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 \( f_1 = 95.26 \) MHz. In an original high current operation of the kicker with the bunch charge up to 3.2 nC at the bunch frequency of \( f_b = 476.3 \) 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 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

\[ E_z (r) = \begin{cases} 
0 & |r| < 0.5 \\
A \sin \left( \frac{2\pi}{\lambda} r \right) & 0.5 \leq |r| < \frac{\lambda}{2} \\
0 & \frac{\lambda}{2} \leq |r| < \lambda 
\end{cases} \]

where \( \lambda \) is the free space wavelength of the medium. Figure 1 shows the electric boundary condition was set.

![Figure 1: The axis-plane was cut and the electric boundary condition was set.](image)

Figure 2: The vertical profile with the lowest node location (without blending the corners).
The vertical profile of the field shows that both the endpoint 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 have 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.

![Diagram of blending to symmetrizer and outer conductor](Image)

**Figure 3:** The blending to the symmetrizer and the outer conductor was reduced. Here $H_{re}$ 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.

**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

$$S_{21}[dB] = 20 \log \left( \frac{2\sqrt{\beta_1 \beta_2}}{1 + \beta_1 + \beta_2 + 2|Q_0|f/\delta f} + K_2 \right),$$

$$\approx 20 \log 2\sqrt{\beta_1 \beta_2} + K_2.$$  \hspace{1cm} (1)

Here $K_2$ is cable loss, $\beta_1$ input coupling, $\beta_2$ pickup coupling, $Q_0$ is unloaded quality factor of the cavity, $\delta f$ 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 $\beta_1$ 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, $\beta_1$ is computed as ratio of the longitudinal cavity impedance $R_\parallel$ to the wire impedance

$$|\beta_1| = \frac{R_\parallel Q_1(x_1, y_2)}{Q_0} \Theta + K_2(a)$$

where $\Theta = \left( \frac{(x_2 - x_1)^2}{L^2} + \left( \frac{\pi f_s}{c} \right)^2 (y_2 + y_1)^2 \right) \right)$ \hspace{1cm} (3)

where $x_{1,2}$ are vertical coordinates of the station 1, 2 respectively, $R_\parallel = 1.93 \times 10^6 \Omega$ is transverse impedance, $Q_0 = 8860$ is unloaded quality factor, $Q_L = 160 \sim 8560$ is loaded quality factor, $R = 19.05 \text{ mm}$ is beam port radius, $r = 0.125 \text{ mm}$ is wire radius, $f_s = 836.6 \text{ MHz}$ is the 5th mode resonant frequency, $L = 0.58 \text{ m}$ is the total length of the wire extension, $c$ is speed of light, and $K_2(a)$ 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 off-set 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.

![Diagram of wire-stretching measurement setup](Image)

**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 Fig 5(a). The cavity had been equipped with the modified symmetrizer as shown in Fig. 5(b).

![Diagram of symmetrizer and outer conductor](Image)

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

(a) The stretched wire through the cavity.

(b) The modified symmetrizer.
in Fig. 7. The dependence is linear with the estimated rate of $d|S_{21}|/dx = 25.1 \text{ dB/mm}$. 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.

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

To compare with the analytical prediction, the calibration of the constants $K_2 = -50.5 \text{ dB}$, $K_2(a) = 100$ 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.
REFERENCES


