



# Electromagnetic design of the coil ends *- update -*

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In the last meeting at LASA in December 2007 we had presented a configuration for the coil end.

The lay-out of the conductor block had been optimized with Roxie in order to minimize the integral value of  $b_3$  and  $b_5$ .

A configuration with 6 blocks had been selected.

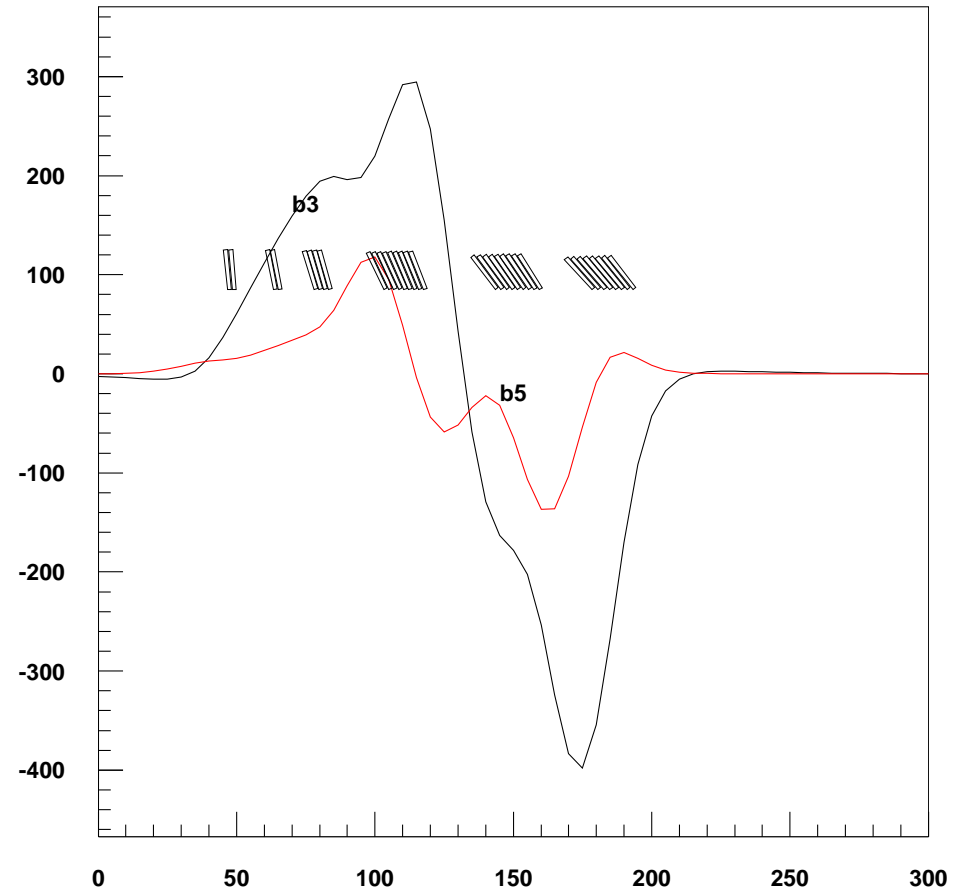
Averaged harmonics in  
symmetric coil-end “**in air**”:

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

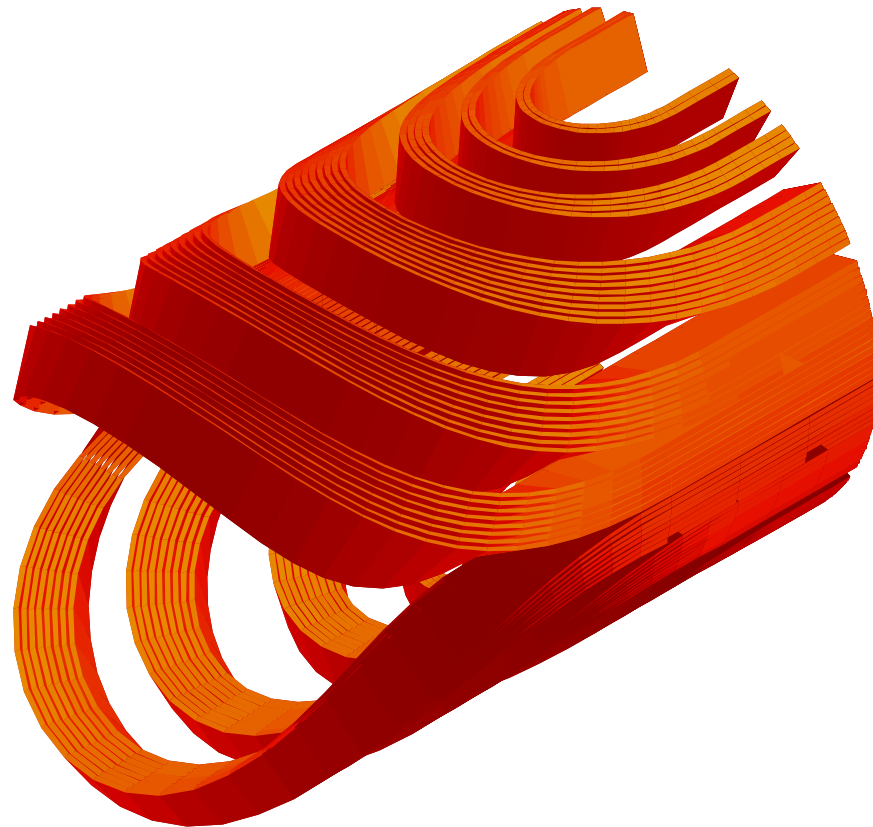
$$b_5^{coil-end} = \frac{1}{B_0} \frac{1}{\Delta z} \int_0^{\Delta z} B_5 dz = 0.04 \text{ units}$$

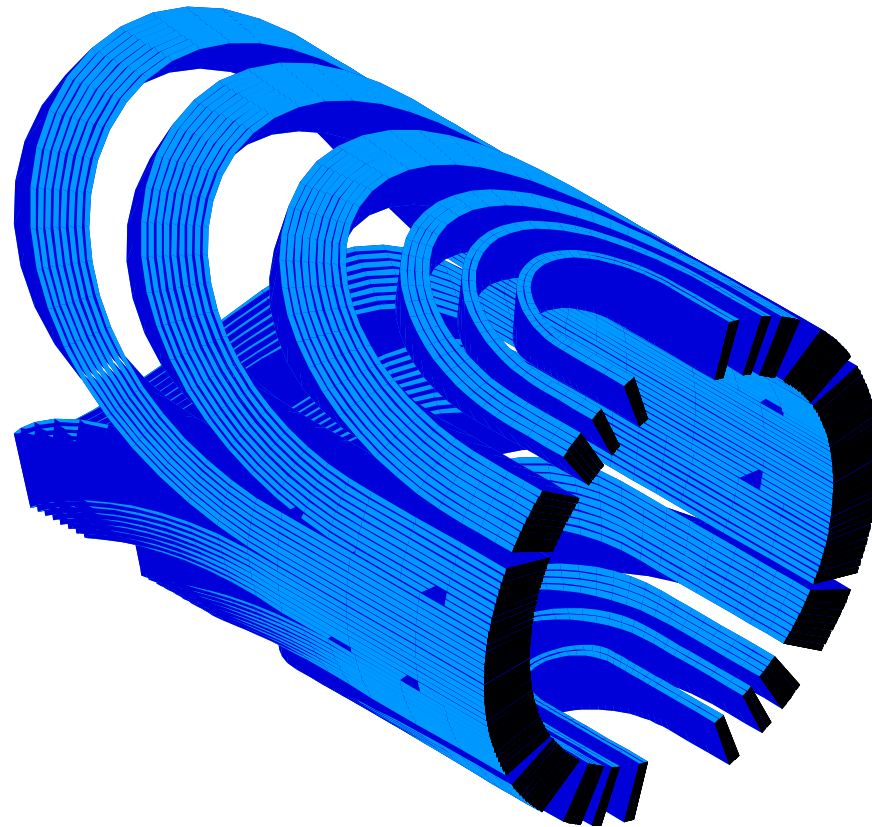
with :

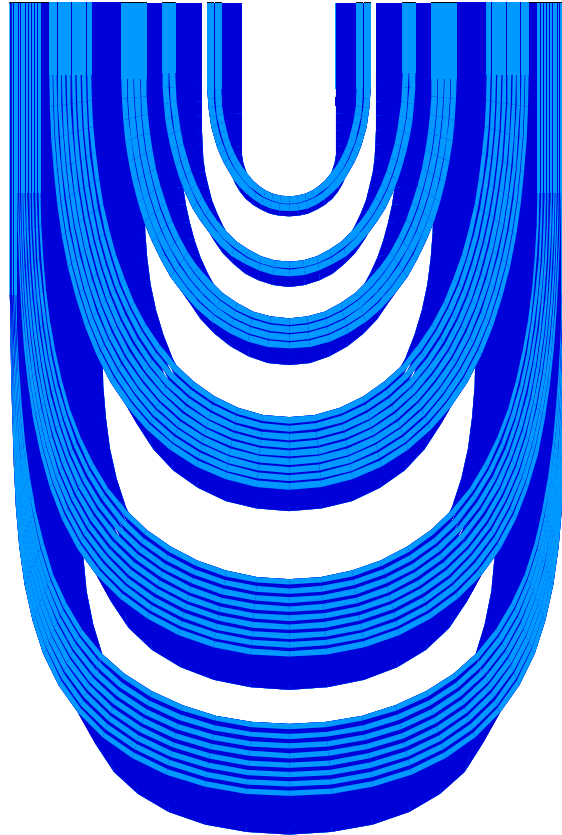
$$B_0 = 4.5 \text{ T}, \quad \Delta z = 300 \text{ mm}$$

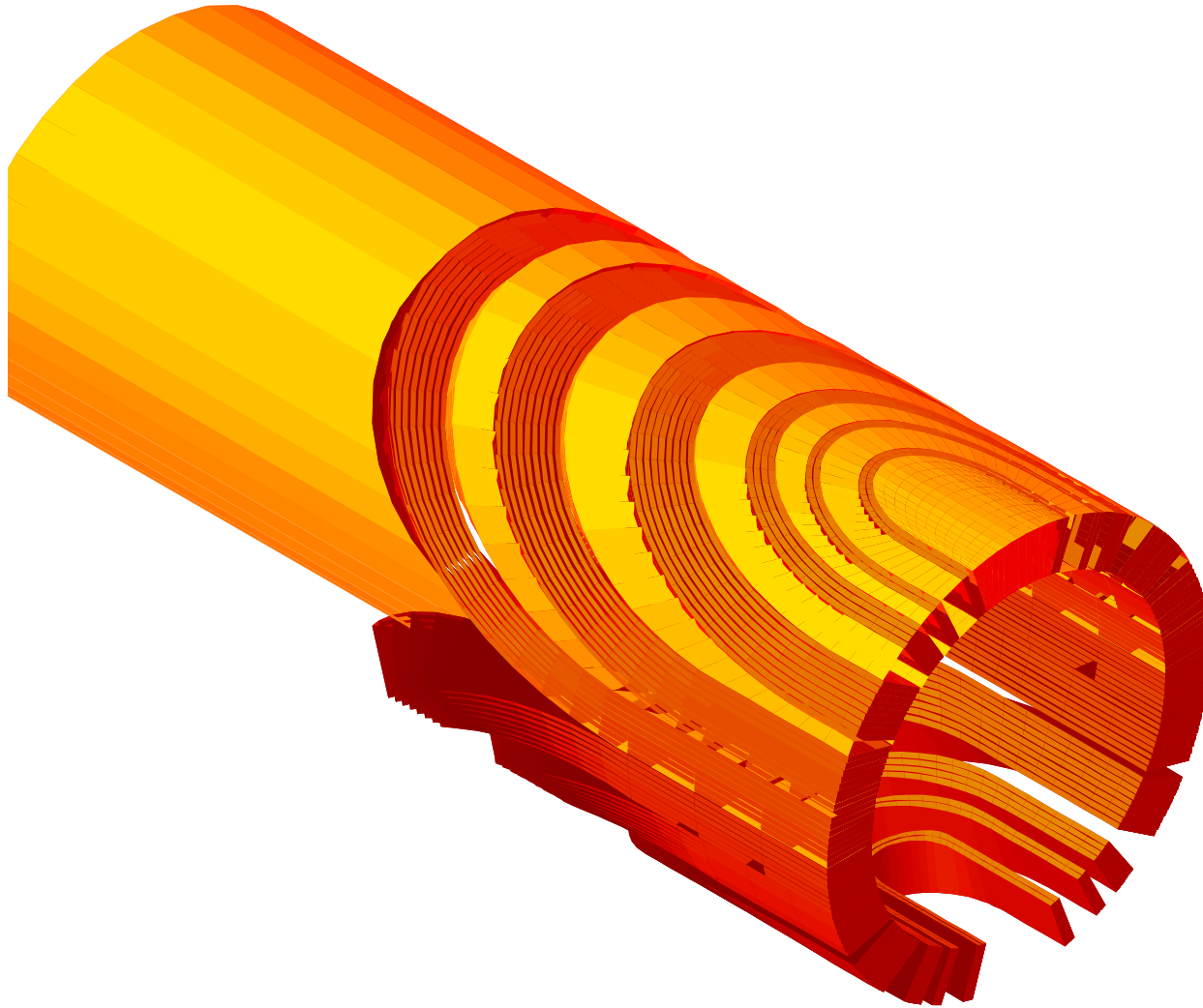


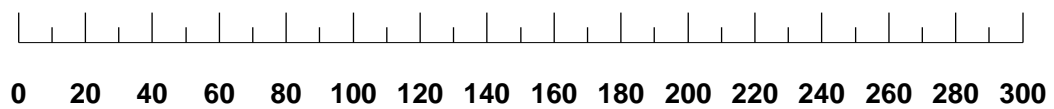
ROXIE<sub>9.0</sub>







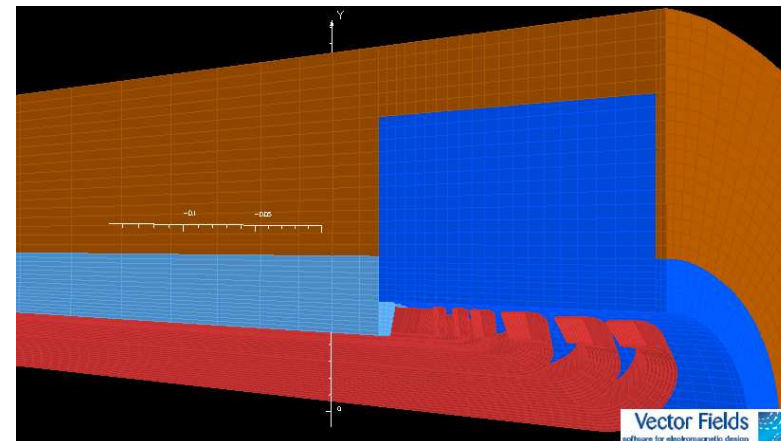
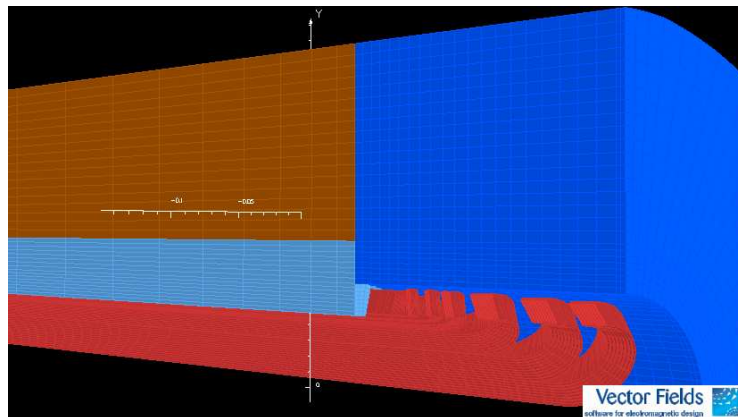
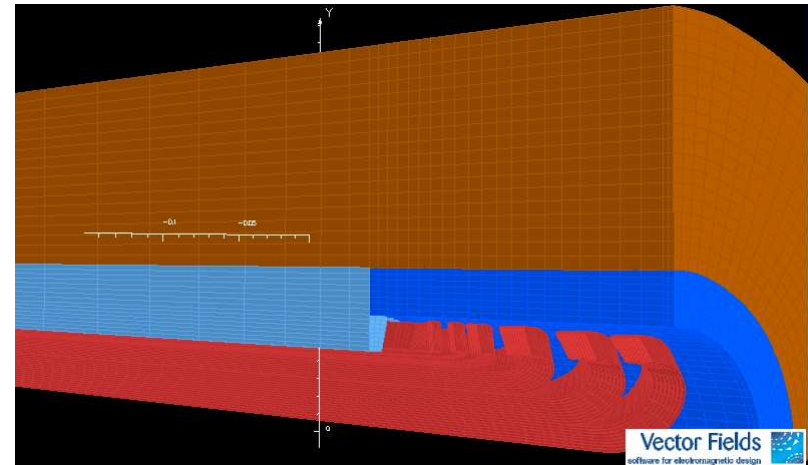






The study of peak field on conductor and of the power dissipated in the yoke and collar had been performed with OPERA 3-D  
Three yoke configurations have been considered:

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



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

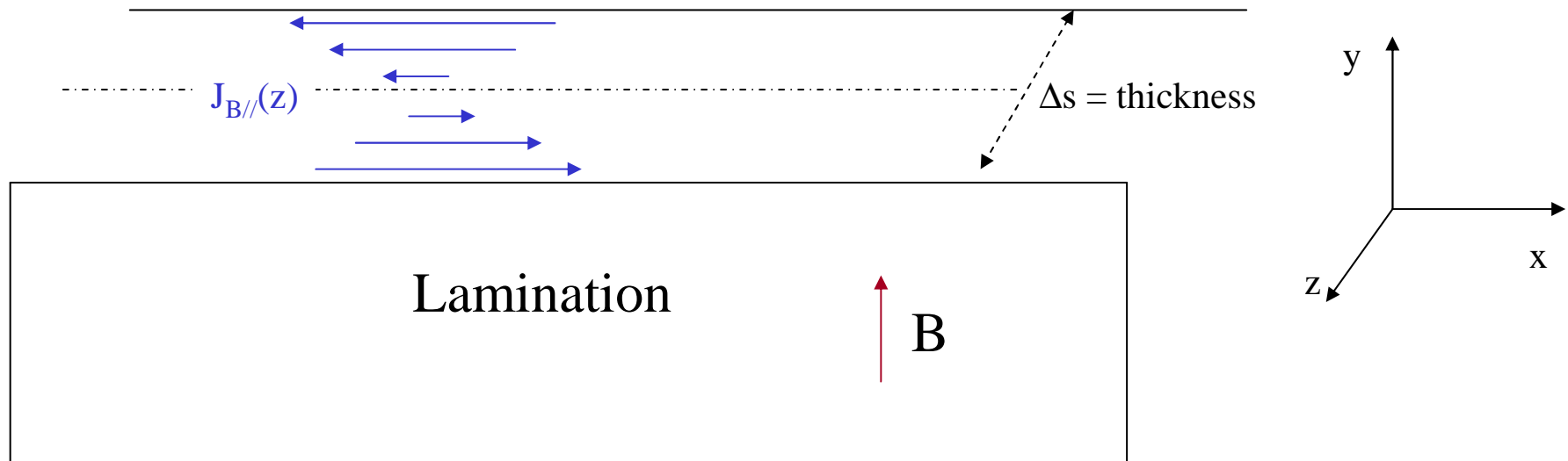
- Yoke inner & outer radius 93 mm & 213 mm,
- non-linear iron of OPERA, stack = 1
- $I = 8720$  A (no current grading in cond.)
- Coil-end between  $z = 0$  and  $z = 195$  mm

		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	Yoke w. 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

## STUDY OF THE LOSSES

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 field respect the lamination;
2. Losses due to the perpendicular component of the field respect the lamination.



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).

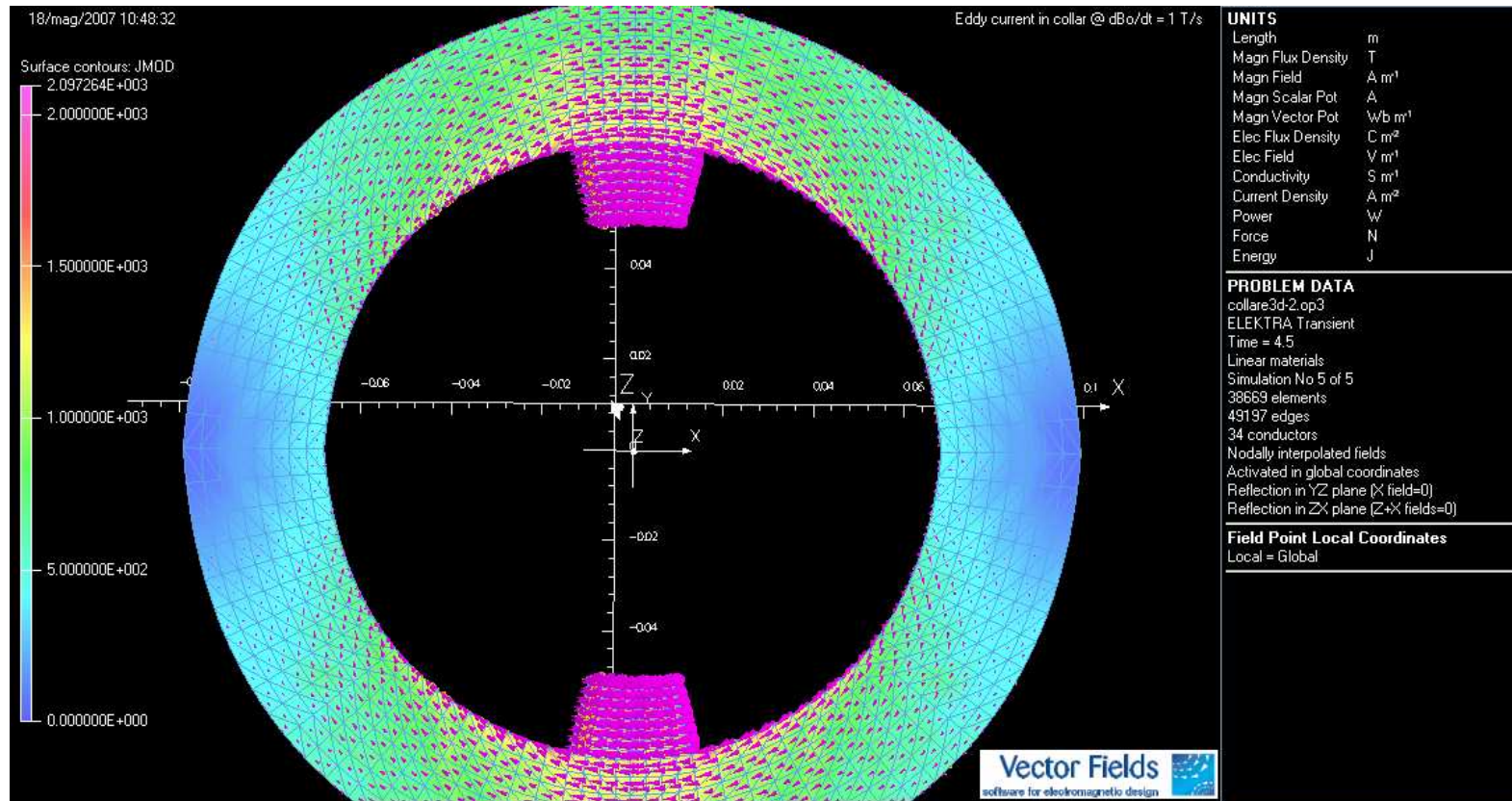
As consequence the volumetric losses in the laminations can be calculated easily:

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

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

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

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



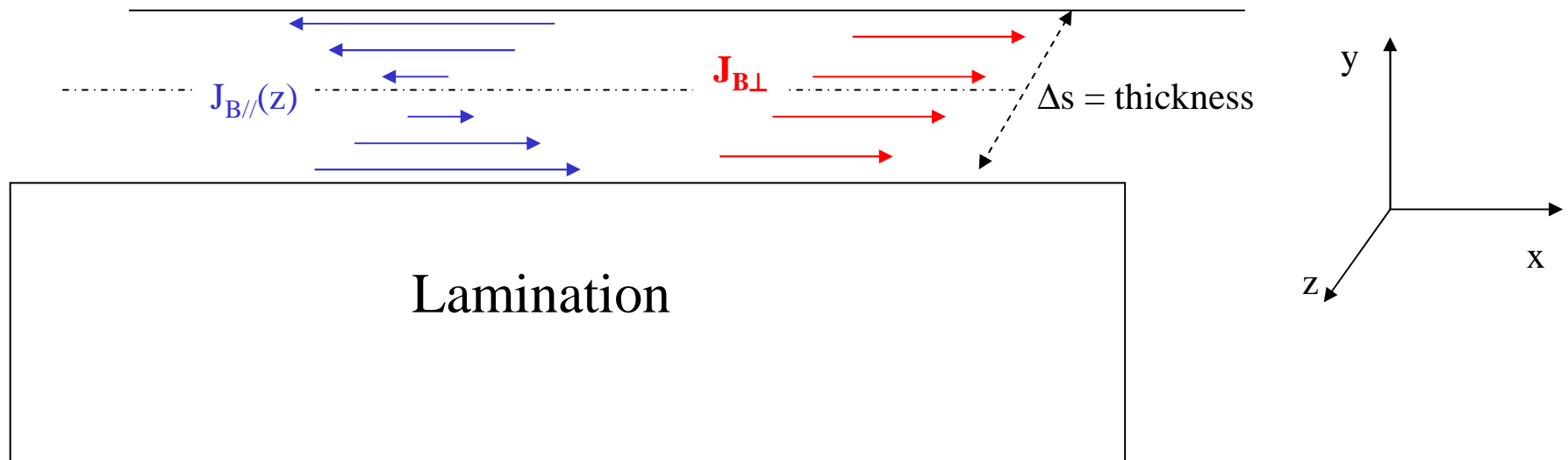
In the **coil end**, there is also the  $z$ -component of the field  $B$  (in addition to the parallel components of the field), which produces *additional* eddy currents  $J_{B\perp}$  in the  $x$  and  $y$  directions.

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  $\sigma$ :

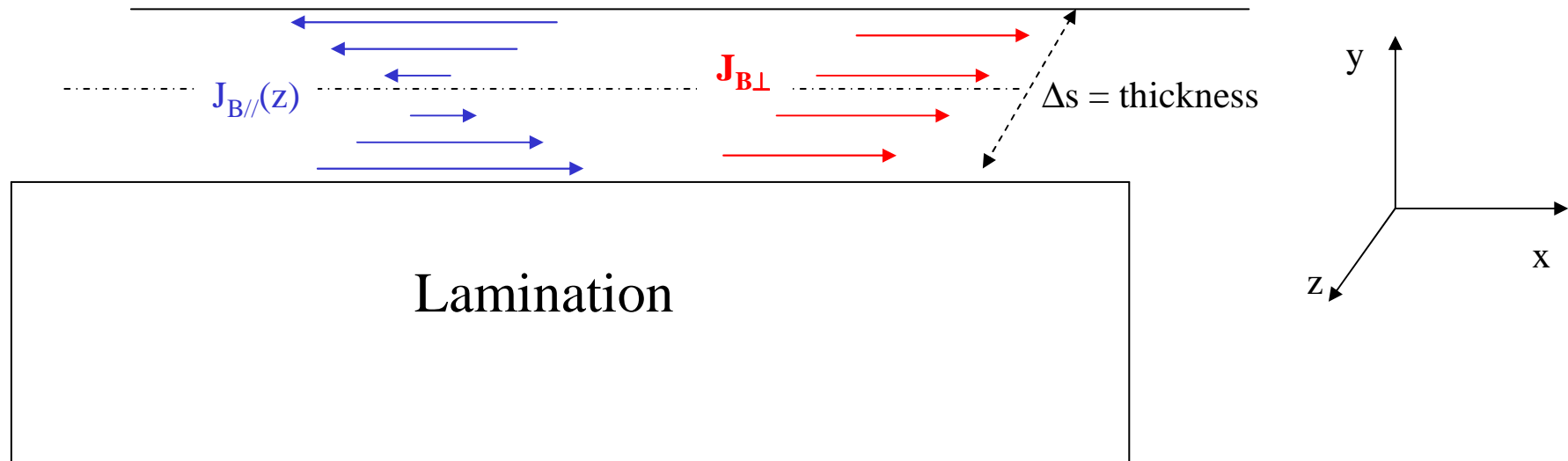
$$\left\{ \begin{array}{l} \sigma_x = 1/\rho \\ \sigma_y = 1/\rho \\ \sigma_z = 0 \end{array} \right.$$

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

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

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





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

The 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!

The analysis done in last December showed that the *short-yoke* configuration had too large value of losses in the coil-ends (up to 10 W @ 4.5 T).

But the power resulted over-estimated because the penetration of  $B_z$  in the lamination had been exaggerated (the actual reluctivity of iron in  $z$ -direction is much lower for the stacking factor).

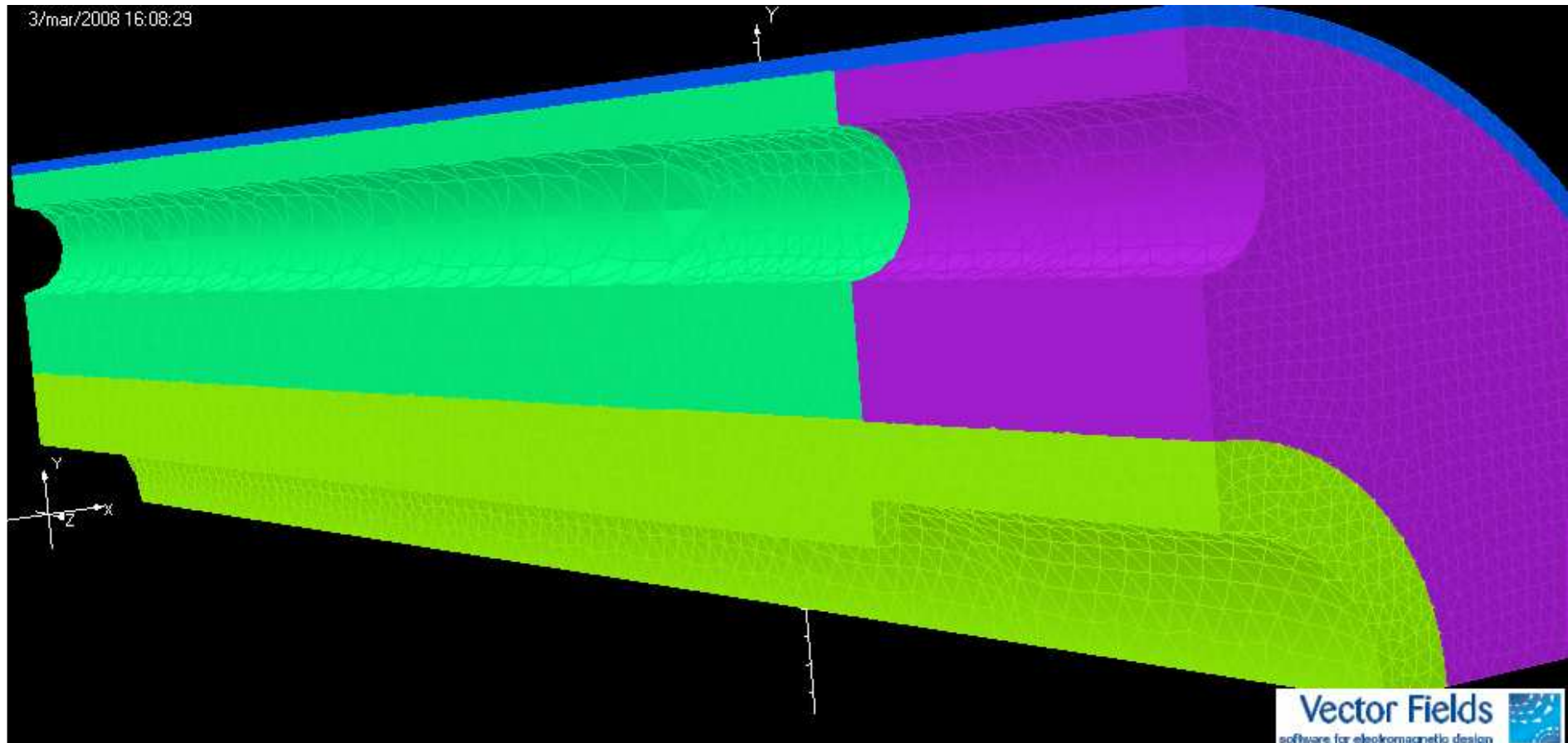
Consequently, with a new release of OPERA-3D, the study has been performed again, considering this time the stacking factor together to non-linear iron.

In the new model we have inserted:

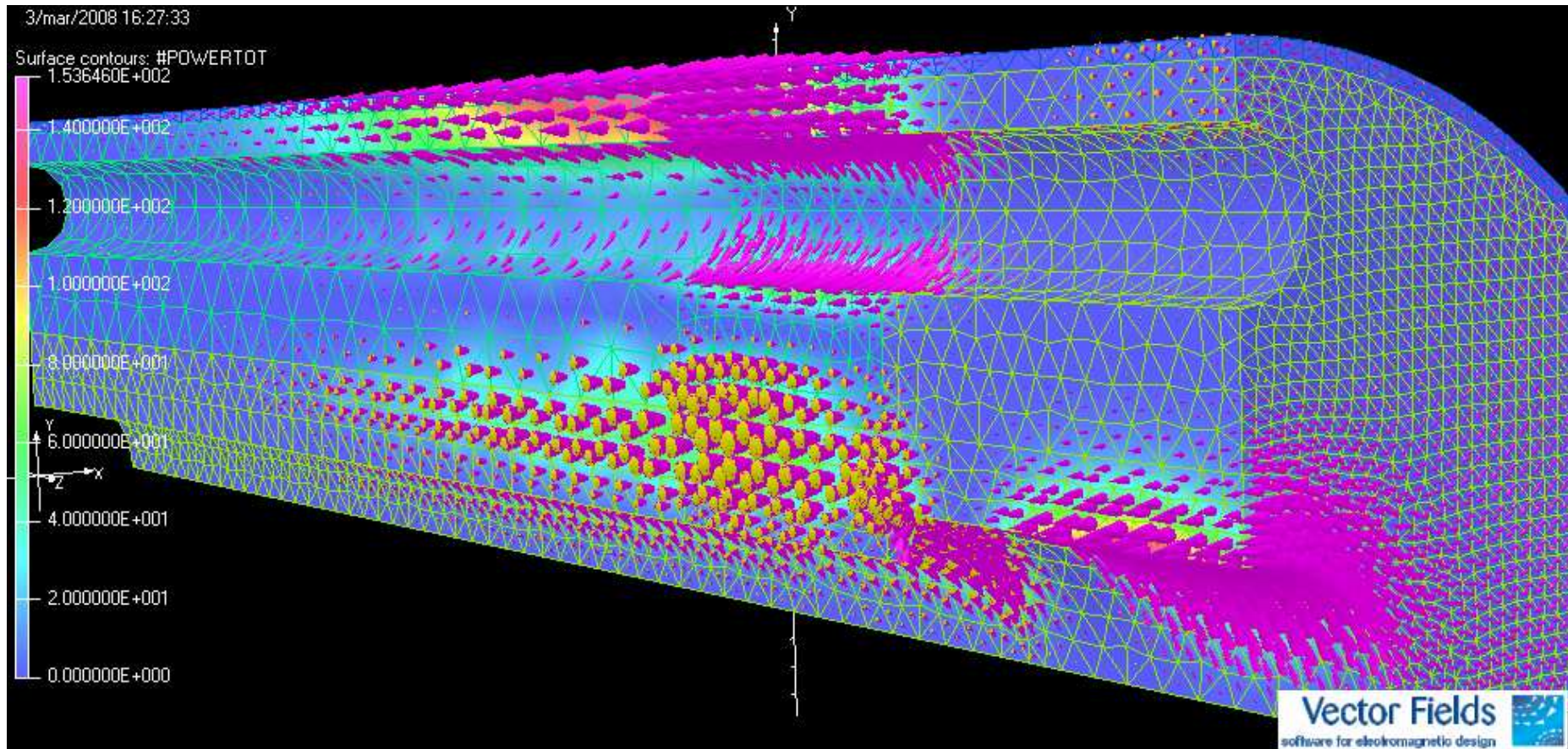
- Stacking factor = 0.98
- The main cooling holes in the yoke.
- The external cylindrical vessel for the He
- The new values for the inner/outer radii of yoke (97 mm / 230 mm)

The case with short yoke had been considered.

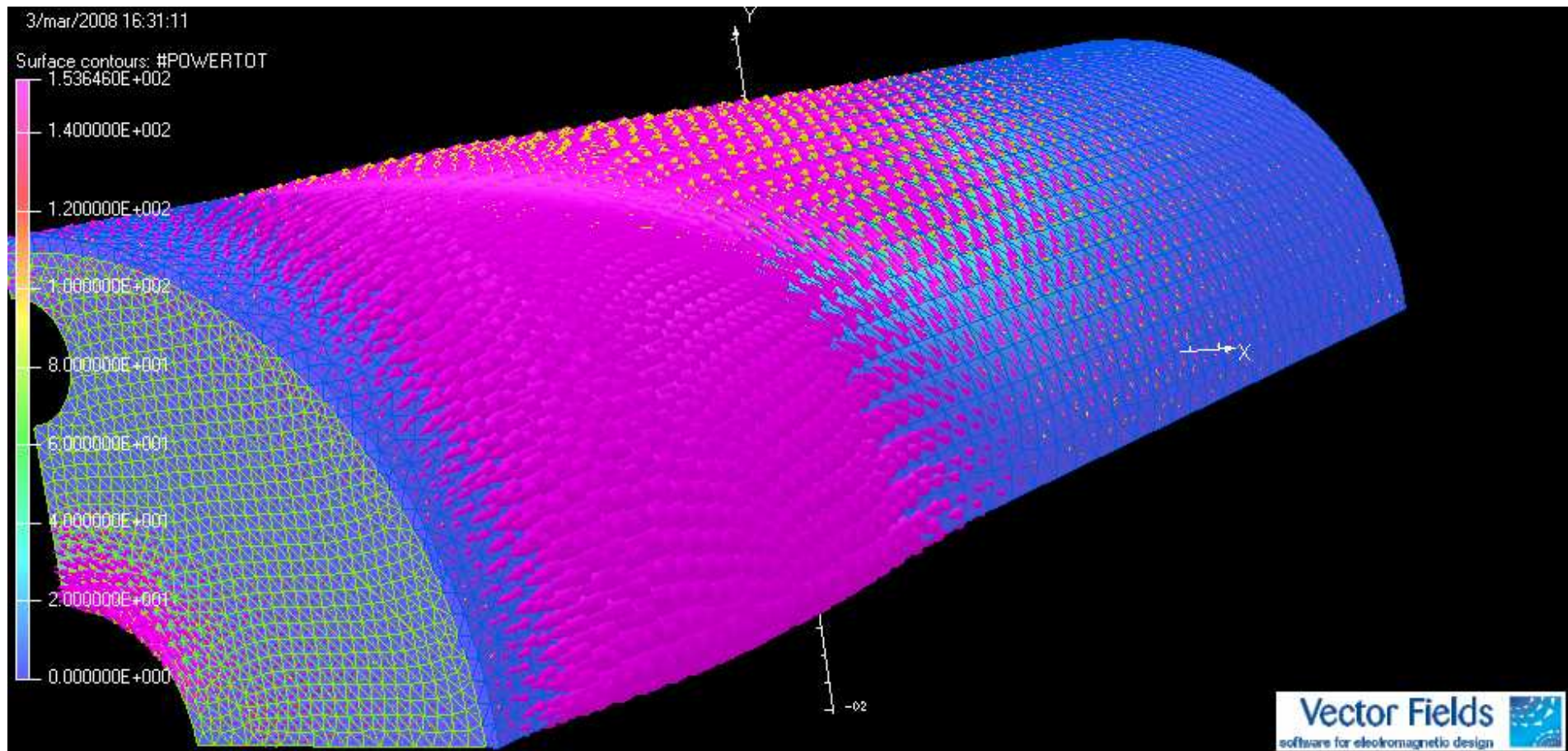
1/8 of the model (1.2 m long)



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

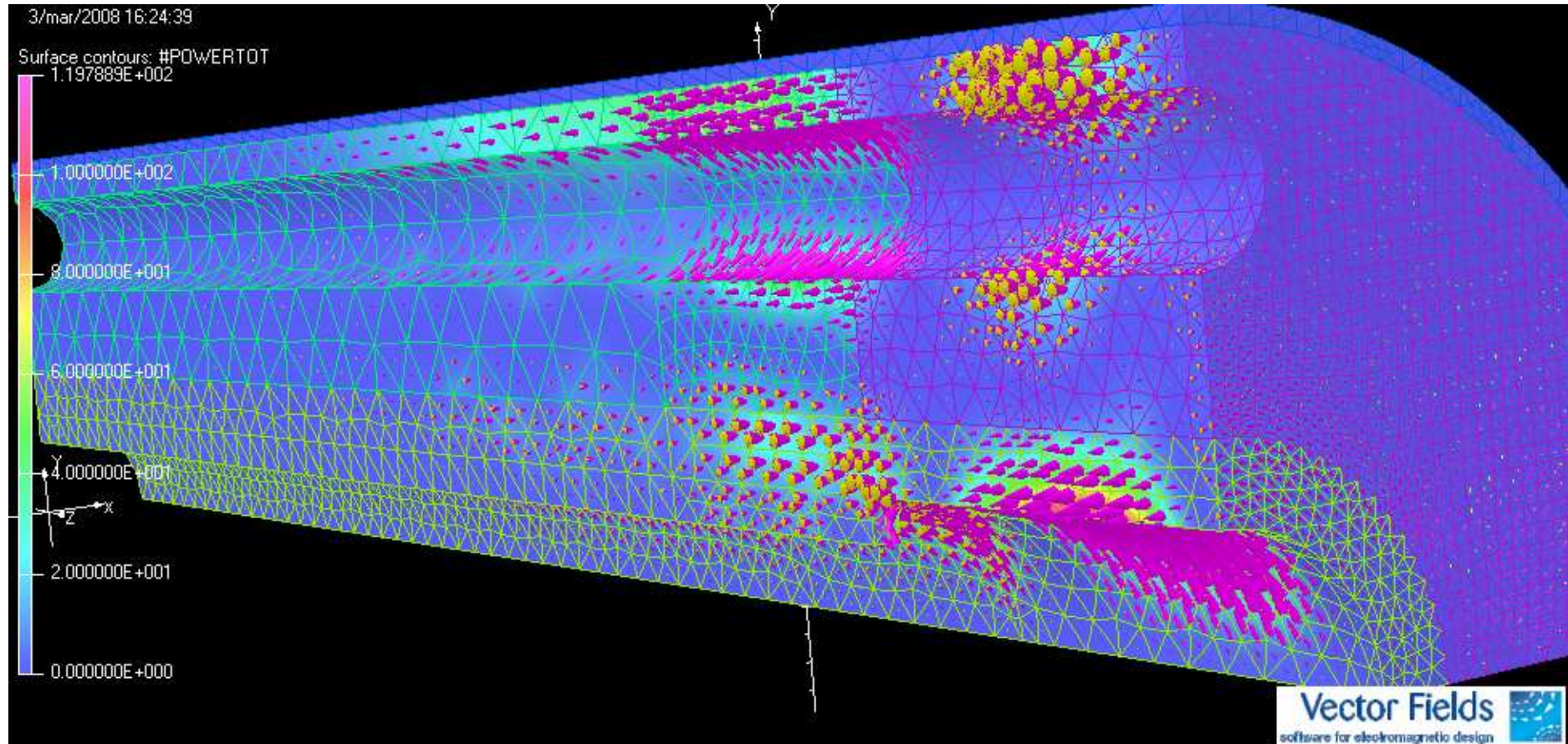


Losses (colours) and current (arrows) @ 4.5 T



## 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



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

(short yoke, stack=0.98, insulated He vessel)

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	0.006	0.002	1.000	1.330	0.630	0.284	0.326	0.195	0.259
3.00	3.300	0.006	0.002	1.000	1.330	0.462	0.579	1.465	0.195	0.259
4.50	2.600	0.006	0.002	1.000	1.330	0.364	0.418	1.834	0.195	0.259

Bo (T)	In the 3.8 m long dipole (W)	In the 7.6 m long dipole (W)
1.5	29.4	55.4
3.0	27.3	48.8
4.5	24.9	43.7

Eddy current losses in laminations for each coil end are up to 2.5 W ( @4.5 T )

In the case of yoke w. insert, they are about 0.5 W/coil-end

The study of losses for eddy currents is preliminary because some details are missing in the model, like:

- keys and clamps in the collar and yoke laminations (they are like short-circuit for eddy current)
- vacuum vessel and thermal shield, especially in the coil end region.

Because the computation times are much large, the complete analysis will be performed when all the main parameters for the yoke will be well defined.

## Conclusion:

- The *long-full-yoke* configuration is not acceptable for the peak field in conductor.
- Losses in the lamination of coil-ends seem manageable in *short-yoke* configuration (10% of total losses for the 7.6 m long magnet)
- In the configuration of *yoke-with-insert* the losses are reduced by about a factor 5 respect to the short-yoke case.
- If these data are confirmed by the final calculation we propose to use the *short-yoke* configuration.