IMPROVEMENT OF WIRE-STRETCHING TECHNIQUE TO THE RF MEASUREMENTS OF E-CENTER AND MULTIPOLE FIELD FOR THE DIPOLE CAVITIES*

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Abstract

After the first publication [1] of wire-stretching technique from its principle to measure the electrical center of a deflecting cavity, more refinements of this techniques including the review of its analytical and simulation results, RF circuit improvement the signal to noise ratio and its application to other cavities have been developed. These applications include the electrical center measurements for the LHC RFD and DQW crabbing cavity prototypes, multi-frequency harmonic kicker cavity for JLEIC electron cooler [2], TE011 cavity developed for the beam magnetization measurement [3], and a separator cavity at BNL [4].

INTRODUCTION

A fast harmonic RF kicker based on the normal conducting quarter wave resonator (QWR) has been developed for the injection/extraction of the electron bunch in/out of the circulator cooler ring (CCR) of the Jefferson Lab Electron Ion Collider (JLEIC) [5, 6]. Its first prototype, half-scaled from the original kick frequency, has 5 odd harmonics of a base frequency of $f_1 = 95.26\,\mathrm{MHz}$. In an original high current operation of the kicker with the bunch charge up to 3.2 nC at the bunch frequency of $f_b = 476.3\,\mathrm{MHz}$, the associated wake field of the kicker would lead to a substantial beam loading and excessive power loss as well as beam quality degradation. To minimize the dissipated power loss for a particular mode, a symmetrizer has been introduced to the cavity so that the beam axis coincides with the electric center of the cavity, where the longitudinal electric field of that mode vanishes. In this report, we describe the design of the symmetrizer (also simply called the "bump") and the experimental measurement to find the electric center in the cavity by using the wire-stretching technique. The thin wire is extended approximately along the beam axis and an input signal is fed into the cavity via wire. If the wire is along the electric center, the coupling will be minimum.

DESIGN OF THE SYMMETRIZER

For demonstration, we symmetrize the 5th mode of the prototype cavity. Preliminary simulation of the E_z, a longitudinal field of the 5th mode in the harmonic kicker, using CST-MWS [7] shows that while the TEM modes in co-axial region has a periodic structure with the standing wave nodes, the geometry of a bump with its length terminated at the same distance from the beam axis to the first standing wave node could be arranged for the cavity to have a mirror-symmetric field configuration with the E-center on the beam axis. The simplest way to find such an end point is to cut out a beam axis-plane that contains the beam axis and normal to the vertical axis, and impose the electric boundary condition (i.e., $E_z = E_x = 0$) as in Fig. 1. Then almost identical field configuration to the one in Fig. 2 will be obtained if the sub-volume between the slicing position plane and the beam axis plane is mirror-reflected with respect to the axis plane. More accurate end-point for the reflection is found by subsequent parameter sweeps after implementing the local meshing (in 1 mm step with global hexahedral meshing of 3×10^6) near the beam axis and improving the geometrical symmetry of the cavity by reducing the blending on the end plate (see Fig. 3). The electric center is identified with the minimum amplitude profile on the beam axis (See Fig. 4). The reflection-end point is at 96.8 mm in the given coordinate system, as shown in Fig. 3.

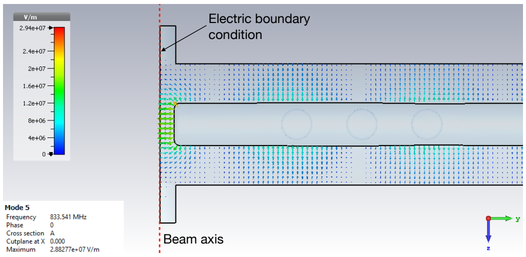

Figure 1: The axis-plane was cut and the electric boundary condition was set.

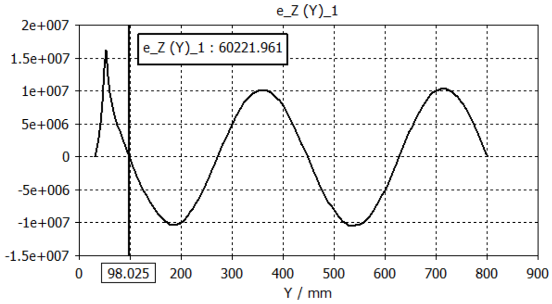

Figure 2: The vertical profile with the lowest node location (without blending the corners).

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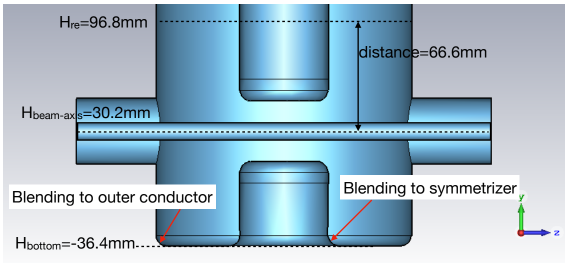


Figure 3: The blending to the symmetrizer and the outer conductor was reduced. Here $H_{...}$ are the coordinates of the CAD model.

In a simultaneous parameter sweep of the blending radius and the reflection-end point shown in Fig. 4, E_z profiles on the axis form a family of bands, with each band corresponding to the different reflection-end point and the graphs within the band having different blending radii. The result shows that the E-center is closest to the axis with the minimum field amplitude ($\leq 2.3 \times 10^3$ V/m) with blending radius $R_{bl} = 0$ mm and the end point location $H_{re} = 96.8$ mm. The vertical profile of the field shows that both the end point and blending radius shifts the vertical position of the center linearly, suggesting dipole component as a dominant contribution. Finally, the frequency of the 5th mode was found to be 833.147 MHz, out of the tuning range of the stub tuners for the original of 857.34 MHz.

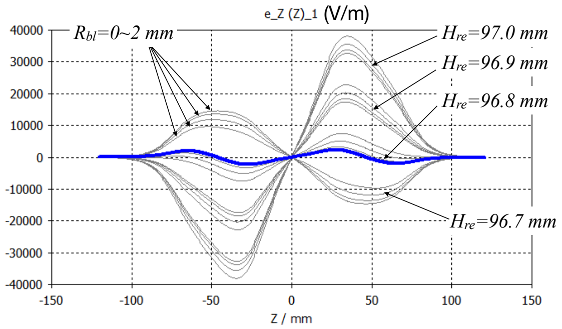


Figure 4: The longitudinal profile at beam axis with a simultaneous parameter sweep of H_{re} and R_{bl}.

THE WIRE-STRETCHING TECHNIQUE

Principles of Wire-stretching Technique

The wire-stretching technique uses a stretched wire traversing the cavity through the beam port as an input coupler as shown in Fig. 5(a). With a loop coupler as a pickup coupler, one can measure the characteristic response of the QWR to the RF signals in terms of the 2-port S-parameters [8], which in weak coupling limit $\beta_1, \beta_2 \ll 1$ is approximated as

$$S_{21}[\text{dB}] = 20 \log \frac{2\sqrt{\beta_1 \beta_2}}{1 + \beta_1 + \beta_2 + 2iQ_0 \delta f / f_0} + \mathcal{K}_2, \quad (1)$$

$$\approx 20 \log 2\sqrt{\beta_1 \beta_2} + \mathcal{K}_2. \quad (2)$$

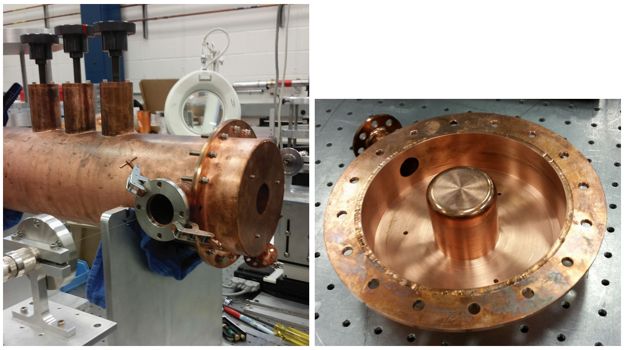
Here $\mathcal{K}_2$ cable loss, β_1 input coupling, β_2 pickup coupling, Q_0 is unloaded quality factor of the cavity, δf is frequency deviation, and f_0 is the resonant frequency of the cavity. The transverse positions of wire ends are controlled by the motorized x-y stations, with one end connected to a network analyzer, and the other is at open-end, respectively. With the coordinate system based on the electric center, the coupling constant β_1 can be expressed in terms of the coordinates of the wire at the stations, x_1, x_2, y_1, y_2 [1]. Setting $y_1 = y_2 = 0$ for simplicity, β_1 is computed as ratio of the longitudinal cavity impedance $R_\parallel$ to the wire impedance

$$|\beta_1| = \frac{R_\perp}{Q_0} \frac{Q_L(x_1, x_2)}{60 \ln \frac{R}{r}} \Theta + \mathcal{K}_2(a),$$

$$\text{where } \Theta = \left[\frac{(x_2 - x_1)^2}{L^2} + \left(\frac{\pi f_5}{c} \right)^2 (x_2 + x_1)^2 \right] \quad (3)$$

where $x_{1,2}$ are vertical coordinates of the station 1, 2 respectively, $R_\perp = 1.93 \times 10^6\,\Omega$ is transverse impedance, $Q_0 = 8860$ is unloaded quality factor, $Q_L = 160 \sim 8560$ is loaded quality factor, $R = 19.05$ mm is beam port radius, $r = 0.125$ mm is wire radius, $f_5 = 836.6$ MHz is the 5th mode resonant frequency, $L = 0.58$ m is the total length of the wire extension, c is speed of light, and $\mathcal{K}_2(a)$ is wire loss. If $x_1 = x_2 = 0$, i.e., the wire is on the electric center, $|S_{21}|$ at the resonant frequency would be minimum.

In the simulation using CST-MWS [7], the wire is offsetted and tilted around the beam-axis. The resulting S_{21} parameters are shown in Fig. 6, confirming the electric center is within 1 mm offset from the beam-axis.



(a) The stretched wire through the cavity. (b) The modified symmetrizer.

Figure 5: The wire-stretching measurement setup.

Experimental Measurement

A thin electrical Discharge Machining (EDM) wire (made of Tungsten) with diameter of 0.25 mm is stretched through the cavity beam axis and place E-center roughly at the center of wire ends connected to the network analyzer in 5(a). The cavity had been equipped with the modified symmetrizer shown in Fig. 5(b).

The electric center was found 0.8 mm off toward the center conductor from the beam-axis. Around the center, non-zero offsets would generate the $|S_{21}|$ with increased peak at resonance frequency of $f = 836.6$ MHz (and also Q_L) as shown

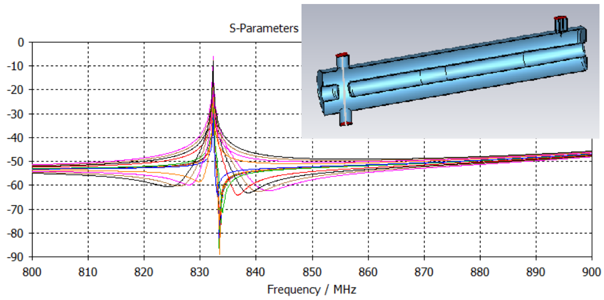


Figure 6: The CST-simulated $|S_{21}|$ parameter with various tilting in the simulation. The profile flips between 0 mm and −1 mm offsets from the E-center.

in Fig. 7. The dependence is linear with the estimated rate of $d|S_{21}|/dx = 25.1$ dB/mm. In Fig. 8, the $|S_{21}|$ with various tilting at zero offset is shown. The tilting with ± slopes would correspond to the flips of the profile at the E-center, defining the resolution of tilting angle to be less than ±0.3 mrad. The slight asymmetry of the flipped profiles might be related to small remaining deviation from the center.

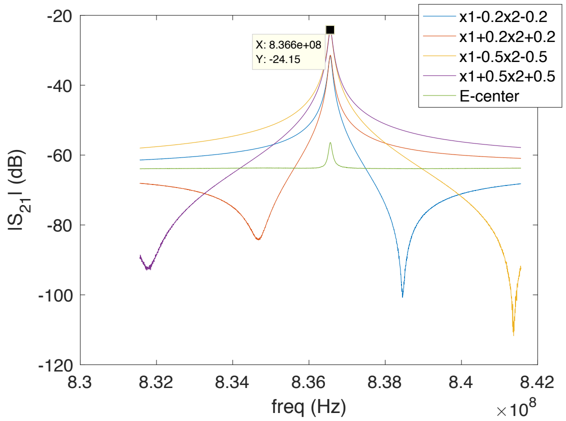


Figure 7: $|S_{21}|$ with various offsets. Here x is vertical offset in deflecting plane.

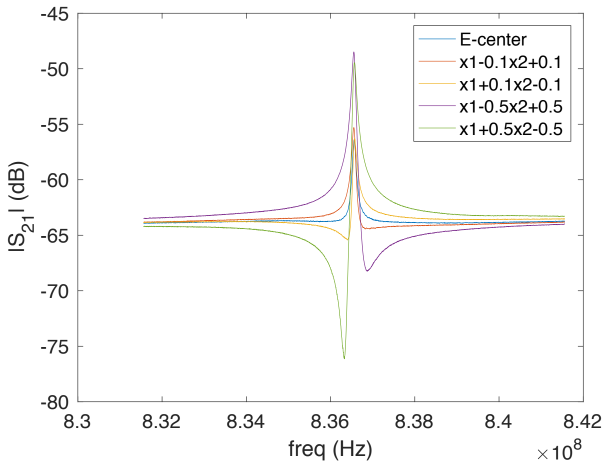
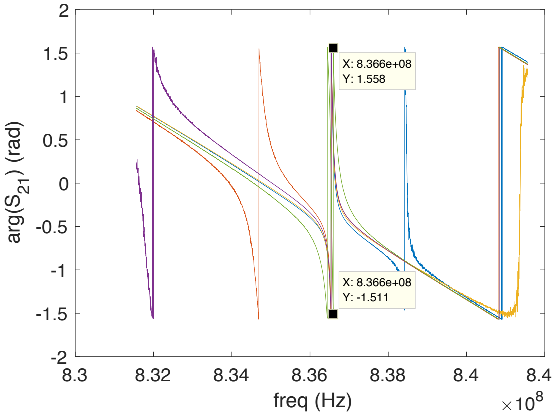
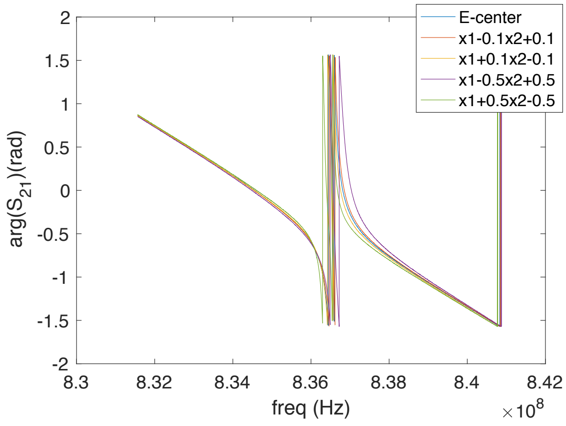


Figure 8: $|S_{21}|$ with various tilting.

The phase signals in Fig. 9 show the crossing zero at the resonance frequency.



(a) arg(S_{21}) with offsets.



(b) arg(S_{21}) with tilting.

Figure 9: The arg(S_{21}) with various configurations of the wire.

To compare with the analytical prediction, the calibration of the constants $\mathcal{K}_2 = -50.5$ dB, $\mathcal{K}_2(a) = 100$ was done in an attempt to fit the measurements (See Fig. 10). While $|S_{21}|$ values agree well with offset deviation, relatively large errors exist as tilting angle increases.

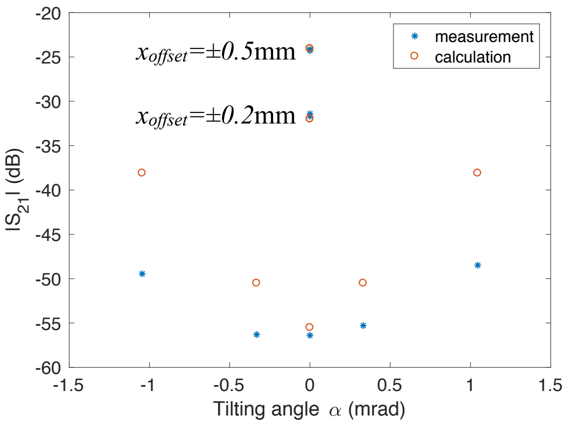


Figure 10: $|S_{21}|$ with various tilting angle.

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