The Tevatron

With a ring of superconducting magnets the Fermilab accelerator will double its proton energy and reduce its electrical power consumption, and will offer the opportunity for colliding-beam experiments.

Robert R. Wilson

Superconductivity is a magic potion, an elixir to rejuvenate old accelerators and open new vistas for the future. The property of zero resistance to the flow of electrical current will allow us at Fermilab to double the energy of the proton accelerator from 500 to 1000 GeV, will make possible colliding-beam experiments with center-of-mass energies up to 2000 GeV, will quite possibly lead to the discovery of the intermediate vector bosons, will save millions of dollars in our electrical bill—and all this at modest cost. The magic of superconductivity need not be confined to accelerators; it may be a key factor in conserving our dwindling energy resources when similarly applied to the production and transmission of electrical power.

A new ring of superconducting magnets, the Super Ring, is being constructed at Fermilab and will be installed directly below the conventional main-ring magnets as shown in figure 1. With new techniques, not available when the accelerator was designed in 1967, we have developed a superconducting magnet that is economical, that can ramp from a low to a high field in tens of seconds, that has a precision field, that has low cooling requirements, and, best of all, that reaches a field of 45 kilogauss—twice that of the conventional magnets. Nearly one thousand of these magnets must be built and installed below their matching conventional counterparts to make the new four-mile-long Super Ring. The basic superconductor is a strand (0.027-inch diameter) of copper wire in which are imbedded 2100 thin filaments of niobium-titanium alloy (NbTi) with a current-carrying capacity of 250 amperes. We need enough of this wire to go once around the world.

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Our intention is to use the present accelerator[1] as an injector for the Super Ring by reducing its energy from 500 GeV to 100 GeV—the electrical energy used to excite the Main Ring thereby being reduced by a factor of over 100. After the 100-GeV protons have been injected into the Super Ring, its field will be ramped to its maximum value in about 20 seconds, at which time the proton energy should reach 1 TeV. Hence the accelerator with the Super Ring, originally called the Energy Double/Saver, is now known as the "Tevatron" (one TeV, or tera-electron volt, is 10^{12} eV, 1000 GeV, or 1.6 erg!). The average intensity for a one-minute cycling time is expected to be about 10^{12} protons/sec. This cycling time includes a 20-second-long flattop, which could be extended to almost any length, thus increasing the duty cycle of counting-rate-limited experiments by an order of magnitude over the present mode.

It is naturally exciting that we can expect to extend our knowledge of particles and forces by using 1-TeV protons for fixed-target experiments; but even more exciting is the possibility of colliding beams,[2] which will provide a tremendous increase in the center-of-mass energy in nucleon–nucleon collisions—from about 30 to 2000 GeV. James W. Cronin is the head of the colliding-beam-experiments department at Fermilab. Many of the ideas relating to the colliding-beams concept[3,4] derive from suggestions made by Lee C. Teng, Richard A. Carrigan, Carlo Rubbia, David B. Cline and Alvin B. Tollestrup.

The plan is to use both the Main Ring and the Super Ring as storage rings. In one mode of colliding beams, figure 2, we can imagine first filling the Super Ring with protons from the Main Ring and then, after acceleration to 1 TeV, clamping the ring so that the protons circulate continuously. Then we can inject protons into the Main Ring in an opposite direction and accelerate to, say, 250 GeV, at which time that ring too will be clamped. It should then be possible to bring the counter-rotating beams into collision in a few of the straight sections with a luminosity as high as 10^{30} cm^{-2} sec^{-1}. (The counting rate for a reaction is obtained by multiplying the cross section by the luminosity.) There are six straight sections, each 50 meters in length, of which three are used for such things as injection and extraction of the beam, radiofrequency acceleration or beam-abort equipment. We can anticipate using the remaining two or three straight sections for colliding-beam studies. At 250 GeV in the Main Ring, the center-of-mass energy will be about 1 TeV. About fifty percent higher energy can be reached in a pulsed mode, but at the cost of average luminosity. These center-of-mass energies are equivalent to those available when protons of an energy of about one million GeV collide with protons at rest. A synchrotron capable of producing such an energy would encircle the whole United States.

Another mode of colliding beams, in which antiprotons are made to collide with protons at interesting luminosities, has been made possible by the development of "beam cooling" by the late Gersh I. Budker and his colleagues in Novosibirsk in the Soviet Union. Beam cooling means reducing the transverse components of velocity of a beam so that it can all be injected into a synchrotron. The beam-cooling work at Fermilab was initiated by Rubbia, Cline and Peter M. McIntyre. F. Russell Huson is in charge of the Fermilab effort.[5]

In our application antiprotons, pro-

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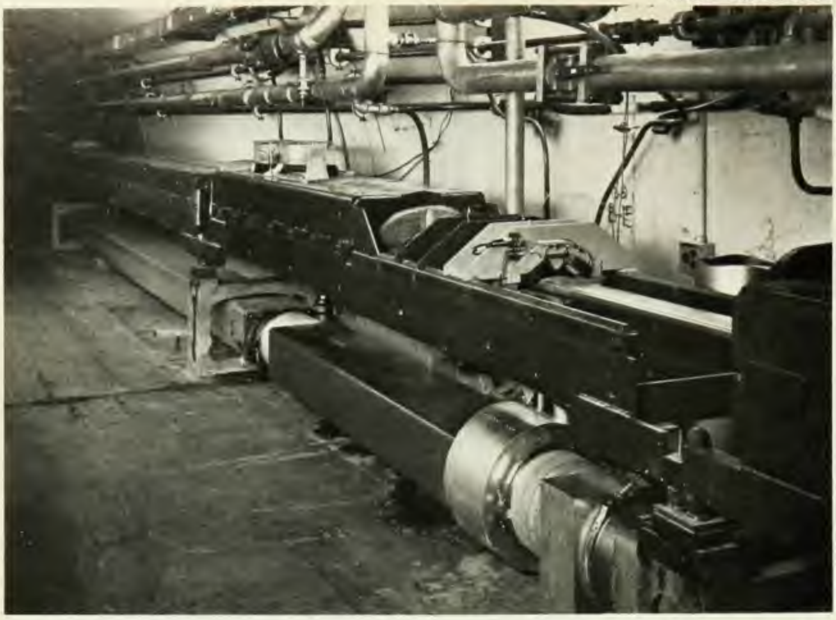


Superconducting magnets mounted directly below the conventional magnets of the Fermilab Main Ring, where extra space was provided for this installation at the time of the original construction around 1971. When the Super Ring is completed the 500-GeV proton accelerator will become the "Tevatron," with its energy increased to 1000 GeV (1 TeV). Figure 1

duced by 100-GeV protons from the Main Ring colliding with a target near the booster accelerator, will be captured in a small storage ring, where they will be cooled and accumulated over many pulses. Then they will be injected into either the Main Ring or the Super Ring and accelerated to any desired energy up to 1 TeV. At the same time protons will be injected in the opposite direction and will simultaneously be accelerated to the same energy as the antiprotons. Collisions between the two counter-rotating beams can then be studied up to 2 TeV (center-of-mass) in the straight sections. It appears that adequate intensities can be obtained for this method to be competitive with, and complementary to, the proton–proton colliding-beam studies.

It is difficult to comment on the cost and schedule of the construction, for so much depends on decisions made elsewhere than at Fermilab. A subpanel of the High-Energy Physics Advisory Panel, the "Woods Hole Committee," recommended \$12.8 million to convert the Super Ring (funded as an R&D project at a cost of about \$40 million) to the Tevatron, and \$10 million in FY 79 for highest-priority projects to begin exploitation of the Tevatron for fixed-target 1-TeV physics. If that recommendation is implemented, we can expect experiments at 1 TeV to start in 1980.

This article reports on the conceptions and the work of a large number of people at Fermilab. It is impossible to give due credit, but let me try; the selected references cited will speak more eloquently for the individuals concerned. William B. Fowler and Philip V. Livdahl[7] have played a major role in the organization of the effort as well as making major technical contributions.

Most important throughout the whole project, from its inception, has been the nurture, care and continued encouragement provided by Edwin L. Goldwasser and Norman F. Ramsey. The work of other important contributors is acknowledged throughout this article.

Superconducting magnets

Applying the art of superconductivity to the construction of accelerator magnets has been an exciting technological adventure at Fermilab. Tollestrup[8] has contributed his physical insights and intuition to the early substantial effort of Paul J. Reardon, Darrell J. Drickey, Donald A. Edwards, Fowler and Livdahl, and is largely responsible for developing the art to its present practical and precise stage. Henry Hinterberger has contributed seminal engineering ideas from the earliest stage of the project; Peter J. Limon[9] has been in charge of testing strings of magnets, and Stanley C. Snowdon[10] has calculated the field strength for various conductor geometries.

When we started this development in 1972, it was quite possible to make dc superconducting magnets—take the 15-ft bubble-chamber magnet, for example. But frozen-in fields and high energy losses due to eddy currents make the application of superconductivity to the ramping field of an accelerator dubious. Furthermore, we did not know if the necessary accuracy of the field (a few parts in 10^4) could be achieved in the supermagnets.

We started out by straightforwardly applying logic and Maxwell's Laws. This attempt only demonstrated the hubris of experimental physicists; there were too many unknown and uncontrollable variables. Our next approach, largely Edisonian, was to build dozens and dozens of supermagnets, each only about one foot long but full scale in cross section. We built on our successes, tried to avoid repeating our failures, and accumulated experience; gradually the magnets improved until by now they are of quite adequate quality for an accelerator or a storage ring. Two rules summarize our experience: Permit little or no motion of the superconductor, and let the helium coolant bathe the superconductor as directly as possible. To this we might add that the superconductor should be as filamented as is practical.

Our goal had been to produce magnets that would reach a field of over 40 kilogauss, and that would have a good field aperture of about 5 cm. They would be 22 feet (7 meters) long, and they would connect together head-to-tail, so that the current and the liquid helium would pass directly from one magnet to the next. They should not destroy themselves in "going normal." The cooling losses and cooling-down time should be minimal, and any iron should be at room temperature and non-saturated. In addition were the requirements that the magnets could be mass produced (we need roughly a thousand of them) at an affordable price and that they could be connected, each one to the next, quickly and reliably. We have met these criteria in the magnet design shown in figure 3 (a and b) and illustrated by the photograph of figure 4.

The superconductor is niobium–titanium alloy, fabricated into Rutherford-style cable. Bruce Strauss[11] has carried the major responsibility for developing this wire, and Ryuji Yamada, Margaret E. Price and Hidehiko Ishimoto have measured[12] its characteristics. The cable is made of 23 strands of basic wire (0.027-in. diameter), which contains 2100 filaments (8-micron dia.) of NbTi imbedded in copper; the amount of copper is about twice that of superconductor. To reduce eddy-current fields and energy losses to a minimum in the rapidly ramping field we desire, the basic wire is twisted with the superconducting filaments spiraling four times per inch. The wires in the cable also spiral, or transpose, at the rate of about once in two inches to reduce ramping losses further.

Although at first we had to fabricate our own wire, now several fiercely competitive fabricators supply us with completely finished cable at a cost of a few dollars per foot. We are presently the largest consumer of superconductor in the world: Of the basic 0.027-in. diameter wire we require some 50 tons (100 million feet) to fabricate the Super Ring.

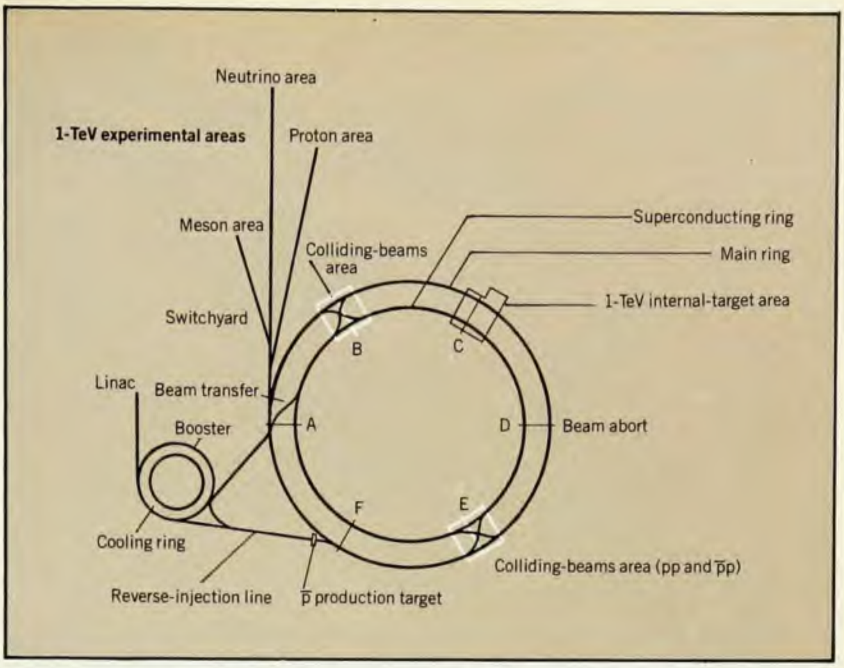
Now let me turn to the fabrication of

magnet coils using the stranded cable. It has long been known that a cosine distribution of ampere-turns is necessary to produce a dipole field (a uniform field) over a cylindrical volume. We approximate that distribution by the two layers of turns in the configuration shown in figure 3a. The resulting field distribution is remarkably precise, considering the simplicity of the construction. Two variables define the coil: the angle subtended by the inner layer, and the angle subtended by the outer layer of turns. Symmetry tells us that the quadrupole, octopole . . . terms are zero; then, by adjusting the two angles, we can make the sextupole and decapole terms zero. It is the nature of the higher poles to be small away from the coil.

The problem is winding the coils so that the relative positions of the cable correspond, to within a few mils, to the ideal uniform distribution of figure 3a. Our simplest and most precise coils have been wound first as flat "pancake" coils, then mashed into the saddle shape that corresponds to the cylindrical shell open at the ends.

Our first magnets "trained" excessively. That term means that while the current was increased in a magnet under test, the coil at some low field (say, 25 kG) would stop being superconducting; that is, it would "go normal" or "quench." On subsequent successive quenches, the current reached would be higher and higher, perhaps because the conductors nestled together better as a result of the large magnetic forces acting upon them, until after about 100 quenches when no further improvement occurred. Fortunately, as we improved the magnets to reach higher ultimate field strength the training became less and less, and in the present magnets only a few quenches are required to reach the designed field strength. Furthermore, once trained a magnet does not need to be retrained after being warmed up.

A particularly serious problem with regard to the 22-ft long supermagnets is getting rid, during a quench, of the electrical energy that is stored in them, about 0.5 megajoule per magnet at 45 kG. In our first tests, a high-field quench would sometimes cause a short circuit to occur between turns of the magnet coil, and sometimes a conductor would melt. The superconducting cable we use is not "stabilized;" that is, the proportion of copper in the wire strands is not enough to take the magnet current continuously without melting should the wire go normal for some reason. What we do is to sense a quench electrically, turn off the power supply, and then extract the energy by an external thyristor circuit that deposits the energy in an external resistor. For simplicity we treat the bending magnets in groups of four, and find that the 2 megajoules of stored electrical energy can be extracted without damage.



In this colliding-beam mode, protons accelerated to 1 TeV circulating in the Super Ring can be brought into collision with protons of, say, 250 GeV circulating in the opposite direction in the Main Ring. This schematic plan represents the two rings for simplicity as concentric and coplanar; see figure 5 for details of possible arrangements in the collision areas. Figure 2

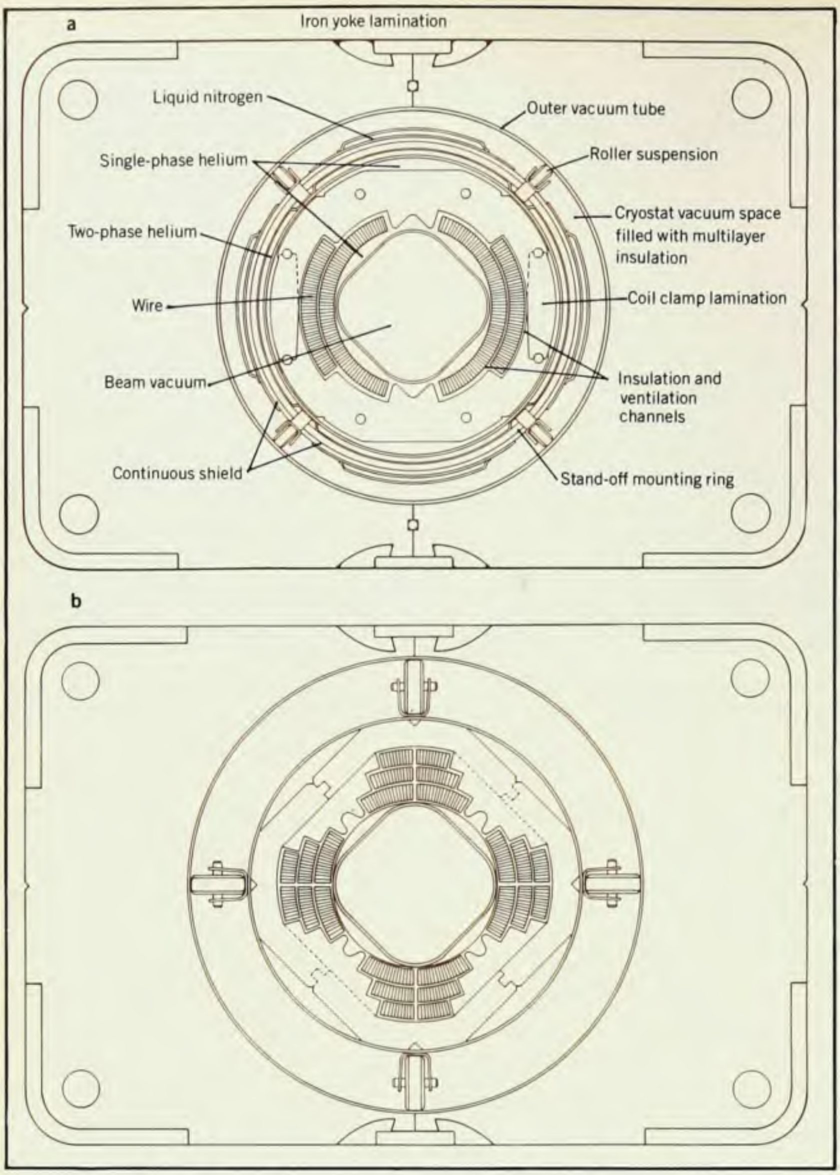
The main problem in extracting the energy rapidly is the high voltage induced across a coil by the rapidly decreasing current. This voltage reaches the kilovolt level, and the coils must be insulated accordingly. The 1-mil-thick wrap of Mylar insulation around the cable appears to be enough to withstand the induced voltage, to prevent turn-to-turn shorts, and yet to allow adequate cooling of the superconducting wire. Each magnet is equipped with a pressure-release valve to vent the helium gas generated during a quench. Quenches do not appear to propagate between magnets.

Conductor motion has been one of the most serious difficulties we have had to solve.[8] To get some idea of the problem, note that the force on a conductor carrying 4600 amperes in a magnetic field of 45 kG is over 100 pounds per linear inch, and the total outward force on the whole coil is over a ton per linear inch. An inelastic motion of the coil through only a few mils generates enough frictional heat to cause a quench in the magnet; an elastic motion of only a few mils can cause the field shape to change with excitation. Now the latter effect could, in principle, be offset by programmed correction coils, but it is desirable to minimize the need for all such corrections.

The solution to this problem has been to preform the coils to a slightly larger size than is eventually desired. In the final assembly, the coils are placed around an accurately machined cylindrical mandrel, and the epoxy-covered stainless-steel collars shown in figure 3a are then assembled around the coils and hydraulically compressed by a force of about 100 tons per foot. At the same time heat is applied to set the epoxy that holds the collars together. Thus the coils are prestressed to a value that will exceed the magnetic stresses that occur upon excitation. Because both the mandrel (which is subsequently cooled and withdrawn) and the collars are made to a precision of better than 0.001 in., the accuracy of the conductor placement and hence of the coil is well determined.

After each magnet has been produced, it is placed on a test stand where its thermal, vacuum and field properties are measured.[13] By such measurements, the whole production process is monitored, and small changes can be made in the tooling and in the collar dimensions to keep the precision within permissible limits. We have made magnets in trial production runs at the rate of one a day. This rate must eventually be quadrupled if the Super Ring is to be constructed, as we expect, in about one year.

After the inner magnet (that is, the coil and its containing collars) has been made, it must be inserted into the cryostat, shown in cross section in figure 3a. George H. Biallas made the detailed designs[14] basing them on the work of Peter C. VanderArend, Fowler and Moyses Kuchnir. The problems we face with the cryostats is to keep thermal losses to a minimum,[15] to keep an adequate flow of the coolant from magnet to magnet as well as to all parts of the magnet, and to do all this at a reasonable cost. At the same time the magnet must be supported firmly, so that transverse motions are not



Superconducting dipole magnet (a) and quadrupole magnet (b) in cross section. About a thousand of these are needed for the Super Ring—774 dipoles, each 7 meters long, and 240 quadrupoles, each 1.35 meters long. The dipoles produce fields of over 40 kilogauss. Figure 3

more than a few mils during excitation or upon cooling from room temperature to that of liquid helium. Because an overall longitudinal shortening of the magnet of $^3/_4$ inch takes place upon cooling to 4.5 K, the thermally insulating supports have been made in the form of rolling wheels.

The cryostat presents a horrendous vacuum problem. It has dozens of complicated welds, and it contains a vast quantity of super-insulation between the liquid-nitrogen-cooled thermal shield and the outer vacuum wall. One leak would be fatal, for once assembled the magnet is essentially inaccessible within the cryostat.

After the cryostat has been assembled around the magnet it is placed within the iron yoke, which is made of laminations that have been stacked and welded into two long halves. The iron enhances the magnetic field due directly to the superconductor by about 15%; it also confines the magnetic field to the close vicinity of the supermagnet. Although the inner magnet and the cryostat have been made straight, the assembly at that stage is quite flexible. The rigid iron core on the other hand has been stacked on a fixture curved to correspond to the beam orbit (the sagitta at 22 feet is about $^1/_4$ inch). The inner magnet in its cryostat adapts easily to this curvature when it is pressed into the half-core. When both half-cores have been welded together around the cryostat the resultant assembly becomes quite stiff.

In addition to the 774 bending magnets needed to guide the protons in a circle, there are 240 quadrupole magnets, each 1.35 meters long, needed to focus the beam within the vacuum tube. The quadrupoles, shown in cross section in figure 3b, use the same conductor and general techniques of construction as do the bending magnets. The geometric aperture of 8 cm diameter is slightly larger than that of the bending magnets, which is 7.5 cm. The quadrupoles reach a field strength of about 25 kG/cm when excited to full energy. George R. Kalbfleisch and John E. O'Meara have been responsible for the quadrupole construction.

Refrigeration

The refrigerator design,[16] which requires a river of sub-cooled liquid helium at 4.5 K to be pumped through the ring, resulted from the work of Fowler, VanderArend, Claus H. Rode, Donald E. Richied, and Ronald J. Walker. To prevent the temperature from rising as the helium passes through the strings of magnets, a counter-flow system of single phase and two-phase helium is used. The inner magnet is supported in the single-phase supply channel, which is surrounded by a return channel through which boiling helium flows in the reverse direction. Thus, at the end of each chain of twenty magnets, the single-phase helium passes through a Joule–Thomson valve and is cooled by expansion for return through the outer channel.

The thermal heat leak in a bending magnet has been measured to be 6 watts to the helium-cooled parts and 22 watts to the nitrogen-cooled shield. The ramping field also produces heat in the inner magnet and cryostat, and this has been measured to be 500 joules per cycle at full excitation. When extrapolated to the whole magnet, the total thermal leak will require 5000 watts of helium cooling, and the ramping field will require an extra 8200 watts of helium cooling for the one-minute cycle. The total standard flow of liquid helium will be about 5000 liters per hour, and 500 liters per hour of liquid nitrogen will flow through the heat shield.

At each of the 24 service buildings, a satellite refrigerator will receive the returning liquid, recool it to single-phase liquid, and then pump it back through the chain; this implies 48 chains around the ring, two at each satellite station. For the extra needs of cool-down of the system, for supplying liquid helium to the satellites and for redundancy if satellites partially fail, a central liquifier is under construction. We were fortunate to have found as surplus an Air Force oxygen liquifier at the Santa Susana test center near Los Angeles. At Fermilab the large motors and compressors are being rebuilt into a liquid-helium plant capable of providing 4000 liters per hour, the largest in the world.

The Super Ring

Having discussed the supermagnets, let me now turn to the assemblage in the main-ring tunnel of the superconducting bending magnets and quadrupoles that constitute the Super Ring. We expect to do this without undue interference with the normal operation of the present main-ring accelerator. Thus, on the customary one day per week when the Main Ring is being maintained and improved, we would expect to move about twenty supermagnets into the tunnel and to connect them together using the gasketed quick-disconnect joints. One can imagine several crews working in parallel to accomplish this rate, which is the same as was achieved in 1971 in installing main-ring magnets.

The simplest arrangement for the Super Ring is to mount the supermagnets directly below their conventional counterparts in the Main Ring, as shown in figure 1. Then the lattice (the arrangement of magnets) will be exactly the same for both rings. We have accumulated over the years a considerable lore about the Main Ring; all that knowledge can thus be applied directly to the Super Ring.

One embellishment we are considering to facilitate colliding beams is to lower the main-ring magnets to the floor in one or more of the six sectors of the ring. For those sectors the supermagnets would then be mounted *above* the conventional magnets as shown in figure 5a. Then the beams of the two rings would be caused to transpose up and down at the straight sections, as shown, by tilting or "rolling" a few magnets in the near vicinity of the straight sections. The desired result is the crossing of the beams, and hence the possibility of collision. Another scheme for bringing the beams into collision without transposition of magnets is the "kissing scheme," figure 5b.

The beam will be transferred from the Main Ring to the Super Ring in straight section A as indicated in figure 2. Thus upon the completion of the Super Ring, our first objective will be to obtain a "coasting beam" at the injection energy of 100 GeV. This step requires the least amount of installed refrigeration (because there are no ramping losses) and the least amount of power supply to excite the Super Ring. After installing a very small amount of radiofrequency acceleration in straight section F, and a slightly larger power supply, we will *slowly* raise the magnetic field and hence the energy of the beam. There is no reason we should not reach 1 TeV in this way.

If the current of protons is large the energy stored in the circulating beam will present a hazard. Thus, with 5×10^{13} protons at 1 TeV, the energy in the beam will be eight megajoules. Such a beam striking any part of the accelerator will vaporize it, and even a small part of this striking the superconducting coil will cause it to go normal—about 3×10^{10} ionizing shower particles per cm^2 per sec passing through the superconductor will

A completed magnet lying on its side in a half core (compare figure 3a). With mass-production techniques at Fermilab these magnets can currently be made in trial production runs at the rate of one a day, a rate that will be quadrupled to meet the goal of constructing the entire Super Ring in a year. Installation is not expected to disrupt the normal operation of the Main Ring; it will be done during the one day each week set aside for maintenance. Figure 4

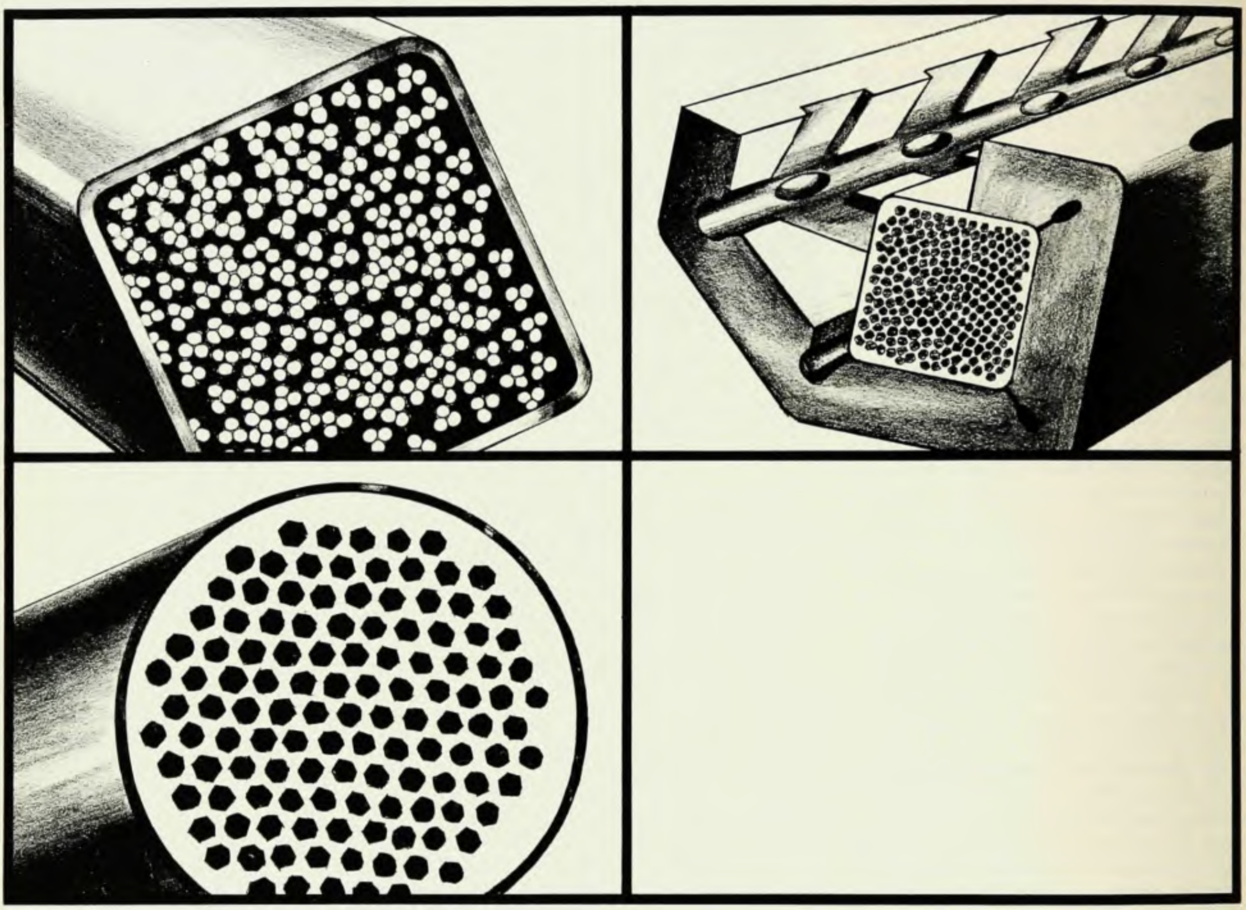
produce a quench. Helen T. Edwards and Andreas J. VanGinneken have constructed computer models of beam loss in supermagnets and have verified results of actual tests made by Edwards and Rode in a 400-GeV beam.[17]

The 100-GeV protons from the Main Ring must be injected into the Super Ring so precisely and so cleanly that few if any of the protons ever strike a part of the magnet. This precision should be possible because the beam at 100 GeV is like a needle (well, a darning needle anyway). We also already know from our experience with the Main Ring that a beam once captured can be accelerated without loss except from gas scattering, and the vacuum in the Super Ring should be several orders of magnitude better. But what if something goes wrong during acceleration or when the beam is stored at high energy—a "glitch" in the power line for example? Well, any electrical aberration of a magnet, or wandering of the beam from the center of the donut, will be electrically sensed and then the beam immediately aborted; that is, it will be completely extracted in one turn and deposited benignly in an external beam dump. Indeed we already have considerable experience of this technique with the main-ring abort system (where the problem, if not as serious, is still of comparable gravity). The beam can alternatively, under favorable circumstances, be decelerated to low energy and then disposed of. The silver lining to this cloud is that once we have a circulating beam, we will then be in a position to start the colliding-beam experiments already described.

For storing a beam in the Super Ring a vacuum of about 10^{-10} Torr (room-temperature equivalent), in other words about 10^7 helium atoms/cm^3, will be required, and this is Limon's responsibility. We will take advantage of the cold bore at 4.6 K to use cryosorption pumping between each magnet. The vacuum in the Main Ring, presently about 10^{-7} mm Hg, is not so critical for storing a beam because the Main Ring can be frequently refilled. In the present system we have observed a beam life of several hours on clamping the Main Ring energy at 200 GeV. However, gas scattering in the main-ring donut gives rise to a serious background of protons in the tunnel, so we expect to improve the vacuum by eliminating the many tiny leaks that exist and if necessary by adding cryogenic pumping. We expect to construct enlargements of the tunnel at a few straight sections soon in order to be prepared to start some serious colliding-beam experiments.

Perhaps the first experiments with the circulating 1-TeV protons incident on protons nearly at rest can be made at straight section C, where internal-target studies have been made since 1972, largely as a Soviet–American collaboration. The facilities already installed there can be used immediately to extend the previous measurements to the TeV range, after which the area might be converted for colliding-beam experiments.

Sketch a superconductor.



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Or the extended-surface clad superconducting system (upper right) being developed for large mirror fusion machines. The copper cladding has spaced holes and channels for liquid-helium flow. The channels also allow the cladding to be formed into a square cross section, around the multifilament core.

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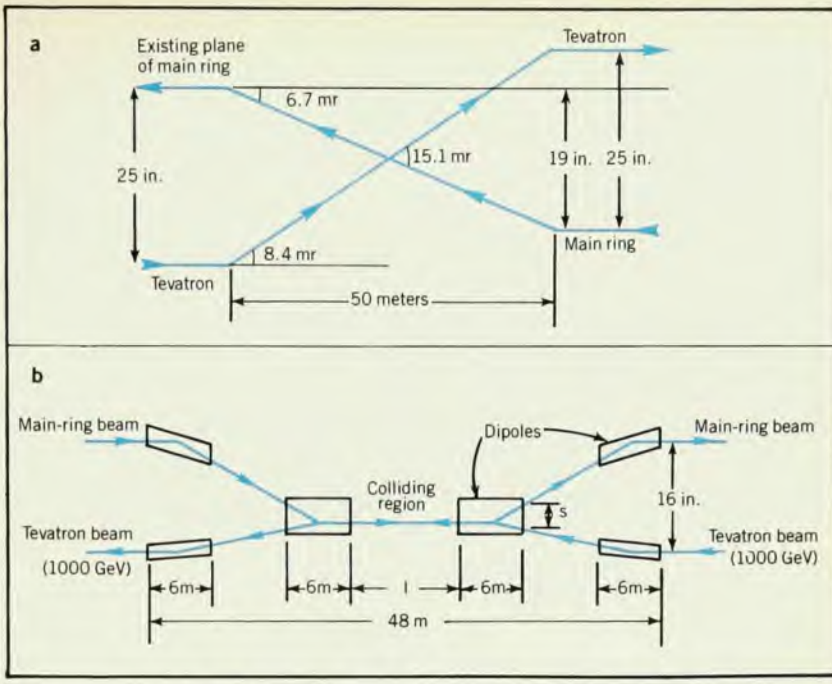
By "Tevatron" we mean a full-fledged accelerator capable of delivering an extracted TeV protons to the external experimental areas. Theoretical calculations for the Tevatron have been made by Teng[18] and by Donald Edwards and Thomas L. Collins.[19] Converting the Super Ring to the Tevatron is Huson's responsibility. Radiofrequency problems have been addressed by James E. Griffin.[3] Beam-transfer problems have been confronted by Helen Edwards and H. Eugene Fisk, and Rae F. Stiening is considering problems of the power supply, of magnet protection and of orbit dynamics. Frank Turkot has the installation of the supermagnet to worry about.

The metamorphosis of the Super Ring into the Tevatron will require a power supply capable of ramping the magnets at the one-minute cycle; it will require refrigeration to make up the ramping losses. It will also require a substantial installation of radiofrequency oscillators capable of accelerating the protons rapidly to one TeV, and it will require a beam extractor. Once the TeV protons are out of the accelerator, the switchyard magnets must be made superconducting to guide the protons to the experimental areas. Finally the experimental areas and the experiments must be hardened to accept the TeV protons.

These are all formidable technical tasks, but are prosaic in the sense that they represent a straightforward extension of the corresponding devices of the present main-ring accelerator. Most difficult will be the extraction of the beam from the Tevatron, because any beam loss or scattering that occurs in the process might quench the supermagnets. Let me say that each of the tasks has been carefully considered and that an economical solution has been worked out. When we built the Main Ring, the possibility of a Tevatron was already envisaged; extra space was provided in the Service Building as well as in the tunnel for its eventual installation. Furthermore, the main-ring power supply, as well as the radiofrequency oscillators, are modular and can be adapted to the needs of both accelerators.



Two schemes for colliding beams. In the transposition scheme (a), the main-ring magnets will be lowered to the floor in one or more of the six sectors of the ring, and the supermagnets mounted above them (the opposite arrangement to that of figure 1). Beam crossover at the straight sections will be caused by tilting a few magnets near these points. The "kissing" scheme (b) keeps the Main Ring above the Super Ring in all sectors, and brings the two beams together over a "colliding region" of length l meters in one or more of the straight sections. Figure 5

Experimental areas

We can assume that by the time the Tevatron is operational, colliding-beam facilities will have been constructed at one or two straights, and that colliding-beam experiments will have been started therein. The internal-target area, as has been said, will need no improvement to be useful at 1 TeV. Once extracted, the TeV protons must be divided in the switchyard and guided to the experimental areas the geographical arrangement of which is shown in the aerial photograph, figure 6, and which were shown diagrammatically in figure 2. John Peoples has organized the improvements[2] that need to be made in the present experimental areas.

Just bringing 1-TeV protons to the targets of the various experimental areas will cause a substantial increase in the intensity of the secondary beams. The increase is partly because the multiplicity increases with energy but largely because the production cone folds forward as the energy increases. In this sense, a fixed-target accelerator is unique in that it can be considered a "center-of-mass accelerator" of secondary particles. Our highest neutrino measurements, for example, are now made up to about 250 GeV, and with 1-TeV protons rather than 400-GeV protons the intensity of 250-GeV neutrinos will increase by a factor of about 20.

The next kind of improvement to be made is to raise the energy of various secondary beams, again usually by replacing conventional magnets with supermagnets. The shielding for such beams in many cases must also be hardened, perhaps by replacing the present earth shielding with iron. Thus in the meson laboratory it appears possible to raise the energy of the M2 pion beam to 1600 GeV, of the M1 beam to 600 GeV and of the M6 beam to 400 GeV—and the last two can be relatively rich in negative kaons and antiprotons if the production angle is more than 3 milliradians.

In the proton laboratory, many of the present experiments can be repeated at 1 TeV just by bringing the protons on target. The new high-intensity pion beam has been designed from its inception to go to 1 TeV when all the supermagnets are installed. It can also operate as an intense high-purity electron beam.

In the neutrino area, by adding iron shielding and iron magnets in appropriate combination, we anticipate that neutrino measurements can be extended to about 750 GeV. A new muon beam has been designed that will provide a flux of about 10^8 muons per 10^{13} protons at an energy of 500 GeV. Energies up to about 800 GeV should be available in meaningful intensities.

Thus, depending upon the desires of the physicists and upon financial resources, a whole spectrum of possibilities is opened by the construction of the Tevatron. Each area might require in the neighborhood of $10 million for improvement, but lesser amounts will also produce an abundance of good physics.

Physics with the Tevatron

It is the nature of research that what can be envisioned is less glorious than the unimagined knowledge that adventitiously turns up. Nevertheless there are phenomena that even now can be seen "as in a glass darkly," and which can be brought into focus and elucidated with the expected fifty-fold increase in definition that will become possible. In principle the least dimension that can be measured with a center-of-mass energy of 2 TeV is about 10^{-17} cm.

Characteristic of such phenomena is the much sought after "intermediate vector boson," the mediating field particle

PHOTO: TONY KELLY

Aerial view of the accelerator and experimental areas at Fermilab. Improvements to the experimental areas are in hand to accomodate the extracted 1-TeV beam when available. Figure 6

that should play the same role for the neutrino force that the photon assumes for the electric force. In direct searches for the intermediate boson, at present energies, the mass limit has been pushed to above 10 GeV. Indirectly, the intermediate boson should show up, due to the propagator effect, as a departure from linearity of the total neutrino cross section when plotted against neutrino energy. The linearity indicated by present measurements (which extend to a neutrino energy of 250 GeV) raises the mass limit to above 30 GeV. The existence of these mediating-field particles has become even more compelling because of recent advances of gauge theories, which unite weak and electromagnetic forces. These theories predict a mass of about 70 GeV for the mediator, so just the doubling of the available neutrino energy by the Tevatron might allow us to confront the existence of the mediator. And then will the mediating particle be charged or neutral? And how about the enigmatic Higgs boson?

If the neutrino energy made possible by the Tevatron (that is, up to 700 GeV) should not be adequate to reveal the intermediate boson, then of course we can bring the big guns of our colliding-beam experiments to bear on the problem. Then the center-of-mass energy will extend up to 2 TeV, and that should be adequate to uncover a whole spectrum of such particles—as is suggested by some of the present theories.

There are portents in rare cosmic-ray observations of new phenomena: the Centauro event at about 500 TeV, apparently with no electromagnetic component, for example, or the Bristol event at about 100 TeV, apparently all electromagnetic. Then the mysterious Tien-Shan calorimeter measurements of hadron cascades appear to show an increase in mean penetration at an energy of greater than about 100 TeV. All this indicates something interesting is up, and it should be emphasized that the beams in collision at Fermilab should give greater energy (the equivalent of about 10^3 TeV in the laboratory) and tremendously greater luminosity than obtain in the cosmic-ray experiments.

Given all the evidence for the quark-like structure of the nucleon, it is hard not to believe in quarks. Then why are they not knocked out of the nucleon? Either they are too massive to have been made by presently available energies, in which case they might be made by the Tevatron, or there is a containment force. It is hard for me to think of anything much more exciting than observing an isolated fractionally charged particle (that is, except for seeing a monopole!). And if all that energy doesn't produce a quark, then at some stage we must admit that we have experimentally demonstrated a new force, and that's as interesting as a new particle—or more so!

It is pleasant to contemplate the spectaculars of discovery, but there is also much physics gold to be found in the more prosaic measurements that become possible because of the higher intensities of the lower-energy secondary beams. The intense neutrino beams should be particularly clean probes of the internal structure of nucleons, because the neutrino interacts with quarks through its weak interaction. And even if proton–proton collisions would seem now to be as complex as two garbage cans in collision, perhaps our present idêas are naive and will be corrected by future information. Perhaps the true center, or essence, of the proton lies concealed beyond the foothills of quark structure.

Not least exciting will be the intense photon beams, with energies of 500 GeV or more, that will be made available by the Tevatron. Photons have a particularly clean electric interaction with nucleons or their constituents. Comparison of the electric and weak interactions, which at these energies are becoming of comparable intensity, will surely teach us much about the unification of forces that is implied by the present fashionable gauge theory. As the energy of the electrons and muons goes higher and higher, the probability of observing a difference in muon and electron interactions must increase—we still don't understand the "why" of muons.

Between the fixed-target experiments that can be made with the highest luminosities, and the colliding-beam experiments that will reach the highest energies, we can anticipate a leap forward in our knowledge of particles and forces—all through the magic of superconductivity.

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