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A Preliminary Analysis of the Options for the Magnet System of the PS2

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Summary

Several options have been considered in the recent past for the magnet system of PS2. Beginning of 2007, a small working group examined the technical feasibility of a normal conducting, superferric and superconducting magnet systems. Preliminary parameters for each system were derived, and cost estimates for the magnet construction made. This report summarizes these findings and draws some conclusions on the options considered and the main issues for an R&D programme.

1. Introduction

The options for the magnet system of the PS2 injector were discussed on several occasions in 2006. The PS2 Working group assumed as the working baseline that the PS2 magnets are normal conducting with a dipole top field of 1.8 T [1]. However, this choice is not the only one and other solutions using superferric magnets have been proposed [2], motivated by the expected savings in the energy bill of the machine integrated over 20 years of operation. With this background information in mind, a small working group [3] was setup at the beginning of 2007 with the goal to examine the technical feasibility of the possible solutions in some detail. The goal was also to produce a preliminary parameter list for the magnets, and to give an estimate of the construction costs based on unit prices derived from the CERN experience in magnet building. We have tried to take into account, wherever possible, the experience and choices adopted by SIS 100 and J-PARC, the two recent machines of similar size and function. This report summarizes the findings, and draws some conclusions on the options and necessary R&D to refine the parameters of the PS2 magnet system.

2. Magnet Parameters

The requirements for the PS2 magnet system, as known at the beginning of 2007, are given in [1]. For convenience, the required parameters of the PS2 dipoles and quadrupoles are summarised in Tables 1 and 2, and the proposed field cycles are shown in Fig. 1. It should be noted that the present parameter set proposes a moderate peak field and ramp rate (1.8 T, 1.5 T/s), both driven by the parameters of the PS2 (in particular the bunch filling scheme), more than by the choice of baseline magnet system. In comparison, the SIS 100 synchrotron has a peak field of 2 T and a ramp rate of 4 T/s, while J-PARC a peak field and ramp rate of 1.9 T and 1 T/s.

2.1. Normal conducting magnets

The preliminary designs of the normal conducting dipoles and quadrupoles for PS2 were done by T. Zickler in 2006. The designs were updated beginning of 2007 to include a reduction of dipole aperture from the initial 100 mm to 70 mm, in accordance with the updated parameter set [1]. The present designs are shown in Figs. 2 and 3, and the magnet parameters are summarized in Tables 3 and 4. Both designs follow a well known route for this type of magnets. The saturation effects are controlled and remain at the acceptable level (3.5 % reduction in transfer function at 1.8 T).

2.2. Superferric dipole

The dipoles represent the largest power load of PS2 and there is a clear incentive to reduce the resistive and inductive loads as much as reasonable. This approach was followed by W. Scandale and D. Tommasini who proposed a superferric dipole design [2], shown in Fig. 4. The cross-section of the magnet is very similar to the normal conducting one, except that the resistive coil is replaced by a superconducting winding cooled at 4.5 K. The current density in the coil is 50 A/mm^2, about an order of magnitude larger than in the conventional coil, such that together with its cryostat it can fit inside the yoke window. The parameters of the dipole are given in Table 5. As the field quality is determined by the pole field, the magnet inherits from its normal conducting counterpart the high aspect ration between pole width and gap height, which also determines the yoke outer dimensions and overall weight of the magnet.

In view of the low number of ampere-turns and the field level in the coil, the current density in the coil is substantially lower than in typical superconducting magnets. The magnet protection is therefore considered easy to solve. A preliminary estimate for the AC heat loads given in [2] is 5 W/m at 4.5 K.

The conversion of the PS2 dipoles into superferric magnets is not extended in [2] to the quadrupoles. Indeed, the configuration of the four poles in Fig. 3 is such that the placement of contiguous cryostats to house coil pairs is almost impossible. An alternative could be to have each coil in a separate cryostat. In this case, however, as the yoke windows are narrow, the coils and cryostats would need to be considerably more compact, complicating the construction and raising issues of AC losses in the cryostat structure. The superferric version of PS2 is therefore limited in the present proposal to a combined magnet system, using both normal (quadrupole) and superconducting (dipole) systems in the machine arcs.

2.3. Superconducting magnets

An alternative to normal conducting quadrupole is a cold-iron superconducting quadrupole, as shown in Fig. 5. In the case of an iron dominated magnet, the coil design can be a very simple single-layer racetrack. A conventional cos(2θ) coil is also possible. In both cases, a Rutherford-type cable is assumed, for example the one given in Table 6. CERN has a long and very successful experience with this type of cables, which should be exploited for future superconducting machines. The coil and yoke are bath cooled (as opposed to forced flow cooling of SIS 100 magnets).

Preliminary studies by T. Nakamoto showed that the field requirements for PS2 can be obtained with coils that have an internal diameter of 140-160 mm and a current density of about 200 A/mm^2. The yoke outer diameter is then in the range of 300-400 mm. In the case of racetrack coils, suitable pole geometry can be easily found giving low field harmonics. Similarly, a single-layer cos(2θ) coil gives an acceptable field quality.

Following the thread of a cold-iron superconducting magnet, a dipole can also be considered such that its yoke diameter matches that of the quadrupole. In this case, however, an open midplane structure (à la superferric dipole) is not possible, and a cos(θ) coil is required. The conceptual design of the magnet is shown in Fig. 6. Initial studies by G. Kirby, using cable parameters given in Table 6, showed that the target field quality can be obtained with a single-layer coil. The inner diameter of the coil, as well as the outer yoke diameter, can vary within large bounds to meet the field requirements and geometrical constraints. As a result, the quadrupole and dipole yoke diameters can be made equal, allowing assembly of several magnets in a cold mass, and several cold masses in a cryostat. The possible parameters of the superconducting dipoles and quadrupoles for the PS2 are given in Table 7.

A major issue for the magnet design, both in the case of a superconducting quadrupole and of a dipole, is its protection. The mitigating factors are the low stored energy and low current density in the coil, which allow relatively slow detection and delayed discharge of the circuit. On the other hand, the ramp rate of 1.5 T/s may impede quench detection during current rise of the full circuit. Preliminary studies show that in both magnet types quench detection could be made on the flat-top, following which the current cycle would normally terminate and the cycling would be stopped. The temperature rise in the quenching magnets stays below 300 K even in the most conservative assumptions (energy of a full cycle dissipated in adiabatic conditions in a coil which quenches at the start of the cycle).

In a system featuring moderately ramping cold iron magnets, the magnetic field is contained within the yoke volume and the AC losses in the cryostats themselves are suppressed. All elements of the cryostat design can then follow the solutions developed for slow ramping machines. The sources of AC losses are within the coil itself, and in the yoke volume, in particular in the end regions, where the field lines close in at a small angle to the end plates and other structural elements. Initial studies made by T. Nakamoto and G. Kirby to verify the scaling of the various components of AC losses in the coils and yokes show that total losses are in the range of 5-8 W/m for the dipole, and 6-10 W/m for the quadrupole. The breakdown of the heat loads is given in Table 8, where the corresponding estimates for SIS 100 are also shown.

The electrical parameters of the PS2 superconducting magnets are summarised in Table 9. Together with the estimate of the heat load of 10 W at 4.5 K per meter of length of the magnet cryostat, they are sufficiently coherent to allow preliminary technical studies and cost estimates of the cryogenic and powering systems.

3. Cost Estimates

The three magnet systems discussed above were compared in terms of construction costs. The unit prices for this estimate are given in Table 10, and are based on experience at CERN in similar magnet construction. Also shown in this table are the unit prices used for SIS 100 cost estimate [4], which should be understood as an upper bound for the costs. The high SIS 100 unit costs also explain in part the decision of GSI to use superconducting magnets for this machine.

The cost estimates for the normal conducting, superferric (combined) and superconducting magnet systems are summarised in Tables 11, 12 and 13. These estimates show that in spite of higher technology costs for superconducting magnets, the total magnet weight remains the driving cost factor.

4. Conclusions

The preliminary studies for the magnet system of the PS2 lead to a conclusion that at this stage of analysis all three systems can effectively provide the required operating parameters and are technically feasible. It was noted that the peak field of 1.8 T is on the high end of the usual range for a normal conducting system, and that at this stage of the PS2 study a more conservative value would be more prudent. On the other hand, the two superconducting proposals have an intrinsic possibility of increasing the peak field and gradient by at least 10 % above the present values without modification of the design, which may be of interest for improving the flexibility of the machine.

The PS2 is conceived as a high beam power accelerator, at the heart of the CERN proton beam complex. The issues of maintenance, reliability, radiation damage and fatigue resilience are a major concern whatever the magnet system, and must be resolved by appropriate engineering. Machines of similar profile based on normal conducting magnets are in operation or in construction (J-PARC) and appropriate solutions are at hand. There is less experience with superconducting accelerators operating in similar regime, and therefore additional studies and R&D are necessary to fully understand the underlying design issues, in particular the onset of structural fatigue. However, the superconducting magnets by concept involve tightly clamped structures, using materials which at cryogenic temperatures have improved mechanical performance, which is a solid basis for improving resilience to fatigue.

Several technical issues, in particular quench protection, are specific for superconducting magnet systems. It is our opinion that this aspect of the superconducting system should not present major difficulties for the ramp rates and field levels considered, but it must be taken into account from the initial design stage. Similarly, the reduction of AC losses and the design of effective coil cooling should be confirmed in an R&D programme.

The estimated costs of the magnet systems revealed (again!) that the total volume of material, rather than the level of technology, is the driving cost element. The superconducting magnets, while containing high technology sub elements, offer even in the low field range a certain cost advantage. The advantage becomes even more pronounced when operating costs over a 20 year lifetime are included. However, one should keep in mind that the cost of the magnet system is only a fraction of the total facility costs (including machine hardware and civil engineering), and that the cost advantage of one system or the other is less pronounced in the general context (including contingency). Furthermore, a cost update seems necessary before a final decision on the magnet system is made, so that cost trends that may not be sufficiently clear from today's perspective can be corrected.

5. References

1. M. Benedikt, "Aperture and field quality requirements for PS2/PS2+ main magnets", Internal Note, 2 Feb 2007.
2. W. Scandale, "First Considerations on a Possible Superferric Option for PS2+", AT-MCS Internal Note, Dec 2006, EDMS 808557.
3. Two meetings of the working group on PS2 magnets were held on the 8 Feb 2007 and 8 March 2007, with the following participation: M. Benedikt, L. Bottura, W. Kalbreier, G. Kirby, K-H. Mess, T. Nakamoto, R. Ostojic, S. Russenschuck, W. Scandale, A. Siemko, D. Tommasini, A. Verweij, R. Wolf, T. Zickler.
4. E. Fischer, "Resistive and Superferric SIS100 Dipoles: 2nd Cost Comparison", GSI, March 2005.

Table 1. Main parameters for the PS2 dipoles (M. Benedikt)

Good field radius:	30 V/ 40 H mm
Field range:	0.15 T – 1.8 T
Field quality:	$\pm 1\ 10^{-4}$
Ramp rate:	1.5 T/s
Cycle time:	2.4 – 3.6 s
Length:	3 m
Total number:	200

Table 2. Main parameters for the PS2 quadrupoles (M. Benedikt)

Good field radius:	50 mm
Field range:	0.95 T/m – 16 T/m
Field quality:	$\pm 3\ 10^{-4}$
Ramp rate:	13 T/m/s
Cycle time:	2.4 – 3.6 s
Length:	1.75 m
Total number:	120

Table 3. Main parameters of the PS2 normal conducting dipoles (T. Zickler)

Nominal magnetic field	1.8 T
Integrated field	5.4 Tm
Gap height	70 mm
Gap width	240 mm
Magnetic length	3000 mm
Total magnet height	700 mm
Total magnet length	3260 mm
Total magnet width	1100 mm
Total magnet weight	15 t
Number of turns	18 turns
Cooling circuits per coil	2
Current density	< 4 A/mm2
Pressure drop	0.3 MPa
Flow rate	25 l/min
Temperature rise	20°C
Nominal current	5775 A
Nominal RMS current	3990 A
Current rise rate	5260 A/s
Resistive load	0.4 Ω
Inductive load	1.2 H
Nominal total voltage	9 kV
Power consumption (100 dipoles)	6.9 MW
Peak power	52 MW

Table 4. Main parameters of the PS2 normal conducting quadrupoles (T. Zickler)

Nominal field gradient	16 T/m
Integrated gradient	28 T
Aperture radius	65 mm
Magnetic length	1750 mm
Total magnet width/height	800 mm
Total magnet length	2020 mm
Total magnet weight	5 t
Cooling circuits per coil	1 per coil
Current density	< 4 A/mm2
Pressure drop	0.4 MPa
Temperature rise	20°C
Nominal current	1200 A
Nominal RMS current	830 A
Resistive load per branch (60 quads)	1.6 Ω
Inductive load per branch (60 quads)	2.1 H
Nominal voltage per branch (60 quads)	4.3 kV
Total rms power consumption	2.2 MW
Peak power per branch (60 quads)	5.1 MW

Table 5. Main parameters of the PS2 superferric dipoles (W. Scandale)

Nominal magnetic field	1.8 T
Gap height	100 mm
Magnetic length	2965 mm
Good field region	120*80 mm x mm
Peak current	5300 A
Number of coils	2
Coil size	30*50 mm x mm
Number of turns per coil	15
Current density	50 A/mm2
Inductance	12 mH
Magnet overall section	1050*750 mm x mm

Table 6. Cable parameters for the superconducting magnets using LHC dipole strand with a reduced filament diameter (G. Kirby)

Cu/Sc	1.65
Strand Diameter	0.45mm
Nr of strands	40
Cable width	9.3 mm
Nr Filaments	8892
Filament diameter	3.0 μm

Table 7. Main parameters of the superconducting magnets for PS2

		Current Dominated Dipole	Iron Dominated Quadrupole	Current Dominated Quadrupole
Field range	T (T/m)	0.15 - 1.8	0.95 - 16	
Length	m	3	1.75	
Coil/pole aperture	mm	120	140--150	160
Current density	A/mm2	~300	~200	
Outer yoke dia	mm	280--400	360--400	280--340
Stored energy	kJ/m	25	10--15	15
Inductance	mH/m	10	5--10	8
Mass	kg	1700--2500	1000--1500	

Table 8. Heat load estimates for superconducting magnets (in W/m)

Heat Loads (W/m)	PS2			GSI
	Current Dominated Dipole	Iron Dominated Quadrupole	Current Dominated Quadrupole	
Thermal shield (50-70 K)	5			
Static (4.5 K)	0.3			1
AC (4.5 K)				14.5
Coil	3--6	2.5--5	4.5--9	
Iron (hysterisis)	1	1--3	1--3	
Beam tube/Anticryostat (4.5 K)	1			3.5
Total load (4.5 K)	5.3--8.3	4.8--9.3	6.8--13.3	19

AC load given for a cycle of 2.4 s, 1.5 T/s
AC load in coil given for 3 and 7 mm filaments
AC load in iron depend on the field and mass of yoke
Static loads taken from LHC cryostat design
GSI AC loads at 1 Hz, 4T/s

Table 9. Baseline electrical parameters for the normal and superconducting magnets for PS2

Dipole		**SC**	NC
Nominal field	T	1.8	1.8
Stored energy/magnet	kJ	80	100
Nominal current	A	4000	5775
Inductance/magnet	mH	10	6
Resistance/magnet	mΩ	0	2
Current rise	A/s	3333	5260
RMS current	A	2760	3990
Total voltage/200 magnets	kV	6.7	9
Peak power/200 magnets	MW	26.7	52
Power consumption/200 magnets	MW	-	6.9

Quadrupole		**SC**	NC
Nominal gradient	T/m	16	16
Stored energy/magnet	kJ	14.5	25.2
Nominal current	A	1700	1200
Inductance/magnet	mH	10	35
Resistance/magnet	mΩ	0	26.7
Current rise	A/s	1420	1000
RMS current	A	1175	830
Total voltage/60 quads	kV	0.85	4
Peak power/120 quads	MW	2.9	9.6
Power consumption/120 quads	MW	-	2.2

Table 10. Unit costs for magnet construction

	CERN	GSI
Power	40 CHF/MWh	70 Euro/MWh
NC magnets		
Completed NC coil	32 CHF/kg	50 Euro/kg
Completed NC yoke	6.6 CHF/kg	10 Euro/kg
Testing	3 kCHF/magnet	4.5 kEuro/dipole
SC magnets		
Completed SC coil	250 CHF/kg	14 kEuro/coil set
Completed SC yoke	10 CHF/kg	15 Euro/kg
Cryostating	25 kCHF/magnet	26 kEuro/magnet
Quench detection	1000 kCHF total	770 kEuro/dipoles
Cold testing	10 kCHF/magnet	13 kEuro/dipole

Table 11. Cost estimates for the PS2 normal conducting magnet system

Total costs (kCHF)	CERN price	GSI price
Dipole production	30000	68000
Quadrupole production	9000	20400
Testing	960	2160
Protection, other.	1500	3000
Total	**41460**	**93560**

Table 12. Cost estimates for the PS2 combined magnet system (superferric dipoles, normal conducting quadrupoles)

Total costs (kCHF)	CERN price	GSI price
Dipole production	30000	68000
Quadrupole production	9000	20400
Cryostating	5000	8000
Quad trasfer line	1800	3000
Dipole testing	2000	4000
Quad testing	360	840
Quench protection	1000	1200
Cold powering	2000	*2000*
Total	**51160**	**107440**

Table 13. Cost estimates for the PS2 superconducting magnet system

Total costs (kCHF)	CERN price	GSI price
Dipole production	10000	15000
Quadrupole production	3600	5400
Cryostating	8000	12800
Cold testing	3200	6400
Quench protection	1000	1200
Cold powering	3000	*3000*
Total	**28800**	**43800**

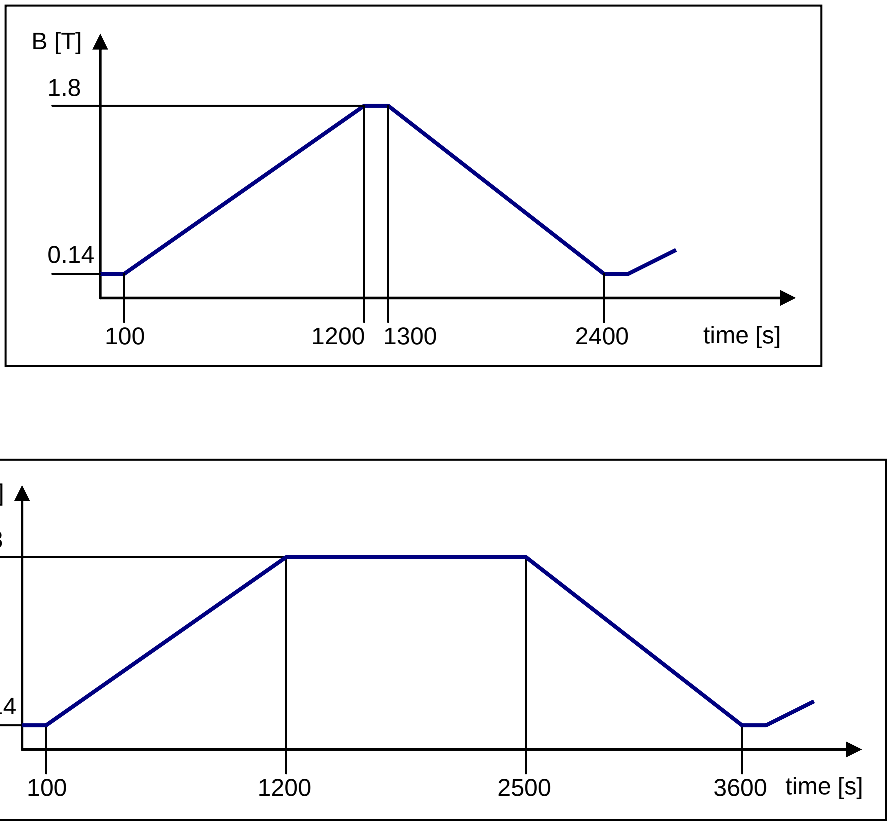

Fig. 1 Simplified PS2 cycles for LHC and CNGS type beams (top), and slow extraction (bottom) (M. Benedikt)

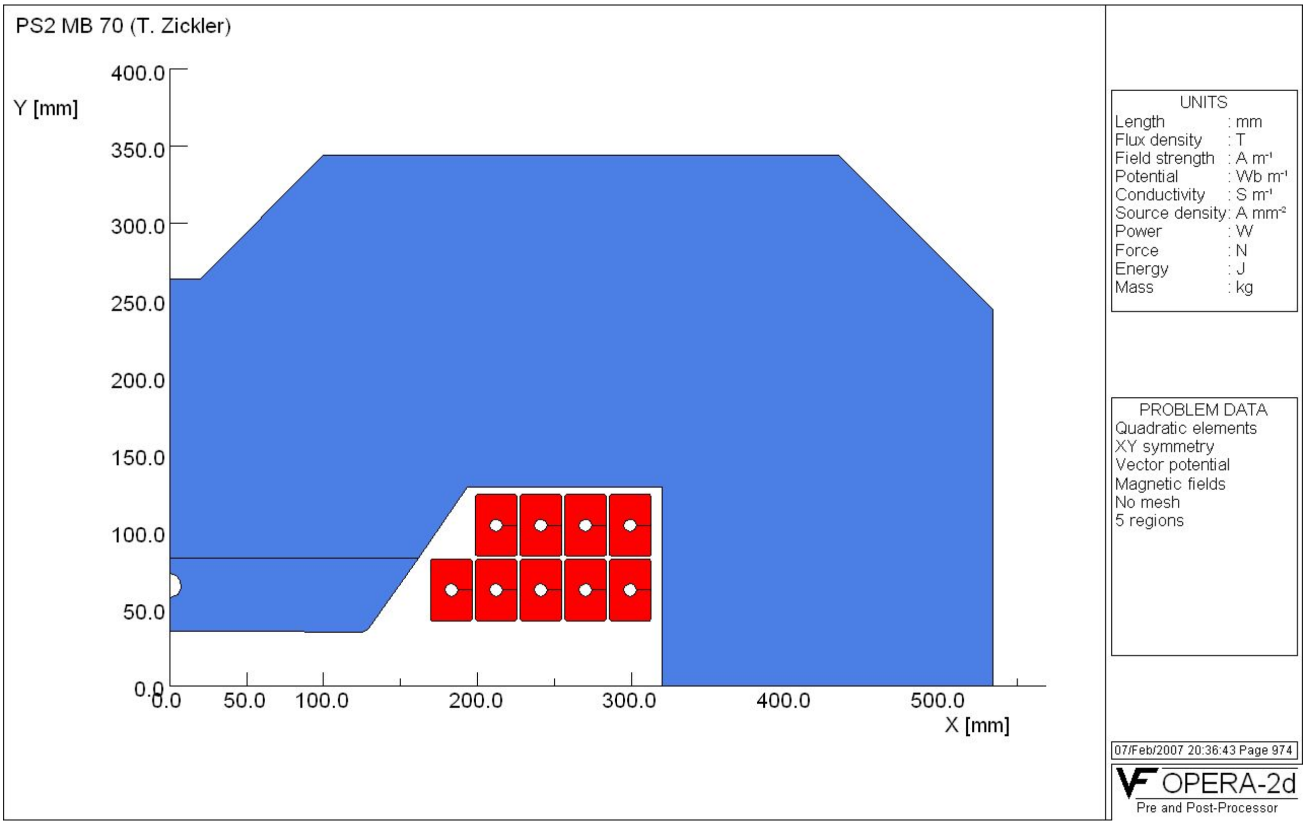

Fig. 2 Cross-section of the normal conducting dipole for PS2 (T. Zickler)

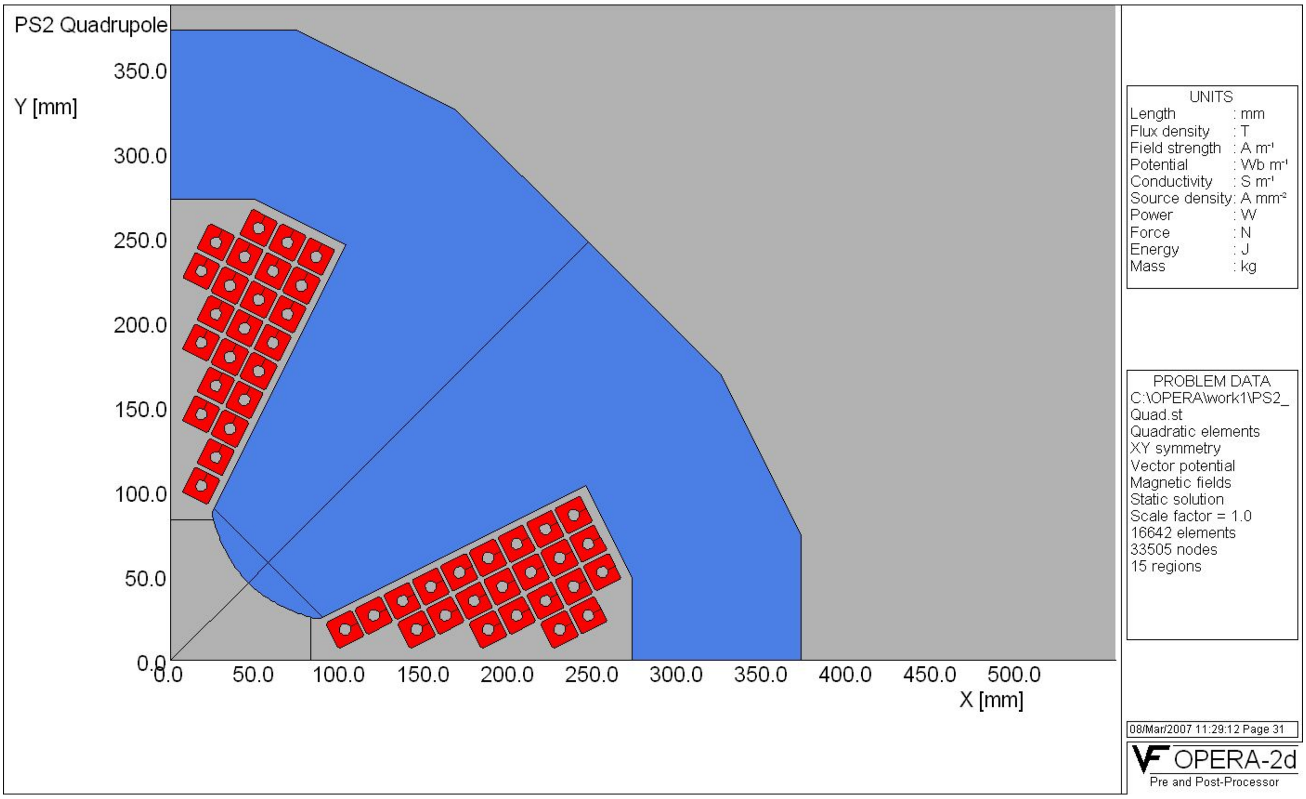

Fig. 3 Cross-section of the normal conducting quadrupole for PS2 (T. Zickler)

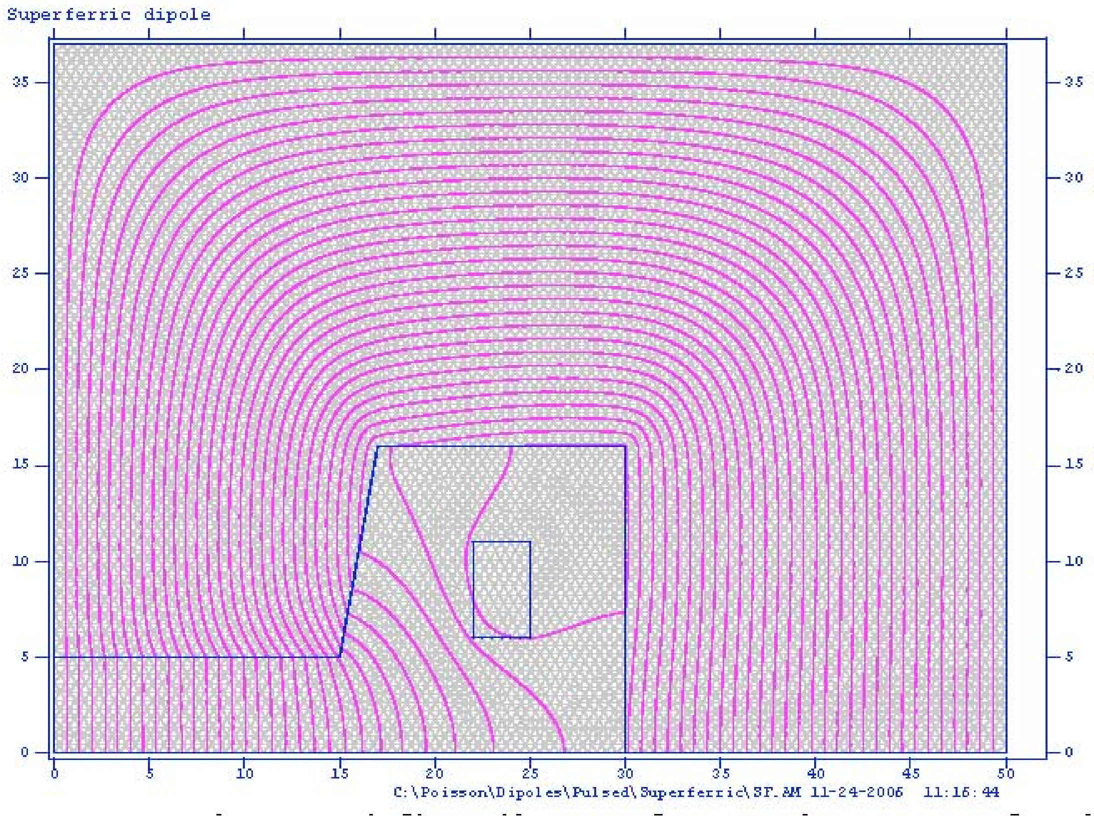

Fig. 4 Cross-section of the superferric dipole for PS2 (W. Scandale)

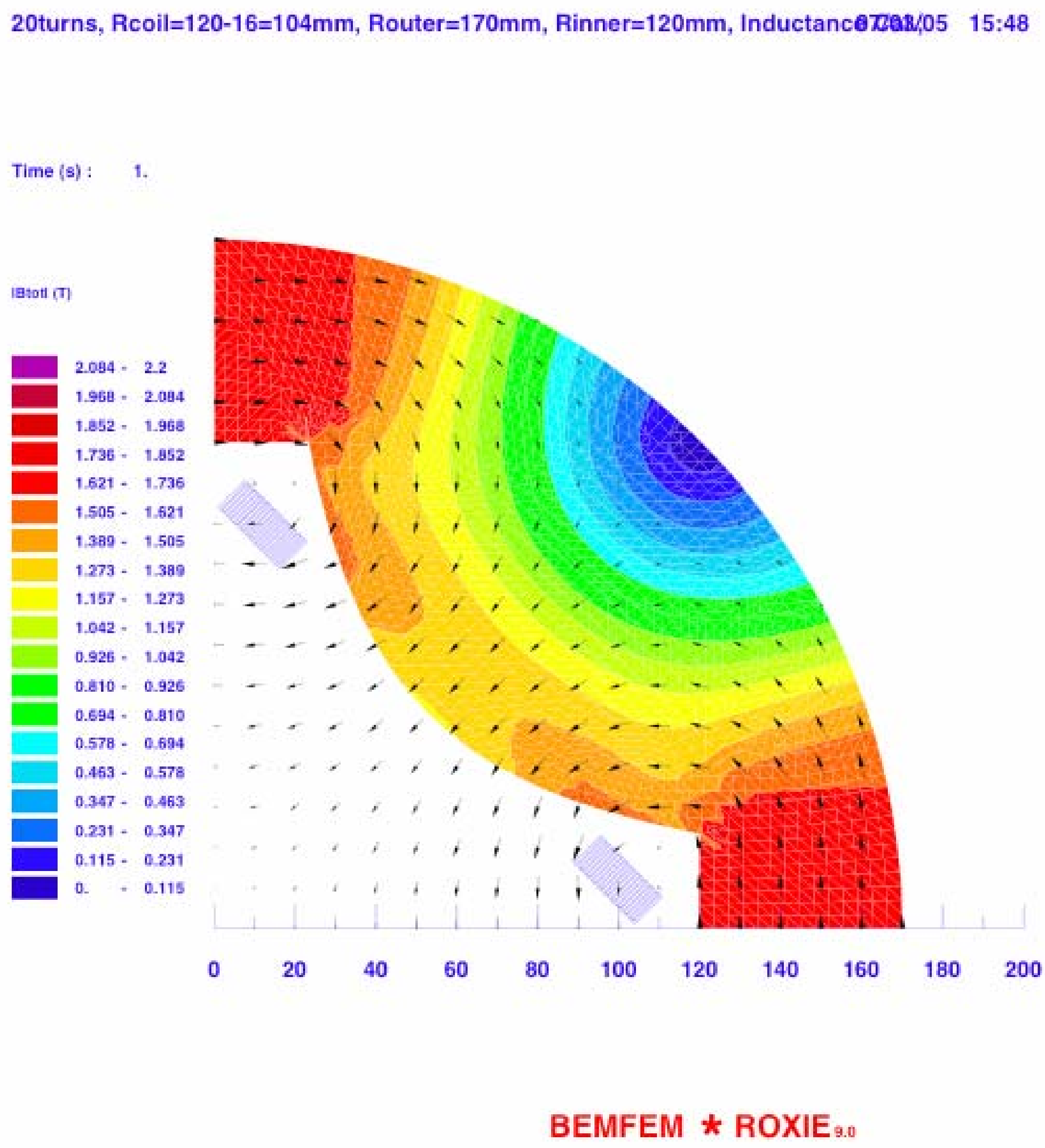

Fig. 5 Cross-section of the superconducting cold-iron quadrupole for PS2 (T. Nakamoto)

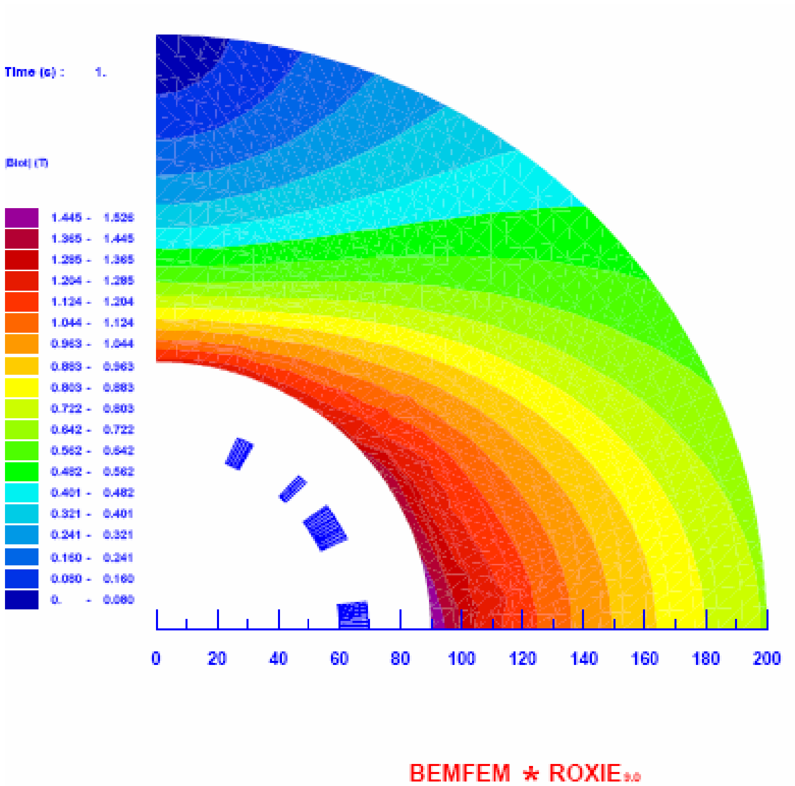

Fig. 6 Cross-section of the superconducting cold-iron dipole for PS2 (G. Kirby)