THEORETICAL MODEL OF EXTERNAL Q TUNING FOR AN SRF CAVITY WITH WAVEGUIDE TUNER*

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Abstract

Brookhaven National Laboratory (BNL) and Thomas Jefferson National Accelerator Facility (TJNAF) are collaborating on the design and construction of the next Electron Ion Collider (EIC) to be built at BNL. The EIC is a unique high-energy, high-luminosity, polarized electron-proton/ion collider. A wide range of electron beam energies (5 – 18 GeV) and beam currents (0.2 – 2.5 A) are planned for the EIC Electron Storage Ring (ESR). The wide range of operating scenarios requires an adjustable coupling factor, ~20, for each of the 591 MHz Superconducting Radio Frequency (SRF) cavity. Each ESR cavity has two fundamental power couplers (FPC) delivering continuous wave (CW) 2 x 400 kW (800 kW total) RF power to the beam. Currently, adjusting external Q of an SRF cavity is done by varying protrusion of FPC's inner conductor in beam pipe or using three stub tuner to adjust external Q value, which either has limit on tuning range or limit on operating power. This paper presents a method of tuning the FPC external Q by a waveguide tuner, which allows for higher power, wide tuning range operations. A prototype of the waveguide tuner was tested up to CW 1 MW. Detail waveguide tuner design and the prototype test results will be presented.

INTRODUCTION

The EIC [1] to be built at BNL will be a discovery machine, providing answers to long-elusive mysteries of matter related to our understanding of the origin of mass, structure, and binding of atomic nuclei that make up the entire visible universe. The hadron beams in EIC will be provided by an upgraded version of the Relativistic Heavy Ion Collider [2] (RHIC) accelerator system at BNL. The electron beams in EIC will be provided by a new electron accelerator, including a pre-injector linac, a Rapid Cycling Synchrotron (RCS) and an ESR. Figure 1 shows the RF systems layout for the EIC. In the EIC ESR, there are 17 single-cell 591 MHz SRF cavities which must operate over a wide range of parameters to satisfy the various EIC operating scenarios. Each cavity has two high power FPCs to deliver up to CW 400 kW each to beam. Table 1 lists the EIC ESR SRF cavity operating scenarios. Notice that the cavity's external Q (Qext) varies by more than a factor of 15 from 2.6E4 to 3.6E5 reducing the total required RF power. Adjusting a Qext under such high power in CW operation is a challenge for the EIC. This paper proposes a high power large range Qext tuning mechanism based on a variable waveguide tuner.

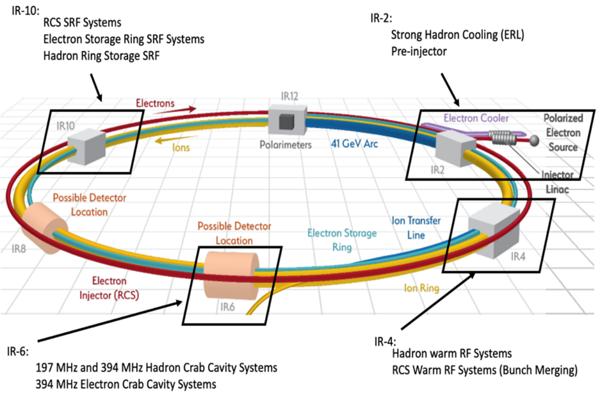

Figure 1: RF systems in EIC.

Table 1: EIC ESR Operation Scenarios

ESR RF Parameter	**Unit**	**18 GeV**	**10 GeV**	**5 GeV**
Number of Bunches		290	1160	1160
Average Beam Current	A	0.23	2.50	2.50
Energy Loss per Turn	MeV	37.0	3.52	0.95
Total Power to Beam	MW	8.4	10.7	2.9
Total Voltage	MV	61.5	21.6	9.8
PhiS	Deg	142.9	170.0	173.1
Power per FPC	kW	296	380	105
Optimal Cavity Q_{ext}		3.6×10^5	3.9×10^4	2.6×10^4

WAVEGUIDE TUNER DESIGN

System Matching Concept

The impedance presented by the beam-cavity system to the RF source determines the power transfer efficiency to the beam. The function of the waveguide tuner is to match the beam to the RF source impedance. Figure 2 (top) shows the simplified schematic diagram of the RF system with a tuner. In practice, the waveguide tuner acts like an additional current I_{tuner}, due to the RF reflection form the waveguide stub. I_{tuner} and I_g, the generator current comprise I_{load}, and I_{load} vector summed with I_b gives I_c, the cavity current. The phasor diagram of the RF system is shown in Fig. 2(bottom) for illustrational understanding. The system matches when the imaginary part of I_{load} and I_b cancel each other. If the waveguide tuner was not there $I_{load} = I_g$, i.e., the generator not only has to provide the resistive contribution to beam loading but also the additional reactive power necessary for cancelling the imaginary part of the beam loading, which is an obviously low efficiency system in spite of its unaffordability. Thus, an adjustable tuner is crucial. As illustrated in Table 1, the beam current in EIC ESR

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varies from 0.23 A to 2.5 A, and the beam power varies from 2.9 to 10.7 MW. Such a wide range of operating parameters requires the optimal Q_{ext} be adjusted by a factor of 20 to maximize the RF power transfer efficiency.

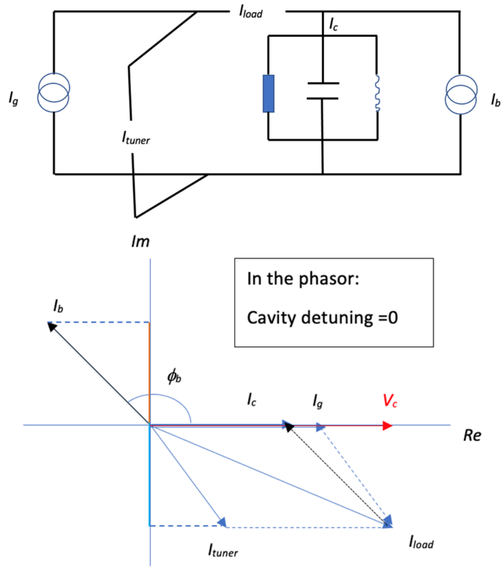

Figure 2: RF systems with a tuner and beam.

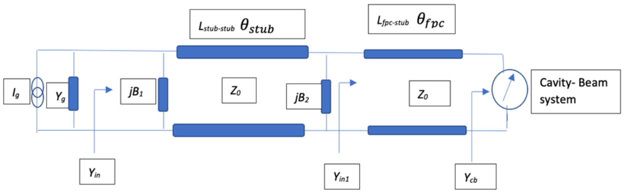

Figure 3: RF system model.

Methodology of System Matching

Figure 3 shows the RF system model, including a loaded cavity (beam, cavity and FPC), two waveguide stubs, RF transmission line, and RF generator. The admittance looking from the FPC to cavity is Y_{cb}, and the distance between FPC and first stub is $L_{fpc\text{-}stub}$ or θ_{fpc}. In our case, the stub is a waveguide section with a moving short at the end, so its admittance can be written as

$$B_{1,2} = \frac{-1}{Z_{0stub}Tan(\beta d_{1,2})} \tag{1}$$

where, $d_{1,2}$ is the length of the waveguide tuner and usually it is smaller than quarter wavelength for a compact system, which means $B_{1,2}<0$. $L_{stub\text{-}stub}$ or θ_{stub} is the distance between two waveguide tuners. The admittance looking at downstream side of waveguide tuner to cavity is Y_{in1}, and the admittance looking at the upstream side to the waveguide tuner is Y_{in}. So, the match condition for the system will be $Y_{in}=1+j0$.

First of all, we need to figure out what the Y_{cb} is. From circuit model, one can find the loaded cavity impedance is

$$Y_{bc} = \frac{\tilde{I}_1}{\tilde{V}_1} = \frac{N^2}{R_s} + \frac{N^2\tilde{I}_b}{\tilde{V}_c} + \frac{N^2}{j\omega L_2}\left(1 - \frac{\omega^2}{\omega_c^2}\right) \tag{2}$$

The real part of the admittance leads to optimum coupling/matching, while the imaginary part of the can be cancelled by detuning the cavity. Obviously, there is only one optimal operation beam current for a fixed coupling. When the beam current differs from the optimum one, a tuning mechanism is needed to maximize RF efficiency.

With the ABCD matrix for RF transportation from FPC to tuner, the normalized admittance looked from the tuner to cavity is

$$\overline{Y_{in1}} = \frac{cos(\theta_{fpc})*\overline{Y_{cb}}+jsin(\theta_{fpc})}{jsin(\theta_{fpc})*\overline{Y_{cb}}+cos(\theta_{fpc})} = \bar{g} + j\bar{b} \tag{3}$$

Secondly, we need to find out the ABCD matrix for the 2-stub tuner.

$$[A]_{tuner} = \begin{pmatrix} \cos(\theta_{stub}) - B_2 sin(\theta_{stub}) & jsin(\theta_{stub}) \\ j(B_2+B_1)\cos(\theta_{stub}) + j(1 - B_1B_2)sin(\theta_{stub}) & \cos(\theta_{stub}) - B_1 sin(\theta_{stub}) \end{pmatrix} \tag{4}$$

With the ABCD matrix and $\overline{Y_{in1}}$, we can get a general expression for total admittance seen by the generator, (Y_{in}). As the matched condition for the tuner system is $\overline{Y_{in}} = 1 + j0$, zero imaginary contribution, the expressions for $\bar{g}$, $\bar{b}$ can be written as

$$\begin{cases} \bar{g} = \dfrac{1}{[\cos(\theta_{stub}) - B_1 sin(\theta_{stub})]^2 + sin(\theta_{stub})^2} \\ \bar{b} = \dfrac{B_2(1 - 2B_1 sin(\theta_{stub})\cos(\theta_{stub})) - B_1{}^2(\cos(\theta_{stub}) - B_2 sin(\theta_{stub}))sin(\theta_{stub}) + B_1(cos(\theta_{stub})^2 - sin(\theta_{stub})^2)}{-[\cos(\theta_{stub}) - B_1 sin(\theta_{stub})]^2 - sin(\theta_{stub})^2} \end{cases} \tag{5}$$

This is the general expression of matching beam parameters with two-waveguide tuner. One can find applicable parameters for the application.

Application for EIC eSR SRF Cavity

To simplify, we choose two stubs' distance to be a quarter wavelength, so the matching conditions became

$$\begin{cases} B_1 = -\sqrt{\frac{1}{\bar{g}} - 1} \\ B_2 = -\bar{g}^2 * \bar{b} - \bar{g} * \sqrt{\frac{1}{\bar{g}} - 1} \end{cases} \tag{6}$$

This implies that there is a matching condition when $\bar{g} \leq 1$.

Case 1: $\theta_{fpc} = n\pi$.

When the waveguide tuner is integer of half wavelength away from FPC, i.e., $\theta_{fpc} = n\pi$, the admittance seen by the tuner is following.

$$\overline{Y_{in1}} = \overline{Y_{cb}} = \bar{g} + j\bar{b} \tag{7}$$

Where

$$\begin{cases} \bar{g} = \frac{1}{\beta}\left(1 + \frac{R_{shunt}|\tilde{I}_b|}{|\tilde{V}_c|}\sin(\varphi_b)\right) \\ \bar{b} = \frac{R_{shunt}}{\beta}\left|\frac{\tilde{I}_b}{\tilde{V}_c}\right|\cos(\varphi_b) - \frac{Q}{\beta}\left(\frac{\omega_c}{\omega} - \frac{\omega}{\omega_c}\right) \end{cases} \tag{8}$$

Figure 4 shows the real part of admittance for 3 operation scenarios in EIC ESR SRF cavity, one can tell that the beam current is limited to be below 0.5 A for satisfying the matching condition $\bar{g} \leq 1$, and there is a matching dead zone for beam current above 0.5 A.

Case 2: $\theta_{fpc} = (2n + 1)\pi/2$

The reason for the dead zone is due to the real part of the beam admittance ($\overline{Y_{in1}}$) being too high. This can be reduced by rotating the RF phase 90 degree away, i.e., $\theta_{fpc} = (2n+1)\pi/2$.

$$\overline{Y_{in1}} = \frac{1}{\overline{Y_{cb}}} = \frac{\bar{g}-j\bar{b}}{\bar{g}^2+\bar{b}^2} = \bar{g}' + j\bar{b}' \qquad (9)$$

Where the new real part of admittance is $\bar{g}' = \frac{\bar{g}}{\bar{g}^2+\bar{b}^2}$, and the imaginary part of admittance is $\bar{b}' = \frac{-\bar{b}}{\bar{g}^2+\bar{b}^2}$. The new matching conditioning is

$$\begin{cases} {B_1}^2 = \dfrac{1}{\bar{g}'} - 1 \\ B_2 = (B_1 - \bar{g}' * \bar{b}')\bar{g}' \end{cases} \qquad (10)$$

In this case, the $\bar{g}' \le 1$ condition is always satisfied. Figure 5 shows that for all operating scenarios in EIC can be achieved.

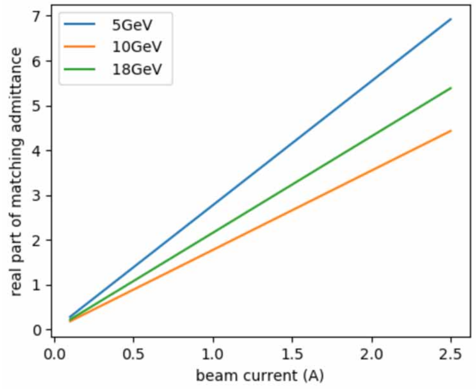

Figure 4: Real part matching admittance for $\theta_{fpc} = n\pi$.

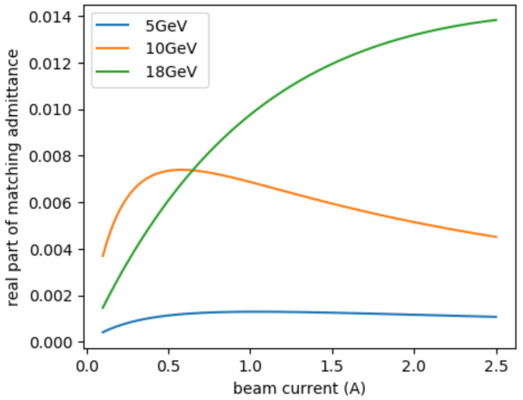

Figure 5: Real part matching admittance for $\theta_{fpc} = (2n+1)\pi/2$.

Application for EIC eSR Cavity

A Python code was developed to calculate the tuning range for each operation scenario, with the plan that using the same waveguide (WR1800) for tuner as the main waveguide for power transportation. Figure 6 shows an example about the stubs' position for 10 GeV scenarios.

Prototype Test.

Figure 7 shows the high power test setup for a two WR1500 waveguide tuner. The test was carried out in 2019, and it went up to CW 510 kW full reflection, all phases. This test demonstrated the power handling capability for EIC eSR application.

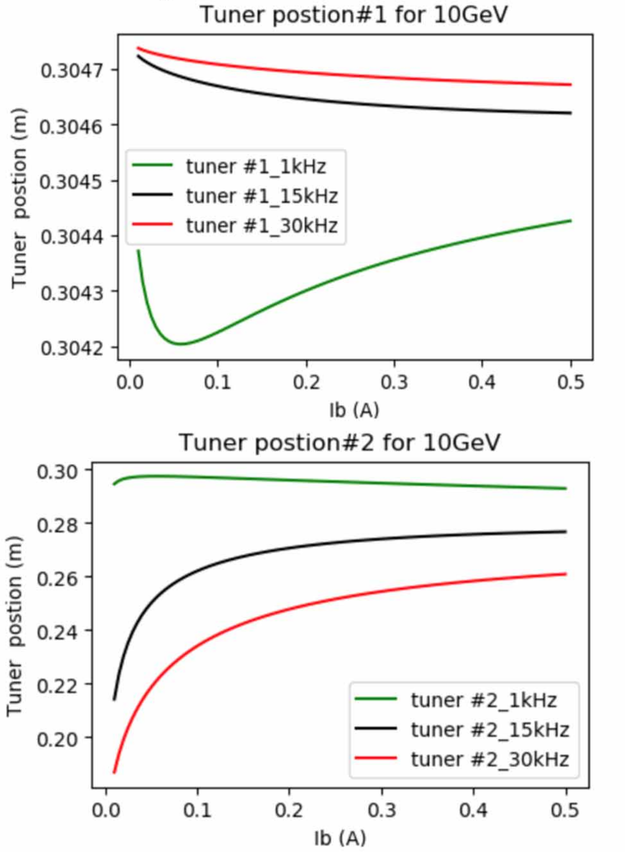

Figure 6. Tuning ranges for 10 GeV for different cavity detuning.

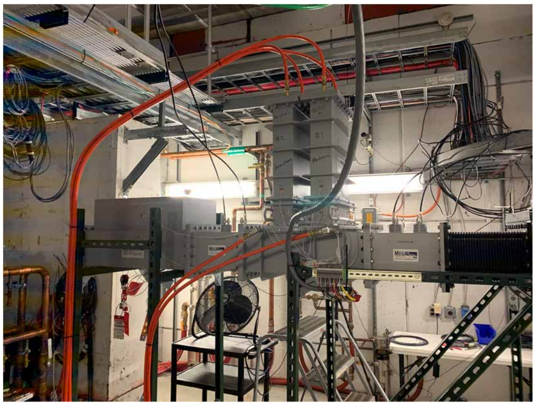

Figure 7. High power test setup.

CONCLUSION

This paper described the procedure used to design a waveguide tuner for EIC eSR SRF cavity, a predecessor of which was successfully tested at BNL. This new design satisfies a wide range of operating scenarios suitable for the EIC. Future work will report on refining these parameters discussed here and a new demonstration experiment.

REFERENCES

[1] EIC CDR, `https://www.osti.gov/biblio/1765663`

[2] RHIC, `https://www.bnl.gov/rhic`