# FAST CYCLED SUPERCONDUCTING MAGNETS FOR THE UPGRADE OF THE LHC INJECTOR COMPLEX

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*Abstract*

An upgrade of the LHC injection chain, and especially the sequence of PS and SPS, up to an extraction energy of 1 TeV, is one of the steps considered to improve the performance of the whole LHC accelerator complex. The magnets for this upgrade require central magnetic field from 2 T (for a PS upgrade) to 4.5 T (for an SPS upgrade), and field ramp rate ranging from 1.5 to 2.5 T/s. In this paper we discuss under which conditions superconducting magnets are attractive in this range of operating field and field ramp-rate, and we list the outstanding issues to be adddressed by a dedicated R&D.

## MAGNET NEEDS AND R&D TARGETS

### *Magnet requirements*

The main motivation for a CERN R&D program on fast cycled superconducting magnets comes from the need to upgrade the LHC injector chain. A definition of the objectives of this R&D at CERN was initiated at the workshop ECOMAG [1], pursued in several proposals for specific magnet work [2], [3], and appeared among the declared Magnet R&D objectives of the medium term plan (2008-2011) for the Scientific Activities at CERN [4]. Following the discussion at the workshop LUMI-06 on luminosity upgrades for the LHC [5], and the outcome of the PS2 Study Group [6], the range of parameters identified for the relevant magnet designs has been narrowed to the values reported in Table I. Aperture requirements are defined for the PS upgrade option PS2a (rectangular, with height and width 60 mm x 84 mm [6]), but not yet finalised for the other magnets and in particular for an SPS upgrade (values quoted in Table I are estimates). The present baseline is a PS2 accelerating to 50 GeV, i.e. option PS2a in Table I. An SPS extraction around 1 TeV would already be desirable for the present LHC, and indeed necessary for an energy upgrade of the collider.

As discussed in [7] superconducting magnets could provide a compact and cost effective alternative to the normal conducting baseline considered for an upgrade of the PS with extraction energy of 50 GeV (maximum field of 1.8 T, option PS2a). Above 2 T, i.e. for an increased extraction energy at the PS, and for an energy upgrades in the SPS, superconducting magnets are *the* enabling technology, and, in practice, the only possible choice. We remark, however, that the present PS2 baseline makes an energy upgrade of the SPS up to 1 TeV quite challenging. The concern is the control of the field quality in superconducting magnets with low injection field (0.23 T) and large field swing (20). HERA, that had working conditions in the same range, was a very slow-ramping accelerator, and yet witnessed difficulties at the level of the compensation of field errors.

Table I. Range of magnet design parameters considered for an upgrade of the CERN injector chain, compiled from [5] and [6].

| | PS2a | PS2b | SPS2a | SPS2b |
|---|---|---|---|---|
| Injection energy [GeV] | 4 | 4 | 50 | 75 |
| Extraction energy [GeV] | 50 | 75 | 1000 | 1000 |
| Injection field [T] | 0.144 | 0.144 | 0.225 | 0.337 |
| Extraction field [T] | 1.8 | 2.7 | 4.5 | 4.5 |
| Good field diameter [mm] | 103 | *≈100* | *≈75* | *≈75* |
| Ramp time [s] | 1.1 | 1.1 | 3.0 | 3.0 |
| Flat-top/-bottom time [s] | 0.1 | 0.1 | 3.0 | 3.0 |
| Field ramp-rate [T/s] | 1.6 | 2.5 | 1.4 | 1.4 |

### *R&D issues*

As far as operating conditions are concerned, the magnet parameters derived from the upgrade requirements of Table I, and in particular the maximum field and maximum ramp-rate, are *per se* not critical. Indeed, the peak field and aperture required for the SPS2 options are those produced routinely at Tevatron (4 T over 75 mm) and HERA (5.2 T over 75 mm), and largely surpassed at the LHC (8.3 T over 56 mm). The difficulty, however, is to achieve the required repetition rate (ramping 30 to 1000 times faster than at Tevatron, HERA and LHC), economically and reliably, as required by an injector. A detailed analysis of the R&D issues is reported in [8]. Technology demonstration is required in the following fields:

- AC loss. The control and reduction of AC loss has foremost importance to reduce the cryoplant investment and operation cost, and limit the temperature excursions in the conductor. This work implies material developments (superconducting strand and cable) as well as specific magnet design and optimization;
- Cooling. The heat loads on the magnet, and especially those originating from the AC loss and beam heating, must be removed efficiently to warrant a margin sufficient for stable operation. Suitable cooling schemes require design, optimization and test in relevant conditions;
- Quench detection and protection. Protection of superconducting magnets is especially demanding in case of fast ramping machines due to the relatively high inductive voltages in comparison to the voltage developed by a resistive transition. Voltage compensation and magnet protection must be proven in the presence of an inductive voltage

during ramps that can be as large as 1000 times the detection threshold;

- Field quality, in particular the contribution of eddy currents in the superconductor and iron yoke is difficult to predict, control and measure at the desired resolution during fast ramps;
- Material fatigue, over several hundreds million cycles, influencing material selection and, possibly, requiring dedicated testing;
- Radiation dose from beam losses, which requires careful material choice, and consideration on shielding and maintenance.

### *Targets for a magnet R&D*

Rather than taking the single design parameters listed in Table I, and address feasibility and performance of each magnet variant, we have attempted to specify a more generic target for magnet R&D. As discussed in [8] and [9], it is possible to specify a generic R&D target for the magnet by taking as performance indicator the product of the maximum field and the maximum field ramp-rate. The envelope of needs for PS2, SPS2, as well as present developments at companion laboratories, recalled in a later section, tend to cluster along a line with $B_{max}$ x $(dB/dt)_{max}$ = 7. This is shown in Fig. 1 (reproduced from Ref. [8]).

A suitable and scalable R&D target for the demonstration of the technology of fast-cycled superconducting magnets is then a magnet model of relevant length (typically longer than 1 m) that achieves:

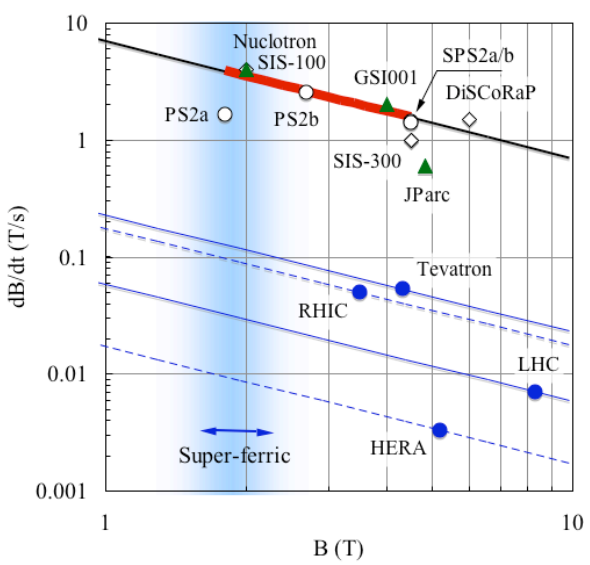


Figure 1. Scatter plot of $(dB/dt)_{max}$ vs. $B_{max}$ for the magnet parameters of Table I (upgrade of the CERN injector chain), and various magnets from operating accelerators, demonstration prototypes and design studies, reproduced from [8]. The solid line represents the R&D target at $B_{max}$ x $(dB/dt)_{max}$ = 7 $T^2$/s. The R&D range is the thick portion of the solid line. The shaded area of field around 2 T is the typical range of superferric magnets.

- nominal operating conditions of peak field and ramp-rate, such that $B_{max}$ x $(dB/dt)_{max}$ = 7 $T^2$/s, cycling over long times (typically more than 12 hours) to prove periodic steady state operation relevant for an accelerator;
- AC loss below 5 W/m of magnet to provide an economic option to normal-conducting magnets (see the discussion in the next section);
- robustness and reliability, demonstrating stable operation in sequences of rapidly varying cycles (i.e. the equivalent of an accelerator supercycle), and a low rate of fake quench detection (typically below $10^{-6}$), possibly undergoing an accelerated life tests to simulate the expected fatigue over 20 years of operation.

This target was specified in [9] at a bore field larger than 2 T (and specifically option PS2b in Table I) with the intention to focus on coil-dominated magnets, rather than iron-dominated magnets that would be the natural choice for a bore field below 2 T. As discussed in the next section, the result of magnet and system design studies have driven towards a reduction of the bore field, yet maintaining the overall objective outlined so far.

## A SUMMARY OF DESIGN STUDIES

A number of design studies were pursued in 2007 to identify the preferred design options and quantify performance of fast cycled superconducting magnets for the upgrade of the LHC injectors.

The first study, described in [7], produced a design and cost evaluation of superconducting dipoles and quadrupoles for the PS2+a, comparing the cost figures to the estimates available for a normal conducting machine [10]. The design chosen, with cold iron, was such that the total magnet volume was minimised, thus reducing the material cost and overall mass. The result was spectacular in terms of saving: the mass of the 3 m long dipole could be reduced from about 15 tons (for the normal conducting design) to about 2 tons (for the superconducting option). For the quadrupoles a similar saving ratio was possible. This saving in capital costs for the magnets was however partially offset by the cost of the 15 kW cryogenic plant, and by the associated operation costs [11]. The reason is that on an accelerator of the scale of the PS2, and with the present cost of electricity (40 CHF/MWh) the trade-off between the costs of a resistive electrical load (absent for superconducting magnets) and that of cryogenic operation (to be considered for superconducting magnets) is around 10 W/m of heat load per unit magnet length. With an estimate AC loss of about 5 to 8 W/m of magnet, the design selected was too close to the point of trade-off.

A second study, originally motivated by the discussion at ECOMAG [1], and completed in [8], was performed on a class of cos-θ magnets with cold iron, in a range of bore field from 2.5 T to 5 T, covering the PS upgrade option PS2b (with high extraction energy), as well as both SPS2

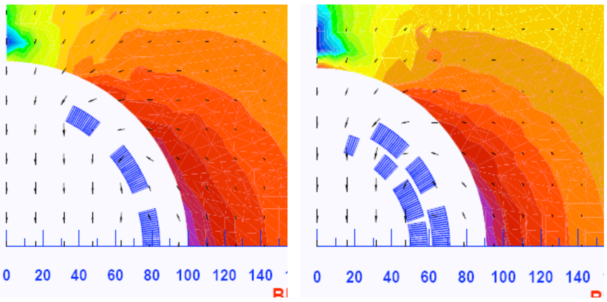


Figure 2. Cross section of the coils considered in the scaling study for PS2 (left) and SPS2 (right) superconducting, cos-θ magnets.

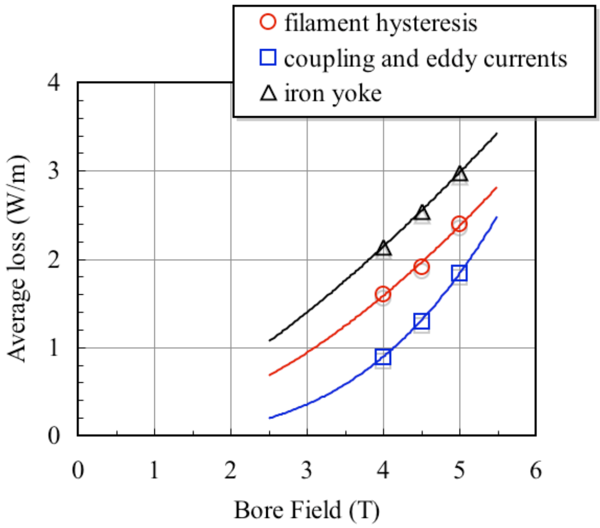


Figure 3. Dependence of AC loss contributions on the bore field in a cos-θ magnet with cold iron yoke. The calculations were performed for the magnet design detailed in [8], and refer to an SPS-like operation cycle lasting a total of 12 s.

options [8]. The typical cross esctions of single and double layer magnets is shown in Fig. 2. One of the main results of this study was a set of scaling law for the dependence of main magnet design parameters, such as volume, mass, inductance, energy and loss, on bore field and diameter. One such result is shown in Fig. 3, reporting the contribution of AC loss (hysteresis in the superconducting filaments, coupling in strands and cable, hysteresis in iron yoke) as a function of the bore field, having assumed a cycle reference as for SPS2 (3 s ramp-up and ramp-down, 3 s flat-top and flat-bottom, 12 s total). The level of loss at a bore field of 4.5 T is 5.7 W/m of magnet length, which in the case of a superconducting SPS2 would require a cryogenic installation of 34 kW @ 4.2 K. This translates to an electrical power need at the level of about 10 MW, which is a significant percentage of the total installed power for the present SPS (60 MW total power).

For a PS2 magnet, similar analysis and scaling by the reduced cycle time lead to the quoted value of 15 kW installed power @ 4.2 K. This corresponds to a required electrical power of approximately 4.5 MW, which represents about half of the present power need for the PS, and tips the balance of operation costs in disfavour of a superconducting option, thus corroborating the results of [7].

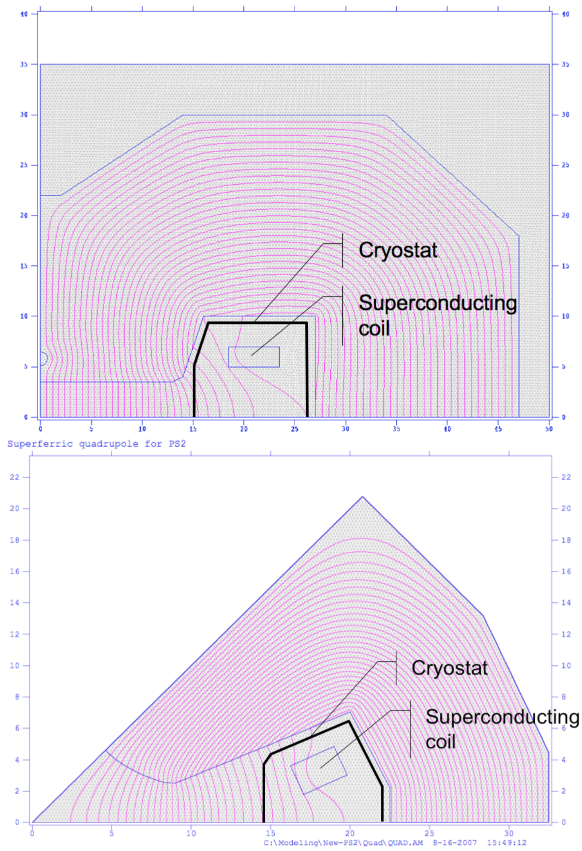


Figure 4. Schematic cross section of iron-dominated (*superferric*) designs of a dipole (top) and quadrupole (bottom) for the PS2.

An AC loss reduction with respect to the projected values is hence mandatory before a superconducting magnet option is attractive for use in the injectors. In addition, examining this result it is also evident that a large part of the loss takes place in the iron yoke. A corresponding saving could be achieved by intercepting these losses at temperature higher than the nominal operating point of 4.5 K, and especially in the case of a warm iron yoke. The drawback is the design complication in the thermal insulation and mechanical support of the coils.

This result motivated us to revisit the design study for a superconducting PS2 magnet, as discussed in [12]. Rather than aiming at the most compact magnet design, in this iteration we tried to achieve maximum efficiency in terms of power requirements and operation costs. This implied a reduction of AC losses to the minimum that can be reasonably achieved with available technology. For the specific conditions of the PS2, this criterion is best satisfied in the case of an iron-dominated magnet, of the type descibed in [13] and somewhat improperly named *superferric*. The iron is at room temperature (thus removing the corresponding loss from the cryogenic load) and the superconducting coils provide the magneto-motive force, but can be placed in a location in the iron yoke where they are not exposed to the maximum field (thus reducing the field swing and ramp-rate, and the associated AC loss) nor the direct loss of beam particles. This choice also allows to minimise the variations with respect to the normal-conducting baseline magnet. The field quality is with good approximation identical in the two cases, being dominated by the shape of the iron pole, and the magnet bore is at room-temperature, with easy access (e.g. for beam pipe and collimation systems).

The main result was that we could produce a conceptual design of the main magnets (dipole and quadrupoles, shown schematically in Fig. 4) that would lead to a projected total power consumption of 7.6 MW, about half of the power required by a normal-conducting PS2, i.e. 14.6 MW. The operation costs would be in consequence significantly lower, by 1.6 MCH/year at the assumed electricity cost of 40 CHF/MWh. This advantage scales proportionally with energy cost, which is expected to increase in the near future. The additional cost for the construction of the magnet system, and associated auxiliaries (e.g. cryoplant) would amount to an estimate of 6 MCHF, which is a small fraction (a few %) of the total PS2 complex.

A *superferric* design with the above properties becomes an interesting option for an injector upgrade such as the PS2. In addition to a long term advantage for the cost of an operation that is projected over 20 years and longer, it provides operational flexibility in the duty cycle, as the absence of significant resistive losses allows long flat-tops, up to steady state.

## ON-GOING R&D OUTSIDE CERN

The above R&D objectives and ideas are not isolated. Comparable to work is in progress at other European HEP and associated laboratories. Below is a summary of the relevant R&D on fast cycled superconducting magnets.

The Gesellschaft für Schwerionenforschung (GSI) in Darmstadt (D) is organizing the construction of a new Facility for Antiprotons and Ion Research (FAIR) [14]. The central part of this complex are the two rings SIS100 and SIS300 that will be built in the same tunnel and will have magnetic rigidity $B\varrho$ = 100 Tm and $B\varrho$ = 300 Tm respectively. To achieve this magnetic rigidity the dipoles of SIS100 will have a bore field of 2 T in a rectangular bore of 130 mm x 65 mm. The dipoles of SIS300 will require a peak field of 4.5 T in a round bore with a diameter of 100 mm. The magnets for these two rings are especially challenging because the operation mode of the complex foresees fast ramping of the energy. SIS100 should undergo a full cycle in 1 s, corresponding to a ramp-rate of 4 T/s. The ramp-rate requirements for SIS300, which will operate as a storage ring, are more soft, but still the aim is to ramp the ring at 0.5 to 1 T/s.

The SIS-100 R&D at GSI is supported by activities at the Joint Institute for Nuclear Research (JINR) in Dubna (R). A synchrotron similar to SIS-100, the Nuclotron, has been in operation at JINR since 1994 [15]. The Nuclotron dipole magnets are operated in the accelerator at a peak field of 1.5 T, ramping at 0.6 T/s, and have achieved a peak field of 2 T, ramping at 4 T/s.

For SIS-300, work has been performed in collaboration with Brookhaven National Laboratory (BNL). A prototype magnet, GSI001 with a single layer coil and similar in construction to the RHIC dipole, was built and tested successfully at BNL, demonstrating operation up to 4 T bore field in pulsed conditions up to 4 T/s. The magnet sustained short pulse sequences between 2 T/s (500 repeated cycles) and 4 T/s (3 repeated cycle) without quenching [16].

Since end 2006, Istituto Nazionale di Fisica Nucleare (INFN) has launched a prototype design and construction activity to demonstrate the feasibility and test the performance of a dipole for SIS-300 [17]. The INFN program, dubbed DiSCoRaP (Dipolo SuperConduttore Rapidamente Pulsato), originally aimed at a peak field of 6 T and a ramp rate of 1.5 T/s, is now focussing on the design and construction of a prototype with peak field of 4.5 T and ramp-rate of 1 T/s (compatible with the recent change of parameters for the SIS-300 dipoles).

The above magnet parameters have been reported in the scatter plot of Fig. 1 for comparison with the target of $B_{max}$ x $(dB/dt)_{max}$ = 7 $T^2/s$.

Finally, CEA has proposed an R&D program (Supra Pulse) that aims at the realization of a demonstrator quadrupole magnet reaching 90 T/m over an aperture of 100 mm, ramping at 1 T/s on the coil.

## PERSPECTIVE AND PLAN

From the discussion above, and given a realistic timeline of the upgrade of the injector complex, it is clear that an R&D on fast cycled superconducting magnets should be focussed in priority on PS2. For this reason we have defined as a primary objective the design, construction and test of a demonstration magnet that should achieve the operating conditions of PS2a ($B_{max}$ = 1.8 T, $(dB/dt)_{max}$ = 1.6 T/s) with a thermal load per unit magnet length of the order of 2 W/m. The same magnet should be capable of operation at the same bore field, but increased ramp-rate $(dB/dt)_{max} \approx$ 4 T/s to demonstrate scalability to the upper limit of present technology, i.e. $B_{max}$ x $(dB/dt)_{max}$ = 7 $T^2/s$, with a thermal load per unit length of magnet well below 5 W/m. In addition to being directly relevant for the PS upgrade, this development is complementary to the work in progress in companion HEP laboratories, thus supplying an element of novelty in the picture. We expect the first results on this program by late 2008 (strand and cable) and during 2009 (magnet construction and test).

A significant portion of this R&D will be devoted to the development and procurement of suitable strand and cable [18]. This R&D is in practice common to all magnet options in the spectrum identified for the upgrade of the

LHC injectors, as well as the work at companion laboratories.

Finally, as a complement to the technology R&D for the PS2 demonstration, we plan to pursue the studies on superconducting options for an upgrade of the SPS by exploring magnet designs with the iron yoke at room-temperature, explicitly including the minimization of the cost of operation among the design targets.

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