Characterization and study of the PACMAN RF-BPM

S. Zorzetti, L. Fanucci, M. Wendt

Outline

- **The Ph.D. research**
  - The CLIC BPM
  - BPM characterization
  - Location of the electrical center
  - BPM-Quad integration

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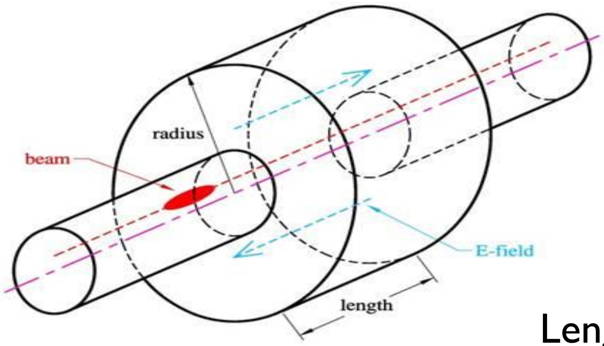
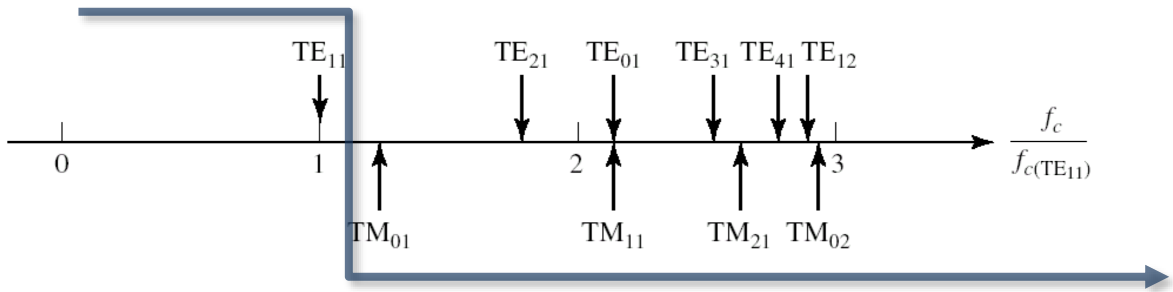
Cavity RF-BPMs

Cavity RF-BPMs can be assimilated to **simple resonators** (pillbox).



Length < 2 radius

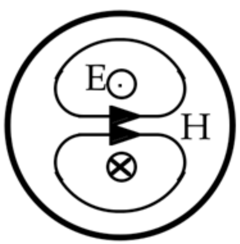


Cut off frequencies of the first TE and TM modes[1]

TM_{010}

Monopole mode: TM010

This is the **fundamental mode** if length<2radius. Longitudinal E-field components are present over the entire cross area



TM_{110}

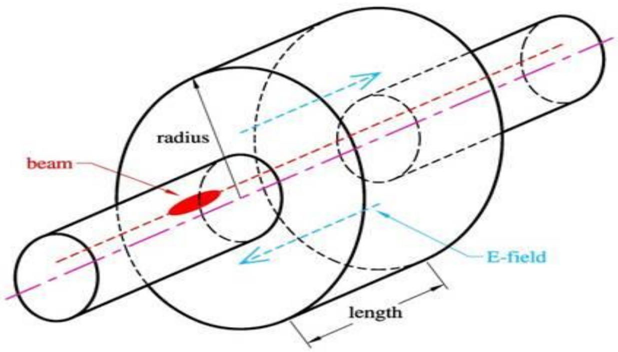
Dipole mode: TM110

The longitudinal E-field components are **null in the center of the cavity**

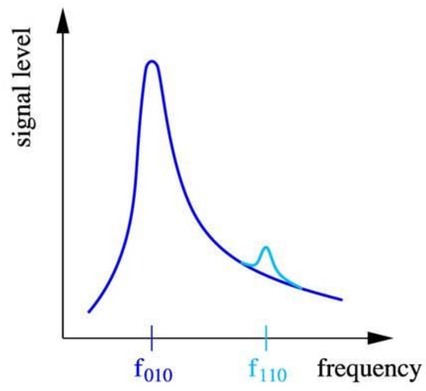
[1]"Microwave Engineering" – David M. Pozar

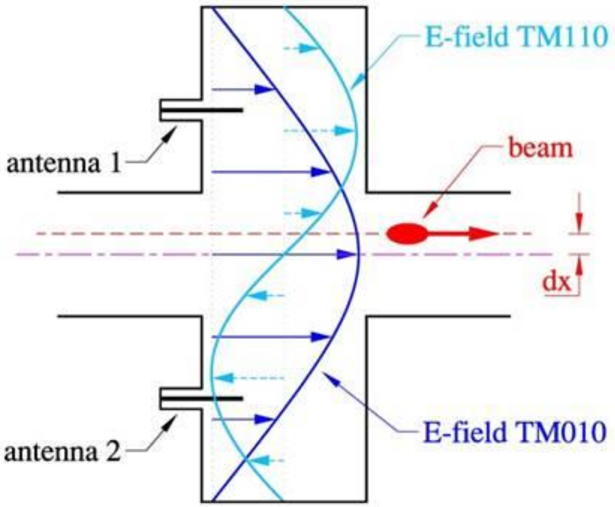
Cavity RF-BPMs

The Cavity RF BPM is not excited by external sources, but by the beam itself.



According to the spectrum of the beam, it couples with the monopole (TM010), dipole (TM110), and higher order modes



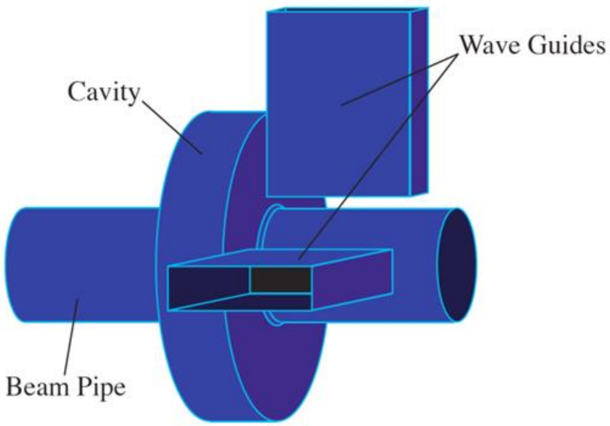


The signal is picked-up by **electrical coupling**, through four lateral antennas.

If the dipole mode (TM110) is discriminated, **the beam displacement around the cavity's center is proportional to the transverse component of the electric field**.

Cavity RF-BPMs

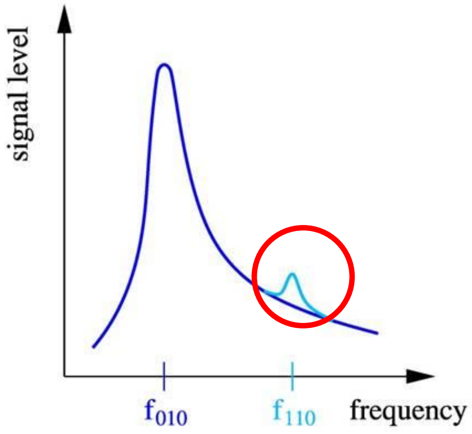
Four **slot-coupled** waveguides act as high pass filter to cancel the monopole modes

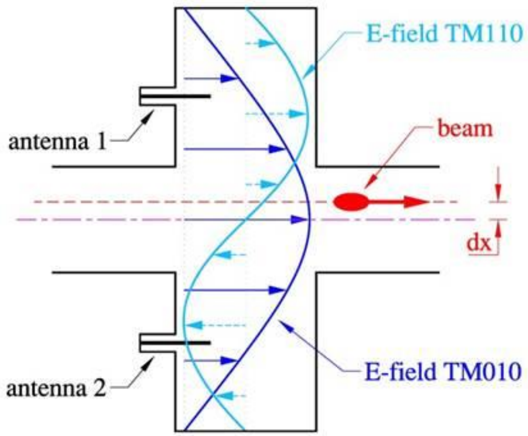


$$f_{TMmnp(cav)} = \frac{1}{2\pi\sqrt{\mu_0\epsilon_0}}\sqrt{\left(\frac{j_{mn}}{R}\right)^2 + \left(\frac{p\pi}{l}\right)^2}$$

$$f_{TEmn\ (WG)} = \frac{1}{2\pi\sqrt{\mu_0\epsilon_0}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$$

$$f_{TM010(cav)} < f_{TE10(WG)} < f_{TM110(cav)}$$

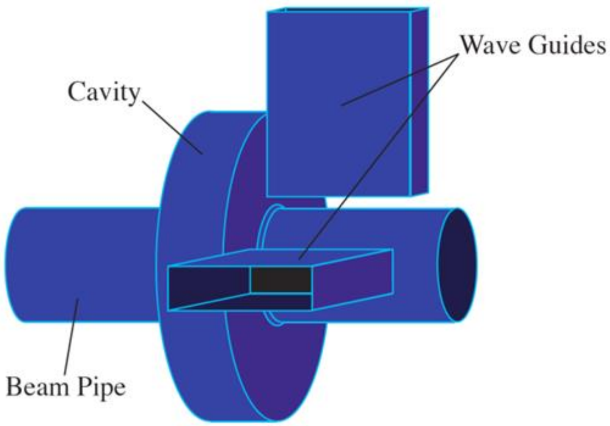


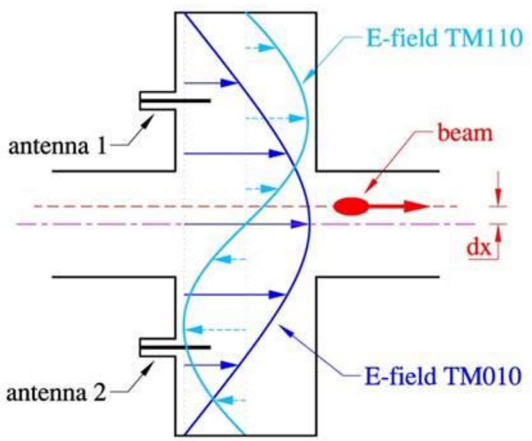


The **electrical center** is the point in which the electric field of the dipole mode (TM110) is null and the picked up signal is at a minimum.

Because of **manufacturing imperfection** the electrical center may not match with the geometrical center.

Cavity RF-BPMs





- Each pickup couples the voltage signal:
  - $V_{pickup} = s(x, y, \omega\ )Z(\omega)I_{beam}(\omega)$
- The motion of a particle along the cavity BPM is characterized by linear and angular position
  - $V_x \propto\ xe^{-t/\tau}\sin(\omega t)$
  - $V_{x'} \propto\ -x'e^{-t/\tau}\cos(\omega t)$
- In a simplistic notation the output voltage the be expressed as:
  - $\boldsymbol{V_{out} \sim Sx + j\ S'x'}$
    - S and S' are the linear and angular sensitivities determined by an appropriate calibration procedure

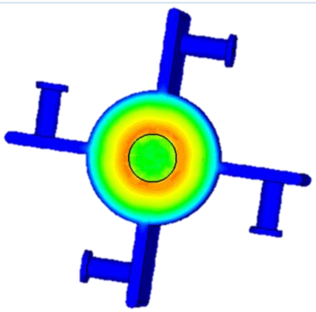
CLIC Cavity RF-BPMs

The CLIC RF-BPM has its dipole mode (TM110) excited at **~15GHz.**

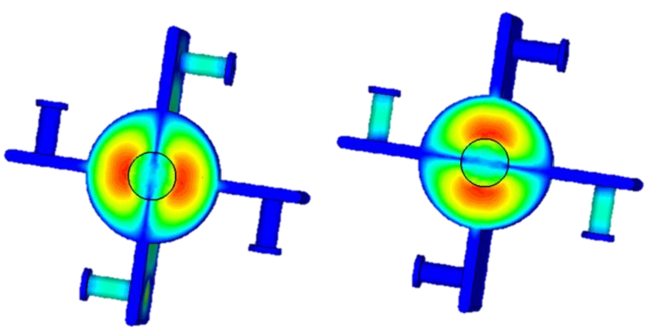
Requirements

- Low-Q
- 50ns time resolution
- **50nm spatial resolution**

CST Simulations



Monopole mode (~11 GHz):
No signal picked up

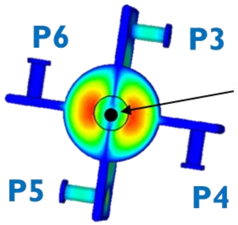


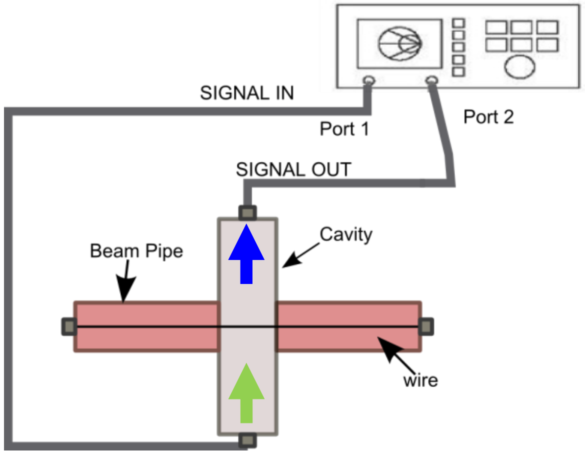
Dipole mode (~15 GHz):
It is excited in two polarizations. According to the polarization the respective set of waveguide is excited

CLIC RF-BPM Characterization

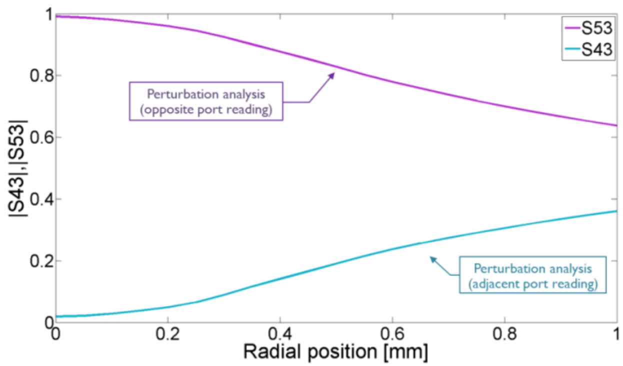
Perturbation analysis

One of the **lateral waveguides is used as source** to excite the cavity. A conductive wire is stretched through the cavity and used to perturb the electrical center. The output signal could be read by opposite or adjacent port.

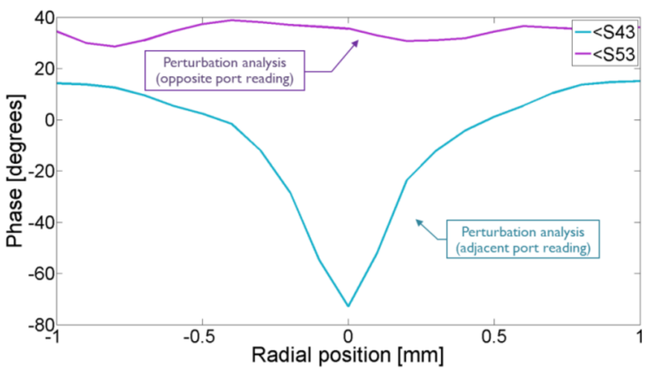




Magnitude characterization



Phase characterization

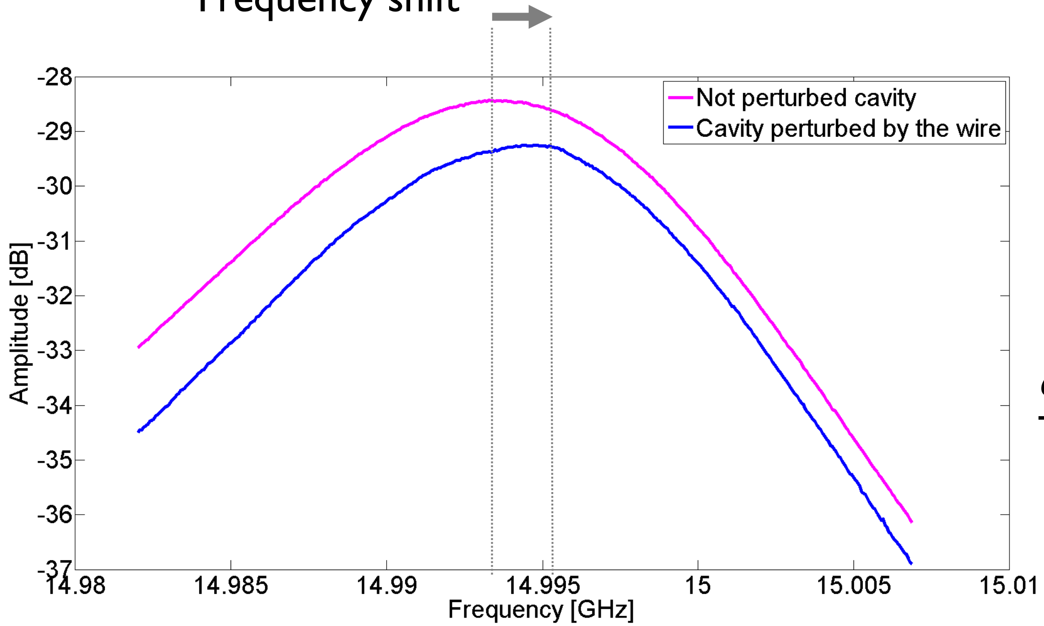


CST
Simulations

Scattering parameters (phase and magnitude), Sij: Excite from Port j and read from Port i

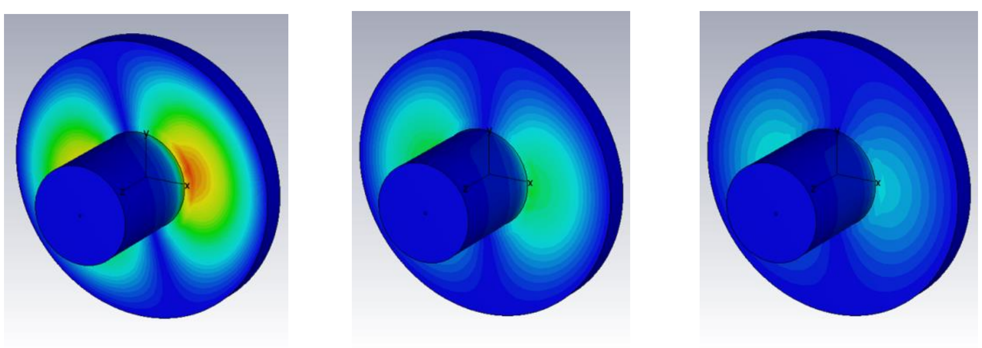
Perturbation analysis

Frequency shift



The **Slater theorem** describes the dipole eigenfrequency shift in an RF cavity due to a metallic or dielectric perturbation

$$\frac{\omega - \omega_0}{\omega_0} \approx \frac{\int\int\int_{\Delta V}(\mu|H_0|^2 - \epsilon|E_0|^2)dv}{\int\int\int_{V}(\mu|H_0|^2 + \epsilon|E_0|^2)dv}$$



Using the wire as passive target it drains power from the cavity, according to the displacement.

Wire displacement

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- Fiducialization of the electrical center
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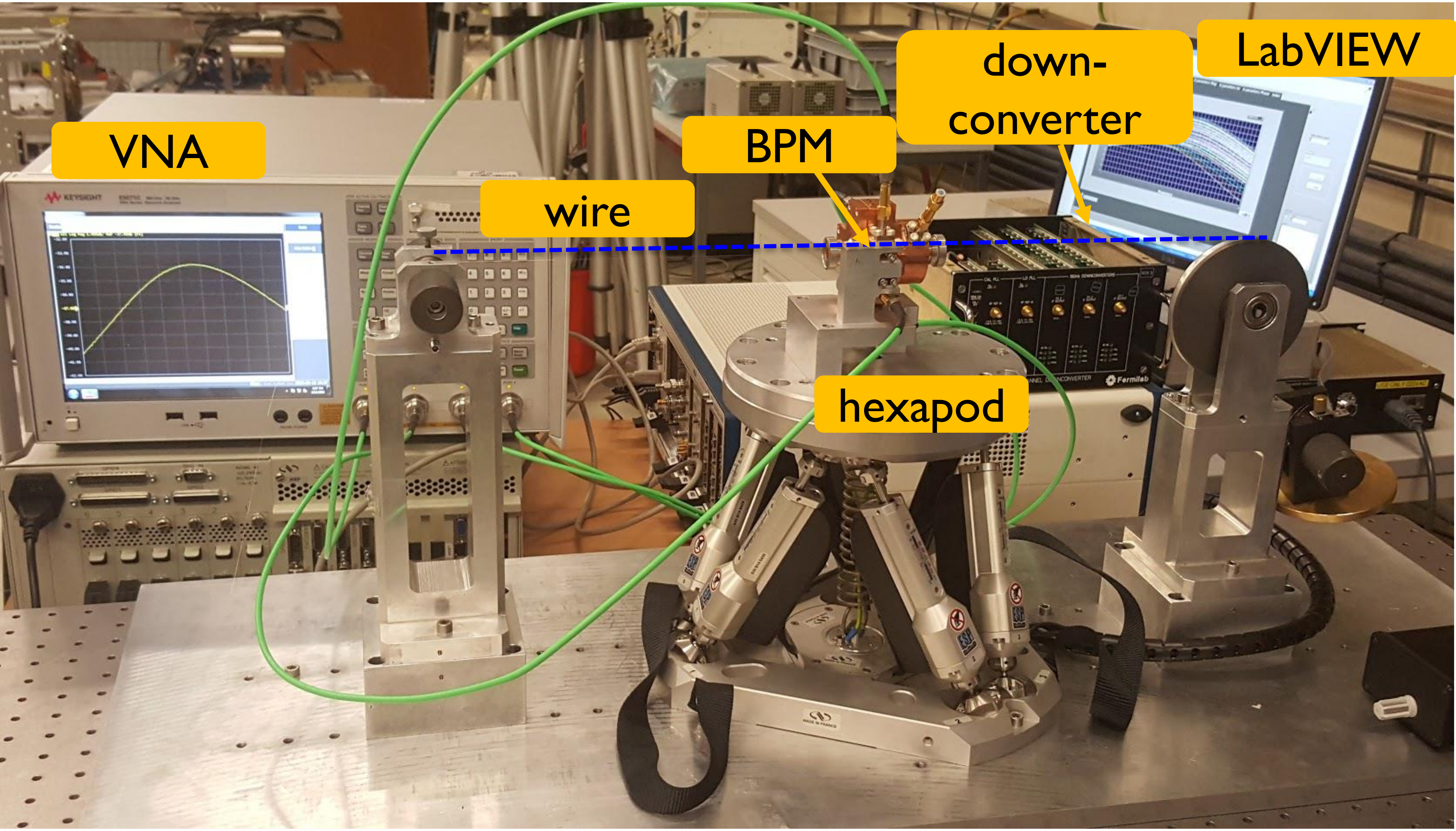
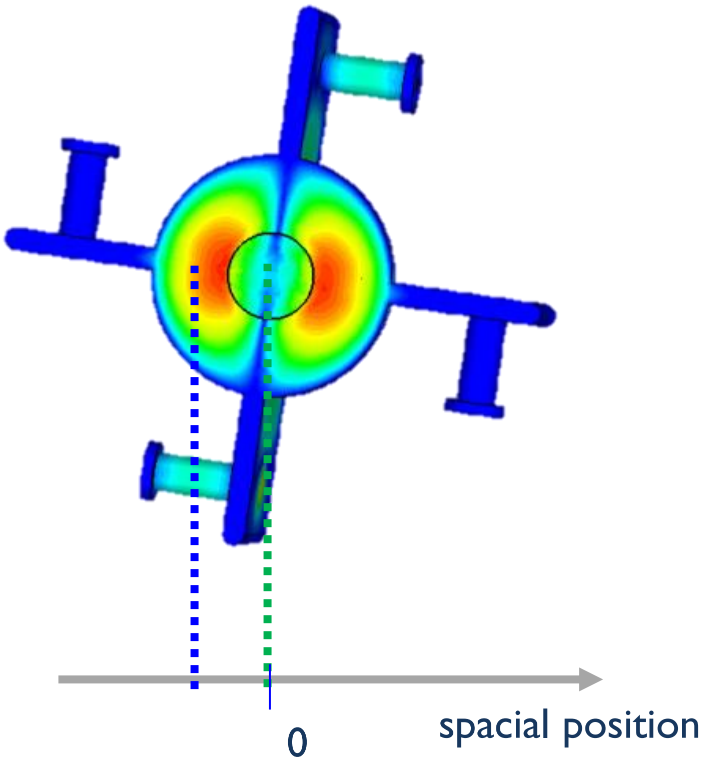
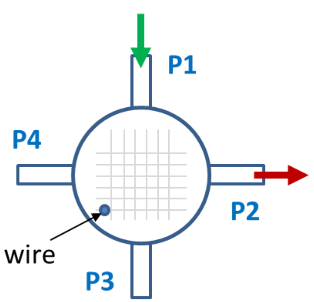
BPM Test Bench



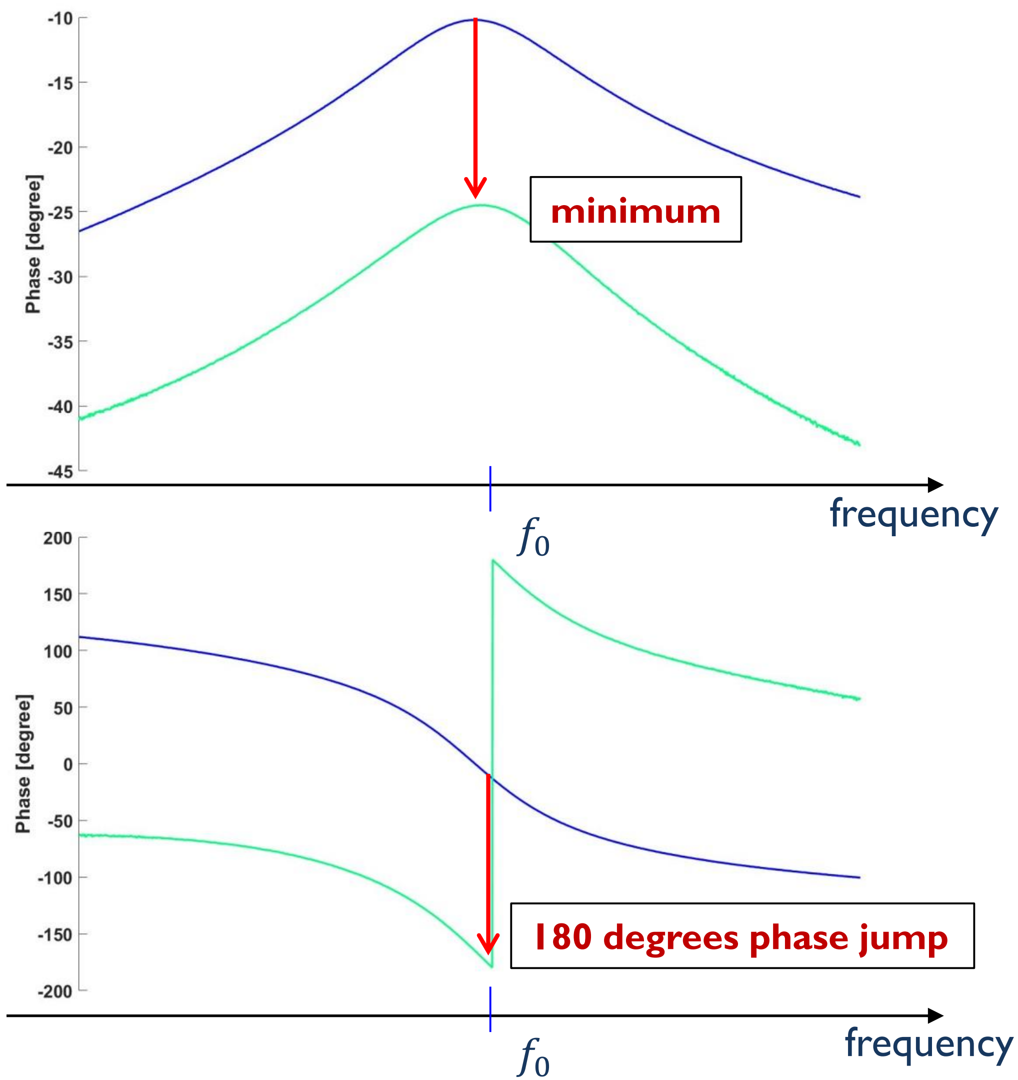
Cavity sensinsing





N.B. : VNA measurements

- *Calibration ON*
- *Phase correction ON*
- *Frequency sweep centered on the resonant frequency*

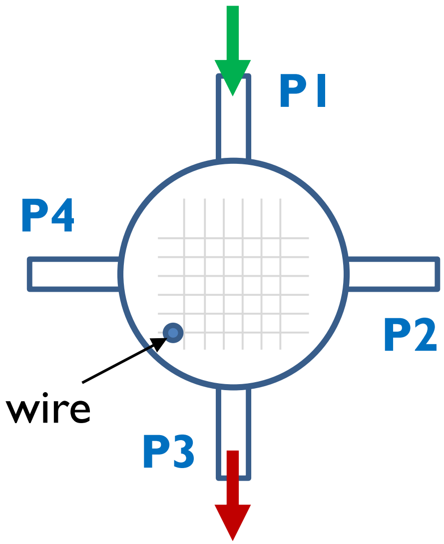


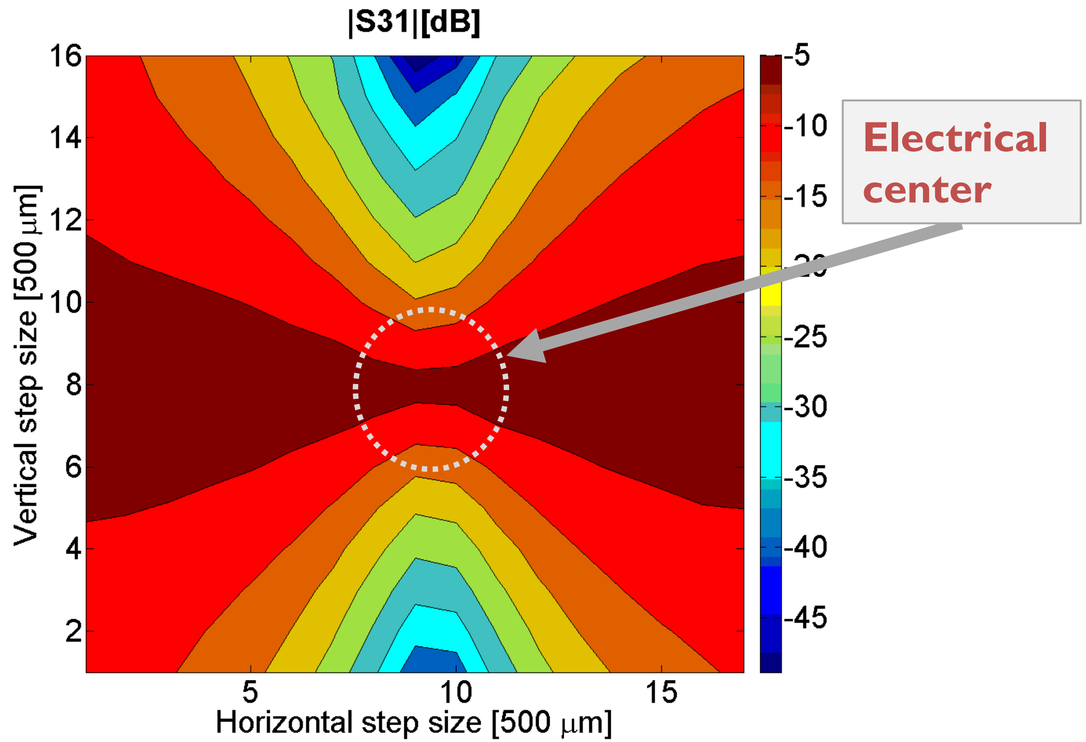
Scan of the cavity – large scale

Looking at the cavity on a **larger scale** in magnitude

- **Magnitude: opposite ports reading**

Step size : 500um



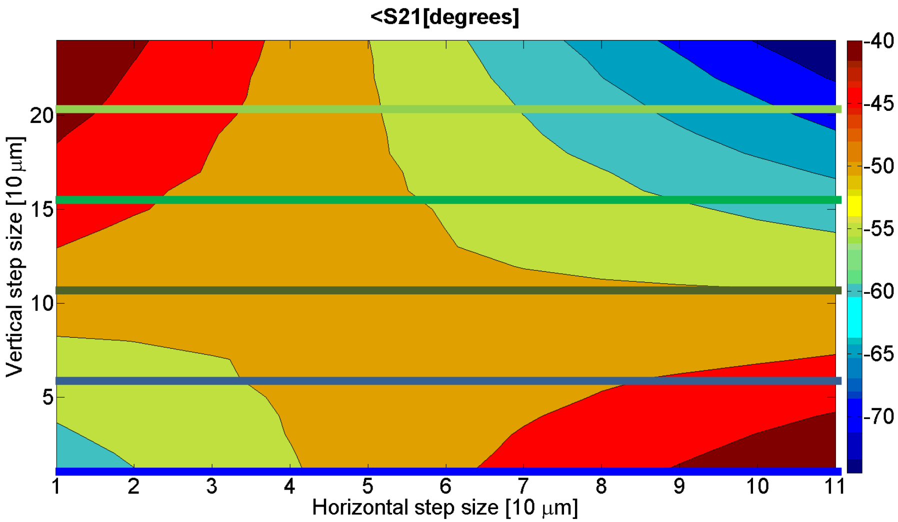


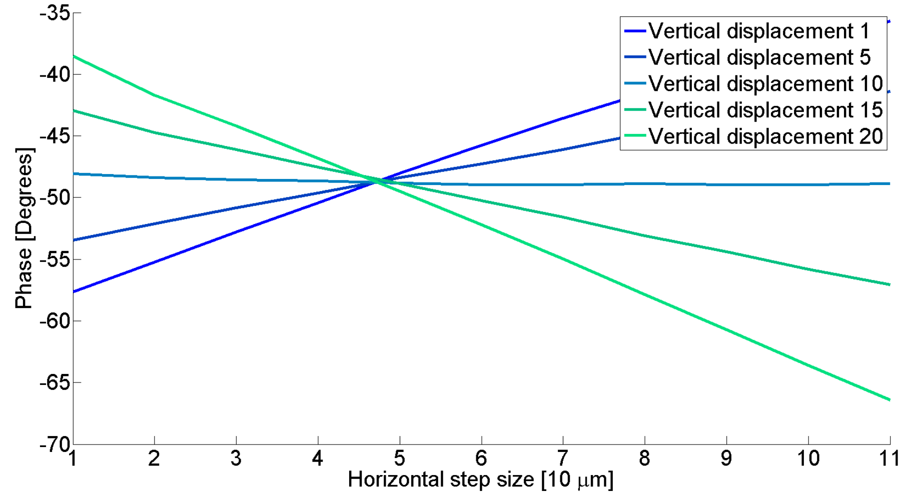
The wire behaves **as a probe** and couple the E-field in the cavity. On a larger scale we observe the **E-field pattern at the dipole-mode in two polarizations**

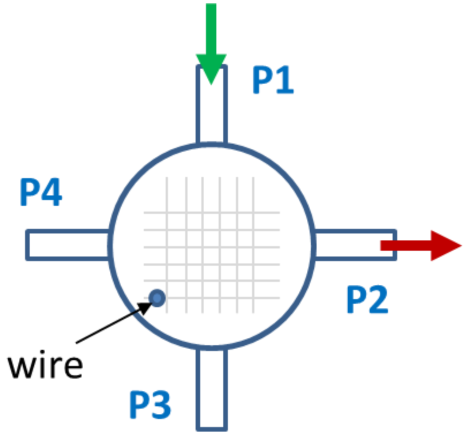
Location of the electrical center

Phase - Adjacent-port

Step size : 10um





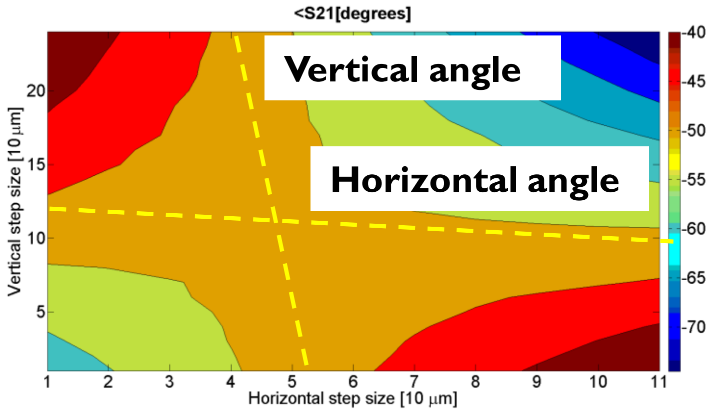


Electrical center interpolation:

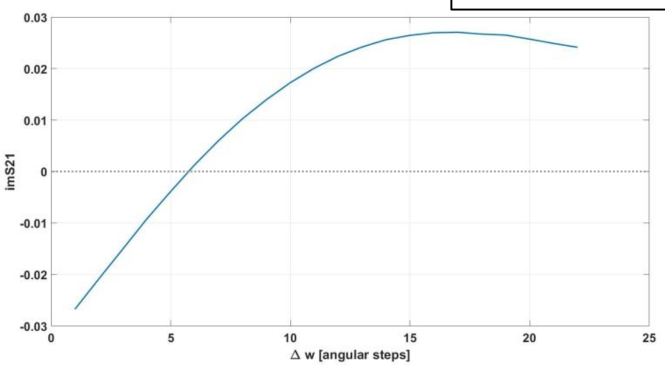
$$x_0 = m_x x + a_x$$
$$y_0 = m_y y + a_y$$

Other measurements

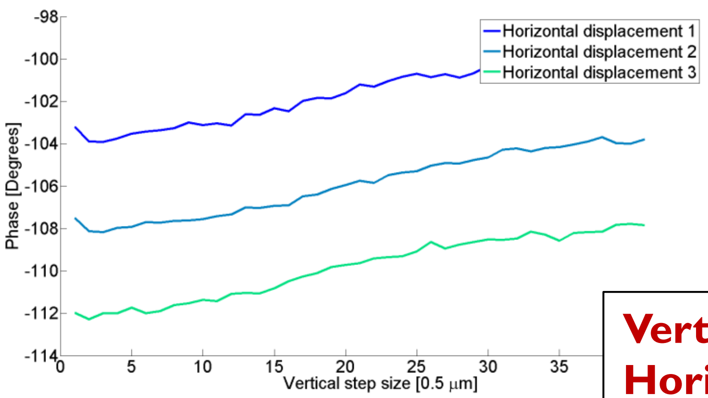
- **Tilt**



Imaginary part

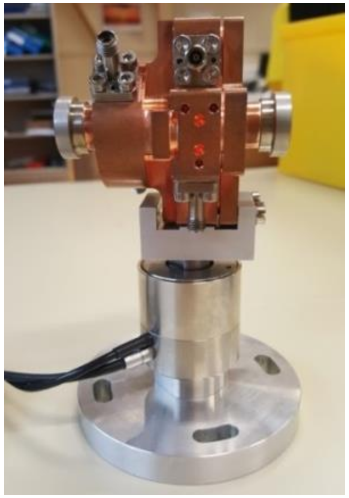


- **Nanometric resolution**



Vertical step size : 0.5um
Horizontal step size: 10um

Hexapod + Piezo



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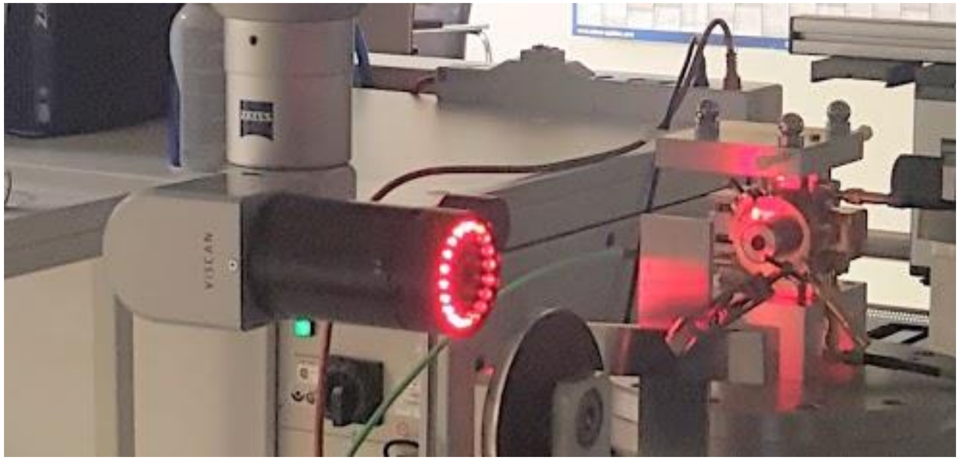
Electrical center fiducialization

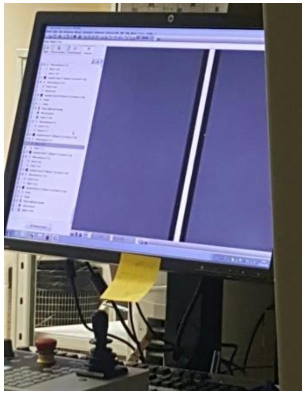
To accurately locate the position of the electrical center with respect to the wire the same measurements have been repeated in the metrology laboratory at CERN.

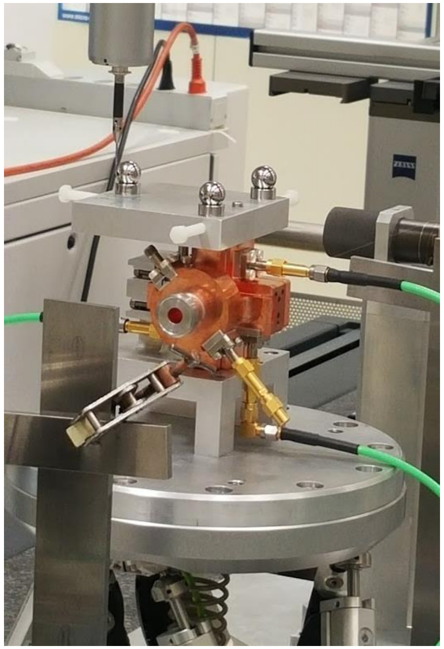
Uncertainty: ±(1.2μm + L/1000)

Electrical center fiducialization

With a camera the CMM detect the position of the wire and set the origin





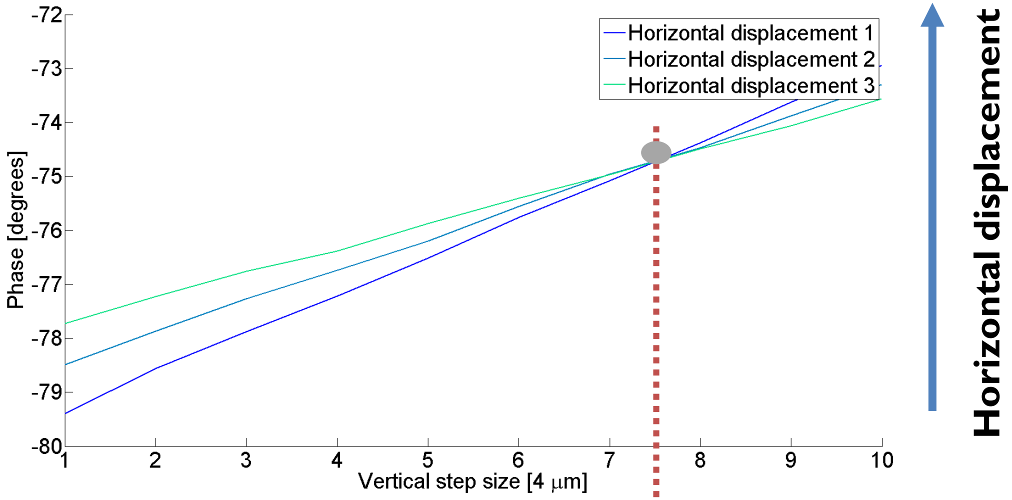


The hexapod scan the cavity to detect the position of the electrical center

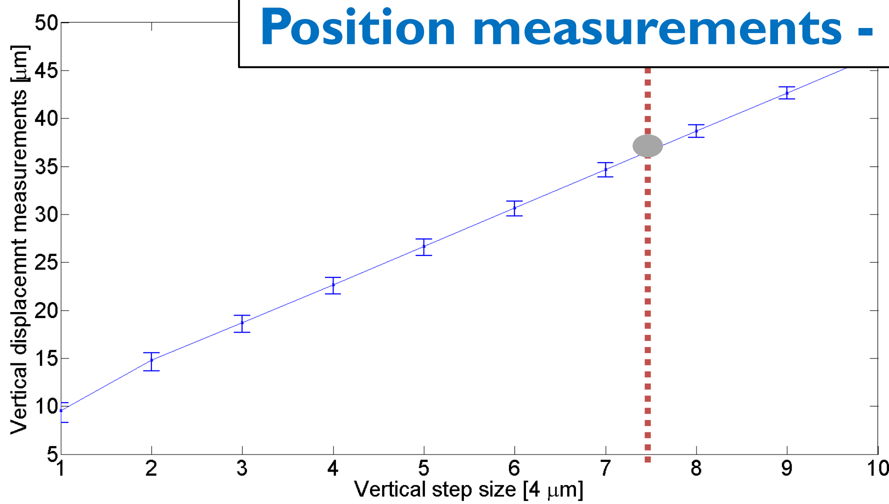
- The CMM detect the position of the hexpod by measuring the position of **targets** on top of the BPM
- The LabVIEW interface acquire the VNA electrical measurements
- Finally the CMM calculate the geometrical center of the BPM cavity by measuring the perimeter of the two attached beam pipes

Electrical center fiducialization

Electrical measurements - VNA



Position measurements - CMM



Vertical step size : 4um
Horizontal step size: 4um

By comparing the **electrical and the position measurements** in the CMM we are able to locate with external fiducials the **electrical center of the Cavity BPM**

BPM geometrical to electrical displacement
40um±4um

Uncertainty: ±(1.2μm + L/1000)

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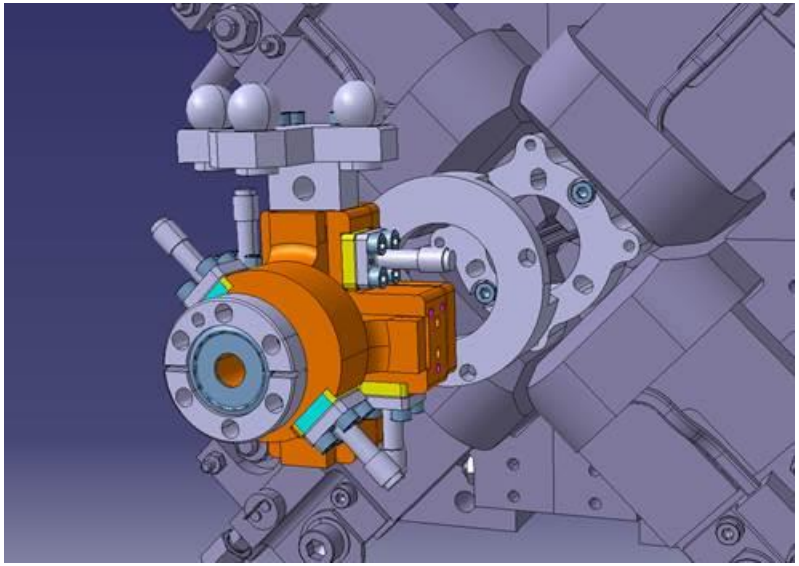
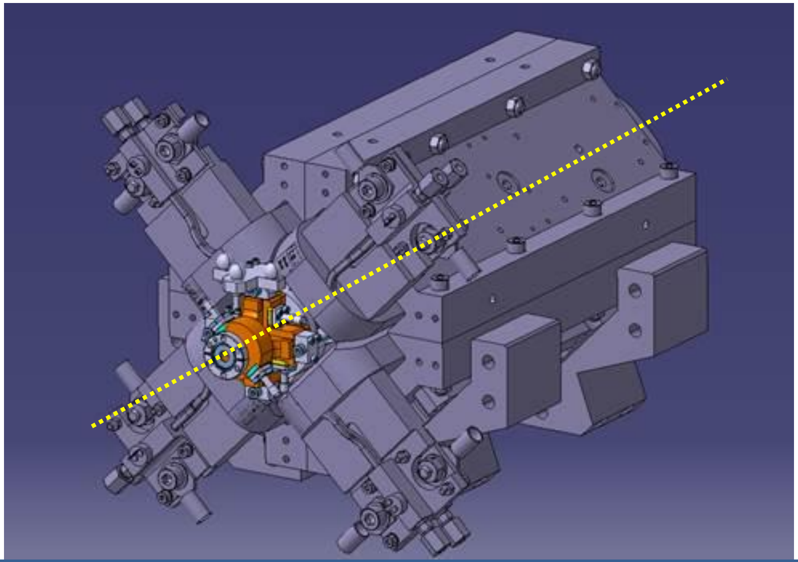
BPM-Quad interface





Two complementary interfaces, associated respectively to the geometrical center of the magnet and of the BPM

BPM geometrical to electrical misalignment **40µm±4µm**	Quadrupole geometrical to magnet misalignment **…FOLLOW MY COLLEAGUES' TALKS**

Stretched-wire measurements on the BPM-Quad module to study:

- magnetic-electrical offset
- repeatability
- maximum misalignment

Thank you!!

CMM metrology validation

Hexapod: 6-axis translation stages

Vendor datasheet

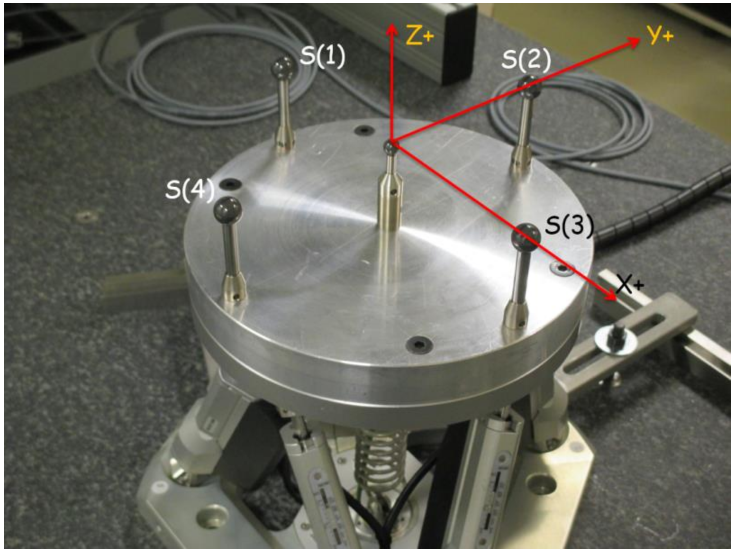
Minimum Incremental Motion (x, y, z)[um]= 0.5, 0.5, 0.25

Uni-directional Repeatability (x, y, z) [um]= 0.5, 0.5, 0.25

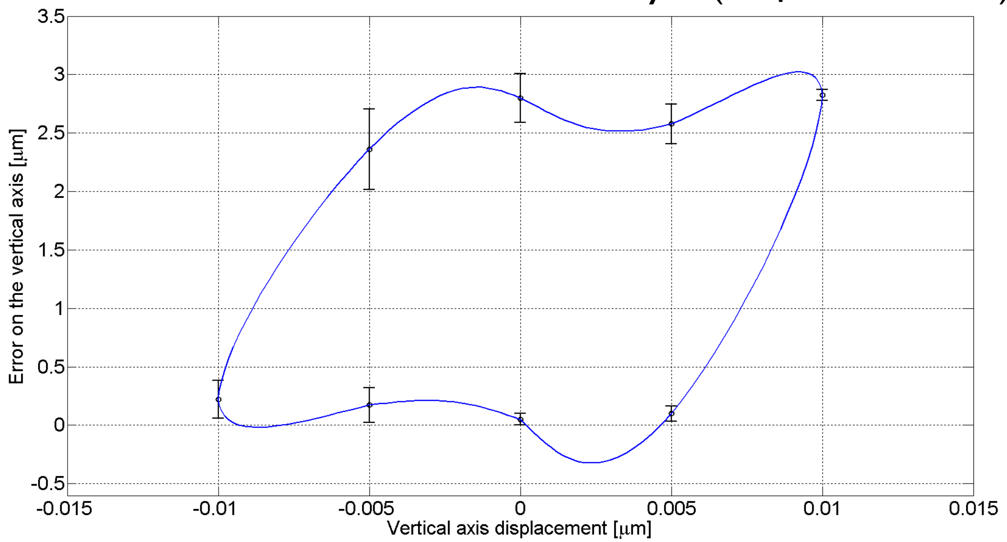
Bi-directional Repeatability (x, y, z) [um]= 4, 4, 2

Cantered Load Capacity [Kg]= 20

Performance double-checked with the CMM at CERN

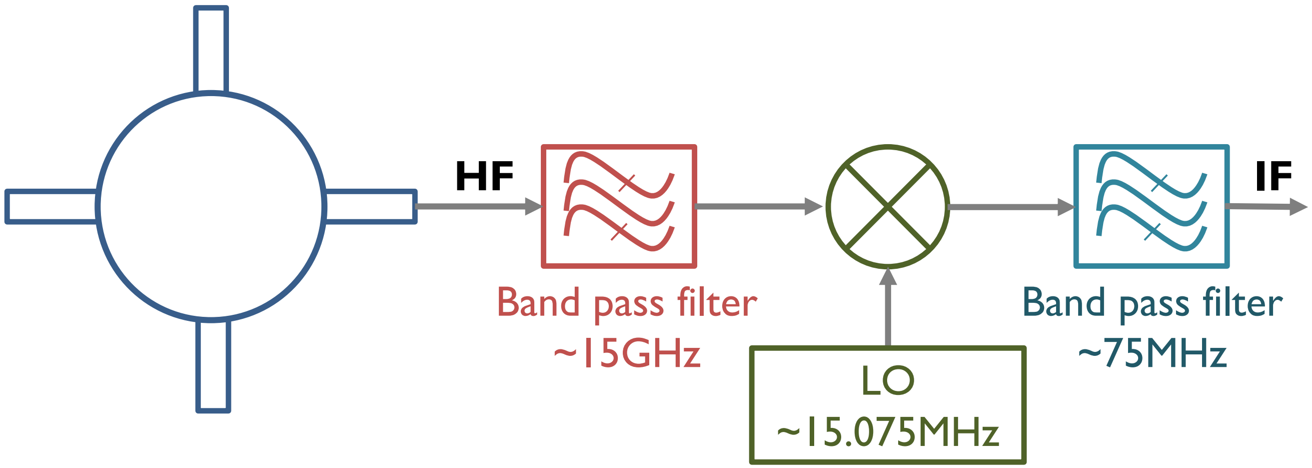


Uncertainty: ±(0.3μm + L/1000)

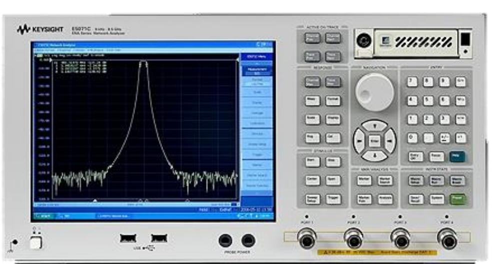


Data Acquisition

CLIC Cavity BPM Downconverter: detailed design and PCB fabrication by **Fermilab**



First tests with the 15GHz downconverter show resolution limits in the order of ~10um in the determination of the electrical center



For characterization purposes, it has been decided to use a **4-port VNA**

- **Max frequency: 20GHz**