<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2. The Energy Doubler in Physics Research</td>
<td>6</td>
</tr>
<tr>
<td>3. Progress to Date</td>
<td>9</td>
</tr>
<tr>
<td>4. Technical Description of the Energy Doubler</td>
<td>12</td>
</tr>
<tr>
<td>5. Magnet Design and Fabrication</td>
<td>14</td>
</tr>
<tr>
<td>6. Helium Refrigerator Studies - Pump Loop</td>
<td>19</td>
</tr>
<tr>
<td>7. Refrigeration</td>
<td>20</td>
</tr>
<tr>
<td>8. Installation</td>
<td>21</td>
</tr>
<tr>
<td>9. Magnet Protection</td>
<td>22</td>
</tr>
<tr>
<td>10. Magnet Tests</td>
<td>23</td>
</tr>
<tr>
<td>11. Cost and Schedule</td>
<td>24</td>
</tr>
<tr>
<td>References</td>
<td>25</td>
</tr>
</tbody>
</table>

**Appendix**

1. Physics of the Doubler                                                J. Peoples
2. Magnet Lattice and Dynamics                                          L. C. Teng
3. Magnet Calculations                                                  S. C. Snowdon
4. Radiation-Damage Considerations                                      P. A. Sanger
5. Superconducting Wire                                                 B. P. Strauss
6. Magnet System                                                        G. Biallas
7. The Magnet Test Program                                              A. V. Tollestrup
8. Tooling and Production Planning                                      W. Hanson
9. Magnet Measurements                                                  R. Yamada
10. Cryogenic Measurements                                              M. Kuchnir
12. Vacuum System                                                        P. Limon
13. Controls for the Energy Doubler                                      B. L. Chrisman
15. Parameters                                                           L. C. Teng
1. INTRODUCTION

The Energy Doubler is a 1000-GeV superconducting-magnet synchrotron to be installed in the existing Main-Ring tunnel of the Fermi National Accelerator Laboratory 500-GeV accelerator. The frontispiece shows a model of the proposed magnet installation under the existing Main-Ring magnets. The Main Ring will serve as injector for the Energy Doubler and accelerated beams from the Doubler will be extracted and transported to existing Fermilab experimental areas through the present Beam-Switchyard tunnels.

The use of the Energy Doubler in extending high-energy physics experiments is discussed in the next section and in more detail in Appendix I. The Doubler represents an inexpensive way of achieving higher energy while preserving the advantages of a fixed-target accelerator. Because two beams are present in the same tunnel, by reversing the direction of the beam, interesting colliding-beams experiments can be made.

It should not be forgotten that there are other significant advantages of the Energy Doubler. With the increasing awareness of a long-range energy shortage and with rising costs of electrical power, an important facet of a superconducting ring is its use as an "Energy Saver".

In routine Main-Ring operation at 400 GeV, a cycle that can be used has a 7-sec repetition rate including a 2-sec flattop. This cycle entails a power consumption of approximately 90MW. The same cycling rate with the same flattop and intensity can also be produced using the Doubler at 400-GeV excitation. For example, protons can be accelerated to 275 GeV in the present accelerator, then transferred to the Doubler, where they can be further accelerated to 400 GeV at the rate of 50 GeV/sec; i.e., 2.5 sec up, 2 sec flattop, 2.5 sec down. The power consumption of the conventional system would then be only 23MW and that of the Doubler would be approximately 7MW. A total of 30MW instead of 90MW would bring a saving of up to $7.5 million per year at present rates, assuming that the accelerator pulsed continuously. The cost of the liquid nitrogen needed for the helium refrigerators, which would be about $1 million, should be subtracted from this
total. We intend to operate the present accelerator at higher energy in the coming year, up to 500 GeV, which we have recently achieved; so the saving could be considerably higher.

Use of the Saver to increase the maximum energy of the accelerator can be achieved with no additional operating cost and any energy up to 1000 GeV should be possible. It is also evident that the length of the flattop—a dominant cost factor for the present accelerator—can be extended without extra cost for the Doubler. As a result of this energy-saving aspect of the Energy Doubler, we sometimes use the name "Energy Doubler/Saver".

We have also investigated the use of the new Doubler ring as a beam stretcher. In this mode, there is no acceleration in the new ring. The beam is transferred from the Main Ring into the Doubler, which is held at constant field. Slow extraction from the Energy Doubler then lasts until the next pulse is available for injection. In principle, a duty factor of close to to 100% could result. For most experiments; i.e., those limited by counting rate, this is equivalent to a five-fold increase of intensity.

We have thus discussed three different possible modes of operation, but there is a continuous spectrum of energy, pulse rate, and flattop length lying between them.

More recently, there have been studies on colliding beams at Fermilab. It now appears that a step-by-step approach to colliding-beam experiments is feasible. Modest outlays of money are expected to give some of the important information expected of a storage-ring program, so that later, more-expensive steps can be better designed. As one example, it is crucial to know at what energy the mediating boson of the weak-interaction neutrino force manifests itself. Simple and relatively inexpensive experiments can be designed that have a good chance of answering this fundamental question. There are many other kinds of information that would unfold in the series of escalating steps that would eventually lead to a full-fledged colliding-beam facility such as POPAE.

One possible step would be a small storage ring (SSR) that will allow 25-GeV protons (or 50 to 60-GeV protons if the small ring uses supermagnets) to collide with the beam in the Main Ring without interference with regular use of the Main Ring. A center-of-mass energy of 200 GeV at a luminosity of about $10^{31} \text{cm}^{-2}\text{sec}^{-1}$ could be available in a few years from the time the experimenters have found the approximately $5$ million that they have estimated is needed for its construction.
The completion of the Energy Doubler will provide for another step. Collisions could be made to occur between protons in the SSR and protons in the Doubler; then the c.m. energy would go up to about 300 GeV. The luminosity would be increased in that case, perhaps by a factor of ten, because the Doubler could also be used as a storage ring in which the beam from the Main Ring could be stacked. What has allowed the use of the Doubler as a storage ring is that the aperture has been increased to 7.6 cm in order to be able to extract the beam efficiently to the experimental areas.

An important and perhaps even more economical step than the one just described is inherent in the construction of the Doubler. It is feasible to bring about collisions between protons in the Main Ring with those in the Doubler. For this, the direction of the beam in the Main Ring must be reversed for reversed injection into the Doubler. We can make it possible to do this reversal by adding a small length of tunnel near the Booster injector, so that the beam can be reversed upon injection and then accelerated to full energy.

In order to facilitate bringing the two beams into collision, the position of the Doubler has been moved from the top of the tunnel to just below the Main Ring, as shown in the frontispiece and in the drawing of Fig. 1. Thus, for a very modest extra expense, i.e., the reversing tunnel, which might cost a few hundred thousand dollars, important exploratory experiments could be made at luminosities of about $10^{31}\text{cm}^{-2}\text{sec}^{-1}$ and at c.m. energies of up to approximately 1000 GeV. This energy corresponds to 250 GeV in the Main Ring incident on 1000 GeV in the Doubler. Higher energies could be reached by pulsing the Main Ring, but at the cost of duty cycle.

With such a program, it would be possible to have a significant colliding-beam facility at Fermilab that would be able to explore the deepest part of the proton at c.m. energies well above 1 TeV and at luminosities up to $10^{31}\text{cm}^{-2}\text{sec}^{-1}$.

Since September 1972, when Energy-Doubler effort by Fermilab began, substantial technological progress has been achieved in the areas of superconducting magnets and cryogenic-system development. This work has benefited by the ERDA-supported programs at the other labs, such as BNL and LBL. An important milestone was reached on March 12, 1976, when the first full-size Energy-Doubler prototype magnet successfully achieved its design field. This success established the
Fig. 1. The Energy Doubler installed in the Main-Ring tunnel.
technical feasibility of the Energy Doubler and provided a strong basis for confidence in the cost estimates, because simplified techniques applicable to production magnets were used in the prototype. There are still other objectives that must be satisfied, such as the ultimate magnetic-field quality, but the potential stumbling blocks of satisfactory "training" behavior and ramping capabilities have already been overcome.

We conclude that the technology has reached an appropriate state for initiation of Energy-Doubler magnet production. By July 1976, six magnets are scheduled to have been wound and a rate of one magnet every two weeks achieved. With high priority given to the Energy Doubler in FY 1977, there should be sufficient progress to complete the accelerator in FY 1978, provided the funds are available.

This report records the progress in the design and development work and the considerations underlying design decisions. The work reported here depends on the earlier Energy Doubler reports, but this report is written to be understood without reference to the earlier reports.
2. THE ENERGY DOUBLER IN PHYSICS RESEARCH

The Energy Doubler can be used as a colliding-beam device, as described above, but its primary use is expected to be as fixed-target accelerator. A fixed-target accelerator may not be as efficient as colliding beams in producing large available center-of-mass energies, but it does have the great advantage of large interaction rate; its luminosity is of the order of a million times greater than that of a colliding-beams device.

The large interaction rate allows the production of intense secondary beams of various particle types, which uniquely allows the study of strong interactions of π-mesons, K-mesons, neutrons, and so forth. Only in this way can the inner structure of hadrons other than the proton be explored. It is of utmost importance to exploit the ability of the fixed-target accelerator to produce very high-energy neutrino, electron, muon and photon beams. For example, with 1000-GeV protons, useful fluxes of neutrinos at 750 GeV would be produced, allowing a sensitive test of $W^+$ masses up to 60 GeV/c².

Progress in elementary-particle physics has been characterized and guided by advances toward higher-energy beams. Higher energies mean shorter wave lengths and shorter wave lengths mean higher resolving power with which to examine the internal structure of the proton and the neutron. There are many ways in which an increase in energy can contribute to studies of the elementary particles. Three of the most important are the following:

1. New and massive particles have been postulated to play an important role in the structure and interactions of matter. In order to produce such particles, an energy commensurate with the mass of the heavy particle is required. Thus, if particles such as quarks, intermediate bosons, or magnetic monopoles exist beyond the range of present explorations, it is of the utmost importance to extend the available bombarding energies in order to further our understanding about the possible existence of such particles.
2. To explore the deepest parts of a nucleon, glancing collisions are not enough. It is necessary to have intimate collisions between a bombarding particle and the target particle. In such collisions, large amounts of momentum are transferred between bombarding and bombarded particle. Large momentum transfers occur with much greater frequency for high-energy bombarding particles than for low. Thus, higher-energy beams provide a more effective probe of the inner structure of fundamental particles.

3. Much of the important work in exploring the structure of matter is carried out through the use of beams of secondary particles such as pions, kaons, muons, neutrinos, electrons, photons, and hyperons. The intensity of such secondary beams, as well as their energy, is an extremely important factor in the capability they provide for studying some of the most unusual and often the most interesting interactions. The higher the energy of a beam of primary protons, the greater the multiplicity of secondary particles that is produced in a primary proton interaction. The higher the multiplicity, the greater the intensity of the secondary beams of particles, at lower secondary energies as well as higher.

Now, although a fixed-target accelerator is inefficient compared with colliding beams in producing large center-of-mass energies between colliding particles, the energy remaining in the moving center of mass is by no means wasted. Even if the secondary particles are produced in the c.m. system at relatively low energy, in the laboratory system they will still share all the incident particle energy. In this sense, a fixed-target accelerator is unique in that it can be considered a "c.m. accelerator" of the secondary particles.

Neutrino physics has become particularly exciting. Because the intensity and energy of the neutrino beam at Fermilab are vastly increased over what previously had existed and because the interaction cross section has also increased with energy, we are now able to observe thousands of neutrino interactions where only tens could be seen at lower energy. Thus neutral-current interactions, indicative of a unification of electromagnetic and weak forces, have been seen in abundance. By now, many dimuon events have also been observed, not, as had been expected, as a clear signal of the intermediate boson, but rather as an unexpected indication of a new particle that very likely carries with it a new kind of quantum.
Effects indicative of granularity in the proton also become more prominent as energy increases. Thus, had we stopped at 200 GeV, the unexpectedly high frequency of particles of large momentum transfers resulting from collisions would barely have been observable, while at 400 GeV the effect is very large. That the high luminosity of a fixed-target accelerator is important is evident in Fermilab experiments in which it was possible to exceed momentum transfers observed at the CERN ISR.

In summary, the proposed addition of a new superconducting ring at Fermilab offers the possibility of the study of a very broad range of fundamental questions in particle physics in a new and presently inaccessible energy region. The profound discoveries made with the present accelerator lead us to expect new phenomena to be uncovered when the Energy Doubler becomes operational. The new experiments, together with the complementary experiments at other facilities, such as PEP, offer great promise of leading to a new depth of understanding of elementary particles and the fundamental laws of physics.
3. PROGRESS TO DATE

During the period in which the present Fermilab accelerator was being designed, we considered but reluctantly rejected the possibility of building it with superconducting magnets—the state of that art was just too primitive then. In choosing conventional magnets, however, we realized that when superconducting techniques were eventually developed, we could double the energy of our accelerator by replacing the conventional magnets in the existing ring by "supermagnets".

A better opportunity would be to use the present Main-Ring accelerator as the injector into a second complete ring of superconducting magnets. Then the injection energy of protons into that ring could be more than ten times the energy of the present booster injection into the Main Ring. In addition, the Main Ring would then continue to operate. A significant economy could be made by placing the superconducting ring in the Main-Ring tunnel. Because such a synchrotron using superconducting magnets could be designed to reach about twice the energy of the protons in the conventional Main Ring, the project was originally called the "Energy Doubler".

Presented by this opportunity of reaching as much as 1000 GeV, we have been careful to maintain the Main-Ring tunnel clear of obstructions or interferences. The 24 service buildings were also designed so that space is left clear for the installation of refrigeration and other ancillary equipment necessary for the supermagnets. The present magnet power supply has the electrical capability and is flexible enough to energize both the Main Ring at 300 GeV and the Doubler up to 1000 GeV at the same time. Indeed, at first we had hoped to be able to build the Doubler within our original $250 million authorization, in the same spirit that we were able to produce 500 instead of 200 GeV. Our work has been in parallel with and has taken advantage of the efforts and experience with supermagnets at other laboratories such as LBL, Brookhaven, and Rutherford.

On March 9, 1971, R.R. Wilson introduced during his testimony before the Joint Committee on Atomic Energy the concept of a superconducting ring in the
Fermilab Main-Ring tunnel to be used to double the energy of the accelerator. Until September 1972, the Laboratory staff was fully occupied in completion of the accelerator and the equipment necessary for its utilization. Beginning at that time, it was possible to devote some attention to the Doubler idea.

For the past four years, work has been in progress at Fermilab to demonstrate the feasibility of constructing the Energy Doubler - an accelerator employing superconducting magnets which would increase the energy of protons available at the Laboratory by at least a factor of two above that provided by the present accelerator system; i.e., 1000 GeV.

At the outset, a number of tentative design principles were established, among which are:

(i) The Doubler cycle time was picked with the realization the first ramping supermagnets to be developed would ramp more slowly than conventional magnets. It was deemed that a desirable goal would be to achieve an average intensity of about $10^{12}$ protons/sec, which implies a cycling time of about one minute. At this cycling rate, the thermal load originating from induced currents should not be a major contributing factor to the refrigeration load. It should be emphasized that there is always the option of increasing the repetition rate and hence the average proton intensity by increasing the refrigeration capacity.

(ii) The magnet dewars would themselves play the role of transfer lines carrying coolant from and back to the refrigerators located in the service buildings.

(iii) The magnets would have a cold beam tube, since the relatively low proton beam current will not have stringent vacuum and surface cleanliness requirements.

(iv) The magnet iron used to enhance the magnetic field would be at room temperature and would be always below saturation, thus insuring linearity with excitation.

(v) The superconducting material would be NbTi. (See Appendix V.)

(vi) The current in the conductor would be consistent with utilization of existing Main-Accelerator power supplies for Doubler excitation at the highest practical current density.
The protons would be extracted and transported into the present experimental areas.

Magnets have been designed with both 2.5-in. and 3-in. bore, which give a good-field circular aperture of 1-2/3 in. and 2 in. respectively. In September 1975, the 2.5-in. magnet series was terminated and 3 in. was chosen as the bore size for the Energy Doubler dipoles. It is prudent to have as large an aperture as is necessary to give sufficient allowance for closed-orbit variations and for optimum slow-extraction efficiency. Clearly, the 3-in. bore is more desirable for bringing the Doubler into operation and it was possible to overcome the problems of additional cost, higher magnet voltage, more difficult magnet protection, and larger refrigerators.

By now, we have built more than 50 magnets. We have demonstrated that the difficulties presented when we began have been overcome to an extent that we initiated in January 1976 the fabrication of full-size Doubler magnets. We still expect to go through further production of model and prototype magnets in order to optimize our present design. Production problems are to be worked out in parallel by winding coils for six 22-ft long magnets by July 1976. At that time the winding rate will be one set of coils for a 22-ft magnet every two weeks.
4. TECHNICAL DESCRIPTION OF THE ENERGY DOUBLER

The Energy Doubler consists of the following major systems:

(i) An extraction system from the present accelerator using electrostatic septa and Lambertson magnets to extract the proton beam from the accelerator, probably at 100 GeV, and inject the protons into the Energy Doubler magnets.

(ii) Approximately 800 22-ft long superconducting dipole magnets capable of being connected together into 48 subsystems, together with 240 quadrupole magnets.

(iii) An rf system and its associated power supplies capable of accelerating the protons up to 1000 GeV at a rate of 50 GeV/sec.

(iv) Power supplies, magnet-protection, vacuum system, and instrumentation and control system required to operate the Energy Doubler.

(v) Helium-refrigeration and transport system required to provide the approximately 4K temperature needed for superconducting magnets.

(vi) Modification of the internal-target station at the C-0 long straight section for experiments using the circulating proton beam.

(vii) An extraction system for the Energy Doubler that allows slow or fast beam to be brought from the Doubler magnets through electrostatic septa, Lambertson magnets and superconducting beam-transport magnets into the present Beam-Switchyard system for use in the Neutrino and Proton experimental areas.

The location of a typical Doubler magnet is shown in Fig. 1. The proton orbit of the Doubler is exactly aligned horizontally with the Main-Ring orbit and 16 in. below. This location facilitates beam transfer into and out of the Doubler and opens the possibility of colliding the Doubler proton beam with the Main-Ring beam. Since we are using the present Main-Ring tunnel, only limited variation from the disposition of magnets in the present accelerator is possible for the Doubler lattice. For example, the presently conceived Doubler geometry will
duplicate the six long and six medium straight sections of the Main Ring. It is possible to use a centerline-to-centerline dipole magnet length for the Doubler magnets of 22 ft rather than the 20 ft of the Main Ring. This keeps the junction for Doubler magnets away from the area where Main Ring magnet junctions occur, in most cases, thereby reducing interferences.

Note added at the time of the second printing:

During the Aspen Summer Study of 1976 on uses of the Energy Doubler, various participants questioned the concept that the best location of the Doubler to facilitate colliding the Main Ring with the Doubler was the 16-in. separation described in this report. The Summer Study report will include a summary of the arguments for positioning the Doubler. Further study is required in order to determine the optimum location. The final location will undoubtedly be in the range of 26 in. to 16 in. below the Main Ring.
5. MAGNET DESIGN AND FABRICATION

We present here a summary of work on dipole-magnet design and fabrication. A cross-sectional view of a dipole is given in Fig. 2. Further details of design philosophy and design parameters appear in Appendices II, III, VI, and VII. Earlier considerations are discussed in References 1, 2, and 3. Our work has been concentrated on superconducting magnet development and we have carried out this development with dipole magnets. Nonetheless, we have also worked on quadrupole design and a cross section of a quadrupole is shown in Fig. 3.

**Beam Tube.** A 0.025-in. thick non-magnetic stainless-steel tube, elliptically shaped to give a horizontal aperture of 2.8 in. and a vertical aperture of 2 in., serves as the separation between the beam vacuum space and the two-phase helium coolant.

**Two-Phase Liquid-Helium Channel.** The two-phase, liquid-gaseous (4.4K) helium coolant is contained between the stainless steel beam tube on the inside and the single-phase concentric tube on the outside. These two tubes touch on the horizontal axis and have 0.25 in. clearance vertically at the top and bottom.

**Inner Single-Phase Helium Tube.** A 0.025-in. thick non-magnetic stainless-steel tube elliptically shaped, 2.9 in. horizontally and 2.6 in. vertically and concentric with the beam tube. The heat exchange between the warmer single-phase and the cooler two-phase helium occurs over the surface area of this tube. The heat flows through the wall of the tube.

**Wire Development.** For our first full-scale magnets, we wanted conductor that could be wound by somewhat conventional techniques and therefore settled on a solid conductor insulated with Formvar. Since then, interest in magnet systems cycling faster than the somewhat arbitrarily selected 100-sec cycle time has increased. At these higher repetition rates, the ac losses in the solid conductor with its large filaments become unacceptable. We have now moved toward Rutherford-style cable construction, which has smaller filaments. This style of conductor is described in Appendix V. We have recently received large
Fig. 2. Cross section of Energy Doubler dipole.
Fig. 3. Cross section of Energy Doubler quadrupole.
deliveries (some 7000 pounds) of cable. The performance of this material exceeds our critical current-density specifications, it has filament size less than 12μ, and it stands up well to handling during winding.

We have also pursued other avenues of wire development. We were able to purchase a large mill run of high resistivity-ratio copper, as well as enough NbTi alloy to fabricate one-sixth of the ring.

Since we decided on the cable style of construction, we have placed essentially identical orders for cable from all commercial manufacturers in order to qualify them with respect to ability to meet delivery requirements and superconducting properties. All conductor in this program is being fabricated with the Fermilab NbTi and copper, so that starting materials are identical. A parallel program, using the same materials, will test certain construction and other processing parameters pertaining to billet extrusion.

Coils. The coils are wound in concentric shells, with overall conductor placement calculated to provide a field uniform to 0.1% over 67% of the area of the bore tube (see Fig. 2). Prior to winding, the wire is cleaned and spiral-wrapped with Mylar tape (0.001-in. thickness) to provide electrical insulation of 1000V. A one-third width longitudinal tape helps to form an approximate trapezoid or "Keystone" shape for better packing of the turns. Finally a fiberglass-epoxy tape (0.008-in. thickness) is spiral-wrapped with 0.060-in. gaps giving open areas for cooling. Thirty-four turns are placed on each inner shell half coil and twenty-one turns are placed on each outer half shell.

Coil Collars. Previous coil-banding methods used in conjunction with bore tubes or bore rings showed coil distortion during excitation and the support of the coils has therefore been recently changed to look more like a cold-iron magnet design. In our case, these close fitting collars are laminations of Nitronic 33 stainless steel half rings 0.062-in. thick. These laminations are compressed into place by external clamps and glued with epoxy or welded. The coils, when collared, appear to be inside a 5-1/8-in. diameter pipe made up out of the collars, with a minimum wall thickness of 3/8 in. Test magnets fabricated with this coil-support system show minimum training and coil distortion during excitation well within acceptable limits.

Cryostat. The helium vessel inside the coil bore is made up of the beam tube and
the single-phase inner tube described above. Outside the coil collars, another 0.025-in. thick round stainless steel tube forms the separation between the single-phase liquid helium and the cryostat vacuum space.

A heat shield kept at 20K by flow of cold helium gas surrounds the magnet and in turn is wrapped with 15 layer pairs of Dimplar superinsulation to minimize heat leak. Finally, a close fitting 7-1/2-in. diameter tube that is in intimate contact with the round hole in the magnet iron yoke serves as the cryostat's outer vacuum wall. At the ends, quick-disconnect couplings that are good for low-temperature operation connect the flow circuits from magnet to magnet. End bells and bellows complete the cryostat, with the exception of the support system to hold the cold parts centered in the structure. This system is described in more detail in Appendix VI. For the metal parts of the vessels, we are adapting production sheet-metal techniques for fabrication in order to minimize the number of machined parts.
The design principles upon which the magnet cooling system is based are reported elsewhere. \(^5\) Basically, subcooled liquid helium is to be circulated by means of pumps located in service buildings distributed around the Main Ring. At a point midway between any two service buildings, the liquid will pass through a Joule-Thomson valve and counterflow back to the pump as boiling liquid helium in an annular space between the subcooled liquid that surrounds the coils and the beam tube.

To verify this concept, a liquid-helium pump loop has been constructed and tested. The loop consists of two lengths of coaxial pipe, each 200 ft long, and associated valving. A large helium refrigerator with a production rate of about 150 l/hr provides liquid. The loop is fully instrumented and a large number of experiments have been carried out.

To date, the basic cooling concept has been verified, as well as the performance of two different circulating pumps. The flow characteristics of helium under these conditions have been measured and several experiments pertinent to the operation of the Doubler have been performed. (See Appendix XI.) The operation of a 20-ft magnet in the loop showed improved performance over a single dipole operated in a pool-boiling helium.
7. REFRIGERATION

In order to provide the large amount of liquid-helium temperature refrigeration required by the Energy Doubler magnets, we have decided on the use of a central helium-liquefier facility that will provide liquid helium for distribution to "satellite" units located around the ring. The central helium plant will utilize "surplus" compressors that we are obtaining from the Santa Susana rocket-engine test center. The capacity of the central liquefier will be 4000 l/hr of liquid helium, which will accumulate in a tank truck of 10,000 gal (40,000 l) capacity. The satellite stations will receive liquid helium from the tanker approximately one a day. By the use of a "reliquefier" principle (see Appendix XI), each satellite will be able to provide the refrigeration needed by the magnets in its portion of the ring and to return high-pressure helium gas via a small pipeline to the central liquefier location. The central liquefier will be provided with a liquid-nitrogen-temperature precooler, which is also to be brought from the Santa Susana plant. This will reduce the requirements of the individual refrigerators for liquid nitrogen, saving about $500,000 annually in operating cost for the Energy Doubler refrigerators.

So far, the three large compressors have been removed from the California installation and protected against corrosion. A reconditioning plan is being drawn up and foundations are being installed at Fermilab. A 50-ft by 180-ft pre-engineered building has been contracted for to house the equipment and will be installed as soon as compressor foundations are complete. The 4000 l/hr helium-liquefier cold box has been under contract since February 1976 and should be delivered by August 1977, the time of the commissioning of the plant. This helium-refrigeration plant will be the largest in the world by more than a factor of two.

We have also designed and constructed a prototype satellite refrigerator station, which is under test. This unit will be installed in a service building and used to cool the first string of Energy Doubler magnets to be installed in the Main Ring tunnel during the summer of 1976.
8. INSTALLATION

One of the tasks that has received the most serious consideration during the design study has been the planning of the installation of the new ring of superconducting magnets into the Main-Ring tunnel without serious interference with normal accelerator operation. We have developed a magnet and cryostat design that we believe will permit efficient installation. Individual magnets are to be moved into the tunnel while the accelerator is in use. During an accelerator down period, the Energy Doubler magnets that are already in the tunnel are lowered to carts, moved into position, and the connections and alignment completed. When the string of magnets is complete and connected to the cryogenic service boxes (there will be a total of 48 independent strings of magnets) pumping, purge and cooldown operations can be accomplished from the service buildings, again during normal accelerator operations.

In order to prove our concepts, a second beam-extraction system has been installed in the Main Accelerator in the B-0 long straight section. With this system, a few percent of the protons can be extracted at an energy of 100 GeV for injection into Doubler magnets. We have already been successful in installing 2.5-ft long and 10-ft long model supermagnets in this beam and operating them in a superconducting mode without interference with the accelerator.

Because of the change of position of the Energy Doubler from the top of the tunnel to 16-in. underneath the Main-Ring magnets, we are relocating this extraction system and our program now is to install a string of ten regular supermagnets in this beam and hence to test our ideas about installation, alignment, and operation under actual conditions in the tunnel.
9. MAGNET PROTECTION

A serious problem could arise should one of the magnets in the ring accidentally undergo a quench if no provision has been incorporated to handle this occurrence without damaging equipment. Of course, quenches occur many times in the course of testing individual magnets, but the magnets are not damaged because we have developed electronic devices to detect the incident quench. When a quench is detected, the magnet current is immediately shunted through an external resistor by means of a thyristor, while at the same time the power supply is disconnected.

One is justifiably concerned when 800 magnets are connected in series, for it is conceivable that the whole energy in the magnet ring, about 300 MJ, or even some small fraction of this, might be deposited explosively in one or more of the magnets.

The magnets are connected in 48 separate groups of 17 magnets each; at the end of each group or string the leads are brought to room temperature and then to 24 power supplies. Thyristors connected to these leads will, upon command from an electronic quench detector, isolate the group in which the quench occurred from the rest of the magnets.

We have several different solutions for isolating the quenched magnet from the 16 other magnets in the group. The surest, but probably most expensive, solution is to bring out a small warm lead at each magnet (it need not carry the full current continuously). Then the current in the quenched magnet can be bypassed through an external individual thyristor, thus isolating it from the other magnets. The power supplies at the adjacent service buildings can then be used to pull the energy out of the quenched magnet and the adjacent magnets to minimize the loss of coolant. Other possibilities that are under study include various schemes of having the protective circuitry within the cryogenic systems to a greater or lesser degree.
10. MAGNET TESTS

Over the past year we have been testing a series of magnets that were constructed with different parameters in order to correlate the effects of various construction techniques with magnet performance. The following areas have been and continue to be under investigation: types of wire, stranding techniques, number of strands, types of insulation, banding techniques, structural restraints, and problems of fabrication.

Most of the testing work has been aimed toward obtaining high-field magnets. Field quality has not been explored in depth in the past year; but both early and recent work indicate that field quality can be made acceptable and reproducible from magnet to magnet.
The Energy Doubler is being built as a research and development project utilizing operating funds, following the recommendation of the Low Committee on High Energy Physics Facilities of the High Energy Physics Advisory Panel. Details concerning the definitions and funding assumptions are given in Appendix XIV. It is estimated that fabrication and installation of all Doubler magnets will be completed in fiscal year 1978 and protons will be accelerated to 1000 GeV at a slow repetition rate. The 1000-GeV proton beam will be extracted and transported to experimental area for use in experiments in fiscal year 1979. To meet this schedule, 270 dipoles will be completed in the mini-year and FY 77 and 530 in FY 78. All 240 quadrupoles will be built in FY 78, with the exception of extracted beam components and their controls, which will be built in FY 79.

Anticipated R&D funding for FY 77 and FY 78 which will achieve a circulating beam is shown below. The cost of a central helium liquefier is not included because we have acquired most of the equipment as surplus and will utilize it for not only the Doubler but also for the rest of Fermilab.

<table>
<thead>
<tr>
<th></th>
<th>FY 77</th>
<th>FY 78</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipoles</td>
<td>5,400</td>
<td>11,600</td>
</tr>
<tr>
<td>Quadrupoles</td>
<td>0</td>
<td>1,800</td>
</tr>
<tr>
<td>Other Components</td>
<td>150</td>
<td>4,400</td>
</tr>
<tr>
<td>Satellite Refrigeration System</td>
<td>450</td>
<td>2,200</td>
</tr>
<tr>
<td>Contingency</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Annual R&amp;D</td>
<td>4,000</td>
<td>5,000</td>
</tr>
<tr>
<td>Total</td>
<td>10,000</td>
<td>25,000</td>
</tr>
</tbody>
</table>
REFERENCES


2 The Energy Doubler Design Study, March 1, 1974, FN-263.


8 B. Strauss et al., Results of Magnet Prototype Evaluation for the Fermilab Energy Doubler Project, ibid.

9 D. Dickey et al., Performance Studies of Superconducting Dipoles for the Fermilab Energy Doubler, ibid.
BIBLIOGRAPHY SINCE REF. 3

15. Fabrication of Cryogenic Electrical Feedthroughs, M. Kuchnir, TM-596, August 8, 1975.

23. AC Loss in Flat Transposed Superconducting Cable, H. Ishimoto et al., TM-636, October 1975.


