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SUPERCONDUCTING MAGNETS AT BROOKHAVEN NATIONAL LABORATORY (AGS High Energy Unseparated Beam Line Dipoles and ISABELLE Ring Magnet Prototypes)*

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INTRODUCTION

In the last two years the ISABELLE[†] Division of Brookhaven National Laboratory has constructed various superconducting dipoles in their search for the optimum magnet on which to base the storage ring design. This paper will report data taken for two of the larger size systems that have been completed to date. The first system is composed of four large superconducting dipoles used in the 20° bend of the multiparticle spectrometer (MPS) beam line of the 30 GeV Alternating Gradient Synchrotron (AGS). These 25 cm inner diameter (i.d.) dipoles bend the High Energy Unseparated Beam (HEUB) 5° each and have a stored energy of one Megajoule which can and is internally dissipated. The four magnets have operated in excess of 4.0 T after a few training quenches. The single layer cosine θ turns distribution dipoles have been operating under the direction of the 'AGS' control computer for about six months. These magnets are of a similar design even though certain details are not identical to the 'ISABELLE' prototype ring magnets. During the same time period, six full-size ring dipoles and one ring quadrupole have been completed with a seventh dipole under construction. The present 200 x 200 GeV storage ring accelerator design requires ring magnets that are 12 cm i.d. 4.25 meters long and ramp from 0.58 T to 3.97 T in 150 sec and that have impurity content of on the order of $10^{-6}/\text{cm}^{N-1}$ (for the $N\theta$ harmonic) or less. The standard ring prototypes have exceeded the

*Work performed under the auspices of the U.S. Energy Research and Development Administration.

†200 x 200 GeV Intersecting Storage Accelerating proton-proton rings proposed at Brookhaven National Laboratory.

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design requirements. The ring magnets employ a forced flow helium gas refrigeration mode [1]. In order to meet the stringent requirements of field quality the ring dipoles have "3 θ " sextupole and "5 θ " decapole correction windings for iron saturation effects. The magnets employ a cold iron shield. The quadrupole contains a correction 2 θ quadrupole for high and low- β requirements for different sections of the machine and a 6 θ duodecapole winding for iron saturation correction and all of the working line control coils for machine operation (dipole, octupole, sextupole, and decapole).

There has been partially tested a multilayer cosine θ dipole designed for a higher intensity magnetic field. The magnet has an 8.5 cm i.d. and one meter length. The coil has obtained a maximum bore field of 6.2 T to date. There are several small single layer magnets (8 cm i.d. and 90 cm length) that have been constructed from NbTi and Nb₃Sn [2] multifilament wire braid, but data for this series will not be discussed in this paper.

DESIGN

The basic design philosophy behind both the HEUB and 'ISABELLE' prototype dipoles is that of a single layer cosine θ turns distribution saddle coil [3-5]. The maximum field that can be derived from this type of structure for a given current density 'J' is dependent on the aspect ratio of the conductor. The larger the aspect ratio (width/thickness) of the conductor in the magnets the higher the peak field obtainable from a given layer of a magnet. This braided compacted NbTi, Cu, and Cu-Ni composite has been discussed in earlier papers [6-8], and is shown in Fig. 1. A photograph of a quadrant of an ISA dipole and various highly magnified photomicrographs of various sections are shown in Fig. 1 as well. The general design other than size is very similar in both magnet systems with the major differences being the refinements of the later generation ISABELLE (ISA) dipoles MK-III and higher. The end field harmonics (namely sextupole) are the opposite sign of that of the straight section for the coils, therefore, in a simple beam line magnet they tend to cancel, in the integrated path, as the particles pass through the magnet. This cancellation is not sufficient for the requirements of the ISA ring magnets, therefore, each end is integrally corrected by placing spacers between segments of turns to reduce the integral impurities through the end to less than those typically found in the straight section before correction [9].

The design parameters for both the ISA ring magnets and the HEUBs are listed in Table 1. Figure 2 shows the turns distribution of the quadrupole ring magnet and its various windings. Figure 3 shows a drawing of the

Table 1. Prototype Magnet Parameters

	ISA (4.25 m) SERIES DIPOLES						HEUB				DOUBLE LAYER
	I	II	IIF	III&IV	V&VI	QUAD I	I	II	III	IV	
<u>MAGNETIC FIELD</u>											
(T) ^a	3.92	3.97	3.97	3.94	3.95	3.21	3.8	3.8	3.8	3.8	6.0
Grad. (mT/cm)	0.36	1.0	2.4	0.51	0.51	508	0.5	0.16	0.4	0.15	0.5
B/I (mT/A) _{μ = ∞}	1.246	1.26	1.26	1.255	1.255	1.0	1.514	1.514	1.514	1.514	2.23
B/I (mT/a) air	0.72	0.73	0.73	0.73	0.73						
Max B(0,0) or Grad. Achieved	3.6	4.7	4.95 ^b	3.75	4.9 ^c	710	4.02	4.0	4.1	4.14	6.2 ^d
First Quench	2.9	4.0	3.95	3.6	4.12 ^f	527	3.5	3.24	2.97	3.8	4.96
No. of Quenches	8	22	21	2	9	15	6	8	7	5	24
<u>DIAMETER (INNER) cm</u>	12.15	12.15	12.15	12.15	12.15	12.15	24.8	24.8	24.8	24.8	8.5
Min. Temp. (K)	4.25	4.25	4.1	4.25	4.6	4.25	4.25	4.25	4.25	4.25	4.25
<u>1st TO LAST QUENCH (%10⁻¹²Ωcm)</u>	54-66	75-88	75-98	68-71	98-102	67-96	65-77	63-73	54-76	72-78	73-97
<u>CURRENT DENSITY "J" kA/cm²</u>											
(incl. insul.) ^a	24.8	24.8	24.8	24.8	24.8	24.8	18.1	18.1	18.1	18.1	21.9
(Braid & filler) ^a	30	30	30	30	30	30	20.1	20.1	20.1	20.1	26.7
Max J in series	24.0	35.5	39.4	27.0	38.5	43.2	22.0	21.1	21.9	22.3	29.2
<u>HARMONIC COEFF</u>											
b ₂ (3.2T) × 10 ⁴ cm ⁻²	- 0.46	- 2.7	- 0.7	- 0.2	- 0.1		- 0.32	- 0.01	- 0.2	0.07	- 0.75
b ₂ (3.2T) × 10 ⁴ cm ⁻⁴	0.56	8.0	1.36	3.9	0.18		- 0.001	0.001	0.001	0.001	17.0
b ₅ (3.2T) × 10 ⁷ cm ⁻⁵											2.0
<u>ENERGY COIL DISSIPATED, kJ</u>	294	570	688	333	655	70	1062	979	1060	1094	216
<u>MAGNETIC LENGTH (cm)</u>	410.7	405.6	405.6	408.8	408	146	230	230	230	230	98.6
<u>10 K RESISTANCE (mΩ)</u>	270	250	250	255	255	98	315	315	315	315	105
<u>INDUCTANCE (mH)</u>	78	73	73	75	75	8	280	280	280	280	48
<u>MAGNETIZATION</u>											
Time Const. (1/e) sec	18.5	38	38	18.5	38	18.5	82	82	82	82	38
Loss/ISA φ (meas) W/m		1.36		1.30							
<u>REFRIGERATION MODE</u>	Pool	Pool	FF ^g	Pool	FF	Pool	Pool	Pool	Pool	Pool	Pool
<u>QUENCH TIME CONST. (1/e)sec</u>	0.8 ^h	0.25	0.25	0.69	0.17	Unk.	0.38	0.57	0.58	0.42	0.35
<u>REASON FOR TERMINATION</u>	Opened	done	done	Shorted	Time	done	done	done	done	done	Liquid
	turn			turn	gone						gone
<u>WEIGHT OF COIL + IRON, kgx10³</u>	4.8	4.8	5.0	4.8	5.0	1.0	11	11	11	11	0.7

^aDesign; ^b4.1 K; ^c4.63 K; ^dStill training; ^e1/e Current decay with 5 mΩ across magnet during superconducting to normal state transition; ^f5.6 K; ^gforced flow high pressure gas. ^hEstimated.

double layer prototype dipole's cross section. The outer layer is the same as the single layer ISA ring dipole (4.25 m long). Figure 4 is a HEUB magnet cross section with the number of active turns indicated in each current block. As can be seen in the above-mentioned Figs. 2 through 4, the magnets are of essentially the same design with only differences being parameters such as increased metal packing fraction, quench velocities, and higher overall current densities as the series progresses. In Figs. 5 and 6 the differences from the evolution from a pool boiling system dewar design (HEUB) and to a forced flow system (ISABELLE) can be seen. The elimination of the various transfer lines and level controls adds to the simplicity of the forced flow system.

MAGNET AND SYSTEM PERFORMANCE

HEUB

Of the four dipoles built, half of them reached 4 T or greater by the fifth quench and all of them exceeded 4 T by the eighth. The magnets use a warm diode (back to back diodes) window [10] to limit the ramp rates, therefore, when a quench occurs they must absorb their energy internally. The HEUB dipoles are summarized in Table 1 and the specific harmonic data are given in Table 2. The two magnets shown in Fig. 5 are actually the downstream pair in the MPS beam line. The total weight of a HEUB magnet and cold Fe shield is 11 000 kilograms (kg).

The refrigerator used in the HEUB system is the largest 4000 CTi unit built and is presently in operation with a capacity of 1.5 kilowatts at 4.5 K with liquid N₂ cooling. The unit has been tested at loads in excess of 1.2 kilowatts. It has two expansion engines each capable of full capacity operation. The system has on line a 4000 liter storage system that may be used as a reserve. The first two magnets were operated in September 1976 and the remaining two in December 1976. The total load seen by the refrigerator from the system magnets, lines, etc. is approximately 550 watts at 4.5 K. The beam line has operated without incident with the exception of the accidental introduction of some contaminated gas that plated out on a heat exchanger costing 3.5 dunning days to be lost [11].

ISABELLE Ring Dipoles

The results of the various prototype dipoles are summarized in Table 1. The ISA dipoles consist of two series. The first series is called a standard series. The magnets in this series contain all of the desirable features that are obtained in the various experimental prototypes of the

second group. For example, magnets MK-V and VI are a combination of field quality (three-dimensional) and metallurgy of MK-II, III, and IV. The double-layer prototype dipole represents a construction complication that will increase the maximum bore field by about 1.4 Tesla for the expenditure of 1.6 times the amount of material per meter of magnet and loss of 37% of the aperture.

Table 2. Measured Harmonic Components

Magnet No.	b_1	b_2	b_4	$\int b_1$	$\int b_2$	$\int b_4$
Field (Tesla)	$\times 10^{-4}/\text{cm}$	$\times 10^{-5}/\text{cm}^2$	$\times 10^{-8}/\text{cm}^4$	$\times 10^4/\text{cm}$	$\times 10^5/\text{cm}^2$	$\times 10^8/\text{cm}^4$
I (1.0)	1.25 ^a	5.1 ^a	2.5 ^a			
II	0.41	7.6	6.6	0.9	21.5	36.0
III	0.60	5.5	2.5	0.8	17.0	28.0
IV	0.08	6.2	4.6	2.0	17.0	23.0
I (2.0)	1.28 ^a	4.9 ^a	1.3 ^a		17.3 ^a	
II	0.37	7.6	3.6	0.9	21.0	35.0
III	0.65	5.0	2.4	0.7	16.3	28.0
IV	0.12	6.1	3.5	2.1	16.5	26.0
I (3.0)	0.96 ^a	- 0.5 ^a	1.5 ^a		12.3 ^a	
II	0.33	2.6	14.0	0.9	17.0	44.7
III	1.00	0.4	14.0	0.45	11.1	37.0
IV	0.13	0.9	12.0	2.0	11.7	38.0
I (4.0)	0.1 ^a	-14.0 ^a			1.6 ^a	
II						
III				0.6	1.0	35.0
IV	0.38	-10.4	5.0	2.0	0.9	30.0

^aMeasurements taken using a stepping motor. All the rest of the data was acquired with a 370 rpm system.

All of the refinements obtained in the single layer coil are applicable to the double-layer with the above gains and penalties. The quench performance of the double layer is essentially the same except for 50 msec delay before the next coil immediately above or below it quenches. This, therefore, leads to higher thermomechanical stresses during the quench with the double-layer magnet. The dipole prototypes of the standard series are capable of dissipating their own stored energy. These magnets employ a cold diode [10] limiting the forward voltage and a combination of energy extraction from magnets that are still superconducting [12] while venting the warm gas from the quenched magnet (absorbing its own energy) via electrically operated blow-off valves to the warm gas return of the

refrigerator. The first multimagnet series test is shown in Fig. 6 and should be in operation by the time of the conference.

The total weight of the present ISA dipole is 5000 kg. The latest standard dipole MK-V essentially "trained*" from 98% short sample to 102% of the 10^{-12} Ω -cm strand equivalent resistivity. These data were clouded in that the earliest quenches were at a higher magnet temperature. The temperature of the upstream end of the magnet was 5.6 K which clouds the training data. The 1st quench was 4.12 T which is higher than the 3.95 T needed and at 5.6 K rather than 4.5 K the highest proposed temperature in the magnet string. The harmonic content of the magnets are shown in Figs. 8 and 9. The effects of iron saturation on the B/I characteristic of the magnet is shown in Fig. 10. The dipoles have operated with B(0,0) as high as 4.9 T at temperatures from 4.1 K (MK-II) to 4.6 K (MK-V). The total number of magnet quenches on each magnet when the maximum field was reached was 21 (total on coil 43) (MK-II) and 9 (MK-V). The harmonic content with the correction coils powered is given in Table 3. An alternate means of increasing the peak field of the dipoles is the reduction of temperature at the outlet of a magnet string. In Table 4 the temperature dependence of the maximum fields obtainable with MK-V are shown.

Table 3. Harmonic Analysis of Dipole Magnet with Correction Coils Powered

Harmonic		Magnetic Field					Units (Dipole = 1.0)
		1 T	2 T	3 T	4 T	4.5 T	
Quadrupole 2θ	b_1	1.2	1.3	1.3	1.2	1.0	$10^{-4}/\text{cm}$
Sextupole corrected	b_2'	-8.0	-7.0	-3.0	6.0	10.0	$10^{-6}/\text{cm}^2$
Decapole corrected	b_4'	6.0	6.5	8.0	9.0	3.0	$10^{-8}/\text{cm}^4$
Eighteen-pole 9θ	b_8	0.7	0.5	0.5	0.5	0.5	$10^{-8}/\text{cm}^6$

Operating and quench characteristics are summarized in Table 1. The maximum temperature during quench was calculated to be 80 K for MK-II and less than 50 K for MK-V [13]. This result was obtained utilizing the quench voltage profiles to reconstruct the temperature.

*The term "training" in a superconducting magnet implies that a magnet quenches prematurely before the critical current of the conductor, but upon subsequent magnet superconducting to normal transitions "quench" obtains a higher current.

Table 4. Temperature Dependence of Standard Dipoles

Temperature (Outlet)	Maximum Field (T)	
	°K	MK-IIIf MK-V
	3.7	5.3 ^a 5.7 ^a
4.1	4.9 5.4 ^a	
4.3	4.7 5.2 ^a	
4.6	4.4 4.9	
5.2	3.9 ---	
5.6	--- 4.1	

^aExtrapolatedQuadrupole (ISA)

There has been one ring quadrupole constructed to date. The major quadrupole performance characteristics are given in Table 1. The quadrupole was wound with identical conductor as that of the dipole as well as the same winding fixture. The quadrupole is powered in series with the dipoles thereby eliminating the phasing problem of their power supplies in a storage ring. The quadrupole has been operated in a vertical liquid helium dewar (pool boiling). The magnet obtained 0.527 T/cm on the first quench and after 14 quenches a gradient of 0.71 T/cm had been attained. The quadrupole can internally dissipate its stored energy. In Fig. 6 the quadrupole is shown on the right hand side of the photograph in its standard ring configuration in the half-cell. The total weight of the quadrupole plus working line coils, correction coils and iron shield is 1000 kg. The harmonics of Quad I are given in Table 5 [14]. The B/I (for the high field point) for QUAD I is shown in Fig. 10.

Table 5. Harmonic Analysis of Quadrupole Magnet-I

Harmonic	Magnetic Field					[Units]
	(High Field Point)					
	1 T	2 T	3 T	4 T	4.5 T	
Quadrupole $b_1(2\theta)$	0.185	0.185	0.185	0.183	0.181	Dipole = 1.0 cm ⁻¹
Sextupole $b_2(3\theta)$	1.4	1.4	1.2	0.9	0.7	$\times 10^{-5}$ cm ⁻²
Octupole $b_3(4\theta)$	4.1	4.3	3.6	3.1	2.9	$\times 10^{-6}$ cm ⁻³
Decapole $b_4(5\theta)$	5.6	5.6	5.1	4.1	3.9	$\times 10^{-7}$ cm ⁻⁵
Duodecapole $b_5(6\theta)$	1.1	1.04	0.74	-0.03	-0.15	$\times 10^{-6}$ cm ⁻⁵
Dodecapole $b_9(10\theta)$	3.5	3.4	3.6	3.25	3.4	$\times 10^{-10}$ cm ⁻⁹

The cryogenic system used by both the ISA dipoles and quadrupoles is shown schematically in Fig. 11. A more detailed explanation of its operation is given elsewhere [1]. A short summary would be as follows. Single phase high pressure (15 atm \rightarrow 12 atm) helium gas (HPG) from the refrigerator passes through a precooler. The precooler reduces its (HPG) temperature to around 4.5 K from 5 K. The HPG now passes through the subcooled liquid pot and leaves at about 3.8 K. Then the HPG enters the magnet structure (see Fig. 6) which allows the HPG to pass with little significant resistance. There is a small amount of HPG which travels down symmetric slots on the outside of the iron shield to keep the superconducting bus cold. The HPG leaves the last magnet in the string and a small portion is bled through the current leads and returns to the warm gas bag, the rest returns down the cold shield interrupting any heat coming from the outside walls of the vacuum vessel. The HPG then goes to the primary ejector nozzle which has a J-T valve in series with it in case the mass flow is in excess of sonic velocity. The ejector pumps the subcooler and its liquid level to about 0.5 atm pressure. The system planned for ISABELLE will replace the ejector with a turbocompressor and expander combination and the development work test will start in late 1977 [15].

The half-cell will eventually contain ISA MK-V and MK-VI and Quad I with the option of leaving MK-II on line as well for quench propagation tests. The system is presently being pumped and consists of ISA MK-II, MK-V and Quad I. (See Fig. 6).

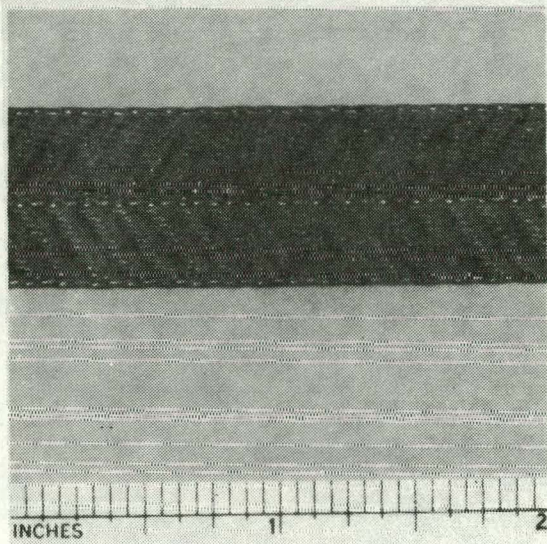
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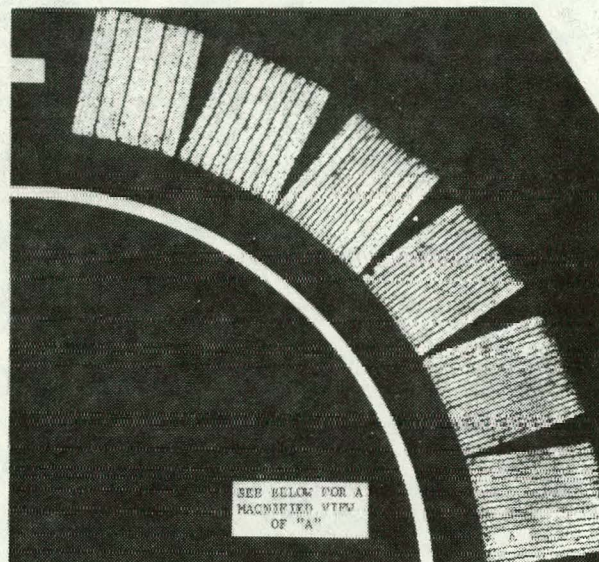
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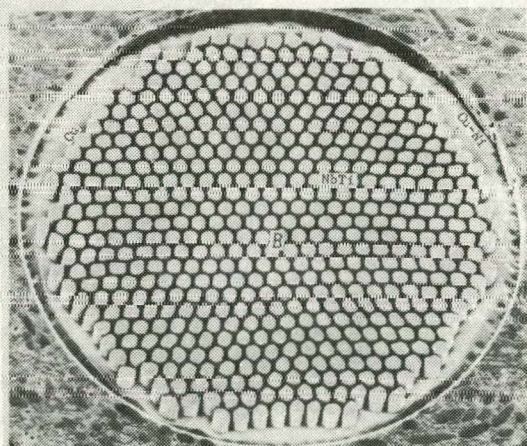
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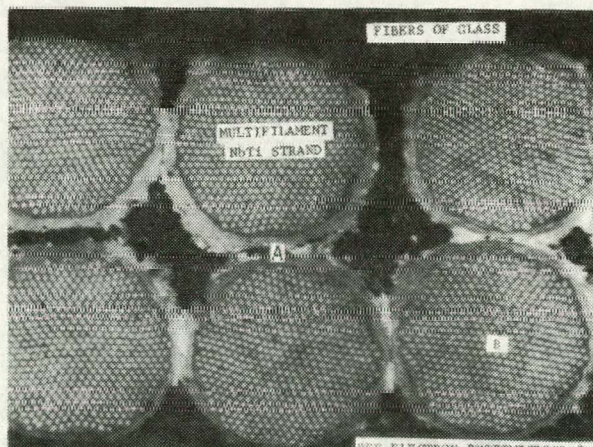
BRAIDED ISABELLE CONDUCTOR



PHOTOGRAPH OF CROSS SECTION OF QUADRANT OF THE ISABELLE DIPOLE WINDING



ELECTRON PHOTOMICROGRAPH OF A STRAND FROM THE ISABELLE BRAIDED CONDUCTOR



PHOTOMICROGRAPH OF BRAIDED CONDUCTOR

Fig. 1. This is a composite photograph showing the ring magnet's braided conductor on the left and an actual photograph of a real magnet cross section (one quadrant). The photomicrographs below show finer degrees of detail with each higher magnification.

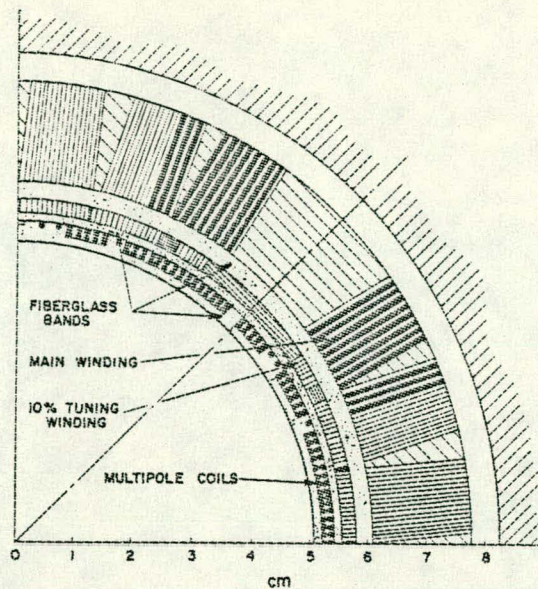


Fig. 2. A cross section drawing of the ring magnet QUAD I showing all of the various windings for iron saturation and working line control of the beam.

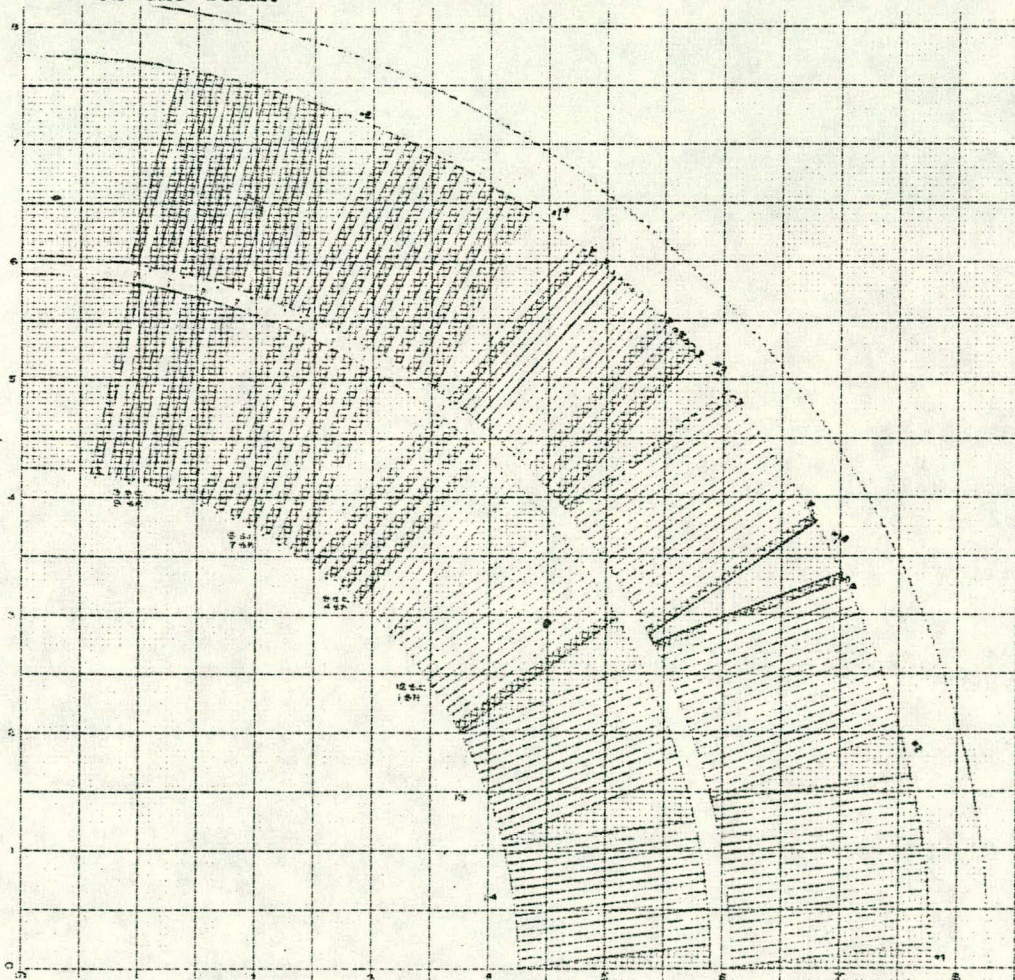


Fig. 3. The turns distribution for the double-layer dipole is shown. The outer layer is the same distribution as that of ISA MK-V and VI.

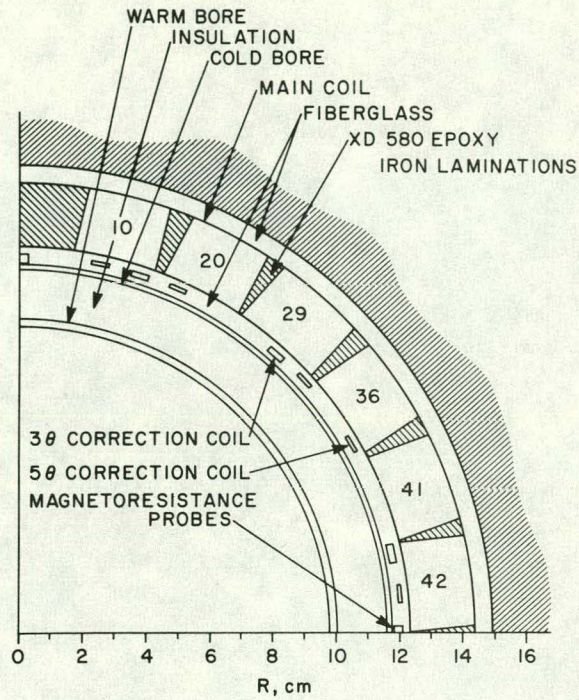


Fig. 4. A cross section drawing of a 'HEUB' dipole. The numbers in the current blocks indicate the total number of active turns in that block.

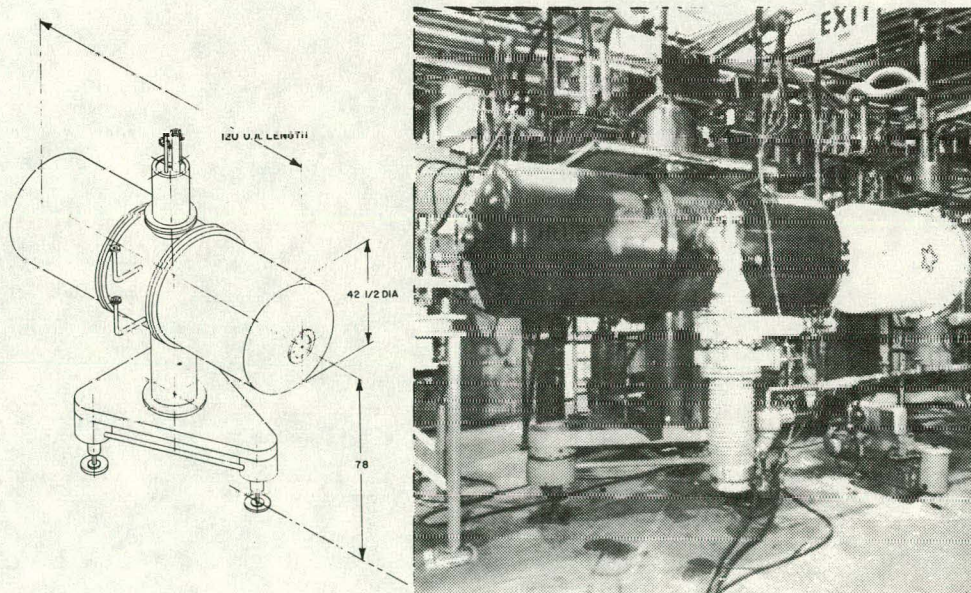


Fig. 5. The isometric drawing on the left gives the overall dimension of the HEUB dipoles in inches. The photograph on the right is the downstream pair HEUB I and II.

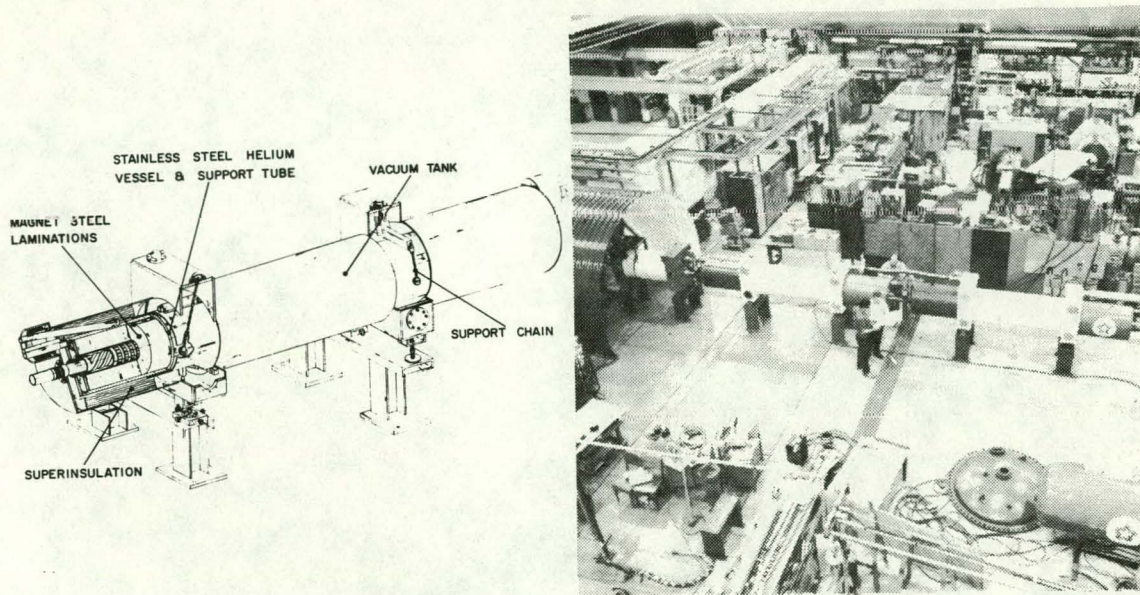


Fig. 6. The isometric drawing on the left shows most of the major details of the final assembled magnet. The coils are placed on the helical bore tube and retained there by the slotted bands. The photograph on the right shows the half-cell MK-II, V and QUAD I with a part of the ring tunnel showing.

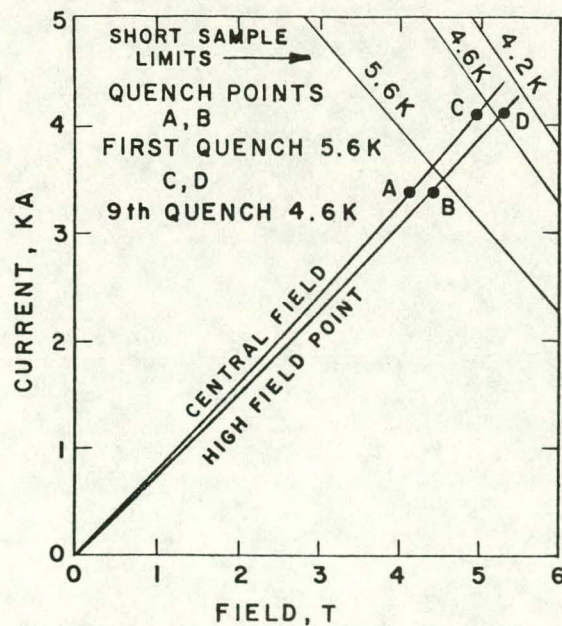


Fig. 7. " I_c " critical current vs magnetic field for the braided conductor in ISA MK-V for three isotherms with the load line and quench points plotted for this magnet.

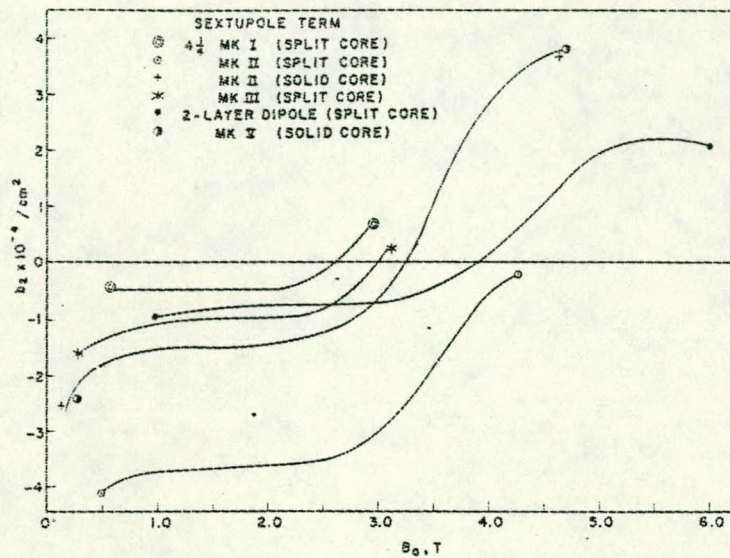


Fig. 8. The sextupole impurity plotted vs field for the various dipoles.

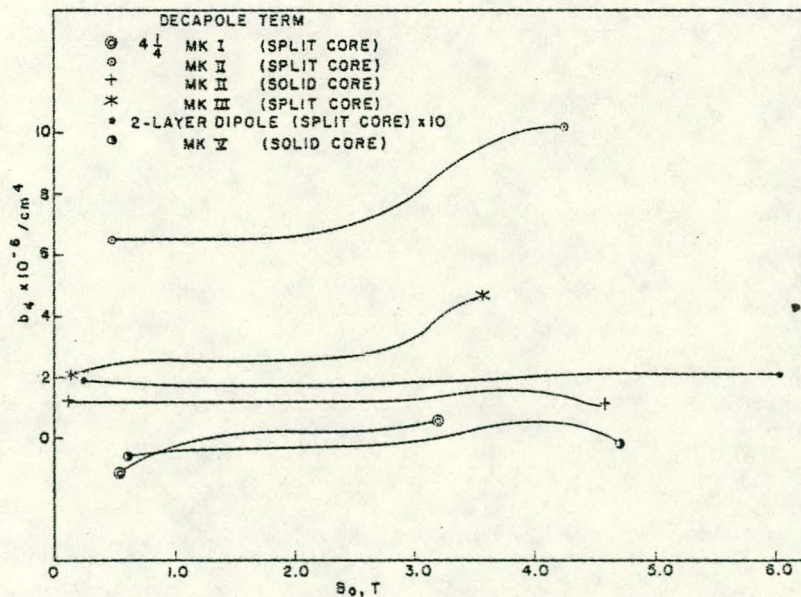


Fig. 9. The decapole impurity plotted vs field for the various dipoles.

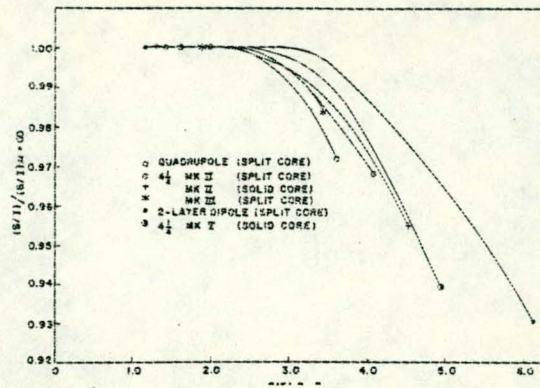


Fig. 10. The differential B/I is plotted vs B for the various ring magnets.

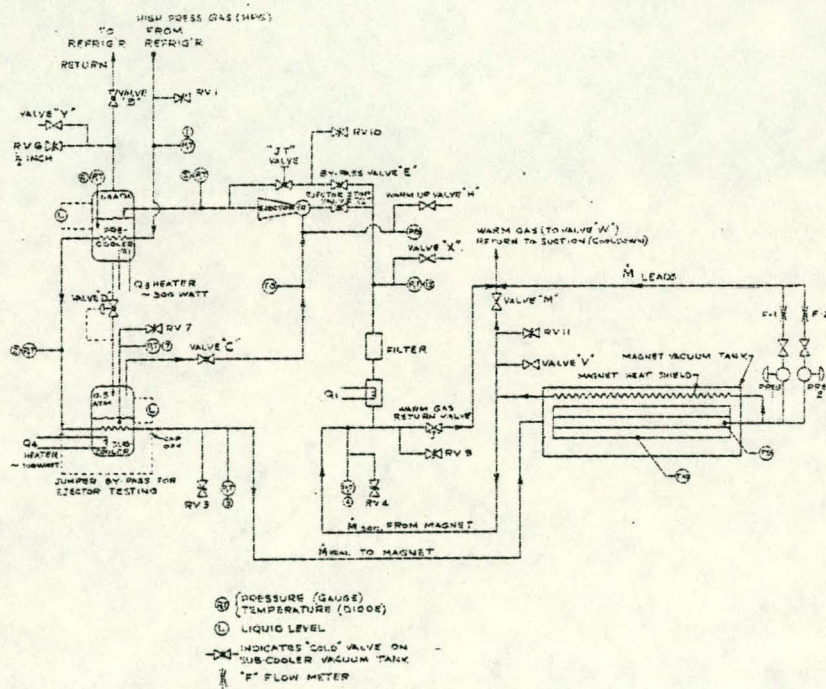


Fig. 11. The above HPG "high pressure gas" flow diagram that was used during the test of ISA MK-II.