RF CHARACTERIZATION AND MEASUREMENT OF A FULL SCALE COPPER PROTOTYPE OF 5-CELL ELLIPTICAL SHAPE SUPERCONDUCTING RF LINAC CAVITY

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Abstract

Design, Analysis and Development of high-β multi-cell elliptical shape Superconducting RF linac cavity has been taken up by VECC, Kolkata, India. A 5-cell elliptical shape SCRF cavity has been designed and a full-scale copper prototype has been fabricated at 704.4 MHz for RF characterisation and measurement. RF characterization of the cavity is mainly described by the frequency of resonant modes, field profile, Q-value, shunt impedance (Rsh) and Rsh /Q values at different modes, cell to cell coupling etc. Perturbation measurement technique was employed to evaluate the field profile and Rsh/Q at different modes. In perturbation technique, a small perturbing object perturbs the stored energy of the resonant cavity by a very small amount, which results in a small shift in the resonant frequency. This small frequency shift is very difficult to measure due to instability. So, measuring the phase-shift, corresponding frequency shift is derived. As frequency, field profile, cell to cell coupling and Rsh/Q are completely geometry dependent parameters and independent of cavity material, RF measurement with copper prototype cavity are excellent providing a good idea about the RF characterisation of superconducting niobium cavity.

INTRODUCTION

Multi-cell (N) accelerating cavities have N numbers of degenerated modes. Five distinct fundamental modes (TM010 like mode) exist in the 5-cell cavity and the accelerating mode is π-mode in which each cell operates at same frequency with phase difference of 180^o between two neighbouring cells.[1]The different modes have different field profile distributions. Frequencies have been measured for five fundamental modes and field profile for each mode has been obtained using perturbation technique. From this field profile, π-mode (accelerating mode) has been determined and Rsh/Q has been found for all the five modes using perturbation technique.

PERTURBATION MEASUREMENT

Perturbation measurement involves drawing a perturbing object (metal or bead) through the central axis of the cavity while monitoring the cavity's resonant frequency shifts as the object travels its entire length. This frequency shift is related to the relative electric (E) field and magnetic (H) field strengths in the area of the bead. This method is the most commonly used technique to measure the field distribution inside the Radio frequency (RF) cavity.

Relevant Theory

According to the classical Slater perturbation theory[2], if a cavity volume is changed by very small amount ΔV or a tiny perturbing object, more commonly referred to as bead having volume, ΔV perturbs the stored energy of the resonant system by a very small amount, there will be small shift in resonant frequency which is given by [2][3]

$$\frac{\Delta f}{f0} = \frac{\Delta U_E - \Delta U_H}{U} = \frac{\Delta V^{\iiint \varepsilon_0 E^2 dV} - \Delta V^{\iiint \mu_0 H^2 dV}}{4U} \qquad \text{........ (1)}$$

For the case of a small non-conducting sphere with radius "r", where the unperturbed field may be considered uniform over a region larger than the bead, equation (1) reduces to following relation[3][4].

$$\frac{\Delta f}{f_0} = \frac{\Delta U}{U} = -\frac{\pi r^3}{U}\left[\mathcal{E}_0 \frac{\mathcal{E}_r - 1}{\mathcal{E}_r + 2} E_0{}^2 + \mu_0 \frac{\mu_r - 1}{\mu_r + 2} H_0{}^2\right] \text{..........(2)}$$

For a dielectric bead ($\mu_r = 1$) the expression reduces to

$$\frac{\Delta f}{f_0} = -\frac{\pi r^3}{U}\left[\mathcal{E}_0 \frac{\mathcal{E}_r - 1}{\mathcal{E}_r + 2} E_0{}^2\right] \qquad \text{....................(3)}$$

[where, Δf = frequency shift, f_0 = unperturbed frequency, E_0= amplitude of electric field, H_0= amplitude of magnetic field, $\mathcal{E}_r$ = relative permittivity of the bead, $\mathcal{E}_0$ = permittivity of vacuum, μ_r = relative permeability of the bead, μ_0 = permeability of vacuum, U =energy stored in the cavity, ΔU = change in stored energy].

For very small perturbation, it is very difficult to measure the frequency shift using Vector Network Analyzer (VNA). However, the phase shifts at the unperturbed resonant frequency are much easier to measure with VNA. In the present measurement technique, instead of measuring the frequency-shift, phase-shift has been measured and then translated it into frequency-shift.

$$\frac{f_p - f_0}{f_0} = \frac{\tan\phi(f_0)}{2Q} \qquad \text{....................................(4)}$$

where, f_p= perturbed frequency, f_0 = unperturbed resonant frequency, Q = quality factor of the unperturbed cavity, $\phi(f_0)$ = shift in phase angle at f_0.

Calculation of R_{sh}/Q

For RF Linac cavity, shunt impedance R_{sh} is defined by the following equation [3][4],

$$R_{sh} = \frac{V^2}{P} = \frac{\left[\int E_z e^{jkZ}\, dz\right]^2}{P} = \frac{\left[\int E_z \cos kz\, dz\right]^2}{P} \quad ....(5)$$

$k=\frac{\omega}{v}$, v= particle velocity and $\omega = 2\pi f$

From equations (3),(5) and definition of Q

$$\frac{R_{sh}}{Q} = \frac{\left[\int \sqrt{\frac{\Delta f}{f0}} \cos kz\, dz\right]^2}{w\pi r^3} \frac{\mathcal{E}_r + 2}{\mathcal{E}_0(\mathcal{E}_r - 1)} \quad ....(6)$$

Using the perturbation measurement, $\sqrt{\frac{\Delta f}{f0}}\cos kz$ can be measured at discrete intervals of z and integrated using numerical method to obtain $\frac{R_{sh}}{Q}$.

RF MEASUREMENT OF PROTOTYPE:

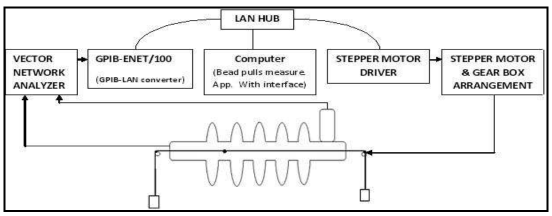
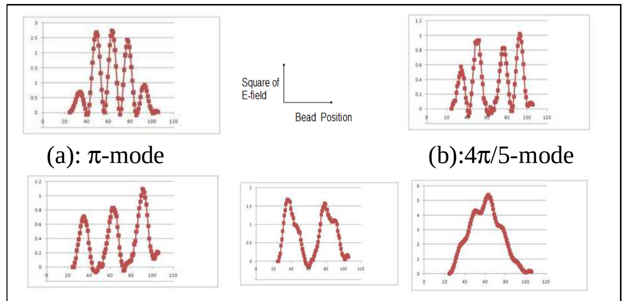


Fig1: Block diagram of measurement set up

A dielectric bead (special type of alumina) with diameter 1 cm. and $\mathcal{E}_r$=11 has been attached to a Kevlar thread which is inserted in the 5-cell linac prototype along its central axis. A stepper motor-gear box arrangement is used to move the bead along the cavity axis and Vector Network Analyzer (Agilent 8753ES) has been used to measure frequencies of 5 fundamental resonant modes and also it measures phase shift of S_{21} parameter for different modes as the bead moves inside the cavity. Thus field profiles and $\frac{R_{sh}}{Q}$ at different modes have been obtained. A JAVA based GUI communicates with the VNA and controls the movement of the bead along the cavity axis through LAN.GUI is used for automation, data acquisition, storage and display of measured data.

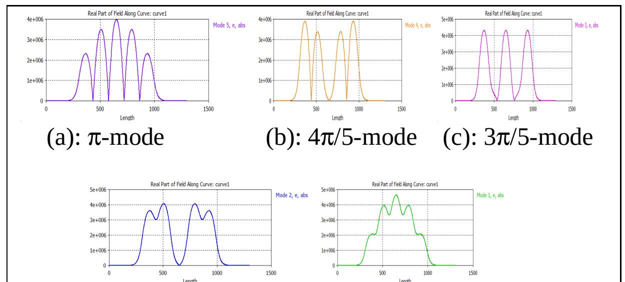
RESULTS

In case of 5-cell copper prototype cavity, five fundamental modes have been found at 704.4MHz, 702.9MHz, 700.8MHz, 698.3 MHz and 696.4 MHz. Measured E-field profiles along cavity axis, using perturbation technique, and CST microwave studio simulated E-field profiles along cavity axis at these frequencies, are shown in Fig.2 and Fig.3 respectively.



(a): π-mode (b):4π/5-mode (c): 3π/5-mode (d): 2π/5-mode (e): π/5-mode

Fig.2. Measured E-field profiles for different modes



(a): π-mode (b): 4π/5-mode (c): 3π/5-mode (d): 2π/5-mode (e):π/5-mode

Fig.3. CST simulated E-field profiles for different modes

At each of the zero-crossing in the field profile curves, there is phase reversal of the electric field and thus we can conclude that π-mode(accelerating mode) is located at 704.4 MHz where phase difference is 180^o between two neighbouring cells. Rsh/Q has been calculated from frequency shift vs. bead position data for all the frequencies considering β=.61 and at π- mode, it has a value of 180 ohm where for other four modes this value is very small which is desired. As end cells are coupled to neighbouring cell at one side only, field at end cells is lower than inner cells and end cell tuning is required to have a flat π-mode with equal amplitude at each cell.[1]

CONCLUSION

E-Field profiles of copper prototype measured by perturbation technique are similar to our simulation result, but somewhat non-uniform. This is mainly due to the fact that quality of copper is not identical for 5 cells and also due to the deformation of the cell after brazing (EB welding was not done). This measurement technique will be used for RF characterisation of niobium cavity and can be used to measure the higher order modes of the cavity.

REFERENCES

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