New technique to localise the EM centre of accelerating structures

Natalia Galindo, UPV
Nuria Catalan Lasheras, CERN
Angeles Faus Golfe, LAL

CLIC Workshop, CERN, Switzerland
January 2018

Outline

1. Introduction
2. New methodology: the perturbative method
3. Experimental stand-alone test bench at CERN
4. Measurements and error estimation
5. Conclusions

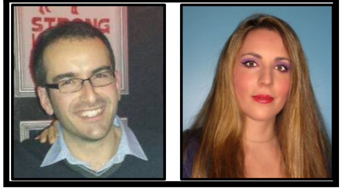
The PACMAN project

Particle **A**ccelerator **C**omponents' **M**etrology and **A**lignment to the **N**anometre scale, a doctoral innovative Marie-Curie Training Network

Objective: **improve the alignment accuracy** of the components to be installed in the next generation of particle accelerators delivering beams in the nano-meter regime, like CLIC.

WP1: Metrology and alignment

WP2: Magnetic measurements

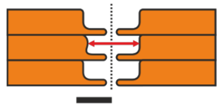
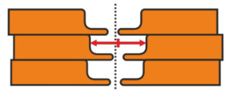
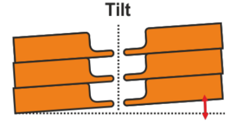


WP3: Precision mechanics and stabilization

WP4: Microwave Technology

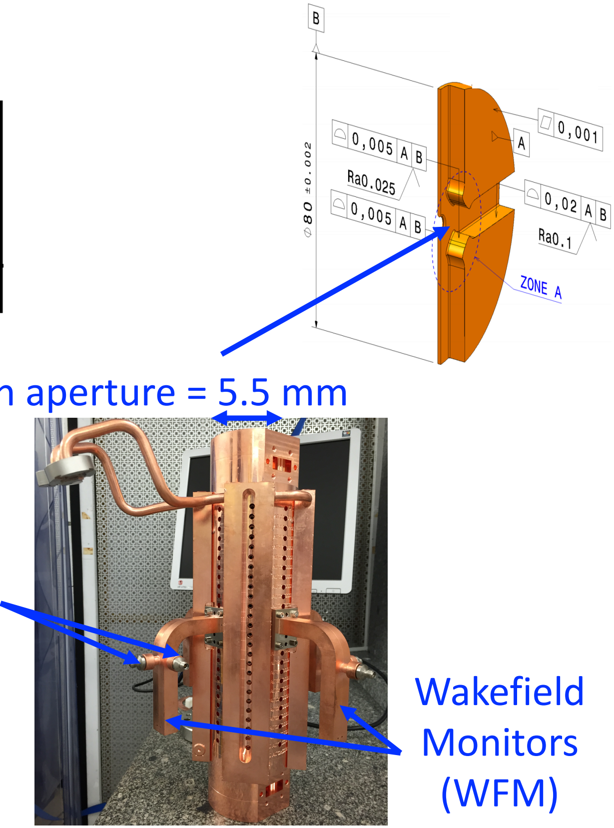
Objectives at PACMAN for Accelerating Structures

1-2 µm disk tolerances achieved and demonstrated with topographic contact-scanners, but **internal tolerances can not be evaluated** after assembly through the small-aperture irises. AS alignment relies on the outer geometric center as reference axes for their positioning in girders.

	Error in cavity shape	Transversal offset	Tilt
Shape error			
Tolerance	1 µm	5 µm	140 µrad

Objectives:

- Development of a technique to **measure the EM axis of AS with an accuracy of 10 µm**, by means of a stretched wire used as reference for alignment.
- Validation of the method within the **5.5-mm-mean-aperture** TD24 AS designed for CLIC.



CLIC TD24 AS equipped with WFM

The perturbative method

Slater perturbation theorem in resonant cavities:

$$\frac{\Delta\omega_0}{\omega_0} = \frac{\int_{\Delta V}(\mu_0 H^2 - \varepsilon_0 E^2)\, dV}{\int_V(\mu_0 H^2 + \varepsilon_0 E^2)\, dV}$$

Cavity EM fields obtained through **frequency shift detection** on the resonance frequency caused by a metallic or dielectric perturbation

ω_0: resonance frequency
$\Delta\omega_0$: frequency shift
ΔV: volume of the perturbation removed from the cavity of volume V
E, H: unperturbed electric and magnetic field amplitudes, respectively

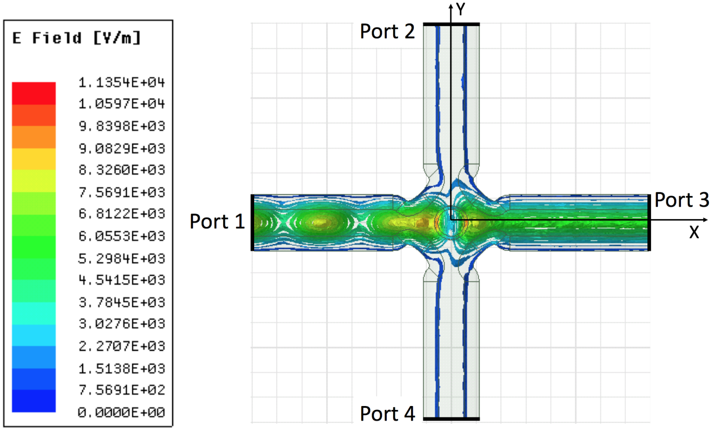
EM fields in traveling-wave structure sensed through **S parameter variation** caused by a wire. Monitor S-parameters as a function of transverse wire position hypothesizing that:

- The wire will **preserve the symmetry of the cell**.
- **EM centre: position of minimum perturbation**.

The perturbative method

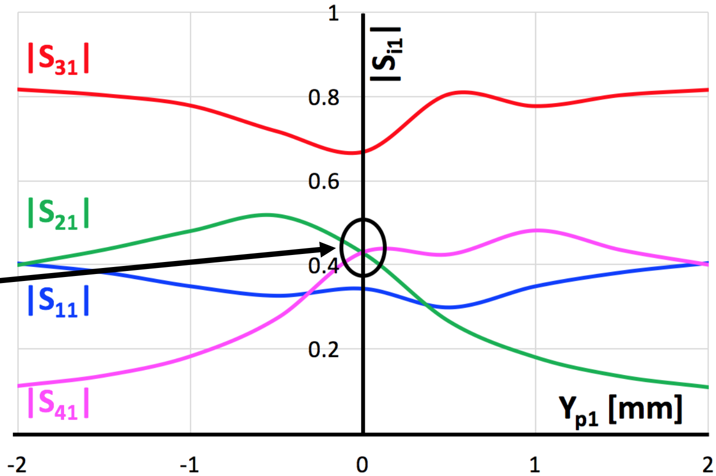
Unperturbed middle cell.
EM field simulation in HFSS
for port 1 excitation:

$|S_{41}|=|S_{21}|$

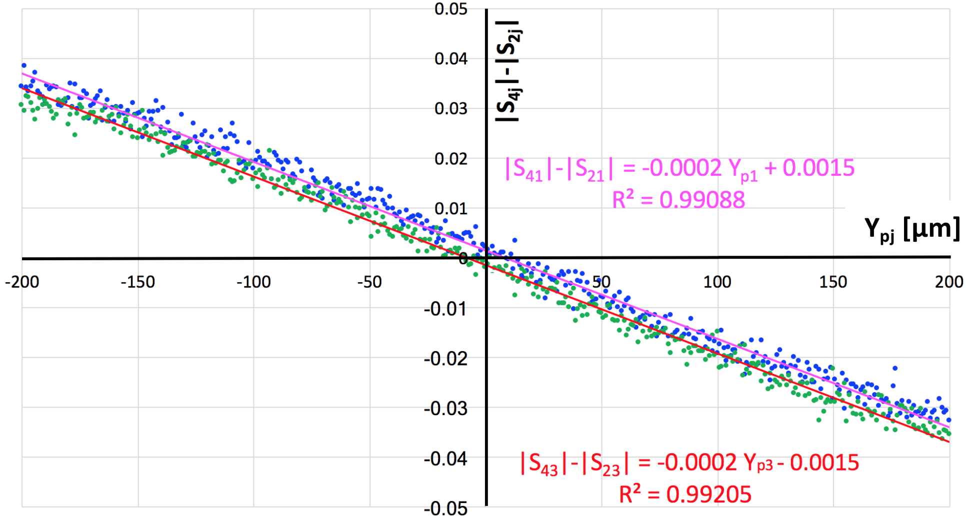


Perturbed middle cell.
S parameters as a function of vertical wire position

EM centre in Y: $|S_{41}|=|S_{21}|$



The perturbative method



Linear S parameter combinations to wire displacement:

$|S_{41}|-|S_{21}|=m_{y,p1} \cdot \mathbf{Y_{p1}} + a_{y,p1}$

$|S_{43}|-|S_{23}|=m_{y,p3} \cdot \mathbf{Y_{p3}} + a_{y,p3}$

Symmetric from EM centre, accounted as **theoretical accuracy limit ±7.5 μm**

Conclusions:

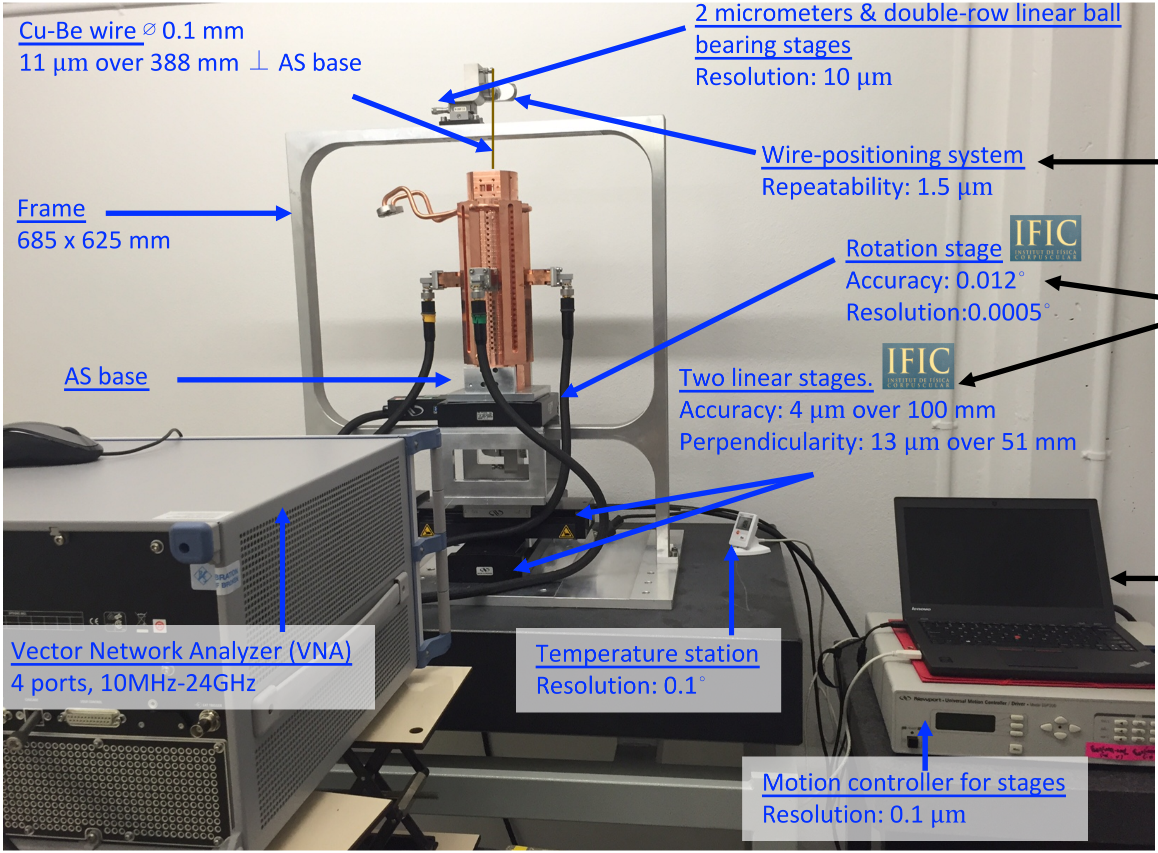
- **EM centre in Y** given by:

$$(|S_{41}|-|S_{21}|)+(|S_{43}|-|S_{23}|) = (m_{y,p1}+m_{y,p3}) \cdot \mathbf{Y_{p1+p3}} \; (a_{y,p1}+a_{y,p3})$$

- Similarly, **EM centre in X** given by:

$$(|S_{32}|-|S_{12}|)+(|S_{34}|-|S_{14}|) = (m_{y,p2}+m_{y,p4}) \cdot \mathbf{X_{p2+p4}} \; (a_{y,p2}+a_{y,p4})$$

Experimental stand-alone test bench at CERN



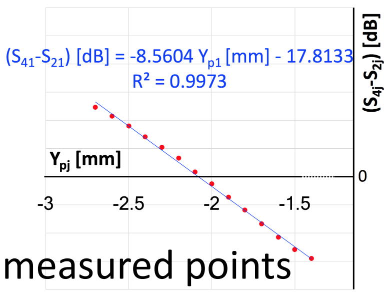
Fix the wire

Move the AS in 3 degrees of freedom

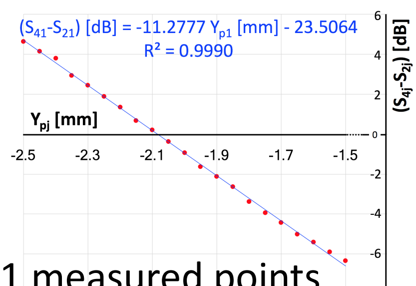
LabVIEW post-processing

First EM centre measurements using WFM

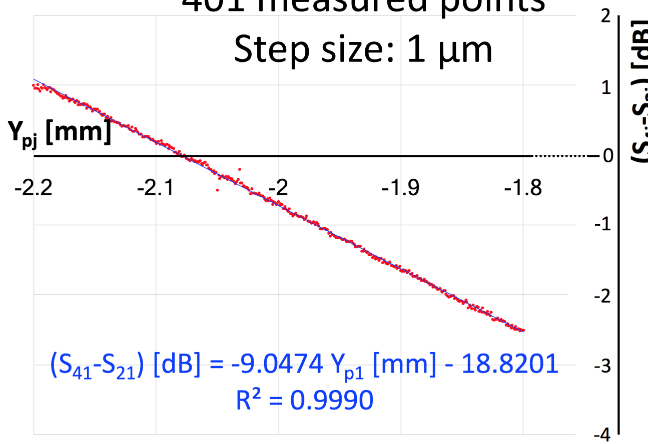
S parameter measurements with different travel ranges and step sizes. As expected, their combination follows a linear dependence with the wire displacement.



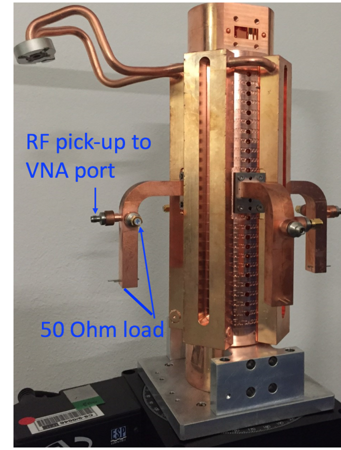
61 measured points
Step size: 100 µm



21 measured points
Step size: 50 µm



401 measured points
Step size: 1 µm



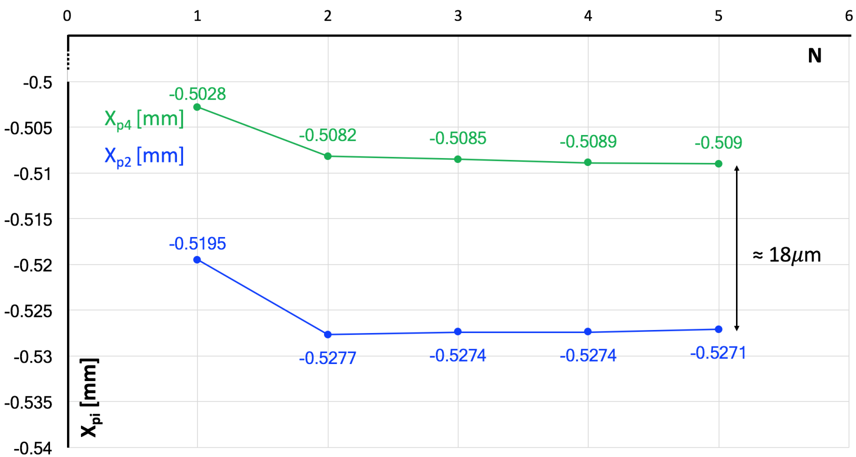
TD24 with WFM. Wire-positioning system not available at that time.

Conclusion:

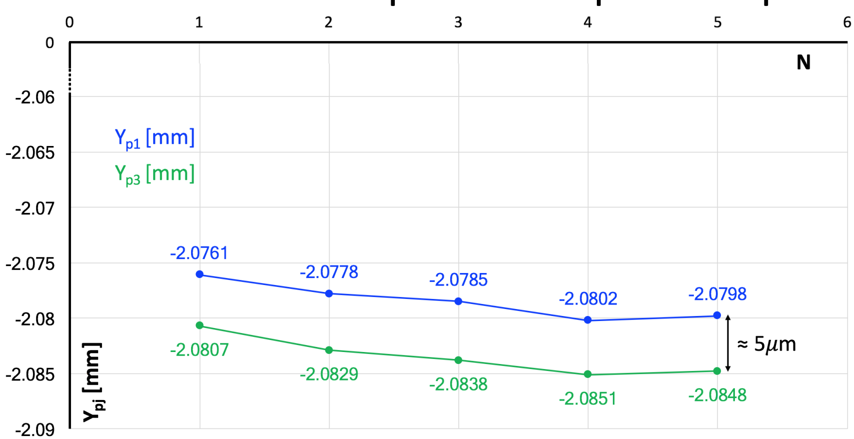
As we approach the required precision (1-2 µm), the signal to noise ratio increases.

First EM centre measurements using WFM

EM centre at every iteration N:



401 measured points. Step size: 1 μm



After the first iterations, **the centre as measured by each port converges** very rapidly into a unique value.

Different value of the centre found in each axis larger than simulations due to WFM optimised to extract HOM power signals instead of input RF. Difference accounted as **measurement error.**

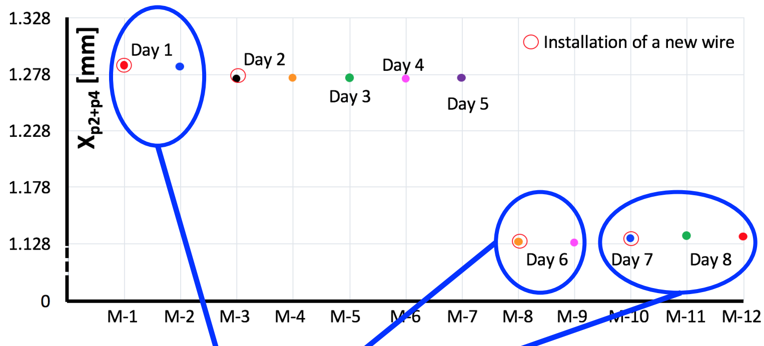
Conclusion:

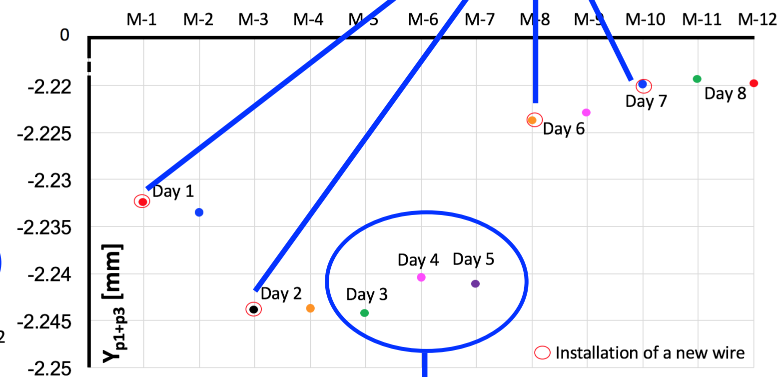
Measurement error improvement expected with full test bench calibrations and tapered transitions implementation in the middle cell replacing WFM.

EM centre measurements using tapered transitions

12 measurements of the EM centre in 8 different days under different experimental conditions for **repeatability analysis**:

Conditions are lost when installing a new wire





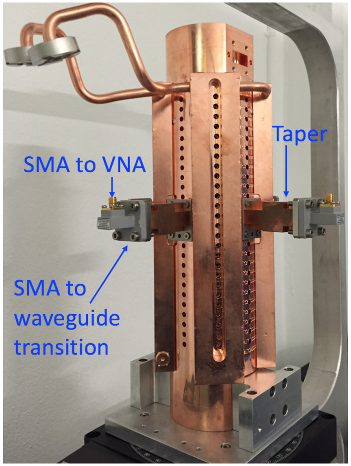
Same conditions of temperature, wire tension and VNA calibration. Repeatability better than **0.5 µm**

Fluctuation due to temperature rise.

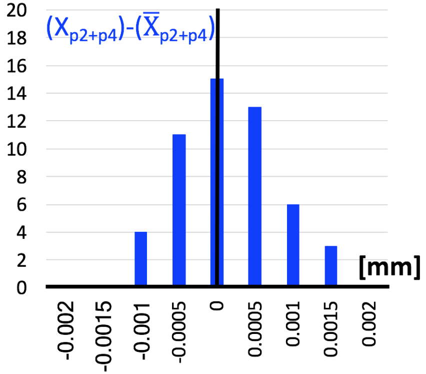
Repeatability better than **5 µm**

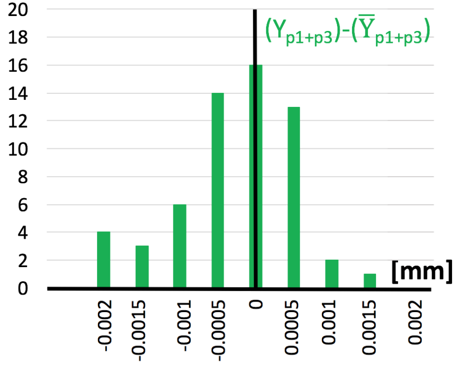
EM centre measurements using tapered transitions

64 consecutive measurements of the EM centre with full bench elements assembly, calibrations and optimised algorithm.



Precision: standard deviation calculated as the difference with respect to the average of each independent measurement.



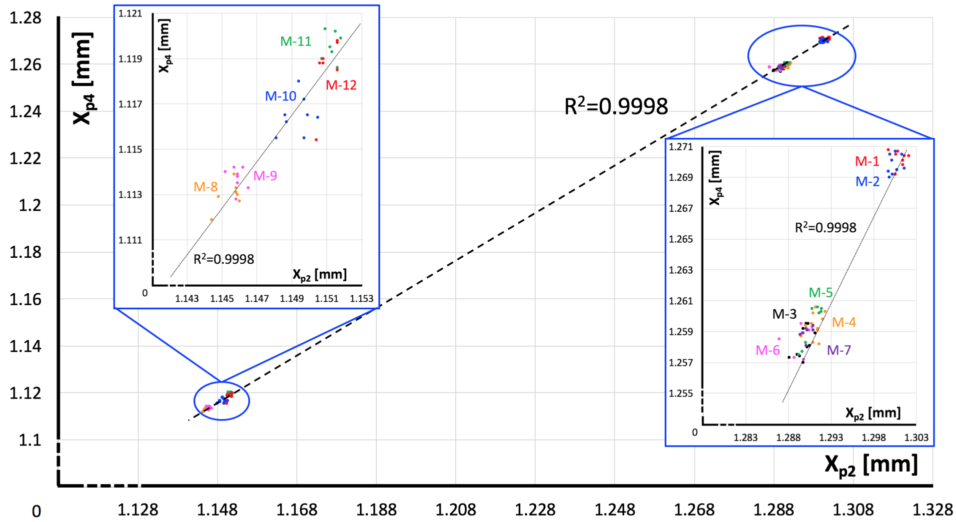


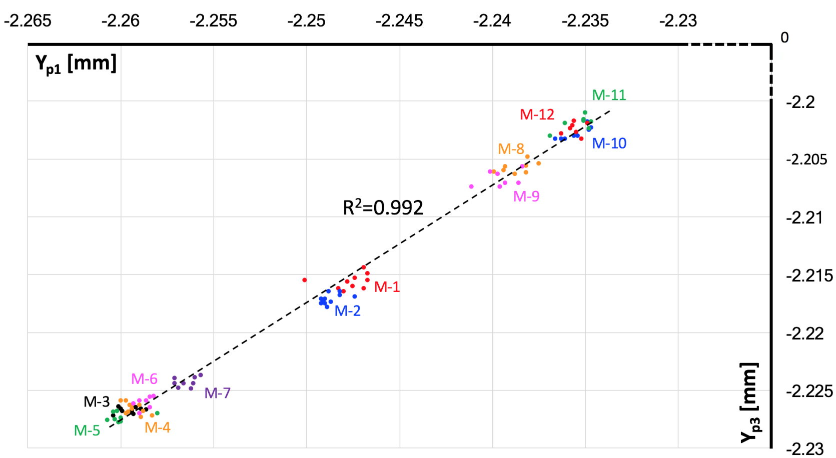
Precision in X = 0.63 μm **Precision in Y = 0.74 μm**

Error ≤ ± 8.5 μm

Conclusion:
Measurement **error below CLIC requirement** of 10 μm.

EM centre measurements using tapered transitions





Observed **correlation between the two centres**, found with the routinely combination of S parameters in both planes, thanks to the integration and calibration of the wire-positioning system.

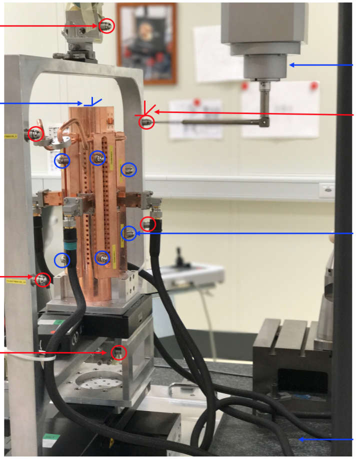
Conclusion:

Noise is not the origin of the measurement error.

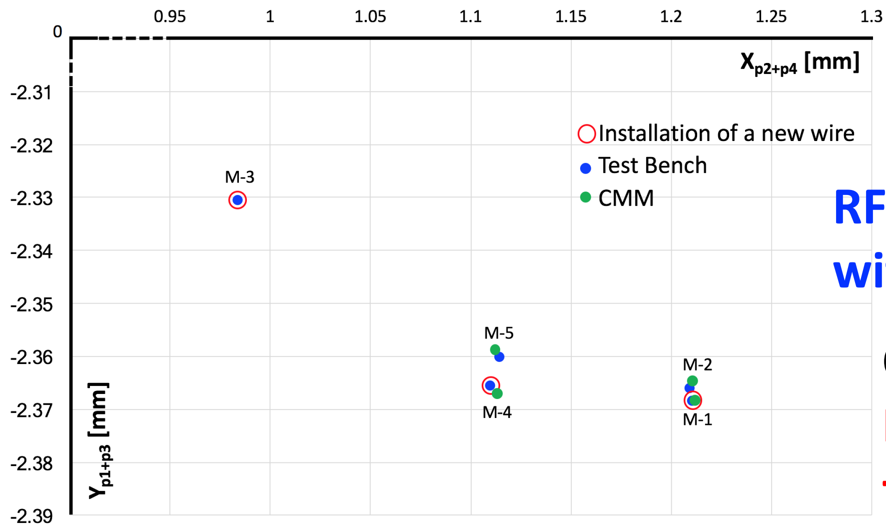
Repeatability analysis in the CMM at CERN

Procedure repeated 5 times:

1. Measure the EM centre (blue dots).
2. Bring the AS to the computed position.
3. Measure test bench fiducials with CMM.
4. Calculate relative AS position wrt absolute wire position (green dots).



Experimental test bench with fiducials.
Wire reference system: red circles.
AS coordinate system: blue circles.



RF measurements agree 0.5-2 µm with CMM relative movement

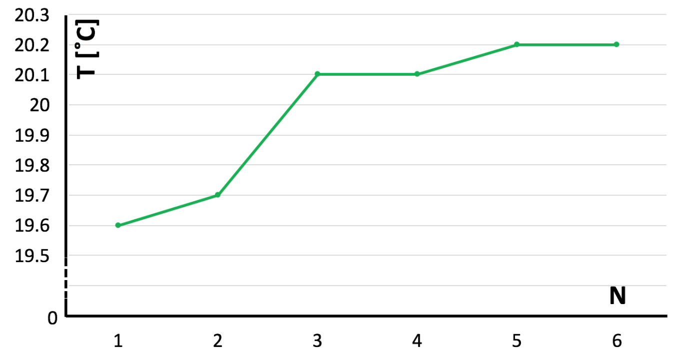
Conclusion:

Reliable method and test bench to measure the EM axes of AS.

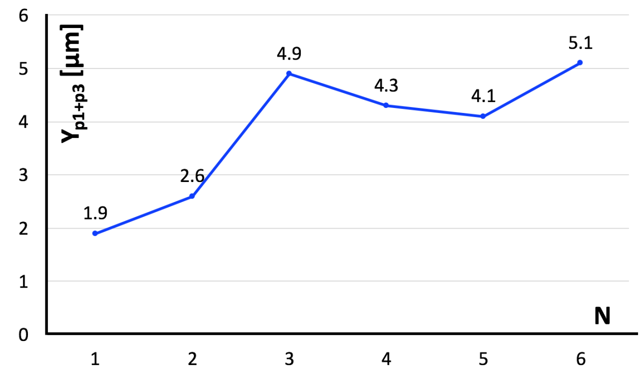
Influence of temperature

Data temperature monitored with respect to the progression of the EM centre in one axis:

Temperature, T, evolution during the EM centre measurement in Y:



Position of the measured EM centre in Y with respect to the iteration number, N:



Drift caused by temperature change: **0.5 µm/0.1°**.

Coupling between tapers and middle cell

EM centre measurements switching ports with each others:

Switching ports 2 and 4 modifies the symmetry in the cell in the Y axis

Experiment number	EM centre (X_{p2+p4},Y_{p1+p3}) [mm]	Precision (X,Y) [μm]
1	(0.7139, -2.3280)	(0.30, 0.65)
2	(0.7031, -2.5431)	(0.28, 0.67)
3	(0.7571, -2.5446)	(0.26, 0.28)

Precision is modified below 0.5 µm.

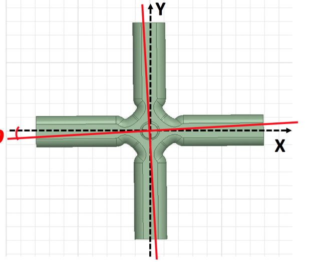
Switching ports 1 and 3 modifies the symmetry in the cell in the X axis

Conclusion:

Position of the EM centre is changed by a few µm in the disturbed axis.

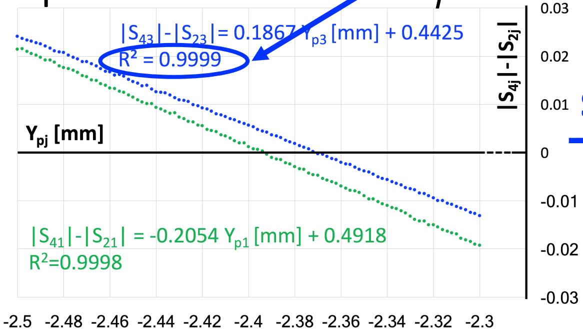
Rotate the TD24 around the longitudinal axis

VNA ports disconnected and connected back before applying the rotation.



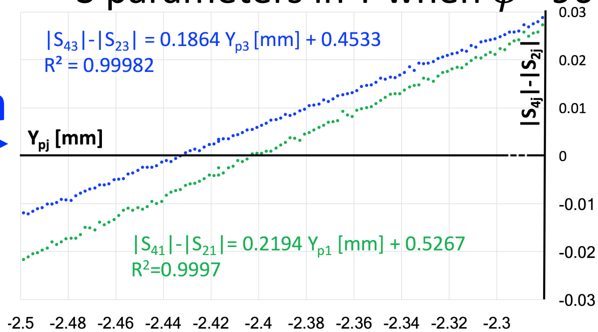
Rotation stage more stable at home position

S parameters in Y when φ =0°

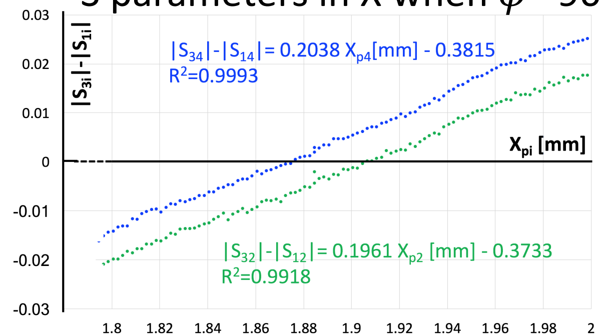


slope inversion

S parameters in Y when φ =90°



S parameters in X when φ =90°



Conclusion:

From simulations, parallel lines in X, contrary to Y, show that **errors come from the cell geometry and potential asymmetry**.

Conclusions

- We have developed a novel intra-cavity technique to measure the EM axes of accelerating structures by means of a stretched wire in a laboratory environment, named as the **perturbative method**.

- We validated the technique in the CLIC TD24 accelerating structure in a relatively inexpensive dedicated stand-alone test bench developed for this purpose. **Precisions** of **0.63 µm** and **0.74 µm** in the horizontal and vertical planes, respectively, are found at a controlled temperature. The **error estimation** is below **± 8.5 µm (compared to 10 µm required at CLIC)**, only 1 µm bigger than the theoretical accuracy limit found with EM field simulation studies in HFSS. Under the same conditions of temperature, wire tension and calibration of the VNA, **repeatability** was better than **0.5 µm**. When the experimental conditions were changed, repeatability was around 5 µm. These results were crosschecked in the CMM, whose agreement ranged from 0.5 µm to 2 µm.

- We have also analysed and laid down the **future lines of research**. They concern the cell-to-cell misalignment measurement, the measurement of the EM axes simultaneously in various cells and the development of a test bench to measure the EM axes of the TD24 parallel to the beam direction.

Thank you for your attention

Special thanks to:

Nuria Catalan Lasheras, Angeles Faus Golfe, Alexej Grudiev, Walter Wuensch, Manfred Wendt, Mika Dehler, Anastasiya Solodko, Serge Lebet, Pablo Sobrino Mompean, Philippe Guyard, Matteo Volpi, Andrej Olyudnin, Helene Minaud Durand, Mathieu Duquenne, Ahmed Cherif, Dominique Pugnat, Cyril Haerinck, Didier Glaude, Andrea Mostacci, Cesar Blanch Gutierrez, Juan Jose Garcia Garrigos, Guy Deferne, Olaf Dunkel, Wilfrid Farabolini, Luis Navarro, Reidar Lunde Lillestol, Botond Barabas, Peter Nemeti and all the PACMAN team.

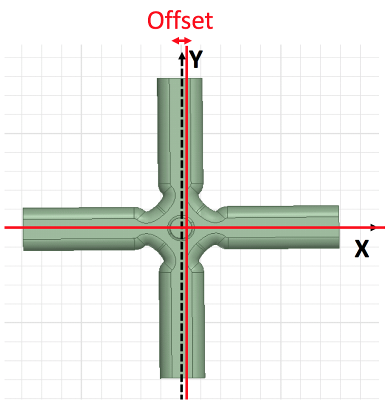
CLIC Workshop, CERN, Switzerland
January 2018

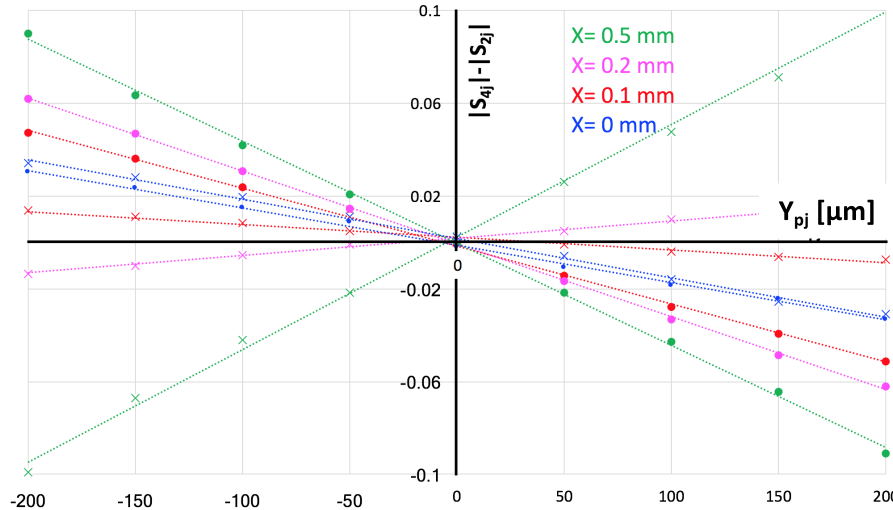
UNIVERSITAT POLITÈCNICA DE VALÈNCIA CERN CLIC PACMAN IFIC INSTITUT DE FÍSICA CORPUSCULAR

Characterization of errors with HFSS

WIRE OFFSET WITH RESPECT TO THE TRANSVERSE PLANE

We simulated a wire moving linearly 400 µm along Y in steps of 50 µm, while its position in X was fixed:



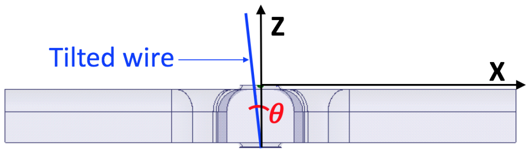


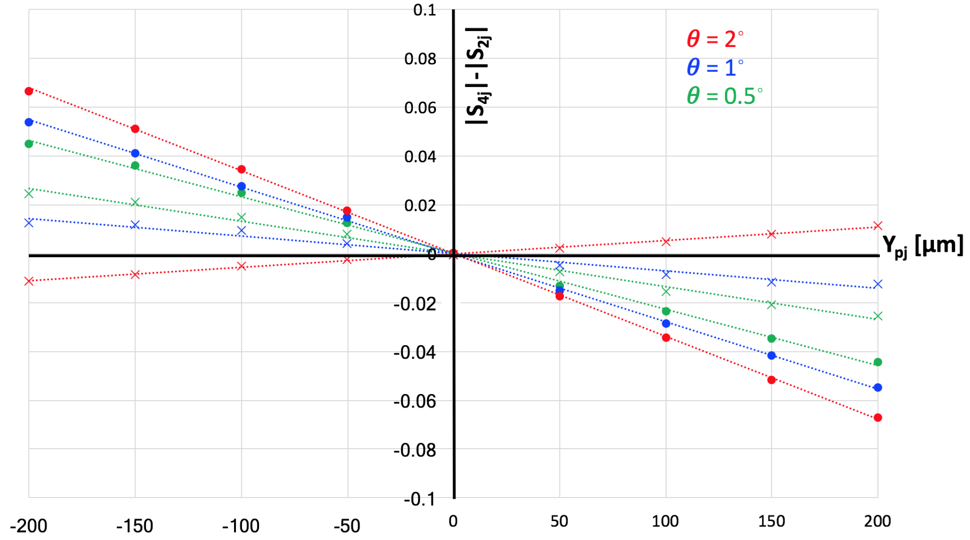
- Results:
    - The slopes increase with the wire offset.
    - S parameters are around zero at the position of the geometric centre, even for off-centred wires.
- Therefore, we can estimate how close the wire is from the centre by comparing the slope of both measurements from opposite ports.

Characterization of errors with HFSS

TILTED WIRE IN THE LONGITUDINAL AXIS

We simulated a tilted wire moving linearly 400 µm along Y in steps of 50 µm, while its position in X was fixed at 0:





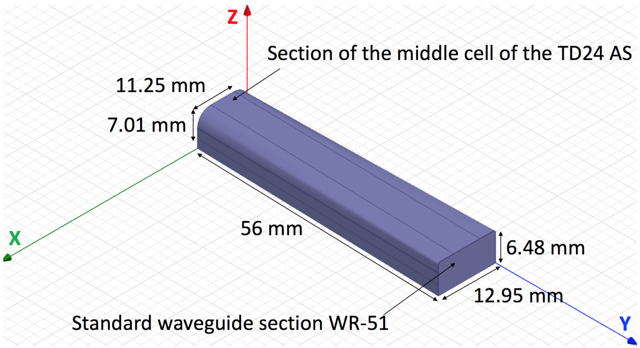
- Results:
  - For all the simulated θ, AM are around zero at the position of the geometric centre.
  - $m_{y,p1} \neq m_{y,p3}$, so the localisation of the EM axes is not inherent to the tilt.
  - Only sensitivity at ports localised in the direction of the tilted axis is affected.

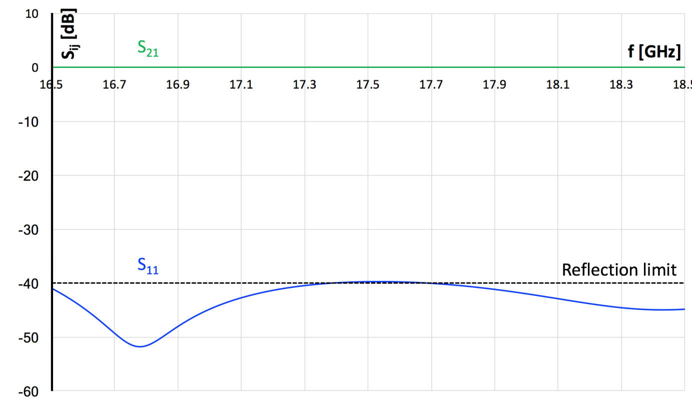
Characterization of errors with HFSS

COUPLING BETWEEN THE MIDDLE CELL AND THE TAPERED TRANSITIONS

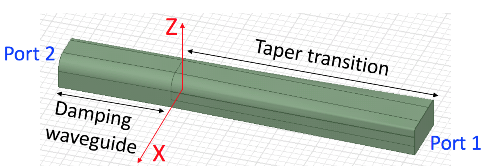
We performed the design of tapered transitions with low reflections, in HFSS, to be connected at the end of the damping waveguides in the middle cell in order to replace the WFM signals. Advantages:

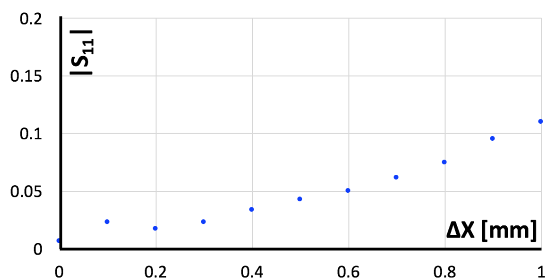
- Symmetry in the cell.
- No RF loads at the end of the WFM, increasing level to noise ratio and decreasing resolution.

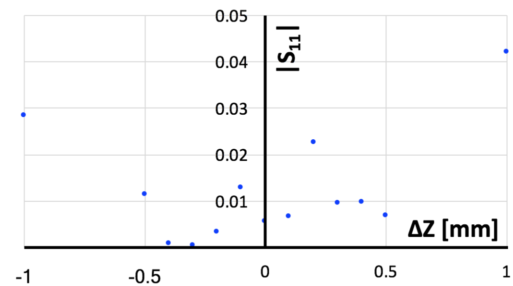




We simulated different couplings between a piece of damping waveguide connected to a tapered transition, by shifting in Z and X. The coupling in X affects more than in Z:





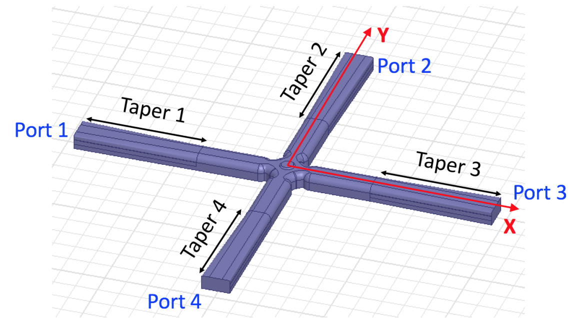


Simulating different cou

COUPLING BETWEEN THE MIDDLE CELL AND THE TAPERED TRANSITIONS

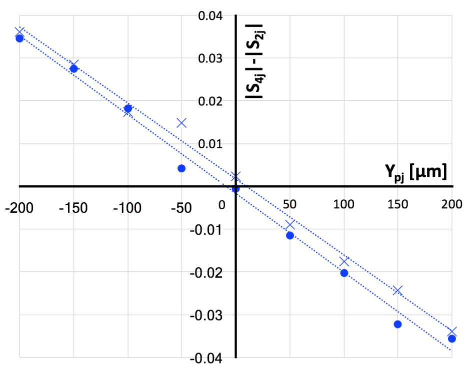
The effect of the global coupling was studied connecting all the tapers at the end of all the damping waveguides, and moving the wire along 400 µm in Y in steps of 50 µm. We performed 3 simulations changing the coupling as follows:

1. Perfect coupling between all tapers and waveguides.
2. Taper 3 shifted 1 mm in Z.
3. Taper 3 shifted 1 mm in Z and taper 2 shifted 1 mm in X



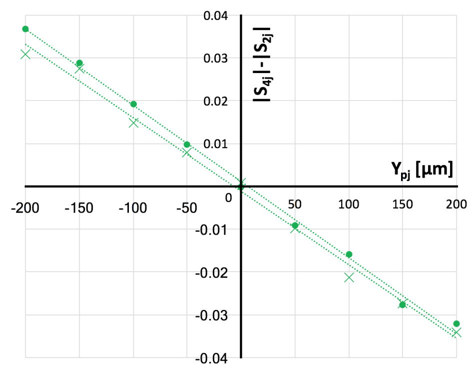
Results: as expected, the position measured for the EM centre is affected by the coupling. We need to achieve a mechanical coupling in all tapered transitions lower than 1 mm to keep the measurement of the EM centre under the requirements of precision.

S parameters from simulation 1



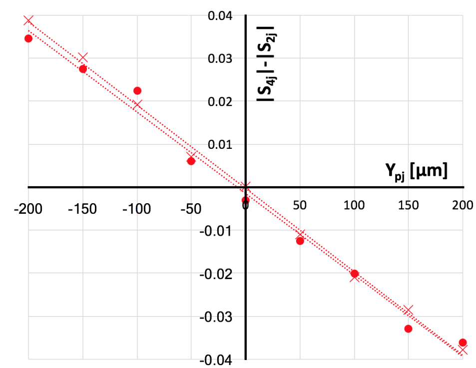
$Y_{p13} = 0$

S parameters from simulation 2



$Y_{p13} = 0$

S parameters from simulation 3



$Y_{p13} = 1.5$ µm