

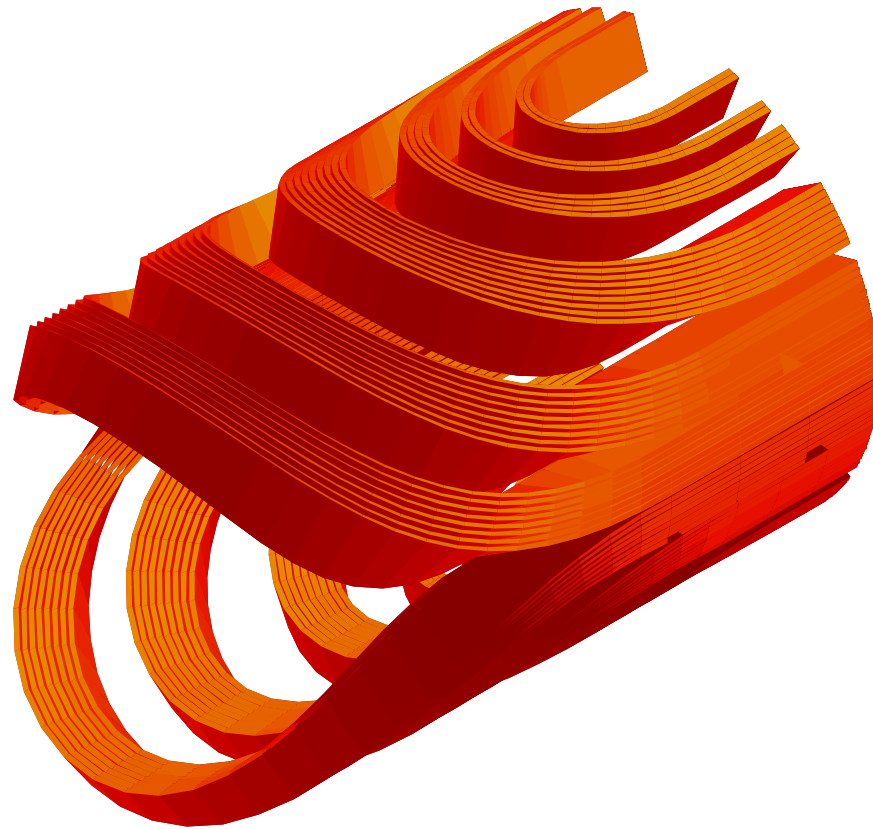


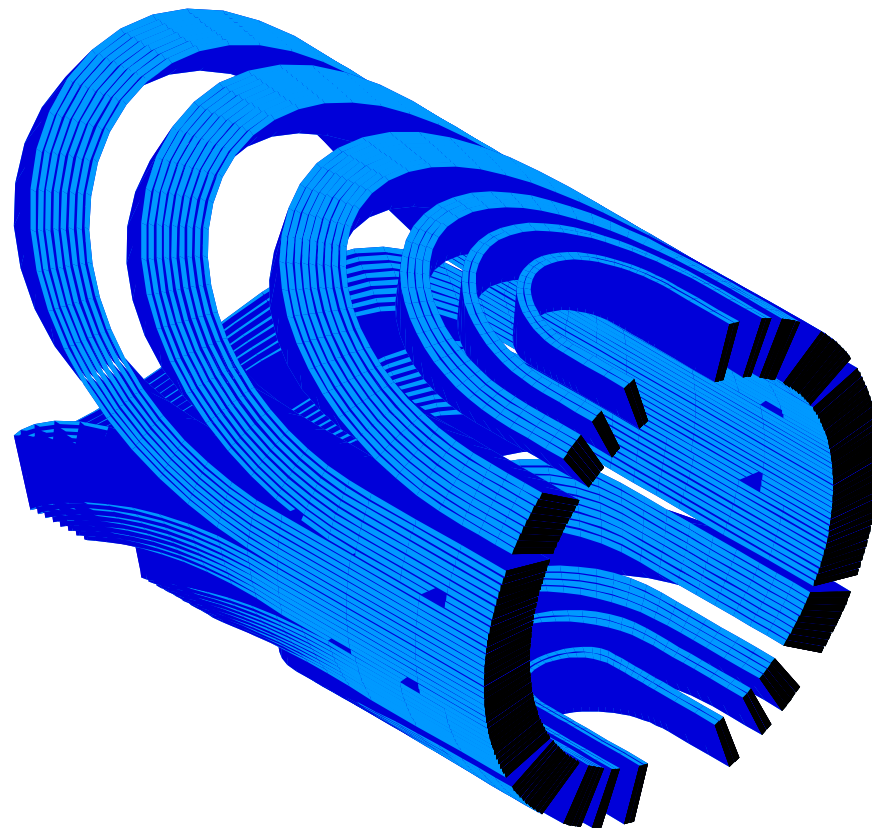
# Electromagnetic optimization of the coil ends

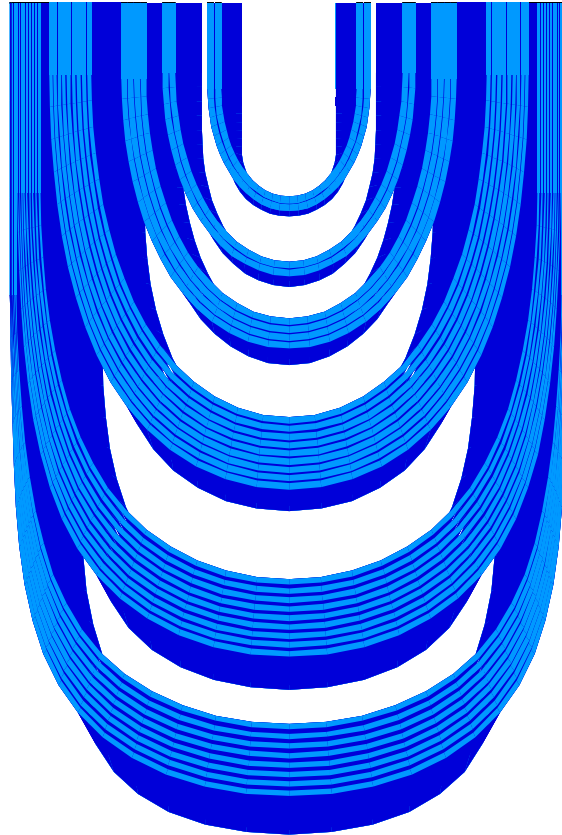
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**Milan University and INFN Sez. di Milano**

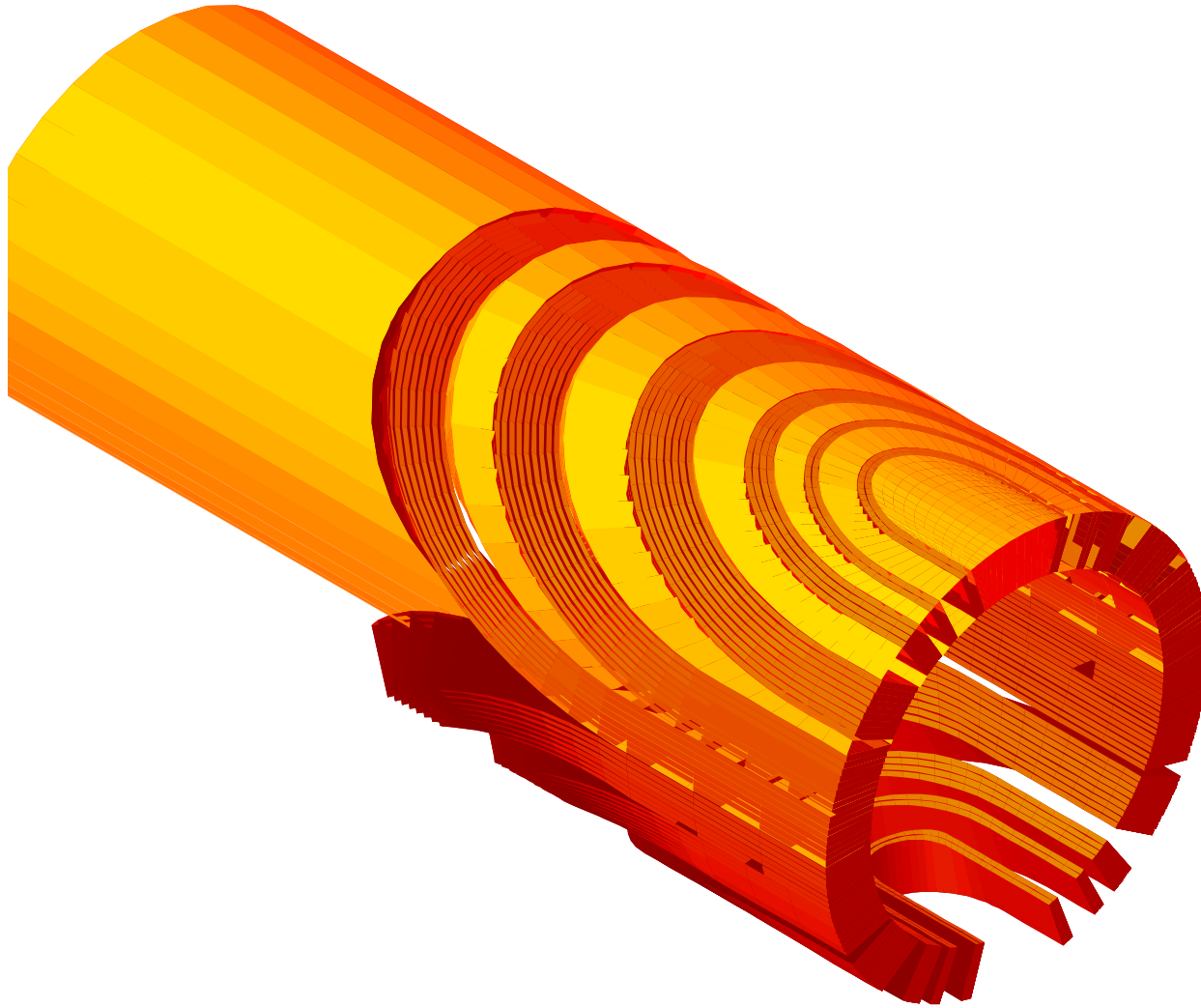
## Contents:

1. 3-D lay-out of the “symmetric” coil end
2. Harmonic optimization
3. Peak field
4. Losses
5. 3-D lay-out of the “no-symmetric” coil-end (connection side)
6. Conclusion











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



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.



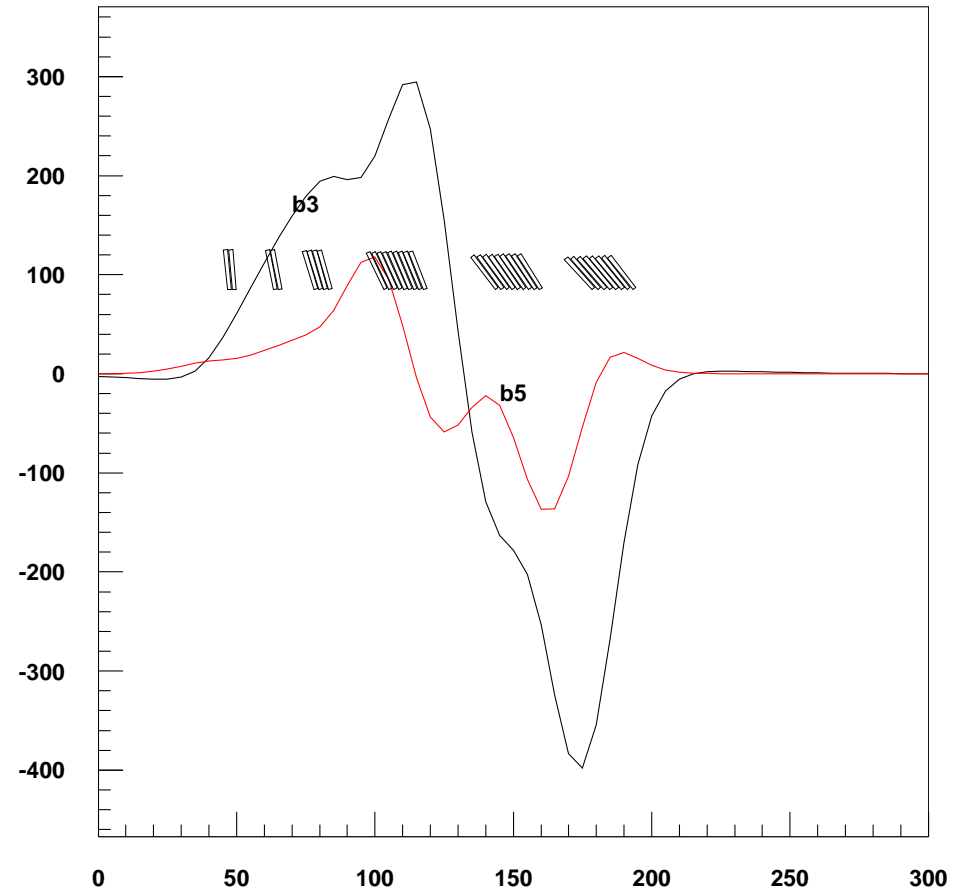
Averaged harmonics in  
symmetric coil-end “**in air**”:

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

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

with :

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

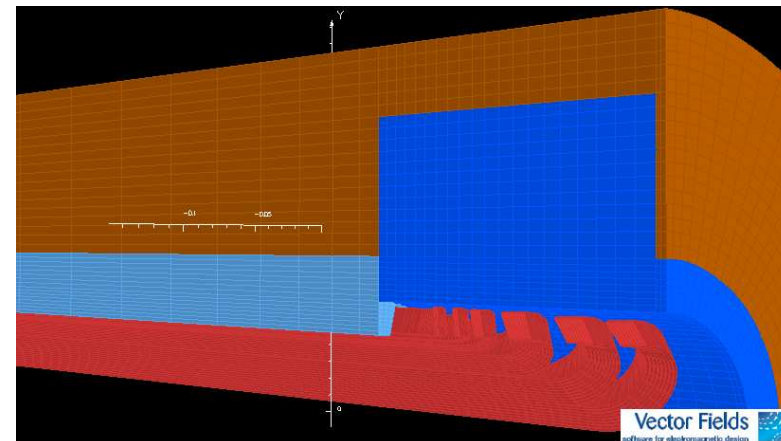
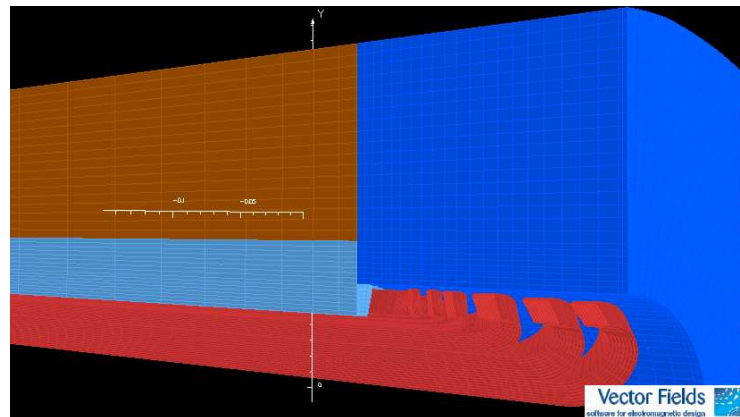
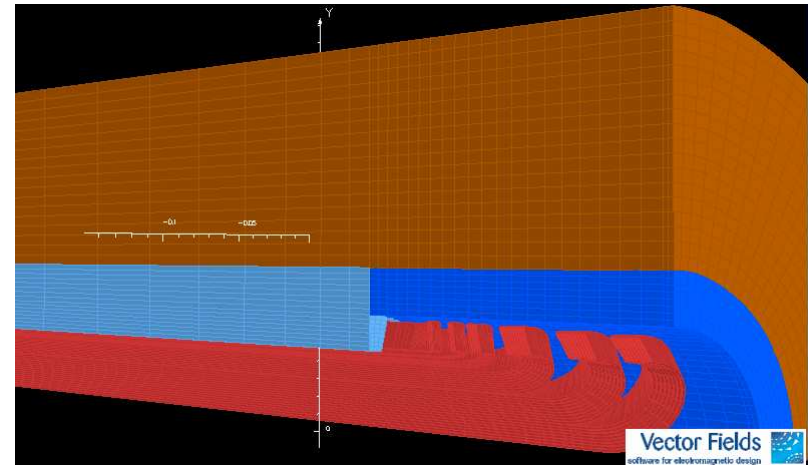


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The influence of the yoke on the peak-field and losses is important.

Three yoke configurations have been considered:

1. Full yoke
2. Yoke with insert
3. Short yoke



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

- Yoke inner & outer radius 93 mm & 213 mm,
- non-linear iron of OPERA, stack = 1
- $I = 8720$  A (no current grading in cond.)
- Coil-end between  $z = 0$  and  $z = 195$  mm

		Long yoke <i>Yoke up to <math>z=206</math> mm</i>		Short yoke <i>No yoke from <math>z=0</math></i>
	<b>2-D analysis</b>	Full yoke	Collar insert up $r=133$ mm + end-cap (6 mm)	No yoke in coil-end
$B_{\text{peak}}$ on cond. (T)	<b>4.87</b>	<b>4.96</b>	4.57	4.59
$T_g$ (K)	<b>5.73</b>	<b>5.69</b>	5.89	5.88
$L_m$ (mm)	-	125.0	106.5	100.7

A further decrease of  $\sim 0.07$  T in peak field can be obtained inserting another spacer in coil-end between the 33th and 34th conductors.

But the gain in field does not justify the complexity increase.

The choice between the configurations “short yoke” or “yoke with insert” has to be determined by the requirements of:

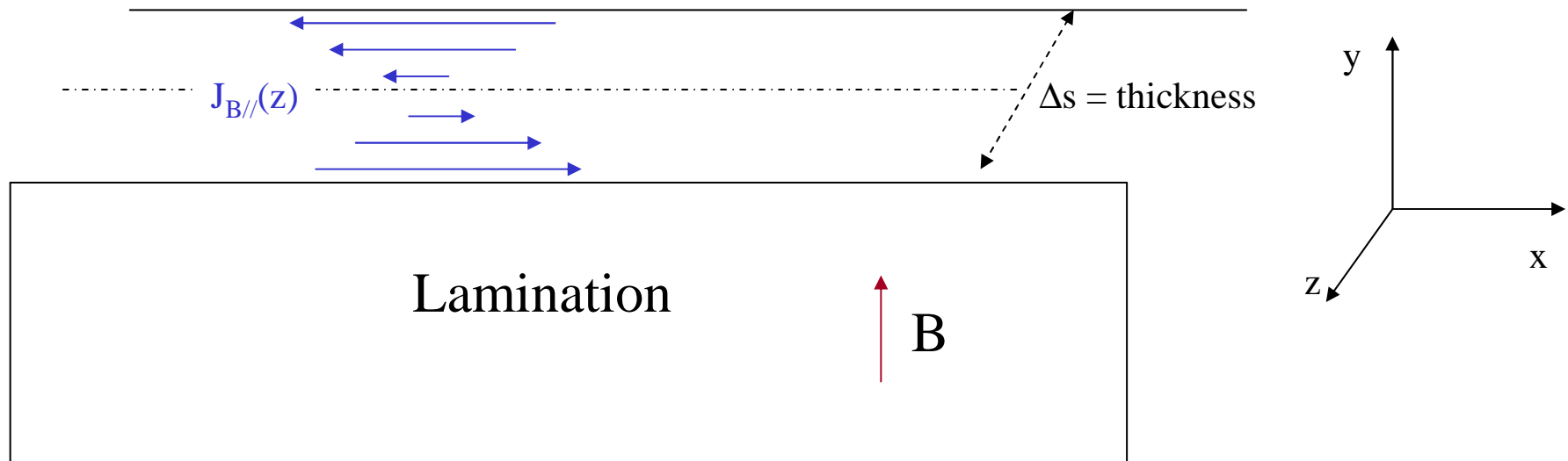
- losses
- stray field
- harmonic contents

## STUDY OF THE LOSSES

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  $\Delta s$ ) 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).

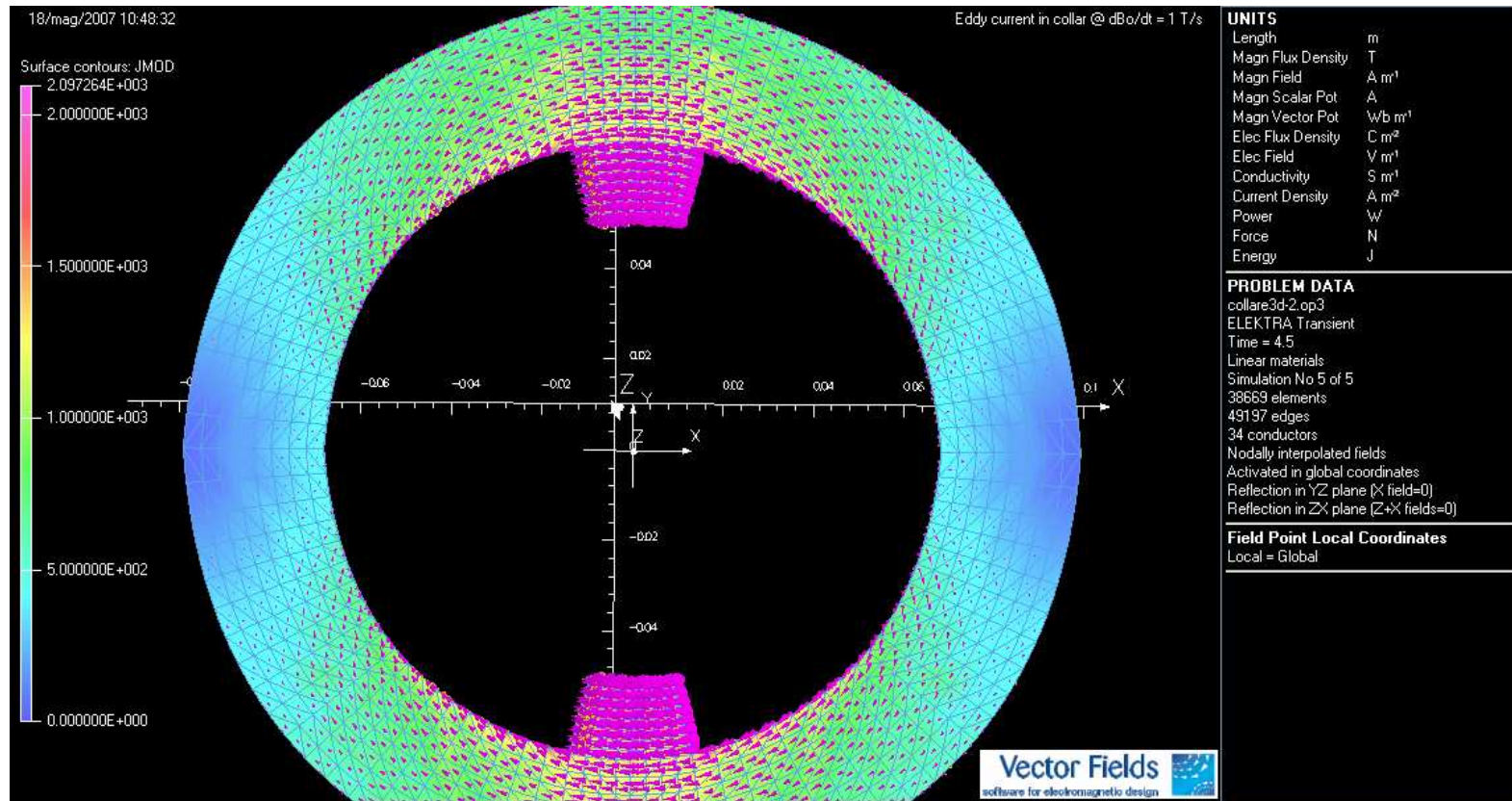
As consequence the volumetric losses in the laminations can be calculated easily:

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

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

$$P_{B//} = \int_{Collar\ area} \frac{1}{12\rho} \dot{B}^2 \Delta s^2 d\Sigma \cong P_{3-D}(ELEKTRA) = \mathbf{2.3\ mW/m}$$

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





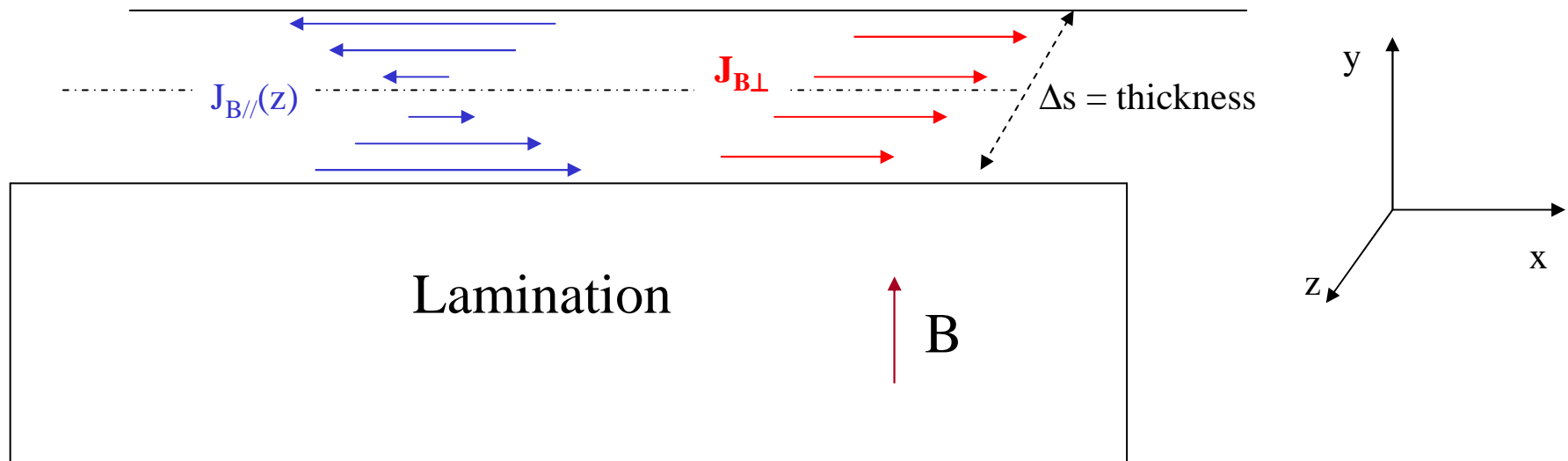
In the **coil end**, there is also the  $z$ -component of the field  $B$  (in addition to the parallel components of the field), which produces *additional* eddy currents  $J_{B\perp}$  in the  $x$  and  $y$  directions.

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

$$\frac{1}{B_z} \frac{\partial B_z}{\partial z} \Delta s \ll 1$$



$$J_{B\perp}(x, y, z) \approx \text{constant in } \Delta s$$



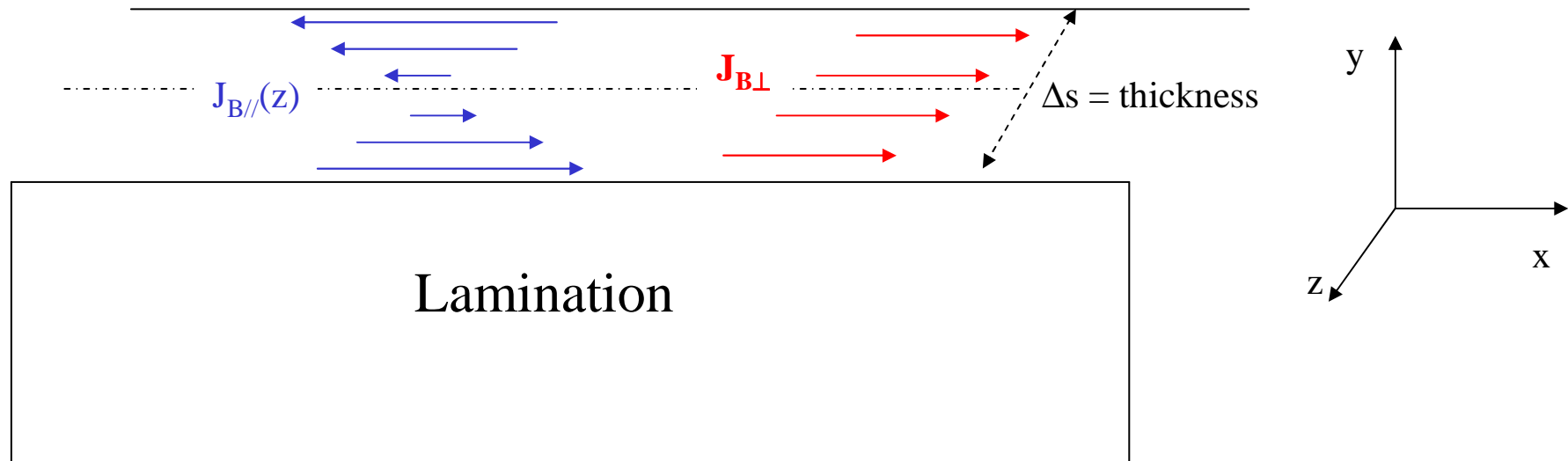
Consequently the  $J_{B\perp}$  can be calculated with ELEKTRA 3-D, assuming, *instead of lamination*, an anisotropic material with electrical conductivity  $\sigma$ :

$$\begin{cases} \sigma_x = 1/\rho \\ \sigma_y = 1/\rho \\ \sigma_z = 0 \end{cases}$$

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

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

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



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

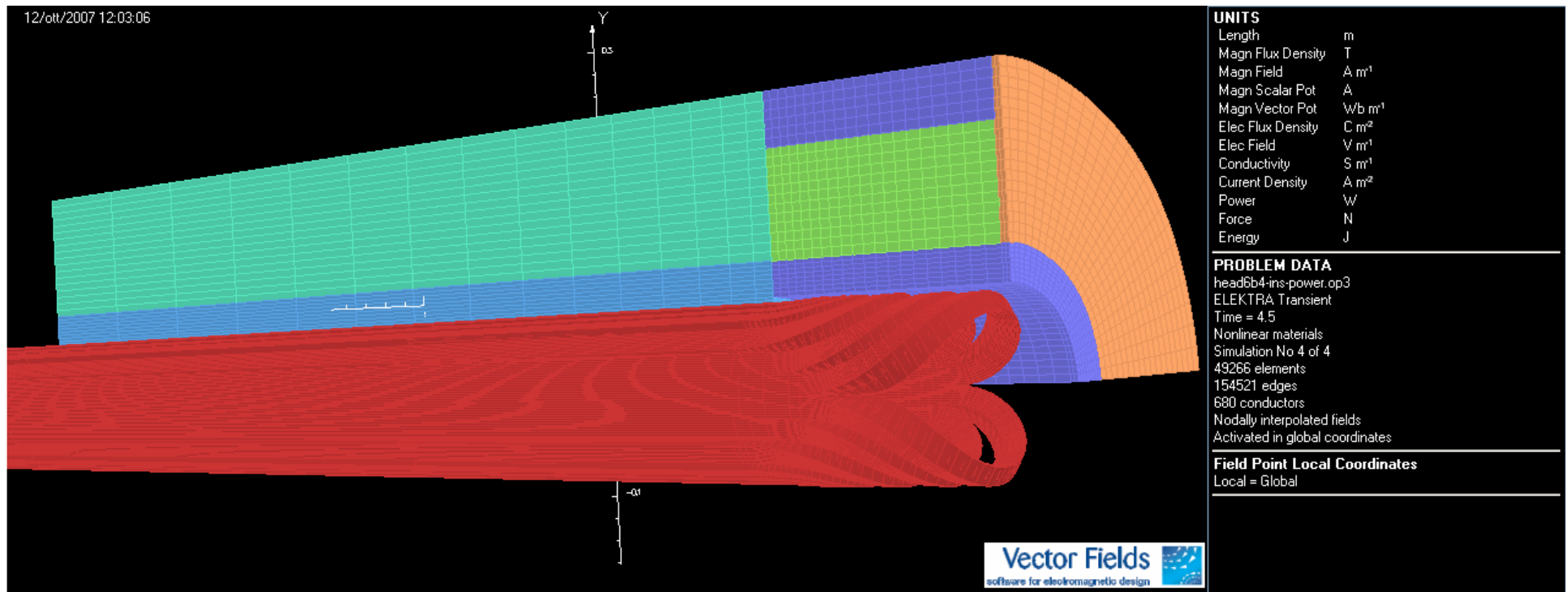
The power:

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

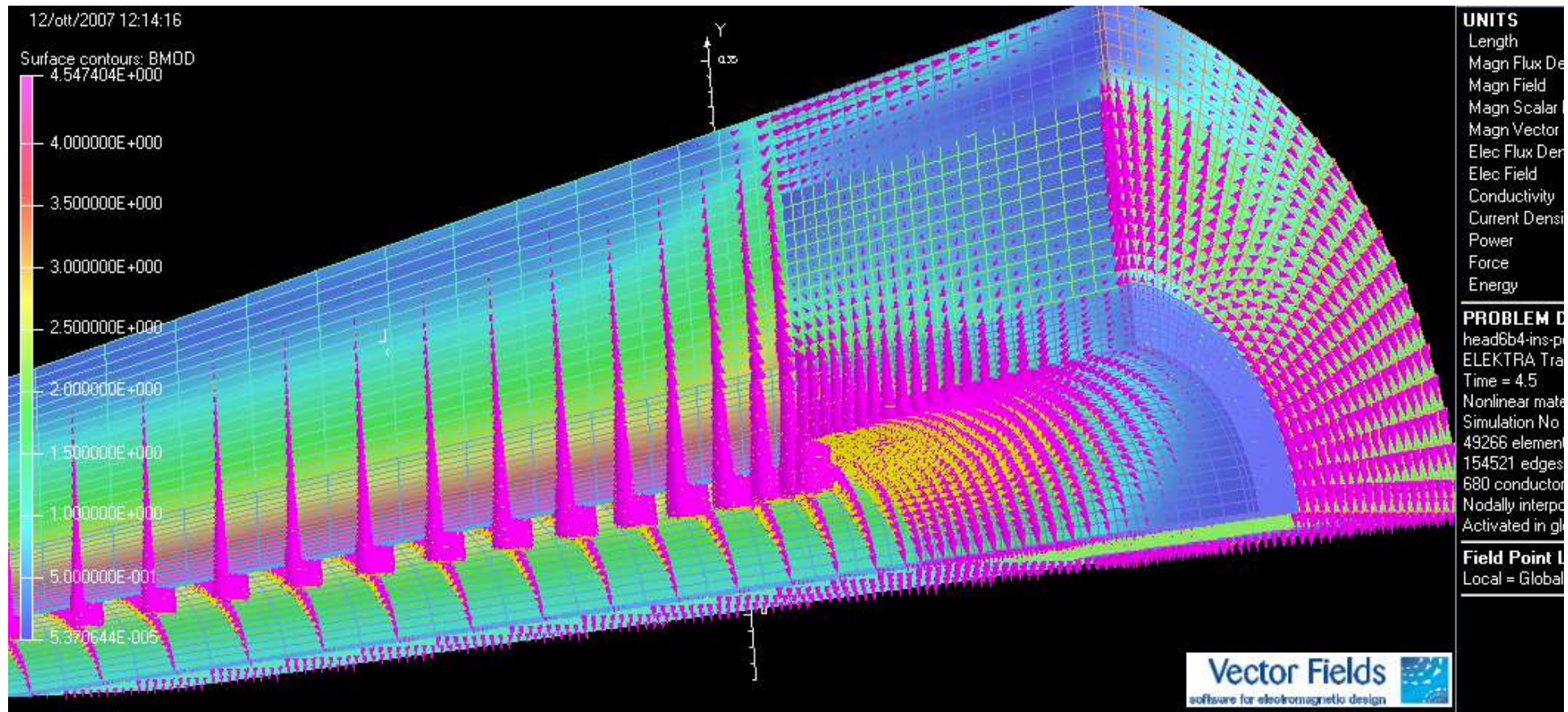
So the losses can be calculated “easily” in all the laminated regions *without* the necessity of modeling each single lamination.

It is possible just to add the two powers!

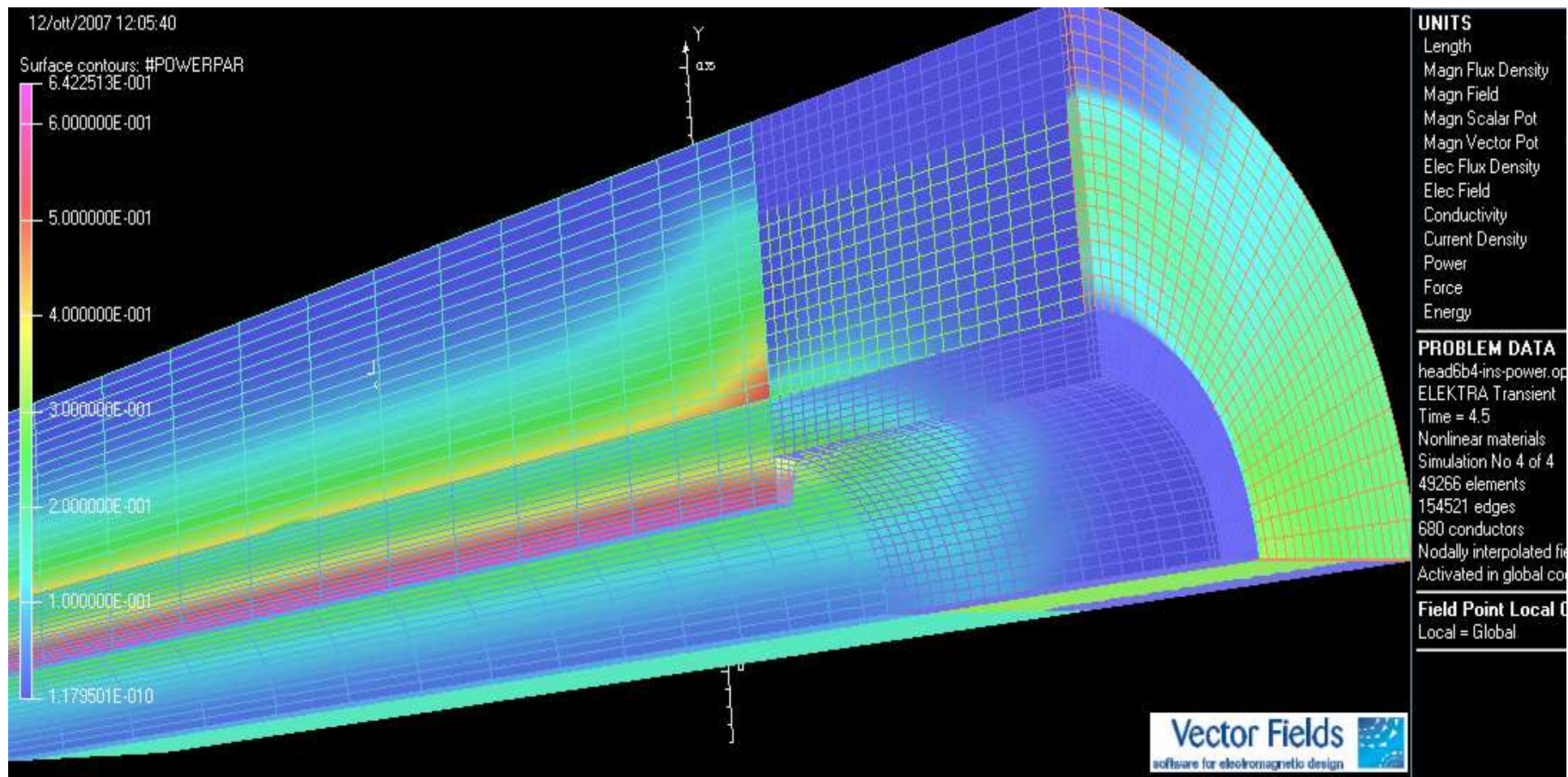
# Case of yoke with insert



# Yoke with insert



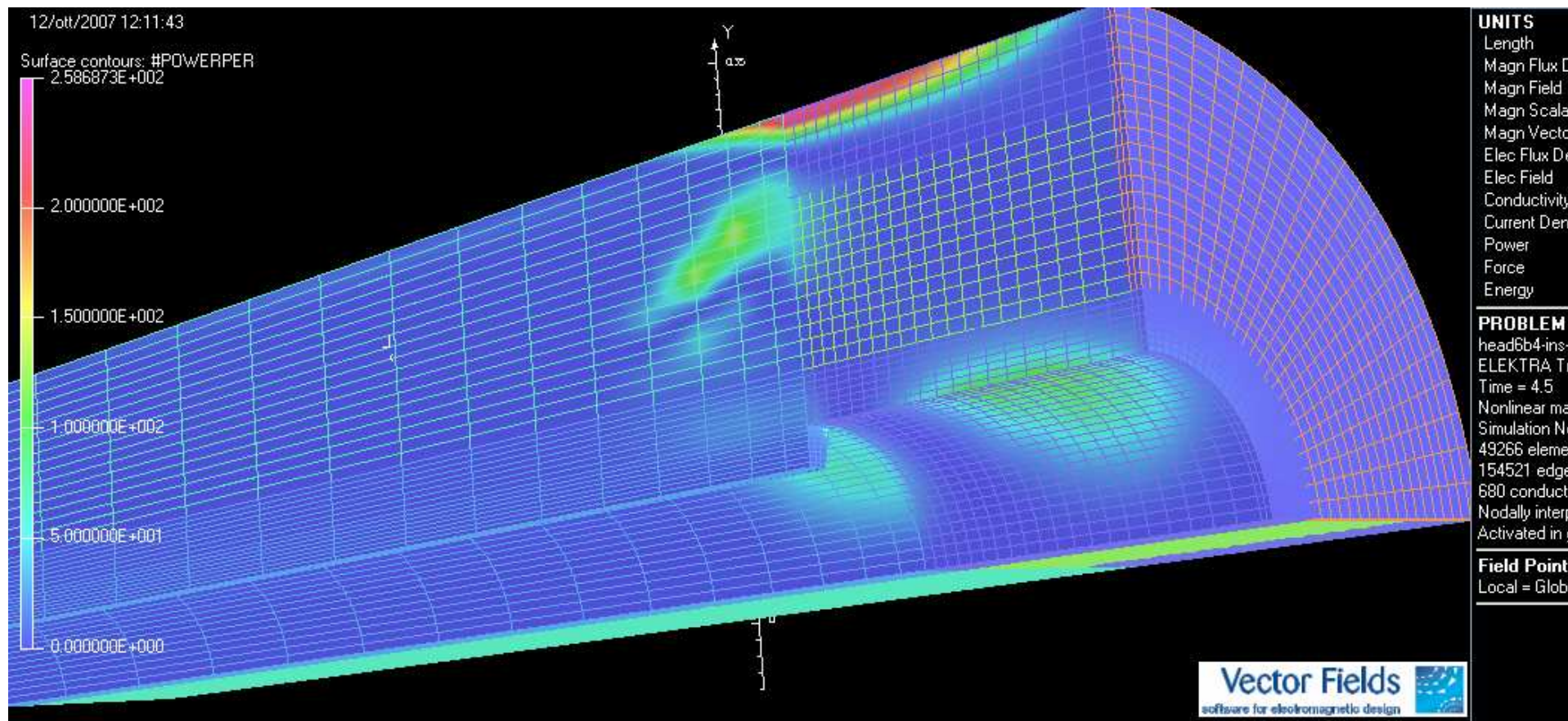
Field modulus  $B$  (colours) and its direction (arrows) @ 4.5 T during ramp-up



Power density  $p_{B//}(x,y,z)$  @ 4.5 T, during ramp-up [W/m<sup>3</sup>]

(power peak: 0.64 W/m<sup>3</sup>)

# Yoke with insert

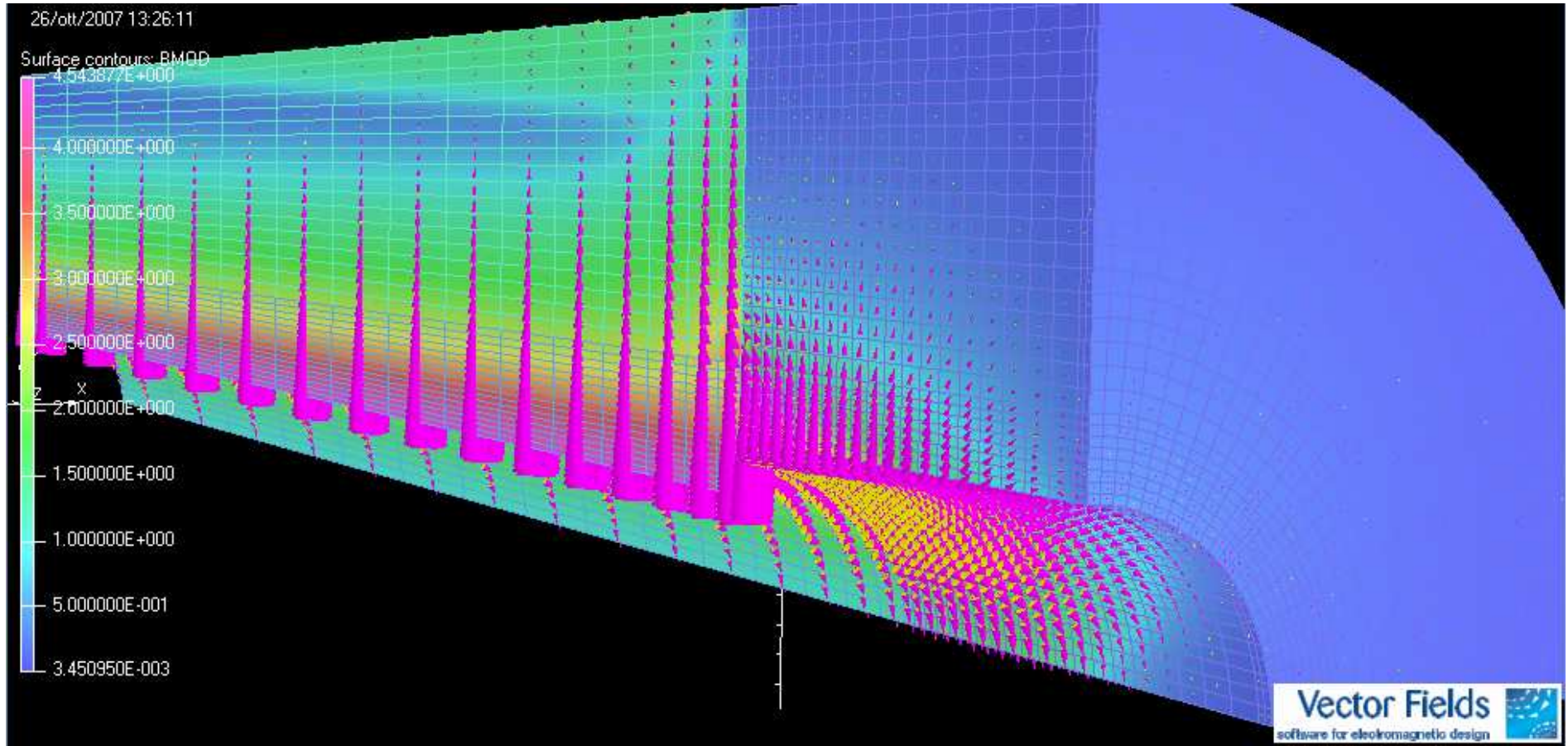


Power density  $p_{B\perp}(x,y,z)$  @ 4.5 T, during ramp-up [W/m<sup>3</sup>]

(power peak: 260 W/m<sup>3</sup>)

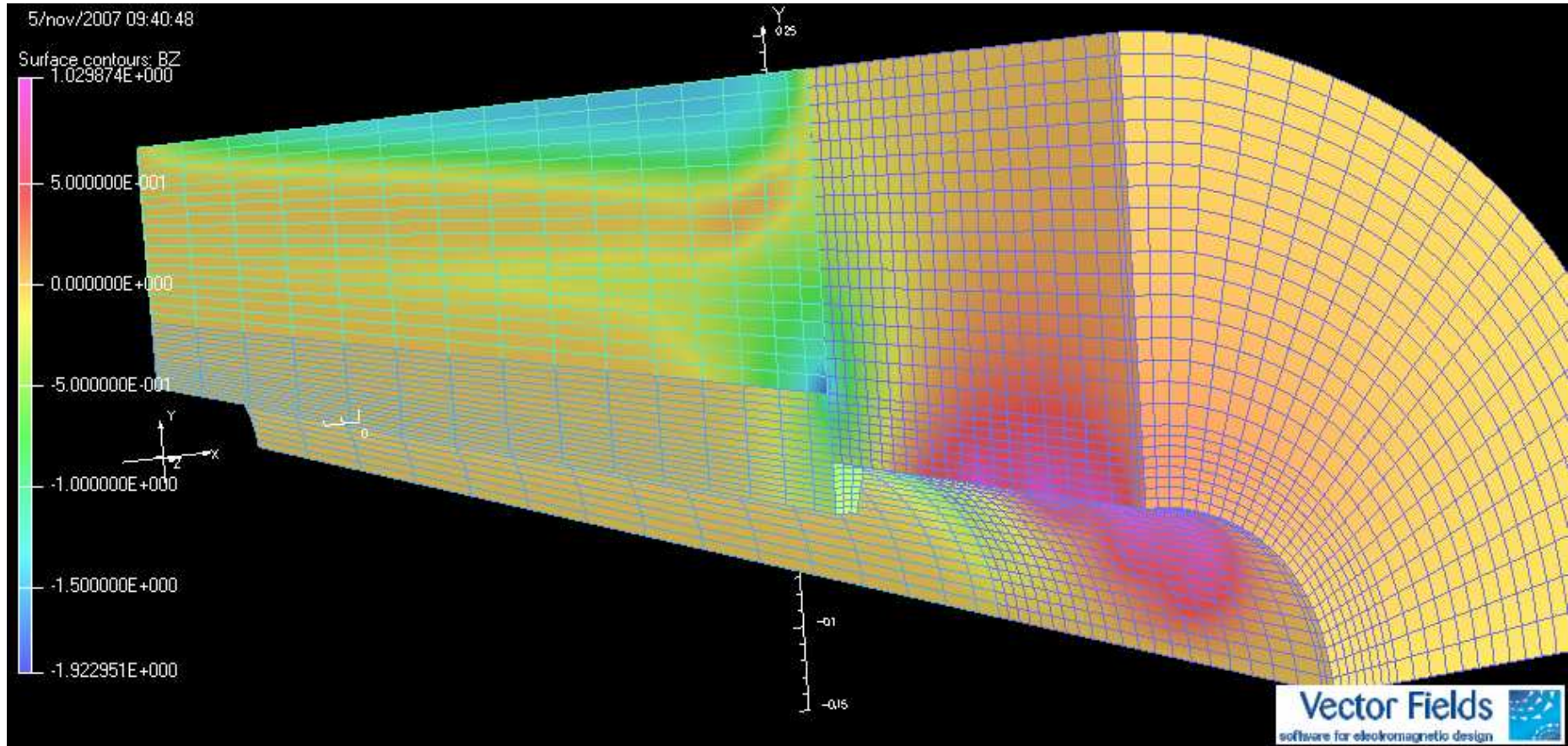


# Short yoke



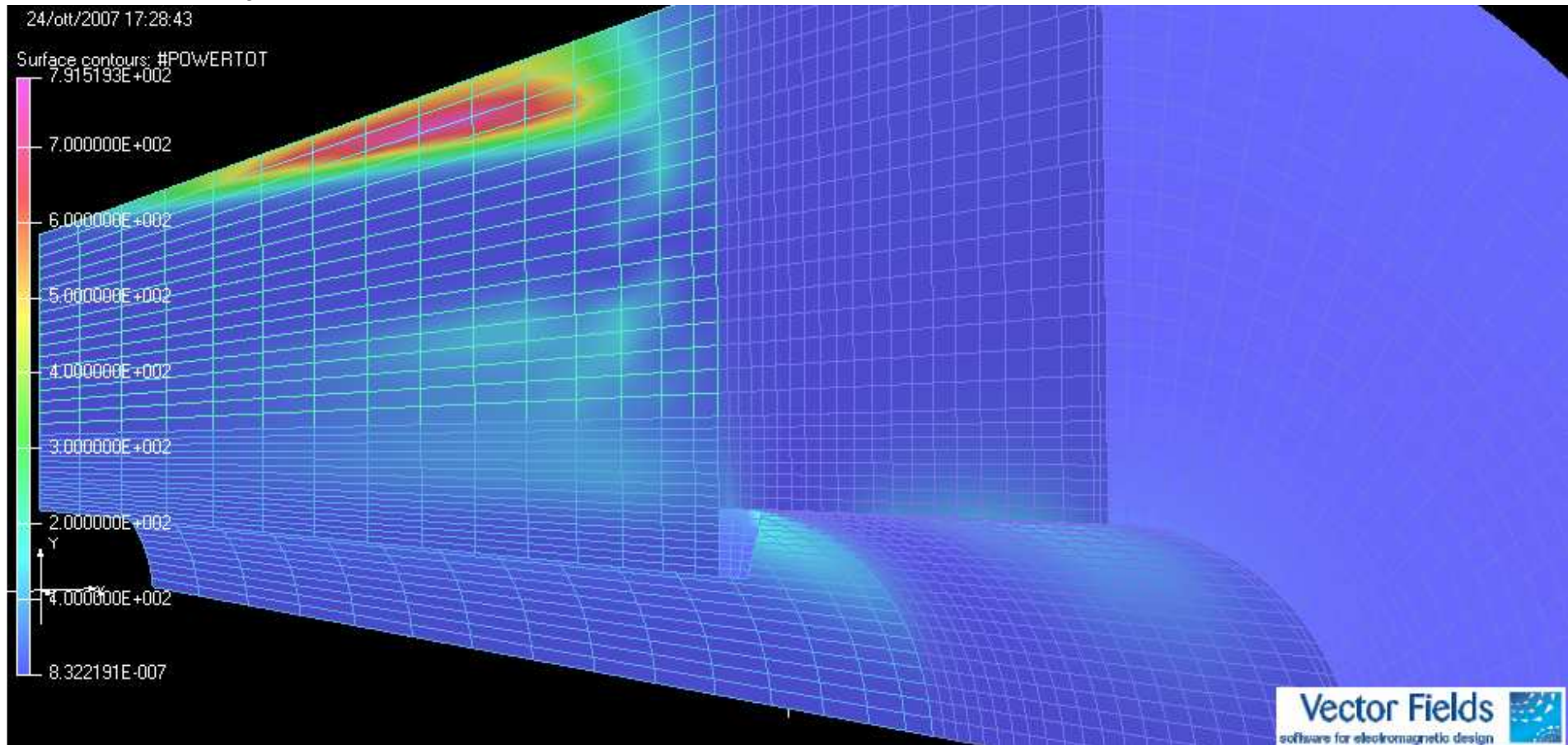
Field modulus  $B$  (colours) and its direction (arrows) @ 4.5 T during ramp-up

# Short yoke



$B_z$  component @ 4.5 T during ramp-up [Tesla]

# Short yoke



Power density  $p_{B\perp}(x,y,z)$  @ 4.5 T, during ramp-up [W/m<sup>3</sup>]

(power peak: 792 W/m<sup>3</sup>)

# Summary of losses for eddy currents in collar & yoke:

- **Short yoke**

- **Yoke with insert**

- No-electrical insulation between collar-yoke

- Electrical insulation between collar-yoke

	Bo (T)	In straight section (mW/m)				In each coil end (mW)				In the 3.8 m dipole (mW)				In the 7.6 m dipole (mW)			
		Short yoke		Yoke with insert		Short yoke		Yoke with insert		Short yoke		Yoke with insert		Short yoke		Yoke with insert	
		no ins.	ins.	no ins.	ins.	no ins.	ins.	no ins.	ins.	no ins.	ins.	no ins.	ins.	no ins.	ins.	no ins.	ins.
Collar $P_{B//}$	1.5	2.3	2.3	2.3	2.3	0.2	0.2	0.3	0.3	9.1	9.1	9.2	9.2	17.8	17.8	17.8	17.8
	3.0	2.3	2.3	2.3	2.3	0.2	0.2	0.3	0.3	9.1	9.1	9.2	9.2	17.8	17.8	17.8	17.8
	4.5	2.2	2.2	2.2	2.2	0.3	0.3	0.3	0.3	9.0	9.0	9.0	9.0	17.5	17.5	17.5	17.5
Collar $P_{B\perp}$	1.5	0.0	0.0	0.0	0.0	185.4	139.6	100.0	73.9	370.8	279.2	200.0	147.8	370.8	279.2	200.0	147.8
	3.0	0.0	0.0	0.0	0.0	351.5	124.4	133.6	62.6	703.0	248.8	267.2	125.3	703.0	248.8	267.2	125.3
	4.5	0.0	0.0	0.0	0.0	379.0	79.0	104.3	37.3	758.0	158.0	208.6	74.6	758.0	158.0	208.6	74.6
Yoke $P_{B//}$	1.5	20.0	20.0	18.7	18.7	0.0	0.0	1.0	1.0	76.0	76.0	73.1	73.1	152.0	152.0	144.0	144.0
	3.0	20.9	20.9	19.5	19.5	0.0	0.0	1.3	1.3	79.5	79.5	76.7	76.7	159.0	159.0	150.9	150.9
	4.5	20.0	20.0	20.0	20.0	0.0	0.0	1.4	1.4	76.0	76.0	78.8	78.8	152.0	152.0	154.8	154.8
Yoke $P_{B\perp}$	1.5	0.0	0.0	0.0	0.0	90.0	76.4	37.2	25.5	180.0	152.8	74.4	51.0	180.0	152.8	74.4	51.0
	3.0	0.0	0.0	0.0	0.0	1140.6	1003.2	185.2	113.2	2281.2	2006.4	370.4	226.3	2281.2	2006.4	370.4	226.3
	4.5	0.0	0.0	0.0	0.0	4612.0	4386.4	467.0	292.6	9224.0	8772.8	933.9	585.2	9224.0	8772.8	933.9	585.2
TOTAL	1.5	22.3	22.3	21.0	21.0	275.6	216.2	138.5	100.7	636	517	357	281	721	602	436	361
	3.0	23.2	23.2	21.8	21.8	1492.3	1127.8	320.3	177.3	3073	2344	723	437	3161	2432	806	520
	4.5	22.2	22.2	22.2	22.2	4991.3	4465.7	573.0	331.6	10067	9016	1230	748	10151	9100	1315	832

Too large!

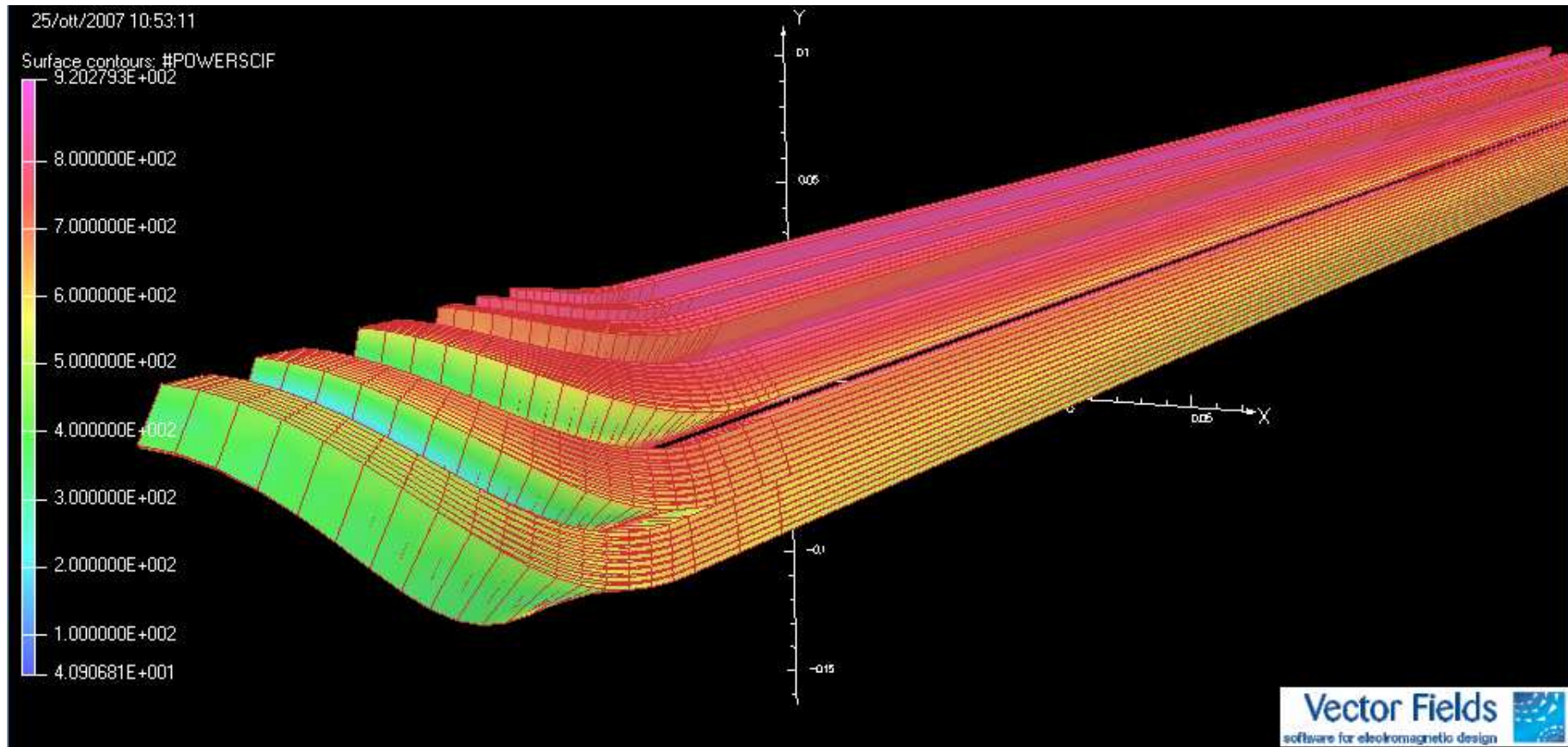
In conclusion, in order to limit the losses, the practicable solution is “**Yoke with insert**”

Bo (T)	In 3.8 m long dipole (mW)	In 7.6 m long dipole (mW)
1.5	280 ÷ 360	360 ÷ 440
3.0	440 ÷ 720	520 ÷ 810
4.5	750 ÷ 1250	830 ÷ 1320

Losses for eddy currents in laminations during ramp-up.

The variability depends by the electric contact between collar laminations with yoke laminations.

## Losses in the coil-end conductors:



Power density in conductors @ 4.5 T, during ramp-up [W/m<sup>3</sup>]  
(persistent currents and inter-filament coupling currents due to *transverse field*)

The power integrated in each coil-end gives the following losses:

$$P_{coil-end} = 220 \text{ mW} \cong 1.1 \text{ W/m}$$

( $B_0=4.5$  T, losses due to persistent & inter-filament coupling currents in *transverse field*),

The contribution due to the inter-strand coupling currents can be estimated to a +10%

The contribution due to the persistent currents for the *parallel component of the field* is  $\leq \sim +50\%$

(see M. Wilson, Superconducting Magnets, p. 164)

The total losses in conductor in the 2-D section are:

$$P_{2-D} \cong 2.6 \text{ W/m}$$

( $B_0=4.5$  T, inter-strand coupling current losses included)

Consequently the **total specific** losses in coil-ends are a fraction (70%) of losses in the straight section.

$$P_{coil-end} = 360 \text{ mW} \cong 1.8 \text{ W/m}$$

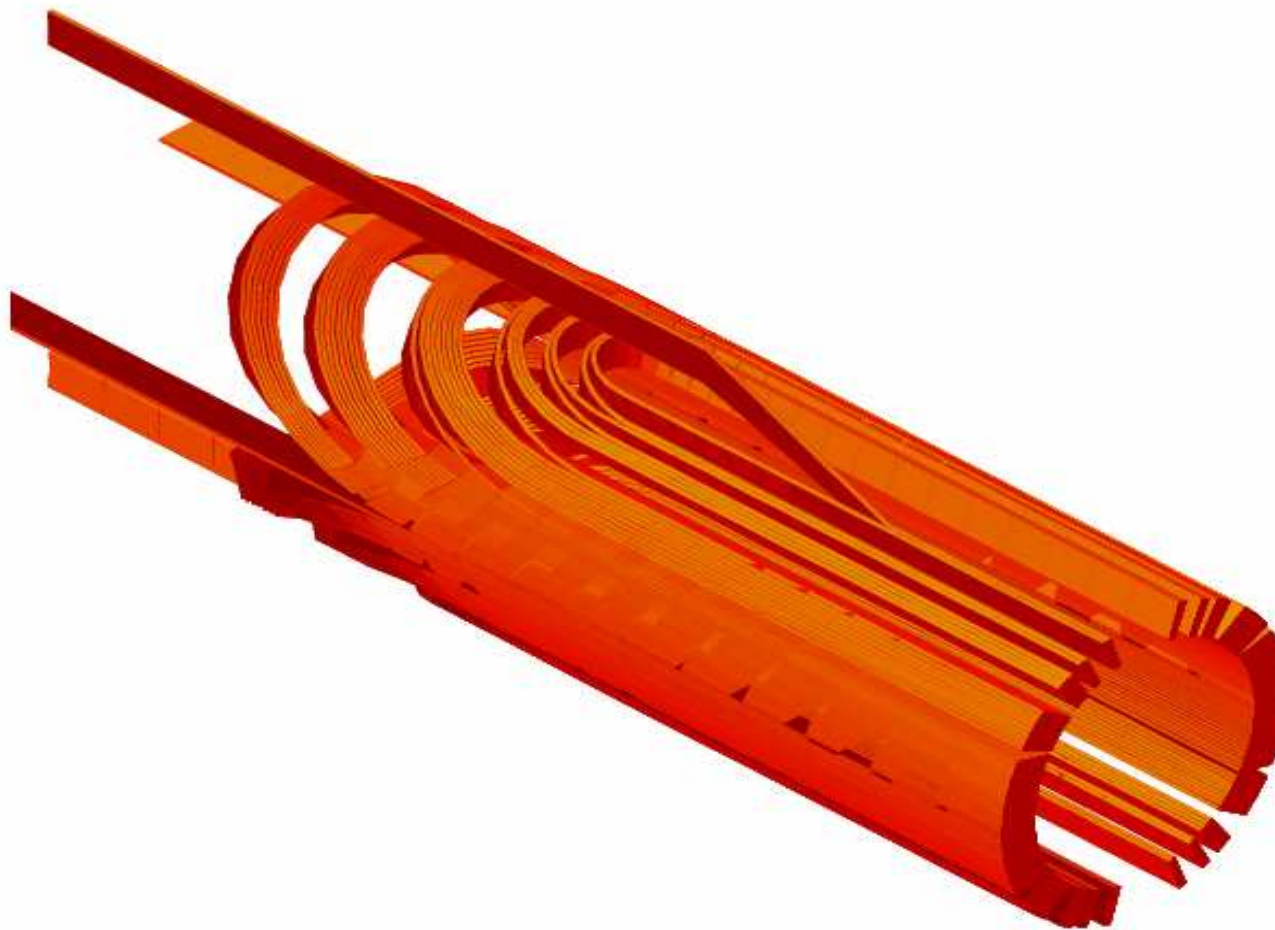
( $B_0=4.5$  T, inter-strand coupling current losses included)

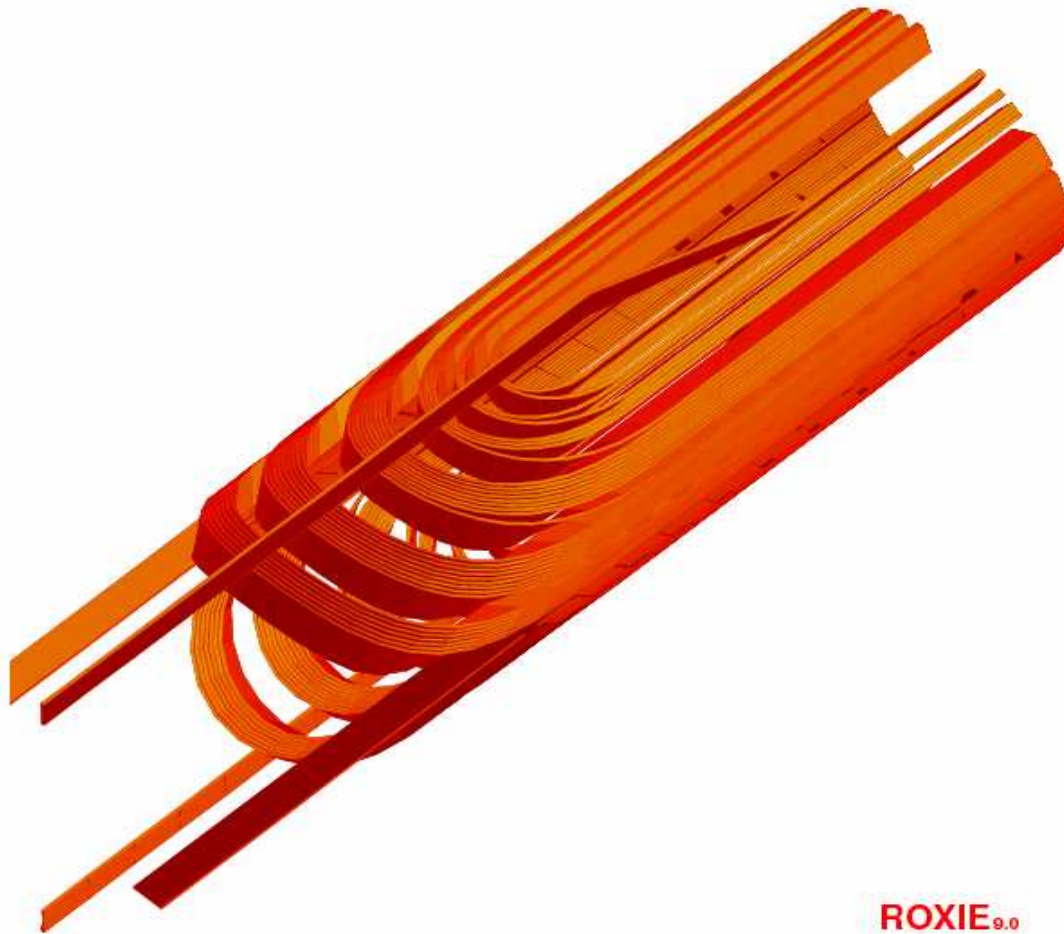


## No-symmetric coil-end lay out

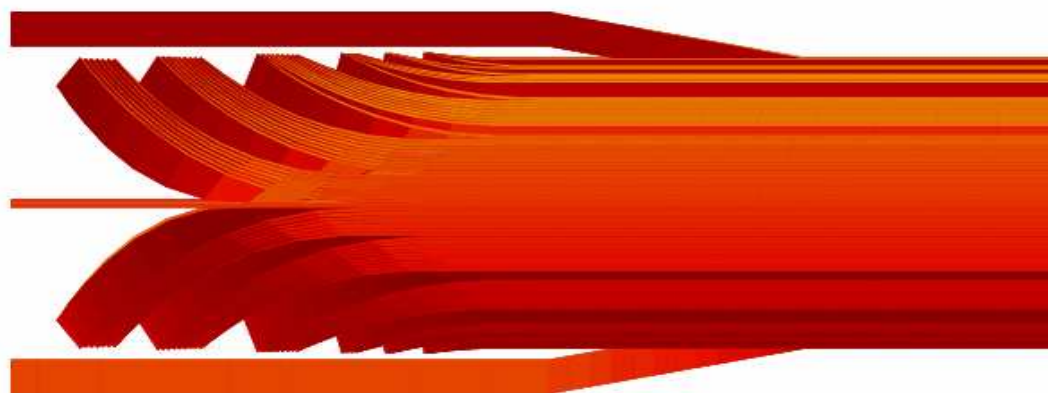
3d asg asymmetric (endspacer design - connection side)

07/10/30 11:09





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ROXIE<sub>9.0</sub>

## Conclusions:

- The design of coil-ends has been carried out.
- The integral value of b3 and b5 harmonics in coil ends are low (calculated in air).
- The peak field in coil end is significantly lower than 2-D peak field with a *short* or *long with insert* yoke
- The geometry of the yoke in coil-end with collar-insert has to preferred respect to the short-yoke, to reduce the losses. Other *free* benefits:
  - ✓ much lower stray field;
  - ✓ much lower harmonic perturbation from eddy currents.
- The losses in conductors and laminations have been estimated.

## Total losses in the magnet during ramp-up at 1 T/s

Bo (T)	In straight section (W/m)					In each coil end (W)				
	Conductor	Collar eddy	Yoke eddy	Beam tube	Yoke hyst.	Conductor	Collar eddy	Yoke eddy	Beam tube	Yoke hyst.
1.50	4.500	0.002	0.019	1.000	1.330	0.630	0.074	0.027	0.195	0.259
3.00	3.300	0.002	0.020	1.000	1.330	0.462	0.063	0.114	0.195	0.259
4.50	2.600	0.002	0.020	1.000	1.330	0.364	0.038	0.294	0.195	0.259

Bo (T)	In the 3.8 m long dipole (W)	In the 7.6 m long dipole (W)
1.5	28.4	54.4
3.0	23.7	45.1
4.5	21.1	39.9

## Conclusions (continued):

Future analysis to refine the calculation:

- Optimize the thickness of yoke in the ends (respect to peak-field and losses)
- Calculate the influence of yoke saturation in the coil-ends on the harmonics (from a preliminary analysis the influence is moderate).