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CONCEPTUAL DESIGN OF SUPERFERRIC MAGNETS FOR PS2

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We analyze feasibility and cost of a superferric magnet design for the PS2, the 50 GeV ring that should replace the PS in the CERN injector chain. Specifically, we provide the conceptual design of dipole and quadrupoles, including considerations on cryogenics and powering. The magnets have warm iron yoke, and cryostated superconducting coils embedded in the magnet, which reduces AC loss at cryogenic temperature. The superconductor has large operating margin to endure beam loss and operating loads over a long period of time. Although conservative, and without any critical dependence on novel technology developments, this superconducting option appears to be attractive as a low-power alternative to the normal-conducting magnets that are the present baseline for the PS2 design. In addition it provides flexibility in the selection of flat-top duration at no additional cost.

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Abstract

We analyze feasibility and cost of a superferric magnet design for the PS2, the 50 GeV ring that should replace the PS in the CERN injector chain. Specifically, we provide the conceptual design of dipole and quadrupoles, including considerations on cryogenics and powering. The magnets have warm iron yoke, and cryostated superconducting coils embedded in the magnet, which reduces AC loss at cryogenic temperature. The superconductor has large operating margin to endure beam loss and operating loads over a long period of time. Although conservative, and without any critical dependence on novel technology developments, this superconducting option appears to be attractive as a low-power alternative to the normal-conducting magnets that are the present baseline for the PS2 design. In addition it provides flexibility in the selection of flat-top duration at no additional cost.

INTRODUCTION

The baseline design for the PS2 [1], [2], the upgrade of the PS injector, requires 200 dipoles totaling a magnetic length of about 600 meters, and 120 quadrupoles, for a total magnetic length of 210 m. The peak field in the dipole bore is of 1.8 T, while the peak gradient in the quadrupoles is 16 T/m. The main requirements for the magnets are summarized from [3] in Table 1. PS2 will be continuously cycled, and the typical cycle time will be in the range of 2.4 s to 3.6 s, in accordance with the scenarios reported in Table 2. The specified field range is typical of normal-conducting magnets, which is indeed the baseline for the PS2 design [4]. With this choice, the magnet mass (dominated by the iron yoke) is considerable, in the range of 4500 tons, and the resistive power is large, around 10 MW on average.

It is hence legitimate to consider the possibility of using superconducting materials to decrease the overall mass of the magnets and the power consumption. We have focused on an iron-dominated magnet design (dubbed here, somewhat improperly, *superferric*), as initially proposed by Scandale, et al. [5]. Specifically, we explore the possibility of a practical magnet design with:

- minimum power requirements and operation costs, to achieve a substantial cost gain in operation, rather than in the initial investment;
- large operating margin to run reliably over a long period of time;
- minimum variations with respect to the normal-conducting baseline, to respect the boundary conditions posed by available magnet bore, access requirements and collimation.

In the following sections we describe the main features of the dipole and quadrupole magnet design, providing some details on the superconducting wire and cable, coil winding, cryostat design, and cryogenics. We show the non-trivial result that a superferric design with warm iron can meet the field quality and operation requirements in a more compact structure than the normal-conducting baseline, requiring significantly less iron mass (a reduction of approximately 50 %). What is most important, the AC loss during operation can be limited by design to a low value, in the range of 1 W/m of magnet. The resulting power requirements and projected operating costs are approximately half those of the normal-conducting baseline.

MAGNET DESIGN

We have taken as a starting point the normal-conducting reference magnet design and modified it to use cryostated, superconducting coils that provide the magneto-motive force. A cross section of one quarter of one of the design iterations is shown schematically in Figure 1. With this choice, the field quality is mainly determined by the shape of the iron pole and issues such as conductor position accuracy or persistent current magnetization are no longer of relevance. The iron yoke is

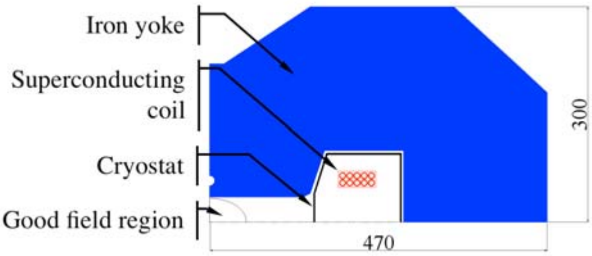
Table 1. Main magnet parameters for the PS2 baseline design (from [3]).

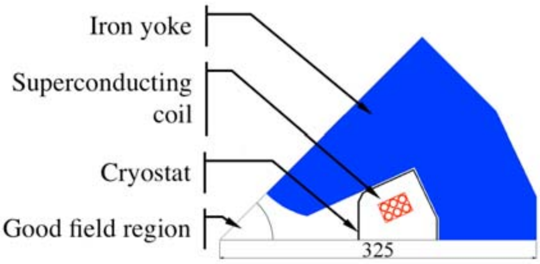
Number of dipoles	200
Field at injection energy [T]	0.15
Field at maximum energy [T]	1.8
Magnetic length [m]	2.965
Good field region at injection [mm x mm]	±41.7 × ±29.6
Good field region at flat-top [mm x mm]	±41.7 × ±11.5
Number of quadrupoles	120
Gradient at injection energy [T/m]	0.95
Gradient at maximum energy [T/m]	16
Magnetic length [m]	1.75
Good field region at injection [mm x mm]	±50.9 × ±36.2
Good field region at flat-top [mm x mm]	±50.9 × ±14.0

Table 2. Reference cycles for the PS2 baseline (from [3]).

	LHC	Slow extraction
Injection plateau (flat-bottom) [s]	0.1	0.1
Acceleration time (ramp) [s]	1.1	1.1
Extraction plateau (flat-top) [s]	0.1	1.3
Ramp-down time [s]	1.1	1.1

Figure 1. Schematic 1/4 cross section of the superferric dipole and 1/8 of the quadrupole designed for PS2.





warm, which is of advantage because the AC loss in the yoke does not enter in the power balance of the cryogenic plant. A further advantage of a design with a warm iron yoke is that it allows the same access to the magnet bore as in the normal-conducting baseline (e.g. for beam pipe and collimation systems).

The coil in the dipole is removed from the magnet mid-plane, which is expected to decrease the heat load and irradiation from the particle lost from the circulating beam. In addition, the magnetic field in the recess of the iron yoke is much smaller than in the iron gap, typically a factor 2 lower for the coil position selected. This has the beneficial effect of increasing the operating margin of the superconductor and decreasing the field variations (and hence AC loss).

Superconducting cable and coil

The superconducting coil design selected is based on an internally cooled conductor cabled with Nb-Ti strands. The 0.6 mm strand is assumed to have a minimum critical current density of 2500 A/mm^2 at 4.2 K and 5 T, which corresponds to approximately 5000 A/mm^2 at the cable design point of 4.5 K and 2 T. The reference cable configuration is similar to the one used for the Nuclotron cable [6], and considered the present baseline for the SIS-100 magnets of FAIR [7]. A 32-strand conductor is designed for operation at 6 kA at 4.5 K and 2 T. Under these conditions the critical current is above 14 kA, and the temperature margin to current sharing is well above 2 K. We recall that the coil is placed in the low-field region of the magnet, and operates at a field which is significantly smaller than the bore field (peak field of 1 T in the dipole coil and 0.75 T in the quadrupole coil). In practice, the operating margin for the cable is estimated to be in excess of 3 K. The uncertainty derives from the difficulty of knowing exactly the low-field behaviour of the critical properties of the strand.

The AC loss properties of the strands are critical to the overall performance of the magnet. We have set a target of 3 μm for the effective filament diameter and 1 ms for the coupling loss time constant. These targets are at the limit of the present standard production routes, but the technology to achieve them has already been demonstrated in R&D billets produced in the past.

Each coil is wound using the insulated, internally cooled Nb-Ti superconducting conductor on a glass-resin coil former. After winding, the coil is wrapped with ground insulation, and impregnated under vacuum/pressure cycles, which provides high voltage withstand. The insulating materials are the same as used for normal-conducting magnets (fiberglass/epoxy and polyimide) and their resistance to radiation is well established.

Intercoil structure and cryostat

Although forces are relatively modest (below 2 tons/m of coil on each limb of a pole), structural issues are a major concern. All unbalanced coil forces need to be transmitted to the iron through cryogenic posts or tie-rods that must be kept small to limit heat inleak. The structure must withstand a large number of cycles (more than 200 Mcycles for a lifetime of 20 years), which is not trivial for structure that will probably include composite materials for reasons of thermal efficiency. Among the various possible solutions, our baseline foresees a stiff inter-coil structure housed inside a vacuum vessel. The intercoil structure links vertically and horizontally the coil limbs, and carries most of the electromagnetic loads. The aim is to limit the deformation of the coil to typically 0.2 mm. The cold supports only need to carry the weight of the cold structure, as well as the electromagnetic forces arising from misalignments and asymmetries. Thermal performance is enhanced by an actively cooled thermal shield at a temperature of 75 K. Both thermal shields and coil casings are covered by a low emissivity surface protection.

Cryogenics

For the evaluation of the thermal loads we have considered that the PS2 will operate continuously with the cycle of Table 2. This is a conservative assumption, as the operation will most likely alternate among different cycles. The thermal loads considered for the design of the cryogenic plant and distribution are:

- AC loss in the cable, evaluated as the sum of filament hysteresis, strand coupling and cable coupling. Based on simulations, we have taken a design load of 1 W/m of magnet length that provides a factor 2 margin with respect to the detailed calculation, and covers any uncertainty in the achievable loss properties of the strand and cable;
- static thermal loads in the magnets and transfer lines, estimated at a comparable value of 0.2 W/m of line. In the case of the magnets we have applied this estimate per unit length of coil winding, which

results in an average value of approximately 1 W/m of magnet length;

- liquefaction for the current leads, estimated to an equivalent of 250 W of refrigeration power at 4.5 K;
- beam loss in the coil, which is expected to be small, because the coils are intentionally placed off the machine midplane, shielded by the iron yoke. Pending a detailed evaluation of beam loss profile and magnitude, we assume that a reasonable average design target, compatible with beam quality and radiation limits, is 1 W/m of magnet.

The nominal capacity required at 4.2 K for the whole complex, including the loads on the thermal shield at intermediate temperature, would be 3.3 kW. An installed capacity of 5 kW, i.e. with a relatively large margin, has been assumed for the evaluation of the cost of the installation and operation, discussed later.

COST ANALYSIS

The total cost of the magnetic and auxiliary systems for a superferric design is summarized in Table 3. When compared to the cost estimate for a normal-conducting PS2 [8], the superferric design is more expensive by about 6 MCHF, which is in the expected range. This cost overhead is relatively small, of the order of 2 to 3 % of the total value of PS2. The costs for operation are estimated taking as a basis a price of 40 CHF/MWh [8], and assuming 6000 hours of operation per year for the accelerator systems, and 7000 hours of operation per year for the cryogenics. With an estimated installed power of 7.6 MW (about half the estimated 14.6 MW for the normal conducting baseline), the cost of electricity is then 1.9 MCHF/year. We need to add the cost of maintenance of the cryogenic plant, estimated at 0.3 MCHF/year (4 % of the value of the cryoplant). The total operation cost is hence 2.2 MCHF/year. These values should be compared to an estimated operation cost of 3.8 MCHF/year for the normal-conducting baseline, implying a gain of 1.6 MCHF/year at the present cost of electricity.

CONCLUSIONS

The superferric dipole and quadrupole magnets described in this study match the requirements of field, field ramp-rate, field quality and aperture specified for the PS2 main magnets. An additional benefit provided by superconducting magnets is the operational flexibility, in particular long flat-top duration, at no additional operation cost. Because of the design chosen (warm iron, cryostated coil assembly) we expect no impact on the optics of the PS2, nor on the available space and access features that should be practically identical to that of the normal-conducting baseline. Hence, the solutions for the vacuum system or the design and location of the collimation and correction systems for the baseline normal-conducting PS2 should be directly applicable to the superferric option described here.

Table 3. Cost estimates for the magnet system of a superferric PS2, including auxiliaries, in MCHF.

Magnets	32
Power supplies	15
Cryogenics (including buildings)	17
Current distribution and current leads	3
Total	67

The main design effort has been directed to achieving a minimum steady and transient load on the cryogenic plant, resulting in a considerable reduction of the size and cost of the cryoplant from previous estimates. The design described here should offer substantial savings in terms of installed power (of the order of 7 MW) and operating cost (of the order of 1.6 MCHF/year, at the present cost of electricity) when compared to the normal-conducting baseline. The price is a slight disadvantage in terms of investment cost, estimated at 6 MCHF, which could be recovered in few years of operation.

A number of critical issues have been clearly identified, i.e. low-loss strand and cable, cold structure and support compatible with eddy currents and limited thermal budget, knowledge of the beam-induced radiation load, robustness and reliability compatible with continuous operation. They are being addressed by a dedicated CERN R&D on Fast Cycled Superconducting Magnets (FCM), expected to produce first test results by beginning of 2009.

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