Overview of electrical axis measurement in TESLA-type cavities

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1. Introduction

The cells of TESLA cavities are mechanically aligned and tuned before the cavities are installed into the cryomodule. The alignment minimizes unwanted interaction of the accelerated beam with the transverse electric field component and the magnetic field of the accelerating TM_{010}-π mode. It also reduces an interaction with higher order modes. The tuning equalizes field amplitudes of the accelerating mode in all cells. Until now, the eccentricity (misalignment) of cells is measured mechanically with residual misalignment after tuning up to 0.4 mm. Unfortunately the mechanical measurement is only weakly related to the electromagnetic fields inside a cavity, both for the accelerating and higher order modes. For improvement of the precision a new method of electromagnetic field mapping inside a cavity, based on small perturbation theory was developed. This method can be applied to modes which do not propagate through the beam pipes. In the setup built for the axis measurement a metallic needle is used as field perturbing object. Conducted tests confirmed high precision of 0.1 mm. Tests on the copper model for which it is possible to excite all of considered modes and on several niobium cavities were performed. In this paper an overview of measurement method, equipment and first results are reported. The detailed report will follow in the near future.

2. Small perturbation theory

The resonant frequency of a mode varies over a certain range when a small perturbing bead is inserted into the cavity interior. The theory is very well explained in [1], [2], [3] and [4]. We assume that the cavity volume V is filled with $\varepsilon_r = 1$ and $\mu_r = 1$ medium (vacuum). Further we assume that an unperturbed mode under consideration has the resonant frequency ω_0 and amplitudes of the electric and magnetic field E_0 and H_0 respectively. The inserted perturbing object with volume v changes locally the permittivity and permeability by $\Delta\varepsilon$ and $\Delta\mu$. We will denote the perturbed electric and magnetic fields by E and H respectively. The relative resonant frequency detuning is then given by:

$$\frac{\omega-\omega_0}{\omega} = -\frac{\int\limits_V \left(\Delta\varepsilon\vec{E}\cdot\vec{E}_0^* + \Delta\mu\vec{H}\cdot\vec{H}_0^*\right)\cdot dv}{\int\limits_V \left(\varepsilon_0\vec{E}\cdot\vec{E}_0^* + \mu_0\vec{H}\cdot\vec{H}_0^*\right)\cdot dV} \tag{2.1}$$

If we assume that perturbation and detuning are small and when the integral in the numerator is known for a given bead shape, the equation (2.1) can be written in the following simplified form:

$$\frac{\Delta f}{f_0} = \frac{1}{W}\left(\varepsilon_0\alpha_E E_0^2 + \mu_0\alpha_\mathrm{M}\mathrm{H}_0^2\right) \tag{2.2}$$

where W is the total energy stored in the cavity, α_E and α_M are the electric and magnetic polarizabilities of the bead depending on the bead material, its shape and dimensions. For a perfectly conducting material we can assume:

$$\varepsilon_r \to \infty \qquad \mu_r = 0 \tag{2.3}$$

because the electric lines of force end perpendicularly to the bead surface and the magnetic lines of force bypass the bead due to the eddy currents induced magnetic field. A complete theoretical analysis including determination of measurement error will soon be published in a detailed report.

3. Measurement equipment

The perturbing metallic needle (12 or 15 mm long and 0.3 mm thick) is hold by a very thin nylon thread and can be moved in all three directions. The phase of the transmission parameter (S21) through the cavity is measured by means of a network analyzer in order to determine the change of the cavity resonant frequency for various bead locations. The controlling software (written in Borland Delphi 6) makes possible to map the electric field along the cavity, to identify polarization planes of dipole modes and to find displacement of cells' centers of electromagnetic symmetry from the cavity axis (the electrical eccentricity) at equator or iris planes for each mode. All measurements can be controlled manually or run automatically and in any arbitrary sequence. The scheme of the measurement and photographs of the setup are shown in *Fig. 3.1* and *Fig. 3.2* respectively.

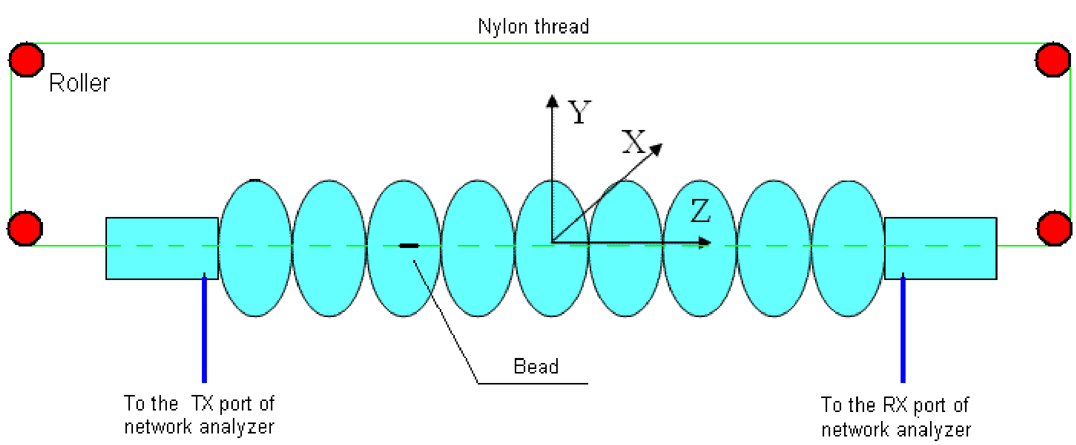

Fig. 3.1 Principle of small perturbation measurement

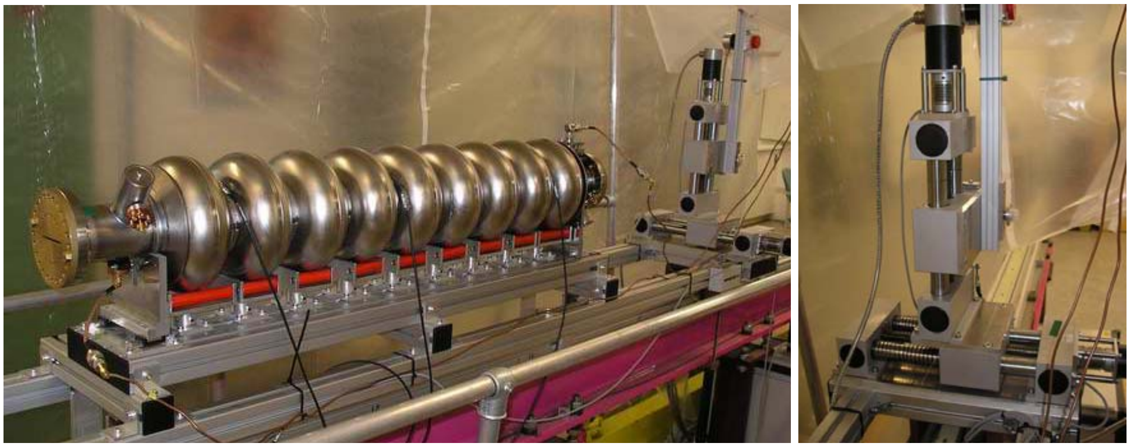

Fig. 3.2 Cavity on the measurement setup (left) and detail of transmissions for transversal bead movement (right)

4. Measurements on copper model cavity

These measurements were performed in order to evaluate the measurement method. The passbands TM_{010}, TM_{110} and TM_{011} were measured in order to find out whether different modes demonstrate the same electrical eccentricity in the same cells. This would be the case when the given cell is (or is not) shifted from the cavity axis, but has no significant deformation of its rotational symmetry. Otherwise different modes can have different centers due to their different field patterns. The advantage of using this cavity is flexibility in positioning of coupling antennas by use of coupling holes drilled in beam pipes and in all cells. The measured eccentricities at equators planes for the TM_{010} passband are shown in *Fig. 4.1* and *Fig. 4.2*.

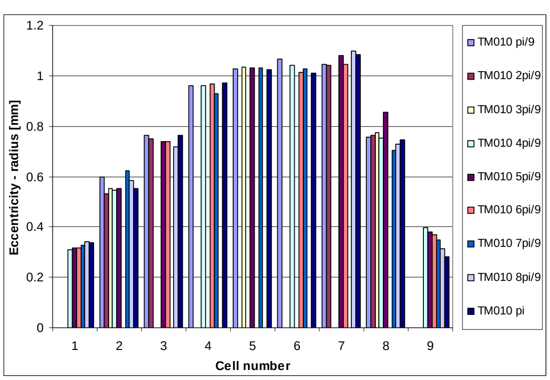

Fig. 4.1 Radius of eccentricity, Cu cavity

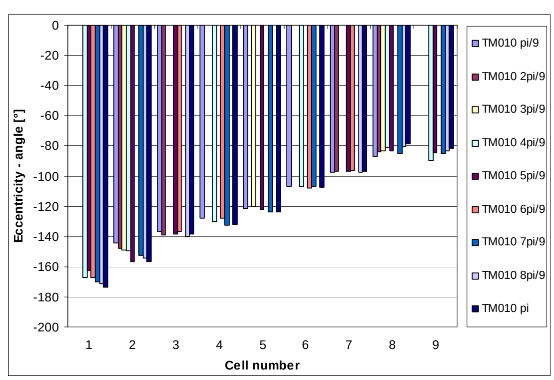

Fig. 4.2 Angle of eccentricity, Cu cavity

5. Measurements on niobium cavity

The experiments with copper cavity are very comfortable and have great scientific value. The measurement on niobium cavities has fundamental constrain. Only the input coupler, HOM couplers and field pickup probe of a niobium cavity can be used to couple the RF power to and from the cavity. For this reason only the measurement of the fundamental passband on equator planes gave reasonable results. The measured eccentricities of the tuned niobium cavity (serial number Z93) are displayed in *Fig. 5.1* and *Fig. 5.2*. The electrical eccentricities are compared to the eccentricities measured mechanically (red bars on the charts). The electrical axis for the accelerating mode (TM_{010}-π) was calculated by minimizing of the sum of quadratic deviation [5] from the electrical centers of all cells. The fixation points and the tilt from the cavity axis are shown in *Tab. 5.1*.

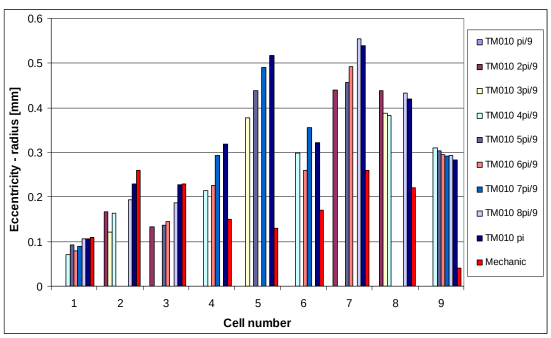

Fig. 5.1 Radius of eccentricity.

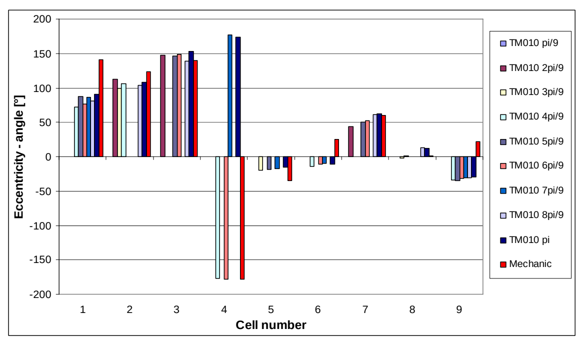

Fig. 5.2 Angle of eccentricity.

Cell 1 equator plane crossing [mm]	Cell 9 equator plane crossing [mm]	Tilt [°]
(-0.139, 0.125)	(0.392, 0.028)	0.033

Tab. 5.1 Electrical axis position for accelerating mode

6. Conclusions

- The possibility of using small perturbation for cavity eccentricity measurement was theoretically analyzed and consequently the measurement equipment was designed and built.
- The precision of measurement is - according to theoretical analysis and random error indicated by standard deviation of repeated measurements - approximately 0.1 mm.
- The measurements of the copper cavity indicate very precise rotation symmetry of individual cells by very low spread of their electrical center positions for each TM_{010} mode, although the center of the cavity is displaced more than 1 mm from the cavity axis.
- In case of niobium cavities bigger spread of electrical centers of various modes indicates deformation of the cavity wall. This happens probably due to mechanical stress release after welding by baking at 800 °C.
- The difference between the mechanical and electrical eccentricities of the niobium cavity lies below the 0.4 mm tolerance, so the correlation between mechanic and electromagnetic measurements is sufficient. In order to increase precision of cavity to beam alignment it is recommended to perform one small perturbation eccentricity measurement of each tuned and aligned (by means of mechanical eccentricity measurement) cavity on the accelerating mode and calculate the position of electrical axis. Then the cavity should be aligned in the cryomodule in a way of making the electrical axis a beam trajectory. To check the symmetry of cells the whole TM_{010} passband has to be measured.

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