COMMISSARIAT À L'ÉNERGIE ATOMIQUE

DSM - DAPNIA

DIRECTION DES SCIENCES DE LA MATIÈRE

* *Laboratoire d'Étude et de Développement des Accélérateurs*

dapnia

saclay

Magnet design and studies at *DAPNIA/SACM/LEDA** – CEA Saclay (France)

Olivier DELFERRIERE

Particle Accelerator Conference *Knoxville-Tennessee, USA May 16-20,2005*

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SACM PRESENTATION

SERVICE DES ACCELERATEURS, DE CRYOGENIE ET DE MAGNETISME

- Activités
- Projets et réalisations
- Thémes scientifiques
- Dossiers pédagogiques
- Sites utiles
- Le coins des étudiants
- Faits marquants
- Séminaires
- CEA
- DSM
- DAPNIA
- SACM/accueil

- Initiation cryogénie
- Qu'est ce qu'un accélérateur
- Cavités radiofréquence
- Introduction supraconductivité
- Vide mode d'emploi
- Protection aimants
- Hyperfréquence
- Les applications des accélérateurs

- ALEPH(1983-2001)
- ATLAS toroide
- CEBAF quadripoles
- CLAS solénoide
- CMS solénoide
- HERA quadripoles
- IPHI
- JHC
- LHC quadripoles
- NEUROSPIN
- MACSE(1990-1995)
- Quadripole en Nb3Sn
- RHIB-GLAD
- SMC
- SOLEIL cryomodules
- SPIRAL2
- Super3HC
- TESLA/TTF
- W7X

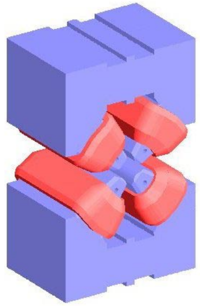
- Traitements de surface des cavités
- Ecoulements d'hélium diphasique
- Dynamique des faisceaux de particules
- Couplage magnétisme,mécanique et thermique
- Hardron thérapie
- Imprégnation des bobines supraconductrices
- Isolation pour conducteurs en niobium étain
- Cavités pour linacs à protons

sance pour les protons du projet IPHI

Le SACM au service des grands instruments de physique.
Les grands accélérateurs pour la Physique des Particules ou la Physique Nucléaire nous demandent de relever des défis techniques importants afin d'obtenir des faisceaux plus puissants, plus intenses, plus stables, avec un meilleur rendement.

L'utilisation des supraconducteurs tant pour les cavités accélératrices que pour les électroaimants ,constitue un progrès décisif dans l'évolution de la physique des accélérateurs.

De nombreuses autres applications (fusion thermonucléaire, source de rayonnement synchrotron et laser X, imagerie médicale...) ont profité des développements autour de ces technologies qui nécessitent souvent de grandes stations d'essais cryogéniques très performantes.



Magnet design and studies at *DAPNIA / SACM / LEDA* – CEA Saclay

Ion source magnets :

- Solenoid magnets for High intensity CW H^+ ECR ion source @2.45Ghz.
- Permanent magnet for 5 mA D^+ ECR ion source for SPIRAL2 project
- PM octupole configuration for an ECR H^- ion source at Saclay

Beam line resistive Magnets : dipoles and quadrupoles

- SOLEIL storage ring dipole and quadrupole

Magnets for corrections or diagnostics

- H+V correctors for IPHI H^+ ion beam
- A *Wien* filter for mass separation and emittance measurements

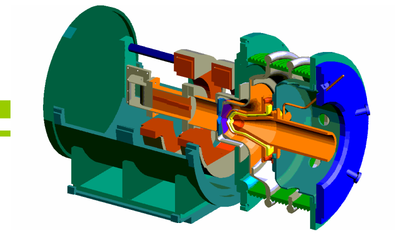
Coils for superconducting magnet

- Nb_3Sn quadrupole and RMN530 solenoid interaction

DTL Quadrupole magnets

- IPHI quadrupole for DTL accelerator

Ion source magnets :



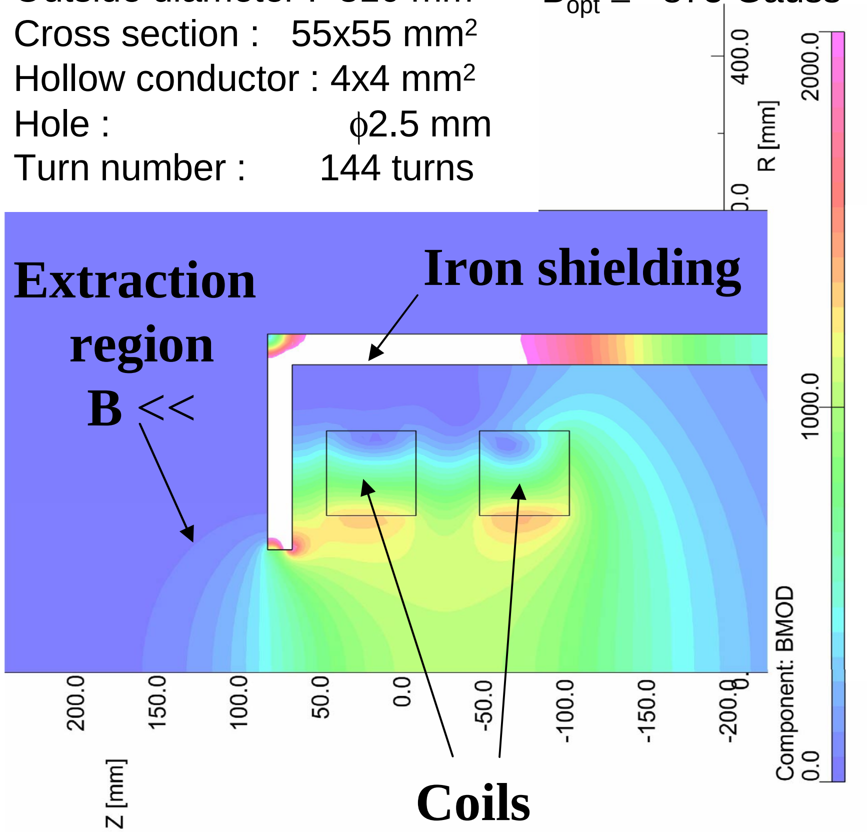
SILHI SOURCE MAGNETIC DESIGN

Solenoid : 15000 At

Inside diameter : 200 mm
Outside diameter : 310 mm
Cross section : 55x55 mm²
Hollow conductor : 4x4 mm²
Hole : ϕ2.5 mm
Turn number : 144 turns

Magnetic field:

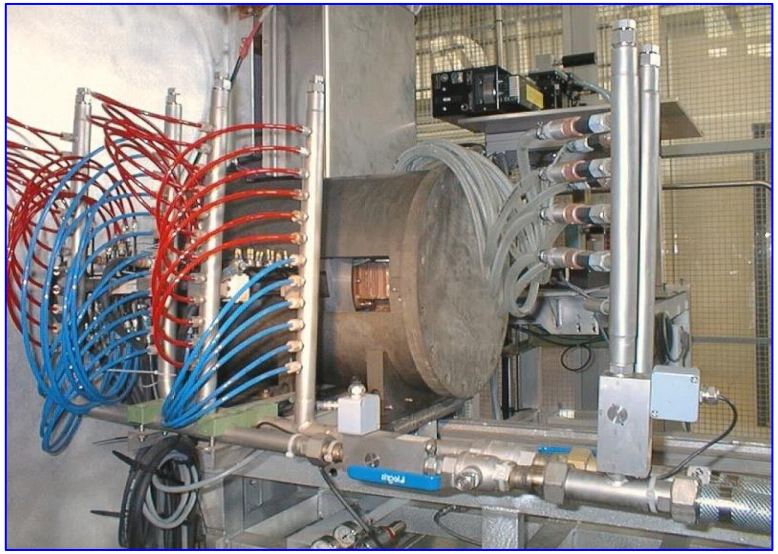
$B_{max} \approx 1600$ Gauss
$B_{opt} \geq 875$ Gauss



2D axisymetric Model

with OPERA-2D ®

2 solenoid configuration



ECR resonance

$B_{ecr} = \omega_{HF} . m_e / e$

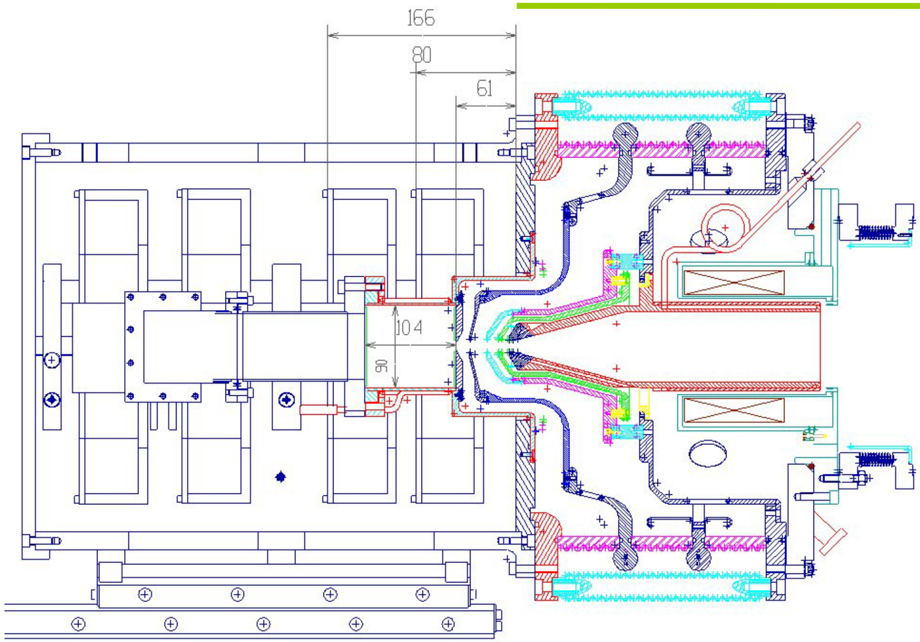
B=875 Gauss

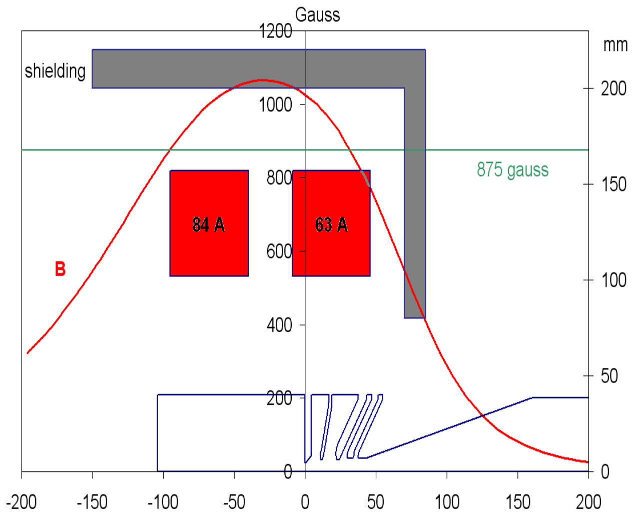
@ ω_{HF}=2.45 GHz

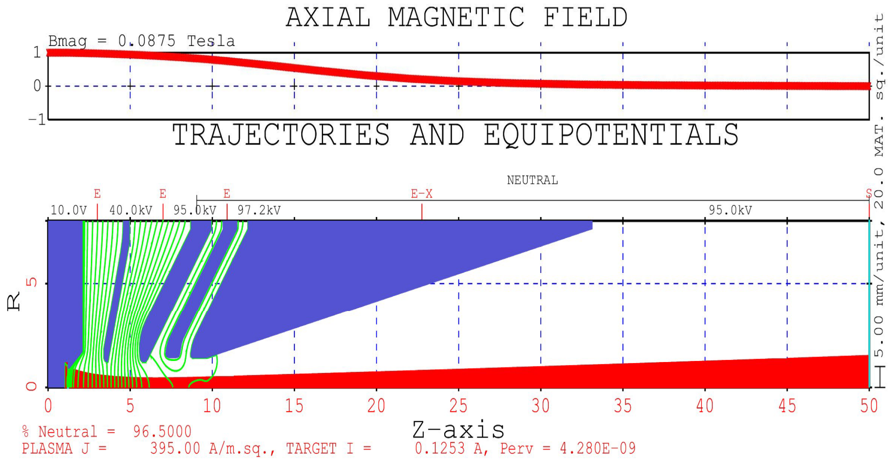
Ion source magnets :

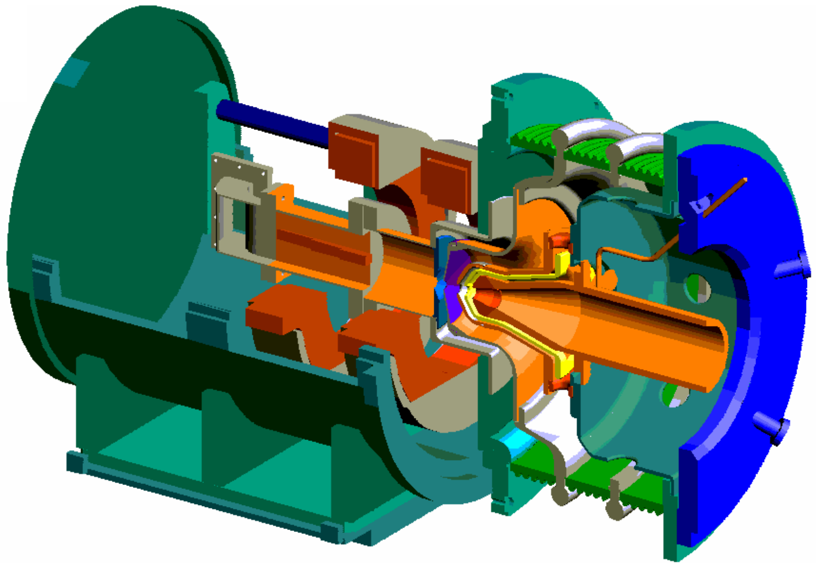
SILHI SOURCE MAGNETIC DESIGN

CW 100 mA H+ beam@95 keV

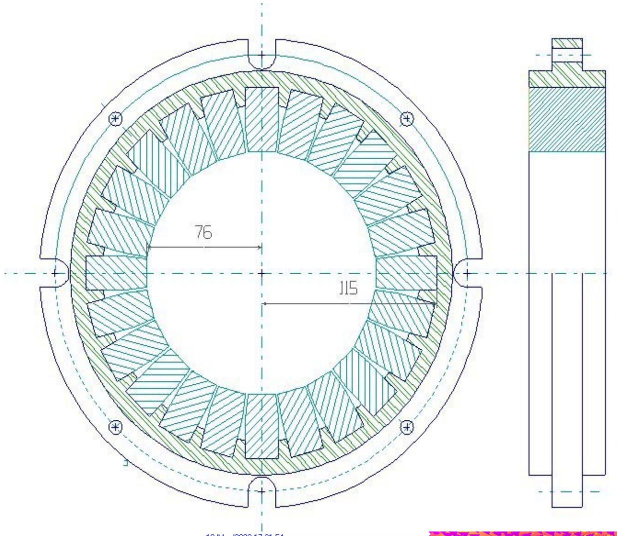




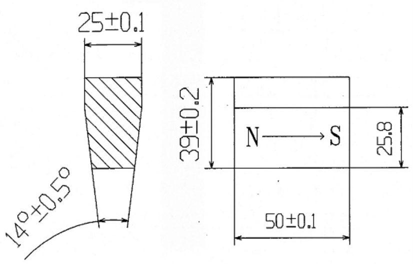


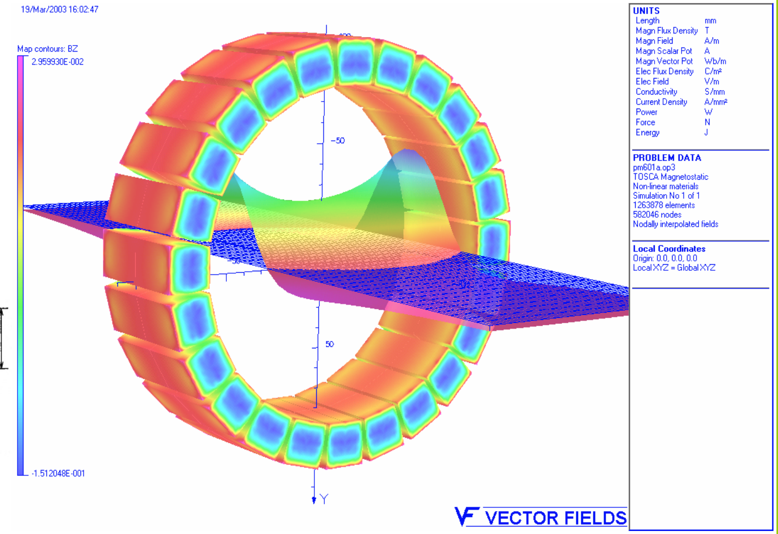


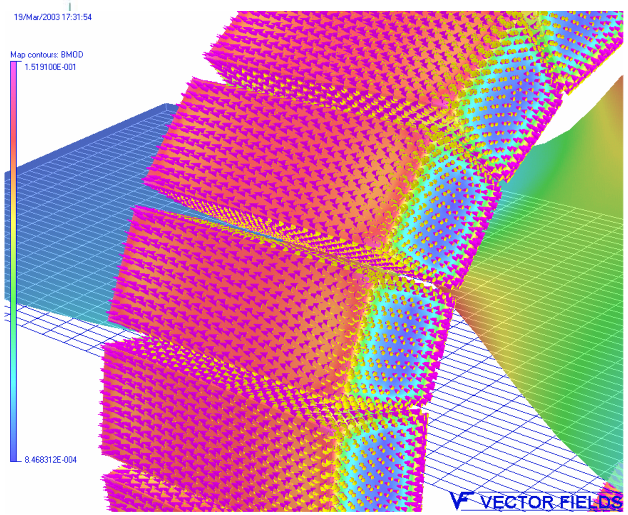
Magnetic design: 3 ring-shaped 24 permanent magnets for solenoidal field

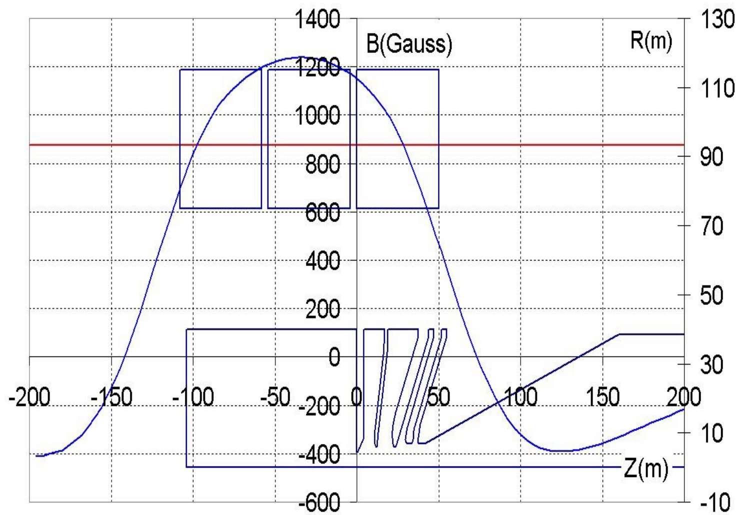


B r min	1.22 Tesla
Hcb min	925 KA/m
Hcj min	1670KA/m
BH max min	280KJ/m3



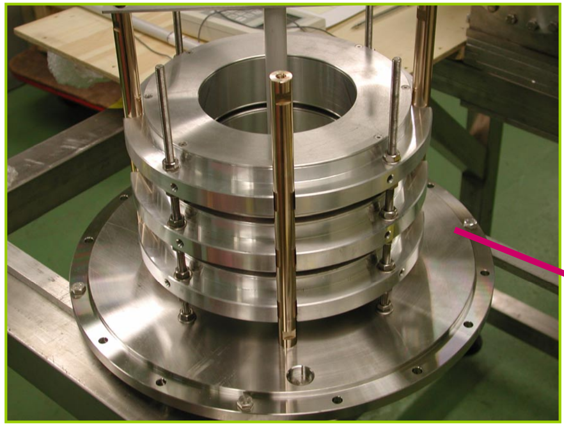


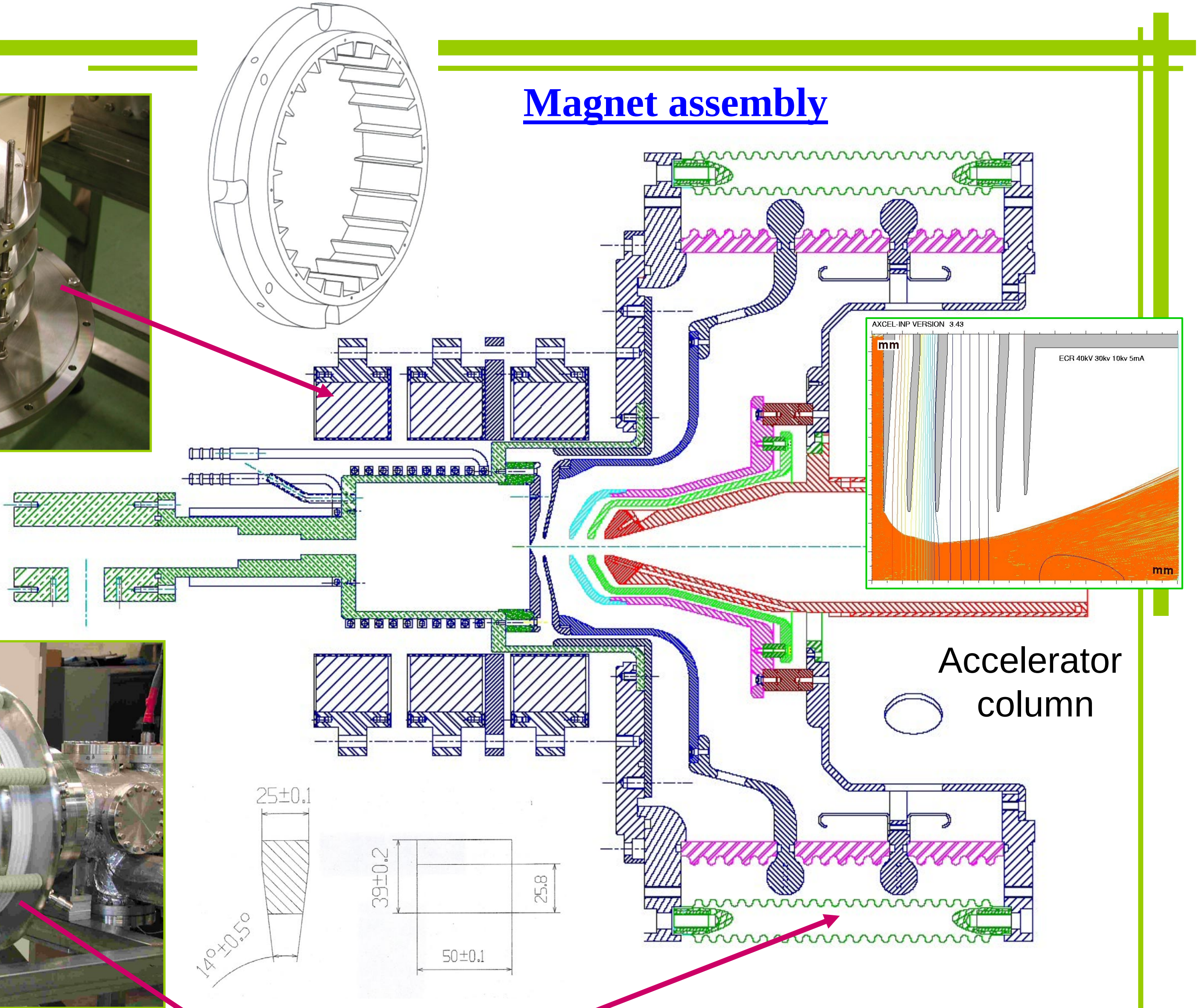




Ion source magnets : *SPIRAL2* 5 mA D^+ ECR ION SOURCE

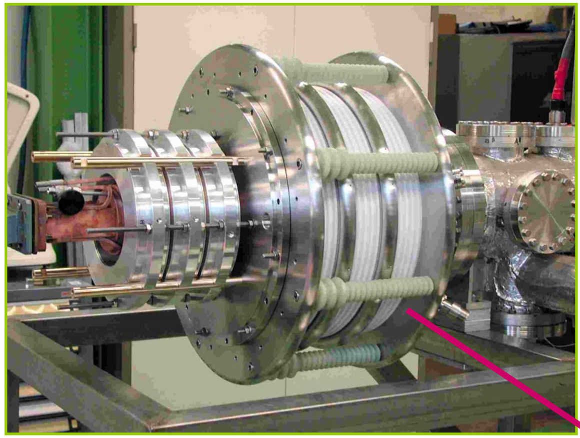
Magnet assembly





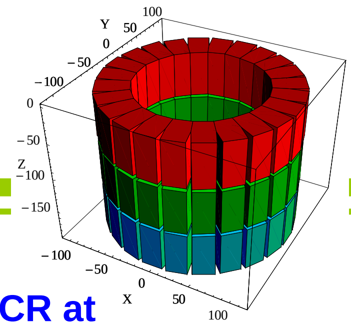
3 solenoïds of
24 permanent
magnets

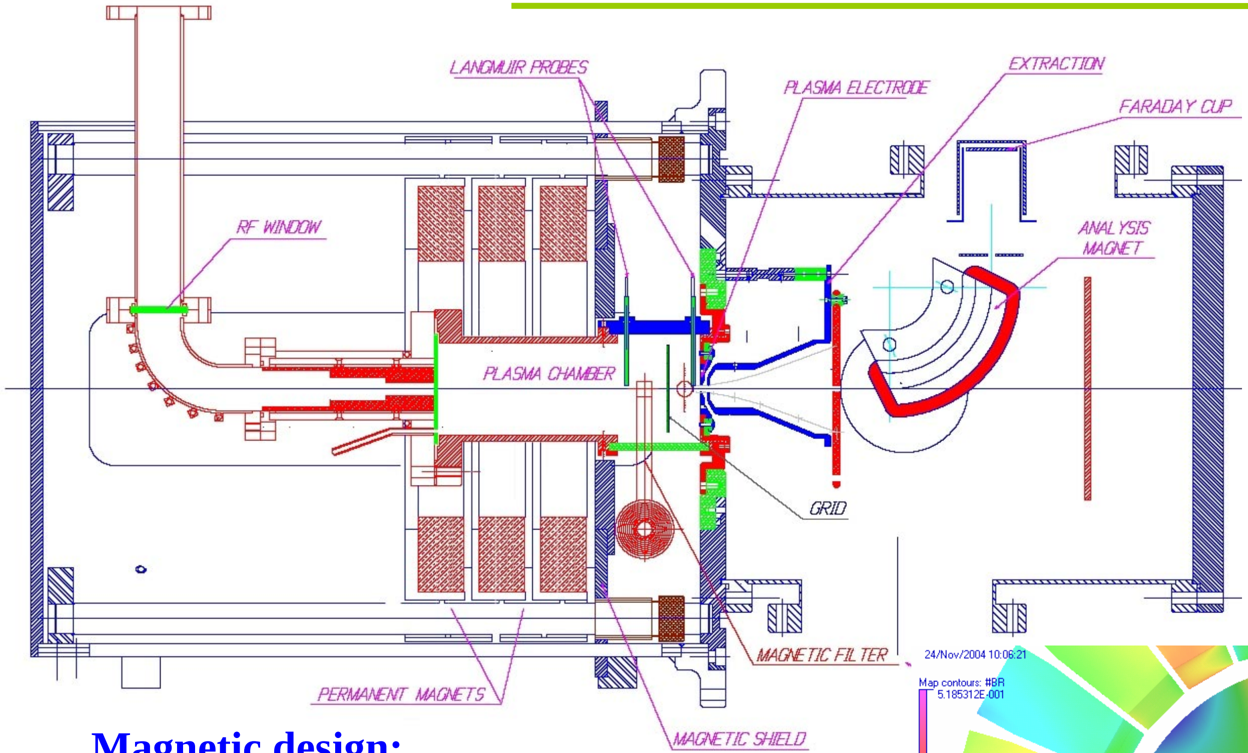
Accelerator
column



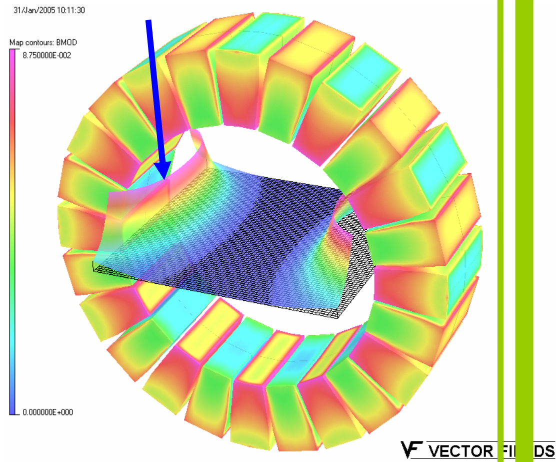
Ion source magnets :

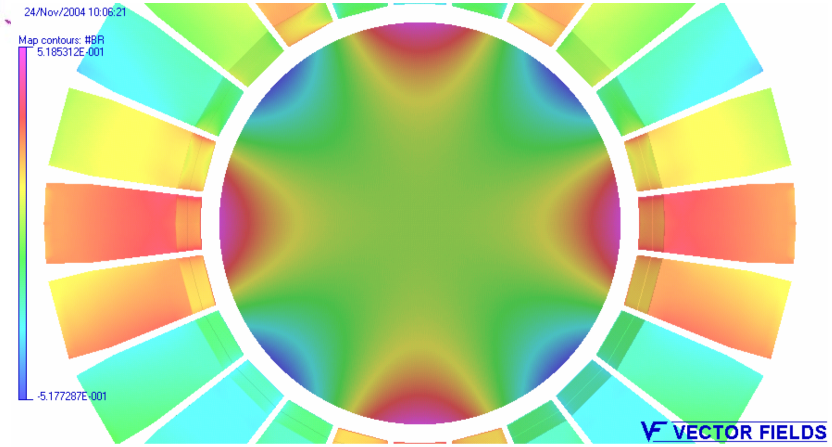
Dvpt. of an H^- ECR ION SOURCE at Saclay





ECR at R=33 mm





Magnetic design:

ring-shaped
24 permanent magnets
in octupolar configuration

B r min	1.22 Tesla
Hcb min	925 KA/m
Hcj min	1670KA/m
BH max min	280KJ/m3

ECR resonance

$$B_{ecr}=\omega_{HF}.m_e/e$$

B=875 Gauss

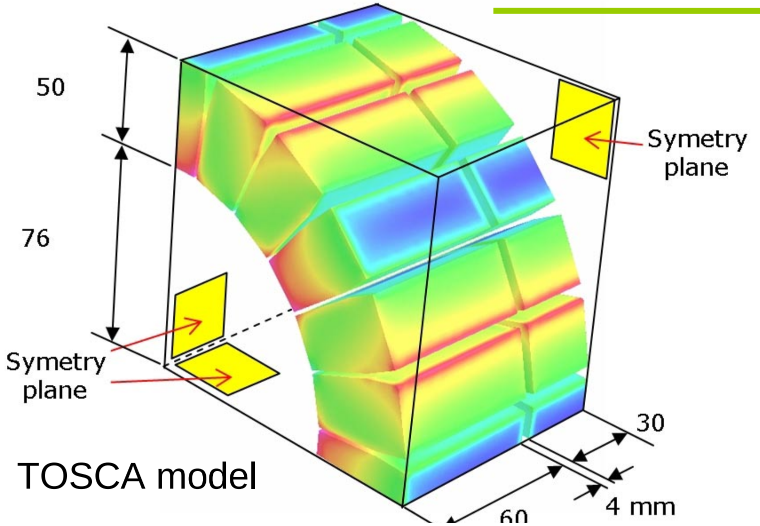
@ ω_{HF}=2.45 GHz

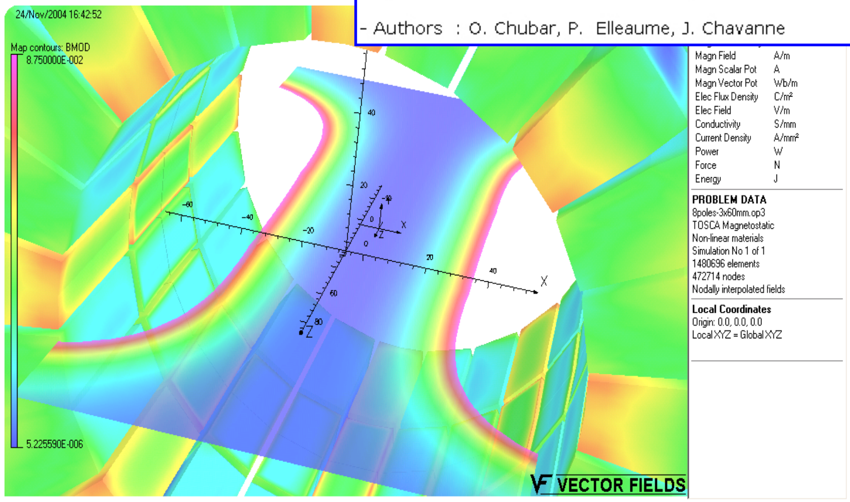
TOSCA / RADIA comparison

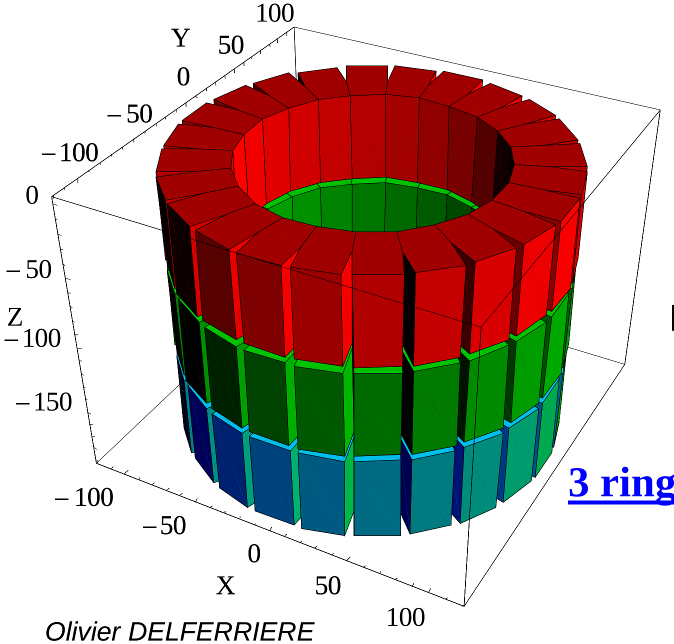
Radia Main features

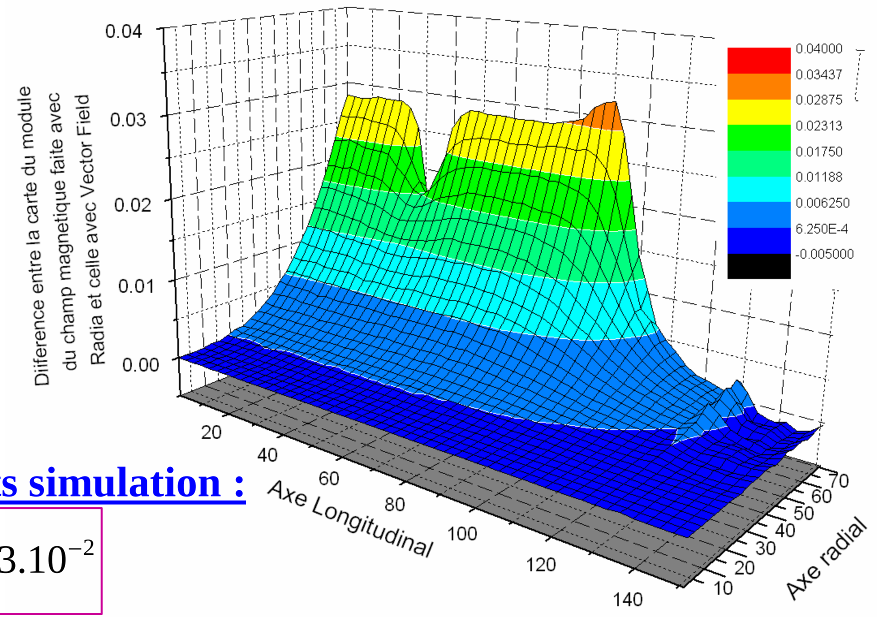
- Saturated iron & anisotropic materials
- Polyhedron shapes
- Straight and curved current coils
- Easy modeling and meshing
- Fast 3D visualization with QuickDraw 3D or Mathematica
- Parameterization of the models in the Mathematica Language
- Fast solving
- Semi-analytical computation of field, field integrals and forces
- Operates on MacOs and Windows 95/NT

- Authors : O. Chubar, P. Elleaume, J. Chavanne









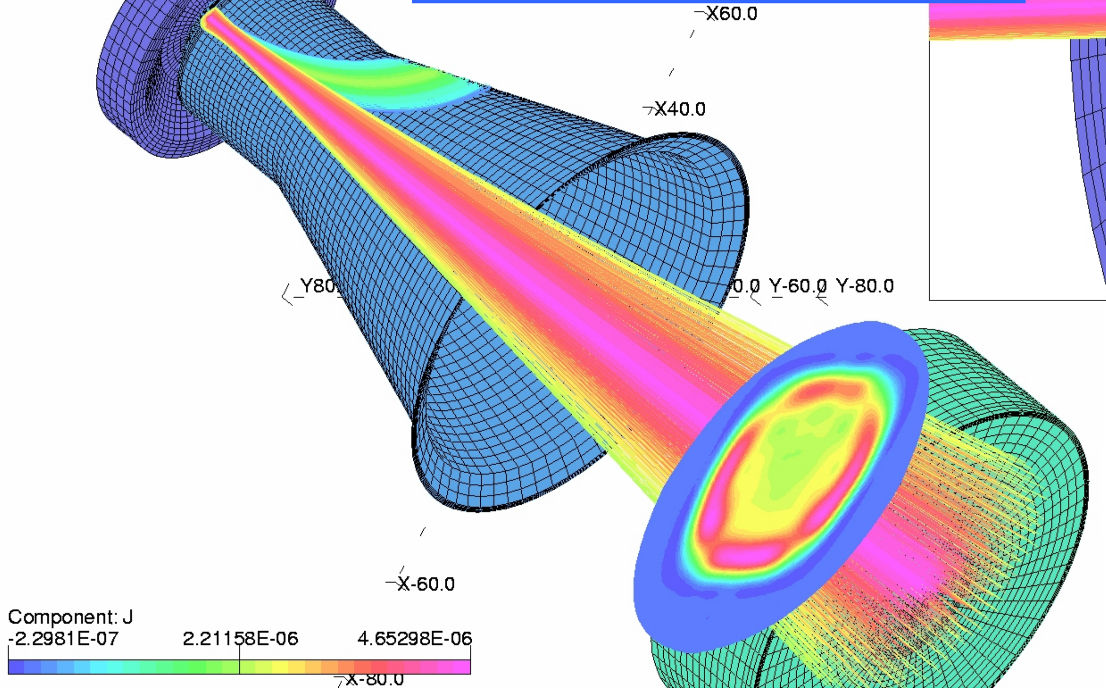
3 ring magnets simulation :

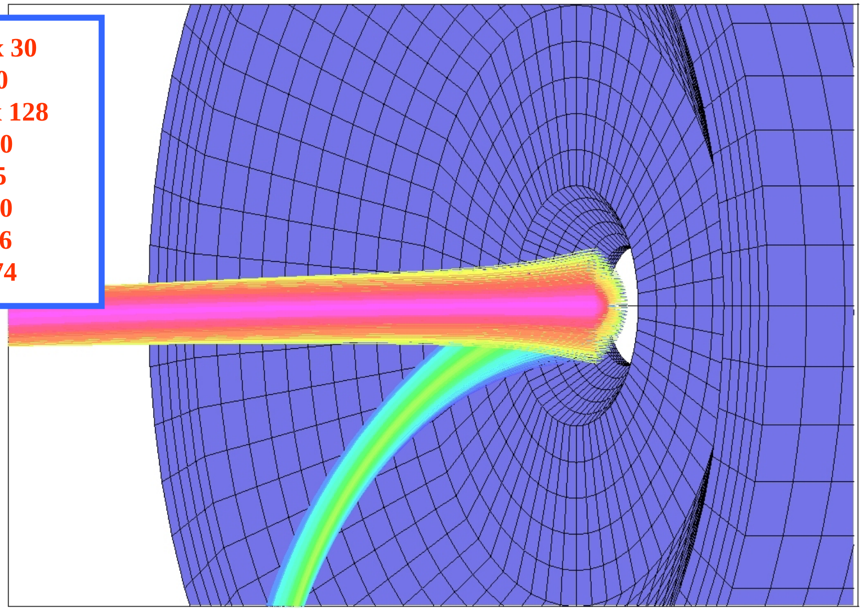
$$\frac{\Delta B}{B} \leq 3.10^{-2}$$

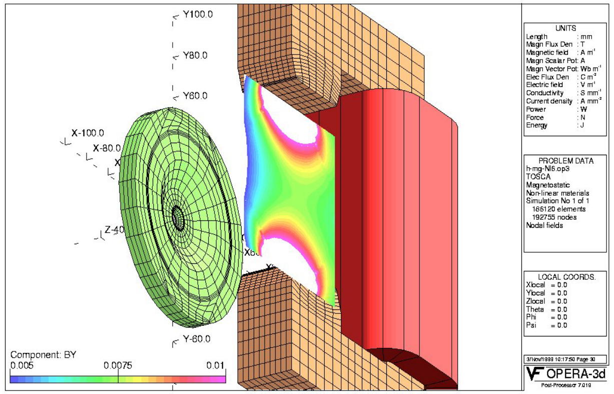
Ion source magnets : H$^-$ / e$^-$ separation at extraction

TOSCA©
&
SCALA©
simulations

Pôles dimensions	X,Z (mm)	**20 x 30**
Gap	g(mm)	**90**
Conductor section	A,B (mm)	**15 x 128**
Amperes-turns	NI(At)	**720**
Peak field on axis	By_{max}(Gauss)	**75**
Field Integrale	$\int B_y.dz$ (Gauss.cm)	**100**
Iron volume	V(cm^3)	**476**
Magnetic circuit weight	P(kg)	**3.74**

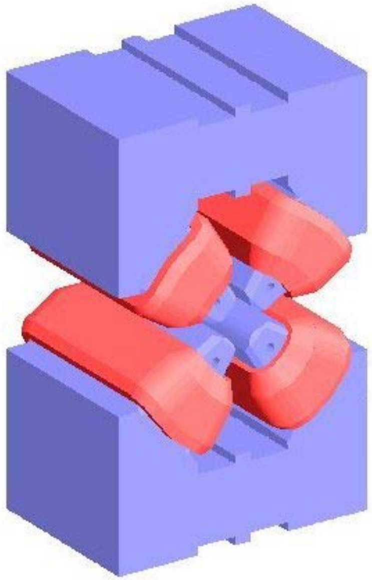






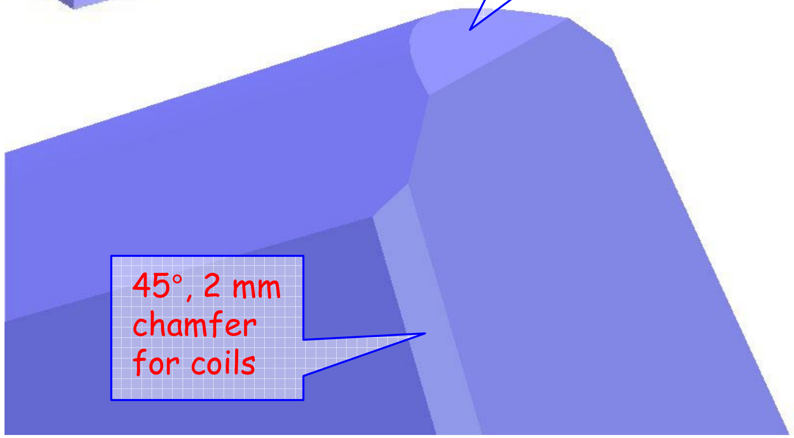
Beam line resistive magnets :

Quadrupole for SOLEIL storage ring

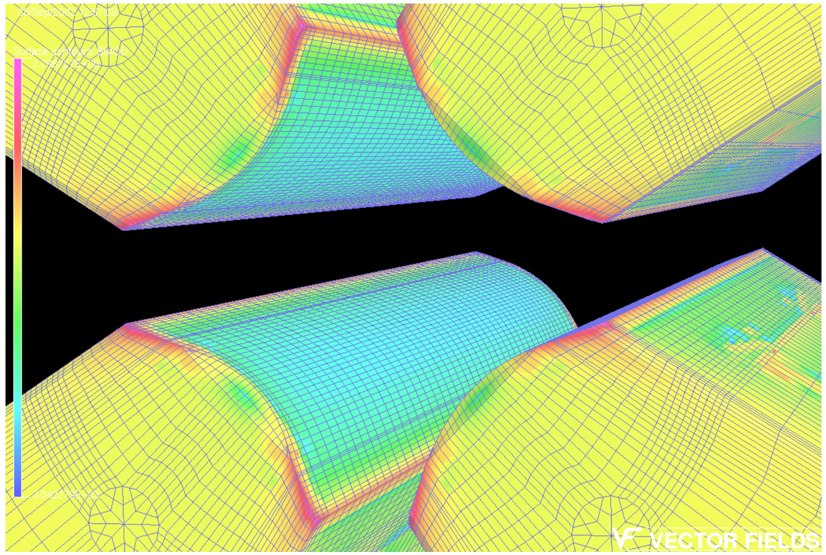


Optimization of 45° chamfer depth to reach 2.10^{-4} **$\int Bdl$** tolerance

45°chamfer :
QP short : 4.6 mm
QP long : 5.0 mm



Quadrupole type	Figure of 8	
	Long	Short
Bore diameter	Φ 66 mm	Φ 66 mm
Tolerance on $\int Bdl$	$2.\ 10^{-4}$	$2.\ 10^{-4}$
Current density	3.5 A/mm^2	2.75 A/mm^2
Amperes-turns	10675. At	8692. At
Nominal gradient	23 Tm^{-1}	19 Tm^{-1}
Iron length	460 mm	320 mm
Magnetic length	480.6 mm	349.4 mm

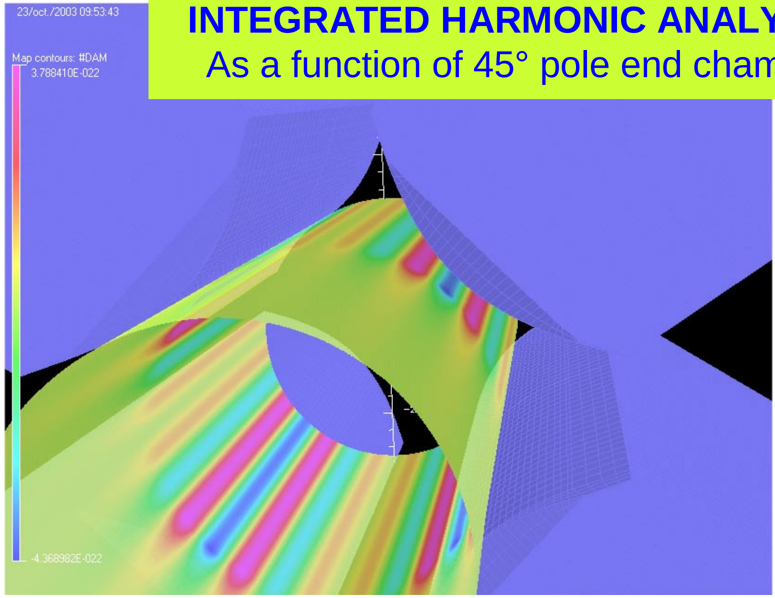


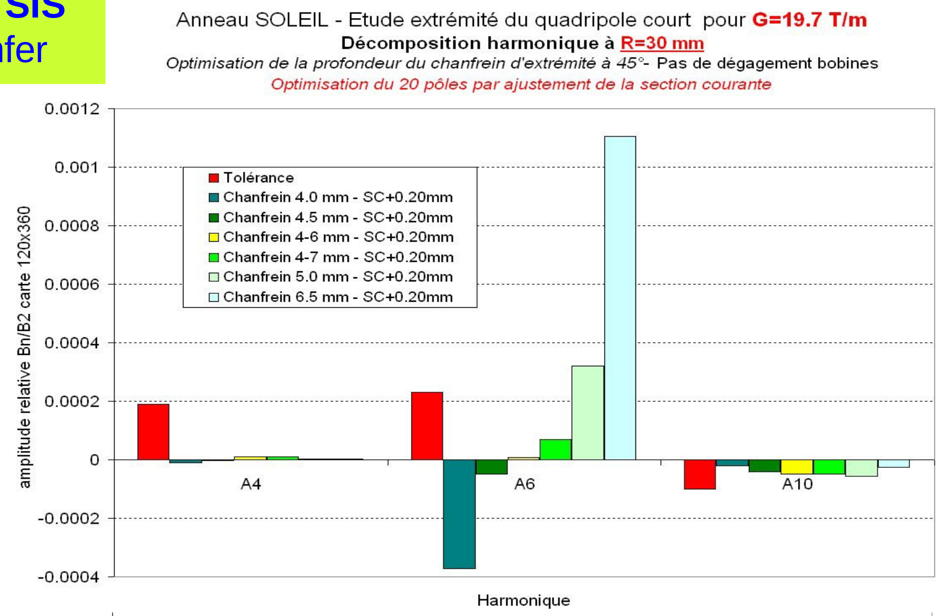
Beam line resistive magnets :

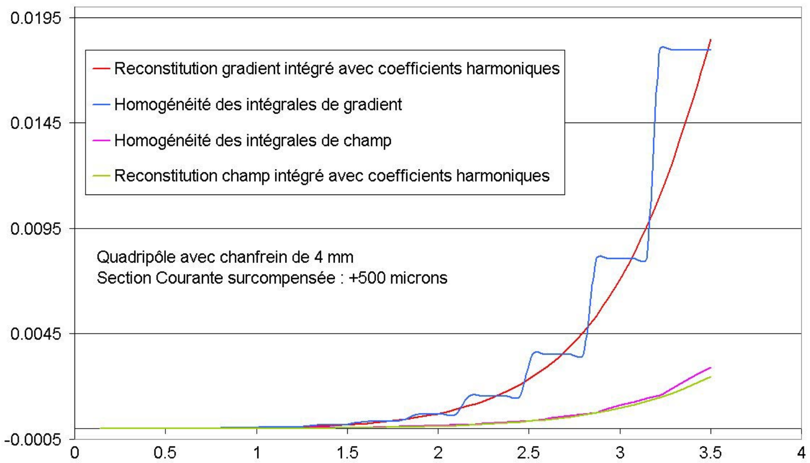
$$A_n = \frac{1}{\pi r^n 2L_m} \int_{-L}^{+L} \int_{0}^{2\pi} B_r(r,\theta)\sin(n\theta) r d\theta dz$$

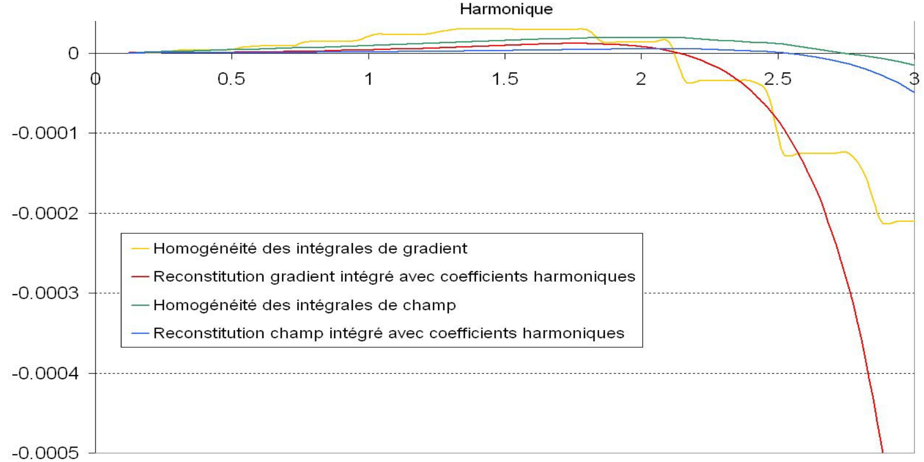
INTEGRATED HARMONIC DECOMPOSITION

INTEGRATED HARMONIC ANALYSIS
As a function of 45° pole end chamfer









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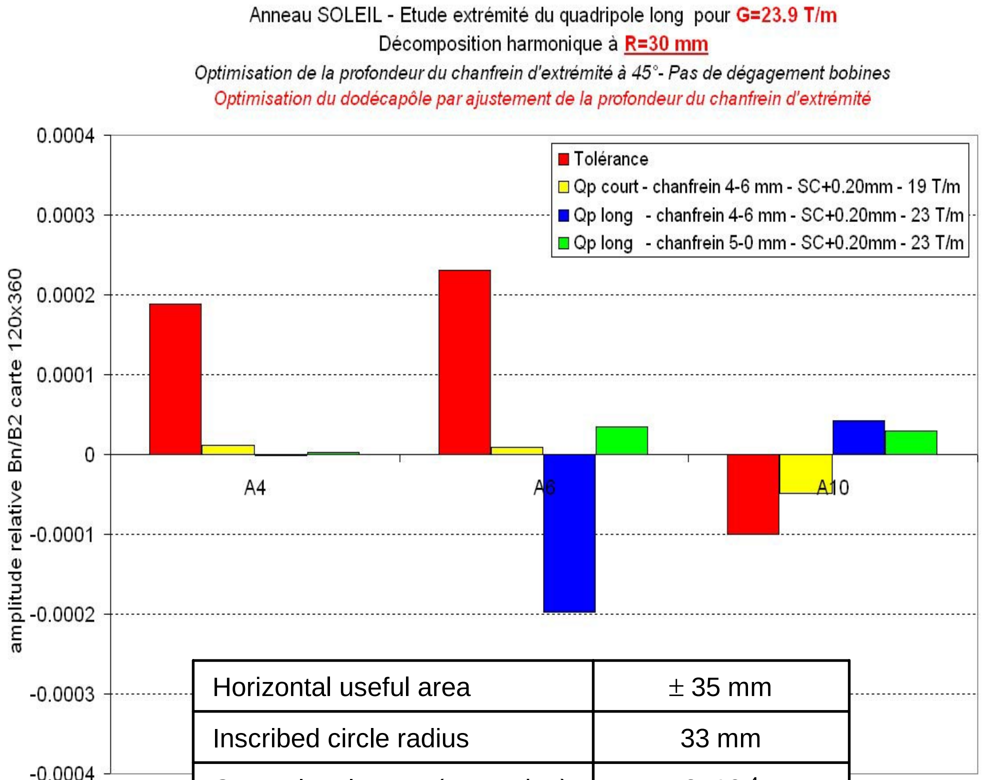
Beam line resistive magnets :

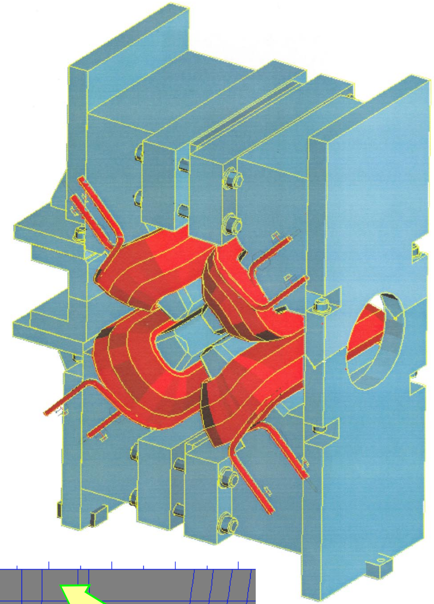
SOLEIL SYNCHROTRON

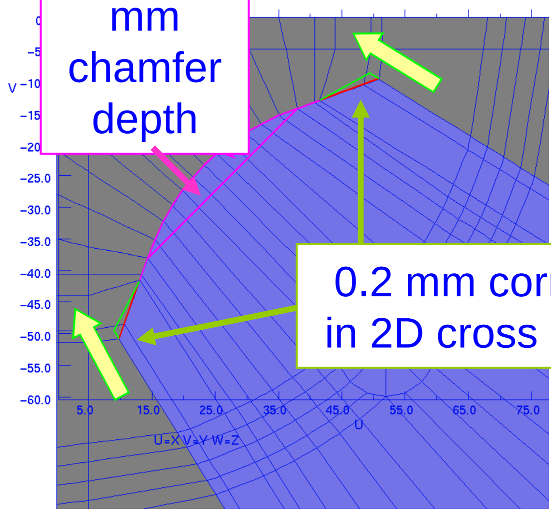
INTEGRATED HARMONIC DECOMPOSITION for SHORT AND LONG QUADRUPOLES



Horizontal useful area	± 35 mm
Inscribed circle radius	33 mm
Octupole tolerance(saturation)	$3.\ 10^{-4}$
Dodecapole tolerance	$5.\ 10^{-4}$
"20 poles" tolerance	$-3.\ 10^{-4}$
Gradient short QP / long QP	$19\ T.m^{-1}/23\ T.m^{-1}$

OPERA-3D
Modeling
&
TOSCA
Simulation

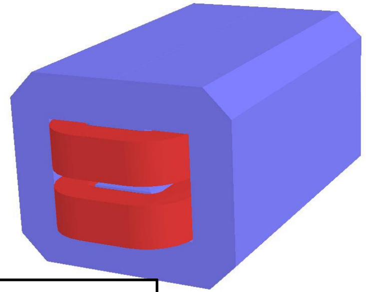




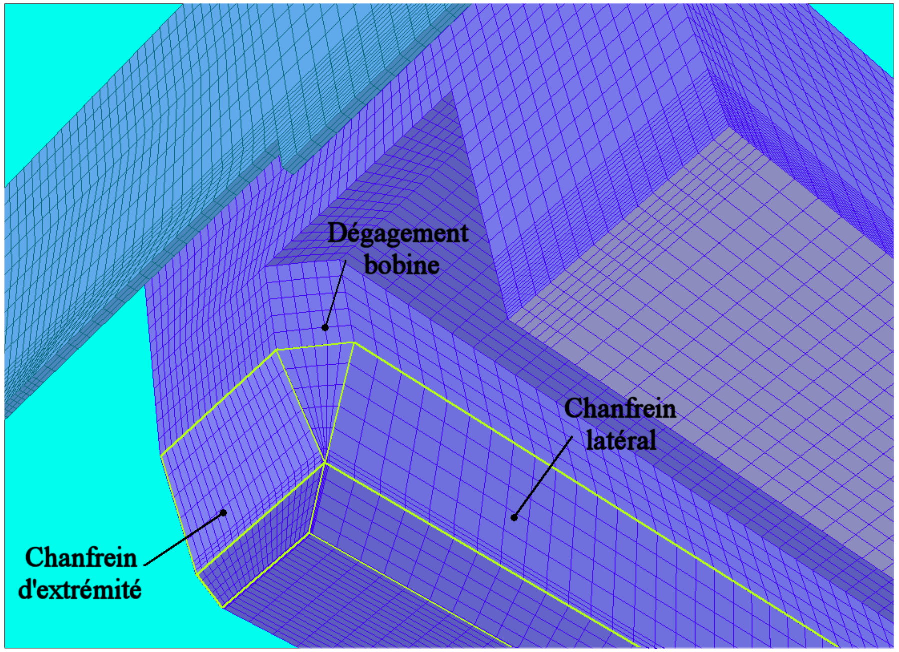
45°, 4.6-5.0 mm chamfer depth

0.2 mm correction in 2D cross section

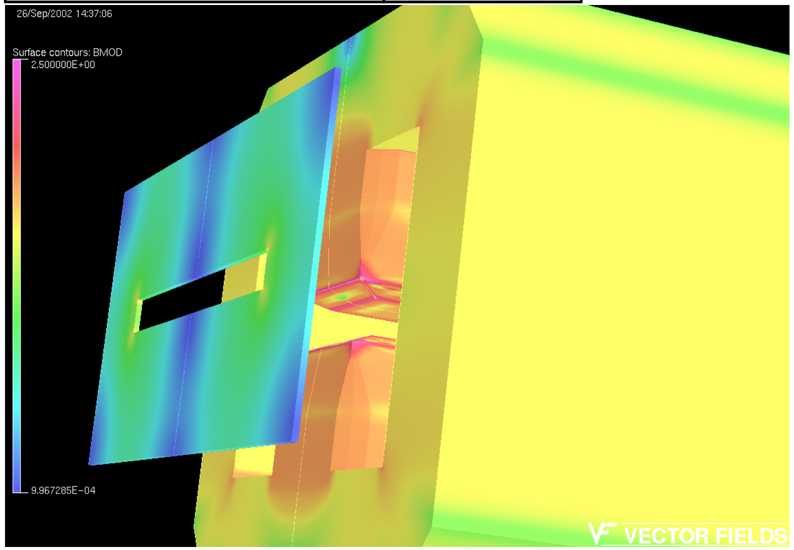
Beam line resistive magnets :



A straight H-shaped dipole for SOLEIL storage ring



Useful transverse area	± 20 mm
Air gap	37 mm
Nominal field	1.71T
Tolerance on ∫B*dl*	5. 10^{-4}
Magnetic length	1052.434 mm
Iron length	1050.74 mm
Ampere-turns nominal	26750. At
Nominal current density	2.1 A/mm^2
Maximum field	1.76 T
Maximum current density	2.35 A/mm^2
Ampere-turns maximum	29940. At



SOLEIL dipole

New study after 1st APD

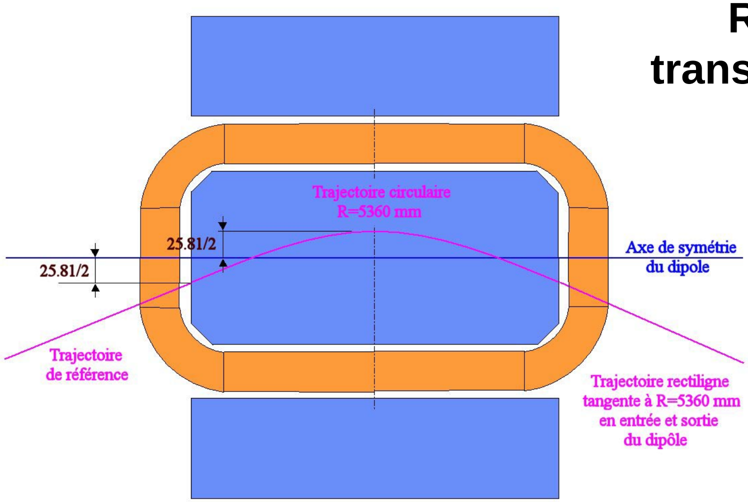
H-shaped and straight

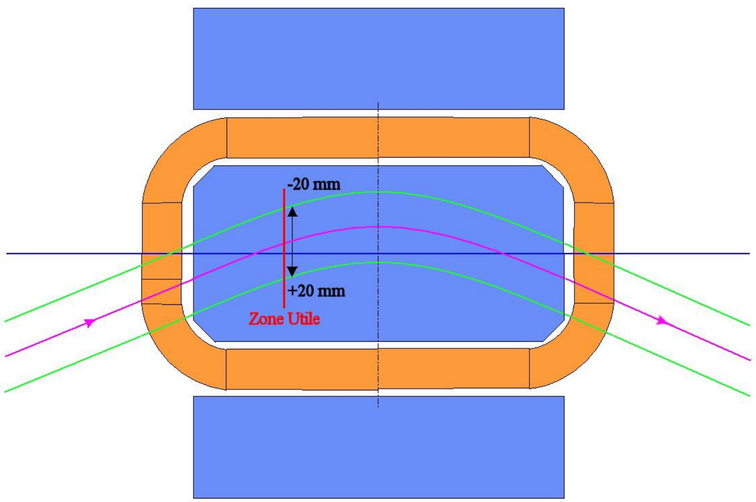
@**1.71** Tesla (up to 1.76)

Beam line resistive magnets :

A straight H-shaped dipole for SOLEIL storage ring

Reference trajectory and transverse section definition



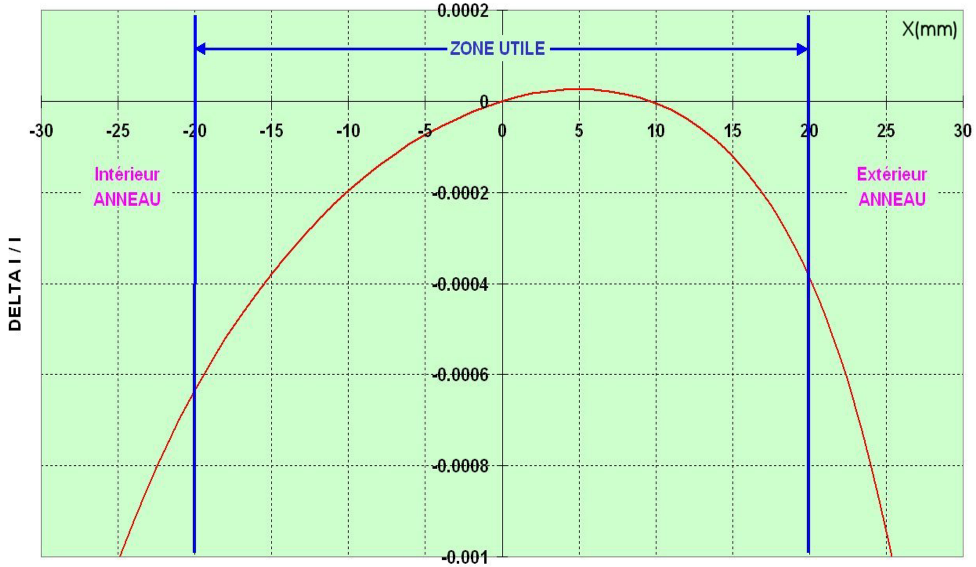


Optimization results :

Transverse integral field homogeneity

$$\frac{\int Bdl - \int B_0 dl}{\int B_0 dl} \leq 5.10^{-4}$$

HOMOGENEITE DES INTEGRALES DE CHAMP du dipôle anneau SOLEIL
Packing factor 0.98 - courbe B(H) ESRF
plaque de garde 6 mm à 129 mm du pôle - chanfrein d'extrémité 13.5 mm / 26.5 mm
NI=26750 At - B_0=17131 Gauss



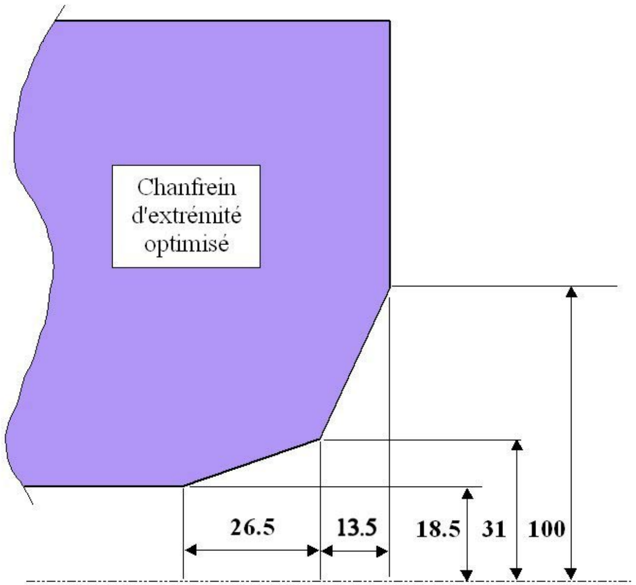
Beam line resistive magnets :

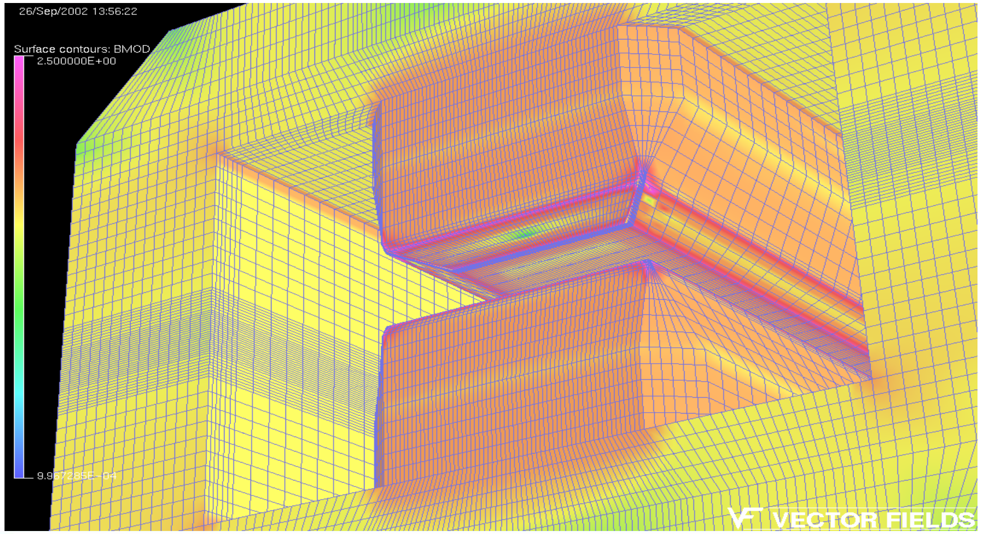
A straight H-shaped dipole for SOLEIL storage ring

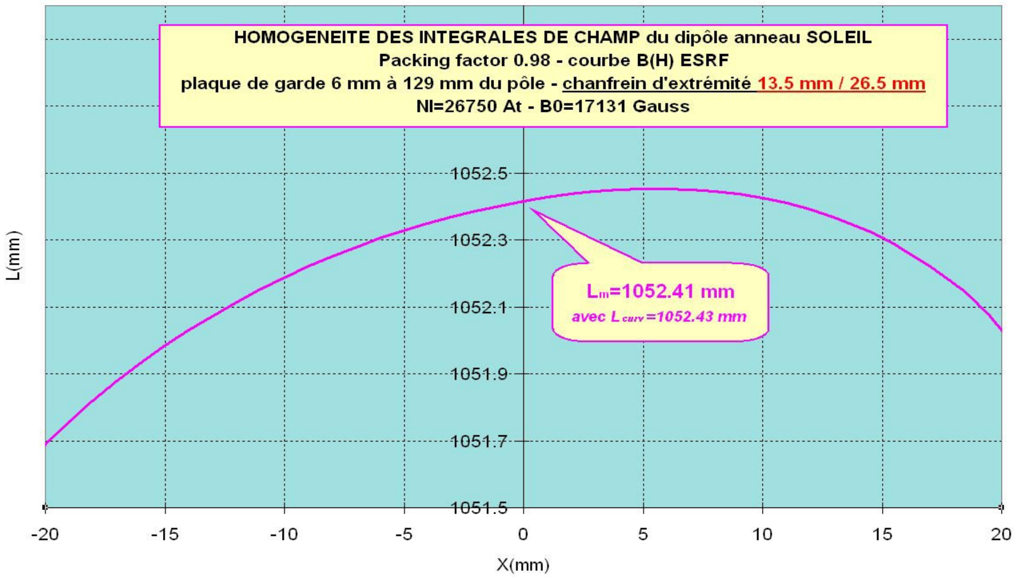
Optimization results :
Double chamfer pole end shape optimization

Magnetic length adjusted to electron path in iron

Lm=1052.41 mm







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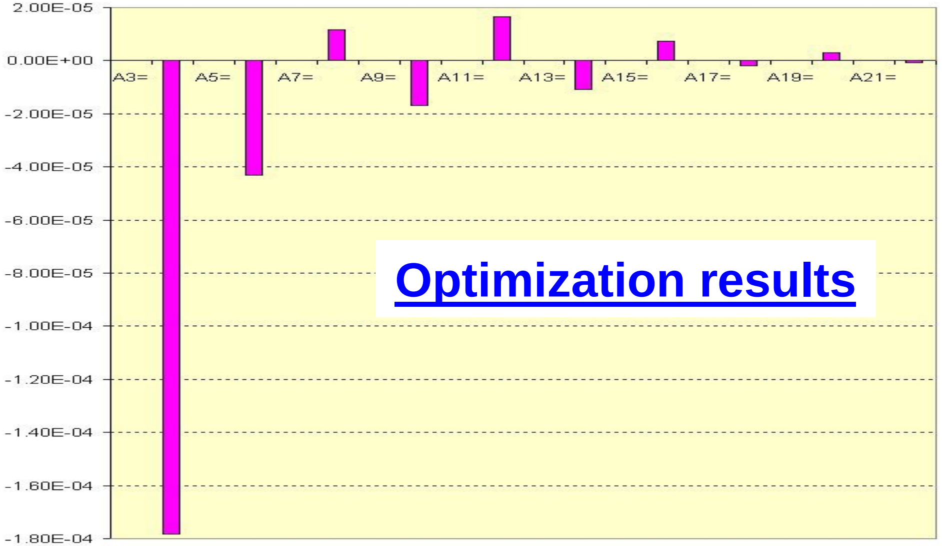
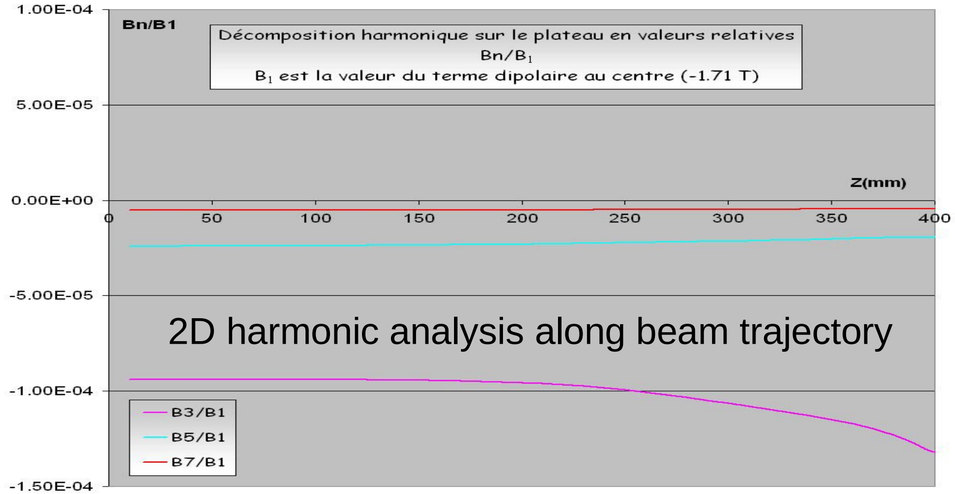
Beam line resistive magnets :

A straight H-shaped dipole for SOLEIL storage ring

Optimization results





2D harmonic analysis along beam trajectory

INTEGRATED HARMONIC ANALYSIS

Terme multipolaire	Coefficient A_n	Valeur B_n (Tesla)	Relatif B_n/B_2
A1	-1.713678982	-1.713678982	1.00E+00
A2	-4.73405E-17	-8.04789E-16	4.70E-16
A3	1.05656E-06	0.000305345	-1.78E-04
A4	7.69614E-17	3.78111E-13	-2.21E-13
A5	8.82767E-10	7.37296E-05	-4.30E-05
A6	5.40157E-18	7.66946E-12	-4.48E-12
A7	-8.24451E-13	-1.99002E-05	1.16E-05
A8	6.28333E-21	2.57829E-12	-1.50E-12
A9	4.14966E-15	2.89471E-05	-1.69E-05
A10	5.46909E-23	6.48568E-12	-3.78E-12
A11	-1.39621E-17	-2.81475E-05	1.64E-05
A12	-4.88147E-27	-1.67297E-13	9.76E-14
A13	3.15013E-20	1.83533E-05	-1.07E-05
A14	6.4772E-28	6.4154E-12	-3.74E-12
A15	-7.39219E-23	-1.24468E-05	7.26E-06
A16	-8.56109E-31	-2.45055E-12	1.43E-12
A17	6.7188E-26	3.26945E-06	-1.91E-06
A18	1.57638E-33	1.30405E-12	-7.61E-13
A19	-3.70321E-28	-5.20786E-06	3.04E-06
A20	-8.27391E-36	-1.97806E-12	1.15E-12
A21	3.12201E-31	1.26886E-06	-7.40E-07

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Beam line resistive magnets :

A straight H-shaped dipole for SOLEIL storage ring

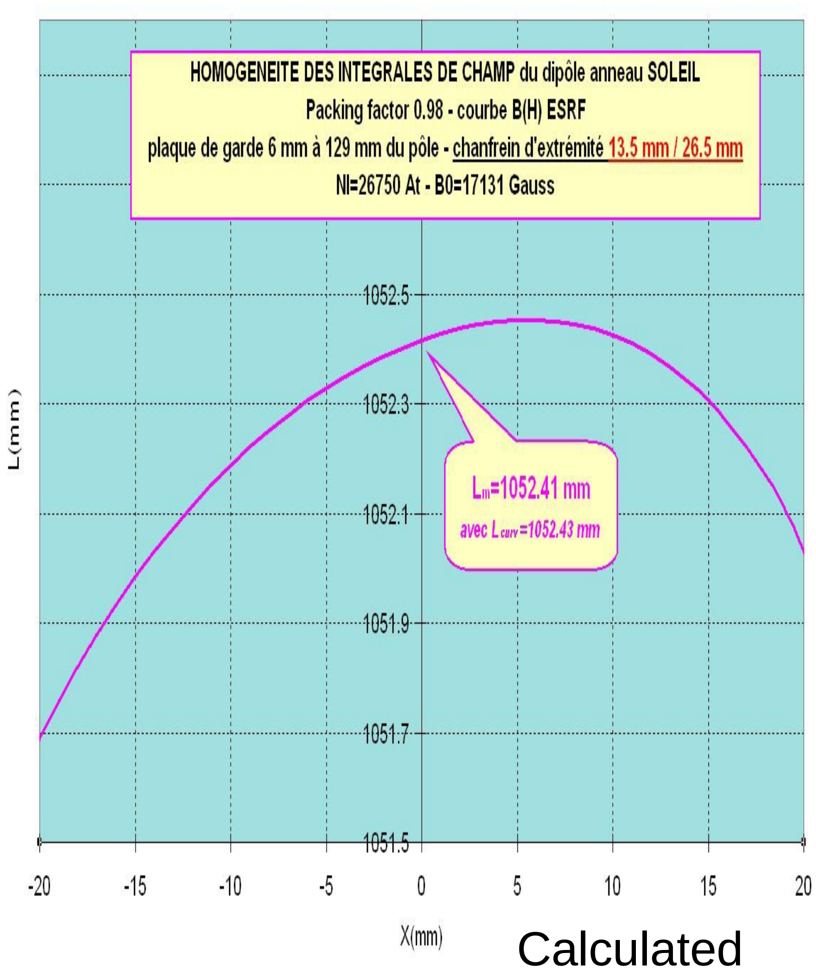
SACM/LEDA in charge of magnet simulation in ***SOLEIL*** collaboration but not in charge of Magnetic measurements and exploitation

Firsts *SOLEIL* Measurements

Intégration sur +/- 685 mm
Analyse multipolaire sur +/- 30 mm DB/B calculé à x = 30 mm

⚠ Obtained by polynomial fit on X-Z plane	Dipôle 1 Sigmaphi	Dipôle 1 BCH15 Mesure 1	Dipôle 1 BCH15 Mesure 2	Dipôle 2 BCH15	Dipôle 3 BCH15 Mesure 2	Dipôle 4 BCH15
Intégrale sur l'axe (T.m)	1.8111	1.8053	1.8064	1.8057	1.7995	1.8028
DB/B Quadrupôle	2.8 10-5	-4.5 10-5	8.3 10-6	1.0 10-5	-3.3 10-5	6.3 10-6
DB/B Sextupôle TOSCA : -1.78E-04	-4.5 10-4	-6.2 10-4	-5.0 10-4	-4.0 10-4	-4.4 10-4	-4.6 10-4
DB/B Octupôle	-2.2 10-6	6.3 10-5	2.0 10-5	-3.1 10-6	-1.3 10-5	8.9 10-6
DB/B Décapôle TOSCA : -4.30E-05	-3.7 10-4	-2.2 10-4	-3.0 10-4	-3.9 10-4	-3.6 10-4	-3.5 10-4

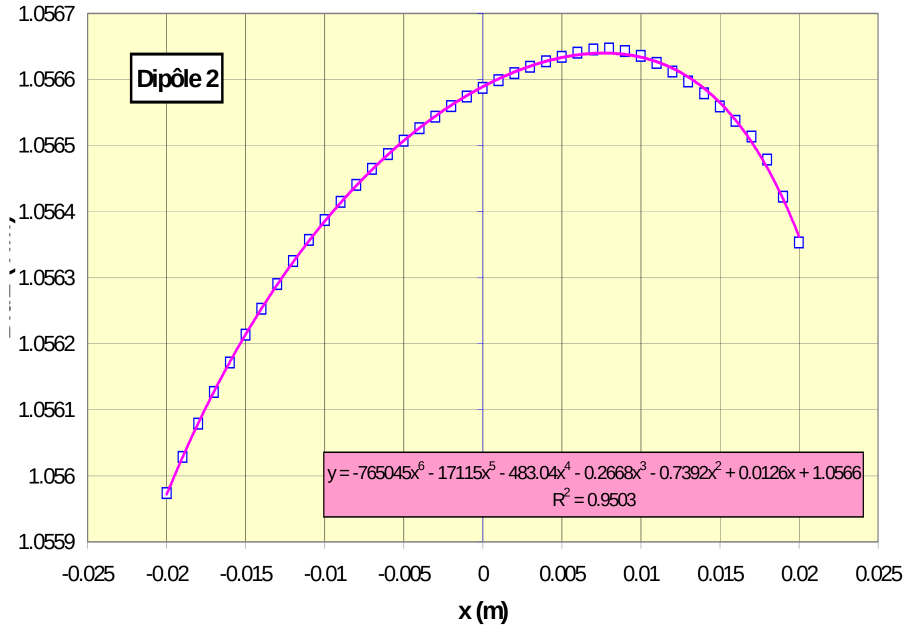
Magnetic length comparison between calculation and measurements



Calculated

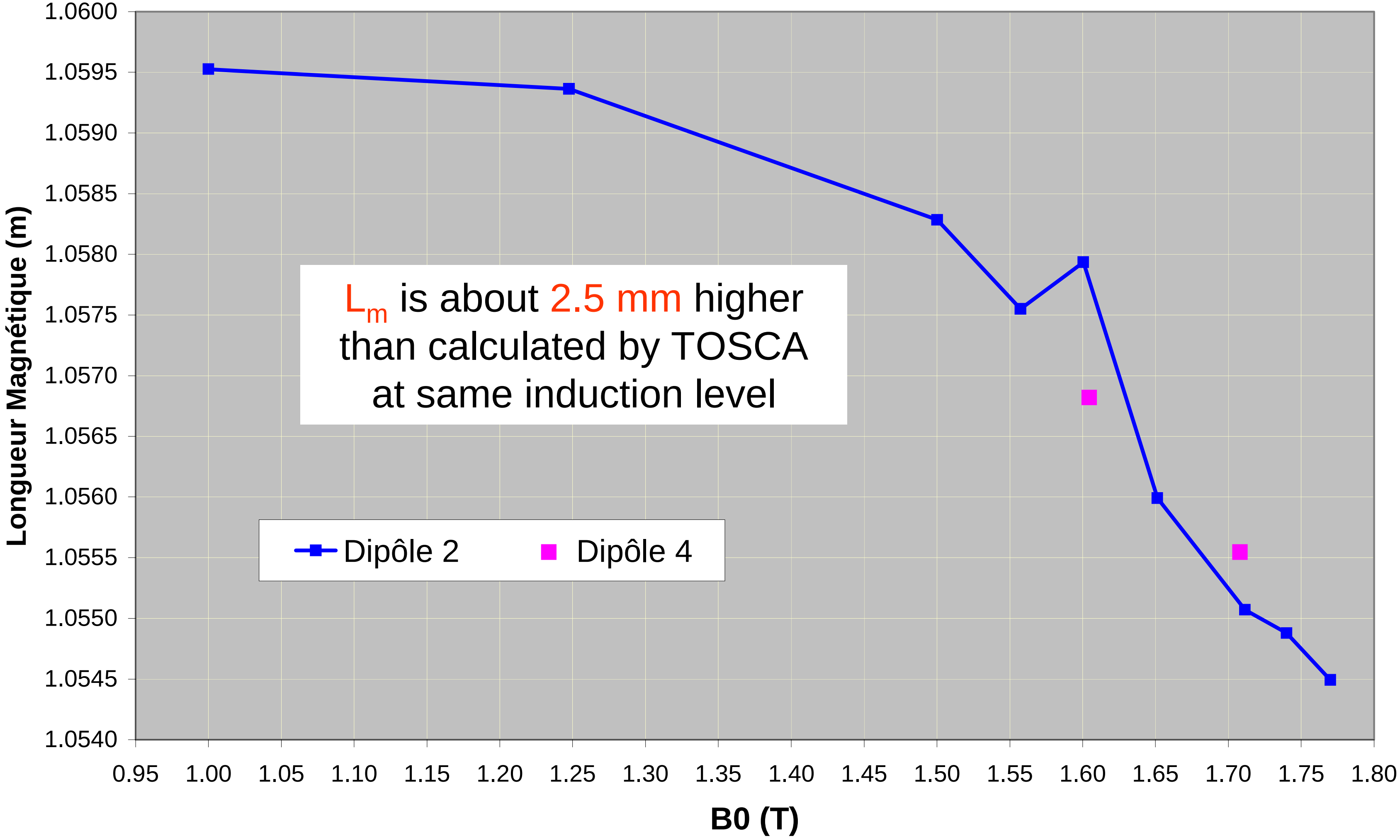
Dipole is shifted from beam axis by x = - 12.9 mm (half sagitta)

L_m longer than calculated

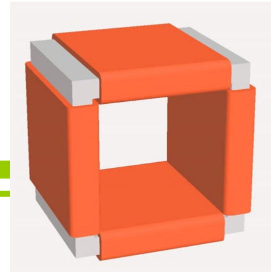


Measured

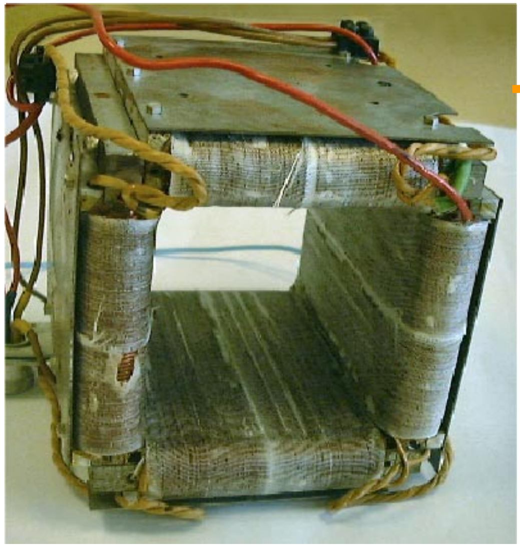
Firsts *SOLEIL* measurements on dipoles

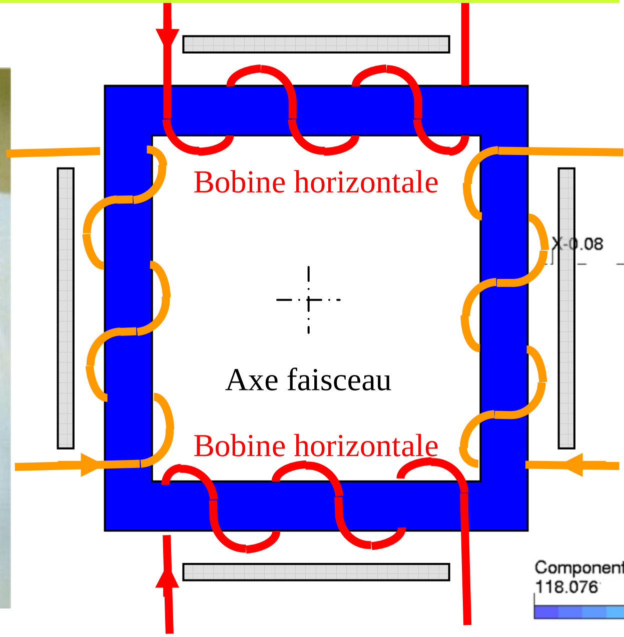


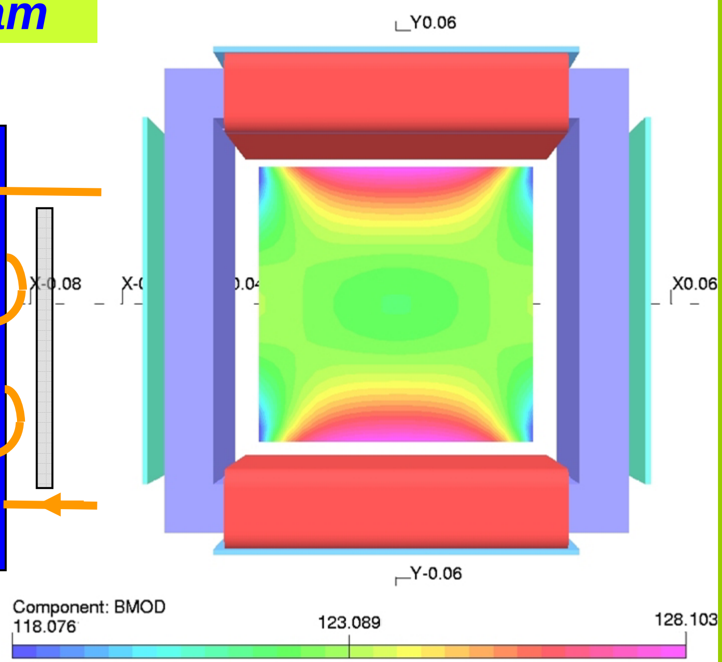
Magnets for correction or diagnostics :



An Horizontal+vertical dipole corrector for IPHI 100 mA CW @95 KeV H^+ ion beam





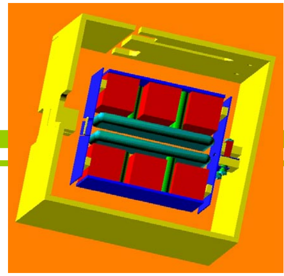


Pour un $B_{nominal}$ de 128 gauss			
Ampère tours par bobine	838 At	Longueur de cuivre par bobine	32.3 m
Densité de courant par bobine	3.54 A/mm^2	Courant par bobine	8.2 A
Surface de la bobine	236.8 mm^2	Tension par bobine	2.15V
Section du conducteur de 1.5mm	2.25 mm^2	Impédance d'une bobine	260 mΩ
Coefficient de foisonnement	6%	Puissance dans une bobine	17.6 W

$$\frac{\Delta B}{B} \leq 3.10^{-2}$$

$$\int B.dl = 18 \text{ Gauss.m}$$

Magnets for correction or diagnostics :

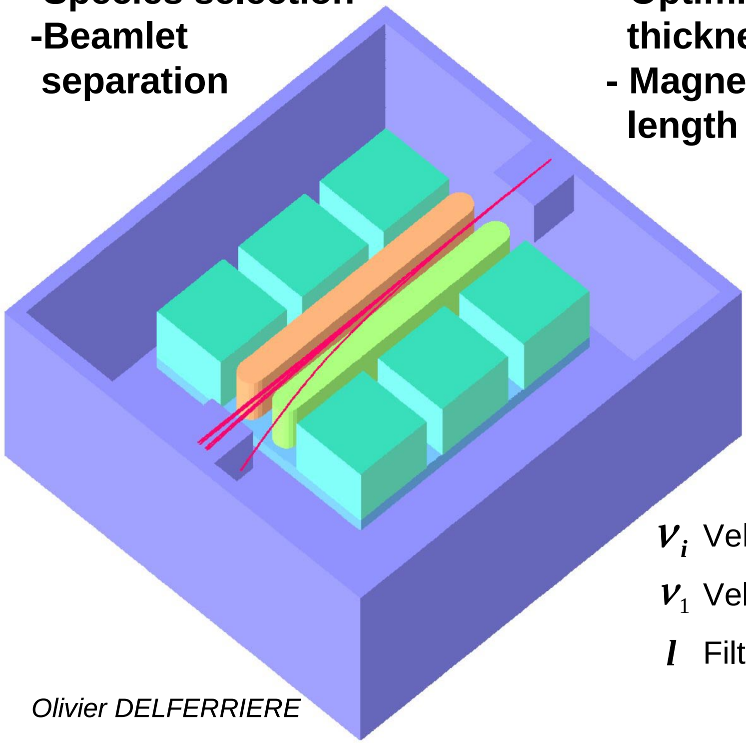


A Wien filter for H^+,H_2^+,H_3^+ separation of SILHI H^+ ion source and Emittance measurement

3D electric and magnetic simulation including trajectories calculation with ***OPERA-3D*** ***and TOSCA***

Trajectories calculation

- **-Species selection**
- **-Beamlet separation**



Electromagnetic simulation

- **Optimization of shielding thickness (weight)**
- **Magnetic and electric length adjustment**

$$F_{in} = K_{in} q B v_1$$

with

$$K_{in} = \frac{v_i - v_n}{v_1}$$

$$\alpha_{in} = \frac{v_1}{2V}(Bl)K_{in}$$

v_i Velocity of non-deviated ion

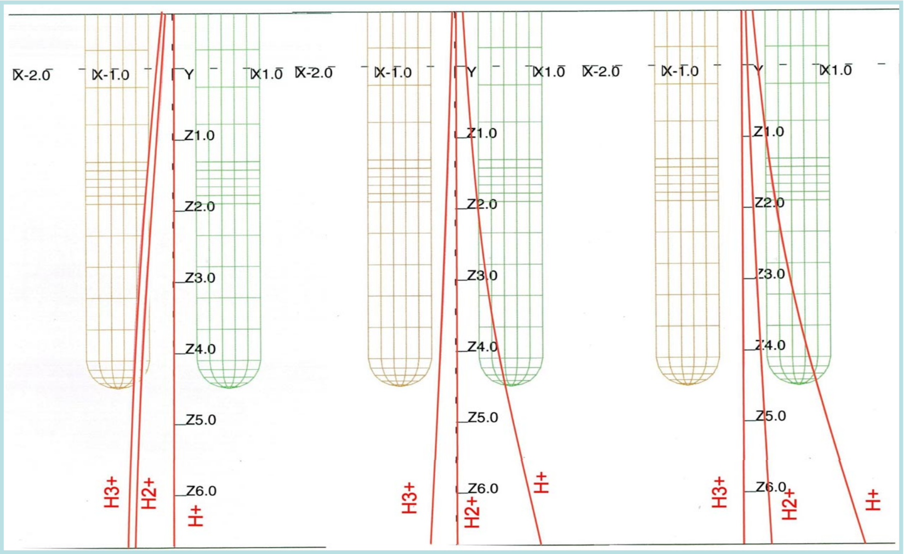
v_1 Velocity of H^+ ion

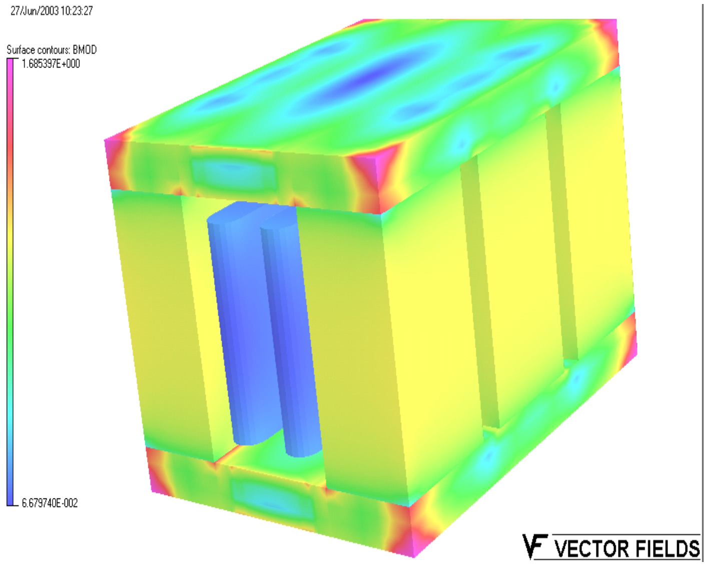
l Filter length

6 Permanent magnets	(mm)
Width	25
Length	26
Height	44
Gap between two units (beam direction)	6
Gap between two units (transverse plan)	30
Shielding	**(mm)**
Thickness (bottom box)	2
Thickness (else side)	4
Shim width	16
Shim height	36
Return shim length	10.5
Pole	**(mm)**
Thickness	5
Length	90
Width	70
Electrodes	**(mm)**
Thickness	8
Length	90
Width	36
Gap between two electrodes	6

Magnets for correction or diagnostics :

SILHI Wien filter for H^+,H_2^+,H_3^+ separation





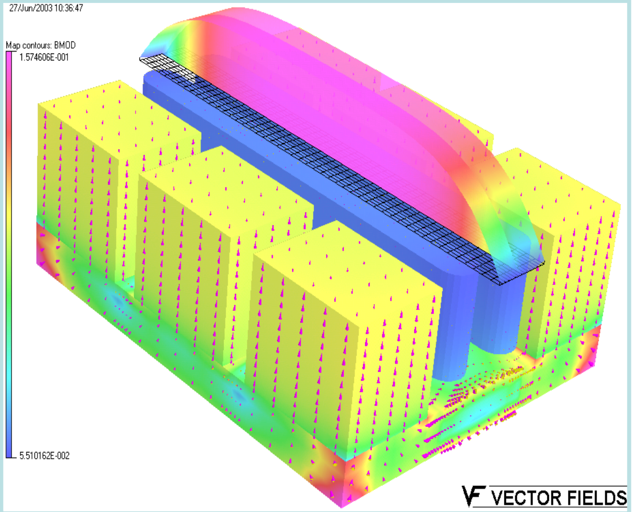
Electrical characteristic		Magnetic characteristic	
Power supply	± 3000 V	Magnetic material	NdFeBo
Maximum electric field	1 MV/m	H_c	H_c≥800 kA/m
Space between two plates	6 mm	B_r	B_r≥1.1 Tesla
Minimum separation angle	50 mrad	Magnetic field	0.1936 Tesla
Integrals $\int E.dl/E_0=\int B.dl/B_0$	0.9 m	Air-gap	44 mm

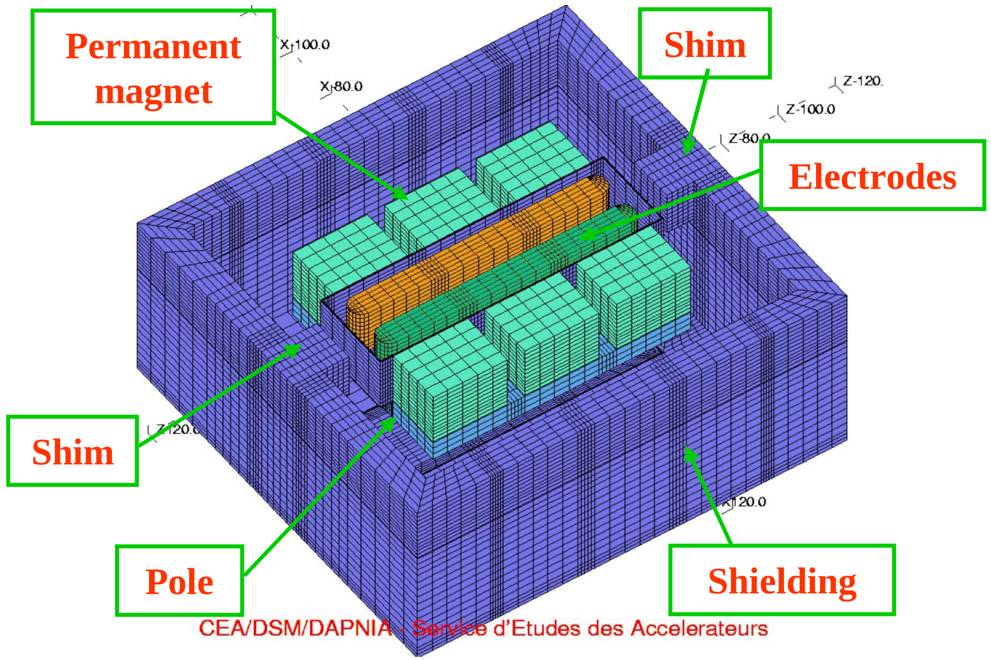
Electrode voltages :		Running parameters	
H^+_1 strait line	± 2820 V	Maximum energy	100 KeV
H^+_2 strait line	± 2000 V	Sampler hole	ϕ 0.4 mm
H^+_3 strait line	± 1613 V	Acceptance	$\pm 5.10^{-3}$ rad

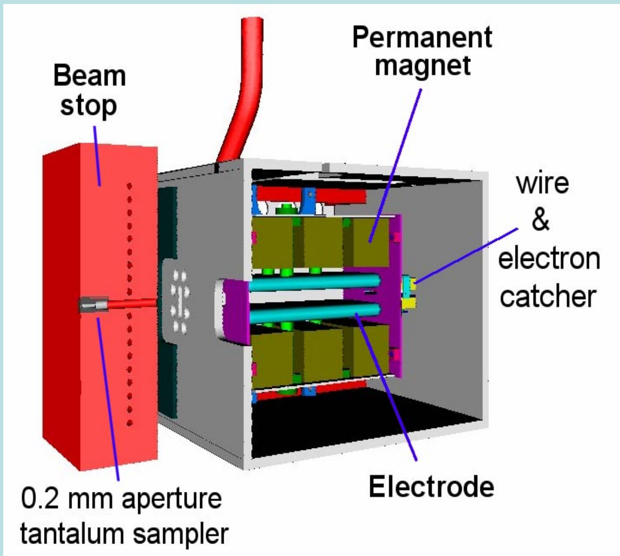
It is composed of a 0.2 Tesla window-frame magnet and 2 electrodes inside with adjustable voltage. The permanent magnets are separated in 6 blocs for better pumping and easier assembly. They are put between 2 iron plates (poles), and all the system is enclosed in an iron box for magnetic shielding. The magnetic length is adjusted by shimming at filter entrance and exit, and equal to the electric length.

Magnets for correction or diagnostics :

SILHI Wien filter for H^+, H_2^+, H_3^+ separation



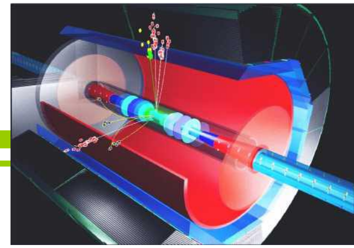




Emittance Measurement Unit device description

- 0.2 mm diameter tantalum sampler managed in a water cooled copper bloc
- permanent magnet Wien filter with adjustable electric field
- wire for beamlet intensity measurement
- Polarized plate in front of the wire minimizes the secondary electron effects
- The sampler crosses step by step (as low as 0.1 mm) the beam along a diameter by stepping motor
- Automatic procedures allow emittance measurements within less than few minutes

Coils for superconducting magnet :

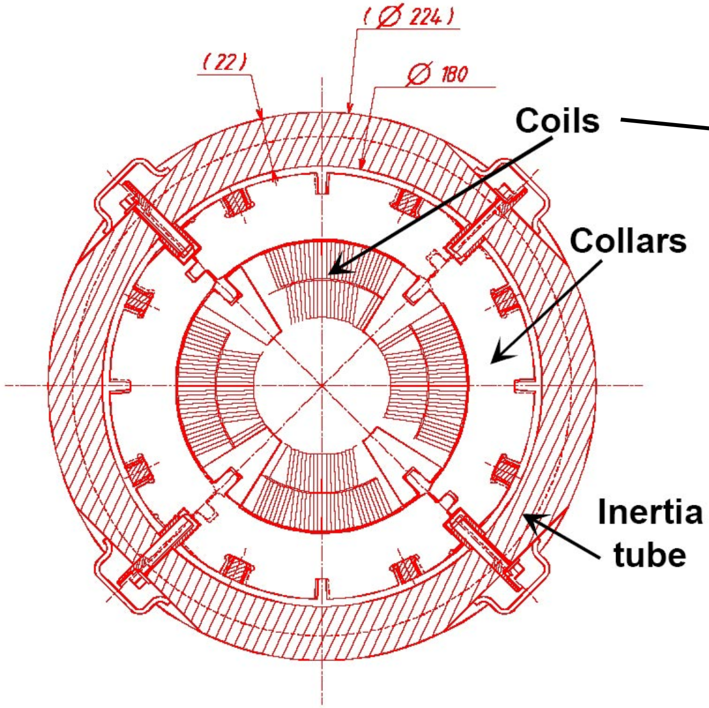


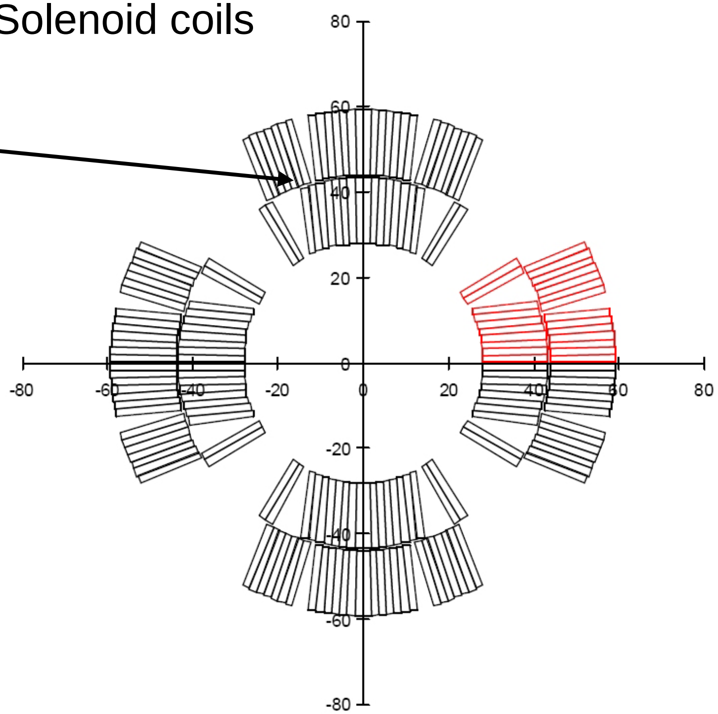
Nb_3Sn Final focusing quadrupole magnet for TESLA :

Preliminary conceptual magnet design for interaction region (e^+/e^-@250 Gev)
LHC-like quadrupoles + large solenoid

OPERA-3D/POST calculation:
- -Magnetic field
- -*Lorentz* forces

3D simulation of coils :
- -Quadrupole coils Including connections and transition between the 2 layers
- - + Solenoid coils

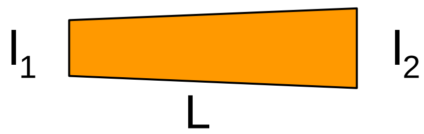


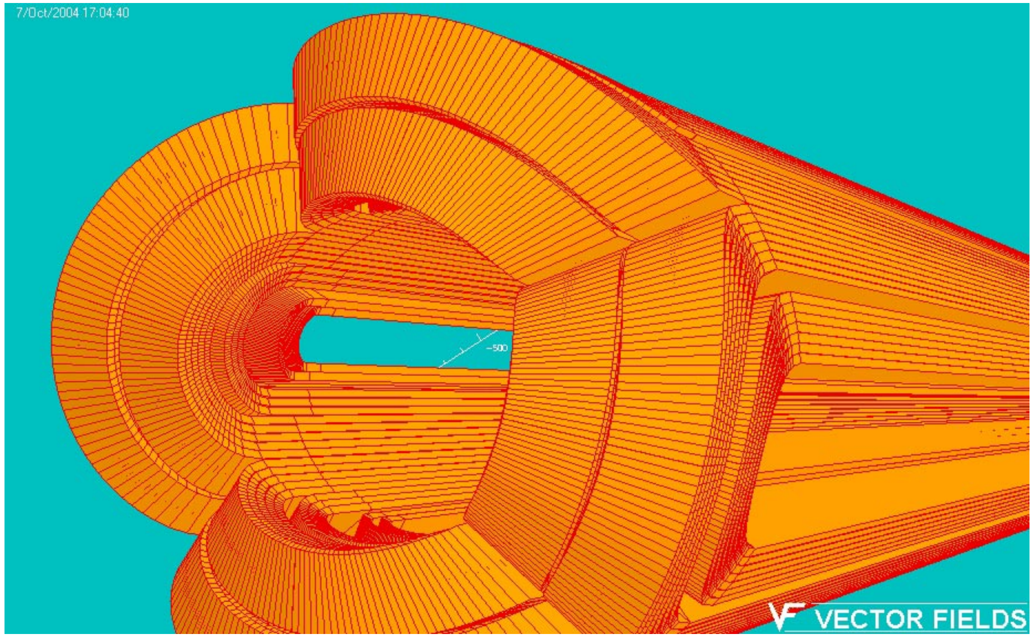


Coils for superconducting magnet :

Study of 1m long LHC-like Nb_3Sn quadrupole (250 $T.m^{-1}$) surrounded by RMN530 solenoid* (2 T)

Quadrupole field simulation





Cable cross section :

36 x 0.25mm strands
Minor edge l_1=**1.362** mm
Major edge l_2=**1.598** mm
Width L=**15.1** mm

One coil simulation :

2861 8-node BRICKS (OPERA-3D conductors)

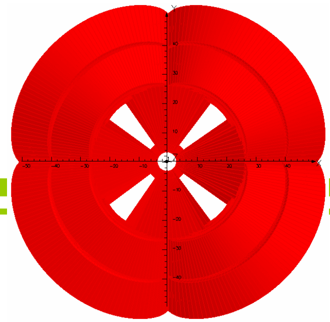
- Node coordinates of each cross section are converted into conductor file (*.cond*) by external interface program
- Conductors are loaded by *.comi* files into OPERA-3D

Quadrupole calculation :

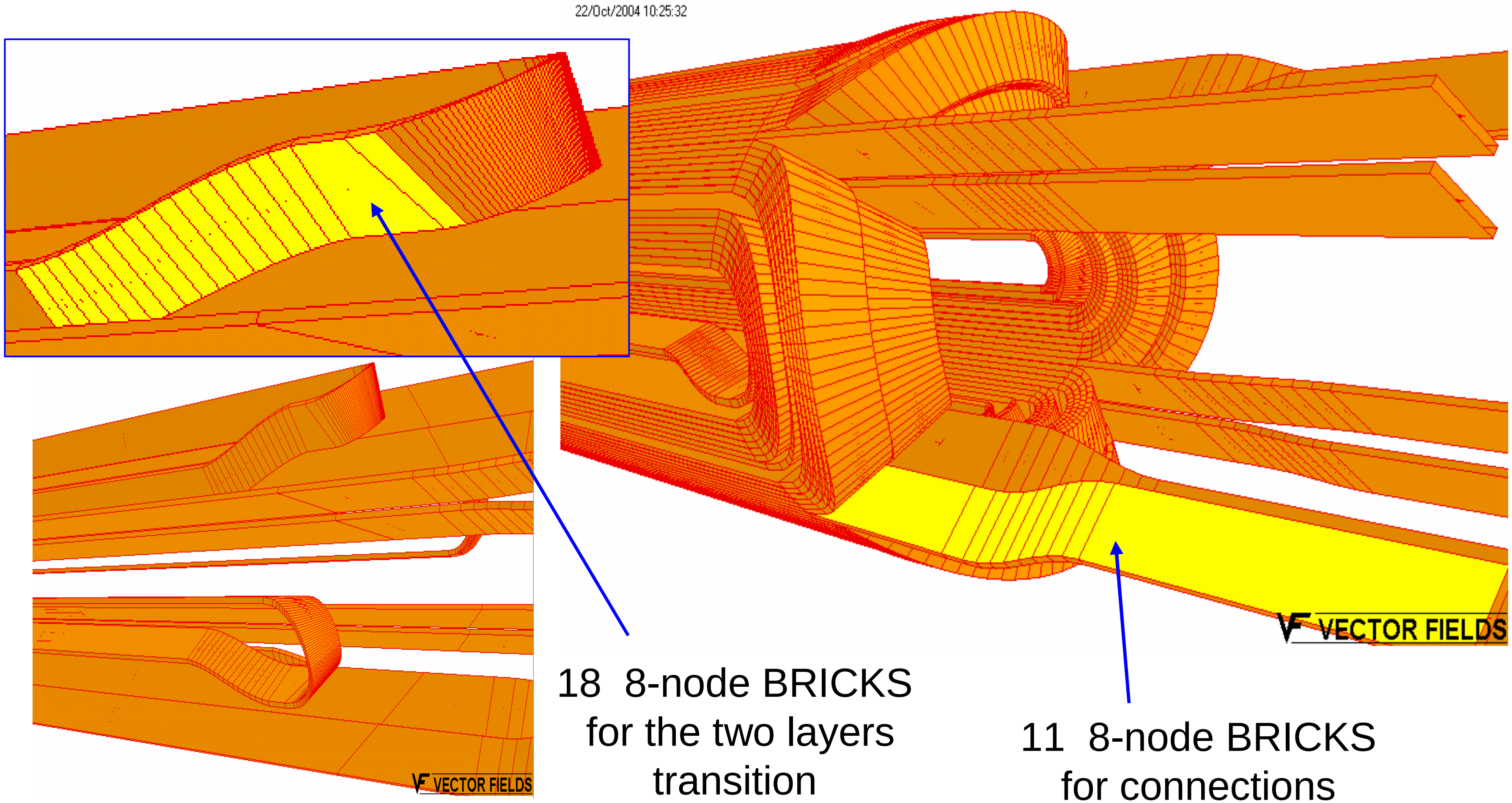
Replication by rotation

* Large superconducting magnet build by CEA for NMR spectroscopy studies on humans at ORSAY hospital - *France*

Coils for superconducting magnet :



Nb_3Sn quadrupole (250 $T.m^{-1}$) ***Quadrupole field simulation***

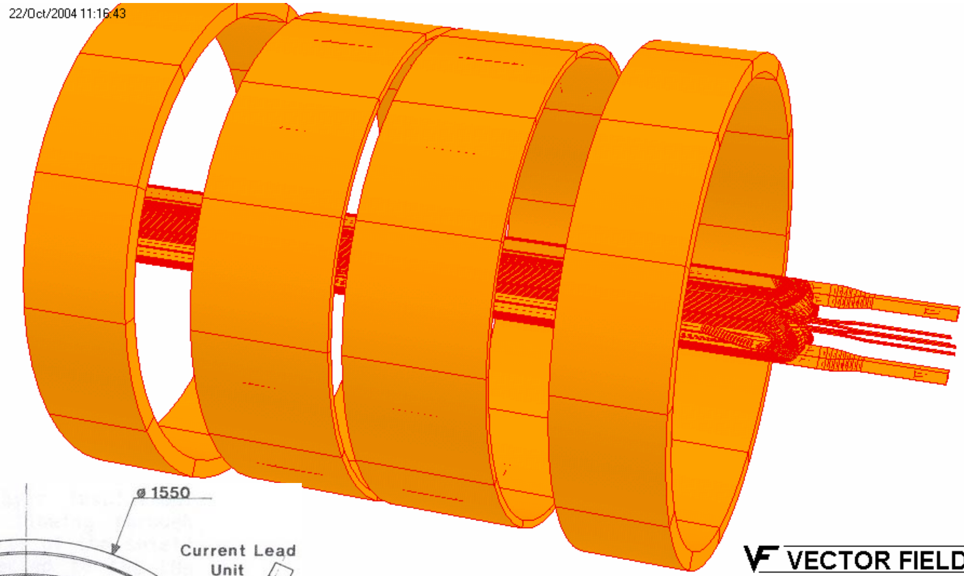


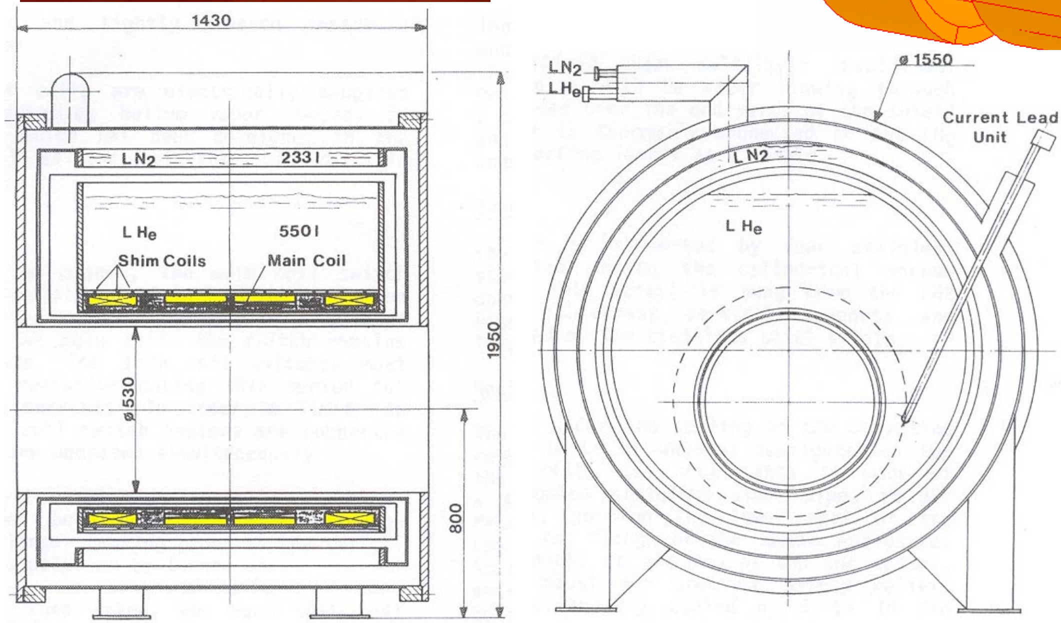
18 8-node BRICKS
for the two layers
transition

11 8-node BRICKS
for connections

Coils for superconducting magnet :

RMN530
Solenoid
(2 T)





RNM530 solenoid with
Nb_3Sn quadrupole inside

- Main coil parameters

SECTIONS :	central	lateral
Winding diameter mm	670	670
Axial length mm	200	155
Center position mm	110	377
Turn number	1904	3570

Central field	2 T
Peak field	3,7 T
Rated current	200 A
Inductance	45 H

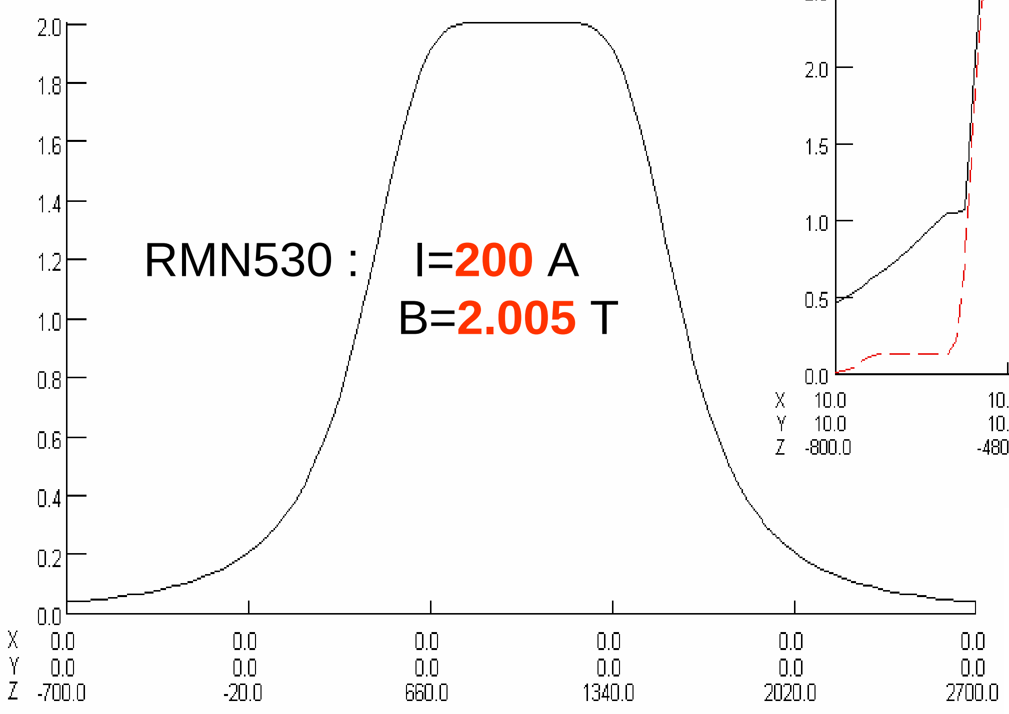
Coils for superconducting magnet :

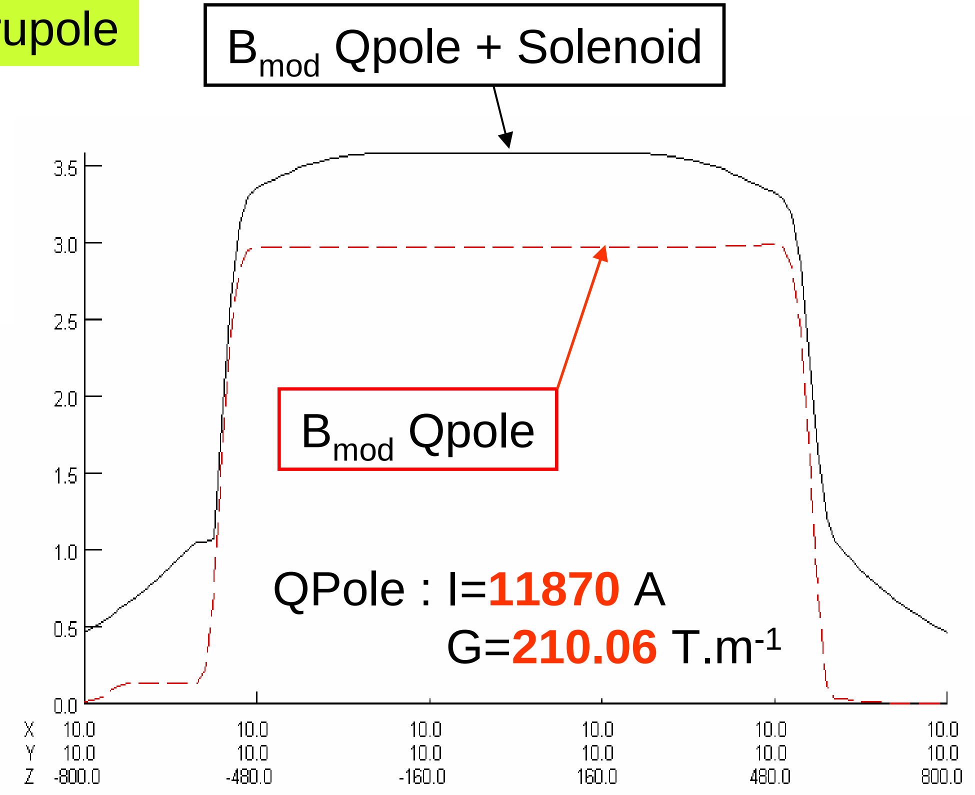
RMN530 Solenoid + Nb3Sn Quadrupole

Field calculation results

Solenoid simulation

Field B_z on axis





Quadrupole simulation

Field B_{mod} off axis at :

X=10 mm

Y=10 mm

Coils for superconducting magnet :

Calculation of forces in conductors : $F = \int J \wedge B.d\tau$

Typical post-processing results : *Lorentz* force components at each centroid of each cross section of each 8-node brick conductor

```
At 30.6175925  18.3454225  -515.383854 force = 96.5374942596389  -97.950520904347  -19.630795677998
At -18.3454225 30.6175925  -515.383854 force = 90.6077490163124  103.110091884179  -19.105527790665
At -30.6175925 -18.3454225 -515.383854 force = -96.537494259639  97.9505209043473  -19.630795677998
At 18.3454225  -30.6175925 -515.383854 force = -90.607749016313  -103.11009188418  -19.10552779066
Total force on coil     2 = -3.6948E-13  -1.4211E-13  -77.4726469 N
Total torque on coil     2 = -8.1855E-11  1.72804E-10  -19221.6599 Nmm
At 30.22806     19.00907875 -517.606129 force = 105.986311273746  -118.31202192674  -80.692035056847
At -19.0090787 30.22806     -517.606129 force = 95.2518995281092  136.204169473935  -78.561775989032
At -30.22806    -19.0090787 -517.606129 force = -105.98631127375  118.31202192674   -80.692035056847
At 19.00907875 -30.22806    -517.606129 force = -95.251899528109  -136.20416947394  -78.561775989033
Total force on coil     3 = -3.8369E-13  -3.6948E-13  -318.507622 N
Total torque on coil     3 = -1.2733E-10  1.54614E-10  -22549.6294 Nmm
```

Because each conductor has a rotational symmetry (-4)

Lorentz forces calculation is done automatically using *.comi* file with **OPERA-3D/PostProcessor**

Then results are transferred to
3D mechanical program, CASTEM (CEA code),…
to optimize all the mechanical assembly of the magnet

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Coils for superconducting magnet :

Command file *.comi* for *Lorentz* forces calculation

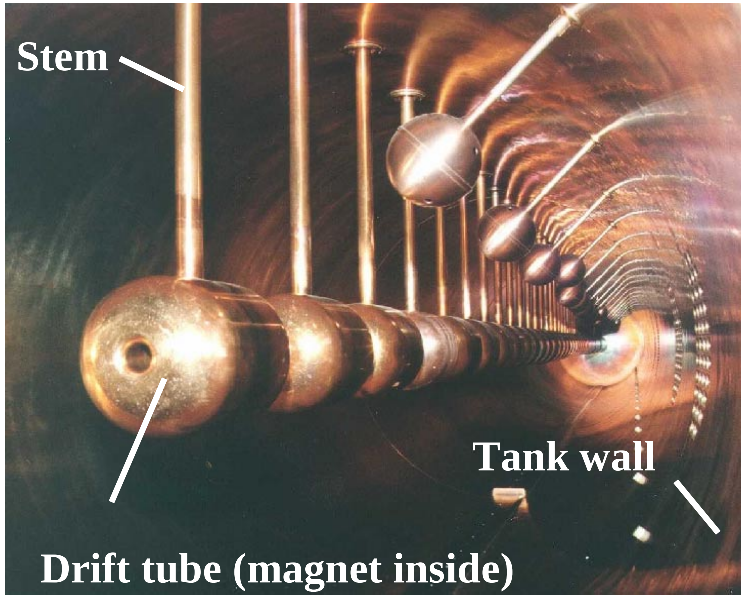
```
/calcul Forces de Lorrentz
/O. Delferriere
/----------------------------
$os rm Force-Lorrentz.dat
$os rm bobine-qpole.cond
COLOUR OPTION=LOAD LABEL=Background
COLOUR OPTION=SET RED=255 GREEN=255 BLUE=255
COLOUR OPTION=LOAD LABEL=Text
COLOUR OPTION=SET RED=0 GREEN=0 BLUE=0
WINDOW AXES=NO
$FORMAT 1 expo 12
$FORMAT 2 STRING 2 STRING=' '
$FORMAT 7 STRING 41 STRING='Force de Lorrentz au CDG du conducteur n°'
/
$open 3 Force-Lorrentz.dat WRITE
/
UNIT LENG=MM FLUX=TESLA FIEL=AM SCAL=AMP VECT=WBM DISP=CM2 ELEC=VM COND=SM CURD=AM2,
    FORC=NEWTON POWE=WATT ENER=JOULE
SET JCOIL=YES
/----------------------------------
/Chargement des conducteurs:
/----------------------------------
$COMI D:\USERS\DELFERRI\VF\Nu-Fact\cond\Définitif-L1m\chargt-couche-interne.comi MODE=CONT
$COMI D:\USERS\DELFERRI\VF\Nu-Fact\cond\Définitif-L1m\chargt-couche-externe.comi MODE=CONT
CONDUCTOR ACTION=IMPORT FILE=D:\USERS\DELFERRI\VF\Nu-Fact\cond\Définitif-L1m\chgt-couche45.cond
CONDUCTOR ACTION=IMPORT FILE=D:\USERS\DELFERRI\VF\Nu-Fact\cond\Définitif-L1m\S-extremite.cond
CONDUCTOR ACTION=IMPORT FILE=D:\USERS\DELFERRI\VF\Nu-Fact\cond\Définitif-L1m\S-ext1.cond
CONDUCTOR ACTION=IMPORT FILE=D:\USERS\DELFERRI\VF\Nu-Fact\cond\Définitif-L1m\S-ext2.cond
/
CONDUCTOR ACTION=ADD, | COND LABEL=ALL_CONDUCTORS
$CONS #IC 11870*1e6
CONDUCTOR ACTION=MODIFY CURD=#IC/AREA TOLERANCE=1.0E-04 PHASE=ONE XCEN1=0 YCEN1=0 ZCEN1=0,
        THETA1=0 PHI1=0 PSI1=0 XCEN2=0 YCEN2=0 ZCEN2=0,
        THETA2=0 PHI2=0 PSI2=0 IRXY=0 IRYZ=0 IRZX=0 SYMMETRY=-4
CONDUCTOR ACTION=DEFAULT
CONDUCTOR ACTION=DEFRESET
CONDUCTOR ACTION=EXPORT FILE=D:\USERS\DELFERRI\VF\Nu-Fact\bobine-qpole.cond
/
CONDUCTOR ACTION=REMOVE, | COND LABEL=ALL_CONDUCTORS
CONDUCTOR ACTION=DEFAULT
CONDUCTOR ACTION=DEFRESET
/
$do #I 1 CONDUCTORS
CONDUCTOR ACTION=ADD, | COND LABEL=%int(#I)
BODY N1=2 N2=2 N3=2 X0=0 Y0=0 Z0=0
/
$assi 7 1 2 1 2 1 2 1 2 1
$write 3 #I FX FY FZ FMOD
/
CONDUCTOR ACTION=REMOVE, | COND LABEL=%int(#I)
$end do
$close 3
```

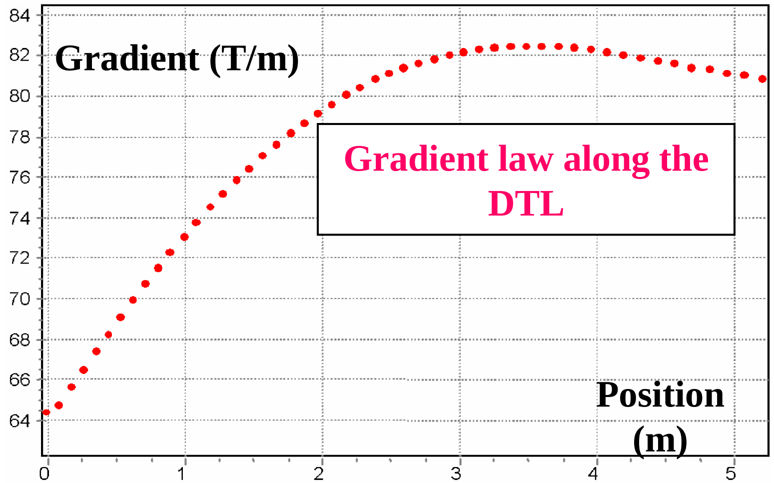
conductor loading

Current density and symmetry assignment

Conductor number Selection
Lorentz force calculation
and results stored in *.dat* file

DTL quadrupole magnets :





Quadrupole for IPHI Drift Tube Linac

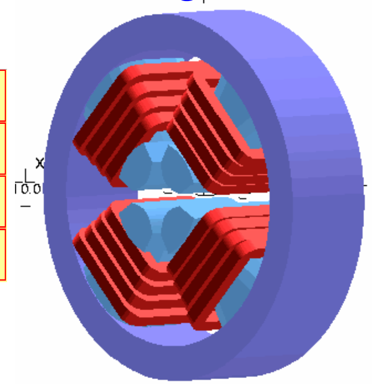
The IPHI project is a 10-MeV, 100 mA demonstrator for a future high power cw proton linac. It includes a 100-keV ECR source, a 5-MeV RFQ, and a 10-MeV drift tube linac (DTL). The source has been operational for several years, and the RFQ is being constructed.

The DTL design is a conventional Alvarez resonant (352 MHz) cavity, incorporating quadrupole (QP) electromagnets in single-stem drift tubes (DT) to focalize the proton beam during the non-accelerating phase of the radio-frequency wave.

Design requirement

- **Largest bore radius & realistic gradient values**
- **Very low power losses to avoid activation**
- **Standardization with all the 52 identical magnets**

Number of quadrupoles	52
QP bore diameter (mm)	16,00
Maximum gradient (T/m)	82,39
Relative gradient tolerance	± 0.005

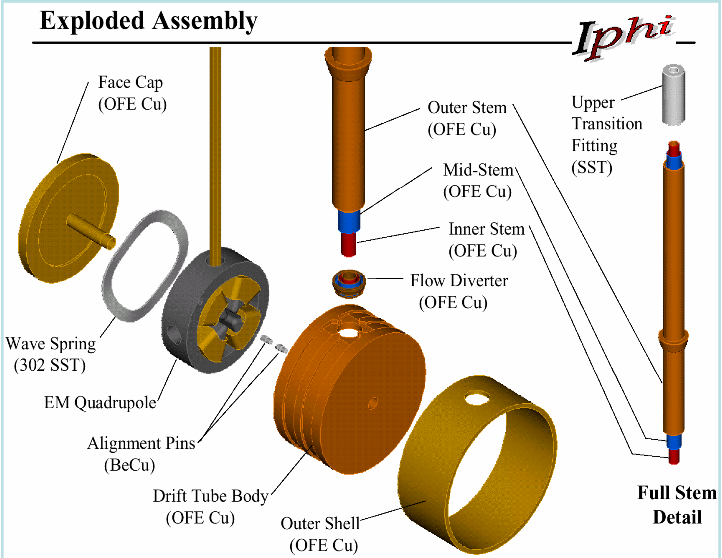


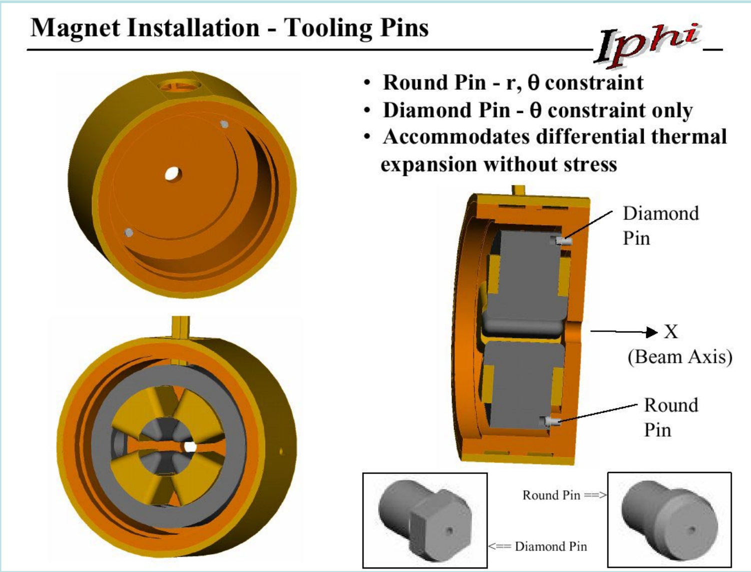
DTL quadrupole magnets :

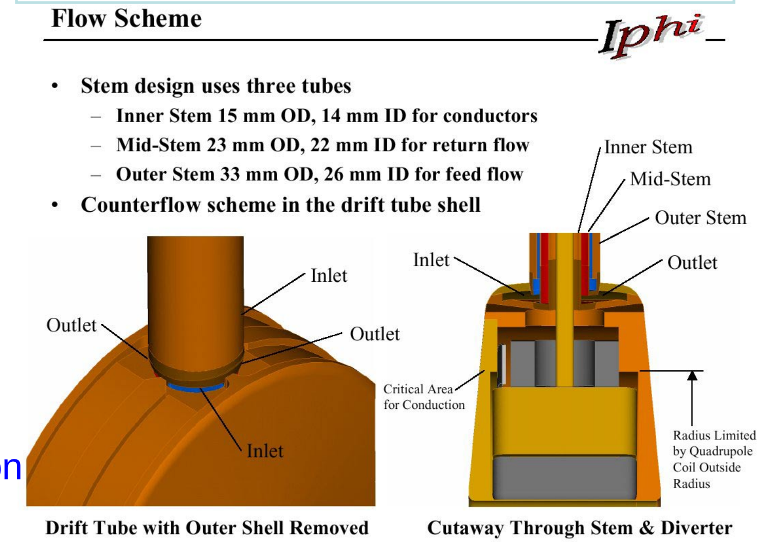
Quadrupole for IPHI Drift Tube Linac

Conventional drift tube magnet assembly

Drift tube body made of 4 pieces
Stem made of 3 concentric tubes :
- cold water in
- hot water out
- magnet hollow conductors in and out



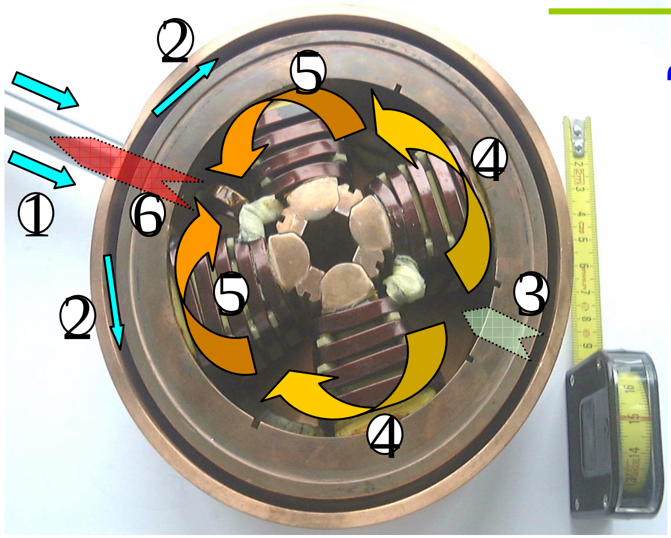




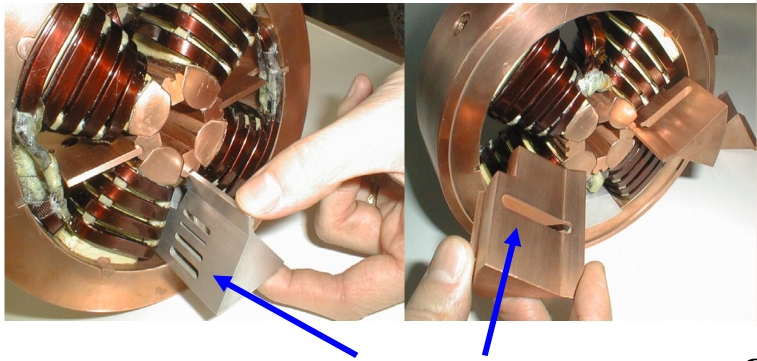
Water flow : 50 l/min ΔT= 19°C.
The main source of displacement is the thermal expansion of the tank, depending on machine support structure.

DTL quadrupole magnets :

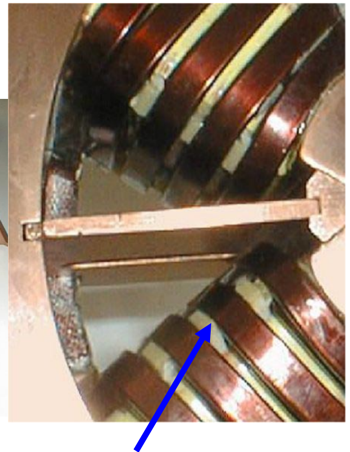
Quadrupole for IPHI Drift Tube Linac



"Flood" cooled drift tube magnet



Test of different water flow guides



Cruciform glass fibber wedges

Originality and characteristics

- Single water circuit for drift tube, walls and magnet
- More space available for the magnet (saturation effects)
- Mechanical design simplified :
  - *Stem made of only 2 coaxial tubes
  - * DT in 2 pieces
  - * Non hollow flat conductors easier for winding round the poles
- QP magnet assembly:
  - * Poles and yoke electrolytic copper plated to avoid electrochemical corrosion
  - * Poles edges are chamfered to allow the bending of the flat conductor.
  - * 2 layers of conductors wound directly on the poles
  - * Conductors spaced with cruciform glass fiber wedges for better cooling
  - * Enamel coating for conductor insulation

- No hot spot on magnet conductors
- Water flow turbulence strong enough to ensure a good cooling of the magnet
- No additional piece needed to guide the water flow
- With a water flow of 9 l/min, ΔT <12°C

But, erosion resistance of the magnet and DT, especially in water high velocity zones has to be tested

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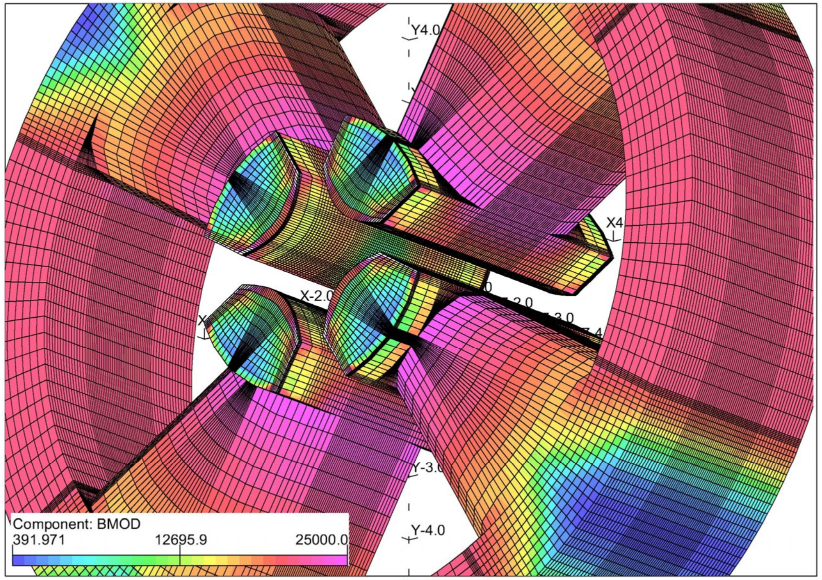
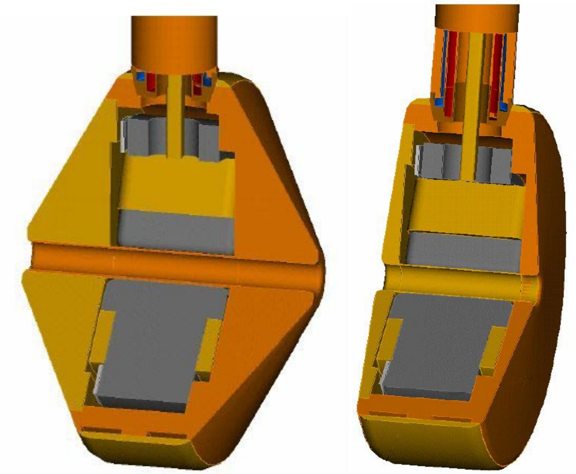
DTL quadrupole magnets :

Quadrupole for IPHI Drift Tube Linac

OPERA-3D and TOSCA simulations





Drift tube dimensions variation with the same quadrupole

QUADRUPOLE TYPE	Hollow conductors	Solid conductor
Gradient transverse intégré	4,70 T	4,70 T
Gradient quadripolaire	83,79 T/m	75,89 T/m
Longueur magnétique	56,09 mm	61,94 mm
Longueur totale	48 mm	56,16 mm
Longueur des pôles	36 mm	42 mm
Diamètre externe	140 mm	157 mm
Diamètre d'ouverture	16 mm	16 mm
Ampères-tours	2 750	2 317
Nombre de spires par pôle	5,5 en 1 couche	9 en 2 couches
Dimensions des conducteurs	5x5 mm	5,6x2 mm
Isolant	0,25 mm par face	0,07 mm par face
Intensité par spire	500 A	258 A
Densité de courant	27,88 A/mm²	23,04 A/mm²
Résistance totale	6,1 mΩ	15,3 mΩ
Puissance électrique	1 524 W	1 018 W
Débit nominal	1,68 l/min	
Echauffement de l'eau	13°C	Refroidissement externe
Perte de charge	6,22 bars	

Minimum length (mm)	**62.49**
Maximum length (mm)	**114.25**
External diameter (mm)	**170.00**
End cap face minimum angle (degree)	**4.18**
End cap face maximum angle (degree)	**28.60**

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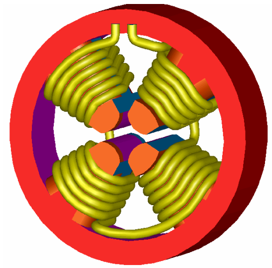
DTL quadrupole magnets :

Quadrupole for IPHI Drift Tube Linac



- 1 layer of standard hollow conductors
- "Permendur" alloy for poles and yoke
- Poles rounded for conductors bending

Overall length (mm)	48.00
External diameter (mm)	140.00
Bore diameter (mm)	16.00
NI (Ampere-turns)	2525.00
Joule dissipation (Watt)	1030
Conductor section (mm)	5.0x5.0
Hollow conductor hole diameter (mm)	3.0
Current density (A/mm²)	25.6

Magnet simulation

- Cooling external to the non-hollow conductors
- 2 layers of flat conductors
- Lengthened and broadenened geometry to fill the DT
- Standard iron for poles and yoke

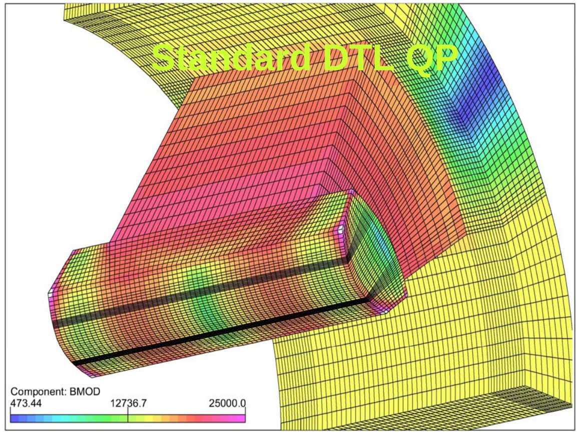
•Max dimension to fit the DT walls

•Cross section with conical pole shape optimized for saturation and coils adjustment

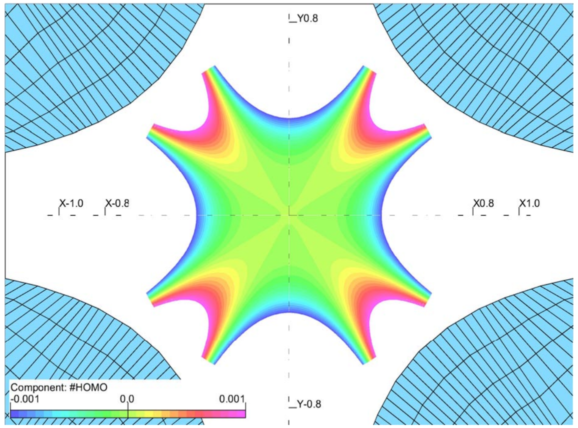
•High permeability material

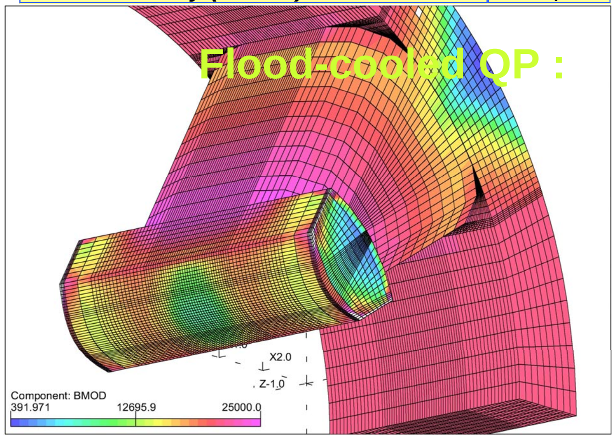
•"Mushroom-shaped" pole to increase magnet length

Overall length (mm)	56,20
External diameter (mm)	157,00
Bore diameter (mm)	16,00
NI (Ampere-turns)	2900,00
Joule dissipation (Watt)	1600
Full conductor section (mm)	5.6x2.6
Current density (A/mm²)	18,1



Integrated gradient homogeneity





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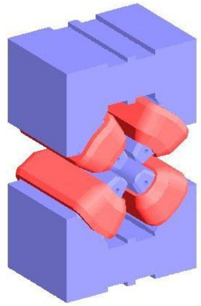
Many thanks to all people who have been involved in these magnet studies and building



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