ELECTRICAL AXES OF TESLA CAVITIES

Anton LABANC, DESY, Group MHF-SL, Hamburg, Germany

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Abstract

Precise alignment of cavities to the beam is one of strong requirements in order to obtain high quality beam. A missalignment could cause unwanted interaction between the beam and electromagnetic fields in the cavity, both accelerating field and wakefields. Up to now the eccentricity of cells is measured mechanically on the outer side of cell equators. In this way measured eccentricity could be not precise in case of not uniform cavity wall thickness or in case of cavity wall deformation on other place than measured equator. Therefore an alternative method based on small perturbation field mapping was developed and applied on some cavities.

INTRODUCTION

The cells of TESLA cavities must be tuned to the operating frequency and aligned (*Fig. 1*) before they are installed into a cryomodule. The mechanical eccentricity measurement setup is shown in *Fig. 2*. A set of linear position sensors are driven around cavity equators and the geometrical centers of cells are calculated as centers of mass of obtained enclosed curves.

When the last alignment and tuning (before welding of liquid helium tank) are finished, the eccentricity of each cell and electric field flatness at the accelerating mode are measured once more. The residual differences of electric field intensity among cell must lie below 2 % and the geometrical eccentricity must not exceed 0.4 mm. The geometrical centers of cells are fitted by a line called geometrical axis. Then the cavity is mounted into the cryomodule in means of identifying the geometrical axis with the beam trajectory. The up to now used measurement and tuning method does not measure electrical axis and it is expected, that the offset of the electrical axis is not greater than 0.5 mm and the tilt is not greater then 500 μrad in respect to the geometrical axis.

In order to check this expectation and possibly to increase the precision of measurement and cavity to beam alignment a small perturbation based measurement method and measurement setup were developed. In this way the measurement error can be reduced to 0.1 mm.

Fig. 1: Tuning and alignment

Fig. 2: Eccentricity measurement

DEFINITION OF TERMS

Cavity axis:
- straight line connecting centers of cavity's reference rings (welded on each beam pipe). The cavity axis is identical to the *z*-axis of the measurement setup.

Geometrical eccentricity:
- displacement of the geometrical (mechanical) center of considered cell from the cavity axis.

Geometrical axis:
- linear fit of geometrical centers of all cells

Electrical eccentricity (for given mode):
- displacement of the center of electromagnetic field symmetry of considered resonance mode in considered cell from the cavity axis.

Electrical axis (for given mode):
- weighted linear fit of electrical centers of all cells; optimal trajectory of the beam to minimize its unwanted interaction with considered mode.

The cavities are up to now mounted into cryomodules in order to identify the geometrical axes to the beam trajectory. The improvement by use of small perturbation based eccentricity measurement is the identifying of the electrical axis to the beam trajectory.

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] and [3]. 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:

$$\frac{\omega-\omega_0}{\omega} = -\frac{\int_v \left(\Delta\varepsilon \vec{E}\cdot\vec{E}_0^* + \Delta\mu \vec{H}\cdot\vec{H}_0^*\right)\cdot dv}{\int_V \left(\varepsilon_0 \vec{E}\cdot\vec{E}_0^* + \mu_0 \vec{H}\cdot\vec{H}_0^*\right)\cdot dV} \qquad (1)$$

If we assume that perturbation and detuning are small and when the integral in the numerator is known for given bead shape, the equation (1) can be written in the following simplified form:

$$\frac{\Delta f}{f_0} = \frac{1}{W}\left(\varepsilon_0 \alpha_E E_0^2 + \mu_0 \alpha_M H_0^2\right) \qquad (2)$$

where W is total energy stored in the cavity, α_E and α_M are so called electric and magnetic polarizabilities of the bead which depend on the bead material, shape and dimensions. For a perfect conducting material we can assume:

$$\varepsilon_r \to \infty \qquad \mu_r = 0 \qquad (3)$$

because the electric lines of force end perpendicularly to the bead surface and the magnetic lines of force bypass the bead due to eddy currents induced magnetic field.

Typical bead shapes are spheres, needles (used here) and disks made of metal (used here) or high permittivity dielectric.

MEASUREMENT EQUIPMENT

The perturbing metallic needle (12 or 15 mm long and 0.3 mm thick) is held by a 0.1 mm thin nylon thread and can be moved in all three directions. The phase of the transmission parameter (S21) through the cavity is measured with network analyzer in order to determine change of the resonant frequency for various bead locations. The control software (written in Borland Delphi 6) makes possible to map the electric field along the cavity, to determine polarization planes of dipole modes and to find the electrical centers of cells at equator or iris planes. All measurements can be can be controlled manually or run automatically in any arbitrary sequence. The scheme of the measurement and photographs of the setup are shown in *Fig. 3* and *Fig. 4* respectively.

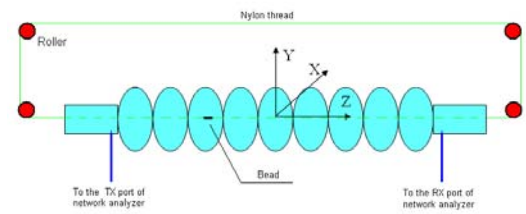

Fig. 3: Principle of small perturbation measurement

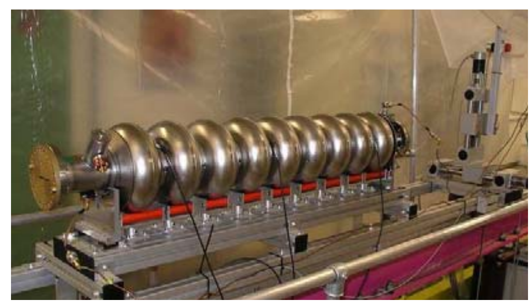

Fig. 4: Setup for small perturbation measurement

In order to guarantee the 0.1 mm precision 10 measurements of TM_{010} modes on equator planes must be averaged. The measurements of TM_{010} modes on iris planes and measurements of higher order modes are less noisy and averaging of 3 measurements is sufficient.

MEASUREMENT RESULTS

The measurements were performed first on copper model cavity in order to evaluate the method. The copper cavity has a lot of drilled coupling holes in beam pipes and cells. This allowed optimal coupling of RF power to and from the cavity for all modes of TM_{010}, TM_{110} and TM_{011} passbands. The goal was to find out whether all modes demonstrate the same electrical eccentricity in the same cells. This would be a 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 measured eccentricities at equator planes for the passband TM_{010} (fundamental), TM_{110} and TM_{011} are shown in *Fig. 5 - Fig. 10*. The trial to measure TE_{111} passband was not successful - the perturbation from needle is negligible and spheres, disks or cylinders are too heavy resulting in several minutes long thread vibration.

The spread of electrical eccentricities of the TM_{010} passband is very small and lies below the measurement error. This indicates good cell shape precision, though the whole cavity is more than 1 mm deflected. The electrical eccentricity spread at high order modes is slightly higher.

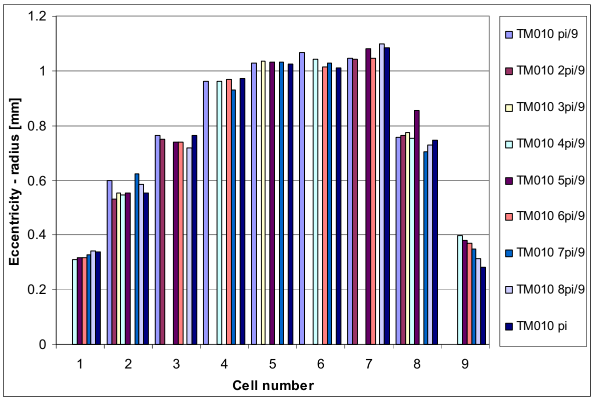

Fig. 5: Radius of electrical eccentricity on equator planes, copper cavity, passband TM_{010}

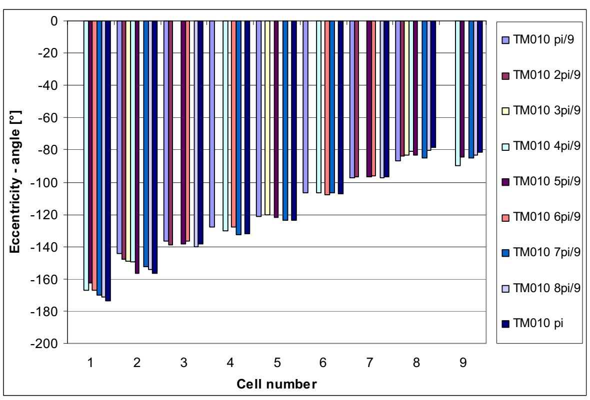

Fig. 6: Angle of electrical eccentricity on equator planes, copper cavity, passband TM_{010}

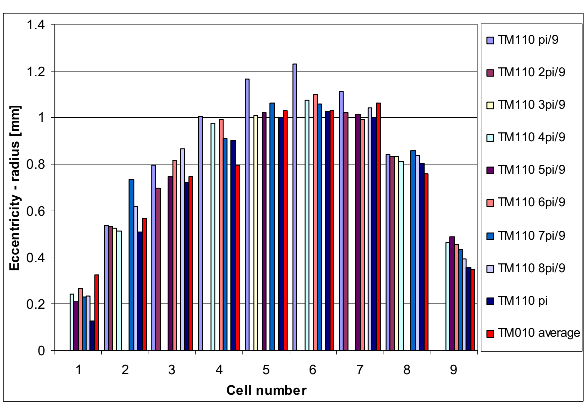

Fig. 7: Radius of electrical eccentricity on equator planes, copper cavity, passband TM_{110}

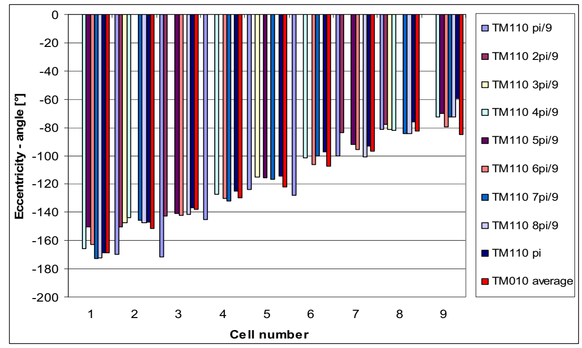

Fig. 8: Angle of electrical eccentricity on equator planes, copper cavity, passband TM_{110}

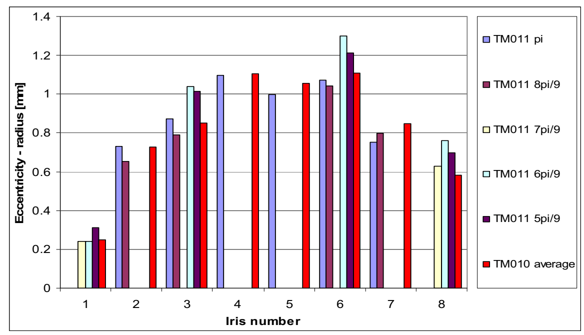

Fig. 9: Radius of electrical eccentricity on iris planes, copper cavity, passband TM_{011}

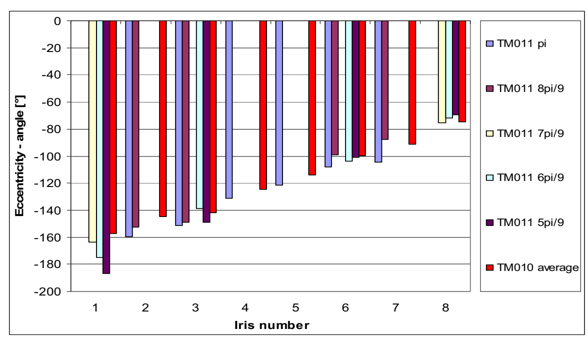

Fig. 10: Angle of electrical eccentricity on iris planes, copper cavity, passband TM_{011}

The reproducibility of measurement results at the accelerating mode is shown in *Fig. 11* and *Fig. 12*. The measurements were performed in lapse of one month.

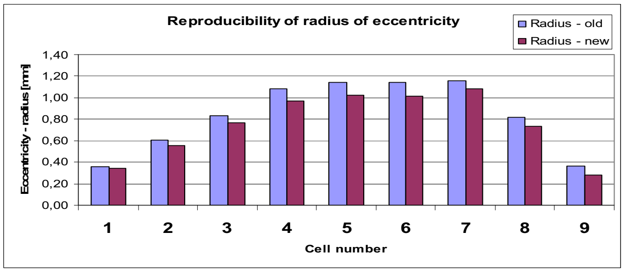

Fig. 11: Reproducibility, radius of electrical eccentricity

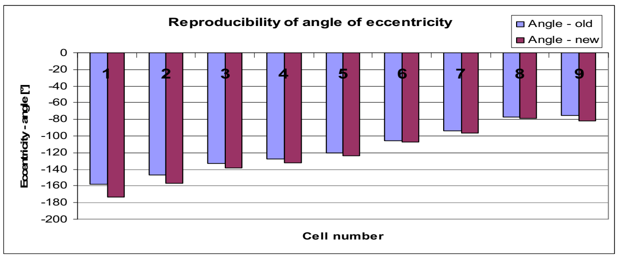

Fig. 12: Reproducibility, angle of electrical eccentricity

The next set of measurements was performed on a tuned niobium cavity (Z93). In this case the measurement has fundamental constrain. Only input coupler and cavity field probe can be used to couple the RF power. For this reason only measurement of the fundamental passband on equator planes gave reasonable results (*Fig. 13, Fig. 14)*. The spread indicates slight deformation of cavity walls. The differences between electrical and geometrical eccentricities are below 0.4 mm.

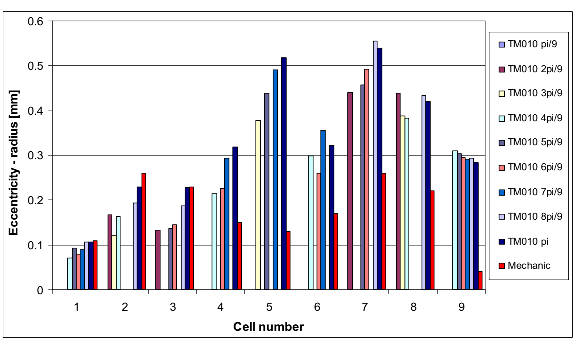

Fig. 13: Radius of electrical eccentricity on equator planes, niobium cavity

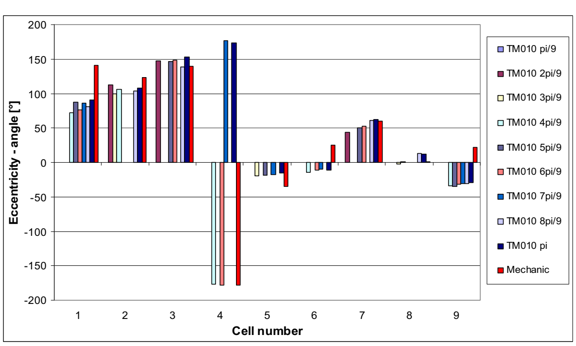

Fig. 14: Angle of electrical eccentricity on equator planes, niobium cavity

The position of electrical and geometrical axis is shown in *Fig. 15* as their cross-section with equator planes of the first and last cell. *Fig. 16* illustrates position of the electrical axis when the geometrical axis is aligned with the beam. Its tilt of 216 μrad satisfies the requirement. Measurements of cavities A14, Z110 and Z115 gave similar results.

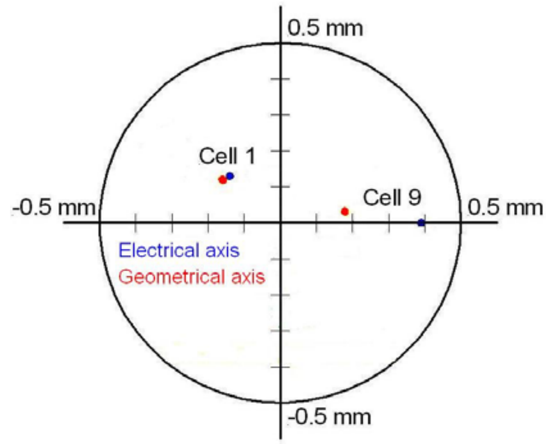

Fig. 15: Cross-section of electrical axis of TM_{010}-π mode and geometrical axis with equator planes of the first and last cell, niobium cavity

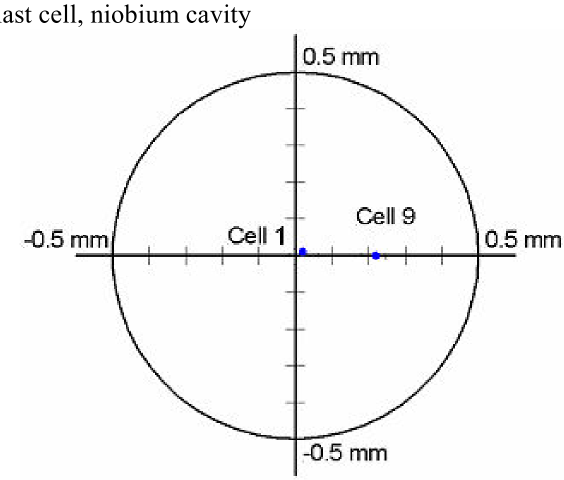

Fig. 16: Position of electrical axis of TM_{010}-π mode in respect to the geometrical axis, niobium cavity. The tilt is 216 μrad

CONCLUSIONS

The possibility of using of small perturbation for cavity eccentricity measurement was theoretically analyzed and consequently the measurement equipment was designed and built.

- The measurement error, calculated and also indicated by standard deviation of repeated measurements, lies below expected 0.1 mm in rectangular coordinates.

- The spread of electrical eccentricities at the TM_{010} passband in the copper cavity lies below the noise level. This indicates that the cell's asymmetry is very small though the center of the cavity is more than 1 mm deflected.

- The differences of electrical eccentricities of niobium cavities in order of few tenths of mm indicate slight deformation of cavity walls. The electrical eccentricities as well as the offset and tilt of the electrical axis in respect to the geometrical axis are small and lay in the range of tolerances. This proves that the mechanical measurement precision is sufficient for the TESLA technology. But the reserve is not large and in case of higher requirements in future projects electrical axis measurement would be necessary.

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REFERENCES

[1] COLLIN, R., E., "Foundation for microwave engineering", *McGraw-Hill, 2-nd edition, USA, 1992, ISBN: 0-07-112569-8*, p. 541 – 545

[2] MILOVANOV, O., S., SOBENIN, N., P., "Ultra high frequency engineering", *Atomizdat, Moscow, Russia, 1980*, p. 132 – 135.

[3] MAIER, L., C., Jr, SLATER, J., C., "Field Strength Measurements in Resonant Cavities", *Research laboratory of Electronics, MIT, Cambridge, Massachusetts, USA, 1951*, p. 69 – 75.