High accuracy alignment of accelerator components

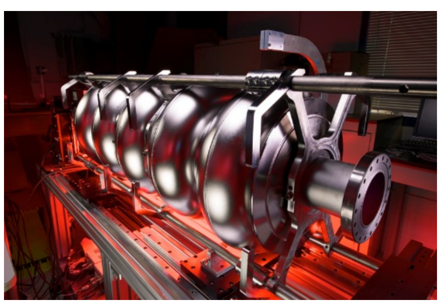
Silvia Zorzetti

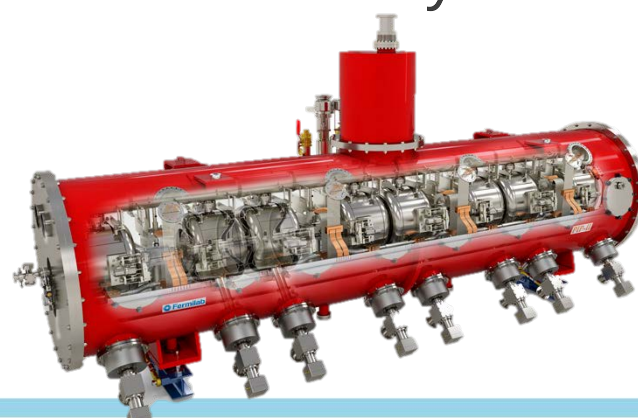
LCWS 2018

Outline

Pre-alignment of the CLIC components

Relative alignment of the PIP-II cryomodules

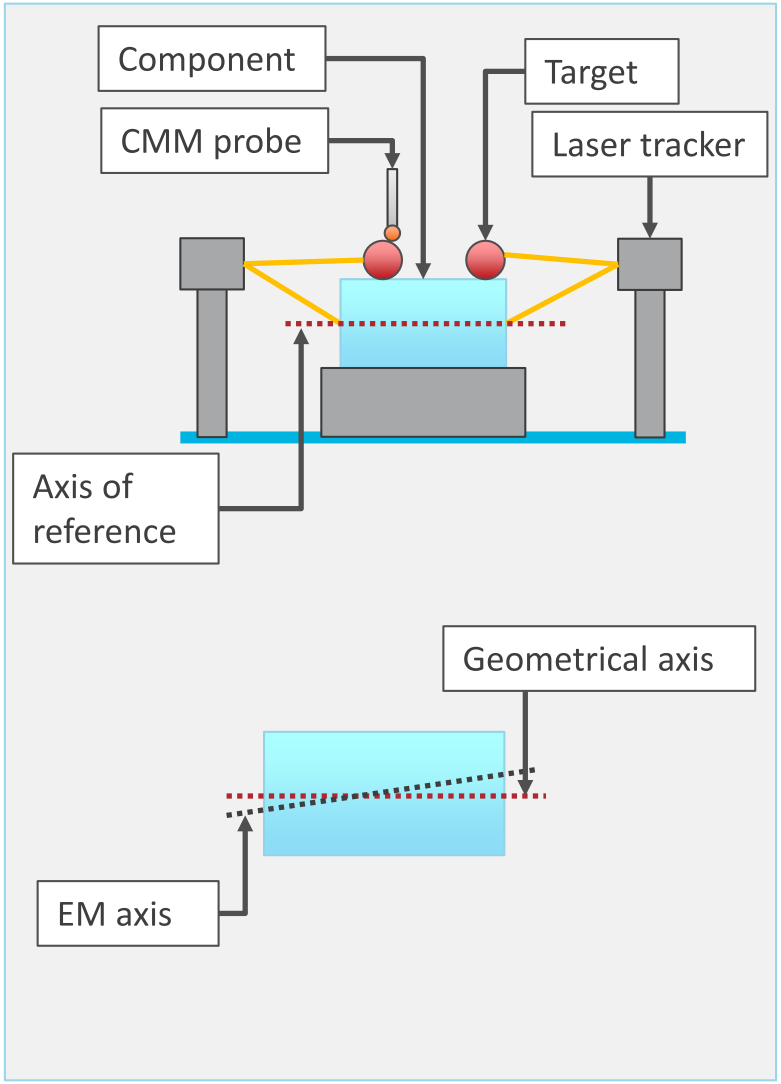




Accelerator components fiducialization

- Each component is equipped with exteral targets (fiducials). The position of the point of interest, e.g. geometrical axis is referred to those points
  - Laser tracker, CMM and other tools to refer the axes position
- Absolute position and tolerances are the results of beam simulations and studies

- The geometrical and electromagnetic axes may not match due to manufacturing imperfections and tolerances in the design
  - Aligning on the geometrical center is preferrable, but it needs to be understood if the offset is within the beam dynamics specifications

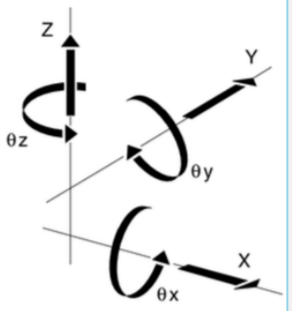


H. Mainaud Durand, 10th LC School - Alignment

Alignment and position monitoring

Single components fiducialization

- Degrees of freedom (DOF)
  - Usually 4DOF



Alignment on a common support

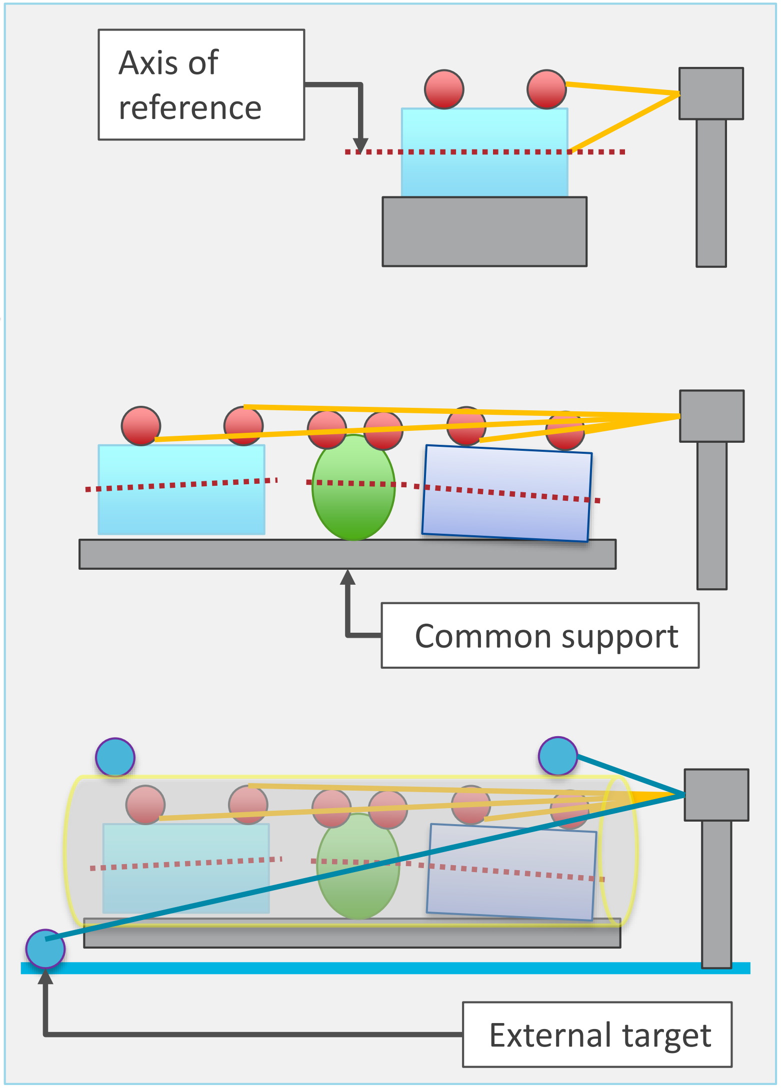
- The components in a module or cryomodule are aligned on a common support with reference to external fiducials

Final alignment in the tunnel

- Based on cryomodule fiducials and wire measurements

Relative alignment

- Components position monitoring



H. Mainaud Durand, 10th LC School - Alignment

Alignment challenge for the CLIC experiment at CERN

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1400	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		354	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	80	80/100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	2.3	3.2	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	1.4	1.3	2
Main tunnel length		km	13.2	27.2	48.3
Charge per bunch	N	10^9	6.8	3.7	3.7
Bunch length	σ_z	μm	72	44	44
IP beam size	σ_x/σ_y	nm	200/2.6	∼ 60/1.5	∼ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	2350/20	660/20	660/20
Normalised emittance (IP)	$\varepsilon_x/\varepsilon_y$	nm	2400/25	—	—
Estimated power consumption	P_{wall}	MW	272	364	589

Large scale accelerators

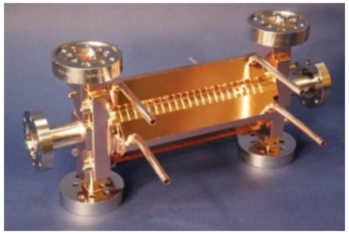
Sub-am beam size

- Two linear accelerator of about 20km in length
- 20k modules
- Small beam size (nm) translates in very stringent alignment requirements for the emittance preservation

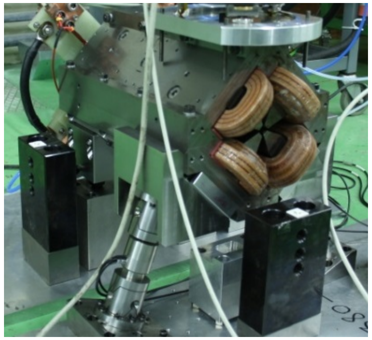
The PACMAN Project

***P**article **A**ccelerator **C**omponents' **M**etrology and **A**lignment to the **N**anometre scale*

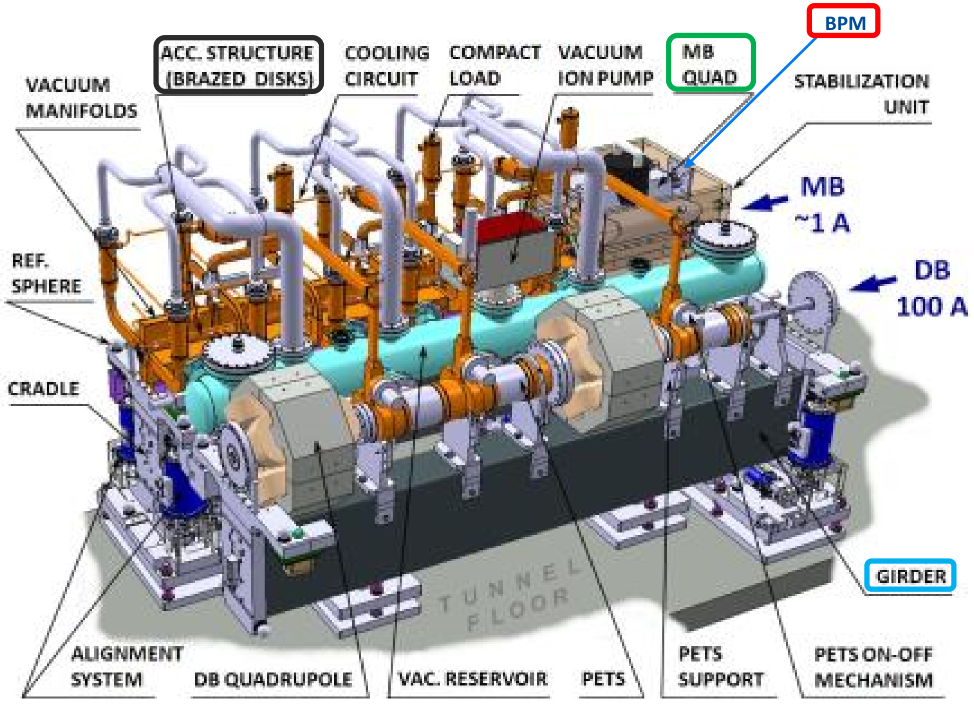
- Funded under the European Union's 7th Framework Program Marie Sokolowski-Curie actions, with the technical development supported by the CLIC experiment.
- Development of an innovative, accurate and time-efficient strategy for the pre-alignment of accelerator components
- Industrial and academic network – 10 Ph.D. students – Sept. 2013 to Aug 2017



Accelerating structure Normal conducting cavity



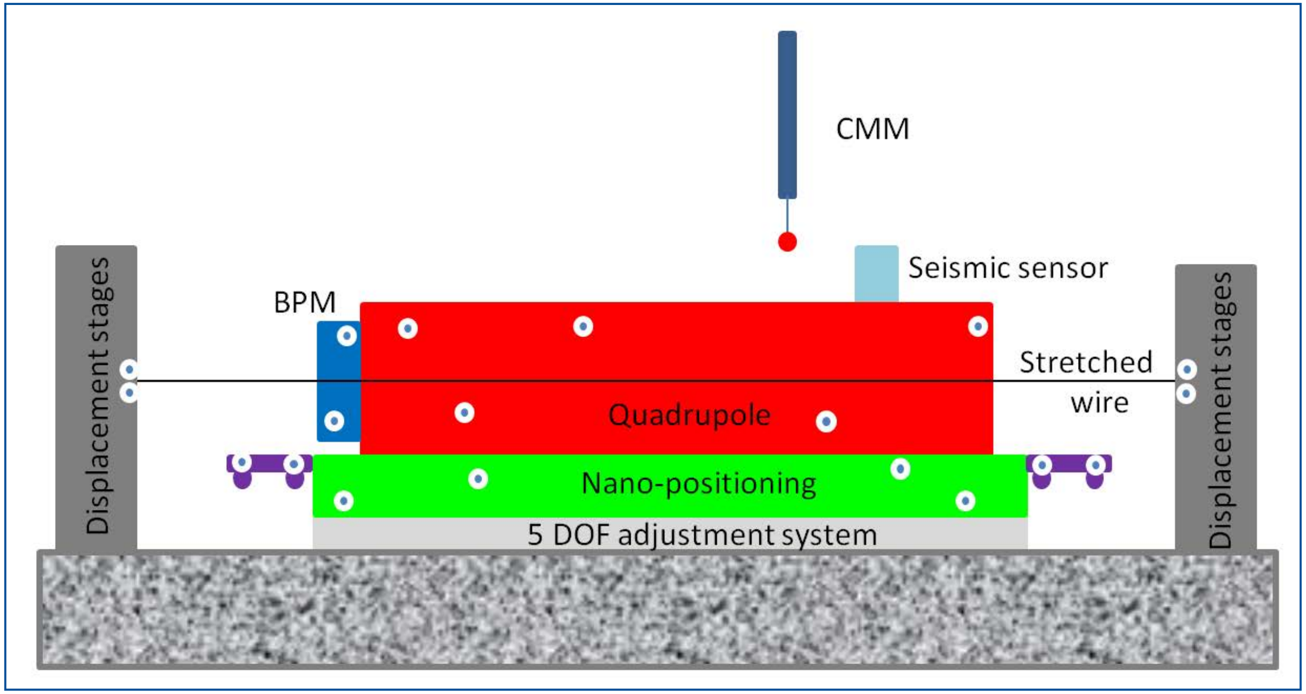
Main Beam Quadrupole



Beam Position Monitor (BPM)

Alignment on a common girder

Prototype alignment bench



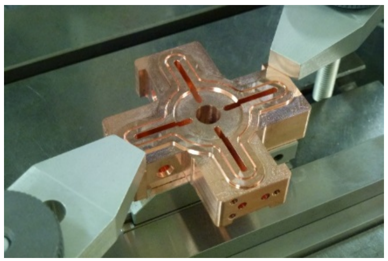
Alignment requirements

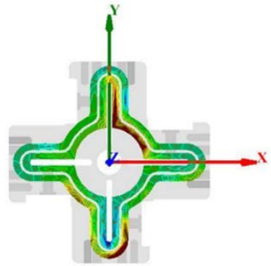
- BPM, AS:
  ± 14 µm over 200m
- MB Quad:
  ± 17 µm over 200m

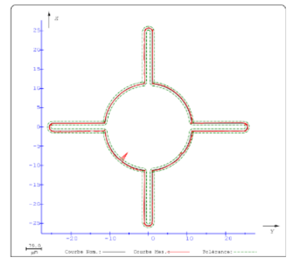
- RF measurements on the BPM
- Vibrating wire characterization of the quadrupole
- Mechanical alignment
- Fiducialization of the single components and the common module
- A vertical test bench was used for the alignment study on the accelerating structures

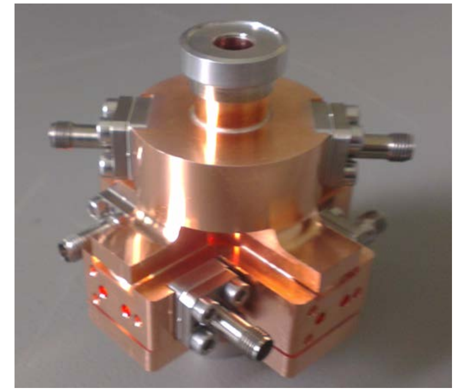
BPM characterization

- A calibration is needed to understand the geometrical to electromagnetic offset of the components, due to manufacturing and brazing
- Metrology survey of the RF-BPM

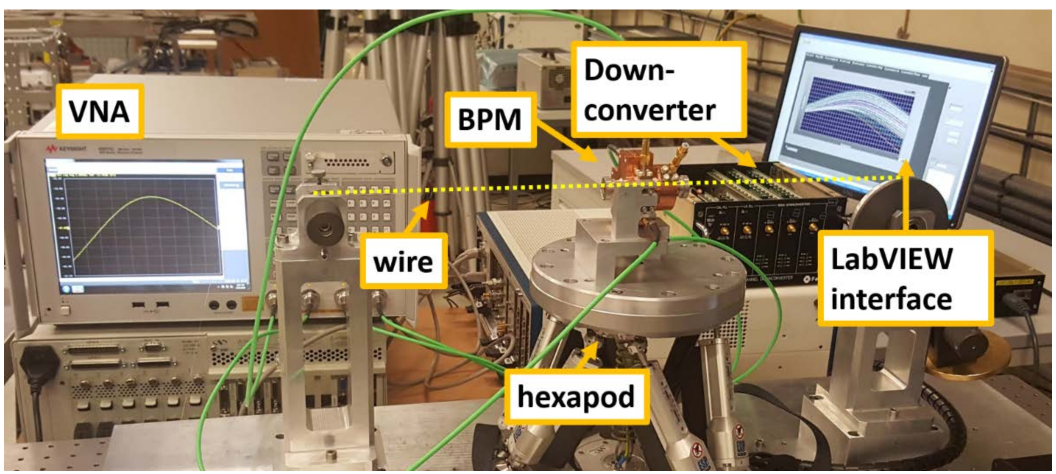








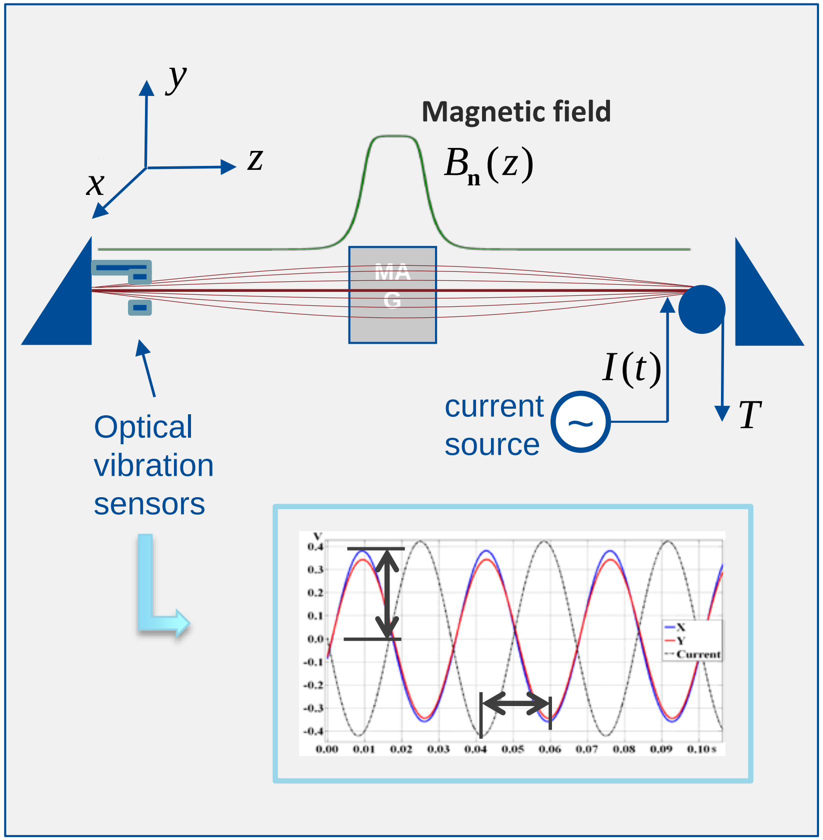
- A standalone test bench was developed to perform stretched wire measurements using an accurate, automated and time-efficient procedure



- RF measurements at 15GHz
- Study of the RF perturbation introduced by the wire
- A similar bench was used to demonstrate the nanometric resolution of the cavity BPM (~ 12nm)

Quadrupole characterization

State of the art / Vibrating/oscillating wire method



Feeding the wire by alternating current (Lorentz force)

⇩

Measure wire vibrations (X and Y components)

⇩

Relate vibrations to magnetic field

- High sensitivity also for low field and small apertures
- Used in particular for alignment and magnetic field quality (multipoles)

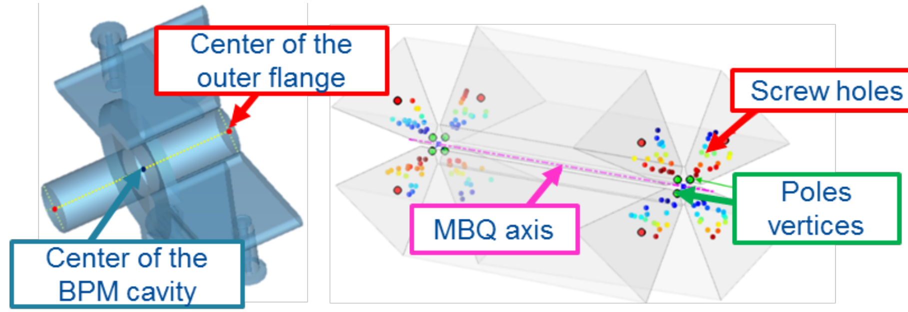
- **A. Temnykh**. "Vibrating wire field-measuring technique". *Nuclear Instruments and Methods in Physics Research,* **1997**.
- **P. Arpaia, M. Buzio, J. G. Perez, C. Petrone, S. Russenschuck, L. Walckiers**. "Measuring field multipoles in accelerator magnets with small-aperture by an oscillating moved on a circular trajectory". *JINST – Journal of Instrumentation,* **2012**.

P. Arpaia, **D. Caiazza** et al. - Correcting for background fields and multipole field errors in the localization of the magnetic axis in quadrupole magnets, 2018NIMPA.895..112A

Mechanical interface

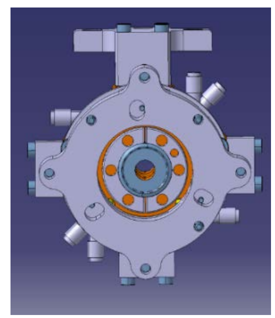
Mechanical axis

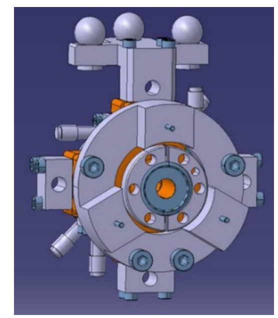
- Components assembled through the geometrical axis
  - BPM axis through the external flanges
  - Quadrupole through the center of the poles
  - From the calibration we know that the offset will fall within the linear region of the BPM

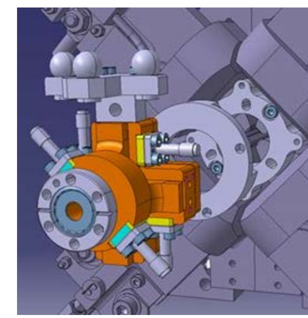


Design

- Two complementary mechanical parts to attach the BPM and the MBQ
  - Quadrupole interface: three concentric ellipses that center the mechanical axis of the quadrupole;
  - BPM interface: three pins matching the slotted holes on the complementary part.

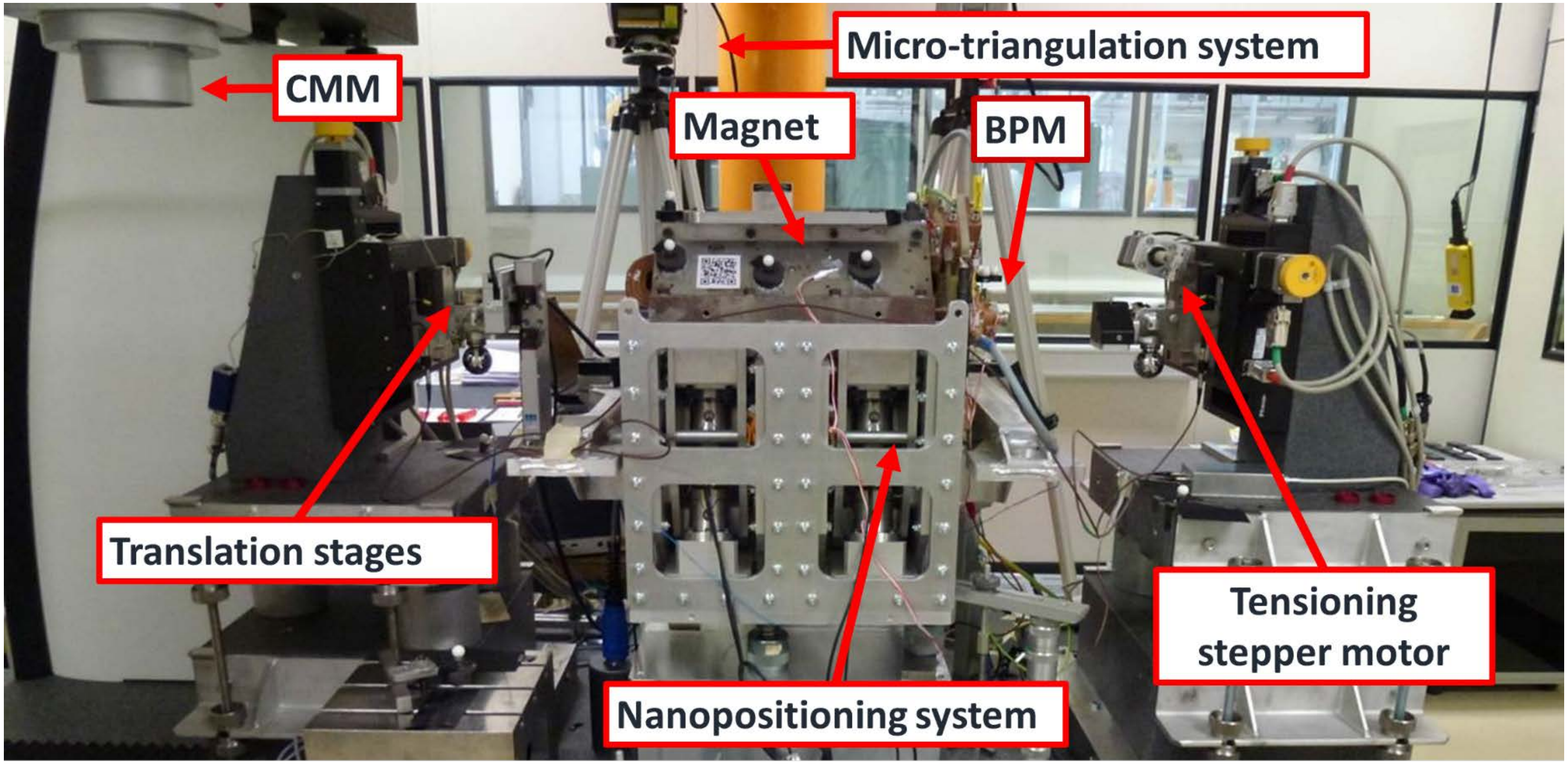






Design, measurements and manufacturing from K. Artoos, F. Morel, P. Naisson, V. Vlachakis, D. Caiazza and the metrology workshop at CERN

The prototype alignment

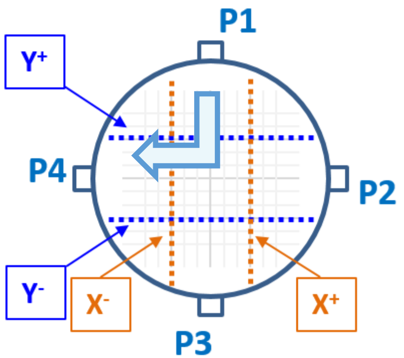


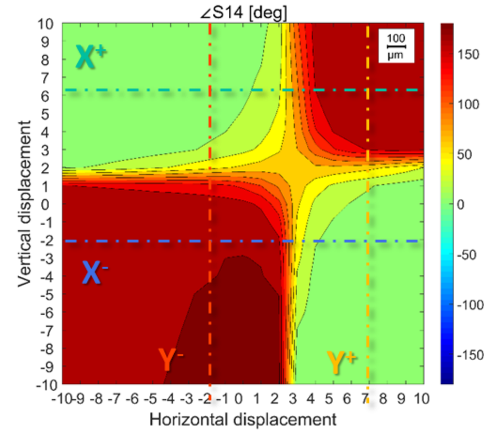
- The centers of the quadrupole and the BPM are located using respectively vibrating and stretched wire measurements methodologies
- Fiducialization: the position of the axis is referred to external targets
- Main achievement: measurement uncertainty below 5µm

D. Caiazza, N. Catalan Lasheras, H. Mainaud Durand, M. Modena, C. Sanz, D. Tshilumba, V. Vlachakis, M. Wendt, and S. Zorzetti - New solution for the high accuracy alignment of accelerator components Phys. Rev. Accel. Beams 20, 083501

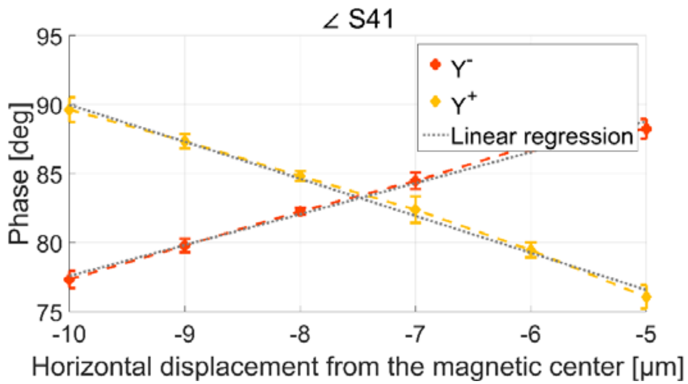
CLIC Module, final alignment measurements

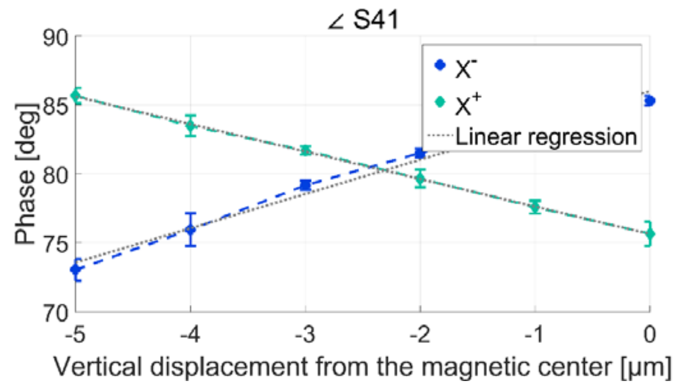
- **The magnetic axis of the quadrupole is located through vibrating wire measurement**
- **The electrical center of the BPM is located through stretched-wire measurements**
- Measure of the electromagnetic offset between the two components





Step size Δ = 1µm





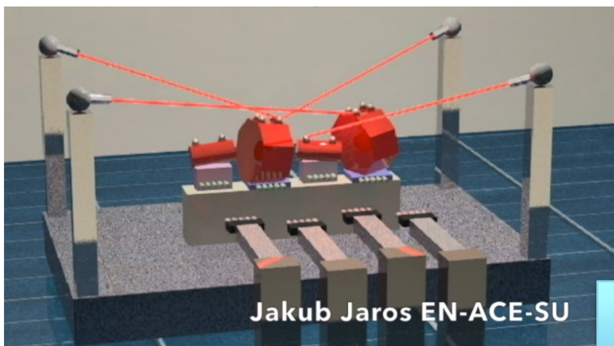
7.5 µm on the horizontal axis

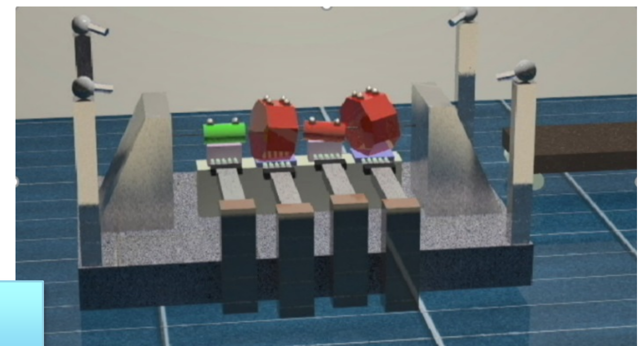
2.3 µm on the vertical axis

S. Zorzetti, Ph.D. Thesis - Radio frequency characterization and alignment to the nanometer scale of a beam position monitor for particle accelerators

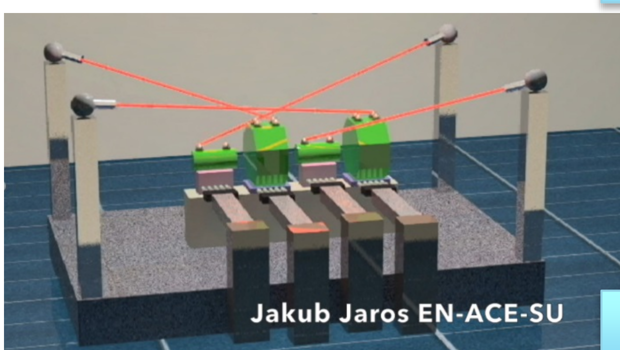
PACMAN proposals for the CLIC alignment

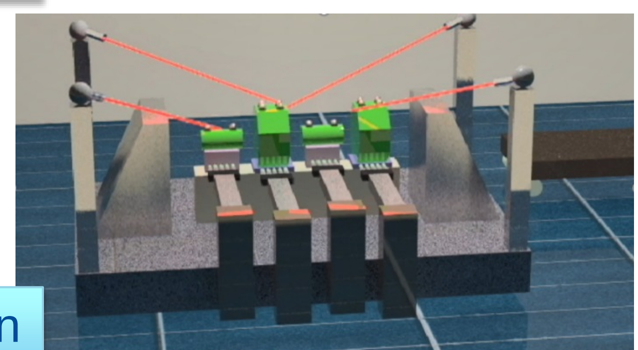
- Fiducialize each component using stretched-wire measurements
- Fiducialize the components on the same support through stretched/vibrating wire
- Components aligned by means of plug-in systems
- FSI and micro-triangulation technologies for portable and accurate measurements





Alignment





Fiducialization

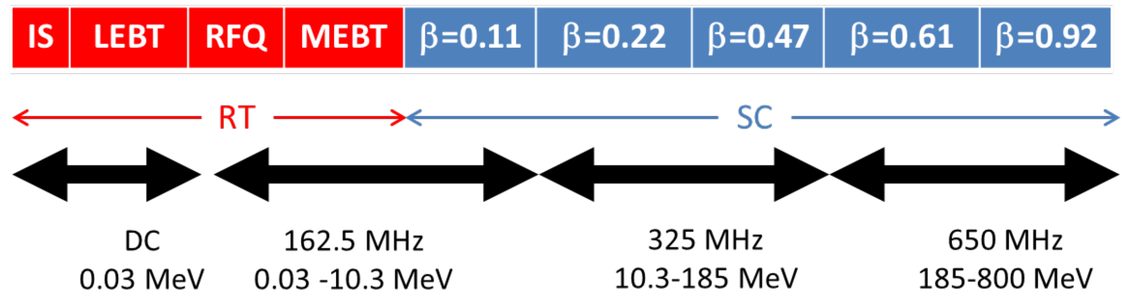
H. Mainaud Durand - CLIC pre-alignment strategy: final proposal and associated results – IWAA 2018

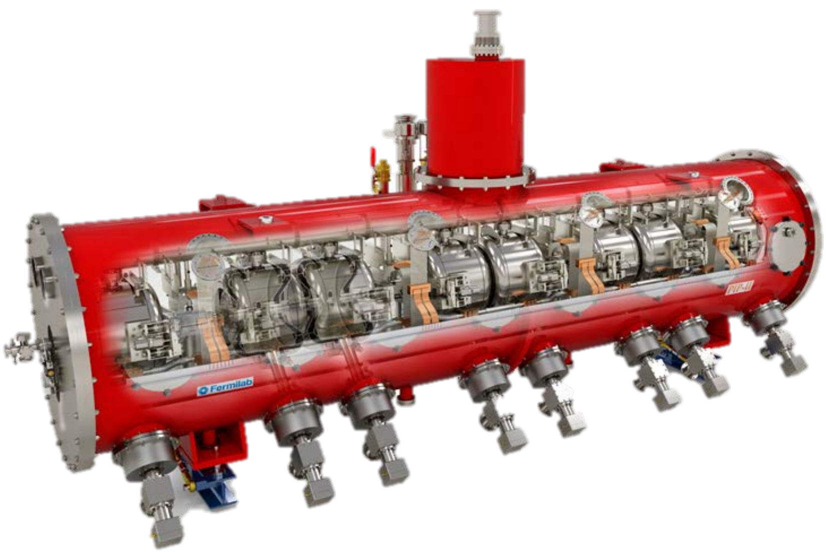
PIP-II – SSR1 cryomodule alignment

Fermilab is planning to enhance the capabilities of the existing accelerator complex to support the delivery of 1.2 MW proton-beam power for a world-leading neutrino program over the next several decades.

Proton Improvement Plan-II (PIP-II)

- an 800-MeV superconducting linear accelerator
- five types of superconducting cavities,
- 25 cryomodules





- **Alignment requirements for the SSR1 Cryomodule**

Transverse cavity alignment error, mm RMS	<1
Angular cavity alignment error, mrad RMS	≤10
Transverse solenoid alignment error, mm RMS	<0.5
Angular solenoid alignment error, mrad RMS	<1

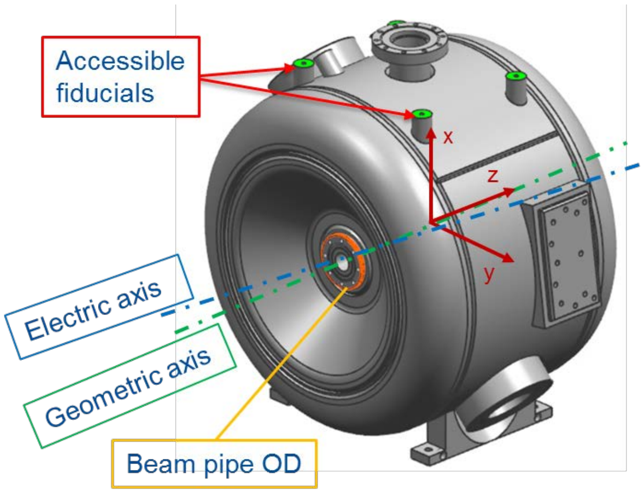
- **Cryomodule in the tunnel:** maximum deviations of the vacuum chamber alignment from the reference straight line should not exceed 5% of its aperture or about 1.5 mm.

D. Passarelli - Alignment strategy of the SSR1 cryomodule for the PIP-II project at Fermilab – 3rd PACMAN workshop

SSR1 Cavity calibration

<u>**SSR1 Cavity**</u>

- Bead pull measurements to identify the electrical axis
- Laser tracker used to define the geometric axis
  - Data cross-check with CMM measurements
- Electric to geometric offset from 0.31 mm ÷ 3.59 mm

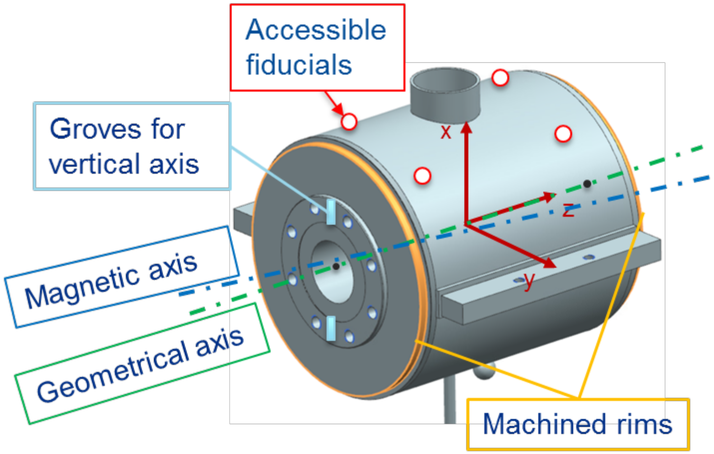


- **Cavities will be aligned on geometric axis** since the transverse kick induced on particles traveling on geometric axis have been found to be within the dipole corrector range and a beam trajectory deviation inside the cryomodule is within acceptable value
  - An alignment on the electrical axis would result in a reduction of the beam aperture

Solenoid and BPM characterization

Solenoid

- Vibrating wire at room temperature
- Rotating probe at 4K
- Results meet the specifications



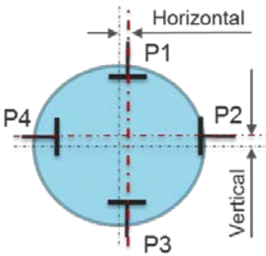
System ID	Probe position Z (mm)	ΔX (μm)	ΔY (μm)	dX/dZ (mrad)	dY/dZ (mrad)
C-1856M	-64	-93	-54		
	+64	-24	-135	+0.54	-0.135
C-1896M	-64	+39	+67		
	+64	-64	+45	-0.8	-0.17
C-1897M	-64	0	103		
	+64	-70	25	-0.55	-0.61
C-1898M	-64	75	-43		
	+64	63	75	-0.09	+0.92
C-1899M	-64	-57	-81		
	+64	59	-34	0.91	+0.37

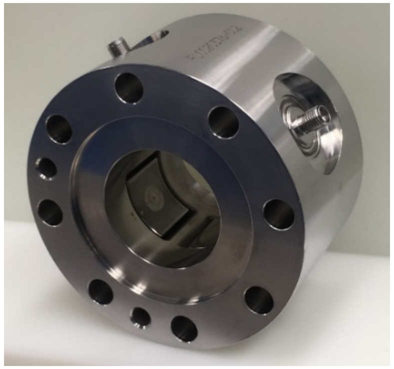
Summary of the magnetic axis position in the SSR1 lenses

Transverse solenoid alignment error, mm RMS	<0.5
Angular solenoid alignment error, mrad RMS	<1

Button BPM

- Linear region anticipated by simulations
- Stretched-wire to locate the electrical center
- Misalignment in the order of 0.3mm

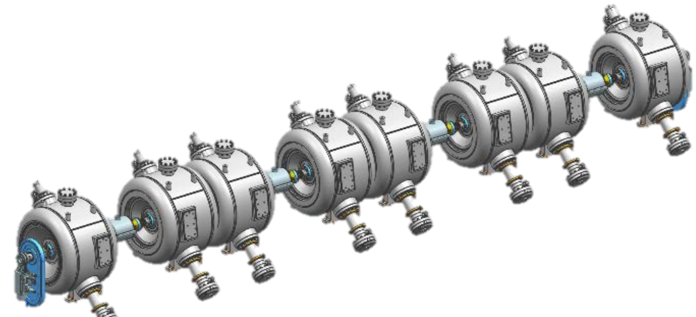


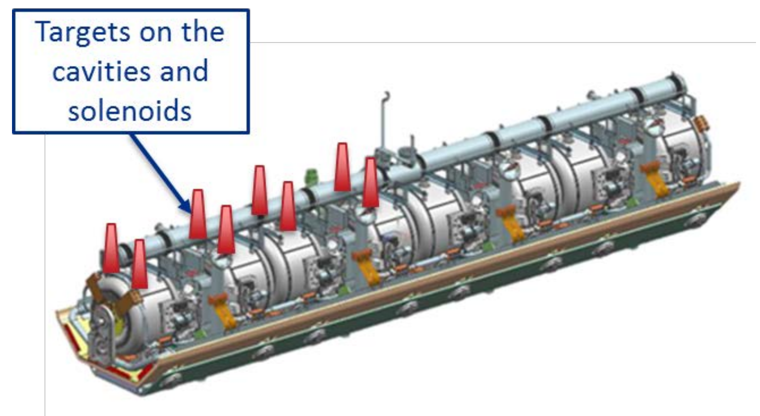


The alignment proposal for the SSR1 cryomodule

String assembly and cold mass alignment

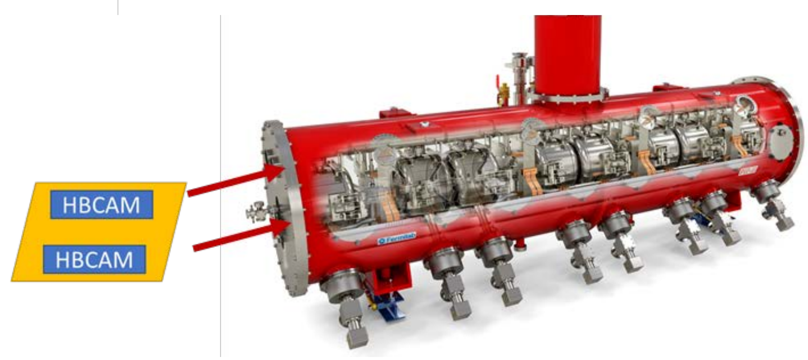
- Initial alignment of the components on a common support
- Align the key components with reference to their fiducials by using laser tracker
- Accessible fiducials to align the cryomodule axis in the tunnel





Relative alignment

- **Position monitoring during tests, transportation, cool down, warm up**
- Use imaging techniques (HBCAM) to monitor the alignment of the cavities and solenoid
- New proposal for a more accurate reading



The HBCAM technology

- HBCAM (BCAM evolution): Brandeis CAMera
  - Developed by Brandeis University for the alignment of the ATLAS experiment at CERN
  - Produced by OSI (Open Source Instruments, based in the USA

- Specifications
  - Radiation tolerance: 475 Gy (not in the cryomodule)
  - Resolution angle: 5urad
  - Accuracy: 50um, can be improved with calibration

- Measurement principle
  - Image reading on CCD sensors

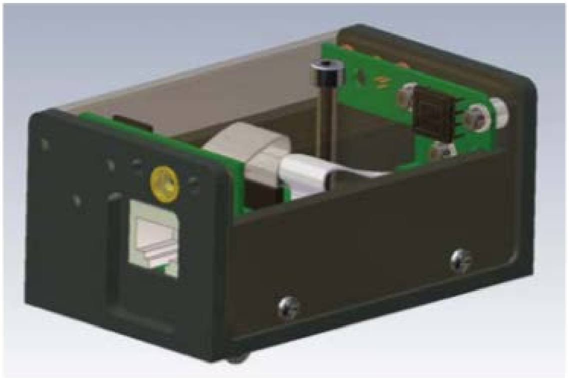


Figure 1: CAD drawing of a double ended BCAM, containing two cameras and four laser diode light sources. The enclosure is 91 mm long. The lid is shown transparent.

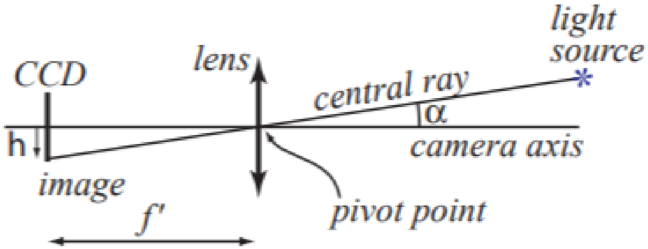
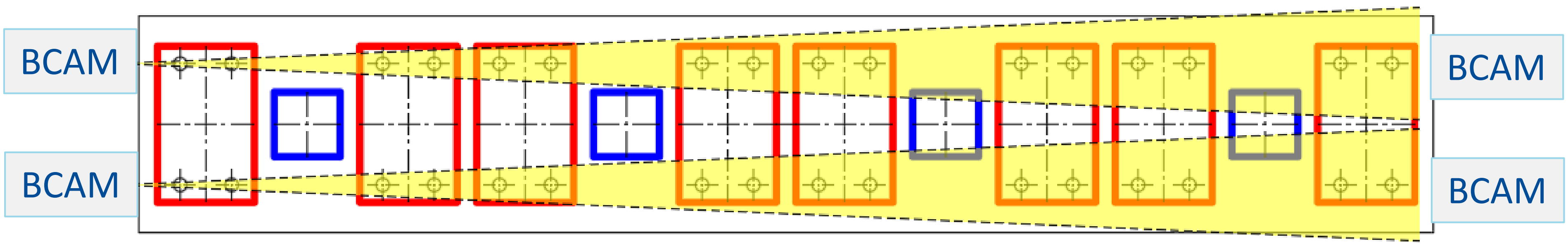


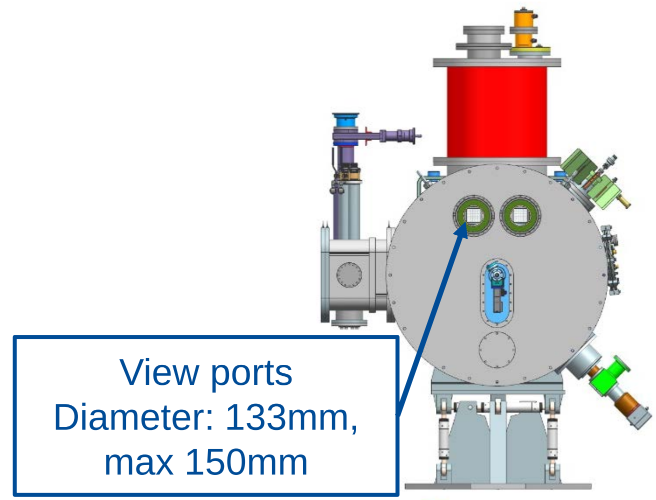
Figure 2: The measuring principle of a BCAM.

Brandeis University High Energy Physics Electronics Shop

The alignment design for the SSR1 cryomodule

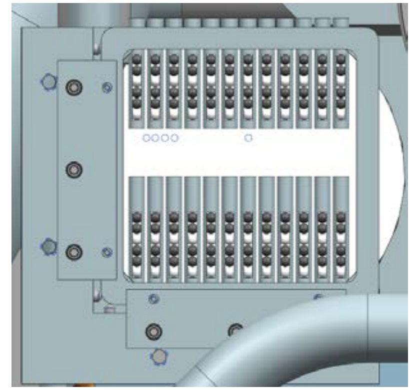


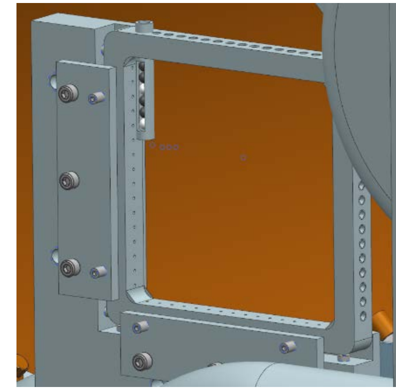
- HBCAMs on the cryomodule flange
- Two BCAMs per side to monitor the relative position of the components in the cryomodule
  - Each BCAM is bi-directional, can be used on two adjacent cryomodules
- An additional couple of BCAMs reading external, fixed targets would enable absolute or CM-to-CM position measurements

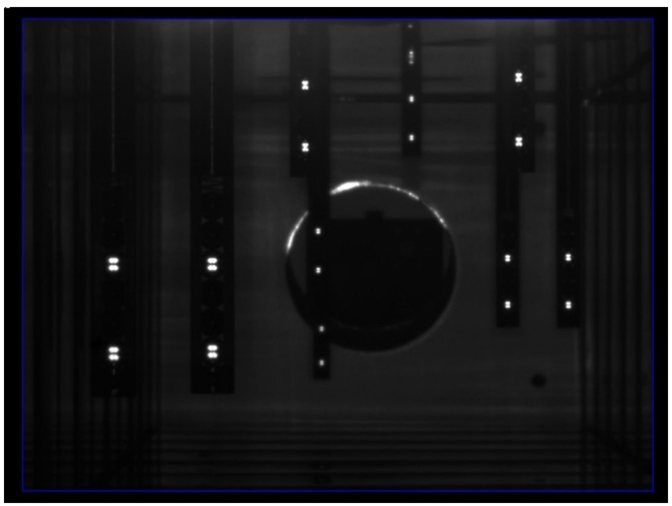


Optical targets design

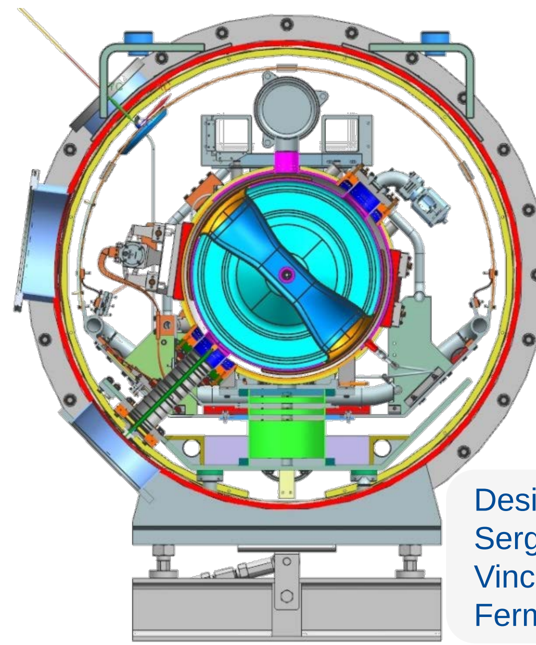
- Similar concept used for the HIE-ISOLDE experiment at CERN*
- High index glass balls used as targets
- Target offset to allow reading of all the components in the cryomodules
- Multiple targets for 5-DOF measurements







Picture from HIE-ISOLDE cryomodule



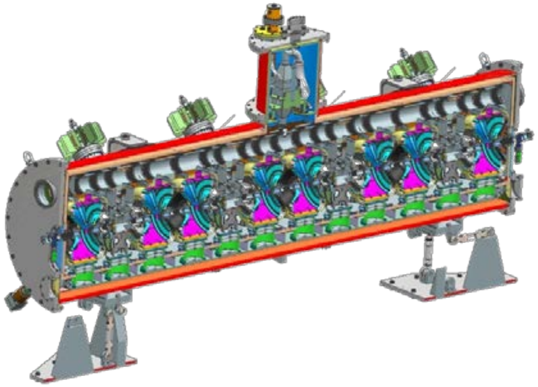
Design from Sergey Cheban, Vincent Roger - Fermilab

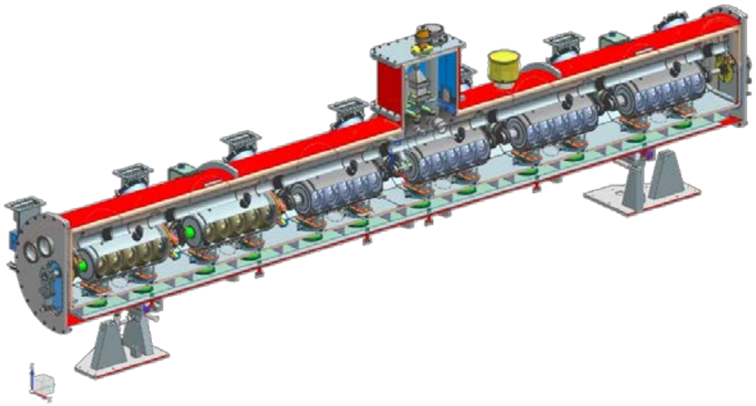
* **G. Kautzmann, J-C. Gayde, F. Klumb, Y. Kadi** – ISOLDE General Presentation of MATHILDE – IWAA 2014

HBCAM summary and outlook for PIP-II

- The relative alignment based on the HBCAM is already used for the ATLAS detector and the HIE-ISOLDE cryomodules

- For PIP-II a similar concept was proposed
  - Longer cryomodules and more components
  - First tests as a proof of concept on a single resonator using the CMM for validation
  - First design and implementation for the SSR1 cryomodule, to be extended to the 650





- Possible solution for other SC accelerators, i.e. ILC

Acknowledgments

- My former PACMAN team
- PACMAN project leader H. Mainaud Durand
- Beam Position section leader at CERN: M. Wendt

- PIP-II SSR1 and 650 L3 managers:
  - D. Passarelli, S. Chandrasekaran
- Mechanical Eng. Group at Fermilab: V. Roger
- Cryomodule Engineering group at Fermilab: S. Cheban

- G. Kautzmann, J-C. Gayde from the ISOLDE experiment at CERN
- K. Hashemi from OSI