Theoretical Model of External Q Tuning for a SRF Cavity with a Waveguide Tuner*

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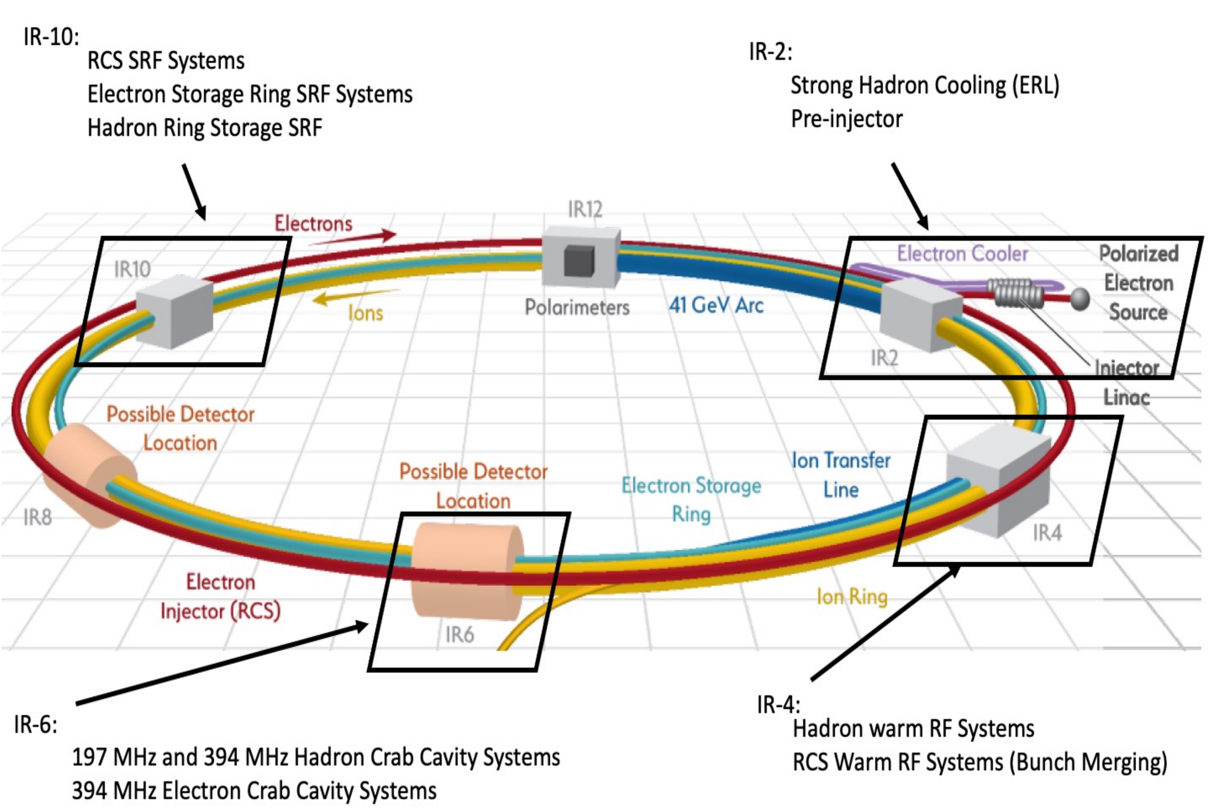
ABSTRACT: Brookhaven National Laboratory (BNL) and Thomas Jefferson National Accelerator Facility (TJNAF) are collaborating on the design and construction of the next Electron Ion Collider (EIC) to be built at BNL. The EIC is a unique high-energy, high-luminosity, polarized elec-tron-proton/ion collider. A wide range of electron beam energies (5 – 18 GeV) and beam currents (0.2 – 2.5 A) in EIC Electron Storage Ring (ESR) operating scenarios requires a capability of adjusting coupling factor up to a factor of 20 for the 591 MHz Superconducting Radio Frequency (SRF) cavities, which contains two fundamental power couplers (FPC) delivering continuous wave (CW) 800 kW RF power to the beam. Currently, adjust-ing external Q of a 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 high power, wide tuning range operations.

INTRODUCTION

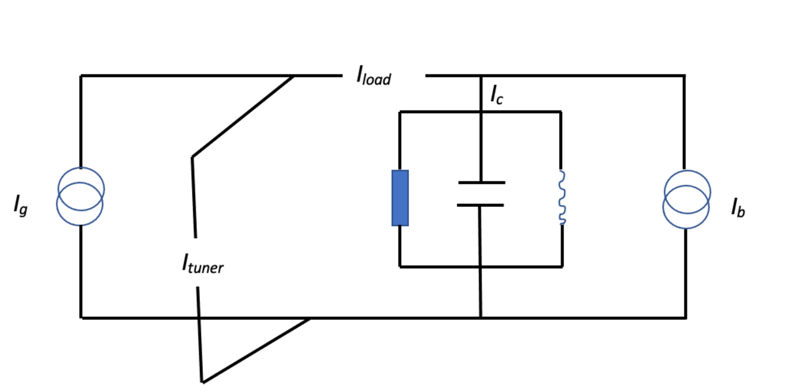
The EIC to be built at BNL will be a discovery machine, providing answers to long elusive mysteries of matter related to our understanding of the origin of mass, structure, and binding of atomic nuclei that make up the entire visible universe. The hadron beams in EIC will be provided by an upgraded version of the Relativistic Heavy Ion Collider(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, geographically, the RF systems in EIC. In EIC ESR, there are 17 single-cell 591 MHz SRF cavities to operate at a wide range of parameters space to satisfy the various EIC operating scenarios. Each cavity has two high power FPCs to deliver up to CW 380 kW each to beam. Table I lists the EIC ESR SRF cavity operating scenarios. Notice that the cavity's external Q (Qext) has to adjust in a factor of 15 from 2.6E4 to 3.6E5 to minimize the total installed RF power. Adjusting a Qext under such high power in CW operation is a challenge for EIC. This paper proposes a high power, large range, Qext tuning mechanism based on waveguide tuner.

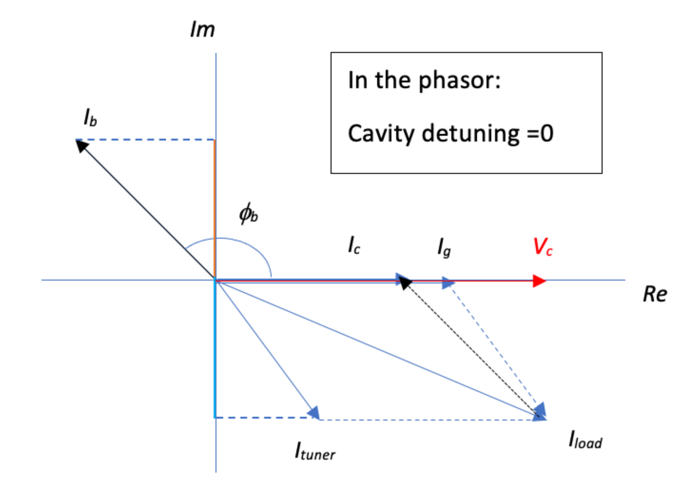


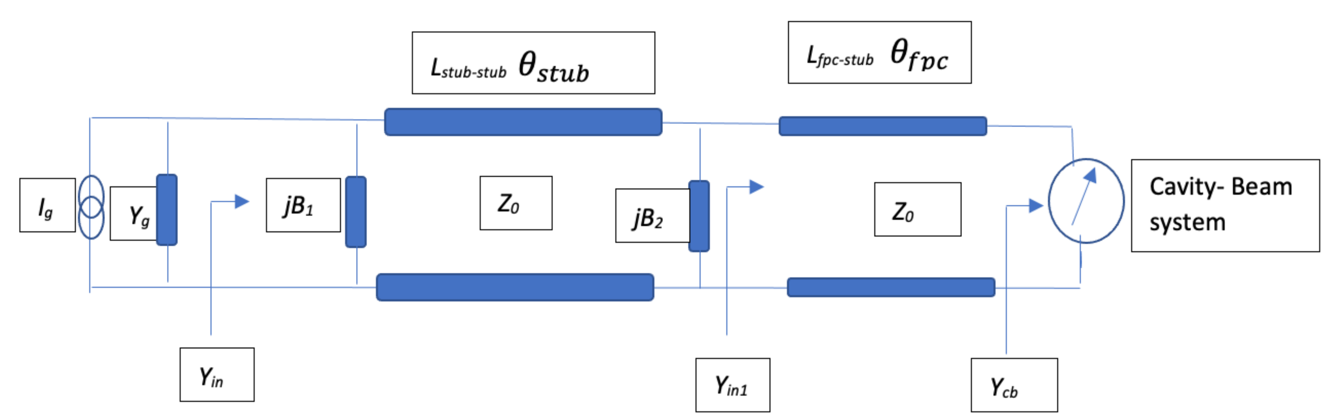
ESR RF Parameter	Unit	18 GeV	10 GeV	5 GeV
Number of Bunches		290	1160	1160
Average Beam Current	A	0.23	2.50	2.50
Energy Loss per Turn	MeV	37.0	3.52	0.95
Total Power to Beam	MW	8.4	10.7	2.9
Total Voltage	MV	61.5	21.6	9.8
PhiS	Deg	142.9	170.0	173.1
Power per FPC	kW	296	380	105
Optimal Cavity Q_{ext}		3.6×10^5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

Waveguide Tuner Design

The impedance seen by a RF source determines the power transfer efficiency to the beam, so the function of the tuner is to match beam impedance to the impedance of RF source.







The admittance of a waveguide a moving short at the end is

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

The beam loaded cavity impedance (looking from FPC) is

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

$$\begin{cases} Re(Y_{bc}) = \dfrac{1}{\beta Z_0}\left(1 + \dfrac{R_{shunt}\left|\tilde{I}_b\right|}{\left|\tilde{V}_c\right|} sin(\varphi_b)\right) \\ Im(Y_{bc}) = \dfrac{R_{shunt}}{\beta Z_0}\left|\dfrac{\tilde{I}_b}{\tilde{V}_c}\right| \cos(\varphi_b) - \dfrac{Q}{\beta Z_0}\left(\dfrac{\omega_c}{\omega} - \dfrac{\omega}{\omega_c}\right) \end{cases}$$

The normalized admittance looked from the tuner to cavity is

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

As the matched condition for the tuner system is $\overline{Y_{in}} = 1 + j0$. One can derive that the expressions for normalized $\bar{g}, \bar{b}$ are

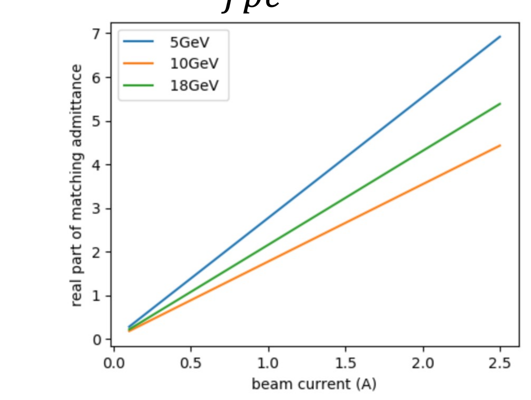
$$\begin{cases} \bar{g} = \dfrac{1}{[\cos(\theta_{stub}) - B_1 sin(\theta_{stub})]^2 + sin(\theta_{stub})^2} \\ \bar{b} = \dfrac{B_2(1 - 2B_1 sin(\theta_{stub})\cos(\theta_{stub})) - {B_1}^2(\cos(\theta_{stub}) - B_2 sin(\theta_{stub}))sin(\theta_{stub}) + B_1(cos(\theta_{stub})^2 - sin(\theta_{stub})^2)}{-[\cos(\theta_{stub})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

choke

When Stubs distance is integer of a quarter wavelength

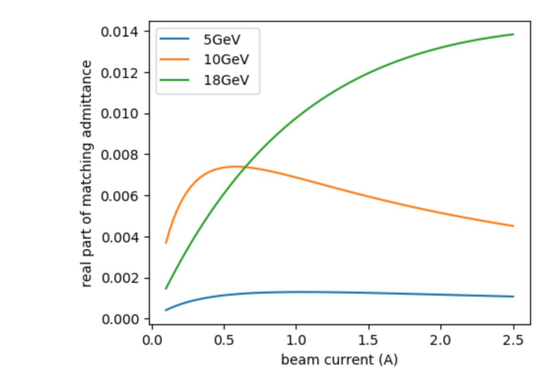
$$\begin{cases} B_1 = -\sqrt{\frac{1}{\bar{g}} - 1} \\ B_2 = -\bar{g}^2 * \bar{b} - \bar{g} * \sqrt{\frac{1}{\bar{g}} - 1} \end{cases}$$

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



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.

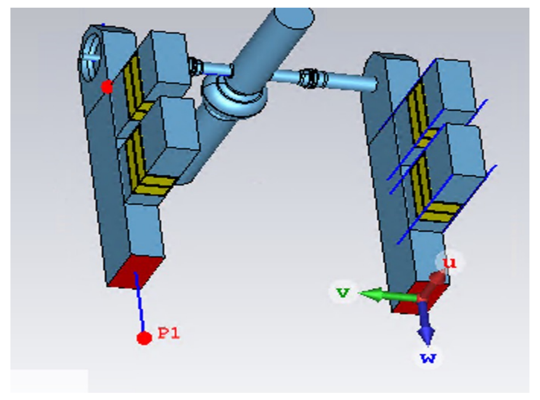
Case 2: $\theta_{fpc} = (2n+1)\pi/2$

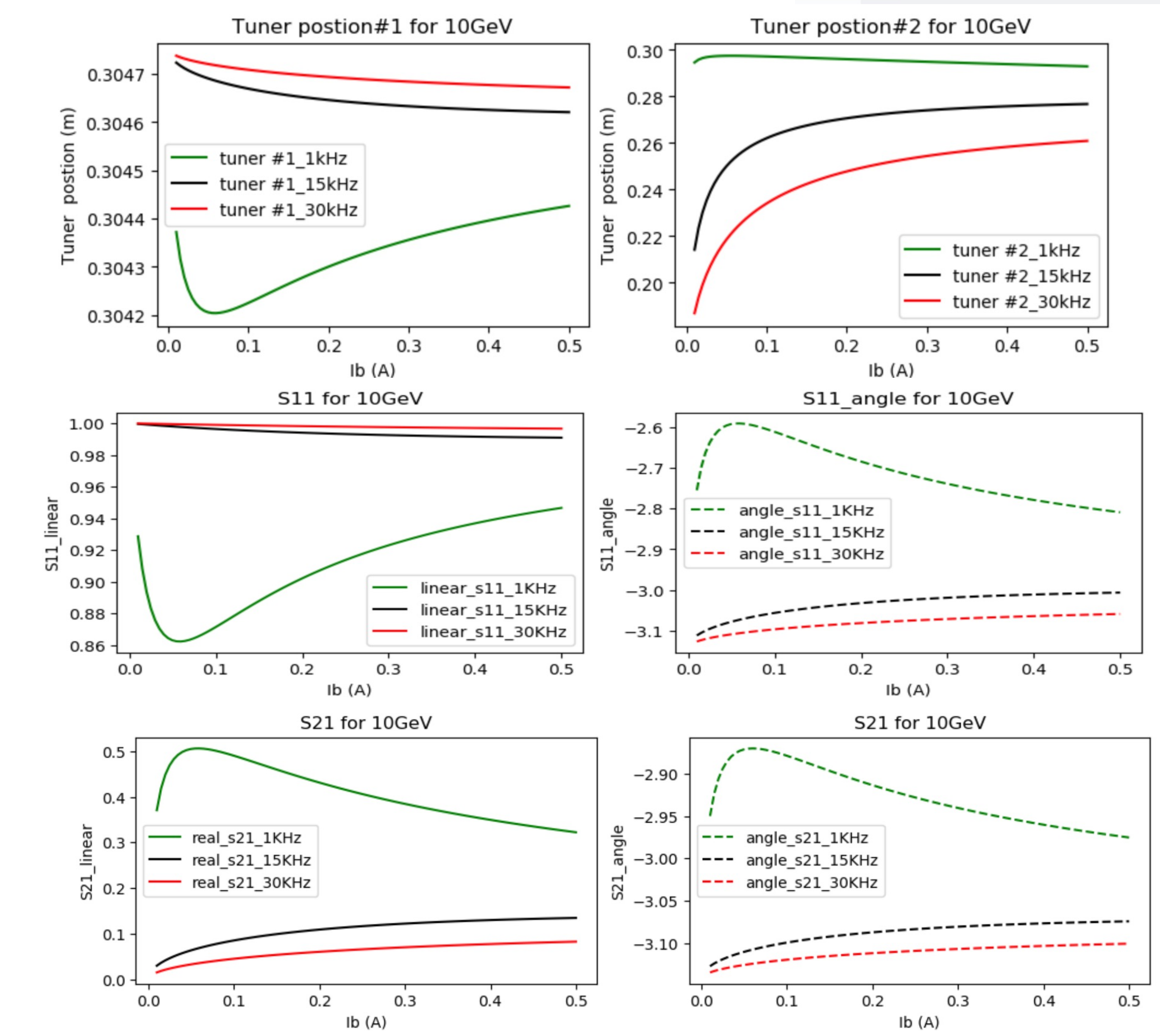


No dead zone!!

3D model and results

A Python code was developed to calculate the tuning range for each operation scenarios, with the plan that using the same waveguide (WR1800) for tuner as the main waveguide for power transportation.





Conclusion

This paper describes the procedure to design a waveguide tuner for EIC eSR SRF cavity, so as to satisfy wide range of operating scenarios. The work is still ongoing.

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