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ISABELLE - A PROGRESS REPORT

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Summary

This paper discusses the ISABELLE project, which has the objective of constructing a high-energy proton colliding beam facility at Brookhaven National Laboratory. The major technical features of the intersecting storage accelerators with their projected performance are described. Application of over 1000 superconducting magnets in the two rings represents the salient characteristic of the machine. The status of the entire project, the technical progress made so far, and difficulties encountered are reviewed.

Introduction

The quest by the high energy physics community for bigger and better machines has for many years provided the stimulus and support of significant research and development in the field of superconductivity. After a long march, the efforts begin to pay off with large scale application of superconducting magnets becoming the essential ingredient in the building of new accelerators. In 1978 the construction at Brookhaven National Laboratory of a proton-proton colliding beam facility under the auspices of the U.S. Department of Energy was authorized.[1] This facility, known as ISABELLE, will represent one of the most powerful instruments available world-wide in the 1980's to carry out particle physics research. This paper attempts to give a general review of the technical features of the project and the status of the major accelerator components. In line with the special interest of this audience, emphasis will be placed on the discussion of superconducting magnets as well as the associated cryogenic and vacuum systems. Further information may be found in earlier reviews and publications.[2,3]

From its inception, ISABELLE was intended to serve as a major high energy facility which implied the following design criteria:

i) Available Energy - Originally conceived as 200 + 200 GeV storage rings, the energy objectives were increased to 400 + 400 GeV reflecting the expectations of the high-energy physics community as expressed by the 1977 Woods Hole panel. Equal to the top energy in importance is ISABELLE's broad operating range covering the energies from injection at 30 GeV to peak field at 400 GeV.

ii) High Interaction Rate - Reaching a high luminosity remains ISABELLE's strongest asset, in particular now that two other higher-energy colliding beam experiments at CERN and FNAL are under construction. The luminosity at ISABELLE is projected to be 2×10^{32} cm^{-2} sec^{-1} in the standard insertions at top energy. At lower energy the luminosity decreases with beam height or the square root of energy. Modifications to the insertion layout should eventually allow luminosities of about 10^{33} cm^{-2} sec^{-1}. These luminosity levels can be achieved with 8 A beams in each ring. In order to assure long beam life time and low radiation background operation of ISABELLE for colliding beam experiments will use coasting unbunched beams. Even so, the expected interaction rate reaches about 40 MHz resulting in a total particle production rate at top energy on the order of 1 billion per second at each crossing, clearly a nontrival detection problem.

iii) Experimental Flexibility - In colliding beam experiments the clear distinction machine/experiment disappears. An adequate number as well as an appropriate design of insertions thus becomes of paramount importance. Financial constraints restricted the number of crossing points to six. Each beam crossing will take place in the center of 60-m magnet-free straight sections.

iv) Superconducting Magnets - Although a topic of considerable debate at the inception of ISABELLE, the use of superconducting magnets has been accepted by now as the best overall solution for highest-energy proton accelerators and storage rings and no further justification is here required. The optimum choice of peak field is, on the other hand, not so obvious. The relative ease with which 40 kG (i.e. the design value of the 200 GeV version) was reached and even exceeded[4] suggested that 50 kG would be a responsible design value for the 400 GeV rings. However, the new superconducting magnet technology is turning out to be more arduous than had been anticipated and the recent full size preproduction dipoles performed below expectation. The magnet status and the R&D efforts to improve it will be discussed in some detail.

v) Expandability - Retaining the option of expanding the scope of ISABELLE by adding more rings, either for protons or electrons, is one of the basic design criteria. Presently under consideration is the possibility of an electron ring of about 12 GeV energy in a separate tunnel. The option of adding a booster to permit acceleration and colliding beams of heavy ions arouses equal interest.

General Description

The configuration of ISABELLE is essentially a hexagon with rounded corners. The machine consists of two identical rings for the accumulation, acceleration, and storage of proton beams. The two rings, identified as blue and yellow, are in the same horizontal plane allowing for intersections at six crossing points where the counter-rotating beams collide with each other. The two rings are magnetically separated to allow operation with unequal energies. Since the rings are to be filled from the AGS using synchronous beam transfer, their circumference was chosen as exactly 4-3/4 times the circumference of the AGS, or 3833.8 m. Almost half of the circumference is contained in the six insertions, the rest in the regular arcs. It has become customary to distinguish inner and outer arcs as well as inner and outer half insertions by their clock position.

Conventional Facilities

The ISABELLE facility is located in the northwest corner of the Brookhaven site (Fig. 1). The complex encompasses an area of approximately 600 acres of which about one-half will be occupied by the main ring tunnel, experimental areas, access roads, and utility right-of-ways. The tunnel consists of a multiplate arch erected on a continuous reinforced concrete slab; its construction is scheduled for completion in July 1981.

*Work performed under the auspices of the U.S. Department of Energy.

DISCLAIMER

The circular tunnel structure has a width of 5 m and is 3.4 m high. The tunnel dimensions are tight but adequate as the experience with the First Cell test tunnel demonstrated. Transport of magnets alongside magnets already installed is facilitated by using special rail-guided vehicles. The ring seperation in the regular arcs is 95.2 cm from quadrupole center-to-center. ISABELLE beam level is 1.27 m above floor.

The largest and central service facility is the ISABELLE Service Building. This building is located at the 5 o'clock position in the ring and is the center of all machine operations. This structure contains about 50,000 square feet gross area and supports the three main functions, i.e., cryogenic, main magnet power and rf, and the main control for the accelerator. Physical separation of the compressor building was necessary in order to keep noise of the helium compressor at a minimum. Three equipment alcoves per sextant, in addition to the areas in the support buildings at the experimental areas, provide the necessary space for electronic racks and support equipment in the ring. Space for the rf cavities is provided in a special enclosure structure at the 5 o'clock sextant, and space for injection and extraction equipment exists in the vicinity of the injection tunnels.

The experimental areas consist of a Wide-Angle hall at 6 o'clock, major facilities at 8 o'clock and 10 o'clock, and a Small-Angle hall at 2 o'clock. There are two open areas at 12 o'clock and 4 o'clock which initially will be hard stands without any detailed structures. Construction of the Wide Angle hall, open area at 4 o'clock, and Small Angle hall has started. Conventional construction for the project is scheduled to end by April 1983. Progress so far is impressive and no delays are expected.

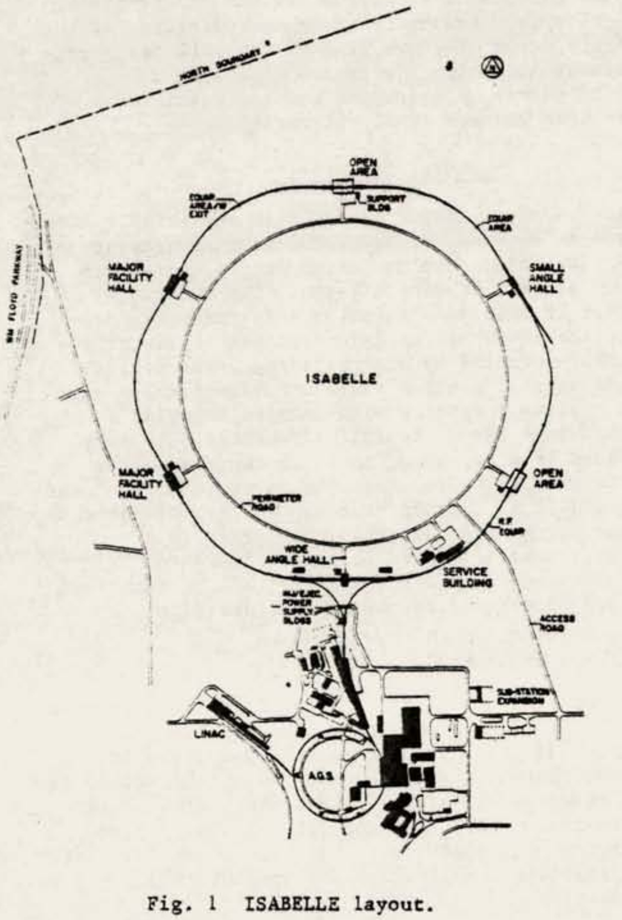

Fig. 1 ISABELLE layout.

Lattice and Experimental Insertions

The design of the magnetic focussing structure resulted from a compromise between aperture considerations and the desire to inject well above the transition energy. The resulting lattice configuration is shown in Fig. 2. The transition energy is 17.6 GeV, sufficiently below injection with 29.4 GeV. The tune of the machine is nominally 22.6, both in the horizontal and vertical planes. The contributions to the tune from the insertions is 9 (i.e., 6 x 1.5) with the regular arcs providing the rest. Inner and outer arcs are constructed with identical separated function magnets. The resulting small gradient differences are corrected by quadrupole trim coils. Each arc contains 9 mirror symmetric regular cells with a QF/2 BBB QD BBB QF/2 configuration and designed for 90° betatron phase shift. The average cell length is 39.5 m, the effective length of dipoles 4.6 m and of quadrupoles 1.6 m. The average radius of curbature in the arcs is 381 m with the bending radius in the dipoles 267 m. The two rings require 732 dipoles and 348 quadrupoles. The insertion magnets, some of which differ in length from the regular cell magnets, are included in these totals.

The insertions determine the luminosity and other characteristics of the beam at the crossing points, the space available for experimental apparatus, and they are the location for beam injection/ejection. The insertions are thus decisive for the usefulness of the machine for physics experiments but at the same time they exert a major influence on design and performance of the accelerator itself. The crossing angle of the standard insertion is fixed at 11.187 mrad and the total insertions length is 283 m. The free space between the nearest quadrupoles available for experimental equipment is 60 m. Each half insertions consists of an 80 m long drift space, interrupted by a longitudinally staggered quadrupole doublet in the middle, followed by three half cells, similar to the cells in the regular arc, arranged to make the crossing areas dispersion free. The standard insertion is designed for the beta values at the crossing point of 7.5 m vertically and 43 m horizontally. The resulting interaction diamond dimensions at top energy are 1 mm height and 26 cm length, based on a normalized emittance of 15 x 10^{-6} rad.m. The luminosity of the standard insertion is 2 x 10^{32} cm^2 sec^{-1} at top energy decreasing with the square root of the energy.

Beam Transfer

The AGS will serve as injector of 30 GeV protons for ISABELLE. The beam will be ejected from the AGS into the existing U-line to the north area by means of a fast bunched-beam extraction system (Fig. 1). The W-beam transfer line transporting the beam to the ISABELLE rings will branch off through an achromatic 2 x 10° bending section. Within this bend, the beam level is lowered by 1.8 m and is then directed into either of the big-bend X and Y line, each providing almost 90° bending. Together the big bends are roughly equivalent to half of the AGS. All beam transfer magnets are conventional, with the big bend using combined function magnets. Power consumption is kept to a minimum by limiting the vertical aperture to about 3.5 cm.

The beam is injected into the outer arcs of ISABELLE utilizing the free spaces between magnets as shown on Fig. 3. The beam approaches the ring horizontally, about 2.5 cm above the median plane, and is brought above the injection orbit by means of a sequence of horizontal deflections, provided by two

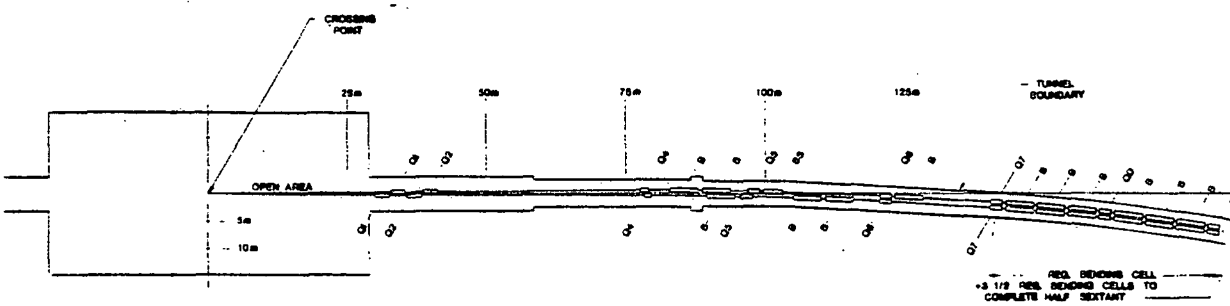

Fig. 2. Lattice and Insertion Magnet Elements.

3 m long current septa and a 3 m long Lambertson septum. A short vertical trim septum and the vertical fast kicker bring the beam to a vertical landing on the injection orbit near the junction of insertion and regular arc. The septum magnets will be pulsed with millisecond pulse duration. The fast kicker will have a rise time to full amplitude of 150 nsec to permit successive insertion of five pulse trains from the AGS onto the same orbit. Design of the kicker, conceived as a shutterless device, is most demanding and model work has been started.

At peak energy of the protons, about 40 MJ is stored in each beam. Serious damage to vacuum chamber and adjacent magnets could result if control was lost and the beam hits machine components. Therefore, the capability for fast single-turn beam extraction will be provided. In the so called Q4 ejection scheme the kicker magnets are located in the free space at Q6 and the first thin-septum magnet unit starts downstream of Q4 as shown in Fig. 3. Ejection is vertical with the beam passing about 1 m below the crossing point. The transverse beam dimensions are blown up to 37 cm^2 in a subsequent defocussing quadrupole and the beam is stopped in the beam dump, which initially is conceived as a silicone carbide/sand block, (3+3.5)m x 1.1m x 06m. With a 0.5 microsec risetime of the ejection kicker and a 0.5 mm septum thickness, a beam loss of less than 5 x 10^{-4} is expected. At full beam current the energy deposited on the first septum will take it very close to the thermal limit.

A related problem is the energy deposited in superconducting magnets by particles scattered out of the septum magnets. It has been estimated that quenching of magnets by scattered particles can be prevented provided that septum losses of about 2.5 x 10^{11} protons at 400 GeV are not exceeded. In support of the ejection system design, an AGS/ISABELLE task force has been making a study of the radiation threshold for quenching of superconducting magnets.[4]

Stacking and Acceleration

Filling the ISABELLE rings with 8 A proton current will be performed by stacking in momentum space, the method which is used at the CERN ISR. In preparation for injection, the peak rf voltage in the AGS is reduced from 300 kV to approximately 65 kV in order to match the AGS bunch shape to the buckets of the ISABELLE stacking rf system. The ejected AGS intensity is reduced from the nominal 10^{13} protons/pulse to 2.7 x10^{12} to optimize phase space density (normalized transverse emittance 15 π 10^{-6} rad m and 1.06 eV sec longitudinal phase space per bunch). Eleven of the 12 AGS bunches are injected synchronously into waiting matched buckets of the ISABELLE stacking rf system. This procedure will be repeated until 55 of 57 buckets present on the injection orbit are filled. The injected beam is then accelerated in energy, slowly debunched, and deposited on the stacking orbit. Nominally 62 stacking cycles requiring a minimum stacking time of 10 min are sufficient to build up the total 8 A of stored beam. The largest aperture requirements, 67 mm at QF, exist during beam injection. One stacking cavity per ring operating at 4.45 MHz is capable of providing the maximum voltage of 12 kV. However, a second wide band cavity with 1.9 kV capabilities will be provided for a longitudinal feedback system and could also serve for suppressed-bucket operation.

In order to accelerate the beam, it will be adiabatically rebunched by another rf system operating at the third harmonic, f = 235 kHz. The third harmonic was chosen in order to provide the option of bunched beam operation and to permit synchronous beam transfer from an optional stacking ring. The peak rf voltage of 36 kV per ring will be provided by 3 ferrite-loaded cavities. The cavities are driven by 3 x 165 kW tubes operated as cathode followers. Acceleration time is nominally 8 min.

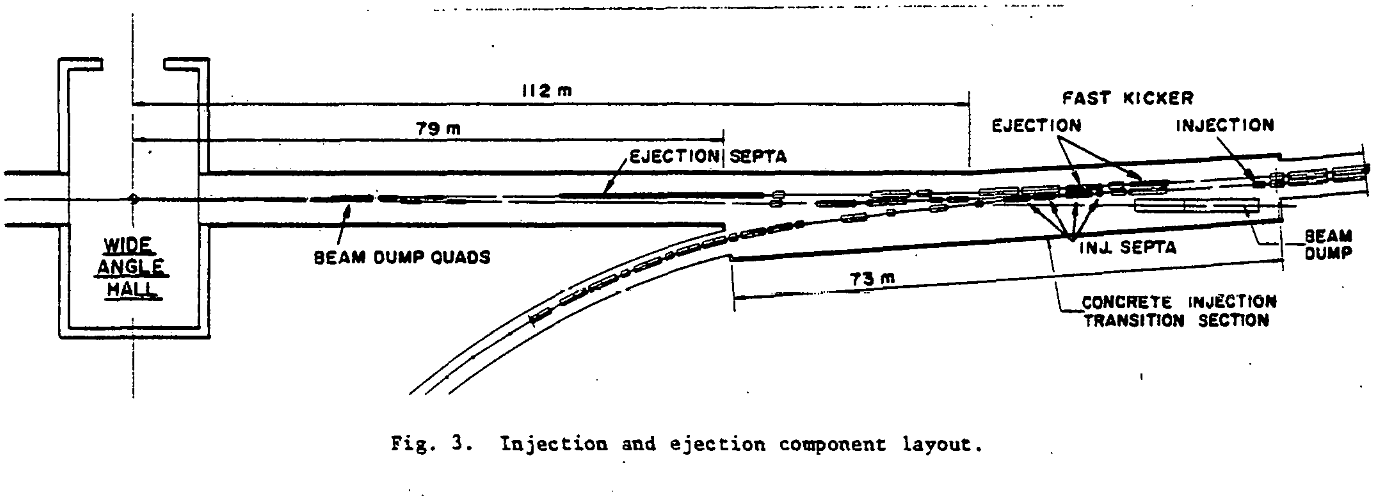

Fig. 3. Injection and ejection component layout.

Vacuum Systems

In the ISABELLE rings, there will be two completely independent vacuum systems.[5] One, which operates in the low 10^{-11} Torr region provides the required clean environment for the circulating proton beam. The other system maintains an insulating vacuum of better than 10^{-4} Torr in the superconducting magnet vessels, since at this pressure the heat convection becomes negligible. Both vacuum systems for a full cell of magnets (6dipoles and 2 quadrupoles) have been constructed, assembled, and tested confirming the design assumption.[6]

The major decision in the design of the UHV beam vacuum consisted in opting for a warm-bore solution. Going this way made available the information on proton storage rings collected at the ISR thereby minimizing the technical difficulties and the required development work. At an earlier time, aluminum vacuum tubes were considered but later on stainless steel tubes were adopted because of their lower secondary electron emission. Basically, the beam vacuum system consists of a circular chamber with inside diameter of 8.8 cm pumped at 5.5 m intervals by titanium sublimation and ion pumps at 714 stations per ring. This arrangement has demonstrated to produce a hydrogen pressure of better than 3×10^{-11} Torr. Such a vacuum has been estimated to be adequate for operation when one considers beam life time due to nuclear scattering or multiple Coulomb scattering, beam neutralization by electrons from ionized residual gas molecules, and radiation background.

The beam tubes are fabricated from 304 LN stainless steel with a 1.5 mm wall thickness and a 1 mm plated copper layer. Appropriate surface treatments including Argon glow-discharge cleaning and in-situ bake out at about 250°C are expected to practically eliminate the pressure bump phenomena (with the ISABELLE geometry allowing desorption coefficients of 4). The installed beam tubes are insulated with 20 layers of crinkled aluminized Kapton and 16 layers of NRC2 superinsulation filling the nominal 1 cm between vacuum tube and cold bore. The measured resulting heat load flowing into the 4 K magnet cooling system is less than 2 W per magnet.

The insulating vacuum is maintained below the 10^{-4} Torr limit by turbo molecular pumps, which should be capable of handling small He leaks as long as these are below the detection level at room temperature. Additional Helium pumping on cryogenic surfaces, to which activated charcoal is bonded, will be provided. The vacuum vessels rely on a completely welded construction with no gaskets and flanges at cryogenic temperatures.

Refrigeration System

The ISABELLE refrigeration system must function in a variety of situations: normal operation, cooldown, bake out of vacuum chamber, magnet quenching etc. The systems requirements are set by the normal operating conditions with all magnets excited to full field. The design operating temperature for the superconducting magnets is 3.8 K with excursion to 4 K permitted during ramping of magnets. The most cost effective system to obtain this temperature is by means of a single refrigerator utilizing forced circulation of helium at supercritical pressure. The helium leaves the refrigerator at a pressure of 5 atm and a temperature of 2.6 K. The cryogenic distribution system feeds each sextant at its midpoint thereby cooling the 45 magnets of one half sextant in series (Fig. 4).

The estimated steady-state primary heat load at 4 K is 15.5 kW and the secondary heat load at 55 K is 36.8 kW. Contributions to the primary heat load are made by the superconducting magnets (33%), the magnet power leads (21%), the helium distribution system (34%), and refrigeration requirements of experimental areas. The allowed load per dipole magnet is 4.6 W of which about 2 W is due to the warm bore. Measurements on the Engineering Test Magnet have demonstrated that these design values can be achieved at an insulating vacuum below 10^{-4} Torr. Magnets and transfer lines have heat shields at about 55 K, representing the secondary heat load. No nitrogen is used in the refrigeration system.

The refrigerator, which utilizes the Claude cycle, is designed for a 23.5 kW primary and 55 kW secondary capacity, i.e., a nominal 25 kW total. The magnet coolant is circulated in an essentially closed loop by a 3 kW centrifugal compressor operating at 3.5 K. The main refrigerator removes heat from the circulating coolant in a subcooler heat exchanger and replaces gas diverted for cooling of the power leads. The compressors will be of the oil-lubricated screw type, consuming a total of 16 MW electric power. Two steps of compression are required with 20 parallel

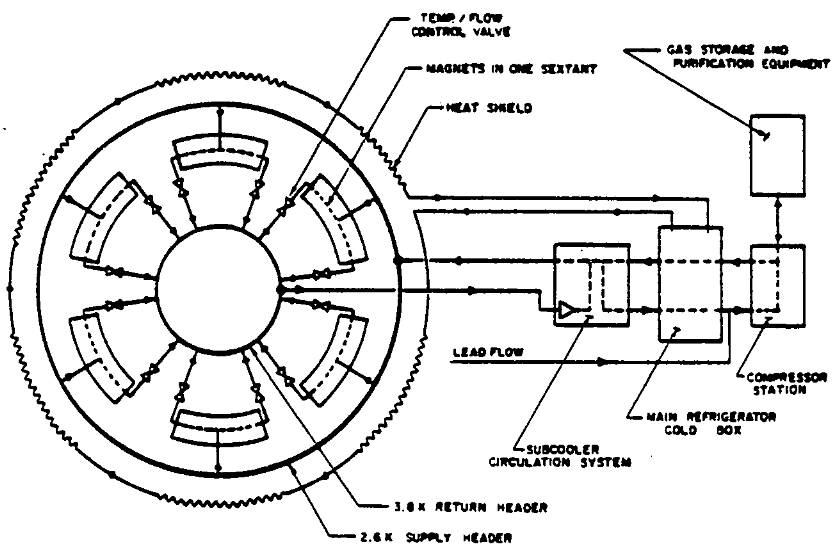

Fig. 4. Cryogenic distribution system.

units in the first and six in the second stage. An order has been placed for the refrigerator, which is expected to be operational in September 1983.

Superconducting Magnet System

Magnet Configuration

The magnet system will be superconducting with the lattice structure assuming dipole magnets which are in the regular cells 4.75 m long and operate at 50 kG to achieve 400 GeV beam energy. The regular quadrupoles are 1.65 m in length and will operate with a gradient of 6.14 kG/cm. There will be a total of 732 dipoles (of which 12 are special magnets in the matching sections) and 348 quadrupoles (including 72 for the insertions) in both rings. Dipoles and quadrupoles are connected in series and will operate at a nominal 3.9 kA. Dipoles and quadrupoles are similar in design. The magnetic field is produced by superconducting braid which together with spacer turns is formed into a single layer coil with an approximate cosine current density distribution (Fig. 5). The braid is made up of 97 twisted composite wires, 0.3 mm in diameter, each containing about 500 superconducting Nb Ti filaments of 9 micron diameter. The nominal dimensions of the bare braid are 16.3 mm x 0.6 mm resulting in a filling factor of 74%. The braid is filled with an alloy of Sn-3 wt% Ag to give mechanical rigidity and is insulated with a B-stage epoxy-impregnated fiber glass tape 0.05 mm thick. The wires in the braid have a 0.01 mm thick Cu-10 wt% Ni jacket to decrease eddy current effects. The short sample quench current of the braid is specified as 4.35 kA at 55 kG and 4.2 K.

The coil is shrink-fitted into a cold laminated iron core. (Fig. 6) The resulting interference fit of about 0.1 mm at helium temperature provides the necessary precompression of the coil, counteracting the magnetic pressure of about 4000 psi azimuthally. The laminations are contained within an accurately machined heavy wall stainless steel support tube. End plates welded to the support tube form a closed pressure vessel for containment of the helium coolant. The magnet assembly is mounted in a vacuum tank and thermally insulated by multiple layers of super insulation with an intermediate temperature aluminum heat shield (Fig. 7).

The dipoles and quadrupoles will each have sets of windings to provide complete control over the working line and to correct errors in the field shape of the magnets. Dipoles will be equipped with trim windings for sextupole, octupole, and decapole, whereas quadrupoles will have trim quadrupole and decapole coils. Correction of the random errors leading to closed orbit deviations will be possible using separately exicted dipole coils located in the quadrupoles.

Magnet Performance

The decision of adopting a 50 kG design field was at the time based on the performance of magnets in the original Mark series (12.1 cm coil i.d. and 4-1/4 length). The best performing magnet in this series, MK-V, exceeded 40 kG on the first quench and reached 50 kG with few training quenches.[8] The small number of training quenches was considered acceptable and the desirable safety margin was expected to come from lowering the operating temperature under 4 K and from conductor improvements involving additional heat treatments and higher braid compaction. Magnets subsequent to MK-V served in the exploration of design parameters and led to MK-XIV which reached the peak field of 51.2 kG after 52 quenches, indeed meeting the 50 kG design goal.

Construction of a full-aperature, full-length industrial first cell (6 dipoles + 2 quadrupoles) was initiated in 1978. The results from these magnets can be summarized as follows:

i) In the average the dipole performance was below expectations with first quenches at 37 $\pm$ 1.8 kG, reaching 42.4 $\pm$ 2.7 kG after training. The highest field of 48.5 kG was measured in one magnet after about 100 quenches. The first quadrupole performed as expected reaching the design current after few quenches and a maximum of 4.5 kA. The second quadrupole was disappointing with a maximum current of 3.7 kA.

ii) The static overall field quality over the good field aperature of 3 cm seems to be acceptable with $dB/B = 3.2 \times 10^{-4}$ rms in the dipoles and $dG/G = 6.6 \times 10^{-4}$ rms in the quadrupoles (the tolerances are 3.7×10^{-4} and 8.8×10^{-4} respectively). However individual harmonics, in particular the sextupole component, are above their tolerance.[9] More definite statements must await further measurements on larger samples including those with long coils. Rate dependent effects are substantially above tolerance and, if uncorrectable, would require increasing the acceleration time to about one hour.

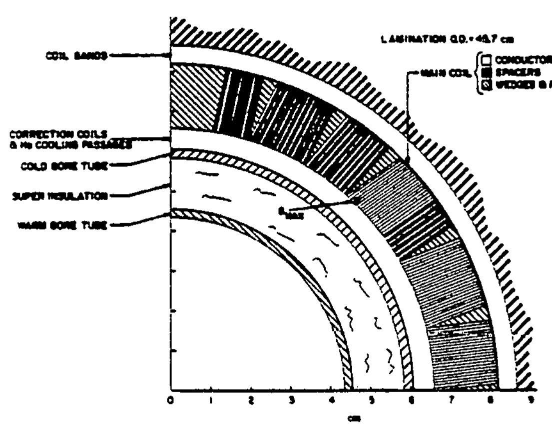

Fig. 5. Dipole coil cross section.

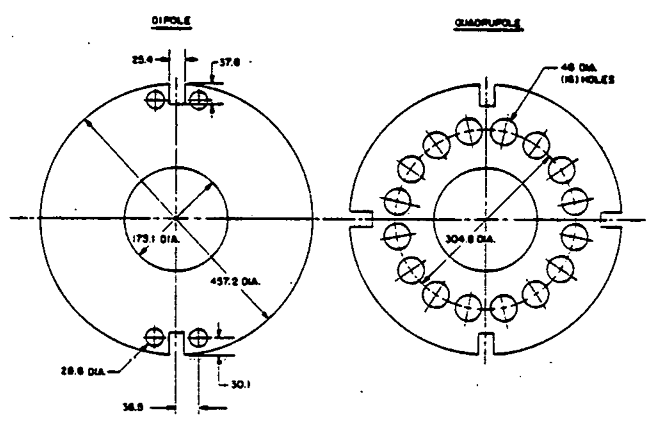

Fig. 6. Lamination geometry (Dimensions in mm).

iii) Some of the dipoles were unable to absorb their own energy during quenches resulting in coil damage. The heat deposition in the superconductor is conveniently expressed by the integral $\int I^2 dt$; melting of filler material and degradation of insulation in the monofilar turns was observed to occur at about $4\ kA^2$ sec.[10] If azimuthal quench propagation is too slow, than coil damage due to heating will occur.[11] However, coil damage can also occur as a result of insufficient electrical insulation leading to arcing and it was not established with certainty what caused coil damage on these magnets.

A second industrial dipole series was executed with CuNi (instead of Cu) spacer turns in order to accelerate quench propagation. These magnets were indeed self-protecting, but at the expense of reduced peak field performance. A summary of magnet performance is given in Table I in which the field at the first quench, B_{1st}, the maximum field reached B_{max}, and the number of quenches required to reach 40 kG are listed. For sake of simplicity, no distinction as to operating temperature or cooling mode was made in quoting B_{max}.

Corrective measures to improve quench propagation by a different turn sequence (e.g. as shown in Fig. 5) have been subsequently suggested and are under evaluation. Furthermore it is suspected that increasing coil precompression will significantly improve quench propagation thus reducing its importance as parameter in the coil design. In any case, the use of active quench triggers would remove the need for self protection if this proved to be incompatible with peak field performance.

Magnet R&D Efforts

Substantial efforts have been mobilized to develope an adequate understanding of the dipole

Table I. Dipole Performance.

Dipole	B_{1st} (kG)	B_{max} (kG)	#Q/40 kG	Comments
MK-V	41.1	53.1	0	Cu Spacer
MK-XIV	31.8	51.2	10	CuNi Spacer
		FULL-APERTURE MAGNETS First Industrial Series		
0001	36.1	41.8	24	Cu Spacer
0002	38.5	41.5	4	"
0003	37.4	48.5	3	"
0004	38.7	39.9	-	"
0005	37.7	44.4	2	"
0006	33.4	38.4	-	"
		Second Industrial Series		
0007	24.0	40.0	57	CuNi Spacer
0008	25.6	39.9	-	"
0009	28.6	38.1	-	"
0011	29.2	39.0	-	"
0012	29.7	44.5	25	"
		R&D Series		
MK-XV	29.3	45.2	22	Ti-rich SC
XVI	36.9	45.0	19	SC wire without CuNi
XVII	31.5	44.3	16	Cu Spacer
XVIII	32.4	51.9	3	Cu Spacer, Precompression
XIX	39.8[a]	42.5	1	SC Spacer
XXI	32.9	36.0	-	Cu & CuNi Spacer
XXIII	31.2		3	Same as XVII
XXIV				Same as XVIII

[a]Eddy current induced quenches not counted.

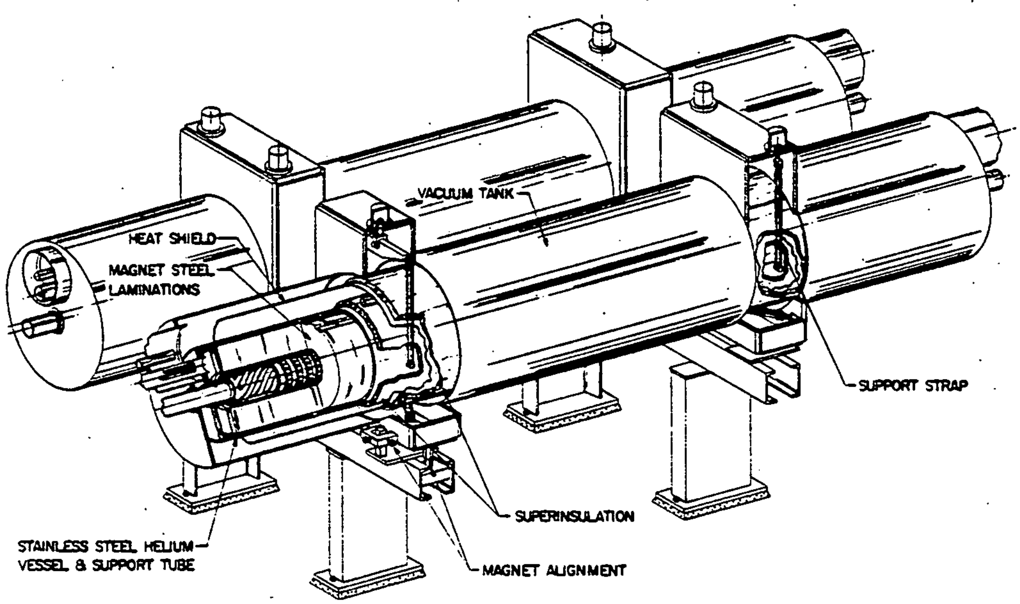

Fig. 7. Isometric view of dipole magnet assembly.

limitations and to improve the performance of the ISABELLE magnets. The immediate objectives are an increase of the field at the first quench and of the gain per training step. The R&D program involves small scale tests, coil simulation experiments, and the construction of full-scale magnets in continuation of the Mark series. A detailed discussion of the program is beyond the scope of this paper, but one may say that the main avenues of pursuit lead towards improvement of the superconducting braid, reduction of mechanical disturbances, increase of magnet stability, and simplification of the overall coil design.

The short sample critical current of the unfinished braid as delivered by industry is specified in the range of 4.9–5.5 kA at 5 T and 4.2 K (i.e. over 4.5 kA at 55 kG taking into account the field enhancement). At Brookhaven the braid undergoes soldering, heat treatment and rolling to dimensions which reduces the quench current by several hundred amperes. Procedures are being developed to assure I_Q (55 kG, 4.2 K) better than 4.35 kA. The use of Ti-rich superconductor has been tried, but degradation during rolling has so far nullified the gain in short-sample current of individual wires. Elimination of the CuNi jacket has resulted in improved performance but at the expense of an enhanced rate dependence. The parameter governing induced eddy currents is the interstrand resistance, which is now measured to be about 5 micro-ohm i.e., an order of magnitude lower than in magnets of the original Mark series. Metallurgical studies identified cracks between the superconducting wire and SnAg filler produced during rolling as controlling the interstrand resistance. It is speculated that the low resistance braid could have also magnetic instabilities in addition to generating eddy currents. Heat treatments to develop a high resistance braid have been found[12] and will be tested soon in a full size magnet.

Several approaches are being explored to reduce the quench inducing mechanical disturbances. Examples are:

i) the unbonding of the coil from the center post to prevent tensile stress in the coil,

ii) application of prestress (about 4 kpsi) by the double shrink method using Al bands to reduce motion,[13]

iii) individual anchoring of current blocks to avoid stress accumulation,[14]

iv) use of kapton on major slip planes to reduce frictional heating,

v) reduce epoxy/superconductor contact via an all-kapton insulation,

vi) improve elastic properties of the coil (modulus, visoelasticity) by curing under pressure and mechanical pre-cycling.

Methods to increase the magnet stability are being studied. Pertinent ideas are helium penetrating a porous coil, the use of Cu or superconducting spacer turns, replacement of bifilar turns by thick braid operating at half current density, etc.

Significant improvements in the manufacturability of the coils are expected from a coil redesign.[15] Potential advantages are:

i) an improved quench propagation due to the elimination of quadrufilar (i.e. superconducting plus three spacer) turns,

ii) the suppression of so called restarts (Fig. 5 shows 1 restart) through the use of a thick wedge,

iii) and elimination of hand insulation during coil winding resulting in coils without turn-to-turn shorts.

A number of magnets in the second Mark series have been built and tested (Table I). Great progress has been made in understanding the ISABELLE magnets. It is most encouraging to have again magnets (Fig. 8) which have exceeded the mythical 50 kG value and are comparable to the best examples of the original Mark series. Notwithstanding the recent success, it is clear that more work remains to be done to sort out the relative importance of quench inducing disturbances versus magnet stability and to optimize the overall design. To summarize the magnet situation, one can state that the original 40 kG is solidly in hand and that the ongoing R&D program stands a good chance of producing magnets capable of performing at the 50 kG design level.

Achnowledgements

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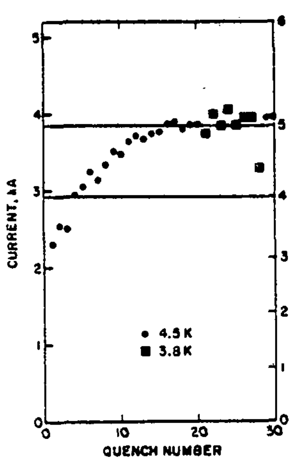

Fig. 8. Training curve of MK-XVIII.