WIRE STRETCHING TECHNIQUE FOR MEASURING RF CRABBING/DEFLECTING CAVITY ELECTRICAL CENTER AND A DEMONSTRATION EXPERIMENT ON ITS ACCURACY*

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Abstract

A new wire stretching technique combining with the RF measurement on the cavity dipole modes has been developed and demonstrated on the bench to detect less than 10um offset and 0.1mrad tilt angle resolutions on the RF signal when the wire is deviated away from the ideal electric centre line. The principle of this technique and its difference from the use in other applications are reviewed and compared. Empirical formula, simulation and experiment results on the RF signal responses to the E-centre line offset and titling angle have been developed.

INTRODUCTION

First two types of LHC Superconducting crab cavities, RF Dipole (RFD) developed by ODU and Double Quarter Wave (QWR) developed by BNL have arrived at Jefferson Lab for further Electron Beam Welding (EBW), Buffer Chemistry Polishing (BCP), High Temperature Bake (HTB) and finally vertical qualification cold tests. The specified accuracies for cavity fabrication, tuning and component assembly alignment are very restricted due to the requirement of crabbing beams for the Large Hadron Collider High Luminosity Upgrade [1]. Like the cavity rotation is $<0.3^o$ per cavity, 3 cavities systematically are $< 1.0^o$. The cavity beam axis offset in the crabbing plane is <0.5 mm. It is very hard for the crab cavity fabrication process to achieve this requirement since the cavity is formed by niobium sheet metal. Even the cavity dies could be machined very accurately, the spring back after the stamping can be very precisely controlled, the later EBW and BCP processes can deteriorate these accuracies easily due to unknown welding shrinkage, chemistry bath temperature et al. In addition, the cavity's crabbing or deflecting electric centre is not well defined, so the cavity's mechanical axial centre has been used as the ideal beam line centre due to the cavity has been designed with structure symmetry relative to the perpendicular plane of the crab crossing. However any additional change by the assembly of couplers, tuner's unsymmetrical tuning deformation, cryomodule cooldown et al., the actual electric centre could be changed later.

Precision 3-D bead-pulling measurement and laser scanner survey tool have been tried out. Their achievable accuracies are questionable due to the bead vibration and accumulated errors on the portable device. Their associated costs are also high.

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TECHNIQUES HISTORY

The Single Stretched Wire (SSW) has been used for the magnet electric centre survey and multipole filed measurement [2]. By measuring the integrated flux changes with various types of wire motion, the magnetic centre accuracy can be achieved in the displacement of ~30μm and the field direction in 0.1mrad.

The Wire Position Monitor (WPM) has been also used for the SRF cryomodule components alignment [3]. A 50 Ω strip-line BPM with the wire-carried RF signal can be processed to live monitor the cavity reference line change during cooldown. Meanwhile this BPM can be also used as the microphonic measurement with a cavity shaker. Its accuracy in displacement can be <7μm [4].

The Wire Method (WM) is also widely used for the coupling impedance of beam devices [5]. This method is not entirely reliable because the stretched wire perturbs the boundary conditions, introducing a TEM wave with a zero cut-off frequency. Below the pipe cut-off frequency, this WM produces an additional power loss which drastically lowers the high Q resonance of the device. Above the cut-off frequency, the impact of the wire is not as dramatic as below the cut-off. The Mode Matching (MM) technique like tapering cones is then used. A large discrepancy appears below cut-off frequency, while above cut-off, for certain ranges of parameters, an acceptable agreement can be found. For dipole mode impedance, a Twin-Wire (TW) and hybrids are used to measure the transverse impedance.

A surface wave signal transmits through a stretching wire with horn launcher and receiver is also used to calibrate BPMs [6]. The Goubau line can be made with a thin dielectric coating or a surface roughness on the wire to transmit RF slow-wave in an open space. A thin Tungsten wire (0.25mm dia.) used for Electrical Discharge Machining (EDM) is a good Goubau-line. It has been used for the CEBAF strip-line type BPM calibration. Its accuracy is about 100 μm in 2cm×2cm grid area. The same line has been used for the following wire stretching setup.

WIRE STRETCHING SETUP

A 499 MHz RFD cavity has been used for this demonstration experiment as it shown in Figure 1. The EDM wire passing through the cavity beam pipe flanges was held in tension by two RF connectors on the table anchored X-Y stations. Each X-Y stage can be step-motor controlled in x (crabbing direction) and y in 1μm resolution. By moving wire position (x_1, y_1) and (x_2, y_2), any offset and tilting angle of the wire relative to the cavity flange-to-flange centres line can be produced. By looking at the RF transmission S21 or reflection S22 signals, the E-centre line can be established. It has the minimum coupling between the wire antenna β_1 and the cavity pickup probe β_2. This technique is very sensitive to both wire offsets x_1, x_2 and wire tilting angle α.

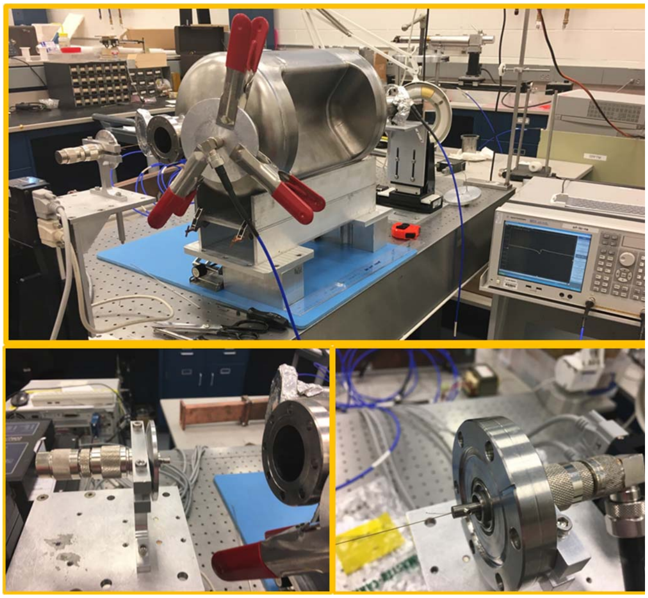

Figure 1: Wire stretching setup (top), with the VNA's Port 1 drives the wire line (bottom right), other end of wire is terminated with a 50 Ω load (bottom left). The RF transmission signal S21 is picked up from the cavity probe Port 2. Two small lab stands, one of them shown in the picture are used to fine tune the cavity rolling so a nearly prefect E-centre line can be found.

PRINCIPLE AND WIRE GEOMETRY

Any crabbing or deflecting RF cavity, no matter its TM, TE or TEM type, it must follow the Panofsky-Wenzel (P-W) theorem [7, 8] which states that on the beam path there is a must longitudinal electric field E_z in transverse gradient dE_z/dx. As shown in Figure 2, if an electrical conducting wire is stretching perfectly perpendicular to the transverse electric field, the wire would not be induced any line voltage as the wire is infinitely thin. The E-centre line is then defined here by the P-W law, a line of zero longitudinal electric field points where the E_z field is changing the direction. However, experimentally this line could be used for the E-centre line alignment. Integrated voltage will not be zero due to x_1, x_2 and α. Zero voltage can only happen when $x_1=x_2=0$ or $Z=L/2$, $x_1=-x_2$ Following derivation is a proof for the RF signal estimation when both β_1 and β_2 are very small. As equation (3) indicates, the titling angle α has the same order of response to the line coupling (or line voltage implied by the P-W law) as the offset x.

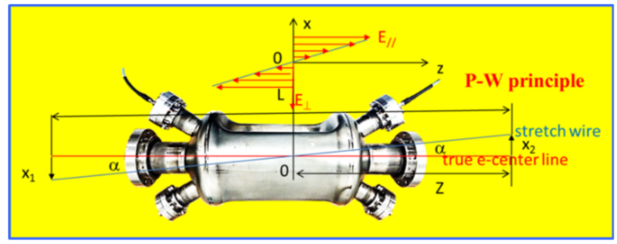

Figure 2: Wire stretching geometry relative to the crab cavity's longitudinal electric field.

$$\begin{cases} tan\alpha = \dfrac{x_2}{Z} = \dfrac{x_1}{Z-L} \quad Z=\dfrac{Lx_2}{x_2-x_1} & \text{When } x_1x_2<0 \text{ and } x_1 \neq x_2 \\ tan\alpha = \dfrac{x_2-x_1}{L} & \text{When } x_1x_2 \geq 0 \end{cases} \tag{1}$$

S21 from wire (port 1) to cavity pickup (port 2):

$$S_{21}(dB) = 10\log\left[\frac{4\beta_1\beta_2}{(1+\beta_1+\beta_2)^2}\right] + K_2(dB) \qquad K_2 \text{ is cable loss}$$

When coupling β_1~β_2<<1,

$$10^{\frac{S_{21}(dB)}{10}} \approx 4\beta_1\beta_2 10^{\frac{K_2(dB)}{10}} = K_0\beta_1 \quad K_0 = 4\beta_2 10^{\frac{K_2(dB)}{10}} \text{ is a constant} \tag{2}$$

$$\sqrt{\beta_1} = \frac{1}{\sqrt{Z_0}}\frac{\int E_{//}dz}{\sqrt{\omega U}} = \frac{1}{\sqrt{Z_0\omega U}}\int\frac{dV_{//}}{dz}\frac{dz}{dx}dx = \frac{1}{\sqrt{Z_0\omega U}}\int\frac{dV_{//}}{dx}\frac{dx}{dz}dz$$
$$= \frac{1}{\sqrt{Z_0\omega U}}\int V_\perp\frac{\omega}{c}tan\alpha dz = \frac{V_\perp}{\sqrt{Z_0\omega U}}\frac{\omega}{c}tan\alpha\left[\int_0^Z dz - \int_0^{L-Z} dz\right]$$
$$= \sqrt{\frac{R_t/Q}{Z_0}\frac{\omega}{c}}\begin{cases} tan\alpha(2Z-L) & \text{When } x_1x_2<0 \text{ and } x_1\neq x_2 \\ (2x_2-Ltan\alpha) & \text{When } x_1x_2\geq 0 \end{cases} \tag{3}$$

In reality, due to finite transverse radius of wire *a*, minimum of wire antenna coupling to the cavity field is:

$$\beta_1 = \frac{R_t/Q}{Z_0}\left(\frac{\omega}{c}\right)^2\begin{cases} tan^2\alpha(2Z-L)^2 & \text{When } x_1x_2<0 \text{ and } x_1\neq x_2 \\ (2x_2-Ltan\alpha)^2 & \text{When } x_1x_2\geq 0 \end{cases} + K_2(a)$$

Now empirical formula can be written as:

$$10^{\frac{S_{21}(dB)}{10}} = K_1\begin{Bmatrix} tan^2\alpha(2Z-L)^2 & \text{When } x_1x_2<0 \text{ and } x_1\neq x_2 \\ (2x_2-Ltan\alpha)^2 & \text{When } x_1x_2\geq 0 \end{Bmatrix} + K_2(a) \tag{4}$$

Here $K_1 = K_0\frac{R_t/Q}{Z_0}\left(\frac{\omega}{c}\right)^2 = 4\beta_2 10^{\frac{K_2(dB)}{10}}\frac{R_t/Q}{Z_0}\left(\frac{\omega}{c}\right)^2$ is a cavity/pickup probe geometry related constant.

PROOF OF PRINCIPLE SIMULATION

The first CST simulation on this principle was on the APS crab in 2010. The simulation for this 400MHz RFD cavity was only performed after the second experiment. Figure 3 shows its cavity vacuum model and line segment setup for the wire stretching. Figure 4 shows its simulation result. The insertion of pickup antenna at Port 3 has been found to cause a slightly asymmetric effect and the wire diameter determined the signal baseline. Zero responses on both amplitude and phase crossing the resonance frequency when $x_1=x_2=0$ are as shown in Figure 3. S31 has a similar response as the S32's. S11 and S22 have a less dynamic range (~28dB) compare to S31, but nearly 360 degree of phase change as S31's.

FIRST EXPERIMENT OBSERVATION

The first experiment was carried out in April, 2016. The wire scan in x (crabbing) plane gave the amplitude response of S21=-13.3dB/mm in Figure 4 which is closed to the result of Figure 3. The phase detection is more sensitive when locking at the resonance frequency, which is 0.35°/µm as shown in Figure 5.

The wire scanning at Y (non-crabbing) plane has to be done at a dipole HOM in y polarization at 1336 MHz frequency. The cavity Q is lower due to the damping through the couplers. However the sensitivity of ~0.015°/µm could be measured with a data smoothing.

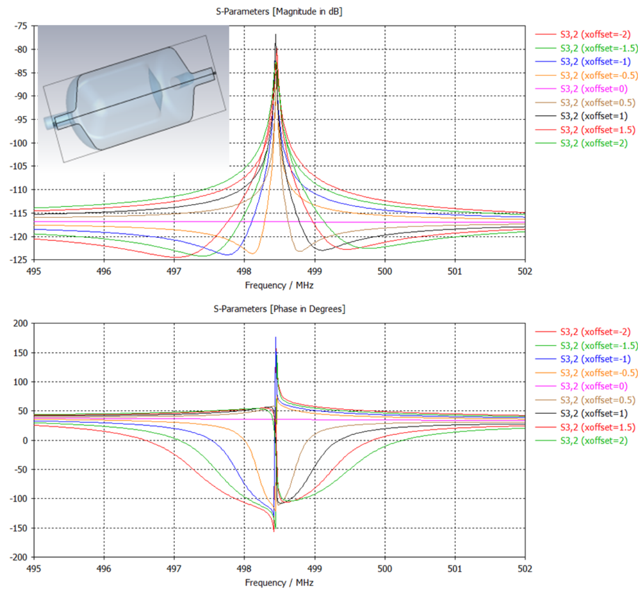

Figure 3: CST geometry setup (top insert) for the S parameter simulation. Port 1 and Port 2 are on the wire ends, Port 3 is at the cavity pickup, same side as Port 2 on left (cut away in this view); S32 amplitude (top) and phase (bottom) responses to the stretch wire offset from x_1=x_2=-2mm to 2mm.

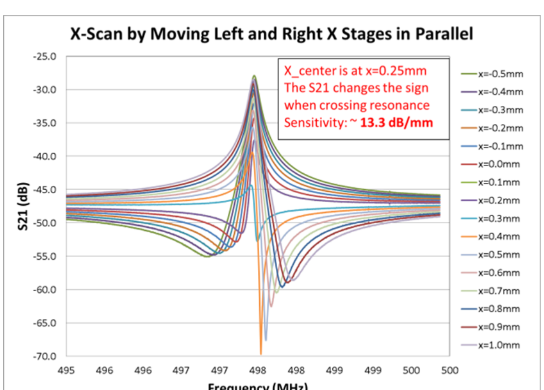

Figure 4: S21 amplitude measured on the 499MHz RFD cavity when moving wire offset from x=-0.5mm to 1.0mm.

SECOND EXPERIMENT RESULT

The second experiment was carried out after the Equation (4) had been derived with a goal of testing the dependence of titling angle. The measurement data is then used to compare the Equation (4) calculation by fitting K_1 and K_2, since β_1 and β_2 could not be precisely measured by the reflections. A good agreement can be obtained in Figure 6 which validates the angle and offset dependency in Equation (3).

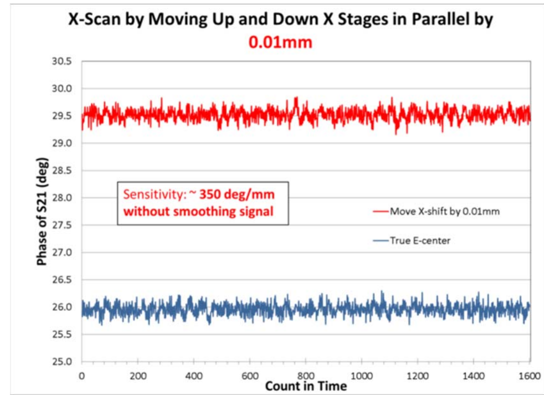

Figure 5: S21 phase measured at peak RFD working frequency when moving wire offset from x=0 by 10µm.

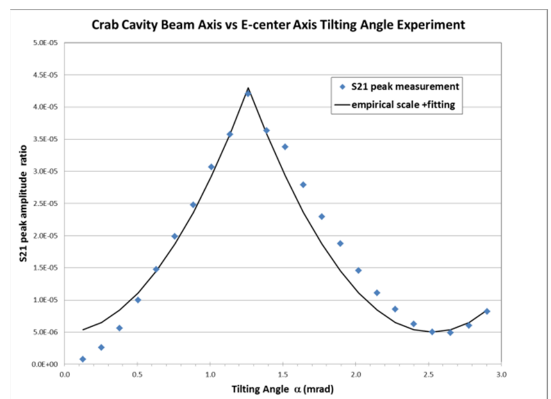

Figure 6: S21 amplitude response to wire titling angle.

CONCLUSION

E-centre line change in less than 10µm of offset and with less than 0.1mrad of tilting angle to the crab cavity mechanical reference have been measured with the S21 amplitude and phase measurement on the RFD crab cavity. Roll and pitch of the cavity's E-centre plane can be also developed from this scheme. For the LHC-HLU crab cavity alignment procedure, before removing the stretched wire from the cavity string assembly, the last E-centre registry can be transferred from the wire fiducialization to tooling balls on the cavity flanges and then to helium vessel rabbit ears. Once the registration is in the data base, the WPM apparatus can be used to track the E-centre line change during cooldown of the cryomodule. This technique can be also used for other applications like the dipole HOM based BPM calibration [9], tune the crab mode field symmetry and leaking power to the LOW/HOM coupler. A wire-scanning technique based on this principle can be also developed for bench measuring the higher order multipole components of a SRF/NCRF cavity.

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