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Limits to High Field Magnets for Particle Accelerators

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Abstract

What is the ultimate limit to high fields in superconducting magnets for particle accelerators? In this paper we review the present status of the technology, outlining the main limitations. We first analyse the needed margin for operating a magnet in an accelerator. We then review the relation between current densities, coil widths, and fields in the magnets build so far. The issue of stress and the dependence on the coil lay-out is then discussed: a careful optimization between current density and coil width can be needed to keep the forces and associated strain within acceptable limits. The main issues related to cable lay-out (strand diameter, filament size) are then discussed. We conclude by giving a hint on the requirements on a HTS conductor, and a summary of Nb-Ti and Nb₃Sn.

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Limits to high field magnets for particle accelerators

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Abstract — What is the ultimate limit to high fields in superconducting magnets for particle accelerators? In this paper we review the present status of the technology, outlining the main limitations. We first analyse the needed margin for operating a magnet in an accelerator. We then review the relation between current densities, coil widths, and fields in the magnets build so far. The issue of stress and the dependence on the coil lay-out is then discussed: a careful optimization between current density and coil width can be needed to keep the forces and associated strain within acceptable limits. The main issues related to cable lay-out (strand diameter, filament size) are then discussed. We conclude by giving a hint on the requirements on a HTS conductor, and a summary of Nb-Ti and Nb₃Sn.

Index Terms—superconducting accelerator magnets, dipoles, quadrupoles, low-temperature superconductors

I. INTRODUCTION

THE quest for higher and higher fields in accelerator magnets is a good paradigm of advancement in science and technology. On the one hand, superconducting magnets allowed increasing the bore magnetic field of one order of magnitude, from the ~ 1.5 -2 T limit of resistive magnets to the world record of nearly 14 T in a sizeable bore [1]. On the other hand, the progress since the first accelerator magnets in the 70's [2], [3] may look slow: 4 T in Tevatron at the beginning of the 80's, 5 T in Hera in the 90's, and 8 T still to reach for the Large Hadron Collider operation.

Nb₃Sn has the potential to be the workhorse of the 21st century accelerators, but a magnet made with this technology with all the features necessary for reliable operation is still to come. What is clear is that a considerable work is needed to achieve results: every additional tesla is gained with considerable efforts, trials and errors, and without massive research programs nothing happens. Nature does not make presents in this field. Nevertheless, the experience from solenoids [4] shows that the potential is there, and a considerable performance is at hand. In these pages we will summarize the present status of high field magnets for accelerators, pointing out the main open issues.

II. MARGIN

The maximum performance reachable by a superconducting magnet is estimated through (i) an electromagnetic (e.m.)

model of the conductor lay-out and (ii) critical current measurements of the superconducting strand and/or cable. The e.m. model provides the so-called *loadline*, i.e. the relation current density versus bore/peak field in the coil – this is a straightforward estimate based on Biot-Savart law and on a finite element model for the iron saturation if this is relevant. On the other hand, the cable performances in terms of critical current are much more difficult to estimate, and are affected by an error which can easily reach 5% for Nb-Ti, and even more for Nb₃Sn and HTS due to stress sensitivity.

The intersection of the loadline with the critical surface provide the maximum performance of the magnet (see Fig. 1), usually called *short sample* limit. Never forget that due to the limited knowledge of the critical surface of the superconductor within the magnet, this quantity is known at most within 5%.

Fig. 1: j_{sc} versus B for Nb-Ti and Nb₃Sn at 1.9 K, loadlines for 8.3 T (LHC dipole) and a possible 13 T dipole, and operational points (dots).

The magnet is not operated at the short sample limit: a margin is needed. For the LHC case, short sample is 9.7 T and operational field is 8.3 T so the *loadline margin* is $(9.7 - 8.3)/9.7 = 14\%$. How much margin is really needed is a relevant question: for magnets in the range of 20 T short sample, a 20% margin means 4 T, i.e. the field of the Tevatron dipoles!

In Table I we list the loadline margin for the main magnets used in particle accelerators: values range from 20 to 30%, with the relevant exception of Tevatron [3], working with $\sim 5\%$ margin. HERA energy was increased from 820 to 920 GeV lowering the operational temperature from 4.6 to 3.9 K, and keeping the same 23% margin. RHIC has been built with a comfortable 30% margin. The LHC dipoles were designed with a lower margin – the machine is running today at half of the energy for doubts on the interconnections, but one sector (154 dipoles) has been re-trained up to 6.6 TeV, i.e. 7.8 T field, corresponding to 19% margin, with about 25 quenches. The empirical rule one can deduce is that a 20% loadline

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margin is needed. When the iron nonlinearity becomes relevant, loadlines are not lines but curves and there are two different margins on field and current.

TABLE I. MARGIN FOR DIFFERENT ACCELERATORS

	Nominal			Actual		
	Temp. (K)	Field (T)	Margin	Temp. (K)	Field (T)	Margin
Tevatron	4.6	4.3	4%	4.6	4.2	6%
Hera	4.6	4.7	23%	3.9	5.3	23%
RHIC	4.5	3.5	30%	4.5	3.5	30%
LHC	1.9	8.3	14%	1.9	7.8*	19%

* reached in one eight of the LHC during hardware commissioning (no beam)

One can argue that what really counts for the magnet is the energy margin: nevertheless, the loadline margin is a concept that is widely used – and rarely discussed on paper. In the following we will try to address this issue.

We first consider a family of magnets with different loadlines and 20% margin: for instance, for Nb-Ti at 1.9 K the operational field will range from 1 to 10 T, the latter case corresponding to a very flat loadline. Then we compute for each case the temperature margin using the known parameterizations [5] – [7] for the critical surfaces. Results are shown in Fig. 2: firstly, a fixed margin on the loadline has the pleasant feature to correspond to a temperature margin which is nearly independent of the field. For Nb-Ti there is a temperature margin of about 2 K at 1.9 K and 1 K at 4.2 K. Note that we take a different operational field corresponding to the 20% loadline margin at that operational temperature: therefore the difference in temperature margin is not simply the difference in operational temperature.

For Nb₃Sn, due to the different shape of the critical surface, the margin is larger by a factor ~2.5, giving 4.5 K to 5.5 K at $T_{op}=1.9$ K and 3.5 K to 4 K at $T_{op}=4.2$ K.

Fig. 2: Temperature margin versus operational field for Nb-Ti and Nb₃Sn at 1.9 K (thick lines) and 4.5 K (thin lines) – case of 20% loadline margin.

A larger temperature margin at lower operational temperature is reasonable, since the specific heats decrease when $T \rightarrow 0$. To obtain the energy margin from the temperature margin one has to integrate the specific heats, which are usually modeled by a linear plus a cubic part: this provides a quadratic and a quartic dependence on T , i.e. something which is far from being linear. For Nb-Ti we consider non impregnated coils, and helium contribution can be relevant especially at 1.9 K. For Nb₃Sn we consider

impregnated coils, and for the superconducting material we use an expression derived in [8]. The final comparison between four designs, all with 20% loadline margin shown by markers in Fig. 2, is given in Table II. The estimate depends on the cable, and especially on the copper to non-copper ratio. We considered an LHC cable for Nb-Ti (Cu/Non-Cu=1.65) and the HQ [9] conductor (Cu/Non-Cu=1.17) for Nb₃Sn. For both materials, the 20% loadline margin provides about 1/3 larger energy margin at 4.2 K w. r. t. 1.9 K – therefore this rule makes operation at 1.9 K more challenging than at 4.2 K.

The comparison between Nb-Ti and Nb₃Sn also shows that the latter one has about a factor four more in energy margin. Unfortunately, this does not imply that the 20% loadline margin used in Nb-Ti can become 5% for Nb₃Sn, since other aspects have also to be considered (see next sections).

TABLE II TEMPERATURE MARGIN AND ENERGY MARGIN FOR Nb-Ti AND Nb₃Sn AT 1.9 K AND 4.2 K WITH 20% LOADLINE MARGIN

	Oper. temp.	Short sample field	Oper. field	Loadline margin	Temp. margin	Energy margin
	(K)	(T)	(T)		(K)	(mJ/cm ³)
Nb-Ti	4.2	8.0	6.4	20%	1.13	4.1
Nb-Ti	1.9	10.0	8.0	20%	2.13	3.2
Nb ₃ Sn	4.2	12.0	9.6	20%	3.50	15.6
Nb ₃ Sn	1.9	13.0	10.4	20%	4.75	11.4

III. CURRENT DENSITY AND COIL SIZE

In a dipole having a sector coil of width w , without copper wedges, the central field is given by

$$B = \kappa_d j_o w \quad (1)$$

where j_o is the *overall current density*, i.e. including the stabilizer in the strand, voids and structural material which are part of the coils. The term engineering current density, widely used, usually does not include insulation. If j_o is given in A/mm² and w in mm, for a 60° sector coil one has $\kappa_d = 0.69 \times 10^{-3}$ T mm/A [10]. In a quadrupole one has a similar equation for the field gradient

$$G = \kappa_q j_o \log\left(1 + \frac{w}{r}\right) \quad (2)$$

where r is the aperture radius and $\kappa_q = 0.69$ in the horrible but very practical units (T/m)/ (A/mm²) [11]. These equations can be generalized to include the influence of the iron, but we use ironless approximations to have a first order guess of the main parametric dependence.

The presence of copper wedges in the coil can be taken into account by defining an *equivalent coil width* w_{eq} which is the width of a 60° sector having the same cross section surface A of the coil [10]:

$$w_{eq} \equiv r \left[\sqrt{1 + \frac{3A}{2\pi r^2}} - 1 \right]. \quad (3)$$

The equivalent coil width is in general around 10-15% smaller than the total width of the coil in a cos θ lay out. For instance in the LHC dipole one has a coil width of 30.8 mm (2 layers of 15.4 mm width insulated cable) and the $w_{eq}=26.9$ mm. The

same equation holds for a quadrupole, where a 30° sector is considered. The main advantage of this definition is that it allows a direct comparison between $\cos\theta$ and block lay-outs.

The two obvious paths to high field and high gradients are *larger current densities* and/or *larger coils*. In Fig. 3 we show the relation between bore field and coil width for the main Nb-Ti accelerator magnets (operational field) and for some Nb₃Sn models. To be fair to the glorious Nb-Ti, for Nb₃Sn models 80% of the short sample is taken at 1.9 K. One finds that notwithstanding the different designs and the two superconducting materials, current density is typically around 400 A/mm² (see Fig. 4). Please note that for graded magnets one has two values corresponding to the densities in inner and outer layer, the outer being the larger value.

Fig. 3: Operational field versus coil size – dipoles (80% of short sample at 1.9 K for Nb₃Sn models and for Fresca facility).

Fig. 4: Operational overall current density versus coil size – dipoles (80% of short sample at 1.9 K for Nb₃Sn models and for Fresca facility).

Considering that the fraction of superconductor in an insulated coil can range from one third to one fourth, this means to have the superconductor operating at 1200 A/mm² - 1600 A/mm². Given the superconductor critical surfaces, this sets a natural limit of ~ 8 T for Nb-Ti and ~ 13 T for Nb₃Sn (see Fig. 1).

Critical current in Nb-Ti has been optimized since a long time and it has already reached the maximum limit. For Nb₃Sn there has been a considerable progress [12,13] in the past 10 years. With the present conductor performance, 13 T operational field is close to the limit. Using grading one could possibly reach 15 T with coil widths that are still within 80 mm.

In order to reach the level of 16 T one should improve the current density in that region (optimization has been focused

up to know in the 12-15 T region): a very ambitious target of 1500 A/mm² at 20 T would allow to get at 16 T operational field with a reasonable size of the coils.

If larger current densities cannot be obtained above 15 T, the alternative is to use lower current densities and larger coil, i.e., reduce the slope of the loadline of Fig. 1. An estimate of the operational field (with 20% margin) versus the coil size is given in Fig. 5, based on the scaling laws presented in [10]. If 40 mm coil gives 12.5 T operational field, doubling the coil width provides only two additional Tesla: the game becomes pretty expensive – with grading on can save about one third of conductor, but to get to operational fields of 15 T with present conductor performances looks at the limit (or probably slightly beyond the limit) of the Nb₃Sn technology.

Fig. 5: Operational field versus coil width for a 20% margin from critical surface.

In Fig. 6 and 7 we present the case of the quadrupoles. We plot the gradient versus the factor $\ln(1+w/r)$ since this is the term which is proportional to the gradient via the current density (see Eq. 2). The spread in the current density (Nb₃Sn models are again considered with 20% margin on 1.9 K short sample) is more relevant than in dipoles. In particular, the two Nb₃Sn magnets made by the LHC Accelerator Research Program (LARP) are in the range of 600-750 A/mm² (see Fig. 7). With a few exceptions, Nb-Ti operational current densities are in the range of 300 A/mm² to 500 A/mm². In general, Nb₃Sn coils provide about 50% larger gradient for the same aperture w. r. t. Nb-Ti [11].

Fig. 6: Operational gradient versus coil width – quadrupoles (80% of short sample at 1.9 K for Nb₃Sn models).

Fig. 7: Overall current density versus coil width – quadrupoles (80% of short sample at 1.9 K for Nb₃Sn models).

IV. FORCES, STRESS, STRAIN

Large current densities provide higher fields or more compact coils. But they induce higher stresses, and stress can be a major issue for two different reasons:

- For the Nb-Ti a soft limit is set by the damage of the insulation of the coil – present types of insulations can withstand up to 200 MPa, and LHC coils during collaring were compressed up to 150 MPa.
- For Nb₃Sn there is a hard limit which is the critical current degradation induced by strain. This limit has a strong dependence on the strand lay-out and fabrication: in some cases measurements have shown significant degradation already at the level of 50-100 MPa. The RRP, which is the workhorse of the LARP, has shown negligible degradation up to more than 150 MPa [14,15]. These measurements are particularly tricky since the real condition of stress of the cable in the magnet is hard to achieve in a sample. A few experiments on magnets, loaded with increasing stress, have shown negligible performance degradation up to 200 MPa [16]. Indeed, the larger stress is on the lower field regions and one should always be extremely careful in generalizing these results.

One can estimate the maximal stress in the midplane for a dipole sector coil according to the following equation [17]

$$\sigma \approx j^2 \frac{\mu_0 \sqrt{3}}{6\pi} \text{Max}_{\rho \in [r, r+w]} \left[2\rho^2 + \frac{r^3}{\rho} - 3\rho(r+w) \right] \quad (4)$$

The stress obviously scales with the square of the current, plus a geometric factor which is a function of the magnet aperture and of the coil width. If we compensate a lower current density with a larger coil width, it turns out that the geometric factor grows slower than j^2 : the same field obtained with a lower current density has a significantly lower stress. This is shown in Fig. 8, where the following estimate is carried out: for a given current density and operational field we compute the coil width to reach that field - Eq. (1) - we estimate the stress with Eq. (4). The LHC main dipole, having 70 MPa stress with 380-420 A/mm² current density, fits rather well with the estimate. The 400 A/mm² used in many magnets provides a field of 13 T with about 110 MPa, and 150 MPa at 16 T, which is still in the tolerable range. Increasing the current density one can reduce the coil size, but stress

becomes larger. For instance, if 200 MPa is considered as the ultimate limit, 400 A/mm² give a maximum field of ~20 T whereas with 700 A/mm² one stops at ~15 T. The dependence on the aperture is steep but not dramatic: doubling the aperture from 40 to 80 mm at 15 T induces an increase in the stress of about 50% from 120 to 180 MPa (see Fig. 9). Please note that these estimates should be used with a pinch of salt since they neglect the detail of the structure: they give an educated guess with a ~20% error, and, what is more precious, the trends with the dependence on the main parameters.

Fig. 8: Stress versus field for different current densities, and 56 mm aperture - dipoles.

Fig. 9: Stress versus field for different apertures, overall current density 450 A/mm² - dipoles.

In quadrupoles one has a similar equation, with a different geometric factor [18]

$$\sigma \approx j^2 \frac{\mu_0 \sqrt{3}}{16\pi} \text{Max}_{\rho \in [r, r+w]} \left[\rho^2 - \frac{r^4}{\rho^2} + 4\rho^2 \ln \left(\frac{r+w}{\rho} \right) \right] \quad (5)$$

but one has different results w.r.t. the dipole case. For a small aperture as the LHC arc quadrupole (56 mm), different current densities give very similar stresses (see Fig. 10). For larger apertures, lower current densities provide lower stresses, but without the large difference found in the dipole case (see Fig. 11 for the 120 mm case). In both figures we do not show data corresponding to coil widths larger than 100 mm: this is why the curves suddenly stop in some cases. We also added the working point of LHC MQ and LARP HQ, which fit reasonably well in our plot. For quadrupoles, stress is not

putting such a tight upper limit to the critical current density as for the dipoles.

Fig. 10: Stress versus gradient for different current densities, 56 mm aperture.

Fig. 11: Stress versus gradient for different current densities, 120 mm aperture – HQ has 600 A/mm² overall current density (see Fig. 7).

V. GRADING AND COST

Grading the current density, i.e. putting a high current density in the outer layer where the field is lower, is a well-known strategy. The main advantage is a considerable decrease of the amount of conductor needed for the outer layer, which brings a reduction in the coil size and in the cost. The drawback is that the stress is increased. Therefore for cases in which the stress is already at the limit, grading is not the right solution: grading looks more appealing for high gradient (or large aperture) quadrupoles than for high field dipoles.

The second possibility is *grading the material*. In this case the current density is kept constant, and the less performing material is placed in the low field region. The coil size is not reduced, but stress does not increase. This grading has a large impact on cost, since there is about a factor five between Nb-Ti and Nb₃Sn, and at least another factor five between Nb₃Sn and a possible HTS conductor for accelerator magnets (which is still under development). Grading the material is a must for a main dipole accelerator magnet above 10 T. This implies hybrid coils, i.e. developing a technology that allows to put together materials with different needs in terms of heat treatments, with different mechanical and thermal properties. Whereas this is done routinely for solenoids, little experience is present in this field: an hybrid Nb-Ti / Nb₃Sn magnet

showed that this option is viable but a careful ad hoc design of the structure is needed [19].

VI. THE CABLE: PROTECTION, HYSTERESIS, INSTABILITIES AND RAMP RATE

Having fixed the material, overall current density, and width of the coil, one has to choose the cable. The copper-non-copper ratio affects the overall current density, and has to be large enough to guarantee protection. Usually it ranges from 1 to 2 in most cases, i.e., 50% to 66% of copper in the strand. A larger quantity of copper also provides a larger energy margin.

The second crucial parameter is the strand diameter. Large strands allow larger cables carrying more current and reducing the inductance. On the other hand, smaller strands can be easier to wind. There is an upper limit to the number of strands and the strand diameter present in a cable – typically 40-50 is already large. Finally, the strand diameter also plays a relevant role for the self-field instabilities, larger diameter strands being less stable [20].

The third relevant parameter is the filament size. If for the strand diameter one has pro and cons for both large and small strands, and the same is for the choice of the copper/non copper ratio, in the case of the filament size the receipt is simple: make it as small as possible. There are a number of different physical effects which scale with the filament size, mainly (i) magnetization, giving a relevant change of transfer function and multipoles difference between injection and high field currents, and (ii) instabilities, limiting quench performance. The first aspect can be less critical for magnets which are dominant only at high field, as the final focus quadrupoles, but the second one is a severe showstopper that blocked a research program for a few years (see HFD01-3 in Fig. 12, [21]): when a new strand with smaller diameter and filament has been adopted the instabilities were cured (see HFD05-7 in Fig. 12).

For the Nb-Ti magnets a size of 5-7 μm can be routinely achieved. On the other hand, Nb₃Sn is still one order of magnitude away from this ambitious target.

Fig. 12: Filament size versus filament diameter.

The last issue we want to briefly outline is the interstrand resistance. This parameter is related to ramp rate effects induced by current loops in the cable, and in Nb-Ti magnets this can be kept high through oxidizing the strand. This procedure cannot be used for Nb₃Sn: a possible solution is to insert a resistive core in the cable - this allows to control

interstrand resistance, breaking the loops. Little experience has been acquired on winding cored cables, even though the few results are encouraging [22]. Cored cables have shown to be effective also for avoiding a degradation of performance with high ramp rates.

VII. TOWARDS 20 T

The above considerations suggest that to move towards a 20 T operational field one needs an HTS superconductor:

- Able of carrying 400 A/mm^2 overall current density in operational conditions above 20 T;
- Without significant stress degradation up to 200 MPa (or larger ...);
- With a filament size of the order of $10 \text{ }\mu\text{m}$;
- Available in Rutherford cable; this last requirement is controversial since one could explore other possibilities (for instance, Roebel cable).

Today Bi-2122 is below of at least a factor two for current density, is available in Rutherford cables but has a large degradation with strain (see Fig. 14). The alternative YBCCO has a much larger current density and a good resistance to stress but it is not available in cables. In both cases the price is also a major issue. Having long cable lengths is also an important manufacturing issue.

Fig. 13: Critical current in the superconductor [23].

VIII. PERFORMANCE

In Fig. 14 we summarize the performance of the Nb-Ti and Nb₃Sn dipoles, plus the Nb₃Sn quadrupoles made for the LARP. We plot the maximum achieved peak field in the coil after training, allowing a direct comparison between dipoles and quadrupoles, and a guess percentage of short sample reached. Remember that this field is not usable, since it is in the coil. The comparison is not totally fair since some magnets have been tested at 1.9 K, and others only around 4 K. Anyway, Nb₃Sn clearly proves its potential to overcome the 10 T barriers and to reach 15 T in the coil.

The criteria to judge the performance of a magnet are always widely debated. We report the opinion of a recent discussion triggered by the LHC upgrade [24], stating that a good performance is given by three factors:

- Rapidly reaching nominal (without or with one quench);
- Showing the ability to reach maximum performance, (90% of short sample with “a few” quenches);

- Showing the ability of keeping the training (no quenches after a thermal cycle to reach nominal).

These are criteria for magnets which are present in the accelerator in several tens of units: the criteria can be relaxed if one has only a few units in the machine, i.e. one can withstand some training after installation.

Nb₃Sn made impressive progress in the past years but there are still some issues, namely

- In general, a longer training w.r.t. Nb-Ti in the range 80-90% of short sample;
- In many cases the additional 10% provided by 1.9 K w.r.t. 4.2 K is not reached, or it is only partially reached. Instabilities are considered as the main source, and smaller filament size and high residual resistivity ratio should help in reducing them.
- The scaling in length from 1 m to 3.4 m has been proven on one magnet [25], but more statistics and experience should be gathered. Longer lengths make some aspects of coil manufacturing much more critical – in particular all issues related to thermal contraction and different mechanical properties of the different materials. Finally, another factor three is needed to go from 3.4 to 10 m.

Exciting research programs with ambitious goals are set in in the US, Europe and Japan for this decade, the LHC luminosity upgrade [26] being the major testbench for the application of these technologies. In a few years the community will be able to establish if magnets in the range of 10-15 T can operate in an accelerator, and if there is hope to approach the 20 T.

Fig. 14: Peak field in the coil reached after training, and estimate of the fraction w. r. t. short sample.

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