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BNL SUPERCONDUCTING STORAGE RING MAGNET UPDATE* CONF-780952--31

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ABSTRACT

This report updates the various performance data, design and specifications for the storage ring and experimental series dipole and quadrupole magnets as well as the working line and correction coil systems. The working line system includes the closed orbit dipoles, the quadrupole trim, sextupoles, octapoles, decapoles and duodecapoles. These are the magnets in the standard subunits of the Brookhaven National Laboratory Intersecting Storage Ring Accelerator "ISABELLE". There have been 14 full size single layer dipole prototypes 4.25 to 4.75 m long constructed. There have been two 1.5 m long full size quadrupoles built. A one meter double layer dipole was built in order to obtain high field > 6.0 T data. A subunit of the original 200 × 200 GeV version of the ISABELLE lattice was assembled to study systems operation. (ISABELLE now has the design goal of 400 × 400 GeV.[1]) This subunit utilized the proposed ISABELLE form of refrigeration, namely "high pressure helium gas forced flow". The array composed of two dipoles and a quadrupole with auxiliary working line and correction coil systems was serially connected both electrically and cryogenically. One of the major design goals, that of the magnets being protected by the ability to absorb their own energy, proved to be attainable. This is accomplished without external intervention, i.e. external extraction or driving the magnets normal by an active external circuit. This simply means the magnets L/R time constants during a quench are short enough to prevent thermal damage or run away. There are two series of prototypes. The first one is the so-called "standard" which will become the ring magnets for "ISABELLE" when the machine design is frozen. The second is that in which various characteristics and/or limits of various parameters are explored. Various parameters such as maximum ramp rate and other $\dot{B}$ dependent phenomena are bracketed even though the present standard parameters are workable. There has also been obtained in the last two years operational data on four large (25 cm cold aperture, 2.5 m long) pool boiling dipoles. They have been an integral part of the High Energy Unseparated Beam guiding particles to the MPS (multiparticle spectrometer) of the AGS (30 GeV alternating gradient synchrotron, ISABELLE's injector).

INTRODUCTION

The operation of devices at high magnetic fields (~ 5.0 T) for long periods of time is an ideal application for superconducting magnets. The dissipation of energy inherent in the cyclic operation of superconductors is minimized due to the low duty factor (repetition rate) of the modern high energy storage ring accelerator. The excellent current densities "J" available in modern superconducting composites lead to increases of greater than an order of magnitude in the maximum coil winding densities attainable compared to standard copper windings, therefore resulting in much higher field intensities being produced efficiently. With these advantages, however, there are several additional constraints imposed on the system that are either nonexistent or much less severe in a conventional room temperature magnet string. The iron of the magnets acts as a mirror for the conductors resulting in the magnetic field quality being almost totally dependent on the conductor placement accuracy. Due to the very high fields and currents involved, the coil forces are very large and must be carefully contained. One of the more challenging constraints is that an uncontrolled release of a few joules or millijoules can cause the superconductor in the magnet winding to become unstable and revert to the normal resistive state. This constraint is imposed in a unit whose total stored energy is greater than a megajoule. This problem is therefore both interesting and challenging. The latest evolution of a magnet design and the data on which it is based is contained in this paper. The design must operate within the aforementioned constraints and still retain the desirable features needed for machine construction and operation of ISABELLE.

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MAGNET DESIGN

An ISABELLE ring magnet can be simply described as single layer cos Nθ turns distribution saddle coils that are preloaded by the cold iron shield that surrounds them. The coil winding fixture and coil half are shown schematically in Fig. 1. This elevated temperature molding technique usually produces a very monolithic type of structure as shown in the upper left hand corner of Fig. 2. The actual construction details and techniques have been thoroughly covered in previous papers.[2-4]

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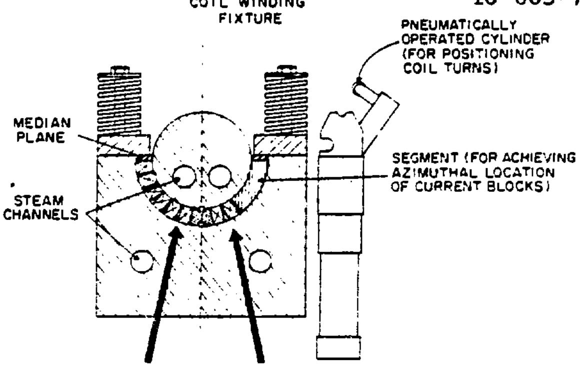

Fig. 1. This is an end view drawing of the winding fixture for the "cosine θ" saddle magnet. It is a steam heated steel fixture. Newer version of the fixture used hydrolically operated cylinders in place of the die springs on top.

Important design parameters that are addressed in the prototype program can be divided roughly into two categories: material properties and magnetic properties. One of the more important material characteristics is the compatibility of the materials in the coil winding assembly, first in contraction in the 300 K to 4 K cycle and second in the ability to withstand the high compressive pressures encountered at both ends of the temperature range, i.e. the molding pressure at 140 C and the magnetic pressure at 4 K. The third material property required is as high a thermal conductivity of the winding package as possible. The most important magnetic properties required are: predictability and reproducibility of the magnetic field shapes with the ability to alter those shapes for the requirements of machine operation, and particularly the highest reliable magnetic field intensity possible within the economic constraints given. The materials that have evolved as well as the winding and molding techniques used in conjunction with the prestressing of the coil structure by the iron shield have resulted in a design that nominally produces magnets which achieve the following desired properties:

i. The quench characteristics of the magnets are such that there are no thermomechanical distortions of the turns when all of the stored energy of the device is internally dissipated. The high azimuthal quench velocity (turn-to-turn) causes the energy to be distributed over a large volume of the coil. The high velocity is a result of the following three conditions being met: a) There are no finite thicknesses of epoxy or thermoplastic from the pole tip to the midplane wedge on the inner diameter edge of the coil with the exception of the fiberglass epoxy insulation tape. b) The fiberglass epoxy insulation tape is very thin and has a very high glass to resin ratio (see Fig. 2). c) The high aspect ratio of the conductor (width to thickness 23/1) results in a large turn-to-turn surface area to volume ratio. One-seventh of the azimuthal path of the inner diameter of the coil from the first current block to the midplane is occupied by fiberglass and "B" stage epoxy, the rest is metal.

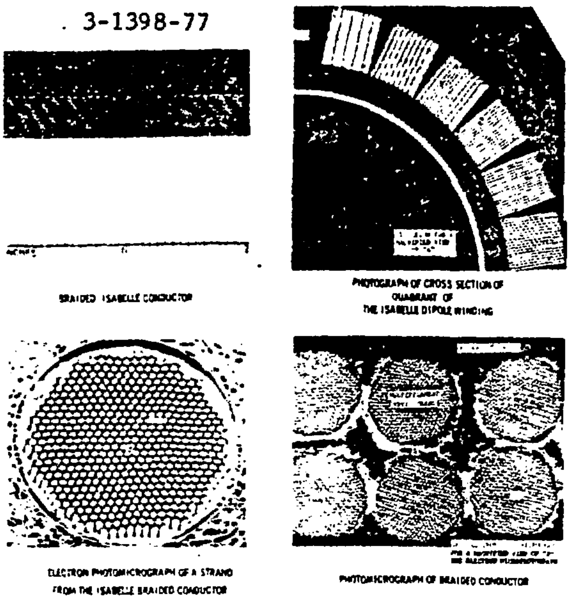

Fig. 2. This is a composite photograph showing the bare compacted braid conductor, its position in a typical dipole and photomicrographs of various details such as the filaments in the strands.

ii. The coil package is preloaded radially and azimuthally by the interference fit in the iron shield. This is accomplished by inserting the coil package at 77 K into the laminated room temperature iron shield. This preload, if all of the components fill the radial extent of the coil package, results in the magnet reaching the short sample performance of the conductor with a minimal amount of training.

The parameters that have been explored in the experimental series are shown in the following list and will be referred to by number in the results section.

1. The transfer function of the magnet has been increased.
2. The current density available in the basic conductor has been increased.
3. The effective current density of the winding has been increased.
4. The effective resistivity of some components of the magnet winding has been increased. This is to increase the quench propagation and decrease the B dependence of various magnet parameters.
5. Better mechanical control of the materials that compose the coil package has been achieved.
6. Better saturation parameters of the iron shield due to geometry has been achieved.
7. The effective resistivity of some part of the winding has been decreased. This is to improve stability and thermal conductivity.

The various experimental and standard magnets have led to the present design which is shown in Fig. 3. The design of the double layer magnet is essentially identical with that of the single layer except one magnet winding nests inside the other. The inner layer is wound first, then banded and the outer layer is clamped onto the inner magnet's outer bands. The cross-over joints (i.e. the lead coming out orthogonally to the post is lapjointed with the lead from the other magnet half) for both inner and outer coil, were positioned outside the outer coil.

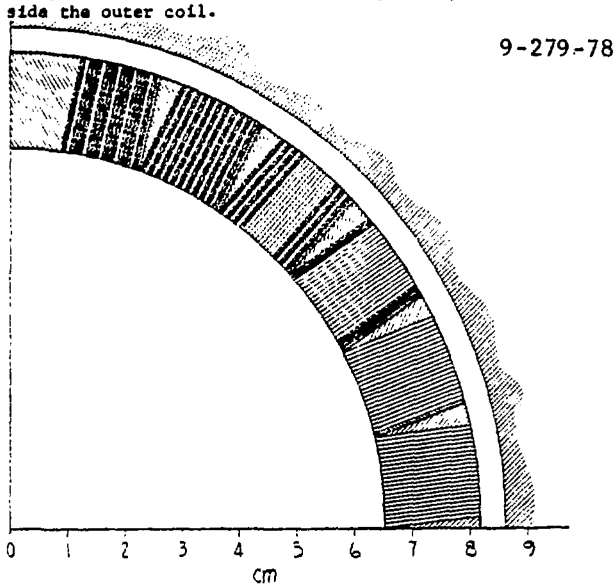

Fig. 3. The final dipole winding cross section is shown schematically drawn for one quadrant.

The design of the "HEUB" dipoles was a simple extension of ISA MK-II design to different aspect ratios. The cold aperture of the magnet is 25 cm, the length of each magnet is 2.5 m, and the operating field is 3.8 T. There are four magnets which bend the high energy (30 GeV) unseparated beam of BNL's AGS through 20° enroute to the multiparticle spectrometer. This is a single layer design (see Fig. 4) as well.

MAGNET AND MAGNET SYSTEMS PERFORMANCE

The four large aperture "HEUB" magnets reached or exceeded the design field after only a few quenches. These liquid helium cooled magnets store ≈ Megajoule at 4.0 T. The magnets operate in separate cryostats supplied by a CTi 4000 unit refrigerator which has a capacity of 1.5 kW at 4.5 K. Their combined load with associated piping is 550 W. The magnets are controlled by the AGS computer which is in command of other magnets in the beam line. Their performance and characteristics are given in Table I.

This beam line has operated without incident, with the exception of a few cryogenic impurities blocking the primary heat exchanger, from Sept. 1976 to present. It should be noted that this set of heat exchangers are the only major part of the refrigerator without redundancy.

The experimental series of prototypes and parameter characterization magnets have been varied in purpose and performance. The performance and characteristics are given in Table II.

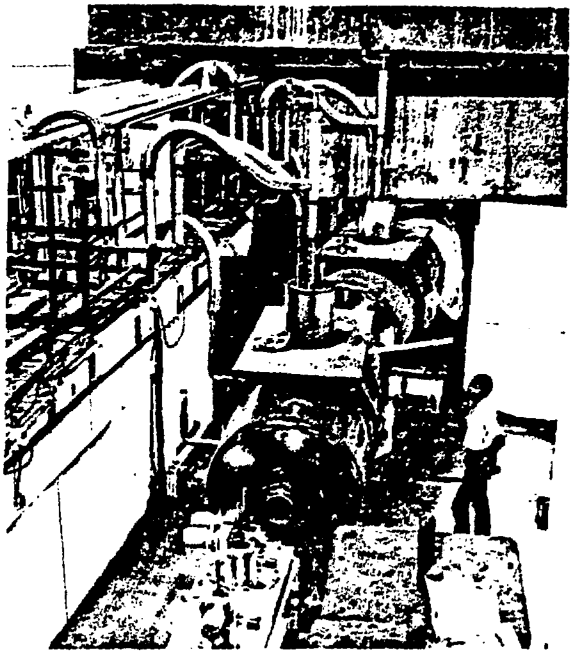

Fig. 4. This is a photograph of the last two HEUB magnets in the beam line to the MPS of the BNL Alternating Gradient Synchrotron.

TABLE I. HEUB Parameters

Inductance = 280 mH, i.d. = 24.8 cm, Magnetic length = 230 cm

Magnetic Field	I	II	III	IV
Design Field (T)	3.8	3.8	3.8	3.8
B/I (mT/A)μ==	1.51	1.51	1.51	1.51
B(max 0,0) Attained	4.02	4.0	4.1	4.14
First Quench	3.5	3.24	2.97	3.8
No. of Quenches	6	8	7	5
% Short Sample				
1st to last Quench	65-77	63-73	54-76	72-78
Current Density "J" kA/cm²				
Design (incl. ins.)	18.1	18.1	18.1	18.1
Design Braid & Filler	20.1	20.1	20.1	20.1
J(max) Attained	22.0	21.1	21.9	22.3
Harmonic Coeff (3.2 T)				
$b_2 \times 10^4$ cm^{-2}	-0.32	-0.01	-0.2	0.07
$b_4 \times 10^6$ cm^{-4}	-0.1	0.1	0.1	0.1
Energy Dissipated (MJ)	1.06	0.98	1.06	1.09
10 K Resistance (MΩ)	280	280	280	280
Time Constants (1/e)				
Magnetization (sec)	82	82	82	82
Quench (L/R, sec)	0.38	0.57	0.58	0.42
Weight (kg × 10³)	11.0	11.0	11.0	11.0

The standard magnet series parameters which represent a compromise of all the parameters that yield the most reliable performance economically are given in Table II for comparison. There have been two full size quadrupoles built and tested or in the process of being tested. The quadrupole data is given in Table II as well. Typical data behavior for a standard magnet with the latest iron geometry is given by Figs. 5 and 6.

TABLE II. ISABELLE Magnet Parameters

	Experimental Series Prototype Dipoles								Double	Standard Dipole Series								Quads	
	I	II	III	IV	VII	XII[a]	XIII[b]	XIV[c]	Layer[c]	IIF	V	VI	VIII[j]	IX	X[a]	XI[a]	XV[a]	I	II[c]
Field (T)[e]	3.92	3.97	3.94	3.94	3.97	3.97	5.0	5.0	6.0	3.5	3.95	3.95	4.0	4.0	4.0	4.0	5.0	3.21	3.21
B/I (mT/A)	1.25	1.26	1.26	1.26	1.29	1.29	1.35	1.25	2.23	1.26	1.26	1.26	1.25	1.25	1.28	1.28	1.35	1.0	1.0
$B(0,0)_{max}^{(reached)}$	3.6	4.6	3.75	3.8	3.74	—	3.93		6.2	4.9	4.9	4.1	4.0	4.7				4.5	4.4
1st Quench	2.8	4.0	3.5	3.8	3.2		3.78	3.2	4.96	3.9	4.1	3.75	3.4	3.95				3.2	3.1
# Quenches	8	22	2	1	16		9		24	21	9	15	23	13				16	15
i.d. cm	12.2	12.1	12.2	12.2	12.2	12.2	12.3	12.2	8.5	12.2	12.2	12.2	12.2	12.2	12.2	12.2	13.1	12.1	12.2
% Short Sample																			
1st Quench	54	75	68	72	62		70	58	73	73	98	75	65	80[i]				67	66
High quench	66	88	71	72	72		73		97	98	102	81	81	91				96	94
Current Density "J" kA/cm²																			
Incl. Ins.[e]	24.8	24.8	24.8	24.8	26.4	26.4	29.9	34.1	21.9	24.8	24.8	24.8	24.8	24.8	26.4	26.4	32.0	24.8	24.8
Conductor[e]	30.0	30.0	30.0	30.0	30.4	30.4	34.7	39.3	26.7	30.0	30.0	30.0	30.0	30.0	30.4	30.4	38.2	30.0	30.0
Max Achieved	24.0	35.5	27.0	27.4	28.3		25.8		29.2	39.4	38.5	31.0	30.0	36.5				43.2	40.4
Parameters[f] Varied	—	7,5	4	4	1,2	1,2	4,1,3	2,7	6	BNL[d]	BNL[d]	Grumman[d]	6	Airco[d] 6	6	6	BNL[d]	BNL[d]	BNL[d]
Harmonic (3.2 T)																			
$b_2 \times 10^4$ cm^{-2}	-0.5	-2.7	-1.2	-1.6	-0.5			-0.25	-0.8	-0.7	-0.1	-0.7	not	+0.2					
$b_4 \times 10^6$ cm^{-4}	0.6	8.0	3.9	2.8	-1.3			1.6	17.0	1.40	20.0	-0.5	aval.	-0.3					
Grad. mT/cm																		508	508
Energy Dissipated (MJ)	0.29	0.57	0.33	0.35	0.35		0.37		0.22	0.69	0.68		0.44	0.61				0.07	0.08
Mag. Length (m)	411	400	409	409	406	406	402	402	99	406	408	408	461	461	461	461	400	146	160
10 K Res. (mΩ)	270	250	255	255	338	262	286	272	105	250	255	255	278	278	288	290	325	98	98
Induct. "L" (mH)	78	73	75	75	77	77	80	77	48	73	75	75	85	85	87	87	97	8	9
Time Const. 1/e																			
Magnetization sec	18.5	38	18.5	18.5					38	38	38	38	38	38				18.5	38
Quench (L/R)[g]	0.8	0.3	0.7	0.7	0.12		0.4		0.4	0.25	0.17	0.17	0.17	0.17				Unknown	
Loss ISA ϕ W/m	—	1.36	1.3	1.3	—	—	—	—	—									1.2	1.2
Ref. Mode	Pool	Pool	Pool	Pool	Pool	Pool	Pool	Pool	Pool	FFC	FCC	FFC	Pool	Pool				Pool	Pool
Damaged	Y	N	Y	Y	N		Y	N	N	N	N	N	R[h]	N				N	N

a) not tested yet; b) arced to ground plane before tests were completed; c) tests not completed yet; d) coil fabricator; e) design; f) these numbers explained in design section; g) 1/e current decay time with 5 mΩ across magnet terminals during a quench; h) repairable without performance loss; i) percentage of undamaged conductor; j) not completely inserted into iron shield.

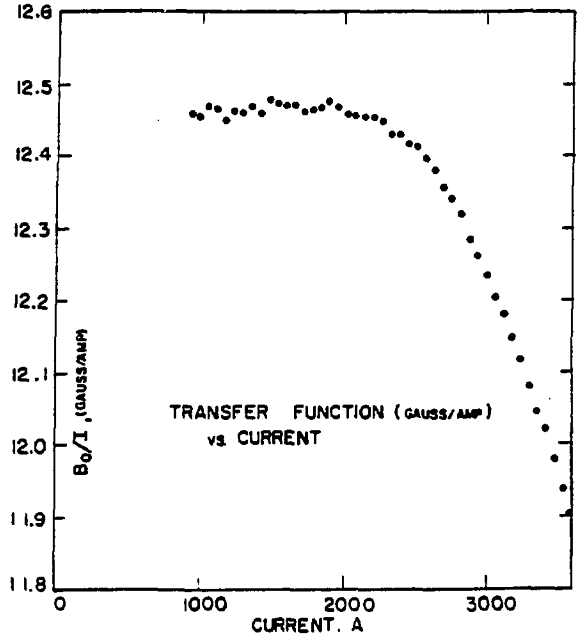

Fig. 5. This is a plot of the transfer function of ISA MK-IX as a function of current.

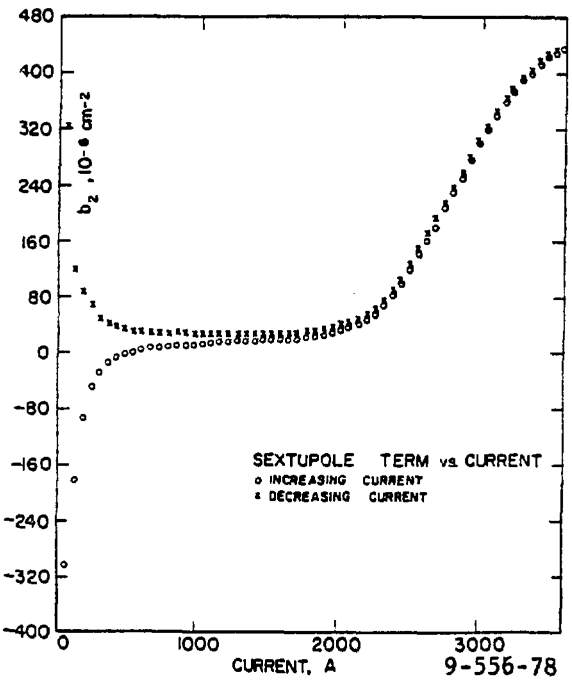

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Fig. 6. This is a graph of the sextupole component of the main dipole field of ISA MK-IX as a function of current.

The Half-Cell series test was performed to gain information in the proposed serial operation of the magnets both cryogenically and electrically. The Half-Cell was that of the older 200 x 200 GeV version of the ISABELLE lattice consisting of two dipoles and a quadrupole (MK-II, V, and QUAD I). In the force flow system, high pressure helium gas entered the first dipole (MK-II) and passed through to the second dipole (MK-V) and then went on to quadrupole (Quad I) before returning to the refrigerator via the intermediate shields which enclose each magnet.[5] The superconducting for the main and working line coil system are routed through the high pressure helium gas lines from coil to coil. The iron core laminations and the stainless steel tube that holds them doubles as the high pressure vessel and inner dewar. This standard Half-Cell structure would be repeated 108 times in the 400 x 400 GeV lattice with the exception of 3 dipoles, not 2, would be used per Half-Cell. The quench protection for this Half-Cell was a combination of opening relief valves on both sides of the quenching magnet and a cold diode across the magnet's terminals which limits the forward voltage.[6] The purpose for opening of the the relief valves is twofold. First, it reduces the pressure of the hot gas wave that is generated in the quenching magnet and second it assures a high enough mass flow past the interconnecting bus in the case of two or more magnets in series simultaneously quenching to prevent it from being damaged. The cold diode virtually eliminates external energy from being dumped into the quenched coil. This magnet array had external leads connected to the intermagnet buses, in case the cold diode scheme proved unworkable. These leads, however, had very high losses and therefore limited the lowest temperature attainable. The system reached a temperature of 5.5 K at the warmest magnet. The quench current at this temperature was 3.5 kA which corresponds to a dipole field of 4.3 T. The system was operated for a period of five weeks without accidental quenching. The quench protection scheme (i.e. cold diodes and relief valves) worked exceptionally well on the scheduled quenches. In all but two transitions of the magnets to the normal state, the transition was confined to the initiating magnet and in those cases where it was not the succeeding magnets were at a much lower power level by the time they transitioned.

The latest auxiliary working line coil system contained in a prototype dipole performed to the power supply current limit which corresponds to 58% of the short sample characteristics of the strands. The dipoles sextupole and decapole windings were checked at 4.4 T. Those of the quad have been checked at low field.

ACKNOWLEDGMENTS

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