PROGRESS REPORT ON MAGNET DEVELOPMENT†
(APPENDIX TO SUPERCONDUCTING SYNCHROTRON DEVELOPMENT AT BNL)

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The following, prepared and reported by A. van Steenbergen, summarizes the to-date status of the BNL superconducting magnet program. It is based on the work carried out by G.T. Danby and co-workers, G. Parzen, W.B. Sampson and co-workers, and others of the BNL Accelerator Department.

Introduction

At BNL, high field (≥ 40 kG) magnet design has, until recently, proceeded along two distinct routes: (i) Development of a low temperature (12°K) window frame magnet with rectangular pure aluminum conductor winding blocks[1]; (ii) Development of an air core type magnet, with a cos θ current distribution over the surface of a circular aperture making use of filamentary superconducting wires woven into conductor braids.[2] With the advances made in the development of stable performance, low loss, superconducting materials for relatively high $\dot{B}$ operation, the use of cryogenic pure metal coils remained an economically practical alternative only for fast cycling synchrotrons. Therefore, more recently, the use of NbTi conductor or Nb_3Sn ribbon coils, interleaved with high purity aluminum ribbon for stabilization, is being pursued for use with the window frame magnet.[3] Also, for the air core type cos θ coil magnet, the importance of a thick iron shield enclosing the azimuthally distributed superconducting coil blocks, was recognized rather early in the development of this magnet.

Consequently, even though there remain important differences between the two types of basic magnet circuits, especially with respect to the presence of inherent aberrations at high field, the sensitivity to conductor location errors resulting in field aberrations and the ease of construction of the dipole for operation at 4.5°K, the general construction details are now somewhat analogous.

The various magnet circuit options, under development at BNL, are indicated in Fig. 1. Also shown is a cos θ distribution dipole of the constant current density type,[4] having the distinctive feature that the contour of the boundary between conductor and iron shield has been so developed as to minimize the sextupole component of the field both at high and low field values.

Magnet Circuit Design

Air Core Type Circuit With Cos θ Current Distribution and Iron Shield

The basic cos θ distribution dipole; as executed in the BNL design,[5,6] consists of four discrete multiconductor blocks per quadrant, surrounded by a thick iron shield. The required azimuthally varying current density in each block is achieved by winding ribbons of conductors in parallel with ribbons of inert material. For dipole magnets of up to 40 kG peak field, using NbTi material, conductors in the form of a wide ribbon (5/8 in.) braided from small diameter (0.008 diam.) composite wires and arranged in a single layer of conductor blocks, are used.

The dominant advantages of an iron shield in closest proximity to the dipole aperture, as compared with an air core dipole with iron shield outside the dewar envelope, are (i) field enhancement; this may be expressed in terms of the "iron enhancement factor" (IEF) which for a specific single layer, 40 kG dipole design is as high as a factor of 1.5, (ii) the simultaneous availability of a rigid structural member within the dewar envelope for the suitable mechanical construction of the dipole unit, and (iii) the reduction of the stray field outside the dipole structure proper. With regard to the sextupole component which arises at high field due to partial saturation of the iron shield, the existence of a "critical iron thickness", which minimizes the sextupole component has been found as a result of the field computations of the cos θ dipole configurations for various iron shield thicknesses.[7,8] For a single layer, 40 kG, dipole the critical shield thickness value, t_c, is approximately 2.2 in., a value slightly larger than that previously adopted for practical reasons and near optimum field enhancement in the aperture. In addition, it is intended to incorporate a separate sextupole correction winding (At < 0.5% of main winding At) in each dipole unit for, typically, the ISABELLE project magnets.

The often cited disadvantage for a.c. superconducting dipoles of having the iron shield in the domain of high field, in connection with iron core losses, is unfounded when taking into account realistic synchrotron cycling rates, as was done for the CMS system,[9] i.e., for a typical 4 s synchrotron cycle, 40 kG dipoles, the iron core losses constitute less than 16% of overall magnet "dynamic" losses, (less than half the conductor hysteretic losses). This was calculated for a 1.5 in. full aperture dipole.

Window Frame Magnet

The basic window frame geometry studied at BNL is shown also in Fig. 1. Typically, a square aperture of 2 x 2 in.^{2} is bounded on each side by a 2 x 2 in.^{2} coil block for field excitation surrounded by a square iron yoke with sides approximately 3 times the total "window" width. The optimization of the geometry with respect to aperture aspect ratio, window and coil dimensions, has been extensively studied at BNL by means of field computations and experimental work with model magnets. That the iron yoke is still very effective in coupling to the gap notwithstanding the high level of saturation is indicated by the fact that the increase in field excitation (ampere turns) as compared with the case of infinite permeability is only approximately 30% for a field value of 40 kG. Concomitant, however, with the high state of saturation of the iron, and its

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partial use in generating the field distribution in the gap is the presence, at high field, of a large percentage of field non-linearity. Expressed as B'/B_0, its dependence on geometrical parameters, at various field levels, has also been studied. For the geometry indicated above, at a radius value of 0.6 in. this value is $(B'/B_0) \cong 3{,}2\ m^{-1}$. Since this is mostly sextupole component, its correction with separate sextupole windings has been adopted (also indicated in Fig. 1). With a sextupole winding excitation of 3% to 5% of the ampere-turns required for the main dipole windings the field aberrations are reduced to acceptable magnitude.[3] A modification of the window frame magnet has been pursued by G. Parzen[10] whereby an exceptionally flat field is obtained by means of the introduction of a real pole and two separately excited coils, as also indicated in Fig. 1. With the proper choice of the current ratio (I_2/I_1) it is possible to eliminate the sextupole term in the median plane magnetic field at all field levels. For the small aperture values being considered for a superconducting synchrotron it may, however, not be sufficient to eliminate this term only. In order to further reduce the higher order field components, the pole height and pole face "shim" are also adjusted independently for minimum non-linearity at two specific field excitation values.

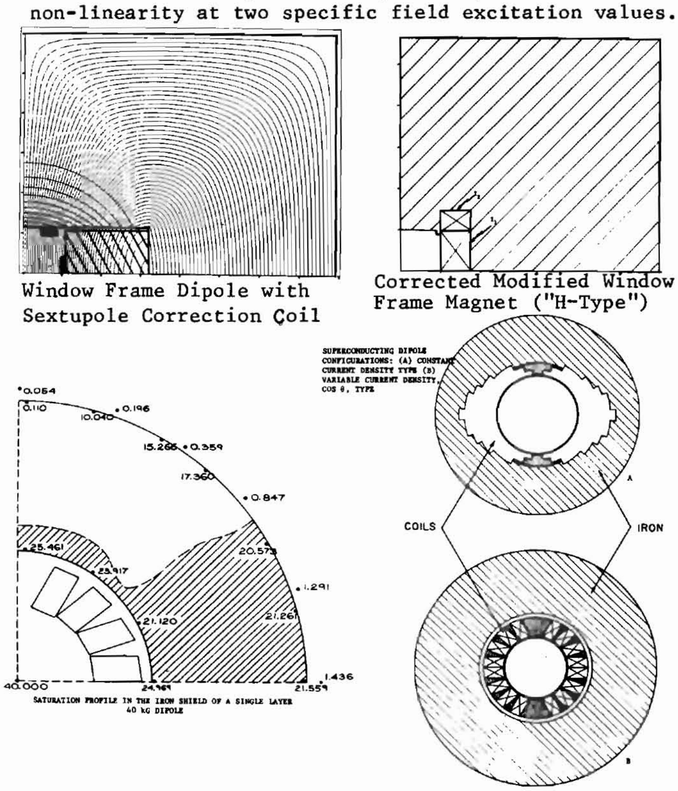

Fig. 1. Superconducting Magnet Details.

Magnet Conductors

At BNL great emphasis has been placed on superconductor material development for a.c. dipole applications. Significant progress has been made in the development of the NbTi superconductor composites and fully transposed braids, and in the area of advanced conductor development making use of, typically Nb_3Sn or V_3Ga.

Two recent publications describe extensively recent Brookhaven work on superconducting synchrotron magnets[11] and developments on multi (composite) wire braids.[12] Further developments and results obtained since then are also included below.

NbTi Composites

Based on the fundamental work by Bean, Hancox, the Rutherford Group, and others; the verification by the BNL group of some of the theoretical predictions especially with regard to loss dependence on superconducting filament diameters and twist rate of the composite wire and the actual development work carried out on braided conductors and magnet designs at BNL, a set of criteria evolved for the desirable properties of twisted multifilamentary wires.

Based on this quantities of superconducting NbTi composite wire were ordered from the three (American) firms with capabilities in this area, (Airco, Cryomagnetics and Supercon) with the following specifications: wire size, 0.008 in. (0.2 mm) diam.; number of filaments > 300; filament size < 0.0003 in. (7.6μm) diam.; twist pitch ≅ 10 turns/in.; current density > 40 kA/cm² at 60 kG; superconducting content 40-50%; matrix resistivity ratio 20-100; ratio $J_{c,30kG}/J_{c,60kG} \le 2$. Two quantities of wire, one with Formvar insulation, the other with a silver-tin eutectic coating were obtained from these 3 sources.

This material has been used now extensively in small test solenoids, large pancake coils and synchrotron dipole models. For the latter 2 applications fully transposed braids are woven consisting of 132 wire strands, resulting in a braid of ≅ 0.625 x 0.020 in.², as shown in Fig. 2.

Notwithstanding that magnets produced with these multifilamentary conductors should exhibit low losses and be theoretically stable, conductor motion in a dynamic field normally leads to higher losses and degradation in performance, i.e., $(J_{max}/J_c) < 1$.

Two approaches are being pursued. The first is the search for an effective coil casting system such as thermoplastics, etc. Recently, promising results have been obtained with impregnation of the coils with the thermoplastic "Polybondex". Linear behavior (loss/cycle vs B) up to 20 kG (30 kG field equivalent for dipole plus shield) has been obtained. The second is the use of braided conductors in a metallic matrix. With the latter approach the matrix prevents motion of the individual wires and allows the braid to be accurately dimensioned by rolling. Early results with this metallic insulated and bonded braid in synchrotron dipoles indicated indeed that non-degraded performance could be obtained, however, the wires in the braid suffer from higher coupling at relatively low $\dot{B}$ values, consequently leading to higher losses. In essence, the conductor is equivalent to a second order multifilamentary composite in which the wires play the role of filaments, i.e., the transposition length is analogous to the twist rate in the wire composite.

Recently extensive work has been carried out to increase the $\dot{B}_{min}$ for total coupling. The coupling of multifilament wires in a braid may be similarly calculated as for filament coupling in a wire, therefore, the fundamental approach developed by the Rutherford group is applicable. This work has been extended by G. Morgan of the Brookhaven group[13] which led to the approach[12] to increase the "effective" resistivity of the total conductor matrix. This is achieved by sequential heat treatment of the braided conductor, woven from AgSn coated multifilamentary wire composite, and coated with a InTl eutectic, providing for a moderately rigid, well cross linked conductor.

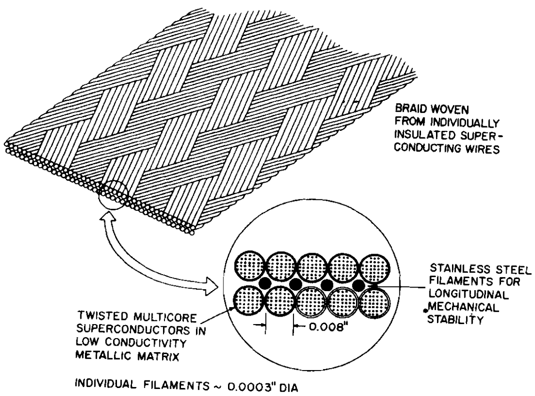

Fig. 2. A.C. superconductor.

Nb_3Sn, V_3Ga Conductors

Efficient high field dipole designs, operating at a lower cost, could result from the application of the intermetallic component Nb_3Sn because of its inherent higher critical temperature. This material is readily available in the form of a composite tape with copper as a stabilizer, and in this form, is presently being used at BNL in the development of d.c. magnets (see below). Problems may exist, however, as a result of diamagnetic currents and degradation in large coil units. Development work has been done at BNL to produce a filamentary Nb_3Sn conductor. In cooperation with industry short samples have been produced by reducing niobium surrounded by tin foils in a copper matrix and subsequently heat treating this to form Nb_3Sn. Early results were promising. Presently, however, progress with Nb_3Sn filamentary wires development has slowed down in favor of the development of a filamentary V_3Ga composite. Metallurgically, these intermetallic compounds are similar, for this reason any progress in the development of a V_3Ga composite will benefit the Nb_3Sn development. Multifilamentary superconducting V_3Ga wires in a Cu-Ga solid solution matrix have been prepared (starting with 361 Vanadium wires in the Gallium-bronze matrix, and going through specific heat treatment cycles) and short sample tests have been carried out.[14] Presently a quantity of 10,000 ft of multifilamentary wire is being produced for standard measurements.

Performance of Test Solenoids and Model Synchrotron Magnets

Extensive measurements have been done with the NbTi composite wire, as obtained from the various sources, woven into a braided conductor, as described above. Following short sample measurements, performance data were obtained by means of a standard small solenoid configuration using approximately 3000 m of the wire in the form of a 33 strand, fully transposed flat braid and producing a maximum field in the range of 30 kG to 60 kG; subsequent to which the conductor was tested in the form of a large spiral or "pancake" winding using approximately 10 kM of wire in the form of a 132 strand braid and finally, using the same braid, model synchrotron dipoles were constructed and tested with and without iron shield. The pancake winding was so chosen as to have an identical load line to the model synchrotron magnet with iron shield.

The collective performance results have been presented by P. Dahl at the recent National Particle Accelerator Conference,[15] here only the most significant data are presented in summarized form, updated by results obtained in the intervening period.

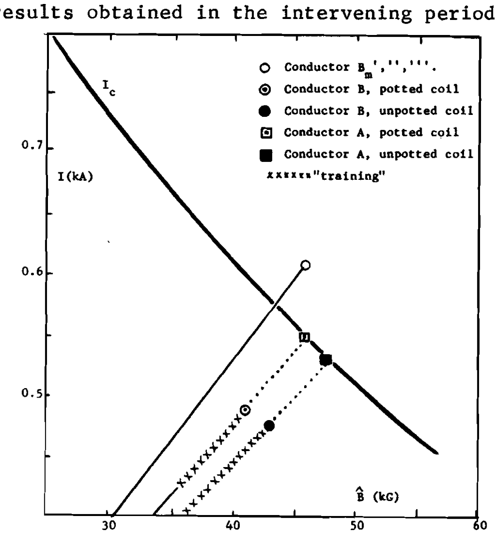

Fig. 3. Test solenoid magnet performance.

The conductors used may be listed as follows:

Multifilament NbTi Composite	Number Filaments	Percent Supercon	Insulation
Type A	120	30	Formvar
B	300	50	Formvar
B_m	Same	Same	AgSn

In the case of the metallic insulated composite wire, the woven braid was given sequential metallurgical processing, as described in the foregoing, this will be designated as conductor B_m' through B_m''''. The "performance" of the small solenoid, pancake winding and model synchrotron magnet is given in Figs. 3 and 4. As shown, under no condition could short sample performance be obtained for small solenoids with the Formvar (conductor B) insulated material, with the exception of a test run with the small solenoid whereby conductor A (lower percentage superconductor) was used. Nevertheless, a number of solenoids reached 90% of short sample performance. Even though a wide variety of potting materials have been used for solenoid potting, all solenoids using the Formvar insulated material exhibited "training" to various degrees. The unpotted coils showed this behavior over a wider range of excitation. In contrast, for solenoid tests, using the metallic conductor, it was found that better a.c. performance was obtained than d.c., provided the cycling period was short enough that the normal region could not propagate. For test runs with the pancake coil, short sample performance could similarly be obtained with the "metallized" braid only. This is not quite so for the model synchrotron magnet when using this conductor, although (I/I_c) values of up to 90% were routinely obtained. The peak field in the dipoles is the same as that of the pancake windings, but field distribution and magnetic force distribution is completely different.

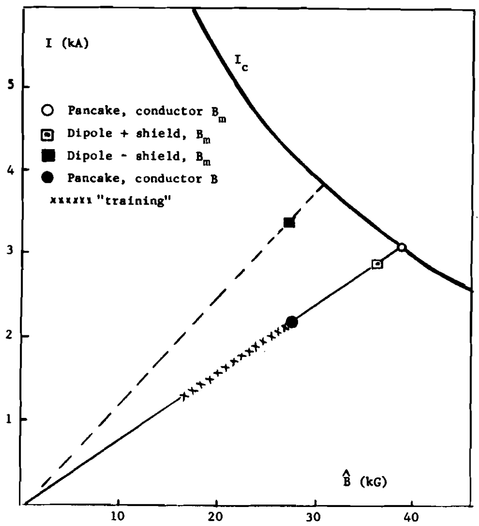

Fig. 4. "Pancake" winding and model synchrotron magnet performance.

It should be noted that the performance of the dipole magnet with shield is significantly better than without shield, since the presence of the iron increased the field by nearly 50%.

Notwithstanding the excellent results obtained with the metallic and intermetallic insulated braid, the penalty associated with the early versions of this conductor is the significant increased coil dissipation associated with the currents crossing the inter wire resistivity layers (coupling). This loss behavior has been analyzed by Morgan[13] predicting that for low values of the cycling frequency, ω, the (loss/cycle) is proportional to ω, whereas for high ω values it is inversely proportional. This is born out by the experimental results, as is shown in Fig. 5, where the loss per cycle is plotted versus $\dot{B}$ for the small solenoid coil using the metallized conductor B_m' and B_m'''' (basic difference, reduction of coupling by means of the increase of interwire resistivity as a result of further formation of high Sn content bronze on the surface of the individual wires in the conductor braid). For the highly coupled case the losses are very high indeed, nevertheless, the coil still performed in an undegradated fashion. With the increase of inter wire resistivity the losses per cycle could be substantially reduced and the minimum $\dot{B}$ value for total coupling would be increased.

The magnitude of the loss per cycle for a solenoid with the metallized braid conductor, B_m'''', may be compared with that of a solenoid using fully insulated braid, conductor B, as shown in Fig. 6 where the loss/cycle is shown as a function of B for various cycling periods. (In the latter case the loss/cycle is frequency independent, it was measured using a typical 4.4.4 cycle.) The lowest cycle used, while obtaining loss data for the solenoid with conductor B_m'''' is indicated by $\dot{B} \rightarrow 0$. When corrected for d.c. resistivity the latter dissipation values agree well with that measured for the "uncoupled" braid solenoid; the conductor used in that case did not exhibit any significant d.c. resistivity. Its dissipation values are a factor of two higher than calculated by using the Bean model.

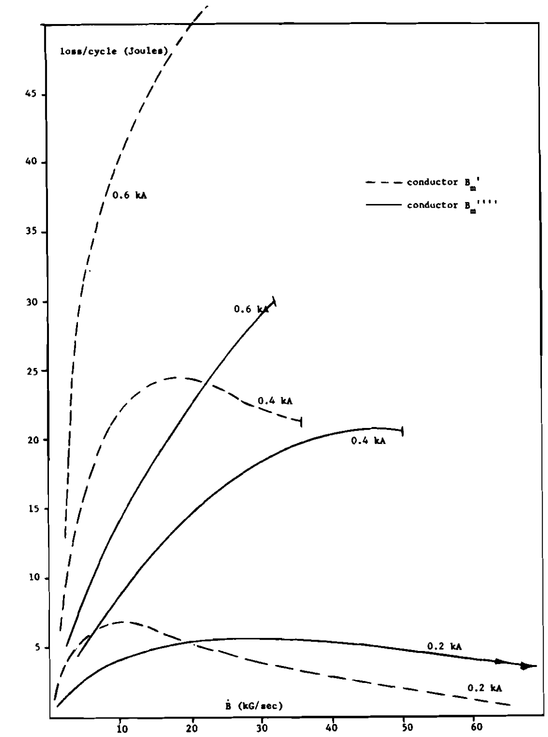

Fig. 5. Solenoid a.c. losses vs $\dot{B}$.

Summarizing the performance data, lowest dissipation values are obtained with potted coils using fully insulated braids. The loss/cycle is cycling frequency independent and a factor of two higher than obtained from computations using the Bean model. In this case significant degradation is encountered and model magnet dipole performance only up to 75% of short sample performance has been obtained. Nearly undegraded performance with essentially no training present, of test solenoids, pancake windings and model synchrotron magnets can be obtained using the "metallized" braid conductor. The loss per cycle is frequency dependent and several times larger than for the uncoupled braid conductor for reasonable synchrotron cycles. For a $\dot{B}$ value $\rightarrow 0$ losses are comparable with that of an "uncoupled" braid coil.

Actual synchrotron dipole dissipation values, for specific dipoles under consideration, as typically the 1.5 in. aperture dipole for the CMS, have been presented in the preceding report.

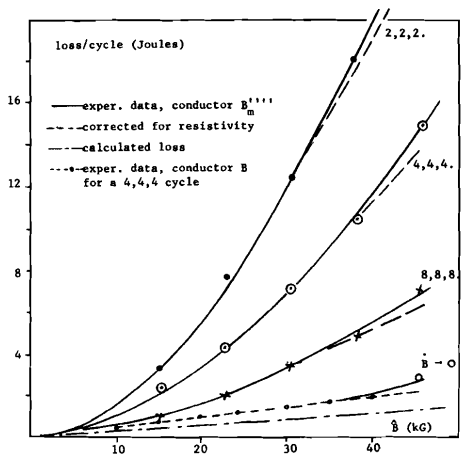

Fig. 6. Solenoid coil a.c. losses vs $\hat{B}$ for various cycles, using the metallized braid conductor.

Future Work

Recently, the emphasis in development of superconducting magnets has shifted towards d.c. applications, directly connected with the objectives of, short range, incorporation of superconducting magnets in the AGS primary and secondary beam lines and, somewhat longer range, development of superconducting storage ring magnets. The status of superconducting components under test or construction at BNL for immediate application are indicated in Table A.

For the 200 GeV superconducting storage rings engineering studies are in progress of the magnet-dewar system and the associated long dipole units. Refrigeration system studies are continuing and further heat transfer studies will be done making use of liquid helium immersion of supercritical He flow.

TABLE A: Superconducting Magnet Components Under Test or Construction

Magnet	Conductor	Remarks
Short a.c. dipole magnet cos θ type, 2 in. aperture 14 in. long.	NbTi transposed braid, 0.625 in. x 0.020 in. 132 wires, 0.008 in. ∅; 320 filaments, 7 μm ∅; 50% s.c.; insulation Formvar or metallized braid with Polybondex.	40 kG, single layer dipole. Testing of casting materials. Development of engineering design concepts. Part of a sequence of model dipole development. Status: in assembly.
Long d.c. dipole model 2 in. aperture, 10 ft. long.	- - -	Storage ring dipole engineering design. Status: in design.
D.c. dipole magnet cos θ type, 3.5 in. aperture 42 in. long, iron shield 2.5 in.	NbSn, 0.500 x 0.006 in^2, Cu foil composite. Wound with 0.002 in. 1000 RR Al. as stabilizer. Block current density 50 kA/cm^2.	Unit tested at 44 kG, 50 kA/cm^2 block current density, time constant ≃ 30 min. Objectives: end field measurement cos θ dipole, diamagnetic current perturbation. Beam transport magnet for SEB, primary proton beam.
D.c. beam splitter magnet, aperture twice 2.5 in. x 0.875 in., length 49 in. Window frame magnet with midplane high current density septum.	NbSn tape with Cu stabilizer, 0.120 in. x 0.007 in. tape, insulation st. st. tape 0.0005 in. current density 44 kA/cm^2 at B = 18 kG.	SEB switchyard beam splitter magnet. Status: in assembly for operation February 1972. Model magnet reached current density of 90 kA/cm^2 at 22 kG.
D.c. beam transport magnet model unit, window frame magnet with sextupole correction. Aperture 3.75 in. x 3.75 in.	NbTi conductor, 0.057 in. x 0.114 in., 44% s.c., twist 1/in., 360 filaments 0.003 in. ∅, conductors interspaced with anodized pure Al with vertical channels for He cooling conductor current density 27 kA/cm^2, (coil package 13 kA/cm^2).	Model unit for corrected window frame beam transport magnet. Status: in assembly.
D.c. beam transport magnet 2 ea. 6 ft. length units, window frame magnet with sextupole correction aperture 3.75 in. x 3.75 in. B = 40 kG.		Beam transport magnet (8^o bend, 30 GeV protons) for primary proton beam. Status: in design; in beam line operation, Summer 1972.

Specifically with regard to dipole development a variety of casting materials will be tested in order to eliminate conductor motion, with the objective of obtaining low dissipation, undegraded dipole performance. Also, realistic assemblies of long model dipoles will be made to assist engineering design concepts, develop conductor block location tolerances and test coil package containment methods. Further, support and alignment systems are being designed for the magnet-dewar system.

Precision field measurements will be done with the short model magnets using a harmonic component test coil. Also end field distribution will be measured more accurately by point coil measurements in order to ascertain the correctness of dipole magnet coil end assemblies.

In conclusion, the status of superconducting magnet development at BNL may be summarized as follows: Basic conductor and magnet circuit development are well in hand and do not provide any significant obstacles. The problems which remain are primarily those of engineering design of providing for magnets with such conductor tolerances, at 4.5°K, that sufficiently precise field distributions can be obtained in a reliable and reproducible manner.

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DISCUSSION

P.F. SMITH: I would like to correct the statement that the objectives in overall current density for the Brookhaven coils is higher than that generally proposed elsewhere. In fact, the proposed Brookhaven figure of 3×10^4 A/cm^2 at 40 kG corresponds exactly to the figure of 2.5×10^4 A/cm^2 at 45 - 50 kG specified in designs at Rutherford, Saclay, and Karlsruhe; the latter designs would also give 3×10^4 A/cm^2 or more at the reduced field of 40 kG.

G.K. GREEN: There may be differences in detail, but we are certainly all agreeing that we must go to the highest practical current density.

H. BRECHNA: What are the coupling losses in a braid (cable) of the In-Tl system compared to fully decoupled (insulated) cable.

G.K. GREEN: The coupling losses are larger for fast rise but are comparable at very slow rise. They can be deduced from Figure 6.

A. ASNER: Can you state the 4° K resistivity figure of the Bi-poisoned In-Tl solder you use for "metallic" impregnation?

G.K. GREEN: I do not remember the exact numbers. However, the resistivity of the In-Tl, the bronzed matrix and the interfaces are altered in complex ways by the metallurgical heat treatments.

G. LOEW: Could you say a few words about your work with Nb_3 Sn, if you are still pursuing it actively?

G.K. GREEN: We are using Nb_3 Sn ribbon which we have on hand but are not actively extending the ribbon work. We are at present not active in multifilament Nb_3 Sn.

J.H. COUPLAND: I quite agree with you that the iron should be placed as close as possible to the coil; it could result in significant savings in superconductor and stored energy. However, may I ask what field quality you get in the beam aperture when the iron contributes 17 kG to the field?

G.K. GREEN: Calculations indicate that proper proportioning of the iron can give good field quality: perhaps $1 - 2 \times 10^{-3}$ at r = 0.8 of aperture. We must soon begin precision measurements.

G. BRONCA: You showed, on the last slide, lower losses for the potted coil compared to the unpotted coil and your explanation was that it was due to more movement. I would like to mention that we had similar results with a coil having heat drains. In one case the drains were cut short and the cooling became bad but the losses were smaller than expected from theory. Higher temperatures mean lower losses but also more degradation. Did you also see more degradation for the potted coil compared to the unpotted coil.

G.K. GREEN: Yes, if the mechanical motion is small. If the unpotted coil is wound and held very tightly, then its degradation is less than a potted coil <u>without</u> heat drains.

D.B. THOMAS: In describing your metalized braid, you have said that for a cycle with 2 s rise, 2 s flat top and 2 s fall, losses were about a factor 2 or 2.5 times that of fully uncoupled filaments. What size filaments are you using?

G.K. GREEN: The filament size was 7 μm.

D.B. THOMAS: Then for 4 to 5 μm filaments the factor could be 3 or 4. I believe that such a factor makes the metalized braid unacceptable for a pulsed synchrotron. To keep losses low enough, completely uncoupled 3 - 5 μm filaments are necessary.