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ISABELLE: BROOKHAVEN INTERSECTING STORAGE ACCELERATORS*

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1. Introduction

At Brookhaven we have been thinking about colliding beams of protons since the early 1960's. In 1963 we held a summer study on colliding beams and super-energy accelerators; at that time the great majority of our users advised us to leave colliding beams to CERN and to concentrate on improving the AGS.

More recently, with the great success of the CERN ISR and with the NAL machine and the CERN super-accelerator both aiming at 1000 GeV, we have concluded that colliding proton beams of about 200 GeV should provide the next step upward in center-of-mass energy toward the point where weak interactions become strong, and who can tell what happens to strong interactions.

Accordingly, we are working on the design of ISA — intersecting storage accelerators for 200 GeV each. The device has been nicknamed ISABELLE. It will use the AGS as a 30-GeV injector and will use superconducting magnets operated at 4 tesla.

Studies on the design of ISABELLE have been in progress since 1971 and a number of alternate designs have been discussed. A firm final design has been chosen and will be described in a construction proposal to be submitted to the U.S. Atomic Energy Commission early in 1974.

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2. Lattice Configuration

The two rings will be identical in configuration and will be located with one ring about 30 cm above the other. Each ring has four-fold symmetry with four quadrants of about 220 m mean radius separated by four straight sections about 250 m long to be used as experimental areas. The precise dimensions will be chosen to make the total ISA circumference exactly three times the circumference of the AGS.

The basic lattice consists of alternating units each including three 3 m long dipole bending magnets and a horizontally focusing or defocusing quadrupole. The quadrupoles, which will have pole strengths of about 4 T, will be about 1 m long. Three dipoles and one quadrupole of each ring will constitute one Dewar-included unit of the cryogenic system.

Since, as will be discussed later, the injection system will involve energy stacking as is used in the CERN ISR, and since, in the lattice just described, this will require additional aperture, a lattice modification is under consideration in which the injected momentum spread will demand less additional aperture.

3. Magnets

Superconducting magnet windings make possible the achievement of fields well above those at which ferromagnetic materials saturate, and conventional magnet designs are no longer applicable. It now becomes necessary to provide a coil configuration which, without iron, gives the desired field. It can be shown rather easily that dipole fields are provided by coils of cylindrical cross section in which the current density is proportional to cos θ, where θ is the angle between the horizontal plane through the cylinder axis and the plane under consideration, also passing through the cylinder axis. Quadrupole fields are produced when the current density is proportional to cos 2θ. Windings of this type have come to be known as "cosine windings".

Since one is limited in actual construction to windings that include finite numbers of turns, and since one prefers to run these turns in series so that each carries the same current, some compromise evidently is required in coil design. This problem has been analyzed in some detail by Dr. Beth at Brookhaven. He has shown that the coil can be made up of current blocks where position and width can be chosen to eliminate two Fourier components of undesired field. In practice, with about six blocks, it is possible to reduce undesired field components to less than a few parts in ten thousand. The coil design that results is shown in Fig. 1.

With the air-core coil just described there are still advantages in inclusion of iron in the magnetic circuit. An automatic first reaction is to include iron only in regions where it will not saturate. Further study shows this assumption to be naive. Iron directly surrounding the cylindrical coil will add about 1.5 T to the useful field for a given coil current, it can be used as a powerful mechanical restraint against the magnetic forces, and it introduces only trivial distortions into the field pattern. These small distortions are greatest for 4-5 T fields; at higher fields they disappear. They can easily be removed, if necessary, by correction windings of negligible proportions.

A number of model magnets of this type have been built and tested at Brookhaven. Field pattern differences between supposedly "identical" magnets indicate that errors in location of conductors are of the order of 50 microns.

The superconductor presently under consideration at Brookhaven is a NbTi alloy available commercially from several American companies.

With superconductors a stability problem exists. As the field is raised in a superconducting magnet using high-field (Type II) superconductors the field penetrates the superconductor in a discontinuous fashion with dissipation of heat at each "flux jump". This heat dissipation may be sufficient to raise the superconductor temperature to a point above its "critical temperature" where it ceases to be superconducting. If this happens it may be impossible to turn on the superconducting magnet. This problem was resolved at a summer study at Brookhaven in 1968, by Peter Smith of the Rutherford Laboratory. He pointed out that such instabilities can be contained and effectively eliminated by two steps. First the superconductor must exist in strands of not more than a few microns diameter and, second, the strands must be transposed or twisted as in Litzendraht.

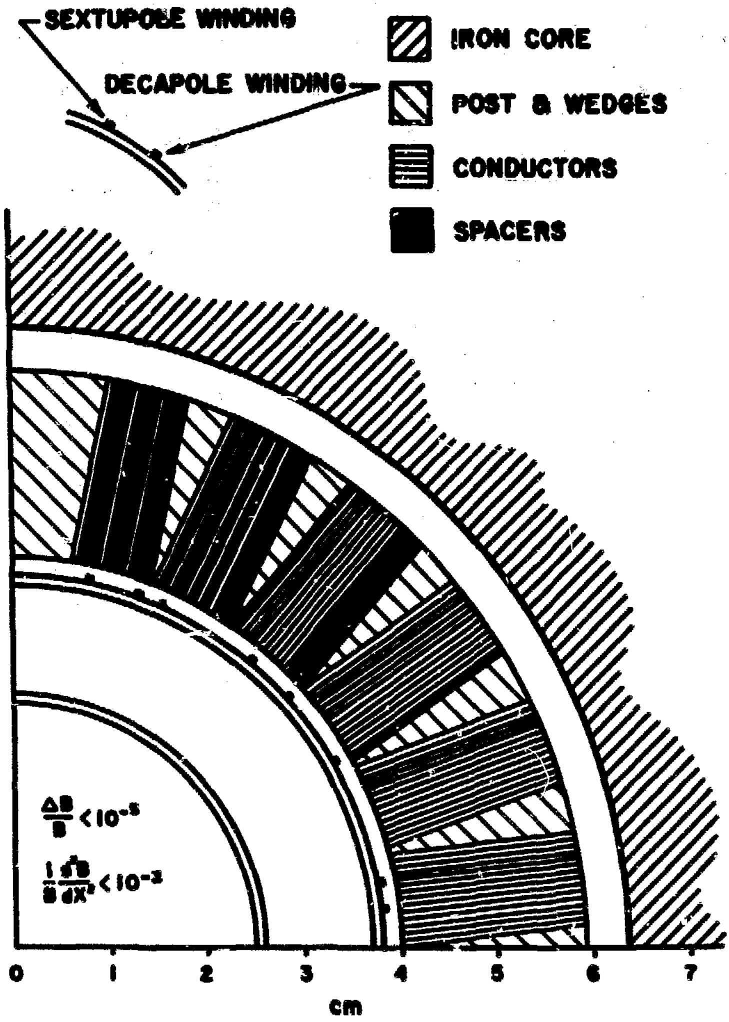

Fig. 1. Cross section through cosine magnet.

Since 1968 Smith and his associates have pressed European manufacturers to produce such superconductors and we at Brookhaven have done the same in the United States. Wire is now available in which several hundred strands of NbTi superconductor are included in a copper matrix wire a fraction of a millimeter in diameter. During the manufacture the wire has been twisted to provide the superconducting equivalent of Litz wire.

Our preference is for wire 0.2 mm in diameter capable, when superconducting, of carrying about 20 amperes. About 200 of these wires are fed into a braiding machine which yields a flat braid about 1.5 cm wide. This braid is impregnated with a thallium-indium alloy of low conductivity and the resulting tape is rolled to a precise size. The tape is convenient for fabrication of cosine windings of the type described above.

The over-all diameter of the 4 T dipole is about 25 cm. Its aperture is 12 cm and its stored energy is about 100 kJ per meter of length.

The quadrupoles are built in the same fashion with a winding whose density is proportional to cos 2θ and is closely surrounded with iron.

Dewars about 11 m long will each house six dipoles, three for each ring, and two quadrupoles, one for each ring. A possible support arrangement is shown in Fig. 2.

4. Magnet Power Supply

The total energy stored in the bending magnets of each ring is about 120 MJ. The requirements for the magnet power supply have, however, been relaxed by the decision that the acceleration cycle will be quite slow. Since the useful part of a cycle of operation will be many hours long, there seems no point in an acceleration cycle shorter than a couple of minutes. During this period the peak energy transfer into each ring will be about 2 MVA.

The power supply voltage will be about 700 V; peak current will be about 3000 A. These are ideal parameters for solid state rectifier-inverters. The power supply will probably be a six-phase SCR system

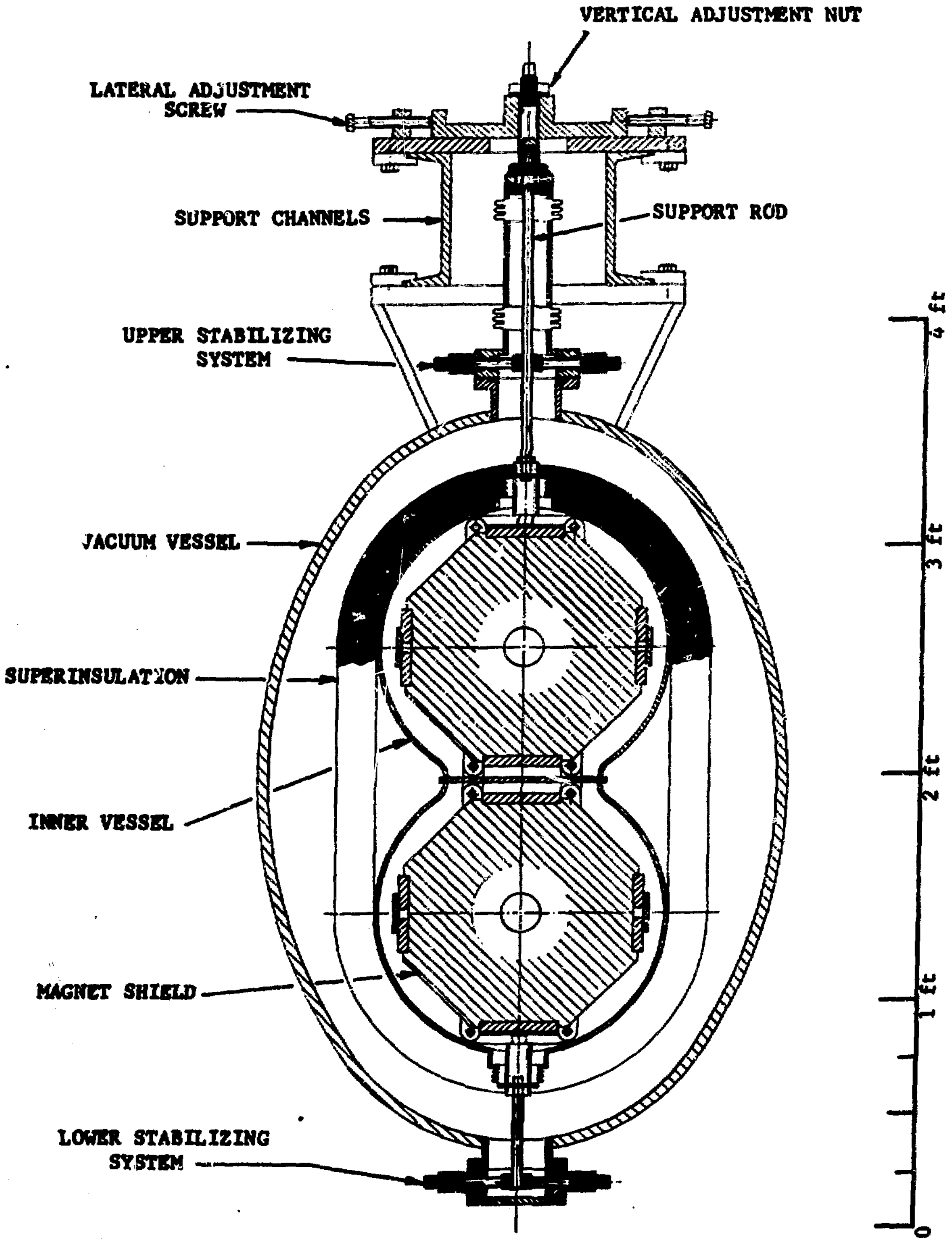

Fig. 2. Section through adjusting mechanism.

including a passive resistance-inductance-capacity filter for removal of ripple.

The quadrupoles and other correcting magnets will be supplied by similar power supplies at much lower power levels.

The large total stored energy makes it important to include fault protection in case a magnet overheats and goes normal. For this purpose we include shunting power diodes which have a voltage threshold for current conduction. Such diodes will be connected across each Dewar. Within each Dewar, each magnet will be shunted by a resistor of a fraction of an ohm in series with a power diode.

5. Injection

A number of injection schemes have been proposed for ISABELLE. They come under the two headings of azimuthal stacking and energy stacking.

The simplest azimuthal stacking scheme consists in simply injecting, by conventional methods, three 12-bunch AGS pulses to fill the circumference of the ISA. When the 36-bunch stack is accelerated to 200 GeV, a luminosity of 10^{32} $cm^{-2}sec^{-1}$ will be achieved.

Other methods for combining each AGS pulse into a single bunch and then stacking the bunches as close to each other as possible in the ISA rings have been worked out in detail and give promise of luminosities between 10^{33} and 10^{34} $cm^{-2}sec^{-1}$. A further possibility is transfer of single AGS bunches and arrangement of the bunches, by rf gymnastics in the ISA so that they are included in the ISA within about one-tenth of the azimuthal space that they occupied in the AGS. This procedure would give a similar luminosity.

Although all of these schemes seem feasible within the limits of present technology, we have come to prefer the method of energy stacking which is used at CERN in the ISR. This is a method having great flexibility and having the further advantage that it has been shown to work. At CERN, the method consists in injecting a pulse from the CERN proton synchrotron and inflecting it with a septum magnet into a closed orbit in the ISR. The circumference of the ISR is 1.5 times that of the PS so there is an appreciable time (about one microsecond) during which the field in the septum magnet can be turned off so that it will not affect the beam on its second revolution. The septum winding is now removed mechanically and the beam is moved by rf acceleration to join a stack of previously injected PS pulses.

When the energy spread in the PS is reduced before the transfer and the beam in the PS is partially debunched, the phase space dilution in the ISR (after the beam in the ISR debunches) can be no worse than a factor of two.

The system is flexible because the same ISR intensity can be built up whether or not the PS is operating at peak intensity.

Only one problem arises in applying this system to ISABELLE: here we hope to inject three AGS pulses before the orbit is shifted by rf. In this case the septum magnet must be capable of turn-on and turn-off in the time between AGS bunches which is about 200 nsec. Although this is entirely possible and is done on the fast kickers in the AGS, it is not a requirement that one would like to combine with the ability to remove rapidly and remotely the septum winding. Accordingly, we propose to do the rapid kicking of the beam by two fast magnets spanning the whole aperture one a quarter betatron wavelength upstream and the other an equal distance downstream from the septum. This method calls for a small increase in aperture because the stacked beam also will be displaced during the kicking procedure.

After thirty stacking cycles, each made up of three AGS pulses, the circulating current in the ISA will be 15 A, which we regard as the design intensity to give a luminosity of between 10^{33} and 10^{34} $\text{cm}^{-2}\text{sec}^{-1}$. The assumed AGS intensity is 8×10^{12} protons per pulse, a level that already has been reached.

Before injection the beam in the AGS will be debunched adiabatically by reduction of the rf voltage from about 400 kV to 36 kV. This will increase the phase width of the bunch from 22° to 41° and will reduce the total momentum spread from about 12×10^{-4} to about 6×10^{-4}. The total energy spread in the injected stack will be about 9×10^{-3} which will be reduced to about 2×10^{-3} after acceleration to 200 GeV.

6. Acceleration

Because of the slow rate of acceleration, severe demands are not placed on the rf accelerating system. It is, however, necessary to satisfy two criteria. First, the accelerating bucket must be large enough to include the total energy spread in the stacked beam. Second, the impedance presented to the beam by the rf system must be low enough to satisfy "Sacherer's criterion" which gives numerical values for the impedance inversely proportional to the beam current. This is a criterion for longitudinal stability of the beam.

In establishing the pertinent rf parameters, we have explored the range of harmonics from the fundamental to the 36th harmonic. At the two extremes we obtain the following numbers:

	Fundamental	36th Harmonic
Frequency (MHz)	0.123	4.45
Peak voltage (kV)	18	144
Shunt impedance (Ω)	433	8020
Number of accelerating gaps	2	15
Total weight of ferrite loading (tons)	5.3	16.3
Total power (kW)	1080	2940

There appear to be no inherent problems in the acceleration of the 15-A circulating current provided only that shunt impedances are kept to sufficiently low values.

7. Vacuum System

A very good vacuum will be required, primarily to keep background low in the colliding beam experimental areas, but also to ensure long beam life. We plan to maintain a pressure of 10^{-10} Torr or better.

At first it would appear desirable to hold the vacuum chamber wall at the magnet temperature of about 4 K, and let the chamber wall serve as a cryopump. But experience at the CERN ISR has led us to the conclusion that the chamber wall must be warm. This is because of the "pressure bump" effect. With circulating currents of a few amperes the potential distribution through the beam is such that ions of residual gases produced by collisions with the protons in the beam will be propelled toward the chamber wall with energies of the order of 1000 V. If there is adsorbed gas on the wall, each ion will liberate a number of adsorbed atoms and the pressure in the region will rise. At some value of the circulating current this process will become cumulative and the pressure will rise to the point where the beam will be scattered and lost. It is this phenomenon that has limited the current in the ISR and it must be kept under control in ISABELLE. It must be possible to bake the chamber at 200-400^{o}C, preferably without warming the magnet, and the chamber must be maintained at a temperature where residual gas is not frozen on its surface, but is removed by external pumps to a point where ions cannot again liberate it.

Hence the vacuum chamber will be thermally insulated from the magnet. It will have a diameter of 8 cm. Since the inner diameter of the magnet is 12 cm, a 2 cm space will be available for thermal insulation.

The circulating beam in the ISA will induce image currents in the chamber wall. To keep losses due to these currents low and to control resistive wall instabilities, the chamber should be made of a material of high conductivity; aluminum has been chosen for the chamber material and experiments are in progress at Brookhaven on the liberation of adsorbed gases on aluminum by ion bombardment, and on its rate of outgassing at elevated temperatures.

8. Experimental Areas

The long straight sections in ISABELLE correspond to the experimental areas of a conventional accelerator and can be expected to change to meet the demands of the experimental program. Most of the experiments foreseen fall into two classes. The first includes the strong interactions where events will be characterized by small transverse momentum and experiments will need long clear spaces close to the beam but very little radial extent. The second class, the weak interactions, give large transverse momentum and so require considerable radial space but very little azimuthal extent.

Design of the first arrangement of experimental areas will be left to the latest possible date so that they can correspond to the latest condition of high energy physics. Some large spectrometer and calorimeter setups can be semi-permanent but other areas will change completely from year to year.

Beam crossings can be at large or small angles or the beams can be run for some distance on collinear paths if desired. To some extent beam crossings must satisfy the criterion that the tune shift due to beam-beam interaction must be lower than a number as yet not completely determined. Originally, from electron ring experience it was thought that the maximum safe tune shift is 0.025. Lately an experiment at CERN indicated trouble for a tune shift of only 0.005 but later experiments have not confirmed this result. Probably a reliable figure will be established at CERN during the next few months.

9. Options

Future work with ISABELLE can include several fields of study in addition to proton-proton collisions. Some thought has been given to use of the rings for studies of deuterons and heavier particles. Antiprotons could be accelerated in one ring but rather low luminosities would make experiments difficult.

There is considerable enthusiasm among ISABELLE's future users for an electron-proton option in which 5 to 15-GeV electrons would be accelerated in a separate ring and brought into collision with the 200-GeV protons in one of the ISA rings.

The electron ring will lie in the same plane as one of the proton rings and will have a slightly smaller circumference. In one possible configuration, the electron ring will be located 25 m to the side of the proton rings; a bypass will take the electrons to one of the long straight sections of the proton rings. There the electron beam will intersect the proton beam twice at an angle of about 10 mrad at points separated by 50 m.

The AGS will serve as the injector for the electron ring. With its present rf system the AGS can accelerate electrons to 4 GeV. Further acceleration in the electron ring will be at a frequency of several hundred megahertz.

Because of the rapid increase with energy of energy loss by radiation, the electron current that can be accelerated decreases as energy increases. As a result the luminosity of the electron-proton system goes through a maximum of 2×10^{32} cm^{-2}sec^{-1} at an electron energy of 11 GeV.

10. Conclusion

In May of 1972 a "Preliminary Design Study" for ISABELLE was assembled to serve as a basis for discussion during the 1972 summer study. Its reference number is BNL 16716 and, because of the color of its cover, it is known as the "grey book". It is now in the process of revision; the deadline for rewritten chapters is January 1st. We hope that the revised grey book will be a definitive description of the new machine and plan to use it as the basis for our construction proposal. We are ready to start construction in the middle of 1975. There is, however, a finite possibility that we may not receive approval as quickly as that.

In any case, we are convinced that colliding beams at energies of the order of 200 GeV will provide the appropriate next step toward understanding of the mysteries of the structure of nucleons.