Electrical axis measurement of fundamental and higher order modes in TESLA-type cavities

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Higher Order Mode Measurements in Superconducting Accelerating Cavities
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Actual state of cavity eccentricity measurement

The cell eccentricity is measured up to now mechanically. As the mechanical measurement is only weakly coupled to the electromagnetic field pattern inside the cavity, the precision of this method is limited. Maximum allowed eccentricity of any cell of aligned cavity is 0.4 mm. In order to rate errors of mechanical eccentricity measurement and in order to increase measurement precision an electromagnetic measurement method based on small perturbation theory was developed.

Definitions

Cavity axis:	A straight line connecting centers of cavity's reference rings. The cavity axis is identical with the *z*-axis of the measurement setup.
Geometrical eccentricity:	Displacement of the center of mass of equator of considered cell from the cavity axis.
Geometrical axis (also mechanical axis):	Linear fit of geometrical centers of all cells. It is up to now being set identical with the beam trajectory when the cavity is being installed into a cryomodule.
Electrical eccentricity (of given mode):	Displacement of the center of electromagnetic field symmetry of considered resonance mode in considered cell from the cavity axis.
Electrical axis (of given mode):	Linear fit of electrical centers of all cells, optimal trajectory of the beam to minimize its unwanted interaction with considered mode.

In an ideally straight cavity both eccentricities are zeroes and the cavity axis, geometrical axis and electrical axis are identical.

Goals

- To build an electrical axis measurement setup and develop a measurement technique using small perturbation method to measure electrical eccentricities of individual cells of TESLA-type cavities. The expected precision is 0.1 mm.

- To test the measurement method on copper model cavity whose construction enables to couple measurement antennas to all modes under consideration; to measure all with the existing equipment measurable modes (passbands TM_{010}, TM_{110} and TM_{011}) and to compare electrical eccentricities of these modes.

- To measure some niobium cavities (the Z93 is included in this report) in order to determine the limitations due to the fixed port (input coupler, cavity field pickup, HOM couplers) positions; to measure all measurable modes; to compare electrical eccentricities of different modes and the geometrical eccentricity (measured in classical way).

- To calculate the position of electrical axis of the accelerating mode

Small perturbation theory [1], [2], [3], [5]

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

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

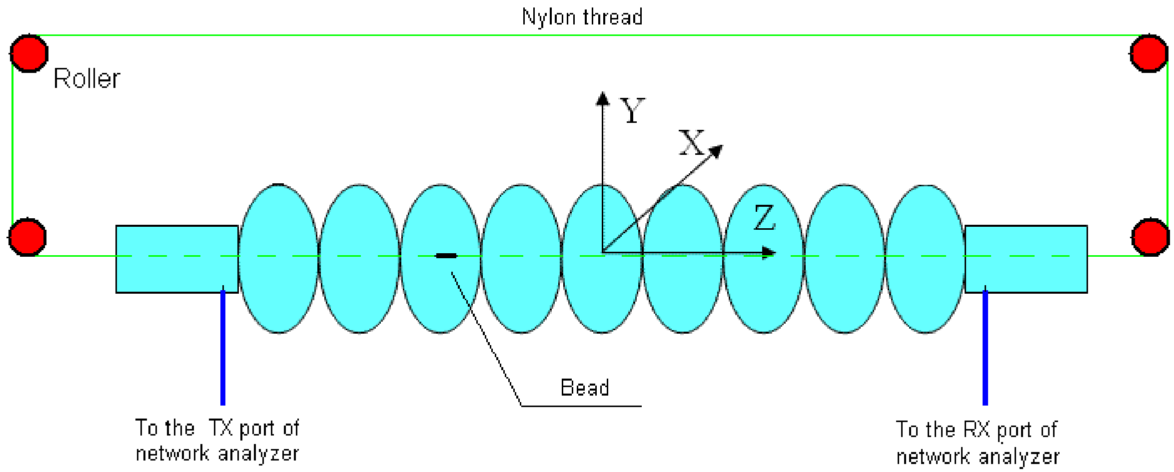
PEC bead:

$$\varepsilon\to\infty$$

$$\mu=0$$

ω_0, f_0	–	not perturbed resonant frequency
ω, f	–	perturbed resonant frequency
E_0, H_0	–	electric and magnetic field intensity without perturbation
E, H	–	perturbed electric and magnetic field intensity
$\Delta\varepsilon$, $\Delta\mu$	–	additional ε and μ due to the perturbation
W	–	energy stored in the cavity
α_E, α_M	–	electric and magnetic polarizability of the perturbing object
V	–	volume of the cavity
v	–	volume of the perturbing bead

Measurement principle



Bead:

- made by winding of 0.1 mm tinned copper wire around the carrying thread
- can be moved in all three directions

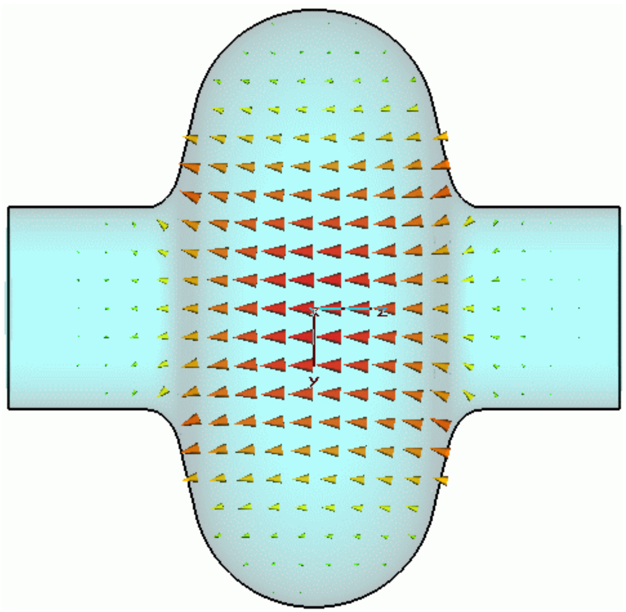
Length: 12 mm or 15 mm *Diameter*: 0.3 mm

Resonance frequency shift measurement:

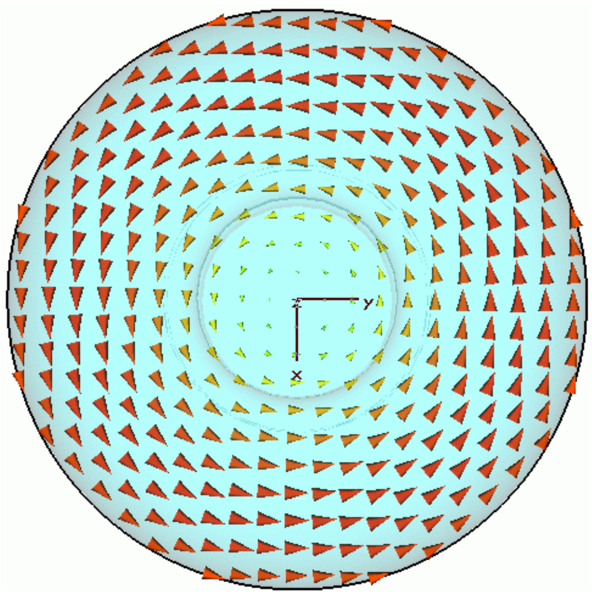
- S21-phase measurement by the Agilent N 3383 A network analyzer

TM_{010} mode

Electric field:



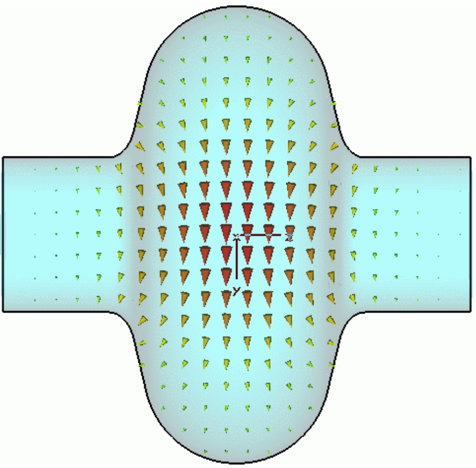
Magnetic field:



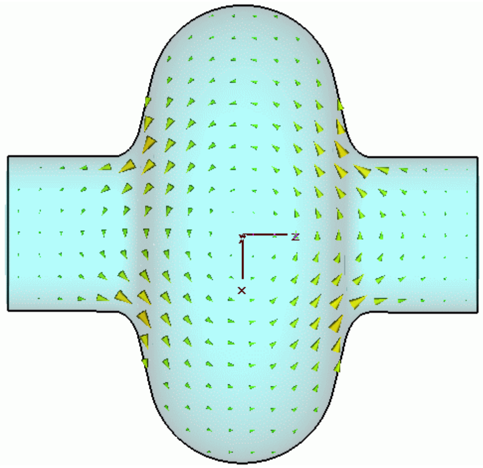
- Accelerating, monopole mode.
- Displaced beam interacts with magnetic field
- Tilted beam suffers kick from transversal component of electric field
- The mode can be measured on equator and also on iris plane by use of *z*-oriented needle.

TE_{111} and TM_{110} modes

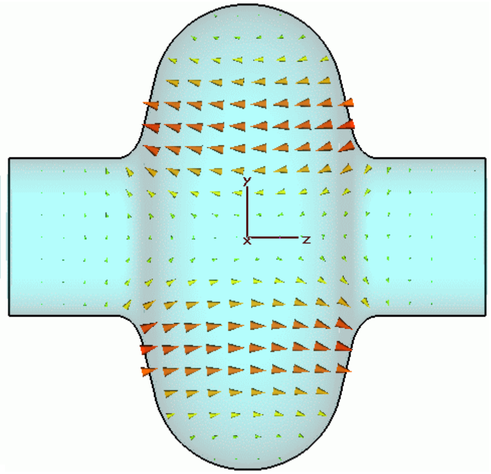
TE_{111}, electric field:



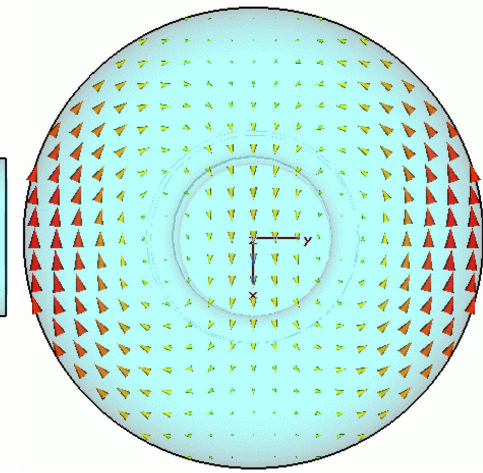
TE_{111}, magnetic field:



TM_{110}, electric field:



TM_{110}, magnetic field:

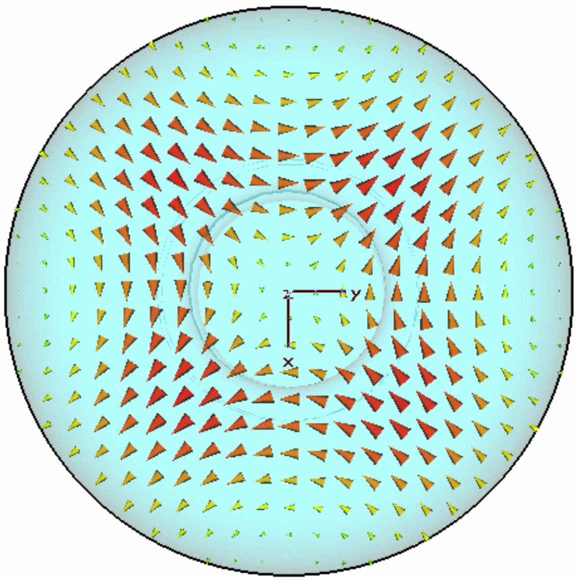


- Dipole modes, in multi-cell structures, build a HEM wave and cause regenerative Beam Blow-Up (BBU) – the most effective BBU mechanism [4]. A displaced beam can store a part of its energy through the TM field component in the cavity and consequently be deflected by excited TE component.

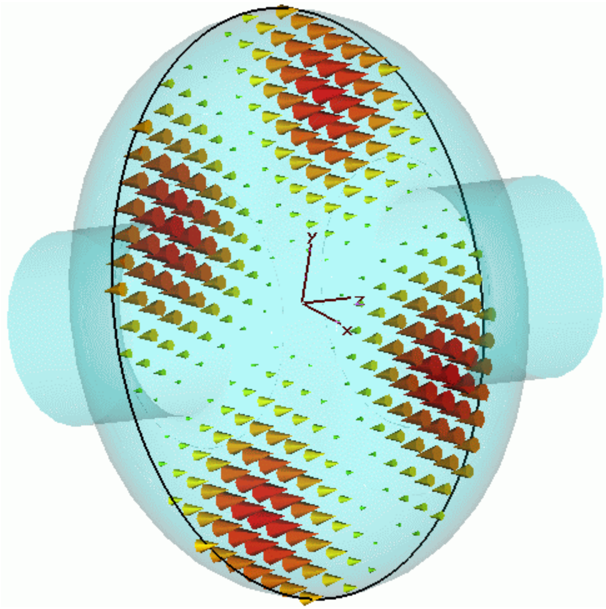
- The TM_{110} modes can be measured by use of *z*-oriented metallic needle, to measure TE_{111} modes one needs a disk or sphere, which was on the existing setup not possible due to mechanical reasons.

TE_{211} mode

Electric field:



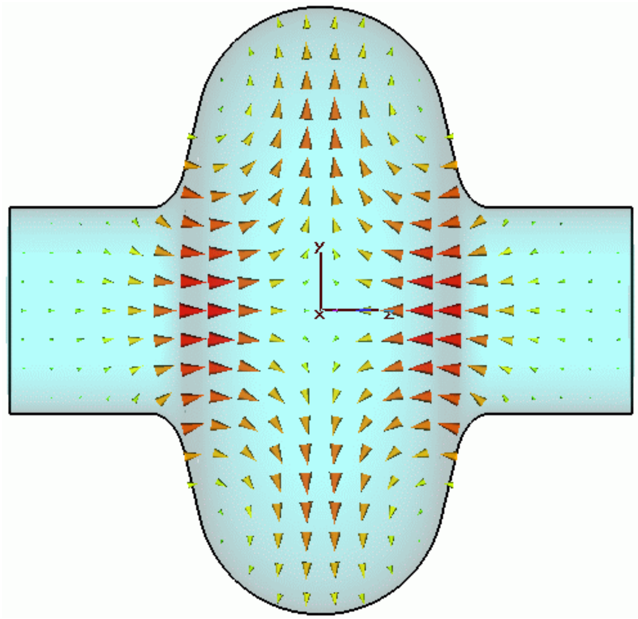
Magnetic field:



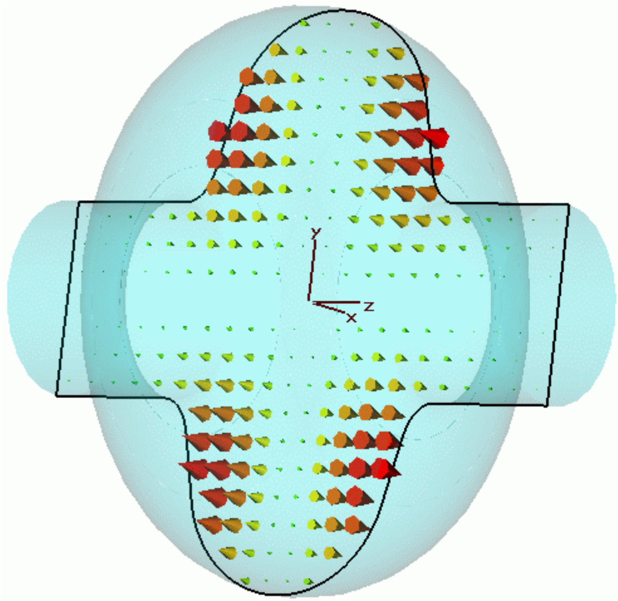
Quadrupole modes (and modes with higher order of azimuth symmetry) couple to the beam inefficiently [4] and therefore their effect is negligible.

TM_{011} mode

Electric field:



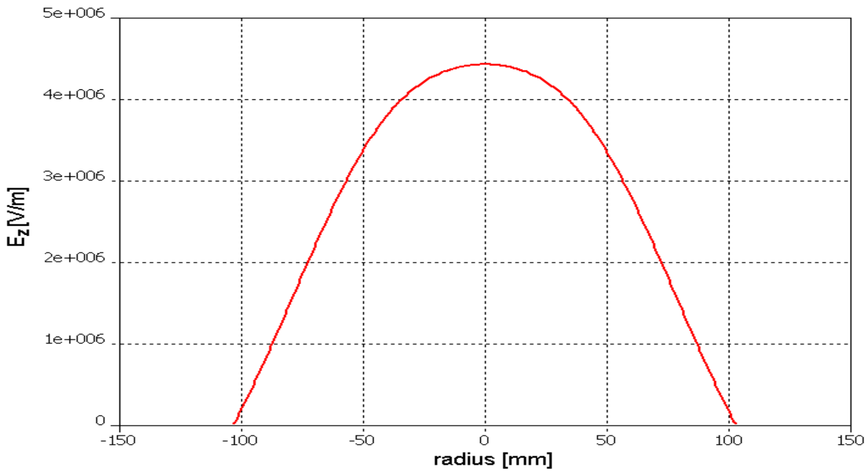
Magnetic field:



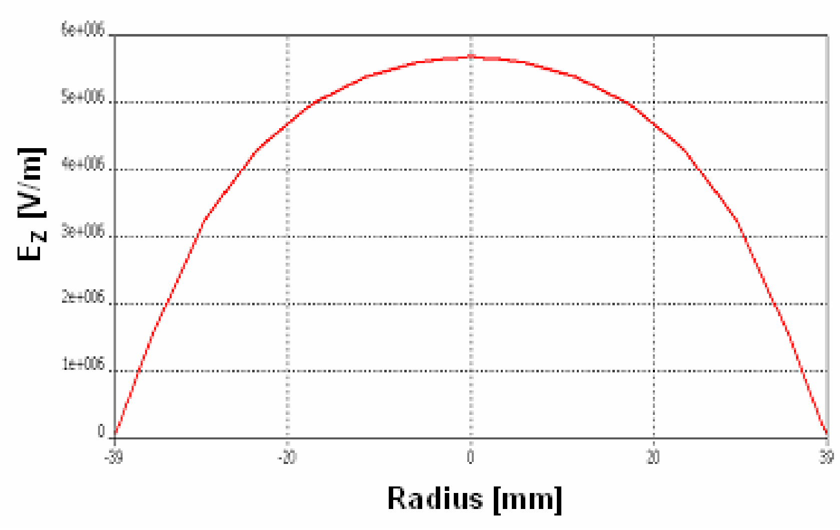
- Monopole mode, if excited, causes energy modulation and if the beam is displaced off axis, interacts with the magnetic field and with the radial electric field component.

- Can be measured with a *z*-oriented needle on iris planes; for measurement of radial electric field on equator planes one needs a disk or sphere. With existing mechanical setup only iris planes were measured.

TM_{010}, E-field on equator and iris planes



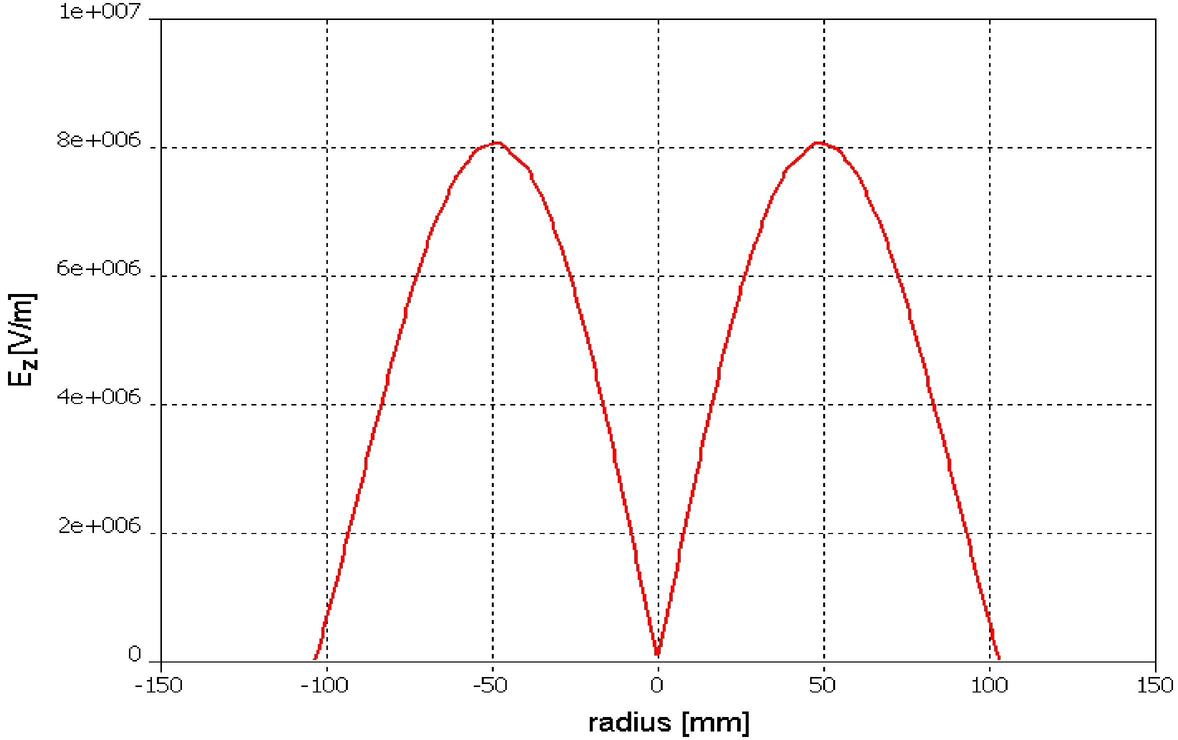
Equator plane



Iris plane

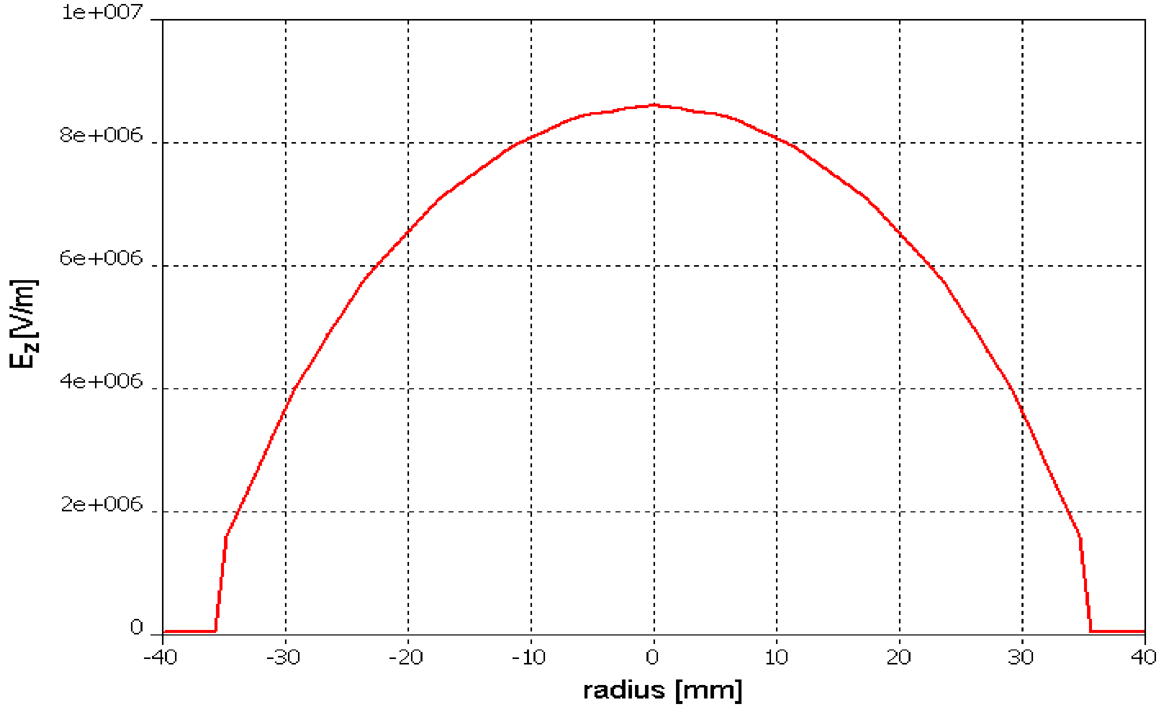
On the equator planes only the top of the curve can be taken, because the transversal movement of the bead is limited by iris radius. Due to very small detuning variation over the scanned radius the results are noisy (loaded by random error) and 10 measurements have to be averaged in order to obtain required precision. The curve on iris planes can be taken almost completely, so the results are less noisy and fewer (3) measurements have to be averaged.

TM_{110}, E-field, equator plane



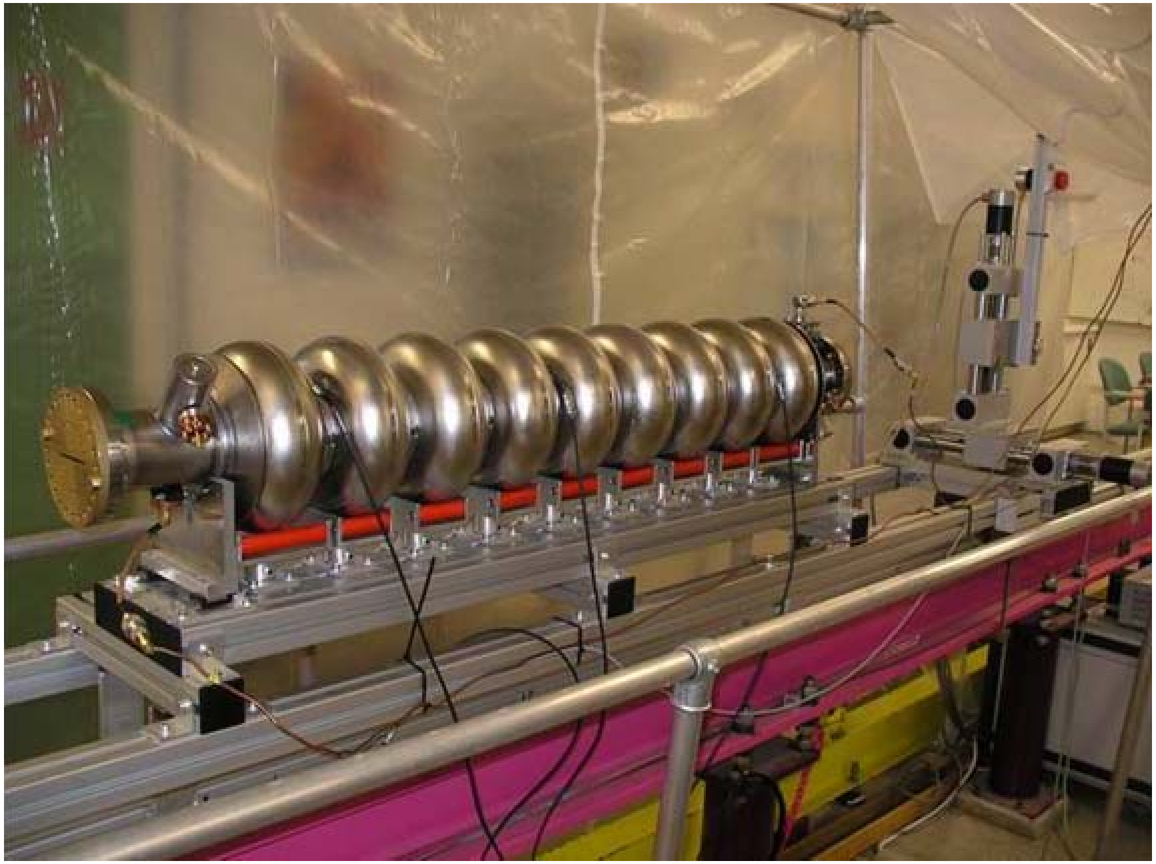
Also here the transversal movement of the bead is limited by iris radius, but presence of sharp minimum makes this measurement much less noisy as in case of the TM_{010} modes. Averaging of 3 measurements is sufficient.

TM_{011}, E-field, iris plane



The bead scans almost the whole field profile and the noise level is very low. Averaging of 3 measurements is sufficient.

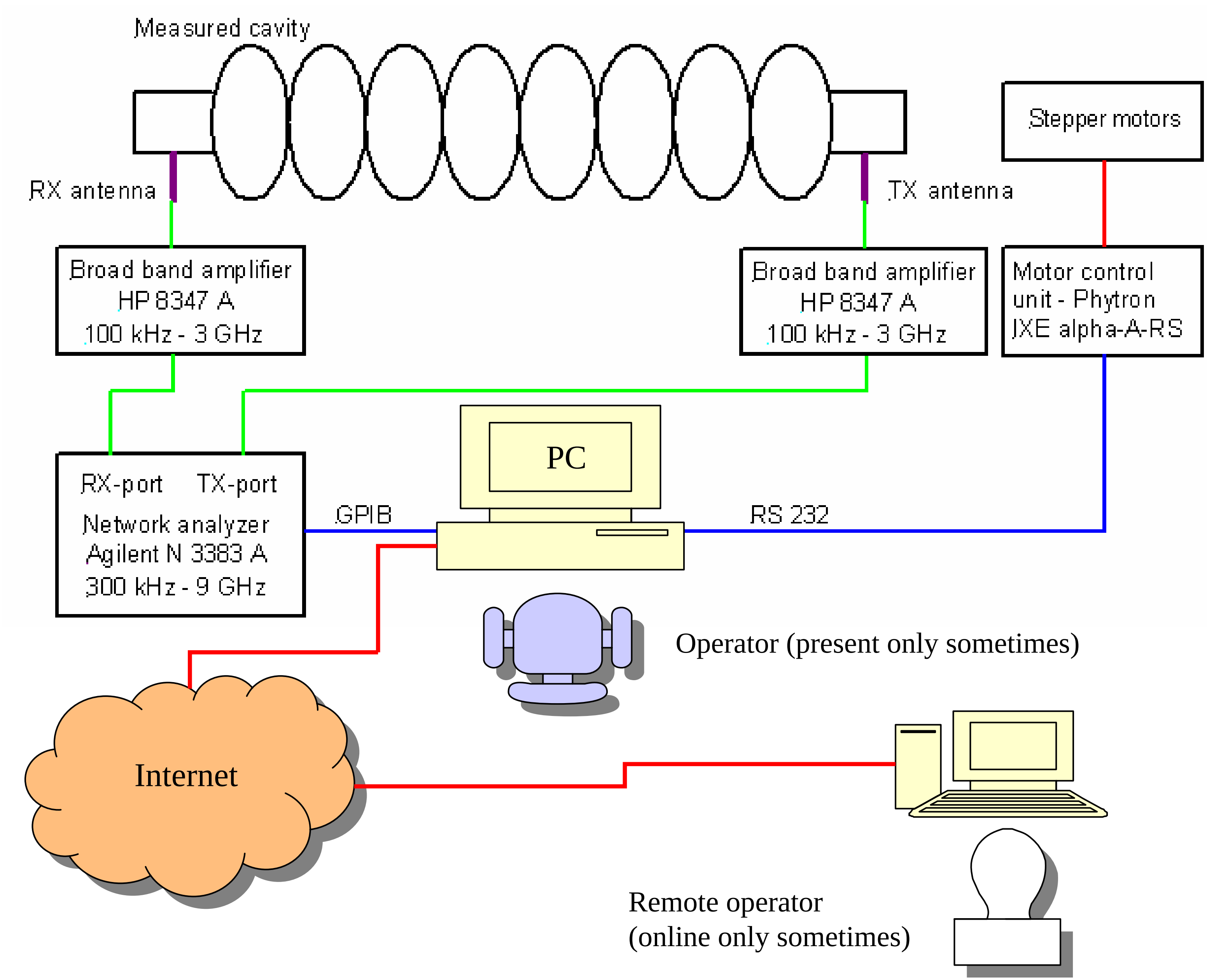
Mechanical setup



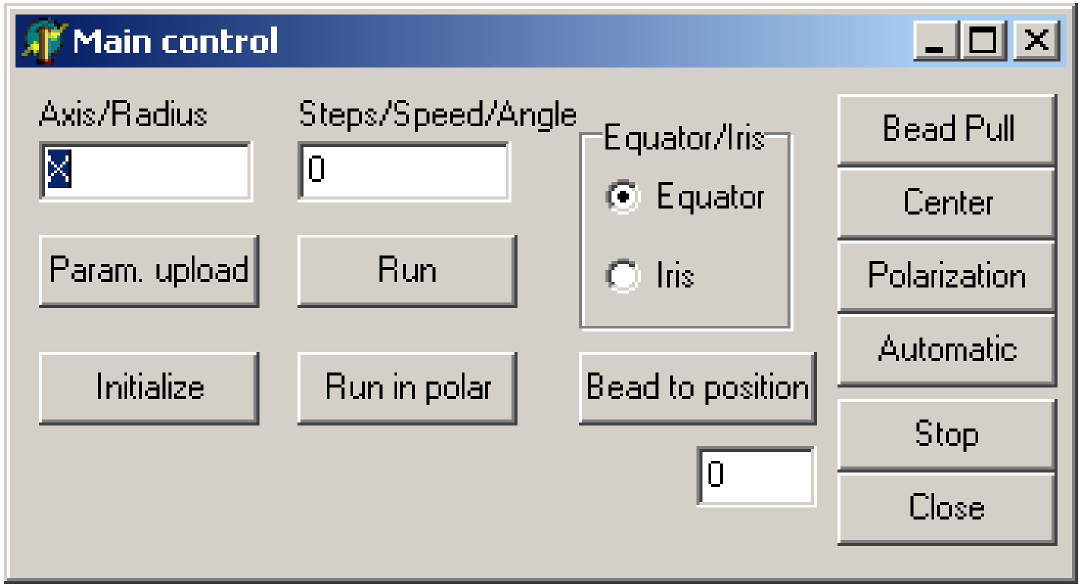
Cavity under measurement

Detail of linear transmissions

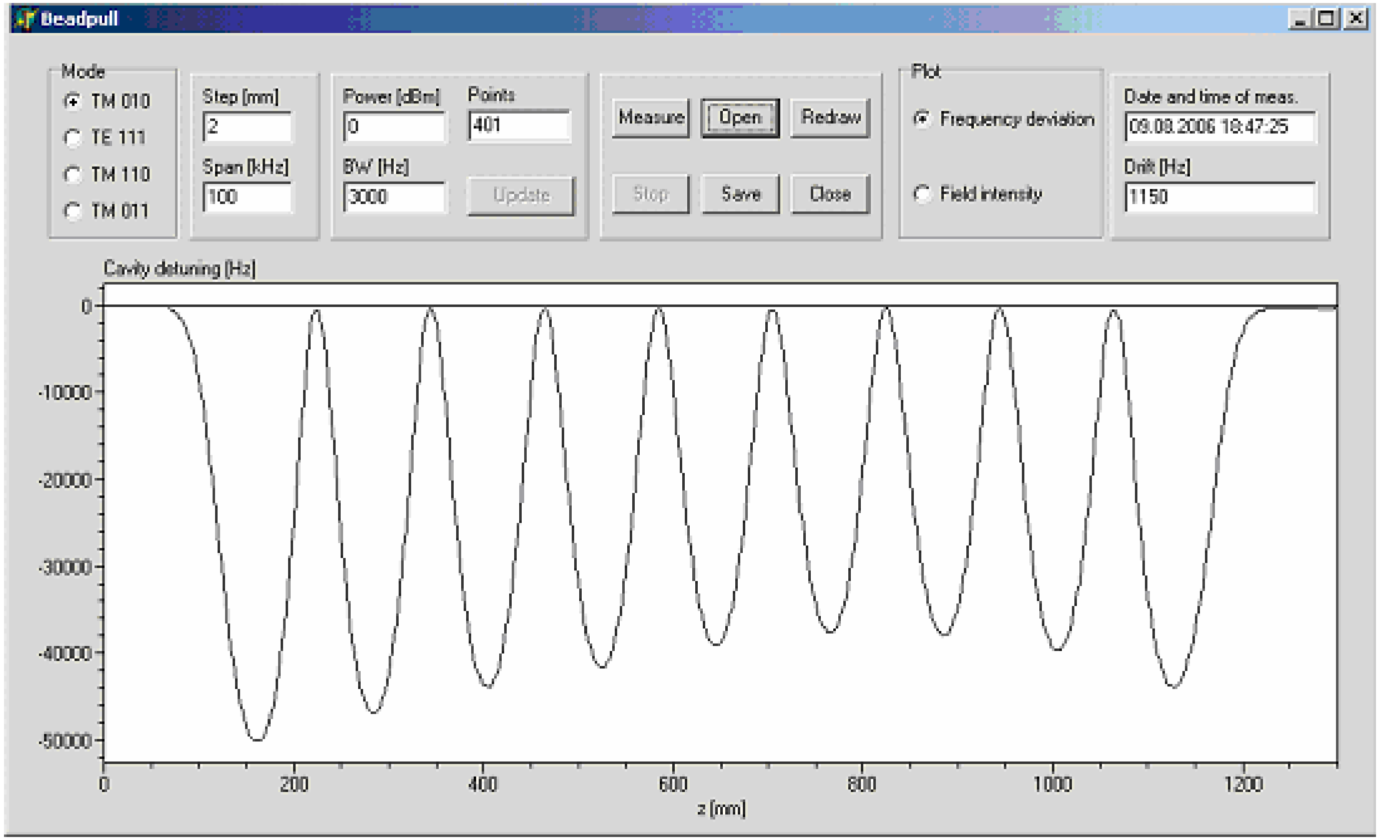
Instrumentation



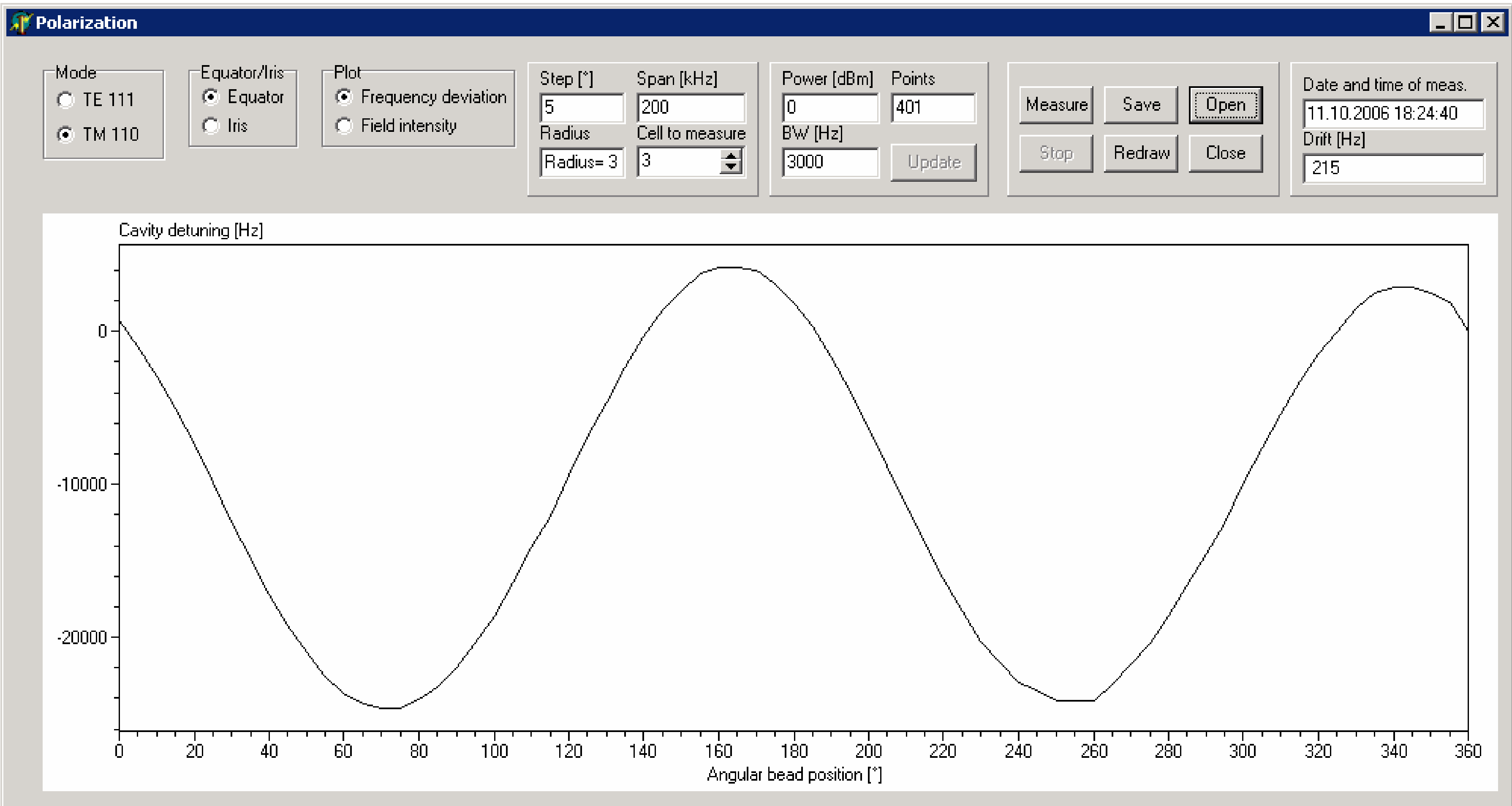
Software – main control subprogram



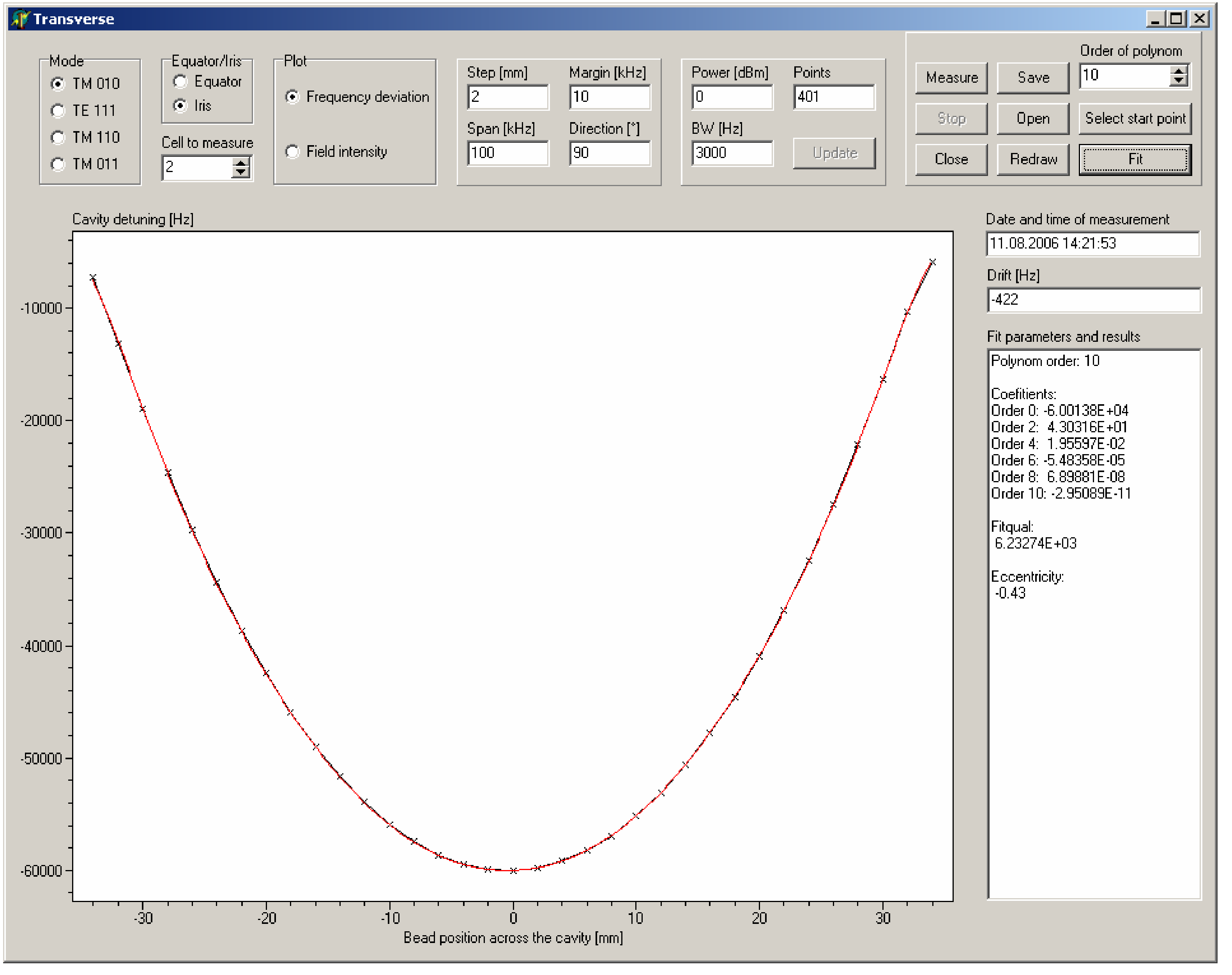
Software – beadpull subprogram



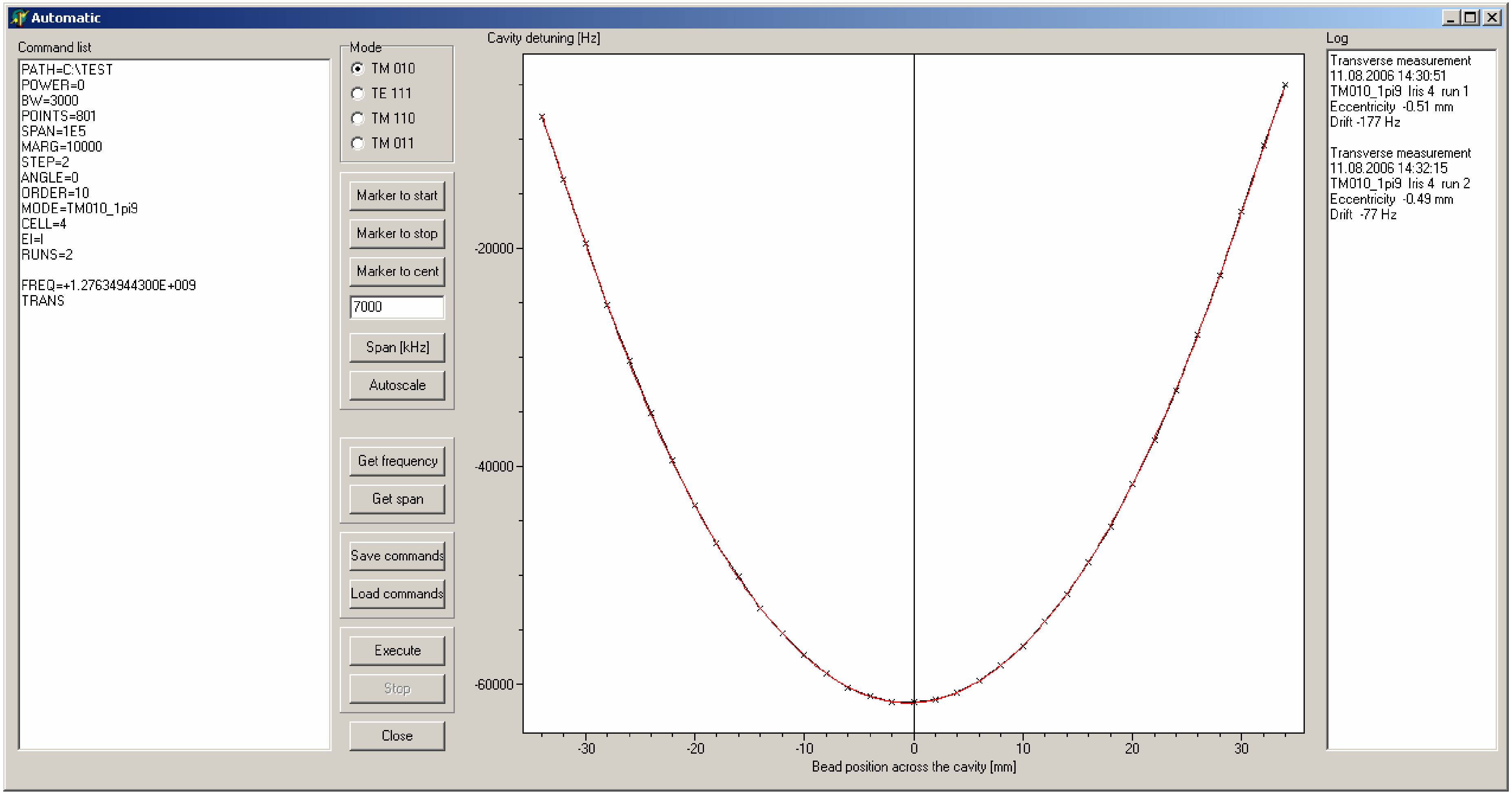
Software – polarization angle measurement subprogram



Software – transverse measurement subprogram

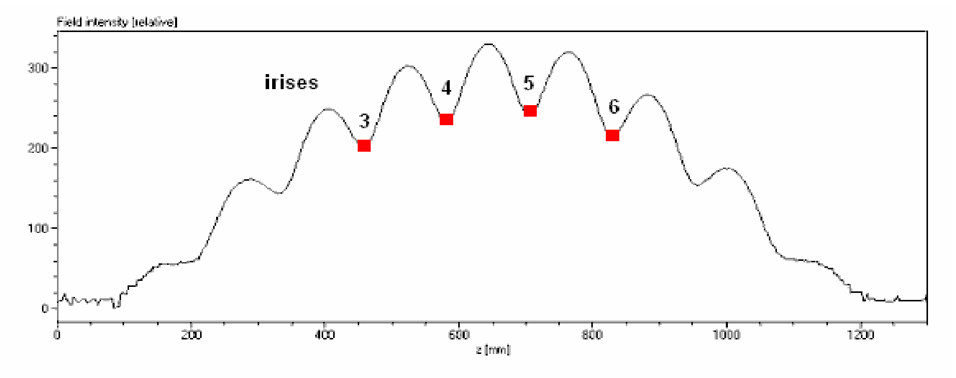


Software – automatic measurement subprogram

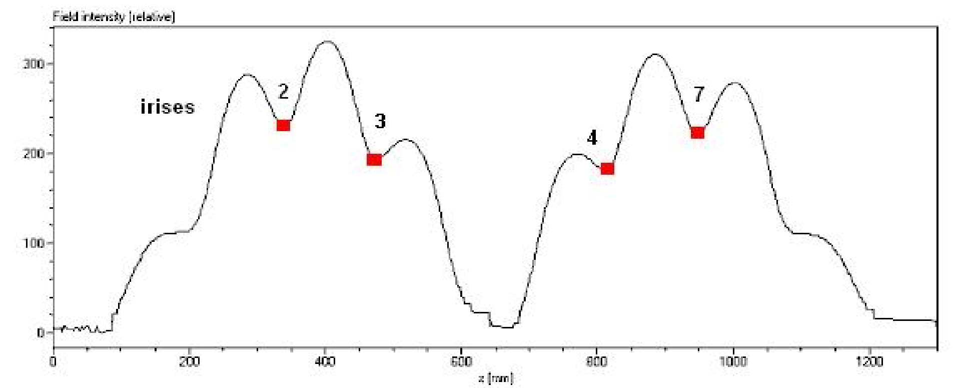


Cu cavity, modes of TM_{010} passband suitable for iris measurements

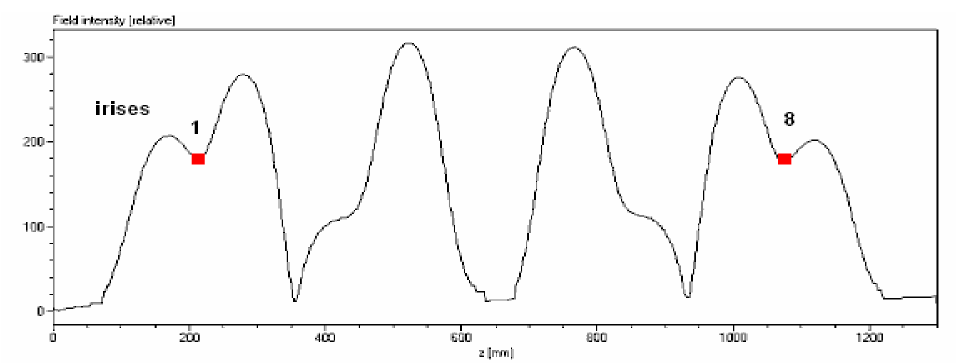
Suitable irises for given modes are red marked - the electric lines of force pass the iris planes continuously and the electric field intensities in the adjacent cells are not too different.



$\pi/9$

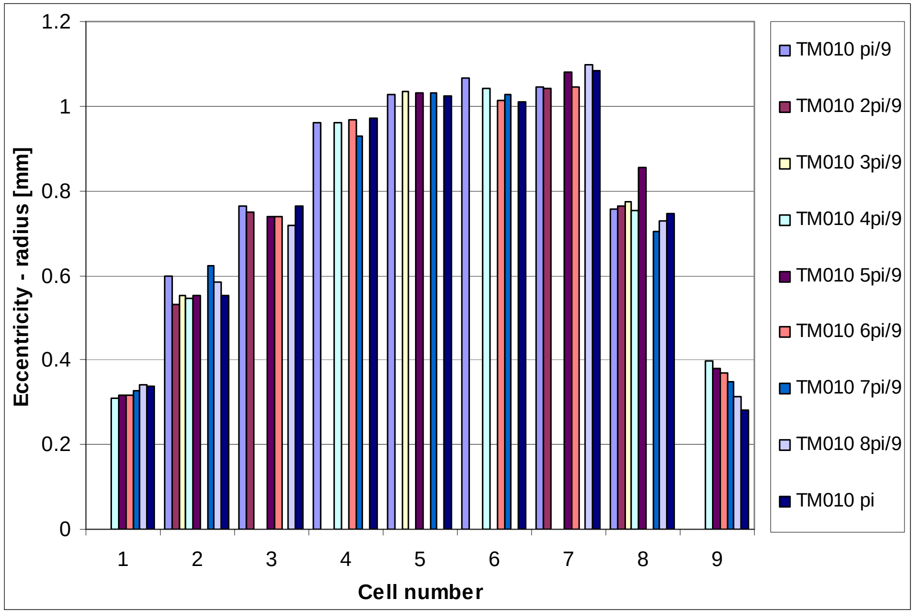


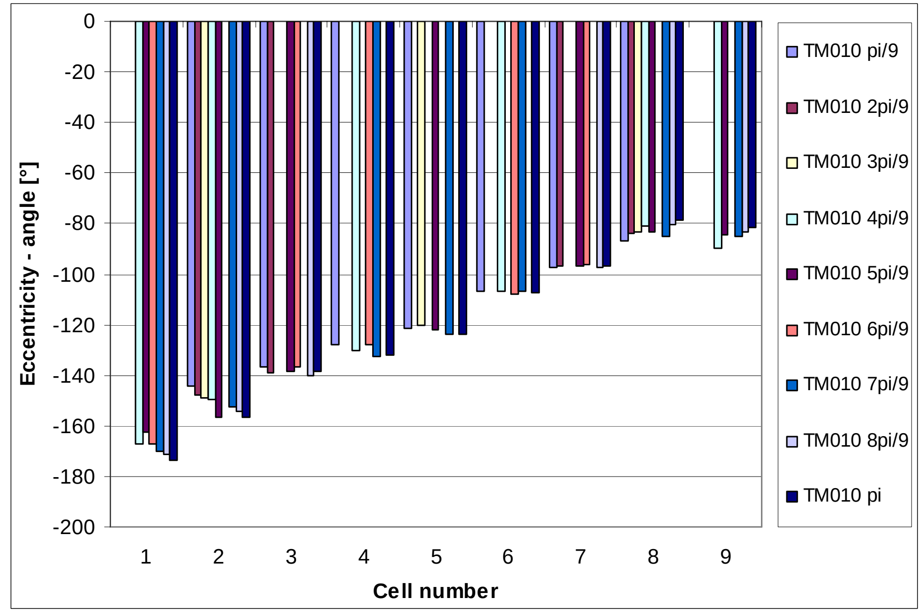
$2\pi/9$

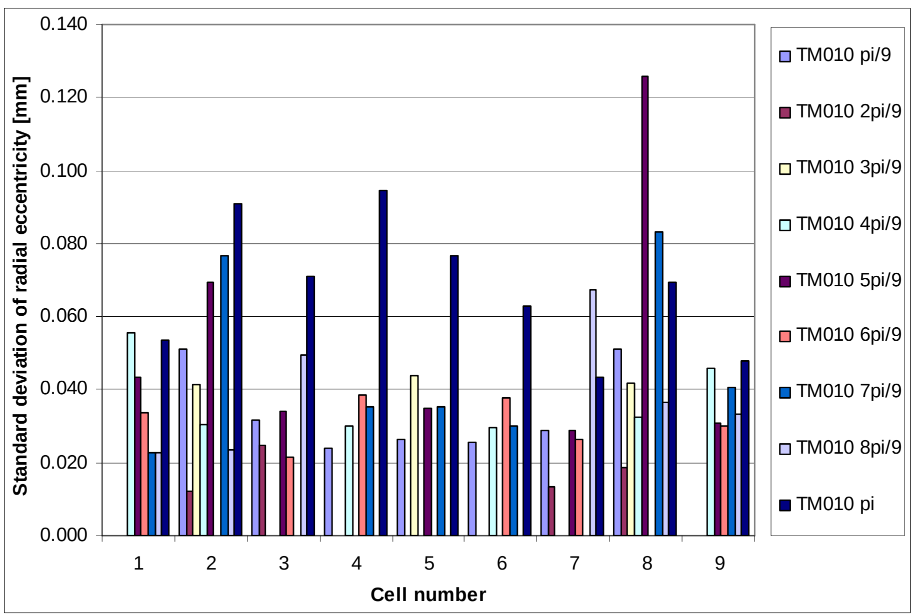


$4\pi/9$

Cu cavity, TM_{010} modes, equators

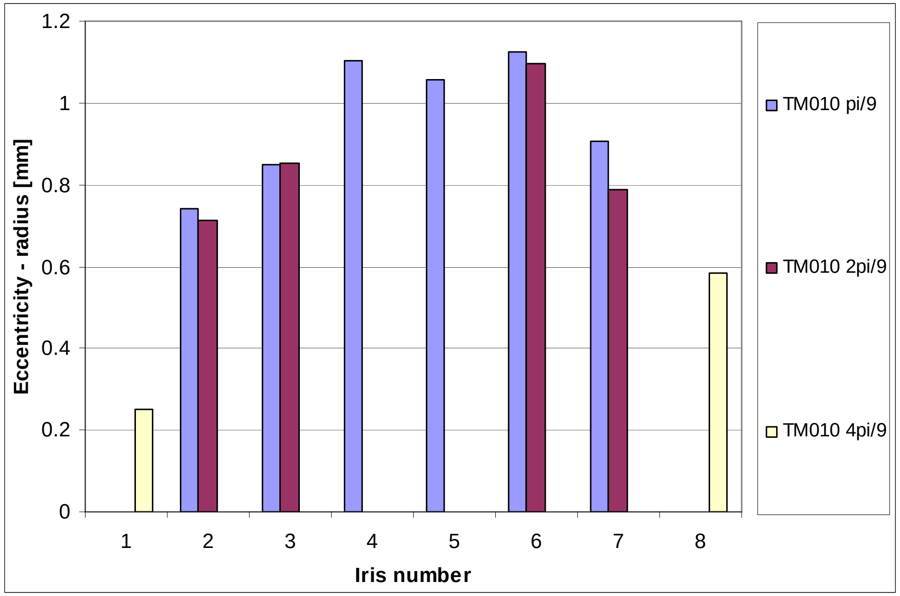


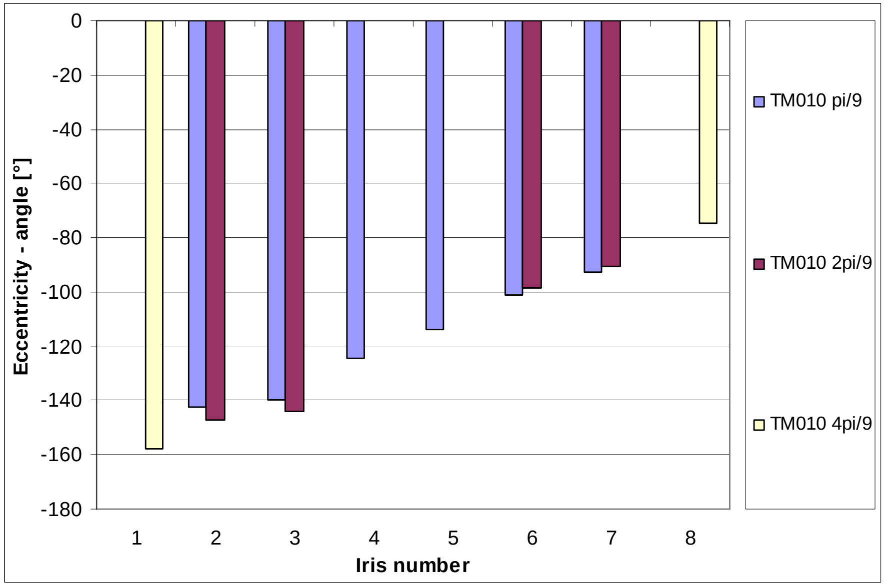


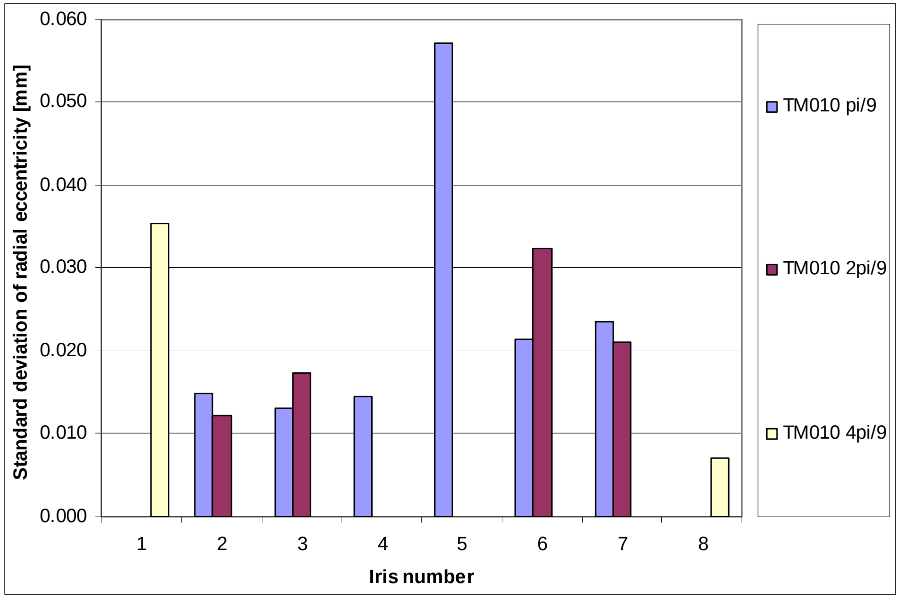


The differences between eccentricity of modes in the same cell are below the measurement error – it means that all modes of the TM_{010} passband have, in respect to available precision, the same electrical eccentricity. This result proves that the deformation of cavity walls (asymmetry) is negligible, although the cavity is strongly deflected.

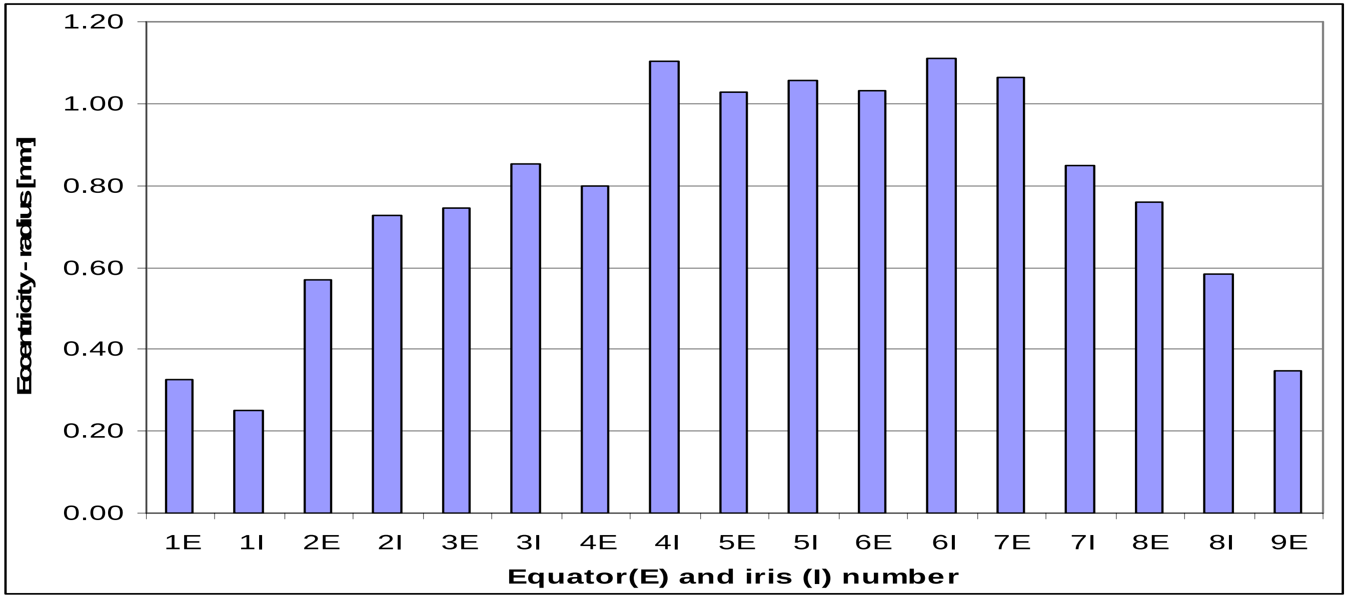
Cu cavity, TM_{010} modes, irises

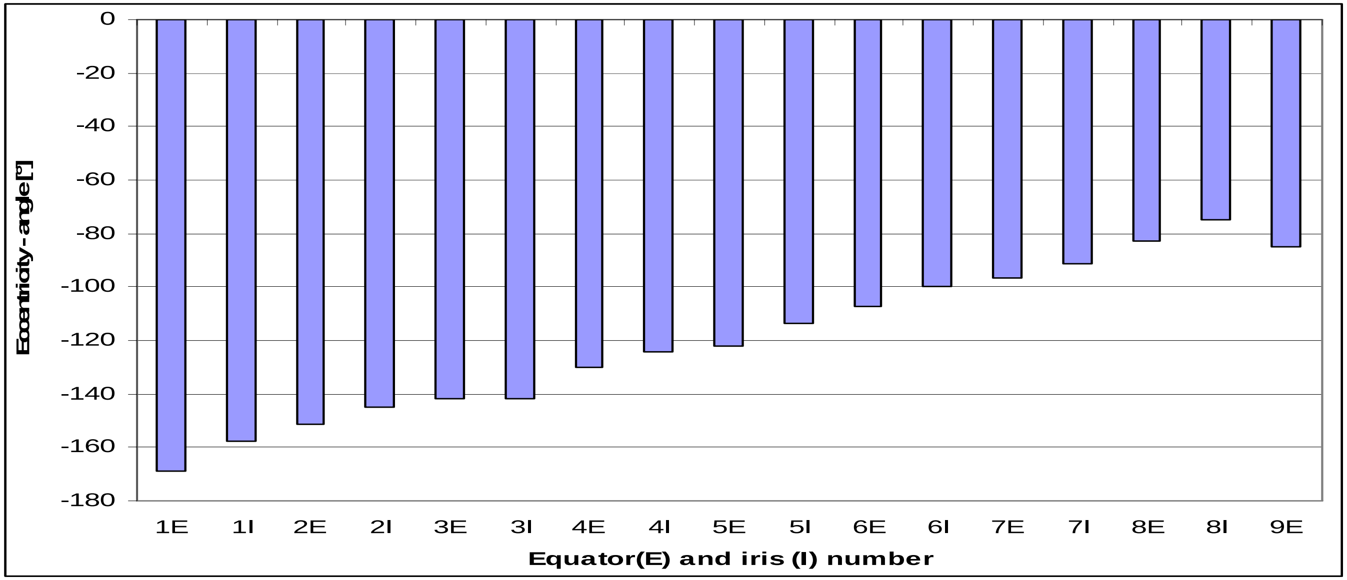






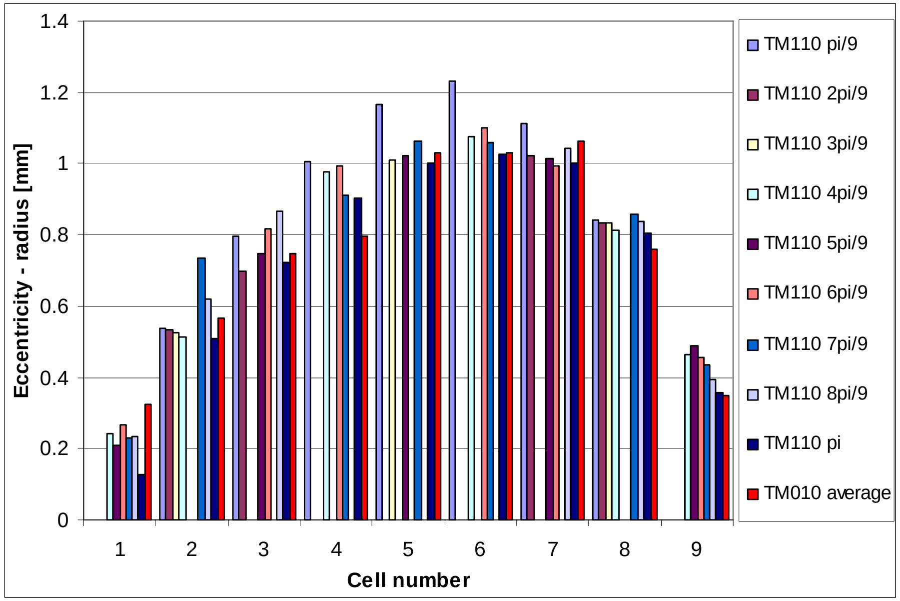
Cu cavity, TM_{010} – comparison between equators and irises

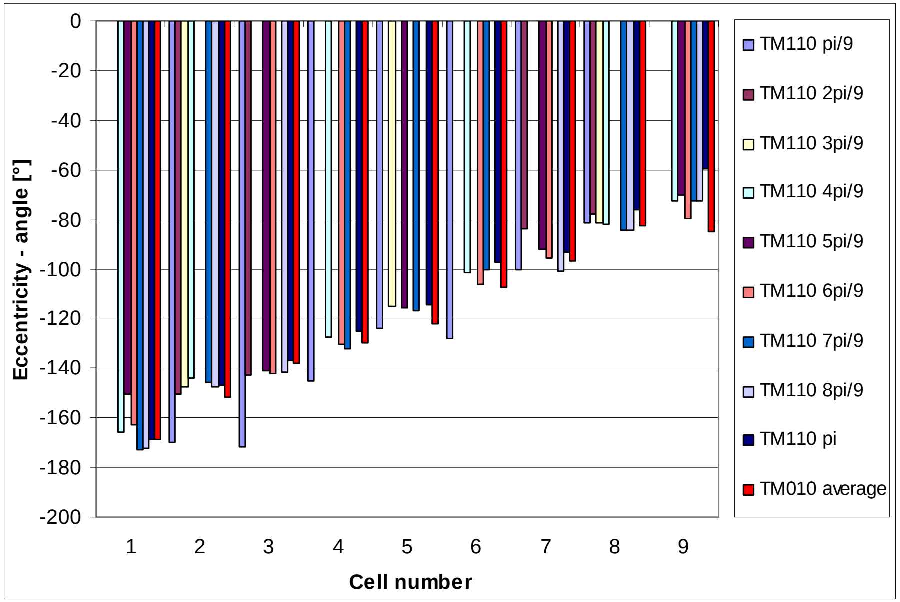


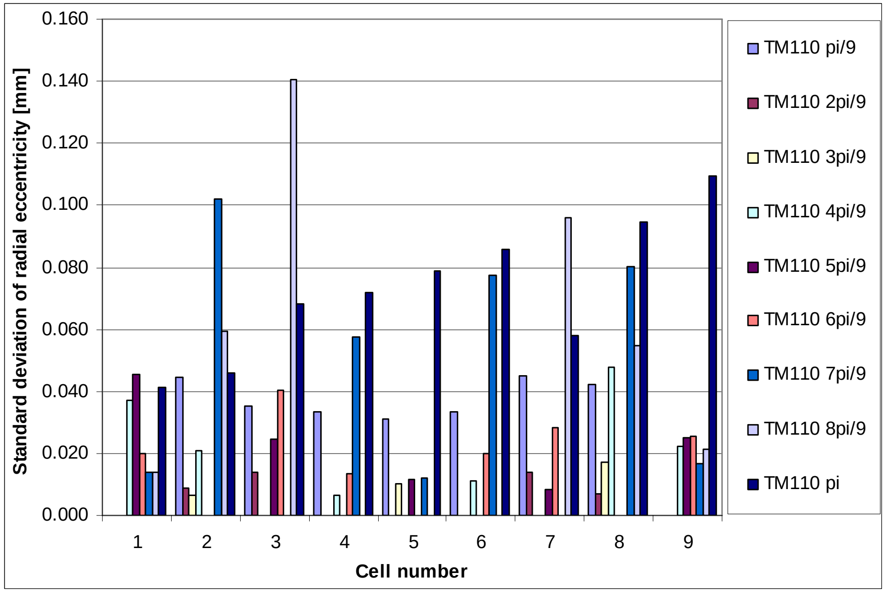


Electrical eccentricities of irises follow the electrical eccentricities of equators with good precision. For less demanding purposes the iris measurement could replace time consuming measurement on equator planes.

Cu cavity, TM_{110} modes, equators

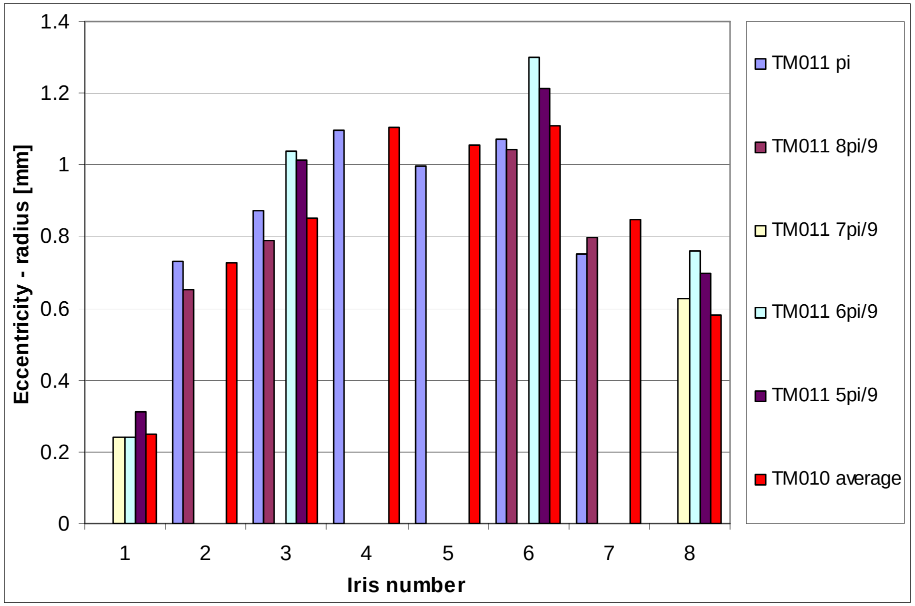


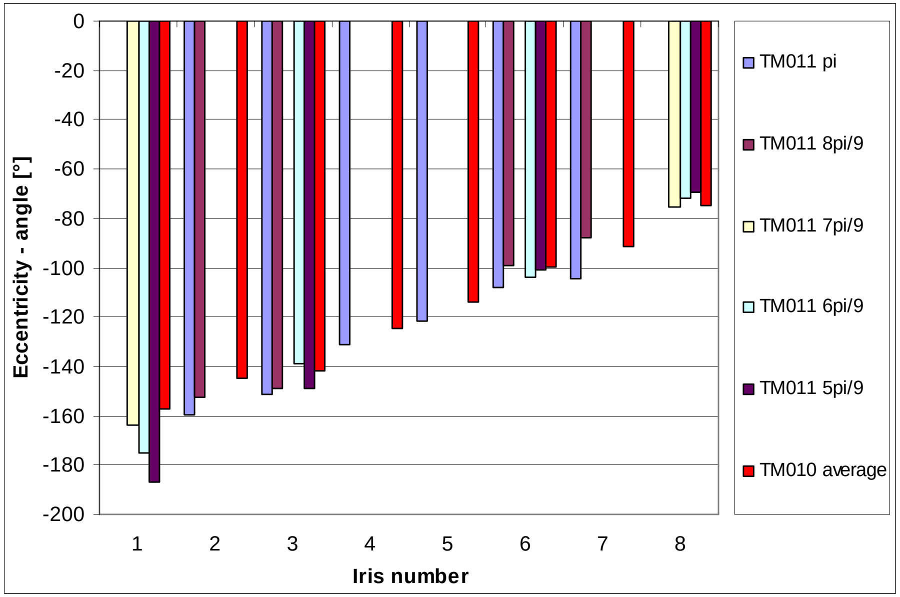


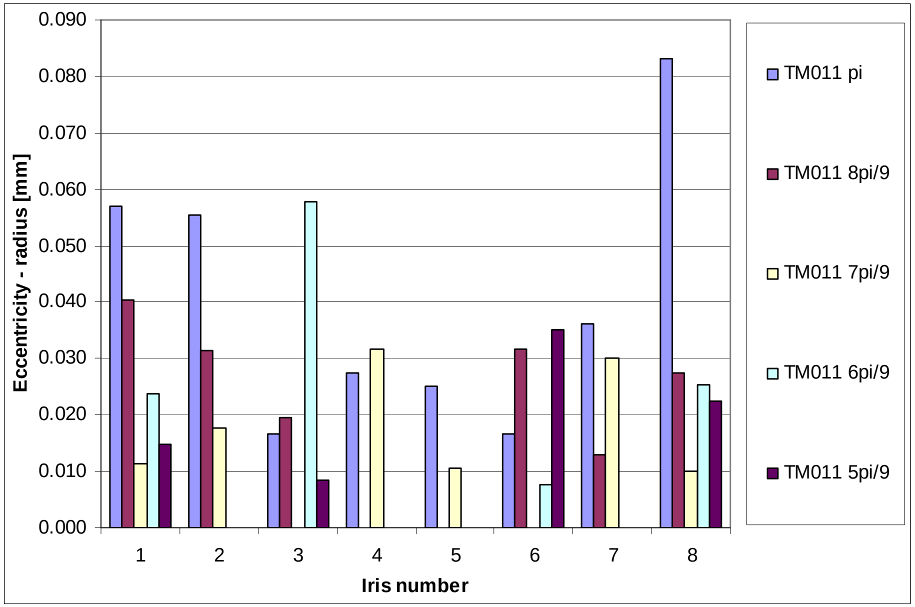


Differences between TM_{110} modes and between them and the average of all TM_{010} modes (red bars) are more significant than within the TM_{010} passband. This indicates higher sensitivity of dipole modes even to small deformation of cavity walls.

Cu cavity, TM_{011} modes, irises

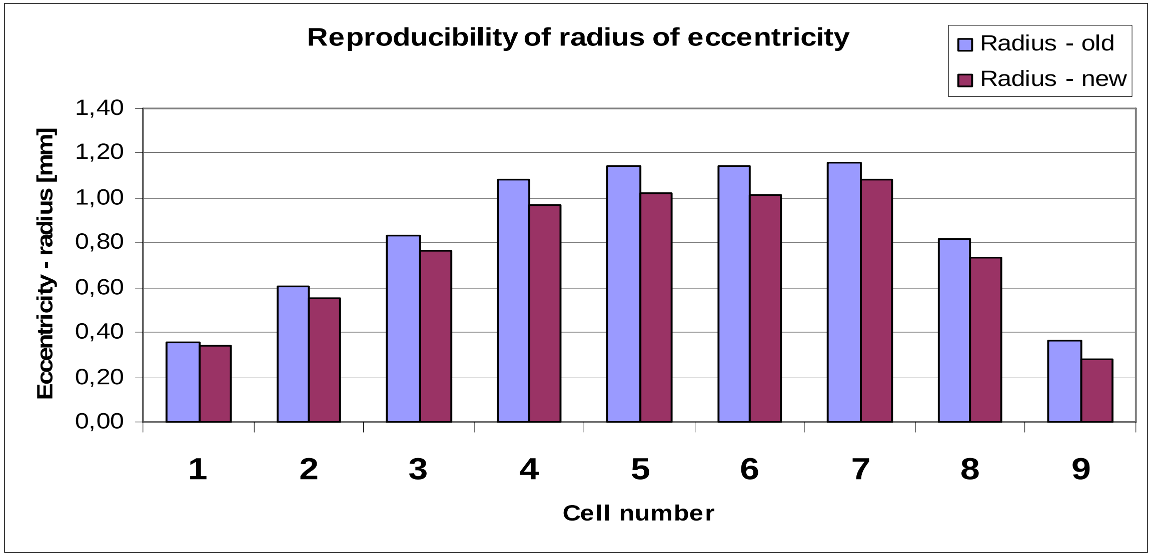


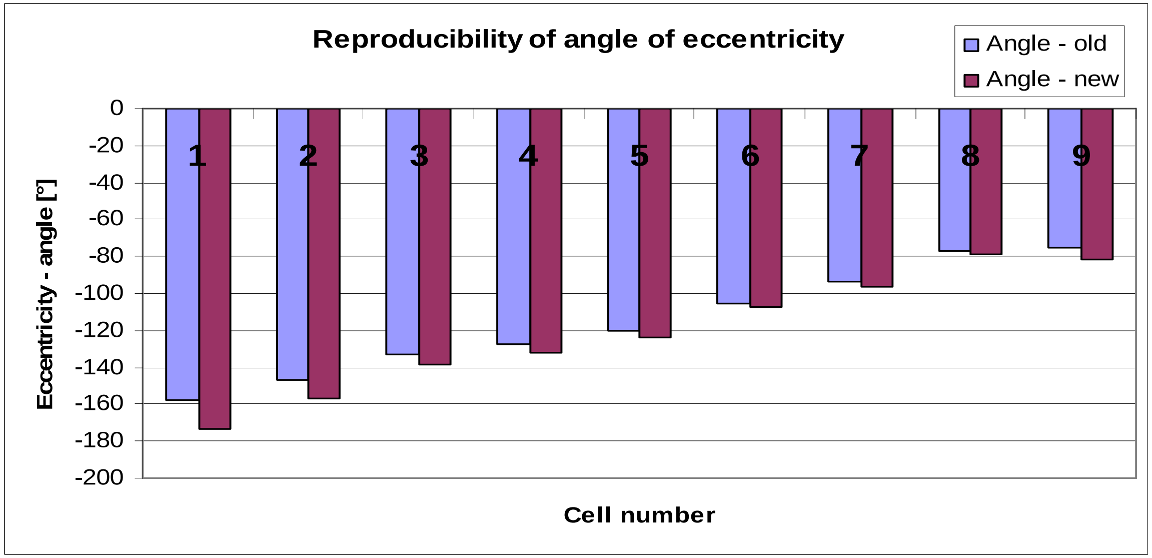




The spread of eccentricities of the TM_{011} modes are also bigger than within the TM_{010} passband. This can be caused not only by cell asymmetry but also by beam pipe imperfection – the coupling between end cells and beam pipes and between adjacent cells at the TM_{011} resonant frequencies is significant.

Reproducibility (Cu cavity, mode TM_{010}-π)





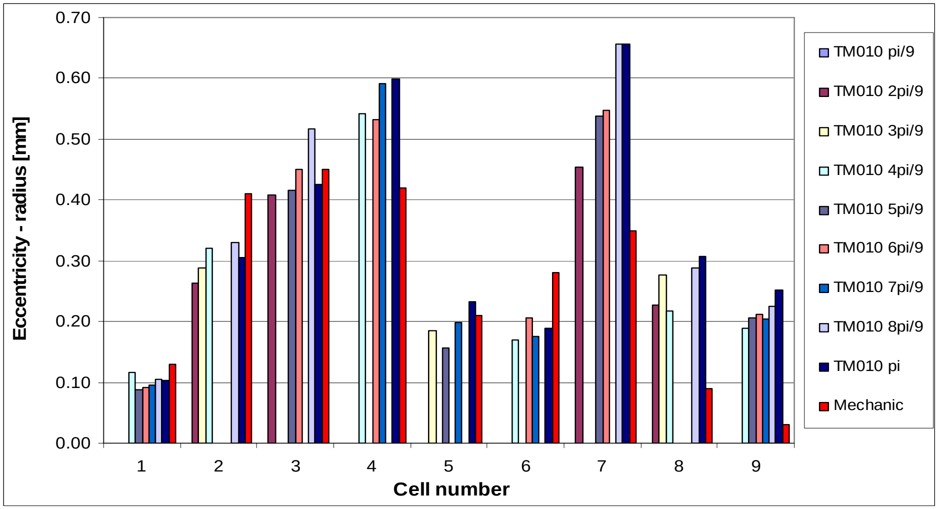
Old: September 9-th 2006

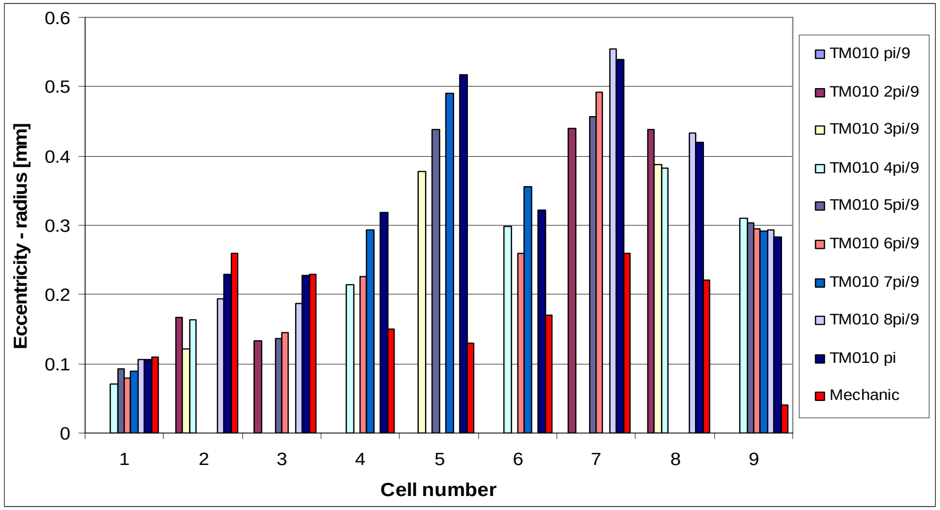
New: October 19-th 2006

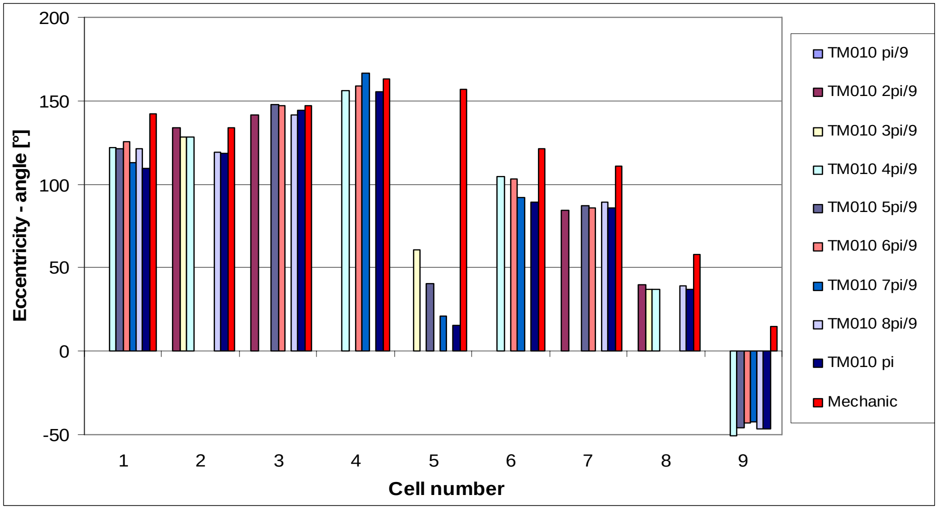
Z93 cavity, TM_{010} modes, equators

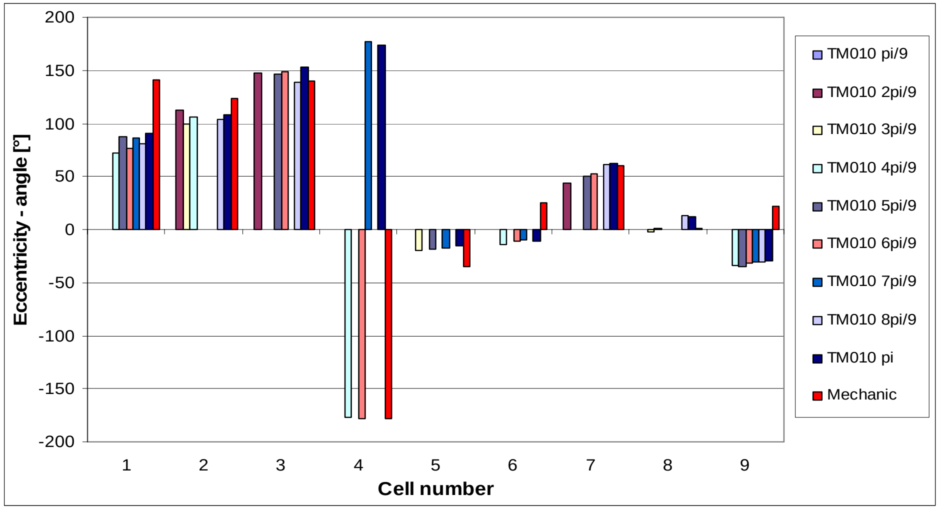
Coarse tuned

Finally tuned





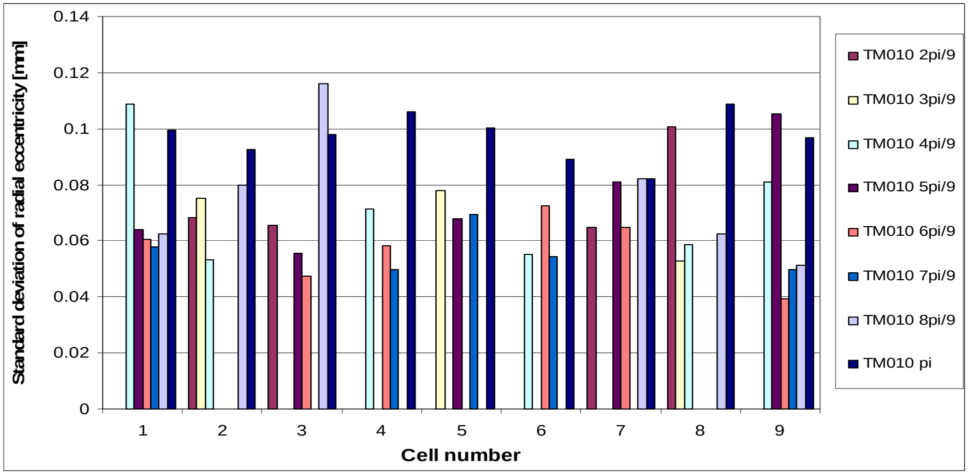




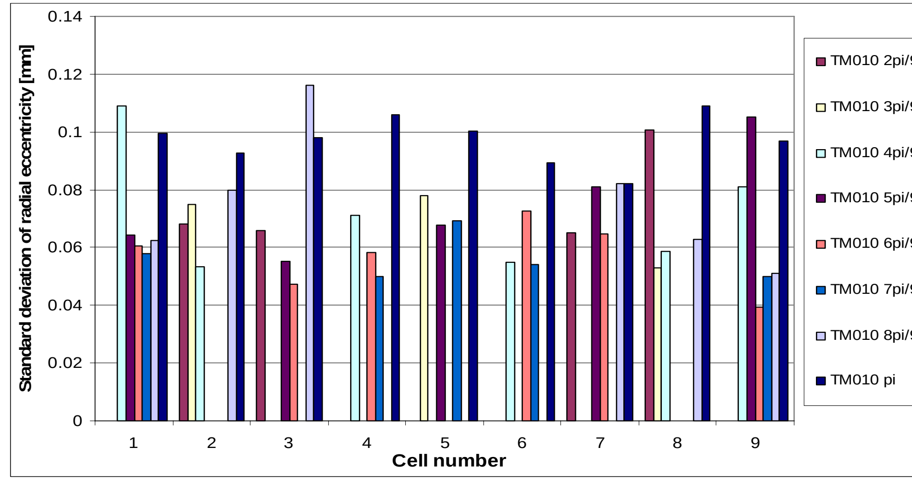
- Bigger spread of electrical eccentricities (in comparison to the Cu cavity) indicates deformations of cells
- Please note that minimization of geometrical eccentricity does not guarantee minimization of electrical eccentricity (see cells 5 and 6)

Z93 cavity, TM_{010} modes, equators

Coarse tuned



Finally tuned



Electrical axis of the accelerating TM_{010}-π mode (minimum sum of quadratic deviations from the electric centers of equator planes of all cells [6]):

Cavity state	Equator plane 1 crossing [mm]	Equator plane 9 crossing [mm]	Tilt [°]
Pre-tuned	(-0.265, 0.238)	(0.181, 0.155)	0.028
Final tuned	(-0.139, 0.125)	(0.392, 0.028)	0.033

Conclusions

- The electrical eccentricity measurement using small perturbation method was tested and found to be a very useful and comfortable technique, which can efficiently support mechanical measurement which has very weak coupling to the real electromagnetic field pattern inside the cavity
- The disadvantage is time-consuming measurement (each run takes approximately 2 minutes and several measurements for averaging must be performed) and extreme temperature sensitivity. These disadvantages of the prototype equipment can be improved in the future.
- Several modes were measured and compared. The centers of different modes are equal only in case of perfectly rotation symmetric cells without deformation.
- All considered modes could be measured only on the copper model cavity. At the niobium cavities due to fixed port positions it was not possible to couple some modes optimally. Due to this reason and due to the HOM couplers resonance at the top of the TM_{011} passband only measurement of the TM_{010} passband on equator planes gave reasonable results.
- Existing equipment allows measurements only with very light bead (needle). Using of disks, spheres, ceramic beads etc. requires moving of cavity and keeping the thread steady to avoid vibrations of the bead.
- The results indicate deformations of niobium cells. Similar results were achieved also by the cavities A14 and Z110. The cells of the copper model are very precise.
- Measured differences between electrical eccentricities of different modes and geometrical eccentricities are below the 0.4 mm tolerance. This indicates sufficient precision of the mechanical measurement. In order to increase this precision it is recommended to perform one electrical eccentricity measurement at the accelerating mode of each cavity after cell alignment in means of fast geometrical eccentricity measurement. Then the calculated electrical axis (instead of geometrical axis) should be identified with the beam trajectory in the cryomodule. To inspect cell deformation the whole TM_{010} passband has to be measured. Due to the above described reasons investigation of higher order modes is only possible in model cavities with flexible coupling possibility.

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- *Guennadi Kreps* and *Wolf-Dietrich Möller* - for many useful practical proposals
- *Daniel Klinke* and *Hans-Bernhard Peters* - for mechanical design

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[5] Martin Nagl, DESY, private communication

[6] Martin Dohlus, DESY, private communication