SUMMARY OF IDEAS FOR A SUPERCONDUCTING STORAGE RING

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Approximately three hours were taken August 27 in discussions primarily between Lee Teng, John Stekly, Mike Green, John Purcell, and myself on the question of SC magnets for intersecting storage rings.

The main subjects which were discussed included: 1) maximum field obtainable in a SC ring, 2) magnetic field precision necessary and obtainable, 3) hazards related to stored magnetic energy, 4) reliability of SC magnets, 5) cost of Nb-Ti vs Cu-Fe magnets, 6) variation of cost with peak field.

For 100 BeV and 60 kG maximum field, 96 dipoles and 48 quadrupole elements would be needed per ring. At 40 kG, the numbers would be 144 dipoles and 72 quadrupoles. Dipole lengths would be approximately 3.5 meters. Or, stating it another way, 21,200 kG-meters of beam bending is required per ring. All magnets are assumed to have either a 10 cm diameter or an elliptical bore with 10 cms width.

Field Level

It was more or less unanimously agreed that one could build dipole magnets of this bore and length up to the 40 kilogauss level. However, skepticism was shown for reaching 60 kG. From our experience at Brookhaven, 60 kG in a ring of 100 magnets of 10 cm bore would not be possible at the present time. Fred

Mills, however, suggests that the magnet development need not be finalized for three years - that is, until the summer of 1971. By that time, 60 kG should be a reasonable design level for such a magnet system.

The field obtainable in a dipole is:

$$H_o = \frac{2\pi\ I_o}{10}\ \text{gauss}$$

where I_o is the peak sheath current in amperes per circumferential centimeter. The formula is correct for elliptical as well as circular cross sections. Since many of our magnets are wound with 1/2" wide ribbon, the formula becomes: H_o = 0.8 J gauss. Putting in frame efficiency of around 87% to take account of wedges between the current section, we get: H 0.7 J gauss. Hence to obtain 40 kG, one will require 57,000 Amps/cm^2 in a single 1/2" winding. The best current density obtained at BNL in a comparable size winding has been 48,000 Amps/cm^2 which is equivalent to 33.6 kG. To obtain higher fields, the most conservative approach will therefore require the use of multiple layers of ribbon.

Similarly for quadrupoles, the gradient is as follows:

$$G = \frac{2\pi\ I_o}{10r}\ \text{gauss/cm}$$

At the same 48,000 Amps/cm^2 and one layer of ribbon we are limited here to G = 5.5 kG/cm ($r \sim 6$cm, frame efficiency = .87). In quadrupoles, the current sheath thickness is relevant and must be minimized for efficient use of the superconductor.

The present performance for a DC dipole (tested in August of 1967) at BNL is 14 kG ±2% over the bore. The magnet has an elliptical bore of 9 x 17 cm by an effective length of 50 cms. The field limit was due to instabilities and corresponded to 27,000 Amp/cm^2 in the gross winding. In extrapolating to storage ring dipoles, a big unknown factor is the amount of degradation one will get in extending the length by nearly one magnitude. It has been our experience that instability problems are proportional to the inductance (and therefore probably the length) of a magnet.

Other dipoles having higher but less uniform fields have been built, notably a 12" bore x 40 kG stabilized magnet for MHD experiments designed and built by Stekly at Avco.

Regarding the relationship between field level and cost, it seems likely that the highest field one can obtain with satisfactory reliability will also be the lowest in cost. This hypothesis is based on the fact that the costs of the tunnel, vacuum system, dewars, interconnections, and refrigeration are all inverse functions of field. Meanwhile, the only costs which rise with field are for SC materials and framework for supporting the SC. Furthermore, the framework cost may be small when mass production is considered and the material costs have generally been a minor percentage of the cost of a complete beam magnet.

Field Precision

The most crucial problem apparently is precision in the magnetic field - not only within individual magnets, but also for the assembly of magnets. The required tolerance is estimated at $\frac{\Delta B \ell}{B \ell} < 5 \times 10^{-4}$ for dipoles and $\frac{\Delta B' \ell}{B' \ell} < 10^{-3}$ for quadrupoles. A great deal of discussion took place about the methods for obtaining precision in a SC dipole. It is agreed that field errors due to diamagnetic effects are much smaller in magnets wound with small wire than they are in magnets wound with ribbon. In a typical Nb_3Sn ribbon wound solenoid, the diamagnetic fields may amount to 5% of the peak working field. It is not known what diamagnetic effect one would get in a dipole made with ribbon conductors placed with their flat surface radial to the beam axis or parallel with the flux lines. There is a good chance that field errors in such a dipole would be very much smaller and perhaps even tolerable.

One method for reducing the diamagnetic error is to develop a ribbon with multiple insulated parallel conductors rather than the present single full width conductor. Another possibility for development of synchrotron magnets that has been proposed at BNL is a stranded, individually insulated, and transposed ribbon-like conductor (like a battery strap) which should have low AC and hysteretic losses.

The conclusions reached about precision were: 1) That the alloy wire superconductors would give much lower diamagnetic errors in field than the compound superconductors in ribbon form. 2) That it would be prohibitively expensive to match the $\frac{dB}{dI}$ of any type of magnets well enough for direct series operation from a single power supply. 3) That separate precision power supplies to run each magnet would be prohibitive in cost. 4) That for a series connection, current leads between magnets could be super-conducting (this looks unreliable from the standpoint of cryogenics). 5) That current leads to room temperature from each magnet would be an unnecessary heat lead (I have reversed my opinion on this).

Rather than discuss the preceding points separately, I shall propose a complete approach to the problem.

First a large effort should be made to develop a Nb_3Sn tape magnet, despite the foreboding diamagnetic errors. The winding accuracy and simplicity possible with tape make its use cheap, low in construction man hours, and low in chances for winding errors. The high current density - probably 60,000 Amps/cm^2 at 60 kG useful by 1971 - and the high critical field (220 kG) of Nb_3Sn make it superior to the known alloys in the range above 60kG. The winding will need to be a double or triple layer of ribbon narrower than BNL's 1/2" standard to reduce diamagnetic problems, unless stranded or effectively stranded and insulated ribbon conductors become available. The ribbon must be laid parallel to the flux lines whenever possible.

Stray Fields

In the author's opinion, the stray field should be cancelled by a reverse current external winding at a radius of approximately 3 times the main winding radius. The loss in field due to the reverse winding will be less than calculated due to the reduction in inductance and resultant increase in stability. The use of an iron shield, despite its attractive addition to the field strength, would add to the inductance, and in the author's opinion thereby reducing the stability of the ribbon and reducing the maximum current density. It would also create mechanical support problems for the low temperature portion of the dewar with a resultant increase in thermal leak to the helium space.

It is probable that local non-uniformities in the field can be neglected if the coil frames are accurately constructed, the turns are properly spaced and made from ribbon machined to precise thickness and width, and no ferromagnetic material is near the magnetic circuit. The absolute value of $\frac{dB}{dI}$ must now be matched to within one part in 2×10^{-4} for all magnets. To achieve this, I suggest the following: Connect all magnets in series to a single power supply (see Fig. 1). This supply would deliver, say, 0 to 1,000 Amperes at a voltage sufficient to reach peak field in 30 to 60 minutes. All magnets will contain uniform internal shunting (essential for quench protection) to give a time constant of 1 to 3 minutes.

Variations in this shunting will introduce field errors between magnets during sweep. External protection against a magnet open circuit, probably in the form of 1,000 A. diodes would also be desirable. Each magnet would have a precision inductance pickup coil of Nb-Ti alloy SC wire within its useful field space to measure $\frac{dB}{dt}$. Small corrector power supplies capable of supplying a floating ± 3% of the main supply current (assuming 3% is the maximum difference between magnets) will add or substract current from each magnet. The control for the corrector supplies will be obtained from the difference between a common signal from the main control and the signal from the pickup coil.

Flux Pump Drive

Since the storage ring magnets will be swept slowly in field level, there is a possibility for driving them with flux pumps. A flux pump could convert very low current 60 Hz power to high current DC power within the dewars. This would eliminate almost all thermal losses caused by the current leads, or approximately 1 watt per lead per 1000 Amps rating. The control circuitry for the pumps would replace the corrector power supplies shown in Fig. 1.

Gradient Precision

DC quadrupole development at BNL is much more advanced than the dipole work. Two precision elements of 10 cms winding bore x 50 cm center-to-center winding length have been built by W. B. Sampson and myself and tested for field uniformity and maximum gradient. Each element contains 760 meters of 1/2" wide x .005" thick RCA Nb_3Sn ribbon. Four current carrying blocks are used per quadrant, according to a mathematical solution developed by R. A. Beth. The measured field uniformity was found to approximate a perfect quadrupole, as given below,[(1)] at a diameter of $\sim$7.0 cms when integrated by a coil 78 cms in length.

Harmonic	Level
2θ	100%
4θ	1/2%
6θ	1/12%
10θ	1/3%

The erros due to the coil ends or turn arounds are included in this table. Most of the integrated field errors that were found were correlated with inconsistencies in the ribbon thickness which produced distortion in the coil frame and errors in the intended current densities. No field errors were traceable to diamagnetic effects - contrary to what we expected from experience with solenoids. No trapped or residual fields were observable when currents were returned to zero, also contrary to solenoid characteristics.

Since August 1967 when these measurements were made, the ribbon mechanical tolerance has been improved by a magnitude (Δt is now $< \pm$ 2.5%). It is presently possible to buy ribbon which has been machined to size and from this technique we expect further gains in dimensional accuracy.

My conclusion about quadrupoles is that a combination of the BNL winding and frame structure with the machined Nb_3Sn ribbon can give the field accuracy required for the storage ring elements.

Hazard

The hazard from the stored energy within the storage ring magnets was discussed in some detail. Differing opinions were: 1) By John Purcell, that stabilized (and 10,000 Amps/cm^2 or less) conductors should be used to avoid the SC quench problem; 2) By M. Green and the author, that high current density ($J > 30{,}000$ Amps/cm^2) should be used to reduce the stored energy combined with shorted windings to make quenching harmless in magnets of the proposed size and field; and 3) By general agreement, that electronic circuitry is required to reduce the chances of multiple quenching along the magnet string. The simplest form of such circuitry is two diodes side by side in parallel with each magnet with forward conduction above about 1/2 volt in both directions. A multiple or complete quench for the entire ring should not be damaging either, but the recooling time in such a case would be a severe annoyance. One could possibly operate the magnets from separate supplies or in series parallel if the triggering effect for a series connection turns out to be difficult to solve.

It should be noted that the BNL quadrupoles and dipoles have been quenched scores of times from the 20 to 25 kG level with no damage to the magnet or associated apparatus or to any personnel in the vicinity.

Reliability

If all magnets are tested to quench level a dozen or more times prior to their installation in the ring, a mathematical estimate of the complete ring reliability can be readily determined. For a Nb_3Sn magnet, instability implies that one cannot always reach the critical current vs field curve for the turns of ribbon in the highest field region. A stable Nb_3Sn magnet always reaches this point for some finite, though perhaps slow, rate of current sweep. The maximum rate for stability is best determined by experiment and is a function of the electrical shunting and the thermal transfer of the winding.

If the storage ring dipoles are unstable, their quench points will be statistically determined. Fig. 2 portrays the quench probability for a hypothetical magnet which would always reach 1050 amperes without quenching. Ten out of 100 tests would reach 1250 Amperes, and six out of 100 tests would reach critical current of 1450 amperes. With 100 magnets like this in series, one could always reach 1000 amps, but the possibility of reaching 1250 Amps would be less than one in a hundred.

If the ring dipoles are stable, the ring failure or first quench point will be the lowest critical quench current found during preliminary tests for any magnet in the ring.

If the ring were operated to no more than 90% of minimum quench currents found in, say, 20 pre-installation tests of every magnet, the chances of a quench would be very small. The chance, also, of a magnet going normal after it has reached equilibrium is nil so far as our experience is concerned. By equilibrium we mean that the current is fixed and the field has stopped rising. We assume, of course, that magnet temperature is not allowed to rise through a fault in the cryogenic system, or for other reasons.

Dipole Cost

The cost of dipoles with shielding would be difficult to estimate at the present time. We can say that Nb_3Sn ribbon conductor 1/2" wide x .005" ± 2-1/2% thick capable of carrying 40,000 to 70,000 amp/cm^2 at 50 kG in lengths of 300 meters has been quoted to BNL at $8.00 per meter. The cost of frame machining, dewar construction and magnet assembly and testing are too strongly affected by mass production to be estimated in this report.

A precisely machined unshielded dipole is presently being built at BNL as follows:

Specifications:

Beam Space: Elliptical, 3.6" x 7.0"

Outside dimensions of frame: Elliptical, 5.2" x 8.6"

Frame construction: machined from thick wall elliptical aluminum tube

Effective field length: 24'

Overall winding length: 24"

Winding center-to-center length: 13.3"

Winding: two coils, four current sections per coil

Turns: 124, 108, 80, and 42 based on 4.9 mils/turn min.

Insulation: Zr chromate paint on frame, SS strip between turns.

Costs:

Frame casting + 100 hours machining	$ 1,200
SC ribbon, 1000 meters	8,000
Dewar Construction, estimate	10,000
	$19,200

A field of 30 kG should be obtained by selecting the best ribbon from many lengths that have been pretested in a solenoidal pancake winding.

The estimated heat leak to the dewar is 5 watts, 2 of which will be from a pair of 1000 ampere leads. The lead losses are expected to be eliminated eventually by the use of a flux pump, for which space has been reserved in the dewar.

Quadrupole Cost

A cost breakdown on BNL's quadrupole doublet is as follows:

Frame for coils (2 units) 550 shope hours each	$11,000
Superconductor - 760 meters x 2 at $8.00/meter (Aug. 1968 quote)	12,200
Dewar - 2 units at 7,000	14,000
	$37,200

The time for winding, assembly, and test is small and has been neglected. The dewar cost can be cut almost in half by installing both elements in one container. The frame design can be a solid structure rather than the composite structure quoted to net a shop time reduction to 1/4 the above. The solid frame must be about 7% larger in diameter and will only hold 80% of the winding density obtainable with the composite. One ends with:

Frames for doublet	$ 3,000
SC ribbon: 1750 meters at $8.00/m	14,000
Dewar	7,500
	$24,500

Clear bore: 10 cms

Element length: 60 cms

Field: 30 to 40 kG at the walls

DC requirement: 600 to 800 amperes

In these estimates, no allowance has been made for magnetic shieldings which will add perhaps 10 to 30% to the cost. The former figure would apply to an iron cylinder enclosing the winding and operating at the temperature of the SC ribbon, namely 4 to 12 K. The higher figure would apply to extra framework and ribbon for a reverse current winding to surround and cancel the stray fields.

Please note that no figure has been included in these costs for refrigeration. Nor will any attempt be made to compare the costs of SC magnets vs Cu-Fe magnets since the author has had no experience with the latter.

REFERENCE

[1]W. B. Sampson, unbpublished.

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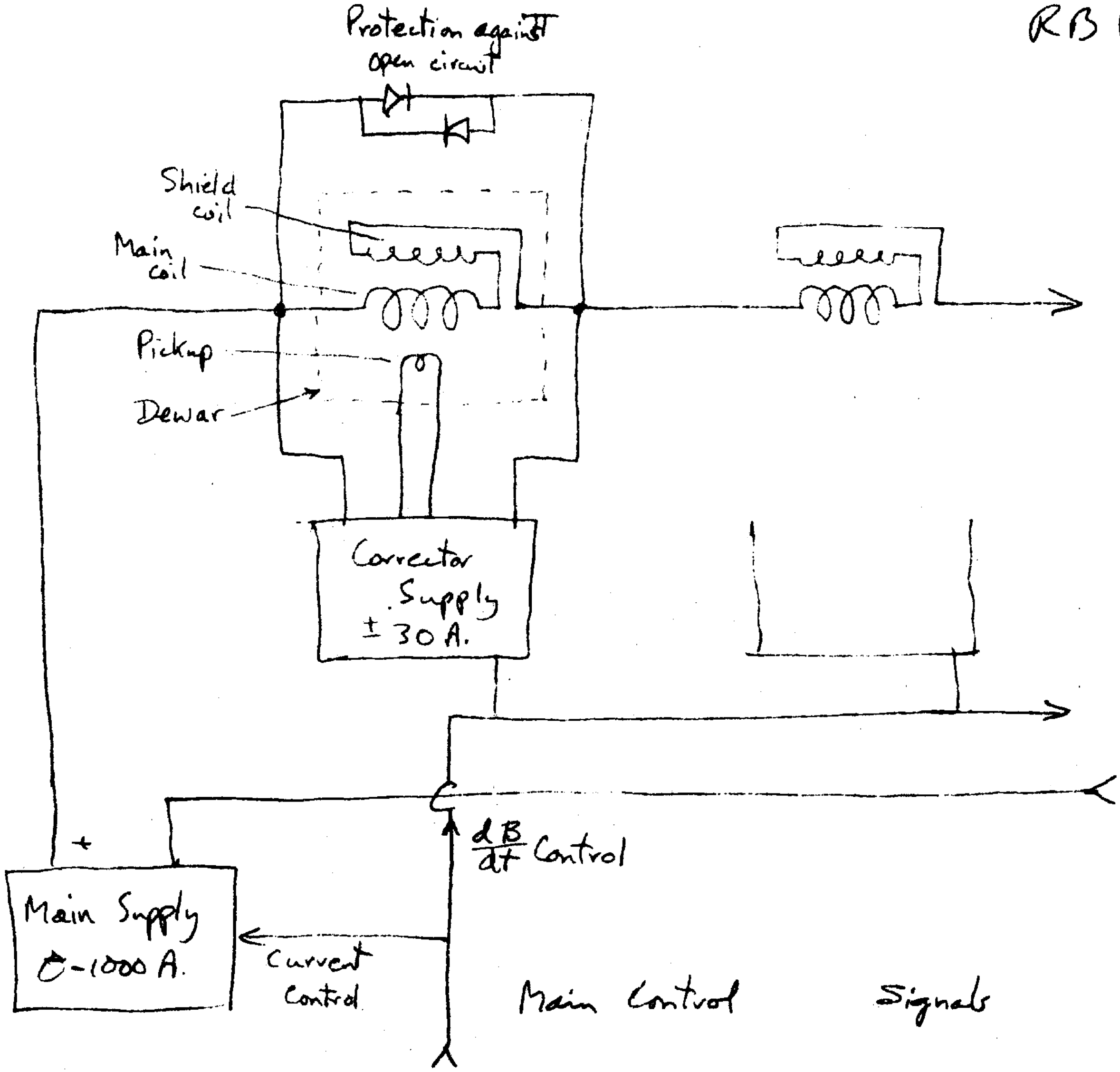

Fig. 1 Magnet Drive System for Precise Field Control

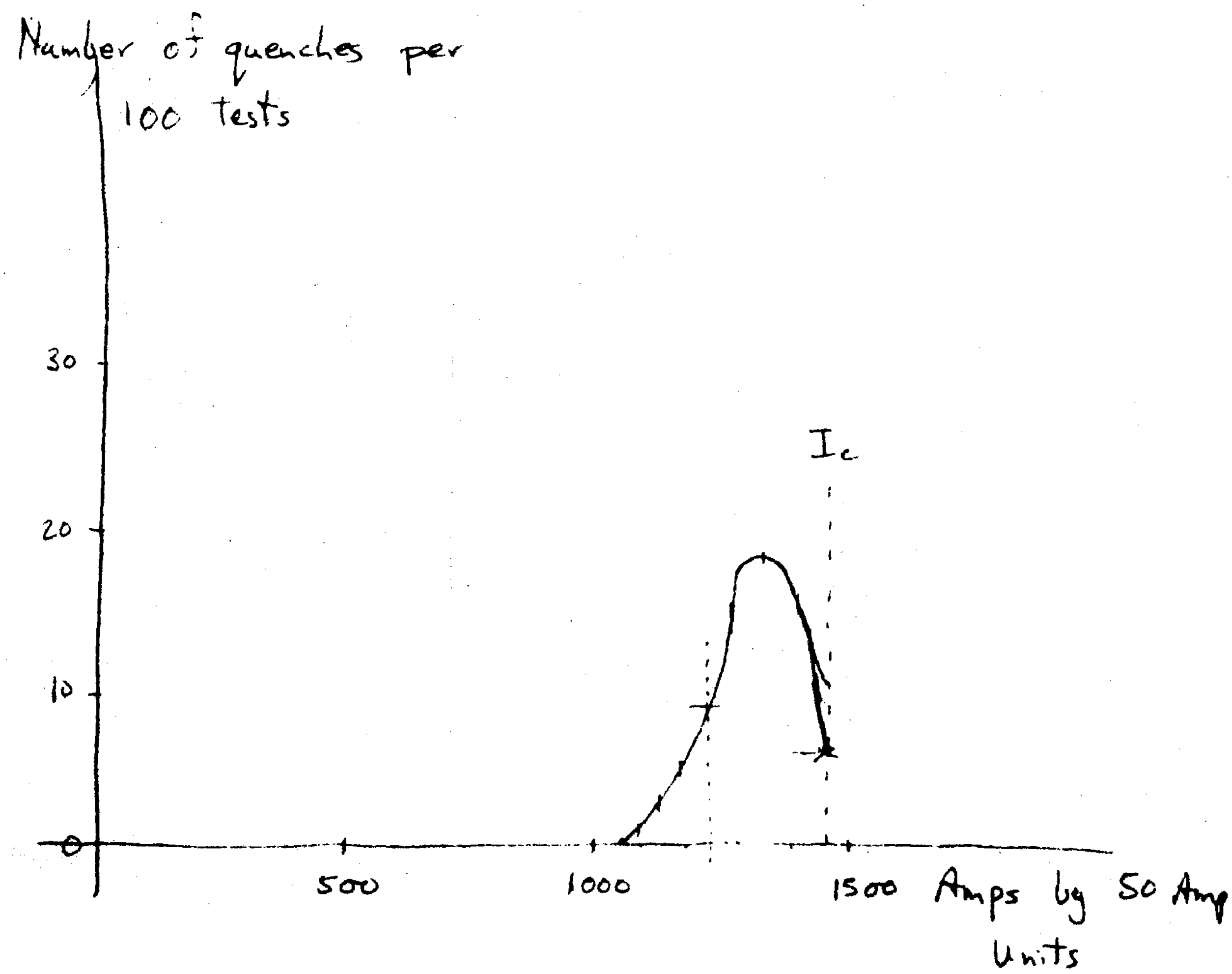

Fig. 2
Probability of quench vs. current for an unstable SC magnet

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