Fermilab

COLLIDING BEAMS AT FERMILAB

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It is a pleasure to participate in this timely workshop at the Lawrence Berkeley Laboratory on cooling antiprotons. In discussing "Colliding Beams at Fermilab," I will take a glance backwards and then a glance forward, trying to avoid our present work for that is to be discussed by my colleagues in following talks.

It is interesting that even in the Berkeley 200 BeV Design Study of 1965 it was envisaged that antiprotons could be produced in nucleonic collisions, stored in the Booster, injected into the Main Ring, and then accelerated simultaneously with protons in a manner surprisingly similar to our presently planned method. Storage rings were also envisaged in the Berkeley report and this led to a criterion that the site of the accelerator should be large enough to contain such rings in addition to the accelerator.

During the Summer Study of 1967 at Oak Brook, Illinois, when the National Accelerator Laboratory synchrotron was being designed, various possibilities for storage rings at NAL were also discussed as options for the future. Ernest Courant was especially interested in "By-Passes," both inside the Main Ring and outside, and considerations of this, as well as of more conventional storage rings, appear in the NAL Design Report of 1967 that resulted from the Summer Study.

In 1968, the question of storage rings at NAL was raised by the Atomic Energy Commission. The Board of Trustees of the Universities Research Association asked us at NAL to design a specific set of storage rings. Although our all-too-small group had quite enough to do at that time, Lee Teng took on the assignment and a number of physicists, including the present LBL Director, came from other laboratories to help. They designed a set of conventional rings that would provide 100-GeV protons in collision with 100-GeV protons at good luminosity (see their design report of 1968). They also worked out an alternative design using superconducting magnets which would reach 200 GeV on 200 GeV.

It seemed that in 1968, just as in 1967 when we had considered the practicality of using superconducting magnets for the Main Ring, the art of superconductivity had not advanced to a stage where one could responsibily risk large sums of money on it. The "frozen-in" fields were much too large, almost of the order of kilogauss, and did not repeat in strength from pulse to pulse or magnet to magnet.

Our next formal involvement with colliding rings resulted from my request in the Spring of 1973 that a representative group of physicists serve as a NAL Long Range Physics Advisory Committee. At that time we were about to proceed to build an "Electron Target" under the direction of Tom Collins.[1] This had been invented during the Summer Study at Aspen, Colorado in 1973 and was to use the old Cambridge Electron Accelerator as an electron storage ring to be built tangent to the Main Ring so that collisions between circulating 3 to 4 GeV electrons against countercirculating 100 to 400 GeV protons in the Main Ring could be made to occur at luminosities up to about 10^{32} cm^{-2} sec^{-1}. Although we had acquired the electron linac injector and magnets of the CEA, the Long Range Physics Advisory Committee advised against this project because the energy available in the collisions seemed to them to be too low. They recommended instead, on the basis of the Summer Study of 1973, that we design POPAE (acronym for Protons On Protons And Electrons), a project to build two 1000 GeV storage rings to make 1000 GeV/1000 GeV colliding proton beams possible, and also to build a third electron storage ring so as to make 20 GeV/1000 GeV electron-proton collisions possible. We followed that advice; first in a preliminary study by Collins and Edwards,[2] and then later on in a collaboration between physicists at Fermilab and Argonne National Laboratory led by R. Diebold.[3]

In retrospect, I am not altogether sure that the committee's advice against building the "Electron Target" was sound. The electron target could well have led to an unfolding program of beautiful colliding beam physics. The POPAE project, although valid scientifically, turned out to be a political fiasco. In several HEPAP "Woods Hole Panel" meetings, it lost out to the ISABELLE project despite what seemed to me (very objectively, no doubt!) to be the technological and economic superiority of POPAE. In any case, the maintenance of three strong centers of high energy physics became national policy, and the construction of the ISABELLE colliding beam project at the Brookhaven National Laboratory became of overwhelming importance in the realization of that goal.

Let me back up a bit to 1971, at which time the so-called Energy Doubler project to build a second ring of superconducting magnets within the Main Ring tunnel was first put forward at Fermilab.[4] We had then essentially built the 200 GeV accelerator and experimental areas, and still had a surplus of funds left over from the initial $250 million for that construction. A ring of superconducting magnets in which 1000 GeV protons could be accelerated seemed to be one way to use up that surplus and to respond to the original challenge of the Joint Committee on Atomic Energy to produce the highest energy possible. Indeed such a possibility had been allowed for in the original design, for space had been kept free both above and below the conventional magnets of the Main Ring for the placement of such superconducting magnets. Those early plans were seriously set back by the crisis in 1972 of bringing the accelerator and the experimental areas into reliable operation. The project was further set back in 1976 when much of the remaining surplus construction funds identified for the Energy Doubler were preemptively withdrawn by the AEC.

Nevertheless the project has persevered and by now reliable, precise, economical, high-field magnets have been successfully developed. Indeed these superconducting magnets are now being installed in the Main Ring tunnel below the conventional magnets as rapidly as the funding of the project allows. If adequate funds are forthcoming, the installation of a full ring of about a thousand superconducting magnets can be anticipated in 1980.

Given the two congruent rings in the Main Ring tunnel, the idea of bringing beams in each of them into collision surfaced frequently. Dick Carrigan (NAL, FN-233) was the first to put something in writing by his suggestions in 1971 to build two superconducting rings in the tunnel. In 1975 the aperture of the superconducting magnets was increased from an elliptical opening 1-3/4 in. high by 2-1/2 in. wide to a circular opening 3 in. in diameter specifically after a study had been made by Teng which indicated that such an aperture would be adequate for the use of the superconducting magnet ring as a storage ring as well as an accelerator, and hence could be used with the Main Ring as a colliding beam facility. Of course, that decision also increased the cost of the magnets.

The next development was the revival of an old scheme to have a low energy ring in the Main Ring tunnel, the Accumulator, [5] and then to bring the beam of low energy protons stored within it into collision with high energy protons stored in the Main Ring. This eventually developed into a more refined proposal[6] to build an independent small 25 GeV Accelerator/Storage Ring, the SSR (Small Storage Ring) at straight Section E of the Main Ring. By bringing the 25 GeV protons into collision with the 400 protons of the Main Ring, a c. m. energy of about 200 GeV could have been obtained with a luminosity of about 10^{31} $cm^{-2}sec^{-1}$.

A little later, a number of suggestions came in from outside the laboratory for various forms of clashing beams. For example, in July, 1975, Carlo Rubbia suggested in a letter that good luminosity might be obtained by colliding the proton beam in the Doubler against the proton beam in the Main Ring, and in August of that year B. Richter and D. Cline made a similar suggestion.

The subject of colliding beams was in the air, so a Fermilab Workshop, [7] under the direction of Alvin Tollestrup, was called at Fermilab for January, 1976. The results of a "stochastic cooling" experiment in the ISR at CERN as well as Budker's results on "electron cooling" were also reported at the Workshop, and the implication of cooling on the production of circulating beams of antiprotons intense enough for studying $\bar{p}p$ collisions was briefly discussed. The Workshop had one immediate effect; it eventually led a group of physicists formally to propose an experiment in which 1000 GeV protons in the Energy Doubler were to be brought into collision with protons in the Main Ring. [8]

Shortly after the Workshop, C. Rubbia and D. Cline[9] came up with an enthusiastically worked out ingenious proposal for studying colliding beams of antiprotons against protons in one ring. They proposed to utilize both "electron cooling" and "stochastic cooling" of antiprotons using a complicated combination of the Main Ring, the Booster and a separate cooling ring. Anticipating luminosities of about 10^{28} cm^{-2} sec^{-1}, they pushed the idea with typical elan. It too was put forward in the form of a formal experimental proposal.

Competition between the proponents of the three approaches to modest colliding beams became rather intense, and the air was cleared only when the PAC, during their meeting of June, 1976, recommended rejection of all colliding beam proposals. [10] At the same time, the PAC recommended that the laboratory continue the development of facilities which would provide for either high energy p-p or $\bar{p}p$ collisions, or for both. We have been proceeding along those lines, and this Workshop is expected to be an important step along that path.

My colleagues will soon discuss the work currently underway, so now let me turn to some future possibilities for colliding beams at Fermilab.

A principal difficulty with the Main Ring and the Doubler for colliding beam experiments is the interference that would be caused with the regular fixed target experiments. Building "Bypasses" could be useful in decoupling colliding beam facilities from the accelerator and would considerably extend the experimental space available for such facilities. I will not dwell here on the many possibilities for Bypasses, or on the construction of a separate Inner Ring which would almost completely separate the colliding beam experiments from the Tevatron fixed-target experiments as well as to allow for higher luminosities, higher energy (up to 3 GeV c. m.), and for extensive experimental space - all at modest cost. [11, 12]

Instead let me look at a grander possibility for future colliding beams at Fermilab, the Pentevac. One of my first efforts on becoming Director of NAL was to have the form of the Site changed from an elongated rectangle to its present shape so that a larger ring might eventually be inscribed within its boundaries. This ring, shown in the diagram, has an average radius of 2.5 km. Installing our presently developed supermagnets to make a magnet ring in that tunnel would allow for the production of about 2.5 TeV, or, if the ring were used as a storage ring for proton and countercirculating antiprotons, then a c. m. energy of about 5 TeV might be reached in $\bar{p}p$ collisions.

However, we do not anticipate that such a large ring will be constructed in the immediate future, so we must ask what magnetic fields might be attainable at the time, say five or ten years from now, that such a ring might conceivably be started. Although by the use of new materials there is no obvious reason not eventually to reach fields of the order of hundreds of kilogauss, I suggest that a factor of two, i. e., 85 kilogauss, is nearly within the state of the art right now. In that case 5 TeV protons could be produced, hence the name Pentevac, and 10 TeV c. m. might be attained in $\bar{p}p$ collisions!

The present limitation of the field in the Energy Doubler magnets is imposed by three factors: (a) the current density that can be reached using the present superconductor, NbTi; (b) the mechanical distortion caused by the tremendous magnetic force on the conductors; and (c) the benign disposition after a quench of the large amount of magnetic energy intrinsically stored in each magnet in a manner such that the conductor is not melted. The forces and the stored energy would quadruple in present Doubler magnets, of course, were the magnetic field to be doubled by simply doubling the current density, if that were possible.

The second diagram shows in cross section a possible design of a supermagnet for the Pentevac which might reach 85 kg and which is based on the present Doubler magnet design. Instead of NbTi, Nb_3Sn would be used as the superconductor, for it will reach the required current density at the required field. It has the advantage of reaching these specifications at a somewhat higher temperature (10-15°K) than the temperature (4-5°K) characteristic of NbTi. The present difficulty with Nb_3Sn is that practical conductors made of it are not ductile enough so that sharp bends in the coils can be made without destroying the superconducting property of the wire. Perhaps by making the filaments of superconductor even finer than at present, this problem can be solved. However, even at present, a technique exists for producing strands of wire made of bronze in which fine filaments of Nb have been imbedded. This material is ductile, so that the coils can be prewound in the appropriate shape. Then if the temperature of the material is raised to about 750° C, the tin component of the bronze will migrate and interact with the Nb to form Nb_3Sn. The coils could then be insulated and installed within the restraining stainless steel collars. The present coil structure of NbTi and insulator tends to be somewhat "squishy"; indeed it might not take a four-fold increase in the forces without collapsing. However, loading the epoxy heavily with alumina powder makes a much stiffer material than the present "B-stage" glass fiber now in use. Magnets made using this material have given some indication of being successful. Sprayed-on glass might also be a good insulator for use with Nb_3Sn and one which might withstand the heat conditioning.

The aperture of the magnet shown in the diagram has been made in an elliptical shape 2-1/2" wide by 1-3/4" high instead of the 3 in. OD circular shape in order to reduce the total force on the conductors and to reduce the stored energy. The reduction in the aperture should be possible because the injected beam of, say, 300-1000 GeV protons, would be considerably smaller and stiffer than the beam of about 100 GeV protons which are to be injected into the Tevatron.

The 3 in. ID circular aperture of the Doubler magnets was chosen partly for the practical reason that a lathe could be used in the fabrication of the precision tooling, and partly to allow for vertical as well as horizontal injection and ejection of the beam. A new technique has been developed for making very accurate laminated tooling out of punchings, hence any shape should be feasible. The reduction of vertical height to 1-3/4 in. need not be crucial for beam transfer.

The energy stored in the magnetic field must be rapidly disposed in the event of an accidental quench. There is great danger that the superconducting cable will melt at the point where it becomes a normal conductor. The stored energy in the present Doubler magnets, 0.5 megajoule per magnet, is absorbed in the coil of the magnet in the event that it goes normal. It is important that the whole coil be driven normal by means of a heater wire once a quench is detected. This can still be expected to work even for the higher field design, partly because the stored energy has been reduced by a factor of nearly two by just making the aperture smaller, and partly because the coil is inherently capable of absorbing more energy. A second design using a "pancake" coil winding is also indicated. The cable and hence the current, is four times larger than in the previous example. The distribution of the conductor is a closer approximation to that desired for a uniform field, hence the accuracy of the field should be better. H. Edwards and J. Walton have successfully built a NiTi super magnet of similar geometry but in which the cable is smaller rather than larger than the Doubler cable.

An extremely serious problem has to do with the inherent kinetic energy of the 5 TeV protons - 8 ergs apiece! If the magnets are similar to Doubler magnets in quenching because of being struck by protons, then about 10^8 protons might cause a quench. The magnitude of this problem, as well as the usefulness of the Pentevac, will depend then on the magnitude of the proton current that is to be stored in the ring. A typical cycle of the Pentevac might consist of a 10 second dwell-time at a field of about 5 kG during which three pulses of 300 GeV protons could be injected to fill the Pentevac; then the magnetic field might be ramped up to 85 kG in an appropriate tiem. The ramping time might be a few minutes, if the Pentevac were to be used as a storage ring, or it might be as short as 10 or 20 seconds, were the Pentevac to be used as a fixed target accelerator. Any length of flat-top could be used, and then the magnet could be ramped down in about 20 seconds.

Even with our present intensity of about 3×10^{13} protons per pulse, an intensity of as much as 10^{14} protons per pulse might be possible in principle, but in that case the total kinetic energy of the protons would be about 100 megajoules. Such a beam would evaporate anything solid with which it came into contact. Even a small fraction, say 10^{-6}, of that beam would drive any superconductor into normalcy. This doesn't mean that the problem of containing such a beam and of benignly aborting it in an emergency is impossible, but it does indicate the seriousness of the problem.

This is not the place to remark about the use of the Tevatron for fixed-target experiments. As the figure shows, if the beam could be extracted, it could be transported to experimental areas as much as 4 km in length, if the transporting magnets were to have a 10-20% greater magnetic field. The Pentevac should make an ideal colliding beam facility if the energy deposition problem can be solved. If beams on antiprotons can be stored in the Tevatron with adequate intensity for $\bar{p}p$ colliding beam experiments at 2 TeV c. m., then those beams could be easily transferred to the Pentevac with the same peripheral density and then accelerated to 5 TeV each. The beams will be automatically narrowed during the acceleration so the luminosity should increase by about an order of magnitude. It is interesting that at this energy, synchrotron radiation emitted by the protons is significant, and will "cool" the size of the beam down by another order of magnitude.

I will leave it as an exercise for the student to work out how to make pp collisions, how to get dys-Pepsia with a 100 GeV electron storage ring in the same tunnel, and then how to collide 100-GeV electrons with 5-GeV protons. The future for Fermilab is frighteningly fantastic!

References

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[11] R. R. Wilson, A Bypass and Inner Ring at Fermilab, 1977 Fermilab Summer Study report, Vol. 2, p. 379.

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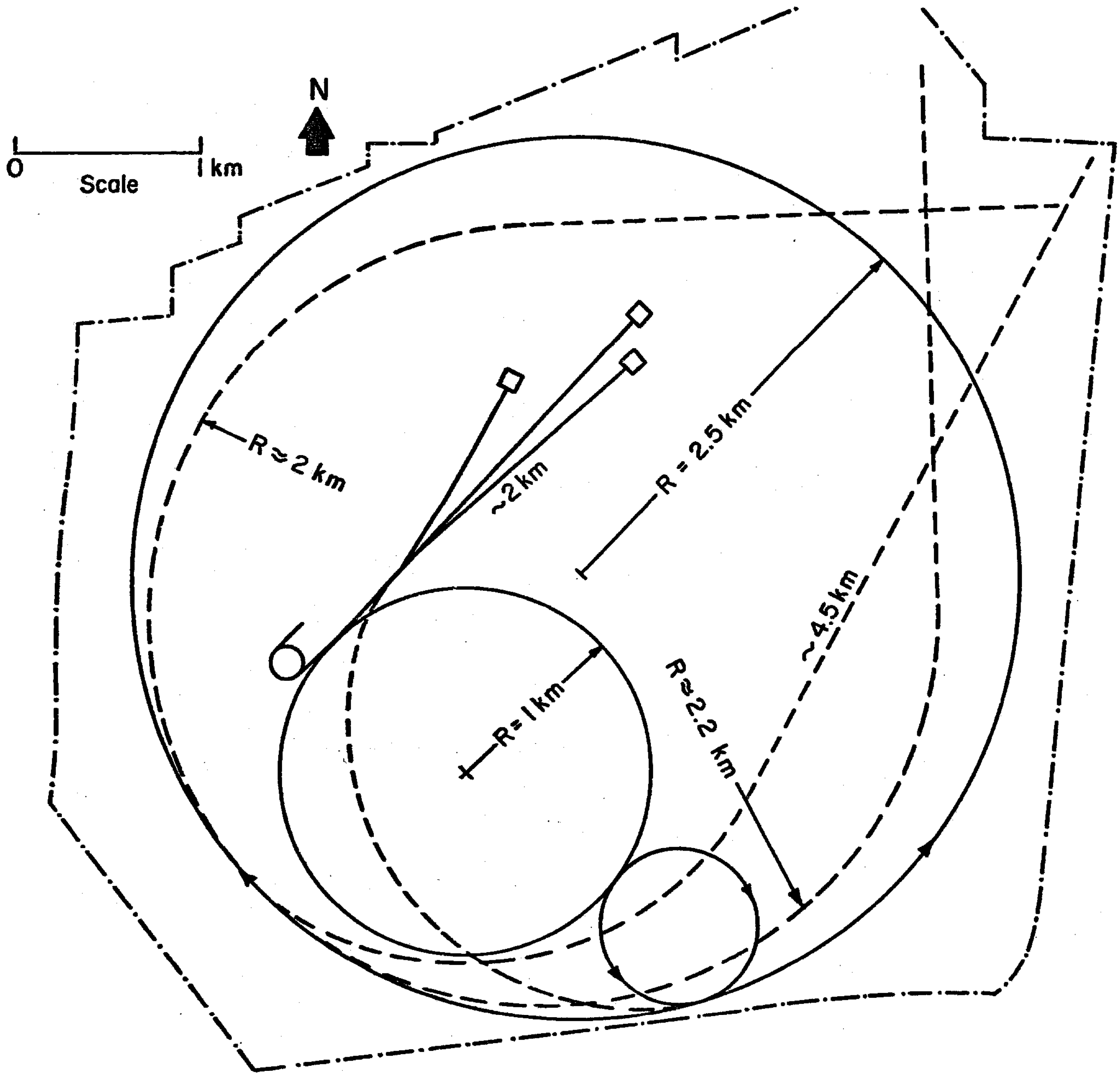
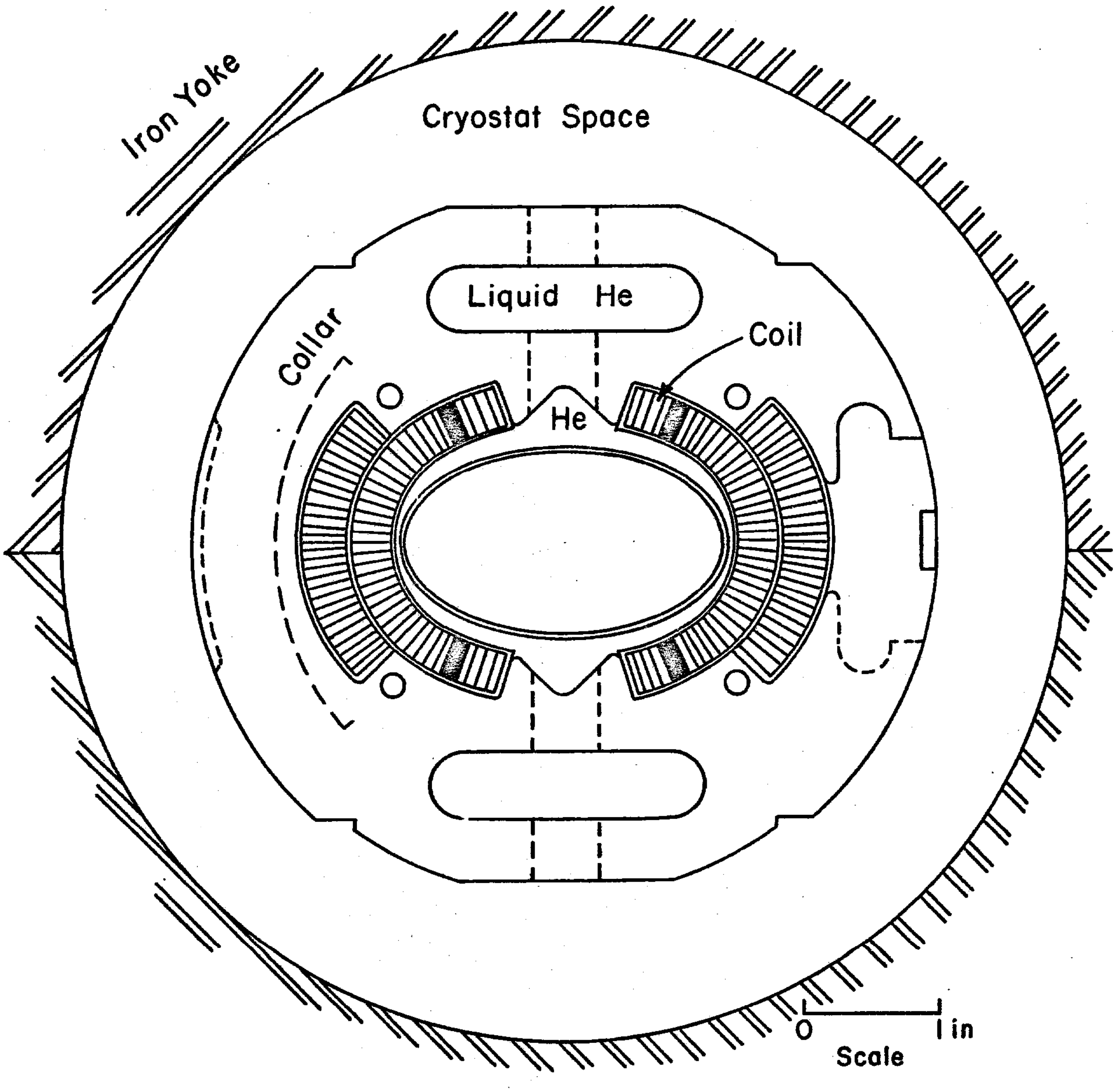


Fig. 1. The Fermilab site with a ring 2. 5 Km in radius inscribed and with possible external beam lines indicated.



Radial Coil

Fig. 2a. A possible design of an 85 KG Doubler-like super magnet with an elliptical magnet opening of 2 1/2" × 1 3/4". It would fit with a standard doubler cryostat. The conductor cable would be made of Nb, Sn cable 0.050" × 0.300".

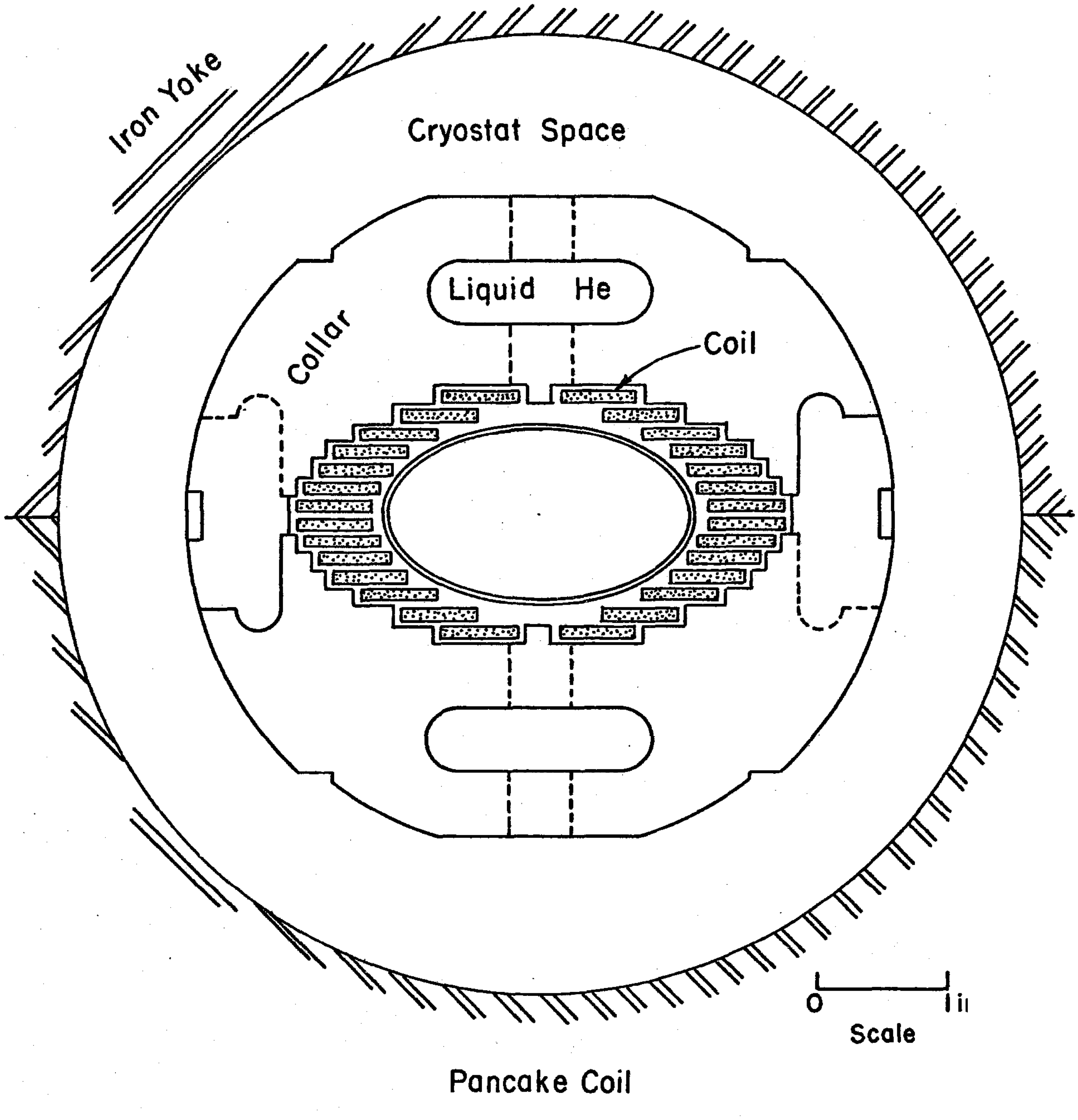


Fig. 2b. A possible design of a high-current "pancake" coil winding for a 85 KG super magnet made 14 turns of Nb_3Sn cable 0.100 × 0.600. The magnet would fit within a standard doubler cryostat.