THE FAST CYCLED SUPERCONDUCTING MAGNETS (FCM) R&D PROGRAM AT CERN

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Abstract

CERN is running a small and focussed program aimed at the demonstration of the technology required to build Fast Cycled superconducting Magnets (FCM) with high energy efficiency, as an option for the planned upgrade of the PS injectors (PS2). This paper gives a concise summary of the main objectives of the FCM R&D program, as well as the present schedule and cost estimates. We will show how the FCM R&D program will provide background for the technical discussion on the upgrade of the SPS.

INTRODUCTION

Background

Cycled superconducting accelerator magnets have been considered as a natural way to increase the maximum energy attainable in synchrotrons since the late 1960's. Early examples of such research and prototyping work can be found in [1] and references therein. The main motivation for this early work on cycled superconducting magnets was to exploit existing installations to increase the beam energy [2], [3], or to attain the same energy as accelerators built with resistive magnets, but in rings of of smaller size and reduced cost*. The range of bore field considered at the time was 4 to 6 T, which is a factor 2 to 3 higher than the typical bore fields attainable by resistive magnets.

Resistive magnets are the established and relatively *easy* technology for accelerator magnets in a range of bore field of 1 to 2 T. In contrast, for bore fields in the range mentioned earlier, i.e. 4 to 6 T and beyond, superconducting magnets are *the* enabling technology. They are in practice the only viable technical alternative, with clear advantages of size and cost over resistive magnets.

This divide has remained essentially the same over the past 35 years, over which period superconducting magnet technology was the leading thread along the path to high energy machines (the Tevatron, HERA, RHIC, and the coming LHC).

Presently, we believe that we are on the verge of a change in this pattern, moltivated by rising concerns on long-term availability and cost of energy. Indeed, there is an increasing number of studies on the use of superconducting magnets to improve the efficiency of installations based on resistive magnets. This is effectively an attempt to displace the established technology of resistive magnets from the range of bore fields of 1 to 2 T, where they are best adapted. In the case of an accelerator system the price to be paid is an increased complexity (additional cryogenics, and protection systems), associated with higher capital cost. The expected return, however, is worthy, namely secure long term operation of experimental installations that depend critically on the availability of electric power.

This work on magnets is not isolated. Indeed, a similar effort is taking place in other fields of relevance. One such example is the case of power transmission and management systems, where superconducting cables, fault current limiters and magnetic energy storage systems are expected to boost grid capacity, increase the efficiency and reliability of the power distribution. Another field where superconductivity could play a relevant role is that of medical applications based on accelerator technology (e.g. hadron therapy). Superconducting magnets can be used to reduce the size of the installation (both accelerator and gantry) and make it suitable for location in standard hospital premises, rather than at specialised centers. Several state and industrial laboratories are engaged in research in these fields.

Opportunities at CERN

Focussing on magnet technology, and restricting our attention to the upgrade path of the CERN accelerator complex sketched in [4], we see two main opportunities for superconductivity on the near term: the PS and the SPS. The PS, built in 1959, accelerates protons from 1.4 GeV to 26 GeV and runs on approximately 8.5 MW electrical power, for an integrated consumption of 32 GWh during 4800 hrs of operation. The PS upgrade, conventionally called PS2 and presently under study,

Table I. Main characteristics of the dipoles and quadrupoles for PS2, resistive baseline.

Injection energy	(GeV)	4
Extraction energy	(GeV)	50
Injection field	(T)	0.144
Extraction field	(T)	1.8
Aperture at injection H x V	(mm x mm)	42 x 30
Aperture at extraction H x V	(mm x mm)	42 x 12
Ramp-up/ramp-down time [s]	(s)	1.1
Flat-top/flat-bottom time [s]	(s)	0.1
Field ramp-rate [T/s]	(T/s)	1.5

* As a side remark, it is interesting to note that already at that time a large portion of the work on fast cycled superconducting magnets was motivated by the discussion on a possible upgrade of the SPS from its nominal energy of 300 GeV to a maximum of 1200 GeV [3].

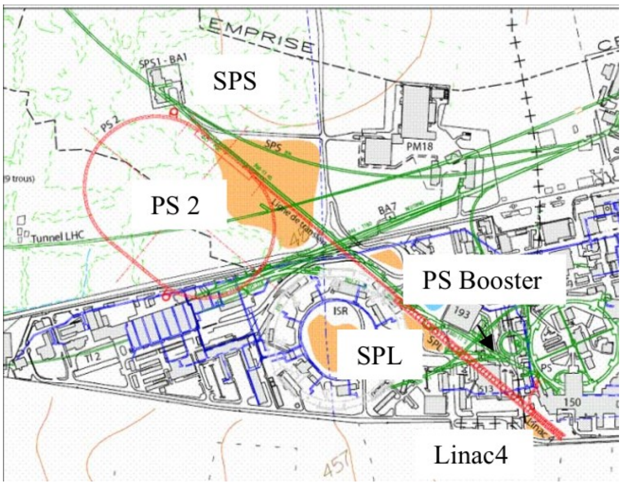

Figure 1. Proposed location of PS2 in the CERN accelerator complex, also showing the Linac 4 (in construction) and SPL (planned).

should accelerate protons from 4 GeV to 50 GeV. The baseline design of the new machine [5], of approximately twice the size of PS, and based on 1.8 T resistive magnets with the overall characteristics reported in Tab. I, would require an electric power of the order of 15 MW. This corresponds to doubling the consumption of the PS complex. The siting studies for the PS2 are on-going, and a proposal for the layout is shown in Fig. 1. According to the present plan, the study of PS2 should be completed in 2011, to present the project for approval in 2012 and start construction in 2013.

The SPS, operating since 1976, requires approximately 50 MW to run, for an integrated consumption of 350 GWh. This is a significant fraction (35 %) of the total electricity needs of CERN. Beyond the continuous maintenance, and the improvements at the level of the beam pipe impedance and surface condition, a major upgrade considered for the long term plan is to increase the SPS energy up to 1 TeV. Such a machine, presently known under the name of SPS+, should improve operating conditions in the LHC (higher injection energy), offer physics opportunities in this energy range, and pave the way for the evolution of the LHC towards the farthest energy frontier [6]. A 1 TeV SPS+ should be based on superconducting magnets with 4.5 T bore field, with characteristics in the range reported in Tab. II. Note that an essential part of this upgrade would be the transfer lines from SPS to LHC, not to be forgotten.

Both upgrades, PS and SPS, present opportunities for superconducting magnet technology. While for the PS the main objective should be on energy efficiency (i.e. superconductivity as a *technology displacer*), in the case of the SPS the objective is both on efficiency and performance (i.e. superconductivity as a *technology enabler* and *displacer*). The timeline of the two projects is however much different. Given the present engagement of CERN in the commissioning and start-up of the LHC, the construction of LINAC4, and the plans for a Low Power SPL followed by the PS2 construction, an SPS+ appears very far in time, on the horizon of 10 years at the earliest. It is hence natural to focus on PS2 as the main opportunity for superconducting magnet technology at CERN. In the following section we outline the R&D program that addresses the issue of feasibility and performance of a Fast Cycled Superconducting Magnet suitable for the PS2.

Table II. Ball-park parameters for a SPS+ dipole design.

Injection energy	(GeV)	50
Extraction energy	(GeV)	1000
Injection field	(T)	0.225
Extraction field	(T)	4.5
Aperture diameter	(mm)	≈ 75
Ramp time [s]	(s)	3.0
Flat-top/-bottom time [s]	(s)	3.0
Field ramp-rate [T/s]	(T/s)	1.4

In spite of this well defined scope, we claim that the results of this R&D are relevant to an SPS+, which is an important result to cope with the fact that any new development of superconducting magnets requiring takes a considerable time (typically measured in years) and financial effort (typically measured in several MCHF).

THE FCM R&D PROGRAM

Following the discussion in the previous section, a logical R&D on Fast Cycled superconducting Magnets should be centered around the design, construction and test of a demonstration dipole for PS2, dubbed here the FCM demo, that should prove feasibility and address the most critical technological issues. The conceptual design studies reported in [7] through [11] have led to the conclusion that a suitable objective for a FCM R&D is to build a demonstration dipole that produces the field required by the PS2 (1.8 T, 1.5 T/s, homogeneity of the order of 10^{-4}), over a relevant aperture (an ellipse with semi-axes H x V of 42 x 30 mm), that can be continuously cycled according to the PS2 specifications (0.1 s injection, 1.1 s ramp-up, 0.1 s flat-top, 1.1 s ramp-down), and would have a projected AC loss of 1 W/m or less for the above operating conditions, and once properly scaled to a full-size magnet of 3 m length. While the aperture (and hence the iron yoke cross section) of the FCM demo needs to be full size, the magnet length can be limited in the order of 1 m of cryostated coils (i.e. an iron yoke pack of approximately 0.5 m length). This has been judged sufficient to establish the performance limits of the concept and to address all manufacturing, assembly and operation issues.

Figure 2 shows the present FCM demo reference design. The magnet appears from the outside much like a resistive magnet, with a large yoke housing the cryostated coils that take the place of copper coils. The yoke has external dimensions of the order of 1 m^3, and a total mass of 4 tons. The magnet bore, with a width of 250 mm and 70 mm, is fully accessible. The design features of the various magnet components and assemblies are detailed in Tab. III, which also gives a summary of the derived

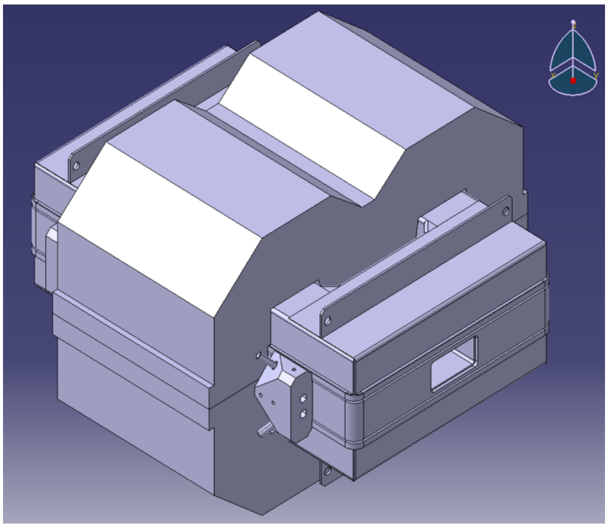

Figure 2. Present baseline design for the FCM demo. The magnet consists of an iron yoke and a cryostated coil that takes the place of a conventional copper coil, and leaves the magnet bore *warm* and accessible.

Table III. Target performance and main characteristics of the FCM demo.

Bore field	(T)	1.8
Ramp-rate rated value	(T/s)	1.5
Ramp-rate target value	(T/s)	4
Good field region (ellipse semiaxes)	(mm x mm)	42 x 30
Field homogeneity target	(units)	≈ 1
Magnet dimensions and weights		
Yoke width	(mm)	1150
Yoke height	(mm)	800
Yoke length	(mm)	800
Aperture (clear bore H x V)	(mm x mm)	250 x 70
Yoke Mass	(tons)	4
Conductor design		
Conductor type	Internally cooled cable (CACC)	
Strand material and composition	Nb-Ti/Cu/Cu-Mn 1:2.4:0.5	
Strand diameter	(mm)	0.6
Strand Jc (5 T, 4.2 K)	(A/mm^2)	> 2500
Strand hysteresis loss (± 1.5 T)	(mJ/cm^3)	< 45
Number of strands	(-)	34
Cable critical current	(kA)	> 10
Cable current sharing temperature	(K)	> 5.75
Cooling pipe diameter	(mm)	5
Cable diameter	(mm)	7.8
Total conductor length (1 pole)	(m)	35
Heat loads and cooling		
AC loss at rated ramp-rate	(W/m)	< 1
AC loss at target ramp-rate	(W/m)	< 5
Maximum heat load capability	(W/m)	> 5
Cooling massflow (2 poles)	(g/s)	2 x 5
Inlet temperature	(K)	< 4.5
Inlet pressure	(bar)	> 3

technology R&D target (e.g. the critical current of the superconducting strand and cable, or the maximum heat removal capability from the coil).

We plan to test the FCM demo to characterise the performance limits, and to address issues such as long term reliability and fatigue. An outline of the test program is reported in Tab. IV. While the main objective of the FCM demo is to demonstrate cycled operation at the rated values of bore field, we stress that such a test is vital to provide a measurement of the operating characteristics such as AC loss, cooling, and mechanical behaviour. To this aim, the magnet coil and iron will be heavily instrumented by temperature sensors, voltage taps, strain and displacement gauges.

Table IV. Test program outline for the FCM demo.

- DC magnet performance
  - Quench current vs. temperature (4.5 K … 6 K)
  - Current sharing temperature vs. current (5 … 10 kA)
- AC magnet performance
  - Quench current vs. ramp-rate (0 T/s … 10 T/s)
- Accelerator cycle runs
  - PS2 cycle simulation
  - SPS+ scaled cycle simulation
- Magnet thermal loss (calorimetry)
  - DC loss
  - AC loss vs. cycles
- Field mapping (AC and DC)
- Quench initiation, propagation and protection tests
- Accelerated life test (cycling at 5×10^5 cycles, cycling current and ramp-rate TBD, monitored by DC performance and insulation tests)
- Survival tests to abnormal operating conditions such as loss of cryogen flow and other TBD

An important part of the test is the accelerated life test, which will consist in sequences of rapid trapezoidal cycles at a current in excess of the rated value, interleaved with a verification of the DC performance and insulation of the magnet to detect any degradation. Provided that the magnet will achieve the rated performance, it should be possible to verify fatigue over a few 10^5 cycles, i.e. approaching asymptotic fatigue limits. Finally, we wish to attempt to assess the robustness of the concept to perturbations of normal operating conditions, e.g. testing the survival time to stop of coolant flow or other events of similar nature.

THE PLAN

The FCM strand and cable procurement is presently running, with the delivery of 10 units length of cable (80 m) for magnet prototypes to be delivered in May 2009. Cable tests and characterization (critical current, AC loss) will follow in the second half of 2009.

After a first design iteration, whose result is shown in Fig. 2, we are presently revising the details of the winding pack geometry, coil support, cryostat and iron, to start winding tests and qualify the fabrication procedure for the FCM demo. The procurement of the components (coil, structure, cryostat, iron) and manufacturing should take place in the second half of 2009.

At the same time the test configuration and instrumentation is being defined, aiming at the preparation of the test station and related infrastructure (cryogenics, power supply, DAQ) by the end of 2009. The performance test is finally expected to take place at the beginning of 2010.

The present cost estimate for the FCM demo, including accessory R&D and the final test, runs at 1.5 MCHF, requiring personnel resources estimated at 7 FTEy.

RELEVANCE FOR FUTURE R&D

As mentioned earlier, the FCM R&D is targeted at the PS2. Nonetheless, as we have discussed in previous works, it is possible to show that comparable cycled superconducting magnets developments follow a broad scaling with the product of peak field and peak field ramp-rate. This is shown in the scatter plot of Fig. 3, where we have reported a collection of the characteristics of magnet designs, magnet prototype performances, and machine specifications collected from the references quoted. As can be seen there, although some single developments and tests may have achieved higher performance, the two leading projects in terms of large size fast cycled synchrotrons (FAIR at GSI and SPS+) aim at achieving a B_{max} x $(dB/dt)_{max}$ of the order of 7 T^2/s. In addition to testing PS2 conditions, we wish to use the FCM demo to show that the B_{max} x $(dB/dt)_{max}$ target of 7 T^2/s can be achieved by this design, thus providing a first proof that the strand and cable produced are applicable for SPS+. The peak field in the FCM demo will be limited by iron saturation to a values close to 1.8 T, and the only possibility is hence to run at higher dB/dt (approximately 4 T/s), which is the reason of the target ramp-rate value reported in Tab. III.

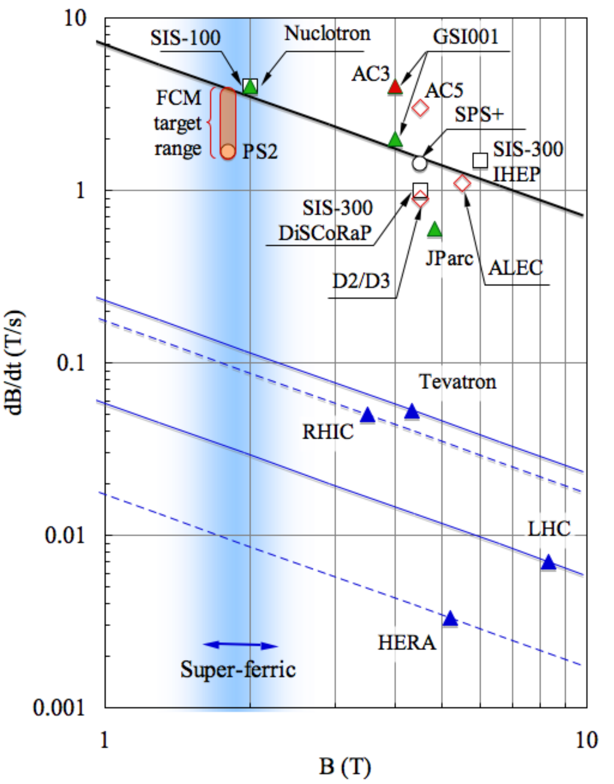

Figure 3. Scatter plot of $(dB/dt)_{max}$ vs. B_{max} for various magnets from specifications, design studies, prototype magnets and operating accelerators. This lines represent values at constant B x dB/dt. The R&D target at B_{max} x $(dB/dt)_{max}$ = 7 T^2/s is indicated by a thick solid line. The shaded area of field around 2 T is the typical range of superferric magnets. The magnet specification or performance reported are derived from the following references:

- AC3 and AC5: Refs. [1] and [2];
- D2/D3: Ref. [1];
- ALEC: Refs. [1] and [3];
- Nuclotron: Ref. [12];
- JParc: Ref. [13];
- GSI-001: Ref. [14];
- SIS-300 IHEP: Ref. [15];
- SIS-300 DiSCoRaP: Ref. [16];
- PS2: see Table I of this paper;
- SPS+: see Table II of this paper;
- FCM: see Table III in this paper;
- Tevatron, RHIC, HERA and LHC values are taken from nominal accelerator operating conditions.

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