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THE U. S. HIGH ENERGY ACCELERATOR PROJECTS
CESR, PEP, DOUBLER-TEVATRON, AND ISABELLE

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I find it is a real challenge to adequately describe all four high energy physics projects that are now under construction in the U.S. It is very gratifying, however, to find so many projects under construction after the long period in which no new starts were being made. We now have a broad spectrum of devices under construction which will certainly in the near future produce results of great excitement in the world of physics. I intend to describe some of the general characteristics of each of the machines and to discuss some of the special points of interest.

In Table I, below, I give the dominant characteristics of each machine. CESR+, the Cornell Electron Storage Ring, and PEP†, the Positron-Electron Project at Stanford, are both electron-positron colliding beam facilities. Their peak luminosities of $10^{32} cm^{-2} sec^{-1}$ are obtained at 16 and 30 GeV center of mass energies respectively. The Fermilab† program is centered around a superconducting ring which will accelerate protons and store them at energies up to 1 TeV. The machine can be used in a number of different ways. As an Energy Saver-Doubler, protons from the main ring at FNAL can be injected at low energy, accelerated to any level up to 1 TeV and held on flat top for a long duty cycle spill. It may also be used as a storage ring either to make pp collisions with the main ring beam or $\bar{p}p$ collisons with counter circulating protons and antiprotons in the doubler ring itself. The Brookhaven Isabelle facility† is the most ambitious. It consists of two separate interlaced superconducting rings to store counter-circulating protons at beam energies up to 400 GeV, thus providing a center of mass energy for pp colliding beams up to 800 GeV. This is a high luminosity machine, designed to provide a luminosity up to $10^{33} cm^{-2} sec^{-1}$.

Table I

Facility	Mode	Beam Energy GeV	Luminosity $cm^{-2} sec^{-1}$
CESR	e^+e^-	8 x 8	10^{32}
PEP	e^+e^-	18 x 18	10^{32}
Saver Doubler Tevatron	p	1000	2×10^{13}/pulse
	$\bar{p}p$	1000x1000	$10^{28} - 10^{30}$
	pp	150 x1000	2×10^{30}
Isabelle	pp	400 x 400	$10^{32} - 10^{33}$

In Fig. 1 is plotted the design luminosity of each of the existing or projected high energy facilities against the center of mass energy for each machine. You will note the points corresponding to the four U.S. machines. Three points are displayed for Fermilab which correspond to the three modes of utilization. Also shown on this slide are two European machines, the $\bar{p}p$ facility at CERN which is now under construction and LEP, the projected large electron-positron European machine. We see that these new machines open up a large new area on this plot.

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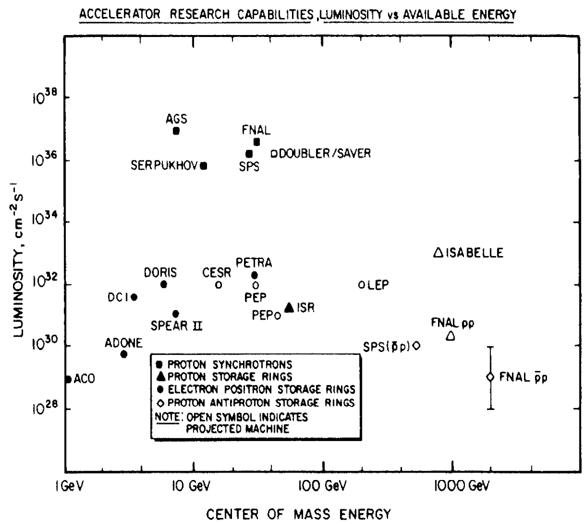

Fig. 1

I would like now to give somewhat more detailed information about the U.S. program. Figure 2 is a time plot giving the history and projected dates of initial operation of the various machines now under construction. CESR is supposed to begin injection in the spring of this year, while PEP will come up in the fall. The Energy Saver is projected to operate in 1982 with initial operation of $\bar{p}$-p colliding beams following soon thereafter. Isabelle is now projected to begin operating at the end of 1985.

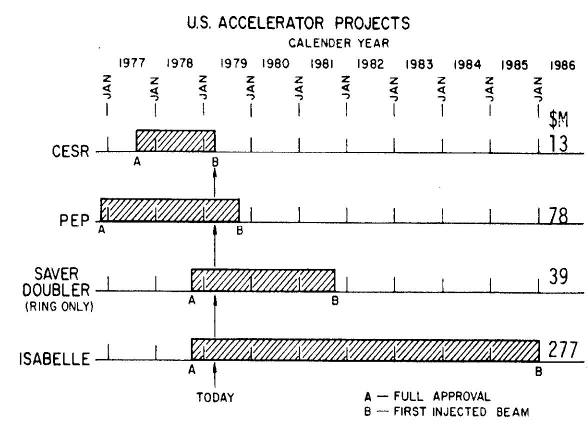

Fig. 2

CESR

The Cornell laboratory submitted a proposal for converting the existing 12 GeV synchrotron facility into the colliding beam facility, CESR, by the addition of a ring of guide field magnets. After two years of work on a development program, a revised proposal[1] was approved in September 1977. Beginning in the following month, the operation of the facility for high energy physics was suspended and the effort of the whole laboratory was dedicated to the conversion program. We are currently within a very few days of achieving our first major goal, the injection of first beam into the complete ring. It is hoped that within a

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few weeks we will be able to obtain stored beams with a measurable luminosity and begin operating in the region of the Υ. Operation at 8 GeV is not expected until the fall of this year.

The tunnel which houses both the synchrotron and the storage ring lies under an adjoining athletic field at a depth of 50 feet below the surface of the field. On the south side, the tunnel passes through the main experimental hall of the laboratory which is situated in an adjacent gorge. Diametrically opposite is the North Experimental Area, a 9 x 12 m cavern with an arched roof. The storage ring has two interaction regions, one in each of these areas.

The synchrotron serves as the injector for the storage ring. After acceleration in the synchrotron, the electrons and positrons are transferred to the storage ring. In order to decrease the filling time for positrons, a system of vernier phase compression is used to coalesce multiple bunches of stored positrons into a single bunch. This is accomplished by extracting the bunches from the storage ring one at a time and recirculating them in the synchrotron for a suitable number of turns before returning them to the chosen r.f. bucket in the storage ring. After the storage ring is filled with positrons, single electron bunches are accelerated in the synchrotron on successive cycles and deposited in a single bucket of the storage ring until it is filled. The whole filling process is expected to be accomplished in about four minutes.

In the South Hall, in order to provide adequate space between the synchrotron and the storage ring for a large detector, a bulge in the orbit has been made. This is shown in Fig. 3. This is accomplished by having a long straight section on either side of the intersection point followed by a stronger than normal bending field. Then, next to the interaction point, very low field magnets are inserted to minimize the synchrotron radiation background at the interaction point. A major colliding beam detector called CLEO is set up at the interaction point. The free length at the interaction region measures 7 M. In the North Area, where there is no bulge between the two rings, the beams are separated by 1.4 m. Experimental apparatus with a 2 m radius about the beam line can be adequately accommodated in this area but provision must be made to pass the 7 cm diameter beam pipe of the synchrotron.

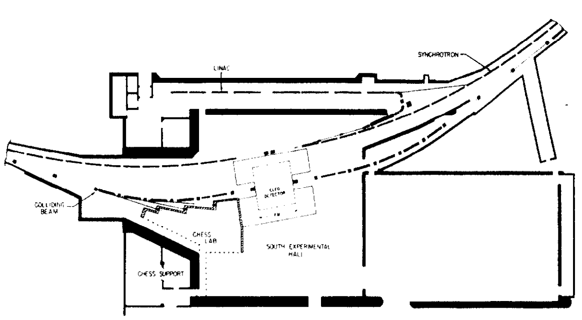

Fig. 3 Floor plan of the CESR south experimenal hall.

The synchrotron radiation spectrum from the high field region in the South Hall is very intense and has a 35 keV critical energy. Because this is a unique source of high energy synchrotron radiation, we have provided three beam ports in this area which will be utilized by experimentalists from a variety of fields who work with synchrotron radiation. A separate management group called CHESS will administer this radiation laboratory under a separate funding arrangement.

The region of the bulge imposes a very large asymmetry and the requirements for low field magnets near the interaction points, space for emerging transfer lines, and other functions have forced us to use a very irregular lattice which has reflection symmetry only about the line through the interaction points. Because of the great irregularity of the lattice and because of our desire for flexibility in lattice control, a large number of independently controlled quadrupole strengths are required. As a consequence, we decided that all focussing elements, except the interaction region quadrupoles, would be driven independently by chopper type, computer controlled power supplies. All multipole correction elements would be similarly controlled. This system provides great flexibility, but of course places great weight on reliability and performance of the controlling power supplies.

The accelerating cavities operate at 500 MHz. A unique r.f. cavity design has been used in order to stabilize the system against the variable loading of the cavity which will arise due to the uneven bunch distribution during the shuffling process. In this system, the individual cells of the cavity are weakly coupled to each other but are closely coupled to a resonant coaxial line which allows the energy in the unwanted modes to be drawn away and dissipated harmlessly in a resistor.

A curve is shown in Fig. 4 which compares the luminosity of CESR to that of PEP and SPEAR as a function of energy. As you see, luminosity of CESR exceeds that of PEP by about a factor of 4 in the range up to 8 GeV, thus the working range of CESR nicely interpolates between that of the lower and higher energy machines.

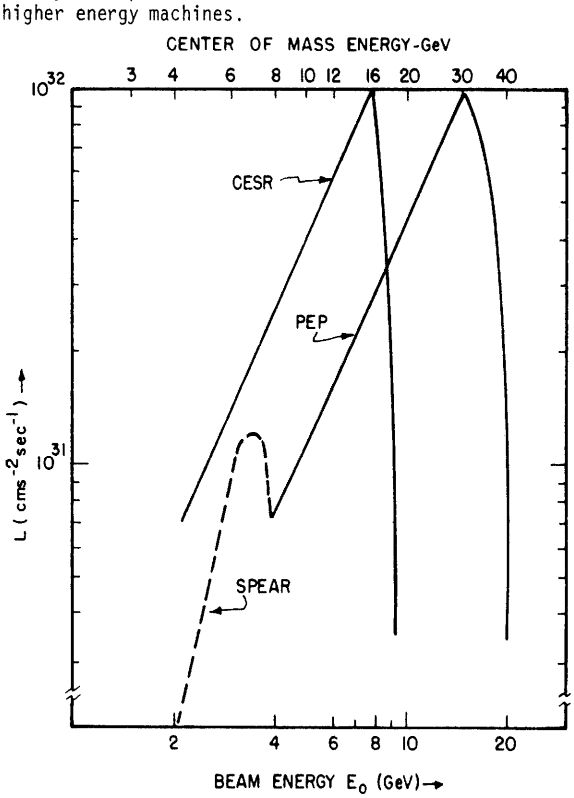

Fig. 4 Plot of the design luminosities of CESR and PEP, and attained luminosity of SPEAR.

PEP

I turn now to discuss the PEP program.[2] This facility was first proposed in April 1974. It received restricted authorization for engineering designs in March 1976, followed by full authorization in November of that year. The scheduled completion date for first beam is October 1979, about six months from now. The storage ring is filled by the Stanford Linear Accelerator which injects the electron and positron beams directly into the ring at the chosen operating energy. The perimeter of the orbit is 2200 meters, i.e., about 1.4 miles. A total of six interaction points are provided. Five of the intersection areas may be provided with experimental halls, while the sixth will be used for beam study and control. The available free length in the straight section is 19 m.

There are a number of special features of the PEP design which should be pointed out. Much effort has been made to maximize the luminosity of PEP for all operating energies. It is planned to introduce wiggler dipoles in three places around the ring which can be used to induce synchrotron radiation to increase the emittance of the beam. For energies below the peak luminosity, which occurs at 15 GeV beam energy, this has the effect of causing the luminosity to fall off only as the E^2 instead of E^4. In order to maximize the luminosity of PEP at high energies, the phase shift per cell was chosen to be about 45° at 15 GeV. Then by increasing the focussing and moving to a higher ν value with increasing energy it is possible to obtain a much higher luminosity than could otherwise be obtained.

In order to obtain these high luminosities in a machine as large as PEP, it is not adequate to control the chromaticity of the machine by a simple two family sextupole function.[3] An optimization program has been used which provides for the selection of a distribution of sextupole fields around the ring to greatly improve the constancy of tune as function of momentum. A total of 9 sextupole families are employed, that is 9 groups of sextupole strengths are distributed around the ring. Figure 5 compares the variation of tune with momentum for two and nine group sextupole families.

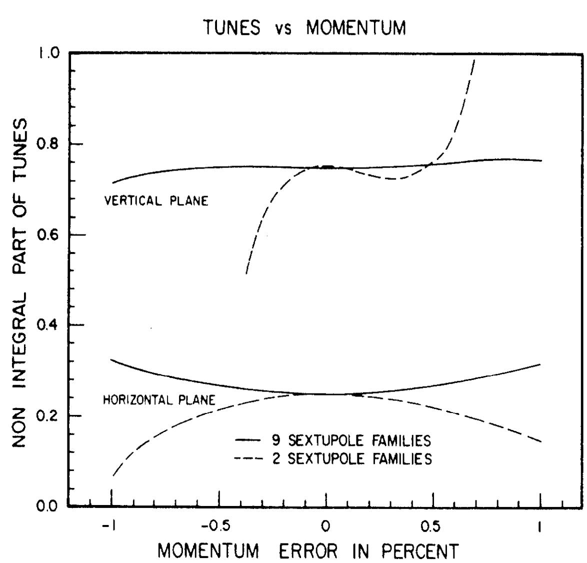

Fig. 5 Plot of betatron tune of PEP as a function of momentum for two configurations of sextupole corrections.

Early experience at SPEAR has shown the necessity for minimizing the effects of the synchrotron radiation background at the interaction regions. SLAC has developed the concept of providing weak field bending magnets adjacent to the interaction area in order to greatly lower the characteristic energy and the flux of synchrotron radiation. These magnets operate at a field strength 15 times lower than that of the normal magnets. The flux originating in the more distant high field bending magnets can be shielded by masks.

Energy Saver-Doubler-Tevatron

We turn now to discuss the activities at Fermi National Accelerator Laboratory.[4] All of the programs there are based on the existing 400-450 GeV proton accelerator. The most immediate goal of the laboratory is the construction of a ring of superconducting magnets to be mounted in the main ring tunnel along with the existing guide field. The long term goal is to use the ring to accelerate protons to 1 TeV and extract them for use in upgraded external beam lines, and to be able to perform colliding beam experiments by operating in the storage ring mode.

At the present time, only one part of the program has been funded as a construction project. This is called the Energy Saver.[5] This is defined to be the construction of a complete ring of superconducting magnets assembled in the tunnel, together with injection equipment, adequate excitation, refrigeration, and r.f. to permit a rate of acceleration of 50 GeV per second. It would be capable of providing very long flat top beam pulses to external areas and would operate for internal target experiments up to 1 TeV. Other funds, not included in the initial construction appropriation would provide for the extraction of the beam at energies up to 1 TeV and transport to external targets. The r.f. system and the refrigeration system would also be supplemented to permit a more rapid rate of acceleration. This stage is called the Doubler. Similarly other funds would be requested to provide for the upgrading of all experimental areas and to provide for colliding beam facilities, including a source of antiprotons and the provision for a colliding beam laboratory area for $\bar{p}p$ and pp colliding beam experiments. This is the Tevatron stage.

A program of development of superconducting magnets for such a ring was begun in 1972. During the course of this development program, extensive experience has been gained in the mass production of superconducting magnets and development of large scale cryogenic equipment. This program was funded in FY79 as a construction project with a total of $39M appropriated for the construction of the Energy Saver ring. Figure 6 shows a cross section of the Saver-Doubler dipole magnet structure. It consists of a central bore tube whose diameter is approximately 7 cm. This is surrounded by a layer of superconductor whose spacial distribution provides a high order approximation to a uniform magnetic field. Surrounding this is a layer of stainless steel laminations which provide banding of the coils to the tube to keep them securely clamped. This whole assembly is then supported in a vacuum cryostat by fiberglass support points, and surrounded by a thermal shield at liquid nitrogen temperature. Single phase liquid He flows around the coil and through the interstices, passes down a length of some 65 magnets and returns as a two phase system. A steel magnetic shield over the outside of the cryostat provides a return path for the flux. The magnet length is 6.4 m and 774 units are required. The quadrupoles are made in a similar manner, and a total of 216 are required.

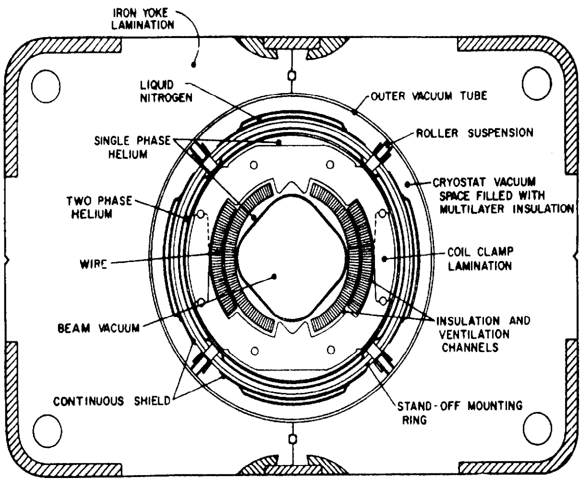

Fig. 6 A cross section view of the Fermilab superconducting Saver-Doubler dipole magnet.

The magnet ring is cooled by 24 local refrigeration loops which are driven by satellite refrigerators, each of capacity 690 watts. A central refrigeration plant of 15 kW capacity, one of the largest now operating in the world, supplies a backup of refrigeration liquid for the satellite refrigerators. This refrigerator is presently operative.

One of the principal goals of the program has been to learn how to make magnets of high quality cheaply, quickly and in a reproducible fashion. A magnet assembly rate of one per day has been attained. The production schedule for the Energy Saver requires a production rate about twice this, a rate which should be attainable. The quality of the magnetic field is such that the good field aperture is ±2.1 cm in the radial direction and ±1.5 cm in the vertical. The magnets consistently show very low training effects. One of the important requirements is that the magnets sustain a ramping rate of 50 GeV per second without inducing quenches. This has been accomplished by using insulated strands in the superconductor. In the event of a quench it is necessary to absorb harmlessly the stored energy of the magnetic field. The arrangement which has been developed involves the use of heater elements in each magnet which are triggered into operation by the first sign of a quench. This has the effect of raising the temperature of the whole coil quickly above the critical point so that the heat from the quench is not dumped into a single point but is distributed throughout the magnet. Meanwhile, the leads of the magnet are shorted so that it is shunted out of the circuit and the quench does not propagate to the adjacent magnets in the string. Simultaneously, the energy is drained out of the rest of the ring. Extensive tests have been made in a four magnet string in order to understand these problems.

The magnet ring for the Saver-Doubler is physically located under the magnets of the main ring. A test of the assembly procedure was made by installing a series of twenty dipoles and five quadrupoles in the tunnel during normal maintenance down periods of the accelerator. A very exciting test of this system has been made during the past two weeks. The magnet was cooled down to the operating temperature along the full length of the sector, a total of about 500 feet, within about 100 hours. Beam of 1.3×10^{13} protons per pulse was injected into the sector at 90 GeV and transported to the end of the line without difficulty. This was a very important test because of the concern that the magnets would quench due to heat from radiation being deposited in the magnet. It was very gratifying to learn that a beam pulse as large as this could be transported without inducing a quench. To my knowledge, this is the longest and most powerful superconducting magnet transport system yet put into operation.

One of the most important questions has been that of whether there is adequate aperture for slow extraction of the beam from the ring. A recent reexamination of this problem has led to a local change in the lattice design which greatly assists the slow extraction. This is accomplished by creating a high beta section in the extraction region which allows adequate space for the insertion of a septum. By the use of this configuration the septum can be moved much further from the circulating beam and the beam jump per turn can be increased by nearly a factor of two. Because any energy lost in the septum produces radiation in magnets downstream, it is very essential to avoid the deposit of this energy in the superconducting magnets. Much thought has been given to the design of radiation shields for the magnets, and some very interesting geometrical arrangements have been devised. Though one cannot guarantee that all such difficulties can be avoided, there is much confidence that solutions exist which will permit operation of the Doubler at full beam intensity.

I wish now to turn to the question of the use of the ring for storage ring experiments. There are two modes: one is for $\bar{p}p$ collisions and the other is for pp collisions. The $\bar{p}p$ mode requires the generation of antiprotons which are accelerated and stored in the Saver-Doubler itself along with a counter-circulating beam of protons. This would provide collisions of center of mass energy up to 2 TeV.

There is, at present, a program at Fermilab to develop an antiproton source for the $\bar{p}p$ colliding beams. This effort is called the "cooling ring experiment". A ring of magnets has been built in order to develop the cooling system. Initially, as a test, protons of 200 MeV will be cooled. Work is proceeding on mapping out the fields in the cooling region and it is hoped that cooling experiments will begin in the next few months. Until now, the emphasis has been almost entirely on an electron cooling system. However, in collaboration with Lawrence Berkeley Laboratory and Argonne National Laboratory, an effort has been begun to study the stochastic cooling methods as well.

In Fig. 7, we show a possible arrangement for obtaining $\bar{p}p$ collisions. Protons are accelerated in the main ring and extracted to a target where the antiprotons are produced. The antiprotons in the energy range near 6 GeV are transported to the booster where they are decelerated in reverse circulation to an energy of 0.6 GeV, then transported to the electron cooling ring. After cooling and stacking, the cycle is reversed. The antiprotons, after acceleration in the booster, are injected backward into the main ring, accelerated to 100 GeV, and then transferred to the Saver-Doubler for storage. Protons are then accelerated to 100 GeV and transferred to the storage ring circulating in the opposite direction. Both beams are then accelerated together in the storage ring to the operating energy.

One of the primary considerations is of course the luminosity of the beam that can be obtained. The plan discussed above is expected to provide a luminosity from 10^{28} to $10^{29} cm^{-2} sec^{-1}$. It is hoped that $\bar{p}p$ experiments can begin in 1983. A precooler has been proposed which would provide about another factor of 10 of luminosity.

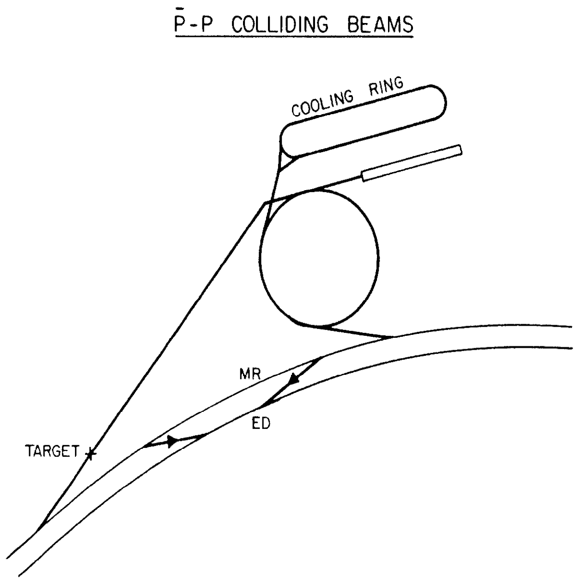

Fig. 7 A possible layout for the $\bar{p}$-p system at Fermilab. MR is main ring, ED is Energy Saver-Doubler. The booster is represented by the circle.

The second colliding beam mode would make pp collisions between the main ring and the superconducting ring. In order to bring the two beams into collision, kissing magnets would be used, that is, both beams would be bent toward each other, intersecting at zero degrees. In this mode the dipole deflection magnets at the end of the intersection region would be common to both beams.

Isabelle

The Isabelle proton-proton storage ring project is the largest of the U.S. programs and projects the furthest into the future. Major research and development funds directed toward this program were appropriated beginning in FY75. The present design[6] provides for 400 GeV beams of protons with a peak luminosity extending to $10^{33}/\text{cm}^{-2}\text{sec}^{-1}$. Full authorization was obtained in October, 1978.

The Isabelle facility will consist of two interlaced superconducting magnet rings which are enclosed in the same tunnel. The AGS will inject at an energy of 30 GeV. After the rings have been filled, the magnets will be ramped slowly to the operating energy. The lattice design provides for six interaction straight sections where the beams from the two rings cross at an angle of about 9 milliradians. The present construction plan anticipates that four completely developed experimental halls will be constructed around the intersection points while the other two will remain available for later development.

A cross section view of the superconducting dipole magnets is shown in Fig. 8. The magnet design is based on a much different philosophy from that of the Fermilab Saver-Doubler. This system, instead of having a cold beam tube has a warm bore which is insulated from the superconducting coil by vacuum and super insulation. A cold bore tube surrounds the beam pipe and carries the electrical conductors. The dipole field is provided by a segmented approximation to a cosine distribution curve of superconducting windings. In order to rigidly constrain the coil so that it will not move and cause quenching, it is enclosed in a steel jacket consisting of a long stack of circular laminations. These laminations not only provide the mechanical forces for constraint but also provide for the return flux of the field. In order to avoid premature saturation, this steel shield is very thick. The whole magnet, which consists of an inner cold bore tube, coil, and magnet iron, is enclosed in a heavy stainless steel support tube. This constitutes a closed system for the helium containment. The supercritical helium flows through this vessel and cools both the coil and outer magnet core to a temperature of 3.8°K. This assembly is suspended by low conductivity supports inside a vacuum vessel which provides the required thermal insulation. Super insulation and a heat shield at liquid nitrogen temperature are provided to reduce the heat load to about 4 watts per magnet. The warm bore tube of the storage ring constitutes the inner wall of the vacuum jacket.

Each magnet core is 4.75 m long and weighs 5500 kg. A total of 732 dipoles are required for the whole system, and 352 quadrupoles of similar but smaller size provide the focussing. A total refrigeration load of 14 kW at 3.8°K is expected. This will be provided by a central refrigeration facility of 19 KW capacity.

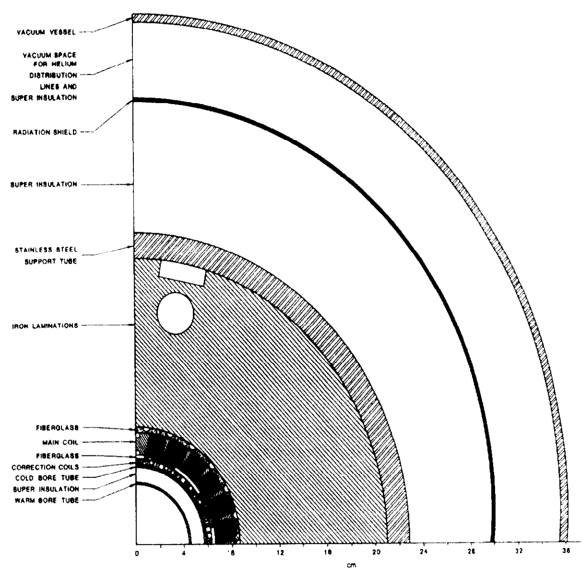

Fig. 8 Quarter section view of the Isabelle superconducting dipole magnet.

The design value for the magnetic field in the dipoles is 5 Tesla. Prototype magnets which function at this field level have been built in the laboratory and now industry has been approached to provide coil prototypes for mass production. Good field quality and reproducibility have been obtained in prototype units though no large number of magnets has been constructed and compared. The requirements of the vacuum system are extremely high. The goal is to provide a vacuum of 10^{-11} Torr in the main part of the ring and better in the interaction region.

It is interesting to compare the requirements and designs of the Saver-Doubler and the Isabelle ring. Both of these facilities are larger than any other superconducting system that has ever been constructed. Hence many of the problems have to do with the scale of the project alone. Between these two programs, the United States is committed to building a total of about six miles of magnets which operate at liquid helium temperature. In the Isabelle design the total weight of material at liquid helium temperature is about 5300 tons, a weight greater than the weight of a destroyer! Because the design of the Saver-Doubler magnet has light compression bands made of stainless steel, with a surrounding vacuum jacket between the coil and the iron shield, the total weight of material at liquid helium temperature is about 10 times less than in Isabelle. As is usual in design concepts, a number of factors conspire to lead to certain configurations. In this case, in order to maintain a large, high quality working aperture in the Isabelle magnets, the inner diameter of the coil is quite large, about 13 cm. As a result, a rather large warm bore tube, 8.8 cm in diameter can be installed and still leave adequate space for the required thermal insulation next to the warm bore. In contrast to this the Saver-Doubler design has coils mounted directly on the cold bore tube with an interior coil diameter of about 7 centimeters. Thus, the whole coil system of the Isabelle ring is much larger than the Saver-Doubler ring. Because of this larger scale, higher excitation is required for the Isabelle design and the forces are consequently greater. The decision to make the iron of the magnet as the coil constraining device greatly increases the total amount of material at the helium temperature. This of course makes for a long cool down time. It is anticipated that the cool down time will be of the order of two weeks, as contrasted to about 100 hours for the Fermilab design. There are however a number of important compensations for this larger size and weight of the Isabelle design. By operating with a warm bore, it is very much easier to install diagnostics and beam manipulation equipment for the system. Furthermore, because the conductors are much further away from the center line of the magnet, it is much easier to obtain a high quality large aperture field and the higher order multipoles in the field are relatively less important.

The question of warm bore vs. cold bore has been a long standing issue. Because of the very large currents that are anticipated to be stored in Isabelle, it was decided long ago that it was necessary to operate with a warm bore in order to avoid the pressure bump problem that comes from the regenerative catastrophic desorption of gases from the wall of the bore tube due to ion bombardment. These ions are produced in the residual gas by the circulating beam and are accelerated toward the wall by the space charge potential of the circulating beam. This effect is of special importance in very high current machines. The Saver-Doubler design however makes use of the cold bore principle, and calculations, together with tests that have been performed recently at CERN, are very convincing that for the beam currents of the Saver-Doubler, there should be no problem from this source.

One major distinction between the requirements of the two ring systems has to do with the rate of rise of the field. Since Isabelle is designed to operate only as a storage ring and not as a fast cycling accelerator, the acceleration rate is not important in that phase of the operation of Isabelle. However, it is of great importance in the case of the Saver-Doubler. Isabelle is designed for an acceleration rate of 1.6 GeV per second as contrasted to 50-75 GeV per second in the Saver-Doubler. This leads to two severe requirements for the Saver-Doubler, one is that the field quality must be maintained free of eddy current effects during acceleration and the second is that heat dissipation in the superconducting coils due to eddy currents or hysteresis must be held to an acceptable minimum in order to avoid premature quenching. This is accomplished by making use of insulated stranding of the superconductor wire. It has been found possible to construct magnets which show no significant effect on the quench point for rates of rise up to 75 GeV/sec.

These two superconducting accelerator projects, the Saver-Doubler and Isabelle are mapping out a new frontier in accelerator technology. We look forward with great interest to the successful completion of these exciting programs.

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