THE PENTEVAC: A SITE-FILLING ACCELERATOR AT FERMILAB

R. R. Wilson

The Fermilab site is large and one might ask, "What is the largest accelerator that can be built within its confines?". The ring shown in Figure 1 has a radius of 2.5 km, and, although a slightly larger circle would also fit, it is well to stay some distance away from the site boundaries. The rigid off-site radiation limitation, whether it be due to muons or neutrons presents a serious problem. Starting with a tunnel 2.5 km in radius, we can ask what might go into the tunnel. Rather than putting three magnet rings in the tunnel so we could attempt every possibility at once, we might instead imagine a scenario in which we would install only one or two rings at a time, ringing the changes in a manner most likely to develop the information about particles that we most want, and thereby drawing out a view of nature as a novelist draws out his story, for the maximum satisfaction of his reader - or in this case, for a maximum amount of insights about the physical world within the limitation of available funding.

(a) 5 TeV Protons on Fixed Targets

Let us consider first the accelerator as a source of protons to be incident on fixed targets. Because it will not be built in the immediate future, we must ask what magnetic field that we can anticipate might be attainable in the magnets at the time, say ten years from now, when such a large accelerator might 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, beyond the field of 42.5 kG which obtains in the Tevatron, i.e., to 85 kG is nearly within the state of the art right now. In that case 5 TeV protons could be produced, hence the name Pentevac.

The present limitation of the field in the Tevatron magnets is imposed primarily 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 removal of the large amount of magnetic energy intrinsically stored in each magnet without melting the conductor. Doubling the magnetic field in the present Tevatron magnets by simply doubling the current density, were that possible, would quadruple the forces and the stored energy.

Fig. 2 shows in cross section a suggested design of a dipole supermagnet for the Pentevac which might reach 85 kG; it is based on the present Tevatron magnet design. Instead of NbTi, Nb_3Sn would be used as superconductor, for it will reach the required current density at the required field strength. 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. Although this problem may be solved, for example, by making the filaments of the superconductor much finer than at present, there is even at present a technique for fabricating the coil. Bronze is used as the matrix material in which fine filaments of pure Nb have been imbedded. This material is ductile so that coils made of it can be wound 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 must then be insulated after having been formed and heat-treated and then installed within the stainless steel collars. The present coil structure of NbTi and insulator tends to be "squishy," and might not withstand a quadrupoling of the force without collapsing. However, loading the epoxy heavily with alumina makes a much stiffer material than the present epoxy-fiberglass (B-stage) material now in use, and there is some empirical evidence that the alumina-loaded material is satisfactory. Sprayed-on glass might also be a good insulator for use with Nb_3Sn, and one which might withstand the heat conditioning. The cable is shown to be much larger than in the Tevatron magnets, in order to reduce the number of turns and thereby also reduce the voltage on the coil during ramping and quenching, and also reduce the work of insulating the turns.

The free opening in the coil shown in the design is roughly elliptical in shape, 2-1/2" wide by 2" high; it is smaller than the opening of the Tevatron magnets, which is circular in shape and 3" in diameter. The smaller opening should reduce the stored energy for a given value of the magnetic field by nearly a factor of two and the total force on the conductors should also be reduced accordingly. The "good" magnetic field aperture as indicated by the calculations of S. Snowdon is about 0.75 inches wide instead of being about 1 inch wide as in the Tevatron magnets. The reduction in aperture should be possible because the size of the injected beam of 300-1000 GeV protons would be somewhat smaller and stiffer than the beam of about 100 GeV protons which are to be injected into the Tevatron. A stronger lattice might also be used to reduce the size of the beam.

The energy stored in the magnetic field, about 1 megajoule per magnet assuming the same length as for Tevatron magnets,* must be rapidly disposed of in the event of an accidental quench in order to prevent the superconducting cable from melting. The stored energy in the present Tevatron magnets, 0.5 MJ per magnet, is absorbed in the coil when it goes normal. It is important that the whole coil be driven normal by means of a heater once a quench is detected. This method can still be expected to work even for the high field design because the coil is still capable of absorbing about twice as much energy without melting or burning the insulation.

As shown in Fig. 1 protons can be transferred from the Main Ring or the Tevatron to the Pentevac through an intermediate ring of average radius 0.5 km. A different possibility not shown, would be to build an external bypass on the Main Ring so as to

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* It is suggested that the magnets be made about 25 M in length rather than the 7M of the present Doubler magnets.

be tangent to the Pentevac ring at one of its straight sections.

A typical cycle might require 60 seconds: it would be comprised of a 10 second dwell-time at low field while three pulses of 300 GeV protons from the Main Ring were successively injected to fill the Pentevac ring head-to-tail fashion, then a 15 second ramping-period to full field, then a flattop of any length but let's say 20 seconds, after which the cycle ends with a 15 second ramp back to injection field. By using tricks such as stacking multiple turns in the Tevatron and then transferring these to the Pentevac, the injection time could be reduced to a few milliseconds, and then by using a faster rise time for the magnets, the total pulse time of the Pentevac, apart from the flattop, might be reduced to about twenty seconds, i.e., comparable to the present pulse time for Main Ring operation at 400 GeV. If we assume that each injected pulse from the Main Ring would contain 3 x 10^{13} protons, the total pulse intensity of the Pentevac would be about 10^{14} protons. When these have been accelerated to 5 TeV, the total beam energy would be a frightening 100 megajoules per pulse. Clearly should a pulse get out of control it could destroy many of the supermagnets. The experience with the present one megajoule level of beam energy is that seldom does the beam get out of control, and, although what is now called "out of control" would correspond in the 5 TeV case to an inadvertent loss of only about one percent of the beam, my judgment is that the beam abort system could be tightened up enough to abort the beam reliably before a dangerous beam loss could occur. Even a smaller loss, as little as about 10^{-6} in one magnet, may be enough to quench the supermagnet. This does not mean that the problem of containing a large beam of protons is impossible, but it does mean that new techniques of sensing a small abnormal growth of the beam would be necessary. Tuning the machine would necessarily become a much more sophisticated exercise than it now is - but not an impossible one.

Beam extraction and targeting are the really serious problems. One solution it to limit the intensity of the beam to levels for which solutions have already been found, and then, as new techniques are developed, slowly to raise the beam intensity. For short flattops, this would mean reducing the envisaged intensity by a factor of about 100. For longer flattops, the rate of energy deposition would be reduced, and thermal cooling could then occur, however, radiation damage and induced radioactivity would still be important. The solution to the problem of extraction lies in increasing the efficiency of extraction. One measure to help increase the efficiency of the extraction process would be to make an insertion of large-aperture magnets in the vicinity of the extractor. These could be arranged in a lattice insertion that would locally increase the betatron oscillation amplitude which would help the extraction process. The large aperture would also decrease the interception by local magnets of the beam lost in the extraction process and thereby allow the radiation to be intercepted by an inert shield,or at lower density in the following magnet structure. The downstream magnets in which the greatest loss can be expected to occur could be of conventional design, and hence capable of absorbing much greater radiation. They would constitute a form of magnetic beam scrapers and apertures.

Increasing the targeting capability is difficult but more straightforward. Both the thermal energy and the radioactivity deposited would be ten times greater per proton than is presently the case, but present techniques can very likely be extended by that factor - although with considerable difficulty.

Without having to confront problems of beam extraction, an internal target area could be built in the Pentevac so that the kinds of experiments which have been done in the Main-Ring internal-target area could be extended to the new energies - but a less-dense gaseous target would have to be used to minimize beam loss in the magnets just downstream from the target.

Assuming that the extraction and targeting problems can be solved, what about the external proton beam and its experimental areas. There are numerous possibilities. Several tangents can be drawn to the ring having lengths to the site boundary of between 2 and 3 km, as can be seen in Fig. 1. For comparison, the present distance from the Main-Ring extraction point to the 15' bubble chamber is about 2 km. By extracting the proton beam inward instead of outward and by bending it as shown in Fig. 1 with a 20% stronger magnetic field than exists in the bending magnets of the Pentevac, then a 4 km-long straight beam line can be drawn to the site boundary. The proton beam would be pointed downward at a slight angle so as to direct muons into the earth. Alternatively, by bending the beam radially inward with a short radius, about 2/3 of that in the Pentevac, the 5 TeV protons could be brought into the present switchyard where, with stronger magnets, the protons might be led to the present experimental areas where some of the present experiments could be repeated at a higher energy, but probably not at the fuel energy. It appears that the distances available on the site are large enough to do almost any experiment presently envisaged for 5 TeV protons or their secondary particles. It is interesting to note that a 5 TeV muon has an average range in earth of 2-3 km. At these energies the stopping power is dominated by the radiation of photons and electron pair production rather than by ionization loss, and the range is given by $R = \log (E + 1)$, where R is measured in muon interaction lengths and E, the muon energy, is measured in critical energy units given by $E_{TeV}/35$. The tunnel must be placed at a low enough level so that the muons produced by an inadvertent loss of protons will remain well below the deepest inhabited level. This requirement suggests that the plane of the tunnel should not be absolutely level, but rather should tilt slightly to correspond to the average tilt of the ground around the site. There may be some economic advantage to be gained by having the accelerator follow the average contour of the surface so that it is not in a plane at all. There are small chromatic effects introduced by this procedure but these might be compensated by a careful choice of the contour.

It appears from the above discussion that eventually 5 TeV protons might be produced in copious amounts at Fermilab and that the site is large enough for the fixed target experiments which can presently be envisaged. With regard to the experimental areas and the experiments that could be made in them, almost everything that was said about the Tevatron in extrapolating from 0.4 to 1 TeV could be further extrapolated in the same way to 5 TeV. The nature of the physics, of course, cannot be foreseen or there would be small reason to build the Pentevac.

A rough estimate of the cost, assuming one pulse per minute and an intensity of 10^{14} protons per pulse, might be about $500 million in 1980 dollars. Of this, $100 million might be identified for conventional facilities connected with the accelerator, $200 million might be identified for the accelerator components, i.e., magnets, extraction, etc., and $200 million might be identified for the experimental areas. For a rough comparison, the Main Ring in 1970 cost about $75 million and the present experimental areas cost about $50 million. Multiplying the Main Ring cost by 2.5 and adding $100 million to provide for roughly the same amount of experimental areas gives $287 million in 1970 dollars. When a factor of 1.8 is allowed for inflation, this comes to about $500 million. My expectation is that the superconducting magnets might be less costly and that the conventional facilities might be constructed at somewhat less cost because of the magnitude of the job. In summary, it should be possible to construct the Pentevac to firm beam in about three years after it is funded and for a cost of less than $500 million - and with the creative imagination of younger designers, for considerably less.

(b) 5 TeV Antiprotons on 5 TeV Protons

By the time the Pentevac in constructed, we can assume that techniques for cooling antiprotons will have been developed and will have been used for colliding beam experiments in the Tevatron. These beams could be transferred directly to the Pentevac ring for slow acceleration to 5 TeV each. Thus we can contemplate the exciting prospect of reaching a center-of-mass energy of 10 TeV in colliding beam experiments in the Pentevac. There would be space galore about the 15 km peripheral length of the Pentevac tunnel in which to design and install colliding beam experimental areas. It is too soon to estimate the luminosity, but presumably it will be somewhat greater than values presently projected for $\bar{p}p$ collisions in the Tevatron, i.e., $\sim 10^{32}$ cm^{-2} sec^{-1}.

The Pentevac magnet ring becomes ready for beam collision studies as its first phase of operation, because at that stage, just as with the Tevatron, it is not necessary to solve the problems of extraction, of beam targeting, and of fast acceleration. Thus studying $\bar{p}p$ collisions in the Pentevac becomes a particularly attractive possibility, particularly if such studies have already been feasible in the Tevatron, because the problems of antiproton production would have been solved, and because there would be little interference with the Tevatron or the Inner-Ring experimental programs.

If it should turn out for some unexpected reason that the cooling of antiprotons is more difficult than is now anticipated and we have not realized high luminosity beams of antiprotons in the Tevatron, then a fall-back position would be to consider collision studies between the 5 TeV protons of the Pentevac with the 1 TeV protons of the Tevatron in an external bypass which might have been built to load the Pentevac in any case. Alternatively, the transfer ring shown in Fig. 3, could be used as a storage ring for 1 TeV protons (85 kG) which could be collided against the 5 TeV protons - both schemes giving about 4 GeV in the center of mass.

Whether to go on and build a second proton storage ring in the Pentevac tunnel should depend on the experimental results forthcoming from one of the above programs, a factor of about two in c.m. energy would result from having 5 TeV upon 5 TeV in collisions rather than 5 TeV upon 1 TeV.

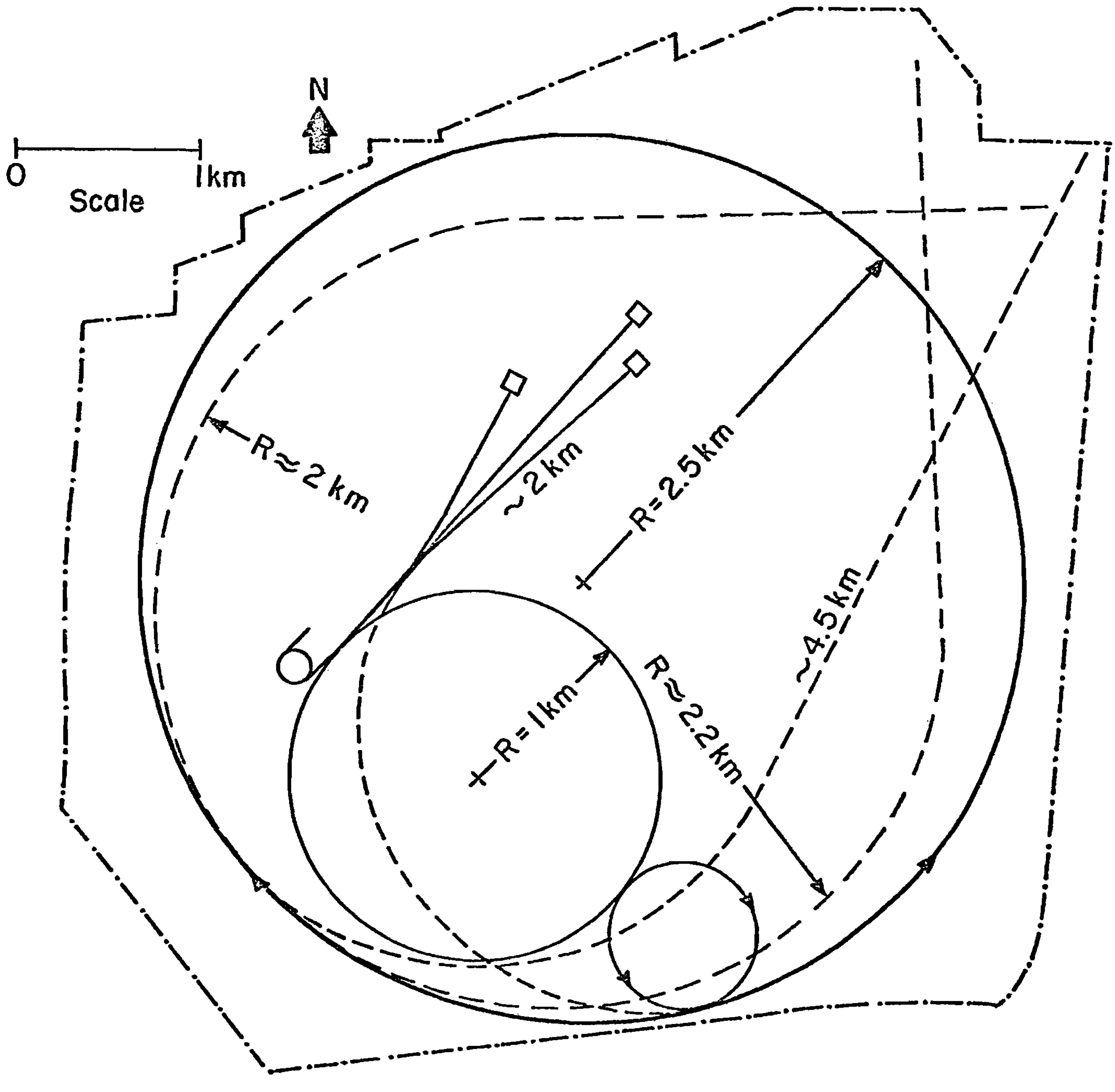

Fig. 1. The Fermilab site with a ring 2.5 Km in radius inscribed and with possible external beam lines indicated.

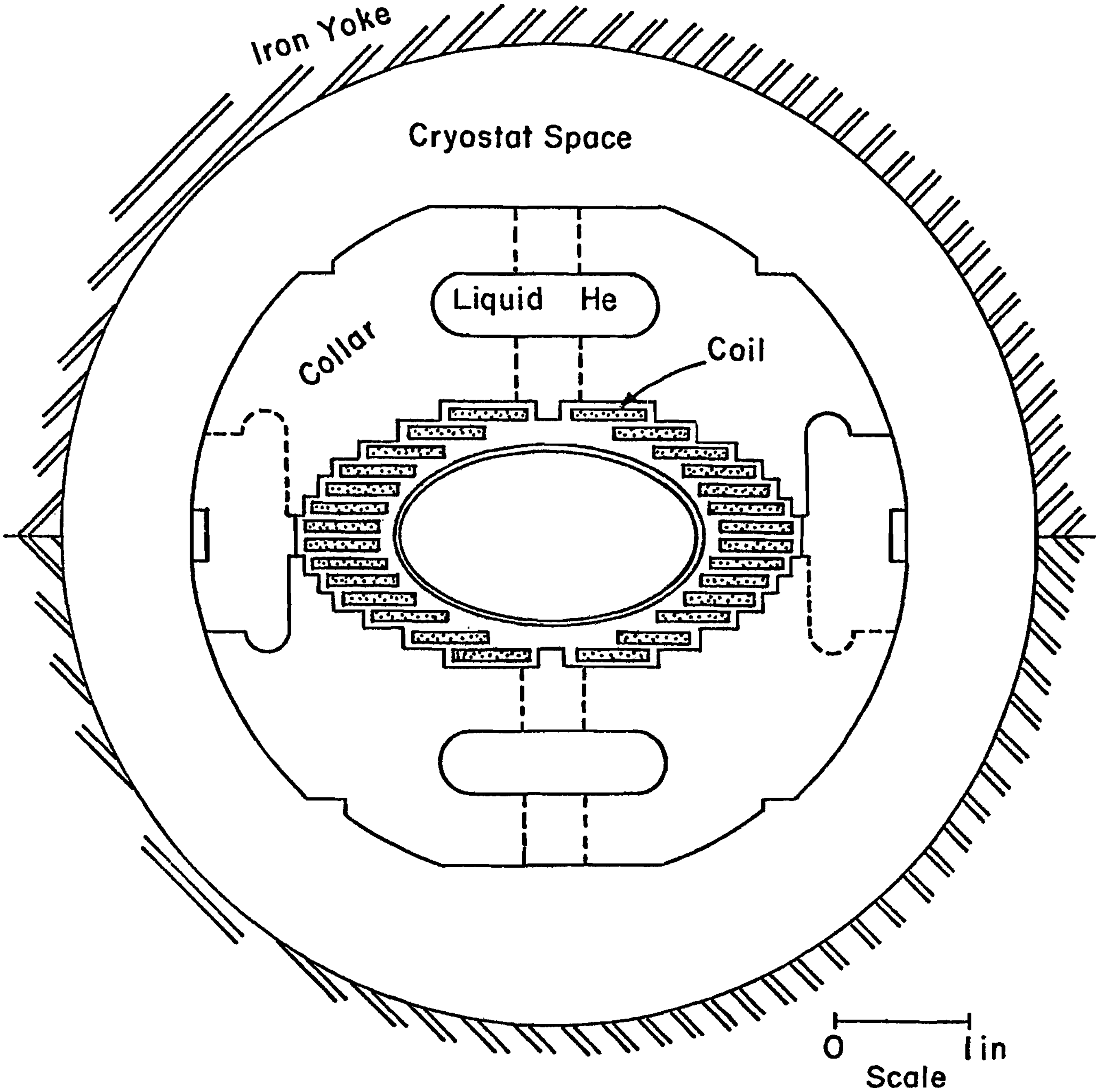

Fig 2. A possible design for an 85 kG magnet for the Pentevac.