



Loss study of the model dipole for SIS300

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The main sources of losses in the cold mass of the dipole are:

1. Magnetic hysteresis in the s.c.
2. Eddy currents in conductor (inter-filaments and inter-strands)
3. Eddy currents in the collar and yoke
4. Eddy currents in the beam pipe
5. Magnetic hysteresis in the yoke

Losses in conductor

The hysteresis losses and inter-filament losses are calculated with

- Opera, Ansys and Fortran code from the conductor magnetization

$$P_{hyst.} = M_{hyst.} \dot{B}$$

$$P_{i.f.} = M_{i.f.} \dot{B}$$

- Roxie

The interstrand coupling losses have been calculated with:

- Excel code (only eddy current through Ra for transverse field)

$$p_{RA} = \rho_{RA} J_z^2 = R_A \frac{b \cdot c}{2p_c} \cdot J_z^2$$

- Roxie

All the methods converge to similar results!

Losses in conductor: comparison between different codes

Average losses, during the ramp between 1.5 T and 4.5 T

	P.C. (W/m)	I.F.C.C.(W/m)	I.S.C.C.(W/m)
Roxie	2.40	0.77	0.45
Opera	2.27	0.71	-
Fortran code	2.27	0.71	-
Excel code	-	-	0.40
Ansys	2.28	0.74	-

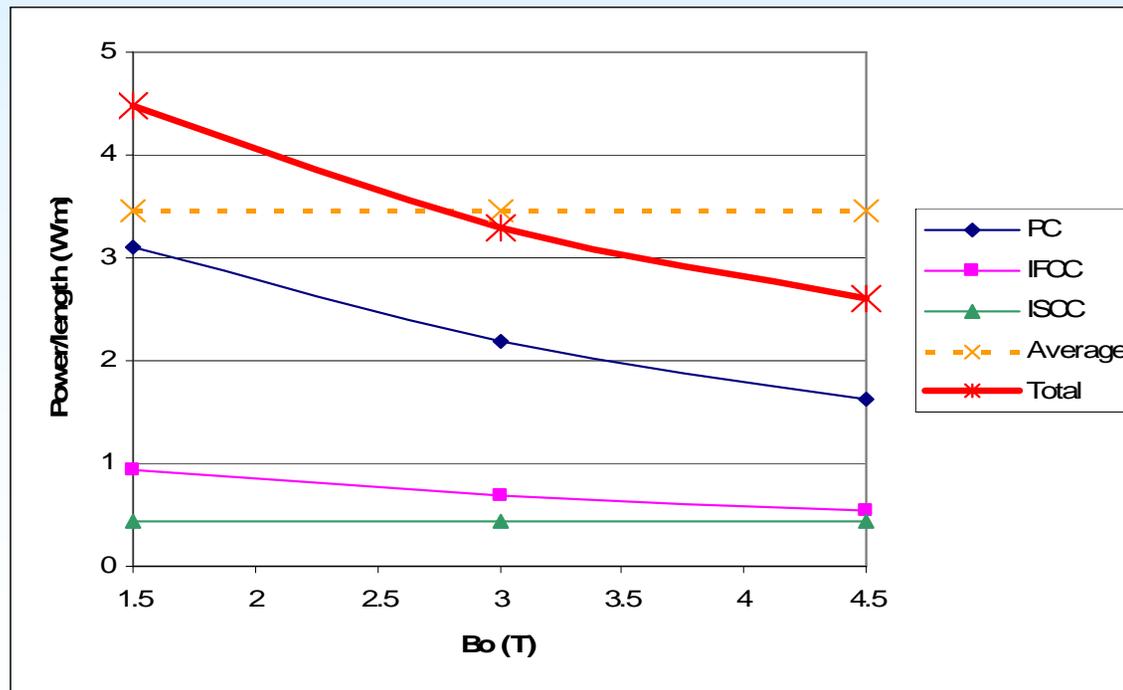
Losses during the ramp are not constant:

@ $B_0 = 1.5 \text{ T}$ $P = 4.5 \text{ W/m}$

@ $B_0 = 4.5 \text{ T}$ $P = 2.6 \text{ W/m}$

Average $P = 3.5 \text{ W/m}$

Does it help for
temperature margins ??

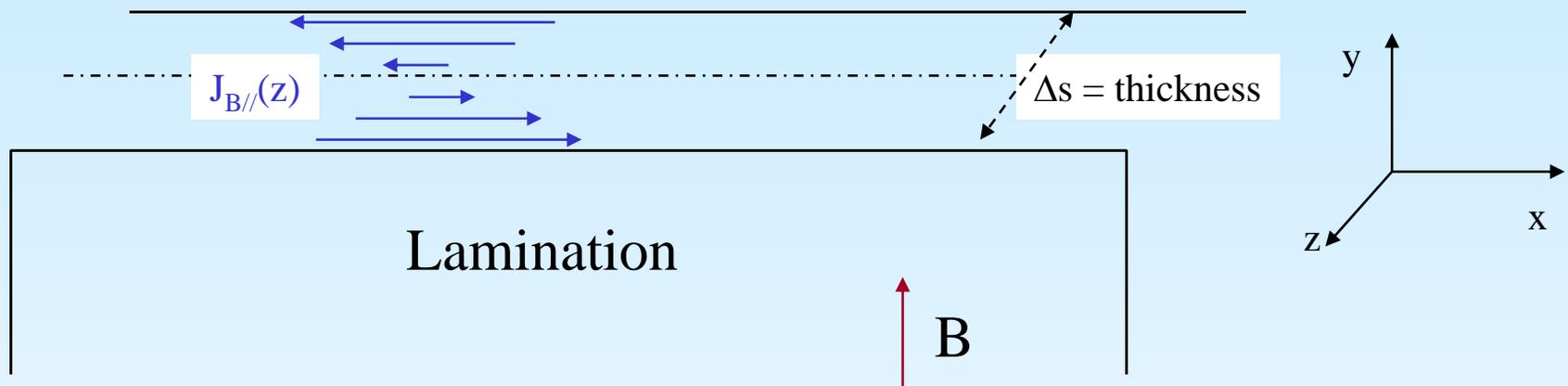


Losses in the collar and yoke lamination

The losses due to the eddy currents in the laminations of the collar and of the yoke can be divided in two types:

1. Losses due to *parallel* component of the magnetic field respect the lamination (in the **2-D** & **3-D** part of the magnet);
2. Losses due to the *perpendicular* component of the magnetic field respect the lamination (only in the **3-D** part of the magnet).

1. Losses for the *parallel* component of the magnetic field:



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).

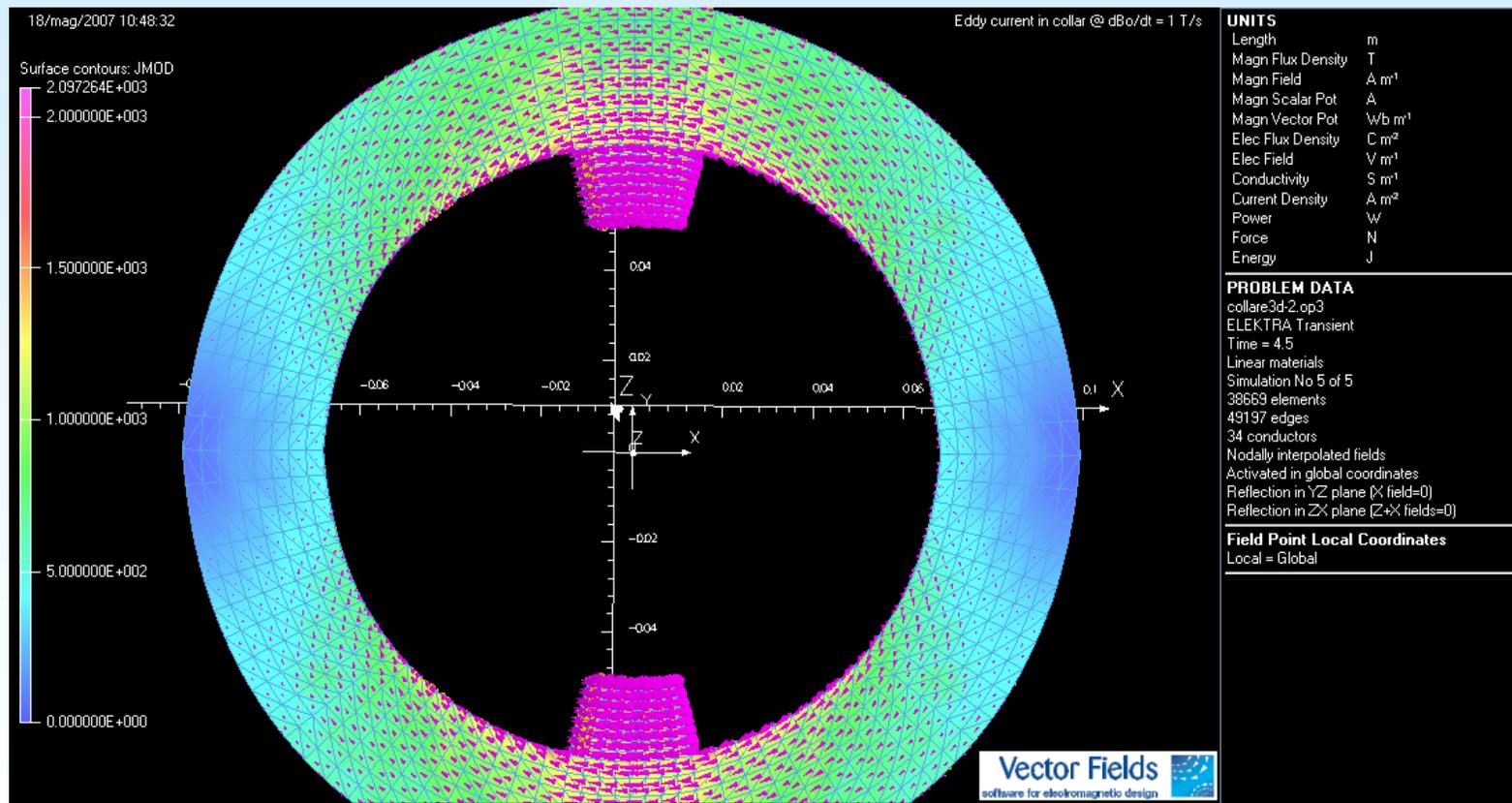
As consequence the volumetric losses in the laminations can be calculated easily:

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

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

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

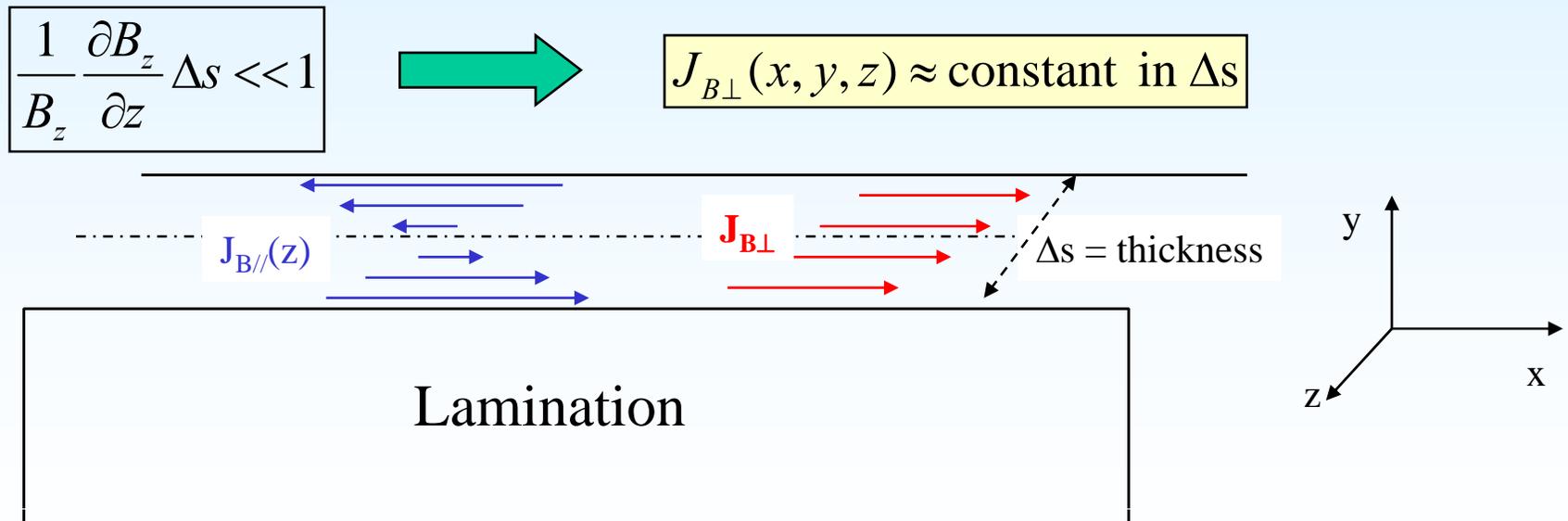
Plot of the eddy current pattern, in a full 3-D description of the collar with the true lamination thickness.



2. Losses for the *perpendicular* component of the magnetic field:

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 :



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

$$\left\{ \begin{array}{l} \sigma_x = 1/\rho \\ \sigma_y = 1/\rho \\ \sigma_z = 0 \end{array} \right.$$

$$\text{with } \rho = \rho_{collar} \approx \rho_{iron} \approx 5.3 \cdot 10^{-7} \Omega\text{m}$$

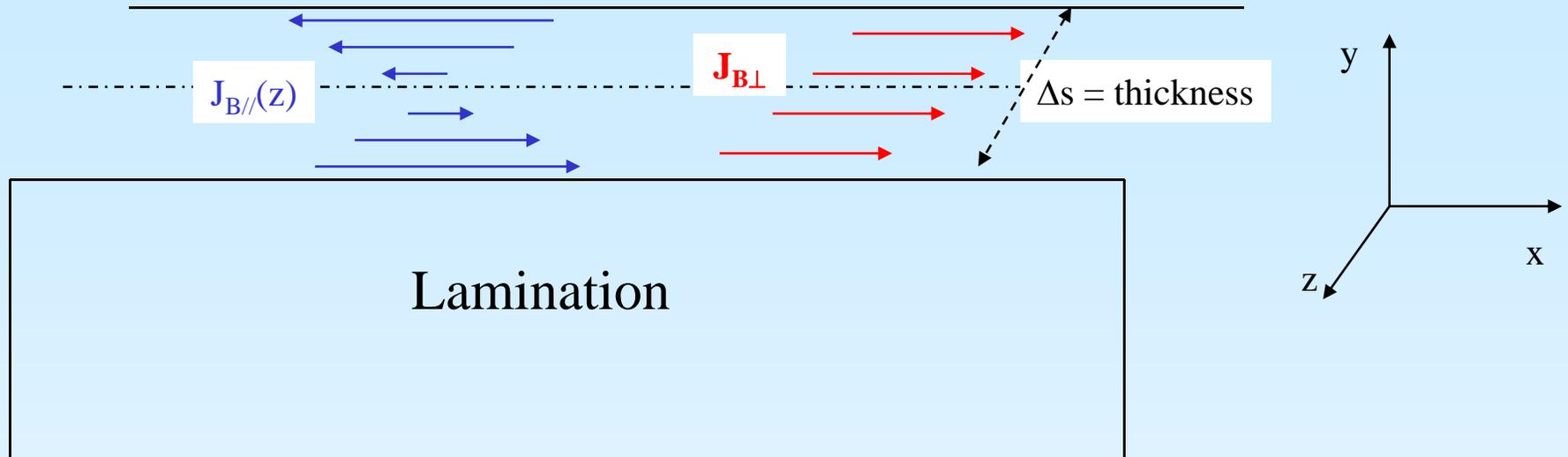
The yoke laminations have an anisotropic behavior also for the reluctivity (stacking factor = 0.97).

The stacking factor reduces the penetration of B_z in the yoke.

Consequently, the yoke laminations have been treated with ELEKTRA 3-D as an *homogenous* material, but with *anistropic* behavior both for the electrical resistivity and magnetic reluctivity.

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

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



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

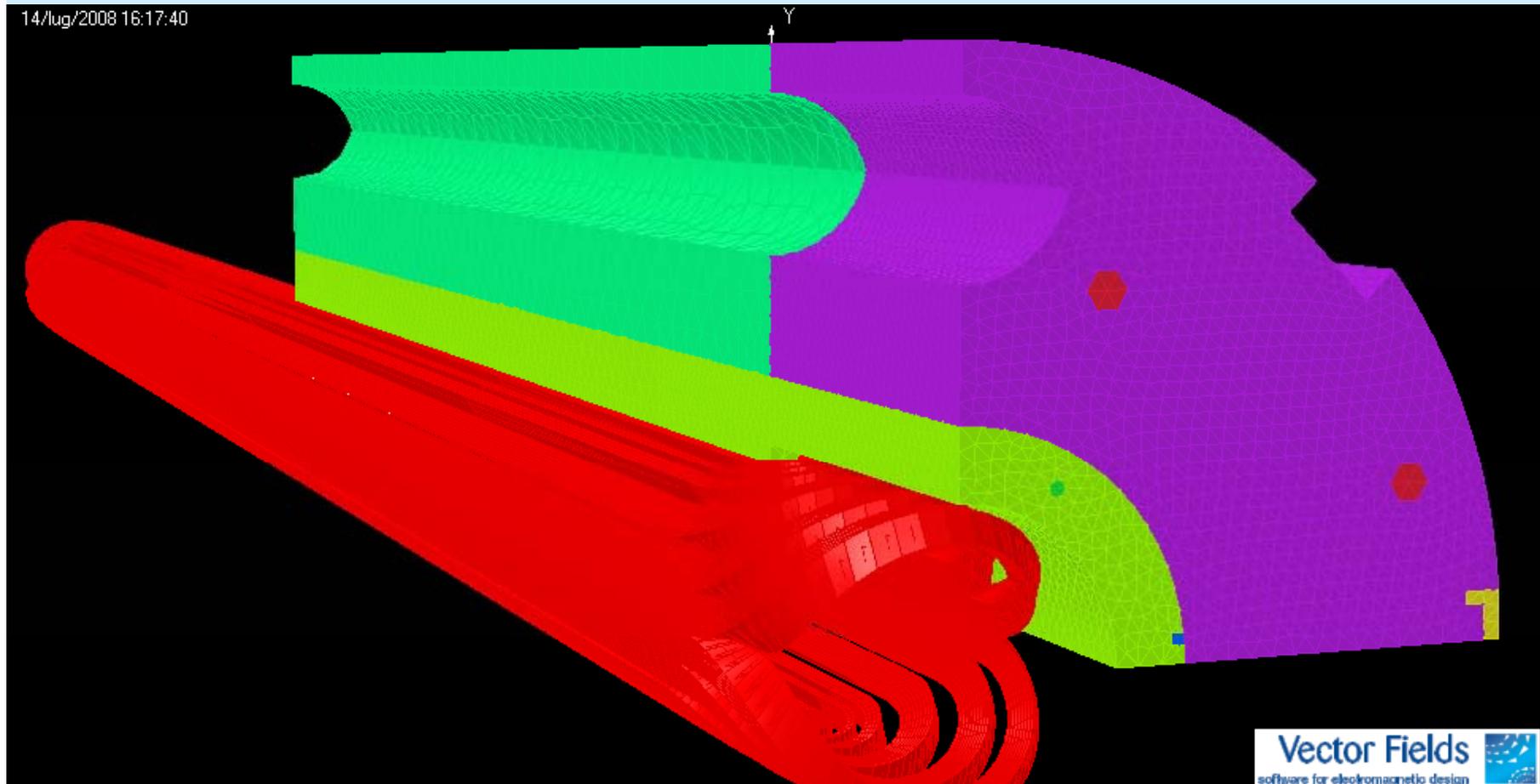
The total power for eddy currents in the laminations:

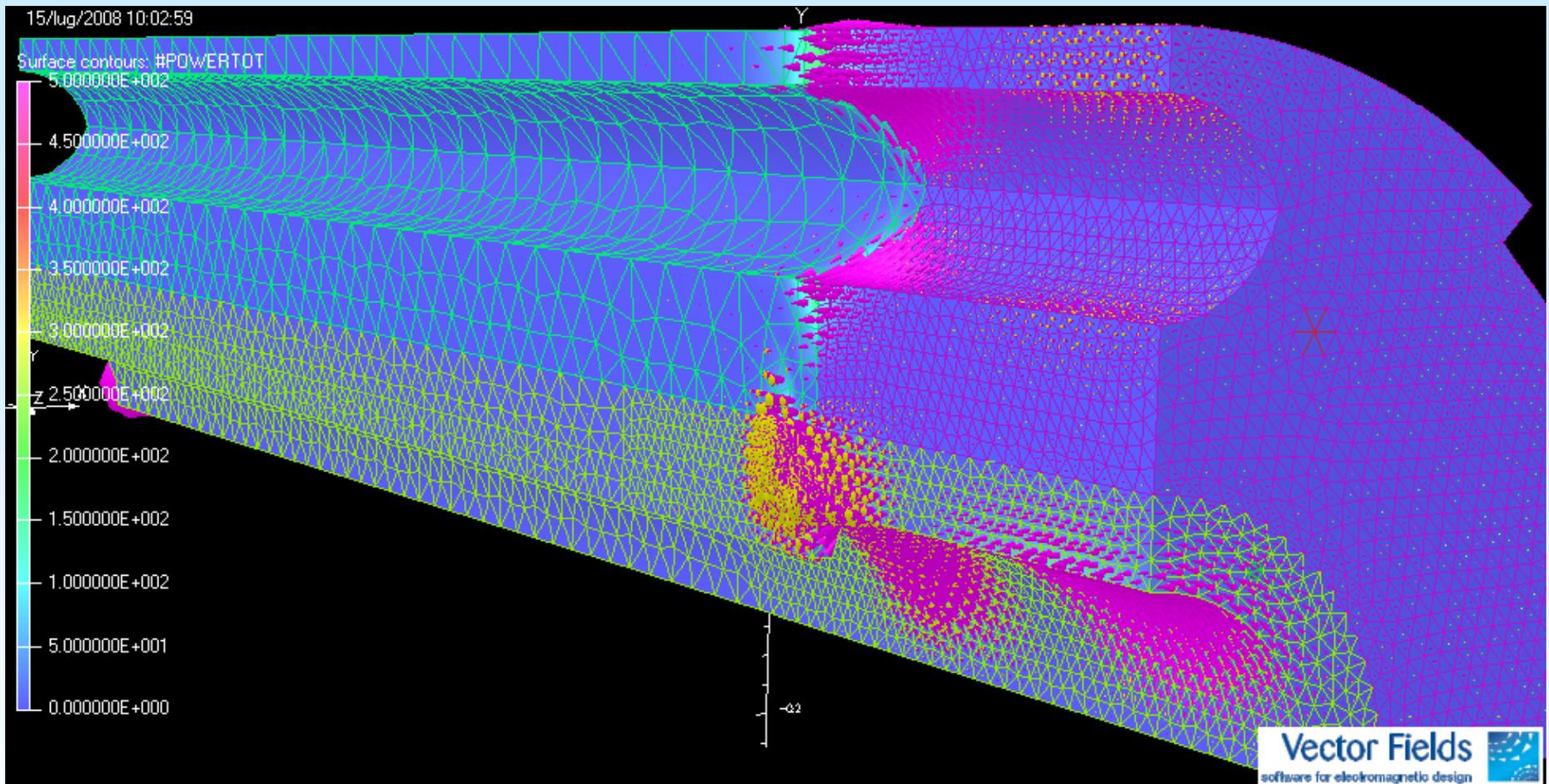
$$p_{\Delta s-av.}(x, y) = p_{B//}(x, y) + p_{B\perp}(x, y) = \frac{1}{12\rho} \dot{B}_{//}(x, y)^2 \Delta s^2 + \rho \cdot J_{B\perp}(x, y)^2$$

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

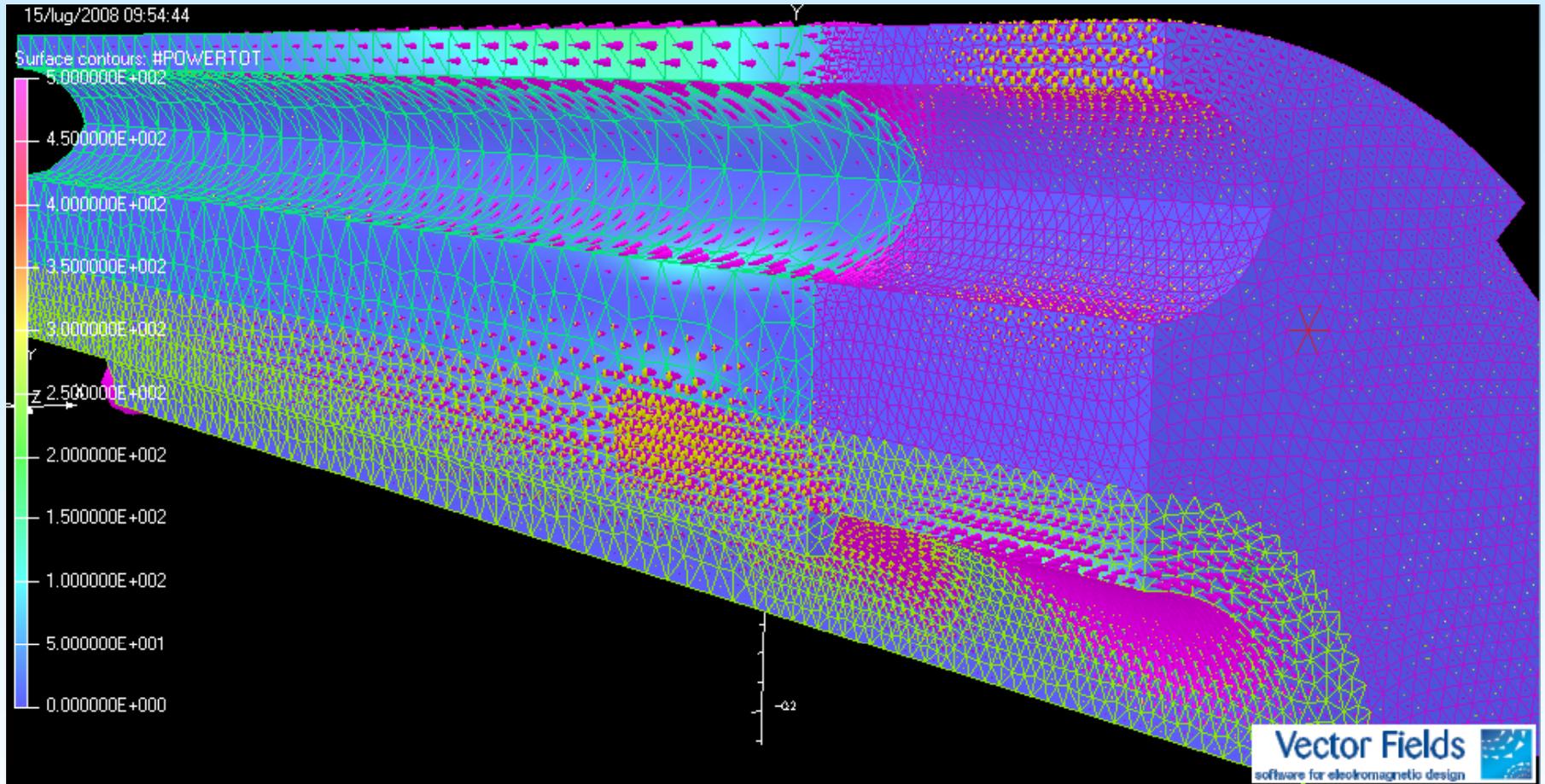
It is possible just to add the two powers!

1/8 of the model (1.2 m long)





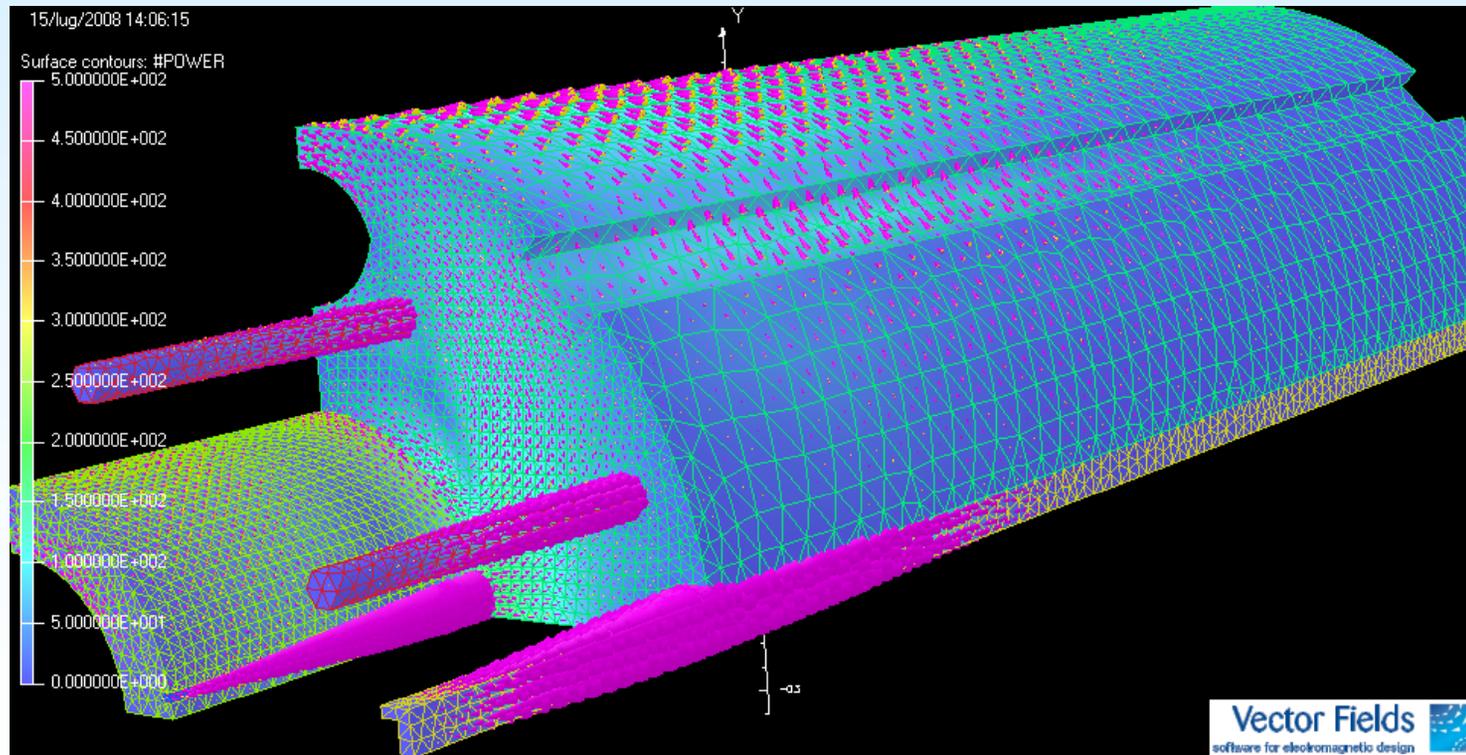
View of eddy currents (arrows) and losses (colors, W/m³) during the magnet ramp-up ($dB_o/dt=1$ T/s), at $B_o=1.5$ T.



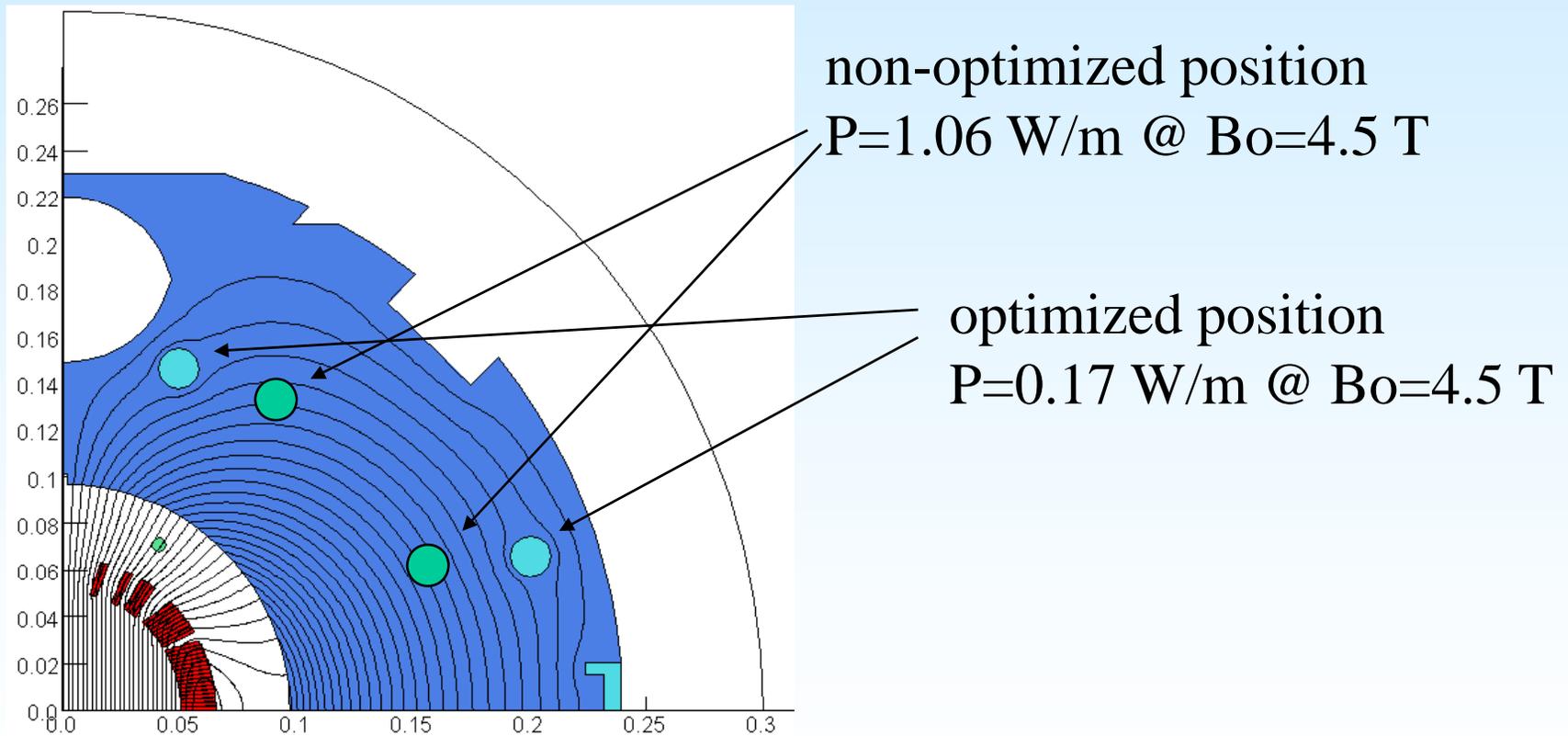
View of eddy currents (arrows) and losses (colors, W/m^3) during the magnet ramp-up ($dB_o/dt=1 \text{ T/s}$), at $B_o=4.5 \text{ T}$.

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)

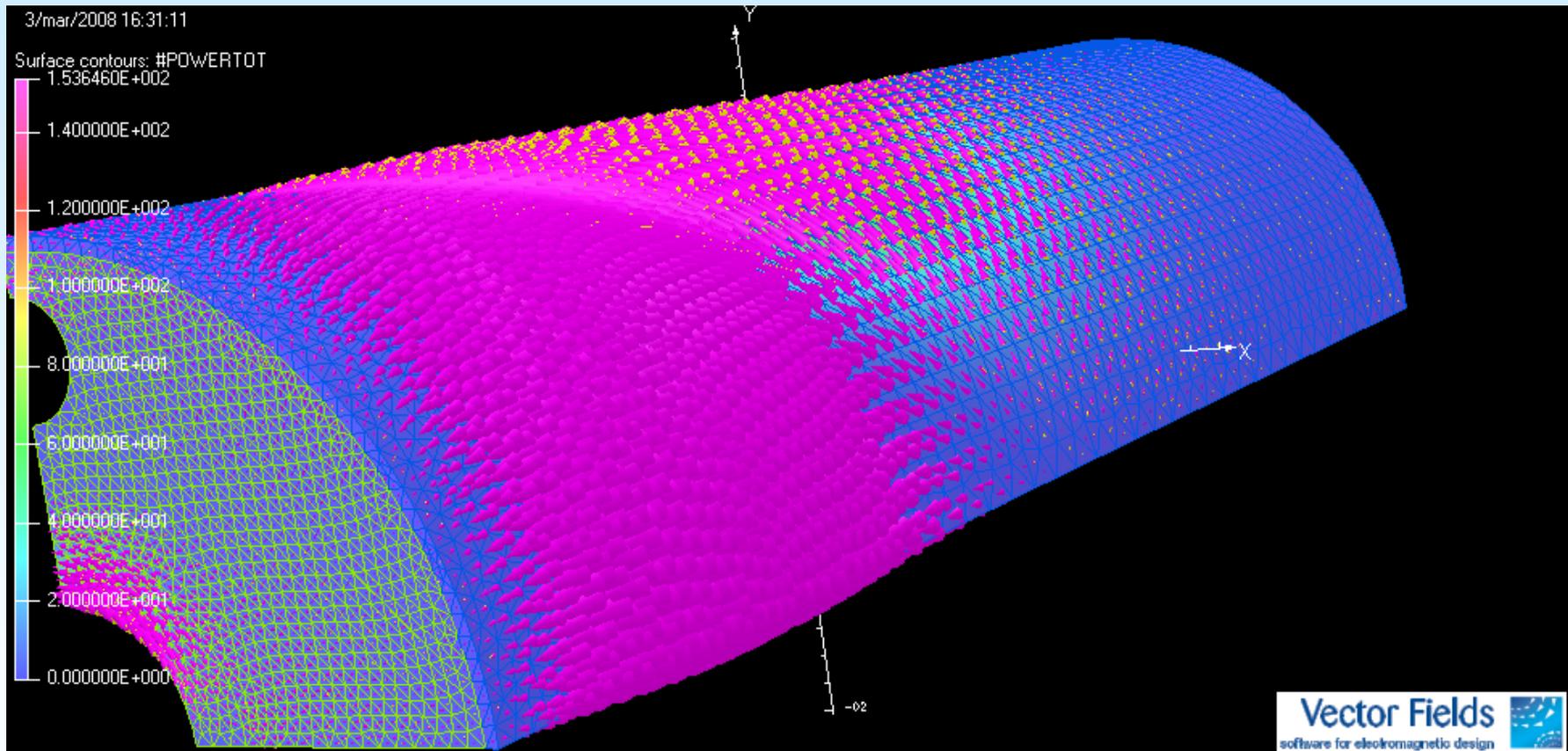
The study of these dissipative powers has been done with OPERA-3D & validated with analytical approaches.



The position of the yoke pins has been optimized in order to reduce the eddy currents and the losses



Another important conclusion is that the electrical contact between the yoke lamination and the He cylindrical vessel must be avoided.



Current in the He cylindrical vessel @ 4.5 T

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

$$P = 1.0 \text{ W/m}$$

(not negligible thermal load for the cooling gas)

Losses for the yoke magnetic hysteresis

- These losses have been estimated starting from the specification given for the material:
- The lamination (used for standard application in ac) is classified as M600-100A (European norm EN 10106-2007)
- The maximum **total** losses is **6 W/kg**, when subjected to a sinusoidal field with frequency 50 Hz and peak field $B_p=1.5$ T, at room temperature.

- From this total losses, the contribution for *eddy current* can be separated easily:

$$P_{ac} = \frac{\pi^2 \cdot v^2}{6\rho \cdot \delta} B_p^2 \Delta s^2 = 2.8 \text{ W/kg}$$

- The contribution for *hysteresis* has been measured in similar materials by IHEP, and is about 1.75 W/kg
- The remaining part is due to the *anomalous losses*, about 1.45 W/kg

- In order to have the same *hysteretic* losses (1.75 W/kg) in an ac field calculation at 50 Hz, a suitable **constant phase lag** of 10° has to be introduced between B and H .
- Using the same constant phase in our operative condition with a 2-D magnetic analysis (code FEMM), we obtained an average **hysteretic losses** of about **1.8 W/m**.
- The anomalous losses scale with $\nu^{1.5}$ and consequently decreases very fast as the frequency ν decreases, and can be neglected in our operating conditions.

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

Bo	In 2-D section (W/m)			In each coil end (W)			% in 3.9 m long magnet		
	1.5 T	3.0 T	4.5 T	1.5 T	3.0 T	4.5 T	1.5 T	3.0 T	4.5 T
Conductor	4.5	3.3	2.6	0.630	0.462	0.364	54%	40%	38%
Collar eddy	0.006	0.006	0.006	0.144	0.393	0.197	1%	2%	2%
Yoke eddy	0.002	0.002	0.002	0.234	1.111	0.978	1%	7%	7%
Collar pins	0.122	0.121	0.089	0.004	0.004	0.004	1%	1%	1%
Collar keys	0.568	0.552	0.436	0.013	0.014	0.014	6%	6%	6%
Yoke pins	0.062	0.533	0.167	0.030	0.035	0.049	1%	6%	3%
Yoke keys	0.000	0.000	0.000	0.058	0.169	0.074	0%	1%	1%
Yoke hyst. (av.)	~1.8	~1.8	~1.8	0.351	0.351	0.351	22%	23%	27%
Beam tube	1.000	1.000	1.000	0.195	0.195	0.195	12%	13%	15%
TOTAL	8.06	7.31	6.10	1.66	2.73	2.23	100%	100%	100%

Bo (T)	In the 3.9 m long dipole (W)	In the 7.8 m long dipole (W)
1.5	33.9	64.6
3.0	33.3	61.1
4.5	27.6	50.8

Conclusions:

- The ramp rate losses range between **28 W** (high field) and **34 W** (low field).
- This means that the specific loss in the cold mass is between **7.0 W/m** and **8.7 W/m** (including coil ends). **Acceptable.**
- The contribution of the conductor only in losses is between **40%** (high field) and **55%** (low field).
- The loss map in the conductor has allowed the thermal analysis for the study of the **temperature in conductors.**

The end

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%

cable twist pitch	p	0.1	m
crossover resistance	R _c	2.00E-02	ohm
adjacent resistance	R _a	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	

The power is averaged on the ramp up

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