SUPERCONDUCTIVITY AND FUTURE ACCELERATORS

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Introduction

For 50 years particle accelerators employing accelerating cavities and deflecting magnets have been developed at a prodigious rate. New accelerator concepts and hardware ensembles have yielded great improvements in performance and GeV/\$. The "great idea" for collective acceleration resulting from intense auxiliary charged particle beams or laser light may or may not be just around the corner. In its absence, superconductivity (SC) applied both to r.f. cavities and to magnets opened up the potential for very large accelerators without excessive energy consumption and with other economies, even with the C.W. operation desirable for colliding beams. HEP has aggressively pioneered this new technology: the Fermilab single ring 1 TeV accelerator - 2 TeV collider is near the testing stage. Brookhaven National Laboratory's high luminosity pp 2 ring 800 GeV CBA collider is well into construction. Other types of superconducting projects are in the planning stage with much background R&D accomplished.

The next generation of hadron colliders under discussion involves perhaps a 20 TeV ring (or rings) with 40 TeV CM energy. This is a very large machine: even if the highest practical field B \sim 10T is used, the radius is 10x that of the Fermilab accelerator. An extreme effort to get maximum GeV/\$ may be crucial even for serious consideration of funding.

Possible Economies of Scale

- 1. A 20 TeV ring will most efficiently utilize a \$\(\) 1 TeV injector. As a result even for quite high luminosities a very small aperture is, in principle, sufficient to contain the necessary phase space. Magnet costs are approximately linearly proportional to aperture so this has potential for great savings. There is a major caviet on this however: serious questions on beam image currents and cavity resonant effects of a very small pipe must be considered. Storage rings require great precision and especially stability of operation in the presence of beam-beam forces, etc. Precision in small magnets is generally harder to obtain. All these questions will have to be studied in detail to arrive at reasonable compromises.
- 2. SC magnets require relatively complex vacuum insulation "packaging". As a result of this and other end effects "3D" costs tend to be large compared to "2D" costs. At Fermilab (1 TeV) and BNL short magnets (quads) when finally installed cost a major fraction of the cost of the much longer dipoles. For a 20 TeV ring, ν will increase by $\nu \sim \sqrt{R}$: each half cell will be several hundred feet long. Very long units are possible, reducing the number of magnets and especially of dewars. If one can learn to make simply very long magnets, the cost per meter could decrease substantially.
- 3. A partial payback for the complexity of a sealed, vacuum insulated envelope for a SC machine is that in principle services in the machine tunnel can be $\frac{1}{2} \int_{-\infty}^{\infty} \frac{1}{2} \left(\frac{1}{2} \int_{-\infty}^{\infty} \frac{1}{2} \left$

minimal, thereby perhaps reducing tunnel costs significantly. A study group at Aspen considered a tunnel of ~ 6 feet diameter containing two 10T magnet rings on either side of a robot, and also a 3 foot diameter "tunnel" or underground pipe version attributed to R. Wilson, containing two 2.5 T magnet rings and a robot.

High Field versus Low Field

- 1. Accelerator design favors small R and large B. At 20 TeV synchroton radiation is a factor favoring low B unless the radiation is screened from the cryogenic environment which may not be easy.
- 2. Present highly developed magnets mostly operate to 5 \pm 1T with Fe contributing 1 to 2T. Tevatron magnets cost ~40K\$,\frac{1}{2} or 2K\$/foot. The SC wire costs 500\$/ft. Total material and labor costs were ~ equal, which is reasonable. For comparison the projected 20 TeV tunnel costs\frac{1}{2} are ~300\$/ft. Even if somewhat more conservative tunnel costs are used, this puts in perspective the importance of magnet costs.
- 3. Experimental magnets for B=10T require superfluid He operation or more advanced superconductors. The cross section of SC and structural materials scale basically as B^2 . In practice the scaling is more rapid than B^2 . Even for a relatively large aperture design the coil cross section will itself appreciably increase the magnet size for B=10T: greater performance per unit cost of SC materials and simply constructed structures are very important.
- 4. Table I illustrates magnet SC requirements, comparing Fe dominated 2.5T with air core $\cos\,\theta$ magnets. For brevity it ignores mixed cases: 10T $\cos \theta$ magnets can pick up 1 to 2T "free" with imaging Fe. Column II lists the volume of SC for poled Fe magnets of vertical gap g=3, 6 and 10 cm. This applies for B \lesssim 2.5T (presaturation) independent of the ratio of aperture gap to width g/w. Columns III through VI apply for various coil thickness Ar (independent of aperture d). Column III shows that for very thin shells, an air core magnet needs twice the volume of SC (but no saturation). Columns V and VI are typical of 5T and 10T magnets respectively. Note that for large magnets (d=10 cm) and $\Delta r=1.2$ cm, typical of most present ~5T magnets, the inefficiency factor for shell thickness is modest. However for small magnets and high B the problem is severe. In the extreme case of d=3 cm, vol. SC 10T/ 2.5T = 18x. For d=6 cm, the volume ratio is 13.3x. Even including imaging Fe the ratio of required total SC volume is at least 10 times higher for 10T magnets. Table 1 makes a strong point. It is emphasized that no firm conclusions can be drawn without absolute costs applied to all factors of the accelerator designs. Parametric exercises usually reveal flat minima of B versus costs. The difficult future question to resolve is are low B magnets systems "simple" to build and operate compared to "complex" high B systems? Even if the question is resolved in favor of low B magnets where land is cheap and easy to construct in, there will still be circumstances where high B is favored, including insertion in existing tunnels.
- 5. Refrigerator power can be kept acceptably low with intermediate heat stationing for either high or low B

^{*}Work performed under the auspices of the U.S. Department of Energy.

magnets. The total cold surface area (diameter times length) is almost independent of B. However, the low B magnets are much lighter to support.

6. In summation, many people recognize there are many unresolved questions in defining a magnet system for 20 TeV. This subject received considerable attention at the 1982 DPF Workshop. The present authors have extensive experience with the development of simple Fe dominated low B superconducting magnets as well as with promising very high B designs. We will outline some relevant features.

Cold Fe Window Frame Magnets

The authors developed small aperture, precision cold Fe magnets before the development of multistrand SC. The early work was done with a 1" x 1" aperture (Fig. 1) and also with a 2" x 2" aperture magnet using a variety of coils. Pure Al conductors first were used in the form of ribbons parallel to B. Nb₃ Sn ribbon stabilized with pure Al was also used and of course rectangular multistrand NbTi. Pure Al coils give a large overall power reduction: 2 although Al is not competitive with SC for dc operation this early work revealed many features still relevant.

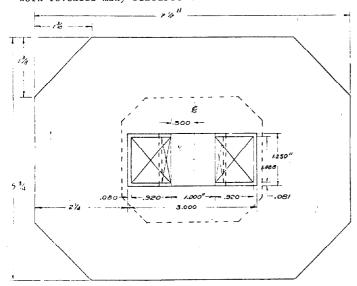


Fig. 1. Early small aperture test model magnet. The O.D. of 7.5" was designed for 4T testing. The dotted lines superimposed show the very small size of a 2.5T version with modern SC.

- 1. Until hard saturation sets in, boundary conditions produce only vertical field in the coil. This greatly reduces sensitivity to eddy currents as well as to magnetization in the case of SC. Vertically elongated conductors are permitted. Even wide conductors are permitted since eddy currents simply produce variation in J with x, not horizontal Bx fields. Magnetization and remanent field in the SC also do not produce Bx fields; the flux returns through the Fe yoke not the aperture region. This is very relevant to field tolerances if one contemplates using coarse high current conductors. We consider such magnets as rectangular solenoidal current sheets with surrounding image Fe. This emphasizes that one wants a single coil block (Fig. 1). Coils discontinuities at the HMP are most serious for field errors; a very difficult problem to control in small magnets.
- 2. Magnet steel has very good thermal conductivity. Pure Al has very large thermal and electrical conductivity, leading to enormous stability. This combinantion plus the heat transfer and enthalpy capacity of

the cryogen lead to thermal <u>flywheeling</u> whereby heat is exchanged efficiently throughout the entire cold volume.² We attempt to retain this feature in our magnets. Great stability will be very important to simple, reliable systems.

- 3. It should be noted that the coil and Fe area in Fig. 1 is excessive for 2.5T. These models and later versions operated to > 4T, using a sextupole correction coil at high fields. For a modern SC single layer coil and 2.5T operation, the size would shrink to ~ one half.
- 4. Above 2.5T. such magnets produce saturation of B/I, sextupole, etc., which grows linearly with incremental field. For high field versions we have increased the ratio of aperture gap height to width g/w from 1 to ~2, reducing saturation and aiding correction. In practice the inefficiency of the larger gap is quite comparable with that of round cosine θ magnets. The advantages of the simple rectangular solenoidal design are retained. Recent very high B designs have modified Fe shape to essentially eliminate saturation. No correcting coil is needed: a series powered Helmholz-like winding corrects field shape at all fields. However, the simplicity of having Bx=0 everywhere in the coil region below 2.5T has been lost. A recent magnet was tested to B=7T.3 This magnet operated to short sample with a very high coil current density: J=58kA/cm2 overall and $J=130kA/cm^2$ in the SC at B=6.7T in boiling helium. The use of pure Al produces ultrastable operation: without quench protection or energy extraction means the coil remains at or below LN₂ temperature. Field quality was extremely good, as in all magnets of this type built. The rectangular solenoidal design has lower integrated stress levels than round magnets, making it attractive for B=10T. (See Fig. 2.) With superfluid helium facilities we are confident that such a magnet is quite practical. Advanced conductors have great potential but are more of a development project.

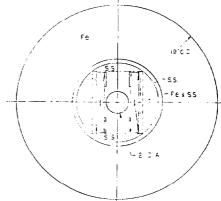


Fig. 2. Conceptual Cross Section of 10T dipole magnet.

Comments on 20 TeV Accelerator Magnetic Design

l. For 20 TeV, the economic motivation to study use of small apertures is especially strong. B=10T magnets suitable for mass production are generally believed to be about the limit because of large forces. Once established, 10T designs will be compared with existing > 5T designs. Within the range where a design works well, the cost per unit of Bp has a broad minimum with the highest B slightly more expensive. When total project costs are included, the highest B is attractive. This does not mean however that all designs have the same cost curve. Where flat and sandy terrain is available, for even conventional tunnels it is possible that 10T designs will always be

expensive. Even if true, the R&D on $10T\ may$ impact favorably on costs of 5 to 7T designs.

- 2. The viability of very cheap design using small low B, so-called "superferric" magnets depends on low magnet system construction costs and on very low tunnel costs. The magnet in a (3-ft.) pipe concept1 would rely on "Man-holes" at each quadrupole to provide access to machine functions. If very long dipoles needed repair they would be excavated. Simplicity and cryostability would seem to be very important to this concept. Another unconventional unmanned "tunnel" concept would be a simple monorail suspension allowing insertion and removal of a "cable car" magnet from a very small pipe. The magnet hangs from the rail which is incorporated into the pipe seam weld. Gravitational self alignment of the critical tolerance, rotation about the beam axis, occurs. Hydraulic damping using oil or water stabilizes the suspension. 10% of the circumference would have larger normal size tunnels wherein magnet strings could be stacked horizontally and vertically. All assembly and repair would be done here.
- A more conservative design is to use a minimal $2\ \mathrm{m}$ tunnel with human access. Small magnets can be suspended side by side on either side of the tunnel, or else on the same side in a common dewar. Another approach taken from an early paper4 that we favor has two 2.5T magnet apertures located in the vertical plane in a common Fe and dewar structure. (See Fig. 3.) Standard saddle type coils in each aperture allow completely independent excitation $\underline{\text{without}}$ coupling of the separate magnet fields. Alternatively they can be powered as a single magnet by the use of two vertically oriented racetrack coils. The top of each coil threads the top aperture and the bottom threads the lower aperture. For very long magnets such racetrack winding seems attractive. The 100% inductive coupling (one magnet) may have advantages for stability and the beam-beam interaction, behaving more like a single pp ring. This may be especially important with vertical arrangement of the two rings (no differential radial jitter). A small double magnet in a common cryostat would permit easy access even in a 2-m tunnel. A variation is to use two open C-magnets with warm Fe, one directly above the other stamped as one piece. A single current carrying "transfer line" is located inside each C-magnet. Each acts as return for the other. These magnets would be considerably larger than the cold Fe versions, but should be considered.

4. A "coffin" type cryostat seems highly desirable for very long magnets wound in place. The central portion of the magnet can be suspended at many points below the top plate as a winding mandrel for the two coils. After winding the remaining Fe is attached, supporting the coil. Preformed "tailored" insulation and the heat shield are already in the vacuum box, with mating pieces on the top plate. This insulation technique has been successfully demonstrated.

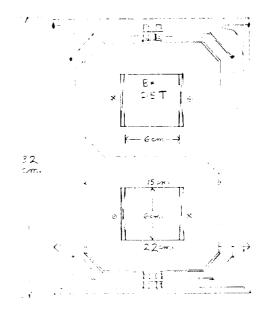


Fig. 3. Double aperture 2.5T magnet. (6 cm x 6 cm aperture)

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- J. Allinger et al; Proc. Applied Superconducting Conference, Oakbrook (1974).
- 5. B. DeVito, private communication (1980).

TABLE 1.	Total	Volume	of	SC	Required	versus	Magr	ıet	Parame	ete	ers≠		
							High	В	cosine	θ	air	core	magnet

Aperture Diameter		Low B Fe pole Magnet*	(no Fe) Ar is SC coil thickness					
d=2r for co Gap g for	s θ magnet.	bon b to posts region	$\begin{array}{c} \Delta r = 0 \\ (J \rightarrow \infty) \end{array}$	Δr=0.6 cm	Δr=1.2cm	∆r=4 cm		
I		II	111	IV	ν	VI		
10	cm	10xB	20xB	(1.06x20)B	(1.12x20)B	(1.4x20)B		
6	cm	6 x B	12xB	(1.1x12)B	(1.2x12)B	(1.67x12)B		
3	cm	3 x B	6xB	(1.2x6)B	(1.40x6)B	(2.33x6)B		

Volume in relative units.

SC vol/TeV \propto SC cross section x total mag length \propto NI x Bx $\frac{1}{2}$ \propto NI B

^{*} This has been named superferric at Fermilab.