CERN Accelerator School

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MAGNETS

Magnet types and performances
Part 2

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Conventional iron dominated magnets

- Conventional iron dominated magnets are components of low/medium energy accelerator systems.
- They can be divided among several different types
- Dipole magnets (special category of gradient magnets)
- Quadrupoles
- Sextupoles
- Correctors (vertical & horizontal steering , skew quadrupoles)
- I will not cover specialized magnets like septum and kickers.

Magnet types and performances
Part 1

- A few things to remember about magnetism
- Think FLUX
- If I was an electron
- Basic concepts
- Example of the SOLEIL magnets
- Details on the SOLEIL Quadrupole and Sextupole magnet

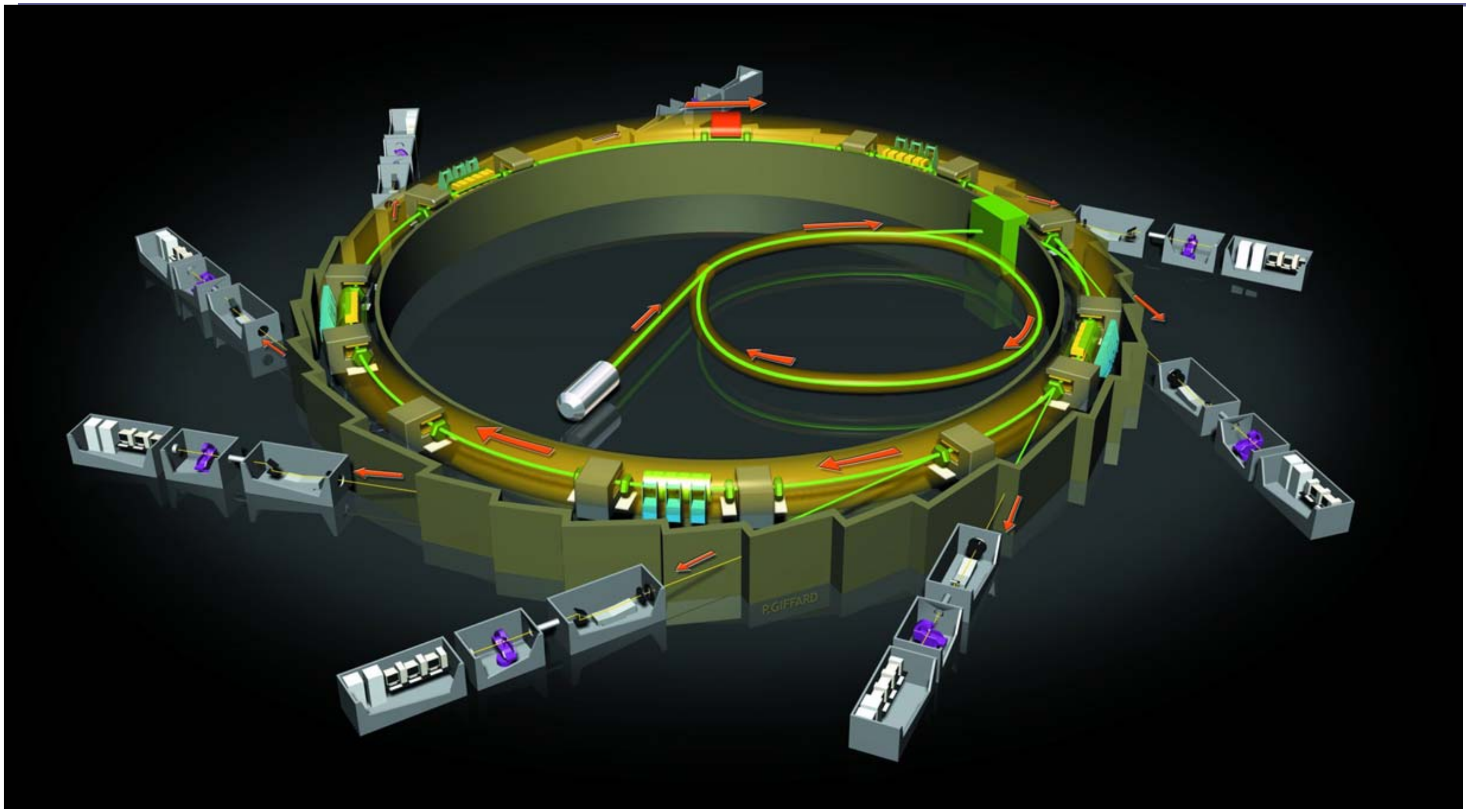
This example will be an introduction to the general talk of Thomas Zickler on Basic magnet design

Maxwell equations : think Flux

James Clerk MAXWELL

- The phenomenons are perfectly known.
- All the day we obey to Maxwell equations to create magnetic field.
- The representation of flux tubes is a very powerful method.
- Flux is going from North to south

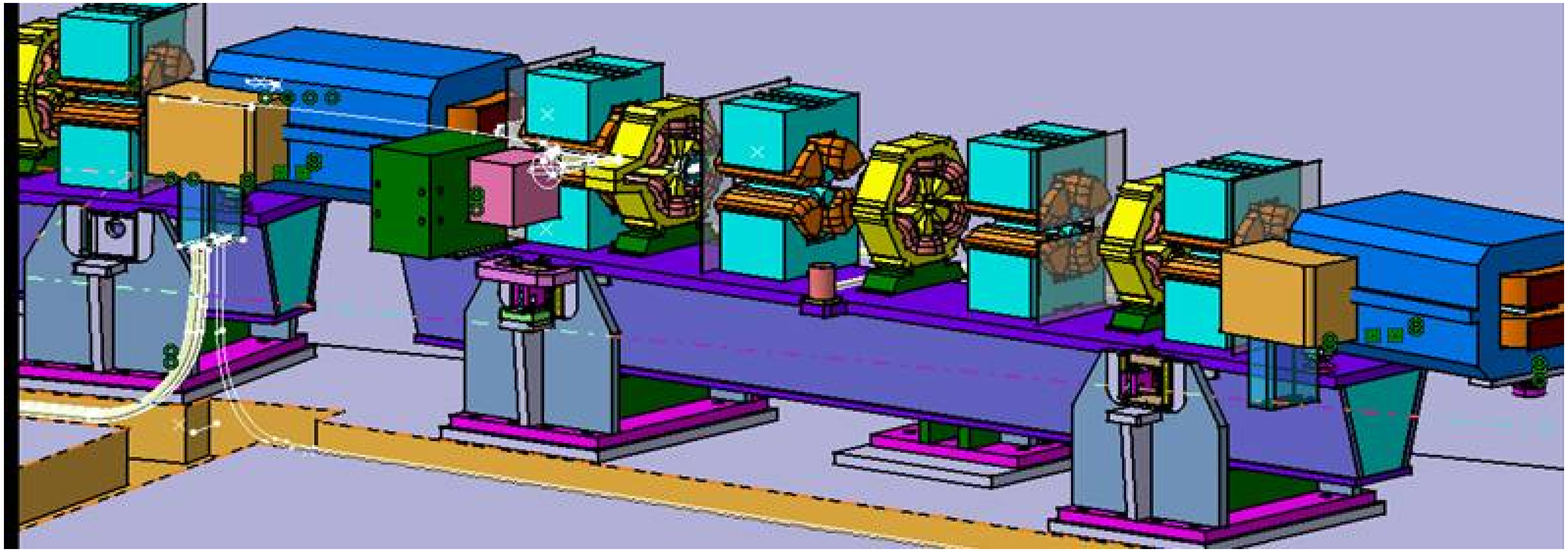
SOLEIL : Chain of accelerators



- **LINAC: electron gun , 2 sections, 100 MeV**
- **BOOSTER: 3Hz, warm cavity, 2.75 GeV**
- **Storage ring: 2.75 GeV electrons (ultrarelativist)**

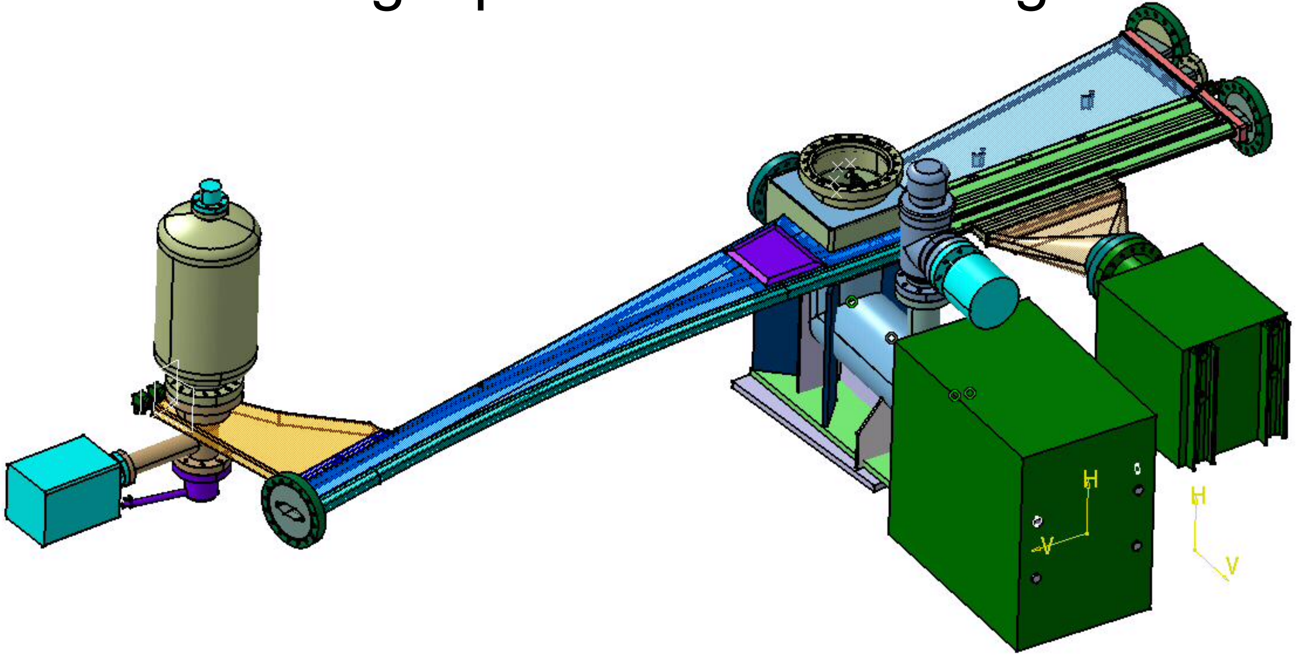
Magnet table SOLEIL

	RING			BOOSTER		
	Dipoles	Quadrupoles	Sextupoles	Dipoles	Quadrupoles	Sextupoles
Number	32	160	120	36	44	28
Force	1.71 T	19et 23 T/m	320 T/m²	0.74 T	11 T/m	16 T/m²
Length(mm)	1052	320 ou 460	160	2160	400	150



Around this vacuum chamber we have to put one dipole, one quadrupole & one sextupole

- Magnet design is strongly depending of vacuum chamber technology and pumping elements.
- Accelerators are more and more compact.
- CAD tools are making it possible to solve tight interfaces

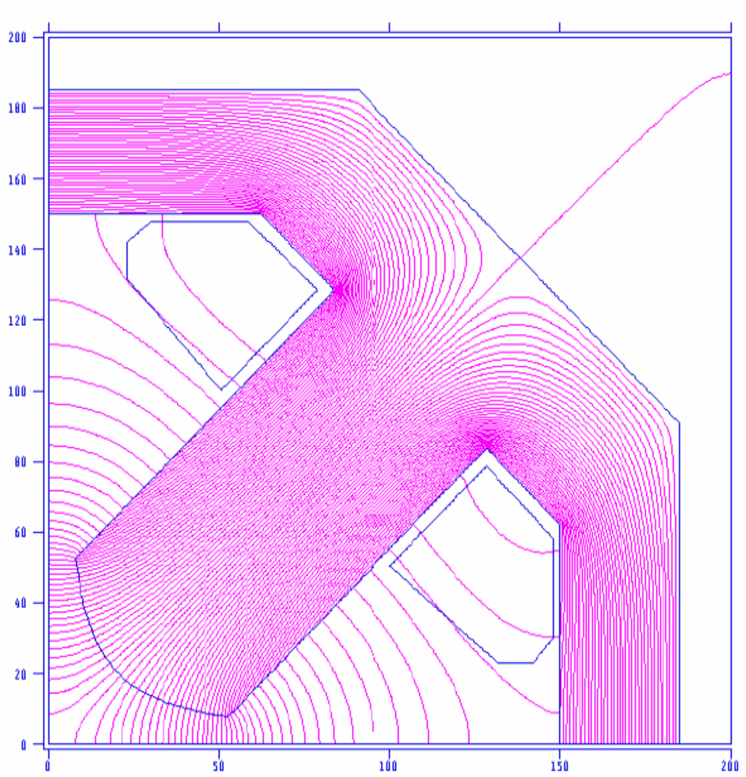


Quadrupole magnetic structure

- The classical quadrupole is an « iron dominated magnet »
- Four alternative poles N, S, N, S, with equilateral hyperbola are creating a field.
  - Bz = G*x
  - Bx = G*z
- “G” is the gradient measured in T/m.
- In a perfect quadrupole “B” modules is constant on a circle of radians 2 et proportional to the radians.
- In practice the hyperbolic equipotentials are finite in order to place the ampere turns.

Flux tubes of a quadrupole

- By symmetry “B” is zero at the center.
- Flux is going from north to south and flux density is perpendicular to the pole face.
- Flux tubes are narrowing when gap is decreasing.
- The coils are creating a supplementary flux.
- The flux circulate in the return yoke with a four fold shape.



QUADRUPOLES Specifications

- 132 short quadrupoles
- magnetic length : 320 mm
- Gradient 19 T/m
- 28 long quadrupoles
- magnetic length : 460 mm
- Gradient 23 T/m
- Bore diameter : 66 mm
- Useful area : +- 35mm

Ampere’s Theorem

- Please remember:

Current	Field	Length
1A Need 10000At	1mT PoleB/2:0.35 factor:350	1.25 mm Factor:32

Technological aspect of quadrupole

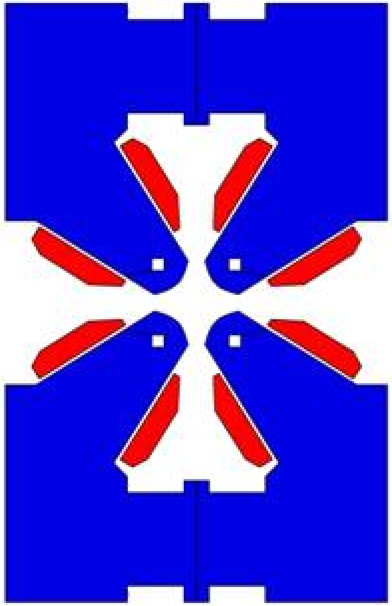
- The hyperbolic profile must be realized with high precision by machining or cutting.
- The 4 poles summits must be precisely located on the lore diameter.
- The geometrical position of the poles must respect the 45° degree axis.
- The magnetic center may differ from the mechanical center and must be determined by magnetic measurement.

Gradient homogeneity

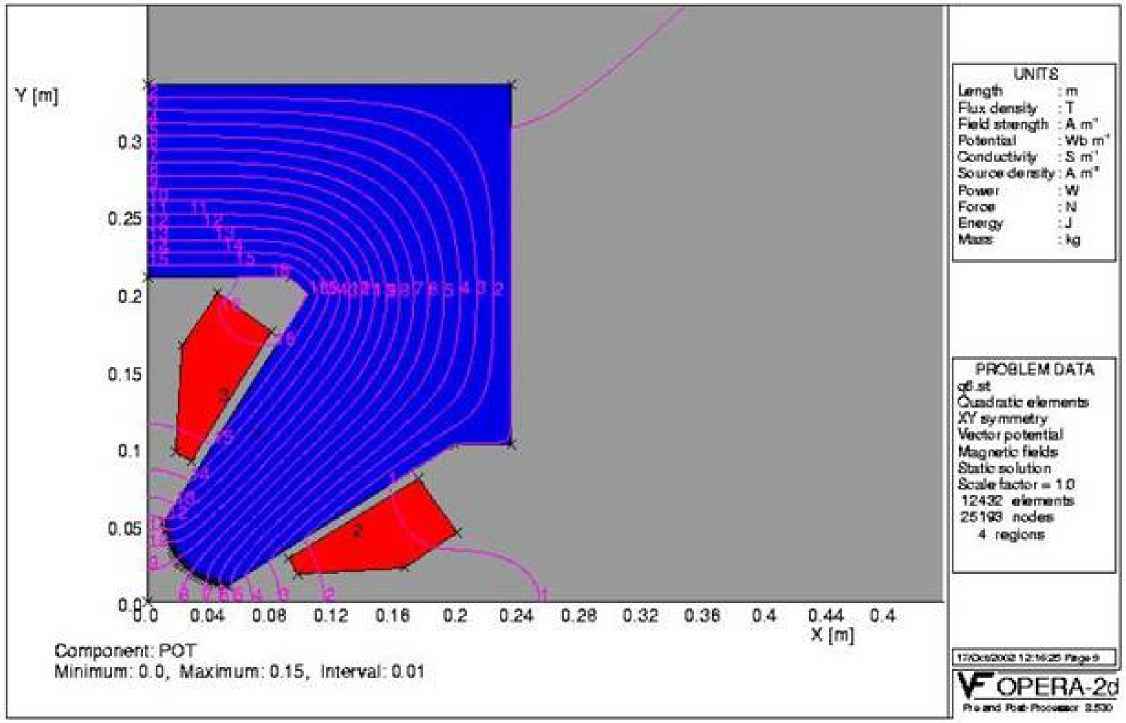
- The gradient is decreasing on the sides as far as the hyperbolas are not infinite.
- The gradient homogeneity is the defect of the gradient relative to the gradient in the center GO
  - Delta G = G-GO
  - Delta G(x) / G(O) = C6* X^5 + C10*X^9
- C6 is the first natural defect of a quadrupole it is a « dodecapole ».
- We define the field harmonics, natural or not, on a reference radius.
- The end of quadrupole, the “3D region”, is creating a intrinsic dodecapole defect.

Magnetic design of the SOLEIL quadrupole

- The SOLEIL storage ring has 2 types of quadrupoles :
  - 128 short quadrupoles (19 T/m)
  - 32 long quadrupoles (23 T/m)
- All these quadrupoles have the same cross section.
- The flux is circulating in « figure of 8 »
- No return flux is crossing the median plane.
- The resulting free space is used for pumps in the inner side and radiation sources in the outer side.



Qudrupole Magnetic design



Component: POT
Minimum: 0.0, Maximum: 0.15, Interval: 0.01

UNITS	
Length	: m
Flux density	: T
Field strength	: A m^{-1}
Potential	: Wb m^{-1}
Conductivity	: S m^{-1}
Source density	: A m^{-2}
Power	: W
Force	: N
Energy	: J
Mass	: kg

PROBLEM DATA
q6.st
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Scale factor = 1.0
12432 elements
25193 nodes
4 regions

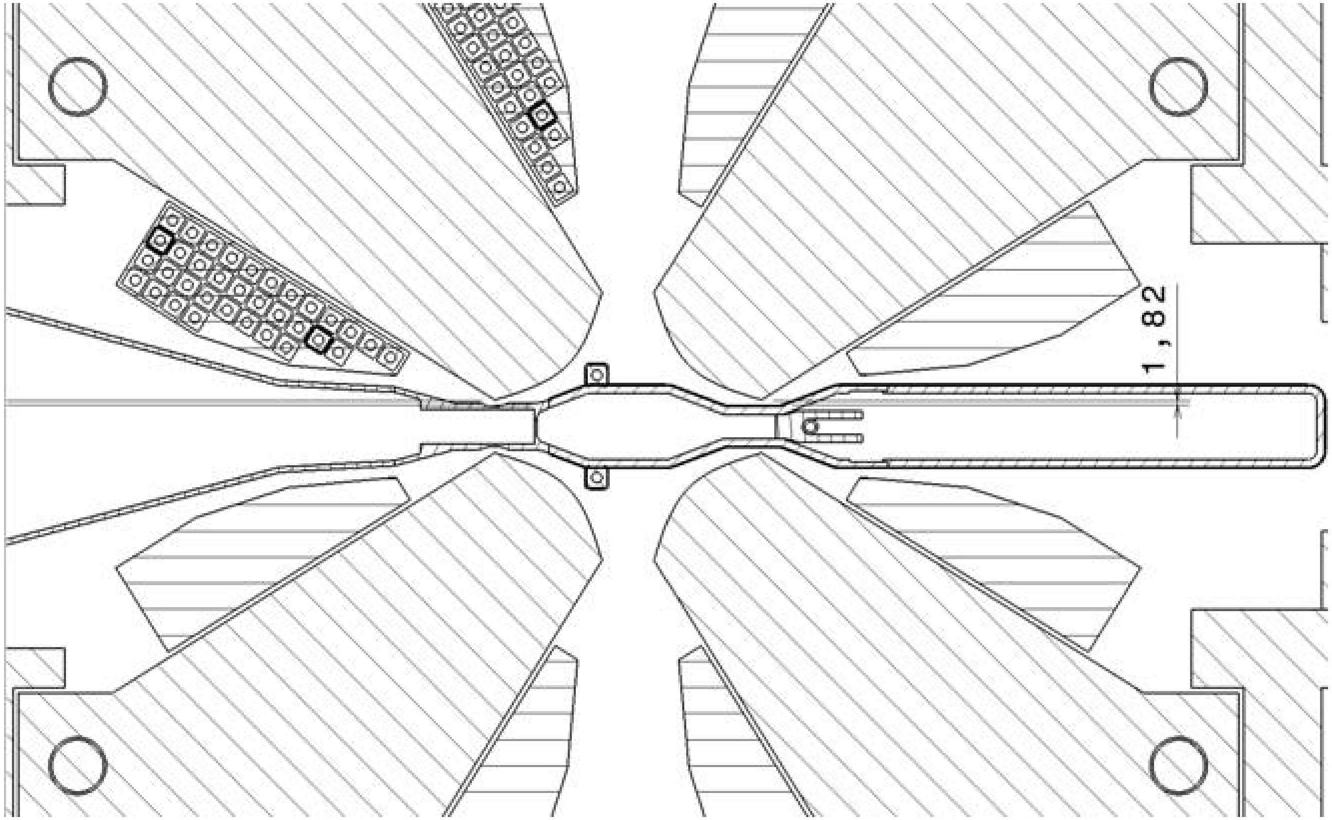
17/Oct/2002 12:16:25 Page 5

Yoke dimensions are optimised for G = 23T/m

Dodecapole component in the ends

- In the ends of a quadrupole, the gradient drop is associated with a strong natural first harmonic.
- A negative dodecapole is appearing.
- It corresponds to a reinforcement of the center of each pole compared to the sides of each pole.
- We can correct this situation by reducing the field in the center of each pole by machining a little chamfer.
- This method was used “empirically”.
- Nowadays the 3D simulations are precise enough.

Quadrupole Technical aspect



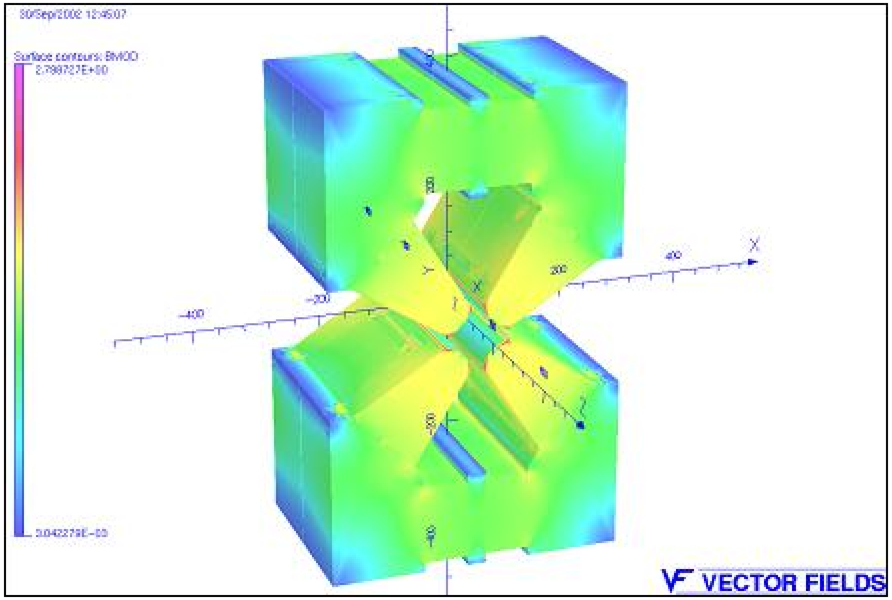
The interface with the vacuum chamber is very tight (DQS chamber)

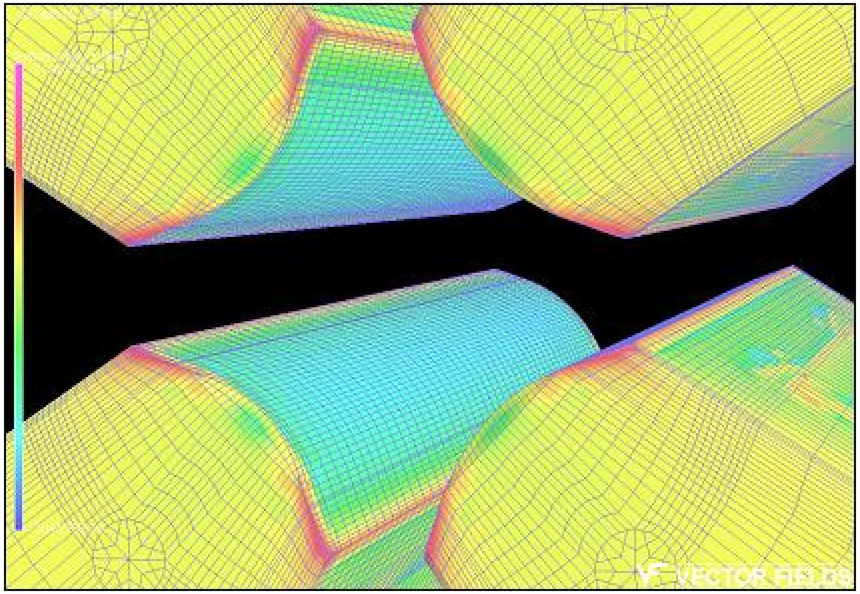
Accelerator Physicist Requests for BMS

- G/I in both polarities with P.S. cycling(CPCI+profibus)
- Magnetic center within 25 microns R.M.S.
- Harmonic analysis at reference radius 30.mm
- ANGLE THETAS WITHIN 0.1mradian R.M.S. i.e. skew quadrupole less than 1.10-4 of normal quadrupole (expressed at the reference radius it is 3 microns)

$\Delta B/B$	**Systematic**	**Random**
Sextupole		$1.2\ 10^{-4}$
Octupole	$3\ 10^{-4}$	$1.5\ 10^{-4}$
Dodecapole	$5\ 10^{-4}$	$2.5\ 10^{-4}$
20 poles	$-3.25\ 10^{-4}$	$1.2\ 10^{-4}$

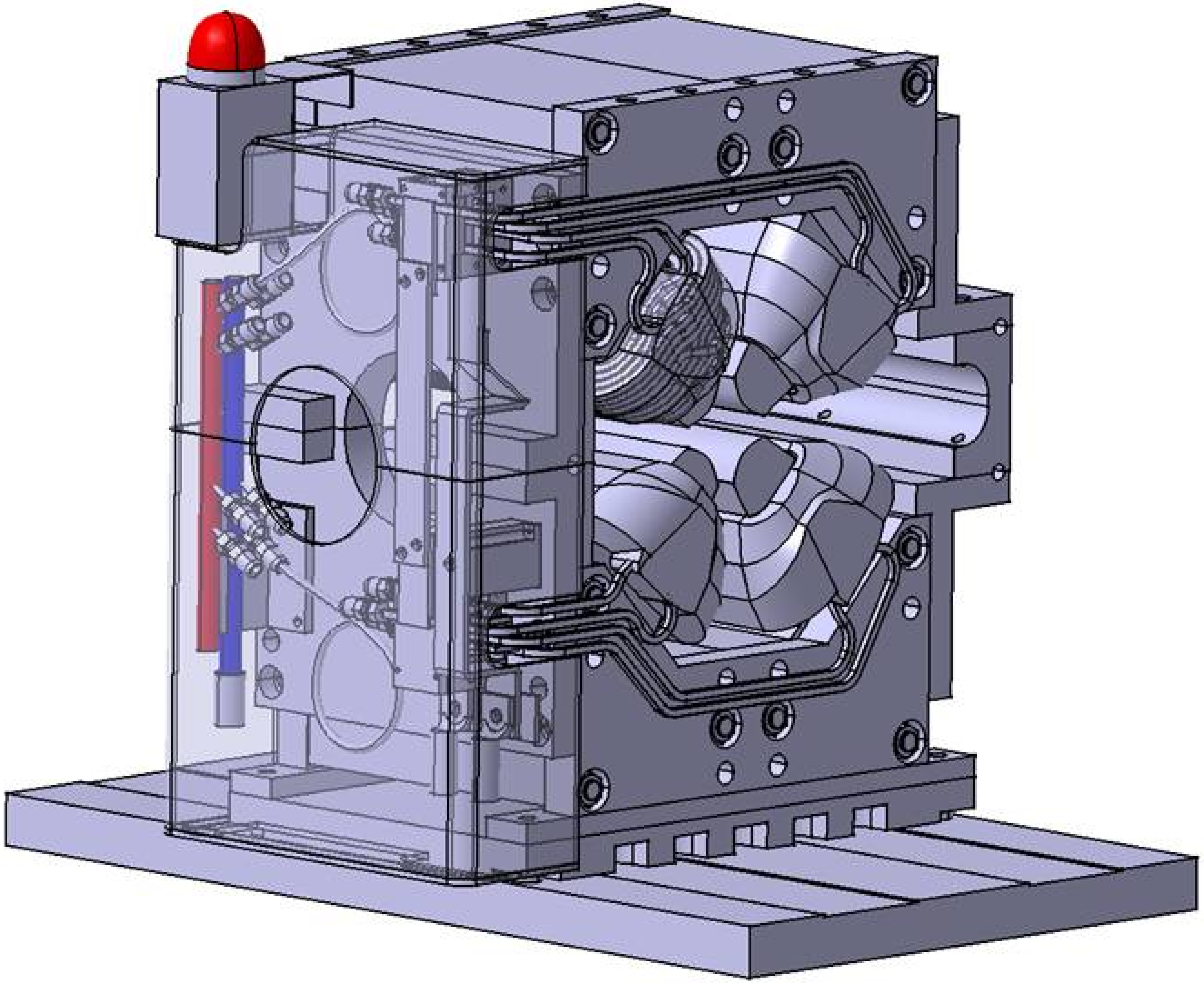
Magnetic design of SOLEIL Quadrupole





Courtesy of CEA/IRFU

- The full 3D model of the Quadrupole has been calculated with TOSCA.
- To achieve the tolerances we need a perfect profile 2D and an optimised end chamfer.



1

2

3

4

5

6

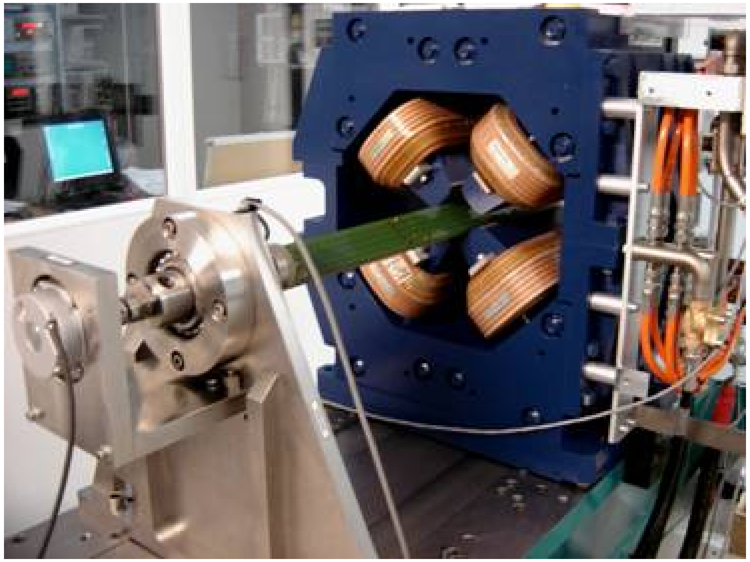
Photos of Quadrupole production:
Mould(1) Coil(2) Lamination(3)
Tooling(4&5) Yoke Quarter(6)

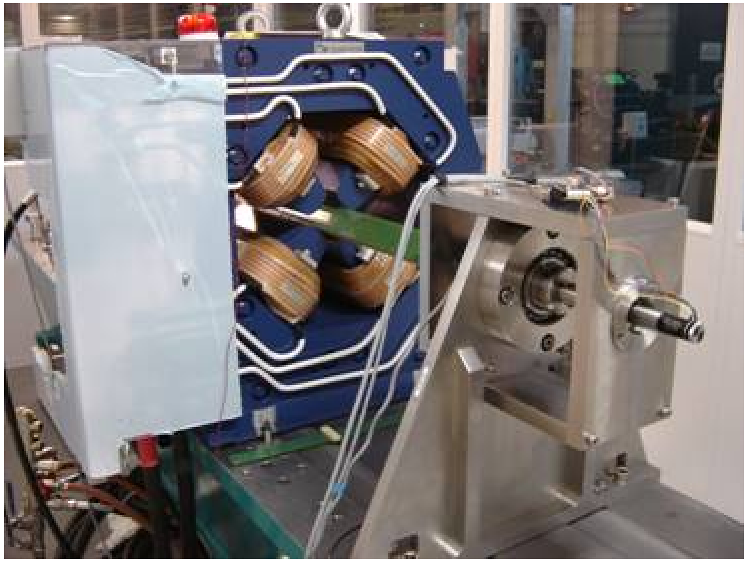
Courtesy of DANFYSIK

BMS description:dedicated harmonic bench « Banc Multipolaire Soleil »

- BMS is based on a SR girder with same mechanical, hydraulical & electrical interfaces
- Two precisely machined « Vés » and a precise steel cylinder are used to adjust the bearing axis on the girder
- Prototype Power Supply is installed in the same temperature stabilised room

BMS components including improvements





- 1 measurement = direct and reverse rotations with 64 tensions integrated by the METROLAB Voltmeter triggered by angles
- Rotation: by controlled DC motor
- Angular measurement: Heidenhain encoder 720000 steps/tour with absolute index

Long quadrupole prototype

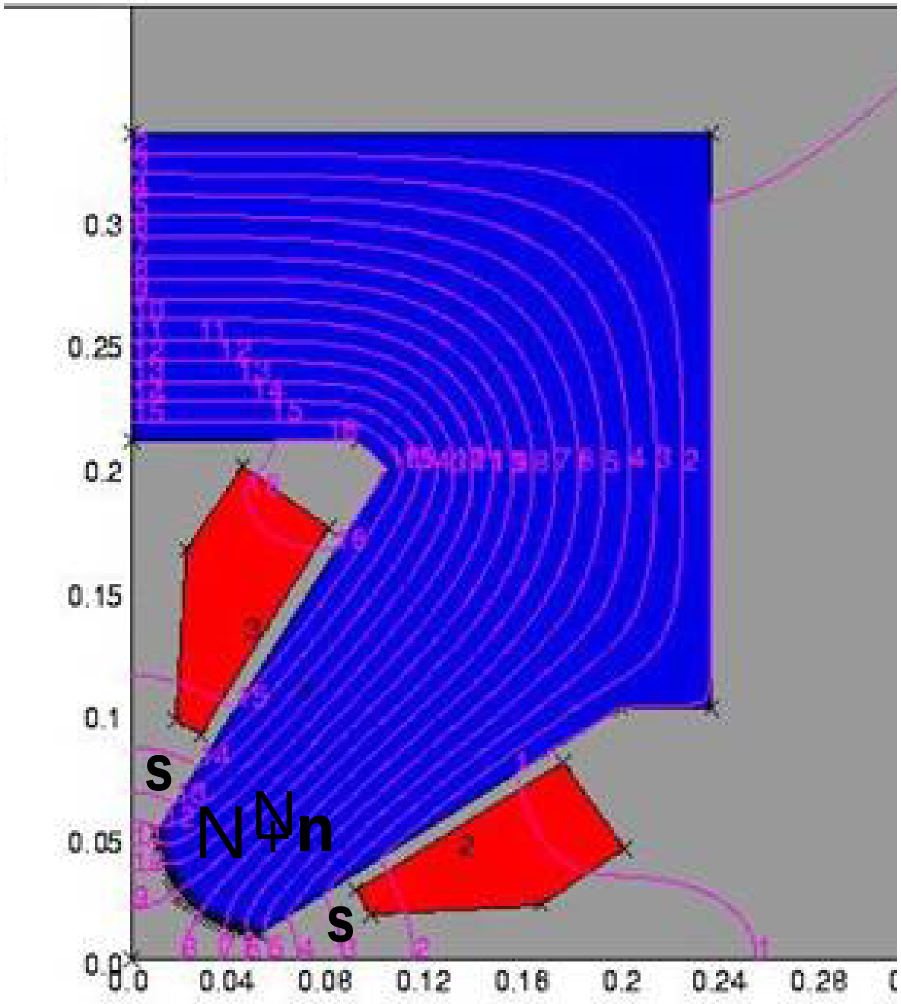
Quadrupoles produced by Danfysik

Long Quadrupole Prototype

Zoom on the chamfer region

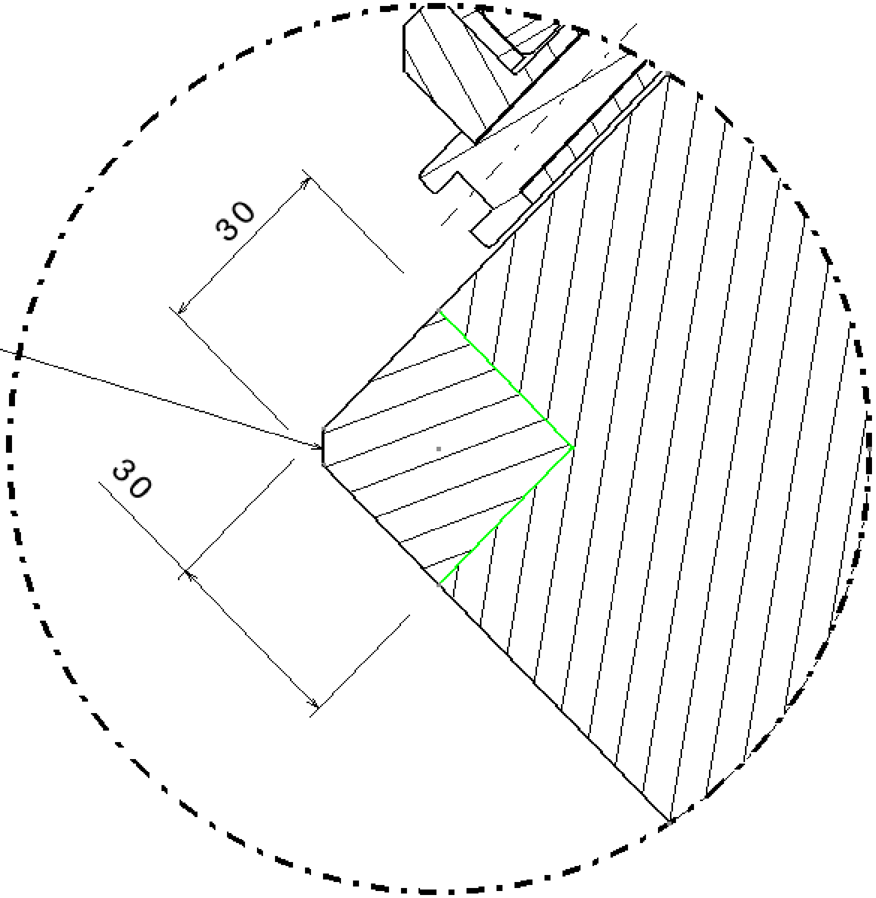
The chamfer is reducing the advantage of the axis region

What happens with flux in the ends:Axis region gets more flux ,the negative dodecapole

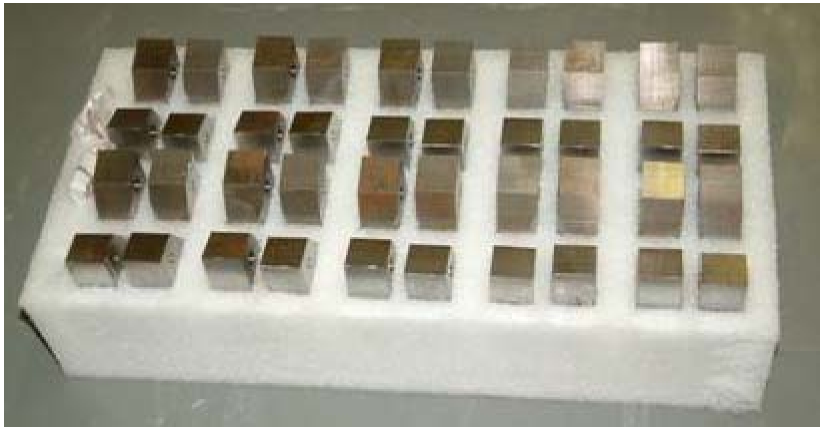


Experimental chamfer optimisation

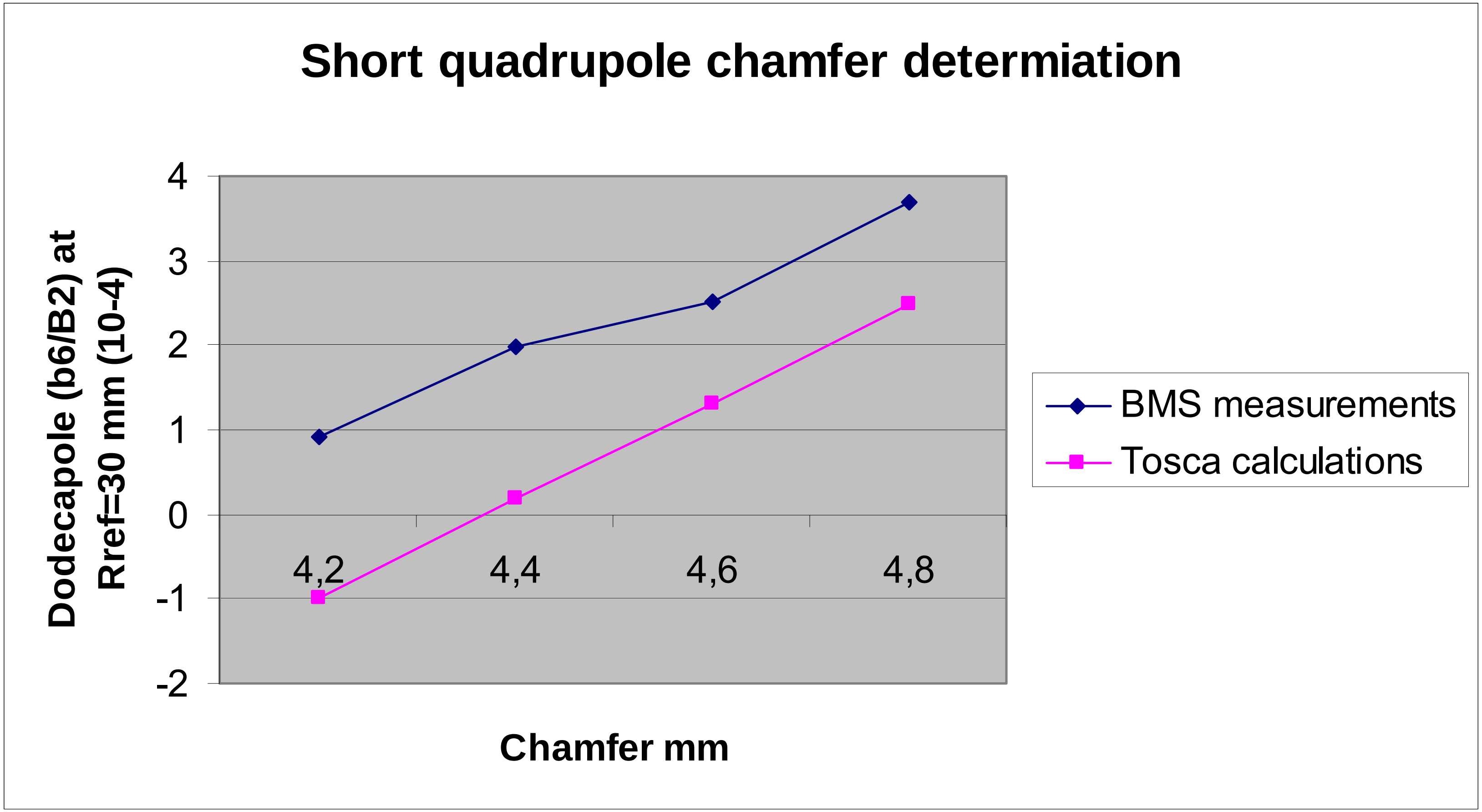
A set of chamfers of different values are tested on the 4 poles and at the both ends



Test Chamfer

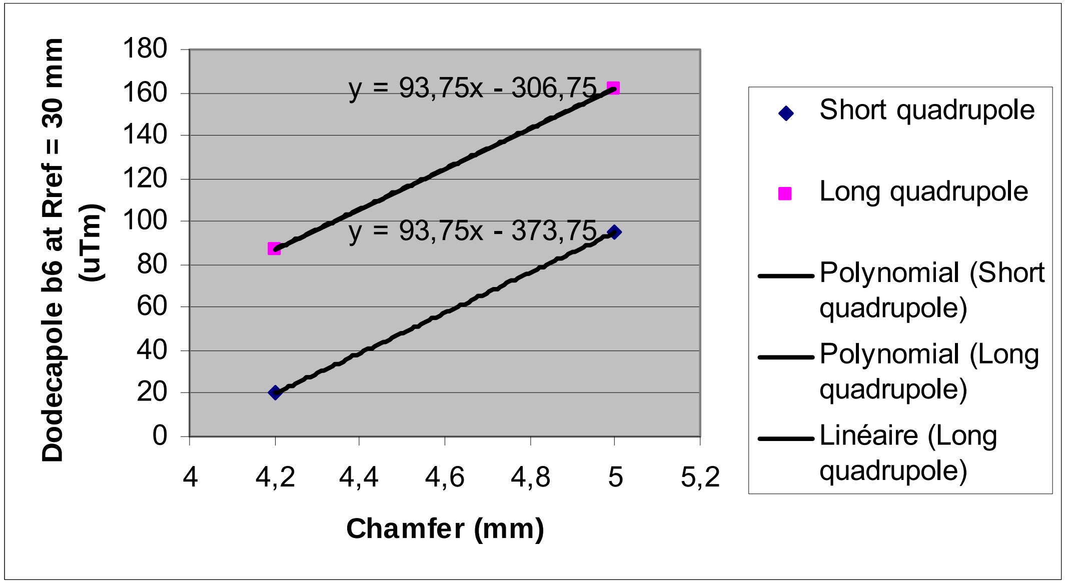


Comparison between calculation and measurement Integrated Dodecapole



calculation and measurement are consistent within 2.10-4

Experimental optimisation of the end chamfers

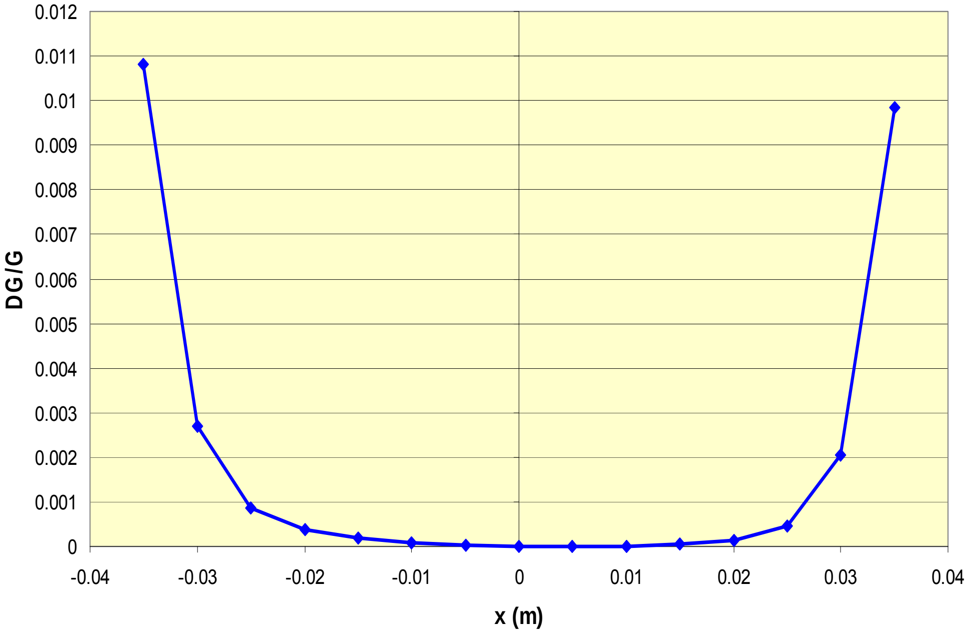


- Both short prototype Quadrupole **QC** & long prototype Quadrupole **QL** have been measure
- 12 pole component behaviour is plotted and fitted
- Final chamfers have been fixed for series production

Resulting gradient homogeneity (Q003)

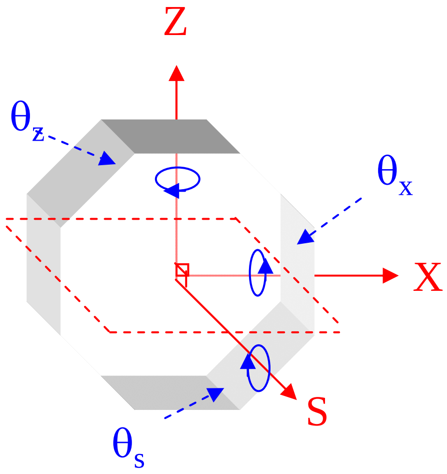
Normal Component	Requested by GPM	Measured by GMI
3	1.2 10-4	-0.42 10-4
4	4.5 10-4	1.43 10-4
5	_	-0.56 10-4
6	7.510-4	0.04 10-4
7	_	-0.01 10-4
8	_	0.59 10-4
9	_	-0.04 10-4
10	4.5 10-4	0.60 10-4
11	_	0.02 10-4

DeltaG(x)/G0 for z=0.

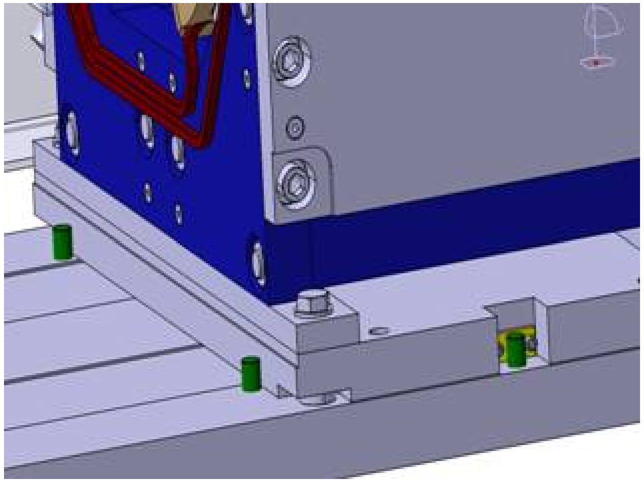


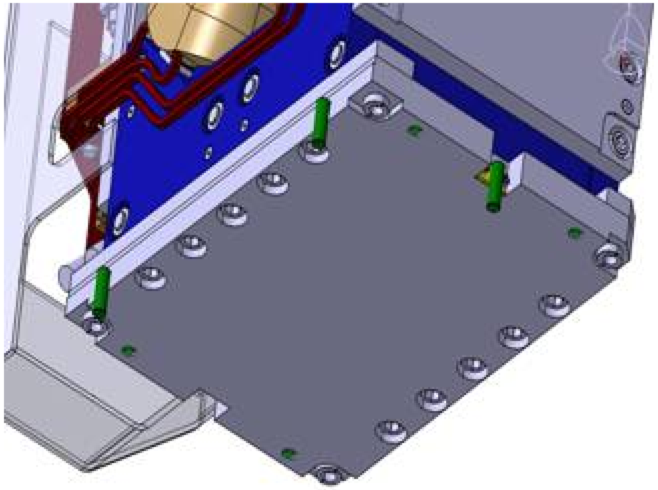
After R=0.032 m the curve is extrapolated

Shimming of the quadrupole on the girder



- (X,Z) and θs are adjusted by 4 washers and 1 lateral shim
- (S) θx, θz are given mechanically by construction.





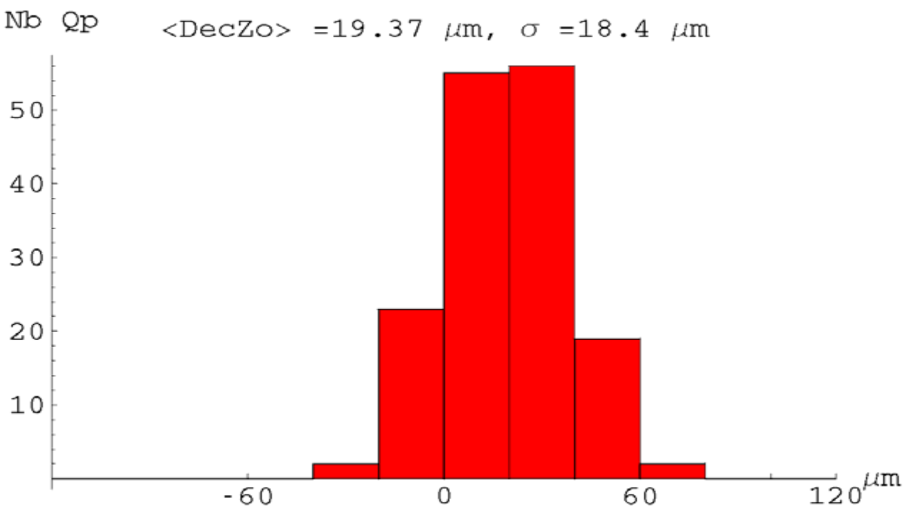
Quadrupole Calibration Magnet integrated gradient = 0.8 T

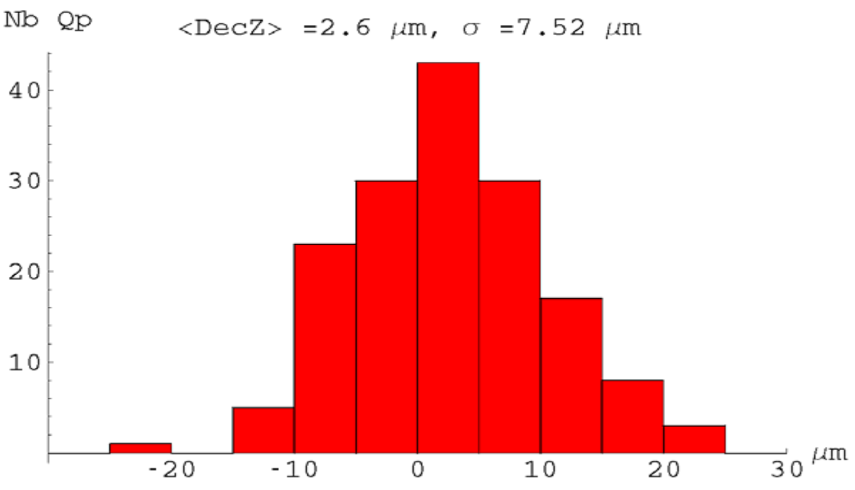
- The QCM has been mounted on the BMS “ mini-girder ” with the standard interface(new support with H&Vplanes)

- The QCM has been presented in reverse position to give the offset errors for instance (+X), (-X) measurement for the magnetic center and rotation of 45^0 for the coupling (Theta S).

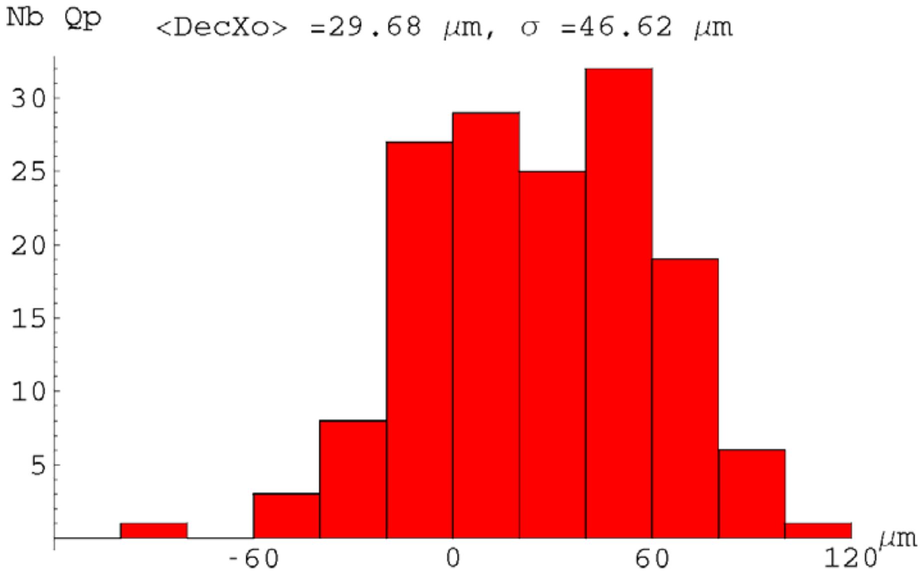
- Cross check of harmonics in all the positions is also possible for Kn verification.

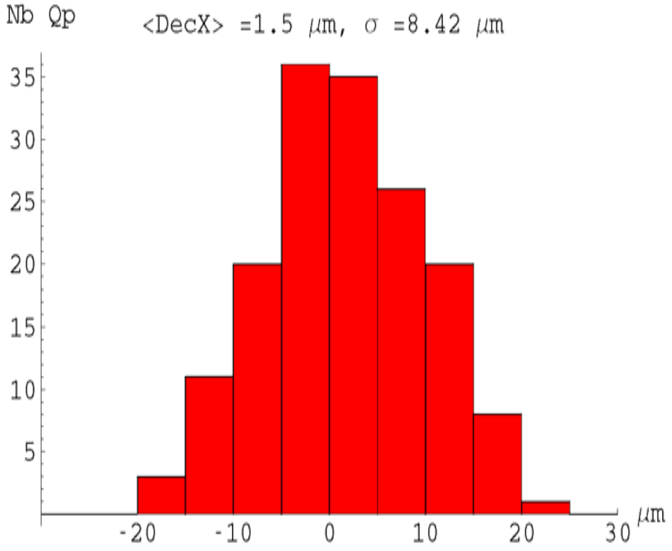
Histograms of magnetic center coordinate Z before & after correction by mechanical shims



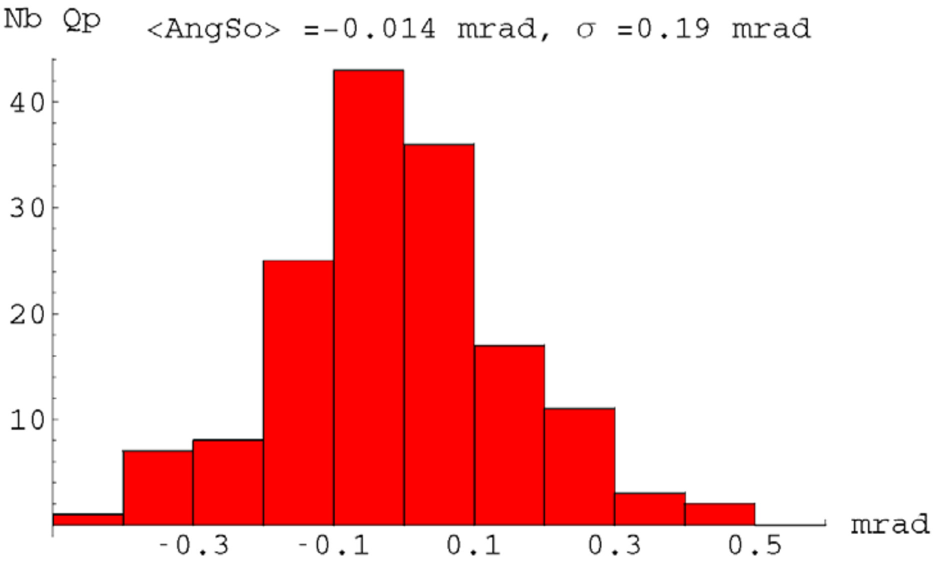


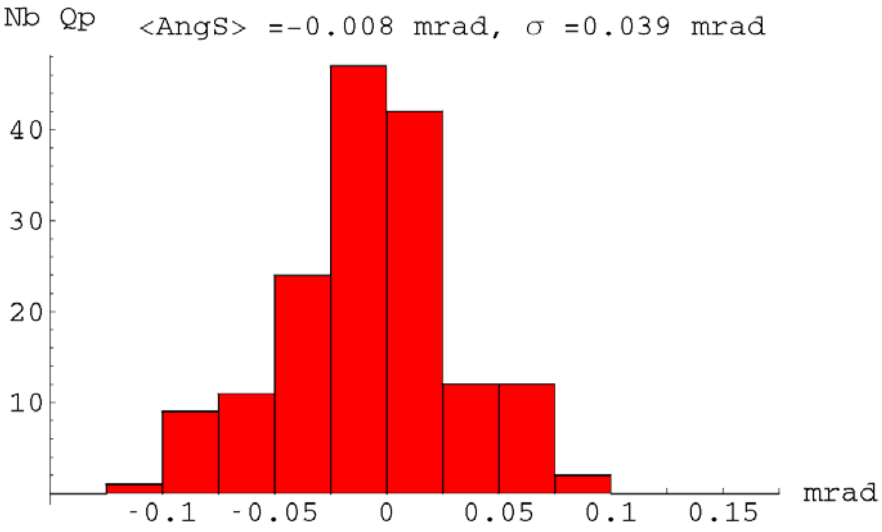
Histogram of Quadrupole Magnetic centre X before & after correction by mechanical shims





Histogram of Quadrupole angles after correction by mechanical shims





What did we learn by measuring the Quadrupoles ?

- The prediction of the field homogeneity by the 3D calculation is very good.
- Accumulation of international experience on harmonic measurement is impressive
- Absolute determination of the magnetic center within 25 microns is possible but delicate & time-consuming .
- Absolute determination and tuning of the angle due to the skew component is extremely demanding on sensor technology.

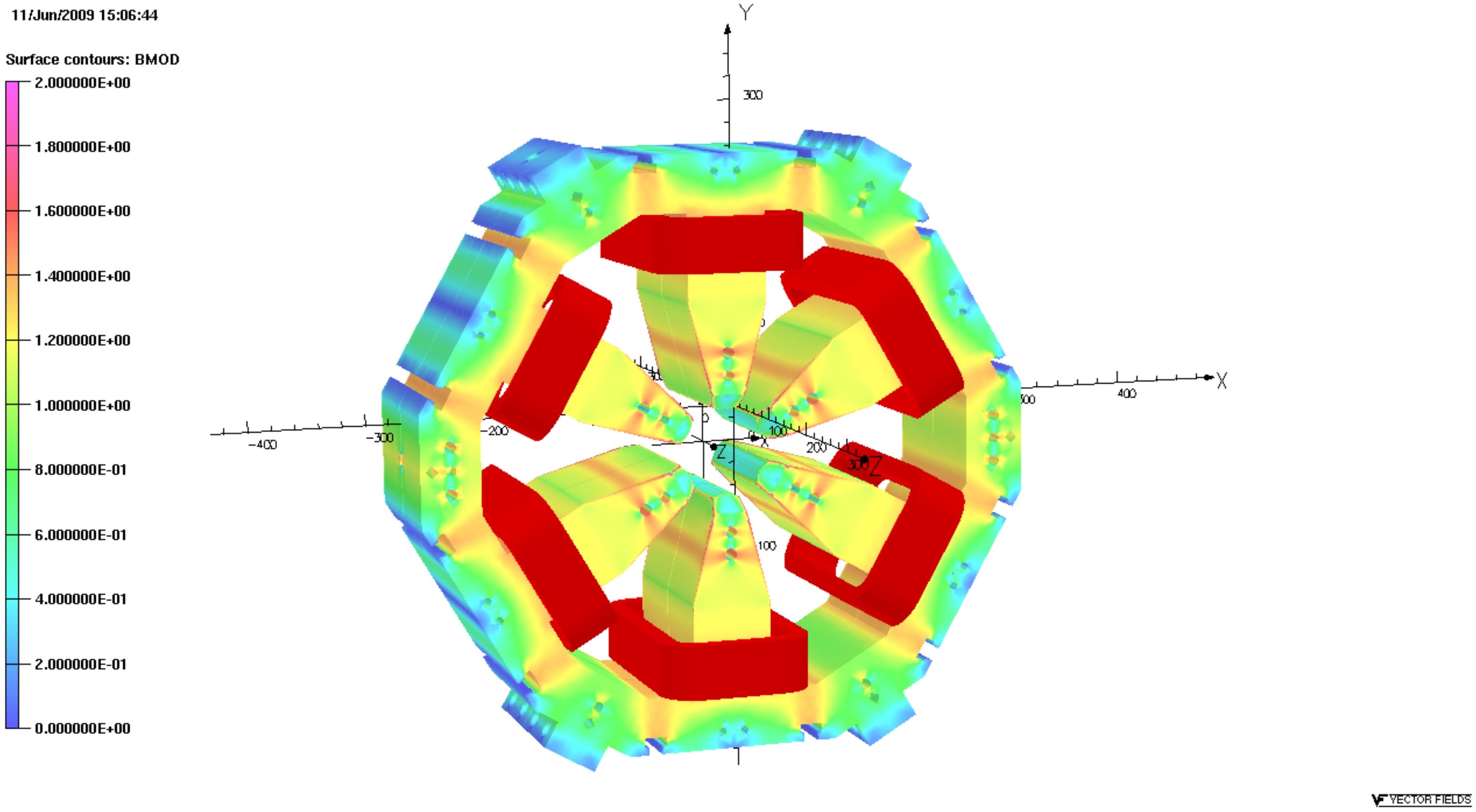
SOLEIL Sextupoles

- Sextupoles are necessary to correct optical aberrations.
- The sextupoles are very important in the SOLEIL storage ring due to the large energy spread of 6%. It helps to collect lost electrons.
- The sextupoles are also equipped with 3 sets of correction coils.
  - Horizontal dipole
  - Vertical dipole
  - Skew quadrupole

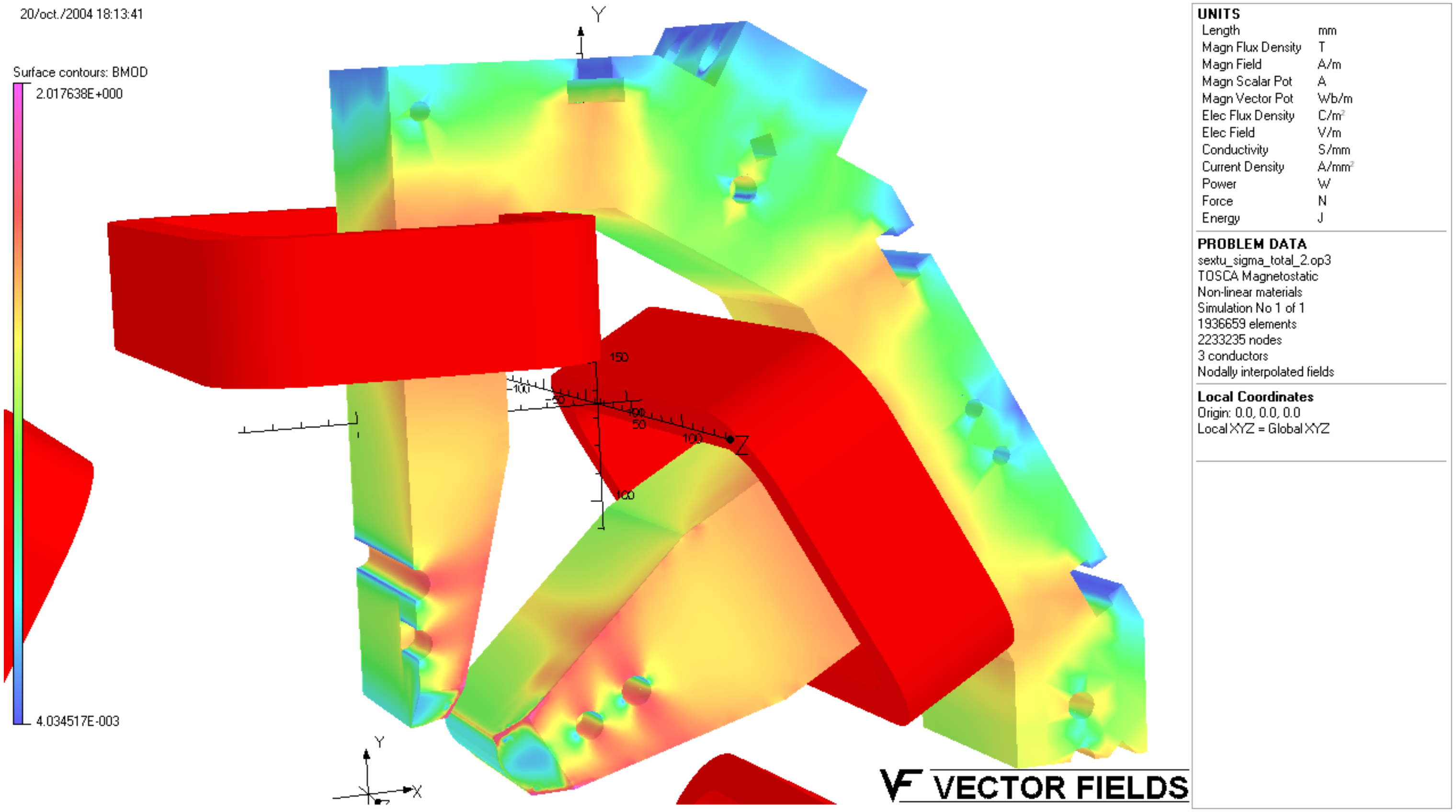
SEXTUPOLES Specifications

- 320 T/m²
- magnetic length : 160 mm
- B2 @ 32 mm :
  - 320*0,16*0,032*0,032= 52,4 mT.m
- Dipole X,Z and skew quadrupole Correctors
  - Bx : 5,5 mT.m (0.6 mrad)
  - Bz : 7,6 mT.m (0.8 mrad)
  - Qt : 2,0 mT.m à 32 mm (Gx=0,39 T/m)

3D calculation with TOSCA



Calcul 3D



UNITS

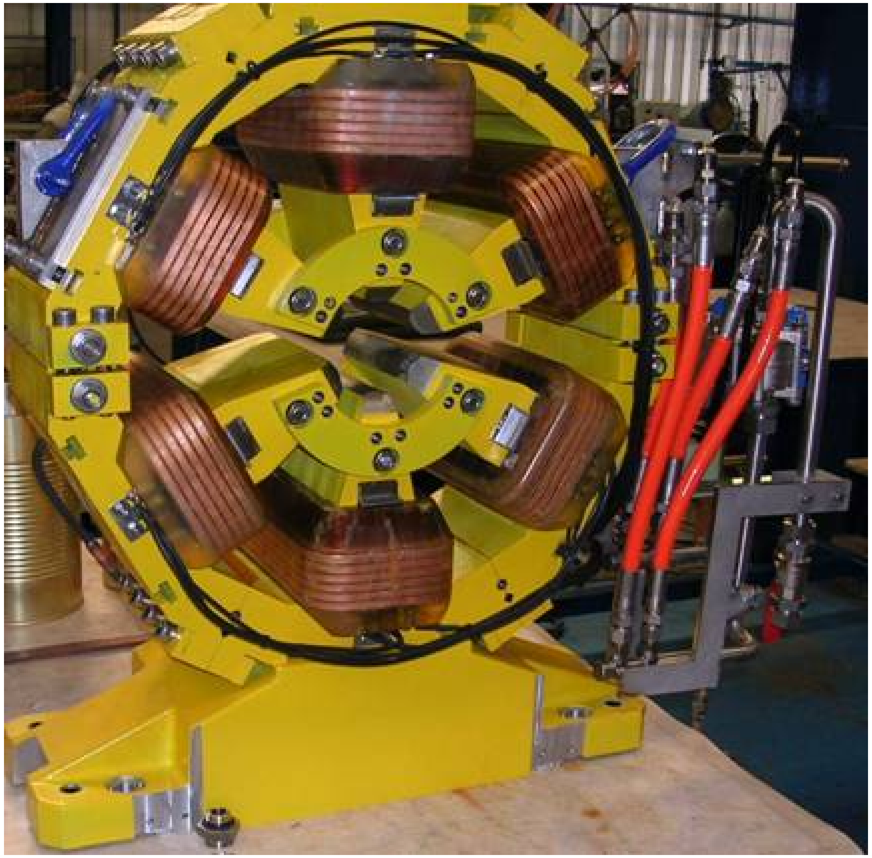
Length	mm
Magn Flux Density	T
Magn Field	A/m
Magn Scalar Pot	A
Magn Vector Pot	Wb/m
Elec Flux Density	C/m^2
Elec Field	V/m
Conductivity	S/mm
Current Density	A/mm^2
Power	W
Force	N
Energy	J

PROBLEM DATA
sextu_sigma_total_2.op3
TOSCA Magnetostatic
Non-linear materials
Simulation No 1 of 1
1936659 elements
2233235 nodes
3 conductors
Nodally interpolated fields

Local Coordinates
Origin: 0.0, 0.0, 0.0
Local XYZ = Global XYZ

Le modèle 3D permet de représenter tous les détails de la construction

A few words about SR Sextupoles

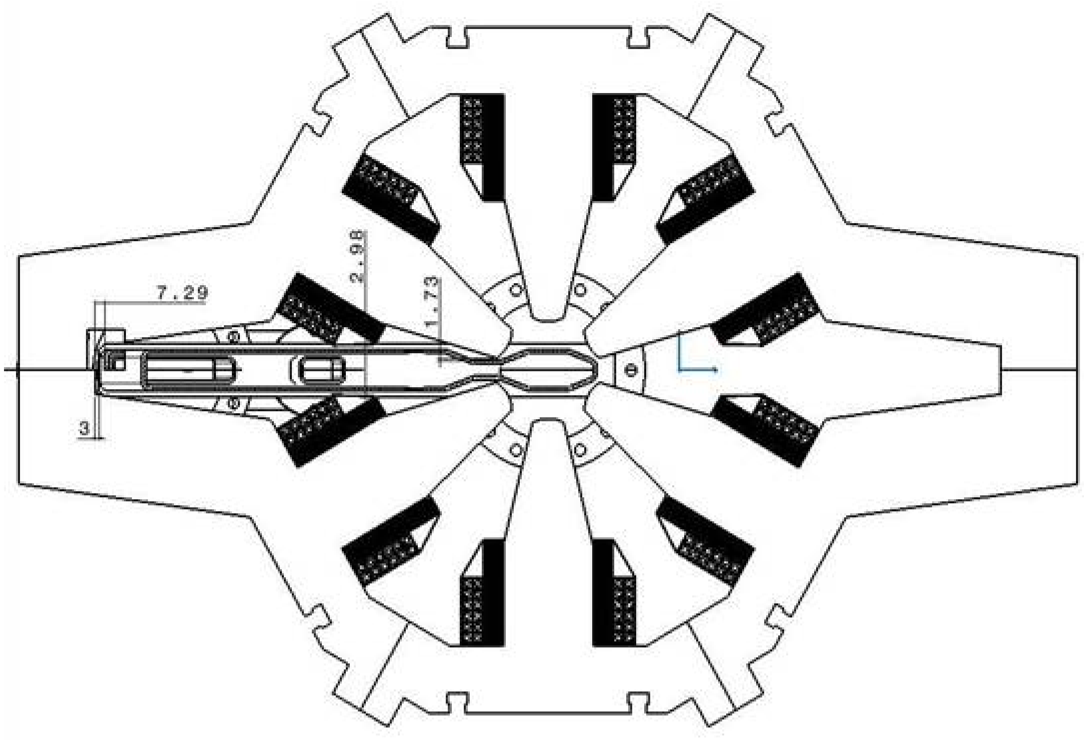


Courtesy of SIGMAPHI

- The production of the 124 SR Sextupoles has been industrially organised by keeping only two types : normal sextupoles and sextupoles with ears
- Magnets produced and measured by Sigmaphi company
- Half rings are keeping the poles at the right location.

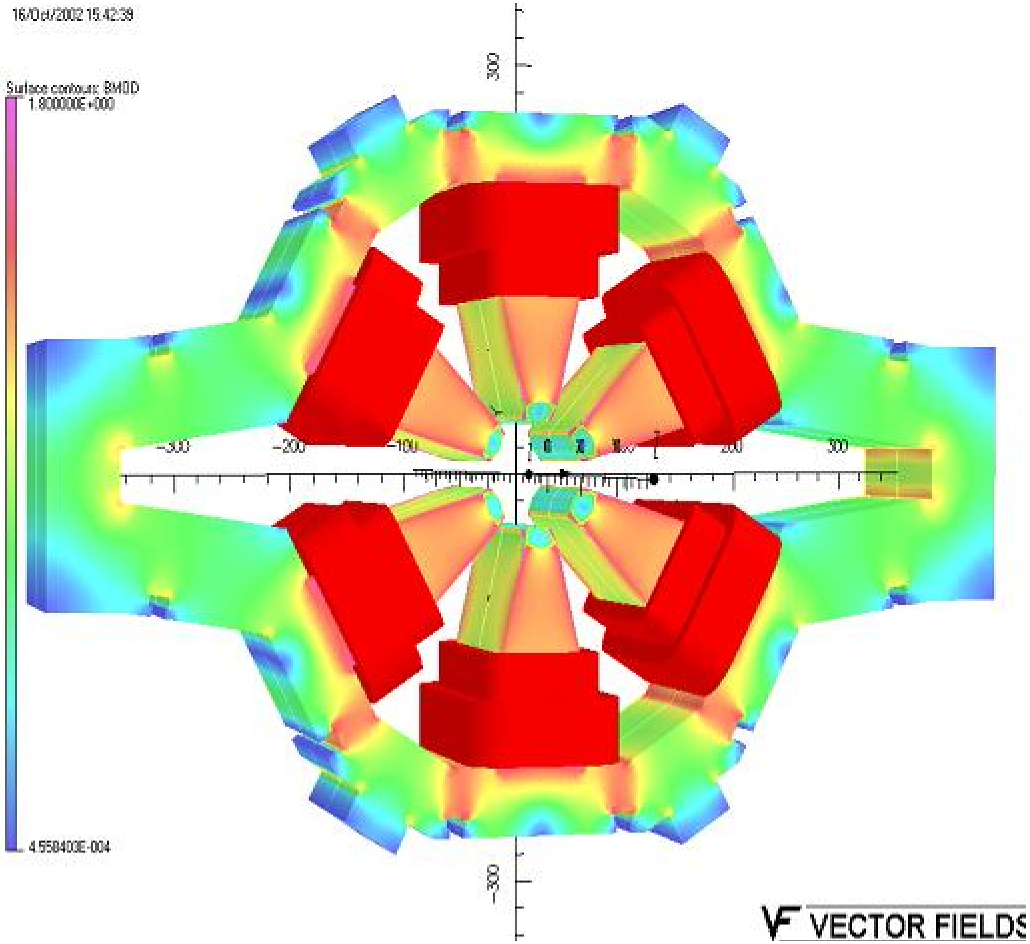
Interface with the vacuum chamfer

- Due to the presence of O°, 1° and 4° light lines we have been obliged to design the so-called sextupole with ears, very similar to Swiss Light Source

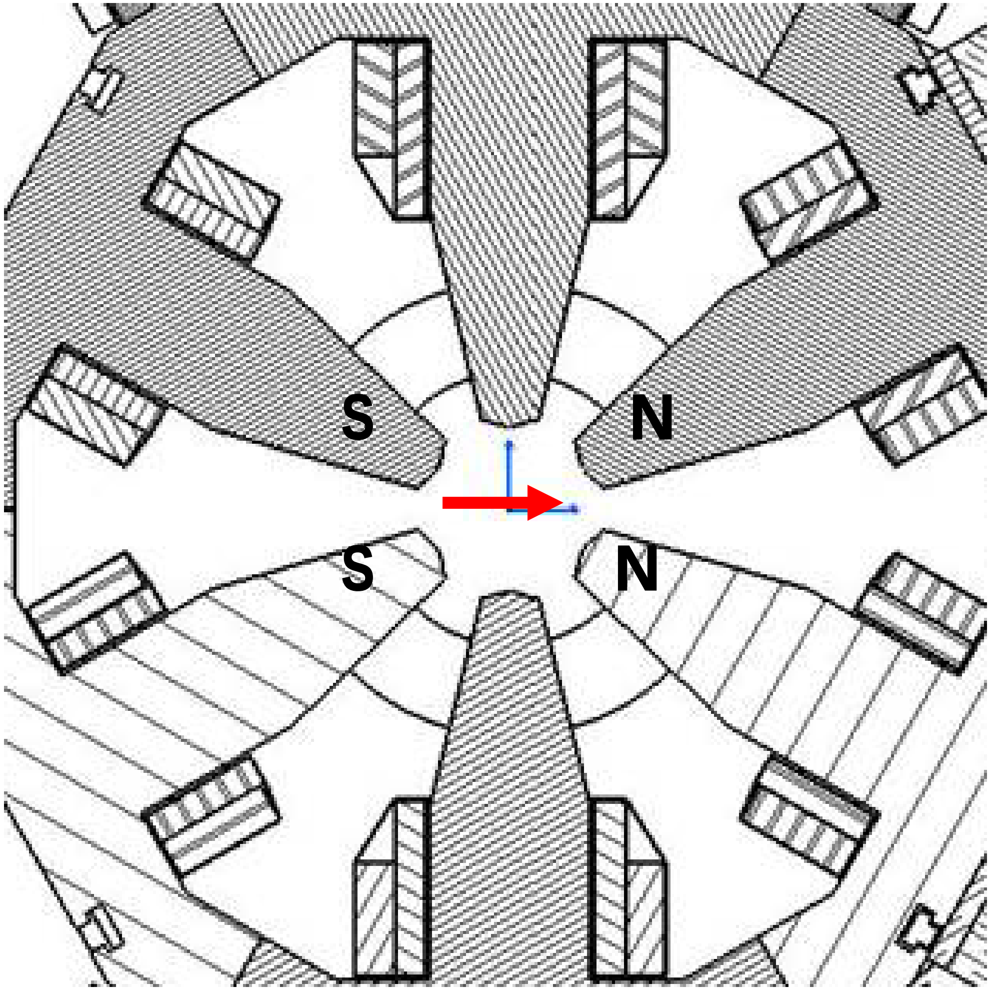


Full 3D calculation of sextupole

- The 3D sextupole with ears has been fully modelized with TOSCA
- Derivation of the flux on the sides requires increased sections and mechanical analysis

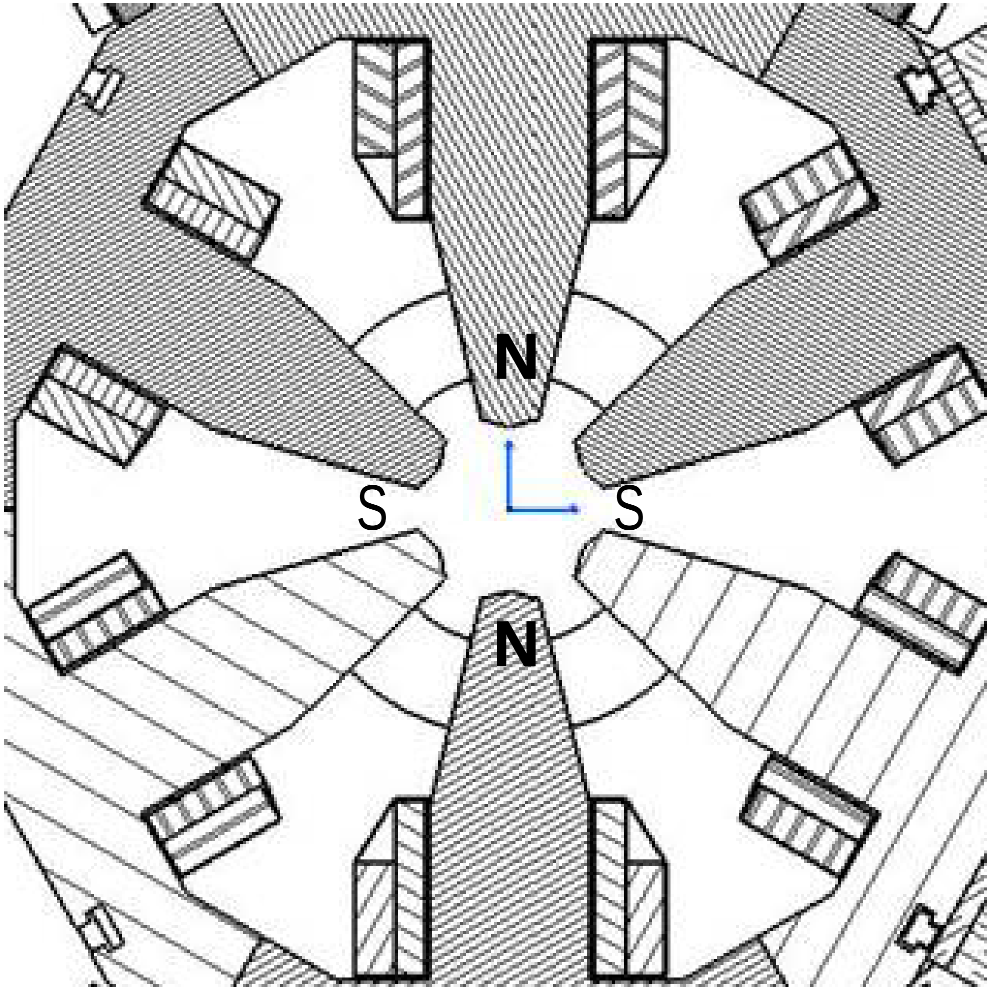


Vertical Steering: horizontal field



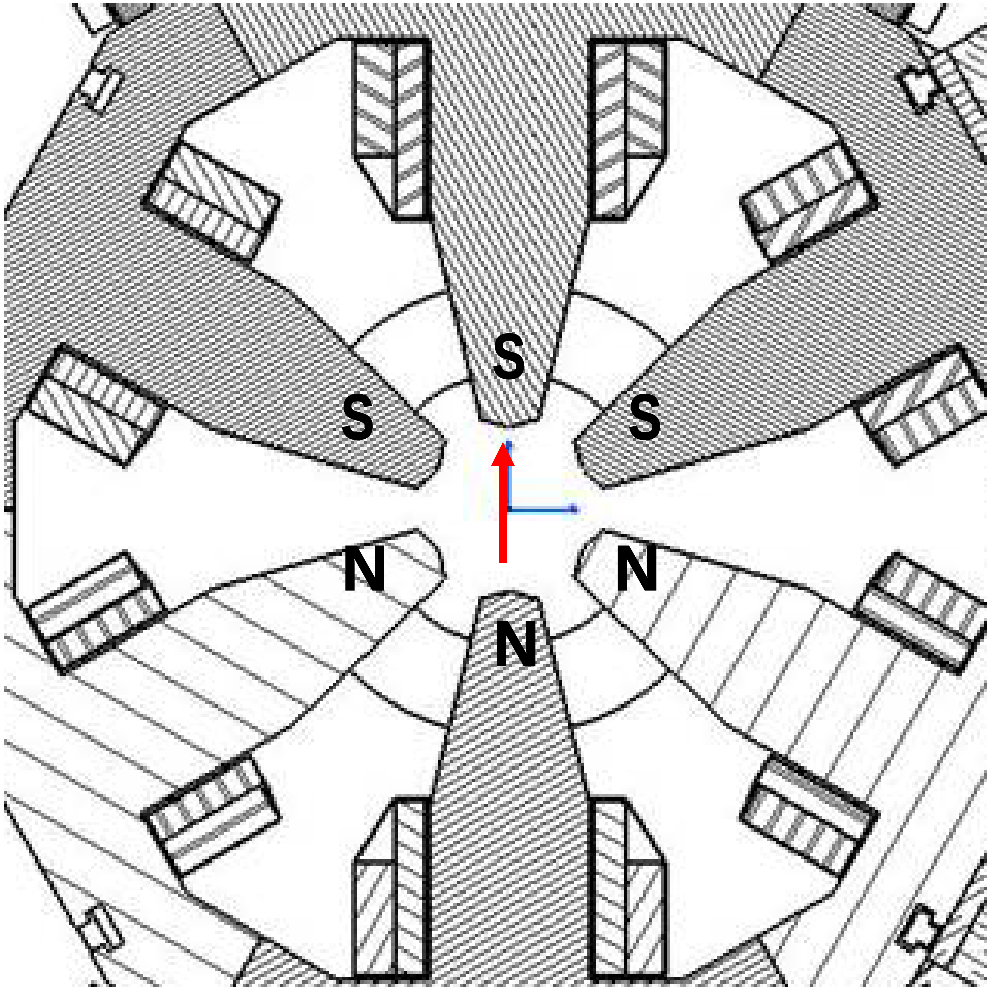
Skew Quadrupole: two poles in opposition

Virtual South poles on the sides



Virtual South poles on the sides

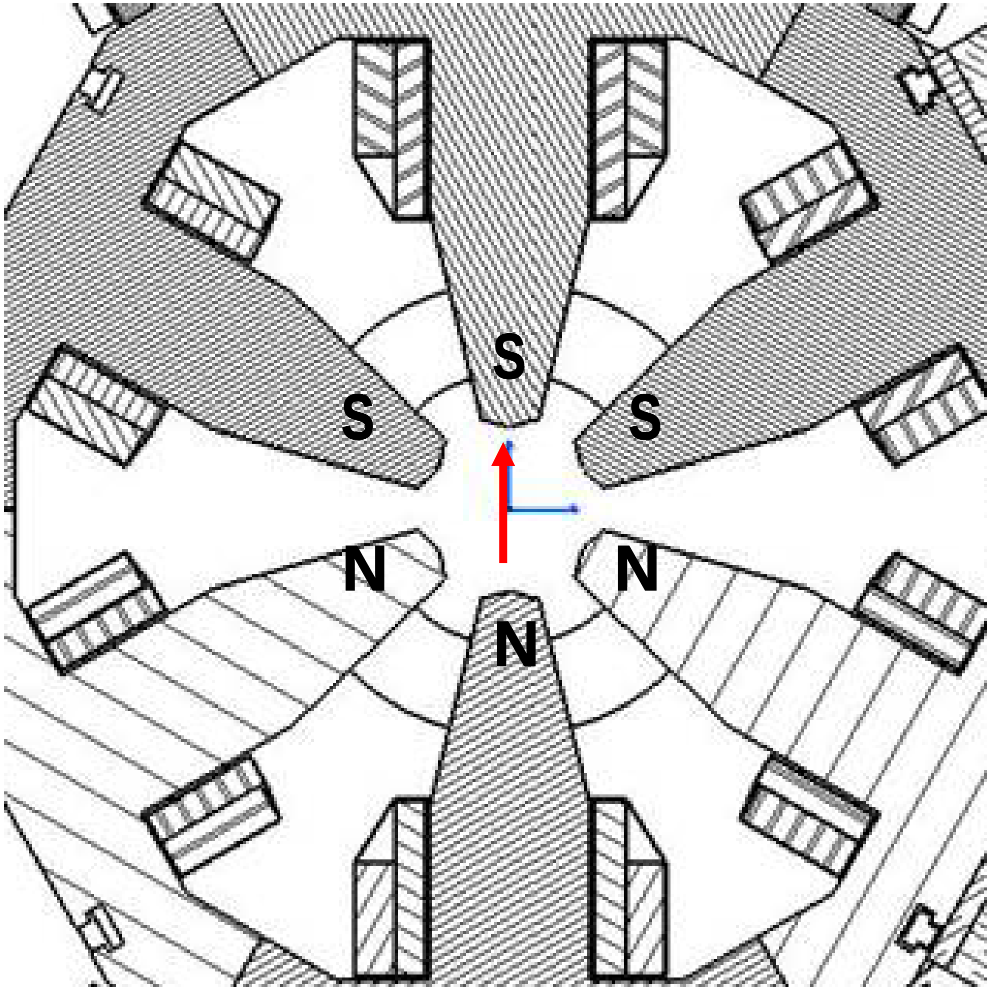
Horizontal Steering: vertical field



Need homogeneity

Ampere Turns ????

Horizontal Steering: vertical field

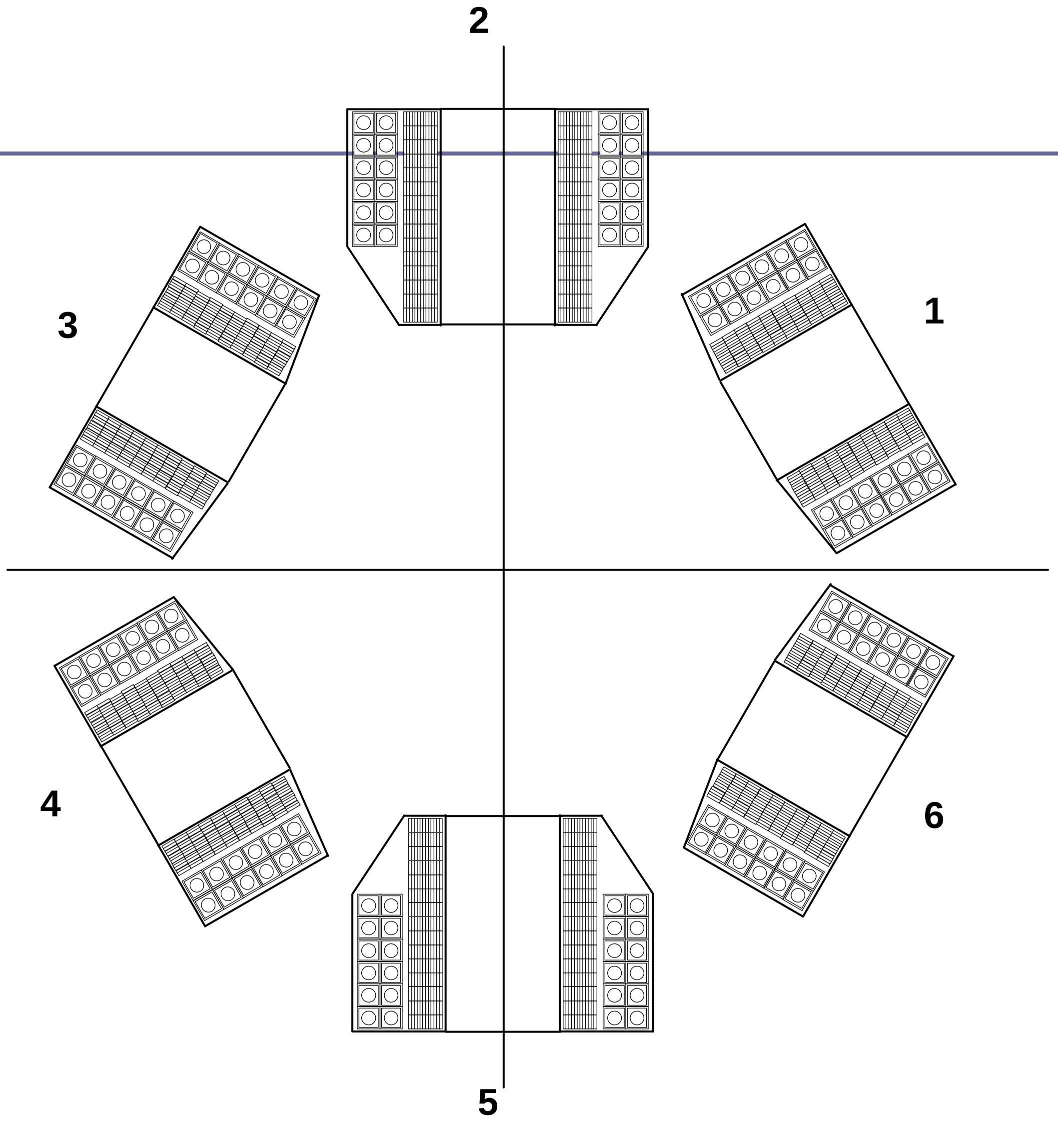


The use of Halbach's perturbation theory gives :

NI2=2*NI1

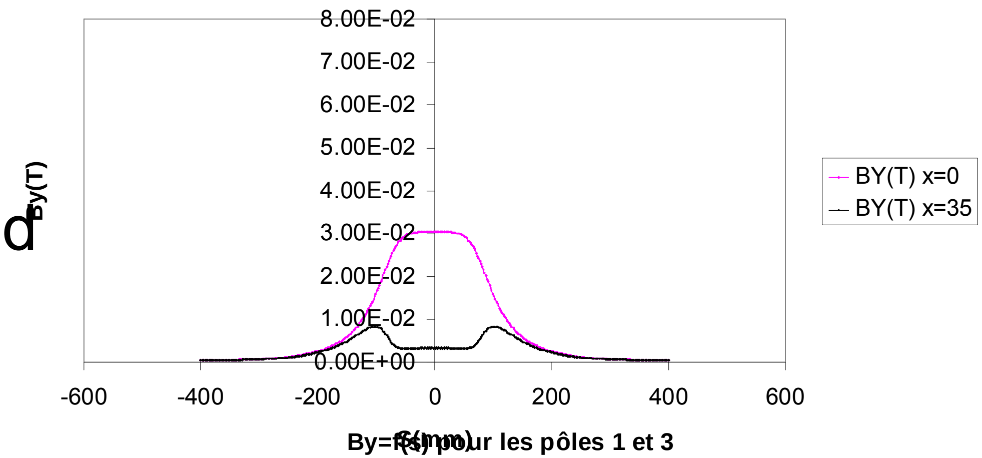
Sextupole=0.

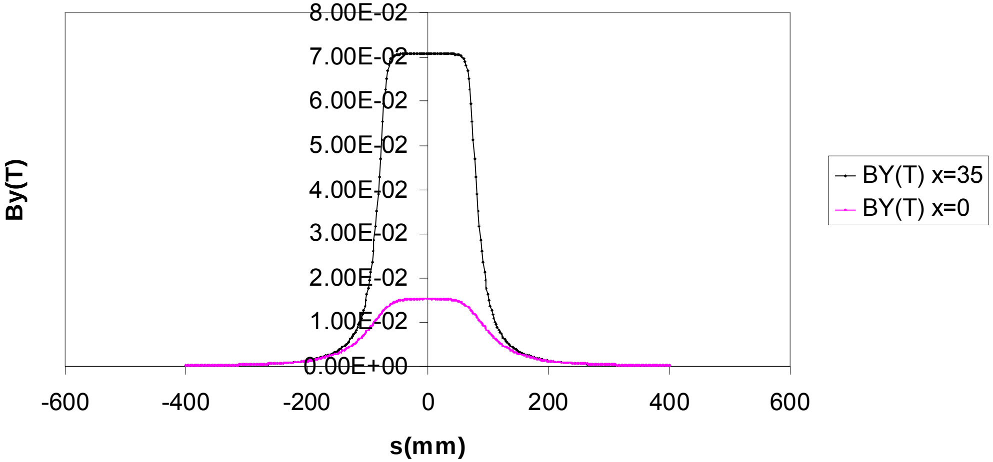
A set of flexible coils indirectly cooled



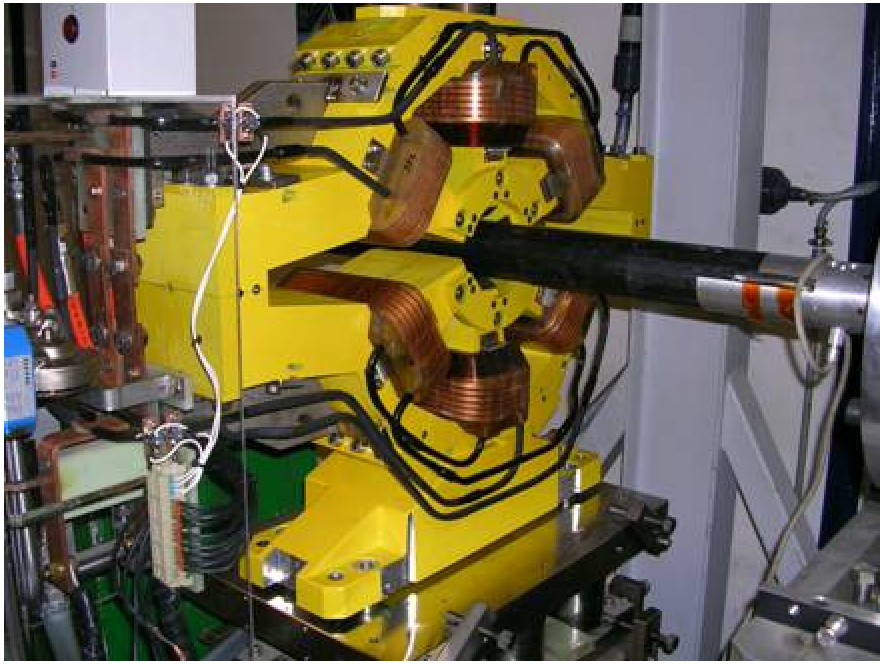
Sextupoles magnetic design

- The 3D model permits prediction of dipole component in the so called « Halbach compensation geometry »


By=f(s) pour le pôle 2


By=f(s) pour les pôles 1 et 3

Sextupole Measurements at SIGMAPHI Company



Courtesy of SIGMAPHI

- Sigmaphi Company has a « State of the Art » bench for harmonic analysis.
- Software developments are exchanged between Soleil & Sigmaphi.
- Crosscheck has been realised both on the « calibration quadrupole » & on a normal SR sextupole.

Sextupole prototype results @ 32 mm

Tolérance
1.3 10-3

Tolérance
5.10-3

	Sextupole with ears		Normal sextupole	
	Tosca Calculation	Sigmaphi measurement	Tosca Calculation	Sigmaphi measurement
b3 (T.m) @32mm	0.0539	0.0547	0.0539	0.0547
18-poles: b_9/b_3	$-5.0\text{x}10^{-4}$	$-9.4\text{x}10^{-4}$	$-5.0\text{x}10^{-4}$	$-9.3\text{x}10^{-4}$
30-poles: b_{15}/b_3	$-7.8\text{x}10^{-4}$	$-8.2\text{x}10^{-4}$	$-7.8\text{x}10^{-4}$	$-8.7\text{x}10^{-4}$
42-poles: b_{21}/b_3	$-20.7\text{x}10^{-4}$	$-21.4\text{x}10^{-4}$	$-20.7\text{x}10^{-4}$	$-21.9\text{x}10^{-4}$

Correctors field @ 32 mm measured by Sigmaphi

@nominal current	H corrector		V corrector		Skew Quad	
	Tosca calculation	Measure-ment	Tosca calculation	Measurement	Tosca calculation	Measure-ment
Main components b1/a1/a2 (mT.m)	12.3	11.8	6.7	6.7	4.7	4.7
8-poles (%) a_4/a_2					-57	-56.2
10-poles (%) b_5/b_1 and a_5/a_1	+30	+28.9	-30	-28.8		
14-poles (%) b_7/b_1 and a_7/a_1	+3.6	+3.5	+3.6	+3.4		
22-poles (%) b_{11}/b_1 and a_{11}/a_1	-1.5	-1.5	+1.5	+1.6		

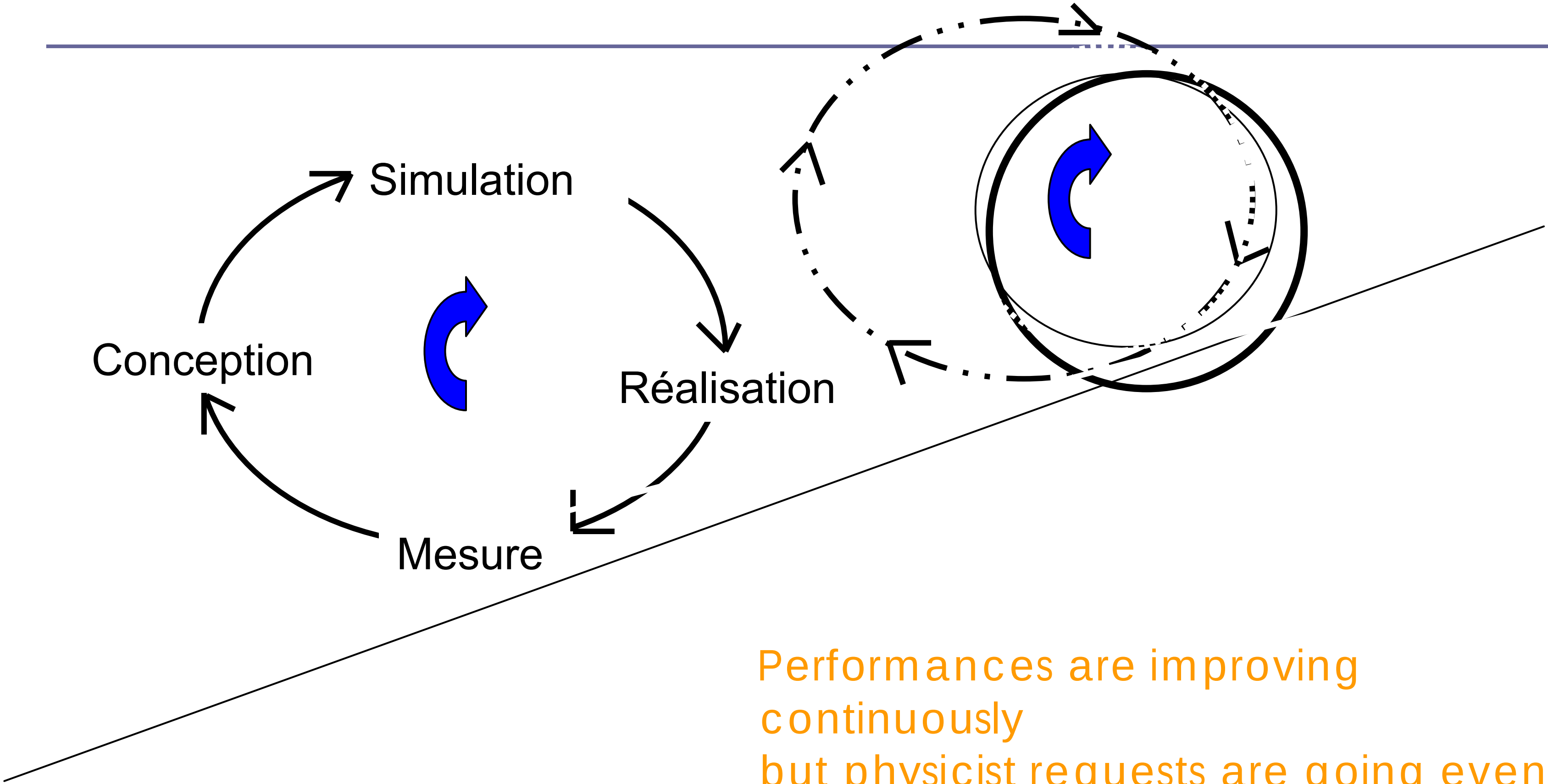
What did we learn with sextupole Measurements ?

- 3D predictions are very good especially after benchmark from SLS magnets
- Even special coils curves could be computed
- Small construction defects are uneasy to simulate in the range of 25 microns
- It is uneasy to find correlation between small mechanical defects and « small » harmonic contents of 2 units.

Synthesis

- The conventional magnets are limited to about 1.8 Tesla for the dipole and 25 T/m for the quadrupoles.
- These values are still matching many accelerator requirements.
- The precision is improving in steel quality, machining and cutting, as well as in magnetic measurements.
- The conventional magnets are dominated by a great variety of magnetic configuration.
- The 3D codes are mastering most of these configurations.

Conclusion



Simulation

Conception

Réalisation

Mesure

Performances are improving continuously
but physicist requests are going even faster…

Bibliographie

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