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SUPERCONDUCTING ACCELERATOR MAGNETS: A REVIEW OF THEIR DESIGN AND TRAINING*

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ABSTRACT

This paper reviews the basic mechanical designs of most of the superconducting magnets developed for high energy hadron accelerators. The training performance of these magnets is compared with an instability factor defined by the square of the current density in the stabilizing copper divided by the surface-to-volume ratio of the strands. A good correlation is observed.

QUENCHING

Almost all accelerator magnets have been built with *Rutherford Cable*. This cable was developed by Wilson et al at Rutherford Laboratory. The cable is formed of strands, each of which is made of many fine (6-15 microns) filaments of superconductor and a significant cross section of pure copper. A number n_s of these strands are formed into a flattened cable. A twist is introduced, so that the strands pass up one side at a finite angle, roll over the top and pass down the other side, passing diagonally over the strands on the first side. The cable is compressed and formed to precise dimensions. The cable is then wrapped with an insulating film—such as kapton—and, after winding into a coil, is bonded with epoxy glass or other glue to form a compact, high-strength composite.

When a magnet is energized, the Lorentz forces cause deflections and motion. With friction and/or weak glued bonds, some of this motion will be sudden and release pulses of heat. If such pulses raise the temperature of the superconductor above its critical value then the superconductor will become resistive, current will be shunted through the copper, and ohmic heating will result. In competition with this, heat will be taken away by conduction down the strands, across to neighboring strands, and into the helium. If the cooling is sufficient, then the local temperature will subside and no quench will occur. If not, the heated region spreads and there is a quench.

The kapton insulation surrounding each cable is a good thermal insulator. It follows that the motions causing quenches can be divided into two classes:

1. Those motions occurring in the bulk coil or support structure. These motions may release large amounts of energy, but will heat the superconductor only slowly (msecs) and over large areas (cms). The combination of the good thermal insulation of the kapton with the good temperature stabilization provided by the helium implies that only relatively large motions should cause quenches. Good engineering should be able to eliminate such motions.
2. Those motions due to strand motion within a cable. These will release far less energy, but will be seen on a fast time scale (microsec) and over relatively short lengths (mm). Examination of the cross sections of a coil reveals, particularly in the inner layer, occasional hair gaps (typically up to 25 microns) between two

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strands. Under the influence of radial Lorentz forces, such gaps could allow a strand to move outward, closing the gap and releasing local energy. It is hard to believe that such gaps could be entirely eliminated.

TRAINING

Because of friction, the sudden motion that caused a quench may not be reversed when the current in the magnet is dropped. If it is powered again, it will not then quench until a higher field is reached, and the higher Lorentz forces cause some different motion to occur. After some number n_q of quenches, all such motions will have occurred, and the maximum field will be limited only by the local current-carrying capacity of the cable (conductor limited quench). Most magnets seem to behave in this way. Some poor magnets never reach their short sample limits: the motions are presumably not held by friction when the current drops, and are repeated on the next cycle at the same field. Very good magnets reach their conductor limit on the first and all quenches.

It is important to remember that, because the critical current is a soft boundary (resistance rising as about the 20th power of the current), a magnet can be stable even when there is negligible thermal margin. If this were otherwise, it would be impossible to attain a *conductor limit;* magnets would train only exponentially towards such a limit.

The copper must temporarily carry most of the current during a local heat pulse. Thus the ratio R_{Cu} of the total cross sections of copper to that of the superconductor is an important parameter. But for the purposes of calculating stability, one must subtract the ratio R_m of copper present within the fine matrix of filaments. In this matrix, the dimensions of the copper are usually smaller than either the phonon or electron mean-free paths and, in addition, the copper is probably poisoned by diffusion from the superconductor. The rate of heating after the superconductor is normal will thus be approximately proportional to j^2_{Cu}, where j_{Cu}—being the current density in the nonmatrix copper—is

$$j_{Cu} = \frac{I}{\pi r_s^2} \left(\frac{1+R_{Cu}}{R_{Cu}-R_m}\right) .$$

If heat transfer to helium is the dominant cooling mechanism, then the stability will be dependent on a parameter α given by

$$\alpha = \frac{j^2_{Cu}}{R_{s/v}} ,$$

where $R_{s/v}$ is the ratio of strand surface to the volume of copper heated by ohmic loss, assuming that the fraction of strand surface exposed to helium is approximately constant. $R_{s/v}$ is

$$R_{s/v} = \frac{4}{d_s} \left(\frac{1+R_{Cu}}{R_{Cu}-R_m}\right) .$$

Simple calculations of heat transfer to helium do not predict a dominant role for helium cooling. These calculations sometimes ignore the transient nature of the process, and also ignore flow and turbulence due to the pressure gradients and the initial rapid motion that induced the heating. In any case, the data seem best fitted with the assumption that the helium is playing a leading role.

MAGNET DESIGNS

Tevatron

The first successful use of superconducting magnets for the main bending magnets of an accelerator was in the Tevatron at Fermi National Accelerator Lab (FNAL). The magnets used Rutherford cable in two layers, with no breaks (wedges) in those layers. There was no longitudinal support of the coil ends. Transversely, the conductor was held by stainless steel collars of only moderate stiffness, whose primary design requirement was to apply significant azimuthal *prestress* to the coil. The thermal insulation was introduced immediately outside the collars, with the Iron Yoke at room temperature. See Figure 1(a).

The average number of training quenches to reach the conductor limit was not compiled (when the required field was achieved, the magnets were inserted without further training), but it is remembered that when magnets were trained to maximum field, the number of quenches was of the order of 4.

Isabelle

At the same time that the Tevatron magnets were being developed with Rutherford cable at FNAL, Brookhaven National Laboratory (BNL) was still developing magnets for the Isabelle project using a single layer of a wide solder-filled braid. The training of these magnets was bad, with typically 40 quenches required. There seem to have been several reasons for this:

- due to the solder, there was no local cooling of the strands;
- in addition, there were no end constraints; and
- the copper-to-superconductor ratio was low (down to 1.1:1), and thus the current density in the copper was high.

The Isabelle magnet was the last attempt to use anything other than a Rutherford Cable for accelerator magnets, but the design did introduced two concepts that have since been widely adopted [see Figure 1(b)]:

1. They allowed the Iron Yoke to be at the same temperature as the conductor, and placed the thermal insulation outside the yoke. This practice, which allows more insulation and multiple heat shields, can drastically reduce the heat losses.
2. They used the yoke itself to support the coil, with only insulated spacers between coil and yoke. Since a yoke is far more rigid than any collar, this provides a stiffer radial support for the coil.

HERA

HERA followed the Tevatron in their use of the cable, two layers with no wedges, a collar to hold the conductors, and no end constraints. But they followed Isabelle in using a cold yoke. The coils were not, however, supported by the yoke, but rather by collars held freely just inside the yoke [see Figure 1(c)]. The main innovation was using aluminum collars whose thermal coefficient was a better match to that of the coil composite. As a result, the prestress does not fall as the magnet is cooled, and a higher final prestress can be achieved. Their collars also had a far stiffer cross section than those in the Tevatron.

The training characteristics were very good, with half the magnets reaching the conductor limit at the first quench. We take the average number n_q as 0.5.

UNK

The magnets developed at Protvino for the 2 TeV UNK project are very similar to the HERA magnets, except that the collars are made of stainless steel. They thus represent a concept intermediate between the Tevatron and HERA designs.

CBA

At Brookhaven, the Isabelle project was renamed the Colliding Beam Accelerator (CBA), and the magnets were redesigned. The new magnets used two layers of the Tevatron cable, but supported them directly on the cold-iron yoke. Two new innovations were introduced [Figure 1(d) shows the two-in-one version]:

1. Both inner and outer coil layers were broken into blocks, and copper wedges were used to space these blocks, and thus improve the field quality.
2. Coil end constraints were provided, and significant initial end load was applied. The HERA experience shows that this is not necessary when the collared coil is free to extend, but when the coil is supported by the yoke, which cannot extend, then the coil should be constrained to avoid longitudinal slipping between the coil and its supports. The magnets, both short and long, initially showed very little training ($n_q \approx 0.5$). It is interesting to note that a later sequence of magnets had worse training, which was traced to a batch of partially pre-cured epoxy: a reminder of how easy it is to make poor magnets.

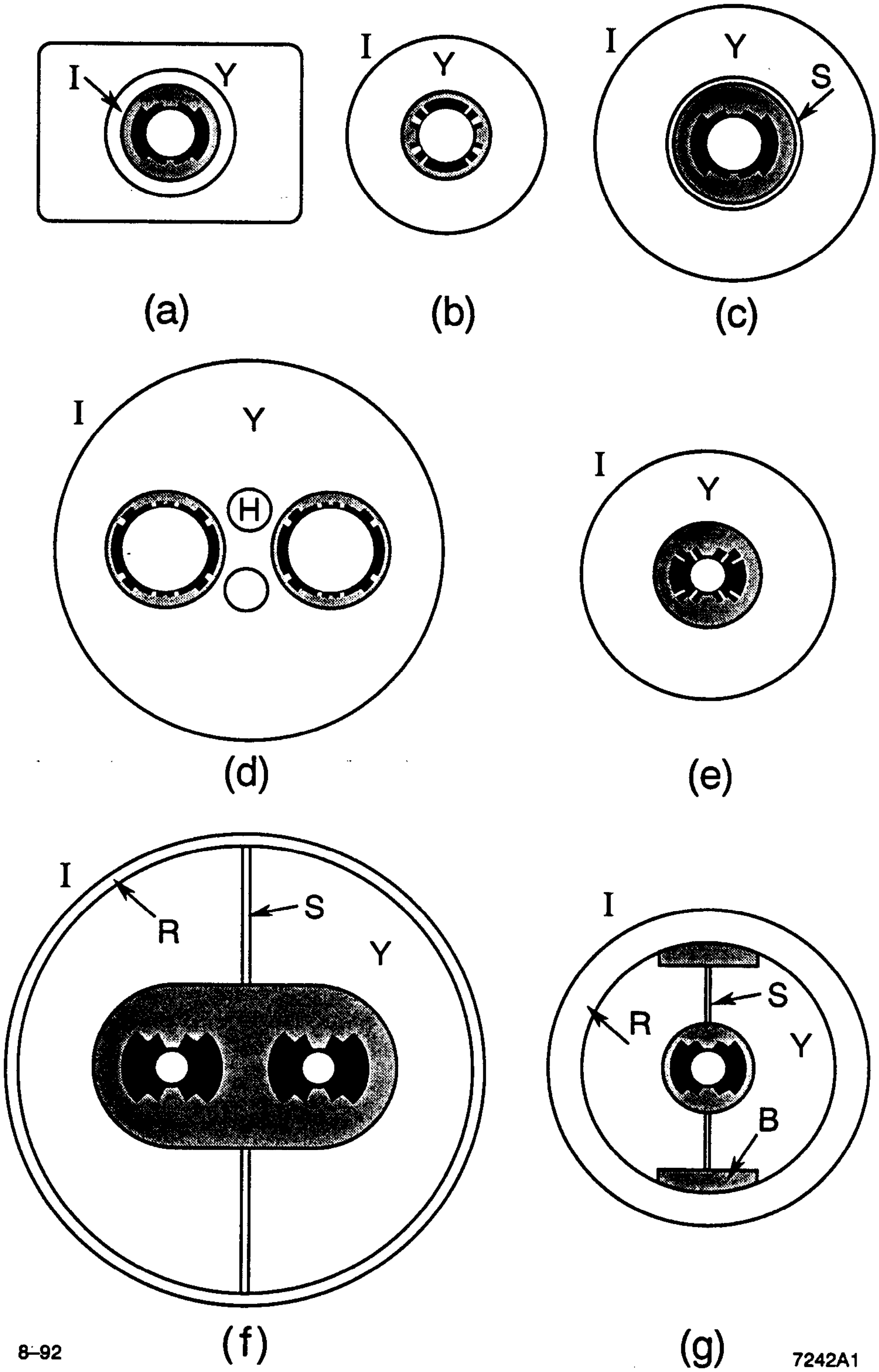

Figure 1. Magnet conceptual designs: (a) Tevatron; (b) RHIC; (c) HERA; (d) CBA Two-in-one (e) SSC; (f) LHC; (g) LBL's D19. Black areas are the coil cross sections, shaded areas are the collars or support spacers, I = thermal insulation, Y = yoke, S = space, B=block, R=ring.

CBA two-in-one

Three tests were made of CBA magnets, with two side-by-side coils in the same yoke [Figure 1(d)]. They worked essentially the same as the single bore magnets.

RHIC

The Relativistic Heavy Ion Collider (RHIC) is now under construction in the Isabelle/CBA/RHIC tunnel. The field requirement for this accelerator is less than for the CBA and has been met by a single layer of Rutherford Cable. The observed training is somewhat worse than that of the CBA magnets ($n_q \approx 1.5$).

SSC

The design of the early 4 cm SSC magnet was much like that of an UNK magnet, but with a somewhat wider cable and a smaller copper-to-superconductor ratio (1.3:1 on the inner layer). The short magnets behaved allright, but the longer versions trained badly ($n_q \approx 20$). The problems were solved in two stages:

- First, by designing the collars to have a line fit with the yoke ([Figure1(e)], the collars were supported by the yoke. Since longitudinal motion was now impeded, the ends were constrained. The training was greatly improved ($n_q \approx 3$), but the margin between the required and the conductor limited fields was still uncomfortably small.
- Second, at the same time that the aperture was increased to 5 cm, the cable was widened and the copper-to-superconductor ratio improved to 1.5:1 on the inner layer. The training was further improved ($n_q \approx 1$), and an adequate margin achieved.

A basic problem with any magnet whose coil is supported by a fixed iron yoke is that the prestress falls as the magnet is cooled. If a significant stress is required at a design field of around 7 Tesla, then very high stresses, and consequent concern about shorts, are required in the magnet when warm. In practice, most of the SSC prototype magnets do not have such high prestress and, at their short-sample limited fields, they have no remaining prestress—yet they show little or no training. A 4 cm SSC magnet with good prestress was taken apart and reassembled with essentially no prestress. When retested, it had no training whatever. It is thus clear that prestress is not always required.

Four two-in-one 4.5 m long, 3.2 cm diameter, SSC prototypes were also made and all worked well with little training.

LHC

Five short prototype R and D magnets have been made at CERN for the Large Hadron Collider (LHC). Magnets for that machine will be required, from space considerations to be in the two-in-one configuration. To achieve a high field, they will operate at 1.8 degrees. The prototypes use a wide cable made from thick (1.3 mm) diameter strands (compare with SSC's .8 mm).

In order to maintain significant prestress at such a high field, aluminum collars were used, supported by the yoke. To do this, despite the differences in thermal coefficients, required an innovation: the yoke was split, and designed to be slightly open at room temperature. When cooled, the yoke closed, following the shrinking collar, driven by the contraction of the tube in which the yoke is enclosed. See Figure 1(f).

The five R and D magnets were made in different institutions and with some variations in detail, but all to this basic design. All show poor training. One magnet achieved 10 Tesla, but only after about 40 training quenches.

D19

This short R&D magnet was built and tested at LBL. The magnet was operated at 1.8 degrees and employed, with a small variation, the same opening split-yoke design used for LHC. Unlike the LHC magnet, however, this magnet [Figure 1(g)] had

- standard SSC cable with strands of a more normal size;

Table 1. Parameters of accelerator magnets. I_q = approximate average conductor limited current; B_q = average short sample central field. For the inner layer: B_{mx} = local maximum field on conductors; n_s = number of strands; d_s = diameter of strands; R_{Cu} = copper-to-superconductor ratio; j_{Cu} = current density in nonmatrix copper; α = instability factor defined in text; and n_q = approximate average number of quenches to reach conductor limit.

	len	bore	T	I_q	B_q	B_{mx}	n_s	d_s	R_{Cu}	j_{Cu}	α	n_q
	m	cm	deg	A	T	T	mm	d_s	A/mm^2	kA^2/mm^3		
Tevatron	6.1	7.6	4.8	4840	4.8	5.4	23	0.68	1.8	1248	.12	4
HERA	8.8	7.5	4.5	6400	5.9	6.2	24	0.84	1.8	1036	.1	0.5
Isabelle	4.5	13.0	4.6	4625	5.0	5.7	96	0.30	1.2	2142	.29*	40
CBA	4.5	13.0	4.6	4100	5.3	5.5	23	0.68	1.8	1057	.09	0.5
RHIC	9.5	8.0	4.6	7500	4.6	5.2	30	0.65	2.2	1427	.18	1.5
SSC4	15.2	4.0	4.4	6700	6.7	7.0	23	0.81	1.3	1633	.19	3
SSC5	15.2	5.0	4.4	7300	7.3	7.7	30	0.81	1.5	1186	.11	1
LHC	1.0	5.0	1.8	15090	10.0	10.3	26	1.29	1.6	1050	.15	40
LHC	1.0	5.0	4.2	11930	8.1	8.4	26	1.29	1.6	830	.09	5
D19	1.0	5.0	1.8	9800	10.1	10.6	30	0.81	1.5	1593	.2	8
D19	1.0	5.0	4.2	6910	7.6	8.0	30	0.81	1.5	1123	.1	1
SSC quad	5.2	4.0	4.4	8400	-	6.5	30	0.65	1.8	1829	.25	8

* Since the Isabelle braid was solder filled, α was calculated using the cable thickness (.8 mm) in place of the strand diameter d_s for the surface-to-volume ratio.

- a very slim collar—if it is to be supported on the sturdy yoke, why make it stiff;
- an oval shape to the inside bore of the yoke, to correct field distortion from the strong saturation of the iron.

Surprisingly, in view of the LHC results, the D19 magnet achieved 10 Tesla with little training (none on the first cool-down, two on the second at 4.35 degrees, eight quenches over two cool-downs, starting at 9.5 Tesla, to reach 10 Tesla at 1–8 degrees).

The only obvious difference between the LHC and the D19 magnets is the use of such thick strand in the LHC.

SUMMARY

Table 1 summarizes selected characteristics and training performance of the magnet designs referred to above. In addition, the characteristics of the SSC quadrupoles are included. The stability parameters are given for the inner layers only, since almost all training quenches were observed in these layers.

In Figure 2, the log of the number of quenches n_q is plotted against the instability factor α defined above. Data for well-engineered magnets with no known problems are given as black discs. The open discs refer to magnets in early development, and/or with known defects. Since the Isabelle braid was solder filled, α was calculated using the cable thickness (.8 mm) in place of the strand diameter d_s for the surface-to-volume ratio. The crosses represent training data from tests of short samples of SSC cable with different copper-to-superconductor ratios.

We note that all the data for well-engineered magnets fall, within errors, on a line whose slope indicates an approximate dependence

$$n_q \approx \left(\frac{\alpha}{0.12\ \mathrm{kA^2/mm^3}}\right)^{2.5} .$$

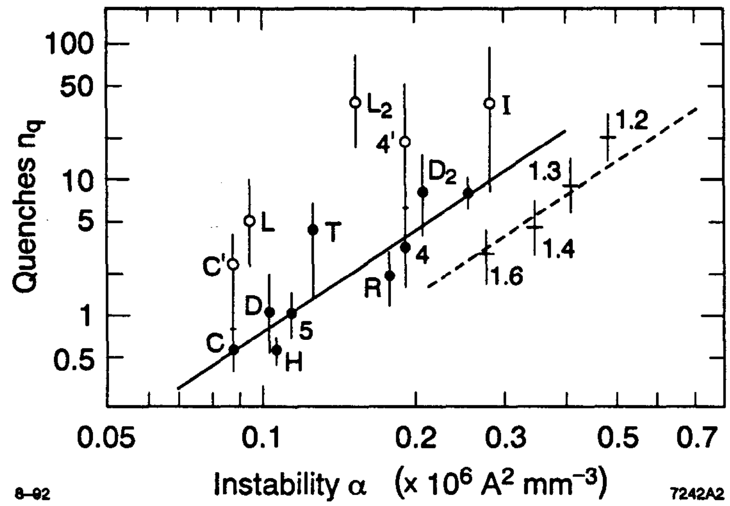

Figure 2. Plot of the number of training quenches versus the instability factor α, as defined in the text, for magnets from : (T) Tevatron; (H) HERA; (C) CBA; (D) DESY; (I) Isabelle; (R) RHIC; (4) SSC, 4 cm; (5) SSC, 5 cm; (Q) SSC, quads; (L) LHC; 1.2, 1.3, 1.4, 1.6 SSC cables with those Cu/sc ratios. When primed, the data refer to early prototypes or magnets with problems. When given a subscrip of 2, the data refer to tests at 1.8°.

Data for the cable tests would not be expected to lie on the same line—the conditions are too different—but they are seen to have the same slope, indicating that the mechanism of the training is probably the same.

The data for development magnets lie, as expected, in a broad band above that of the well-engineered magnets.

The good correlation between training and the single parameter α is remarkable in that it indicates only weak dependence on magnetic field (4–10 Teslas), temperature (1.8–4.8 degrees), helium pressure (1–3 atmospheres), prestress (0–700 atmospheres), thermal margin (0–2 degrees), and magnet/cable length. This is not understood, but suggests a larger role for cooling to helium than is predicted by simple models.

The relatively poor training of the LHC prototypes is also not understood. They appear to be well engineered, yet, when their training is plotted against α, it lies above that of all other magnets. The most reasonable explanation is the existence of a further strand-diameter dependence. This could arise from inductance effects, from mechanical effects within the cable, or from effects tending to leave larger strand-to-strand gaps; for example, difficulties making ends and the inability to use adequate winding tension. Since all the other data is for strand diameters within a relatively narrow range (0.65–0.85 mm compared with 1.29 mm for LHC), an additional strand-diameter dependence would not be shown by this data without that of the LHC.

CONCLUSION

There appears a good correlation between magnet (and cable) training with the current density in the stabilizing copper divided by the surface-to-volume ratio of the stands. The LHC data suggests an additional dependence of training on strand diameter.

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