Optimisation of the current distribution in the IGNITOR poloidal field coils and evaluation of the coils temperatures and resistance during the reference operating scenario

Cocilovo Valter (1), Cucchiaro Antonio (1), Galasso Giuseppe (2), Pizzuto Aldo (1), Ramogida Giuseppe (1), Rita Camillo (1) , Roccella Massimo (1) , Roccella Riccardo(3),

Prof. Coppi Bruno (4)

(1) Associazione ENEA-EURATOM sulla Fusione, C.P. 65, 00044 Frascati (RM), Italy

(2) Ansaldo Ricerche, Corso Perrone 25, 16152 Genova (GE), Italy

(3)L.T.Calcoli

(4) MIT, 02139 Cambridge (Ma), USA

INTRODUCTION

The Ignitor project, devoted to study burning plasmas, requires a very demanding scenario in terms of current intensities on poloidal and toroidal coils , so that :

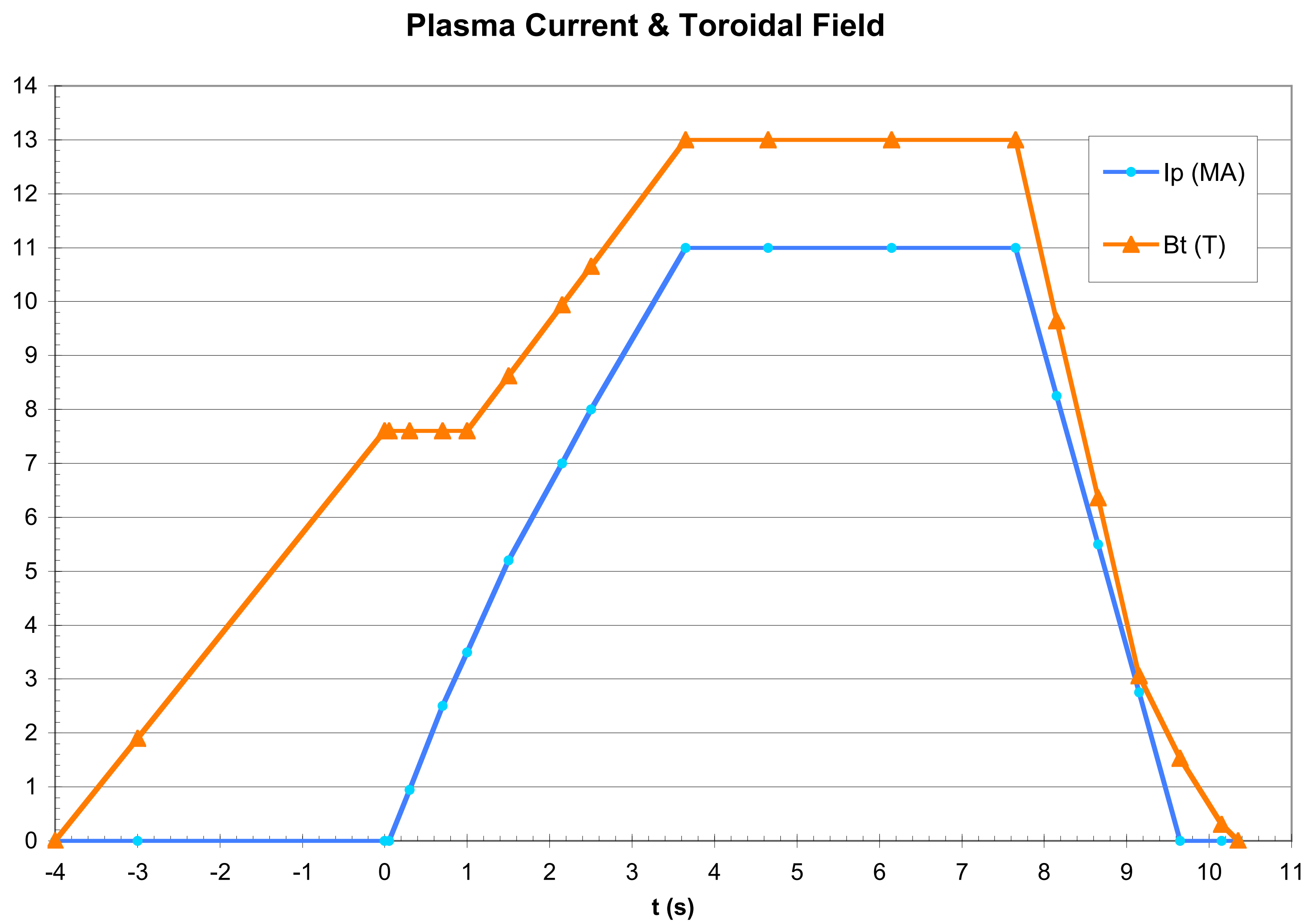
– Complex mechanical interaction (bucking) is forecast between the central solenoid coils and the toroidal field system
– High current density is expected in the central solenoid during the pulse

OVERVIEW

The high current densities in poloidal coils needed by the IGNITOR project scenarios, increase the conductors temperatures and then their resistivity

Conductor resistivity depends also on magnetic flux density magnitude (magneto-resistive effect)

Time durations forecast for the IGNITOR pulses suggest to consider the thermal process as adiabatic (no cooling effect available during pulse)

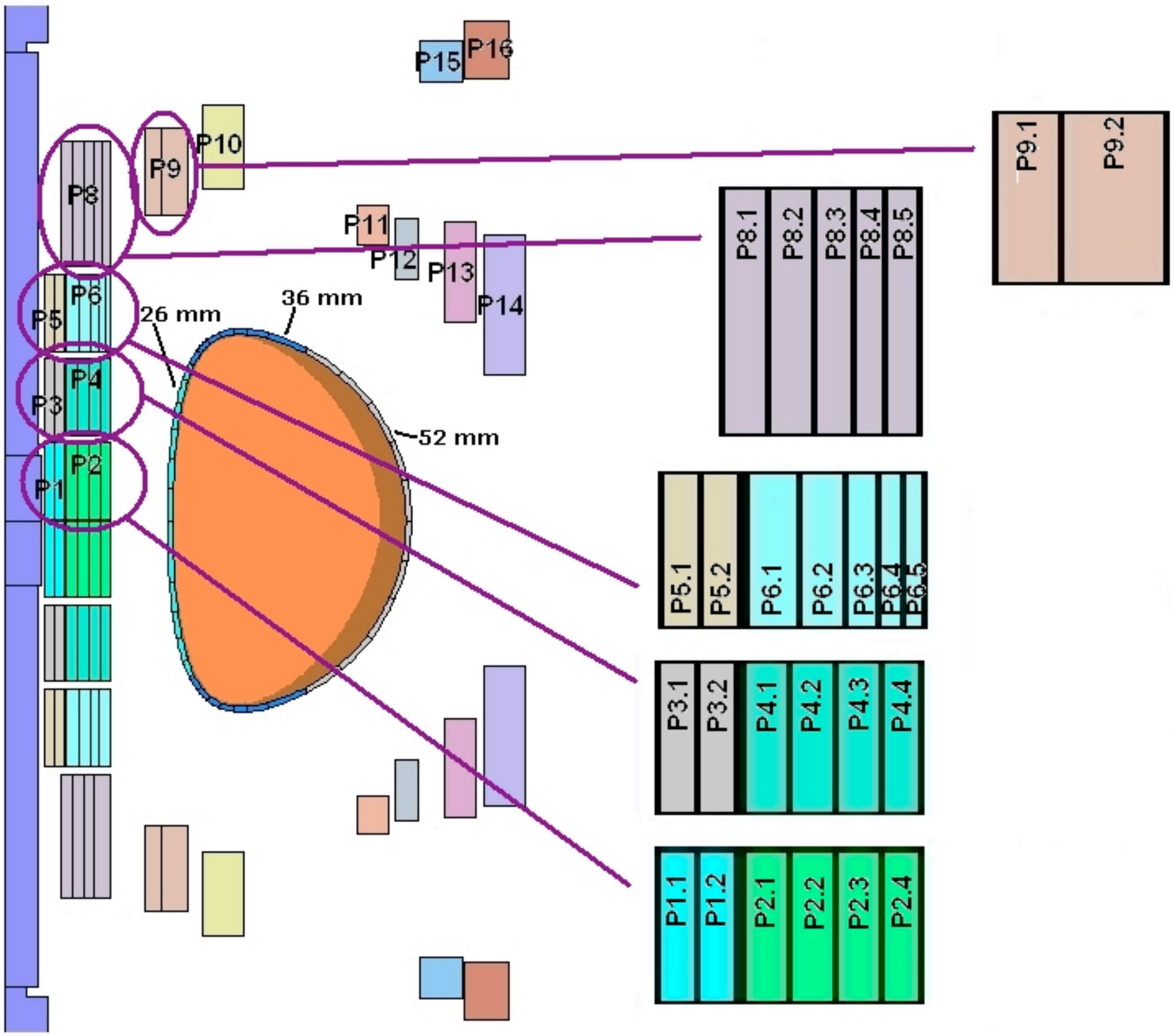


Plasma Current & Toroidal Field
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
t (s)
Ip (MA)
Bt (T)

POLOIDAL COILS

- IGNITOR Poloidal Field Coils (PFC) system is made up of 15 up - down symmetric coils pairs :
  - 1 to 8 form the Central Solenoid to produce the flux variation linked with the plasma column
  - 9 to 14 form the External Coil Assembly to generate the plasma equilibrium configuations
  - 15 and 16 form the Radial Electromagnetic Press to modulate the the axial pressure on the TFC inner legs
- Different types of copper are envisaged in coils manufacturing to better match the severe loads forecast for them

POLOIDAL COILS



MAIN THERMAL PROBLEMS

- High temperature levels at the end of the pulse
- Long cooling times between pulses
- High temperature gradients in central solenoid
- High stresses in conductor materials

MITIGATING ACTIONS

GOALS :

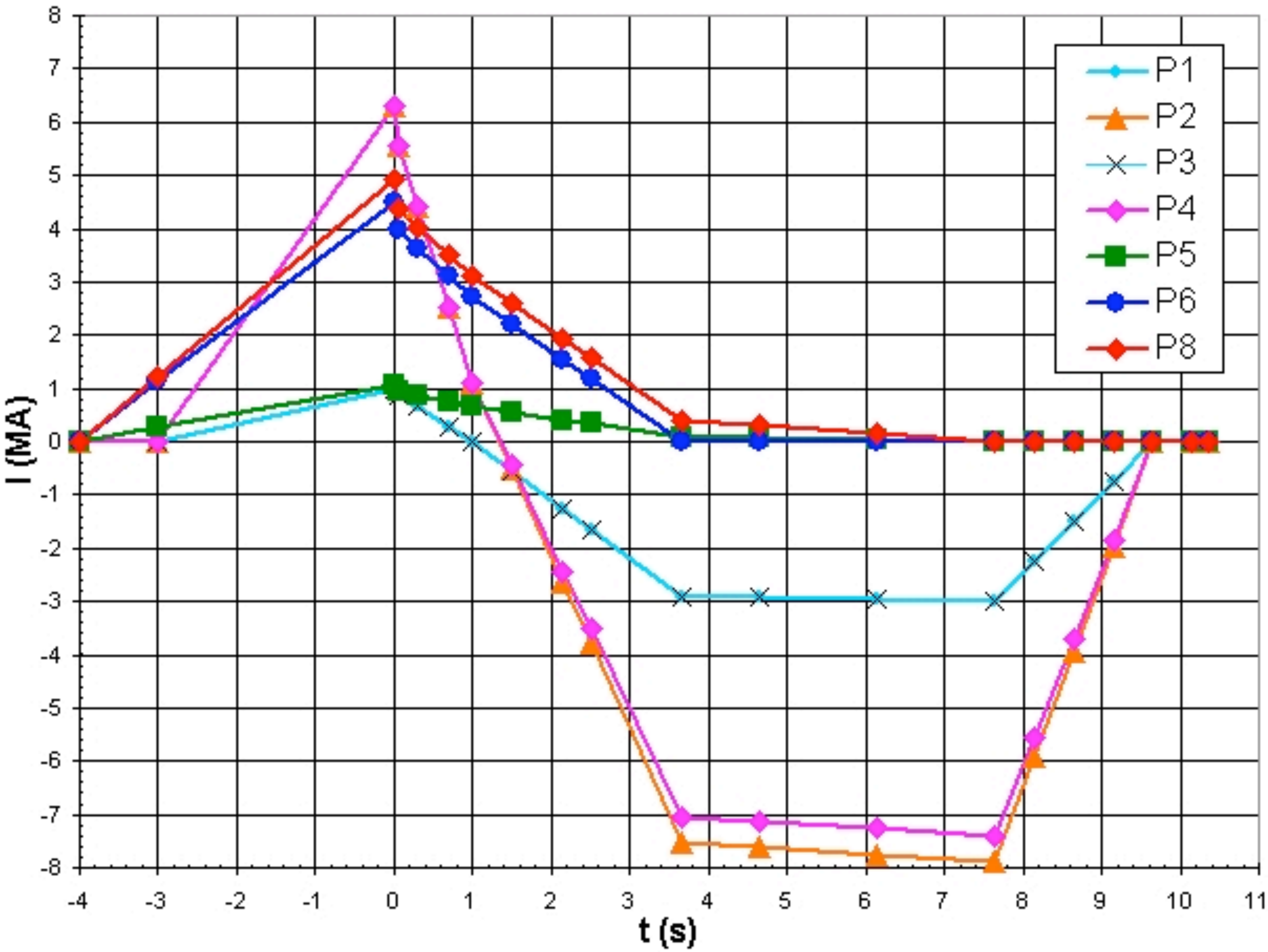
- Redistribution of the currents among coils
- Redistribution of the currents into the coils
- Reduction of the temperature gradient in central solenoid

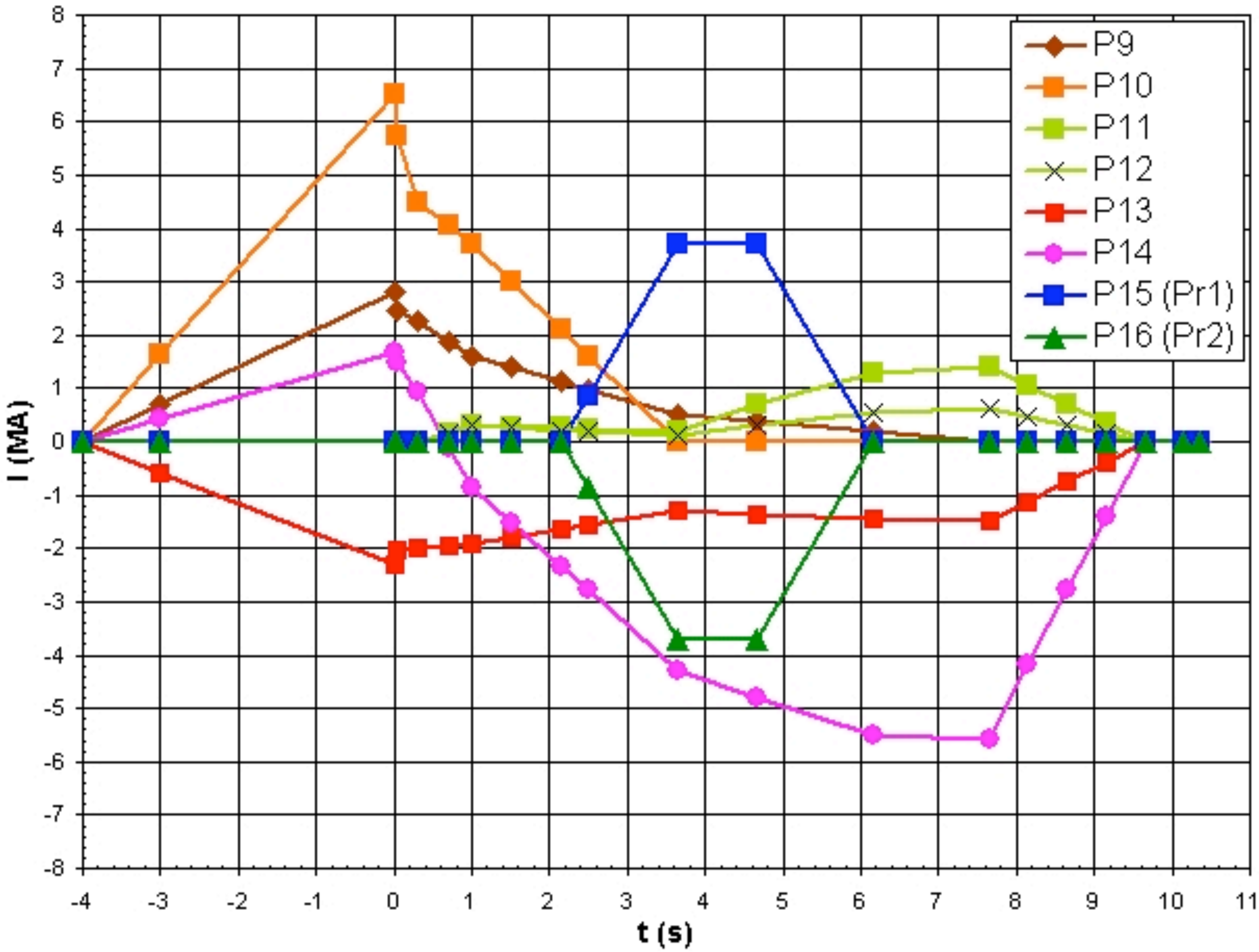
MEANS :

- New optimized operating scenarios
- Current coils grading technique
- Central solenoid optimization (geometry and materials)

NEW SCENARIO

- The previous scenario has been modified by:
  - the redistribution of the currents in the coils decreasing them in the more solicited (P9 , P12 and P13)
  - the avoidance of change of polarity in the coils devoted to plasma shaping (P5 to P13)
  - The series between P1 and P3 and P5 and P8
  - smoothening and starting earlier the ramp-up of the currents in some coils (P5 to P14)


P1
P2
P3
P4
P5
P6
P8
I (MA)
t (s)
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11


P9
P10
P11
P12
P13
P14
P15 (Pr1)
P16 (Pr2)
I (MA)
t (s)
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11

CENTRAL SOLENOID OPTIMIZATION

Maximization of the conductor section in the space assigned to the central solenoid by :

- Minimization of conductor holes for the helium cooling
- Reduction of the coil - mass isolation
- Adoption of fiber slip between the coils of solenoid and the central post and the toroidal magnet steel casing

GRADING TECHNIQUE

- To mitigate the magneto-resistive temperature increase and the electromagnetic loads in the higher field areas , has been used a grading technique to increase the density current in the areas where the magnetic field is lower . This goal was achieved by decreasing the conductor section from the inner to outer layers of the coils , after a careful choose of the conductor materials and analysis of their properties together to a detailed study of the geometric constraints .

COIL MATERIALS

- Three types of copper are used in poloidal coils manufacturing :
  - Copper OFHC RR = 40
  - Copper OFHC RRR = 90
  - Copper OFHC 35% cw 0.15% Ag

SIMULATION

- To analyze the modified configuration of the poloidal coils together with the new reference scenario a 2D time-variant integral code was written in ENEA to solve the coupled electromagnetic and thermal problems , taking in account the resistivity increase due to resistive heating and to magnetic field effect by a relation elaborated by ABB and ENEA , more pessimistic then the NIST one . Furthermore the magnetic fields were compared with those obtained by MAXWELL 2D , a largely used FEM code in electromechancal industry .

Resistivity - Temperature Relation OFHC RR=40

- T< 77K

$$\rho_T = -2.4872 \cdot 10^{-16} \cdot T^4 + 4.0034 \cdot 10^{-14} \cdot T^3 - 1.5045 \cdot 10^{-12} \cdot T^2 -$$
$$+1.9526 \cdot 10^{-11} \cdot T + 3.2802 \cdot 10^{-10}$$

- T>= 77K

$$\rho_T = 6.949 \cdot 10^{-11} \cdot (T - 77) + 2.45 \cdot 10^{-9}$$

Resistivity - Temperature Relation OFHC RR=90

- T< 77K

$$\rho_T = -4.1267 \cdot 10^{-12} \cdot T^5 + 7.6250 \cdot 10^{-18} \cdot T^4 - 6.5141 \cdot 10^{-16} \cdot T^3 + 4.0892 \cdot 10^{-14} \cdot T^2 -$$
$$+1.1251 \cdot 10^{-12} 1.2714 \cdot 10^{-10}$$

- T>= 77K

$$\rho_T = 6.935 \cdot 10^{-11} \cdot (T - 77) + 2.25 \cdot 10^{-9}$$

Resistivity - Temperature Relation OFHC Cu 0.15% Ag

- T< 77K

$$\rho_T = 5.1339 \cdot 10^{-15} \cdot T^3 - 1.5205 \cdot 10^{-13} \cdot T^2 + 1.11604 \cdot 10^{-11} \cdot T + 9.83695 \cdot 10^{-11}$$

- T>= 77K

$$\rho_T = 6.87963 \cdot 10^{-11} \cdot (T - 77) + 2.4 \cdot 10^{-9}$$

MAGNETO _ RESISTIVE EFFECT

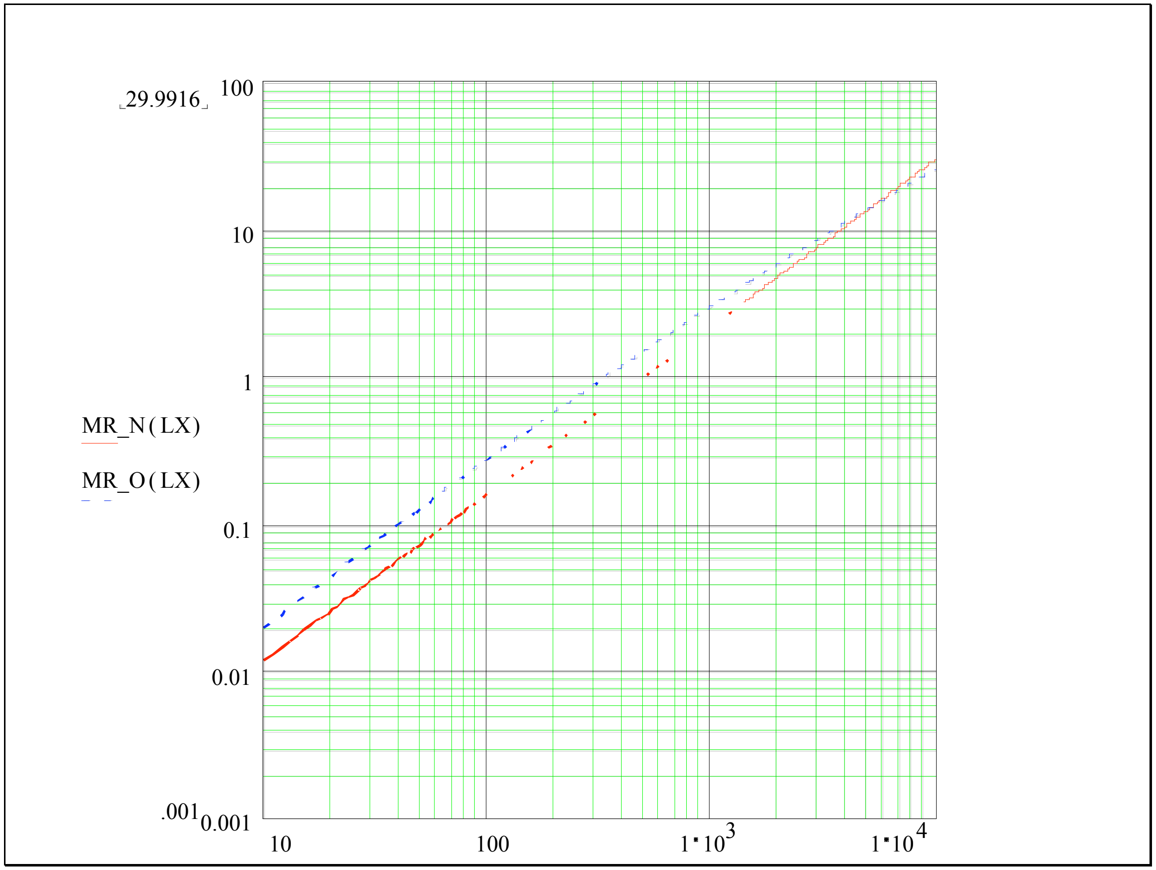
- Resistivity variation with magnetic field is taken in account by the parameter :

$$Lx = \log(Bm \cdot \frac{\rho_{273}}{\rho_T})$$

- Which is used in the expression :

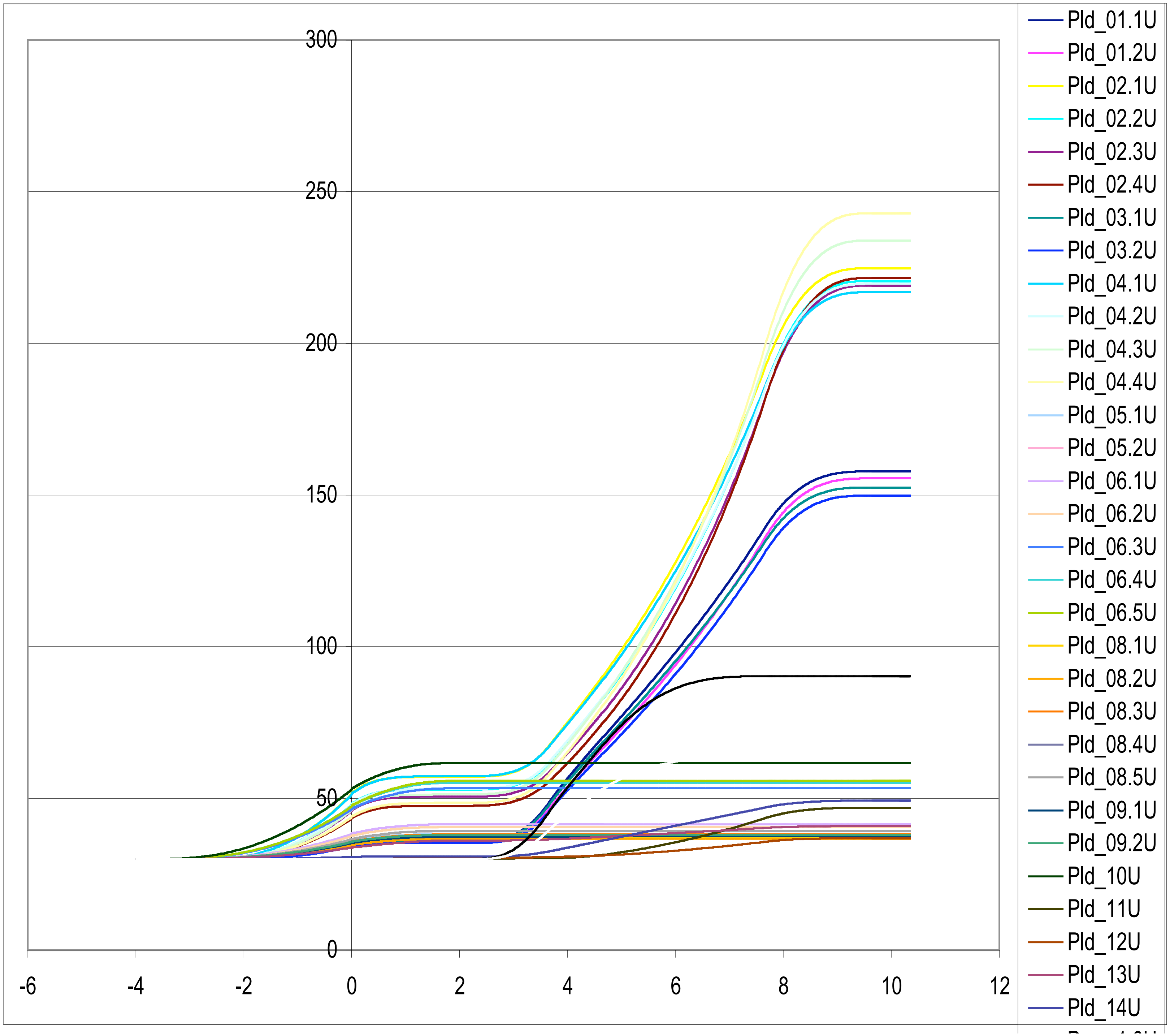
$$\rho_{mag} = \rho_T \cdot (1 + e^{(-0.02221686 \cdot Lx^2 + 1.29288 \cdot Lx - 6.765548)})$$

Magneto-Resistive Relations

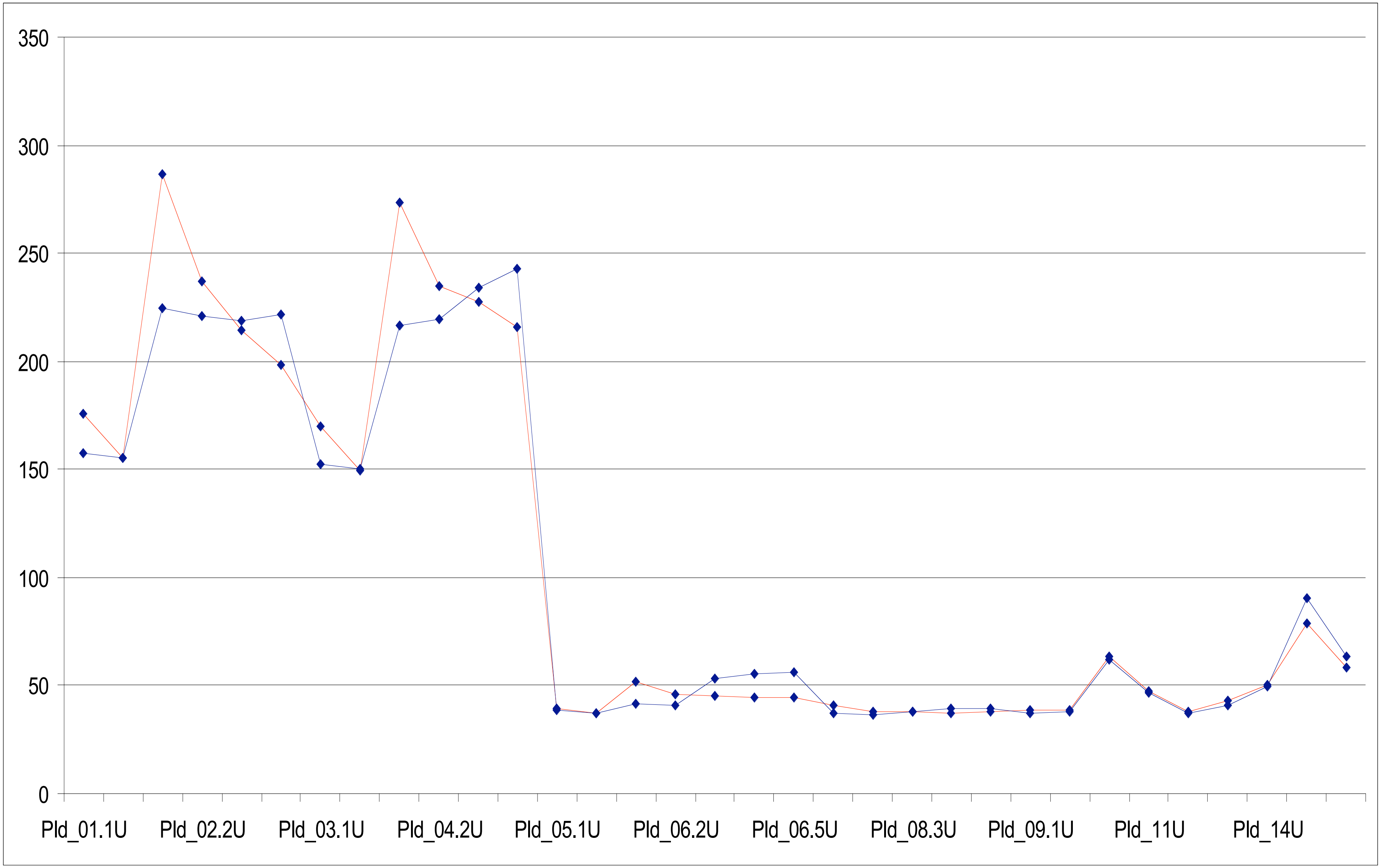


SIMULATION RESULTS

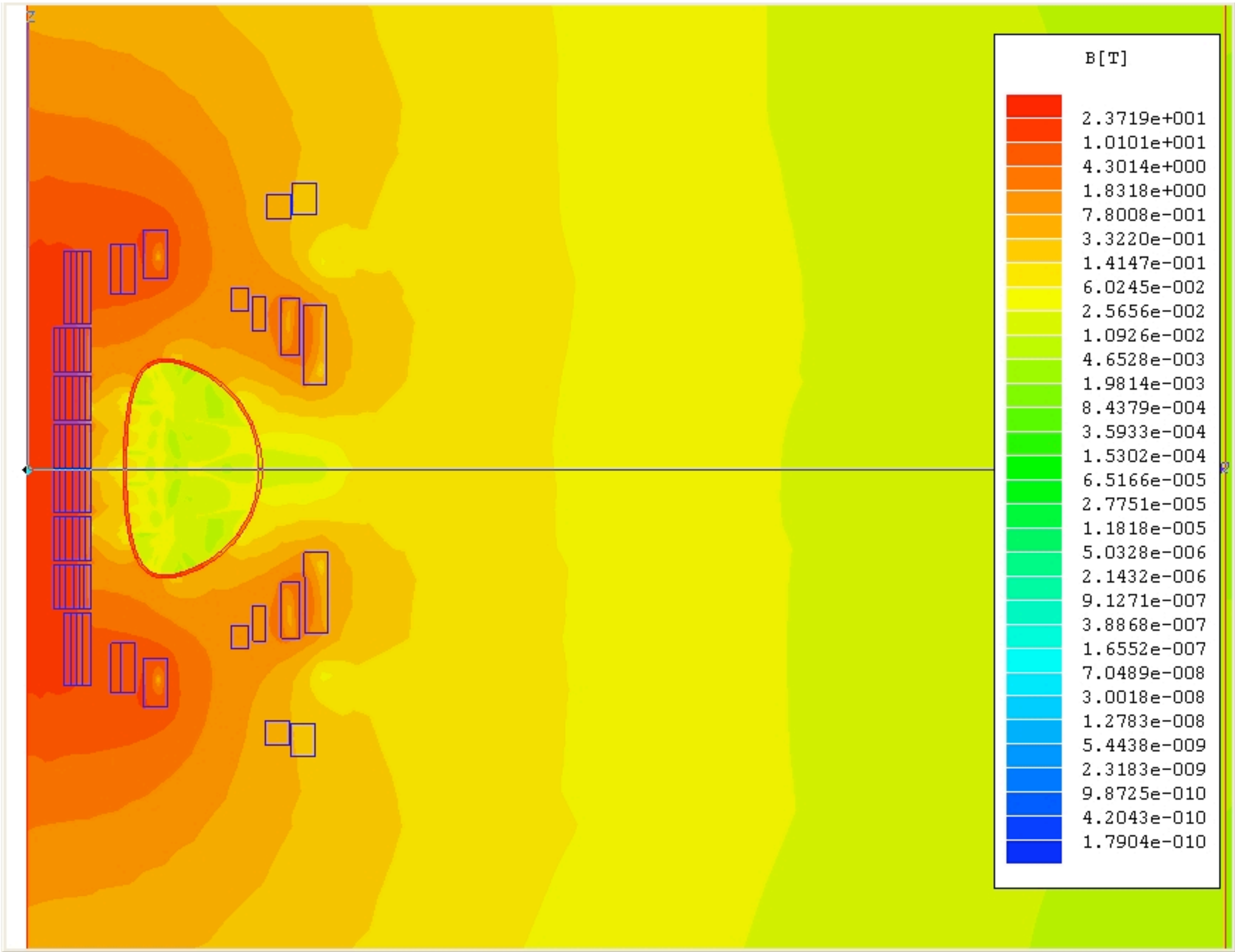
- The simulation has confirmed the expected improvements , showing :
  - Reduction of the temperature differences between layers of the same coil
  - Containement of the temperature differences between radially adjacent coils
  - Lowering of mean and peak temperatures



300
250
200
150
100
50
0
-6
-4
-2
0
2
4
6
8
10
12
Pld_01.1U
Pld_01.2U
Pld_02.1U
Pld_02.2U
Pld_02.3U
Pld_02.4U
Pld_03.1U
Pld_03.2U
Pld_04.1U
Pld_04.2U
Pld_04.3U
Pld_04.4U
Pld_05.1U
Pld_05.2U
Pld_06.1U
Pld_06.2U
Pld_06.3U
Pld_06.4U
Pld_06.5U
Pld_08.1U
Pld_08.2U
Pld_08.3U
Pld_08.4U
Pld_08.5U
Pld_09.1U
Pld_09.2U
Pld_10U
Pld_11U
Pld_12U
Pld_13U
Pld_14U


350
300
250
200
150
100
50
0
Pld_01.1U
Pld_02.2U
Pld_03.1U
Pld_04.2U
Pld_05.1U
Pld_06.2U
Pld_06.5U
Pld_08.3U
Pld_09.1U
Pld_11U
Pld_14U

MAGNETIC FIELD AT START-UP



CONCLUSIONS

- This work , together with the new scenarios, reported in an other poster presented in this conference, has helped to improve the following aspects of the IGNITOR project :
  - Reduction of thermal loads
  - Shortening of cooling times
  - Decreasing of ohmic consumptions

REFERENCES

- 1] B. Coppi and the IGNITOR project Group, Engineering Design Description - Ignitor Program, RLE Report n° PTP 96/03, December 96.
- [2] Ansaldo Ricerche, Progetto Ignitor – dimensionamento del trasformatore centrale, IGN.OHT.N.5103, 03/02/2003.
- [3] A. Coletti, R. Coletti, G. Ramogida, M. Roccella and M. Santinelli, Optimal Temporal Evolution of the Magnet Currents of the Ignitor Machine; Proceedings DPP03 - 45th APS, Albuquerque NM, USA, 2003 October 27 – 31.