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Institut für Experimentelle Kernphysik

GESSS Machine Design Committee Reports 1972

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Summary

The 'Group on European Superconducting Synchrotron Studies' (GESSS) is a collaboration by the laboratories RHEL (Great Britain), CEN Saclay (France), CERN II and IEKP Karlsruhe. The 'Machine Design Committee' of GESSS is concerned with studying possible alternatives from the point of view of accelerator design that may be seen in an extension of the CERN II 300-GeV proton synchrotron to 1000 GeV employing superconducting magnets. Contributions to this committee are compiled here on these topics:

- Cost estimates for a separate ring of superconducting magnets,
- Effects of magnet length and distance on cost and final energy,
- Cryogenic and vacuum-related problems in a given tunnel,
- Effects of aberrations in the magnetic field due to persistent currents on beam dynamics

Beiträge zur GESSS Arbeitsgruppe Maschinenentwicklung im Jahre 1972

Zusammenfassung

Im Rahmen der 'Group on European Superconducting Synchrotron Studies' (GESSS) der Laboratorien RHEL (Großbritannien), CEN Saclay (Frankreich), CERN II und IEKP Karlsruhe, befaßt sich das 'Machine Design Committee' mit beschleunigerphysikalischen Aspekten und Alternativen, die sich aus einer möglichen Umwandlung des normalleitenden CERN II-Beschleunigers in einen supraleitenden 1000 GeV-Beschleuniger ergeben. In den hier zusammengefaßten Beiträgen zu diesen Untersuchungen werden folgende Fragen behandelt:

- Kostenabschätzungen eines separaten supraleitenden Magnetrings,
- Einfluß von Magnetlänge und -abstand auf die Kosten und Endenergie des Synchrotrons,
- kryogene und vakuumtechnische Probleme in einem vorgegebenen Ringtunnel,
- Größe der Störungen des Magnetfeldes durch Dauerströme im Supraleiter und ihr Einfluß auf die Strahldynamik.

eingereicht am: 15.5.73

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1000 GeV Superconducting Synchrotron Cost Estimate. Separate Ring Solution

by Michael A. Green

This report presents the latest cost estimate of a separate ring 1000 GeV superconducting synchrotron which occupies the same tunnel as the conventional SPS machine at CERN. This estimate has been made so that it is consistent with the cost estimates done by CERN in the MC 60 Design report[1]. The cost estimate of the superconducting magnets and their support system was calculated using the superconducting synchrotron cost program which was developed at Berkeley and Karlsruhe.

This report shows the cost of separate superconducting ring its power supply, refrigeration system, R.F. system, vacuum system, transfer system from the conventional ring, and 1000 GeV extraction system capable of delivering full energy beams to the north experimental area. The superconducting ring is assumed to be placed above the conventional ring in the same tunnel, it is further assumed that some of the above ground building contain machine equipment for both rings. The lattice for the two rings is identical.

Reports of the GESSS machine design committee[2] indicate that the separate ring machine is superior in both a technical and economic sense to a machine derived from a mixed magnet solution. There is evidence that later approach may not work at all because of the residual field problems which can occur at injection[3]. It is believed that the separate ring machine will have smaller magnet aperture (hence lower stored energy and lower cost) than the mixed magnet machine.

Table 1 presents a list of parameters for the superconducting synchrotron. It should be noted that the superconducting machine has the same lattice as the 400 GeV version of the conventional machine. The superconducting machine is assumed to have a static power supply with the same power rating as the main ring. The R.F. system requirements are nearly the same as for the conventional ring. The machine cycle time was limited by the static power supply. The magnet aperture is assumed to be the same for all dipoles. The useful aperture number is based on calculations done by members of the GESSS machine design committee[4].

Table 2 presents the cost of a separate ring 1000 GeV superconducting synchrotron. The first column presents the estimated cost for each component. The second column puts a range around each of these costs. In many cases the estimated cost lies near the center of the range. Cases which do not lie near the center of the range will be discussed in some detail later. The third column presents the cost calculation which came from the cost computer program. This program has been quoted extensively by the author in other publications [5], [6], [7] significant deviations in price are explained in the foot notes to table 2.

The largest item in table two is the superconducting magnets. The magnet cost includes the cryostat which is an integral part of the magnet. The magnet cost includes all the dipoles, the quadrupoles, and correction magnets which are assumed to be conventional. About half the magnet cost is superconductor which is assumed by the computer to cost 2.2×10^{-3} per A meter (8.8×10^{-3} Sw. Fr. /Am).. The current price for 10 μ filament superconducting cable delivered in Germany is about 6.6×10^{-3}/Am (2.6×10^{-2} Sw. Fr. / Am) for cable that is delivered in 1 or 2 km lots. The highest figure in the magnet cost range is based on todays price for the superconductor. My justification for believing the price will go down a factor of three is based on discussions with a couple of the US manufacturers. The reasons for assuming a price drop of a factor of three are as follows.

1) Today's prices are based on small lots; a 1000 GeV superconducting synchrotron will require 3000 to 4000 km of 2000 A superconducting cable.

2) Today's price for finished superconductor is 8 to 10 times the cost of the raw niobium-titanium. (Note that the price of finished copper wire or conductor is often less than a factor of two more than raw material cost and copper is a cheaper material). Superconducting cables are made on the same kind of equipment as ordinary copper wire cables are made. The operating, therefore the manufacturing cost of cable, of the equipment drops per unit length when large orders are processed. I therefore feel that using the lower cost in the computer program is entirely justified.

The power supply costs came straight out of MC-60 since the superconducting ring power supply has the same peak power rating as the conventional ring power supply.

The cost of refrigeration is based on the Strobridge estimates[8] I feel these numbers are high because of more recent quotes for large machines are under construction in the USA[9]. The transfer line is assumed to be a separate transfer line. If the transfer line is built as part of the magnet cryostat a reduction of cost and transfer line losses can be achieved.

The R.F. System is assumed to be identical to the one in conventional ring. Therefore the MC-60 cost was quoted minus the development and model cost (2MSF).

The transfer system and extraction system costs are based on the costs quoted in MC-60. These costs also include the beam transport system to the north area and an additional beam dump.

The vacuum system includes the beam transfer line to the north area and the roughing system for the magnet cryostats. The cost seems low; the reason for this is that there are only twelve of the large ion pumps included for the long straight sections.

It should be noted that the magnet has cold bore. The pumping speed for the bore is about 20000 l/sec. per magnet for all gases exept helium. The surfaces don't outgas either.

The control system costs come straight out of MC-60. The 7 MSF difference in cost comes from the fact that some of the conventional ring control equipment can be used on the superconducting ring as well. Some of the the control equipment quoted in MC-60 is included with the magnets in my estimate for the superconducting machine.

The plant equipment cost includes additional cooling towers, power substation equipment, extra cabling and water piping for the superconducting machine, which is not included elsewhere.

Before closing this report it is useful to note what happens when one changes a number of the machine parameters. An increase in energy from 1000 GeV to 1200 GeV (5.4 T magnets) will increase the machine cost about 35%, possibly more if it besomes impossible to use a static power supply. Increasing the energy to 1200 GeV by building a larger ring (if this is possible) in a new tunnel and maintaining a lower field is about the same price. Putting an 800 GeV ring instead if a 1000 GeV ring in the tunnel can save up to 25 per cent. Increasing the superconducting magnet aperture has the effect of increasing the cost of the magnets, power supply, refrigeration and plant. An increase in repetition rate has the effect of increasing the power supply cost, R.F. system cost, refrigeration system cost and other power related costs. For more information see table 3.

It is the belief of the author that the separate ring solution is superior economically and technically compared with a mixed superconducting-conventional magnet solution. The separate ring solution also allows one to apply missing magnet scheme to it. The first stage with half the magnets would have an energy of 500 GeV, the second stage would the increase the energy to 1000 GeV. See table 4 for a rough cost estimate. The separate ring solution is attractive enough that serious study of it should be undertaken before the late 1973 early 1974 day of decision.

Table 1: 1000 GeV Superconducting Synchrotron Design Parameters

A. General Machine Parameters

Final Energy	1000 GeV
Injection Energy	100 GeV
Proton Intensity	10^{13}ppp
Cycle Time	18 sec
Rise Time	6.5 sec
Injection Time	0.2 sec
Flat Top Time	4.8 sec
Injection Efficiency	98 %
Ejection Efficiency	98 %
Tunnel Radius	1100 m

B. Lattice Parameters

Superperiodicity	6
Number of Cells	108
Nominal Working Q	27.75
Transition Energy	~ 25 GEV
Number of Dipoles	744
Number of Quadrupole	216
Lattice Type FODO	same as conventional ring

C. Magnet Parameters

1. Dipole magnets

Length (Cryostat Length)	6.5 m
Average Induction of Length	4.34 T
Central Magnetic Field at 1000 GeV	4.5 T
Maximum Field in the Winding	~ 5.0 T
Useful Aperture Radius	20.0 mm
Coil Aperture Radius	35.0 mm
$\Delta B/B$	$3 - 5 \times 10^{-4}$
Average Coil Current Density	22300 A/cm^2
Ampere Turns	5.25×10^5
Stored Energy per Dipole	487 kJ
Overall Cryostat Diameter	500 - 600 mm

2. Quadrupol magnets

Overall Length (Cryostat Length)	3.0 m
Gradient at 1000 GeV	52.6 T/m
Maximum Field in the Coil	2.6 T
Useful Aperture Radius	30 mm
Coil Radius	40 mm
Ampere Turns	2.06×10^5
Stored Energy per Magnet	23 kJ
Overall Cryostat Diameter	400 - 500 mm

D. Power Supply Parameter

Magnet System Stored Energy	373 MJ
Peak Power	112 MVA

Power Supply Type (same as conventional ring)

E. Refrigeration Parameters

Estimated Refrigeration Load	41 kW
Installed Refrigeration Capacity	55 kW
Number of Refrigeration	6

F. R.F. Parameters

Harmonic Number	4620
Cavity Frequency	200 MHz
Acceleration Rate	140 GeV/sec
Acceleration Voltage	3.3 MV
Acceleration Power	172 kW

Table 2: 1000 GeV Superconducting Synchrotron Cost (separate ring solution)

Component	Estimated Cost	Cost Range	Cost Calculation from Computer
Superconducting Magnet Including Cryostats	116 MSF	100 - 210 MSF	116 MSF
Static Power Supply	22 MSF	18 - 25 MSF	20 MSF
Refrigerator and Transfer Lines	36 MSF	30 - 40 MSF	36 MSF
R.F. System	16 MSF	12 - 22 MSF	18 MSF
Transfer System and Injection into the Superconducting Ring	9 MSF	6 - 12 MSF	4 MSF[a]
1000 GeV Extraction and Beam Transport to the North Area Beam Dump included	30 MSF	24 - 38 MSF	17 MSF[b]
Vacuum System include Cryostat Pumping and Beam Transport to the North Area	12 MSF	10 - 14 MSF	8 MSF[b]
Control System	20 MSF	15 - 25 MSF	11 MSF[c]
Plant Costs includes Cooling Tower, Power Transformers Tunnel Hardware	9 MSF	8 - 12 MSF	9 MSF
Total Cost	270 MSF	223 - 398 MSF	239 MSF

a) Just injection no extraction from conventional ring or beam transfer

b) Does not include beam transport system to the north area

c) 5 percent of the component cost used. This is low 10 % is a more reasonable figure

Table 3 Cost comparison of 800, 1000 and 1200 GeV separate ring superconducting synchrotrons

Costs (Millions of Sw. Fr.)

Component	800 GeV 3.6 T dipole	1000 GeV 4.5 T dipole	1200 GeV 5.4 T dipole
Magnets includes cryostat	81	116	170
Power supply static power supply	12	22	40
Refrigeration	32	36	45
R.F. system	14	16	18
transfer-injection	9	9	9
Extraction to north area	26	30	34
Vacuum system	12	12	12
Control system	20	20	20
Plant costs	6	9	12
Total costs	204	270	360

Table 4 Cost of a 1000 GeV superconducting synchrotron. Missing magnet scheme applied to the separate ring solution.

cost (Millions of Sw. Fr.)

Component	stage A 500 GeV	stage B 500 GeV	cost at the end of stage B 1000 GeV
Magnets (including cryostats	60	60	120
Static Power supply	22	-	22
Refrigeration	33	5	38
R.F.	16	-	16
Transfer and injection	9	-	9
Extraction system	25	10	35
Vacuum system	12	2	14
Control system	20	-	20
Plant	5	5	10
Total	202	82	284

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2. F. Arendt et Al, "Preliminary studies to a 1000 GeV superconducting extension of the European Accelerator" to be published in the proceeding of the CERN international accelerator conference Sept. 1971.

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4. Minutes of the GESSS machine design committee Meeting in Saclay, November 25 and 26,1971

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7. M. A. Green, "Preliminary cost calculations for the European superconducting synchrotron".
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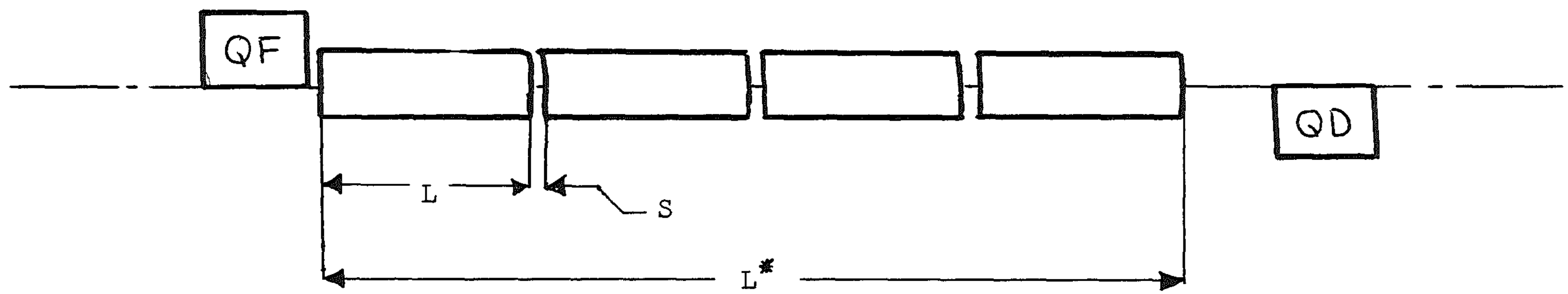
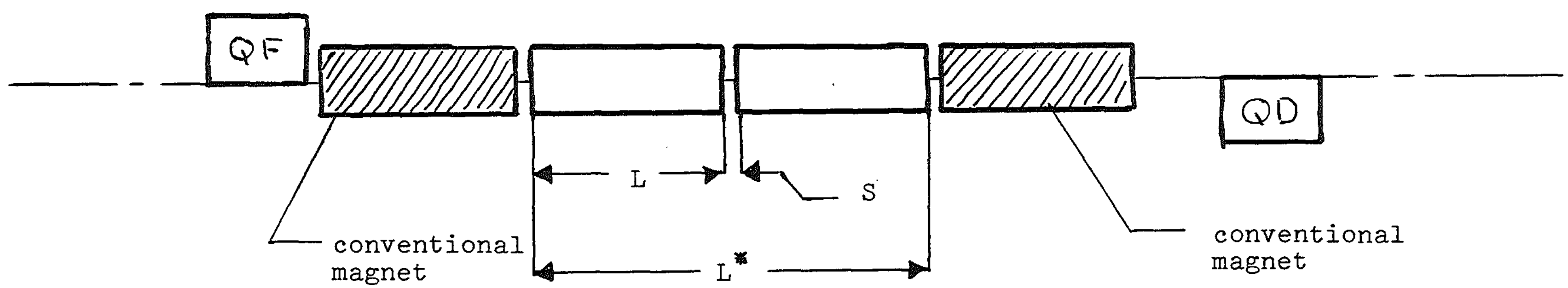
8. T. R. Strobridge, "Refrigeration for superconducting and cryogenic systems", IEEE transactions NS-16 (3), June 1969

9. Private communications with G. C. Coombs of cryogenic technology incorporated Wahltham, Massachusetts, USA, on the price of two recently bid 8 kw helium liquifiers.

Figure 1: Assumed latice for the 1000 GeV separate ring machine and the 500 GeV missing magnet machine

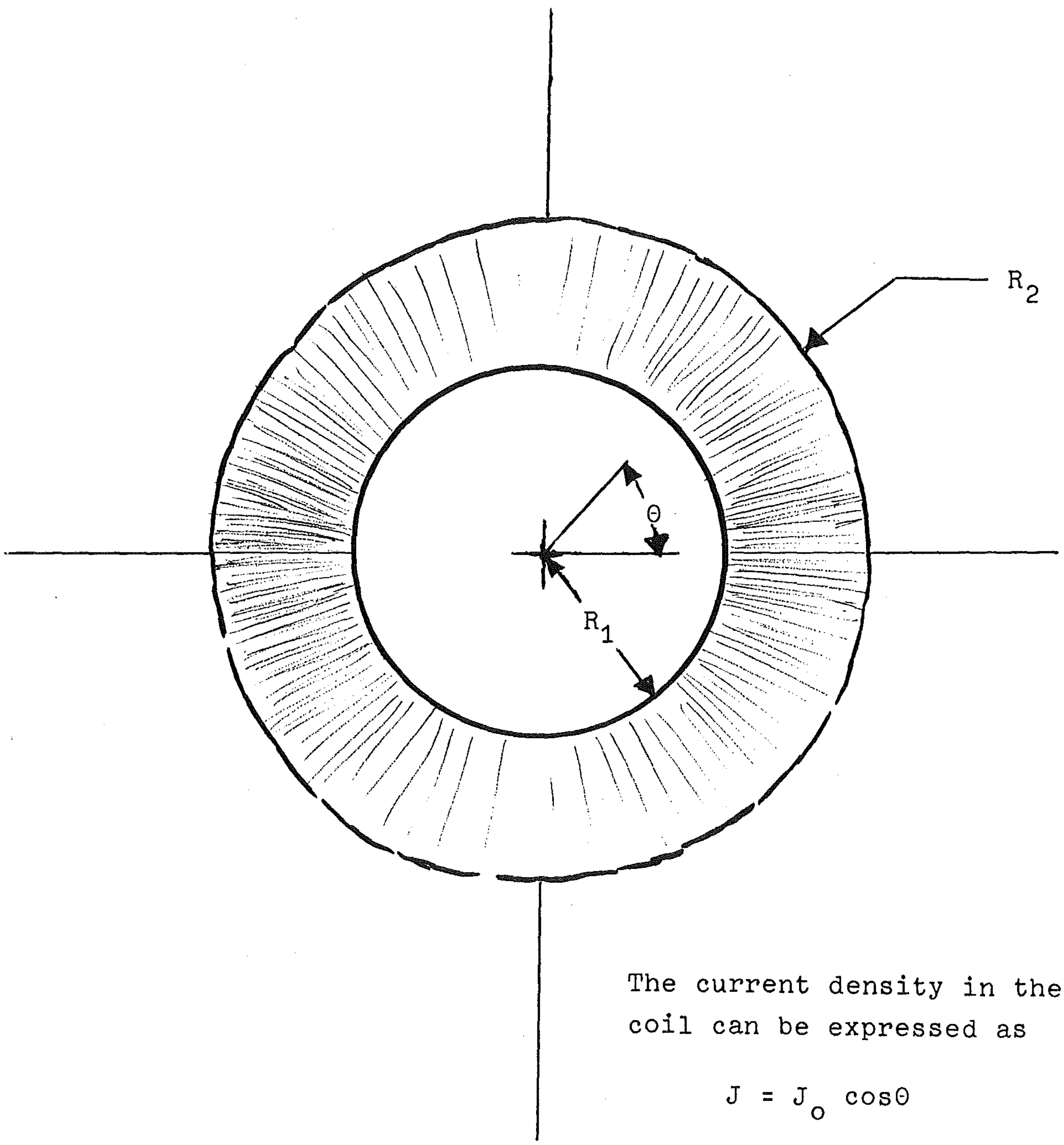


a) 1000 GeV separate ring machine



b) 500 GeV missing magnet machine

Fig. 2: A cosine theta dipole magnet



The current density in the coil can be expressed as

$$J = J_o \cos\Theta$$

Figure 3: Relative magnet coil current density and relative superconductor cost as a function of the highest field in the superconductor

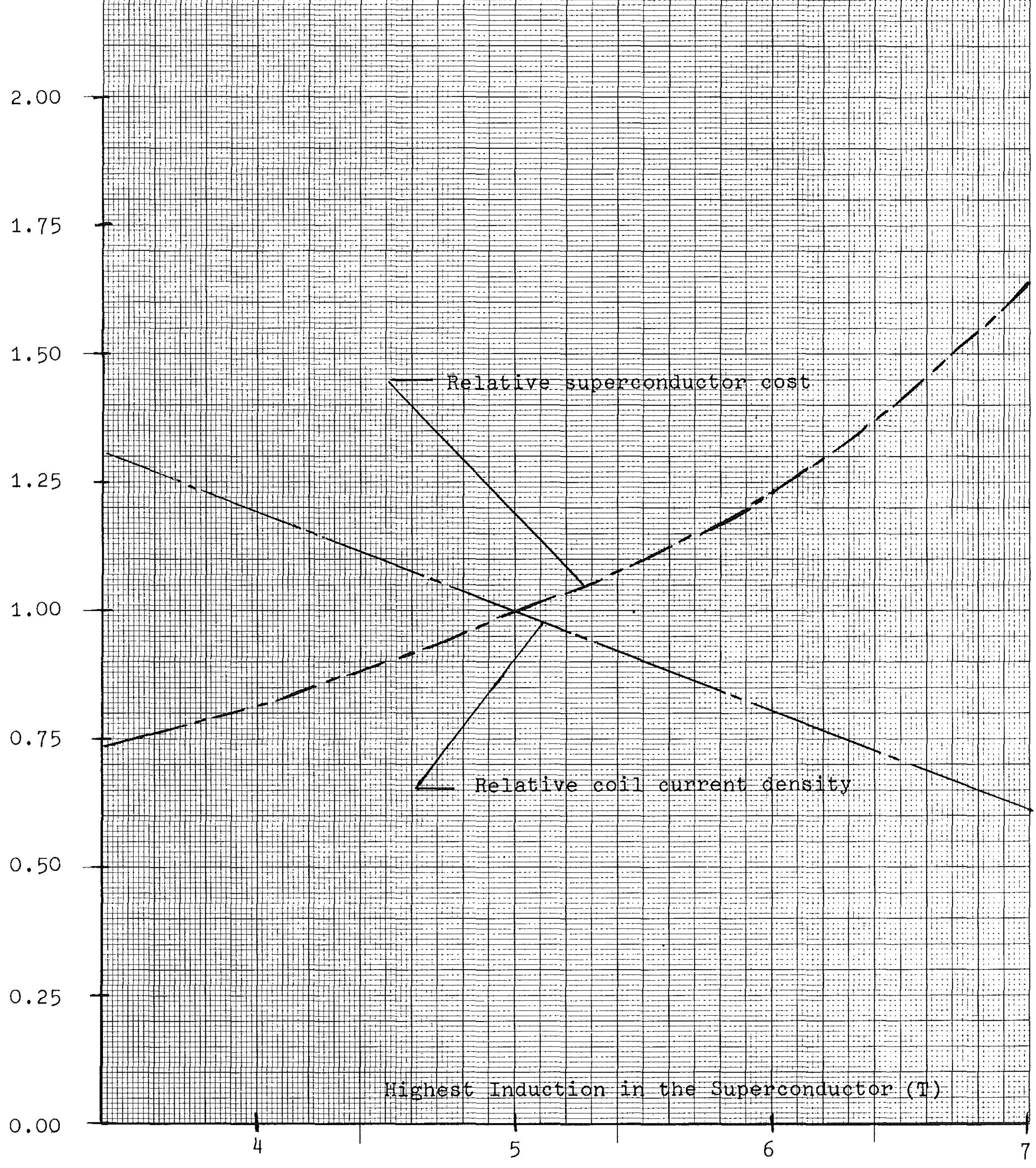
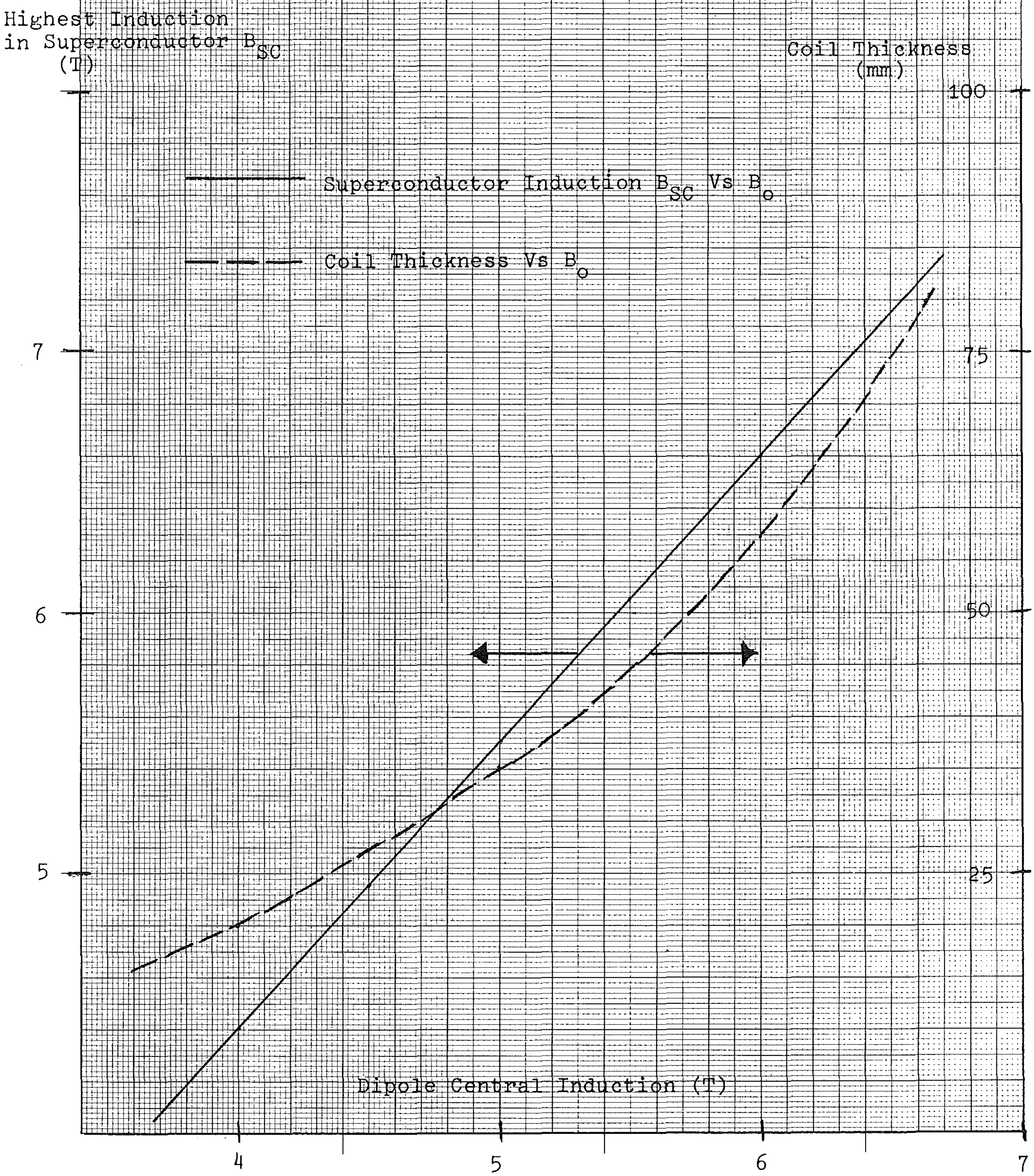


Figure 4: The highest induction in the superconductor B_{SC} and the coil thickness as a function of the dipole central induction



Cryogenic Problems Associated with a Missing Magnet Ring

Michael A. Green

June 2, 1972

This report discusses some of the problems associated with the cryogenic system for a missing magnet superconducting synchrotron. Many of these problems will apply for a separate ring missing magnet synchrotron, as well as a missing magnet synchrotron which has the conventional magnets in the same ring. The problems that are particularly associated with the mixed magnet ring are associated with the existance of the conventional magnets in the ring.

The cryogenic problems which are associated with missing magnet machines can be divided into 2 parts which are:

1) Problems associated with the cryostats and vacuum system.
2) Problems which are associated with the cold helium transport system and refrigerator.

This report will discuss only some of the more important problems.

1. Cryostat and vacuum system problems

The missing magnet machine has the superconducting magnets which are grouped into 216 bunches, two per cell. If one assumes that the missing magnet has conventional quadrupoles, the bunches of magnets would be about 13.2 m long and would be separated by a distance of about 18.7 m. The magnet bunch consists of two magnets which are probably in a common cryostat. The main ring beam vacuum system interconnects the magnet bundles. It is desirable to have a cold bore in the superconducting magnets. The cold bore can cryopump the accelerator vacuum down into the 10^{-9}

or 10^{-10} Torr range.

There is the problem of teminating to cold bore at the end of the magnet cryostat. One can solve this problem by extending a vacuum insulated pipe across the 18.7 m space between the cryostats. There are two difficulties with this approach:

1) The conventional magnets in the mixed magnet ring do not have a large enough gap to easily accommodate the vacuum insulated pipe.

2) The price of a low heat leak pipe between cryostats is not negligible. The heat leak through this insulation system should be considerably less than 5 watts to make it worthwhile.

Let us assume we have no insulated vacuum pipe between the superconducting magnet groups. Heat will enter the dewar by radiation and conduction along the beam vacuum pipe. The radiation heat transfer may be calculated as follows;

$$Q = FA\varepsilon\sigma(T_1^4 - T_2^4)$$

where F = the form factor; for all practical purposes, this is unity.

A = the area of the vacuum pipe cross section; for a a missing magnet machine, this is a circular pipe with an 8 cm diameter.

ε = the emissivity of the hole; black body conditions are nearly fulfilled. Hence, $\varepsilon \approx 1$.

σ = the Stefan-Boltzmann constant.

$T_1 = 300^\circ$ K.

$T_2 = 4^\circ$ K.

Using the preceding equation, one calculates a heat leak into the cold bore of 4.76 watts per magnet bunch. Since there are 216 bunches, the total radiation load into the 4° K region is about 1.03 kw. A reasonable 4° K room temperature termination can be made in terms of heat conduction. Such a termination can be, say, 15 cm long and have a heat leak of 2.6 watts per magnet bunch. The total refrigeration penalty paid for not having a continous ring of cold vacuum pipe is about 1600 watts or 270 watts per superperiod.

Let us assume that this 270 watts is added to an already required capacity of 10 kw. Using Strobridge's equation[1], which relates refrigeration cost C in US $ to input power P in kilowatts, we find that:

$$C = 6000 \ P^{0.7}$$

differentiating

$$C' = \frac{dC}{dP} = 4200 \ P^{-0.3}$$

10 kw of refrigeration at 4° K, using an efficiency factor of 22%, requires 3.4×10^6 watts of power. We then find that C′ = $365/kw of input power. The 270 watts additional required per superperiod requires 92 kw of input power extra. This refrigeration will cost an additional $33500 ($1.29 \times 10^5$ Sw Fr) per superperiod.

The 270 watts per superperiod can be greatly reduced. The question becomes: What does it cost? If a significant reduction of this heat load can be achieved for under $900 (3500 Sw Fr) per magnet bunch, it may be worth doing. For example, one could put a warm bore tube in the superconducting magnet. Unfortunately, this reduces the refrigeration load at the expense of magnet aperture and the vacuum system. It is probably best, economically, to accept the additional 1600 watt load and pay 8×10^5 Sw Fr more for the refrigerators.

The number of cryostat ends per magnet goes up in a missing magnet machine, as compared to a separate ring machine with all the spaces filled. The cost penalty probably is of the order of 0.7 to 1.0 $\times 10^6$ Sw Fr by the time the machine energy has been extended to 1000 GeV. Since these cryostat ends must fit between 2 conventional magnets, the length of the superconducting dipole is shortened. The result is the central field of the magnet is raised, which increases the cost of the superconducting magnet system and it's power supply.

2. Refrigeration and cryogenic transfer line problems

The primary change in the refrigeration system that the missing magnet machine imposes is that the cryogenic transfer line can no longer be made part of the magnet cryostat. As a result, the cryogenic transfer line is made more complicated. This becomes particularly evident when the conventional magnets are left in the ring. Figure 1 illustrates what might be possible solutions to the transfer line problem in a separate ring machine or a missing magnet machine.

The neccessary changes in the cryogenic distribution system is reflected in the additional heat loads which the refrigerator must refrigerate. The transfer line losses in the mixed magnet machine may be 6 - 8 kw higher than for the separate ring machine which is entirely filled with magnets[2]. The cost of this extra refrigeration will be around 4 million Sw Fr. The cost of the additional transfer line sections could possibly be around 4 million Sw Fr also.

The losses per cycle will be greater for a missing magnet machine than for a separate ring machine of the same energy, if the same kind of superconductor is used in both machines. This is probably an academic point because power supply restriction will not permit as short a pulse time for the missing magnet machine as compared to a separate ring machine[3]. If one assumes identical superconductors in both machines, one finds that the total a.c.

loss load for both machines is nearly the same. The pulse time for a separate ring machine will be only about one-half the pulse time for the completed missing magnet machine. Differences in the superconductor between the missing magnet and separate ring machines may increase the refrigeration load for the separate ring machine. The cost of this refrigeration will be compensated for by less expensive superconductors[4].

Technically, all of the cryogenic problems on the missing magnet machine are solvable. There is little question that the static and dynamic losses will be greater for the full ring version of the missing magnet machine (with 10 GeV injection) than for a separate ring machine of the same energy and pulse time.

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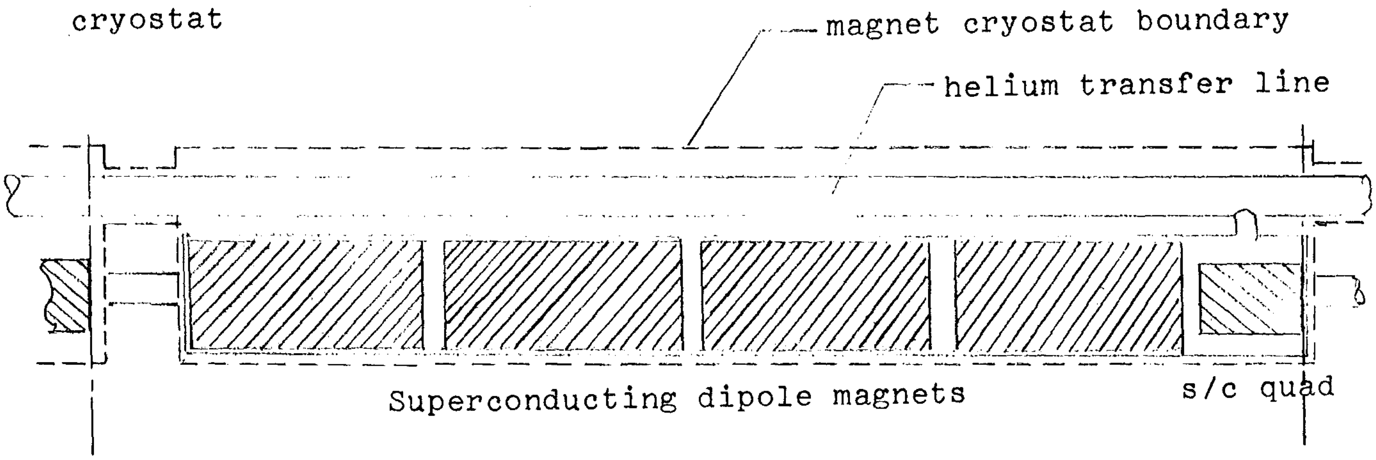
3. F. Bronca, G. Neyret, J. Parain, J. Perot, "Consequences of Replacing Conventional Magnet by Superconducting Magnet in an Existing Synchrotron" May 2, 1972, GESSS MD-25

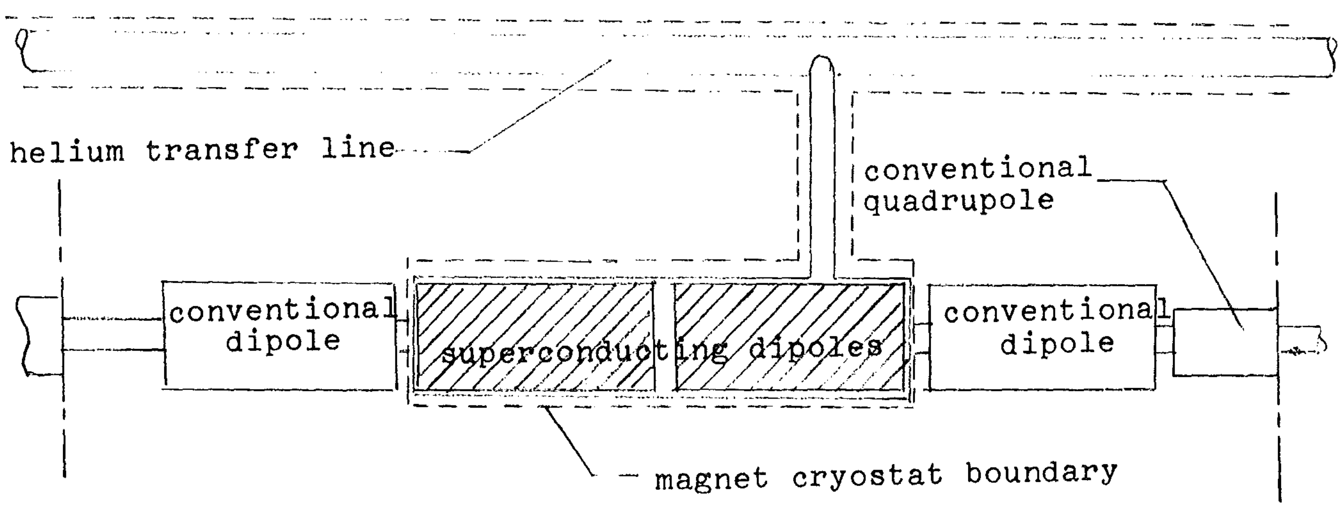
4. M.A. Green, "Magnetic Field Aberrations due to Circulating Currents Induced in Superconducting and Normal Metals" GESSS MD-26 June 2, 1972

Figure 1 Transfer Line and Superconducting Magnet Position in a Normal Half Cell

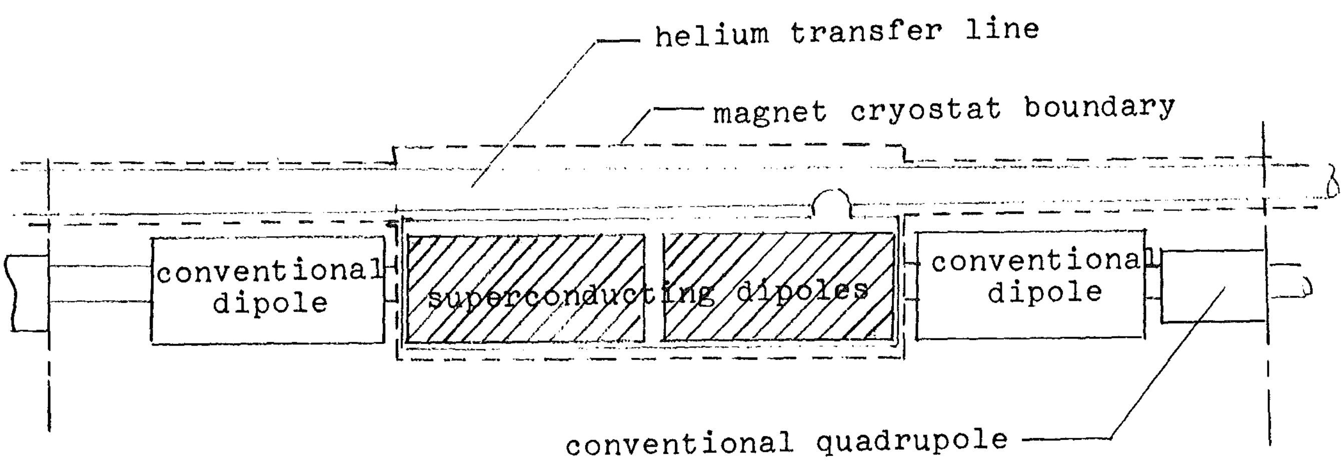
a) 1000 GeV separate ring machine, transfer line inside magnet cryostat



b) 400 GeV missing magnet ring, separated transfer line



c) 400 GeV missing magnet ring, transfer line part of the magnet cryostat



Magnetic Field Aberrations due to Circulating Currents Induced in Superconducting and Normal Metals

Michael A. Green

June 2, 1972

Circulating currents induced by changing magnetic fields will cause aberration in the field produced by pulsed superconducting dipoles and quadrupoles. These circulating currents cause the so-called "residual field" effects and the well known eddy current effects. I divide the aberrations caused by circulating currents into three types of phenomena; residual fields, coupled current fields, and eddy current fields. These three phenomena may have a profound effect on the quality of the magnetic field during injection into a superconducting synchrotron.

The effect of eddy currents, coupled loss effects, and residual fields are lumped together in this report because they have three things in common;

1) The three effects produce aberrations which are important only at low field.

2) The three effects produce predominantly symmetric aberrations[1].

3) The magnitude of the aberration produced by the three effects is directly related to the a.c. loss per cycle produced by the three effects.

The aberrations produced by eddy currents and coupled currents are frequency dependent; residual field aberrations are, on the other hand, independent of the magnet pulsing frequency.

Eddy currents, coupled currents, and circulating currents in the superconductors (the cause of residual fields) all produce magnetic field aberrations in the same way. Eddy currents are circulating currents introduced in normal metals. Coupled currents are nonpersisting eddy currents which are carried by both the normal metal and the superconductor; these currents can behave like eddy currents or superconductor circulating currents, depending on the rate of twist or transposition of the superconductor. The residual fields are generated by currents which circulate in the superconducting material only. These currents persist for very long times; hence, they are a problem even in d.c. magnets.

1. Residual field aberrations

The residual fields are caused by circulating currents in the tiny superconducting filaments of a superconductor. These circulating currents will be present whether the material is twisted or not. If the superconducting filaments have been fully penetrated by the magnetic field, the maximum residual fields will be present. Once the filament has been fully penetrated by the changing field, the magnitude of the residual fields is a function of the local field, not of cycling frequency or flux swing.

The magnitude of the residual generated within a magnet is a function of the superconductor J_c. Thus, residual fields will have a higher absolute magnitude at low fields than at high fields. The 3 T multipole component (T = 1 is a dipole, T = 2 is a quadrupole) of the residual field is particularly high (50 to 90 % of the fundamental multipole number T at the useful aperture radius). This means that the field generated by a synchrotron dipole at injection can have an excessive sextupole or decapole component due to the residual fields generated by circulating currents in the superconducting filaments.

The reasons for the higher multipole structure of residual field can be explained by the use of the doublet theory[2]. Let us start by calculating the magnitude of the field at the center of the filament H_{if} which has been fully penetrated

$$H_{if} \approx \frac{d_f J_c(H,T)}{2}$$

where d_f is the filament diameter and $J_c(H,T)$ the superconductor J_c at the local field H and the local temperature T.

The field outside the filament is directly related to the field inside the filament. If we assume that the filament diameter is small compared to other dimensions, we find that using the doublet theory is a satisfactory thing to do. The magnitude of the field outside of a round filament can be expressed as follows;

$$H_{of} \approx 0.06\ H_{if}\ \frac{d_f^{\ 2}}{r^2}$$

as long as r, the distance from the filament, is much greater than the filament diameter d_f.

The field generated outside a filament carrying circulating currents can be expanded in multipoles. The technique for doing this is discussed in references 2 and 3. The theory given in these references is somewhat simplified; a more complete theory will be published later this year. Even the simplified theory compares favorably with measured data taken in Berkeley[4,5] in 1970 and Rutherford[6] in 1971. Using the simplified theory tempered with experimental results, the following empirical formulas can be developed.

$$\hat{H}_T \approx 0.06\ \frac{d_f}{R_o}\ \frac{J_c(H,T)}{J_{T\ max}}\ H_{max}$$

$$\hat{H}_{3T} \approx \frac{2}{3}\ \hat{H}_T$$

where $\hat{H}_T$ = fundamental residual field magnitude (T = 1 for a dipole, T = 2 for a quadrupole, and so on) (A/m)

$\hat{H}_{3T}$ = the 3 T multipole of the residual field magnitude (the next higher multipole in a symmetrical magnet; note that $\hat{H}_T$ and $\hat{H}_{3T}$ apply at the useful aperture radius) (A/m)

d_f = superconducting filament diameter (m)

R_o = magnet useful aperture radius (m)

$J_c(H,T)$ = superconductor critical current at the local magnetic field H and temperature T (A/m^2)

$J_{T\ max}$ = the maximum transport current density carried by the superconductor filaments when the magnet is excited to maximum field H_{max} (note that $J_{T\ max} \leq J_c(H_{max}, T)$) (A/m^2)

H_{max} = the maximum field generated by the magnet at it's useful aperture at maximum excitation (A/m)

It should be noted that B may be substituted for H in the above equations, if it is desirable to have $\hat{H}_T$ and $\hat{H}_{3T}$, etc. in units of induction instead of field (note that $B = \mu_o H$, $\mu_o = 4\pi \times 10^{-7}$).

In a superconducting synchrotron, the residual field is worst at injection. If we let H_{min} be the injection field, we find that the worst aberration, the N = 3T aberration, will take the following form in a superconducting synchrotron magnet

$$\text{3T multiple ratio} \approx 0.04 \frac{d_f}{R_o} \frac{J_c(H_{min}, T)}{J_{T\ max}} \frac{H_{max}}{H_{min}}$$

The preceding equation is approximately correct if $H_{min} \geq 10\ \hat{H}_T$ and if $H_{min} \leq 0.2\ H_{max}$. The preceding equation even works when H_{min} is of the same order as the penetration field. However, when

H_{min} is of the same order as the penetration field, some care must be exercised in the selection of $J_c(H_{min}, T)$ because of the large variation of H inside the conductor.

Table 1 shows the effect of residual field on magnet field uniformity at injection into the proposed 1000 GeV European superconducting synchrotron. The field uniformity is shown at the useful aperture radius for 3 injection energies and for 4 superconducting filament sizes. During injection, field non-uniformities of 5×10^{-4} to 10^{-3} can be tolerated without corrections. If lumped sextupole and/or decapole correction is applied, a $\Delta H/H$ of $2 - 5 \times 10^{-3}$ may be tolerated.

It is clear from table 1 that injection at 10 GeV into the superconducting machine probably is not possible unless filament sizes of less than 5 microns are used. Continous poleface correction will be needed if the residual field varies badly from magnet to magnet. Injection at 28 GeV is possible with lumped correction elements if the superconducting filament size is reduced below 10 microns. Injection into the machine at 100 GeV is not inhibited even if the superconductor filaments are as large as 10 microns. It is clear that low field critical current is important from the standpoint of aberrations due to residual fields. Measurement of low field critical current densities at LRL Berkeley indicate that they can be very high (5×10^{10} A/m^2 in 3 μm filaments at an average induction of 1 to 2 KG)[7]. Data taken at LRL indicates that low field critical currents can increase as the superconductor is drawn into finer and finer filaments. The development of high field β tungsten material, such as V_3Ga or Nb_3Sn, will probably not improve the residual field aberration problem.

Of the three types of a.c. loss related aberrations, the residual field aberrations may well be the worst. Eddy currents and coupled losses can be limited by reducing the pulsing frequency of a superconducting synchrotron. It is clear that residual field aberrations cannot. There is little that one can do to reduce residual field aberrations except by further reduction of super-

Table 1 Sextupole field aberration in the European 1000 GeV synchrotron dipole magnets at injection due to residual field as a function of filament size and injection energy (note $J_{T\ max} = 10^9$ A/m^2, $B_{max} = 4.5$ T, and $R_o = 4 \times 10^{-2}$m)

a) Injection field and low field J_c as a function of injection energy

	Injection Energy		
	10 GeV	28 GeV	100 GeV
Injection Field	0.045 T	0.125 T	0.45 T
$J_c(H_{min}, T)$	10^{10}A/m^2	8×10^9A/m^2	5×10^9A/m^2

b) Residual field aberration versus injection energy and filament size

	H_3/H_{min} multiple ratio *		
Filament Size	10 GeV	28 GeV	100 GeV
1 μm	> 10^{-3}	3×10^{-4}	5×10^{-5}
2 μm	> 2×10^{-3}	6×10^{-4}	10^{-4}
5 μm	> 5×10^{-3}	1.5×10^{-3}	2.5×10^{-4}
10 μm	> 10^{-2}	3×10^{-3}	5×10^{-4}

* at the useful aperture radius of $R_o = 0.04$

conductor filament size and the raising of the lowest operating field of the magnet. The production of materials which have low, low field critical currents, but high, high field critical currents would dearly be appreciated. Recent work by some of the superconductor manufacturers indicate there is some promise for tailoring the material to have low, low field critical currents.

2. Eddy current aberrations

Ordinary eddy currents have been the cause of magnet aberrations in conventional fast cycling synchrotrons for years. The magnitude of an eddy current is proportional to the impressed voltage and inversely proportional to the resistance of the circuit in which the current flows. The field generated by an eddy current is proportional to the magnitude of that current. Thus, we find that;

$$H_{eddy} \approx \text{constant} \frac{\dot{B}d}{\rho_v}$$

$$\approx \frac{\tau_e}{t_{rise}} H_{max}$$

where

$$\tau_e \approx \frac{\mu_o d}{2T\rho_s}$$

$$\mu_o = 4\pi \times 10^{-7}$$

$T = 1$ for a dipole, $T = 2$ for a quadrupole

The first of the preceding equations relates the eddy current field to the rate of induction change $\dot{B}$, the critical dimension d, and the volume resistivity ρ_v. The constant in the first equation may be derived exactly for an explicit case or may be derived empirically from measured data. The second equation relates approximately the value of the eddy current field to the maximum applied field H_{max}, the magnet rise time t_{rise}, and the eddy current time constant τ_e. The eddy current time constant is a function of d, and the surface resistivity ρ_s (the surface resistivity for a thin-walled tube of diameter d and wall thickness s is $\rho_s = \rho_v/s$. The surface resistivity for a wire or rod of diameter d is $_s = 4\rho_v/d$). For typical metals, τ_e may vary from 10^{-5}sec. to 10 sec. According to basic eddy current theory[8,9], the field generated by the eddy currents has the same structure inside the metal as the field which caused the eddy currents. (No new multipoles are created; the magnitude of higher multipoles compared to lower is decreased.) What this says, in essence, is that if one has a single metallic bore tube in a pure dipole field, the eddy currents generated in the bore tube will generate a pure dipole field inside the tube. Thus, a simple cylindrical metal bore tube will cause no higher multipole aberrations. If, however, the simple metal cylinder is replaced by a series of wires insulated from one another, higher multipoles will be generated. The reason for this is that a pure dipole field is generated inside the wire, but outside the field decays. The decay itself may be expressed in terms of higher multipoles. Magnetic doublet theory can be used to calculate the multipole structure of the eddy current field.

Eddy currents are symmetrical if, and only if, the metal pieces which carry the eddy currents are distributed symmetrically about the origin. Most meaningful symmetrical magnet designs will involve a symmetrical distribution of the metal about the origin.

Eddy currents which have low power levels also produce very low fields. This is because the dynamic resistivity of a superconductor is several orders of magnitude lower than the resistivity of normal metals. Thus, if the hysteresis loss in a magnet exceeds the eddy current losses, the eddy current aberrations will be small compared to the residual field. This is another way of saying that eddy current induced field aberrations will be no trouble in well designed pulsed superconducting magnets.

3. Coupled current aberrations

Multicore superconductors will exhibit coupled current effects[10,11]. These effects are due to large superconducting normal metal eddy currents. When magnetic flux moves through a matrix of superconductor and normal metal, large eddy-like currents are generated. These currents are carried down one side of the conductor in the superconductor, across to the other side of the conductor through the normal metal, up the other side through the superconductor, and then across to the starting point.

These circulating currents do not behave precisely like eddy currents. For instance, when the rise time is much shorter than the coupled current time constant, the magnitude of the coupled current is limited by the J_c of the superconductor. When this happens, the coupled currents behave like the circulating currents found in the filaments. However, when the field rise time is longer than the coupled current time constant, there is no limitation imposed on the coupled current by the superconductor. In this case, the coupled current behaves just like a normal eddy current.

The time constants of these circulating currents vary with the length of untwisted conductor. Twisting the conductor, in effect, breaks up the conductor into pieces (as far as coupled currents are concerned), each with a short time constant for these coupled currents. Short pieces of multicore superconductor (twisted or transposed conductors behave like conductors cut in lengths equal to the twist length) will have the ability to withstand large changes of field without large coupled currents. The concept of a critical twist length ℓ_c can be introduced here. ℓ_c is associated with a particular $\dot{B}$ in the material and is calculated using the following equation:

$$\ell_c^2 \approx \left| \frac{2 \text{ Res } \lambda \; J_c d_f}{\dot{B}} \right| \; \left| \frac{w}{w+d_f} \right|$$

where Res = average resistibility of the normal matrix between filaments (ohm m)

J_c = current density in superconductor (A/m^2)

d_f = filament diameter (m)

$\dot{B}$ = flux change (T/sec)

w = average distance between strands (m)

λ = square root of the packing factor $(\frac{1}{s+1})^{1/2}$

If the twist length ℓ is much greater than ℓ_c, then the conductor will see coupled currents in all their glory. Frequency dependence will be slight; the whole conductor will carry currents, and the coupled current aberration will be much larger than the residual field aberration. The magnitude of the coupled current aberration can be related to the residual field which was calculated in section 1. This relationship is as follows:

$$H_{\substack{\text{coupled}\\ \text{current}}} \approx \frac{d_s}{d_f(s+1)} H_{\text{residual}}$$

when $\ell \gg \ell_c$. In the preceding equation, the following symbolic notations were used;

d_s = the conductor diameter

d_f = the superconducting filament diameter

s = the ratio of superconductor to normal metal

$H_{residual}$ = the residual field due to current circulating in the superconducting strands

$H_{\text{coupled current}}$ = the field due to the coupled currents in the superconductor.

In general, one does not want large coupled currents for a.c. loss and stability reasons. It therefore appears desirable to make $\ell \ll \ell_c$, if possible. In the region where $\ell \leq \ell_c$, the following approximate equation applies

$$H_{\text{coupled current}} = \frac{8}{3} \left(\frac{\ell}{\ell_c}\right)^2 H_{\text{residual}}$$

In a slow cycling superconducting synchrotron, it is not always desirable, for economic reasons, to minimize the coupled currents. There are two reasons for this:

1) There should be a minimum installed refrigeration which is two or three times the static heat load. The reason for this is that adequate refrigeration should be available for cool-down and emergencies. A reduction of the a.c. losses to below twice the static heat load has little effect on cost. A relatively lossy conductor can be tolerated on long cycle time machines.

2) Low loss superconductors are expensive to produce. Superconductors which produce low residual and coupled current fields have, by definition, low a.c. losses. Machines with cycle times in excess of 10 seconds can have higher a.c. losses per cycle than can machines with shorter cycle times. The increased cost of refrigeration which results from increased hysteresis and coupled losses can, in many casses, be more than compensated by the cost saving which comes from not having to buy a complicated superconductor[12].

4. The missing magnet machine versus the separate ring machine

The missing magnet machine has, by definition, a low injection energy of 10 GeV. A result is that residual and coupled current fields become important during injection. A complicated low loss superconductor becomes necessary regardless of the cycle time. The filament diameter in the superconductor must be less than 5 microns. The conductor must be a fully insulated three component conductor (soldered conductor would not be acceptible because of high coupled currents). The fully insulated braid conductor is susceptible to damage and insulation failure. The fully insulated braid is not dimensionally stable during winding. Field uniformity is more difficult to achieve and coil winding costs are increased.

Correction of the injection field aberrations in the missing magnet machine is probably possible as long as there is no variation of these aberrations from magnet to magnet. In order to have no variation from magnet to magnet, the superconductor must have a uniform low field critical current and uniform coupled current properties throughout the machine. I find this difficult to achieve even if the superconductor is supplied by one manufacturer (the high field properties from roll to roll of supposedly identical superconductor can vary 10 - 20 %. I would expect the same variation in low field properties). Variations between a number of manufacturers would be far greater. If it were possible to require the superconductor manufacturer to deliver conductors with uniform low field properties, one would most certainly pay for the privilege. I have serious doubts about whether it is possible to inject into a missing magnet machine at 10 GeV without increasing it's cost by at least 20 million Swiss Francs.

A separate ring machine which has an injection energy of 100 GeV or more has little or no low field aberrations due to various kinds of circulating currents. The superconductor properties can be selected on the basis of a.c. properties, high field properties, and cost. The optimum conductor can be used. In short, if one wants to avoid the low field aberration problem and many other problems, one should build the separate ring machine.

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Cryopumping in a Superconducting Synchrotron

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It has long been felt that one of the advantages of a superconducting synchrotron is that one may obtain a very good vacuum in the accelerator while saving a large amount of money on the accelerator vacuum system. The reasons for this are:

1) The magnets may have a cold bore. This cold bore cryopumps at very high rates and does not outgas.

2) The high vacuum pumping system (ion pumps diffussion pumps, etc) can be eliminated entirely because cryopumping may begin at relatively high pressure (10^{-3} Torr).

3) The cost of the cryogenic pumping system is negligible because a temperature of 4 to 4.5°K has to be provided to cool the magnet anyway.

The above statements are essentially true. However, one must look at the cryogenic process to see that the cryopumping system does not interfere with the operation of the accelerator. (An example of what I mean is the build up of charge on a thin layer of condensed gases on the vacuum chamber wall. This charge build up is the cause of one of the instabilities which has been found in alternating gradient synchrotrons.) This report describes the cryopumping process and how vacuums of better than 10^{-11} Torr can be achieved in the accelerator vacuum system (10^{-11} Torr is 3 or 4 orders of magnitude better than what is required for a normal alternating gradient machine. As beam currents go up, machine performance becomes more dependent on a good vacuum).

This report discusses the equipment necessary to produce a good vacuum without thick deposits of cryogenic gases on the vacuum chamber walls. The report also discusses the vacuum pump down cycle and it's relationship to the cooldown cycle of the superconducting magnet. Finally, the report will try to assess some of the problems which will occur during operation.

1. Basic Theory for a Cryogenic Pumping System

Cryopumping is literally the removal of gases by condensation or cryoabsorption on a cold surface. The pumping speed of such a system is limited by the molecular velocity of the gas to be pumped[1]. If we assume that a gas has a Maxwellian distribution of velocity, the average molecular velocity of a gas $\bar{v}$ can be stated as follows:

$$\bar{v} = \left(\frac{8RT}{\pi M}\right)^{1/2}$$

where $\bar{v}$ = the average gas molecule velocity (cm/sec)

R = the universal gas constant (8.314×10^7 erg $^oK^{-1}$ mole^{-1})

T = the gas temperature (^oK)

M = the gas molecular weight

This average gas velocity $\bar{v}$ is greater than the gas sound speed c which is:

$$c = \left(\frac{\gamma RT}{M}\right)^{1/2}$$

where γ is the ratio of specific heats ($\gamma = 7/5$ for diatomic gases such as H_2, N_2, and O_2, and $\gamma = 5/3$ for monatomic gases such as He, A, and Ne). The maximum pumping speed is directly related to the average gas velocity by the distribution function. If one assumes that only one-half the molecules in a given space can travel toward a pumping surface and if one assumes a Gaussian distribution function (a cos ϕ over a half sphere), one finds that the average speed of the pumped gases $\tilde{v}$ is:

$$\hat{v} = \frac{\bar{v}}{2} \int_0^{\pi/2} \sin\phi \cos\phi \, d\phi$$

$$\approx \frac{\bar{v}}{4}$$

The average pumping speed in liters per second for one square centimeter of surface can be derived from the preceding equation. The resulting equation for s, the pumping speed in liters sec^{-1} cm^{-2}, is[2]:

$$s = 3.64 \left(\frac{T_g}{M}\right)^{1/2}$$

Table 1 The Theoretical Pumping Speed of a Cryopumping Surface as a Function of the Gas Temperature and the Type of Gas

Maximum Pumping Speed ($l\ s^{-1}\ cm^{-2}$)

GAS	TEMPERATURE T_g 293°K	77°K	20°K
CO_2	9.4	4.8 +	2.4 +
H_2O	14.7	7.5 +	3.8 +
N_2	11.8	6.1	3.1 +
O_2	11.0	5.7	2.9 +
A	9.9	5.1	2.6 +
Ne	13.9	7.2	3.6
H_2	44.2	22.8	11.5
He and D_2	31.4	16.1	8.2

\+ Very little of this gas can exist in gaseous form at this temperature. The partial pressure for this species is less than 10^{-8} Torr.

Table 1 shows the maximum theoretical pumping speed for various gases at various temperatures. The actual pumping speed of a surface may be represented as follows:

$$s_{actual} = s\, A_s\, \alpha\, [1 - \frac{P_e}{P}]$$

$$P_e = \sqrt{\frac{T_g}{T_s}}\, P_s$$

where s = maximum theoretical pumping speed (1 sec^{-1} cm^{-2})

A_s = the surface area (cm^2)

α = the gas sticking coefficient (for all practical purposes α = 1 for all gases except helium. α = 1 for helium when the pumping surface is a cryoadsorber or cryotrapping substance)

P_e = the ultimate pressure measured at T_g (Torr)

P = the pressure in the pump (Torr)

T_s = the temperature of the cryopumping surface

P_s = the lowest equilibrium pressure of the vacuum next to a cryopumping surface at a temperature T_s

For air gases, the pumping speed of the magnet cold bore which is at a temperature of 4.5 - 5 °K is near the theoretical maximum as long as the vacuum pressure is above, say, 10^{-13} Torr. The equilibrium pressure for hydrogen is between 10^{-6} and 10^{-7} Torr. This pressure can be reduced to 10^{-12} Torr by the addition of a suitable cryoadsorption surface such as zeolite or activated charcoal. The only problem gas is helium. A cryoadsorber will pump helium; good pumping is best obtained at very low temperatures, say $2^{o}K$.

The vacuum chamber wall should not be permeable to helium gas. Fortunately, nature is kind to us in this respect; the permeability of metals and even epoxy glass composites becomes quite low at liquid helium temperatures. Still, there probably is the need for an occassional ion pump or low temperature cryopump (say a 2 - $2.5^{o}K$ cryoadsorption pump) to pump the small amount of helium which will still permeate through the vacuum chamber walls or through minor leaks in the system.

2. Separated Cryogenic Pumps

Using the magnet bore as a pump should permit one to maintain pressures of lower than 10^{-11} Torr. Let us now look at the pumping speed of a separated cryogenic pump which can pump hydrogen and helium as well as the air gases. It must be assumed that the temperature of the vacuum chamber being pumped is at or near room temperature.

Let us assume that a high pumping speed is required in the vacuum chamber. When the pumping surface becomes large (the pumping surface in this case is the entrance to a tube which connects the vacuum chamber with the pump), the radiation heat load to the cryogenic pumping surface becomes an important factor in determining the refrigeration requirements for the pump.

The radiation streaming onto the cryopumping surface can be reduced by putting a radiation shield between the radiation source and the cryopumping surface. Using Monti Carlo calculations and free molecular flow conditions, it is difficult to build a radiation shield which doesn't stop over 3/4 of the molecular passing by it[3]. Furthermore, each molecule which strikes the cryopumping surface has also struck the shield at least once; this reduces the pumping speed still further. The effective pumping speed, s_{eff}, of the hole in the vacuum chamber thus becomes

$$s_{eff} = \beta \, s_{actual}$$

$$= \beta \, A_s \, s$$

where ß typically is less than 0.25. (ß = 0.23 applies for cheveron type shield[2,3]. The effective ß for a system including piping is typically 0.1 to 0.15.)

We find for a separated pumping system, actual pumping speeds of 1.0 to 2.0 $l\ s^{-1}\ cm^{-2}$ at the junction of the vacuum chamber with the pump. This is still very good; this is quite a bit higher than for conventional high vacuum pumping systems. One can increase this number to 4.8 to 9.0 $l\ s^{-1}\ cm^{-2}$ for room temperature air gases, if radiation heat loads are no problem. When on takes away the shield, the equilibrium pressure will probably rise to the 10^{-9} to 10^{-10} Torr range.

3. Special Problems which Arise from using the Superconducting Magnet Bore as a Cryopump

We have established the fact that cryopumping is a good way to produce high vacuums for a synchrotron. This becomes even more evident when one considers a ring which has 80 - 85 percent of the vacuum chamber surface at 4.5 to 5^{o}K. This vacuum chamber surface does not outgas; instead, it becomes a collector of gases. It is this process of collecting gas that presents a special problem to the superconducting synchrotron designer.

Starting a cryogenic pump is possible at a pressure of 1 atm. It is not practical to do so for two reasons:

1) The layer of cool condensed gases would become thick in a very short time.

2) The consumption of refrigeration would be very high because of the high heat of vaporization and fusion of the air gases.

221 J must be removed from 1 gram air to cool it from 300°K to it's boiling point; an additional 227 J must be removed per gram to liquify and freeze the air. As a result, cryopumping is not started until the pressure has been pumped down to 10^{-3} or 10^{-4} Torr, using a roughing pump system. Even when the pressure is 10^{-3} Torr, 8.4 mW/cm^2 is required to cryopump the air.

The density of air at 10^{-3} Torr is 1.6×10^{-9} g cm^{-3}; the density of frozen air is 0.8 g cm^{-3}. Let us look at the vacuum chamber. If the vacuum chamber diameter is 50 mm (this diameter applies for a separate ring machine), the volume of the chamber is 1960 cm^3/m, and it's surface area is 1570 cm^2 m^{-1}. If all of the vacuum chamber surface is cryopumped at once, an even gas layer of 2.5×10^{-9} cm thickness would form. This thickness is clearly acceptable. Unfortunately, the whole surface does not crypump at the same time. One part of the magnet will get cold before the rest of it does. To avoid local build-up of frozen gases, it appears to be desirable to reduce the pressure to, say, 10^{-6} Torr before the magnet bore tube begins to cryopump.

A reduction of vacuum system pressure from 10^{-3} to 10^{-6} or 10^{-7} Torr is easily obtained using a few separated cryoadsorption pumps per superperiod. Only 3 to 6 pumps per superperiod are needed to do this. A normal room temperature vacuum system must have pumps which are closely spaced (every 30 to 50 meters) because the vacuum system is conductance limited. The rate of outgassing from a room temperature wall is high enough to cause a build-up of pressure as one moves down the chamber away from the pump. The cryogenic pump does not suffer any less from this build-up as long as the magnet bore tube is at room temperature. However, as the magnets are cooled, the vacuum chamber wall outgasses less and less. The widely spaced cryopumps performance becomes less limited by outgassing as the temperature drops; the pressure will drop as the magnets cool. By the time the magnet bore tube temperature drops to 100°K, a vacuum which is in the 10^{-6} Torr range can be achieved by using only a few of the high speed cryoadsorption pumps.

When the magnet bore has cooled sufficiently, the accelerator vacuum will drop quickly to below 10^{-11}, provided there are no leaks. Small cans of activated charcoal or a molecular sieve can also be attached to the end of each magnet unit (say, every half cell a separation distance of 32 m). This activated charcoal or molecular sieve will cryopump out the hydrogen and much of the helium that may remain in the vacuum chamber.

It is useful to look at the rate at which gases will build up on the surface of the bore tube. In the center of a magnet bundle, the equilibrium pressure of the system will be below 10^{-12} Torr. At the magnet ends near a long straight section, which has room temperature vacuum pipe, one might expect the pressure to rise above 10^{-10} Torr. The rate of gas deposition inside the magnet at it's center can vary from $2 - 4 \times 10^{-15}$ g sec^{-1} cm^{-2}, depending on the pressure and the gas species. At the ends of a magnet section near the long straight sections, this rate of deposition may rise to 1×10^{-11} g sec^{-1} cm^{-2}. Even at the end of the magnets, it would take 8×10^{7} seconds (2.5 years) to build up a layer of gas 10 μm thick. One should be able to maintain vacuums at the end of a long straight section which are much better, the 10^{-9} Torr. (The 10^{-11} g s^{-1} cm^{-2} deposition rate is based on a pressure of 10^{-9} Torr.)

4. The Hardware required for a Cryogenic Vacuum System

The accelerator vacuum system consists of a roughing system, a small number of cryoadsorption pumps (say 24 for the whole ring), and the vacuum chamber wall itself. Additional vacuum pumping will probably be required in the long straight sections.

The roughing system can consist of both mechanical and turbomolecular pumps. Any mechanical roughing system which is capable of pumping the machine vacuum down to 10^{-3} Torr would be suitable. The same sort of roughing system which is proposed for the conventional ring will do. A similar system of roughing pumps will be required to pump down the magnet cryostat vacuum. The cryostat vacuum and the accelerator vacuum should not be interconnected. Each superperiod should be capable of being valved off from adjacent superperiods. One should be able to isolate the long straight sections as well. Figure 1 illustrates the isolation valves required for each superperiod.

Vacuum pipe for the beam is only required in the straight sections. In a completely filled separate ring, the magnet cryostats will form 75% of the vacuum system. I currently advocate that the short straight section at the beginning of each half cell consists of vacuum-superinsulated tube. The bore would remain cold in the short straight section. Whether one can do this successfully would depend on whether beam sensor and beam correction elements can be built to operate at 4 to 5 ^{o}K.

Cryoadsorption pumps may be located every five cells in regions which have superconducting magnets. One cryoadsorption pump can be located at each end of the long straight section. In addition, one could, if desired, put two more cryoadsorption pumps in each long straight section (see Figure 2). The cryoadsorption pumps could be designed to deliver 400 - 500 l sec^{-1} of room temperature air gases. The refrigeration required for such a pump (without nitrogen temperature shielding) is of the order of 20 watts. As the temperature of the magnets goes down, the pumps which are located within magnet bunches will require less and less refrigeration. The use of shield pumps in the long straight sections could reduce the refrigeration load to 5 watts per pump. Thus, the total refrigeration required for cryopumping the system is less than 200 watts, which can be supplied from the magnet cooling system.

A separate roughing system is required for the magnet cryostats. Each cryostat would have it's own isolating valve. Roughing vacuums of 10^{-3} to 10^{-4} Torr are adequate for beginning the cool-down. As the cryostat cools down, it begins to cryopump. This process is further enhanced if a bag or two of molecular sieve is connected to the cold part of the cryostat in the vacuum sieve.

Figure 1: The minimum number of vacuum isolation valves required per superperiod in a 1000 GeV separate ring superconducting synchrotron.

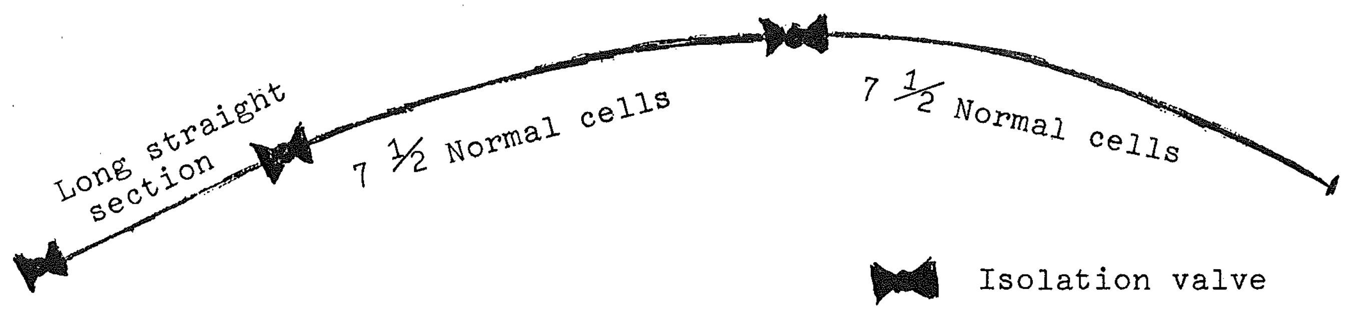
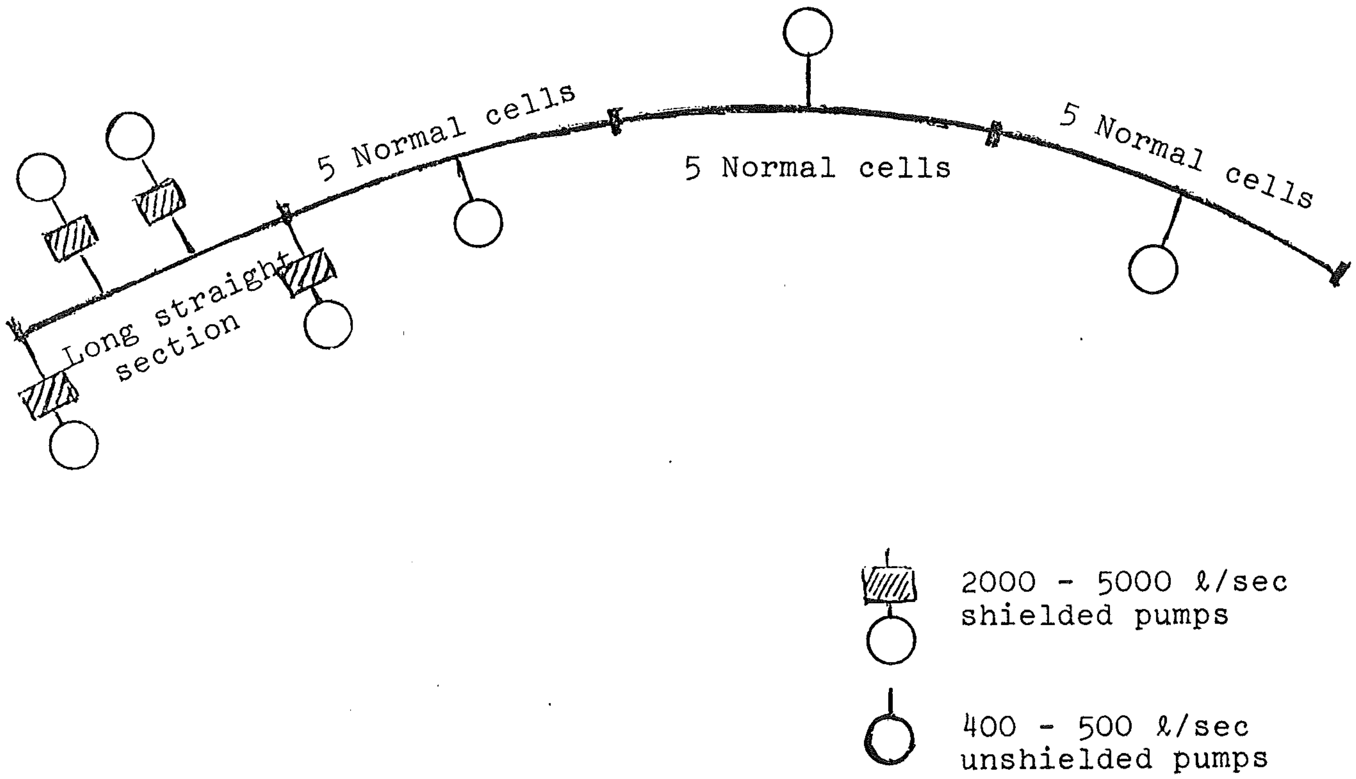


Figure 2: Cryoadsorbtion vacuum pump distribution per superperiod.



As the cryostat temperature drops below 70^{o}K, the vacuum becomes very good. Vacuum of 10^{-7} Torr can be maintained almost indefinitely in a cryostat vacuum system. The cryodeposits, which collect over a period years, become a problem only when the cryostat is warmed up. It is standard cryogenic practice to put a rupture disc or relief valve on the cryostat vacuum. The same technique should also be used on the accelerator vacuum system.

5. Vacuum System Cost

It is useful to compare the vacuum system costs for a conventional and superconducting synchrotron. The cost estimate is based upon MC-60 [4] numbers. The cost estimate involves only the accelerator. The conventional ring costs come straight from MC-60 [4]. The superconducting ring is a 1000 GeV separate ring machine. The superconducting ring vacuum system also includes the system for pumping down the magnet cryostat vacuum spaces (see Table 2).

A mixed magnet machine already has a roughing system and a high vacuum system. Whether or not it is desirable to replace the ion pumps with cryogenic pumps depends on the technical requirements of the system. Cold bore magnets in a mixed magnet ring will be capable of cryopumping vacuums which are better than 10^{-9} Torr. The cost of new components for the mixed magnet machine vacuum system would be about 3 million Swiss Francs, including the roughing system for the cryostats.

In conclusion, one can say that using the superconducting magnet bore as a high vacuum pump is not only technically feasible, but economically desirable as well. The use of the magnet bore as a cryopump permits accelerator vacuums which are three orders of magnitude better than is planned for the conventional 300 GeV machine. In a conventional machine, the greatest cost item in the vacuum system is the high vacuum piping itself and it's various valves. The superconducting magnet bores provide the high vacuum pumping virtually for free. (It costs more to put a warm bore into the cryostat.) The build-up of cryodeposits, which can

Table 2 A Comparison of the Cost of the Vacuum System for a Conventional 300 GeV Accelerator with a 1000 GeV Superconducting Accelerator

Component	Vacuum System Cost (Thousands of Swiss Francs) Conventional 300 GeV Machine	Superconducting 1000 GeV Machine ≠
Accelerator Roughing Units	900	900
Vacuum Pipe	6 000 +	3 000
Ion High Vacuum Pumps and Power Supplies	2 300	100
Cryoadsorption Pumps	-----	400
Measurement and Leak Detection	1 000	1 000
Installation	1 900	1 000
Total Accelerator Vacuum System	12 100	6 400
Cryostat Roughing System	-----	1 000
Total Vacuum System Cost	12 100	7 400

≠ A separate ring 1000 GeV machine

\+ This price does not include 1 100 thousand Sw Fr for the straight pieces and ancillaries at stage A [4].

adversely affect the beam, appears to be easily prevented. The use of the superconducting magnets as a cryopump appears to be desirable, even in a mixed missing magnet machine.

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Residual Field and Injection into a Superconducting Synchrotron

Michael A. Green
30 November 1972

This report discusses further the problem of residual fields which are caused by circulating currents in the superconductor of a superconducting dipole or quadrupole magnet. A theory for calculating these fields is presented in the proceedings for the Brookhaven Magnet Conference.[1] The theory presented there is not totally adequate. Further discussion of the inaccuracys of the theory is presented here.

Several methods for dealing with the residual field during injection into a superconducting synchrotron are discussed here. These methods include: 1) altering the magnet cycle to reduce the magnitude of residual field effects at injection, 2) shuffling of superconducting magnets to take care of the magnet to magnet variation of residual field, and 3) shuffling the superconductor in the superconducting cable. In conclusion, residual field should not prevent injection into a superconducting 1000 GeV SPS machine at energies as low as 10 GeV. However, special precautions must be taken to avoid problems which are caused by the residual field.

Residual Field Theory

The theory for residual field, which will be published in the proceedings of the Brookhaven Magnet Conference, predicts the multipole structure of the residual field quite well.[1] This theory does not predict the actual magnitude of the field correctly, even when the superconducting filaments are small. It is known that the J_c of a type II superconductor rises sharply as the local field drops to H_{C1}, the lower critical field.[2] Type two superconductor theory suggests that $J_c \to \infty$ as $H \to H_{C1}$ going down; the integral under the J_c vs H curve remains finite. As result, in order to calculate the magnitude of the residual field correctly, a good understanding of the low field J_c in the superconducting filaments is needed.

On the other hand, we find that the multipole structure of the residual field is due almost entirely to the orientation of the circulating current. The orientation is influenced strongly by the pattern of the flux lines in the magnet when it is charged. On the other hand, the magnitude of the residual field is due to low field J_c and the distribution of the current in the filament. The theory for residual fields was programed on the Karlsruhe IBM 360. The results show the general sort of behavior that was observed on the Berkeley[3] and Rutherford[4] dipole Magnets. The multipole structure of the residual field in the Berkeley dipole is compared with theory in Table 1.

Table 1: A comparison of measured residual field with theory in the Berkeley dipole (measurement taken in 1970).[3]

Multipole Number	Multipole Ratio* No Iron Theory	Measurement	Iron Theory	Measurement
1	1.000	1.000	1.000	1.000
2	-	0.011	-	0.093
3	1.098	1.274	0.910	0.947
4	-	0.036	-	0.029
5	-0.151	-0.162	0.001	0.060
6	-	0.025	-	0.023
7	0.088	0.101	0.089	0.057
Dipole component of induct.	19.0 G**	21.0 G	31.3 G**	38.6 G

* at 70% of the coil radius, of 5.22 cm

**The agreement is due to the fact a high low field J_c is chosen. There is a factor of 2.2 error when the predicted penetration field is compared with the measured penetration field.

Table 1 shows good agreement when one considers that the random noise of the measurements had a magnitude of 0.3 - 0.5 G. The agreement of the magnitude of the residual field results from the J_c vs H profile chosen for the material. It should be noted that the theoretical penetration induction of 4.5 kG does not agree with the measured value of 2.1 kG. This lack of agreement is consistant when one compares probable J_c vs H behavior of the material with the model used in the computer program. I feel confident that the theory can be improved enough to predict the magnitude of the residual field within 20 - 25 percent.

The residual field theory may do a much better job of predicting residual field at 450 - 900 G than it does when the field is absent. Considerably more data is needed to varify this contention. It is hoped that additional experimental data can be gotten from AC-4. The residual field is probably quite accurately predicted by the theory when the magnet central field is above 1.0 kG. The typical hysteresis behavior seen in various experiments is readly predicted by theory. Figure 1 shows a typical hysteresis loop which can be generated by the residual field (it should be noted that Fig. 1 is computer generated). The hysteresis loop shows the effect of J_c vs H and the effect of the transport current. I do not believe that the hysteresis loop is correct at very low fields. However, it may be used to predict the kind of behavior that can be expected.

Controling the Magnitude of the Residual Field by Altering the Magnet Cycle

According to theory changing the magnet cycle can improve the residual field problem. If one looks at Figure 1 one sees that a $\dot{B}$ reversal (a change from negative to positive dB/dt) caused by an current reversal will be followed by a reversal of the residual field. The residual field is caused by previous $\dot{B}$ in the superconductor. As the reversed $\dot{B}$ penetrates the conductor, so do reversed circulating currents, hence the residual field is changed. Somewhere during this reversal (see Fig. 1) the magnitude of the residual field goes to zero. If

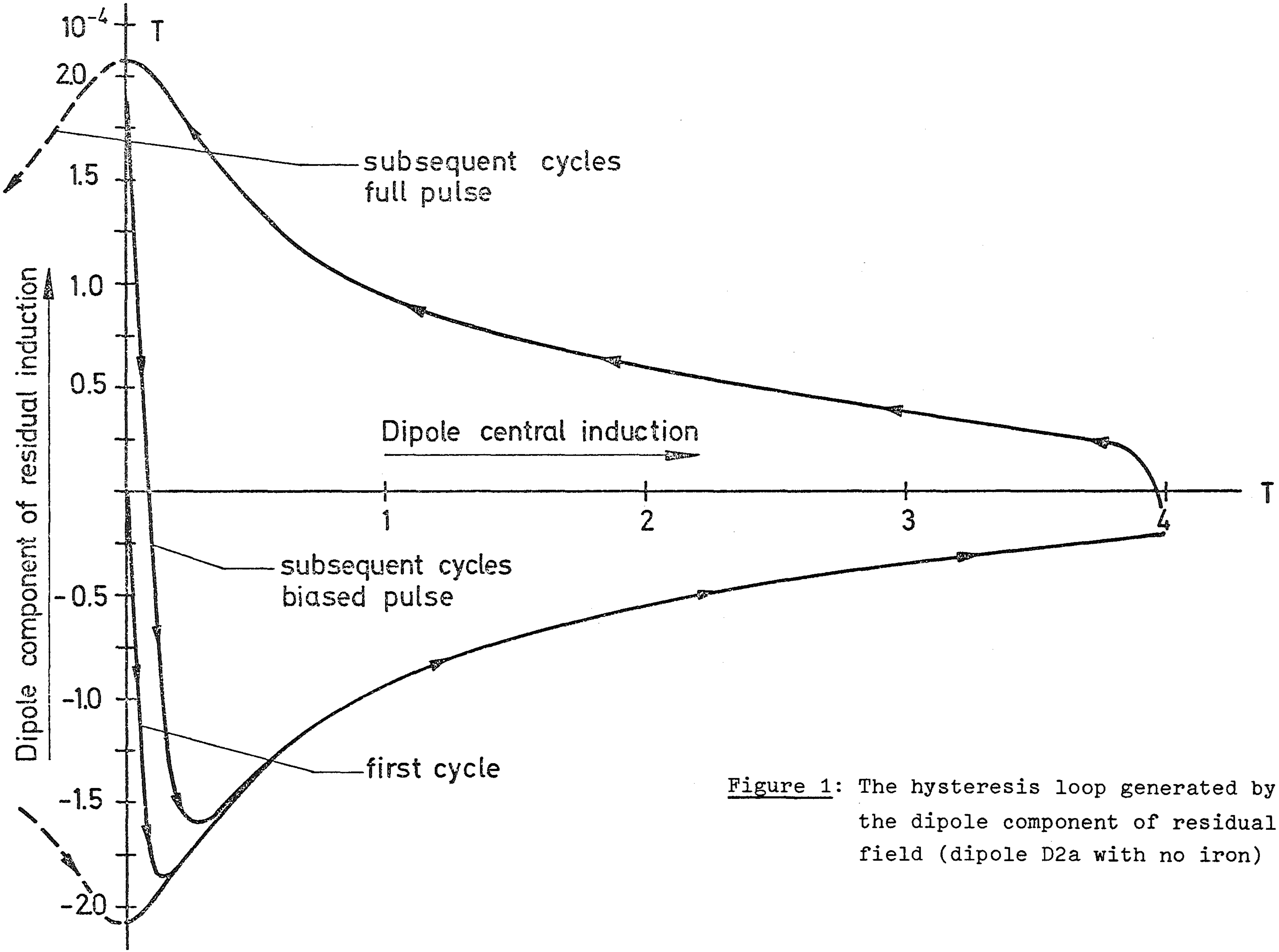


Figure 1: The hysteresis loop generated by the dipole component of residual field (dipole D2a with no iron)

injection can be made to correspond to a point where the magnitude of the residual field is low, then the field due to circulating currents can be reduced over the whole range from injection to transition in a superconducting synchrotron.

Two magnet cycles are illustrated in Figure 2. The first cycle is one where the field in pulsed from + 450 G to + 45 kG and back. There is a pause (or front porch) at 450 G' for injection. The second cycle is one where the field is pulsed from - 200 G to + 45 kG and back. A pause in this cycle occurs at - 200 G and + 450 G; the latter pause is where injection occurs.

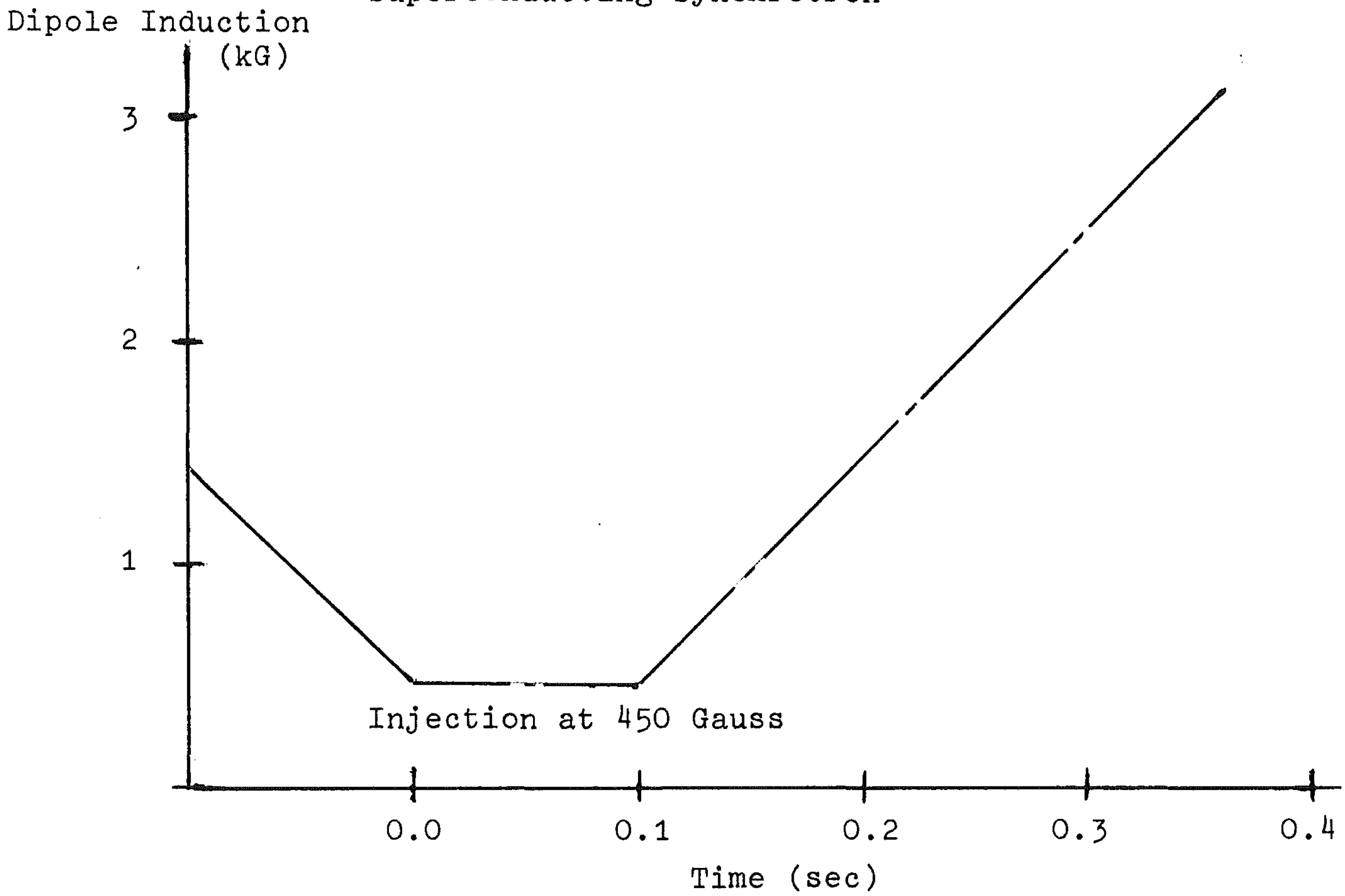
The effect of this cycle change, shown in Figure 3 is rather dramatic. According to residual field theory programed at Karlsruhe cycle 2 has a factor 22 lower sextupole than cycle 1 at a field of 450 G. The reduction of the dipole is not as impressive, a factor of 15. Table 2 compares cycle 1 and cycle 2 residual induction aberation as a function of induction. This table compares the dipole and sextupole components of residual field. The data in this table is given in terms of Ratios residual dipole to transport current dipole (C_1''/C_1') and residual sextupole to transport current dipole (C_3''/C_1'). Note that C_1'' and C_3'' are the dipole and sextupole components of residual field at 75% of coil bore and C_1' is the transport current dipole. The C_n'' and C_n' apply in the following complex field expansions

$$H^*(z)_{residual} = \sum_{n=1}^{\infty} C_n'' \left(\frac{z}{r_o}\right)^{n-1}$$

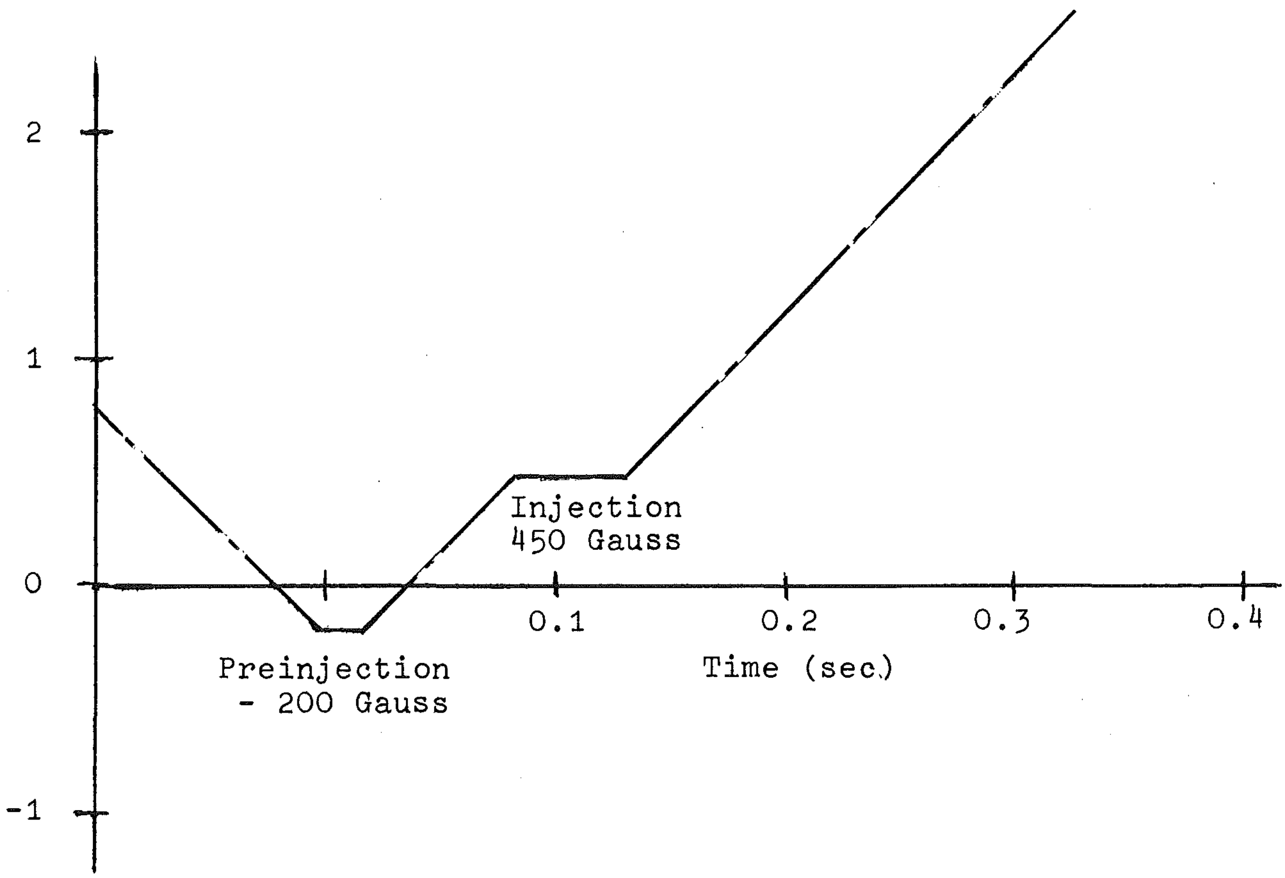
$$H^*(z)_{\substack{transport\\current}} = \sum_{n=1}^{\infty} C_n' \left(\frac{z}{r_o}\right)^{n-1}$$

C_n'' and C_n' are defined in the Brookhaven Magnet Conference paper. $r_o = .75\ r_{innercoil}$.

Figure 2: Two magnet cycles near injection into a 1000 GeV superconducting synchrotron



a) Cycle 1 "The high residual field cycle"



b) Cycle 2 "The low residual field cycle"

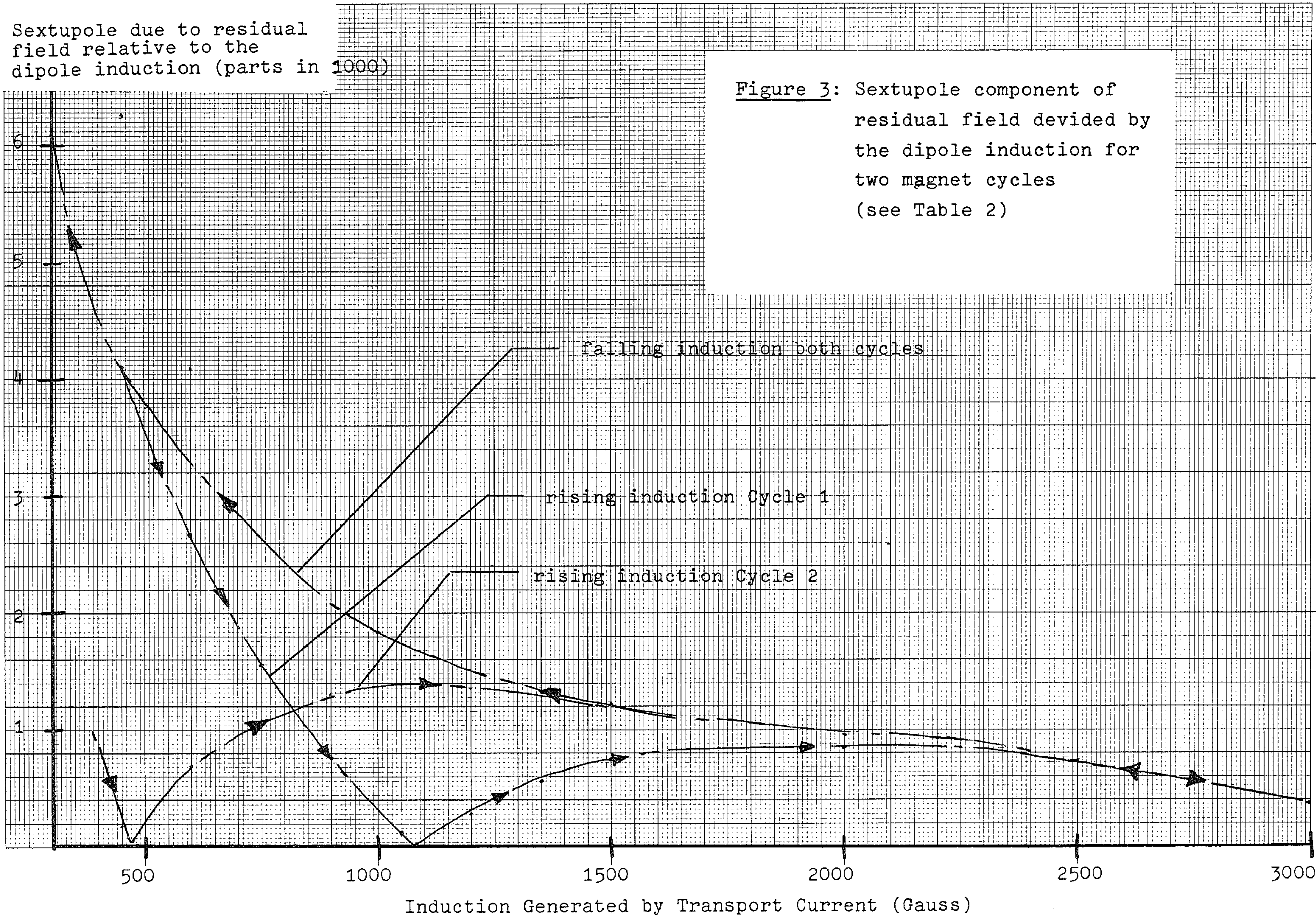


Figure 3: Sextupole component of residual field devided by the dipole induction for two magnet cycles (see Table 2)

Table 2: A comparison of the field aberations due to residual field effects in cycles 1 and 2‡

Transport current field	cycle 1 $\|C_1''/C_1'\|$	cycle 1 $\|C_3''/C_1'\|$	cycle 2 $\|C_1''/C_1'\|$	cycle 2 $\|C_3''/C_1'\|$
	Residual Field Aberations (parts in 1000)			
450 G*	6.27	4.11	0.44	0.18
600 G	4.09	2.67	0.90	0.70
750 G	2.47	1.56	1.55	1.09
900 G	1.22	0.76	1.91	1.31
1050 G**	0.29	0.13	2.04	1.39
1200 G	0.37	0.29	2.00	1.36
1350 G	0.83	0.56	1.93	1.30
1500 G	1.13	0.75	1.80	1.22
2000 G	1.24	0.84	1.35	0.95
3000 G	0.80	0.57	0.80	0.57

* Injection field for a 1000 GeV machine with 10 GeV injection energy.

** Transition field (approximate) for a 1000 GeV machine with a $\nu = 21.75$.

‡ Karlsruhe D2a dipole with a saturated iron shell (J_c vs B of the superconductor given in reference 1).

Removal of Magnet to Magnet Variations

Magnet to Magnet variations of the residual field are important because they determine whether lumped correction methods can be used. In general, in iron copper magnets the magnet to magnet variation in fields is analysed and taken care of in three distinct field regions; 1) low field, 2) medium fields and 3) high fields where the iron saturates. At CERN shuffling of the iron is used to reduce the effects of magnet to magnet variation of field at injection. The medium field magnet to magnet variation is taken care of by making the magnet length correct to 1 mm. The high field or saturation induced variation is taken care of by shuffling the magnets. NAL reduces the low field and high field to magnet variation effects by shuffling the magnets. This shuffling is not well done at NAL.

A superconducting synchrotron is analogous to a conventional machine in that three regions are of interest the low, medium, and high field regions. Accurate placement of the coils and iron will eliminate magnet to magnet variation in the medium field region just as it does in the conventional machine. The high field region is not well understood in superconducting magnets except in the case where the iron is not saturated. More study is required here. Magnet to magnet variations in the low field region is caused by variations of the residual field due to the superconductor and to a lesser extent residual field variations due to the iron.

Superconductor residual field variations are due primarly to: 1) variations of the superconductor J_c at low fields, and 2) variations of the superconducting filament diameter. The field injection may also be affected by coupled currents. The coupled current field variation from magnet to magnet is caused by: 1) matrix resistivity variation, 2) filament diameter variation, and 3) twist pitch variations. In general, I will ignore coupled current variations because the methods for their control are precisely the same as those used to control the magnet to magnet variation of the residual field.

Two methods are available to us for controling the variation of residual field from magnet to magnet. They are; 1) shuffling the magnets within each superperiod and 2) shuffling the superconducting strands within each superconducting cable.

The variation of high field J_c within the superconductor supplied by one manufacturer is about ± 10 percent. The diameter of the filaments within a given matrix can vary about the same order. There is no reason to believe the superconductor J_c variation is any smaller at low fields than it is at high field. As a result the estimated variation of the residual field generated by the superconductor is of the order of ± 15 to 20 percent. The uncorrected magnet to magnet variation can be of the same order.

a) Magnet shuffling

The radius of the SPS is 1100 m. If the machine has a ν of 21.75, the betatron wavelength is about 320 m. If the ν goes up to 27.75 as it does in the conventional machine, then the betatron wavelength drops to 250 m. In the first case one magnet represents less than 2% of a betatron wavelength in the second case this rises to 2.5% of a betatron wavelength. Table 3 shows the number of magnets for each wavelength of the higher harmonics.

Table 3: The number of magnets per harmonic wavelength as a function of the betatron harmonic number and ν

Betatron harmonic number	Number of magnet per harmonic wavelength *	
	ν = 21.75	ν = 27.75
1	53	40
2	26	20
3	18	17
4	13	10
5	11	8
6	9	7
8	7	5
12	4.5	3.3
16	3.3	2.5

*based on magnets with zero spacing

From Table 3, one can see that magnet shuffling is quite reasonable up to the sixth harmonic. The strongest harmonics are likely to be those associated with the superperiodicity of the machine 2, 3 and 6. It seems that magnet shuffling is reasonable way of handling the magnet to magnet variation of the residual field. I could be showing my ignorance by my last statement; but, in fact, NAL handles magnet to magnet variations of their main ring injection field (360 G) by precisely the method described above.[5] I don't think that their shuffling is even very good. To say that shuffling the magnets works well for NAL is a bit premature because many magnet to magnet variation effects may not become important until the beam intensity reaches 10 to 100 times NAL's current intensity of 10^{12} ppp.

The variation in the NAL low field is every bit as great as would be observed in superconducting magnets.[5] The magnitual of the NAL residual field is comparable to the Rutherfords ac-4 measured data.[4] The reduction of residual field which can be achieved by altering the magnet cycle combined with shuffling the magnets should make injection possible into the superconducting machine when the field is 450 G. More measured data and a study of the iron saturation effects will give us a better answer.

b) Superconductor shuffling

The effect of shuffling the superconductor was tested using the Karlsruhe computer program. The residual field was assumed to have a standard deviation which is twenty percent of the value calculated normally calculated by the program. Three cases are analyzed on 16 magnets. (Two full cells worth) they are 1) magnets with unshuffled cable 2) magnets with shuffled 6 strand cable and 3) magnets with shuffled 24 strand cable.

The residual field properties in the first case were calculated by using a random gaussian distribution subroutine built into the computer. The mean value was set equal to 1.0 and the standard deviation was set to 0.2. The resulting number (a gaussian distribution with a .2 standard deviation around 1.0) was multiplied to the residual field calculated for each of the

16 identical magnets. The variation of low field J_c and filament diameter will have only a small effect on the multipole distribution of the residual field. Hence it is reasonable to assume that the value of the lower multipoles relative to the fundamental remains unchanged.

In cases 2 and 3 (the 6 and 24 strand conductor respectively), the random gaussian distribution function was also used. In these cases, the weighting function for the whole magnet was obtained by taking the mean of 6 and 24 random numbers.

Table 4: The dipole component of residual induction for sixteen magnets with unshuffled conductor, with a shuffled 6 strand conductor, and a shuffled 24 strand conductor

	Dipole Component of Residual Induction (G)		
Magnet Number	nonshuffled superconductor	shuffled superconductor 6 strand	24 strand
1	2.35	3.01	2.95
2	2.49	2.96	2.76
3	3.69	2.92	2.58
4	3.23	2.61	2.93
5	3.74	2.79	2.85
6	2.55	3.10	2.89
7	2.78	3.38	2.79
8	2.87	2.92	2.97
9	2.73	2.57	2.74
10	3.25	3.08	2.97
11	2.90	2.68	2.79
12	3.22	3.26	2.88
13	2.68	2.56	3.03
14	3.09	2.77	2.85
15	3.02	2.92	2.69
16	3.24	2.83	2.84
mean induct.	2.99 G*	2.90 G*	2.846 G*
Standard deviation	0.55 G	0.32 G	0.11 G
Standard deviation percent of mean	18.3% **	11.2%	4.0%

* To be compared with 2.87 G when there is no random variation

**Random number generated a gaussian distribution with a standard deviation of 20%. Sixteen numbers is not a very big sample.

The magnet to magnet variation in each of the three cases is compared in Table 4. The mean residual field for the sixteen magnets and its standard deviation is also presented.

It is clear from Table 4 that the shuffling of superconductor does reduce the magnet to magnet variation of the residual field. Superconductor shuffling however, should be avoided for the following reasons 1) large quantities of materials must be stored before cabling which means that production and cabling processes can not proceed in parallel. This factor becomes important when one compares the amount of superconductor needed for a synchrotron with the amount of superconductor needed elsewhere in industry. 2) The trend in superconductor development is towards conductors with fewer and fewer strands. The ideal single strand high current material can't be shuffled. If one must have shuffled material, one must except lower overall current density.

The superconductor order should not be split between more than one manufacturer (this may be unavoidable in Europe) because the variation of residual field properties is most certinly greater when the product of several manufacturers is used. As an example IMI and Vacuumschmelze use entirely different metalurgical processes; differing high field J_c's result (up to 35% different) one can reasonably expect the low field J_c to be different as well. One has to be prepared to live with the low field J_c variation from manufacturer to manufacturer or one must restrict his order to only one superconductor manufacturer.

The Effect of Temperature Variations on Residual Field

The temperature in the magnets of a superconducting synchrotron can vary by as much as 0.3 K^o. Most of this variation is due to pressure drop in the return line of the refrigeration system. There is an additional component which is due to the effects a.c. loss. By and large the temperature variation in a synchrotron is systematic in that the highest temperature will occur at a point furthest from the refrigerator (presumably the correction elements could be corrected for this kind of variation).

A temperature variation of 0.3 K^o (say from 3.8 K^o to 4.1 K^o in the superconductor) will result in a 12 - 15 percent change in the J_c at an induction of 5 Tesla.[6] Due to the nature of the J_c vs T curve at low fields, the expected variation due to a 0.3 K^o temperature variation will be only 6 or 7 percent. This poses no problem if it is systematic. More work is needed when the kind of refrigeration system to be used is developed.

Concluding Comments

In general, the following conclusions can be drawn from this report:

1) The residual field theory has developed to the extent that one can predict the residual field structure reasonably well. The magnitude of the residual field is not well predicted. More work is needed to study low field properties of superconductors.

2) A substantial reduction of the effect of residual field at injection can be achieved by altering the magnet cycle. The price one pays is to increase the residual field at transition and a five percent increase in a.c. loss per cycle.

3) Shuffling the superconductor will reduce magnet to magnet variation of the residual field. While shuffling the superconductor is possible, it is not desirable particularly when one considers the trend of going to conductors of fewer and fewer strands. The shuffling of magnets seems to be a reasonable alternative, particularly if the high field magnet to magnet variation is not too bad. NAL has demonstrated that is approach is workable up to intensities of 10^{12} ppp.

4) Temperature variations will affect the residual field. They are expected to be systematic (therefore correctible) and not very servere (less than 10%).

As a general concluding comment, injection into a 1000 GeV superconducting machine should be possible at 10 GeV. A combination of altering the magnet cycle and shuffling magnets should make the residual field correctable at an injection induction of 450 Gauss. More work is clearly on the low temperature properties of superconductors.

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The Effect of Magnet Length and Magnet Spacing on the Economics of a Superconducting Synchrotron

Michael A. Green
1 December 1972

This report is in reply to comments made by Albrecht[1] of Siemens' concerning the length of superconducting magnets in a superconducting synchrotron. It was Albrecht's opinion at the time that no magnet over two meters long should be built. I disagree with this view, and this report explains why. The questions to be answered are two fold: What is the effect of magnet length and spacing on machine cost, and is there an optimum length and spacing for a superconducting addition to the SPS? This report cannot answer both questions precisely right, but it can indicate the general direction one must go, within well defined limits, in order to make a minimum cost machine.

Before proceeding it is useful to look at the limitations imposed on us by the present machine. These limits are 1) The latice, the number of cells and the distribution of bends in the cell must be the same as the conventional machine. I go one step further and say that the conventional magnet must occupy the same space in each half cell as the conventional magnets do. 2) the maximum length of a single dipole magnet unit is limited to 7 meters because of the difficulty of getting them into the tunnel. I go one step further and say that for economic reasons there must be an integral number of equal length units per half cell.

While the limitations given in the last paragraph eliminate some cases that may be of interest, they do not alter the general conclusions of this report. This report calculates the effect of magnet length (number of magnets per half cell) and magnet spacing on the central field of the magnet and the cost of its superconductor. The superconductor makes up about half the cost of the magnet. It should be noted that the cost of magnet winding and the magnet iron shell are dependent on the amount of superconductor used. In general, it is not bad to assume that the magnet cost varies directly with the amount of superconductor it contains.

Direct calculations of superconductor cost can be made. The direction the magnet cost goes is then easily calculated. The increased amount of superconductor (due to increased central field to achieve a given energy gain) is not the only economic effect magnet spacing and length will have. The cost of the magnet power supply and refrigeration system is also affected to a lesser degree. These calculations are done for both a missing magnet machine and a separate ring machine.

Calculation of magnet length and central field as a function of the number of magnet per half cell and their spacing

A final energy of 1000 GeV and a latice which is identical to the conventional latice is assumed [2] (a missing magnet machine with half the magnets has an energy of 500 GeV). In the case of the missing magnet machine, the space ocupied by the superconducting magnets L^* is the space occupied by the two center magnets of the conventional machine plus the 0.4 m space between them (see Fig. 1). In the separate ring machine L^* is the space occupied by the four half cell dipoles plus the three spaces of 0.4 m between them (see Fig. 1). The product of L^* and B^* is the amount of bending strength needed to bend a 1000 GeV beam in the separate ring machine 1.667°. In a missing magnet machine $L^* B^*$ is the bending strength needed to bend a 500 GeV proton beam 1.667°(see Table 1).

Table 1: L^*, L^*B^*, Energy and Magnet inner Coil Radius for a Missing Magnet and Separate Ring machine

	missing Magnet Machine	Separate Ring Machine
Energy	500 GeV	1000 GeV
L^*	12.96 m	26.32 m
$L^* B^*$	56.5 Tm	113.0 Tm
Inner Coil Radius	0.05 - 0.055 m	0.03 - 0.035 m

The physical length of the magnet (iron length plus end plates) L can be calculated as a function of L^*, the number of magnets per half cell N, and the space between the magnet ends S as follows:

$$L = (L^* - (N-1)\ S)\ /\ N \qquad (1)$$

The magnetic length L_M can be calculated for a magnet of the Karlsruhe or Rutherford type (the iron is extended beyond the end of the coils, 0.025 m thick iron end plates are assumed) using the following expression:

$$L_M = L - \frac{\alpha(R_1+R_2)}{2} - \beta R_2 - 2t \qquad (2)$$

where α and β are constants, R_1 the inner coil radius, R_2 the outer coil radius, and t the iron end plate thickness. A formula for calculating R_2 will be given later (see equation 6). For dipoles of the Karlsruhe design α = 1 to 1.2, β = 1.5 to 1.8. The Rutherford dipoles are not greatly different in their values of α and β.

The central induction of the dipole B_o can be calculated from B^*L^*, L^* and a term for the length lost due to end effects L_{lost}

$$B_o = \frac{B^*\ L^*}{L^*-L_{lost}} \qquad (3)$$

where

$$L_{lost} = (N-1)S + N(L-L_M) + \gamma \qquad (4)$$

where γ as a term which is the thickness of additional cryostat. In the separate ring machine γ = 0 and in the missing magnet machine a γ of 0.1 m was assumed because the magnet pair must fit between two existing conventional magnets. Equation 2 can be given in simplified form when $4.4 \leq B_o \leq 5.0$ T

$$L_M \approx L - 0.21 \quad \text{Separate Ring Machine}$$
(5)
$$L_M \approx L - 0.30 \quad \text{Missing Magnet Machine}$$

The above equations are simplifications which are only valid within the range specified.

Tables 2 and 3 show the magnet length L and the central induction B_o as a function of the number of magnets per half cell N and the spacing between magnets S. Table 2 gives L and B_o for a separate ring machine; Table 3 gives L and B_o for a 500 GeV missing magnet machine. The defination of L and S for each case is shown in Figure 1. One should note that N = 4 in Table 2 and N = 2 in Table 3 are equivalent cases because only the center magnets are assumed in the missing magnet case.

It is quite obvious that when N goes up L goes down and B_o goes up. When S goes up B_o goes up and L goes down. We have assumed for many months that the superconducting magnet length would be the same as the conventional magnet. This results in central inductions of 4.5 to 4.8 T depending on S the magnet spacing. Let us now suppose that the magnet length allowed is reduced to two meters; then B_o will rise between 4.8 to 6.3 Tesla depending on S. The result must be increased cost. The next section shows how the cost is calculated for the superconductor.

Table 2: A separate ring magnet length (L) and magnet central induction B_o as a function of the number of magnets per half cell (N) and their spacing (S) the machine energy is 1000 GeV.

N Number of Magnets per half cell	S = 0.0 m		S = 0.2 m		S = 0.4 m		S = 0.6 m	
	L	B_o	L	B_o	L	B_o	L	B_o
3	8.78	4.40	8.64	4.46	8.50	4.54	8.36	4.65
4	6.58	4.44	6.43	4.54	6.28*	4.65	6.13	4.77
5	5.26	4.47	5.10	4.62	4.94	4.77	4.78	4.93
6	4.38	4.51	4.22	4.70	4.05	4.89	3.88	5.12
8	3.29	4.58	3.12	4.85	2.94	5.16	2.77	5.52
10	2.63	4.66	2.45	5.04	2.27	5.48	2.09	6.00
12	2.19	4.75	2.01	5.23	1.83	5.82	1.65	6.57
16	1.65	4.92	1.46	5.66	1.27	6.66	1.08	8.08

* The steel length compares with the conventional magnet case. The cryostat end is not included in the package length of 26.32 m.

+ All distances are in meters; all inductions are in Tesla.

Table 3: A missing magnet machine magnet length (L) and design central induction (B_o) as a function of the number of magnets per half cell (N) and their spacing (S) machine energy 500 GeV.

all distances are in meters, all inductions are in Tesla

	S = 0.0 m		S = 0.2 m		S = 0.4 m		S = 0.6 m	
	L	B_o	L	B_o	L	B_o	L	B_o
1	12.86	4.50	12.86	4.50	12.86	4.50	12.86	4.50
2	6.43	4.61	6.33	4.69	6.23*	4.77	6.13	4.85
3	4.29	4.72	4.16	4.89	4.02	5.06	3.89	5.25
4	3.22	4.85	3.06	5.11	2.92	5.40	2.69	5.73
5	2.57	4.97	2.41	5.36	2.26	5.79	2.09	6.30
6	2.14	5.11	1.97	5.62	1.81	6.23	1.64	7.01

*Not the same as the 6.28 m conventional magnet because 0.05 m must be added to each magnet for the magnet cryostat. Hence the magnet steel length end plates is 0.05 m shorter than the conventional magnet.

Calculation of Magnet Superconductor Cost

One can calculate the superconductor cost in synchrotron dipole magnets with relative ease provided the basic superconductor cost factors are known. In order to calculate cost, the following assumptions about the coil design are made: 1) the coil has a $J_o \cos(\Theta)$ distribution of current in a coil with an inner radius of R_1 and an outer radius of R_2 (see Figure 2). J_o is the current density on the midplane ($\Theta = 0$); the cosine theta distribution assumption calculates costs which are comparable with those of practical designs such as the Karlsruhe or Rutherford designs. 2) the coil has a moderately saturated iron shell, in other words, the iron shell adds about 1.1 T to the central field. 3) The magnet ends are round. 4) the assumed quench induction for the superconductor B_{SC} is 10 percent higher than the central induction B_o when the superconductor carries enough current to generate B_o at the magnet center.

The cost of the superconductor per ampere meter C_{SC} and the peak coil current density J_o are functions of B_{SC} not B_o. Figure 3 shows the relative J_o and C_{SC} as a function of B_{SC}. The relative J_o and $C_{SC} = 1$ when $B_{SC} = 5.0$ T. The calculations here assume that $J_o = 2 \times 10^8$ A/m^2 when $B_{SC} = 5.0$ T. In GESSS-MD/22, I assumed that $C_{SC} = 2.2 \times 10^{-3}$ US \$/Am at 5.0 T[3]. Table 4 shows the actual cost for a number of superconductors which have been ordered in the last two years. I think the price assumed in GESSS-MD/22 may be reasonable for a large order of 10 μ filament material; IMI agrees that this is possible.[4]

For cosine Θ magnets with moderately saturated shells. The following set of equations can be used to calculate the magnet superconductor cost. First let's calculate the outer coil radius R_2 (see Figure 2).

$$R_2 = R_1 + \left[\frac{2B_o - B_{sat}}{\mu_o J_o} \right] \qquad (6)$$

where $\mu_o = 4\pi \times 10^{-2}$ and we assume that $B_{sat} = 2.2$ T or twice the induction enhancement due to the iron. For unsaturated

Table 4: Superconductor cost per ampere Meter from various manufacturers. All costs are quoted at an induction of 5 T and a temperature of 4.2°K.

Sample	Seller	Buyer	Quote year	Conductor form	Filament size	Order size	Conductor cost US $/Am**
1	cryomagnetics	IEKP	1971	wire	16.3 μ	small	2.7×10^{-3}
2	AIRCO	IEKP	1971	wire	12 μ	small	3.9×10^{-3}
3	AIRCO	IEKP	1971	wire	22 μ	small	2.8×10^{-3}
4	IMI	IEKP	1971	wire	7.8 μ	small	7.6×10^{-3}
5	IMI	IEKP	1971	wire	19.5 μ	small	5×10^{-3}
6	IMI	IEKP	1972	insulated soldered cable	10 μ	small	9.2×10^{-3}
7	VAC	IEKP	1971	wire	20 μ	small	7.9×10^{-3}
8	VAC	IEKP	1971	wire	12 μ	small	9.0×10^{-3}
9	VAC	IEKP	1971	fully insulated cable	12 μ	small	13.5×10^{-3}
10	supercon	IEKP	1971	wire	12 μ	small	4.1×10^{-3}
11	supercon	NAL	1970	flat strip	>100 μ	large*	1.3×10^{-3} +

* 55 tonns of conductor for the NAL bubble chamber

+ GESS-MD/22 uses a cost of 2.2×10^{-3} US $/Am for synchrotron superconductor

** to obtain the cost in SwFr/Am multiply by 3.85

cores, B_{sat} = 2.0 T (the iron saturation induction); for highly saturated cores B_{sat} = 2.5 - 2.7 T. The ampere turns of conductor Ni needed for all cases is:

$$Ni = J_o(R_2^2 - R_1^2) \tag{7}$$

From the ampere turns one can calculate the ampere meters of superconductor needed for the magnet:

$$Am = 2Ni\ [L_S + 1.6\ \frac{(R_1 + R_2)}{2} + \frac{\pi^2}{6}\ (R_1 + R_2)] \tag{8}$$

where L_S the coil straight section length is:

$$L_S = L - \alpha\ \frac{(R_1 + R_2)}{2} - \delta R_2 - 2t \tag{9}$$

α and t are previously defined and given; δ is a constant. For magnets of the Karlsruhe design δ = 4.5 to 4.8. Equation 8 can be simplified to an approximate expression which is:

$$Am = 2LNi \tag{10}$$

The superconductor cost factor C_{SC} can be calculated for any superconductor at a given field B_{SC} by dividing the cost per meter by the current capacity (usually defined as 90 - 95% short sample current) at B_{SC}. Using the superconductor cost factor C_{SC} we find that:

$$\text{Magnet Superconductor Cost} = C_{SC}\ Am \tag{11}$$

Table 5 shows the average coil current density J_o, coil thickness (R_2 - R_1) and the ampere turns needed for coils of various inner coil diameters ($2R_1$), as a function of central induction B_o Figure 4 shows the value of B_{SC} (the induction in the superconductor) and the coil thickness as a function of B_o. The coil current density J_o varies as shown in Figure 3. It should be noted that equation 6 was used to calculate the coil thickness. The results are startling; the coil thickness for a 6.0 T magnet is over double that of a 4.5 T magnet. This is no surprise to people who have built superconducting solenoids.

Table 5: Coil current density (J_o), magnet coil thickness and ampere turns required as a function of central induction (B_o) and coil inner diameter (D_i) (moderately saturated iron assumed B_{sat} = 2.2)

B_o (T)	J_o (A/m^2)	Coil thickness (m)	Ampere Turns D_i = 0.06 m	D_i = 0.07 m	D_i = 0.10 m
4.0	2.21×10^8	2.1×10^{-2}	3.76×10^5	4.25×10^5	5.64×10^5
4.5	2.00×10^8	2.72×10^{-2}	4.60×10^5	5.24×10^5	6.92×10^5
5.0	1.79×10^8	3.5×10^{-2}	5.93×10^5	6.58×10^5	8.43×10^5
5.5	1.58×10^8	4.45×10^{-2}	7.50×10^5	8.06×10^5	10.13×10^5
6.0	1.37×10^8	5.72×10^{-2}	9.17×10^5	9.98×10^5	12.27×10^5
6.5	1.16×10^8	7.45×10^{-2}	11.62×10^5	12.42×10^5	15.08×10^5

Tables 6 and 7 give the relative cost of the dipole superconductor as a function of N and S. Table 6 does this for the separate ring machine Table 7 does this for the missing magnet machine. The results of both Tables is obvious. The larger S the more the superconductor costs and the larger N the more the superconductor costs. An interesting thing one sees in both Tables is the effect of Sagita. As the magnet gets longer the aperture must grow, in order to compensate for the beam Sagita. The result is that an optimum is reached at some point. When S = 0 in Table 6 this optimum is between 5 and 6 magnets per cell. When S = 0.2, 0.4 and 0.6 m this optimum occurs when the magnet number is less than 4 a case which is not of interest.

The effect of Sagita on cost becomes considerable when magnet length approach six meters. One can save 10 to 12 percent on the superconductor cost by making the magnets curved. To save this 10 to 12 percent one runs into the problems associated with curved magnets; these start with fabrication and end with magnetic measurement. A further look at curved magnets is in my opinion in order there may be some rather simple solutions to some of the problems associated with curved dipole magnets.

Tables 6 and 7 show that long magnets with minimum spacing between them are economically the best thing to do. The engineering effort required to reduce spacing between the magnets is not neglegable but neither is the cost saving. Tables 6 and 7 show only the relative cost of the superconductor. The relative cost of the rest of the magnet components changes with the superconductor cost. For instance the cost winding and the preparation for winding goes up in the same way as the superconductor.[5] The iron shield cost rises as R_2 increases and the central field rises. Cryostat costs rise because more weight must be supported and so on. To the first order, the relative cost of the superconducting dipole magnets will be the same as for the superconductor. Hence in Table 6 magnets may be substituted for superconductor with 1.00 = 116×10^6 SwFr in Table 7 the same substitution can be made with 1.00 = 79×10^6 SwFr (see GESSS-MD/22).

Table 6: The relative cost of the superconductor for the dipole magnets in a separate ring machine as a function of the number of magnet per half cell (N) and the space between magnets (S). The machine energy is 1000 GeV straight magnets are assumed.

number of magnets per half cell N	S = 0.0 m straight	S = 0.2 m straight	S = 0.4 m straight	S = 0.6 m straight
3	0.90	0.92	0.97	1.03
4	0.89	0.94	1.00ǂ	1.06
5	0.88	0.96	1.04	1.11
6	0.88	0.98	1.09	1.22
8	0.91	1.06	1.22	1.54
10	0.95	1.18	1.52	1.98
12	1.01	1.32	1.85	2.78
16	1.16	1.76	**	**

** Relative cost is greater than 3.0

ǂ GESSS-MD/22 suggests that 1.00 = 50 × 10^6 Sw Fr

Table7: The relative cost of the superconductor of the dipole magnets in a missing magnet machine as a function of the number of magnets per half cell (N) and the space between the magnets (S) the machine energy is assumed to be 500 GeV.

number of magnets per half cell N	S = 0.0 m	S = 0.2 m	S = 0. 4 m	S = 0.6 m
1	0.95	0.95	0.95	0.95
2	0.93	0.96	1.00*	1.04
3	0.98	1.07	1.13	1.23
4	1.10	1.23	1.43	1.65
5	1.21	1.43	1.81	2.28
6	1.34	1.67	2.27	**

* Using the cost factor given GESSS-MD/22 one finds that 1.00 = 39×10^6 Sw Fr.

** the relative cost is greater than 3.0

The Effect of N and S on other Components of a Superconducting Synchrotron

The number of magnets per half cell and their spacing affect other components besides the magnets. N and S have marked effects on the power supply and refrigeration system while almost no direct effect on the injection system, extraction system, vacuum system, r.f. system, and control system.

As N and S go up so must the magnet stored energy. For a given rise time the power rating of the power supply must also go up. If the power supply is limited either by financial or physical considerations, increasing N and S will result in an increased cycle time. The power distribution system is also affected by N and S. The higher the stored energy means more leads or higher voltages are need.

An increase of N and S result in increased superconductor weight and an increased flux change for a given amount of superconductor. For a given repetition rate, higher a.c. losses will result along with the associated increase in refrigeration system cost. The increased cost of refrigeration can be eliminated by decreasing the repetion rate.

Concluding Comments

The conclusions reached by this study are as follows:

1. It is desirable to reduce N and S if one wants a minimum cost machine. However, the N and S chosen should be consistant with other machine parameters and engineering realities. (An example is that S can't be made too small or assembly and disassambly can be made impossible). For a separate ring machine an N = 4 and S = 0.2 m seem reasonable. For missing magnet machine N = 2 and S = 0.2 m are reasonable. (An S of 0.2 m means careful attension must be paid to assembly and disassembly problems.)

2. It is reasonable to look a curved magnets even through one might decide to reject them. NAL is looking at curved magnets on the energy drubler.

3. N and S not only effect the magnets but other components as well. Real limits on repetition rate may result from power supply and refrigeration considerations.

In short, the development of long magnets appears to be necessary. We are forced to solve the length problem whether we like it or not.

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Bad Field Allowance in Superconducting Synchrotron Dipole Magnets

M.A. Green
1 February 1973

This report presents an improved way of estimating the bad field allowance for synchrotron dipole magnets. In general, bad field is caused by; 1) imperfections of the placement of the superconductor and various coil parts. This report is the result of computer study of magnet tollerance effects at the IEKP Karlsruhe. Sectored coils simular to designs proposed at Karlsruhe and layer coils simular to the Rutherford design were investigated using the Karlsruhe IBM 360 system. Magnets with widely varying coil apertures were investigated.

Causes of Bad Field in Superconducting Synchrotron Magnets

The causes of bad field can be devided into two parts. The first is a function of the basic design of the magnet coil. The second is a function of the errors in placement of various coil parts and errors which are caused by magnetic forces. The errors in magnet construction are **asymmetrical**[1] (all multipoles are introduced). The effect of magnetic forces is **symmetrical** (multipole pair numbers $n = T\ (2p + 1)$ $p = 0, 1, 2...$ are predominent $T = 1$ is a dipole; $T = 2$ is a quadrupole).

a) The effect of coil design

The good field region in a magnet will vary depending on the basic coil design parameters. In general, magnet with coils which have many degrees of freedom have a larger useful aperture ratio (ratio of good field radius to coil radius). On the other hand, coils with many degrees of freedom are harder to wind, have more parts and are more expensive to build. The

Karlsruhe sector coil design and the Rutherford layer design are attemps at symplifying the coil design and the winding process.

The Karlsruhe design has five degrees of freedom; in a practical dipole magnet one can eliminate three multipoles (n = 3, 5 and 7) and greatly reduce two others (n = 9 and 11). The limiting multipole number is n = 13. We find that a perfect Karlsruhe type coil has a useful aperture radius (determined by $\Delta B/B \leq 10^{-3}$ everywhere inside that radius) between 68 and 75 percent of the inner coil radius depending on design details.

The Rutherford AC-4 design has four degrees of freedom which results in four multipoles being eliminated or minimized (n = 3, 5, 7 and 9). The multipole number which potentially can cause truble is n = 11. The Rutherford design is unlike the Karlsruhe design in that the higher multipole structure relative to the fundamental is greatly changed when the iron is removed. (This is not really a problem.) We find that a perfect Rutherford AC-4 type coil has a useful aperture ratio of around 70 percent also.

If the Karlsruhe and Rutherford designs are extended to magnets with widely varying inner coil radii, the useful aperture can not extend 65 - 70 percent of that coil aperture. In magnets with large coil apertures it becomes necessary to use more complicated coil designs in order to increase the perfect coil useful aperture ratio up to as much as 80 percent of the coil aperture.

b) The effect of coil manufacturing errors

Coil manufacturing errors are asymmetrical in nature because the introduce all multipoles not just the multipoles of symmetry (n = 3, 5, 7... in a dipole, n = 6, 10, 14... in a quadrupole). I investigated the following kinds of coil manufacturing errors 1) random conductor placement error, 2) random sector or layer placement, 3) random coil part assembly error (as an example Rutherford's AC-4 has four coil parts, Karlsruhes dipole D2a has ten coil parts, and Karlsruhes dipole D2b has two coil parts), and 4) errors in the placement of the coil in the iron shell. Last, I investigated the effect of in-correct placement of a magnet measurement probe.

The most serious coil manufacturing errors are the errors in assembled coil placement in the iron shell. These errors are characterized by their double side band structure[1] (the worst multipoles are those above and below the fundamental. In a dipole the error introduced is predominently $n = 2$; In a quadrupole one gets both $n = 1$ and 3.

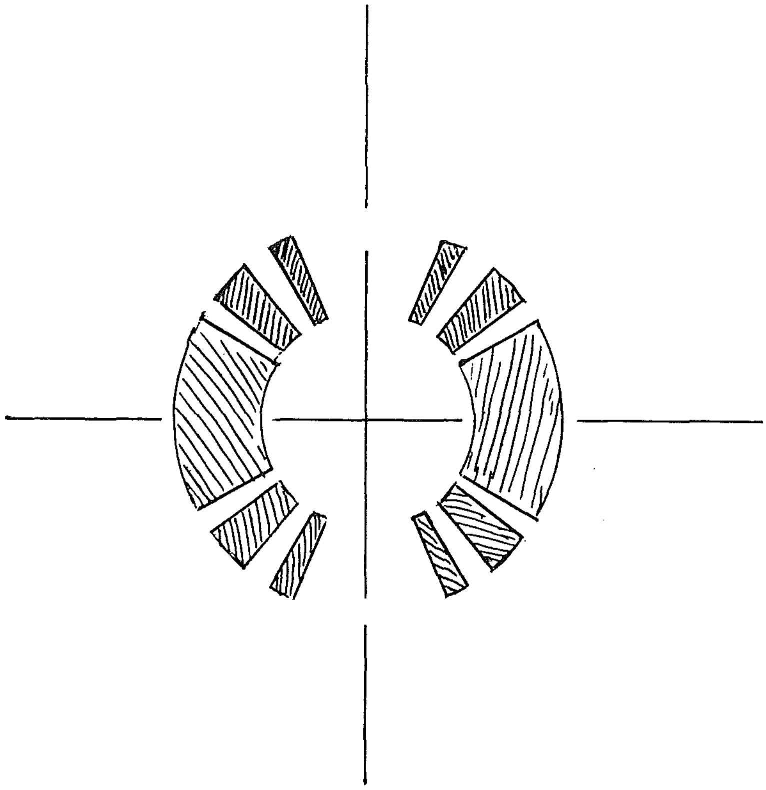
Other serious errors are the sector placement and coil assembly errors. In general, conductor placement errors are not very important unless the number of conductors is small. Coil winding experience at Karlsruhe indicates that the conductors can be wound carefully enough. The placement of the magnetic measurement coil is not important while measuring a dipole but it become very important in a quadrupole if good measurement of the dipole component is required.

The tollerances used in the Karlsruhe computer program are given in Table 1. The movement of the various parts is random inside the tollerance limits.(There must be a 90 percent probability the coil error lies within the tollerance limit.)

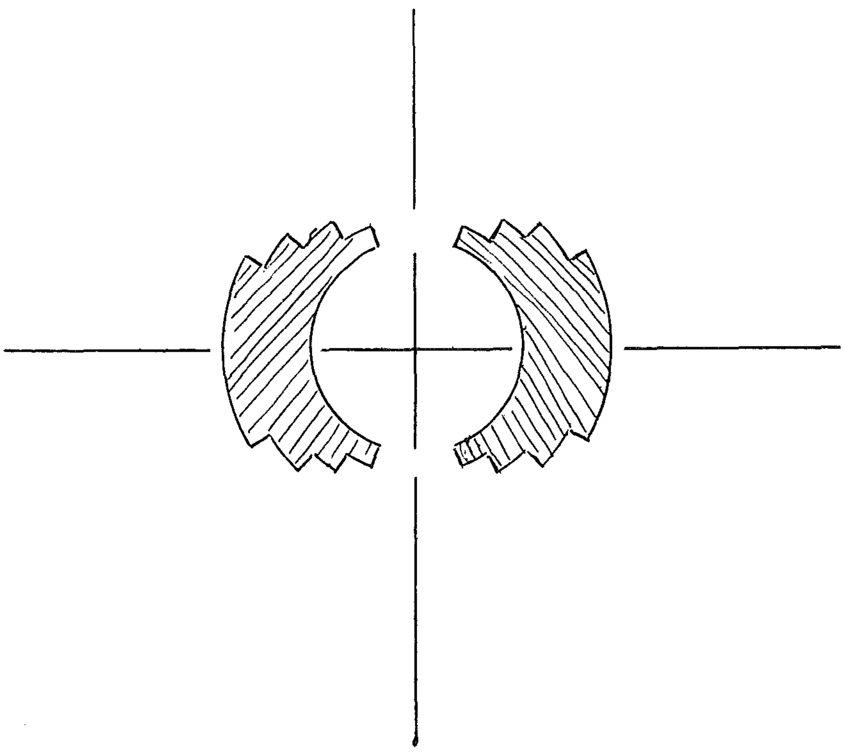
Table 1: Tollerance Limits used in the Karlsruhe IBM-360 Computer Program

	Tollerance limit (mm)	
	dipole	quadrupole
Conductor placement	0.3	0.3
Sector placement	0.1	0.1
Coil part placement	0.1	0.1
Coil - iron shell pl.	0.05	0.05
Measuring coil placement	1.0	0.05

Figure 1: Coils for the Karlsruhe and Rutherford type dipoles



a) Karlsruhe sector dipole*



b) Rutherford layer dipole

*The computer program used a modified version

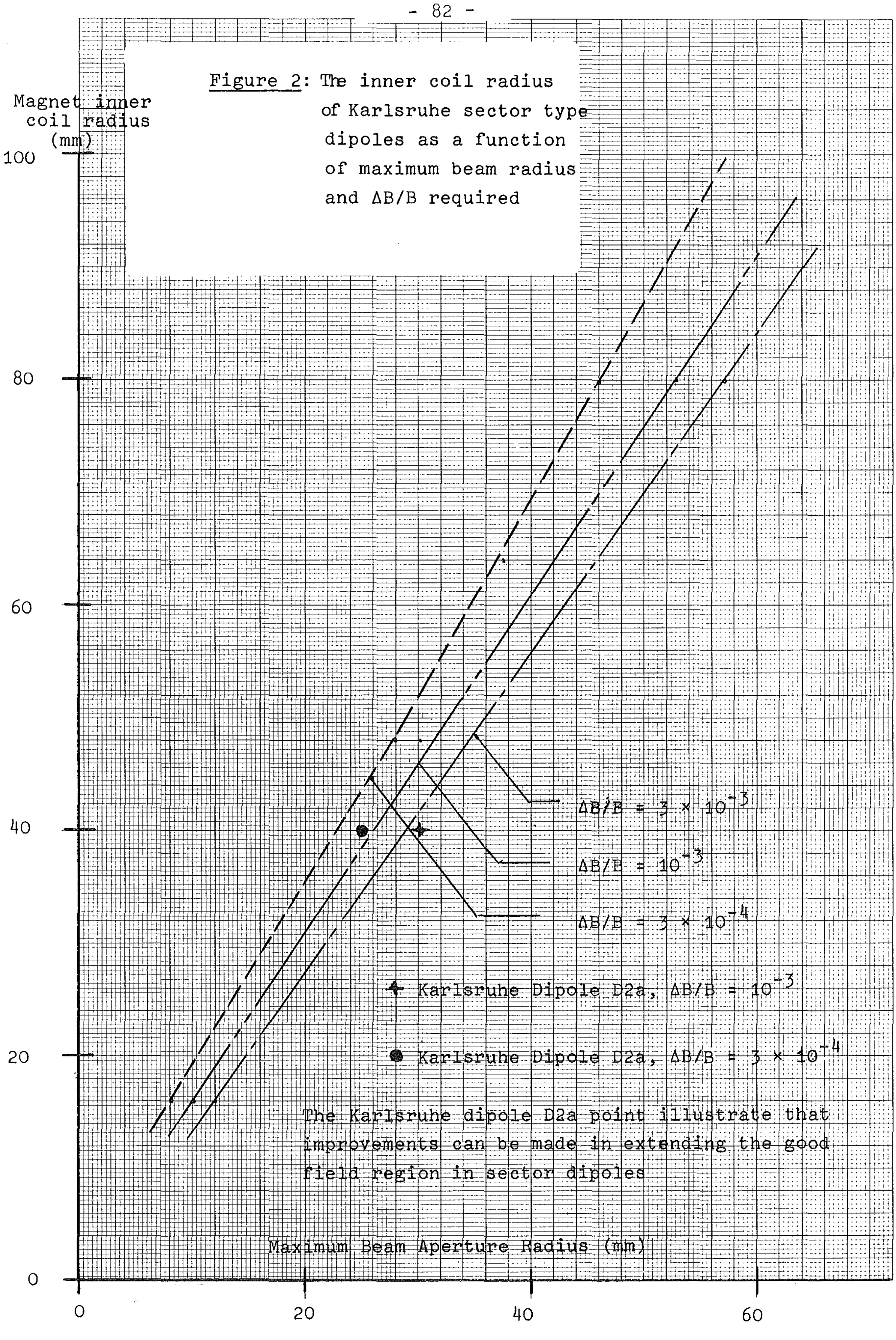
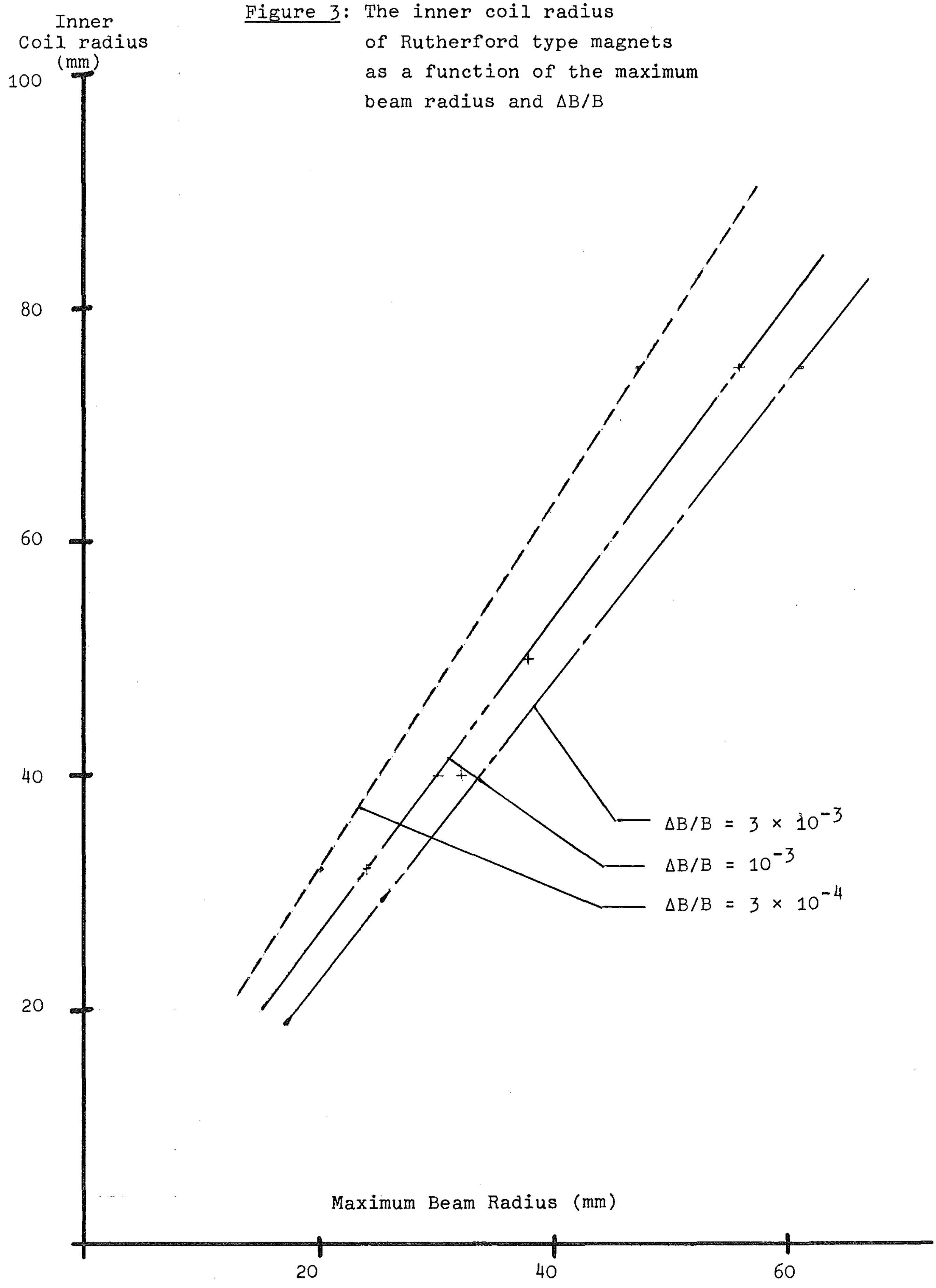


Figure 2: The inner coil radius of Karlsruhe sector type dipoles as a function of maximum beam radius and ΔB/B required
Magnet inner coil radius (mm)
100
80
60
40
20
0
ΔB/B = 3 × 10^-3
ΔB/B = 10^-3
ΔB/B = 3 × 10^-4
Karlsruhe Dipole D2a, ΔB/B = 10^-3
Karlsruhe Dipole D2a, ΔB/B = 3 × 10^-4
The Karlsruhe dipole D2a point illustrate that improvements can be made in extending the good field region in sector dipoles
Maximum Beam Aperture Radius (mm)
0
20
40
60

Figure 3: The inner coil radius of Rutherford type magnets as a function of the maximum beam radius and ΔB/B



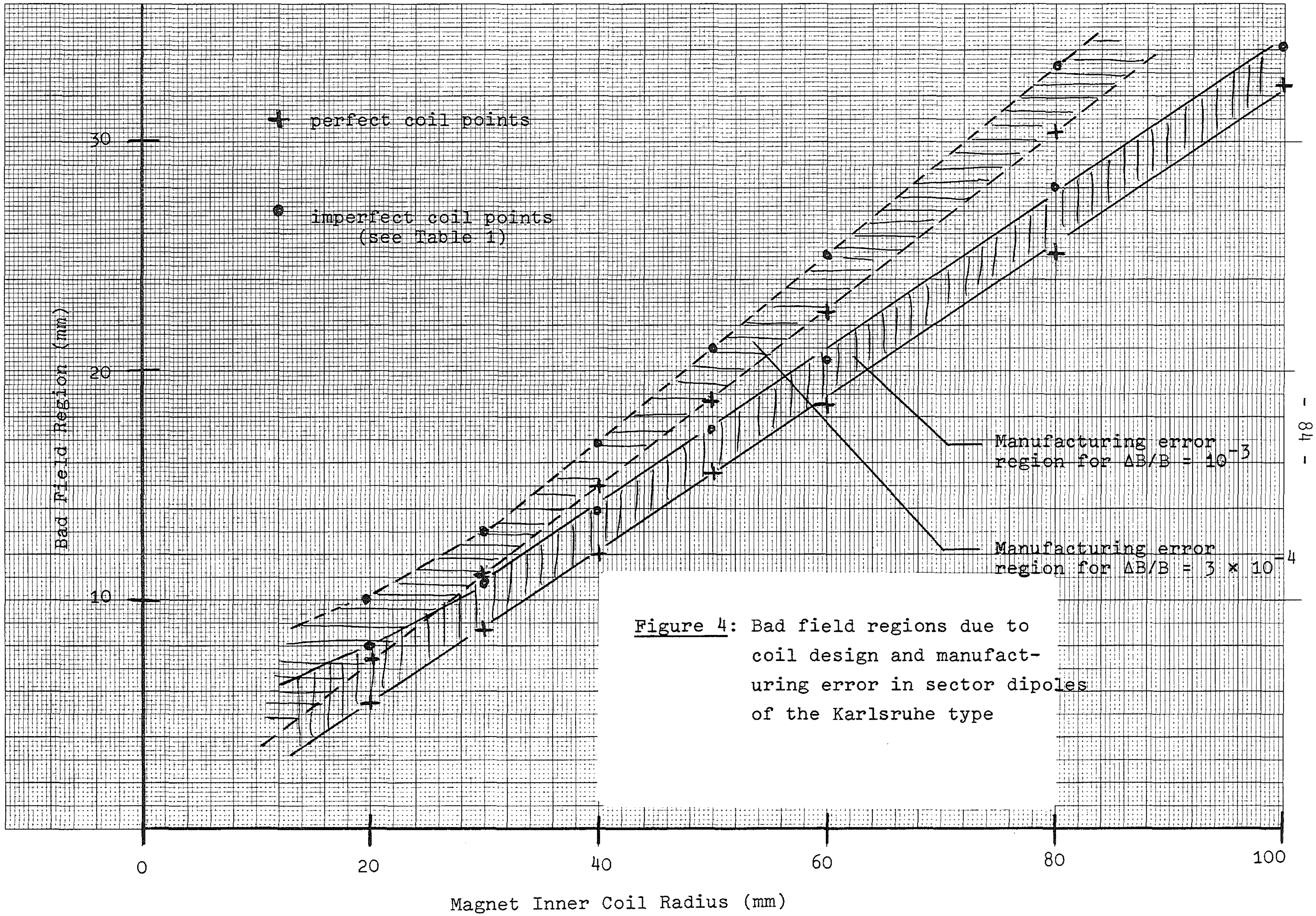


Figure 4: Bad field regions due to coil design and manufacturing error in sector dipoles of the Karlsruhe type

Errors in manufacturing result in almost a constant allowance for bad field which is added to the 30 - 35 percent of the inner coil radius bad field allowance which is due to the coil design. In coils with a 20 mm inner coil radius the bad field due to manufacturing error makes up a large portion of the bad field allowance. On the other hand, coils with a 100 or 125 mm inner coil radius have a bad field region which is caused almost entirely by the coil design. When the magnet is very small a large portion of the coil radius is a bad field region. The good field region can not go to zero because even the worst coils will have some good field region.

c) The effects of other errors

Allowances in the design should be made for low field circulating current effects and high field iron saturation effects. It is hoped that the effect of elastic and inelastic conductor motion due to magnetic forces is small. It is reasonable to assume that these effects are small in current Rutherford and Karlsruhe magnets as long as the coils are well supported (there is no evidence of elastic conductor motion in Rutherfords AC-4[2]). The computer study here ignores these effects.

The Results of the Computer Study

Figures 2 and 3 show the useful aperture as a function of the coil aperture and $\Delta B/B$ for coils of the Rutherford and Karlsruhe design. The position of the useful aperture is investigated for $\Delta B/B \leq 3 \times 10^{-3}$, $\Delta B/B \leq 10^{-3}$, and $\Delta B/B \leq 3 \times 10^{-4}$. The first represents the bad field limit for an injected pencil beam (low intensity) making its first trip around the ring. (It is from this radius that we calculate the first orbit closed orbit deviation allowance.) The second represents the limit for a good injected beam and the limit during acceleration of the beam. The final $\Delta B/B$ represents the limit for an uncorrected slow extracted beam.[3]

It is useful to look at the multipole structure of the terms due to errors in manufacturing. In a dipole 60 percent of the errors in the $\Delta B/B$ is due to the first three higher multipoles (n = 2, 3 and 4 quadrupole, sextupole and octupole. Quadrupole and sextupole make up nearly half the $\Delta B/B$). The first three higher multipoles are correctible (particularly quadrupole and sextupole). If a reasonable correction scheme can be found it should be possible to have the slow extracted beam lie in the region bounded by $\Delta B/B \leq 10^{-3}$ instead of $\Delta B/B \leq 3 \times 10^{-4}$. (This may be of interest in machines where the extracted beam passes into the region bounded by $3 \times 10^{-4} \leq \Delta B/B \leq 10^{-3}$ in say only $\frac{1}{3}$ to $\frac{1}{2}$ the magnets.)

Using the tollerances given in Table 1, the bad field region due to manufacturing tollerances is 2.5 to 3.0 mm. The width of this region is nearly independent of inner coil radius (from 20 mm to 100 mm) and $\Delta B/B$ required (see Figure 4).

Concluding Comments

The following comments can be drawn from this study:

1) The bad field region can be devided into two parts; a region due to coil design and region due to manufacturing errors.

2) The bad field region due to the coil design grows as the inner coil radius coil grows.

3) The bad field region due to manufacturing tollerances is radius independent and $\Delta B/B$ independent to a lesser degree.

4) Large coils must be more complicated in order to control coil design effects. Small coils must have tight tollerances in order to control manufacturing errors.

The bad field allowance for magnets with a useful aperture radius of 22 mm[4] is 12 to 14 mm. When the useful aperture rises to 40 mm the bad field allowance rises to 18 - 22 mm[5] (depending on the $\Delta B/B$ allowed). The use of a constant 15 mm bad field allowance is not justified. It is much better to use 40 percent of the good field aperture plus 3 mm.

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Tracking in Superconducting Synchrotron Dipoles

M.A. Green
2 February 1973

The question of whether dipole magnets with varying inner coil apertures will track was brought up at the January 23 meeting of the GESSS machine design committee. The answer is yes if the iron is not allowed to saturate. The answer is probably no when the iron is saturated.

In order to investigate tracking two identical Karlsruhe sector coil dipoles designs were used. The primary difference is the inner coil radius. The coil thickness is the same for both cases (1.6 cm). In order to make the magnet track the iron dimension is changed. In version I the iron lies 4 mm outside the coils of both magnets. In version II the iron radius is adjusted on the B magnet so that both magnets produce the same field for a given coil current density as long as the iron is unsaturated. In version III the iron of both magnets is adjusted so that the iron remains unsaturated until the central induction rises above 4.5 T.

Table 1: The critical dimensions for magnet A and B for the three versions

Version	Component	Magnet A	Magnet B
I	inner coil radius	50.0 mm	60.0 mm
	outer coil radius	66.0 mm	76.0 mm
	inner iron radius	70.0 mm	80.0 mm
II	inner coil radius	50.0 mm	60.0 mm
	outer coil radius	66.0 mm	76.0 mm
	inner iron radius	70.0 mm	87.2 mm
III	inner coil radius	50.0 mm	60.0 mm
	outer coil radius	66.0 mm	76.0 mm
	inner iron radius	106.7 mm	136.8 mm

Figure 1 shows the coil current density verses central induction for version I with the A and B dipoles. They will not track in any field region. Figure 2 shows coil current density verses central induction for versions II and III. In version II both dipoles track up to just over 3.0 T. As the iron saturates the magnets no longer track. In version III the magnets track all the way to 4.5 T because the iron is not allowed to saturate.

I appears that saturated iron magnets with differing coil apertures will not track. (I will not say it is impossible a closer look may reveal a solution.) One can make all of the magnets of one aperture (the larger) but with saturated iron, or one can make them with differing apertures with unsaturated iron. If half the magnets in a synchrotron are of each type, then the two solutions have nearly the same stored energy (this statement applies only to the example given not all examples). The machine using the one aperture magnets with saturated iron will have magnets with smaller physical dimensions.

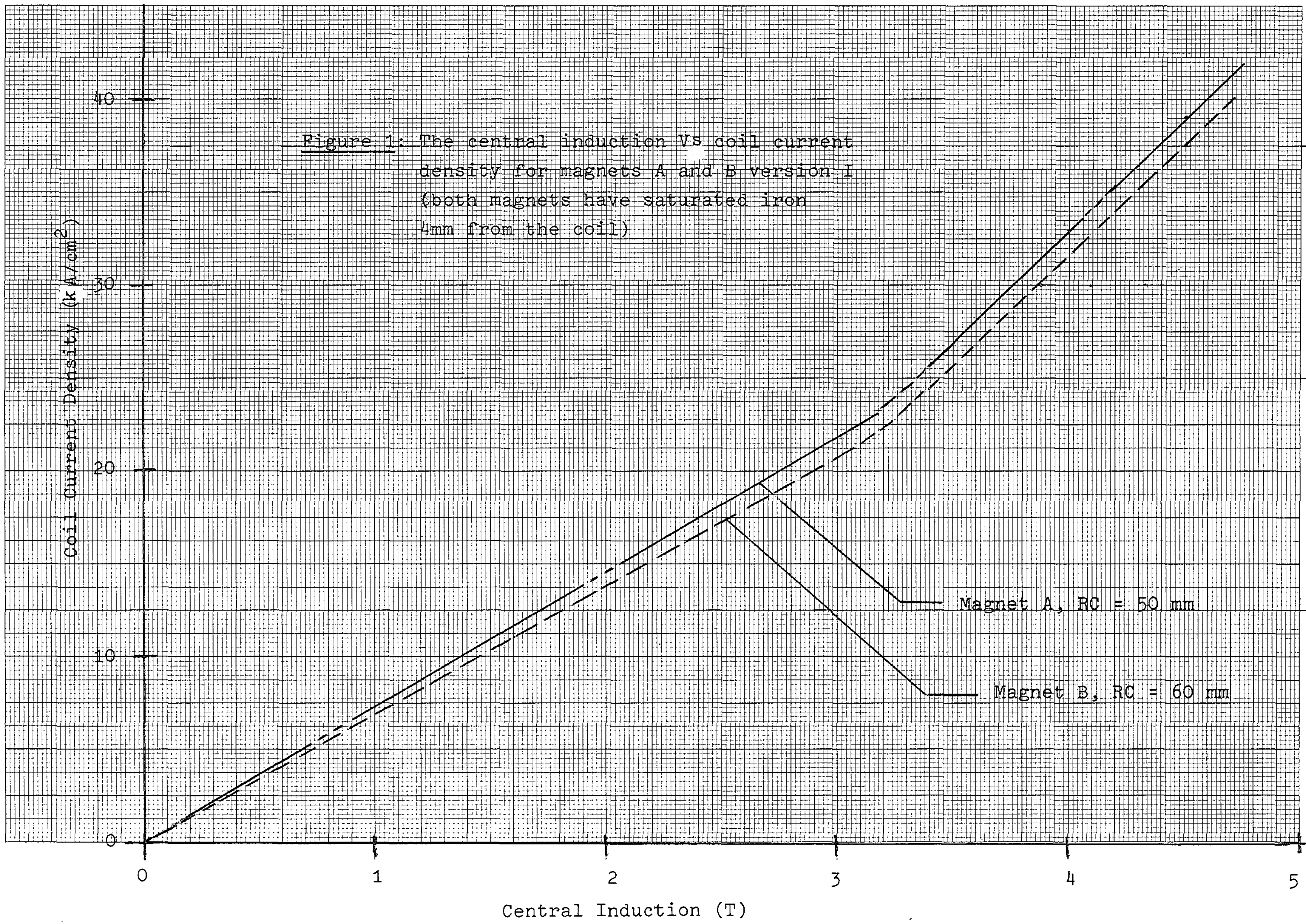

Figure 1: The central induction Vs coil current density for magnets A and B version I (both magnets have saturated iron 4mm from the coil)

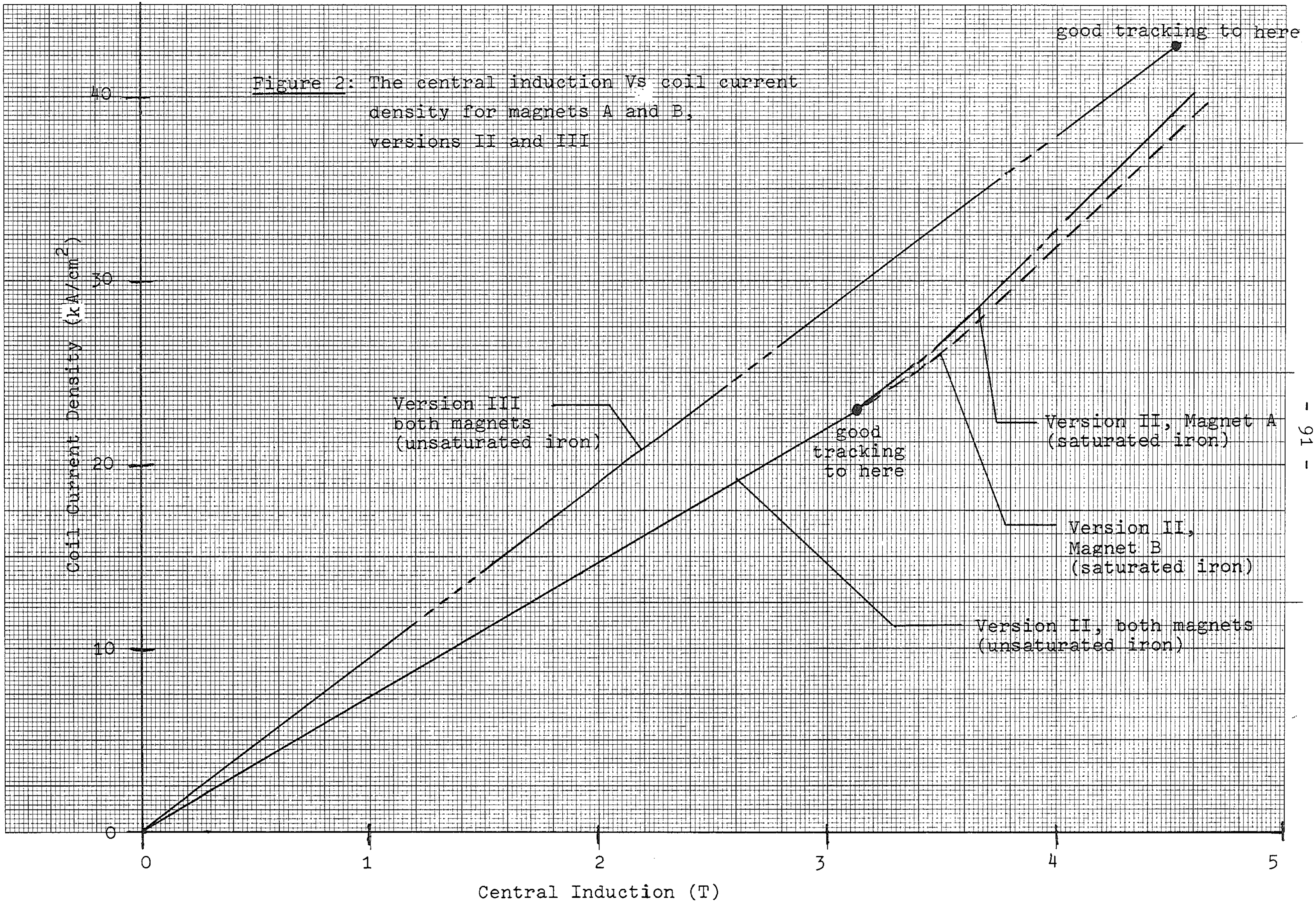

Figure 2: The central induction Vs coil current density for magnets A and B, versions II and III