Elettra Sincrotrone Trieste

R/Q cavity measurement

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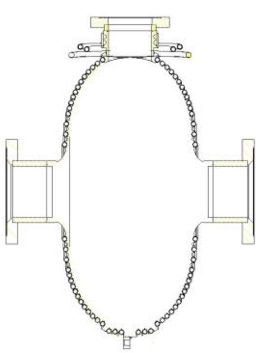
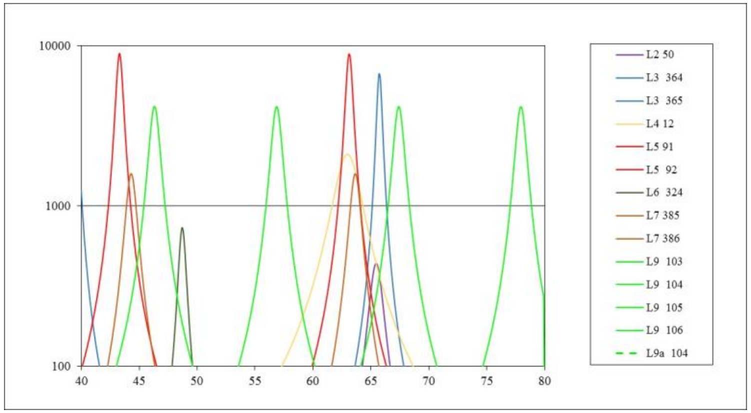
Motivation

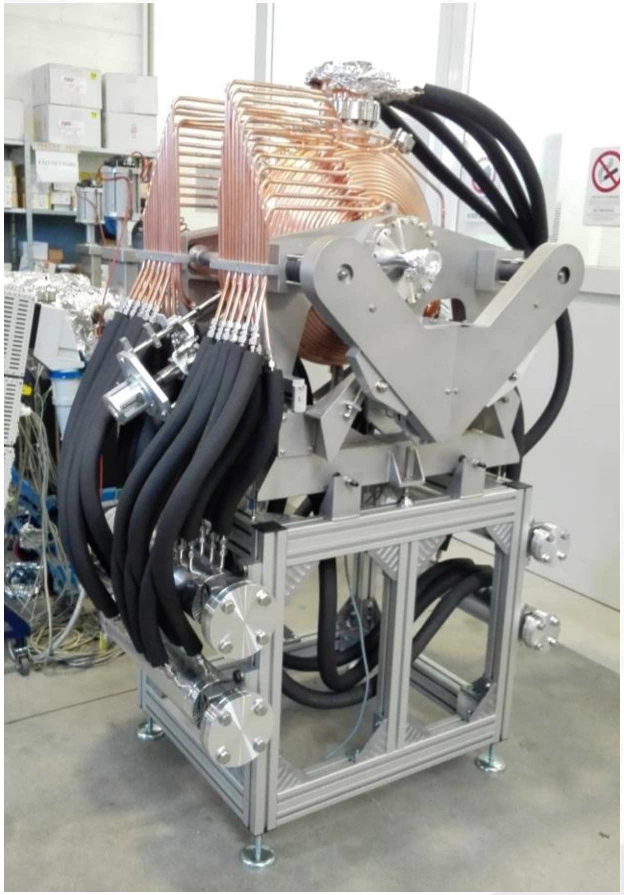
Complete R/Q measurement requested by Sesame (4 cavities @ 500 MHz delivered for the storage ring) and by RRCAT (1 cavity @ 506 MHz delivered to upgrade the Indus II ring).

- ✓ The Elettra cavity is a single cell, normal conducting resonant cavity that runs WITH NO DEDICATED HOM dumpers. The high Quality Factor of each high order mode and the capability to fine adjust the cavity volume (that is the cavity reference temperature and the position of a plunger) give all the means to shift the HOM spectrum and avoid the beam instability driven by the cavity resonances.





Growth rate of the CBMs versus the reference temperature of cavity RF#2 from 40 ^{0}C to 80 ^{0} C



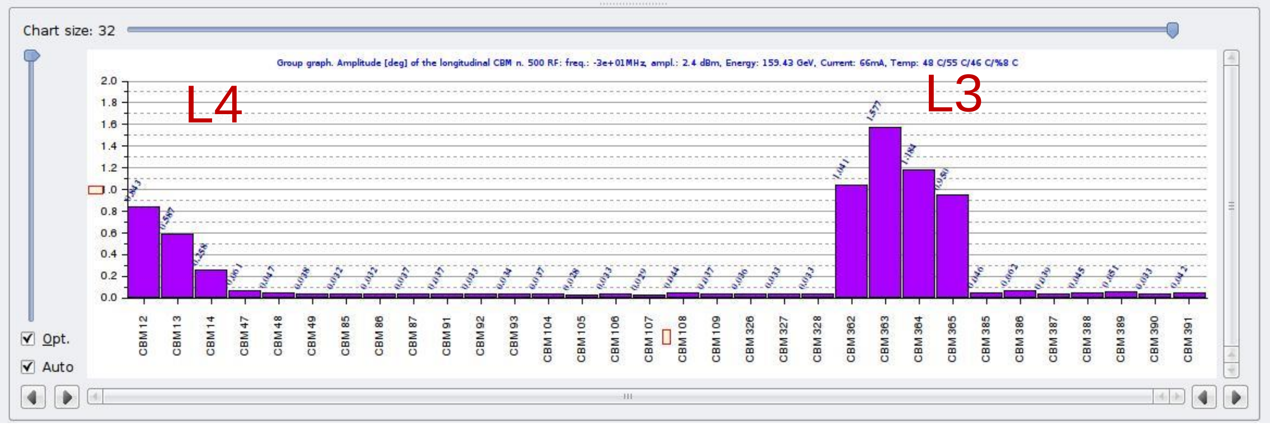
- ✓ Therefore the knowledge of the HOM parameters (Q, Shunt Impedance, Frequency) is of fundamental importance for the beam-cavity interaction study.

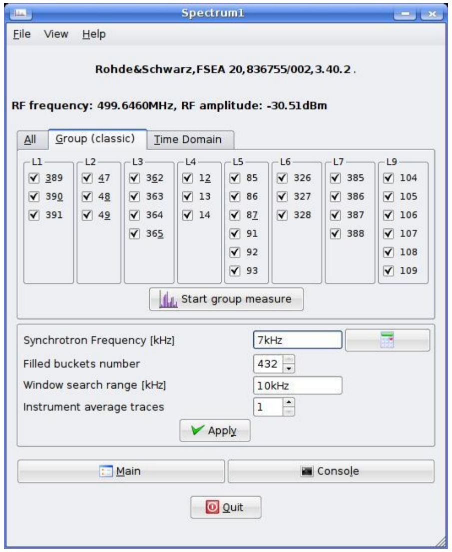
Elettra and Coupled Bunch Mode

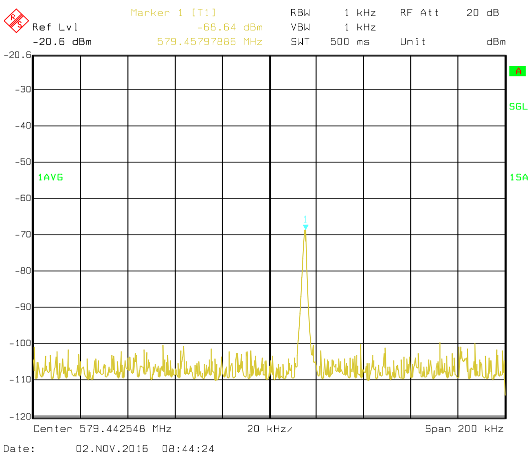
Example of slightly* UNSTABLE BEAM at ELETTRA. Instability measured from a beam button and driven by the cavity RF#2 namely

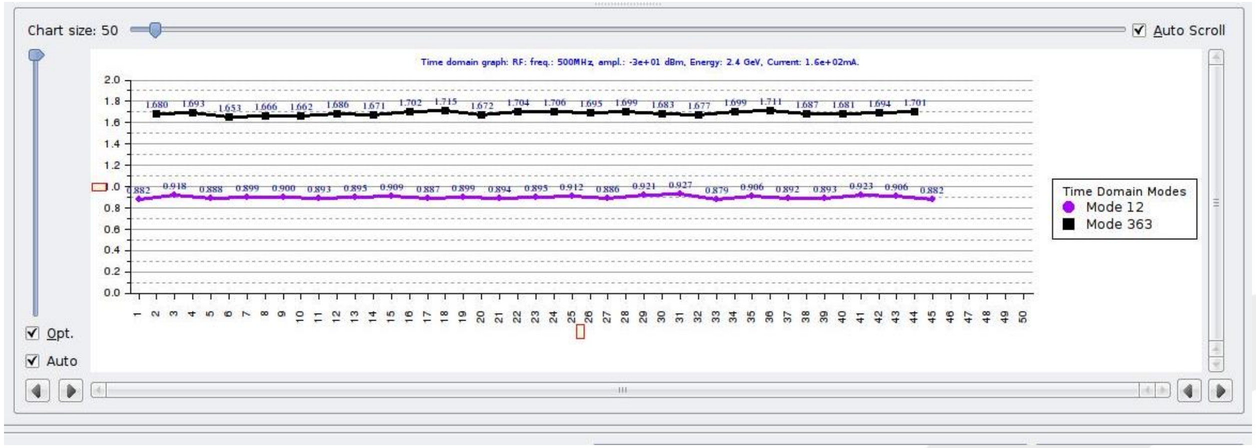
CBM 12 → **L3** 1419 MHz at -39.4 dB with respect to the 500 MHz

CBM 363 → **L4** 1512 MHz at -37.0 dB with respect to the 500 MHz





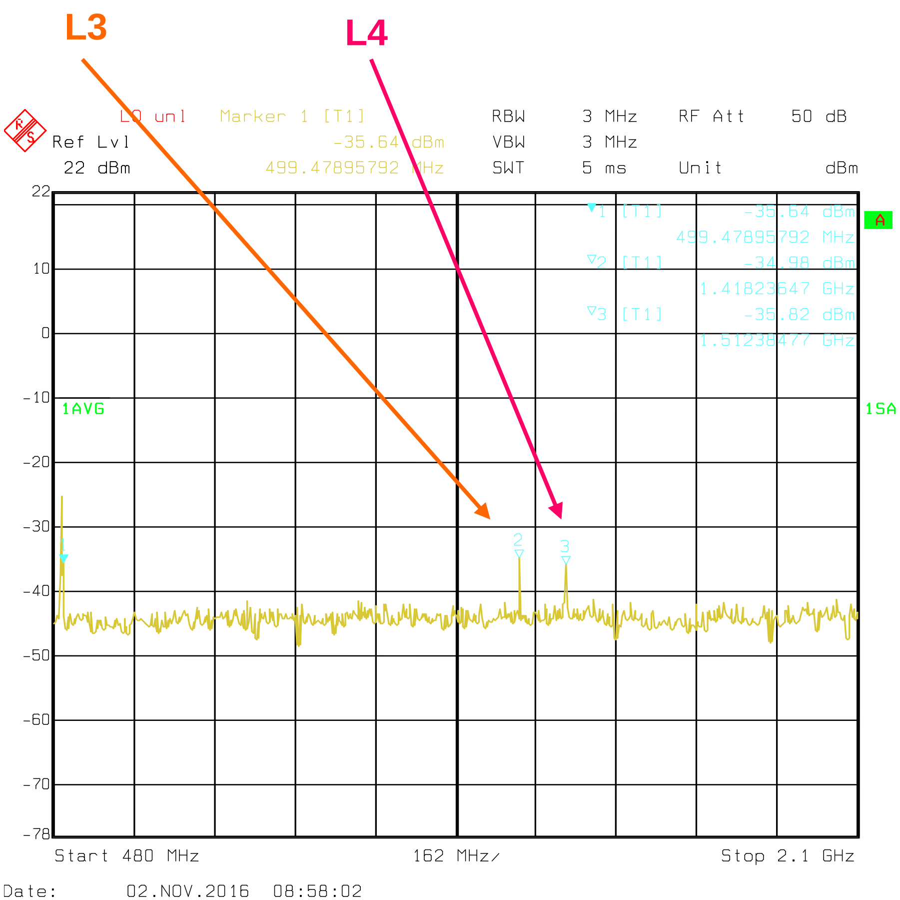




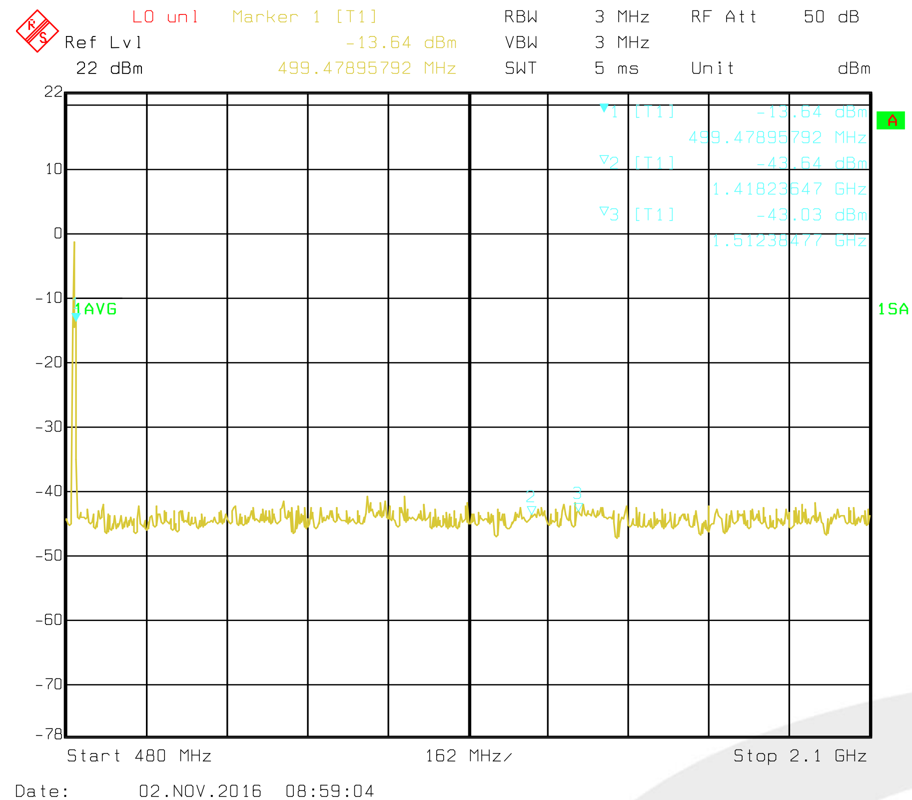
*slightly unstable: the instability is constant and with small amplitude so that it can be measured and the beam does not blow up!

Elettra and Coupled Bunch Mode

Frequency spectrum from 480 MHz to 2.1 GHz of the signal coming from the cavity RF#2 (source of instability) and cavity RF#9 (only noise, no HOM resonances)



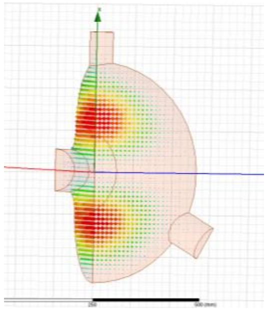
RF # 2



RF # 9

Elettra Cavity HOMs

- Any R/Q measurement shall start after the knowledge of the Elettra cavity HOMs main parameters.
- The longitudinal R′ and transverse R_T impedance due to the TM and TE dipole modes seen by the beam is evaluated with HFSS*



	f [MHz]	Qo-unload	(R/Q)' [Ω]	R' [MΩ]
L0	503.4	43000	79.0	3.40
L1	956.9	46000	29.2	1.34
L2	1062.8	57000	0.6	0.04
L3	1430.2	54000	4.4	0.24
L4	1524.3	60000	4.0	0.24
L5	1607.3	64000	9.8	0.63
L6	1891.3	54000	0.3	0.01
L7	1960.3	80000	1.5	0.12
L8	2069.6	51000	0.0	0.00
L9	2136.6	85000	7.5	0.64

Circular WG cut off TM_{01} = 2.29 GHz

	f [MHz]	Qo-unload	(R/Q)' [Ω] off-axis	R_T [kΩ/m]
D1	747.6	49000	5.04	3867
D2	750.6	48000	16.40	12381
D3	1122.8	43000	12.14	12283
D4	1229.9	93000	0.07	178
D5	1249.6	47000	4.20	5169
D6	1312.8	61000	0.29	485
D7	1548.1	86000	0.00	0
D8	1652.4	62000	2.07	4443
D9	1728.6	71000	1.73	4457
D10	1730.2	76000	0.41	1135

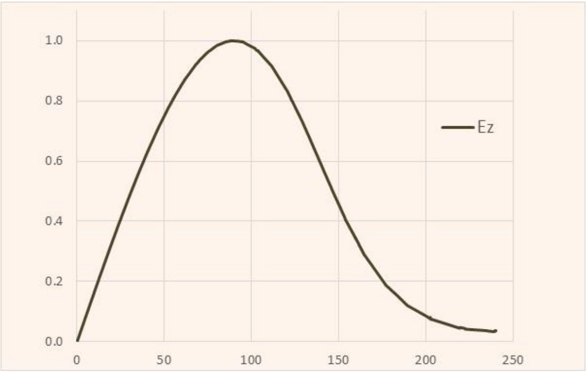
Circular WG cut off TE_{11} = 1.76 GHz

* HFSS coarse simulation with ¼ cavity shape, ~250K mesh points, CPU time 16 hours

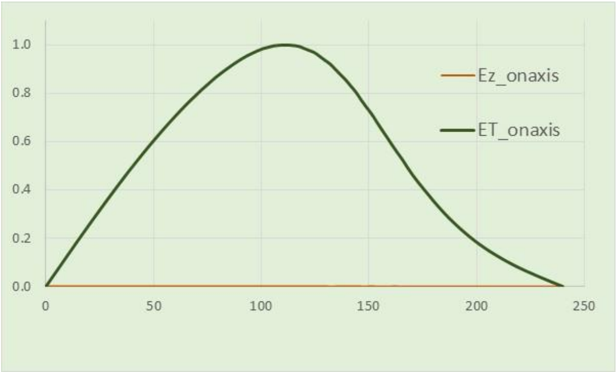
Elettra Cavity HOMs

- The numerical field plot along the beam path shall be used as a guideline to perform the measures to check for the fields properties (symmetries, number of nodes and so on…).
- These plots are obtained form HFSS: half cavity cell; vertical axis: normalized & arbitrary unit

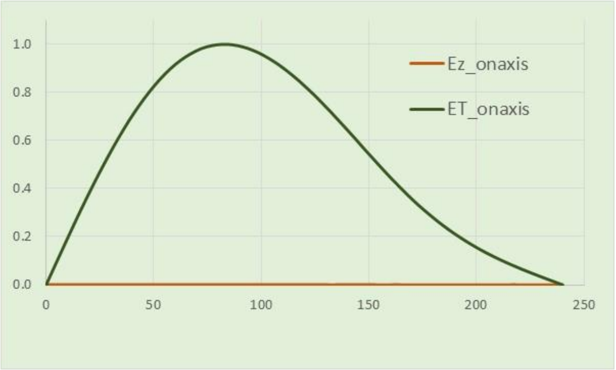
L3 1430 MHz (TM-like, odd)



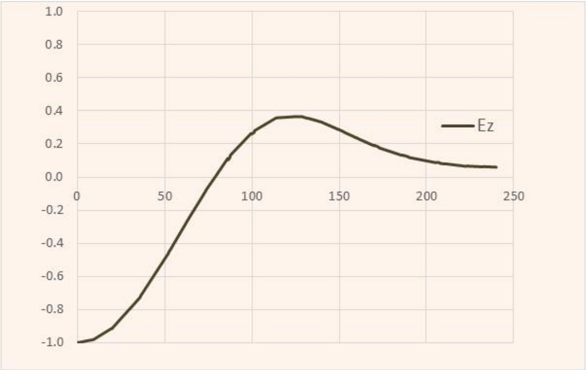
D2 750 MHz (TE-like)



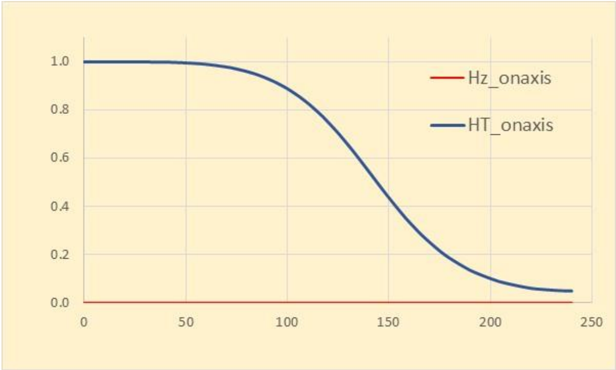
D5 1250 MHz (TE-like)



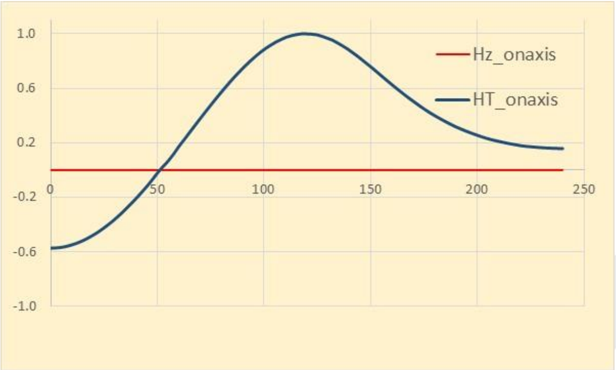
L7 1960 MHz (TM-like, even)



D2 750 MHz (TE-like)



D5 1250 MHz (TE-like)



* HFSS coarse simulation with ¼ cavity shape, ~250K mesh points, CPU time 16 hours

Perturbation Theory

Frequency shift due to the perturbing object along the beam path [1,2]:

$$\frac{\omega_0 - \omega_p}{\omega_0} = -\frac{\tau}{4W}\left[-(k_z^m \mu_0 H_z + k_\perp^m \mu_o H_\perp)H + (k_z^e \varepsilon_o E_z + k_\perp^e \varepsilon_o E_\perp)E\right]$$

where

- ω_p is the perturbed frequency of the resonant mode
- ω_o is the unperturbed frequency of the resonant mode
- $k_{j=\perp,z}^{i=e,m}$ is the form factor of the perturbing object, proportional to its shape and its orientation with respect to the induced static electric field $E_{\perp,z}$ or magnetic field $H_{\perp,z}$
- τ is perturbing object volume
- W stored energy of the resonant mode
- E, H unperturbed cavity field

Proper choice of perturbing object $H_{\perp,z}$= H and $E_{\perp,z}$ = E so that the fields can be derived to evaluate the longitudinal and transverse impedance

Longitudinal impedance (TM modes) $\frac{R_{a,||}}{Q_a} = \frac{\left|\int^L E_{a,z}(r,\varphi,z)e^{-jhz}dz\right|^2}{2\omega_a W}$

Transverse impedance (TE modes) $\frac{R_{b,\perp}}{Q_b} = \frac{1}{\sqrt{\mu\varepsilon}}\left| j \cdot \left[\int^L E_{b,\perp}^2\, e^{-jhz}dz + \int^L H_{b,\perp}^2\, e^{-jhz}dz\right]\right|^2$

[1] “Electromagnetic Field”, J. Van Bladel; pag. 326, ISBN 0-89116-819-2

[2] “Microwave Measurement”, E. J. Ginzton, chap. 10, McGraw-Hill ,(1957)

Perturbation Theory

4 unknowns (E_z, E_T, H_z, H_T) → 4 perturbing objects

Metallic sphere, form factor unrelated to the field orientation:

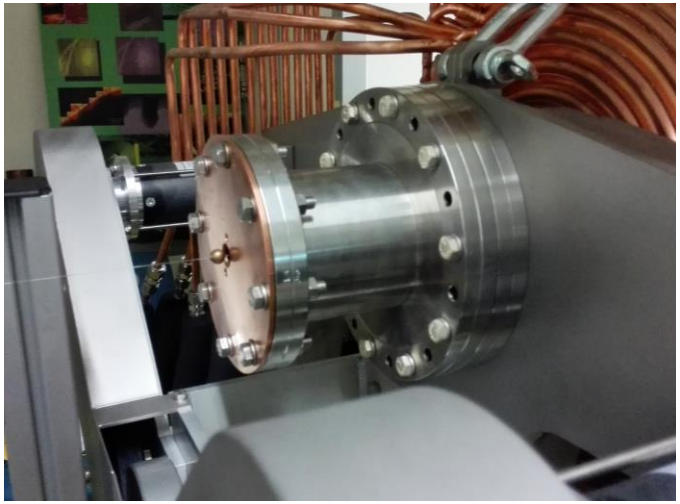
$k^e = \mathbf{3}$; $k^m = \frac{\mathbf{3}}{\mathbf{2}}$

Dielectric sphere, form factor unrelated to the field orientation:

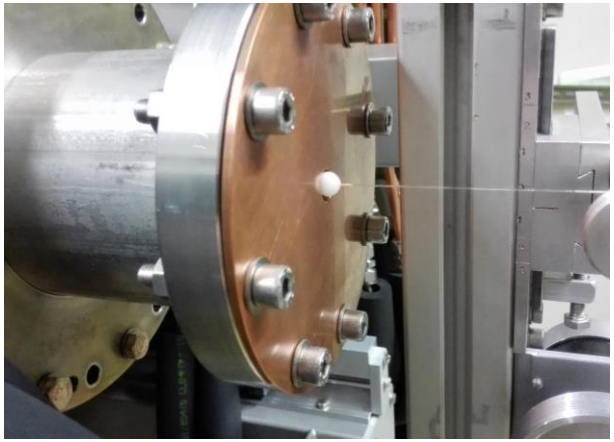
$k^e = \mathbf{3}\,\frac{\varepsilon_r - 1}{\varepsilon_r + 2}$; $k^m = \frac{3}{2}\left(\frac{\mu_r - 1}{\mu_r + 2}\right)$ (if $\mu_r = 1 \rightarrow k^m = 0$)

Maximum frequency shift : 836 kHz @ 1960 MHz *(CU Sphere, L7)*

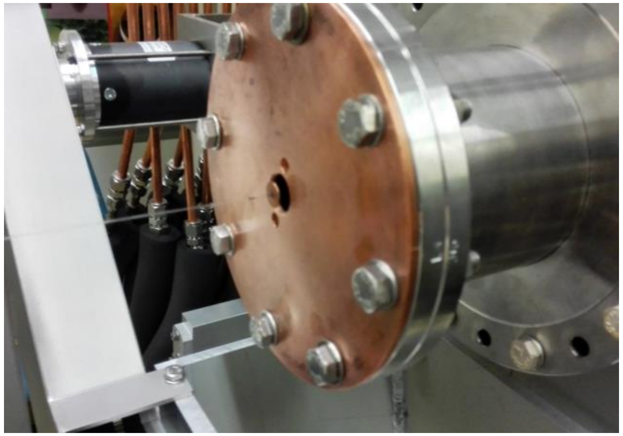
Minimum frequency shift : 12 kHz @ 500 MHz *(needle, L0)*



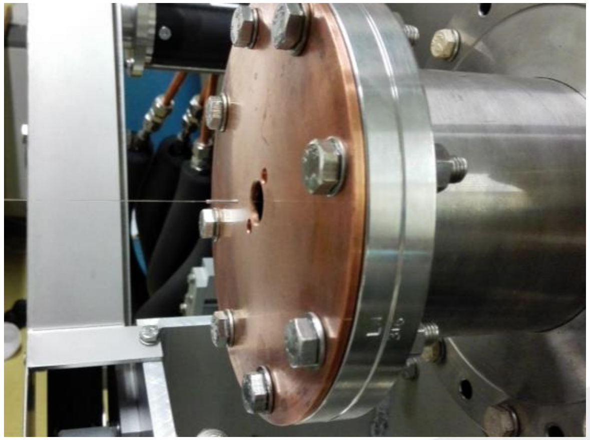
Copper Sphere, Ø ≈ 10 mm



Dielectric Sphere Ø ≈ 10 mm



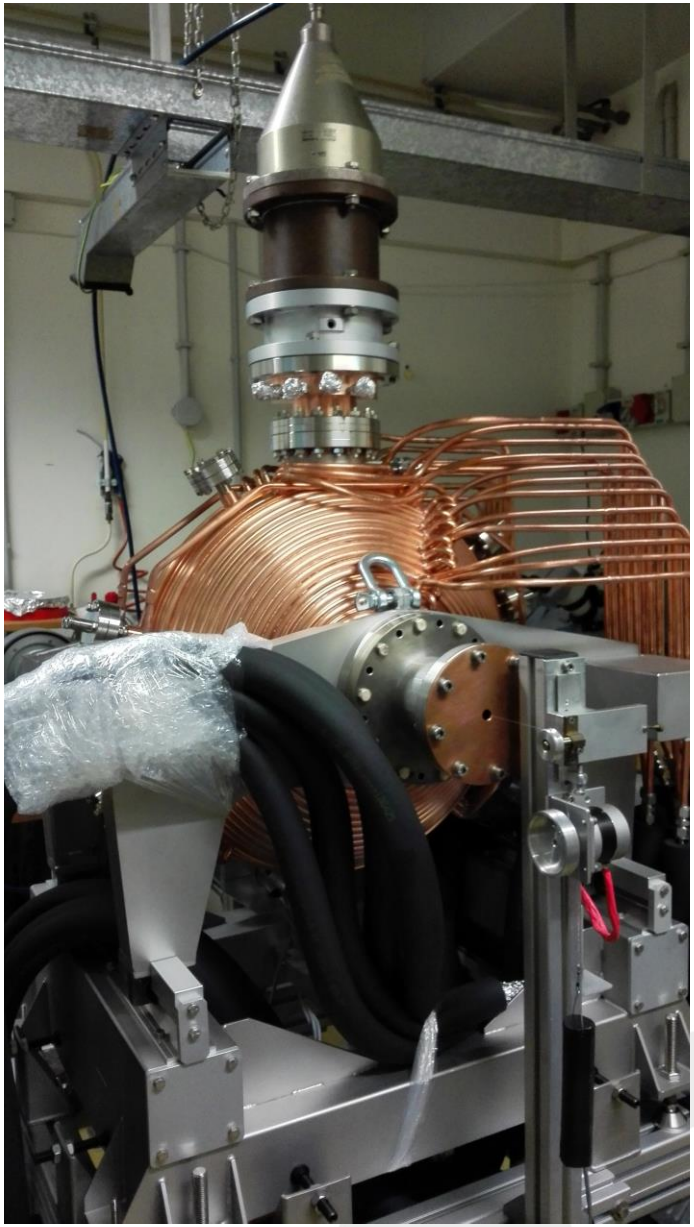
Copper Disk, Ø ≈ 10 mm



Stainless steel Needle, L ≈ 12 mm

Measurement Set Up

- Frequency shift measured from the Input Power Coupler, S11 mode, because it's the largest pick to achieve the better HOM coupling.
- Stepper motor to exactly positioning the perturbing objet
- Dump the mechanical vibrations after each movement of the perturbing object
- Precise alignment of the perturbing object
- Minimize the thermal drift, resonant frequencies depend on the cavity volume that is very sensitive to the room temperature (night acquisition)

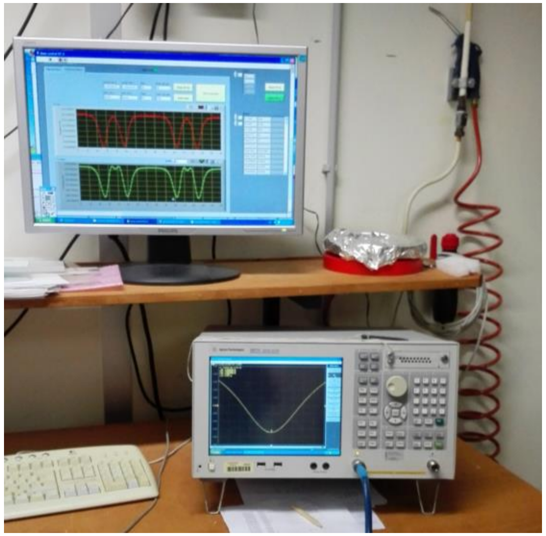


Automatic acquisition program (LabView) :

Input : frequency list, frequency span and resolution, step number, measurement speed

Output: perturbing object position and resonant frequency, whole scan plot

Mea time : 3 hours for a back and forth scan for each mode



Measurement Set Up

- For the R/Q measurement the cavity's condition shall be the closer to the final operating environment so two pipes have been added, 130 mm each, to simulate the cavity's bellows.
- The investigation of the "real" beam path becomes significant at higher frequency.

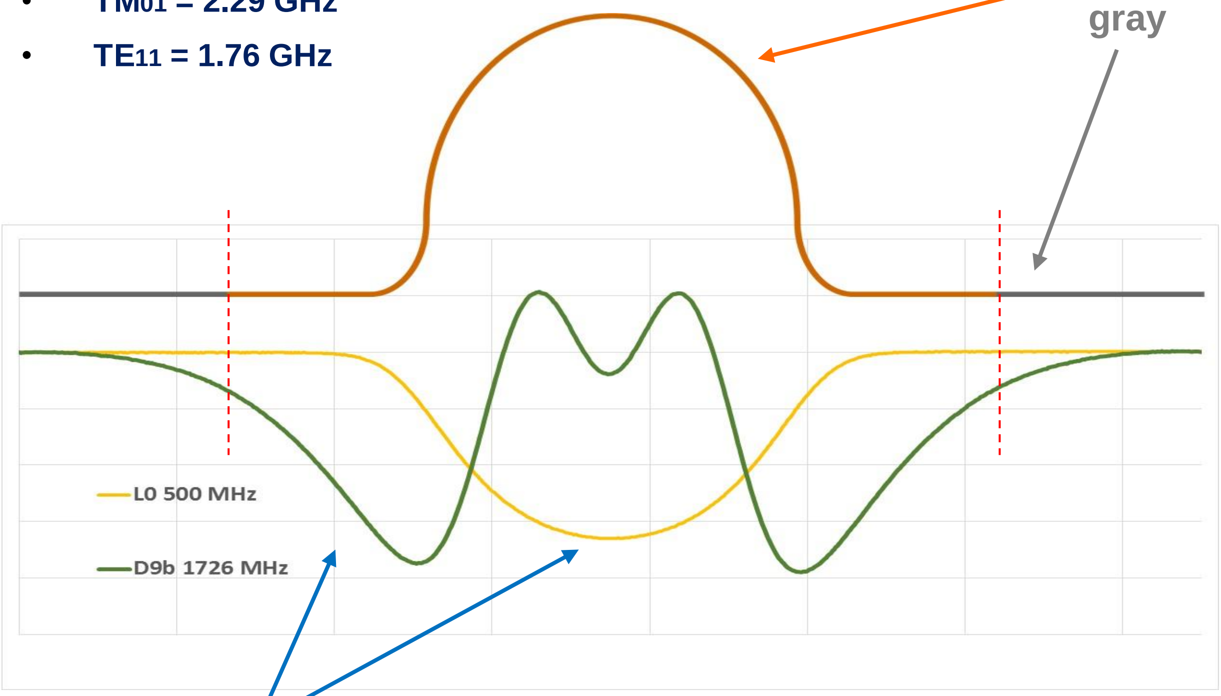
Circular WG cut off:

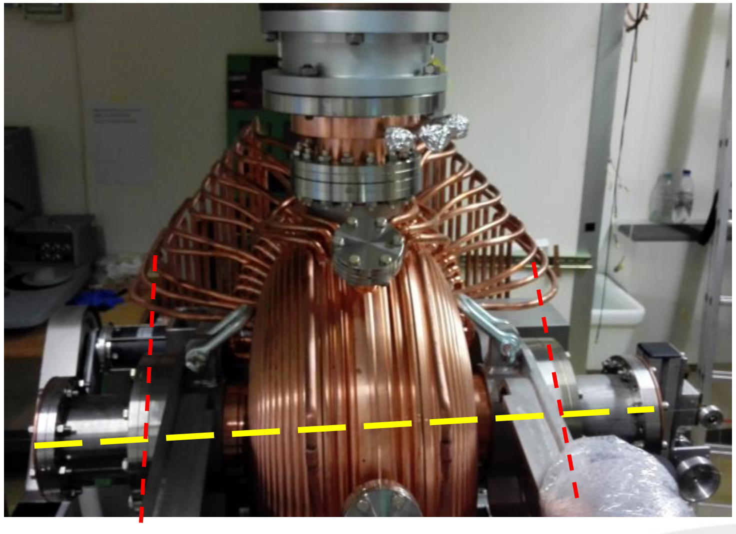
- **TM_{01} = 2.29 GHz**
- **TE_{11} = 1.76 GHz**

Cavity shape profile

orange copper resonator

gray pipes to simulate the bellows



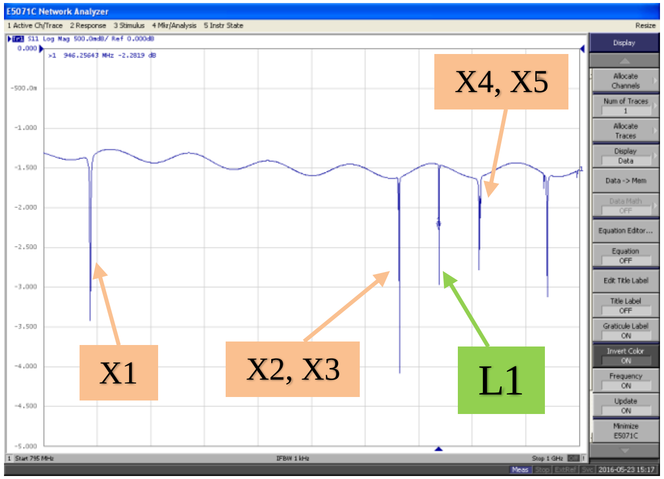


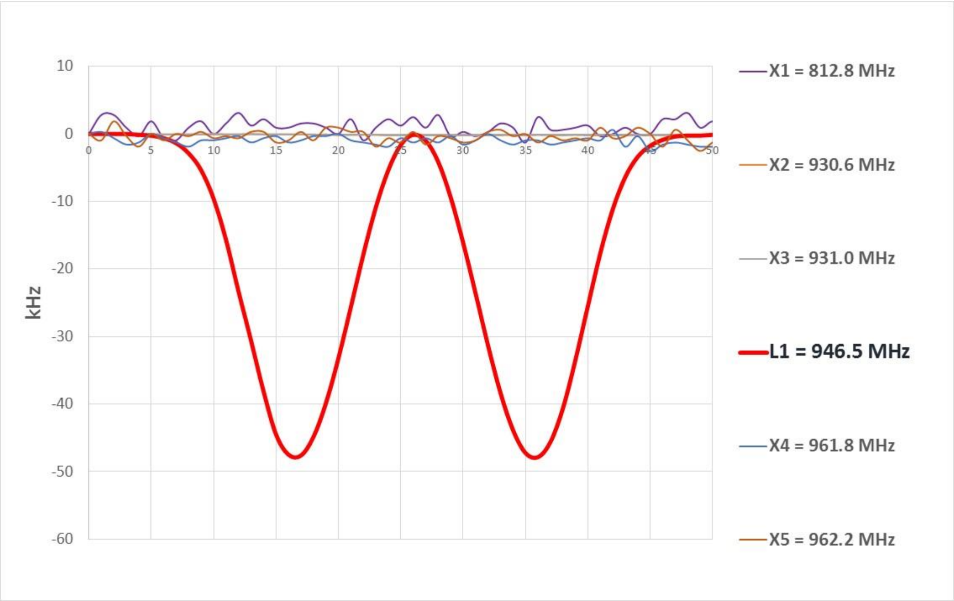
Perturbation measurements, V-axis a.u. not scaled

Mode Identification

- More than hundred cavity's resonances are detected from the Input Power Coupler in the 500 MHz -2.1 GHz frequency range
- The preliminary test to verify which mode contributes to the impedance seen by the beam is to perturb the cavity beam axis with a **metallic sphere**, Ø = 10 mm, that perturbs both the E and H field at the same time. If one resonance is not perturbed by the sphere it means that this mode does not have any E or H field on the beam axis. It does not add to the beam impedance budget.
- This test allows the mode's identification

Frequency scan from 795 MHz to 1.0 GHz. Almost all the resonances but L1 have zero field on the beam axis even if their coupling with the IPC is good

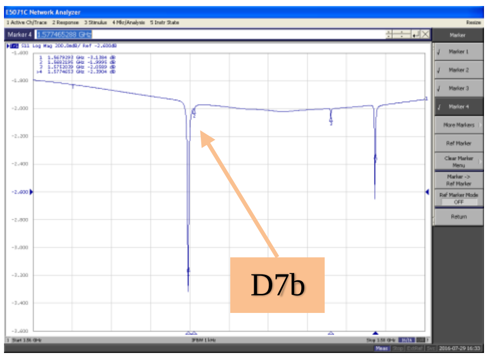




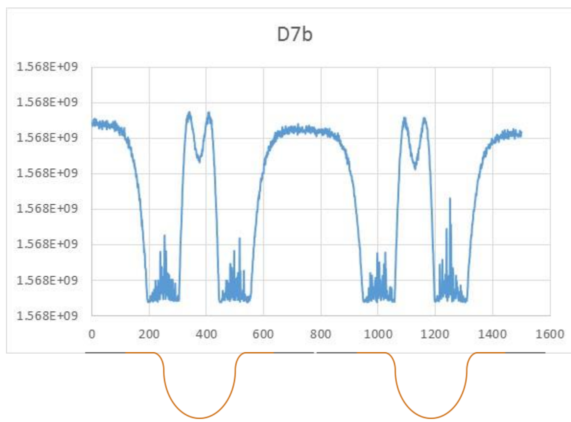
Frequency shift perturbation due to the metallic sphere on the beam axis (cavity axis with no beam pipe added)

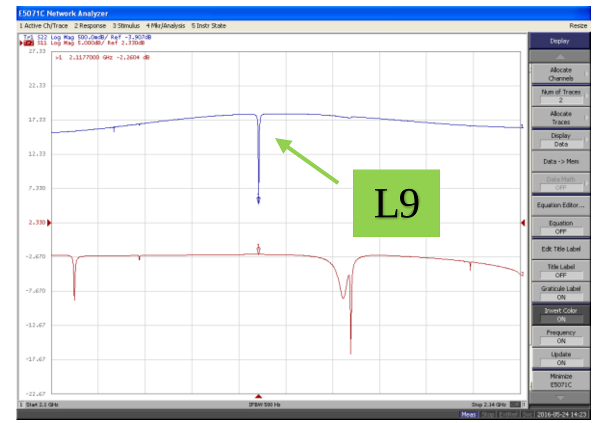
Mode Identification

- The measurement has a good noise to signal ration when the mode is strongly coupled with the IPC, therefore the resonance shall somehow be maximized
- For some modes it is necessary to move the plunger to separate the resonances.
- For L9 mode the excitation was performed on the beam path, otherwise it was impossible to excite the mode.



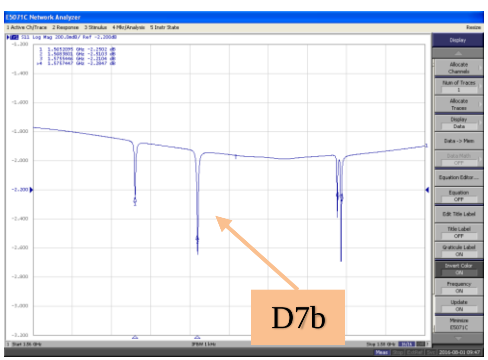
Cavity plunger out



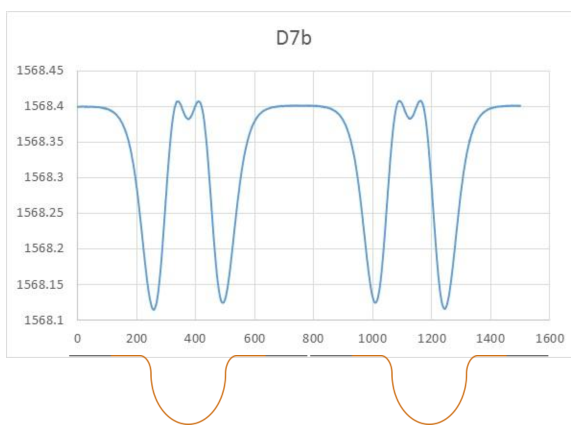


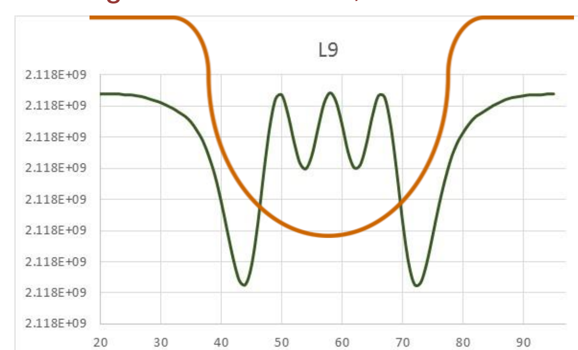
S22: signal from the antenna on the beam axis

S11: signal form the IPC, no L9 measured



Cavity plunger in

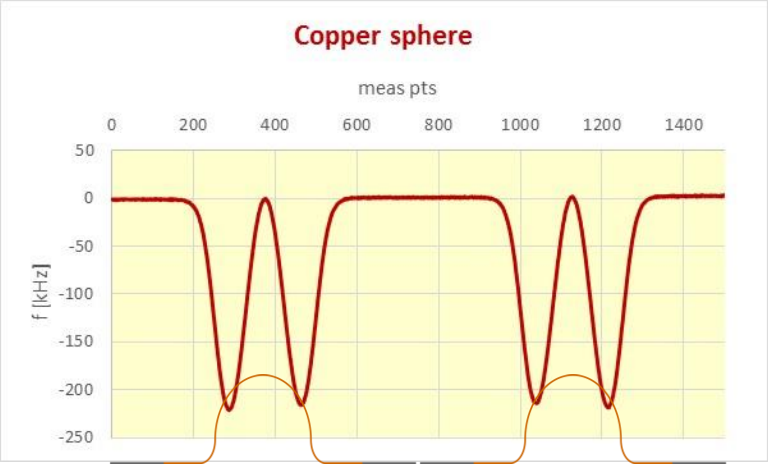


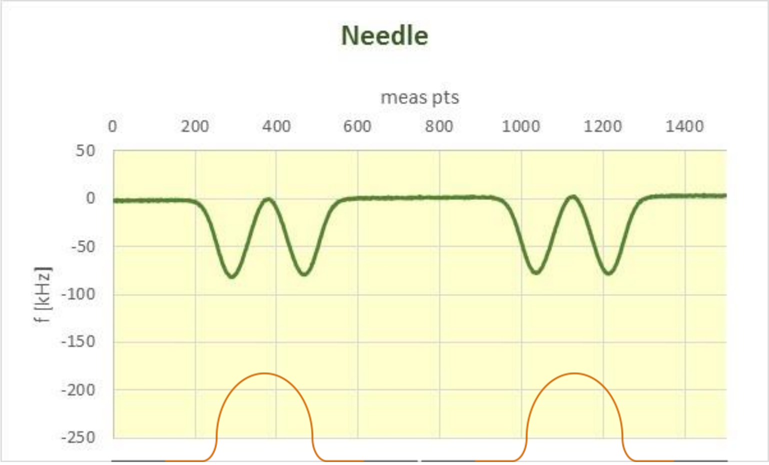


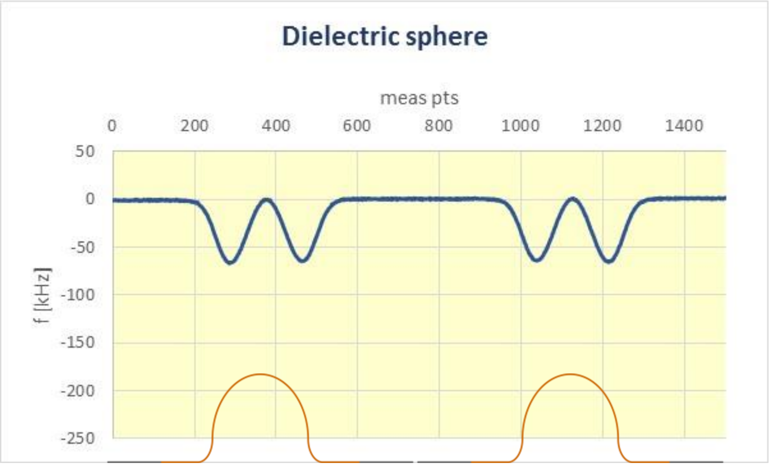
Measurement Result

The R/Q measurement have been done on the **LONGITUDINAL modes** → **Longitudinal E field.**

For example the **L3** frequency shifts (measurements performed "one way and return" along the cavity axial length).







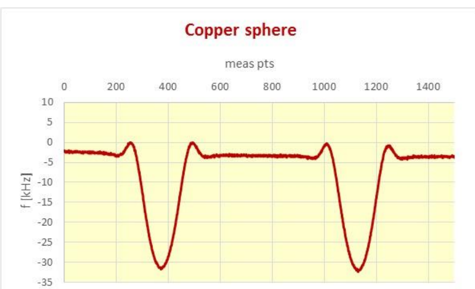
Measurement Result

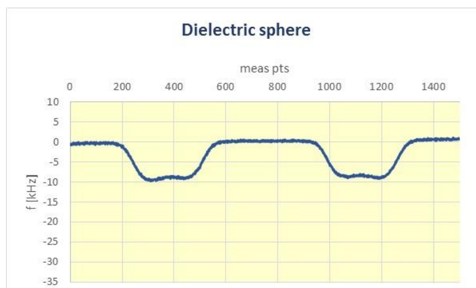
The R/Q measurement focuses on the **DIPOLE modes** → E Transverse & H Transverse

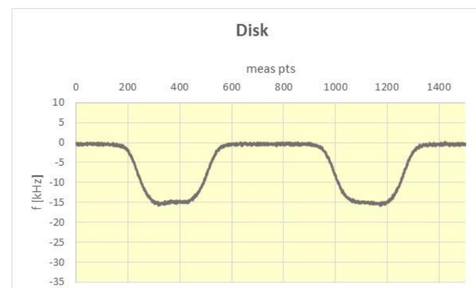
The dipole modes have two polarizations, both are measured.

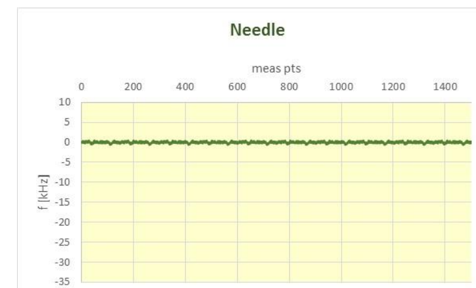
Their different orientation of the transverse field is seen with the disk measurement.

D3a 1119 MHz (TE-like)

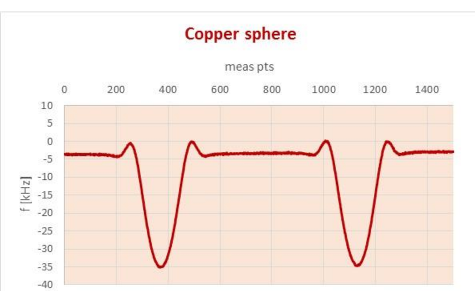


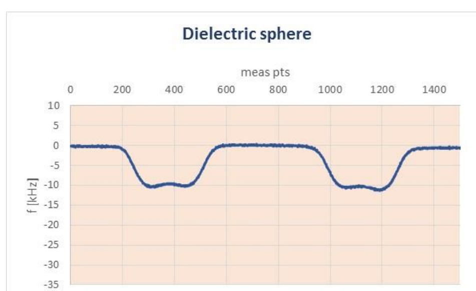


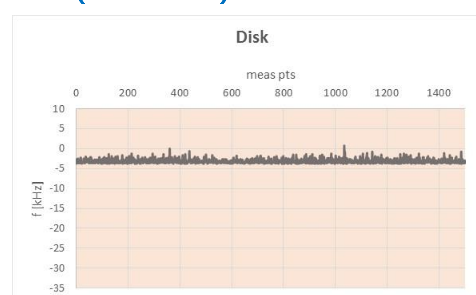




D3b 1120 MHz (TE-like)







Measurement Result

Measurement's ISSUE: Thermal stability of the environment

- The "one way + return" measurement takes 3 hours (1500 measurement points for a stroll > 1480 mm) .
- Cavity's copper body is very sensitive to the room temperature so that the resonant frequency shift accordingly
- Measurement room has no window (a dedicated room inside the detector lab), nonetheless temperature's daily changes are seen by the cavity

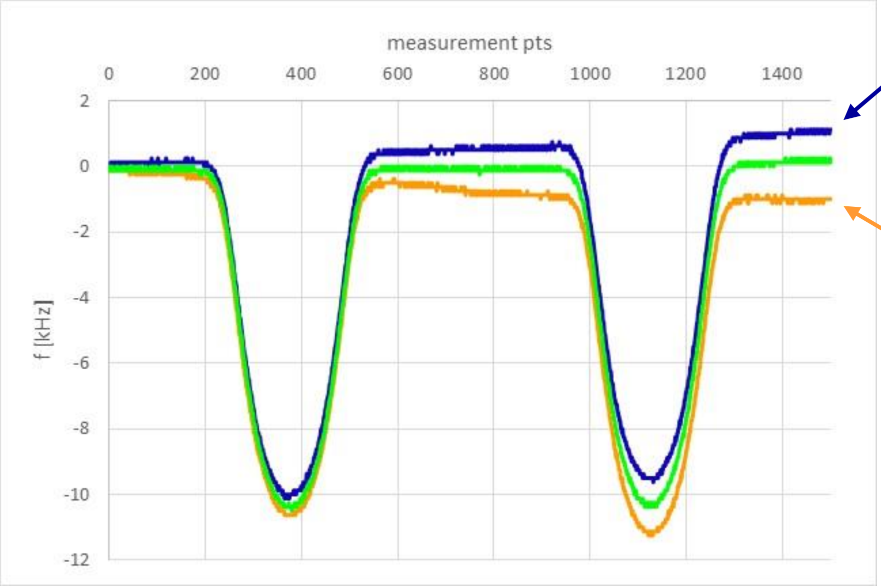
Three measurement of **L0** with dielectric sphere:

Perturbing frequency shift

Δf max =12 kHz

Thermal resonant mode drift

δf =9 kHz/ ^{0}C



Room temperature decreases

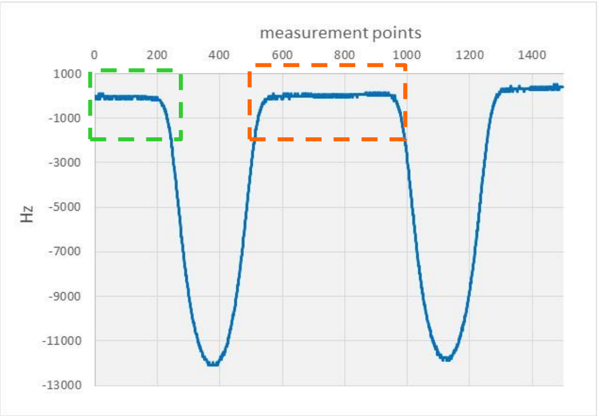
Room temperature increases

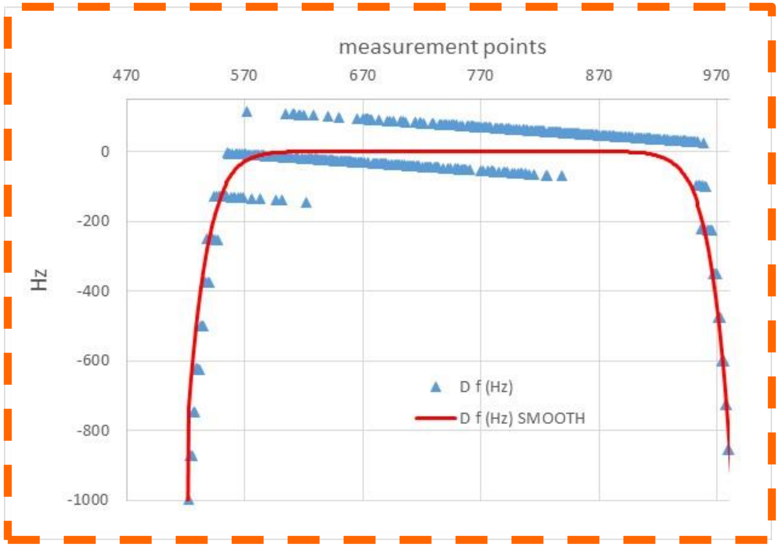
- Solution: repeat the measurement during the proper time (the night one) or remove the drift at the measurement post-processing stage.

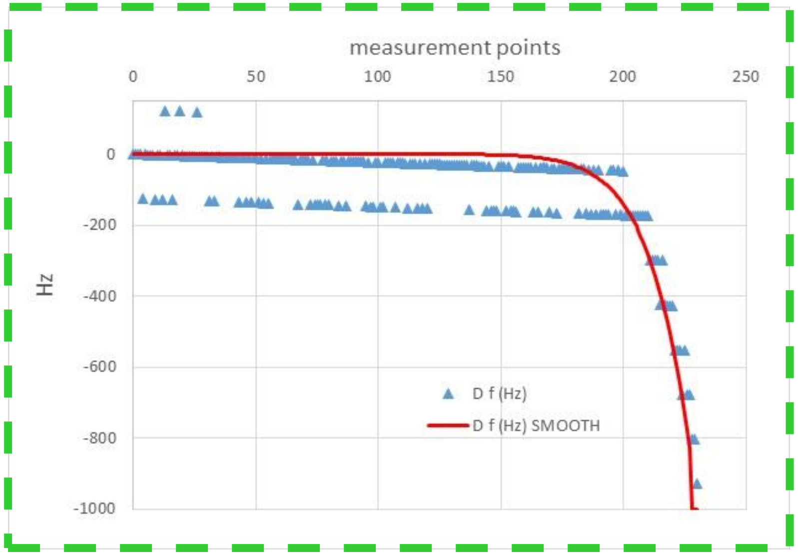
Measurement Result

Measurement's ISSUE: Systematic errors

- Errors due to the VNA and the sampling the S11 minimum peak (not so straightforward task).
- L0 mode measured with the needle (worst example since perturbing frequency shift is Δf max ≈12 kHz).
- The noise (larger for smaller frequency shift) adds up when performing the integration







Solution:

smoothing the curve with the exponential custom fit (red line)

Conclusion

- Together with a numerical electromagnetic field code the R/Q measurement is a powerful tool to understand the HOMs behavior and the interaction between the EM field and the beam, looking directly to what's happen on the beam path.
- The perturbing objects are being calibrated with a pill-box cavity for the final R/Q evaluation.
- Automatic measurement program is required: particular care shall be dedicated to the mechanical vibrations of the system, to the cavity and instrument set up.
- Despite of all the care dedicated to optimize the measurement set up some post-processing of the measured data is required.
- For the Elettra's cavity the quantitative value of R/Q is not the ultimate aim of this technique: it is the most effective way to identify the HOMs. The evaluation of the R/Q is of a great help!

Thank you!

Elettra Sincrotrone Trieste

www.elettra.eu