Electromagnetic Design of the Dipole Model for the FAIR SIS 300

M. Sorbi, F. Alessandria, G. Bellomo, P. Fabbricatore,

S. Farinon, U. Gambardella, R. Musenich and G. Volpini

***Milan University* & *INFN* Sez. di Milano, Genova, L.N.F.**

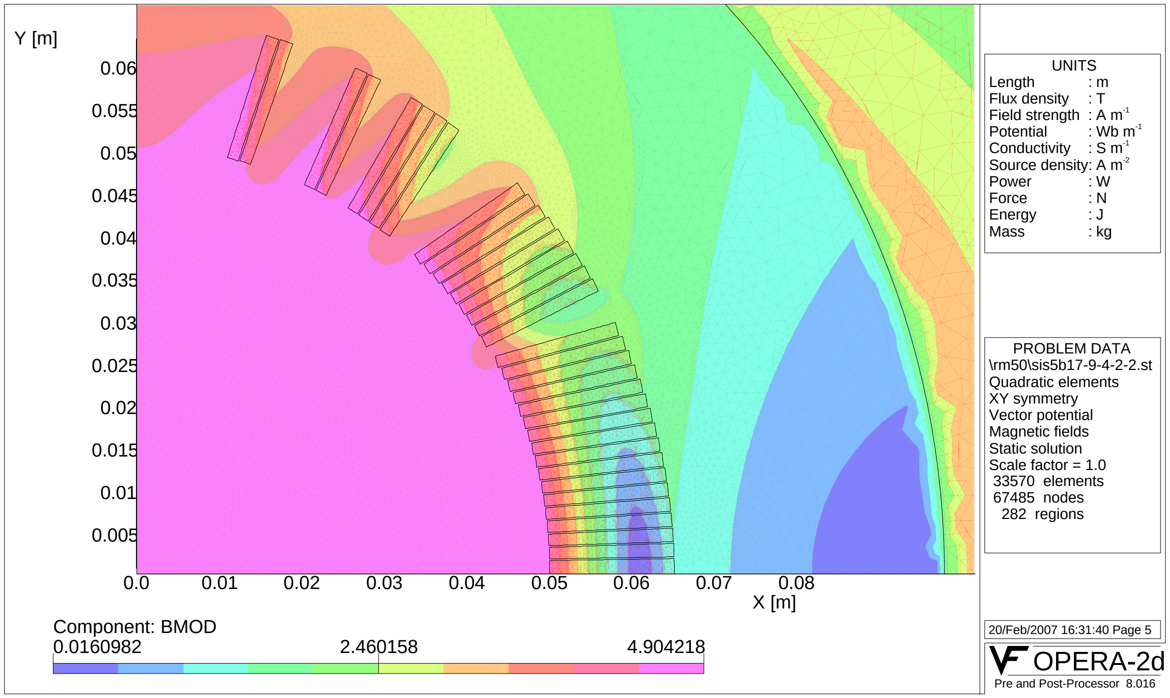
Contents:

Main dipole parameters

MAIN	**Value**
Nominal field	**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 cooling GHe	**4.7 K**
Field quality	$\pm 2*10^{-4}$
Reference radius for field quality	35 mm (70% Rm)
Yoke outer radius	< 250 mm

2-D magnet design

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



(μ_r yoke = ∞)

Harmonics (units 10^{-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

Field perturbation

Different approaches have been used to compute field perturbation

Sextupole and **decapole** field harmonic, due to **persistent currents**
(ref. radius=35 mm, units x 10^{-4})

Bo (T)	**0.5**	**1.5**	**3.0**	**4.5**
	δb3 / δb5	**δb3 / δb5**	**δb3 / δb5**	**δb3 / δb5**
Fortran code	-3.65/-0.44	-0.72/-0.09	-0.25/-0.03	-0.13/-0.02
Ansys dipole	-3.41/-0.55	-0.70/-0.08	-0.24/-0.05	-0.12/-0.03
Opera	-3.67/-0.45	-0.72/-0.09	-0.25/-0.04	-0.13/-0.02
Ansys	-3.54/-0.38	-0.74/-0.09	-0.26/-0.04	-0.14/-0.02
Roxie	-3.49/-0.37	-0.72/-0.09	-0.25/-0.04	-0.13/-0.02

Sextupole and **decapole** field harmonic, due to **inter-filament** coupling currents (ref. radius=35 mm, units x 10^{-4})

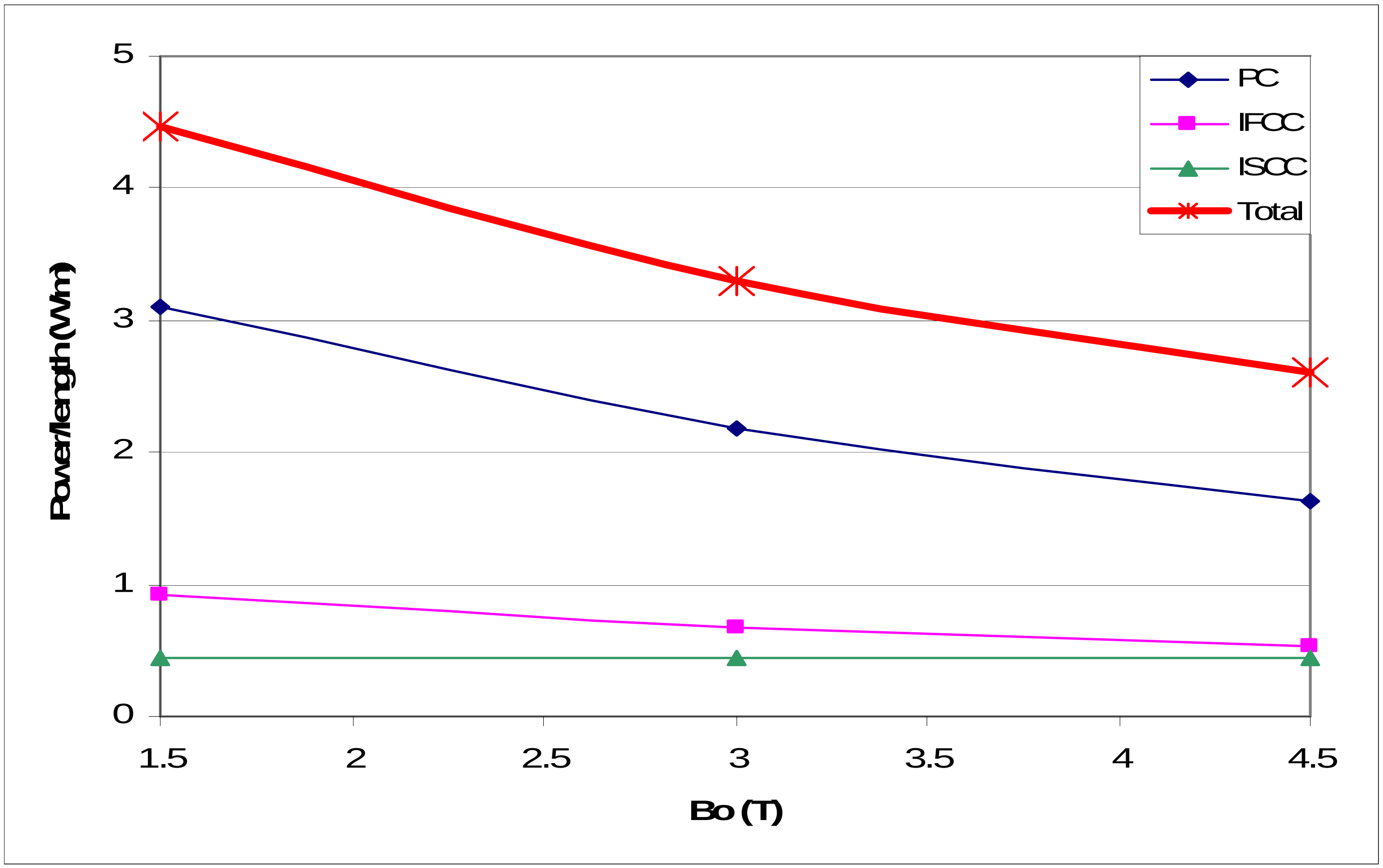
Bo (T)	**0.5**	**1.5**	**3.0**	**4.5**
	δb3 / δb5	**δb3 / δb5**	**δb3 / δb5**	**δb3 / δb5**
Fortran code	-0.63 / 0.10	-0.16 / 0.02	-0.06 / 0.01	-0.04 / 0.00
Opera	-0.63 / 0.08	-0.17 / 0.02	-0.06 / 0.01	-0.03 / 0.00
Roxie	-0.63 / 0.09	-0.17 / 0.02	-0.06 / 0.01	-0.03 / 0.00

Sextupole and **decapole** field harmonic, due to **inter-strand** coupling currents (ref. radius=35 mm, units x 10^{-4})

Bo (T)	**0.5**	**1.5**	**3.0**	**4.5**
	δb3 / δb5	**δb3 / δb5**	**δb3 / δb5**	**δb3 / δb5**
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

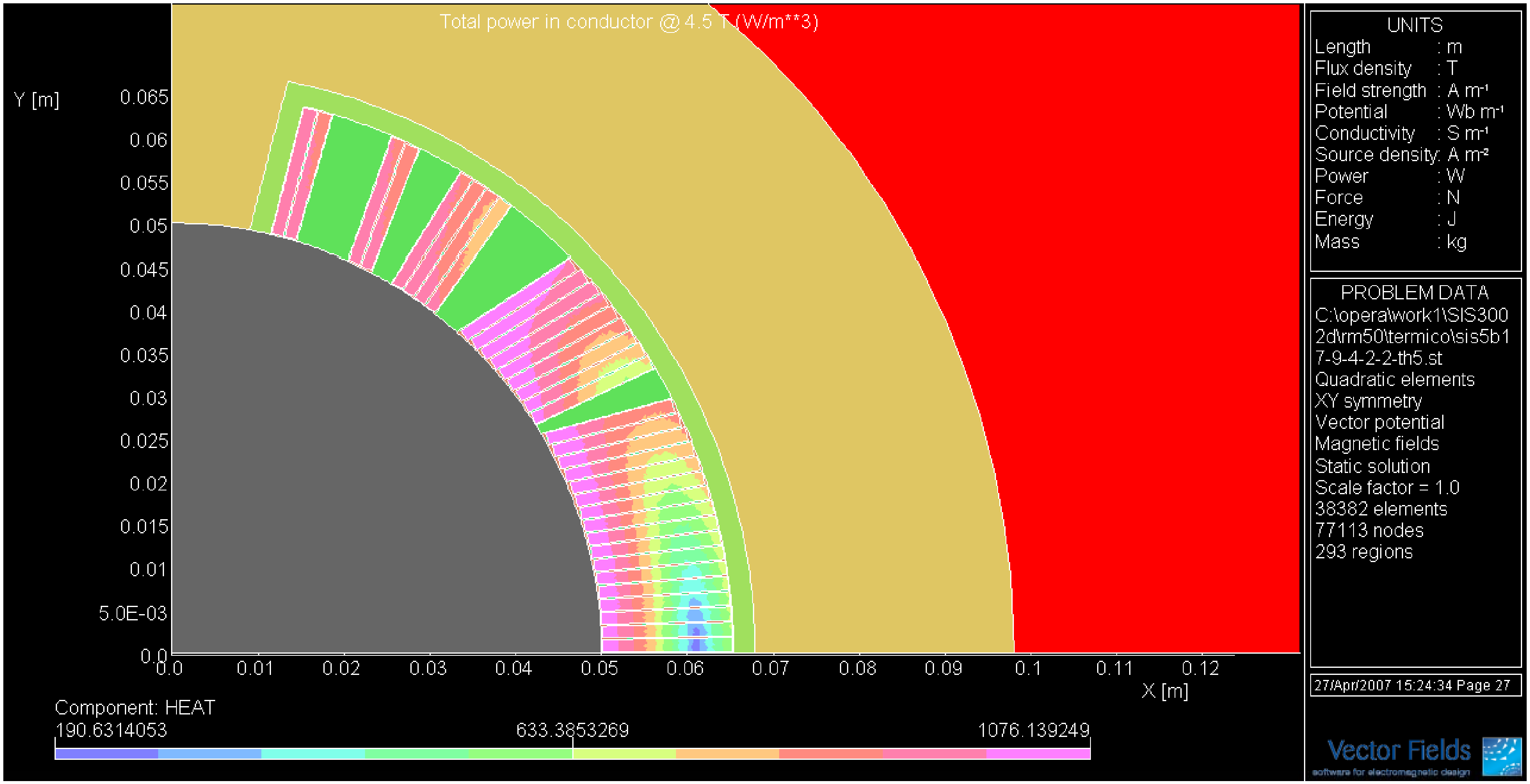
Losses in conductor

Summary of the losses in conductors during ramp-up



Power distribution in conductor @ Bo=4.5 T

[Peak power 1080 W/m^3]

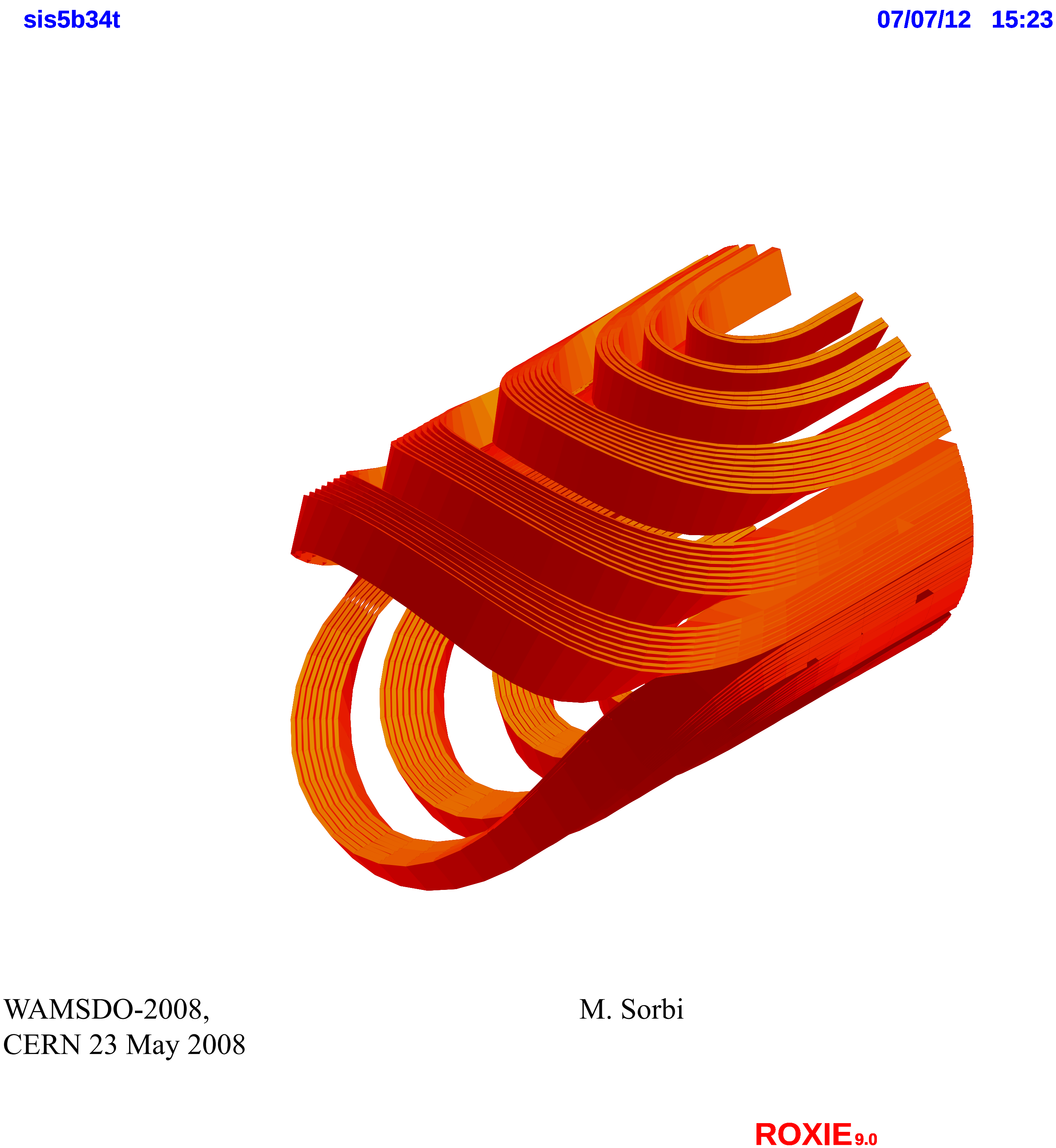


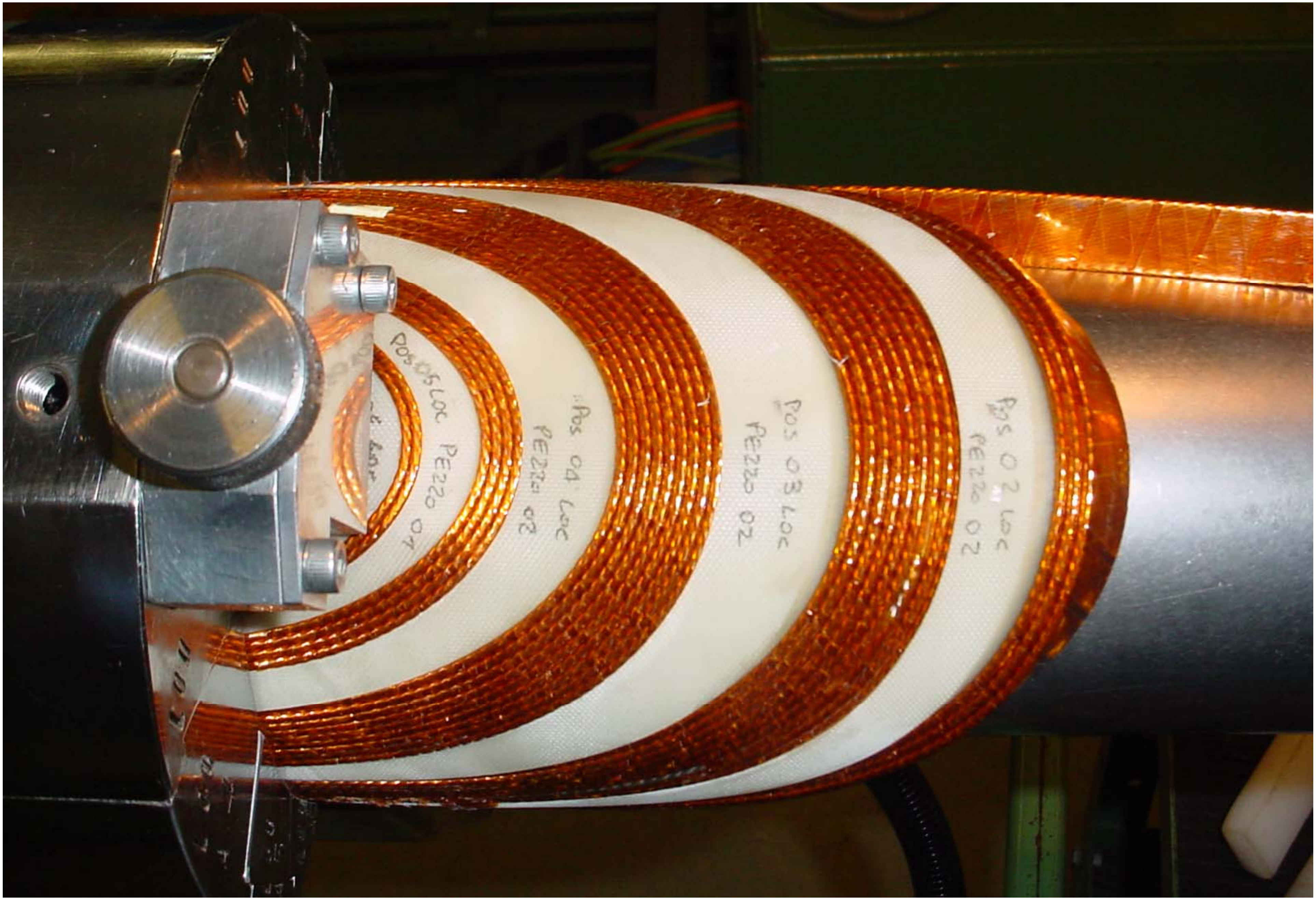
Coil-ends design

The magnetic optimization of the coil-ends has been performed with ROXIE and OPERA 3-D

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.


sis5b34t
07/07/12 15:23
ROXIE9.0


Pos 05 Loc PE220 01
Pos 04 Loc PE220 02
Pos 03 Loc PE220 02
Pos 02 Loc PE220 02

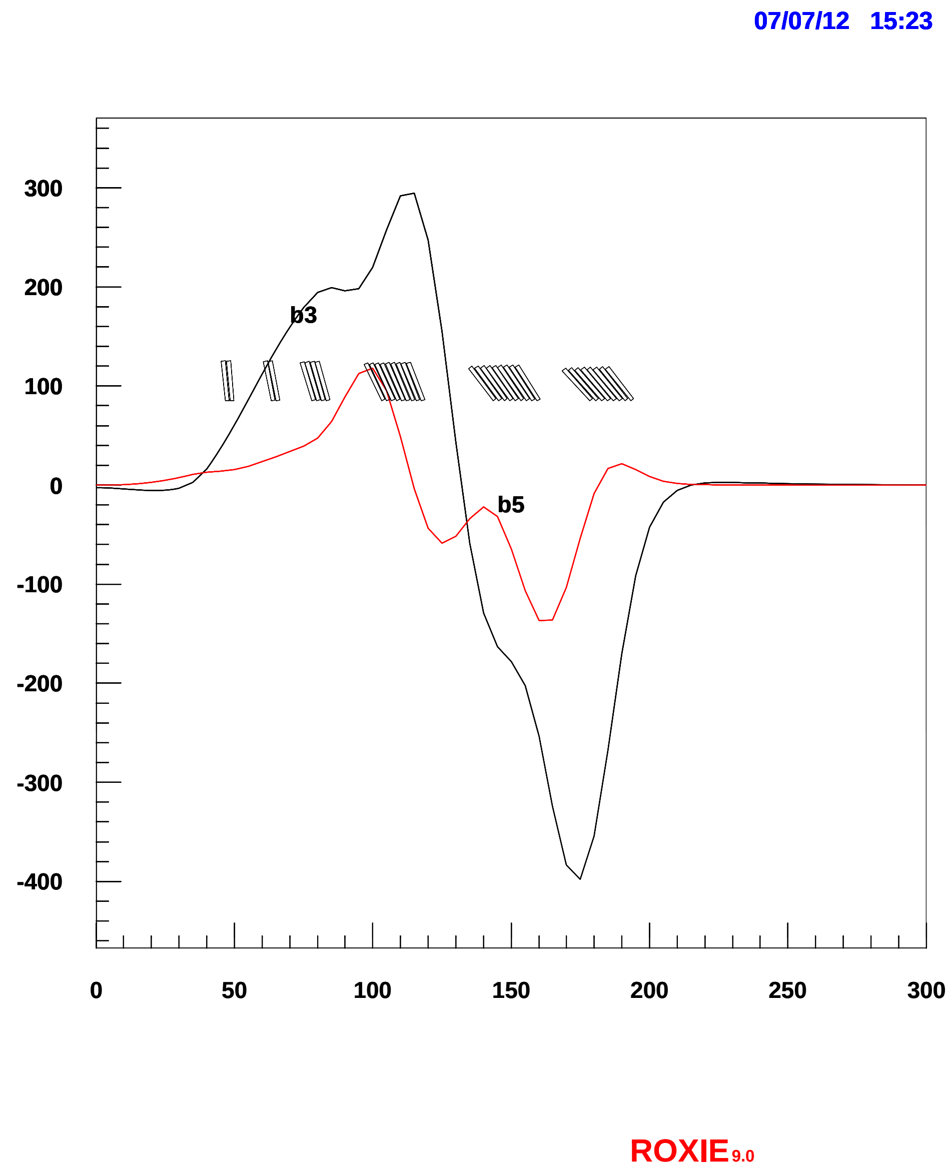
Averaged harmonics in symmetric coil-end “**in air**”:

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

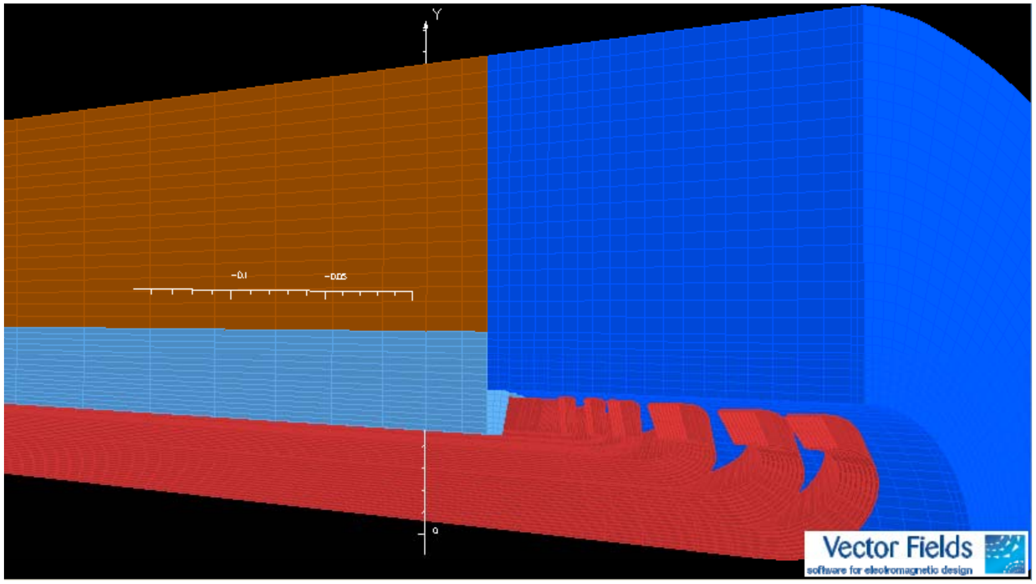
$$b_5^{\,coil-end} = \frac{1}{B_0}\frac{1}{\Delta z}\int_0^{\Delta z} B_5\,dz = 0.04 \text{ units}$$

with :

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



In order to decrease the peak-field in conductor, a configuration with "short yoke" has been adopted.



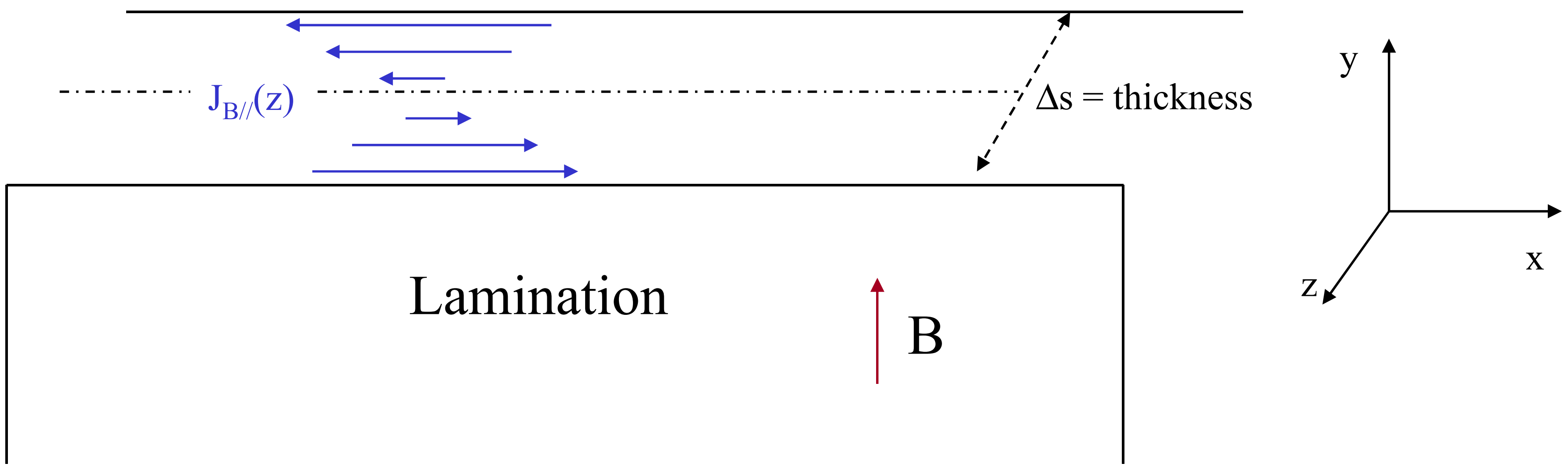
	2-D analysis	Long yoke *Yoke up to z=206 mm*	Short yoke *No yoke from z=0*
B_{peak} on cond. (T)	**4.87**	4.96	4.59
T_g (K)	**5.73**	5.69	5.88
L_m (mm)	**-**	125.0	100.7

Losses in laminations

The losses due to the eddy currents in the laminations of the collar and of the yoke can be evaluated easily **in the straight part of the magnet** with a 2-D analysis.

The 2-D magnetic field *B* has only components parallel to the lamination.

The eddy currents have components *mainly* parallel to the lamination AND have simple symmetries along the thickness.



The RMS current density (averaged on the lamination thickness ***Δs***) can be evaluated analytically with a "1-D analysis":

$$\left[J_{B_{//}}(x,y)\right]_{\Delta s-RMS} = \frac{1}{2\sqrt{3}\rho}\dot{B}(x,y)\Delta s$$

where the magnetic field *B* is approximated to the magneto-static field (the field perturbation due to eddy currents is neglected).

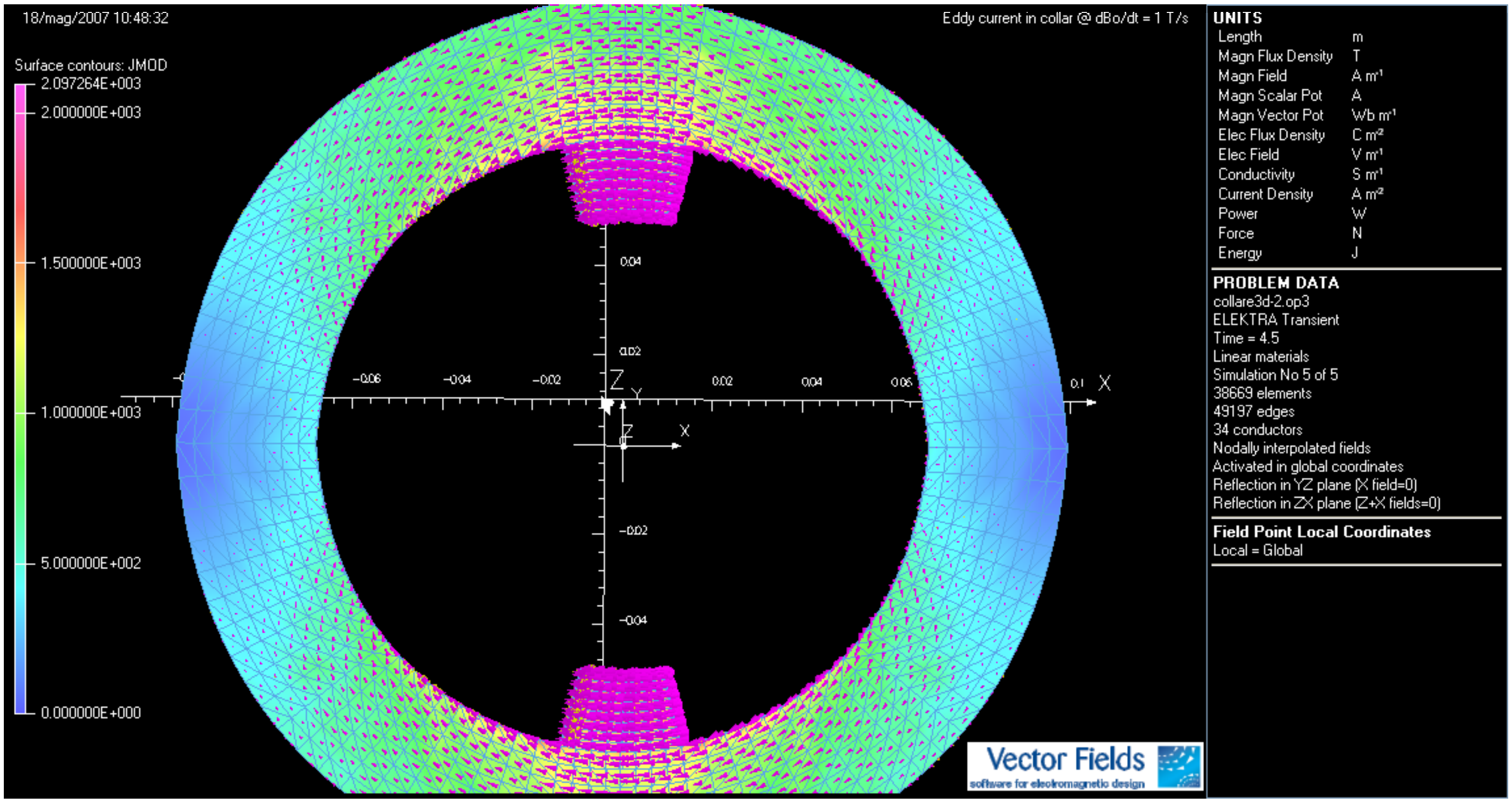
As consequence the volumetric losses in the laminations can be calculated easily:

$$p_{B//}(x,y) = \rho \cdot \left\{ \left[J_{B//} \right]_{\Delta s - RMS} \right\}^2 = \frac{1}{12\rho} \dot{B}(x,y)^2 \Delta s^2$$

This simplified 1-D model has been validated by a complete 3-D description of the collar, with ELEKTRA-3D

$$P_{B//} = \int_{Collar\ area} \frac{1}{12\rho} \dot{B}^2 \Delta s^2 d\Sigma \cong P_{3-D}(ELEKTRA)$$ **= 5.7 mW/m**

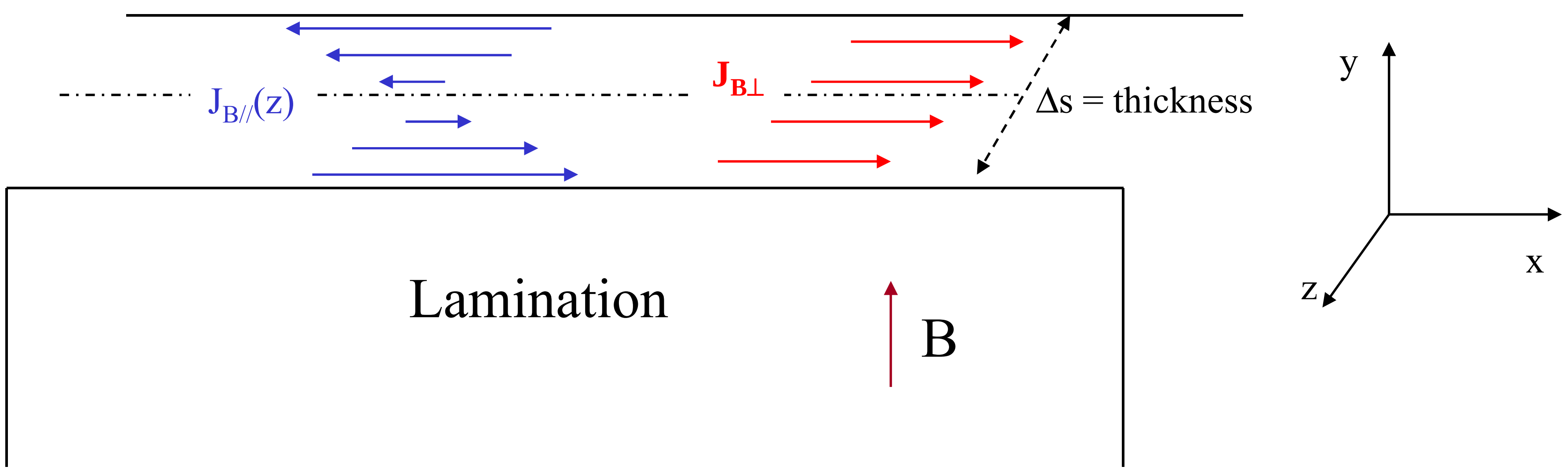
Plot of the eddy current pattern, in a full 3-D description of the collar with the true lamination thickness.



In the **coil end**, there is also the *z*-component of the field *B* (in addition to the parallel components of the field), which produces *additional* eddy currents $J_{B\perp}$ in the *x* and *y* directions.

If the B_z varies smoothly in *z*-direction, we can assume $J_{B\perp}$ is constant in the lamination thickness Δs :

$$\frac{1}{B_z}\frac{\partial B_z}{\partial z}\Delta s << 1 \quad \Rightarrow \quad J_{B\perp}(x,y,z) \approx \text{constant in } \Delta s$$



Consequently the $J_{B\perp}$ can be calculated with ELEKTRA 3-D, assuming, *instead of lamination,* an anisotropic material with electrical conductivity σ:

$$\begin{cases} \sigma_x = 1/\rho \\ \sigma_y = 1/\rho \\ \sigma_z = 0 \end{cases} \qquad \textit{with} \quad \rho = \rho_{collar} \approx \rho_{iron} \approx 5.3 \cdot 10^{-7}\,\Omega\mathrm{m}$$

If we are interested to the total power density in the lamination $p_{\Delta s\text{-}av}(x,y)$:

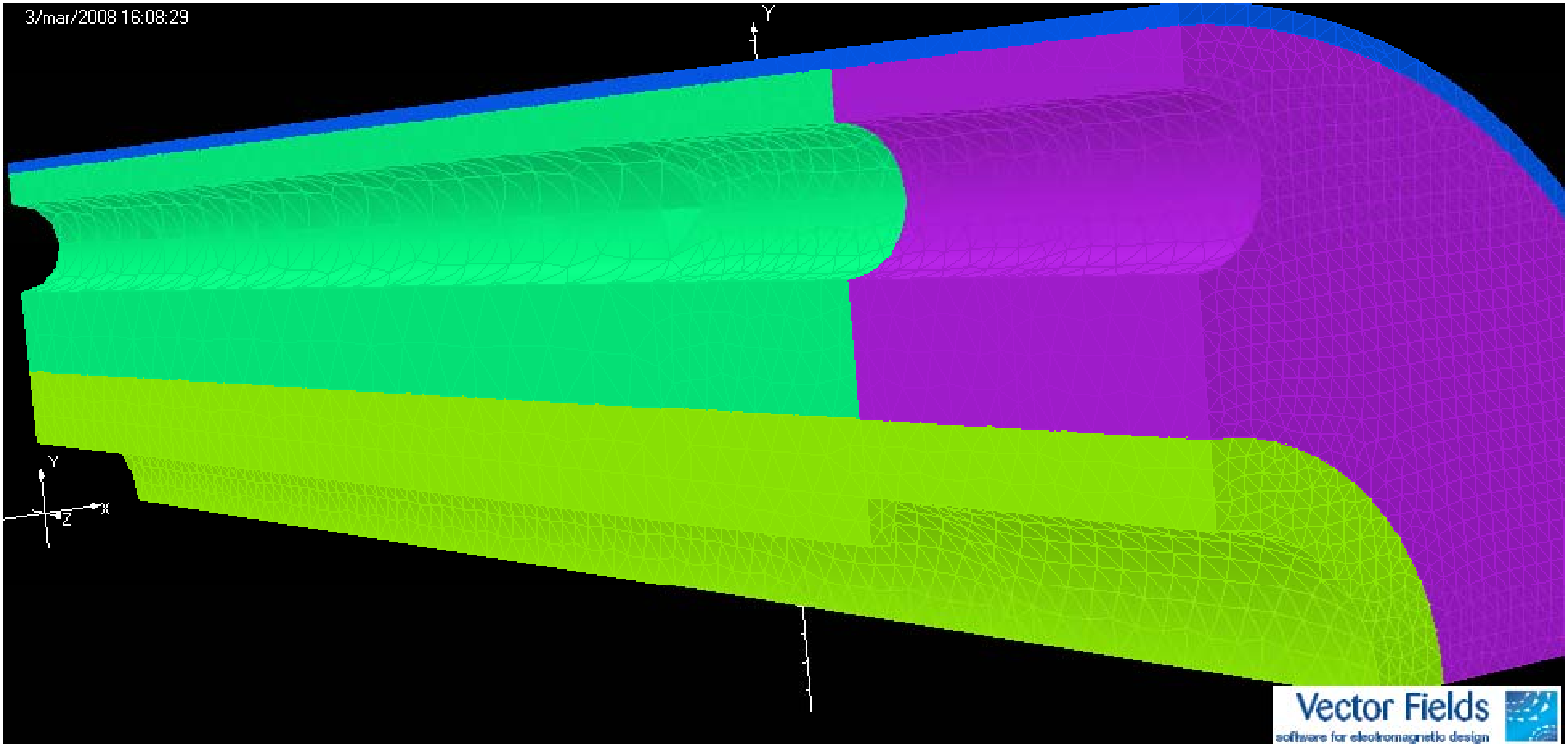
$$p_{\Delta s-av.}(x,y) = p_{B//}(x,y) + p_{B\perp}(x,y) = \frac{1}{12\rho}\dot{B}_{//}(x,y)^2\,\Delta s^2 + \rho \cdot J_{B\perp}(x,y)^2$$

The *Bz* component of the magnetic field in the yoke is strongly dependent by the actual reluctivity of iron lamination, which is reduced by the stacking factor.

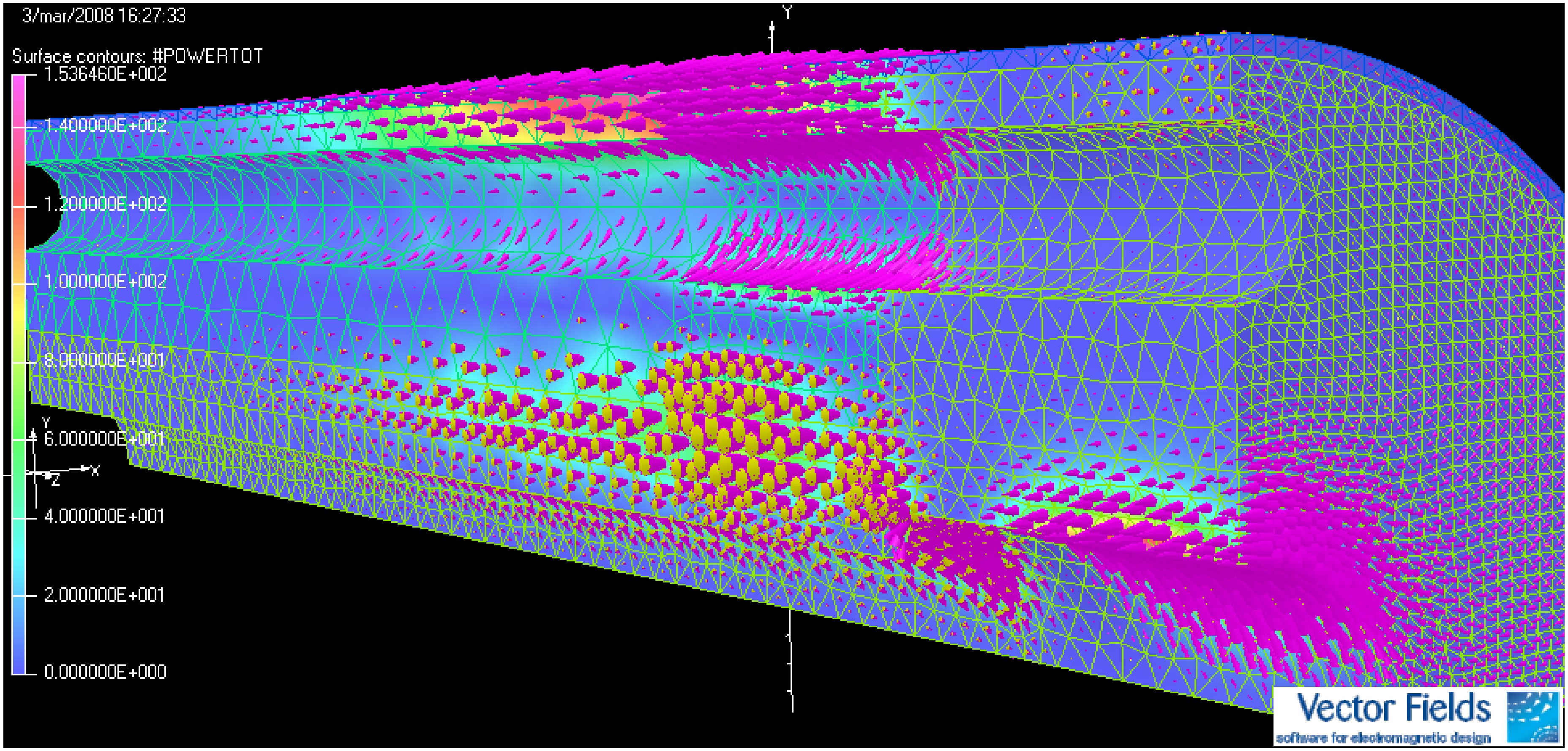
Moreover stacking factor introduces an anisotropic behavior for the magnetic field.

The complete and coupled problem (transient analysis, with magnetic, anisotropic and non-linear material) has been solved with ELEKTRA 3-D.

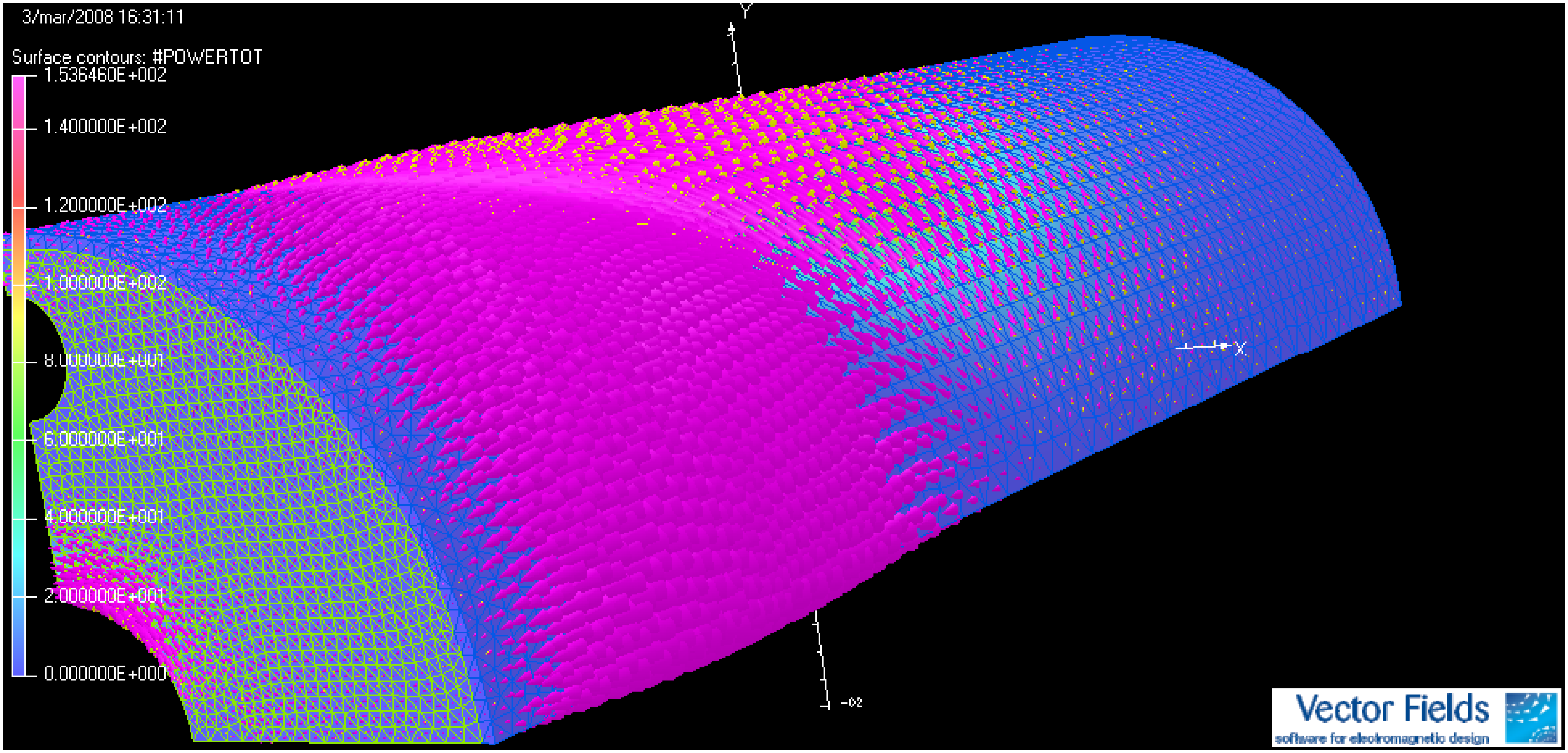
1/8 of the model (1.2 m long)



The first conclusion is that the electrical contact between the yoke lamination and the He cylindrical vessel increases losses.

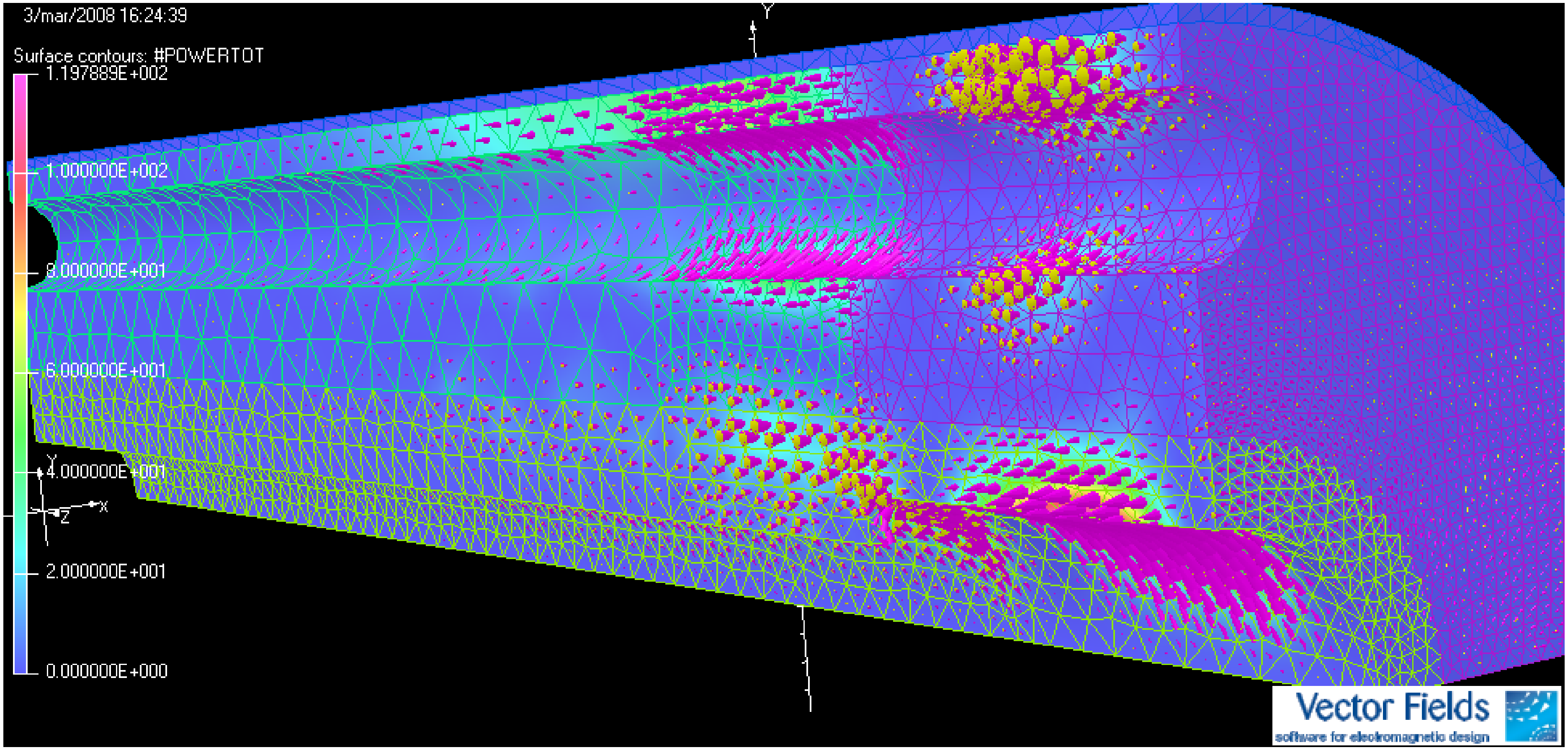


Losses (colours) and current (arrows) @ 4.5 T



Current in the He cylindrical vessel @ 4.5 T

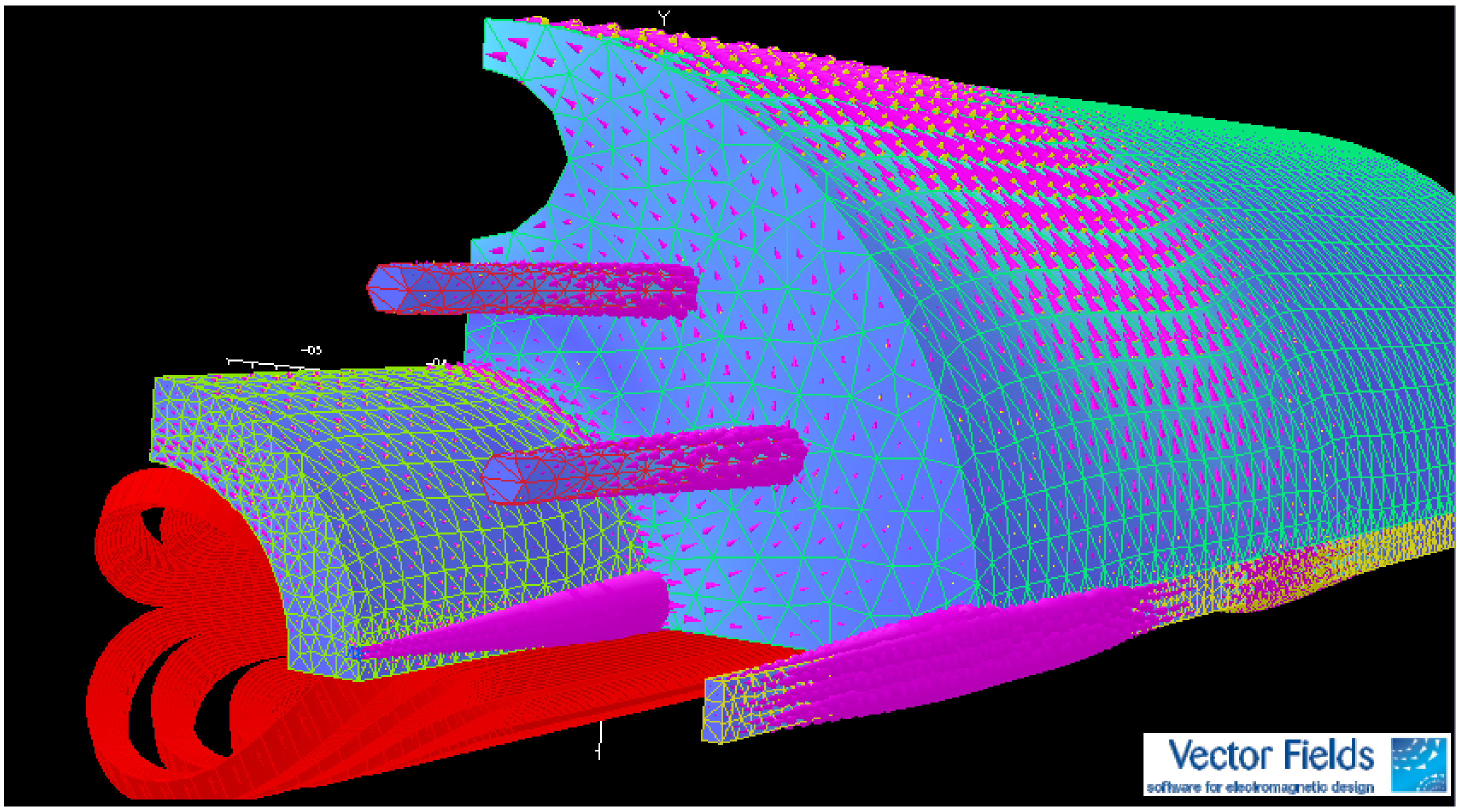
With **no-electrical** continuity between laminations and vessel, the losses are much lower (especially at low field).



Losses (colours) and current (arrows) @ 4.5 T

Other main sources of losses are the eddy currents in pins and keys in the collar and yoke laminations (they are like short-circuit for eddy current)

The study of these dissipative powers has been done with OPERA-3D & validated with analytical approaches.



Summary of losses in the magnet during ramp-up at 1 T/s

	In straight section (W/m)			In each coil end (W)		
Bo	**1.5 T**	**3.0 T**	**4.5 T**	**1.5 T**	**3.0 T**	**4.5 T**
Conductor	**4.500**	**3.300**	**2.600**	0.630	0.462	0.364
Collar eddy	0.006	0.006	0.006	0.284	0.579	0.418
Yoke eddy	0.002	0.002	0.002	0.326	1.465	1.834
Collar pins	0.124	0.124	0.100	0.024	0.024	0.000
Collar keys	0.580	0.572	0.484	0.113	0.112	0.094
Yoke pins	0.316	1.824	1.064	0.408	0.356	0.000
Yoke keys	0.000	0.000	0.000	0.040	0.120	0.044
Yoke hyst.	~1.33	~1.33	~1.33	~0.259	~0.259	~0.259
Beam tube	1.000	1.000	1.000	0.195	0.195	0.195
TOTAL	**7.86**	**8.16**	**6.59**	**2.28**	**3.57**	**3.21**

Bo (T)	**In the 3.8 m long dipole (W)**	**In the 7.6 m long dipole (W)**
1.5	34.4	64.3
3.0	38.1	69.1
4.5	31.4	56.5

Conclusions

• The 2-D magnetic design of the curved dipole for SIS300 is defined.

• Several methods and codes have been used to evaluate the field harmonic perturbation due to pulsed regime of the magnet: the agreement in the results is very good

• The losses on the conductor in the 2-D configuration have been evaluated

• The losses in laminations have been evaluated (both in straight sections and in coil-ends)

• The total estimated power dissipated in the magnet ranges between 6 W/m and 9 W/m.

The end!

APPENDIX

Conductor parameters

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	λf	0.357	
wire trans res'y intercept	$C_{\rho et}$	4.00E-10	ohm.m
wire trans res'y gradient	$m_{\rho et}$	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**	

APPENDIX

SUMMARY OF CABLE LOSSES (averaged 1.5 T – 4.5 T @ 1 T/s)

	ramp'g power W/m	loss/ cycle J/m	fraction of total %
transv'se cros'r	0.11	0.7	3.3%
transv'se adj'nt	0.23	1.4	6.8%
parallel adjacent	0.00	0.0	0.1%
fil'nt coupling	0.69	4.1	20.0%
total hysteresis	2.41	14.4	69.8%
total magnet	3.45	20.7	100.0%

The power is averaged on the ramp up
The loss/cycle is averaged on the full cycle (up and down)

APPENDIX

Magnetization and eddy current in the beam tube.

• Analytical calculation gives zero contribution on harmonics (only very small dipole error *b1* ≈ -0.1 unit)

Magnetization of beam tube

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

Eddy current in beam tube

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

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

(Warning: the LOSSES are not negligible!)

APPENDIX

Eddy current in beam pipe

• In this case the eddy currents are directed in z direction, and the power/length ***P*** can be analytical calculated:

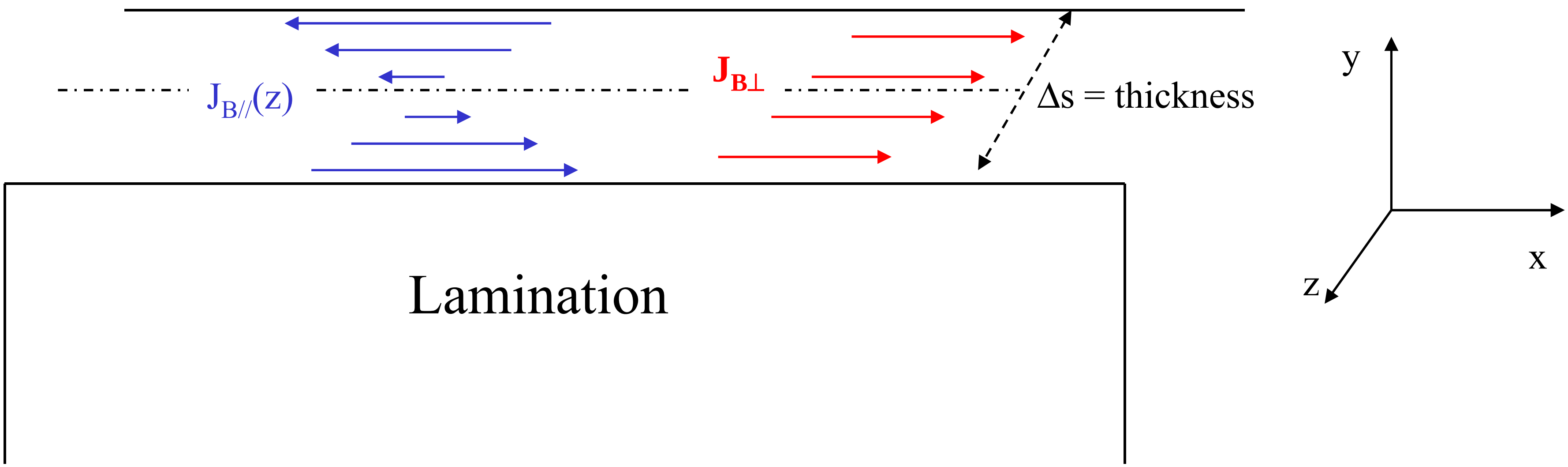
$$P = \int_{r_{inner}}^{r_{outer}} \int_{0}^{2\pi} \rho \cdot J_Z^{\;2} \cdot r \cdot d\theta dr \approx \frac{\pi}{\rho} \dot{B}_0^{\;2} \cdot r_{av}^{\;3} \cdot \Delta r$$

where $\boldsymbol{r_{av}}$**=44 mm** is the average radius of the beam pipe and $\boldsymbol{\Delta r}$ **= 2 mm** is the pipe thickness

$\boldsymbol{P}$ **= 1.0 W/m**

(not negligible as thermal load for the cooling gas)

APPENDIX



$$p_{\Delta s-av.}(x,y) = \rho \cdot \left\{ \left[J_{tot} \right]_{\Delta s-RMS} \right\}^2 = \rho \cdot \left\{ \left[J_{B\perp} + J_{B//} \right]_{\Delta s-RMS} \right\}^2$$

$$\left\{ \left[J_{B\perp} + J_{B//} \right]_{\Delta s-RMS} \right\}^2 = \frac{1}{\Delta s} \int_{\Delta s} \left[J_{B\perp} + J_{B//} \right]^2 dz = \frac{1}{\Delta s} \int_{\Delta s} \left[J_{B\perp}{}^2 + 2 J_{B\perp} \cdot J_{B//} + J_{B//}{}^2 \right] dz =$$

$$= \frac{1}{\Delta s} \int_{\Delta s} J_{B\perp}{}^2 dz + \frac{1}{\Delta s} \int_{\Delta s} J_{B//}{}^2 dz = \left\{ \left[J_{B\perp} \right]_{\Delta s-RMS} \right\}^2 + \left\{ \left[J_{B//} \right]_{\Delta s-RMS} \right\}^2$$

APPENDIX

The power:

$$p_{\Delta s-av.}(x,y) = p_{B//}(x,y) + p_{B\perp}(x,y) = \frac{1}{12\rho}\dot{B}_{//}(x,y)^2\Delta s^2 + \rho \cdot J_{B\perp}(x,y)^2$$

So the losses can be calculated “easily” in all the laminated regions ***without*** the necessity of modeling each single lamination.

It is possible just to add the two powers!

APPENDIX

Stored energy and inductance

2D calculation

Stored energy / length	116.8 kJ/m
Inductance / length	2.9 mH/m
Total magnet energy (7.76 m)	0.90 MJ
Total magnet inductance	22.5 mH
Current ramp (@ dB/dt = 1 T/s)	1980 A/s
L dI/dt	45 V