# BEAD-PULL MEASUREMENT USING PHASE-SHIFT TECHNIQUE IN MULTI-CELL ELLIPTICAL CAVITY

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*Abstract*

The project on the development of high-β multi-cell elliptical shape superconducting rf linac cavity at around 704 MHz has been funded at VECC, Kolkata, India. A full-scale copper prototype cavity has been designed and fabricated. There are 5 distinct modes exist in the cavity and the accelerating mode is π-mode in which each cell operates at same frequency with phase difference of 180º between two neighbouring cells. A fully automated bead-pull measurement setup has been developed for analyzing these modes and field profile distribution at different modes in such type of linac cavity. A special measurement method inside the cavity using phase-shift technique is proposed in this paper, which describes the development of mechanical setup comprising of pulleys and stepper motor–gear arrangement, PC-based control system for precise movement of bead using stepper motor, measurement using VNA, development of software for data acquisition and automation and measurement for the 5-cell copper prototype cavity.

## INTRODUCTION

Multi-cell (N) accelerating cavities have N numbers of degenerated modes and the desired accelerating mode is the π-mode. The different modes have different field profile distributions. In order to measure the field profile for different modes, the bead-pull measurement system using perturbation technique is necessary. Bead pull perturbation method is the most commonly used technique to measure the field distribution inside the Radio frequency (RF) cavity. Information about the field distribution and mode orientation can be obtained by observing the coupling to Electric field (E) and magnetic field (H) components at various places in the cavity. This can be done by introducing a perturbing object of dielectric material or metal in the cavity. Perturbation measurement involves drawing a perturbing object through the central axis of the cavity while monitoring the cavity's resonant frequency shifts as the object travels its entire length.

## RELEVANT THEORY OF BEAD PULL MEASUREMENT

According to the classical Slater perturbation theory [1], a tiny perturbing object, or more commonly referred to as bead, perturbs the stored energy of the resonant system by a very small amount, which results in a small shift in the resonant frequency. This frequency shift is related to the relative electric (E) field and magnetic (H) field strengths in the area of the bead. Introduction of a dielectric object in a region of electric field produces a negative shift in the resonant frequency while introducing a metal object into a region of magnetic field causes a positive frequency shift. If both fields are present when a metal object is inserted the resulting frequency shift will depend on the relative strengths of the E and H fields. So small objects on a string pulled through the cavity can be used to map the field distributions of the modes. 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, it can be shown [2, 3] that

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

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

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

where $\Delta f$ = frequency shift, $f$ = 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, $\mu_r$ = relative permeability of the bead, $\mu_0$ = permeability of vacuum, $U$ = energy stored in the cavity, $\Delta U$ = change in stored energy.

So, with the displacement of the bead along the cavity central axis, if frequency shift of the cavity can be measured with synchronization, electric field distribution of the linac cavity along its length can be obtained. In the present measurement technique, instead of measuring the frequency-shift, phase-shift has been measured and then translated it into frequency-shift.

$$\frac{f_p - f_0}{f_0} = \frac{\tan\phi(f_0)}{2Q}, \quad (3)$$

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

## MEASUREMENT SET-UP

A fully automated bead pull measurement system (schematic of measurement set up is shown in Figure 1) provides movement of the bead along the cavity, measurement of the phase data for different position of the bead and stores these data in a database and displays and plots the data. GUI based software has been developed in JAVA for automation, data acquisition, storage and display. Bead pull measurement set up consists of Vector Network Analyzer (Agilent 8753ES), GPIB to Ethernet converter (GPIB-ENET/100 from

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National Instrument), a 1.8° hybrid stepper motor (TS41 B from Compumotor division) coupled with a gear-box (10:1) arrangement for movement of the bead and GT6k stepper motor driver. A dielectric bead (special type of alumina) with diameter 1 cm. and $\mathcal{E}_r$=11 has been used for the perturbation of the cavity. The bead is attached to an insulating Kevlar thread, which is inserted in the linac cavity along its central axis. Kevlar is used because of its inelasticity and strength under tension. A pulley system guides the Kevlar thread supporting the bead to move through the central axis of the cavity.

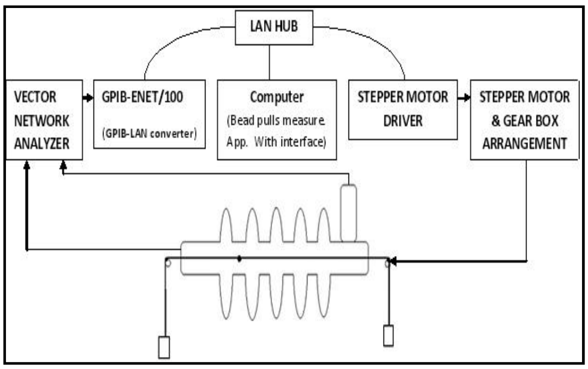



Figure 1: Schematic block diagram of bead-pull measurement set up.

Stepper motor-gear box arrangement provides the movement of the bead and minimum step size of the bead movement is less than 1 µm. Movement of the stepper motor is controlled by the GT6k controller which receives command from the GUI based software running on computer through LAN (local area network). RF measurement of the cavity is done by the vector network analyzer (VNA). The software communicates with VNA having GPIB interface through LAN using GPIB-ENET/100. So it sends command to the VNA for the RF measurement of the cavity and receives the measured data. The photograph of bead pull measurement set up for 5-cell elliptical shape copper prototype cavity is shown in Figure 2.

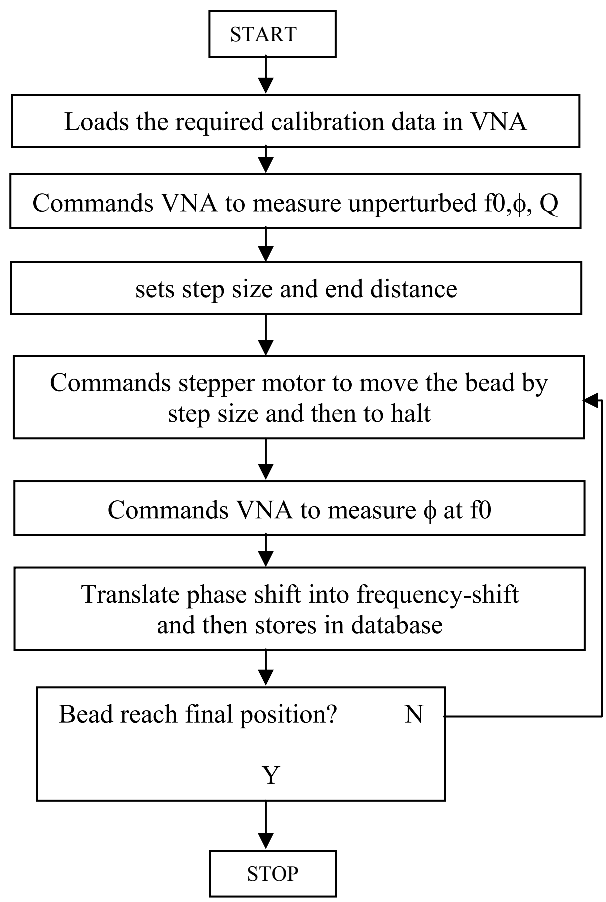
## GUI BASED SOFTWARE FOR BEAD-PULL MEASUREMENT

GUI (graphical user interface) based software, developed in JAVA provides the automation of the bead pull measurement, stores the measured data in a database and displays the data. VNA measures the variation of the phase of $S_{21}$ at unperturbed resonant frequency with the displacement of the bead and phase variation is converted into frequency shift using equation (3). Resonant frequency of the unperturbed cavity and quality factor of the cavity at unperturbed frequency are also measured by the VNA. A program is developed which automates the above measurement procedure.

As the 5 cell linac cavity has 5 distinct modes at 5 different frequencies, GUI based software gives mode selection facility and also for measurement at different modes, start frequency and stop frequency can be sent to VNA. MySQL database has been used for data storage and data can be displayed in both tabular form and graphical form.

Figure 2: bead pull measurement set up for 5-cell elliptical shape copper prototype cavity.

Flow chart for the measurement is given below.




## BEAD-PULL MEASUREMENT RESULT OF 5-CELL ELLIPTICAL SHAPE COPPER PROTOTYPE CAVITY & DISCUSSION

In a multi-cell elliptical cavity, resonant cells are capacitively coupled to each other. In case of a N-cell cavity having N distinct mode, frequency of m$^{th}$ mode is given [4] in terms of frequency of single cell $f_0$, with $k$ being coupling parameter between the cells. In the case of

$$f_m = \frac{f_0}{[1+2k\cos(\frac{m\pi}{N})]^{1/2}}, \quad (4)$$

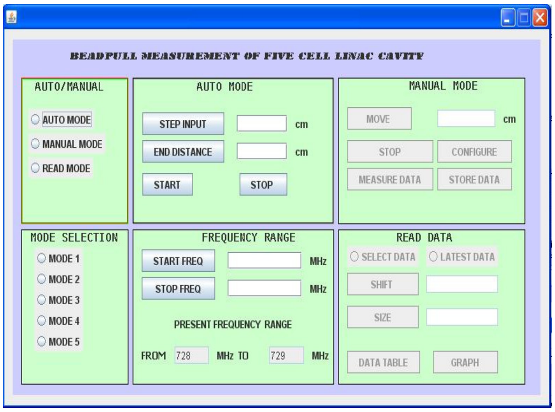



Figure 3: GUI for bead-pull measurement set-up.

accelerating ($\pi$ mode), given by m = N has the highest frequency. Using automated bead pull system, RF field measurement has been carried out for 5-cell copper prototype cavity and five modes have been found at 704.4 MHz, 702.9 MHz, 700.8 MHz, 698.3 MHz and 696.4 MHz. The desired accelerating mode i.e., $\pi$-mode is located at 704.4MHz [5]. The plot of (Electric field)$^2$ vs. Bead position for $\pi$-mode and 0-mode are shown in Figures 4 and 5 respectively.

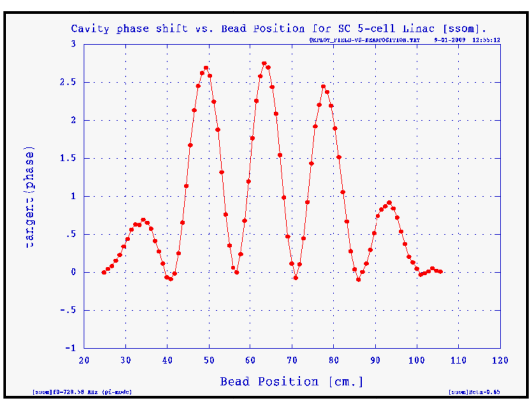



Figure 4: Plot of tan $\phi$ ($\alpha$ $|E|^2$ ) vs. Bead position (for $\pi$-mode).

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 $\pi$-mode (accelerating mode) is located at 704.4 MHz where phase difference is 180$^{\circ}$ between two neighbouring cells.. Similarly, for the 0-mode, the phases in all cells are same and the corresponding measured plot is successfully represented in Figure 5. Rsh/Q has been calculated from frequency shift vs. bead position data for all the frequencies considering β=0.61 and at $\pi$- mode, it has a value of 180 ohm where for other four modes this value is very small, which is desired [5]. As end cells are coupled to neighbouring cell at one side only, electric field at end cells is lower than inner cells and end cell tuning is required to have a flat E-field profile in $\pi$-mode with equal amplitude at each cell [4].

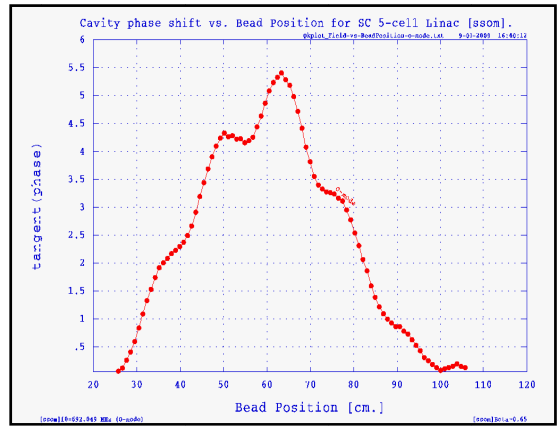



Figure 5: Plot of tan $\phi$ ($\alpha$ $|E|^2$ ) vs. Bead position (for 0-mode).

## CONCLUSION

For very small perturbation, it is very difficult to measure the frequency shift in the peak of the cavity response using Vector Network Analyzer (VNA). Phase locked loop (PLL) may be required to track the frequency deviation in $\pi$-mode. However, the phase shifts at the unperturbed resonant frequency are much easier to measure with VNA. For this reason, the present measurement system has been developed using phase shift technique and performed very well and satisfactorily.

## ACKNOWLEDGMENT

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