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FAST RAMPING SUPERCONDUCTING MAGNET DESIGN ISSUES FOR FUTURE INJECTOR UPGRADES AT CERN

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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 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), for which superconducting magnets are a candidate. Due to the fast field sweep rate of the magnets (from about 1.5 T/s to 2.5 T/s), internal heating from eddy and persistent current effects (AC loss) must be minimized. In this paper we discuss a rationale for the design and optimization of fast ramped superconducting accelerator magnets, specifically aimed at the LHC injectors. We introduce a design parameter, the product of bore field and field ramp-rate, providing a measure of the magnet performance, and we apply it to choose the design range for a technology demonstration magnet. We finally discuss the dependence of key design parameters on the bore field and the bore diameter, to provide an approximate scaling and guidelines for critical R&D.**

Index Terms—**Superconducting accelerator magnets, AC loss**

I. INTRODUCTION

THE CERN injector chain, and in particular the Proton Synchrotron (PS) [1] and the Super Proton Synchrotron (SPS) [1], have operated for decades, feeding reliable beams to the various experiments, the LEP collider, and more recently the CNGS line. The operation of the LHC, presently scheduled for first beam in May 2008, will pose the new challenge for the injector chain. The basic requirements are highly repeatable beam conditions at fast repetition rate, to ease beam injection and capture in the collider, and high availability, to maximise the beam time and integrated luminosity. These considerations have stirred work aiming at optimisation of the operation cycles of PS and SPS, as well as a plan for maintenance of the existing hardware that is affected by mechanical fatigue and long-term exposure to radiation. An LHC luminosity upgrade is already planned on the medium term, five years from the first physics run, consisting in the replacement of the low beta quadrupoles in the high luminosity interaction points as well as an increase of the bunch intensity coming from the injectors. To overcome the limitations in proton intensity in the injector chain, the construction of a new proton linac (the first element in the chain) has already started. A series of studies [2] have shown that the best benefit from this upgrade can be obtained with

new PS and SPS rings, with increased extraction energy. In addition to an increase of the integrated luminosity, an increase in the extraction energy from the injector chain may open the path to a long term energy upgrade at the LHC.

A much simplified summary of this reasoning is reported in Table I, where we have collected main magnet design parameters as appropriate for a PS upgrade (columns PS2a and PS2b) and the corresponding SPS upgrade (columns SPS2a and SPS2b). The bending field required at the dipole magnets is of the order of 1.8 T peak in the option PS2a, which is the present baseline for a PS upgrade, up to 4.5 T for an SPS upgrade. As discussed in [3] superconducting magnets could already provide a compact and cost effective alternative to the normal conducting baseline option PS2a. Above 2 T, i.e. for an increased extraction energy from a PS upgrade, and for any of the envisaged upgrades in the SPS, superconducting magnets are the enabling technology, and, in practice, the only reasonable choice.

Field quality and magnet aperture are so far only loosely defined. For PS2 the good field region extends to a radius of 50 mm, and the quoted request for the homogeneity is $\pm 1 \cdot 10^{-4}$, which is most likely a conservative target. For SPS2 the good field region is smaller, extending to a radius of the order of 35 mm, and we expect similar requirements on homogeneity. This holds over the whole field swing, the ratio of injection to extraction field, which has reasonable values for options PS2a (12.5) and SPS2b (13.3) but is challenging for PS2b (18.8) and especially SPS2a (20).

The reference operation call for appreciable field ramp-rates for both PS2 and SPS2, in the range of 1.5 to 2.5 T/s. In addition, both accelerators will operate continuously, with short injection and extraction times. Under these conditions, AC loss, stability and heat removal become a concern and require strict control. In fact, the magnet parameters of Table I, and in particular the maximum field and maximum ramp-rate, are *per se* not critical. What is more challenging is that they have to be achieved simultaneously, in a magnet that

TABLE I RANGE OF MAGNET DESIGN PARAMETERS FOR AN UPGRADE OF THE CERN INJECTOR CHAIN [2].

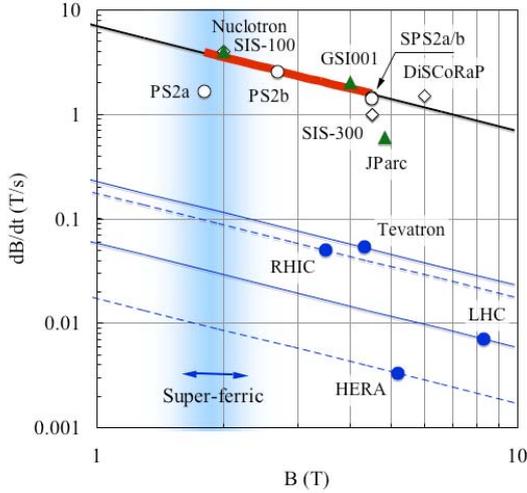|	PS2a	PS2b	SPS2a	SPS2b
Injection energy [GeV]	4	4	50	75
Extraction energy [GeV]	50	75	1000	1000
Injection field [T]	0.144	0.144	0.225	0.337
Extraction field [T]	1.8	2.7	4.5	4.5
Ramp time [s]	1.1	1.1	3.0	3.0
Flat-top/-bottom time [s]	0.1	0.1	3.0	3.0
Field ramp-rate [T/s]	1.6	2.5	1.4	1.4

Fig. 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, as listed in the text. The solid line represents the target for this R&D at $\Pi = 7$ 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.

is cost effective and reliable over a projected machine lifetime of 20 years.

In this paper we discuss the targets for the LHC injector upgrade in the general context of the on-going R&D on fast ramped superconducting accelerator magnets. We then define a design objective, review the main technology issues, and compute the expected performances of superconducting model magnets for a PS and a SPS upgrade. We use the result of this design exercise to establish scaling laws that hold over the whole range of Table I, and can be used to identify priority R&D. Among the many issues in fast ramped superconducting magnets, we have focused in detail on AC loss.

II. A DESIGN OBJECTIVE FOR FAST RAMPED MAGNETS

The range of parameters in Table I spans a factor 3 in maximum field and a factor 2 in field ramp-rate, i.e. a large envelope of performance. We have tried to find a common denominator among the various options by plotting the required field ramp-rate (dB/dt) vs. the peak field in the bore B. In Fig.1 we also report data on the performance of other accelerators in operation (Tevatron [4], HERA [5], RHIC [6], Nuclotron [7]), in construction (LHC [8]) and planned (SIS-100 and SIS-300 at FAIR [9]), as well as the performance of single magnet prototypes tested (the 4 T dipole GSI001 [10] and the 4.6 T combined functions magnet for JParc [11]) or presently in design (DiSCoRaP [12]). We notice an interesting feature in the scatter plot, namely that most of the points for fast ramped magnets are clustered around a curve $B \times (dB/dt)$ = *const*. In fact, the product $\Pi = B \times (dB/dt)$ is proportional to the power per unit volume delivered to (and recovered from) the magnet. Hence, for a given magnet design, an increasing value of Π is associated with higher terminal voltage and AC loss, two of the main issues for ramped magnets. Neglecting the large range of designs reported in Fig. 1, which is a

conscious over-simplification, we can thus use Π as an indicator of the *ramped performance*: magnets with the same Π are assumed to be equally difficult to design and build. Most magnets presently in design or prototyping for ramped applications are aimed at a target value of $\Pi = 7$ T^2/s, which also covers the range of parameters considered for both a PS and an SPS upgrade. We retain this value as the main design objective for our studies.

The second feature that is interesting in Fig. 1 is that with the exception of the Nuclotron, all large superconducting colliders operating to date are well below the target Π, typically by one to two orders of magnitude. This points to the fact that fast ramped superconducting accelerator magnets require an adapted technology. In the following we will focus on the design of two magnet variants, for PS and SPS, that aim at the same Π objective. To a first approximation, and in the range of field considered here, a suitable technology demonstration can be achieved by building a model with the desired Π, with no strong constraint on the actual value of the peak field. This allows choosing a prototype design with relatively low field and thus limits the material costs. In our case, the minimum design range of peak field should be from 2 to 3 T, and corresponding ramp-rate of 3.5 to 2.3 T/s. This range of field is well beyond the saturation of iron, so that this choice in practice eliminates iron-dominated designs (the shaded area marked as super-ferric in Fig. 1). Indeed, the reference design considered later is a coil-dominated magnet, with cos-θ winding, consistent with the expected range of field considered, and in particular the 4.5 T peak field required for a SPS upgrade.

III. TECHNOLOGY ISSUES

A. AC loss

Among the various issues of relevance for fast ramped superconducting accelerator magnets, AC loss control and reduction has foremost importance to reduce the cryoplant investment and operation cost, and limits the temperature excursions in the conductor. CERN injector system studies have shown that the target for cost effective magnets is in the range of 5 W/m of magnet (target) to 10 W/m of magnet (maximum allowable), beyond which the cryogenic consumption outweighs the gain in resistive power. Specific strand, cable and magnet manufacturing techniques are necessary to suppress each of the main AC loss contribution, as listed below.

1) Filament hysteresis loss (P_M)

In the range of interest to us, the hysteresis loss associated with the magnetization of the superconducting filament P_M is proportional to the product of critical current density and filament diameter, $J_C d_{fil}$. Aiming for the highest J_C, the only way to reduce P_M is by reducing filament diameter. Recent experience has shown that a J_C of 2600 A/mm^2 at 4.2 K, 5 T can be attained in Cu-matrix strands with geometric d_{fil} of 3 μm at modest manufacturing overhead with respect to the LHC standard manufacturing route [11]. The magnet designs discussed later are based on these values. A further reduction

of the filament diameter in Cu-matrix strands is known to be affected by proximity coupling and a reduction of J_C, to complicate the billet assembly, and lead to an increase of the strand manufacturing cost. Further R&D is hence required to reach filament size smaller than 3 μm, in an optimised and cost-effective manufacturing process, with limited J_C reduction and filament distortion. Specifically, the excess magnetization caused by the proximity coupling at filament size below 3 μm can be reduced by using a matrix with high resistivity (addition of Ni) or through magnetic inclusion (addition of Mn) or a combination of the two.

2) Inter-filament losses (P_{IF})

The coupling loss between filaments in the strand, P_{IF}, scales quadratically with: the filament twists and strand diameter, and inversely with the effective transverse matrix resistivity ρ_{eff}. It is therefore very important to use small strands and achieve the smallest possible twist without mechanically damaging the wire. The lower limit for the filament twist is in the range of 10 times the strand diameter, and ρ_{eff} can be increased by high resistivity barriers (e.g. Cu−Ni) or matrix (e.g. Cu−Mn). When using such matrix materials, it is important to add high conductance paths (Cu) between bundles of filaments to insure sufficient stability. In addition, the filamentary area must be decoupled electrically from the outer shell of the strand, which is required for protection but should not provide a return path for coupling currents.

3) Eddy current loss in the conductor (P_{eddy})

The eddy currents that flow in any bulk stabilizer portion of the strand contribute a non-negligible portion of the total loss. They scale with the square of the strand diameter, and are inversely proportional to the stabilizer resistivity. One should therefore select a stabilizer material with RRR as low as possible, without jeopardizing the quench protection of the magnet. Resistive barriers can be used to increase transverse resistivity (controlling AC loss) without affecting the longitudinal resistivity (important for protection).

4) Inter-strand coupling loss (P_{IS})

The coupling currents that are generated between the strands of a flat accelerator cable dissipate energy in the contact resistances between adjacent strands (R_a) and crossing strands (R_c). Assuming a constant specific contact resistance, these losses increase with the cube of the cable width w, with the square of the transposition pitch L_P, and are inversely proportional to R_a and R_c. A small cable, tight twist, and high inter-strand contact resistance are therefore necessary to limit this AC loss component. Since the ratio between the losses in R_c and R_a is of the order of $N_S^2/20*(R_a/R_c)$, where N_S is the number of strands in the cable, it is possible to keep R_a much smaller than R_c, which is beneficial for stability. Such anisotropy between the inter-strand contacts can be achieved through the use of a resistive strip inside the cable. A cable twist equal to 7 times the cable width ($L_P=7w$) can be achieved without degradation, which provides a practical design guideline. Finally, P_{IS} mainly depends on the component of dB/dt transverse to the large cable face. The

details of the coil winding (e.g. layout of the blocks and number of coil layers) has therefore a significant effect on P_{IS}.

5) Hysteresis and loss in the cold iron yoke (P_{IRON})

A major source of dissipation is the hysteresis of the cold iron yoke, (as considered here). Silicon steels are used to reduce the coercive field and hysteresis loss well below the level of low carbon steel grades typically used in slowly ramped accelerator magnets. Depending on the material grade, the loss for a 0-1.5-0 T unipolar cycle is between 100 and 200 J/m^3.

6) Other loss mechanisms

Other mechanisms can generate AC loss in the magnet. Two of the most relevant are:

- long range, boundary induced coupling currents generated by variations in dB/dt along the cable, that have a negligible total loss, but can produce local losses relevant for stability;
- eddy currents in spacers, coil wedges, structural components (e.g. coil collars), iron yoke, supports. These losses can be controlled by lamination and adding insulating breaks, which we assume are enough to reduce below the significance level.

B. Cooling

The heat loads on the magnet, originating from the AC loss (5 to 10 W/m) and beam heating (few W/m) must be removed efficiently. The two main issues are heat transfer from the cable to the helium, affecting the temperature margin of the superconductor, and the operating conditions, that need to be optimised to reduce the cryo-plant investment and operating cost. With the limited bore field considered, Nb-Ti has sufficient margin in the 4.5 to 5 K operating temperature range, and the superior (but costly) heat transfer properties of He-II are not required. Considering the properties of He-I, we realise that to remove a heat load of the order of 10 W/m of magnet under a limited temperature increase (below 0.1 K is suitable) will need high helium flow rates through the structure, of the order of 20 g/s per m of magnet cooled. This cannot be achieved by natural convection, and we are hence left with the only option of a forced-flow of supercritical or two-phase helium through the magnet. Because of the high voltages expected during operation and quench, vapor formation should be avoided, and thus supercritical helium is the preferable option.

Heat transfer from the cable to the helium in supercritical helium will be dominated by the thermal barrier represented by the electrical insulation. An estimate of the time constant for the temperature difference between cable and helium, based on a 0.1 to 1.15 mm Polyimide insulation, and conduction limited to the inner radius of the coil, leads to values of the order of 0.3 to 0.4 s. This implies that for the PS2 cycles, with flat-top and bottom of 0.1 s, the heat pulses will accumulate until a steady state temperature distribution is reached. For the SPS, on the other hand, the duration of the flat-top and bottom is 3 s, and the conductor can re-cool after a ramp, recovering the initial temperature, which is an important effect for the estimate of the operating point of the superconductor.

C. *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. The ratio of the inductive voltage during ramps to the detection threshold is typically around 1000, which makes direct discrimination impossible. The detection circuit has to rely on compensation, e.g., using a bridge configuration as already in use for the protection of the LHC magnets. A digital signal acquisition processor combined with high precision input stages and analogue-to-digital converters will give the necessary precision and reliability. The detection threshold could be adapted to the various phases in the machine operating cycle, which is also a technique planned to be used at the LHC. In accelerators such as PS and SPS, the radiation dose on the electronic components will be an issue. It will be favourable to install the protection electronics in radiation free areas. This will give a much wider choice in the design of the electronics, increase its performance and reduce procurement and maintenance cost.

Once a quench is detected, the magnet could be protected by using the high-voltage capability of the power supply to extract the energy into the network. Sufficient copper in the cable is needed to survive the current extraction time. About 6 times a year lightning causes the loss of the network and so a backup system is needed, e.g. high current switches to protection resistors.

D. *Other critical magnet design issues*

Material fatigue over several hundreds million cycles, and radiation dose from beam losses are the two remaining issues that need to be mentioned. Both have influence on magnet design, and require careful material choice, dedicated R&D and testing. Given the bounded scope of this study, we limit ourselves to simply mention them.

IV. A SCALING STUDY

To demonstrate how the issues listed above affect the conceptual design and construction, we have produced a series of magnet designs that spans the whole range of field of Table I. Two parameters were changed in the scan, the bore field B and the bore diameter ϕ. Apart for the coil and cable positions, that has been optimised in each design, we have maintained all other design features constant. This was strictly possible only throughout the parameter set considered for the upgrade of either the PS or SPS. Indeed, when going from low field (2…3 T) magnets to moderate field (4…5 T) magnets, we had to change the coil layout from a single layer to a double layer. We have hence taken two specific magnet designs as a starting point of our analysis, a 2.8 T, 150 mm aperture, single layer dipole for a PS2b, and a 4.5 T, 100 mm aperture, double layer dipole for SPS2, i.e. two points located on our $\Pi = 7$ T^2/s objective.

The magnet cross sections resulting from the optimization are shown in Fig. 2, while the main magnet parameters are given in Table II. Most computed quantities are referred to the unit length of magnet. For all design and calculations we have used a 0.45 mm strand with a Cu:Nb-Ti ratio of 1.65, a J_C at
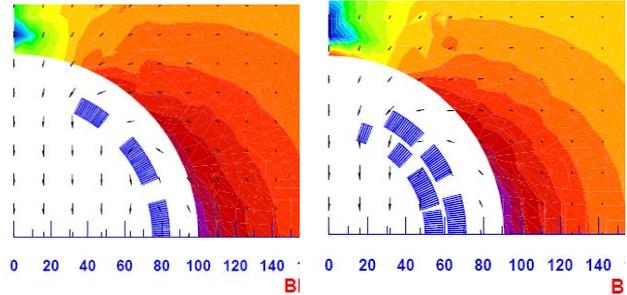

Fig. 2. Cross section of the two reference designs for a PS2b (left) and a SPS2 (right) magnet.

TABLE II REFERENCE MAGNET **D**ESIGN AND PERFORMANCE FOR THE **S**CALING **S**TUDY.

Nominal central dipole field	(T)	2.8	4.5
Coil inner diameter	(mm)	150	100
Nominal current	(A)	3800	3158
Operating temperature	(K)	4.7	4.7
Temperature margin	(K)	1.1	1.1
Stored energy E_{magnet}	(kJ/m)	76	118
Inductance	(mH/m)	10.5	23.6
Inductive ramp voltage V_{ramp}	(V/m)	36	25
Coil volume V_{coil}	(dm^3/m)	1.4	2.3
Iron yoke volume V_{yoke}	(dm^3/m)	123	157
Magnet weight W_{magnet}	(kg/m)	980	1260
Average AC loss in the coil P_{coil}	(W/m)	9.0	3.2
Hysteresis	(W/m)	4.9	1.9
Strand eddy and coupling loss	(W/m)	2.1	0.5
Cable coupling loss	(W/m)	2.0	0.8
Hysteresis loss in iron yoke P_{yoke}	(W/m)	12.6	2.5

4.2 K and 5 T of 2600 A/mm^2, and a RRR of 100. The cable is assumed to be made of 40 strands, 9.3 mm wide and 0.9 mm thick. Further, for loss calculation we have taken a filament diameter of 3 μm, a strand coupling time constant of 0.4 ms, and relatively high inter-strand resistances R_a and R_c, 100 μΩ and 10 mΩ respectively. As already discussed earlier, these values are typical of the best performance that can be achieved with present technology and production control. The average AC loss, also reported in Tab. II, is referred to the total time required for a cycle, which is different for the PS2 and SPS2 (see Table I).

The magnets considered are compact. A 2.8 T, 3 m long PS2b dipole would weigh about 3 tons with cryostat, as compared to the 15 tons of a 2 T, 3 m long resistive magnet [4]. Typical voltages during ramp range from 25 to 36 V/m. This means that the voltage over the 600 m integrated bending length for a PS2 would be around 20 kV, and about 116 kV over the 4.6 km integrated bending length of a SPS2. These values are excessive, and would require custom ground insulation technology. An easy solution to reduce the voltage to few kV, which allows using standard insulation schemes, is to segment the electrical circuit. Partitioning the magnet string requires accurate tracking among the circuits, typically at the level of ppm., which will be proven technology at the LHC.

The calculation of AC loss in the two designs considered shows that, with the strands parameters considered, losses in the coil and in the iron are of comparable magnitude. In addition, AC losses in the coil are dominated by the hysteresis

in the superconducting filaments, accounting for more than half of the total loss in the superconductor. From the absolute value of the loss we can also conclude that the target of 5 to 10 W/m seems achievable in the case of a superconducting SPS2. On the other hand, for a superconducting PS2b, the design considered requires substantial modifications to achieve the loss target, aiming at a reduction of the loss in the iron by a factor of at least 5, as well as a reduction of hysteresis loss by a factor of at least 2. In this respect, a demonstration of fast ramped magnet technology based on the PS2b option would imply the greatest technology challenges within the envelope of parameters considered here, and in line with our Π objective at 7 T^2/s.

We now turn to examine the dependency of the above parameters on variations of the bore field and diameter around the reference designs of Table II. We have considered variations of the bore field of ± 20 % and of the bore diameter of ± 15 % around the reference values. In practice, we find that:

$$E_{magnet} \approx B^2 \phi; \qquad V_{ramp} \approx B^2 \phi^2 \; ;$$
$$V_{coil} \approx B^{1.3} \phi; \qquad V_{yoke} \approx B \phi; \qquad W_{magnet} \approx B^{1.5} \phi;$$
$$P_M \approx V_{coil} \log(B); \quad P_{IF} + P_{eddy} + P_{IS} \approx V_{coil} B^2 \; ;$$
$$P_{yoke} \approx V_{yoke}.$$

At constant bore field, the stored energy and the magnet size (volume of cable in the coil and magnet weight) increase linearly with the bore size. The AC loss per unit magnet volume is approximately constant, so that on the basis of unit magnet length the average loss also scales linearly with the bore diameter. The same is true for the loss in the iron yoke. Finally, the ramp voltage scales approximately with the square of the bore diameter, and variations are more significant. However the dependence of the main design parameters on bore size are relatively small, indicating that the adjustments of aperture in the range considered are not critical.

The dependence of the above design parameters on the bore field at constant bore diameter, instead, is more critical. The stored energy and ramp voltage grow approximately with the square of the bore field. At the same time the coil volume has an inverse $J_C(B)$ dependence, which results in a power-law growth with an exponent ranging around 1.3. The magnet weight also grows with a similar power-law, but a larger exponent, in the range of 1.5. To examine the dependency of AC loss on the bore field we need to distinguish between hysteresis loss, and coupling and eddy current loss. Hysteresis loss per unit volume are proportional to $\log(B)$, while coupling and eddy loss per unit volume are proportional to the square of the bore field (we assume here that the cycling time is given and constant for all magnet variants). The overall dependence of AC loss per unit magnet length on the bore field, once the coil volume is folded in, is hence very strong. The consequence is that a field reduction is a very effective means to reduce the cooling power needs, as well as material and cost. If we apply this property to scale the results of the PS2b magnet in Table II to the conditions of PS2a in Table I, we find that the total AC loss in the superconductor P_{coil} decreases

to 4.3 W/m, while that in the iron yoke P_{yoke} becomes 8.1 W/m. Although much lower, these values are still marginally acceptable, and alternative design and material choices would be needed to make this magnet attractive from the point of view of operation costs.

V. CONCLUSIONS

We have reviewed here our motivations and some crucial issues in fast ramped superconducting accelerator magnets for the upgrade of the CERN injector chain. Among all options considered, the most challenging conditions are those that would be required for the PS2b option discussed here, corresponding to a 2.7 T, 2.5 T/s, 150 mm bore dipole. This set of parameters is our choice for a short magnet model, aiming at the demonstration that the technology is ready, robust and cost-effective. To attain the AC loss target of 5 W/m of magnet, averaged over an operating cycle, we depend on the development and procurement of a low-loss Nb-Ti strand (requiring a filament diameter in the range of 1 to 2 µm) and cable (controlled inter-strand resistance in the range of 100 µΩ adjacent and 10 mΩ transverse). At the same time, the iron yoke will have to be engineered to achieve a substantial reduction of AC loss (a factor 5) with respect to the design adopted here. Beyond these two main concerns, the model magnet should address other key issues that go beyond the scope of this paper, namely the selection of a suitable insulation scheme, the cooling mode and operating conditions, demonstrate reliable quench detection and protection, and test for fatigue in conditions representative of long term ramped operation.

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