

# Magnetic design

1. Effect of curvature
2. 2D design with  $\mu = \infty$
3. 2D design with real iron
4. Fields perturbations
5. Mechanical effects
6. 2D conclusion
7. End coil design

# Curvature

Two possible effects of the curvature:

- Curvature of the windings
- Difference in stacking factors due to iron lamination with constant thickness

It was checked with a simplified model that there are no effects for curvature radius greater than 10-15 m

The magnet can therefore be designed as a straight magnet, therefore simplifying the process.

# 2D design with $\mu = \infty$

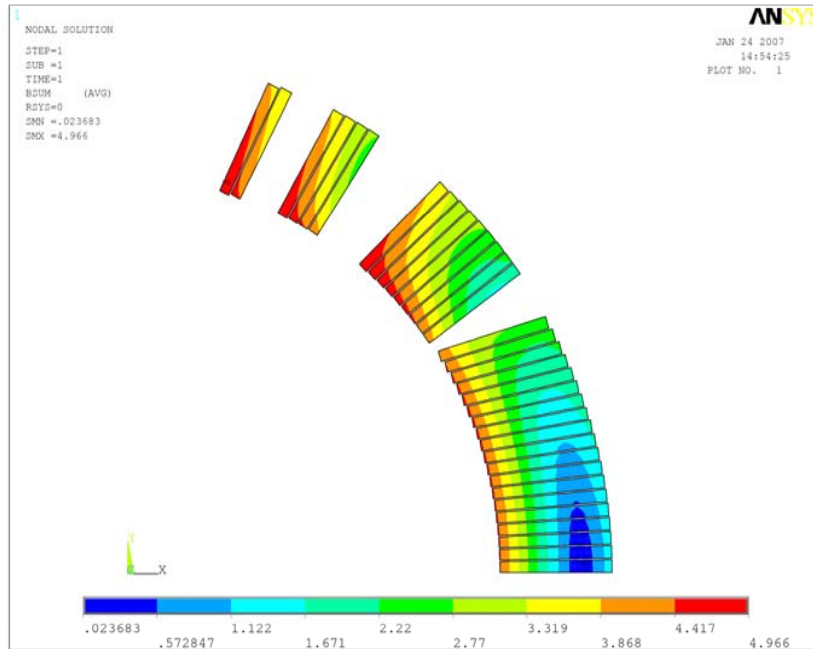
## Main parameters of the magnet.

Nominal field	<b>1.5 – 4.5 T</b>
Ramp rate	<b>1 T/s</b>
Flat top	10 s
Coil aperture diameter	<b>100 mm</b>
Magnetic length (full scale magnet)	7.757 m
Curvature radius	66.667 m
Bending angle	6 2/3 deg
Max temperature of cooling GHe	<b>4.7 K</b>
Yoke outer radius	< 250 mm
Reference radius for field quality	35 mm
Field quality	$2 \cdot 10^{-4}$

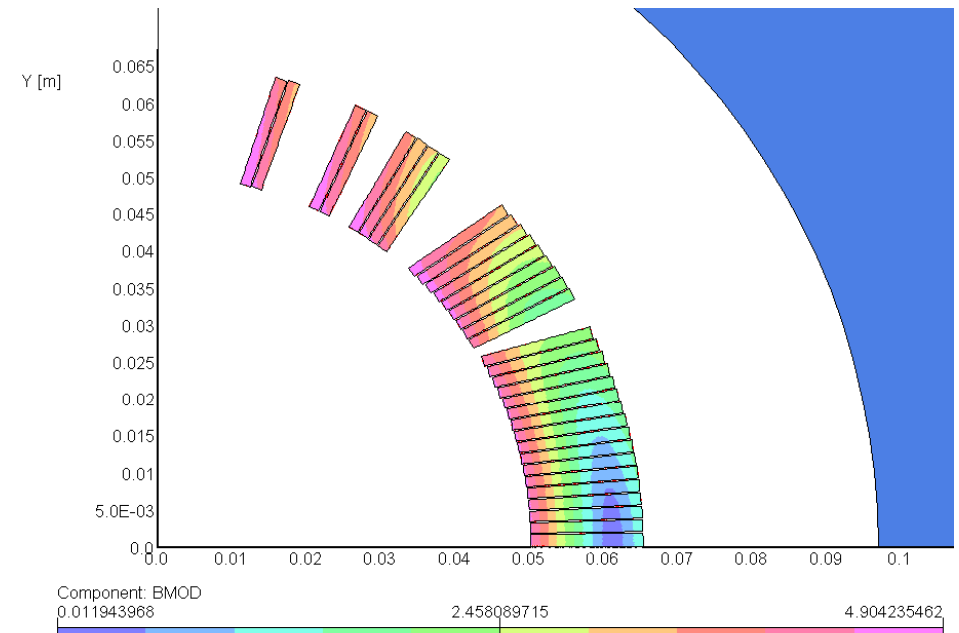
## 2D design with $\mu = \infty$

- Constraints:
  - **one single layer** to reduce the complexity and the cost of the magnet,
  - a **cable** with a number of strands and dimension of the **LHC dipole outer layer** to reduce the developments cost.
- Within the given constraints it is imperative to **maximize the number of turns** per quadrant to have a reasonable temperature margin.
- A deep analysis and optimization has been performed for a cos-theta magnet with **34-35 turn** and **4-5 blocks** per quadrant. Genetic algorithm has been employed in ROXIE and in connection with ANSYS to obtain a configuration with good field quality and maximum temperature margin.
- No solution with 35 turns has been found either with 4 or 5 blocks.
- One solution (not very good) with 34 turns and 40 strands (vs nominal 36)
- **Solutions have been found with 34 turns with 4 or 5 blocks.**

# 2D design with $\mu = \infty$



34 turns, 4 blocks(19+9+4+2)  
 $I=8890$  A,  $B_{peak} = 4.966$  T



34 turns, 5 blocks(17+9+4+2+2)  
 $I=8870$  A,  $B_{peak} = 4.904$  T

Excellent field quality and stability

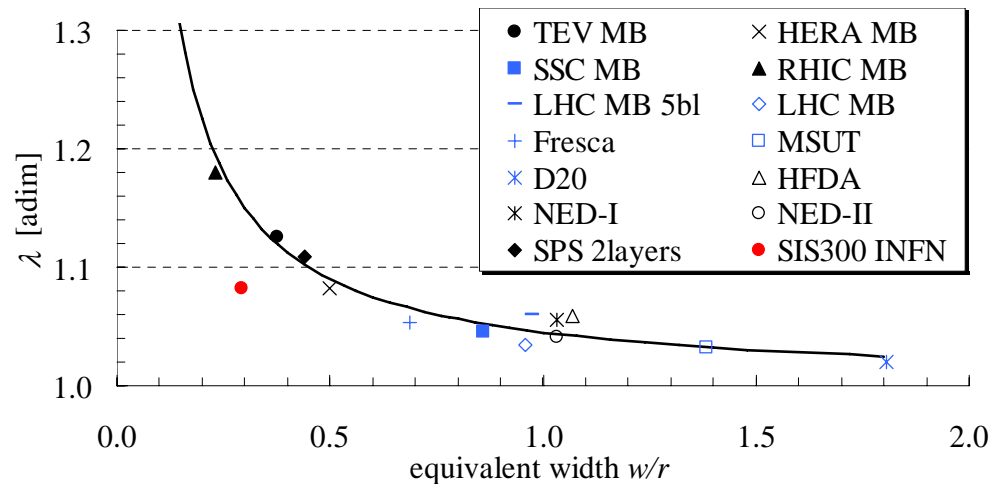
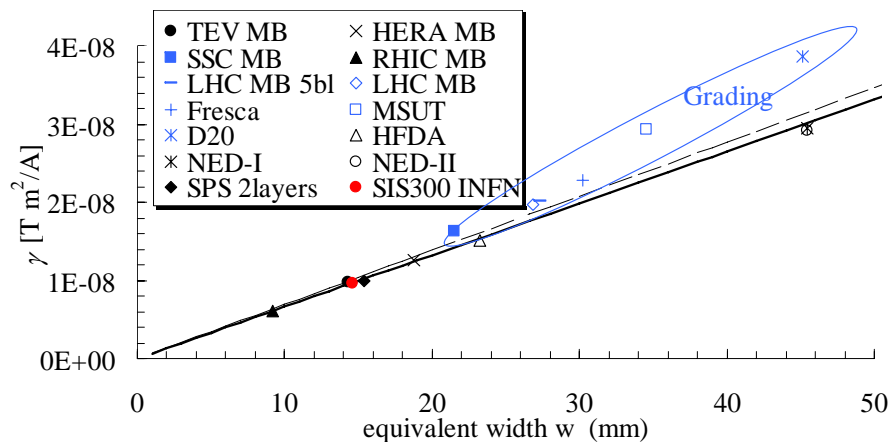
**SELECTED**

# 2D design with $\mu = \infty$

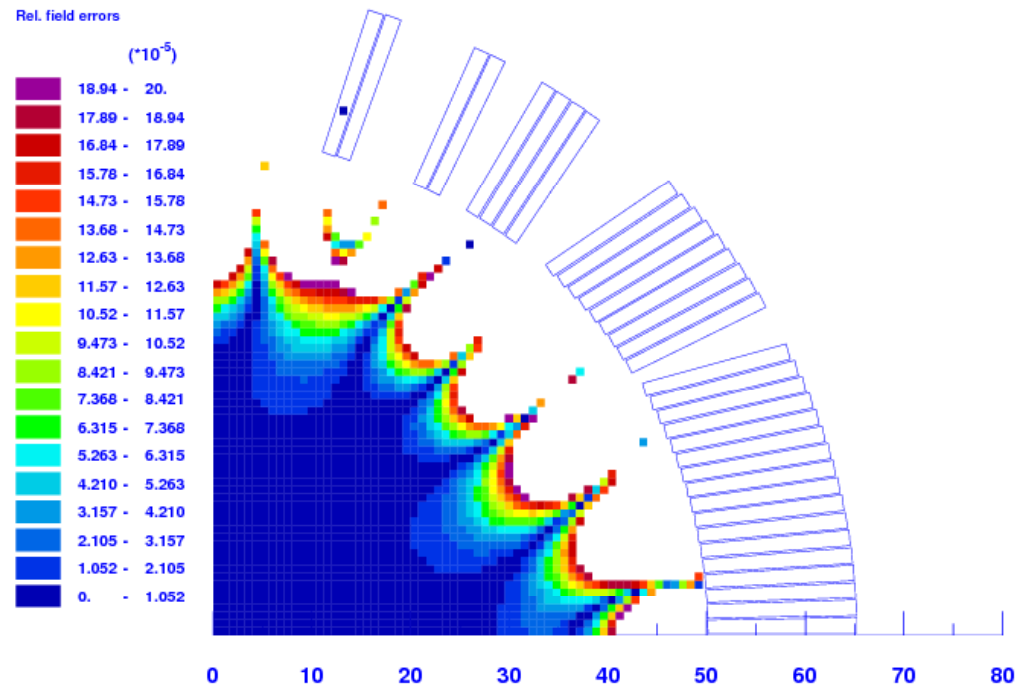
(Ezio Todesco, private email, April 18-2007)

*I send you some comments on the design for GSI proposed by INFN. I use the notations given in the paper ( Rossi-Todesco, PRSTAB 10, 112401, 2007)*

- The parameter  $\gamma$  (central field per unit of current density) is in line with the quantity of cable used (see Fig. 1).
- The parameter  $\lambda$  (peak field to central field) is 7% less of what expected by a  $72^\circ$  sector coil with a wedge between  $48^\circ$  and  $60^\circ$ . For magnets with small  $w/r$  as in your case, one expects around 1.15 (i.e. 15% more peak field than in the centre), but you manage to get 1.08. Please note that you managed to screw up my scaling law which was working very well in all cases!



# 2D design with $\mu = \infty$

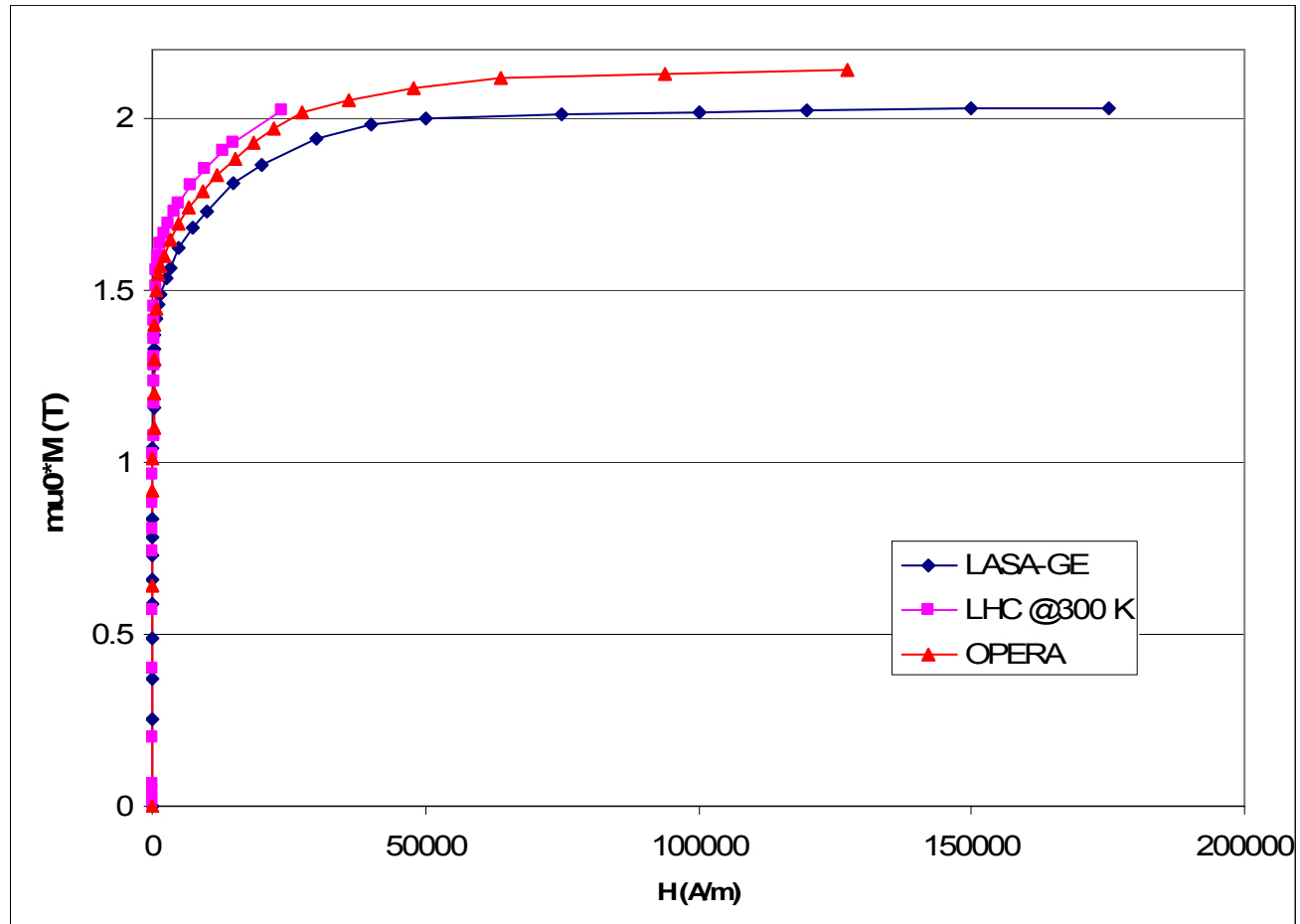


Field harmonics (units) at 35 mm,  $\mu = \infty$  for ideal geometry.

$b_3$	$b_5$	$b_7$	$b_9$	$b_{11}$	$b_{13}$
-0.19	0.07	0.41	0.50	0.97	-1.18

$$B_y + iB_x = 10^{-4} B_0 \sum_{n=1}^{\infty} (b_n + ia_n) \left( \frac{x + iy}{R_{ref}} \right)^{n-1}$$

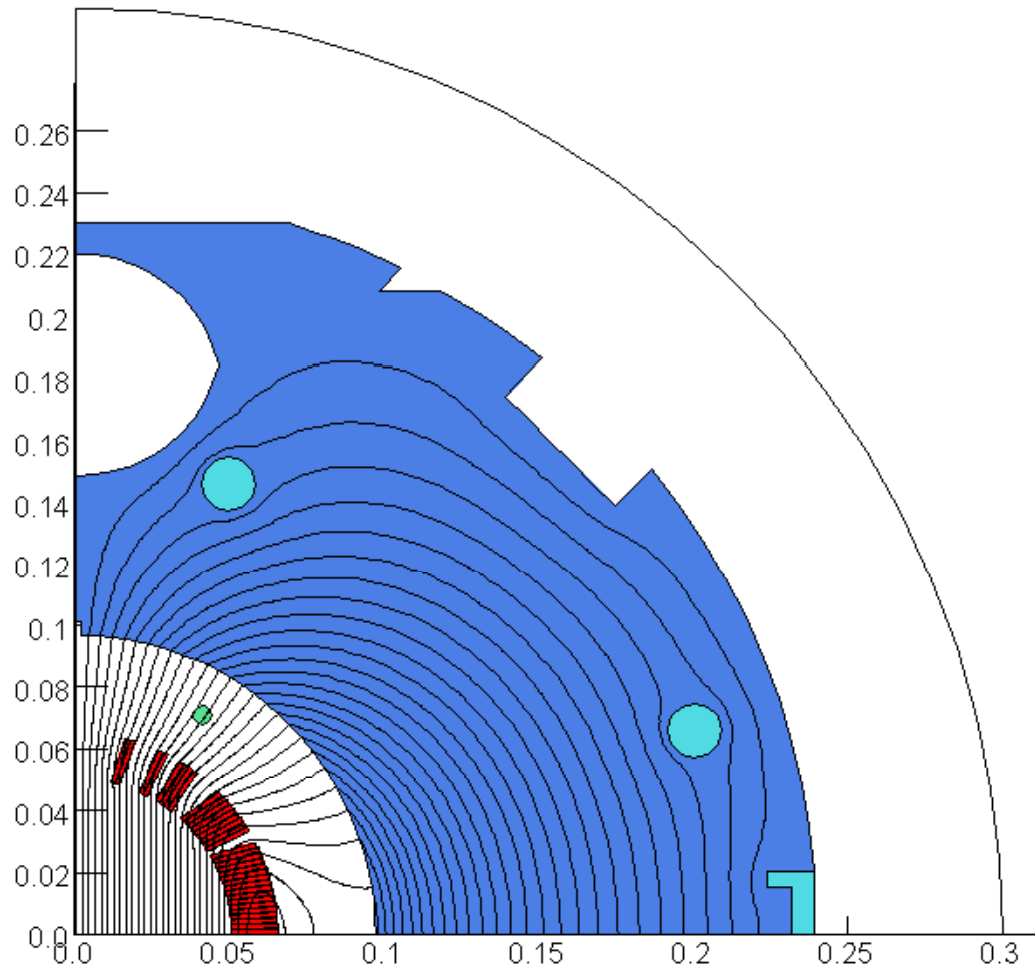
# Iron



Electrical steel M600-100A Si 3% -  $\mu_0 M_{\text{sat}} = 2.030$  T



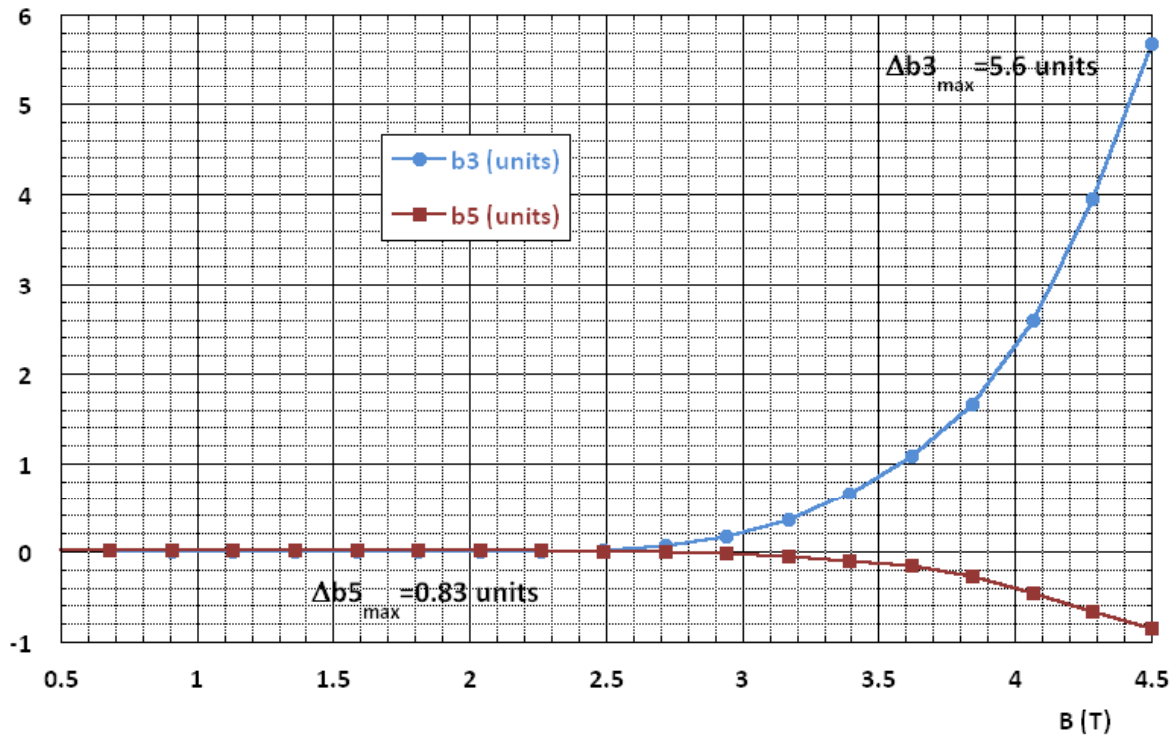
# 2D design with real iron



Operating current ( $B_0=4.5$ T)	<b>8926 A</b>
Peak field on conductor	<b>4.901 T</b>
$B_{peak}/B_0$	1.087
Current sharing temperature	<b>5.69 K</b>
Working point on load line	79.8%
Inductance per unit length	2.95 mH/m

Iron contribution  
 $B_{iron} \sim 1.15$  T (25%)

# 2D design with real iron



**Sextupole and decapole component vs. central field due to the saturation of the iron yoke**

# Field perturbations

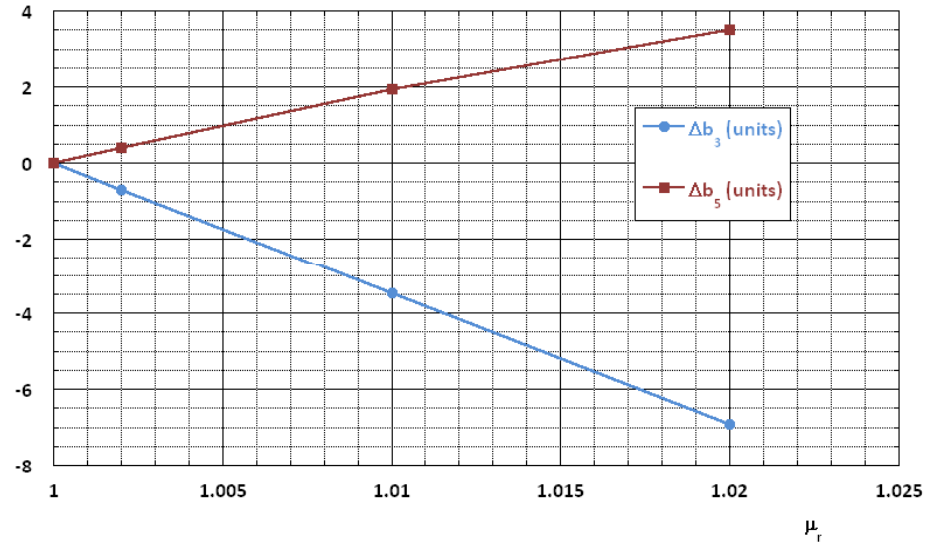
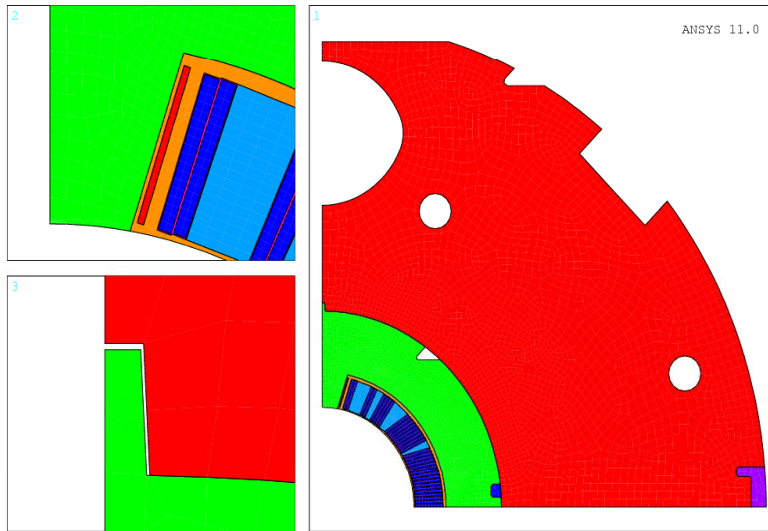
**In static conditions**, the field quality is mainly affected by:

1. the magnetization of **collars**, **shimmings**, collar keys and beam tube
2. the **paramagnetism** of the copper-manganese component of the conductor
3. the **persistent currents** in the superconducting filaments.

**Dynamic conditions**, (during the ramp of the magnet)

1. eddy currents inside the strand (IFCC **inter-filament coupling currents**);
2. eddy currents between the strands of the Rutherford cable (ISCC inter-strand coupling currents);
3. eddy currents in the beam tube.

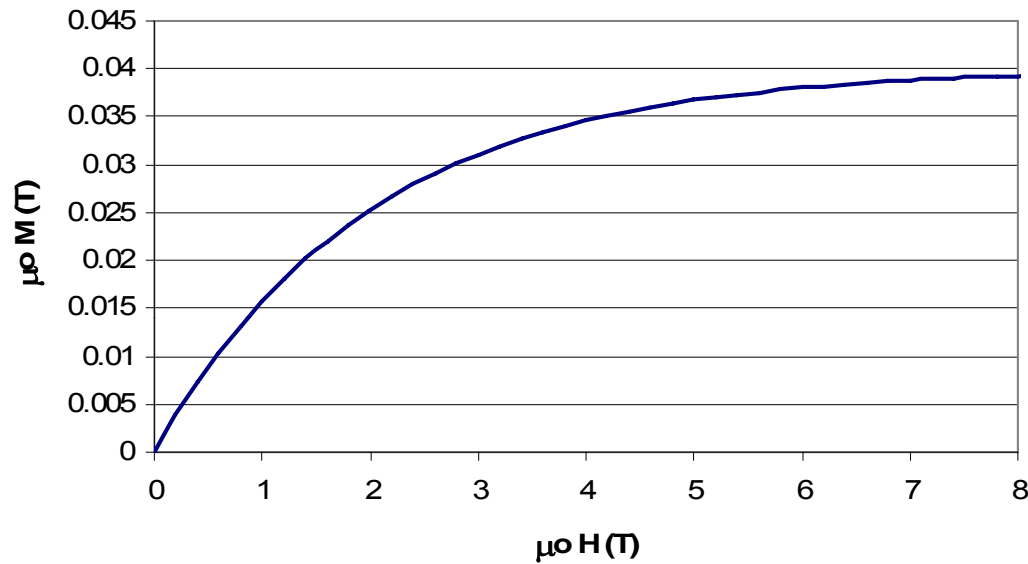
# Field perturbations- Collars and shimming



LHC collars  $\mu_r = 1.002$   
 AISI316  $\mu_r = 1.02$

	db3	db5
Collars ( $\mu=1.002$ )	-0.77	0.39
Shim (1 mm)	-0.39	0.15

# Field perturbations - CuMn paramagnetism



$$\mu_0 M_{\text{sat}} = 40 \text{ mT}$$

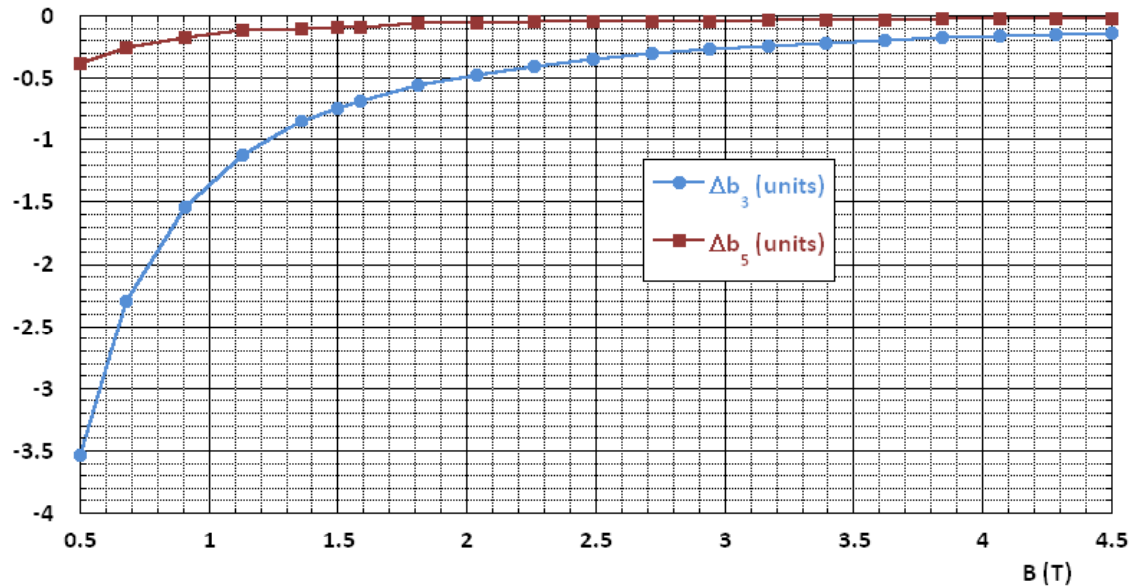
Bo (T)	0.5	1.5	3.0	4.5
db3	0.76	0.65	0.53	0.44

$$\frac{S_{\text{CuMn}}}{S_{\text{cond}}} = 0.18$$

# Field perturbations - Persistent currents

$$m_{pc} = -\frac{1}{6} \lambda_f J_c(B) d_f d_s^2$$

$m_{pc}$  dipole moment per unit length  
 $\lambda_f$  filament filling factor in the strand (0.36)  
 $J_c(B)$  critical current  
 $d_f$  filament diameter (3.5  $\mu\text{m}$ )  
 $d_s$  strand diameter (0.825 mm)



# Field perturbations- Inter-filament coupling currents

$$m_{fc} = -\frac{\pi}{2\mu_0} \lambda_{fb} \dot{B} \cdot d_s^2 \tau(B)$$

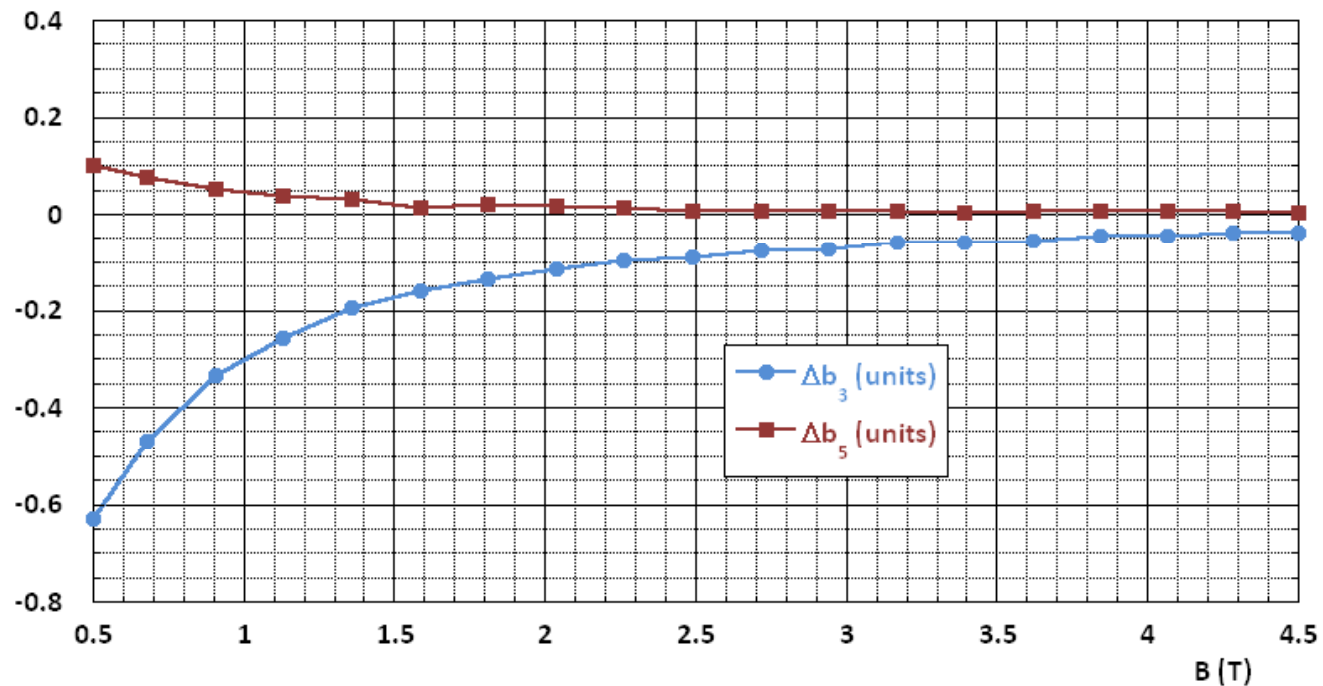
$m_{fc}$  dipole moment per unit length

$\lambda_{fb}$  filling factor ( 0.8)

$B'$  ramp rate ( 1T/s)

$d_s$  strand diameter (0.825 mm)

$\tau$  decay constant



## Field perturbations- Inter-strand coupling currents

These currents are normally separated in three contributions due to :

- crossover resistance,
- adjacent resistance in parallel field
- adjacent resistance in transverse field.

ISCC via **adjacent resistance in transverse field** has been calculated via Excel code starting from the field map

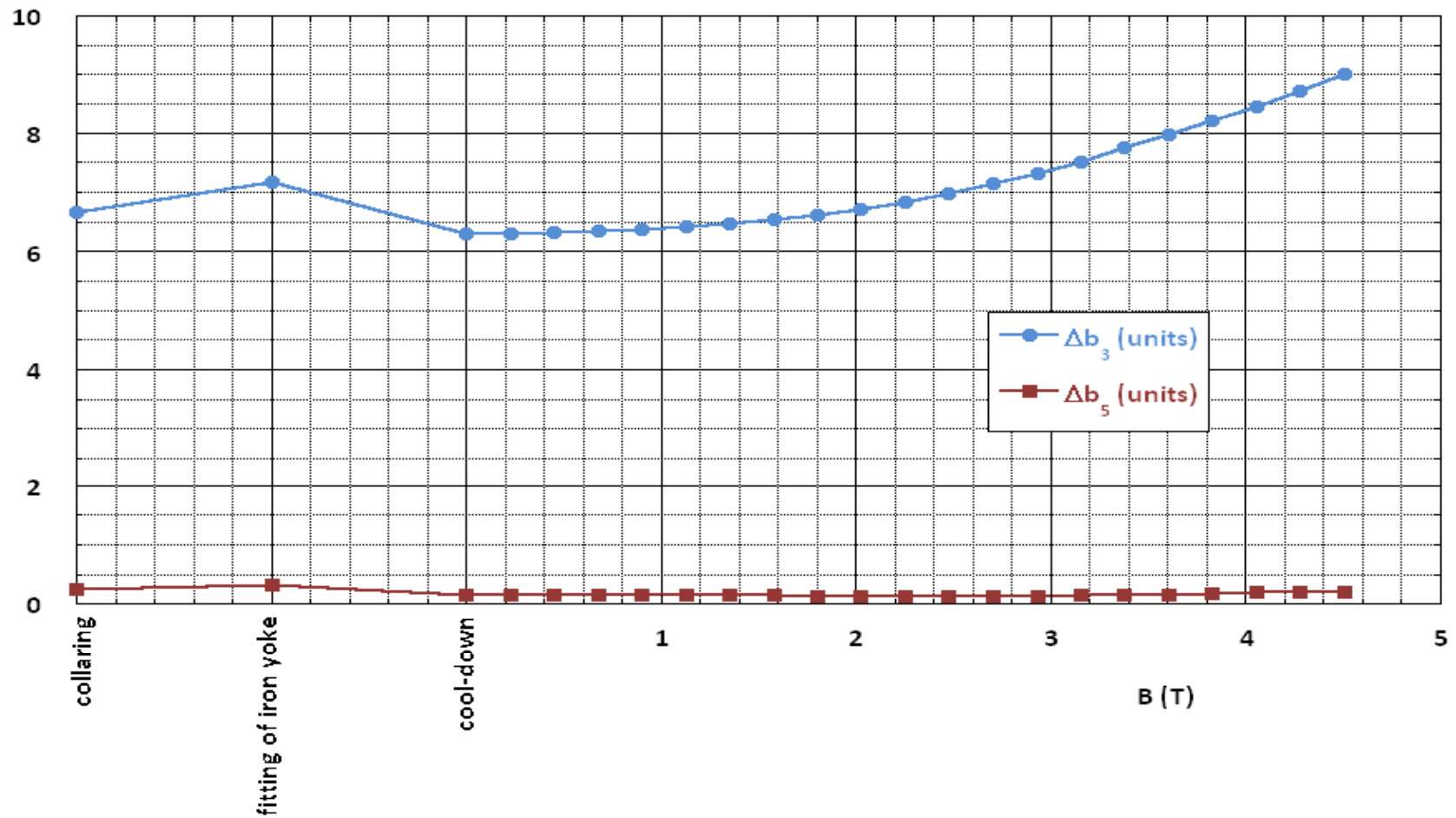
**Roxie** uses a network model for the Rutherford cable and necessarily gives the **integral result of the three contribution**

Sextupole and decapole field harmonics (units) due to ISCC at  $r=35$  mm

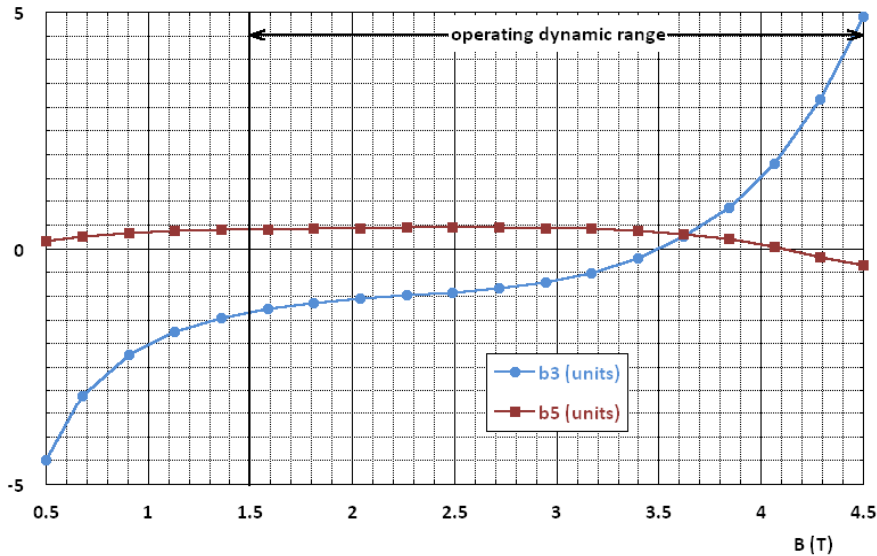
$B_0$ (T)	0.5 $\delta b_3 / \delta b_5$	1.5 $\delta b_3 / \delta b_5$	3.0 $\delta b_3 / \delta b_5$	4.5 $\delta b_3 / \delta b_5$
Excel code	0.03 / -0.08	0.01 / -0.03	0.00 / -0.01	0.00 / -0.01
Roxie	0.04 / -0.15	0.01 / -0.04	0.00 / -0.02	0.00 / -0.01



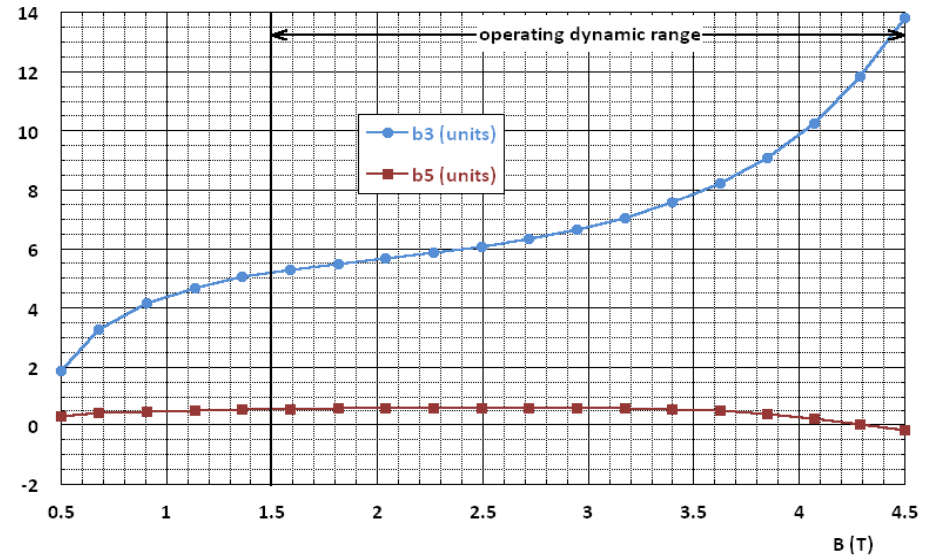
# Thermal and mechanic effects



# Summary



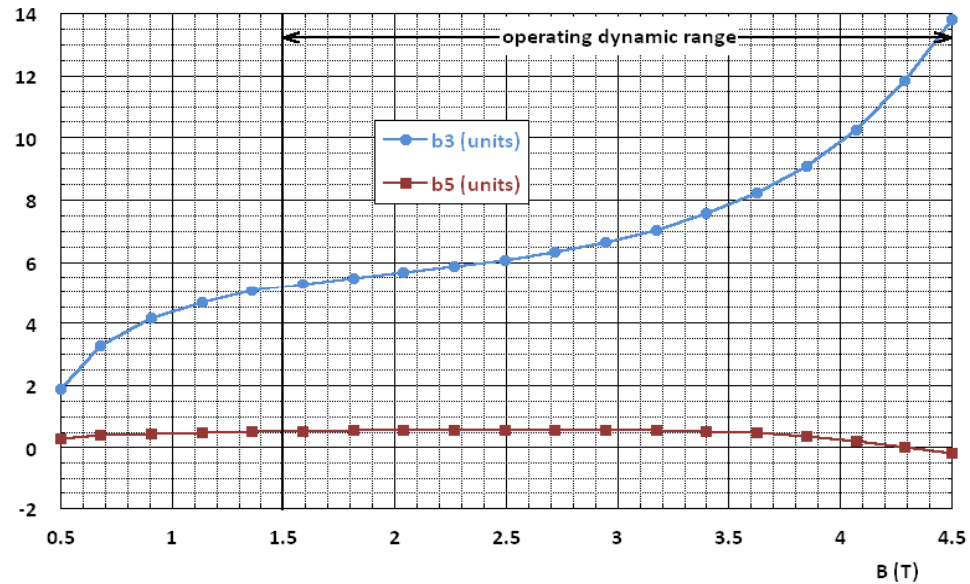
- iron
- collars and shim
- paramagnetism CuMn
- persistent currents
- interfilament currents



- Total
- (includes mechanics effects)

## Dominant effects:

- mechanic
- iron (high fields)
- pers. curr. (very low fields)



b3 (units)

Bo(T)	0.5	1.5	3.0	4.5
iron	0.0	0.0	0.2	<b>5.6</b>
collar,shim	-1.1	-1.1	-1.1	-1.1
CuMn	0.76	0.65	0.53	0.44
PC	<b>-3.65</b>	-0.72	-0.25	-0.13
IFCC	-0.63	-0.16	-0.06	-0.04
mech	<b>6.4</b>	<b>6.5</b>	<b>7.5</b>	<b>9.0</b>
<b>Total</b>	<b>1.8</b>	<b>5.2</b>	<b>6.8</b>	<b>13.8</b>

## Conclusion for 2D design

In our opinion is **not wise to sum all these contribution and try to optimize** the results since there is some uncertainty on the input data for almost all of them.

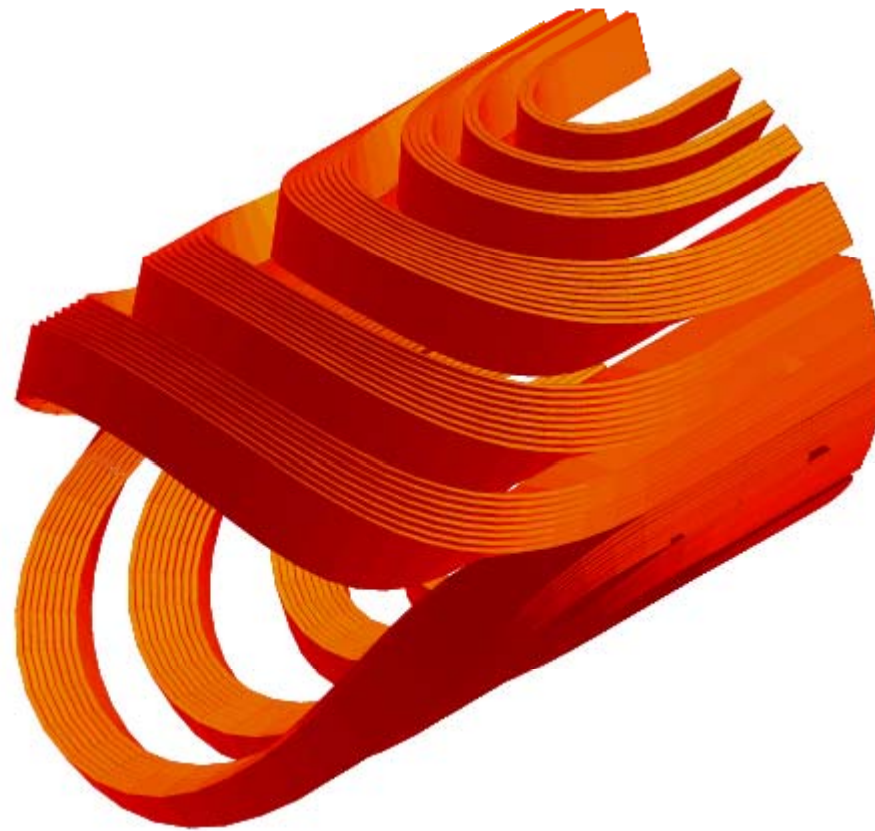
The purpose of the magnet is to show that a fast pulsed magnet can be reliably built and operated; in this respect the **optimization of the field quality can be done at a later stage when the magnet has already been operated and measured** and the influence of the various contributions better understood.

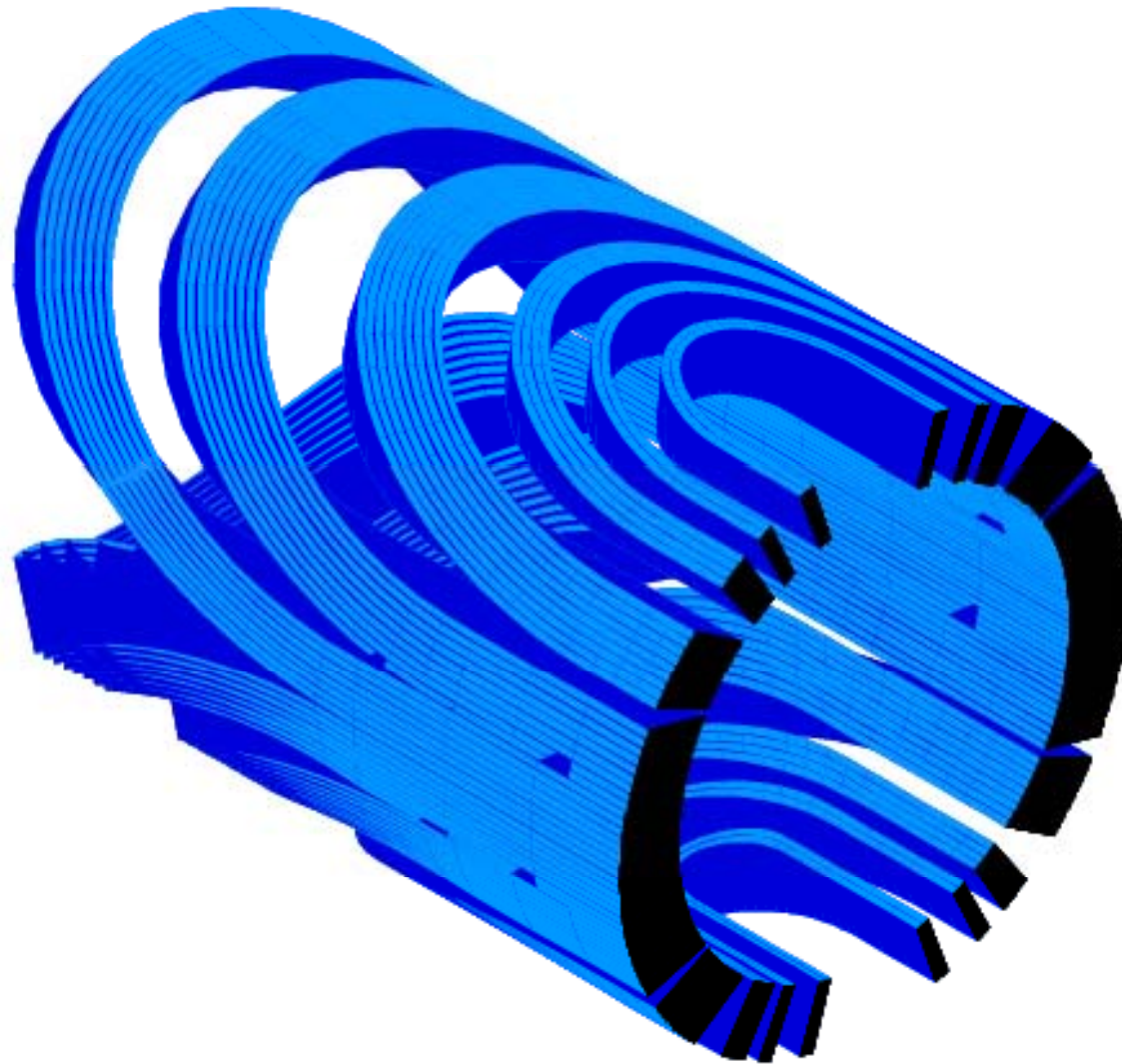
## Coil end design

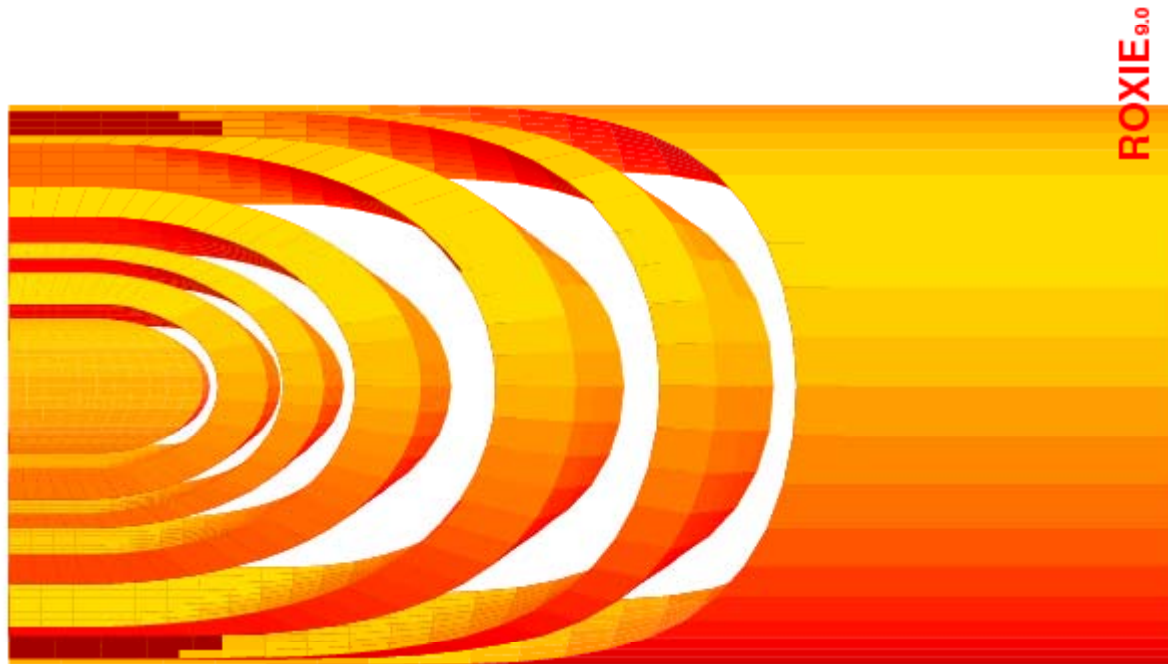
To speed up the winding test the design of the coil end has been done ignoring the iron ( **aircore design** )

The lay-out of the blocks has been chosen to satisfy the following conditions:

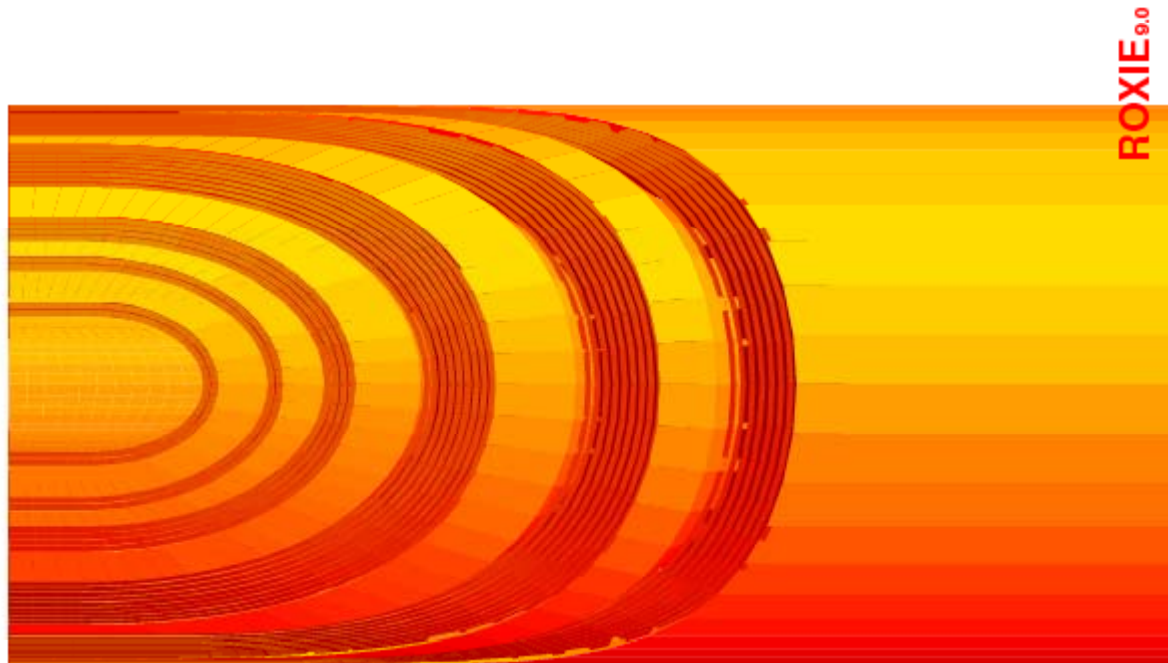
- Minimize the stresses on the conductor (“constant perimeter” condition);
- Reduce the integral values of sextupole and decapole;
- Control the peak-field on the conductor.

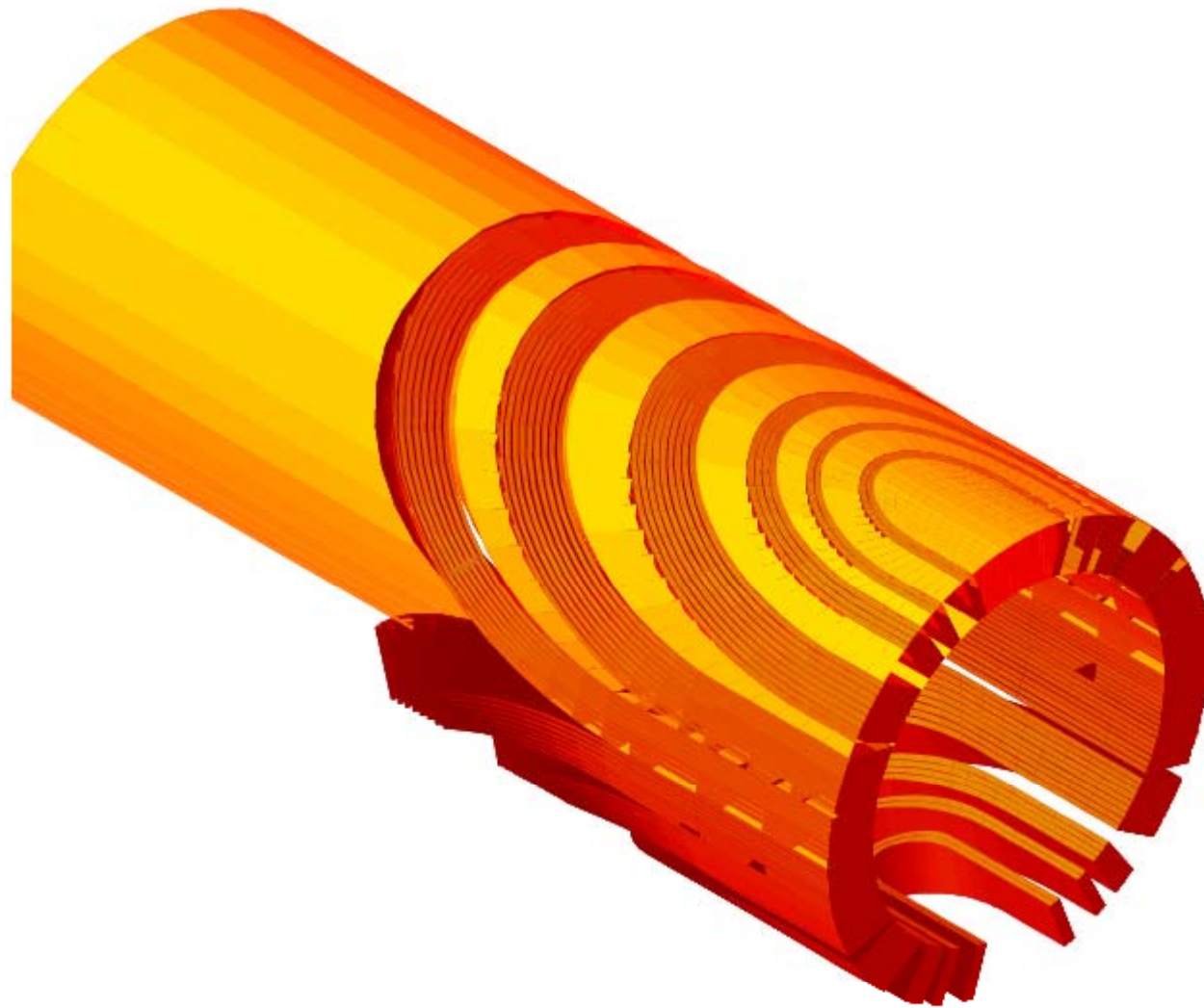








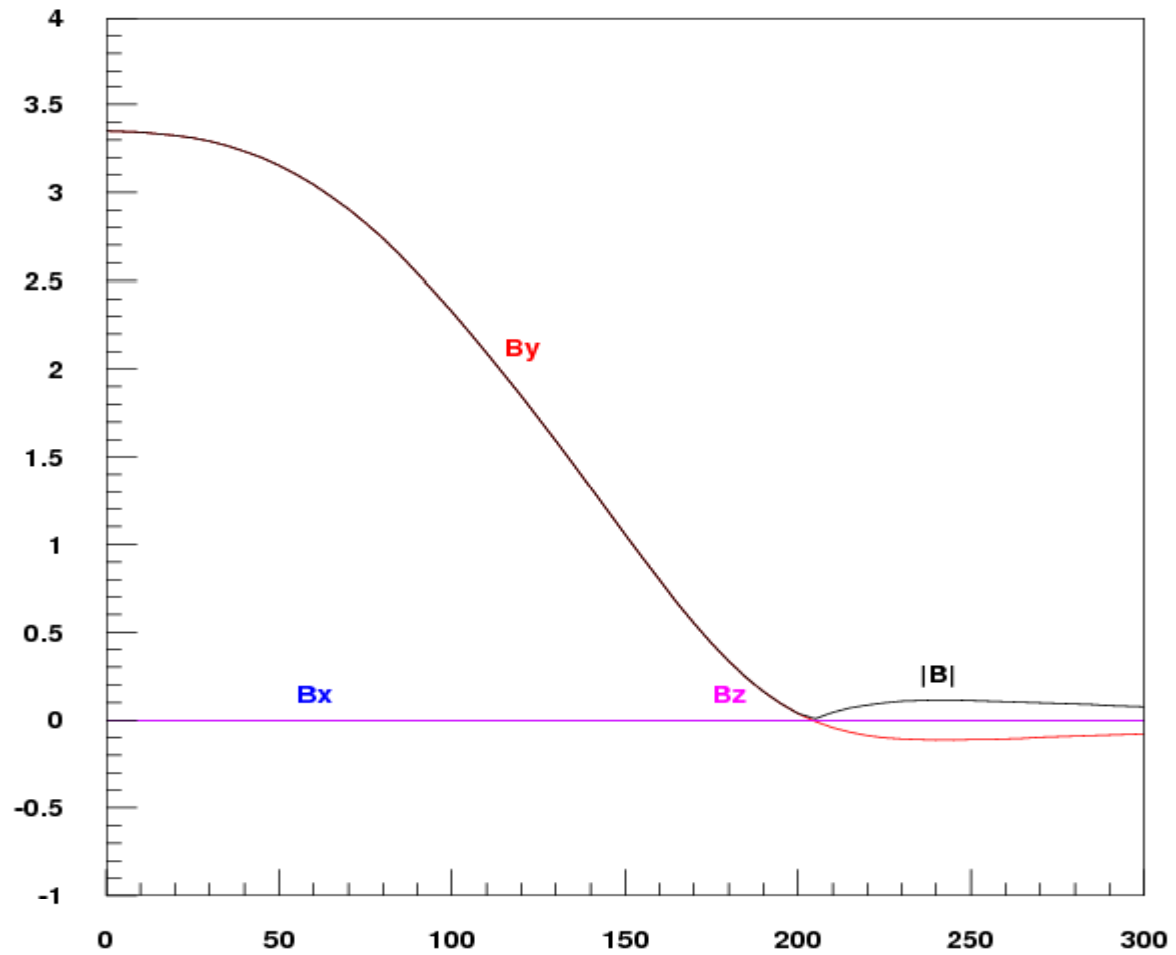






0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300





Aircore magnetic length 126 mm ( $z=0$  beginning of the coil end)

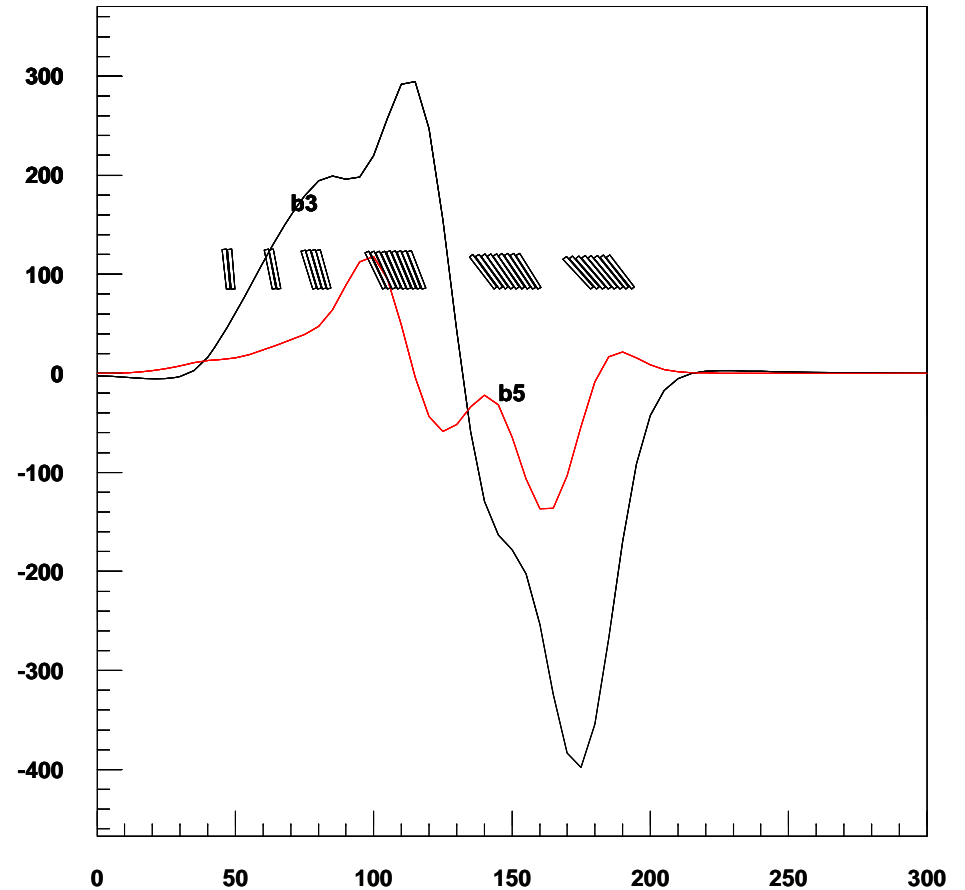
Averaged harmonics in  
symmetric coil-end “**in air**”:

$$b_3^{coil-end} = \frac{1}{B_0} \frac{1}{\Delta z} \int_0^{\Delta z} B_3 dz = 0.63 \text{ units}$$

$$b_5^{coil-end} = \frac{1}{B_0} \frac{1}{\Delta z} \int_0^{\Delta z} B_5 dz = 0.04 \text{ units}$$

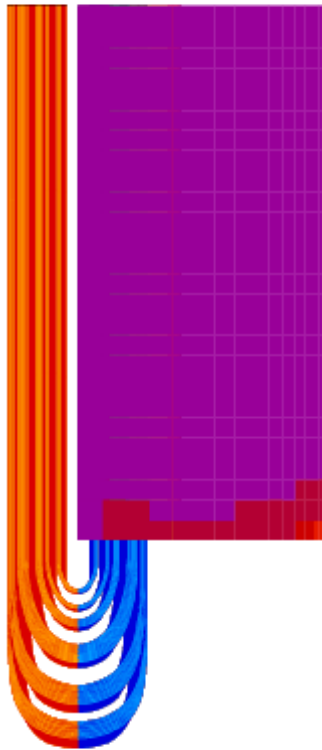
with :

$$B_0 = 4.5 \text{ T}, \quad \Delta z = 300 \text{ mm}$$

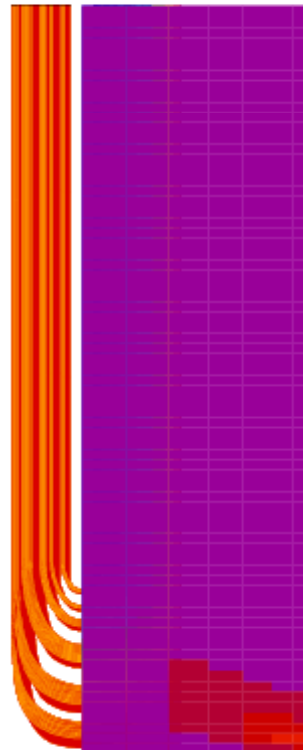


ROXIE<sub>9.0</sub>

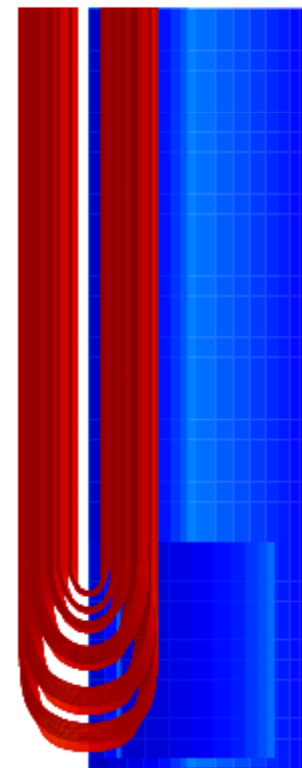
# Yoke end configurations



short yoke



long yoke



yoke with steel insert  
( as LHC )

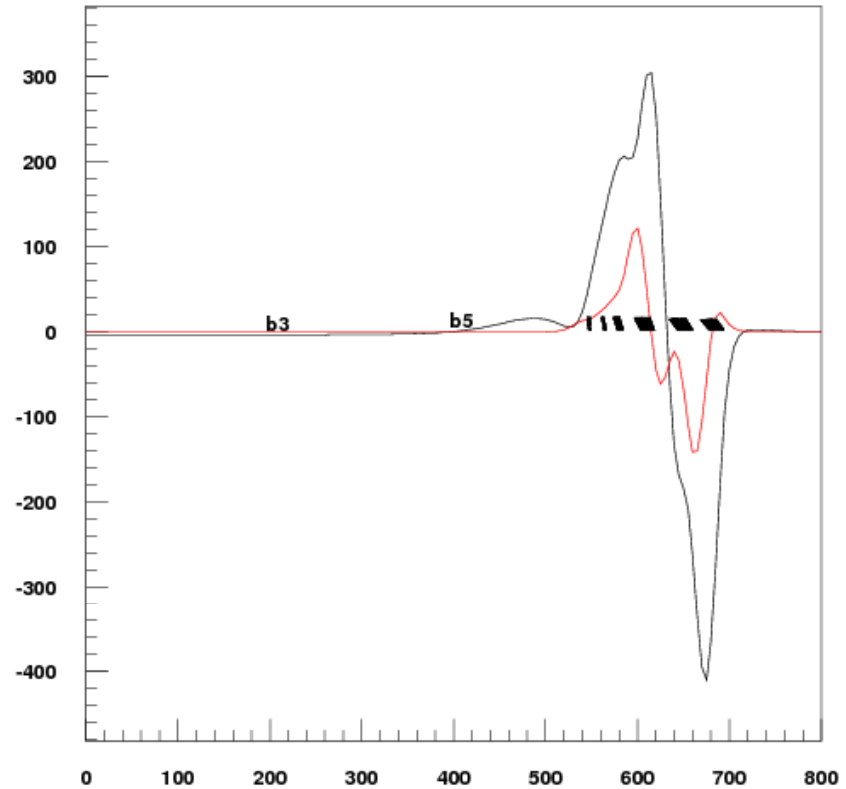
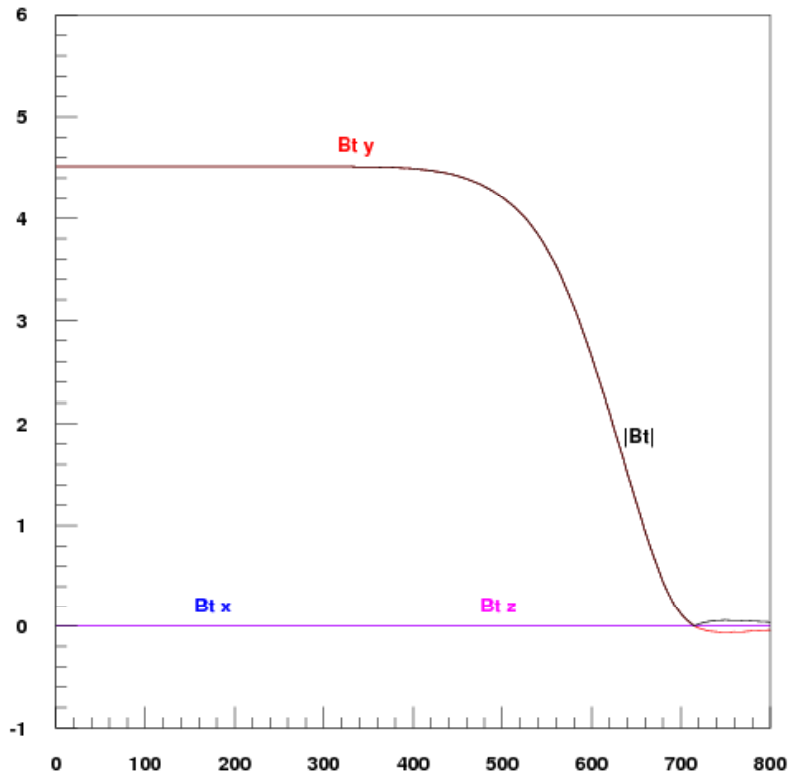
# Choice of the yoke end

- Long yoke: too high field in the coil end
- Long yoke with steel insert ( as LHC):  
low field, low fringing field, lower losses, complicated to build
- Short yoke: low field, simple to build

## Short yoke selected

- peak field 4.580 T (at  $z=0$ ), 4.471 T (at  $x=0$  on top of spacer)
- eff. magn. length  $l_{\text{end}} = 100.6$  mm (from  $z = 0$  beginning coil end)

# Short yoke – $B_0 = 4.5 \text{ T}$

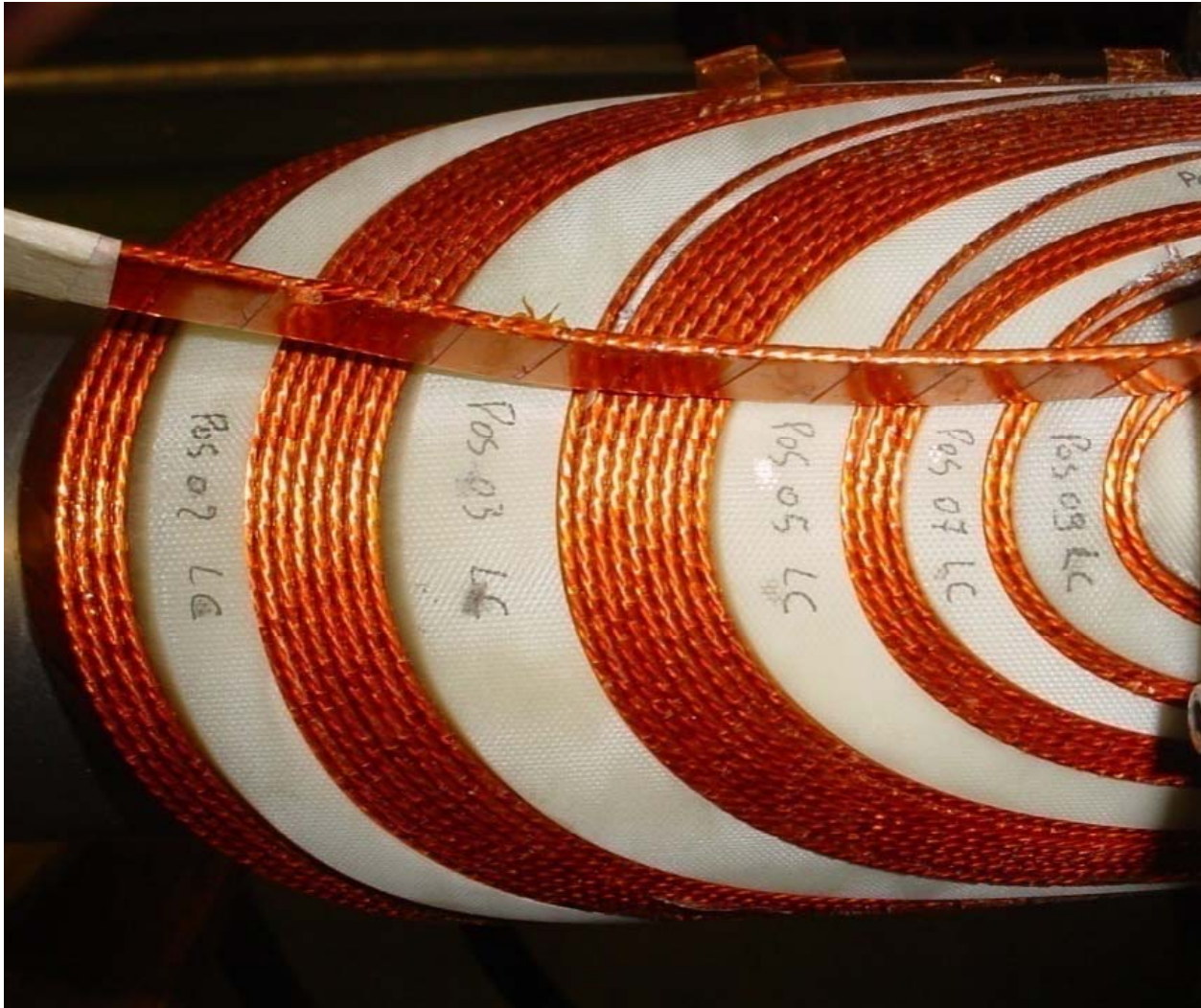


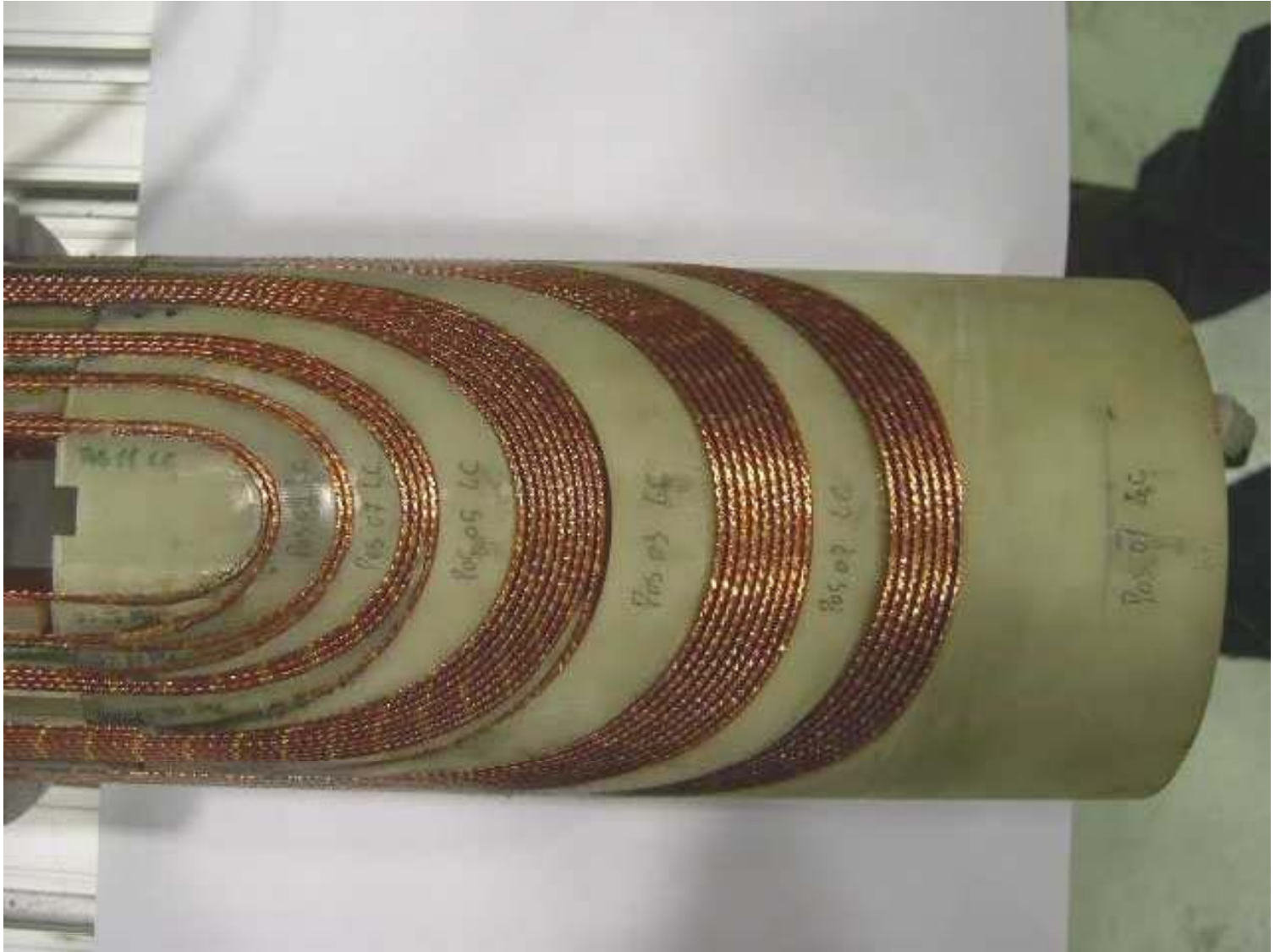
Eff. magn. length 0.6045 m  
 Eff. magn length for the coil end  
 $I_{\text{end}} = 104.5 \text{ mm}$

Averaged (over 0.8m) multipole content

db3	db5	db7
0.70	-0.18	-1.26







## Preliminary measurements of the coil end ( symmetric side)

For the design of the coil end nominal values for the insulated conductor (at 50 MPa) plus a constant 0.05 mm in transverse dimension have been used

Preliminary measurements on the two more external end block indicated an **increased average value of the short side** thickness of the order of

$$\Delta w \sim 0.25 \text{ mm}$$

An analysis, still in progress, seems to show that few modifications of the end spacers can correct the problem. This will be done in the construction phase

The peak field on conductor depends on the geometry of the yoke.

- Yoke inner & outer radius 96.85 mm & 240 mm,
- non-linear iron, stack =0.97
- Coil-end between  $z = 0$  and  $z = 195$  mm

	<b>2-D analysis</b>	Full yoke	Collar insert + end-cap (6 mm)	Short yoke
$B_{\text{peak}}$ on cond. (T)	<b>4.904</b>	<b>4.96</b>	4.57	4.580 (4.471)
$L_m$ (mm)	-	125.0	106.5	100.8

Short yoke selected : simple construction and low field

