled bunch instability (CBI) limited threshold with bunch-to-bunch longitudinal feedback system (LFS) on. The threshold determination will be described in next section.

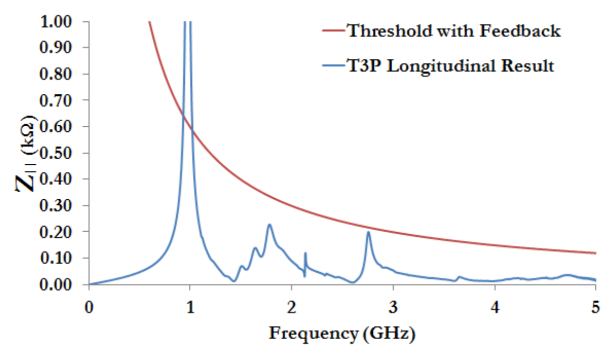

Figure 5: Blue: longitudinal cavity impedance spectrum from T3P results. Red: coupled bunch instability threshold with bunch-to-bunch longitudinal feedback system on.

CBI AND LFS

The electron ring will operate from 3 GeV to 10 (later 12) GeV. When the thousands of bunches of JLEIC circulate in the ring, interacting with the RF cavity impedance, coherent oscillations could induce instabilities, the so-called coupled bunch instability.

For $\boldsymbol{M}$ evenly spaced bunches in the ring, there are $\boldsymbol{M}$ possible modes of coherent oscillations. Each mode has many lines in the spectrum,

$$f_{nm,p} = (n + pM)f_{rev} + mf_s$$

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Where $\boldsymbol{n}$ = 0, 1, 2 … $\boldsymbol{M}$-1 is the coupled bunch mode number, $\boldsymbol{m}$ = 1, 2, 3… is the synchrotron oscillation mode $\boldsymbol{p}$ = …-2, -1, 0, 1, 2….. When a mode of oscillation $\boldsymbol{n}$ is excited by the field from the cavity impedance, the motion is intrinsically stable or unstable depending on the sign of the damping time τ_i:

$$\frac{1}{\tau_i} = \frac{\alpha I}{4\pi E/ev_s} \sum_p \omega_{nm,p} \Re\left[z\left(\omega_{nm,p}\right)\right] e^{-(\omega_{nm,p}\sigma_t)^2}$$

The instability can be suppressed by the synchrotron radiation damping, τ_{SR}.

$$\frac{1}{\tau_{SR}} = \frac{E_{loss\ per\ turn} f_{rev}}{E} \propto E^3$$

So, the total damping time is

$$\frac{1}{\tau_a} = \frac{1}{\tau_i} - \frac{1}{\tau_{SR}}$$

But we can see that τ_{SR} increases dramatically when energy $\boldsymbol{E}$ drops close to 3 GeV. The current in the impedance damping time expression indicates that we would need to lower the current at low energy operation of JLEIC to stabilize the beam, even when we decrease the cavity number to minimize the total impedance. In order to counteract this, a PEP-II or DAΦNE type bunch-by-bunch longitudinal feedback system [4, 5] should be included for stable operation with 3 A current at low energy. The damping time of the LFS is

$$\frac{1}{\tau_{fb}} = \frac{f_{rf}\alpha}{2v_s E/e} G$$

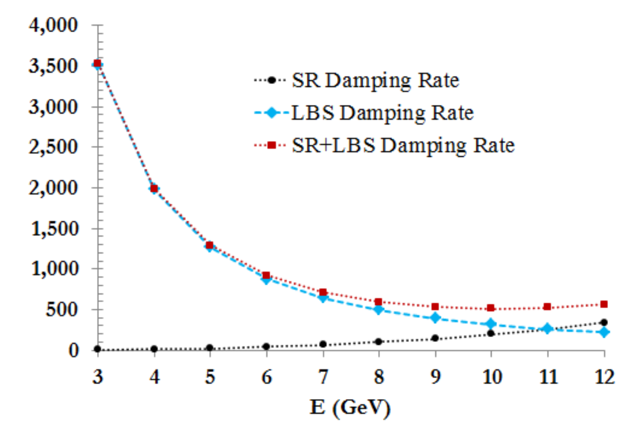

Figure 6: Damping rates from synchrotron radiation (black), LFS (blue), and total (red).

$$\frac{1}{\tau_a} = \frac{1}{\tau_i} - \frac{1}{\tau_{SR}} - \frac{1}{\tau_{fb}}$$

Where, $G = \frac{\delta V}{\delta \theta}$ is the LFS loop gain in unit of V/rad, δV is the LFS kicker voltage, the minimum value of $\delta\theta$ is the phase resolution of the detector. With the help of LFS, the total damping time becomes

The phase resolution $\delta\theta$ is about 0.5° [4]. If we let δV to be 1.5 kV, the damping rates, or the inverse of the damping times, are shown in Fig. 6.

With this damping rate, we can achieve 3 A at low energy in JLEIC electron ring, as shown in Fig. 7. The drop of beam current at high energies is limited by upper limit 10MW of total synchrotron radiation power. This limit is in turn set by the capability of the vacuum system to handle the gas desorption of the radiated photons [6]. Below about 7 GeV the beam current is not limited by impedance but may be held at 3A by other effects.

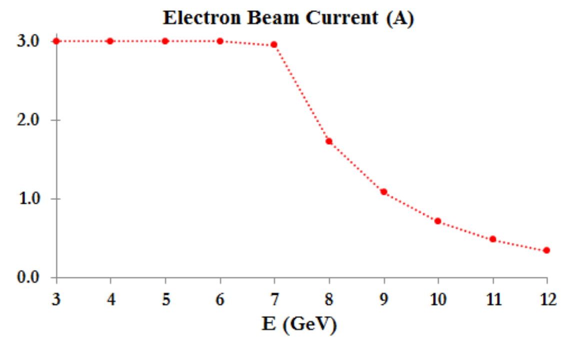

Figure 7: Beam current with bunch-by-bunch LFS.

CONCLUSION

We have performed the initial design of a low HOM impedance SRF cavity for JLEIC. High gradient requirement in ion collider ring and high current stable operation in low energy section of electron ring operation can be fulfilled with this design and implementation of a bunch-by-bunch LFS. Further work will focus on transverse impedance analysis, waveguide iris optimization and detailed specifications of the feedback systems.

ACKNOWLEDGMENT

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