



2-D magnetic design of the 7.8 m dipole for SIS300

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2. Overview of the configuration
3. Effects of magnetization in field quality
4. Conclusions

Main parameters of the dipole (reference design)

MAIN

Nominal field

Value

1.5-4.5 T

Ramp rate

1.0 T/s

Radius of curvature

66.667 m

Magnetic length

7.756 m

Bending angle

6 2/3 deg.

Coil aperture diameter

100 mm

Max operating temperature of LHe

4.7 K

Current sharing temperature

≥ 5.7 K

CONDUCTOR (@300 K)

Strand number/cable

36

Critical current density in s.c. @ 4.2 K & 5 T

2700 A/mm²

Strand critical current @ 4.2 K & 5 T

515 A

Width

15.10 mm (*bare conductor*)

Short side

1.362 mm

Long side

1.598 mm

Main parameters of the dipole (reference design)

MAGNET CROSS SECTION

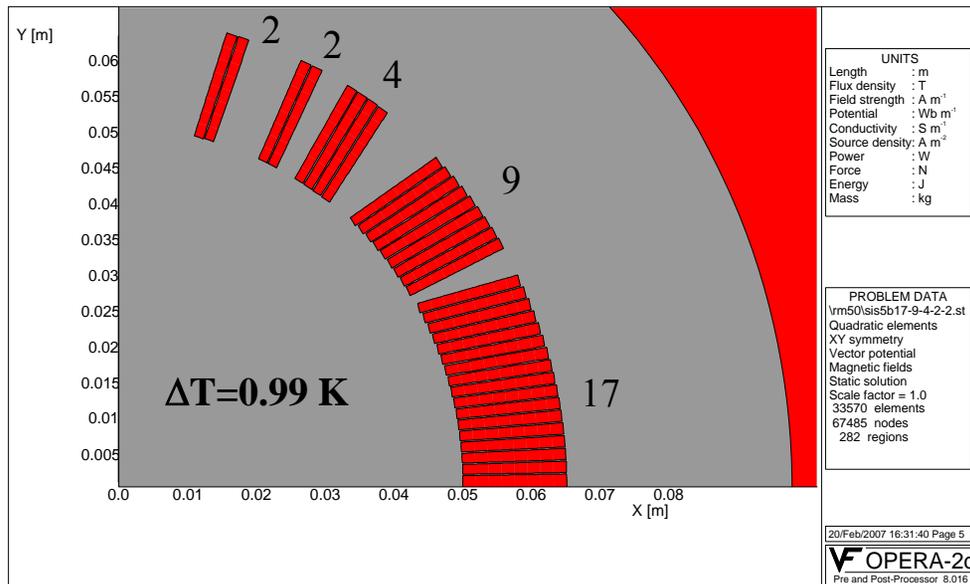
	Value
Field quality	$\pm 2 \cdot 10^{-4}$
Reference radius for field quality	35 mm (<u>70%</u> Rm)
N. of layer	1
N. of block	3-4- 5
Yoke inner radius	98 mm
Yoke outer radius	< 250 mm
N. of large holes in the yoke	2
Diameter of the yoke main holes	50-70 mm

We explored many configurations, with the purpose to maximize the number of conductors in order to decrease the current density.

The main conclusions are:

- 3-blocks: NO ACCEPTABLE SOLUTIONS.
- 4-blocks: some solutions with 34 turns
- 4-blocks: one solution with 35 turns and 40 strands cable.
But not convenient for higher losses and for constructions worries.
- 5-blocks: no solutions with 35 turns and 36 strands cable
- 5-blocks: solutions with 34 turns

5-blocks solution selected:

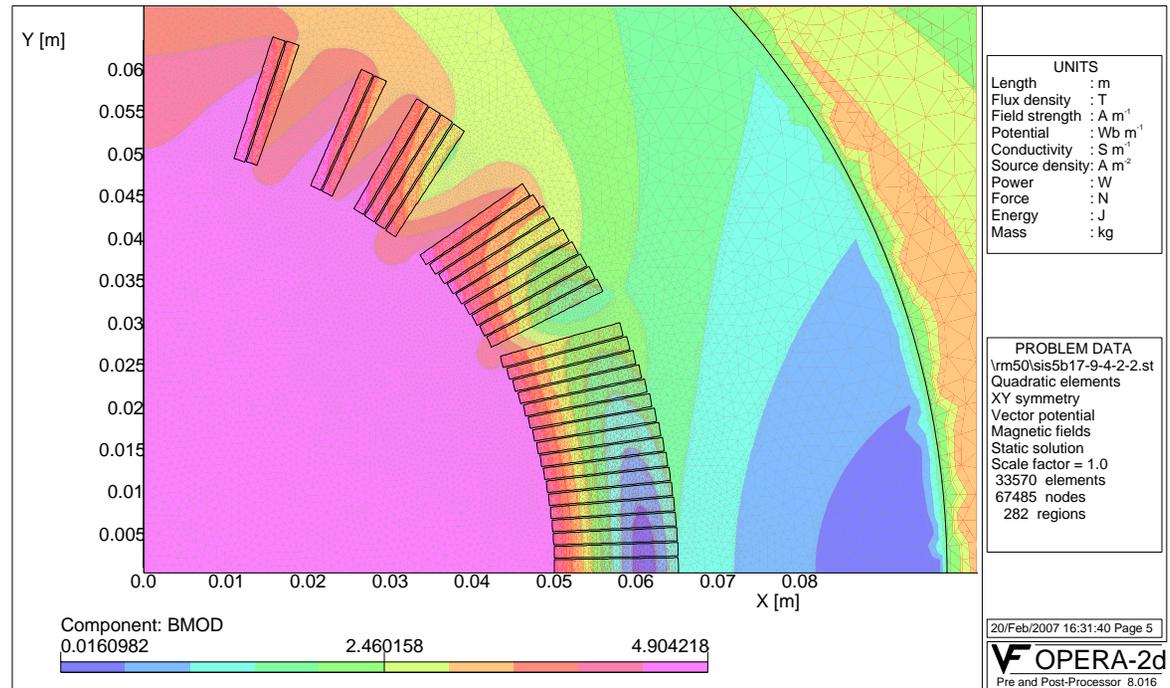


Optimized solut. for temp. margin

- Blocks are almost radial
- For the field quality, the solution is good and stable
- The temperature margin is the largest of all explored solutions

5-blocks selected configuration:

Block number	5
Turn number:	17-9-4-2-2
Current	8924 A
Bpeak (with self-field)	4.90 T
Bpeak / Bo	1.09
Temperature margin	0.99 K
Coil inner radius	50 mm
Yoke inner radius	98 mm



$$(\mu_r \text{ yoke} = \infty)$$

Harmonics (units E-4) at ref. radius R=35 mm

b3	b5	b7	b9	b11	b13
0.10	0.10	0.40	0.48	0.95	-1.11

Comments on the magnetic configuration:

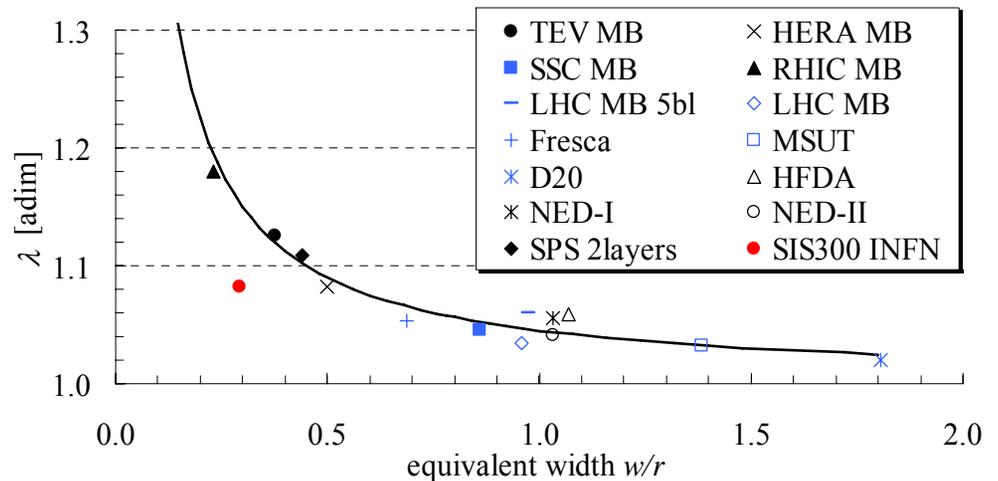
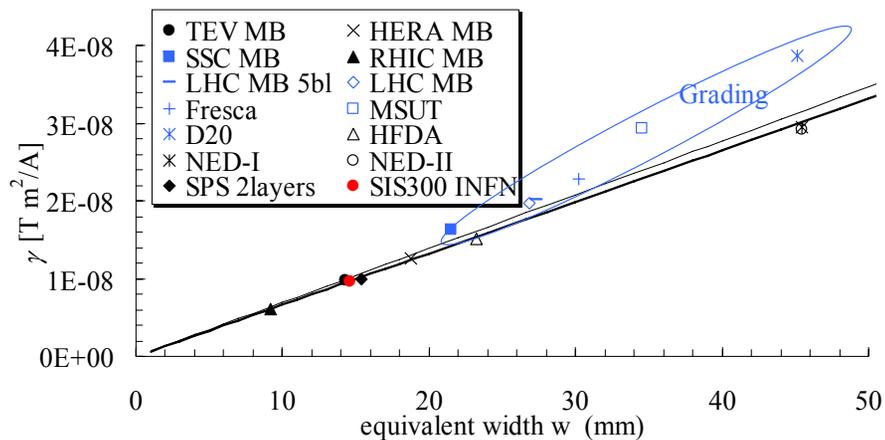
We are quite confident that this configuration has been well optimized to maximize the temperature margin; indeed the subdivision of conductors/blocks has been searched in order to decrease the peak field.

We had an informal review with Ezio Todesco (CERN), who recently has been working on general scale-law for practical superconducting dipole/quadrupole.

His comments confirm (and encourage) our convictions:

“I send you some comments on the design for GSI proposed by INFN. I use the notations given in the PRSTAB paper.

- The parameter γ (central field per unit of current density) is in line with the quantity of cable used (see Fig. 1).*
- The parameter λ (peak field to central field) is 7% less of what expected by a 72° sector coil with a wedge between 48° and 60° . 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!*



- *I find a critical field of 6.5 T. This puts you at 69% of the loadline, i.e. a margin of 31%. Usually magnets work with 20% margin, but here you have the losses.*
- *With respect to my scaling law, I find that you managed to have 4.0% more in critical field (compared to a case with the same quantity of cable), or 1.7% more in critical field (compared to a case with the same width of cable, i.e. using a classical cross-section with 36 turns).*
- *Therefore, the comments I made in our meeting at CERN (try to increase the critical field putting more conductors) are wrong. I think it is very well optimized, congratulations.*”

(Ezio Todesco, private email, 18 April 2007)

STORED ENERGY AND INDUCTANCE

<i>2D calculation</i>	<i>New design</i> <i>($\varnothing = 100 \text{ mm}$)</i>	<i>Old design</i> <i>($\varnothing = 92 \text{ mm}$)</i>
Stored energy / length	116.8 kJ/m	97 kJ/m
Inductance / length	2.9 mH/m	2.7 mH/m
Total energy (7.76 m)	0.90 MJ	0.76 MJ
Total inductance	22.5 mH	21.0 mH
Current ramp (@ dB/dt = 1 T/s)	1980 A/s	1880 A/s
L dI/dt	45 V	40 V

Magnetization effects

The main perturbation on b3 (and b5) due to magnetization of the materials are:

1. Persistent current in the s.c. filament
2. Inter-filament coupling current
3. Inter-strand coupling current
4. Paramagnetism of CuMn component of conductor
5. Magnetization and eddy current of beam tube
6. Magnetization of collar
7. Saturation effects of the iron yoke

1. Persistent current & 2. inter filament coupling current.

It has been calculated with different approaches/codes. In all cases the magnetization of the strand has been calculated following the M.N. Wilson approach.

$$M_w = \frac{2}{3\pi} \lambda_f J_c(B) d_f + \frac{2}{\mu_o} \lambda_{fb} B'_i \tau(B)$$

$$\tau = \frac{\mu_o}{2\rho_i(B)} \left(\frac{p}{2\pi} \right)^2$$

The different codes are:

- *Roxie* (a bit more sophisticated model for p.c.)
- Analytical *fortran code*
- *Opera & Ansys* with non-linear B-H curve for conductor
- *Ansys* with the description of current loops on each strand

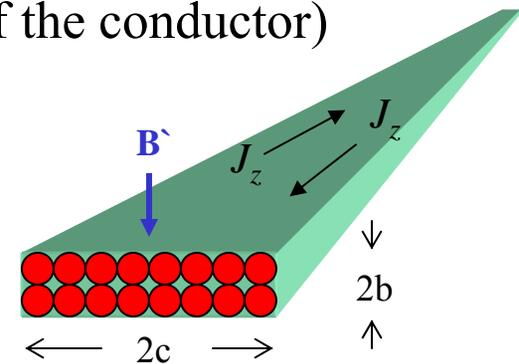
3. Inter strand coupling current via adjacent resistance and transverse field.

Calculated with:

- *Roxie* (Network modelization of Rutherford cable)
- Analytical *Excel code* (Wilson model)

(integration of the tranverse field B_t along the width of the conductor)

$$J_z(x) = \frac{p}{2R_A b \cdot c} \left(\int_0^x \dot{B} dx' - \frac{1}{2c} \int_0^{2c} dx'' \int_0^{x''} \dot{B} dx' \right)$$



3. Inter strand coupling current via crossover resistance and coupling current via adjacent resistance in parallel field .

- Calculated only with *Roxie* (Network modelization of Rutherford cable)
- Not further investigated because negligible for field perturbation (also the losses are much lower than other contributions)

Comparison between different codes

		P.C.		I.F.C.C.		I.S.C.C. (Ra)	
		$\delta b3$	$\delta b5$	$\delta b3$	$\delta b5$	$\delta b3$	$\delta b5$
B0 = 0.5 T	Roxie	-3.49	-0.37	-0.63	0.09	0.04	-0.15
	Opera	-3.67	-0.45	-0.63	0.08	-	-
	Fortran code	-3.65	-0.44	-0.63	0.1	-	-
	Excel code	-	-	-	-	0.03	-0.08
	Ansys dipole	-3.41	-0.55	-	-	-	-
	Ansys magn	-3.54	-0.38	-	-	-	-
B0 = 1.5 T	Roxie	-0.72	-0.09	-0.17	0.02	0.02 / 0.00	-0.05 / -0.04
	Opera	-0.72	-0.09	ok	ok	-	-
	Fortran code	-0.72	-0.09	-0.16	0.02	-	-
	Excel code	-	-	-	-	0.01	-0.03
	Ansys dipole	-0.70	-0.08	-	-	-	-
	Ansys magn	-0.74	-0.09	-	-	-	-
B0 = 3.0 T	Roxie	-0.25	-0.04	-0.06	0.01	0.01 / 0.00	-0.02 / -0.02
	Opera	-0.25	-0.04	ok	ok	-	-
	Fortran code	-0.25	-0.03	-0.06	0.01	-	-
	Excel code	-	-	-	-	0.00	-0.01
	Ansys dipole	-0.24	-0.05	-	-	-	-
	Ansys magn	-0.26	-0.04	-	-	-	-
B0 = 4.5 T	Roxie	-0.13	-0.02	-0.03	0	0.00 / 0.00	-0.02 / -0.01
	Opera	-0.13	-0.02	ok	ok	-	-
	Fortran code	-0.13	-0.02	-0.04	0	-	-
	Excel code	-	-	-	-	0.00	-0.01
	Ansys dipole	-0.12	-0.03	-	-	-	-
	Ansys magn	-0.14	-0.02	-	-	-	-

Summary of magnetization of conductor: (p.c., i.f.c.c., i.s.c.c)
 (missing CuMn paramagnetic effects)

- Acceleration mode (dB/dt = 1 T/s):

Central field	1.5 T	3.0 T	4.5 T
Δb_3 (units)	-0.89	-0.31	-0.16

- Flat top @ 4.5 T (dB/dt = 0)

$$\Delta b_3 = -0.13 \text{ units,}$$

$$\Delta b_n < 0.02 \text{ units (n=5,7,9,...)}$$

- Stretcher mode @ 0.5 T (dB/dt = 0)

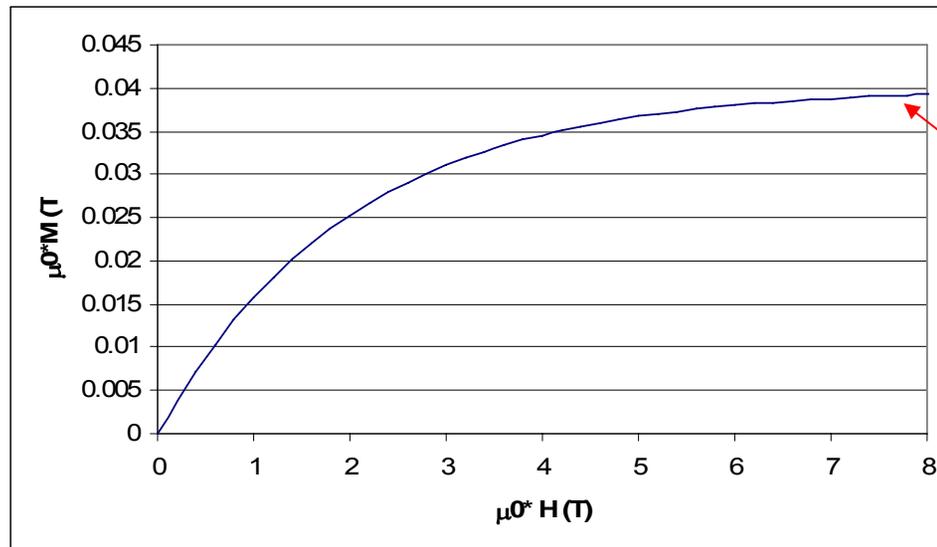
$$\Delta b_3 = -3.6 \text{ units,}$$

$$\Delta b_5 = -0.5 \text{ units}$$

cable twist pitch	p	0.1	m
crossover resistance	Rc	2.00E-02	ohm
adjacent resistance	Ra	2.00E-04	ohm
number of strands	N	36	
radius of fil't boundary	a _{fb}	0.3690	mm
matrix ratio	mat	1.800	
filament filling factor	λ_f	0.357	
wire trans res'y intercept	C _{pet}	4.00E-10	ohm.m
wire trans res'y gradient	m _{pet}	2.00E-10	ohm.m/T
wire twist pitch	p _w	5.00E-03	m
filament diameter	d _f	3.50E-06	m
cooking factors		1.00	

4. Paramagnetism of CuMn matrix .

- By preliminary measurements, the paramagnetic component of CuMn has the approximate behaviour:



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

- The perturbation in the field quality is less than 1 unit:

Central field	1.5 T	3.0 T	4.5 T
Δb_3 (units)	0.67	0.53	0.44
Δb_5 (units)	-0.11	-0.10	-0.04

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

5. Magnetization and eddy current in the beam tube.

- Analytical calculation gives zero contribution on harmonics (only very small dipole error $b1 \approx -0.1$ unit)

Magnetization of beam tube

$$B_{inner} = B_0 \left[1 - \frac{(\mu_r - 1)^2}{4\mu_r} \left(1 - \frac{r_{int}^2}{r_{ext}^2} \right) \right]$$

Eddy current in beam tube

$$J_{Zeddy}(\vartheta) = -\frac{1}{\rho} \dot{B}_0 r_{av.} \cdot \cos(\vartheta)$$

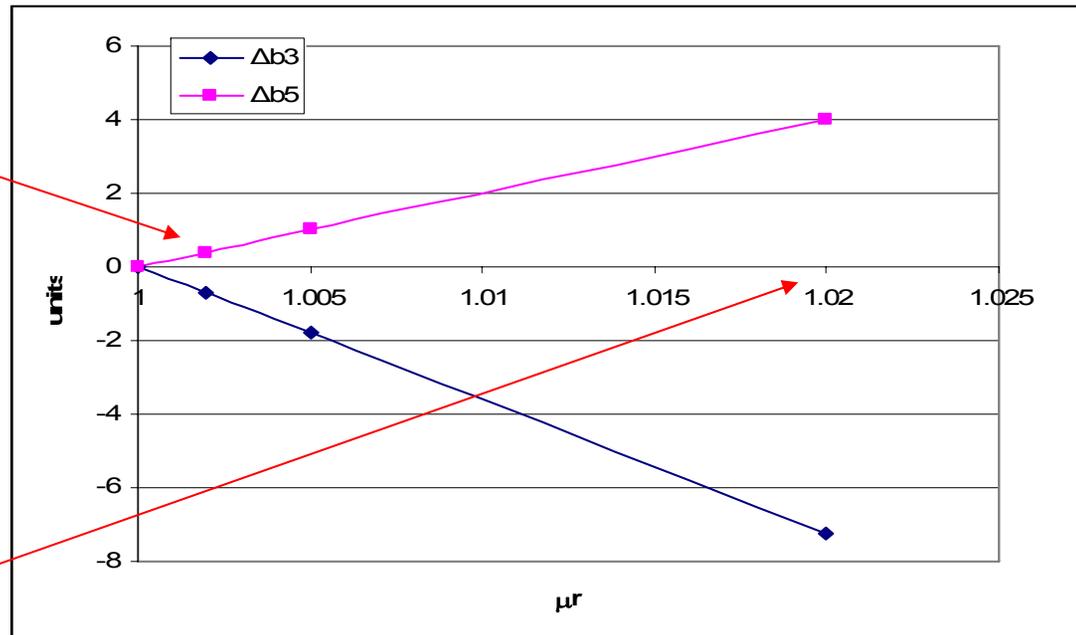
- These results are confirmed by 2-D calculation with OPERA

(Warning: the LOSSES are not negligible!)

6. Magnetization of collar

LHC value: $\mu_r = 1.002$

Standard AISI316
 $\mu_r = 1.02$



In order to keep the effect below 1 unit, it is necessary to use very qualified stainless steel (for example Nitronic 40).

7. Saturation of the iron yoke

- The effect is strongly dependent on the real geometry and properties of the yoke:

- yoke outer radius
- ancillary holes (bus bars, etc.)
- actual geometry of the inner surface of yoke
- actual B-H curve of iron

- The harmonic variation between $B_0=1.5$ T-4.5 T is about:

$$\Delta b_3 = -2 \text{ units}, \quad \Delta b_5 = -0.2 \text{ units}$$

- These perturbations can be corrected, **but** a more detailed definition of the above parameters is required.

Conclusions:

The proposed 5-blocks configuration with larger aperture has:

- Good field quality
- The perturbation on field quality due to magnetization of materials can be calculated with enough accuracy (according to present models), and all methods converge to the same results.
- Moderate harmonic perturbation during the ramp
- More informations are needed to complete the yoke cross section
- Some confirmation measurements for paramagnetism of CuMn should be given