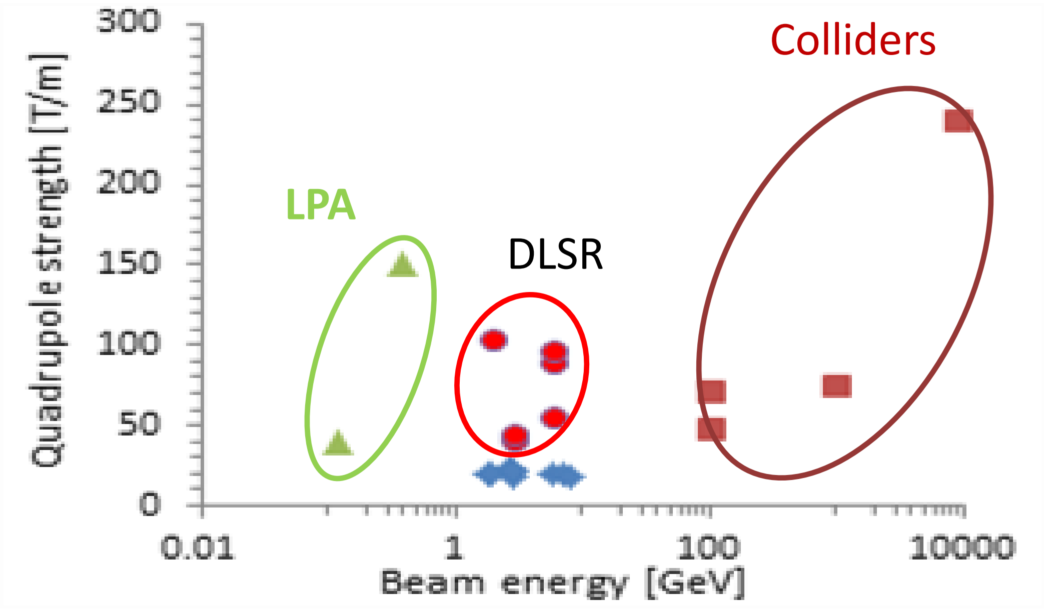
QUAPEVAs

QUAdrupole **PE**rmanent magnet based with **VA**riable gradient

A. Ghaith, C. Kitégi, F. Marteau, M. Valléau, T. Andre, A. Loulergue, , M. E. Couprie, Synchrotron SOLEIL

In collaboration with SIGMAPHI

Motivation



- Colliders
- Diffraction limited light sources
- 3rd generation light sources
- .....

<u>Laser Plasma Acceleration:</u>

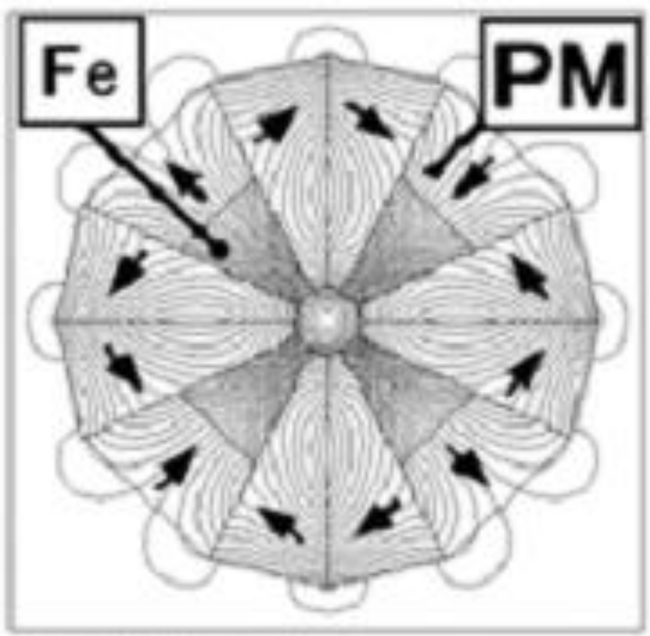
- GeV beam within a cm scale accelerating distance
- Up to 10 kA peak current
- Few fs bunch length

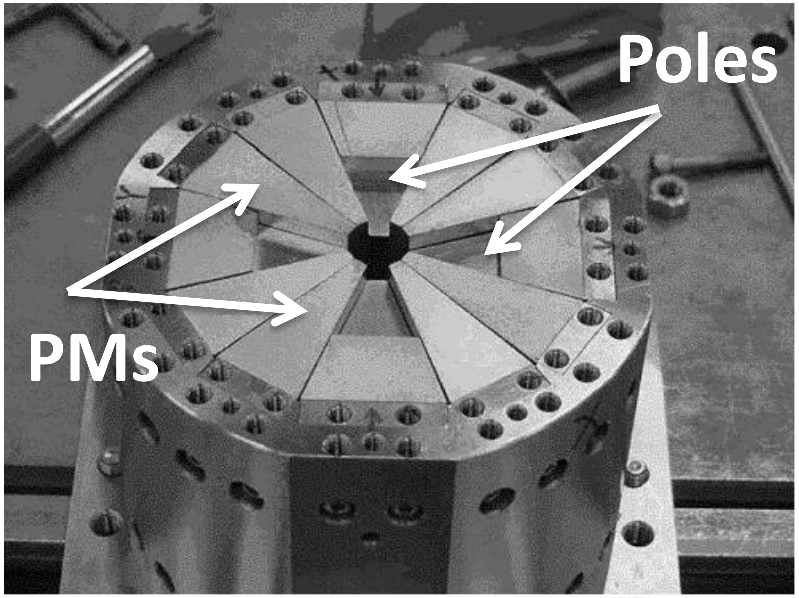
But high divergence (few mrads)!

State-of-art

Linear Collider application:

(Fixed gradient)





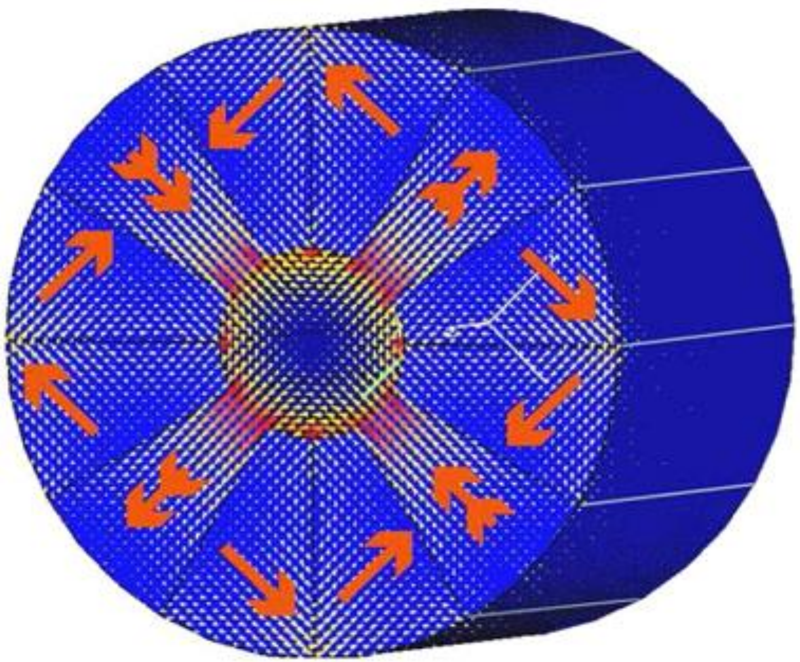
Bore diameter: 14 mm
Gradient: 285 T/m
Magnetic Length: 100 mm
Integrated Gradient: 28.5 T

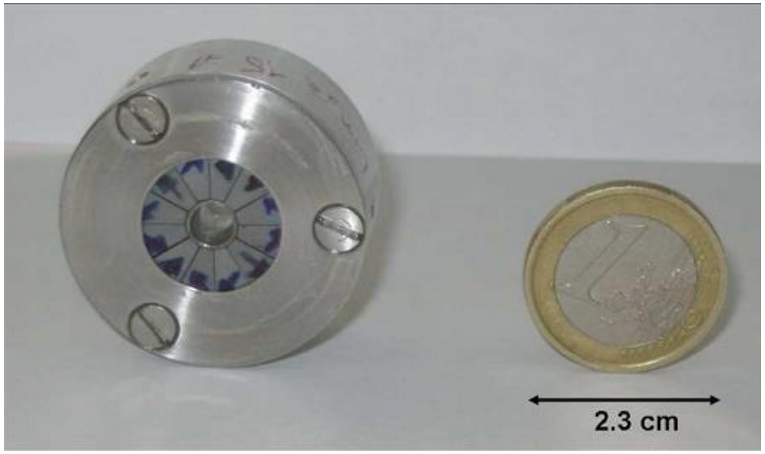
T. Mihara, Y. Iwashita et al, Super strong permanent magnet quadrupole for a linear Collider. *IEEE* Journal of applied superconductivity

State-of-art

LPA based FEL application:

(Fixed gradient)





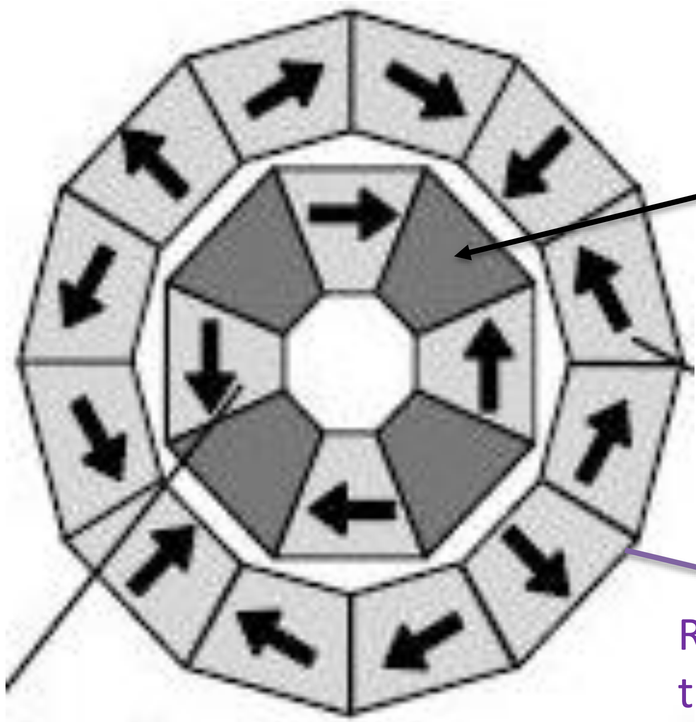
Bore diameter: 6 mm
Gradient: 503 T/m
Magnetic Length: 17 mm
Integrated Gradient: 8.5 T

T. Eichner et al, Miniature magnetic devices for laser-based, table-top free-electron lasers. *PRST Accelerators and beams 10, 082401 (2007)*

State-of-art

Linear collider application:

(Variable gradient)



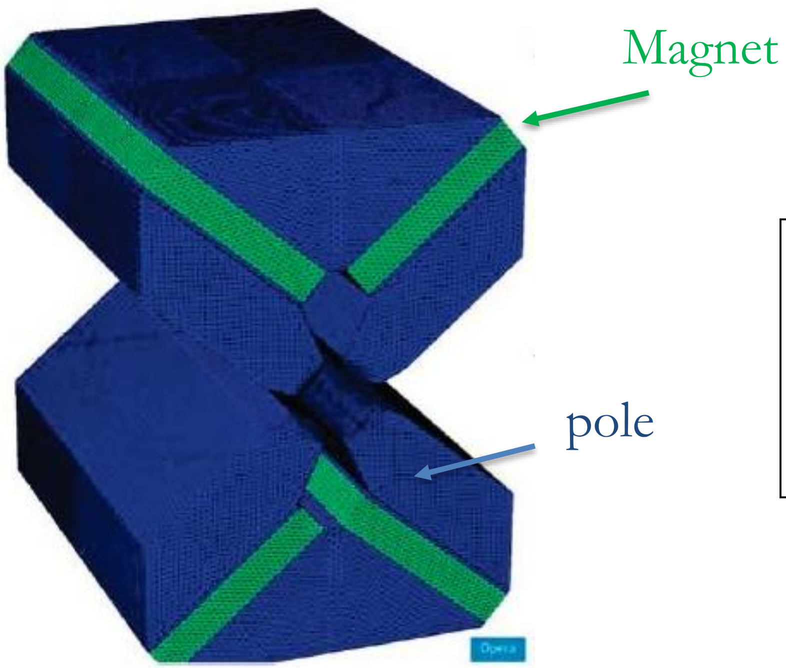
Bore diameter: 20 mm
Gradient: 115 T/m – 17 T/m
Magnetic Length: 200 mm
Integrated Gradient: 24 T

T. Mihara et al, Variable permanent magnet quadrupole. *SLAC – PUB – 10248, February 2004*

T. Mihara, Y. Iwashita et al, Super strong adjustable permanent magnet quadrupole for the final focus in the linear Collider. *Proceeding of EPAC 2006, Edinburgh, Scotland*

State-of-art

CLIC: 3 TeV electron-positron collider application:

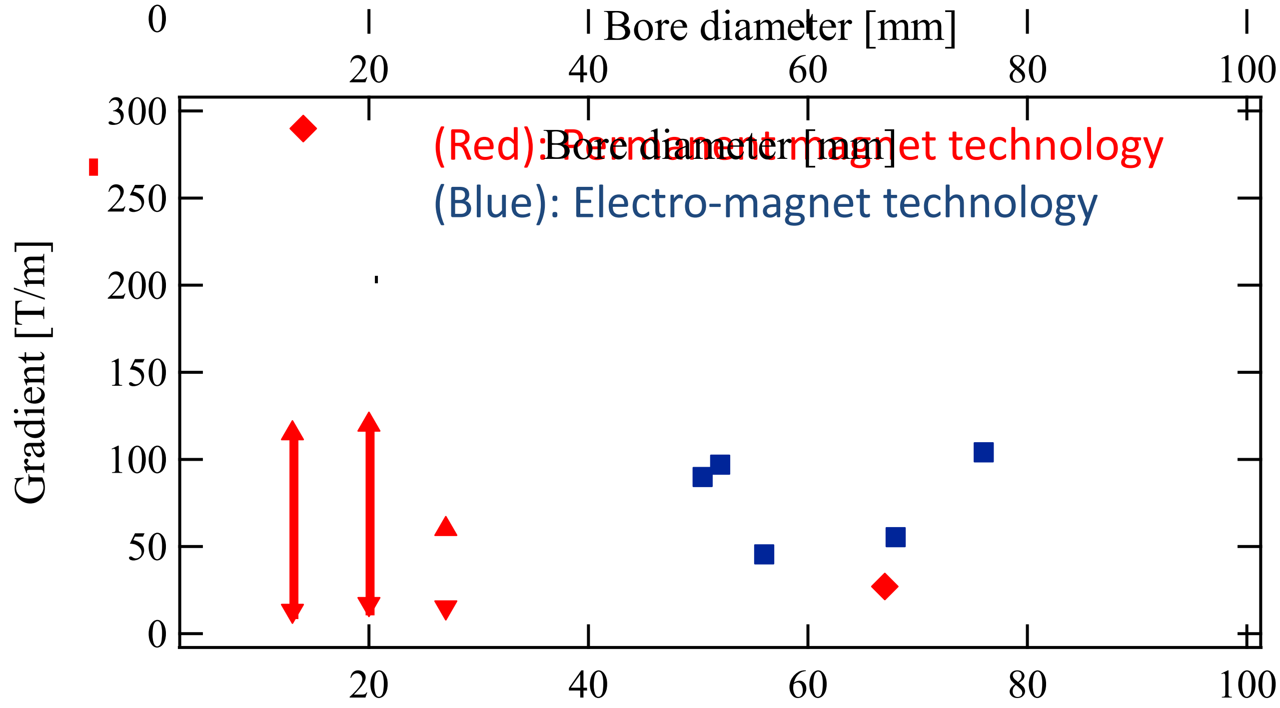


(Variable gradient)

Bore diameter: 13.6 mm
Gradient: 15 T/m – 60.4 T/m
The gradient variation is done by moving the magnets vertically.

B.J.A. Shepherd et al, Construction and measurement of novel adjustable permanent magnet quadrupoles for CLIC, *Proceeding of IPAC 2012, New Orleans, USA*

State-of-art (Summary)

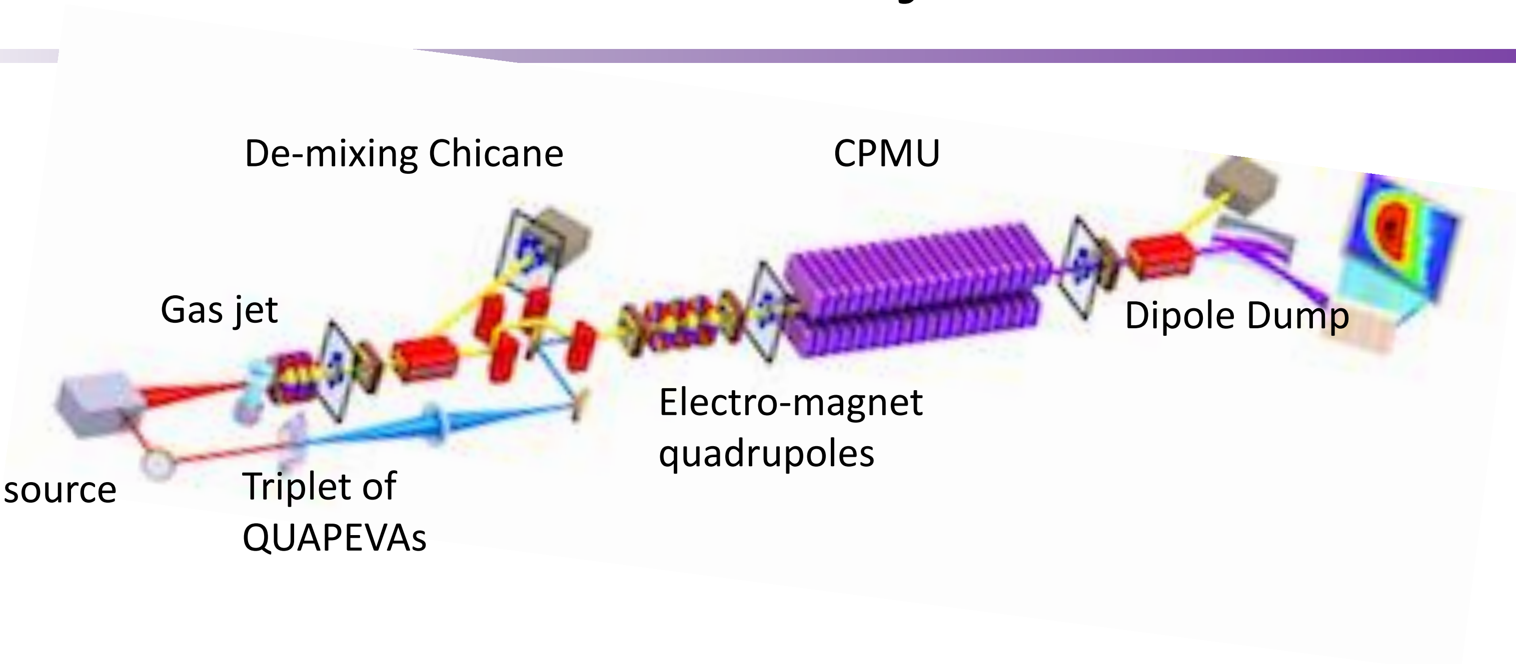


Gradient = 560 T/m — Lim, J. K., et al. "Adjustable, short focal length permanent-magnet quadrupole based electron beam final focus system." *Physical Review Special Topics-Accelerators and Beams* 8.7 (2005): 072401.

Gradient = 575 T/m — M. Modena et al., Design, assembly and first measurements of a short model for CLIC final focus hybrid quadrupole QD0," in *Conf. Proc.*, vol. 1205201, p. THPPD010, 2012.

Gradient = 82 T/m — Ngotta, G. Le Bec, and J. Chavanne, \Hybrid high gradient permanent magnet quadrupole," *Physical Review Accelerators and Beams*, vol. 19, no. 12, p. 122401, 2016.

COXINEL Project

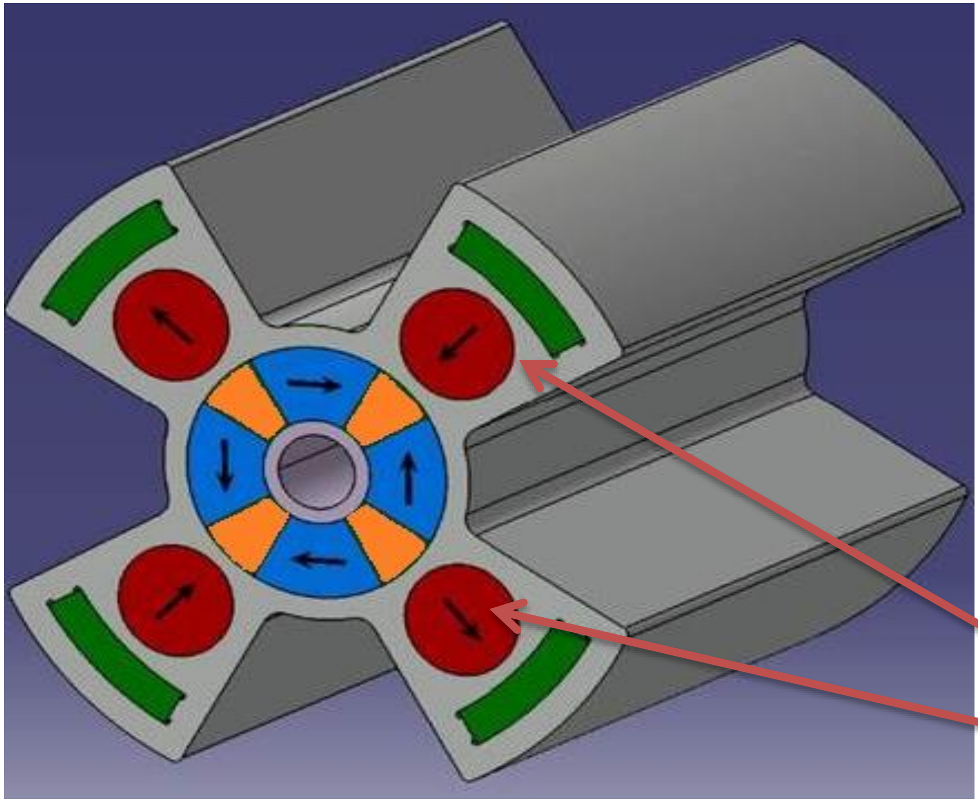


1) M. E. Couprie et al. J. Physics B : At., Mol. Opt. Phys. (2014) 234001
2) A. Loulergue et al.., New J. Phys. 17 (2015) 023028 (2015)
3) M. E. Couprie et al., Plasma Physics and Controlled Fusion, Volume 58, Number 3 (2016)

7 systems with different magnetic lengths:

- First triplet to focus a 176 MeV beam
- Second triplet to focus a 400 MeV beam
- A prototype

Concept



Maximum Gradient

Concept was patented (QUAPEVA program-Triangle de la Physique, SOLEIL/Sigmaphi collaboration)

C. Benabderrahmane, M. E. Couprie, SOLEIL, F. Forest, O. Cosson Sigmaphi, "Multi-pôle magnétique réglable", patent application WO2016034490 (10 March 2016).
C. Benabderrahmane, M. E. Couprie, SOLEIL, F. Forest, O. Cosson Sigmaphi, "Adjustable magnetic multipole," Europe patent application WOBL14SSOQUA/CA (27 August 2015)

Halbach hybrid ring producing a fixed gradient

Cylindrical magnets that can rotate around their axis providing gradient tunability

F. Marteau, A. Ghaith, P. N'Gotta, C. Benabderrahmane, M. Valléau, C. Kitegi, C., ... & Le Bec, G. (2017). Variable high gradient permanent magnet quadrupole (QUAPEVA). *Applied Physics Letters*, *111*(25), 253503.

Specifications (COXINEL)

Parameters	Value	Unit
Length	26-100	mm
Section	90 x 90	mm^2
Gradient	$\geqslant$ 100	T/m
Gradient Tunability	$\geqslant$30	%

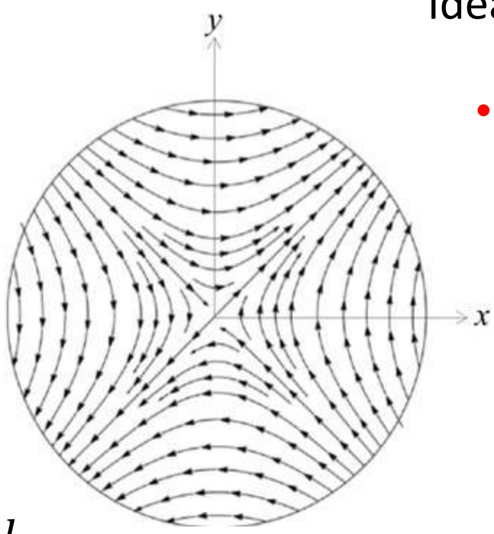
- Resistance against demagnetization
- Adapted to in-vacuum environment

Multipole contents:

$$B(z) = \sum_{n=1}^{\infty} (B_n + iA_n) \frac{z^{n-1}}{{r_0}^{n-1}}$$

n: Multipole order
B_n: Normal multipole term
A_n: Skew multipole term
r_0: Good field region
Z: **X+iY**

$$b_n = \int B_n . dl$$



Ideal Quadrupole (n=2):

- All terms are zero except:

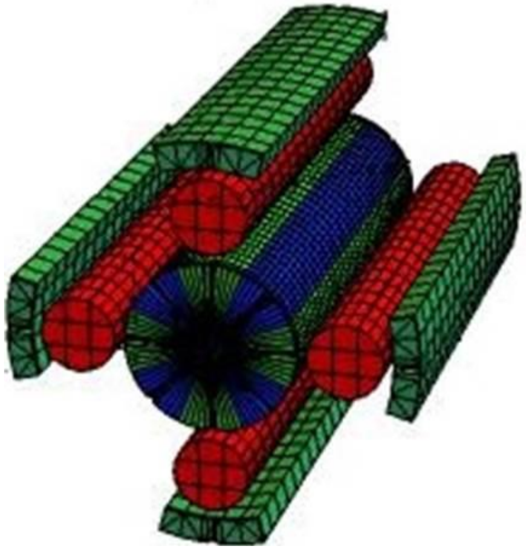
bn(2m+1): b2, b6, b10, …

b_6/b_2	$\leqslant$ 3	%
b_{10}/b_2	$\leqslant$ 1.5	%

Modeling

❑RADIA

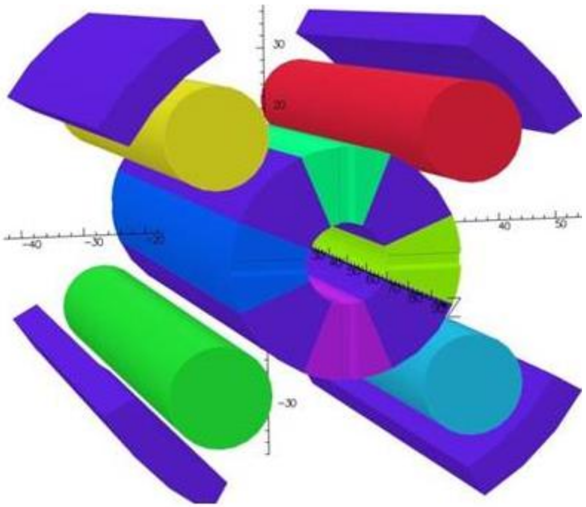
A magnetostatic code based on boundary integral method



O. Chubar, P. Elleaume, J. Chavanne, A three-dimensional magnetostatics computer code for insertion devices, Journal of Synchrotron Radiation 5 (3) (1998) 481–484.

❑TOSCA

A finite element magnetostatic code



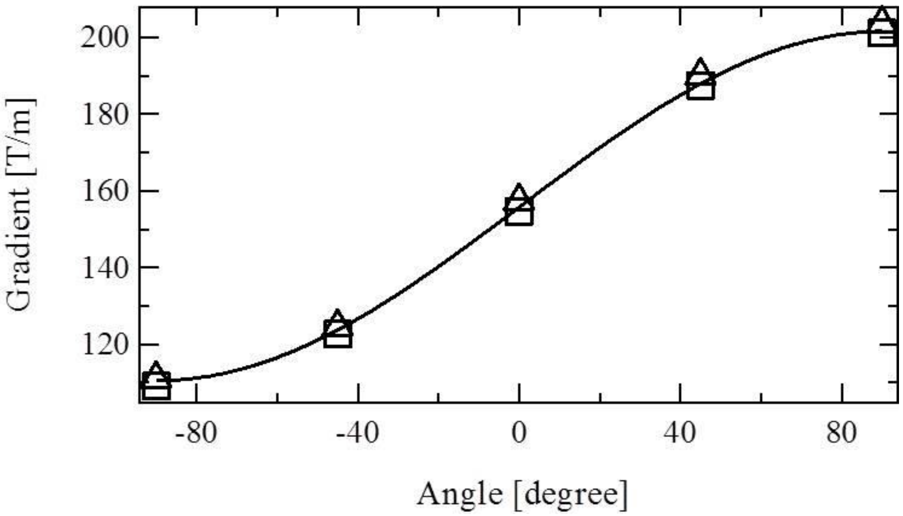
J. Simkin, C. Trowbridge, Three-dimensional nonlinear electromagnetic field computations, using scalar potentials, in: IEE Proceedings BElectric Power Applications, Vol. 127, IET, 1980, pp. 368–374

Modeling

Magnet and pole characteristics:

Parameters	Value	Unit
Gradient (G)	110 - 210	T/m
Remanent Field (B_r)	1.26	T
Coercivity (H_{cj})	1830	kA/m
Pole Saturation	2.35	T
Radius for Good Field Region (GFR)	4	mm
$\Delta G/G$	< 0.01	at 4 mm

Gradient variation versus angle:

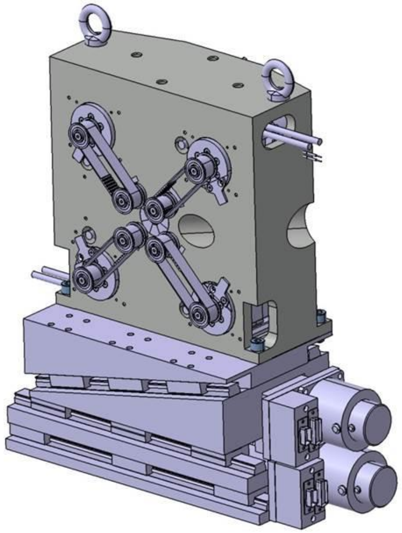


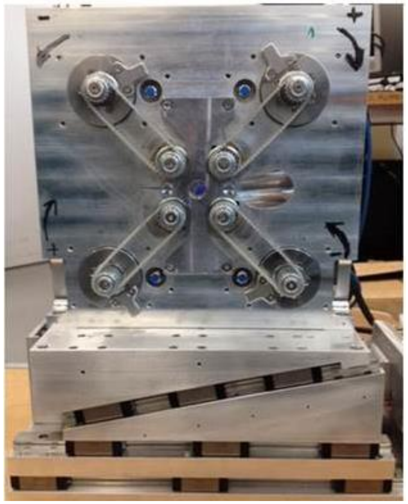
Maximum gradient and Tunability:

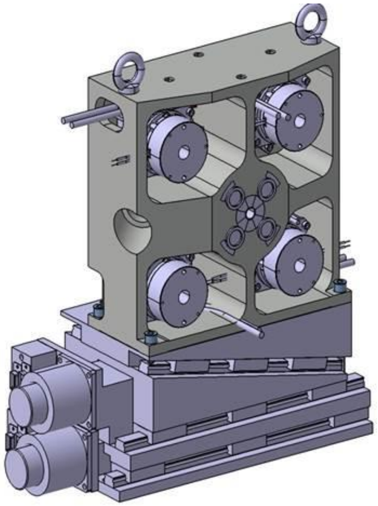
Magnetic length	G_{max} [T/m]	ΔG [T/m]
100 mm	201	92
81.1 mm	195	89
61 mm	190	88
47.1 mm	184	86
44.7 mm	183	86
40.7 mm	180	85
26 mm	164	78

- **The longer the magnetic length, the higher the gradient and tunability**

Mechanical Design







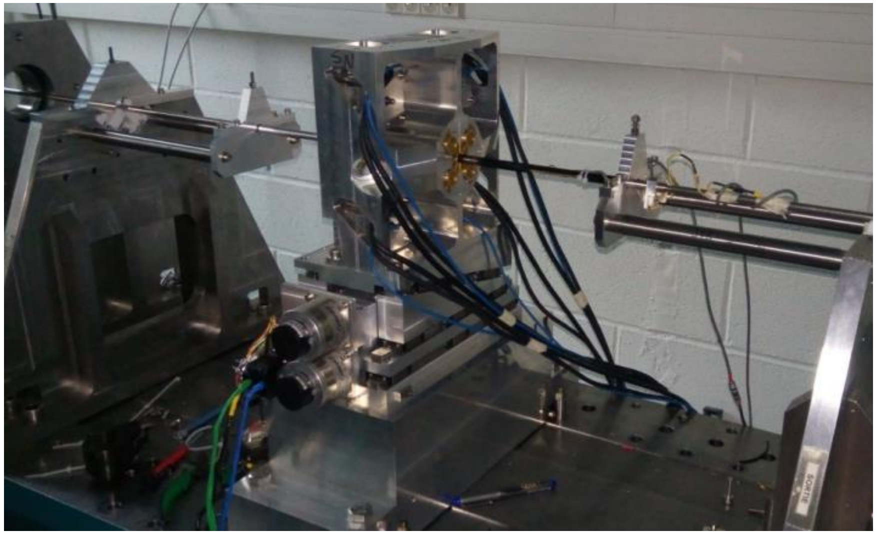
- Built on a translation table to align the magnetic center with the electron beam, also to compensate the magnetic center excursion as the gradient is varied
- Adapted to laser beam passage
- Compatible with a vacuum environment
- Built into an Aluminum frame to counter-act the magnetic forces

Motors HARMONIC DRIVE, FHA-C mini Motors

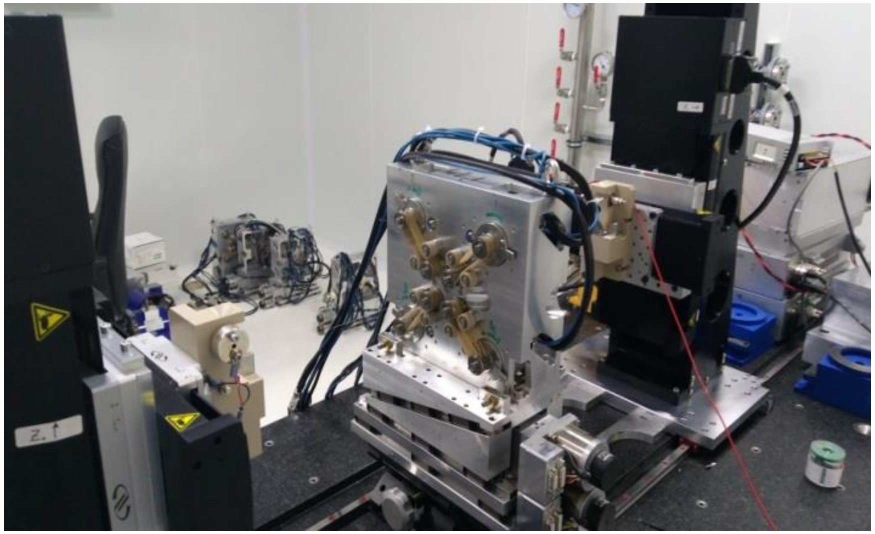
- Very Compact (48.5 x 50 x 50 mm3)
- Each rotating magnet is connected to one motor to prevent the magnetic center excursion due to asymmetry
- Non magnetic belt connects the cylindrical magnet to the motor

Magnetic Measurements

(Rotating coil at SOLEIL)



(Stretched wire at LAL)



- **Measure the field integral**

$$\frac{\int B_2.dl}{RL}\ [\mathrm{T/m}]$$

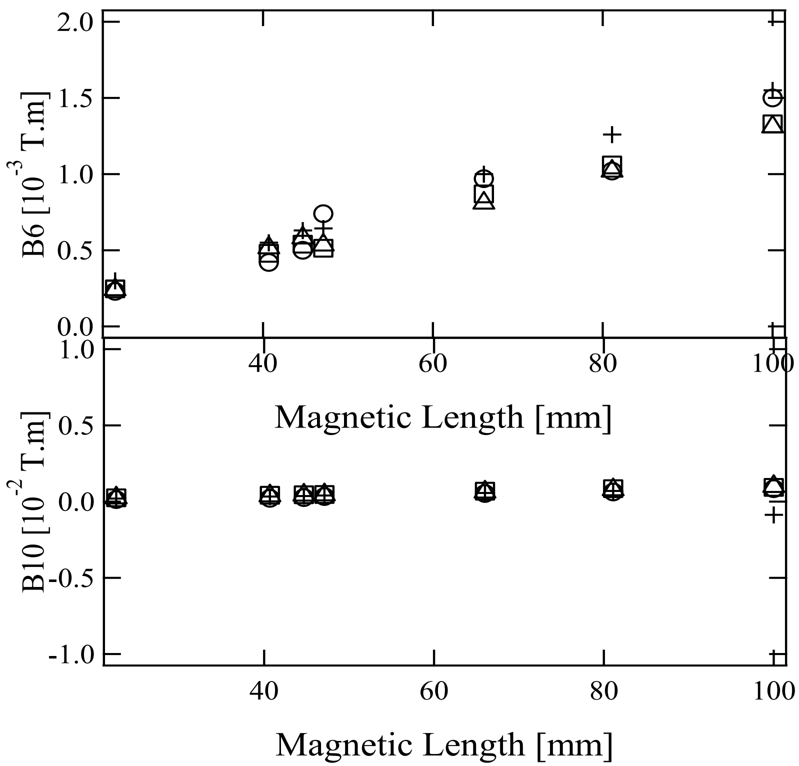
B2: Normal quadrupolar term
R: Coil radius
L: Magnetic length

- Multipole terms (Including gradient)
- Magnetic center excursion

$$\begin{cases} \Delta x = \dfrac{R(a_1a_2+b_1b_2)}{a_2^2+b_2^2} \\[2ex] \Delta z = \dfrac{R(a_1b_2-a_2b_1)}{a_2^2+b_2^2} \end{cases}$$

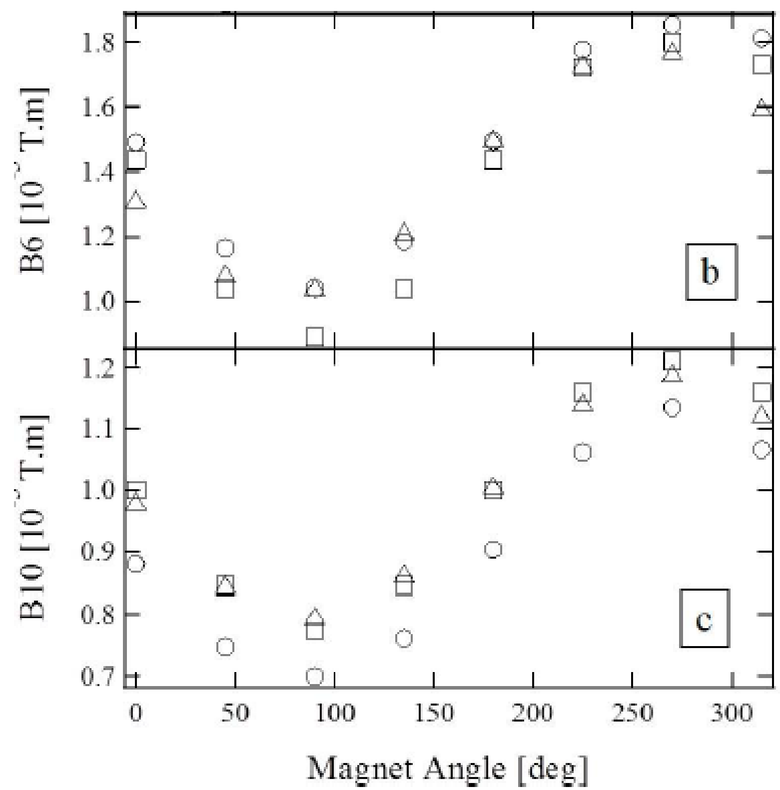
Multipole terms

B6 and B10 for each system:



(□) RADIA, (△) TOSCA
(○) rotating coil measurement
(+) Stretched wire measurement

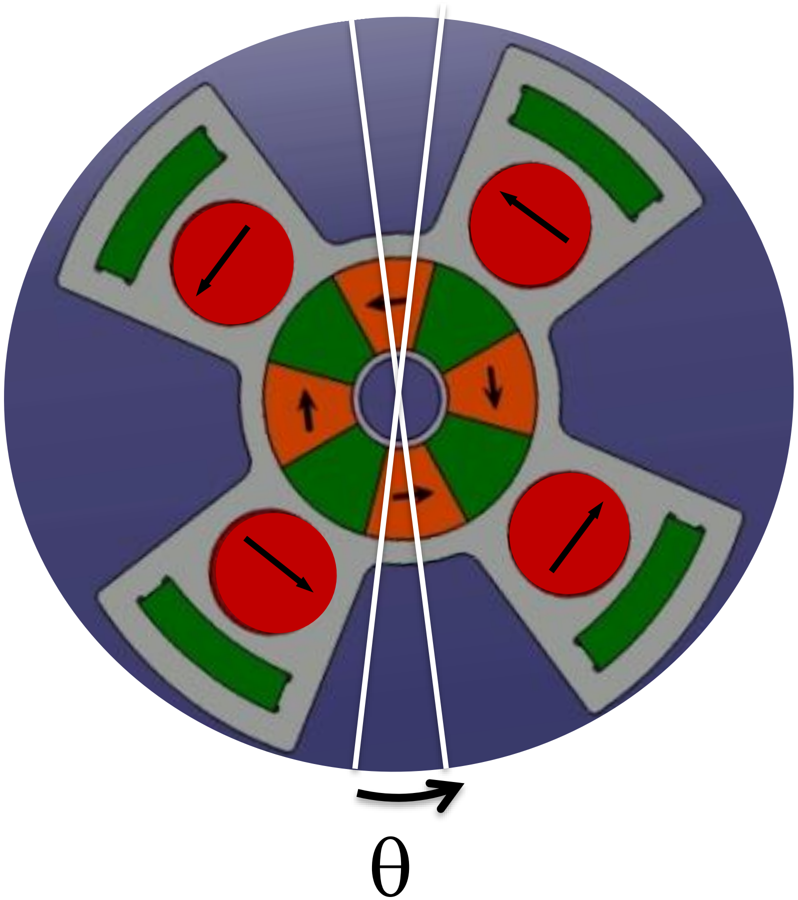
B6 and B10 as a function of angle:



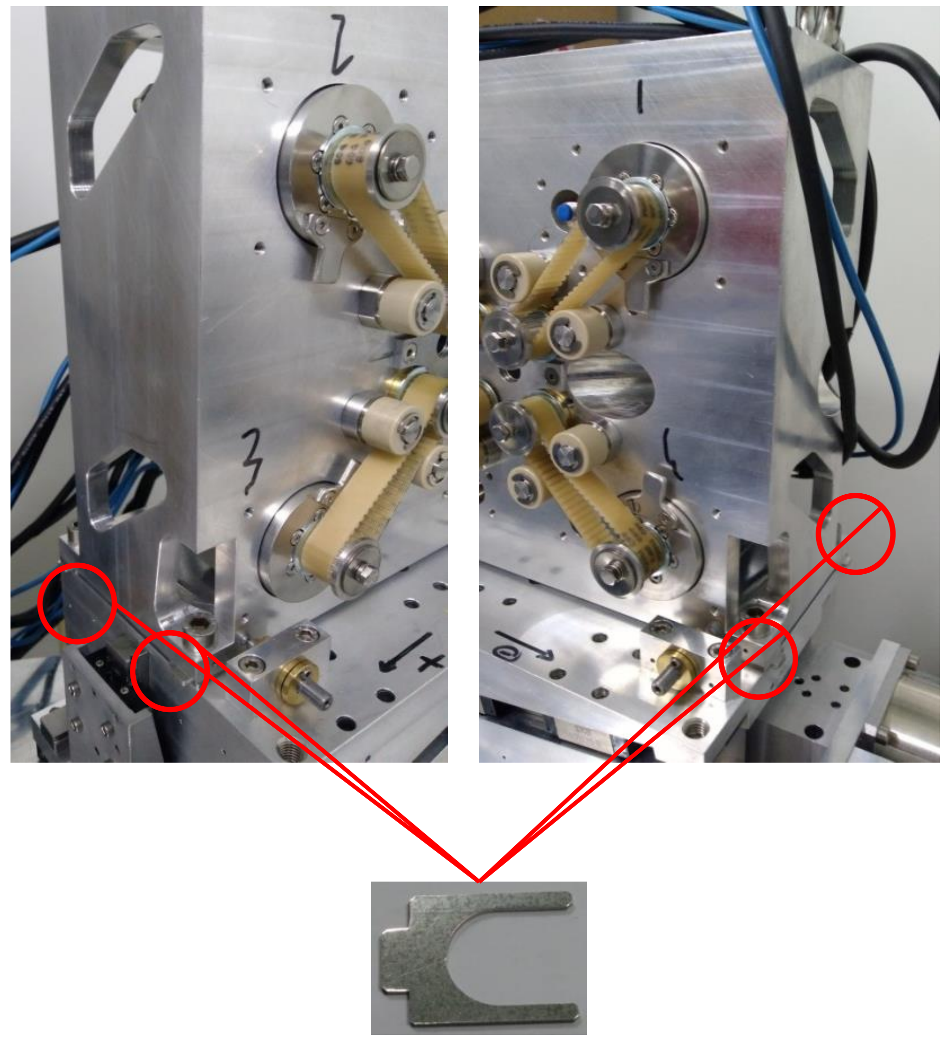
- $\frac{B_6}{B_2} = 2\%$
- $\frac{B_{10}}{B_2} = 1.5\%$

LUNEX5

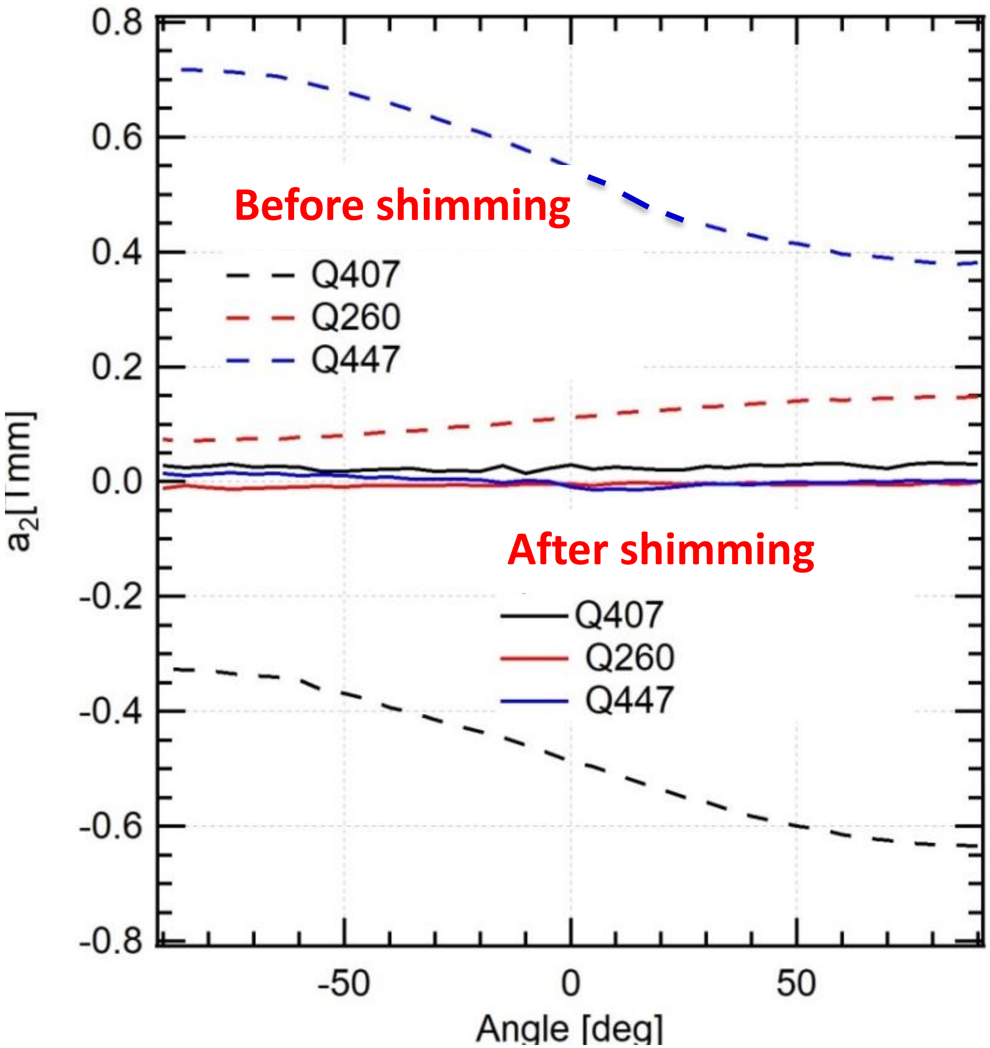
Skew quadrupole: (Mechanical shimming)



$$\boldsymbol{\theta = \frac{1}{2}\arctan(\frac{a_2}{b_2})}$$



Skew quadrupole: (Mechanical shimming)



$$\theta = \frac{1}{2}\arctan\left(\frac{a_2}{b_2}\right)$$

(dashed) : Before shimming

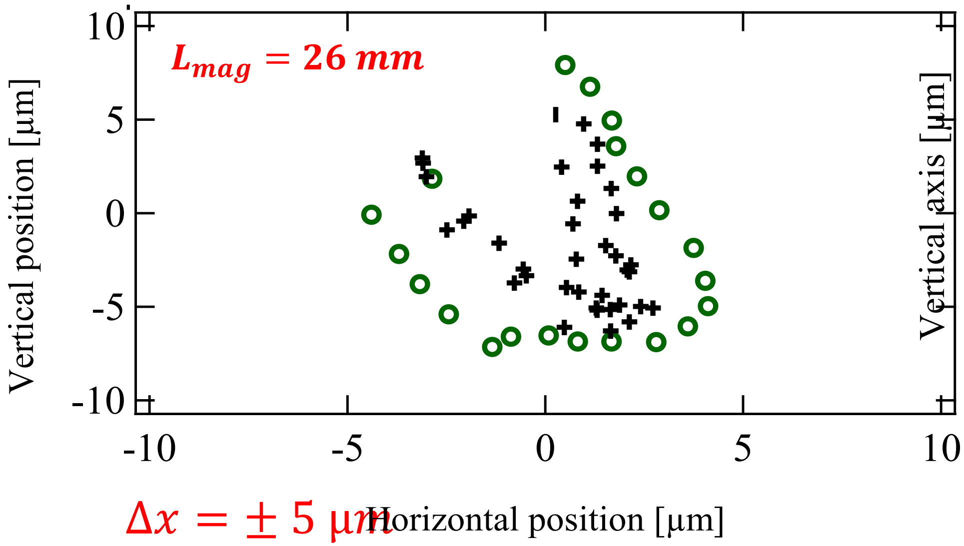
$\theta_{before} \approx 2 - 5\ mrad$

(line) : After shimming

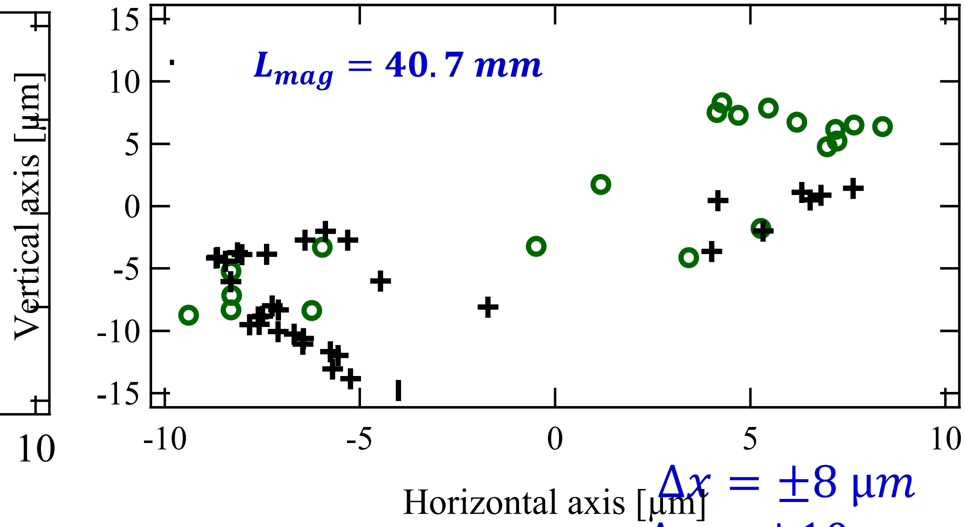
$\theta_{after} \approx 0.02\ mrad$

LUNEX5

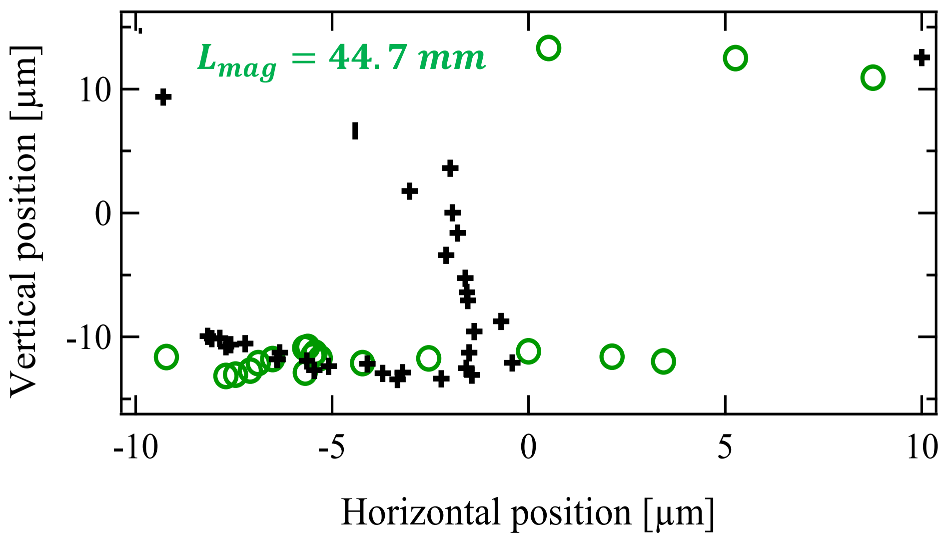
Magnetic center evolution



$\Delta x = \pm\, 5\ \mu m$
$\Delta z = \pm\, 6\ \mu m$



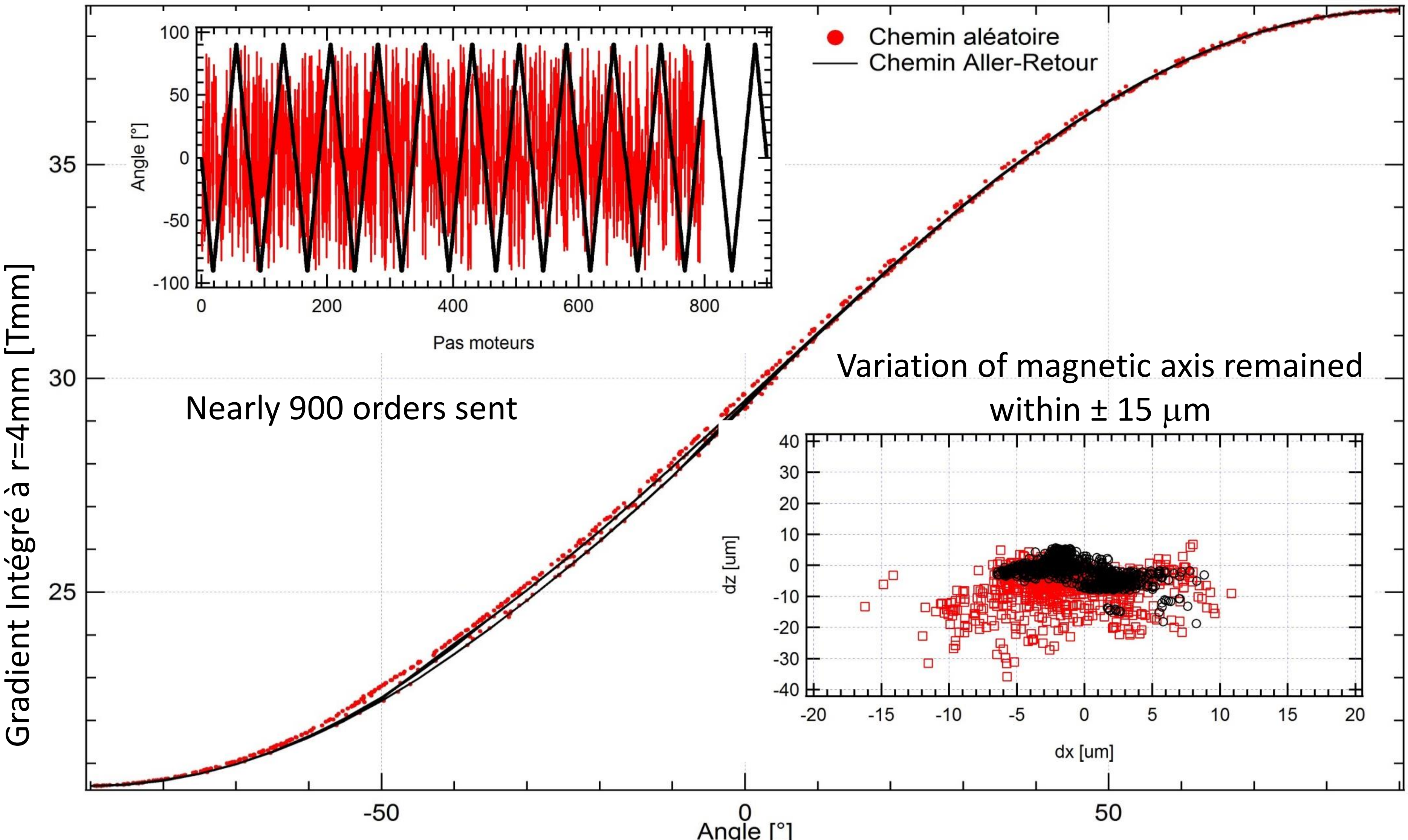
$\Delta x = \pm 8\ \mu m$
$\Delta z = \pm 10\ \mu m$



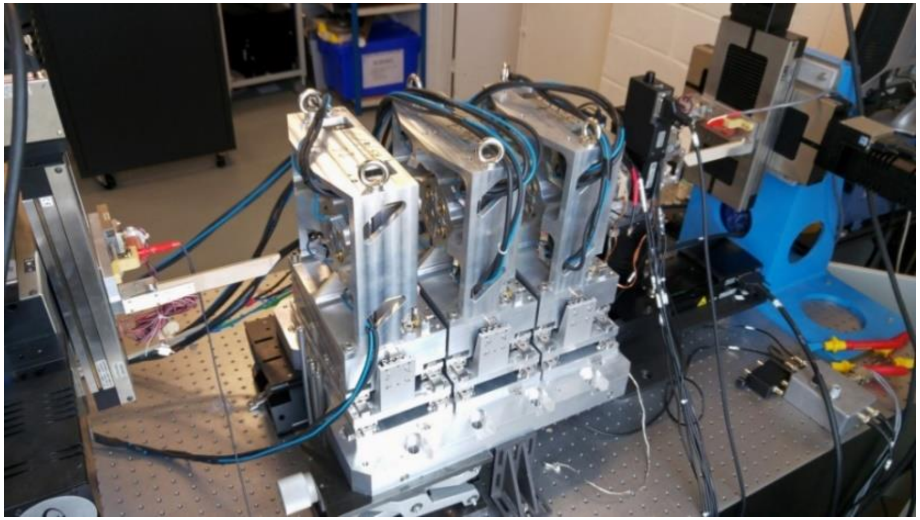
$\Delta x = \pm 10\ \mu m$
$\Delta z = \pm 13\ \mu m$

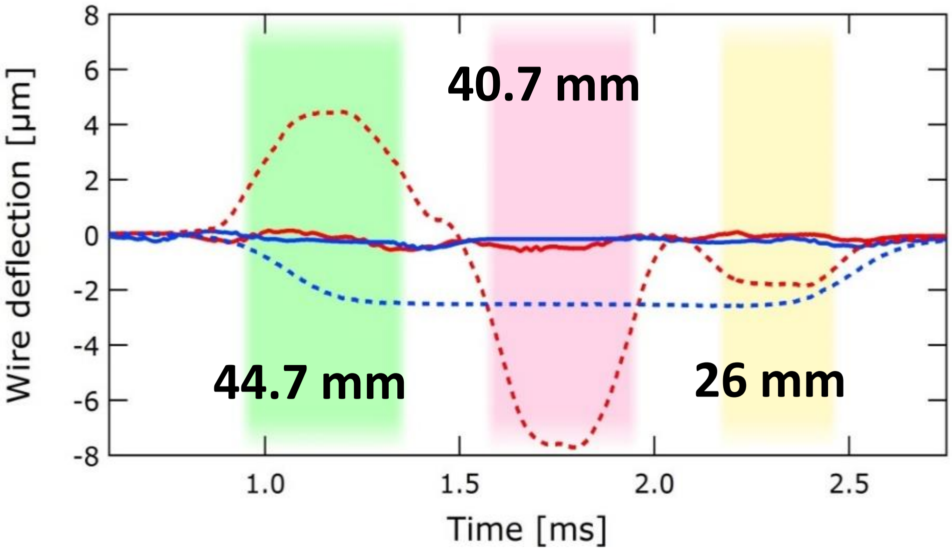
LUNEX5

Stretched Wire Repeatability test



Pulsed Wire Measurement:



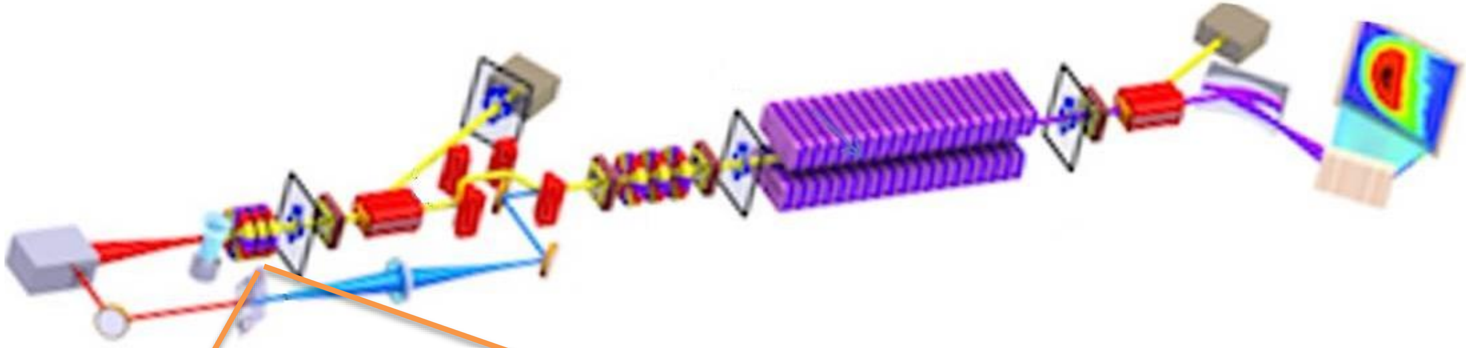


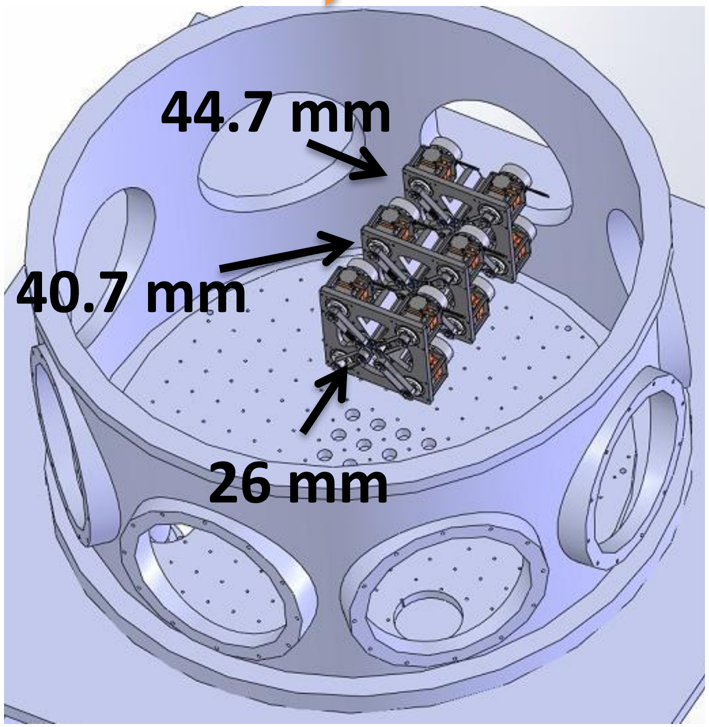
- **Place the three QUAPEVAs on the bench**
- **Send a short square pulse into a Tungsten wire passing through the 3 systems**
- **Track the wire deflection using a laser sensor which is proportional to the magnetic field**

(Dashed) before the alignment
(line) after alignment

vertical axis
horizontal axis

COXINEL:

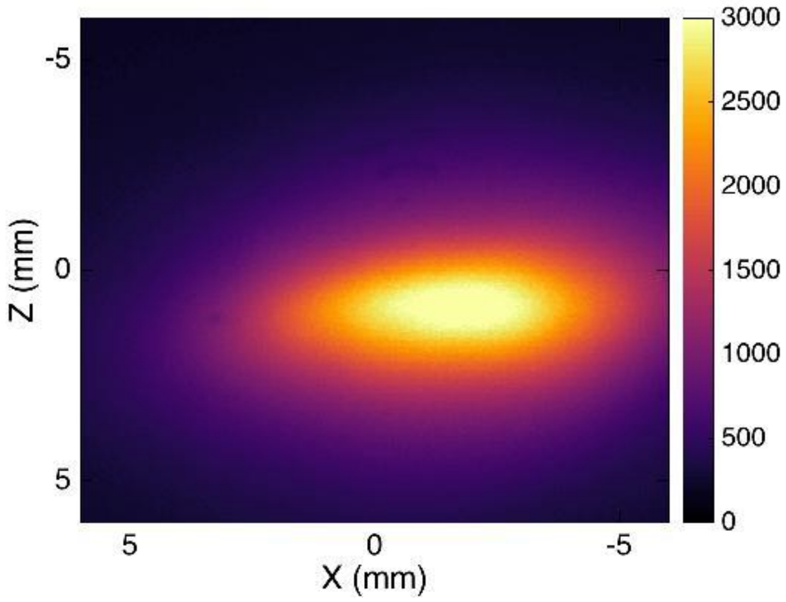




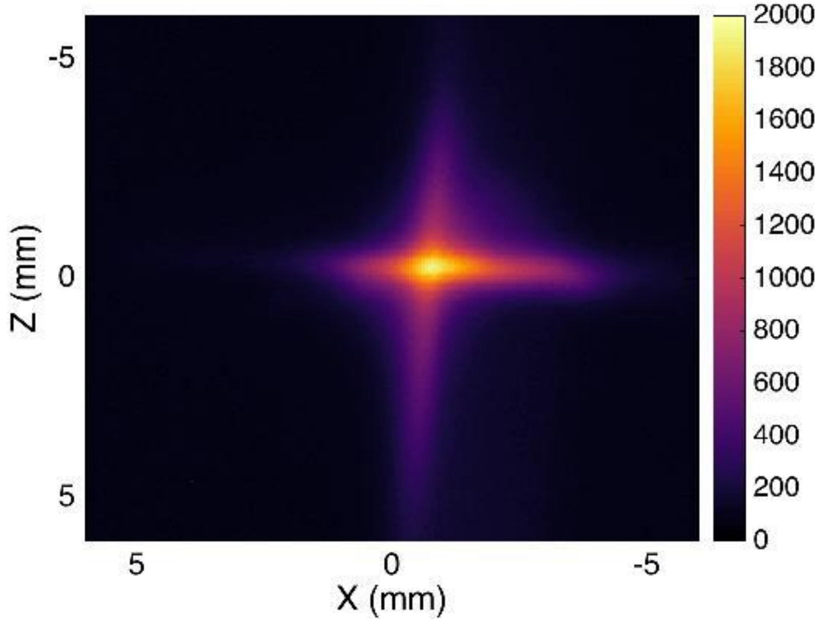
Electron Beam measurement

- A LANEX screen placed 64 cm away from the third QUAPEVA

Beam without QUAPEVAs



Beam with QUAPEVAs



Beam size reduction:
4.6 down to 1.8 mm (x)
1.8 down to 1 mm (z)

LUNEX5

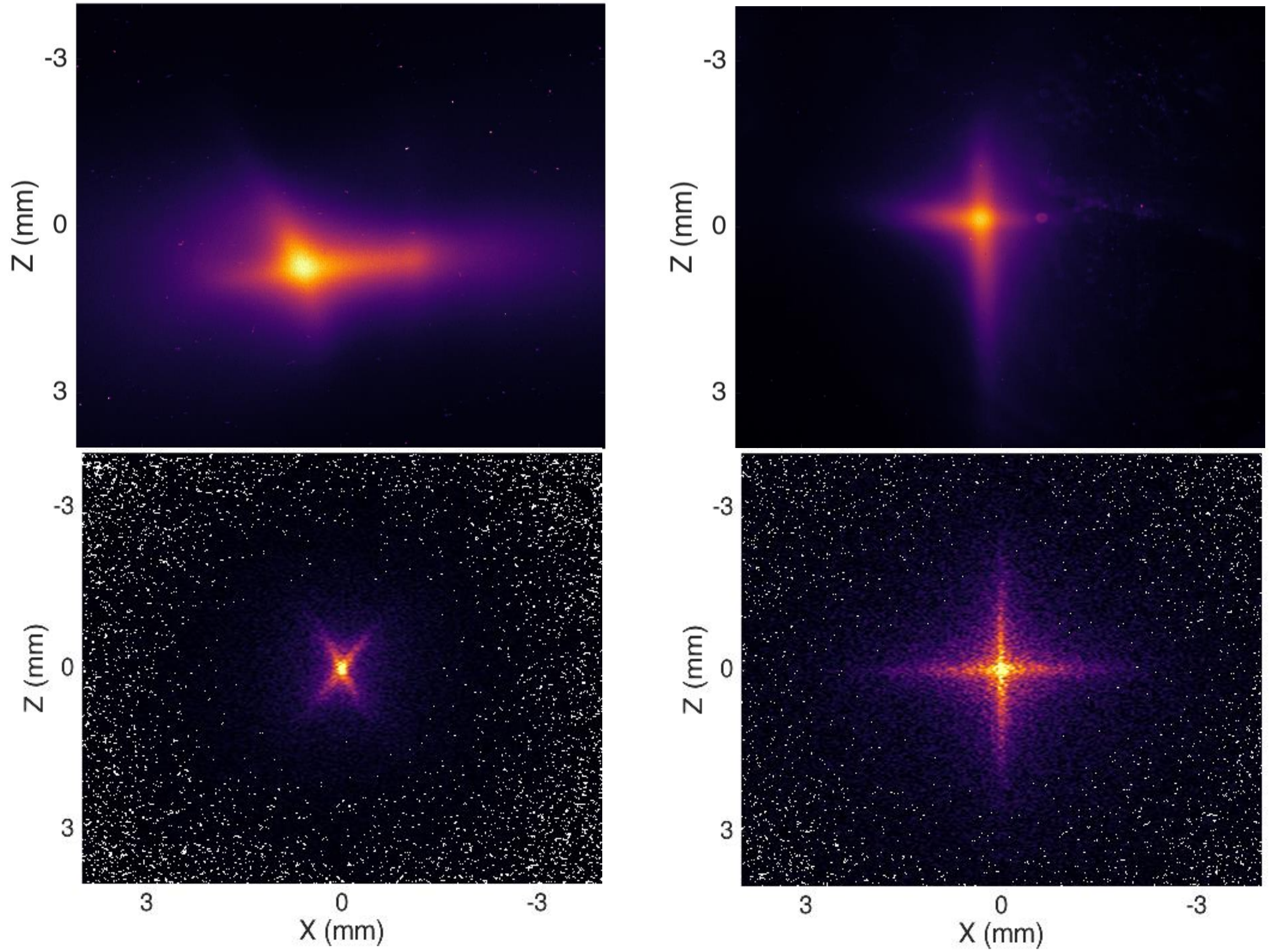
Electron Beam measurement (Skew quadrupole correction)

Measurement

- A LANEX screen placed 64 cm away from the third QUAPEVA

Simulation

RUN3: RUN4:

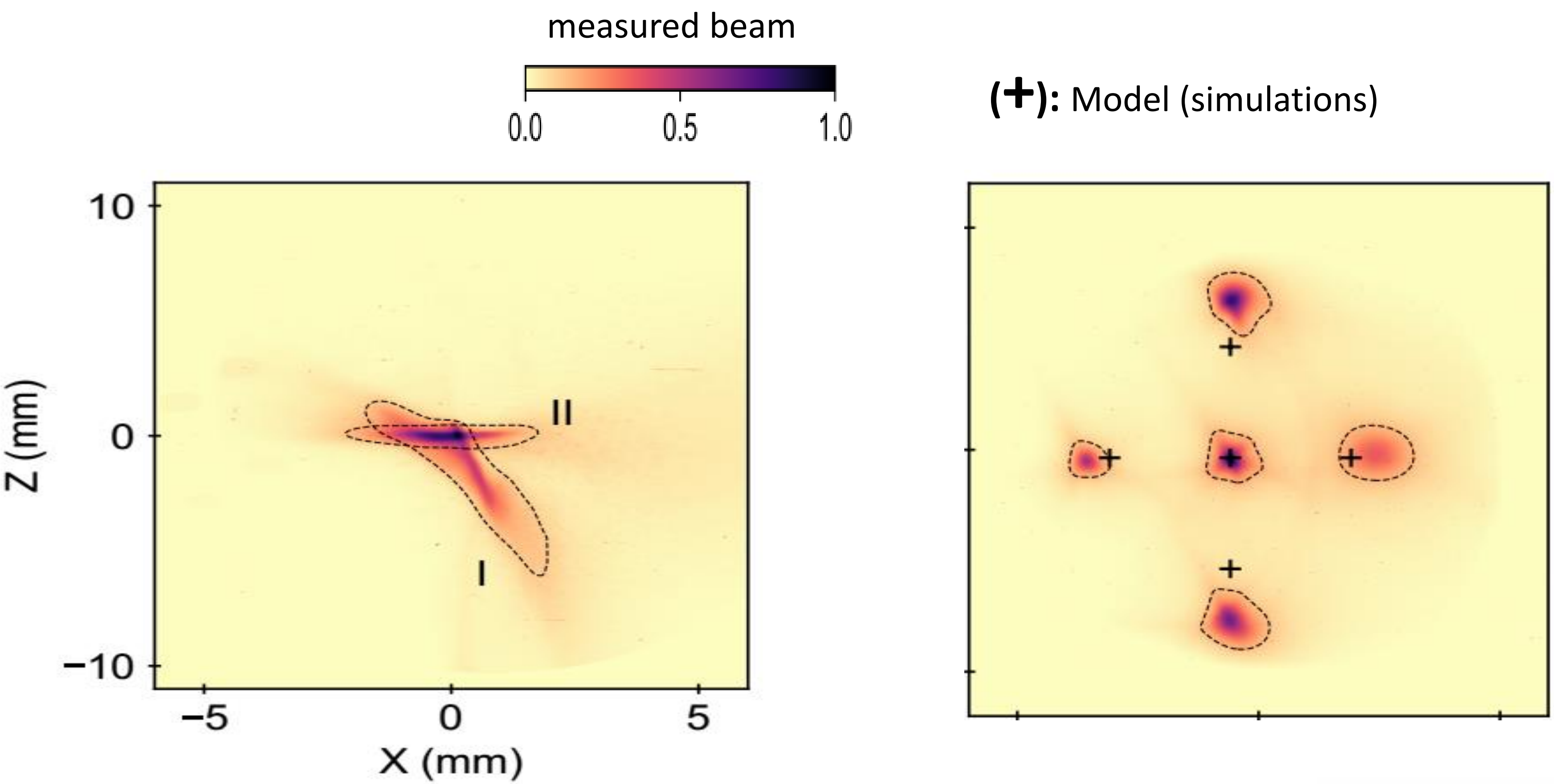


Before shimming **After shimming**

QUAPEVAS Enable BPAC

computing theoretical response matrix (A)

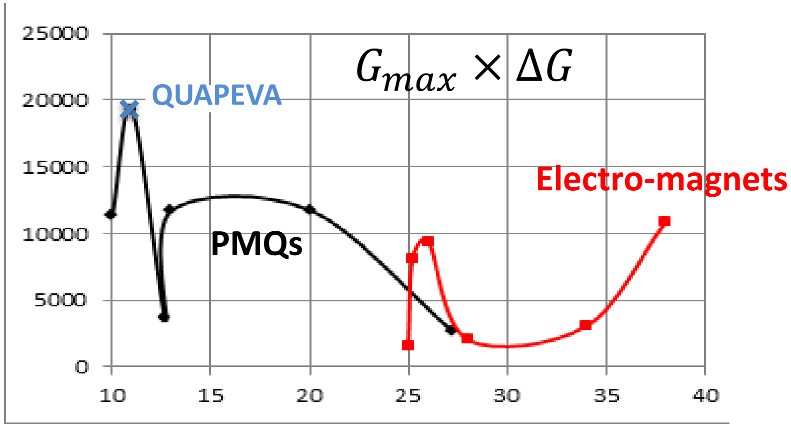
$$\begin{pmatrix} \vec{X} \\ D_X \end{pmatrix} = A \, \Delta_{\vec{X} \ gap} \quad \Longrightarrow \quad \Delta_{\vec{X} \ gap} = A^{-1} \begin{pmatrix} \vec{X} \\ D_X \end{pmatrix}$$



Conclusion:

Magnetic performance:

- High gradient (200 T/m) + Large tunability (45%) achieved
- Low magnetic center excursion of ± 15 µm has been achieved



Bore diameter [mm]

Application to COXINEL:

- A triplet (26 mm, 40.7 mm, 44.7 mm) has been installed at COXINEL and enabled us to transport, control and manipulate a highly divergent beam.
- One of the first tunable permanent magnet based quadrupoles commissioned in an accelerator line.
- The translation tables allowed for a BPAC (beam pointing alignment compensation).

Prospects:

- ❑ Integrate a cooling system and using PrFeB magnets, to further enhance the gradient.
- ❑ Use hyperbolic shaped poles to decrease the non systematic multipole terms.

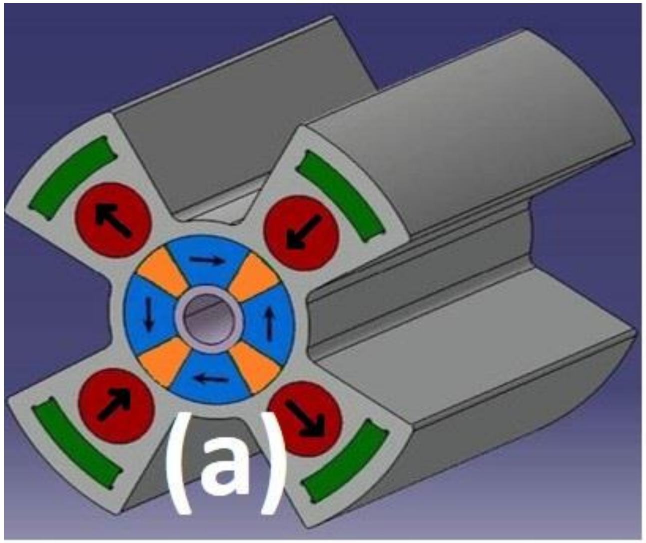
Acknowledgement:

Thanks to

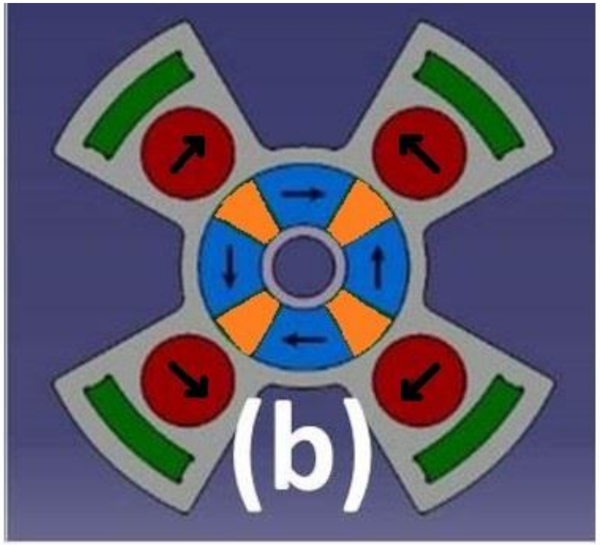
- The European Research Council for the advanced grant COXINEL (340015)
- The Fondation de la Cooperation Scientique for the Triangle de la Physique / valorisation contract QUAPEVA (2012-058T).

Thank you for your attention

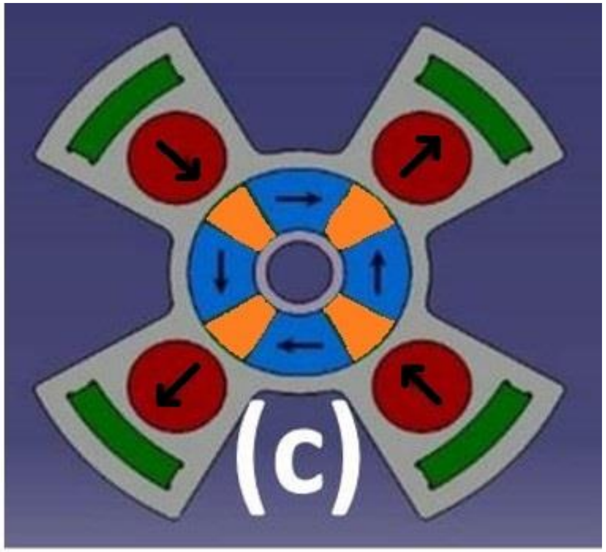
Maximum Gradient



Intermediate Gradient



Minimum Gradient



Length [mm]	26	40.7	44.7	47.1	66	81.1	100
G_0							
a_3	14.6	35.1	-130.2	32.1	91.1	130.3	-2.9
a_4	-9.1	-14.9	-27.1	-100.4	-0.2	-68.6	-57.4
a_5	-20.3	-12.1	-38.6	8.3	0.84	-26.9	30.2
b_3	87.3	-34.8	-141.9	282	120.5	-108.5	-277.7
b_4	-1.5	-51.5	-25.1	13.4	24.2	-51.8	-8.9
b_5	-7.2	12.3	28.5	-4.8	-28.3	11.4	-49.5
G_M							
a_3	12.5	-153.1	-81.4	-19	120.4	124.9	40.3
a_4	-16	-19.9	-19.8	-95.7	-1.7	-76.5	-54.4
a_5	-22.2	-8.1	-45.6	13.5	0.2	-35.1	26.4
b_3	-1.6	-29	91.2	-309.4	131.4	-174.3	-190.4
b_4	-2.7	-45.8	-15.6	15.9	21.6	-45.2	10.1
b_5	-16.7	18.9	27.7	-10.2	-30.5	5.3	-41.2
G_m							
a_3	85.4	-107.5	-7.5	-21	148.8	1.3	8.3
a_4	-11.2	7.5	-38.7	-105.1	0.4	-0.6	-59
a_5	-27.5	3.9	-60.5	22.1	1.6	-0.2	25.9
b_3	39.1	36.8	211.4	-344.9	183.4	-1.3	-237.9
b_4	0.6	-67.3	22.6	9.4	11.7	-0.51	10.4
b_5	-9	32.7	52.5	-15.3	-18.4	0.1	-43