eli beamlines

INFN LNS

Errors and optics study of a permanent magnet quadrupole system

F. Schillaci

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Prague, Czech Republic

And

INFN-LNS
Catania, Italy

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ELIMED

MEDical application @ ELI-Beamlines

25th International Conference on Magnet Technology,
Amsterdam 27 August – 01 September 2017

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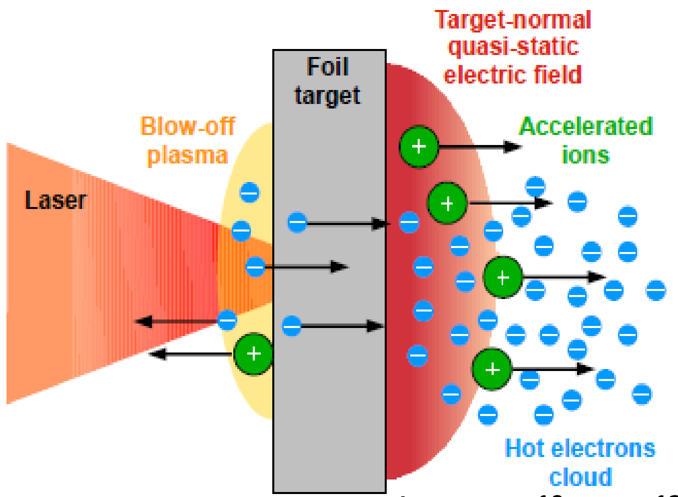
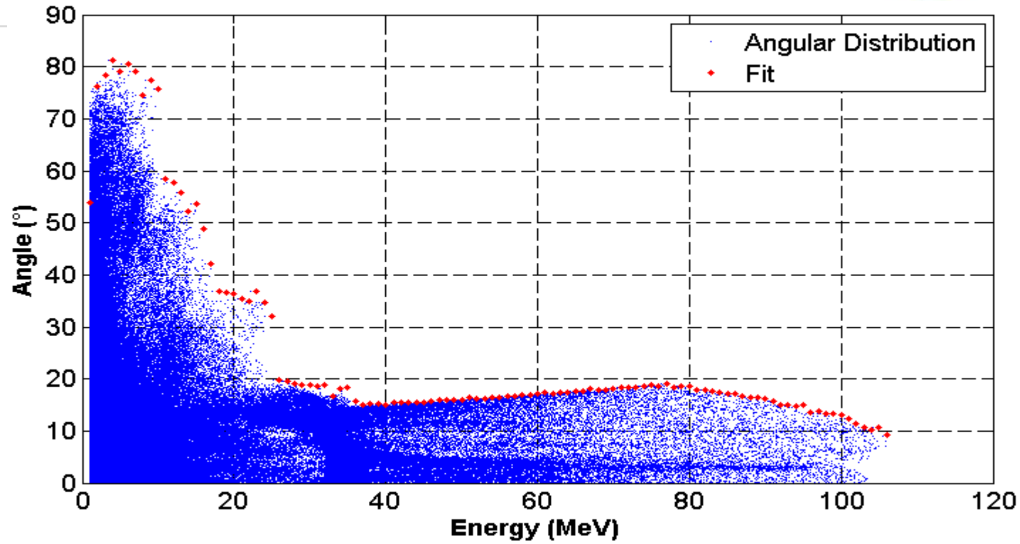
Laser-driven ion *beams*





- Large proton number: $\mathbf{10^{10} \div 10^{13}}$
- Short bunch duration: **few psec**
- High Beam Current: **kA**
- *<u>!Low Emittance!</u>*: $\mathbf{5x10^{-3}\,\pi}$ **mm mrad**

  (microscale spot size but...)
- Wide Angular Aperture: **10 – 20°**

  (if we are lucky**!**)
- High Energy Spread: **ΔE/E >> 10%**
- Low shot-to-shot reproducibilty

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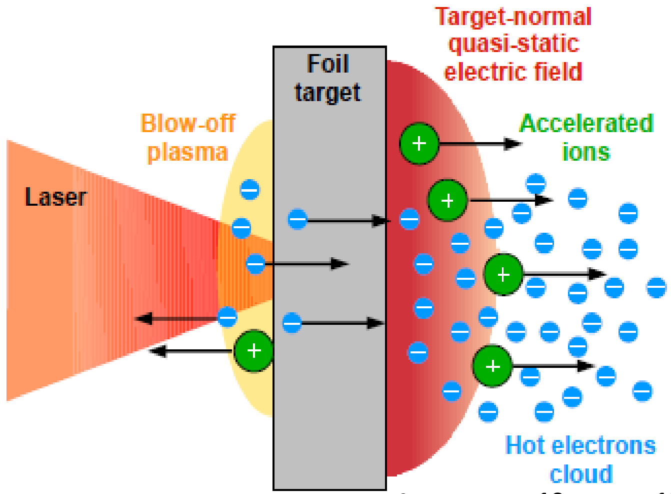

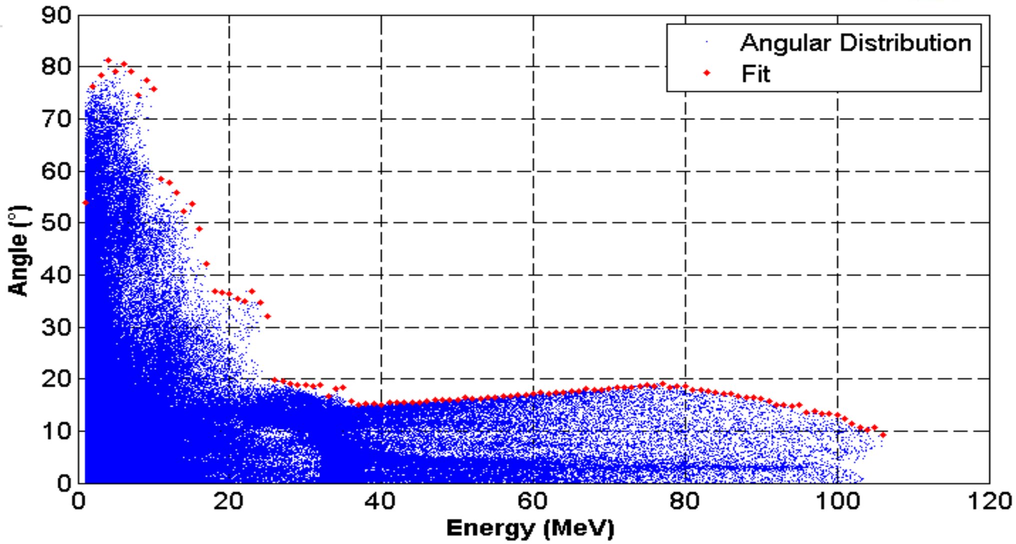

- Large proton number: **$10^{10} \div 10^{13}$**
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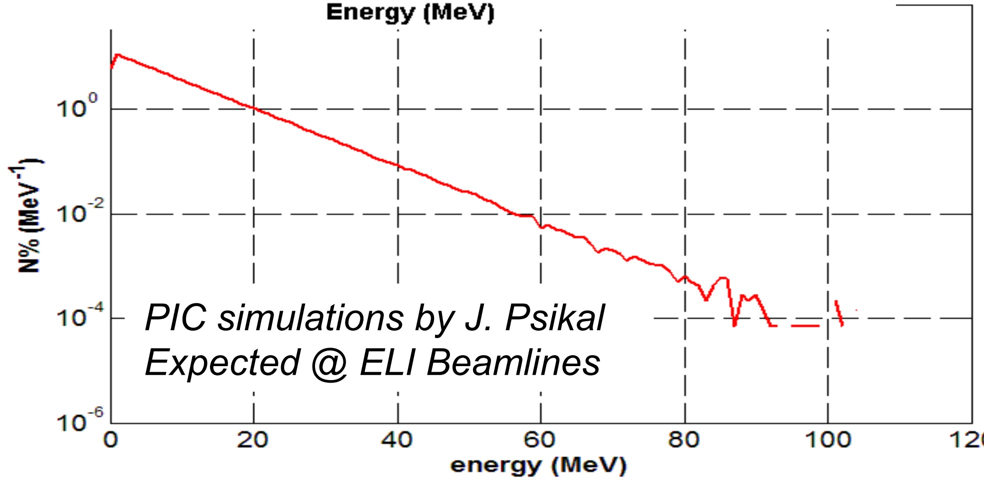

- Wide Angular Aperture: **10 – 20°** (if we are lucky)
- High Energy Spread: **ΔE/E >> 10%**
- Low shot-to-sho reproducibilty
- High dose-rate per bunch: ~10^9 Gy/sec

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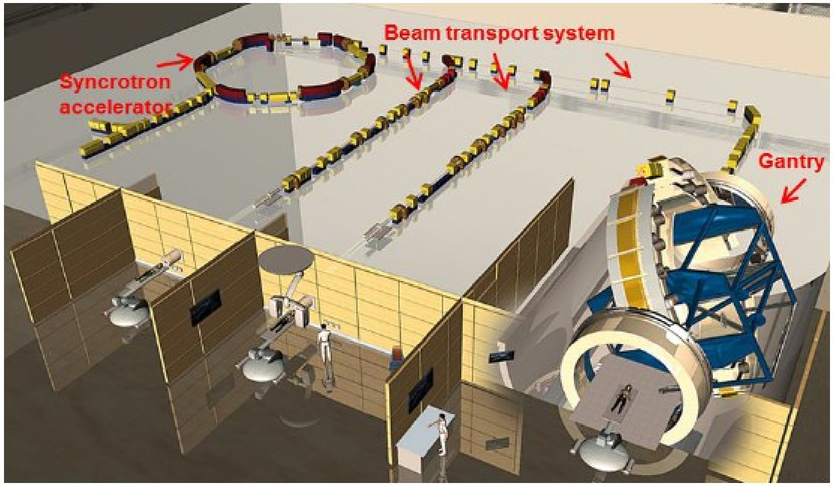
Laser-driven hadrontherapy

http://newscenter.lbl.gov/2010/10/18/ion-beam-therapy/



Conventional hadrontherapy facilities:

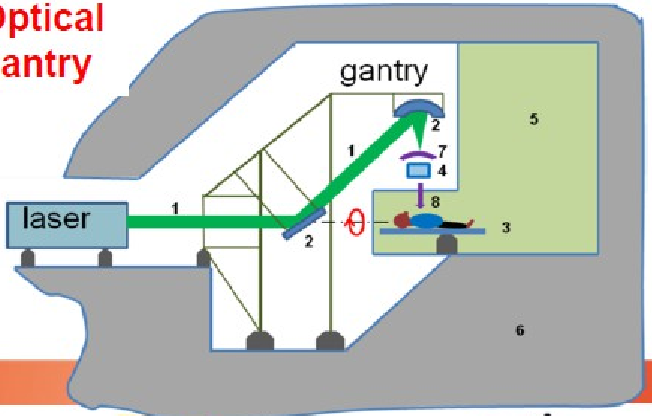
- ***High complexity for the beam, acceleration, transport and delivery***
- ***High cost***

Laser-based hadrontherapy facilities:

- ***Compactness*** (hospital-room size)
- ***Cost-reduction*** (optical gantry)
- ***Innovative treatment modalities:***
  - Variable energies in the accelerator (no degraders needed)
  - Hybrid treatment (protons, ions, electrons, gamma-rays, neutrons)
  - In-situ diagnostics (PET, X-rays)
  - Low emittance: normal-tissue sparing?
  - High fluence rate (ultrashort pulses): higher RBE???

Bulanov & Khoroshkov, Plasma Phys. Rep. (2002)

Optical gantry



Cell irradiation experiments with laser-driven protons

- *Yogo et al, Appl. Phys. Lett., (2009)*
- *Kraft, et al. NJP (2010)*
- *Doria et al., AIP Advances (2012)*
- *Bin, App. Phys. Lett (2012)*

Laser-driven hadrontherapy

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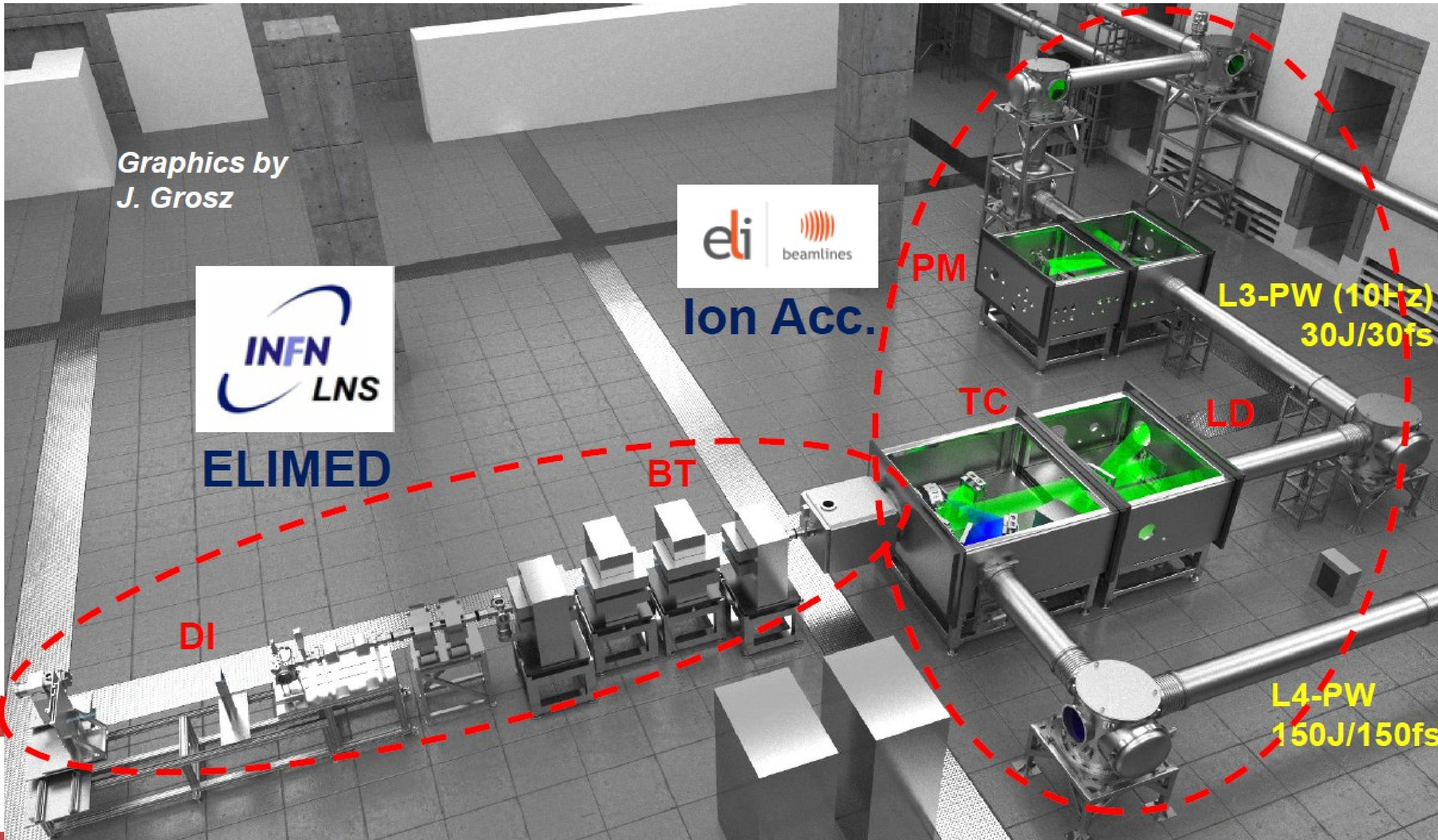
ELIMAIA & ELIMED

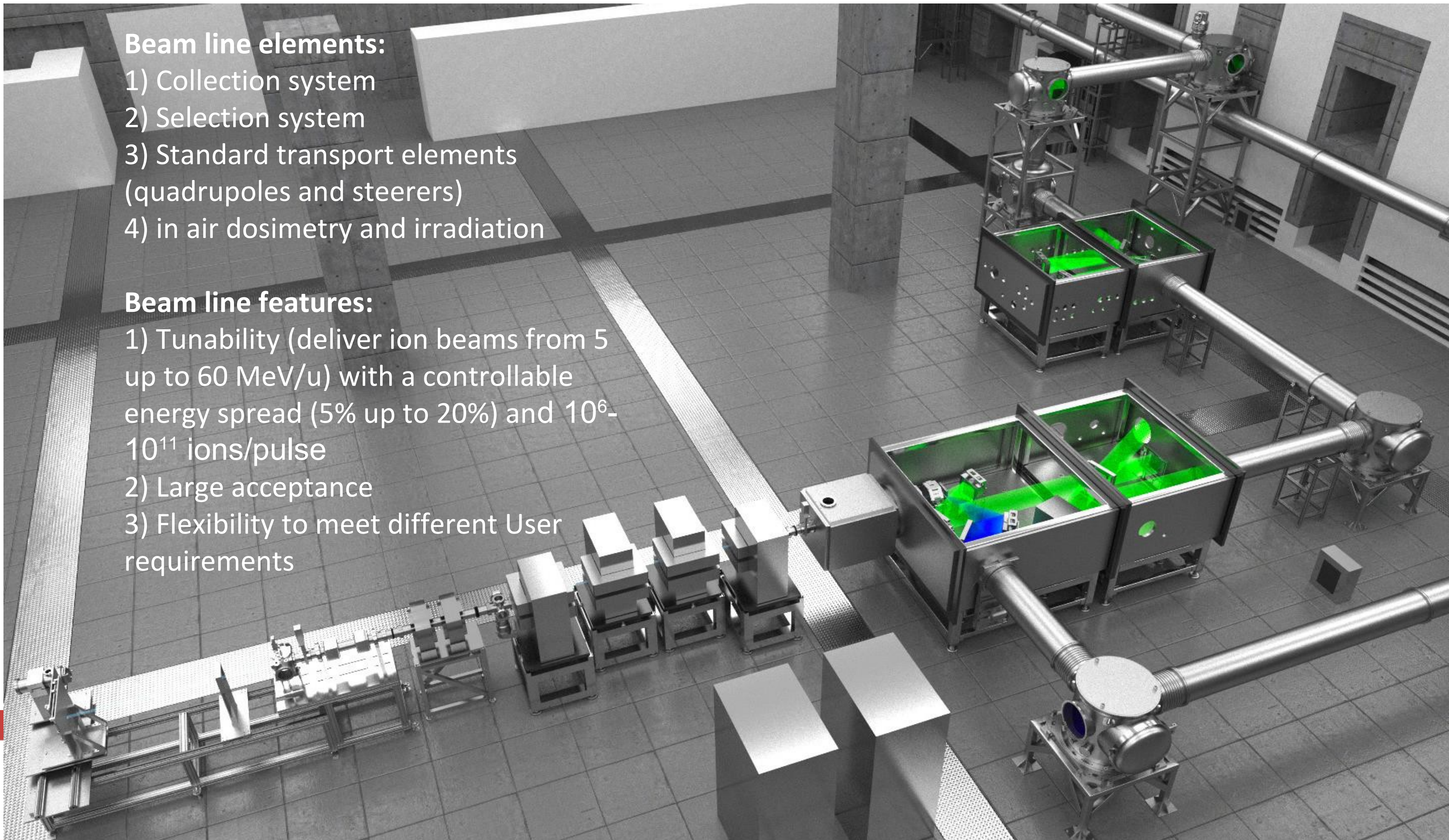
ELI Multidisciplinary Applications of laser-Ion Acceleration



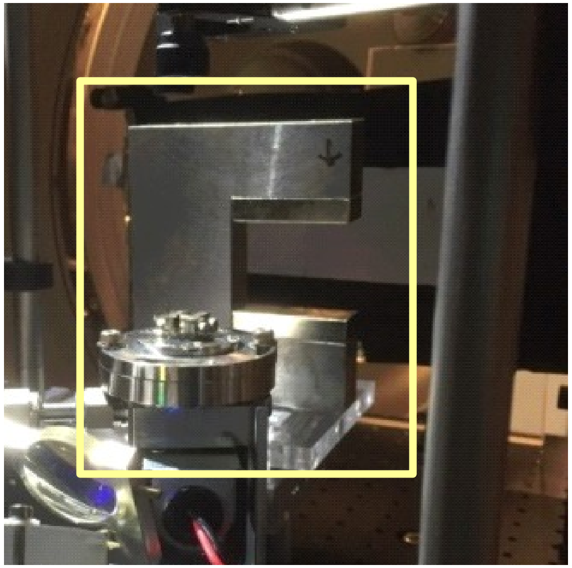
ELIMAIA & ELIMED

Beam line elements:
1) Collection system
2) Selection system
3) Standard transport elements (quadrupoles and steerers)
4) in air dosimetry and irradiation

Beam line features:
1) Tunability (deliver ion beams from 5 up to 60 MeV/u) with a controllable energy spread (5% up to 20%) and 10^6-10^{11} ions/pulse
2) Large acceptance
3) Flexibility to meet different User requirements

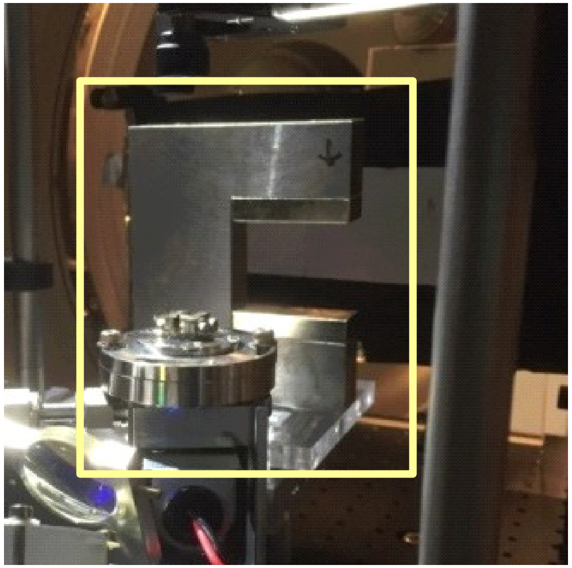


Magnets for laser-driven particles



- 20 mm long dipole
- 50 mm gap
- C-shape
- NdFeBo magnets + iron yoke

Magnets for laser-driven particles



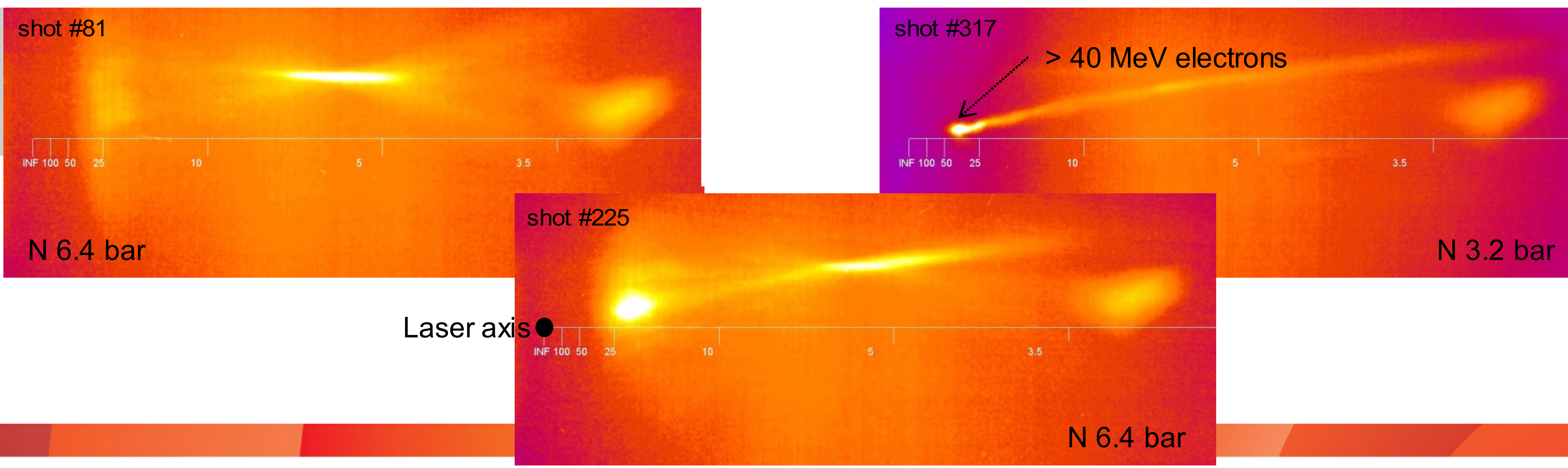
- 20 mm long dipole
- 50 mm gap
- C-shape
- NdFeBo magnets + iron yoke

- **Electron spectrometer!**

The general idea of laser-people is:

"I need X Telsa, just put a random magnet there and it will work"

Magnets for laser-driven particles



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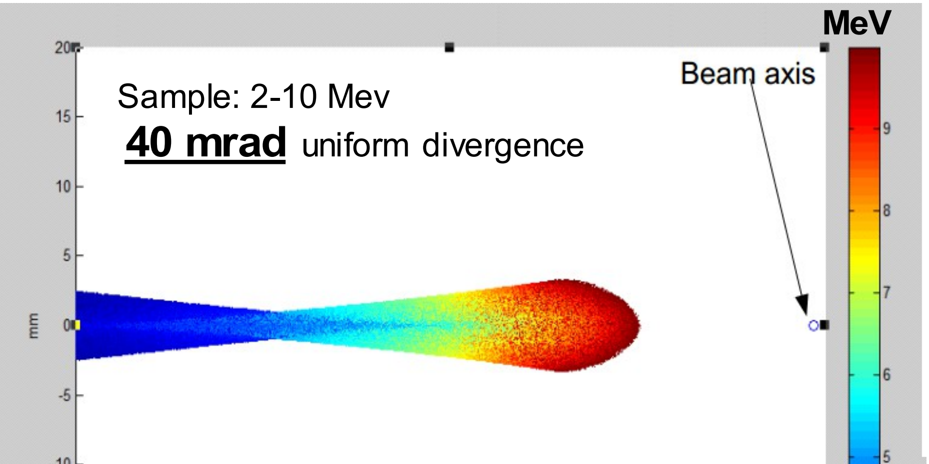

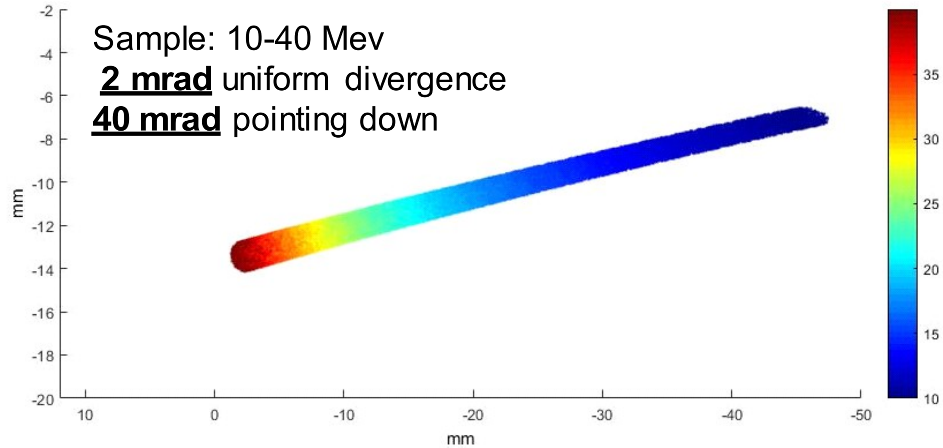

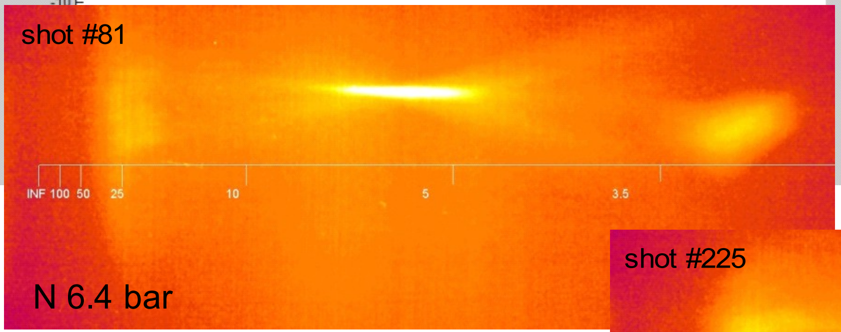

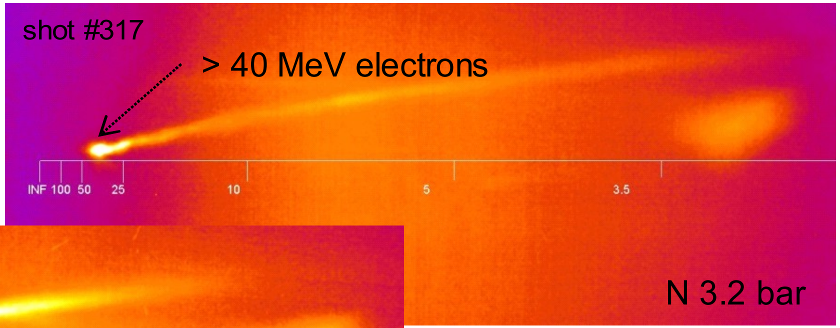

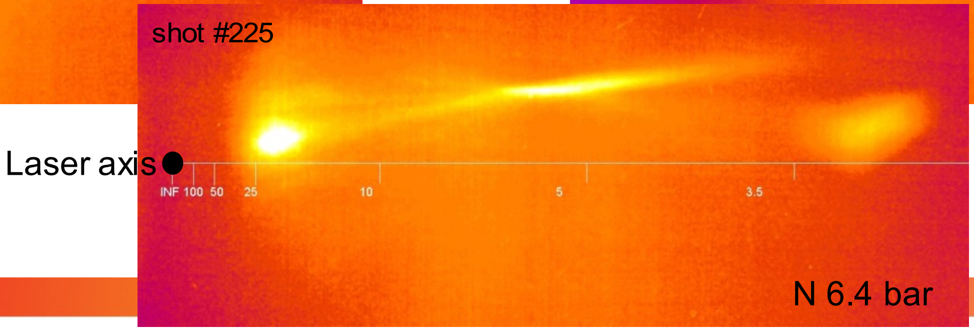

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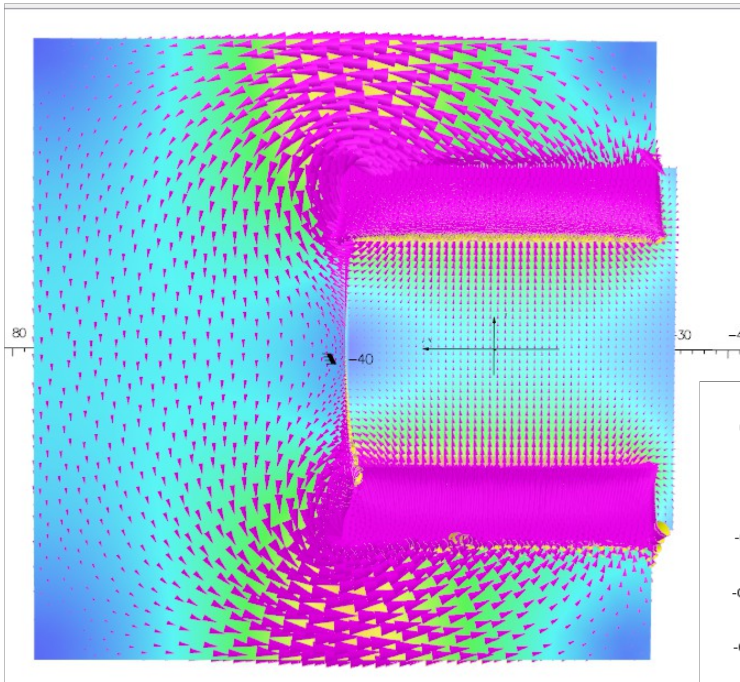
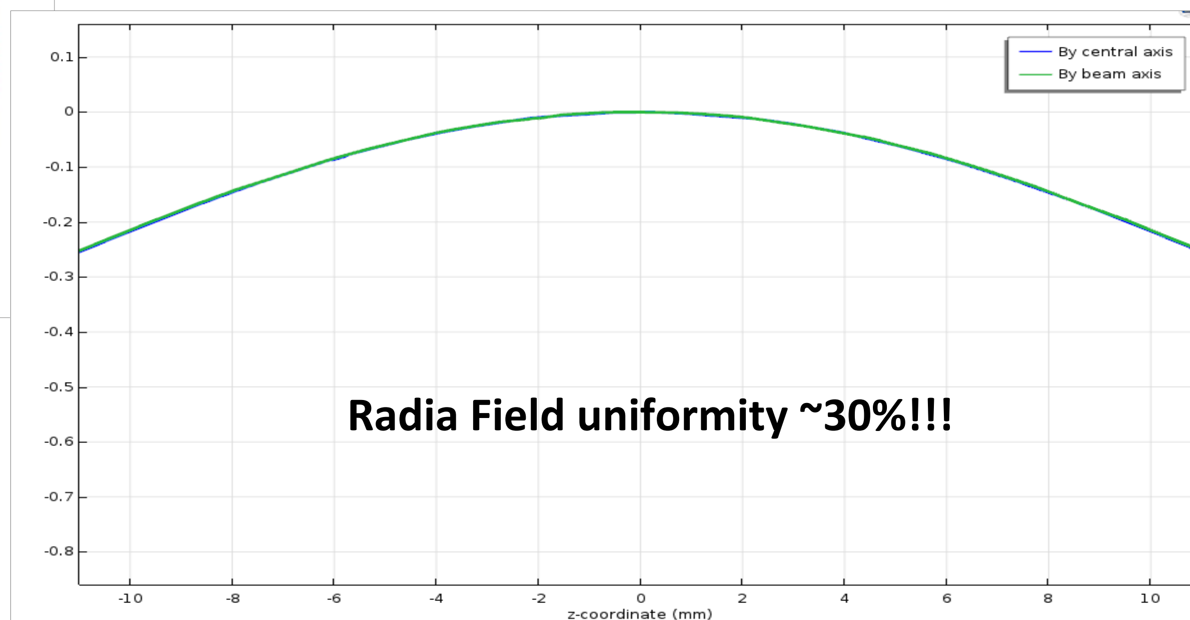
Magnets for laser-driven particles



20 mm long dipole
50 mm gap
C-shape
NdFeBo magnets + iron yoke

Electron spectrometer!



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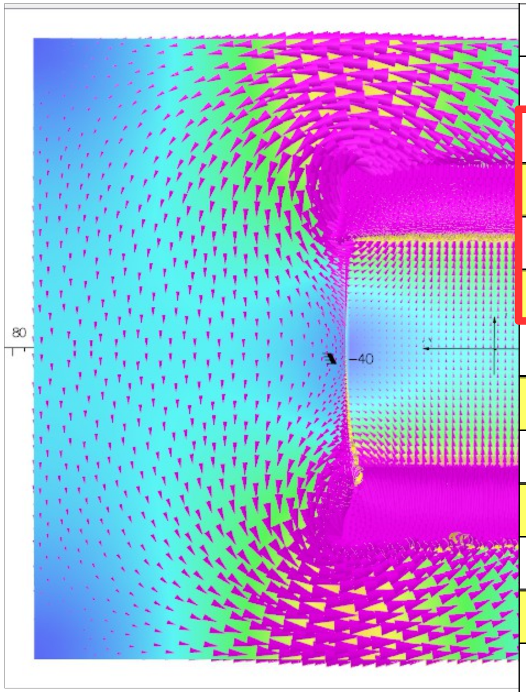
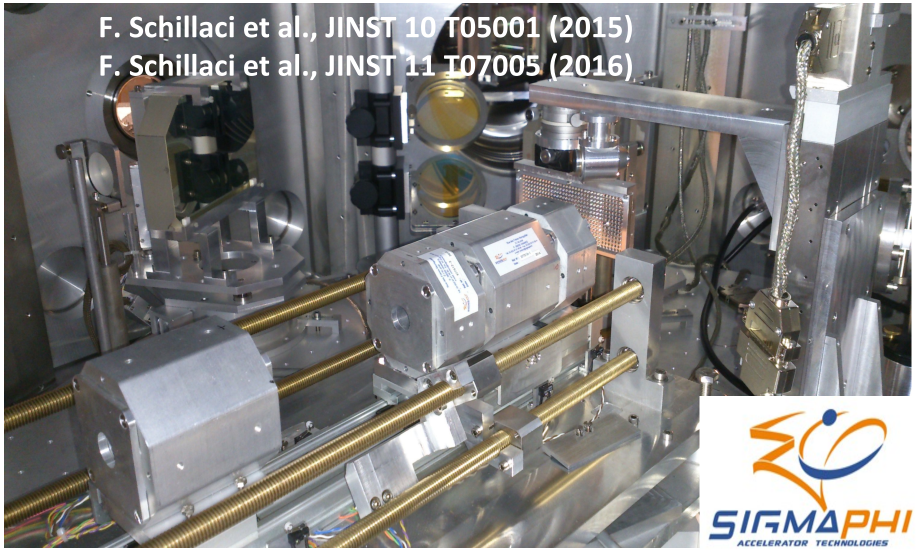
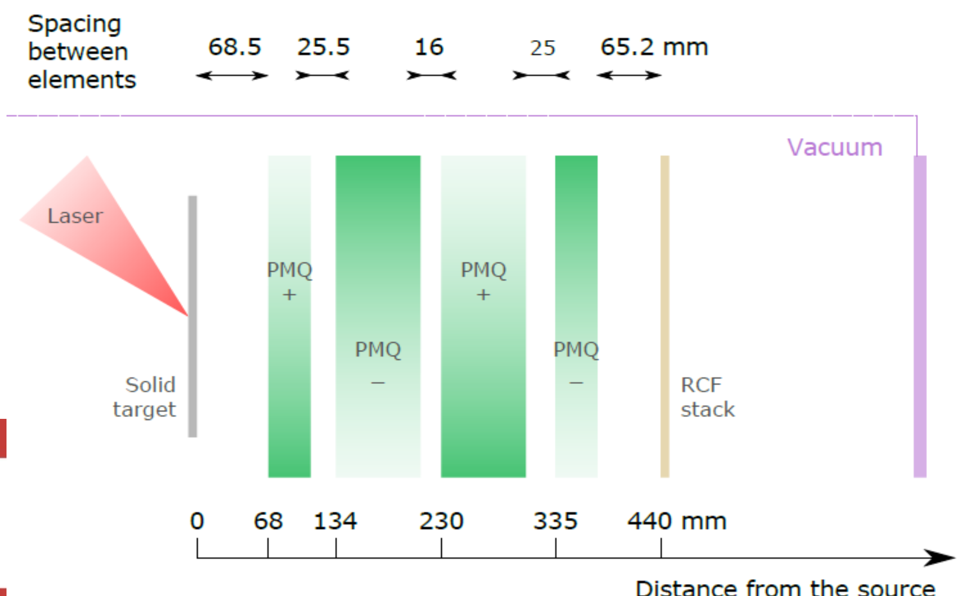
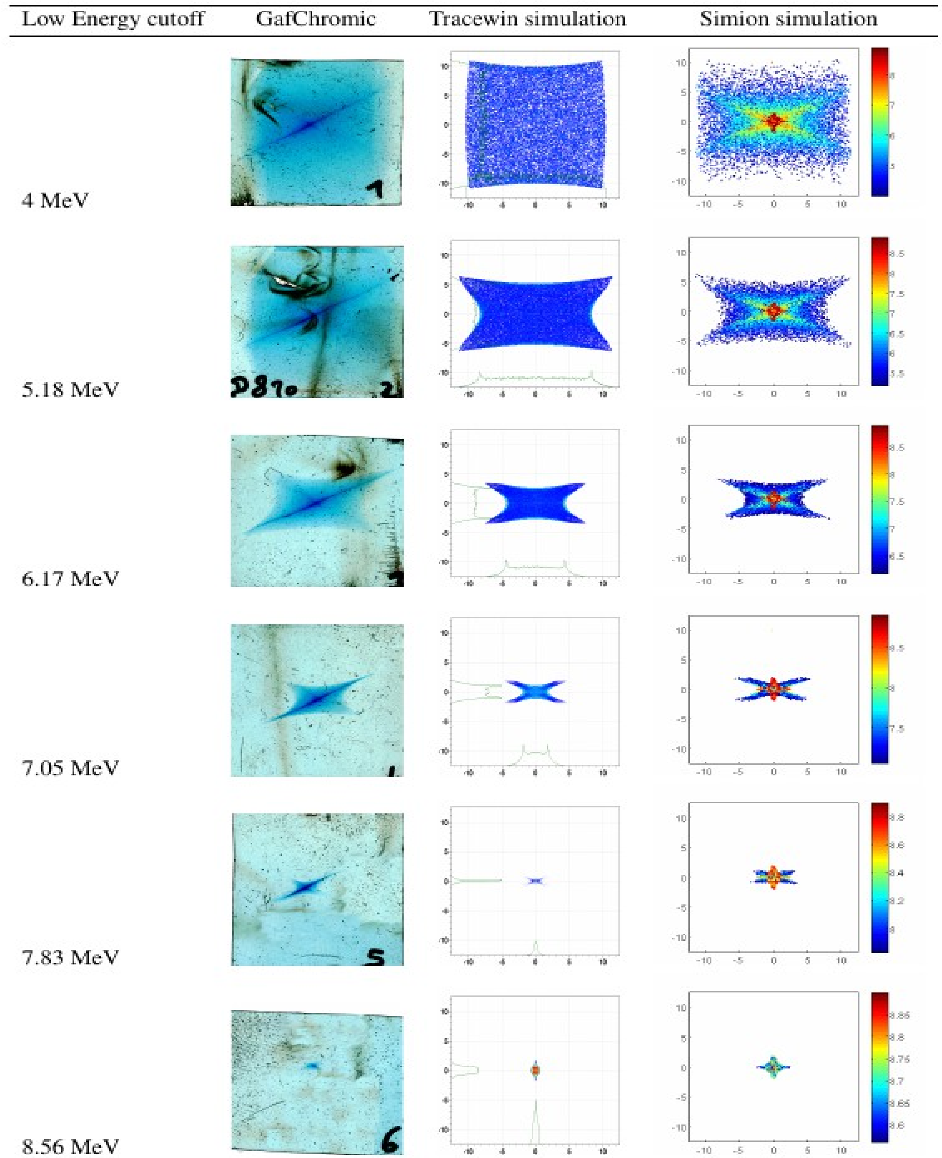


	An (Skew)	Bn (Normal)	an	bn	cn
1 (dipole)	**-5,199e-4**	**22,956**	**11,478**	**10000**	**10000**
2	-0,002	-1,562	0,781	-680,256	680,257
3 (hexapole)	-0,003	-6,436	3,218	-2803	2803
4	-9,601e-4	-0,49	0,245	-213,46	213,45
5	0,003	-0,166	0,083	-72,141	72,153
6	0,001	0,017	0,008	7,212	7,234
7	-6,218e-4	0,105	0,052	45,577	45,578
8	0,001	0,016	0,008	6,895	6,916
9	0,002	0,012	0,006	5,351	5,394
10	-0,001	0,002	0,001	0,784	0,905
11	-0,003	-0,003	0,002	-1,094	1,604
12	0,002	-6,346e-4	0,001	-0,276	0,951
13	0,003	-0,001	0,001	-0,496	1,237
14	-6,071e-4	1,533e-4	3,131e-4	0,067	0,273
15	-0,003	-0,002	0,002	-0,666	1,411
16	-0,002	0,001	0,001	0,497	0,924
17	0,002	0,002	0,001	0,912	1,182
18	0,002	-0,001	0,001	-0,645	1,243
SUM				-3705	3846
%				37%	38%

Permanent Magnet prototype test results @ LOA (Fr)







OUTLINE

- Quadrupole features
- Error source in magnets and modelling
- Fixing the tolerances
- Beam transport (simulations and experiment)

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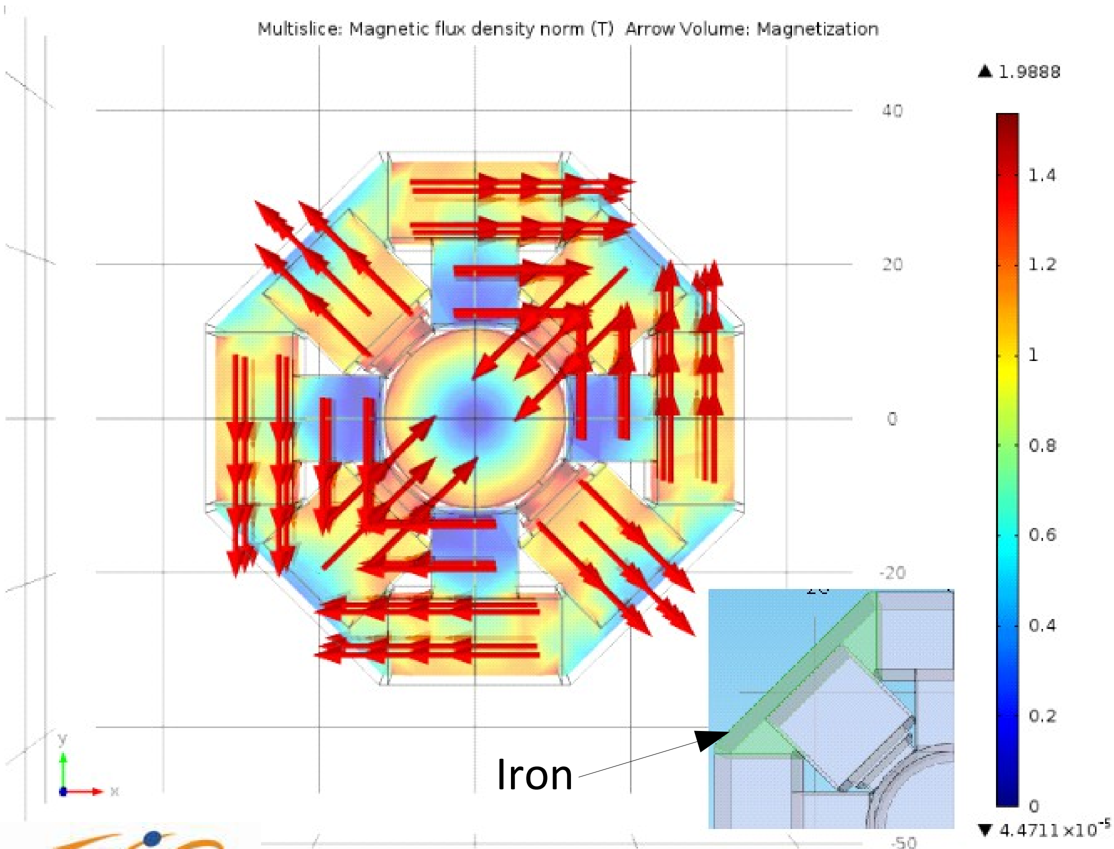
Quadrupole layout



4 PMQs features
(simulations)

- 2 elements 40 mm long
- 2 elements 80 mm long
- 22 mm bore – 20 mm clearance
- 100T/m field gradient
- NdFeBo N50 permanent magnets
- Gradient homogeneity: -6% @ R = 8mm
- Integrated gradient homogeneity: -1% @ R = 8mm
- Harmonic content $B_n/B_2 < 2\%$
- **Cost-effective prototype**

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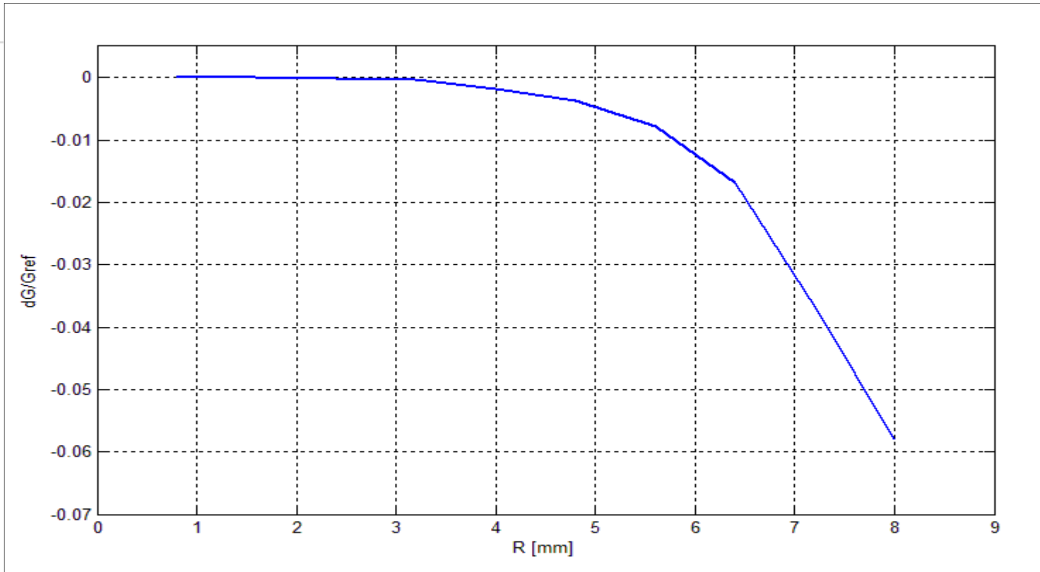
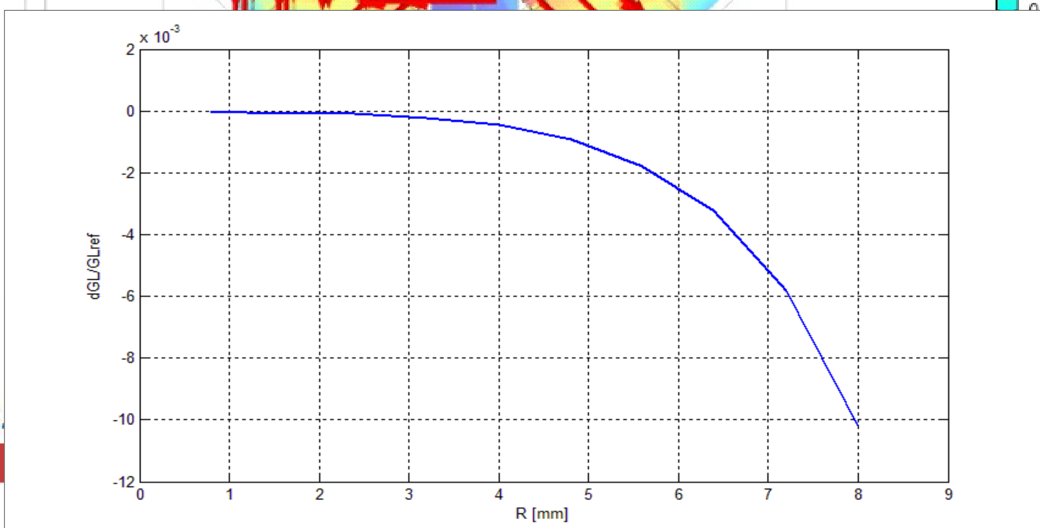
Quadrupole layout





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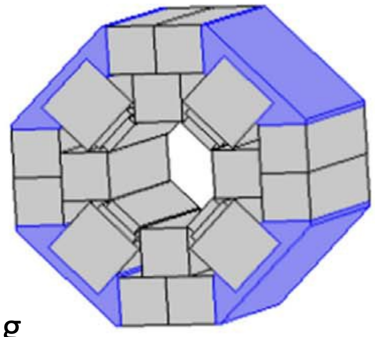
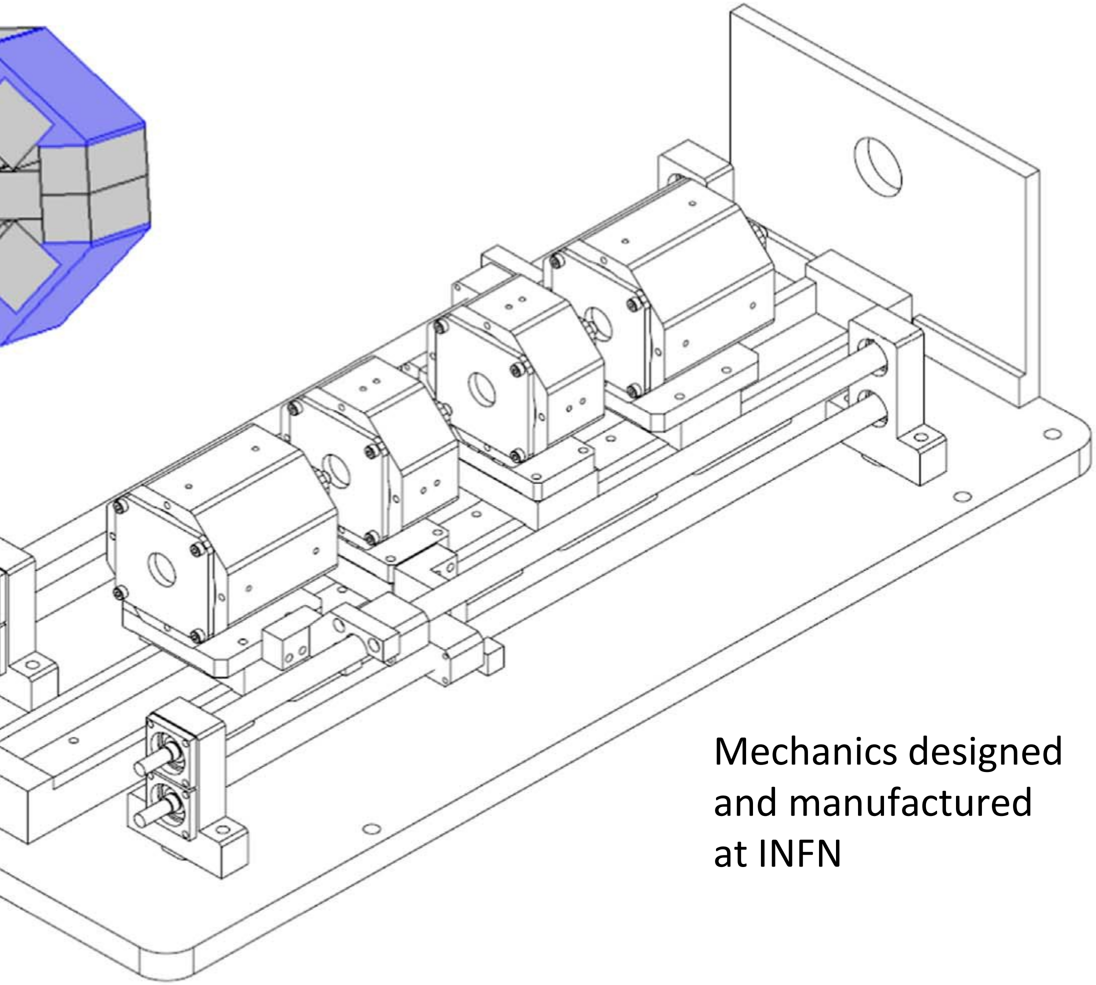


Magnetic design
and manufacturing



Mechanics designed
and manufactured
at INFN

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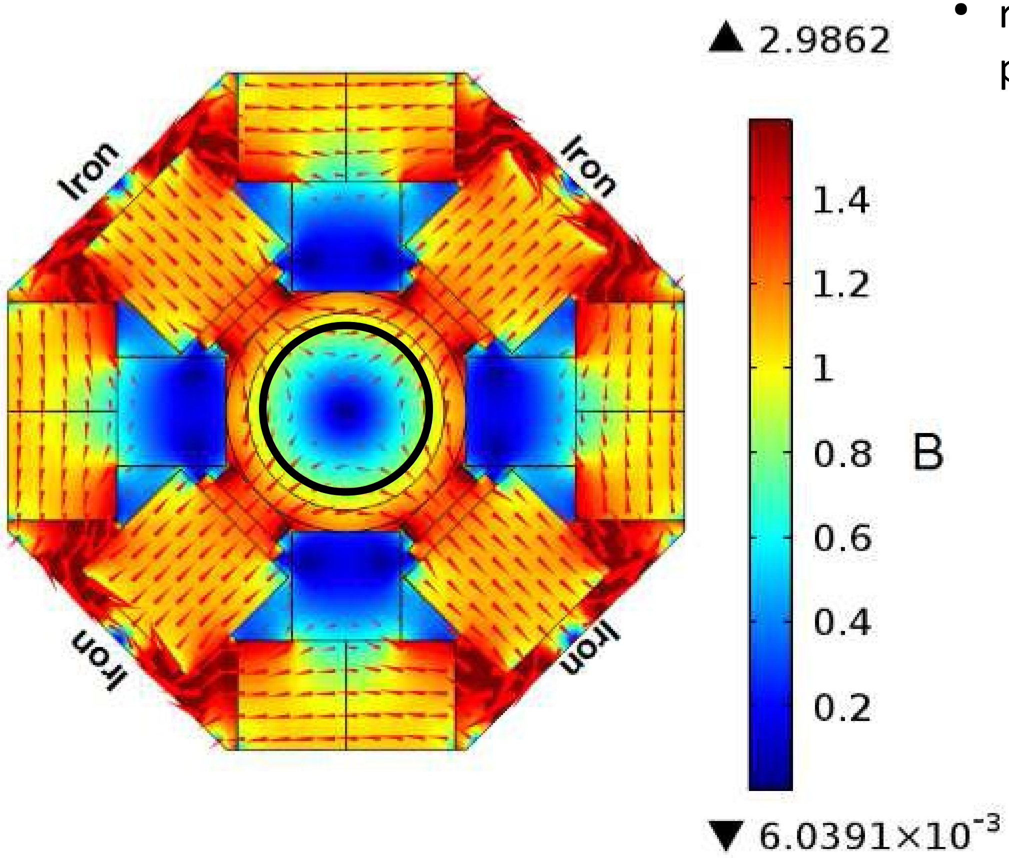
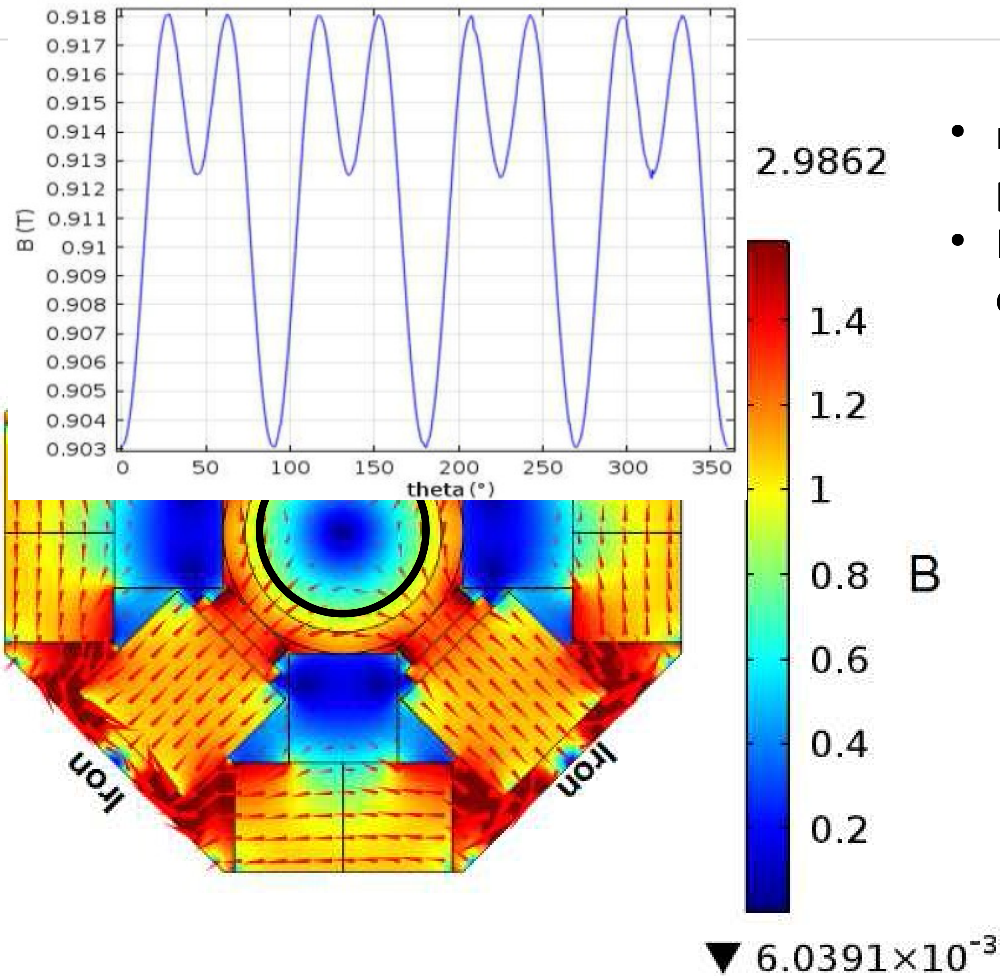
2D Harmonic analysis



2D simulations:

- r0 = 8 mm radius reference circle for B-field post-processing and harmonic analysis

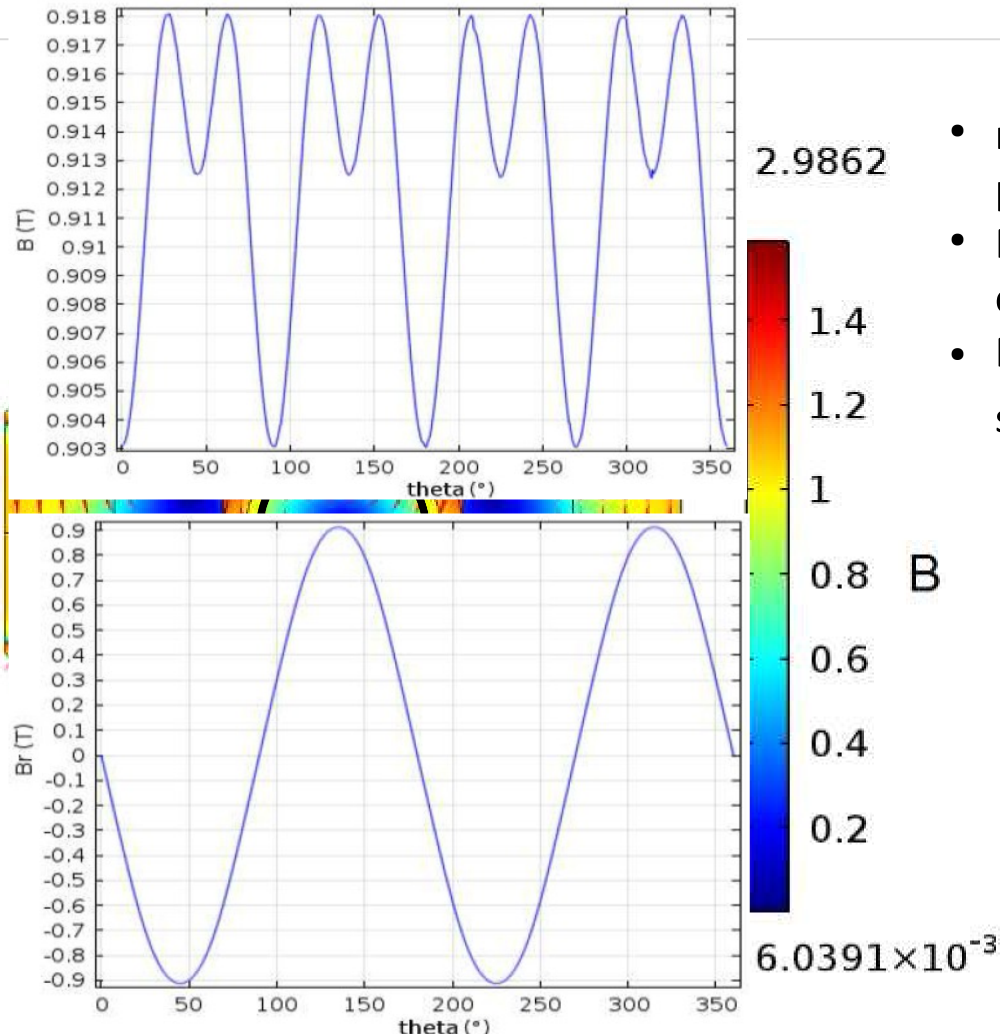
2D Harmonic analysis



2D simulations:

- r0 = 8 mm radius reference circle for B-field post-processing and harmonic analysis
- Modulus of induction |B| should be constant

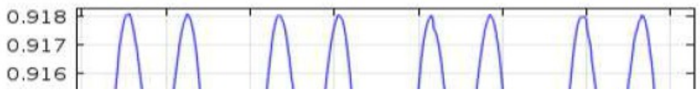
2D Harmonic analysis



2D simulations:

- r0 = 8 mm radius reference circle for B-field post-processing and harmonic analysis
- Modulus of induction |B| should be constant
- Radial component B_{rad} = Bx (x/r0) + By (y/r0) should be purely sinusolidal

2D Harmonic analysis



Harmonic n	$\|C_n\|$ Value [T/m]	$\|C_n\|$ Value (units of 10^4)	B_n Value (units of 10^4)
1	6.394e-4	0.111	-0.092
2	57.547	10000	10000
3	8.942e-5	0.016	0.015
4	1.886e-5	0.003	-0.002
5	1.676e-5	0.003	-0.002
6	0.38	66.089	-66.089
7	1.281e-5	0.002	0.002
8	5.153e-5	0.009	6.005e-4
9	3.546e-5	0.006	0.002
10	0.292	50.821	-50.821
11	4.335e-5	0.008	0.007
12	9.066e-6	0.002	2.351e-4
13	2.819e-5	0.005	-0.002
14	0.032	5.519	5.519
Sum		1.22%	1.114%

2D simulations:

- r0 = 8 mm radius reference circle for B-field post-processing and harmonic analysis
- Modulus of induction |B| should be constant
- Radial component B_{rad} = Bx (x/r0) + By (y/r0) should be purely sinusolidal
- Fourier expansion of B_{rad} gives the magnitude of the harmonic components Cn:

$$C_n = \frac{1}{N} \frac{\sum_{N-1}^{k=1} B_{rad\,k}}{r_0} \exp\left(ik\left(2\pi\frac{n}{N}\right)\right)$$

- Deviations from ideal behaviour affect the field quality and the beam transport can show filamentation, emittance growth, steering

OUTLINE

- Quadrupole features
- Error source in magnets and modelling
- Fixing the tolerances
- Beam transport (simulations and experiment)

Error source in a magnet

- Magnetization of permanent magnets (remanence, magnetization angle, ...)
- Manufacturing errors (assembly, pole shimming, ...)
- Alignment (skew components)
- Eddy currents (see my talk *Status and realization of an high efficiency transport beamline for laser-driven ion beamline* [Wed-Mo-Or19])
- ...

If one or more error sources are introduced symmetry is broken!

In order to minimize the errors the tolerances have to be stated for each possible error source.

The tighter are the tolerances the higher will be the cost!

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If one or more error sources are introduced symmetry is broken!

In order to minimize the errors the tolerances have to be stated for each possible error source.

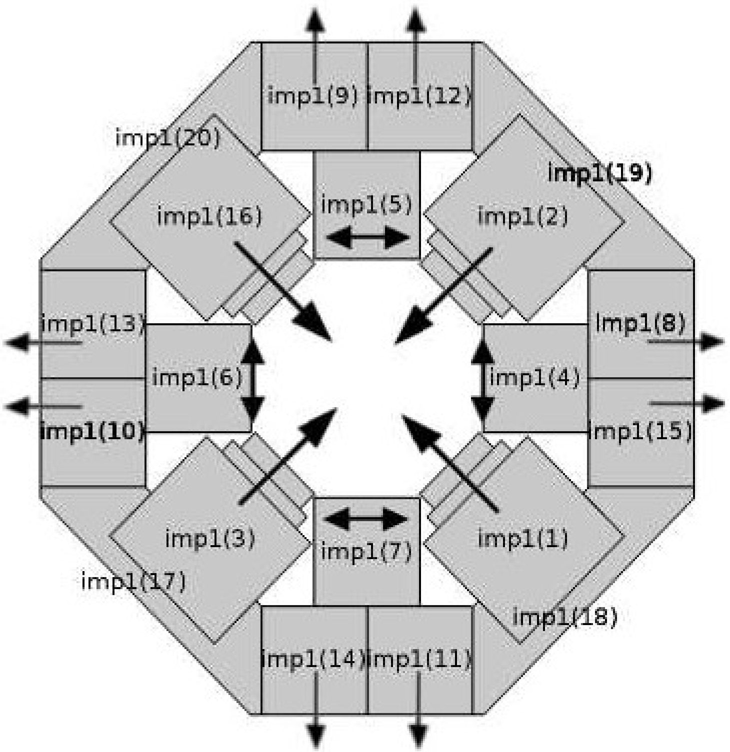
The tighter are the tolerances the higher will be the cost!

The goal here is to have no more than **3%** of total harmonic component

How to introduce errors in simulations:

Remanence: The remanence *Mr* of each rare-earth piece is multiplied by a random number, *rand1*, with a fixed seed depending on the block identification number and on the ordinal number of themagnetic configuration produced (401 in total).
rand1 is uniformly distributed around the mean value 1 with a range of ±0.03 and ±0.06, making the remanent magnetization increasing or decreasing up to 3% and 6%.

Assembly:



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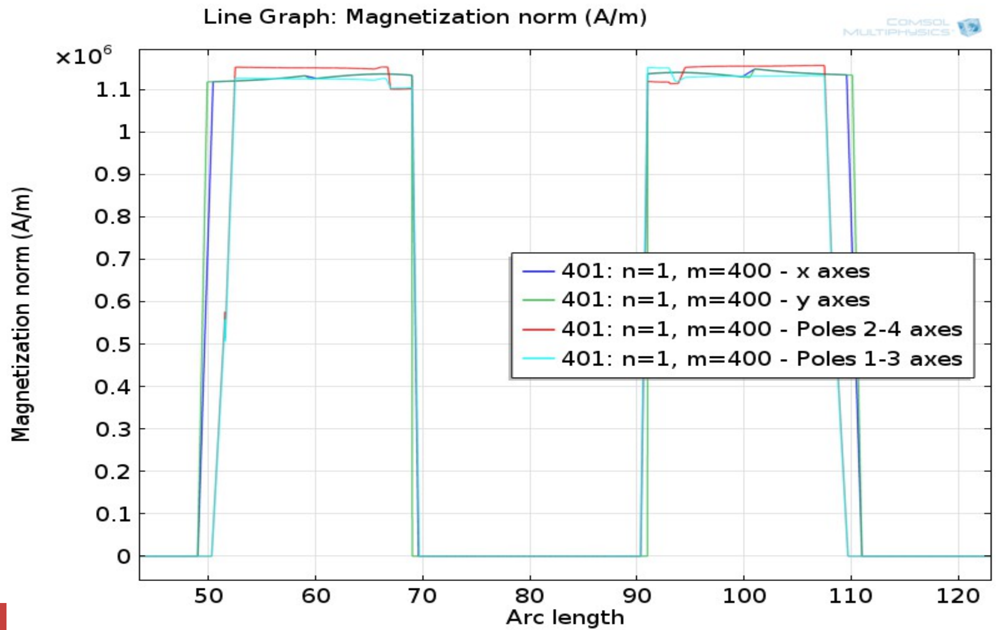

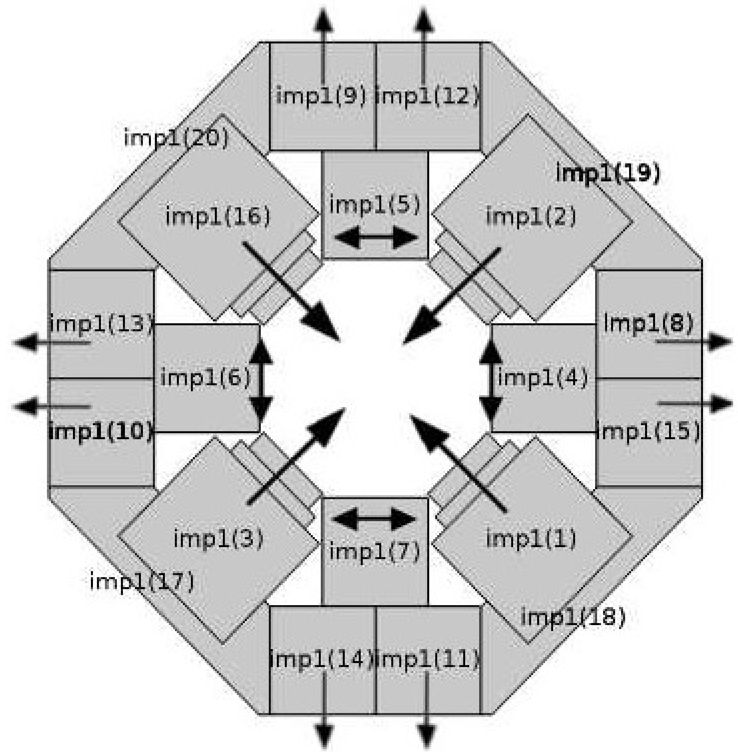

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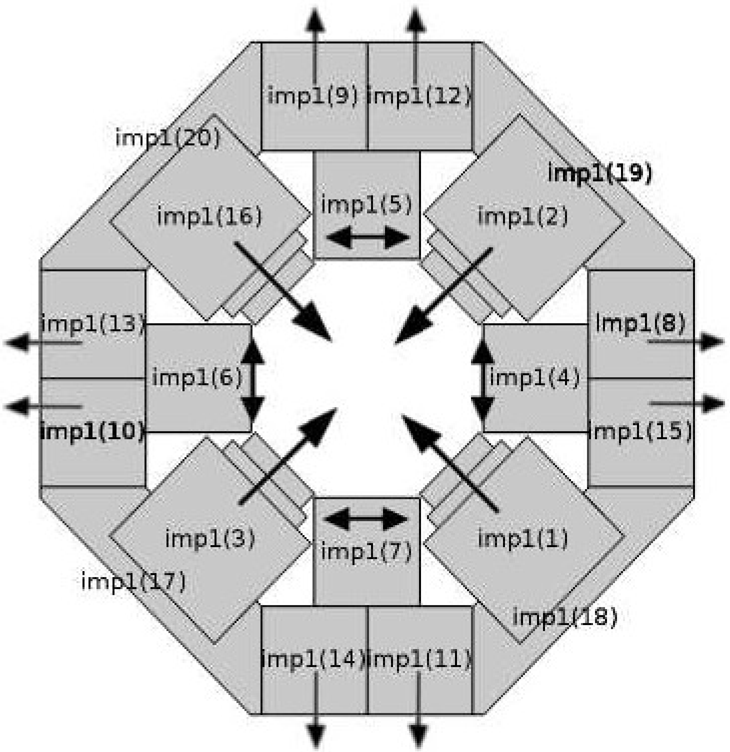

Assembly: The mechanical assembly errors is simulated introducing a different displacement for each block controlled by a random number *rand*2 with fixed seed.
The direction has been forced to avoid overlapping of the magnets (iron parts are considered fixed).
The T-like pieces between two poles are treated as three independent blocks, even if they will be realized as a single one; this allow to take in account not only errors due to the assembly but also errors due to the machining of these parts.
*rand*2 is been defined as uniformly distributed around the mean value 0 with a rangeof ±0.1 and ±0.2. In this way each block is shifted from the ideal position up to 100µm in the first case and up to 200µm in the second case.

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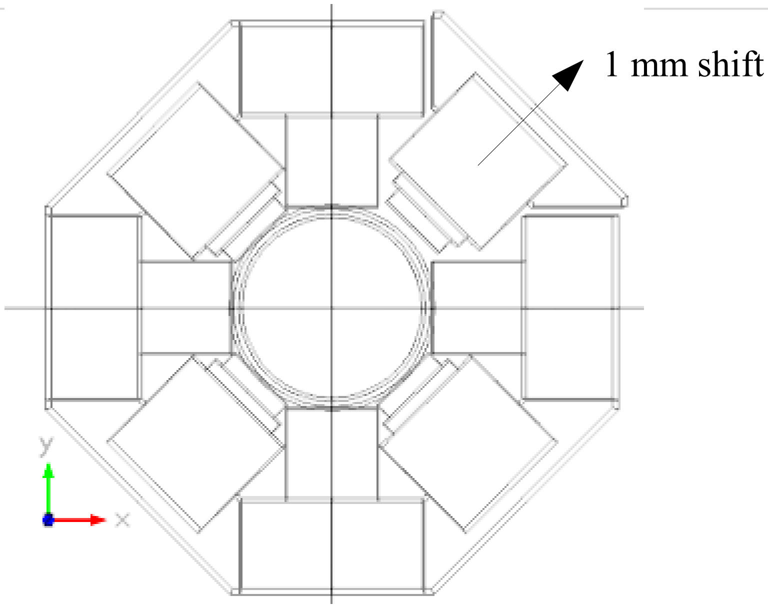
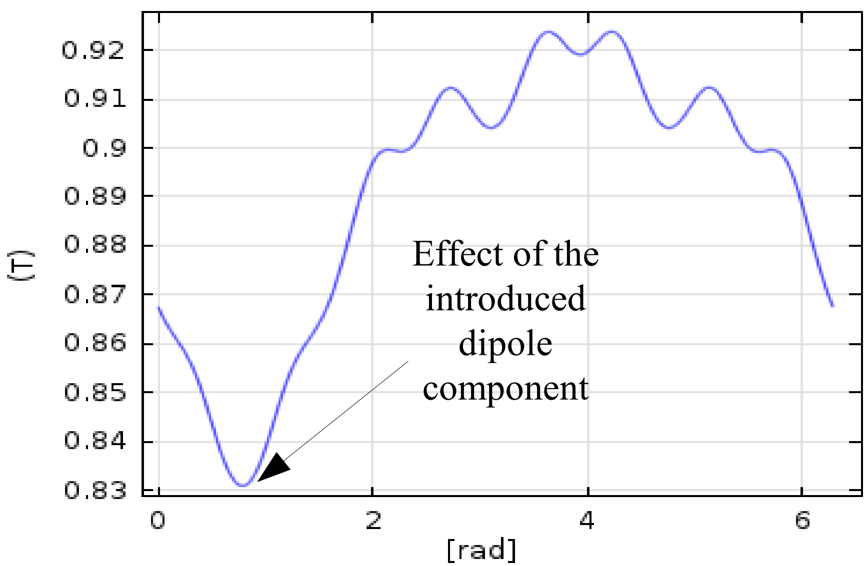
Model validation I
Ideal B_1 = 0.092 units

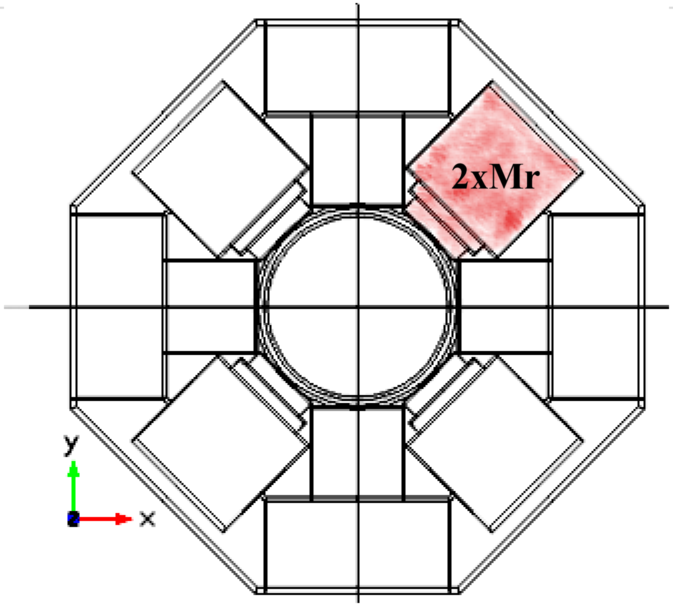


R	A_1	B_1	Phase [°]
1	1.572	1.572	45
2	1.571	1.571	45
3	1.571	1.571	45
4	1.570	1.570	45
5	1.569	1.569	45
6	1.568	1.568	45
7	1.566	1.566	45
8	1.564	1.564	45
9	1.559	1.559	45

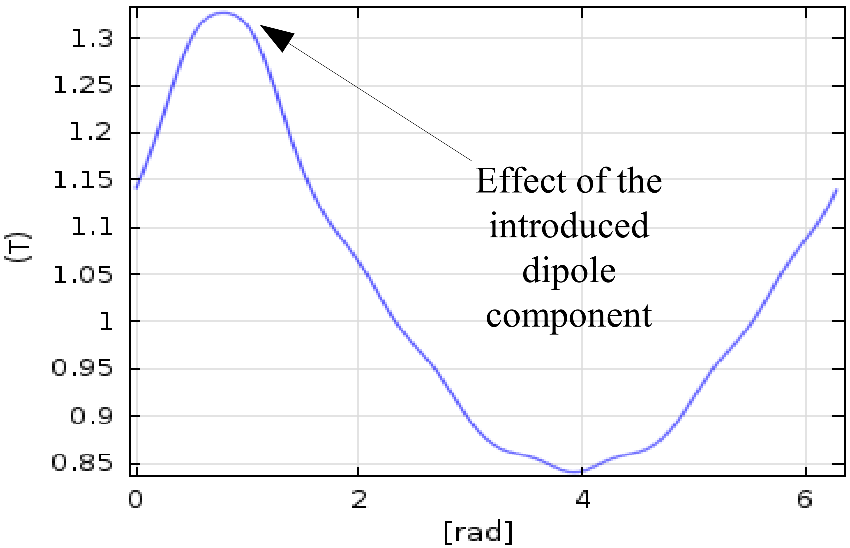


The radial displacement of the pole at 45° produces a small decrease in the peak of B_{rad} at the same angle. The loss of symmetry produces a dipole contribution in the opposite direction of the pole shift. The real and imaginary parts of the coefficient C_1 are equal to each other even if the field is analysed at different reference radii, which means that the phase of the dipole component is $\vartheta = arctan(B_1)/(A_1) = 45°$, namely in the direction of the displaced pole.

Model validation II
Ideal B_1 = 0.092 units



R	A_1	B_1	Phase [°]
1	-12,644	-12,644	45
2	-12,644	-12,644	45
3	-12,643	-12,643	45
4	-12,643	-12,643	45
5	-12,642	-12,642	45
6	-12,642	-12,642	45
7	-12,639	-12,639	45
8	-12,637	-12,637	45
9	-12,634	-12,634	45



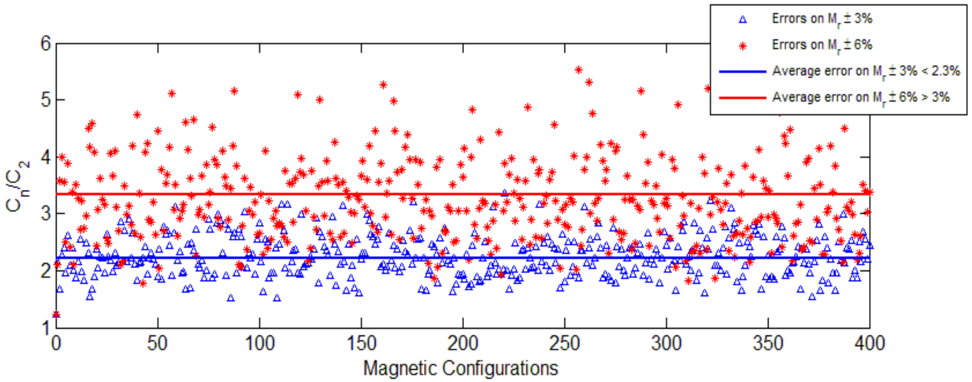
If the pole is in its ideal position but its remanence is increased by a factor of two there is a strong increase in the peak of B_{rad} as the loss of symmetry produces a dipole contribution in the same direction of the pole magnetization direction.

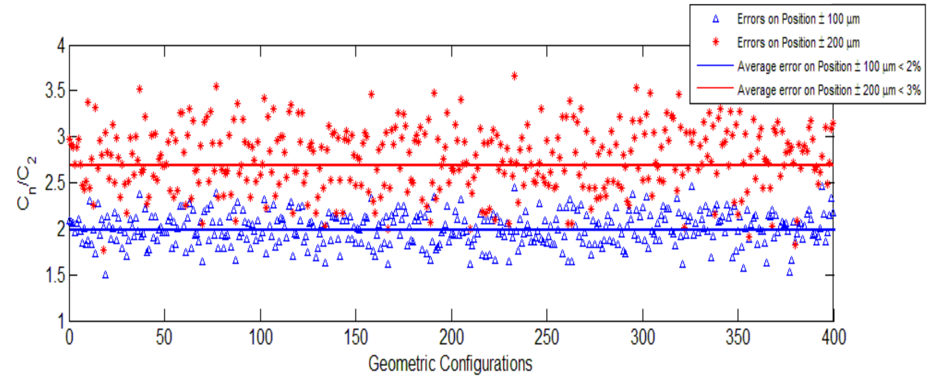
OUTLINE

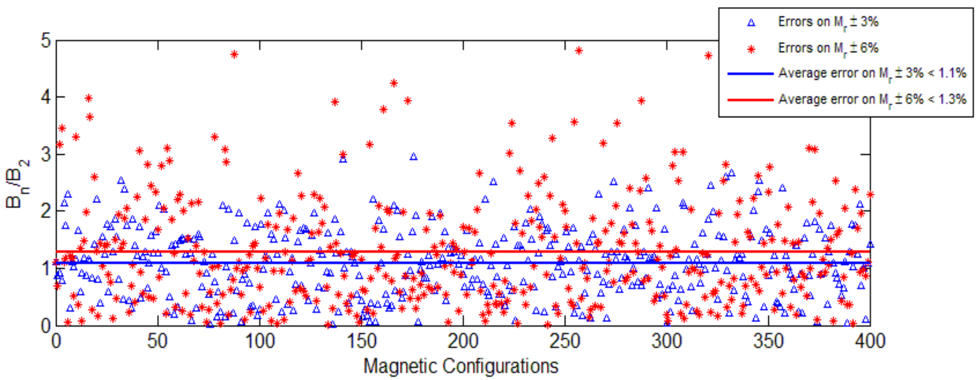
- Quadrupole features
- Error source in magnets and modelling
- Fixing the tolerances
- Beam transport (simulations and experiment)

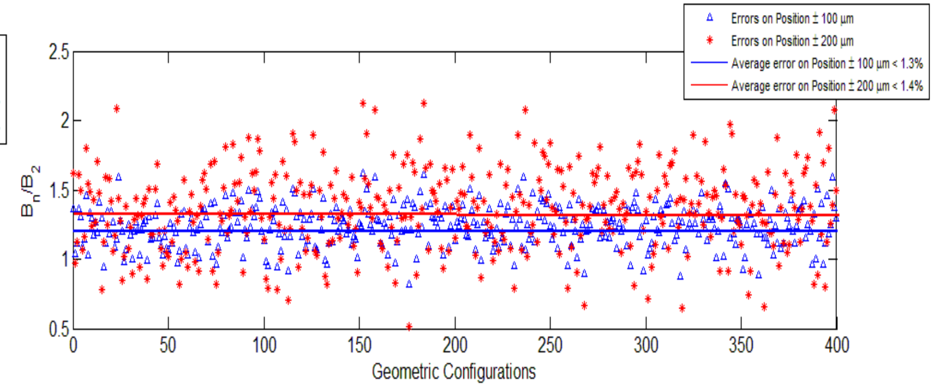
Random Errors

400 different simulations per range of variation of M_r and magnet position



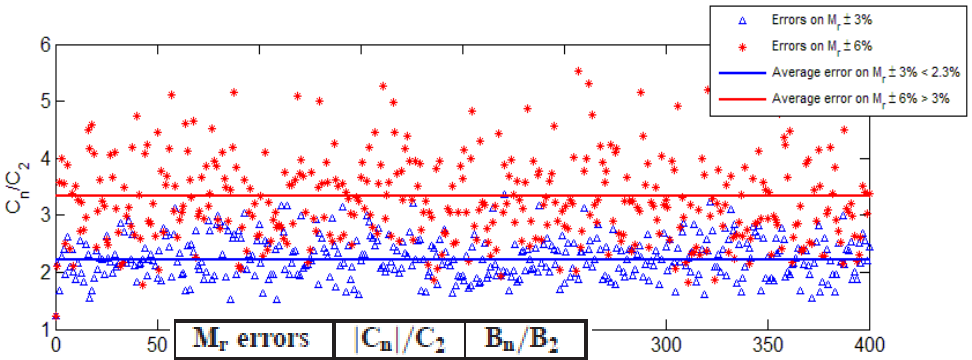




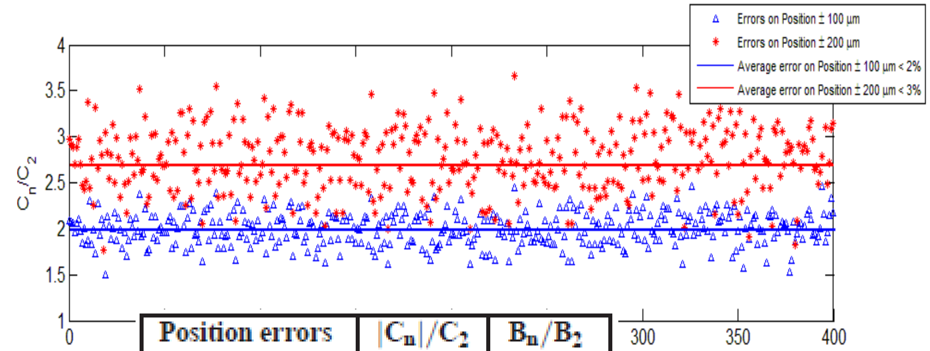


Random Errors

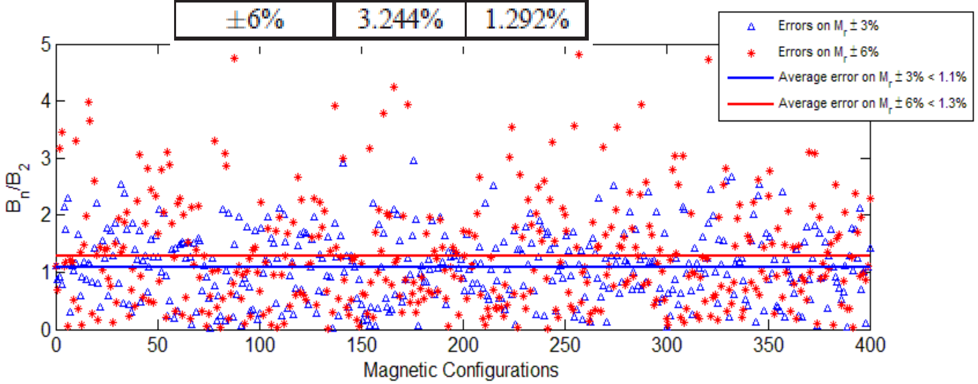
400 different simulations per range of variation of M_r and magnet position

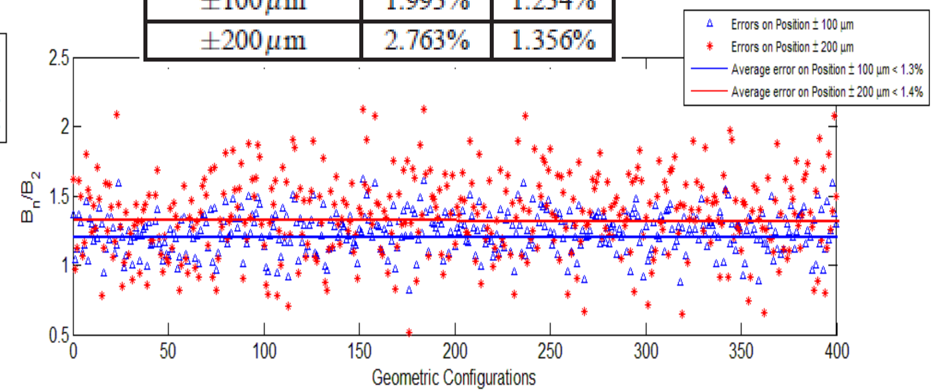


M_r errors	$\|C_n\|/C_2$	B_n/B_2
±3%	2.249%	1.097%
±6%	3.244%	1.292%



Position errors	$\|C_n\|/C_2$	B_n/B_2
$\pm 100\,\mu m$	1.993%	1.234%
$\pm 200\,\mu m$	2.763%	1.356%



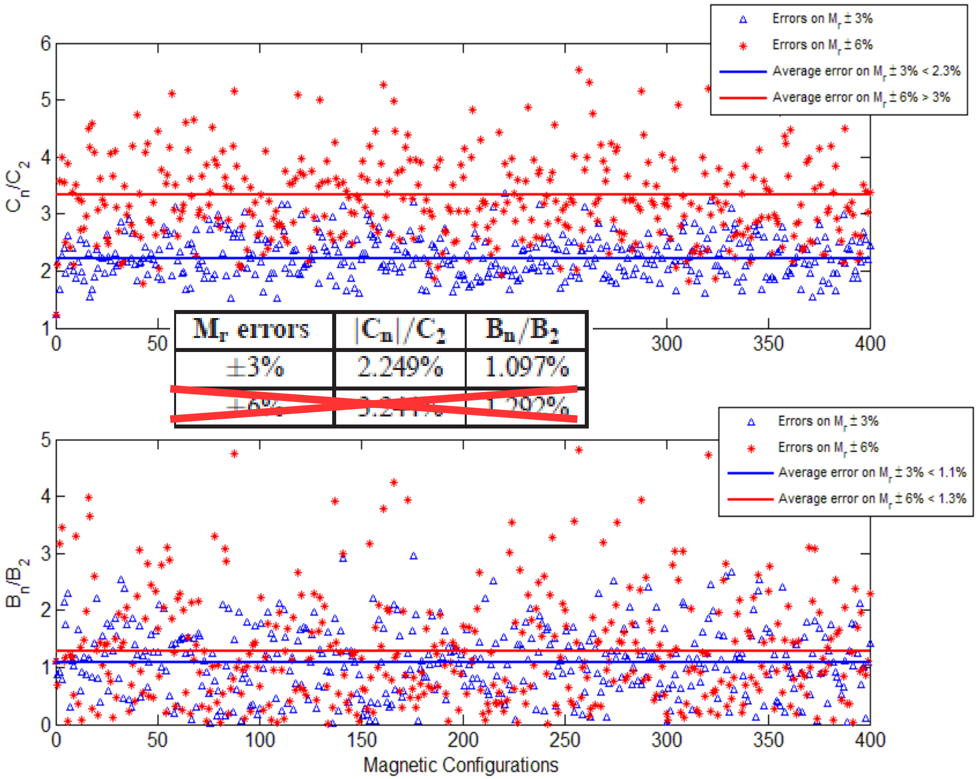


Ideal case results

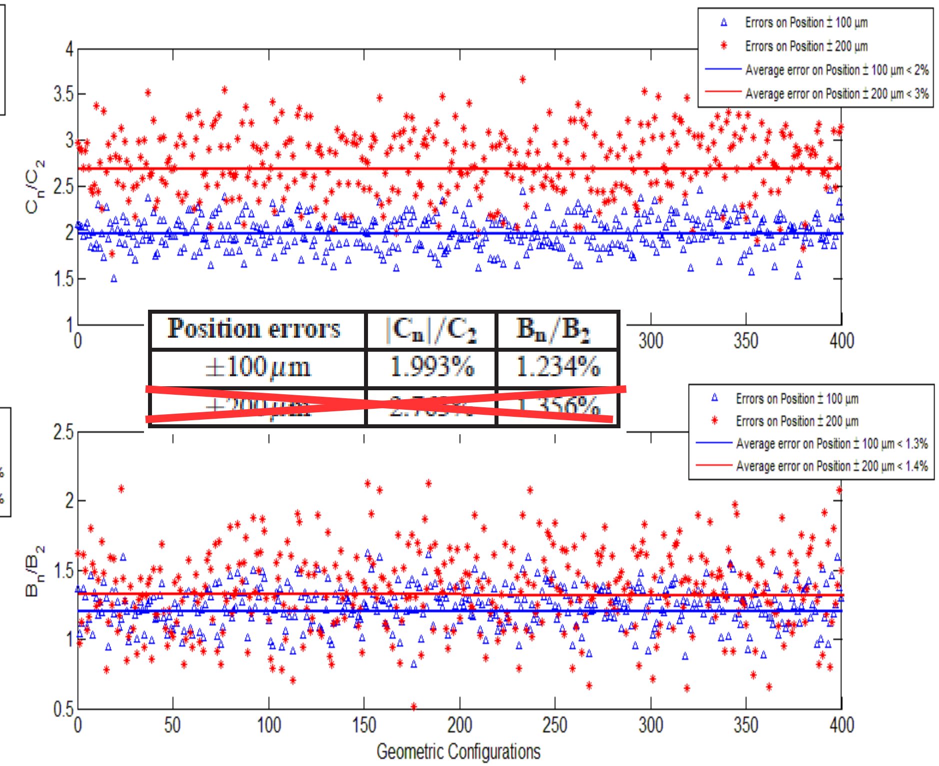
Harmonic n	$\|C_n\|$ Value (units of 10^4)	B_n Value (units of 10^4)
Sum	1.22%	1.114%

Random Errors

400 different simulations per range of variation of M_r and magnet position



M_r errors	$\lvert C_n \rvert / C_2$	B_n/B_2
$\pm 3\%$	2.249%	1.097%
~~$\pm 6\%$~~	~~3.241%~~	~~1.292%~~



Position errors	$\lvert C_n \rvert / C_2$	B_n/B_2
$\pm 100\,\mu m$	1.993%	1.234%
~~$\pm 200\,\mu m$~~	~~[illegible]~~	~~1.356%~~

The normal content (B_n) does not increase significantly with the increasing of the errors

The complex harmonics (C_n) are strongly affected by the errors and their contribution is about 3% of the main harmonic if the errors range in the wider interval.

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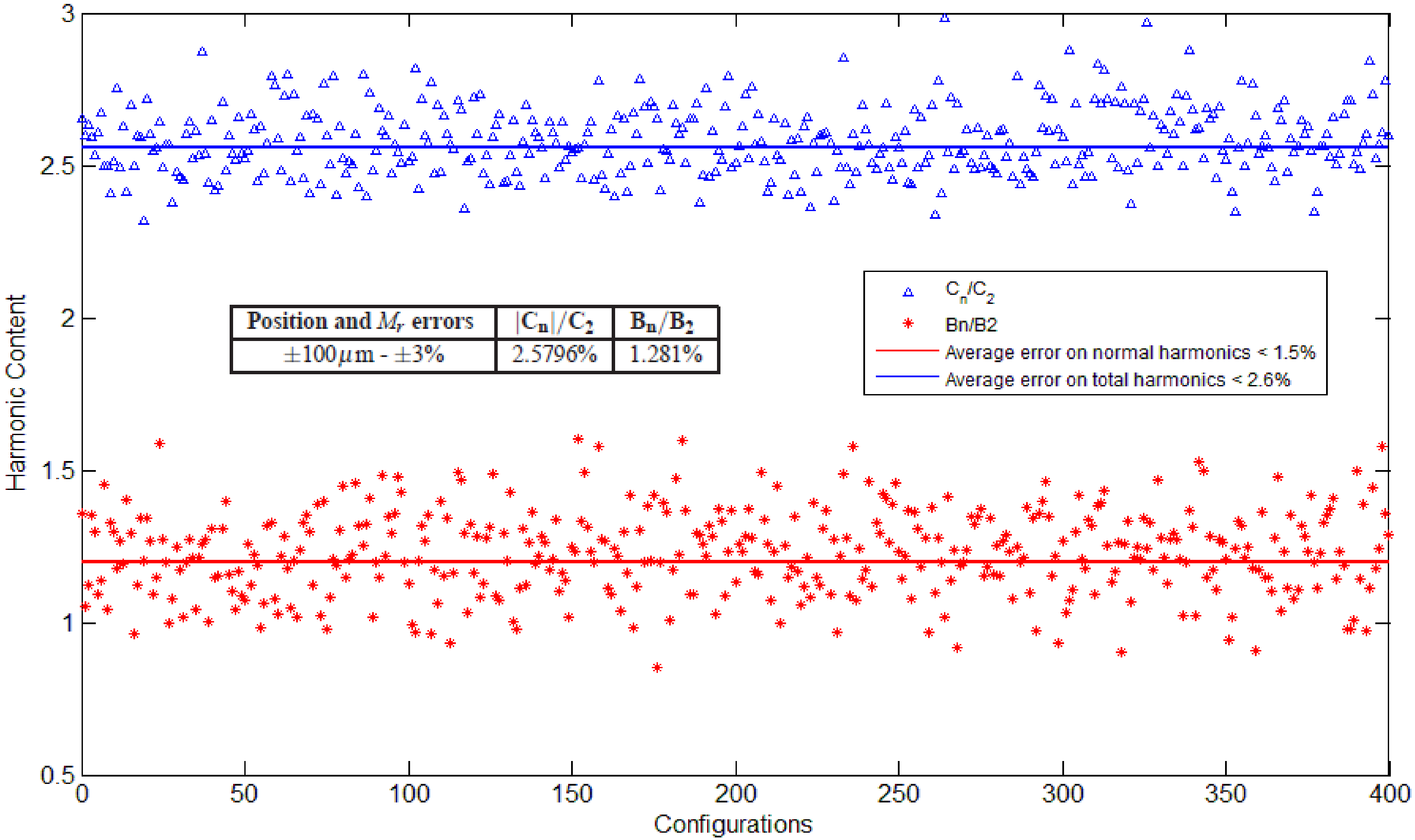
Random Errors

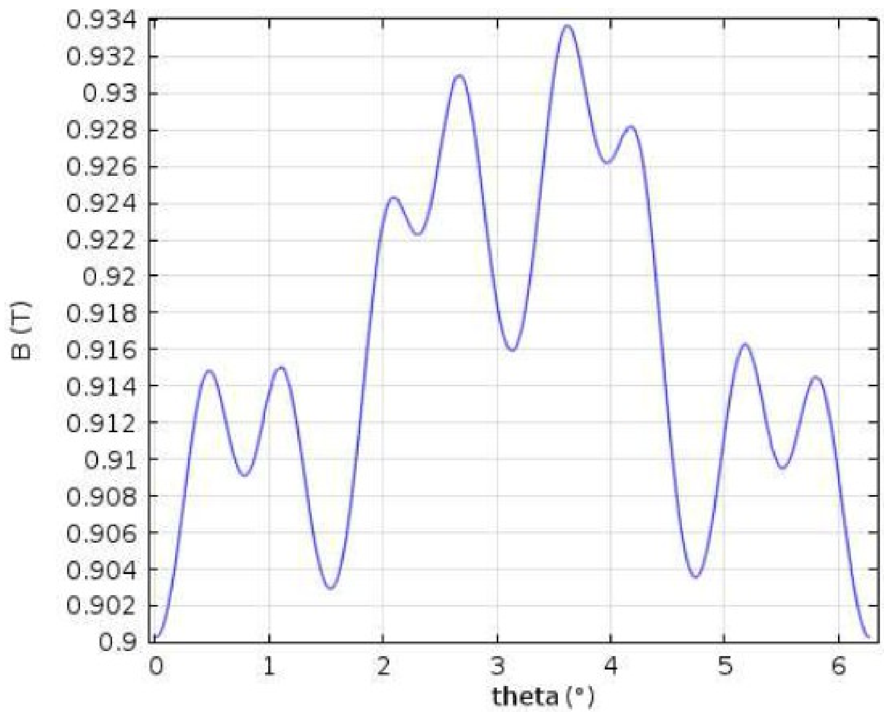
Combining errors on M_r and magnet position

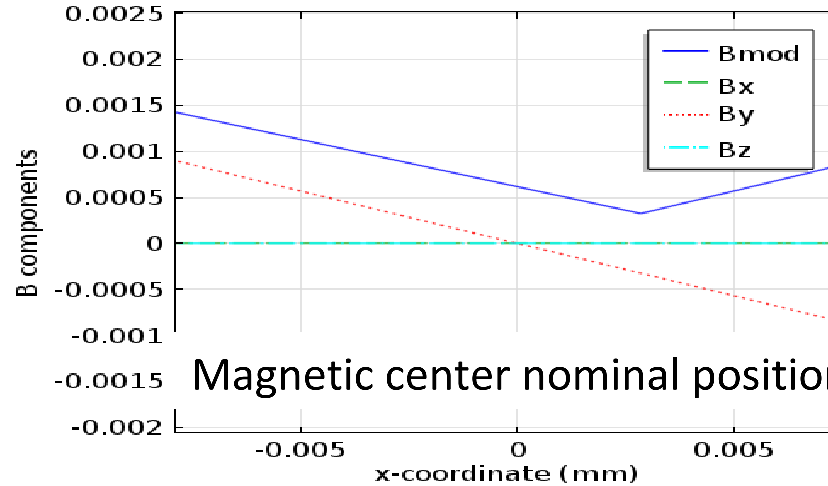
each magnetic configuration is reproduced on all the different geometric configurations (400 x 400 simulations)

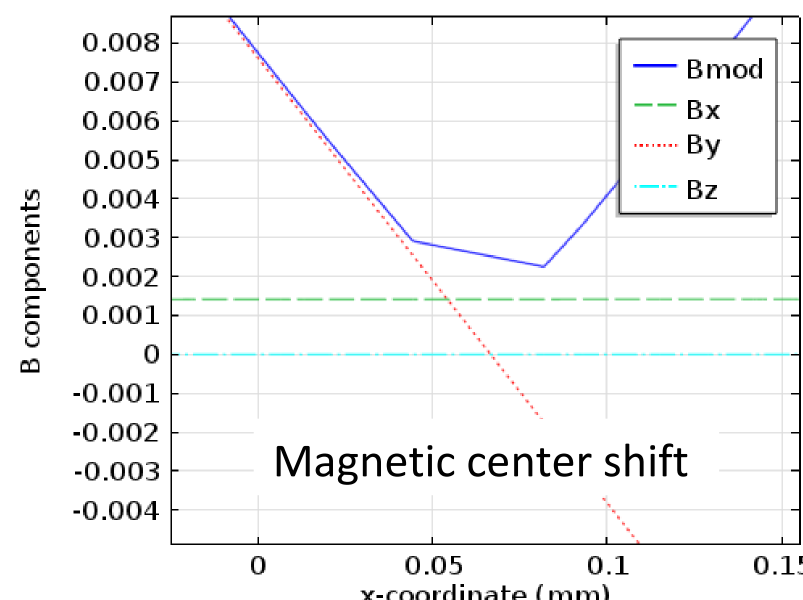


Random Errors

Effects on the field quality

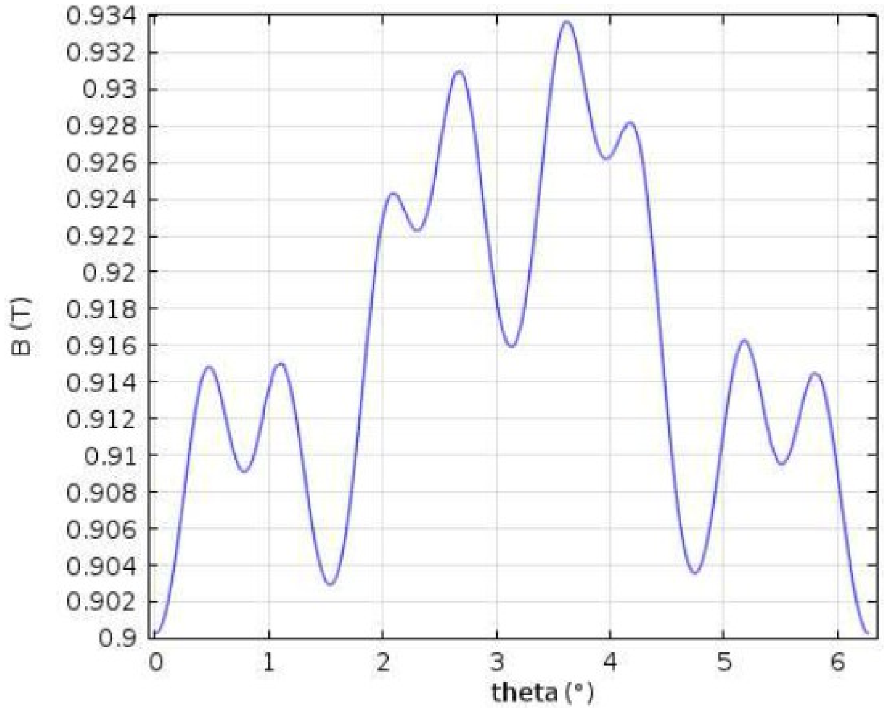


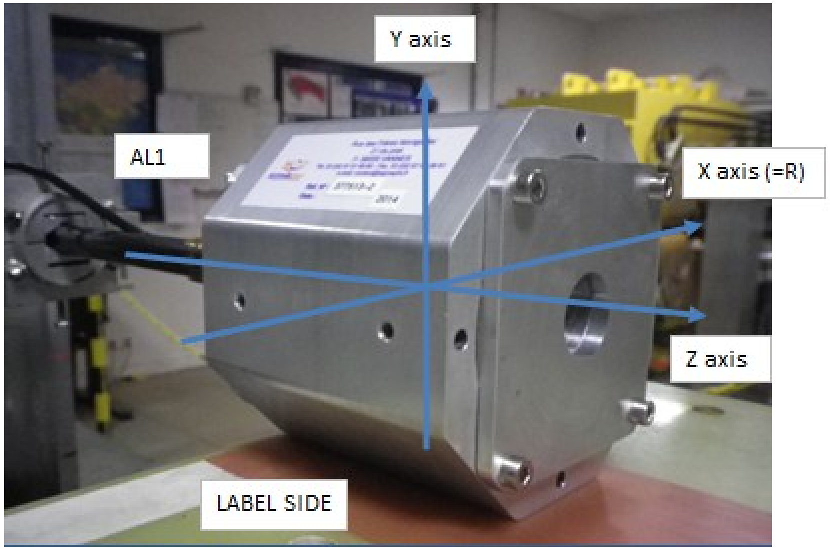




Random Errors

Effects on the field quality





Magnetic measurement

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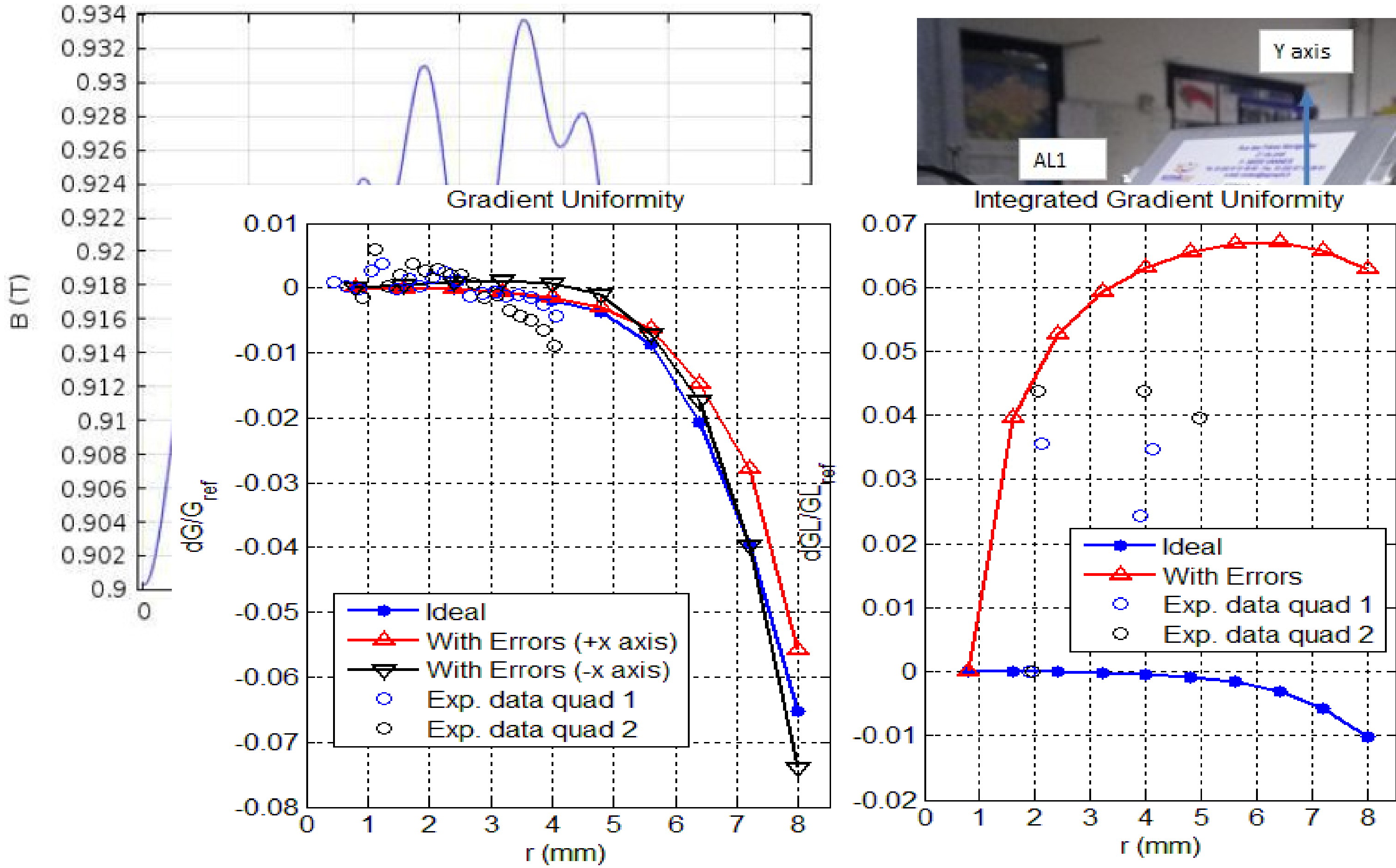
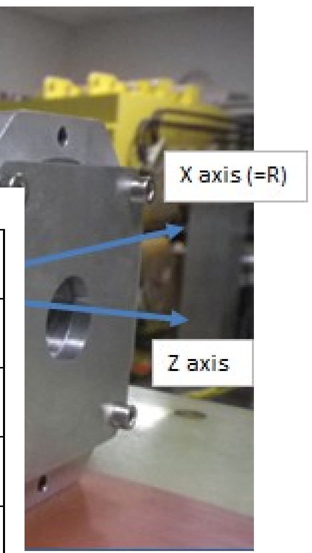
Random Errors

Effects on the field quality





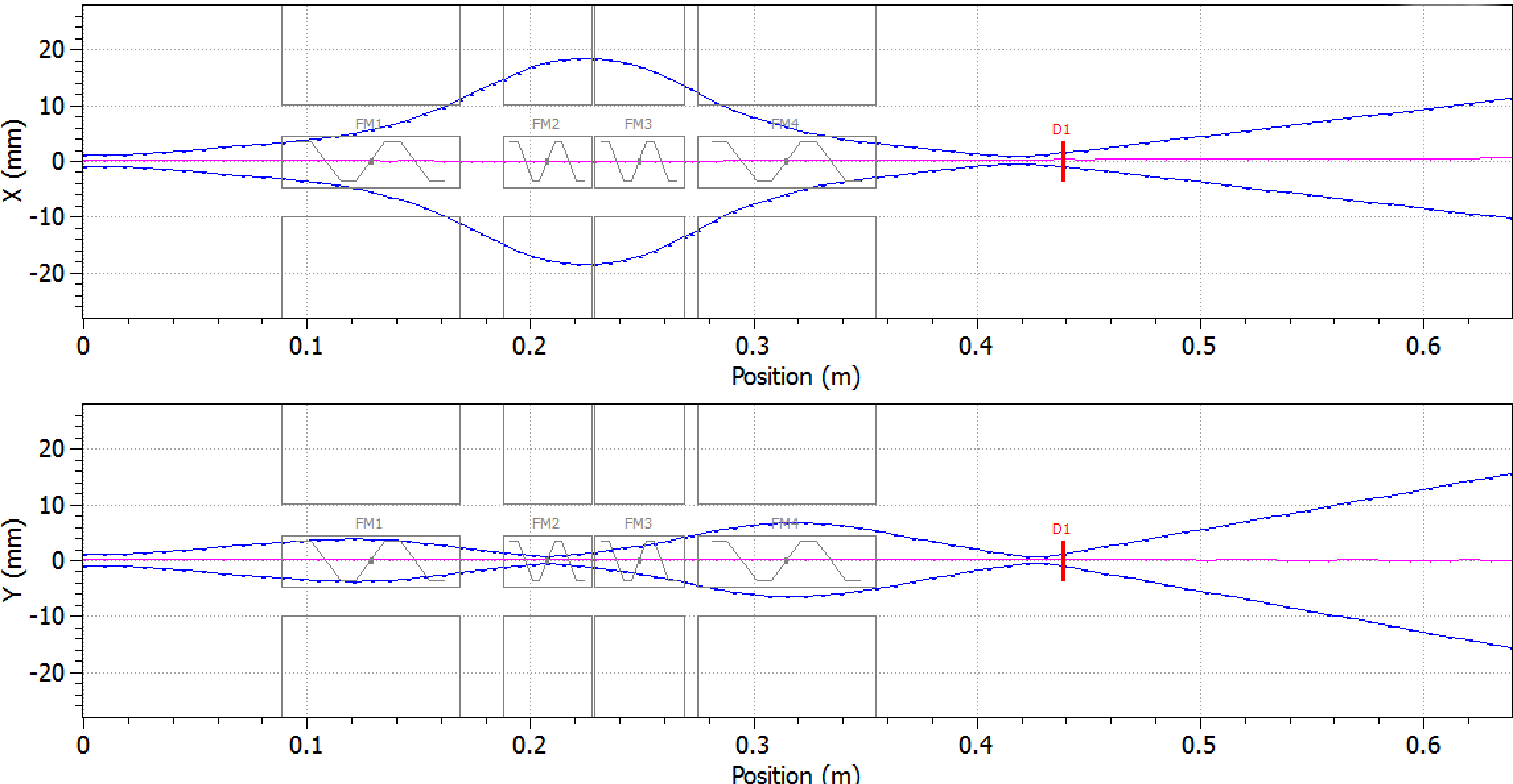
SIGMAPHI

Magnetic measurement

OUTLINE

- Quadrupole features
- Error source in magnets and modelling
- Fixing the tolerances
- Beam transport (simulations and experiment)

Beam Transport Simulations



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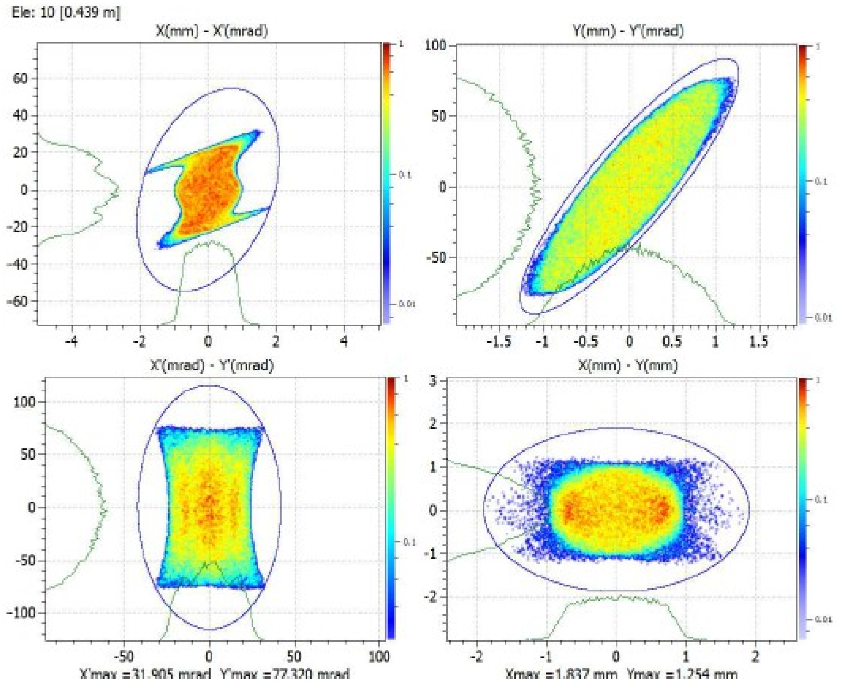
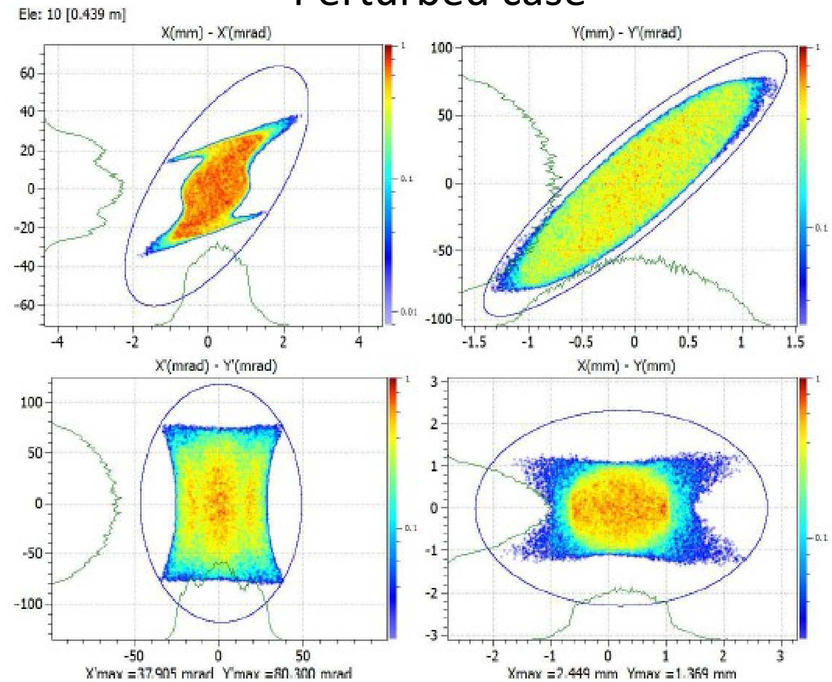
Beam Transport Simulations

Ideal case



Perturbed case



	Ideal Quadrupole System	Perturbed Quadrupole System	
Space	ε_i(rms)	ε_p(rms)	$\Delta\varepsilon/\varepsilon_i$
(x,x')	0.6572π.mm.mrad	0.6661π.mm.mrad	0.0135
(y,y')	0.9322π.mm.mrad	0.9360π.mm.mrad	0.0041
(x',y')	5.1267 mrad^2	5.9272 mrad^2	0.1561
(x,y)	0.2583 mm^2	0.3163 mm^2	0.2245
Centroid position	$dx = -0.0016$ mm, $dy = 0.0016$ mm	$dx = 0.2304$ mm, $dy = 0.0003$ mm	

1.4% Emittance growth

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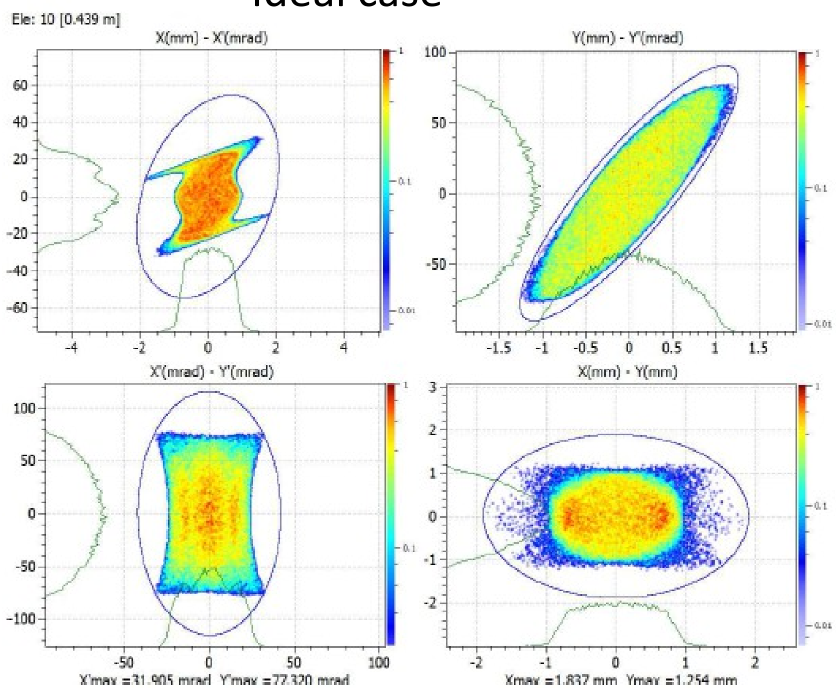
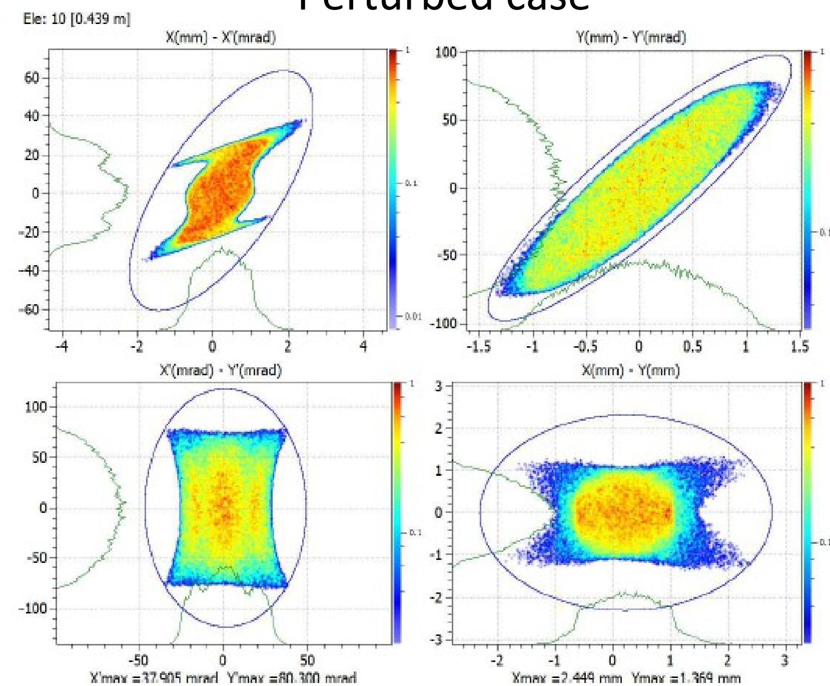
Beam Transport Simulations

Ideal case



Perturbed case



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Centroid position	$dx = -0.0016$mm, $dy = 0.0016$mm	$dx = 0.2304$mm, $dy = 0.0003$mm	

1.4% Emittance growth

0.5° bigger angular aperture and more filamentations

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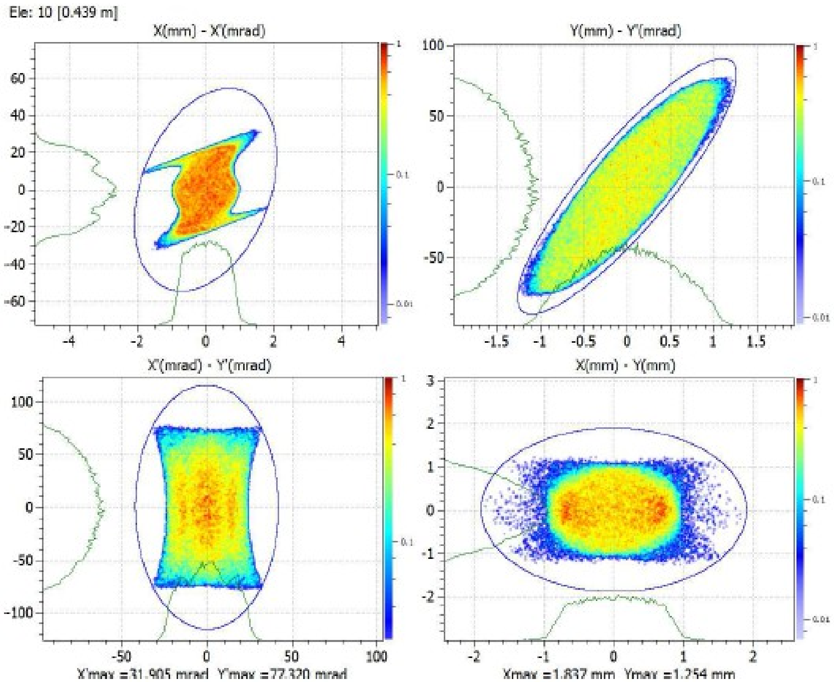
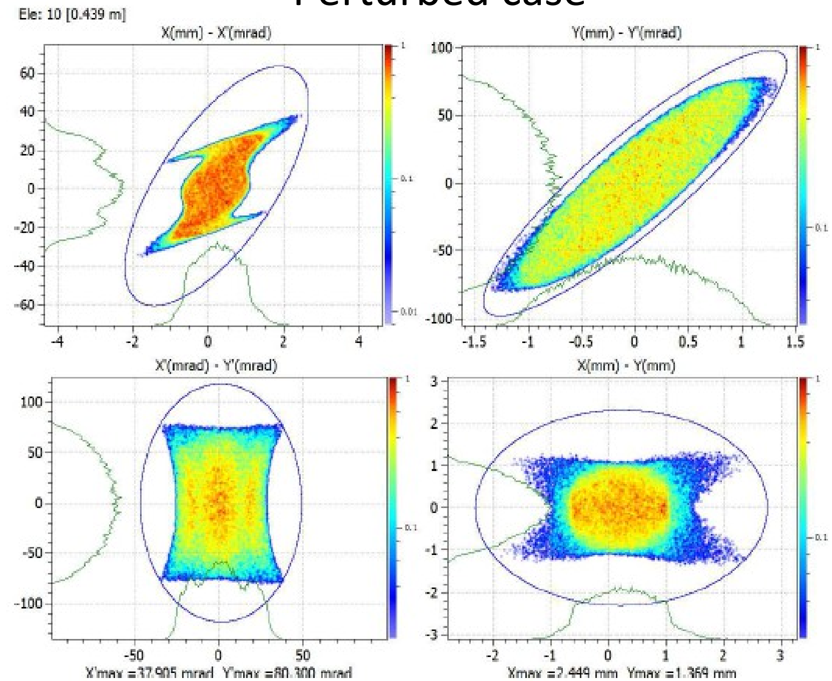
Beam Transport Simulations

Ideal case



Perturbed case



	Ideal Quadrupole System	Perturbed Quadrupole System	
Space	ε_i(rms)	ε_p(rms)	$\Delta\varepsilon/\varepsilon_i$
(x,x')	$0.6572\,\pi$.mm.mrad	$0.6661\,\pi$.mm.mrad	0.0135
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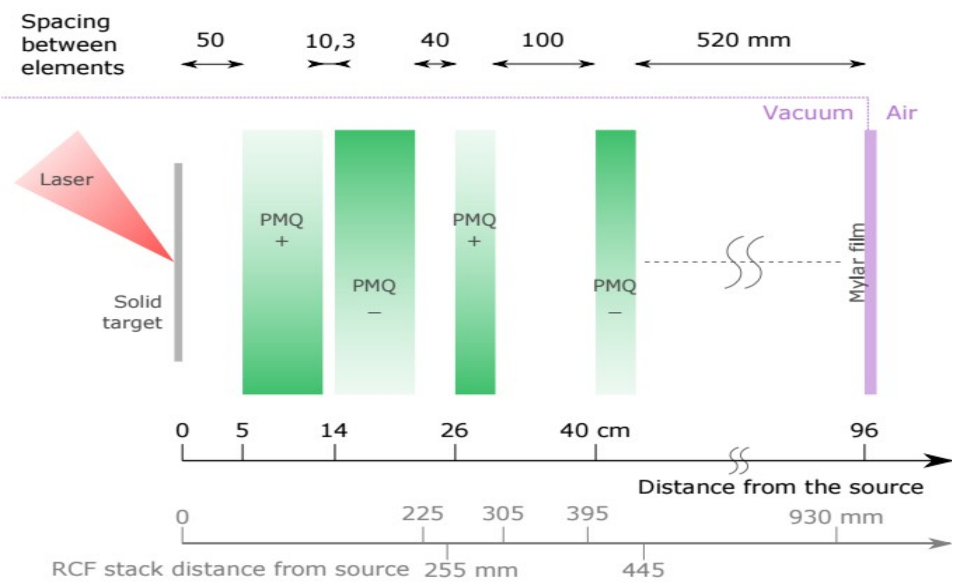
1.4% Emittance growth

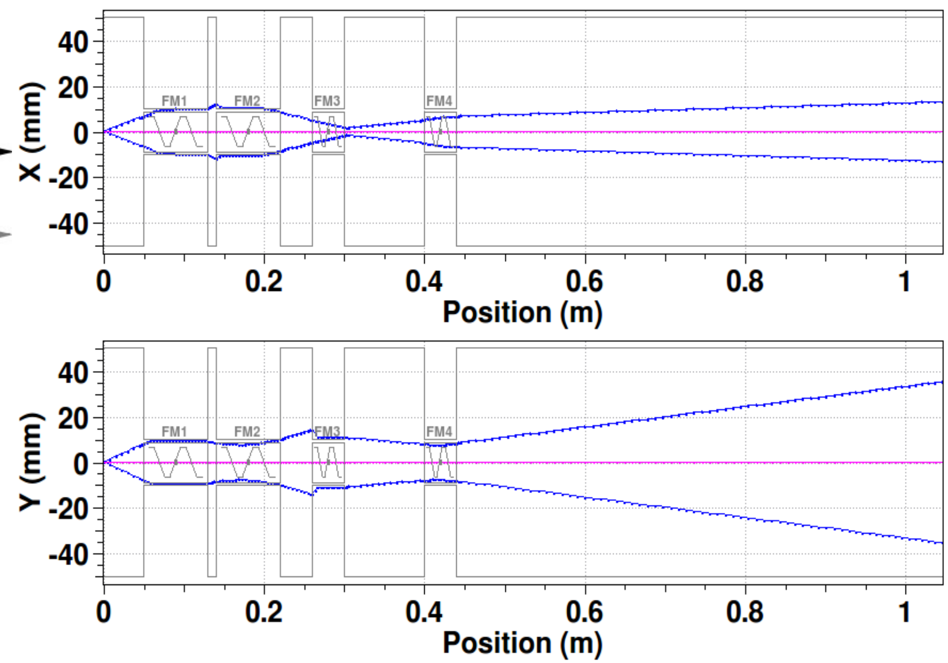
0.5° bigger ang aperture and more filamentations

Not negligible steering effect on the radial plane (as expected)

Beam Transport Test

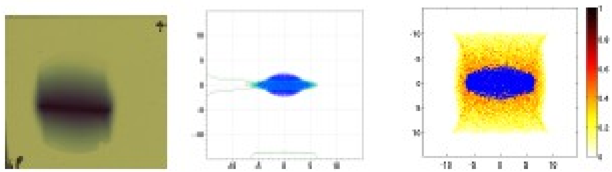
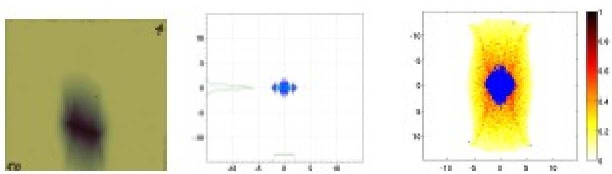
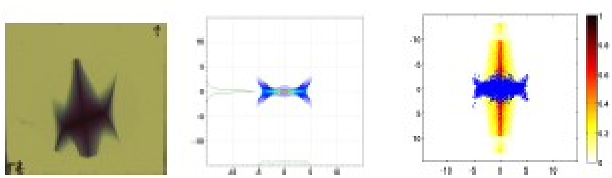
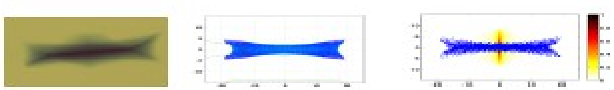
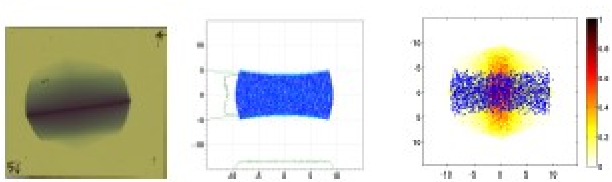
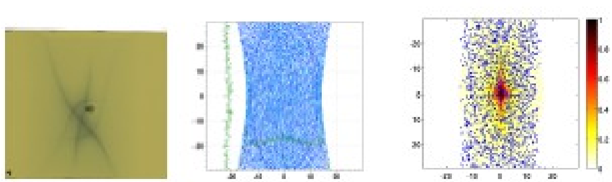


Wide big spot size for cell irradiation

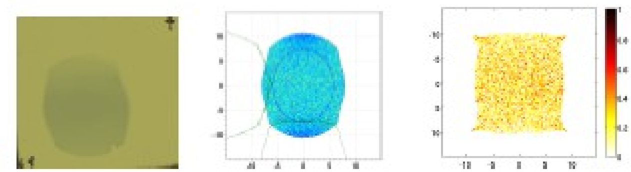
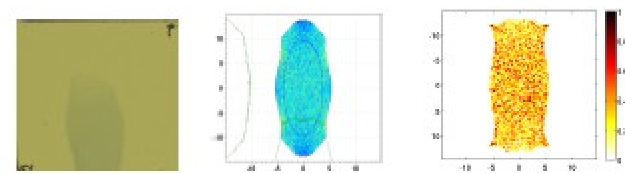
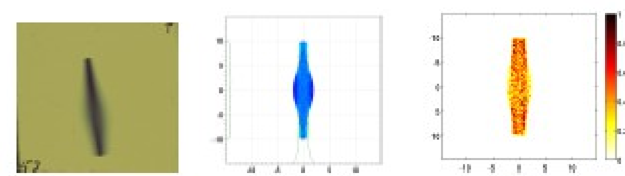
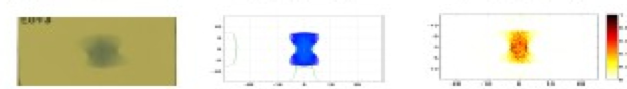
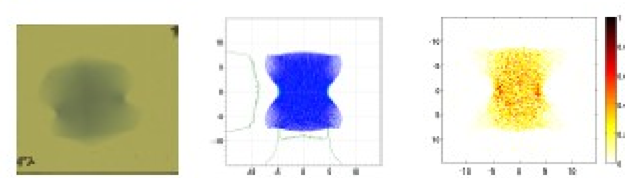
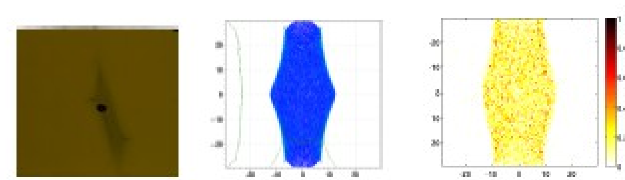


Beam Transport Test @ LOA (Fr)

3.5 MeV

Gaf Position	Film dimension	GafChromic / TraceWin simulation / Simion simulation
225 mm	29.6x29.6 mm	
255 mm	29.6x29.6 mm	
305 mm	29.6x29.6 mm	
395 mm	29.6x51.6 mm	
445 mm	29.6x29.6 mm	
930 mm	57.8x57.8 mm	

6.5 MeV

Gaf Position	Film dimension	GafChromic / TraceWin simulation / Simion simulation
225 mm	29.6x29.6 mm	
255 mm	29.6x29.6 mm	
305 mm	29.6x29.6 mm	
395 mm	29.6x51.6 mm	
445 mm	29.6x29.6 mm	
930 mm	57.8x57.8mm	

Beam Transport Test @ LOA (Fr)

3.5 MeV

Gaf Position	Film dimension	GafChromic	TraceWin simulation	Simion simulation
225 mm	29.6x29.6 mm			
255 mm	29.6x29.6 mm			
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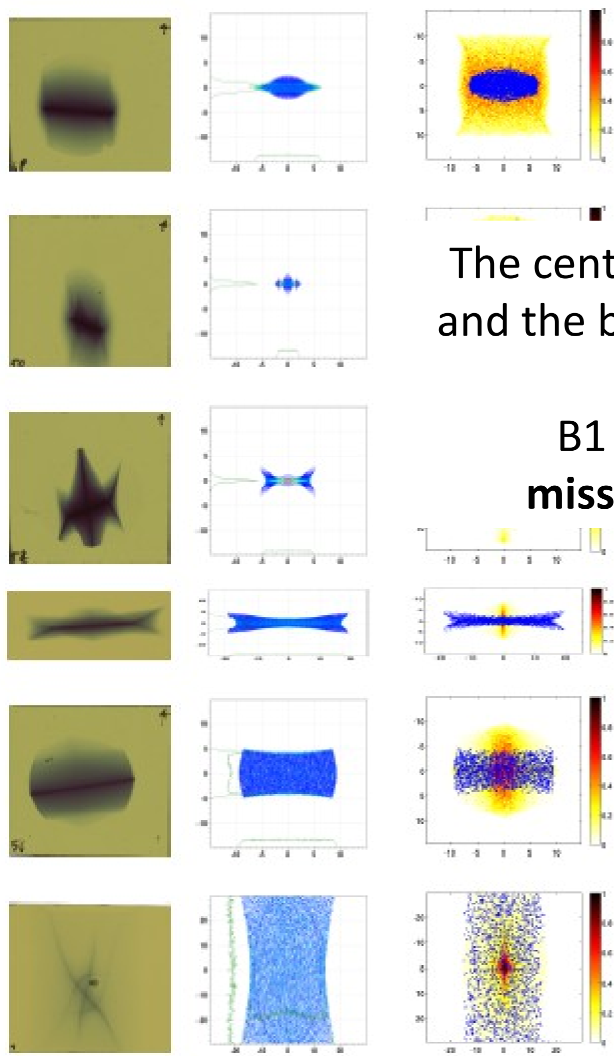
395 mm	29.6x51.6 mm			
445 mm	29.6x29.6 mm			
930 mm	57.8x57.8 mm			



The centroid is shifted and the beam is rotated

B1 + skew + **missalignment**

6.5 MeV

Gaf Position	Film dimension	GafChromic	TraceWin simulation	Simion simulation
225 mm	29.6x29.6 mm			
305 mm	29.6x29.6 mm			
395 mm	29.6x51.6 mm			
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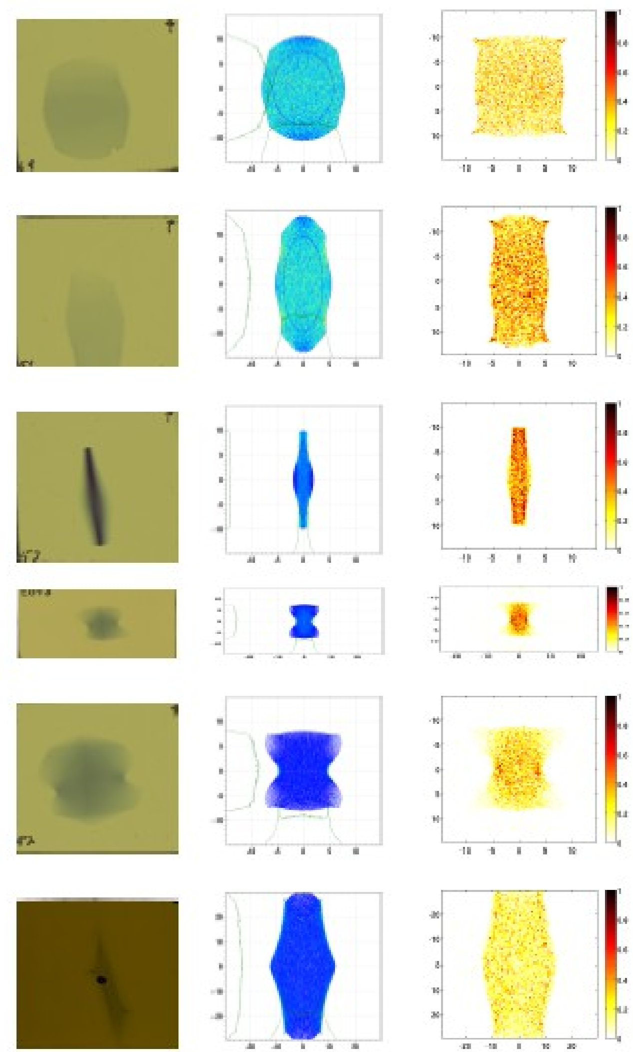

Conclusion

- A model to study random errors in PMQs is proposed
- Validated in simple cases
- Effects of the harmonic contents on beam dynamics results in agreement with the dipole component produced by the loss of symmetry due to the introduction of imperfection on magnets
- The method results to be robust and reliable
- This model is useful to state tolerances on magnet assembly
- The model is completely general and can include any kind of error source... if you have enough time to run and analyse thousands of simulations

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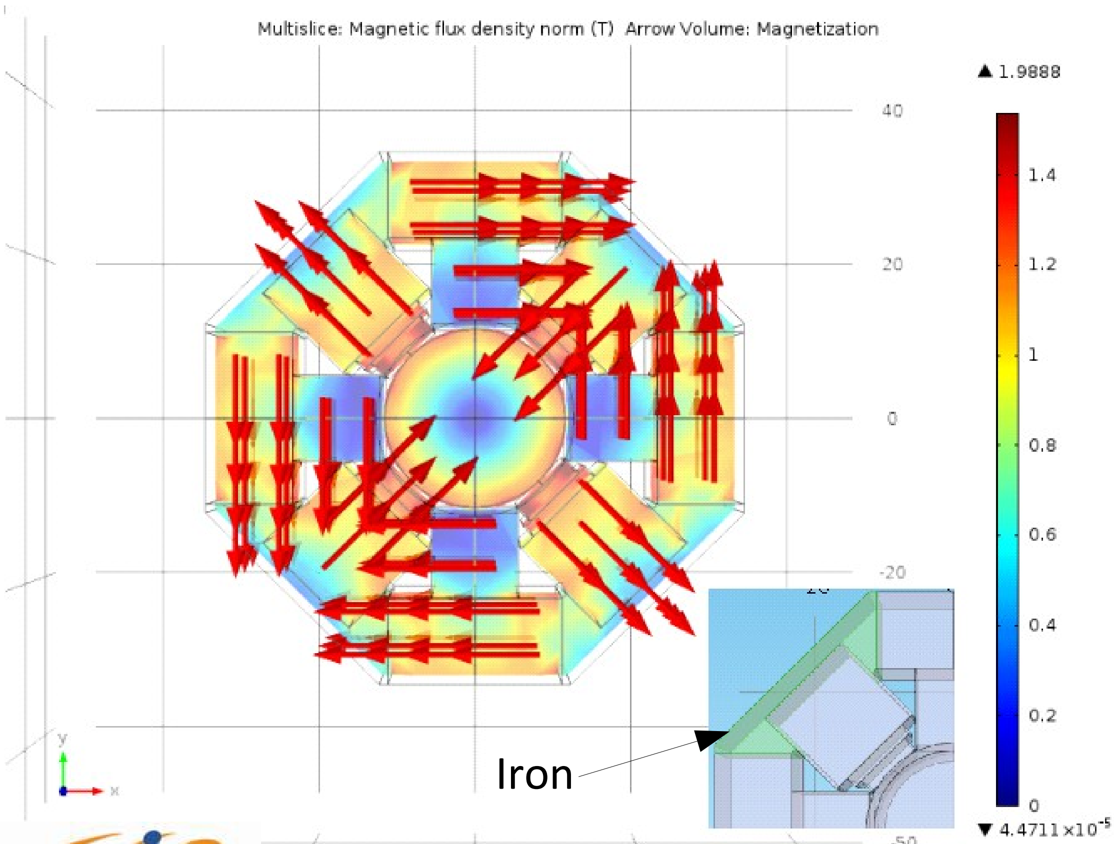
Thank you for your attention

http://www.eli-beams.eu/

INFN: F. Schillaci, M. Maggiore, G. A. P. Cirrone, G. Cuttone

Thanks to W. Beeckman (SigmaPhi) for advice and discussion

Quadrupole layout

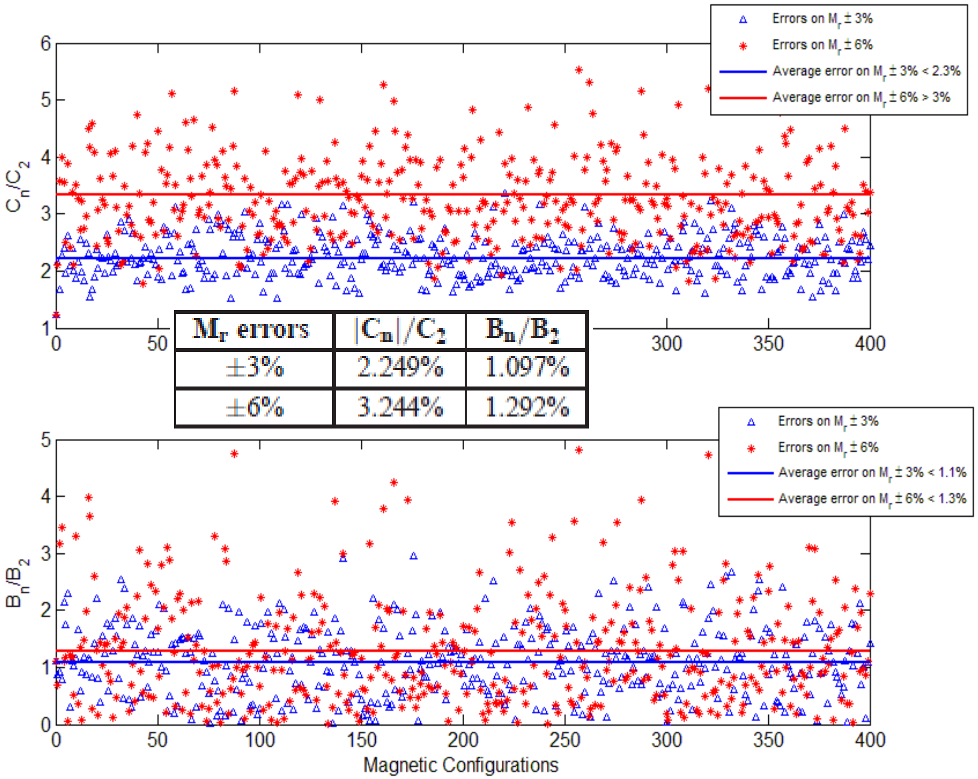


4 PMQs features
(simulations)

- 2 elements 40 mm long
- 2 elements 80 mm long
- 22 mm bore – 20 mm clearance
- 100T/m field gradient
- NdFeBo N50 permanent magnets
- Gradient homogeneity: -6% @ R = 8mm
- Integrated gradient homogeneity: -1% @ R = 8mm
- Harmonic content $B_n/B_2 < 2\%$
- **Cost-effective prototype**

Random Errors

400 different simulations per range of variation of M_r and magnet position



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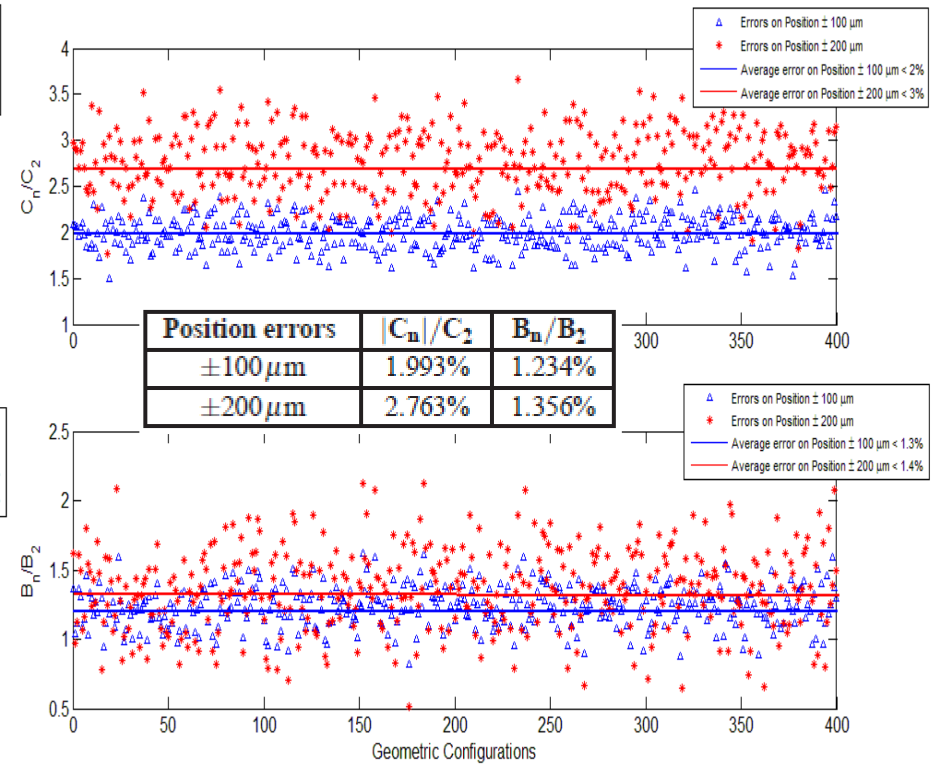

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$\pm 100\,\mu m$	1.993%	1.234%
$\pm 200\,\mu m$	2.763%	1.356%

The normal content (B_n) does not increase significantly with the increasing of the errors

The complex harmonics (C_n) are strongly affected by the errors and their contribution is about 3% of the main harmonic if the errors range in the wider interval

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