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THE FERMILAB ENERGY DOUBLER, A TWO-YEAR PROGRESS REPORT

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Summary

Work has been undertaken for a period of about 2-1/2 years at Fermilab on feasibility studies for the Energy Doubler/Saver. This activity has centered on the technology of building Energy Doubler/Saver magnets and their cooling system. Energy Doubling would be accomplished by installing in the 4-mile tunnel of the Fermilab accelerator a ring of superconducting magnets. Energy Saving would use the same ring of superconducting magnets operating in a power saving mode. The motivation for the saver would be to obtain the same energy, intensity and duty cycle of the present machine but with a significantly reduced electrical power bill.

Introduction

The Fermilab synchrotron which was initially intended to be a 200-GeV machine now regularly operates at 300 GeV and sometimes at about 400 GeV. Early in the life of the project it was recognized that even higher energy and an improved duty cycle was conceivable if a ring of superconducting magnets could be installed in the same enclosure as the main ring, converting the main ring into an injector. Because superconducting mangets can be designed to reach 4.5T, twice the field in the conventional ring at 500 GeV, the project was called "Energy Doubler".

With the rising costs of electrical power, another use for a superconducting ring presents itself, a mode of operation called the Energy Saver. The present main accelerator ring, operating at 300 GeV with a 6-second cycle time and one-second flattop, requires an average power of over 33 MW. This increases rapidly with energy and duty factor. As an example of a possible Energy-Saver cycle the main ring could be run as an injector at 300 GeV with essentially no flattop, and the superconducting ring used to accelerate from 300 to 400 or 500 GeV. This type of consideration was first introduced in the summary paper given by Edwards at the International Accelerator Conference.[1]

Early Work

After the accelerator came into operation in 1972 and high-energy physics experiments got underway, it was then possible to devote some attention to the Doubler idea. Of the funds authorized for construction of the Laboratory some $30 million remained uncommitted at that time. Of course, it was expected that a significant portion of this sum would be needed to bring the accelerator and experimental areas to an operational state of completion and almost $10 million has since been spent for those purposes. But if it were possible to obtain the major components of the Doubler - the magnets and their associated refrigeration system - at a cost in the neighborhood of say, $20 million then the opportunity would present itself for a further increase of the energy capability of the Laboratory within the initial $250 million authorization.

The emphasis of the work thus far has been on magnets and refrigeration. Given the limited resources that could appropriately be diverted from higher priority activities associated with improving accelerator performance in terms of intensity, reliability, proton splitting and beam spill and with initiating the ambitious experimental program at the Laboratory, it was clear that the focus of the study should be on those aspects of the Doubler most intimately associated with new technology.

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

- the Doubler cycle time was picked to be less than 100 seconds so that the thermal loads originating from time varying currents are not the major factor in determining refrigeration system capacity and cost; that is, of total refrigeration load only a small percentage, say 10-30% of total heat generated, would be due to pulsing. Provision for later operation at faster repetition rates would be kept as open an option as possible.

- the magnet dewars will themselves play the role of transfer lines carrying coolant from and back to the refrigerators located at the service buildings.

- the magnets will have a cold beam tube since the relatively low Doubler beam current will have less stringent vacuum and surface cleanliness requirements than a storage ring.

- the magnet enhancement iron will be at room temperature and will be always below saturation. These criteria are intended to provide magnets whose fields are linear with excitation and with the smallest total cross-section. This should also aid in reducing the refrigeration requirements for reasonable cool-down times.

- the superconducting material will be NbTi.

- the current in the conductor will be consistent with utilization of existing main accelerator power supplies for Doubler excitation at the highest practical current density.

General Descriptions of the Energy Doubler Location and Magnet Distribution

The position that the Doubler might occupy is shown in Fig. 1; at the top of the tunnel its orbit would be some 3 feet inside of and 4 feet above that of the main ring. Since we are using the present main-ring tunnel, only limited variation from the disposition of magnets

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in the present accelerator is possible for the doubler lattice. For example, the doubler geometry must duplicate the six long and six short straight sections of the main ring. Some of the flexibility that remains may be used to advantage to facilitate injection and extraction. We have adopted a length of 10 feet for our superconducting dipole prototypes. Some early considerations of injection and extraction schemes was done by Helen Edwards at the 1973 Aspen Summer Study.[2]

Uses for the Doubler

As an Accelerator Beyond 500 GeV. The original conception of the Energy Doubler was as a slow cycling accelerator operating from an injection level of 100 to 200 GeV to a final energy of 1 TeV. The superconducting magnet ring, which would be installed in the existing main-ring tunnel, would be required to operate from 4.5 kG to 45 kG in covering these energy ranges. Extraction from the present main ring would be single turn with injection into the Doubler occurring on the up ramp. The current versus time operating waveform would be trapezoidal in nature with no dc injection level and about 20% extraction flattop. Some typical operating cycles are shown in Table I. For current planning the 60-second cycle is taken as nominal.

TABLE I

Typical Energy Doubler Acceleration Cycles (assuming Injection = 100 GeV, Extraction = 1 TeV)

Total Cycle Time	Up Ramp	Flat Top	Down Ramp	$\dot{E}$
100 sec	40 sec	20 sec	40 sec	22.5 GeV/sec
60	24	12	24	37.5
30	12	6	12	75.0

As an Energy Saver. This concept envisions a superconducting accelerator ring of less capability and cost than the Energy Doubler, one which would accelerate protons from an injection level between 100 and 300 GeV to any final energy between 300 and 500 GeV. An almost limitless variety of operating modes are possible. As an example consider the 12 second, 470 GeV cycle shown in Fig. 2. The main accelerator ring is used as an injector to the Energy Saver at 300 GeV utilizing single-turn transfer from one machine to the other. The main ring would be operated without flattop and cycled only once every 12 seconds. Average power required for the main ring and saver, neglecting other Laboratory requirements, would be 17 MW. If the main accelerator were to be used without the Energy Saver, the extraction flattop would be limited to 1 second instead of the 2 second saver flattop shown in Fig. 2, and the average power required would be 65 MW, again neglecting other Lab power loads. The power needed in this example of Energy Saver operation is a factor of about 3-3/4 less and allows a duty factor not possible with the present main ring power distribution system, which limits extraction flattop in the main ring to $\leq$ 1 second for final energies above 450 GeV.

As a Beam Stretcher. In this mode, the Doubler does not accelerate at all. Rather the beam is transferred to it from the main ring at the peak of the main-ring cycle of the latter, and slow extraction from the Doubler lasts, hopefully, until the next pulse is available for injection. In principle, a duty factor of close to 100% could be obtained.

As an Injector to Storage Rings. The Fermilab Long Range Advisory Committee has recommended that the Laboratory's long-term planning center around the design of "POPAE" storage rings (Proton On Proton And Electron), with the proton rings to accommodate energies of 1000 GeV. The Doubler could be the proton injector to POPAE, thereby providing protons at the storage energy and making it unnecessary to contemplate acceleration of the high current in the storage rings.

Progress To-Date

Progress on the Pump Loop

The design principles upon which the magnet cooling system is based are reported elsewhere indepth.[3,4] 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 such service buildings, the liquid will pass through a J-T valve and counterflow back to the pump as boiling liquid helium in an annular space that surrounds the subcooled stream.

To verify this concept a Liquid Helium Pump Loop has been constructed and tested. The loop consists of 2 lengths, each 200-feet long, of coaxial pipe and associated valving. A large refrigerator with a minimum production of 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 has been measured and several experiments pertinent to the operation of the Doubler have been performed. The operation of a 20-foot long magnet in the loop showed improved performance over a similar dipole operated in pool boiling helium.

Recently we have also studied an alternate cooling scheme. This investigation, carried out by Peter Vander Arend of Cryogenic Consultants, utilizes a device that he developed while he was at Gardner Cryogenics and that has been proved in the field. This reliquefier principal allows the transfer of liquid helium with very little loss of liquid in the transfer process. This then opens up the possibility of a central liquefier of about 2500 liters per hour capacity for the transport of liquid helium to each of the local pump stations, called satellite stations. In this scheme each satellite requires about 180 horsepower of compressor capacity and a heat exchanger with two expansion engines. At this time a net saving of horsepower for the entire refrigeration system seems to be possible, however, further study is required.

Magnet Design and Fabrication

We present here a summary of work on dipole magnet design and fabrication. Fig. 3 shows the basic four-shell dipole cross section.

The Beam Tube. The beam tube is made of stainless steel with an integrally wrapped shell of epoxy fiberglass. The stainless steel provides the vacuum integrity and is only about 1/32" thick whereas a heavy layer of epoxy fiberglass about 3/16" thick provides the inner support for the coils and some helium ventilation. In assembly the coils are mounted on the bore tube and tightly clamped with outer banding. For this reason it is necessary that the beam tube be rigid. It is also important that the coefficient of thermal expansion of the beam tube match or be less than the coefficient for the coil assembly so that as the magnet cools down the support for the coils is maintained. We are presently examining various other beam tube designs such as ceramic or metal rings over a metal tube. The ring idea is intended to provide a more favorable expansion match. The ceramic is particularly desirable since it has a low coefficient of thermal expansion, thus causing the stress on the coil assembly to become more compressive after the magnet is cooled down.

Coils. The coils are wound in four concentric shells, with overall conductor placement calculated to provide a field uniform to 0.1% over 75% of the area of the bore tube. The conductor is graded in size to allow flexibility of wire placement in our very restricted geometry, the smaller cross-section wire being used in regions of lower field. Prior to winding the wire is keystoned and barber pole wound with glass-epoxy tape to provide cooling passages.

Coil Banding. The coils are held against the beam tube by pretensioned bands, with a periodicity determined by cooling passage requirements. At present we are using stainless steel ribbon, which is sandblasted and epoxy coated. Before setting the epoxy the ribbon is tensioned and spot welded. Because this banding effort takes so much time we expect to go to a monolithic barber pole band that is wound from end to end. In order to avoid the effects of twisting this banding will be applied in two layers of opposite twist pitch.

Cryostat

The helium vessels are formed by two concentric stainless steel cylinders, separated by force transfer blocks. We are adapting production sheet metal techniques to the fabrication of these vessels in order to minimize the number of machined parts. A support system to hold the helium vessels in the vacuum tube and against the iron has been developed.[6] Basically, a G-10 spider structure that is heat traced at the 20K level by the thermal radiation shield, it now meets the total heat leak criterion that we have established for this component.

Iron Shield. In order to minimize stray magnetic fields, an iron shield consisting of two laminated half cores is planned. The iron contributes less than 10% to the total magnetic field.

Wire Development

For our first full-scale magnets we wanted conductor that could be wound by more or less conventional techniques and, therefore, settled on a monolithic conductor insulated with Formvar. The wire contained 2300 NbTi filaments, 35 μm in diameter, embedded in a copper matrix, with overall outside dimensions of .075 x .150 inch. The short sample test requirement was specified to be 3500A at 5T field at 4.2K. To obtain this high-current density in the magnets the vendor chose a high titanium alloy with which he had little experience. Unfortunately, the actual performance of this wire was less than specified.

In the interim, interest has centered on magnet systems cycling at rates faster than the original 100-second cycle time, and ac losses in the monolithic conductor with its large filaments and large overall size have become unacceptable. We have now moved toward cables of the Rutherford style of construction and of the same overall dimensions as the original monolithic conductor. The first deliveries of cable had the same depressed overall critical current as the solid conductor. However, because of smaller filament size and mixed matrix construction, magnets built with this conductor had better performance. Just recently we have received cable that exceeds our original critical current specifications, has small filament size (12 μm), and stands up to the rough handling during winding. The calculated losses for this conductor are acceptable for both the Saver and Doubler modes of operation.

The Laboratory has also pursued other avenues of wire development. We were able to purchase for stock 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 compare delivery and superconducting properties. All conductor on this program is being fabricated with the Fermilab NbTi and copper so that starting materials are identical. A parallel program with Wah Chang also using the same materials will test certain construction and other processing parameters pertaining to billet extrusion. A total of six billets will be fabricated during this project.

Test Program

Magnet Tests. Magnet testing is reported in detail elsewhere in these proceedings.[5] 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 on magnet performance. The following areas were examined: wire, insulation, and structural restraints. In all cases magnets wound with cable performed better with respect to both training and ultimate field levels than magnets wound with solid monolithic conductor. There is still a problem with the insulation scheme. Because we desire that liquid helium permeate throughout the windings, a barber pole, taped insulation scheme was adapted. Magnets insulated with tapes containing a higher percentage of glass have proved to be more resistant to burn out than those insulated with tapes of high polymer content.

Most of the testing work has been aimed toward obtaining high field magnets. Field quality has not been explored in the past year, but earlier work has shown that field quality can be made acceptable and reproducible from magnet to magnet.

Also, reported in these proceedings are measurements on the magnet suspension system.[6] The supports, which are made of G-10, epoxy-glass laminate, and heat traced at the 20K level, meet the heat leak standards established early in the program.

In order to test the operation of magnets under conditions of beam loading, a main ring to Energy Doubler beam transfer line has been completed and installation of the first Doubler magnet is in progress.[7] Also, an experiment is underway to determine the effect of 300 GeV protons on the resistivity ratio of the matrix material.

Résumé

The changing needs of high-energy physics research and altered funding circumstances have brought some modification to the Energy Doubler program. In particular, strong emphasis is now being placed on examining the advantages of implementation of the Energy Saver concept. Our next goal is to pull together the sundry subsystems into an operating entity that can be used to manipulate a proton beam. In doing so much will be learned about the problems to be encountered in building and operating a total Energy Doubler/Saver accelerator.

References

1. D. A. Edwards, et. al., "Progress Report on the NAL Energy Doubler Design Study," Proceedings of the IXth International Conference on High Energy Accelerators, SLAC, May 2-7, 1974, p 184.

2. H. T. Edwards, "Injection and Extraction for the Energy Doubler," 1973 Summer Study, Fermilab Report SS-73.

3. P. C. Vander Arend, et. al., "Cooling of a System of Superconducting Magnets by Means of Pumped Liquid Helium," Proceedings of 1974 Applied Superconductivity Conference.

4. P. C. Vander Arend, et. al., "Design, Construction and Operation of a Prototype Pumped Liquid Helium System for Cooling Superconducting Accelerator Magnets," IEEE Trans. Nucl. Sci., Vol. NS-22 (1975)

5. D. Drickey, et. al., "Performance Studies of Superconducting Dipoles for the Fermilab Energy Doubler," ibid.

6. M. Kuchnir and P. Sanger, "Thermal Inductance Measurements of Mechanical Supports for Superconducting Magnets," ibid.

7. C. Rode, et. al., "Operation of an Energy Doubler Magnet in the Extracted Beam of the Fermilab Accelerator," ibid.

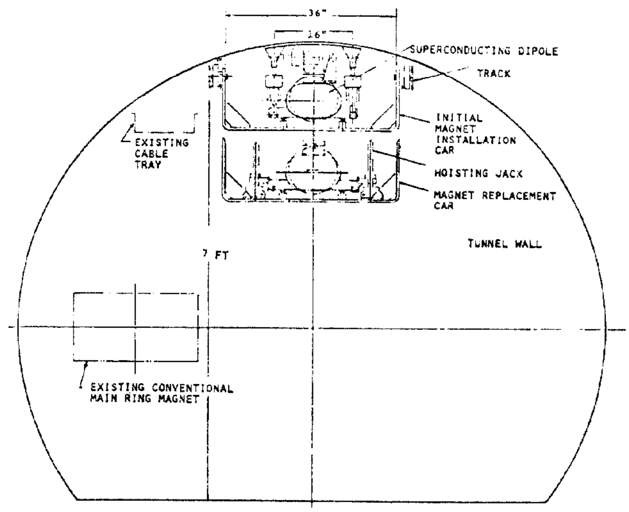

Fig. 1. A Cross Section of the Main Ring Tunnel Showing the Magnet Installation Concept.

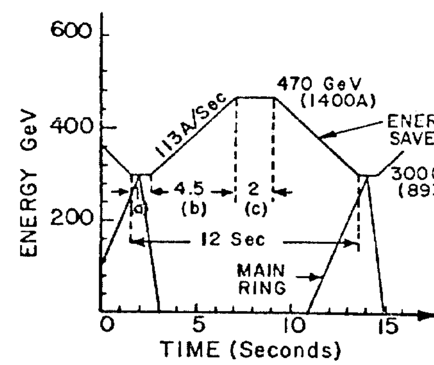

Fig. 2. The "Energy Saver" Cycle.

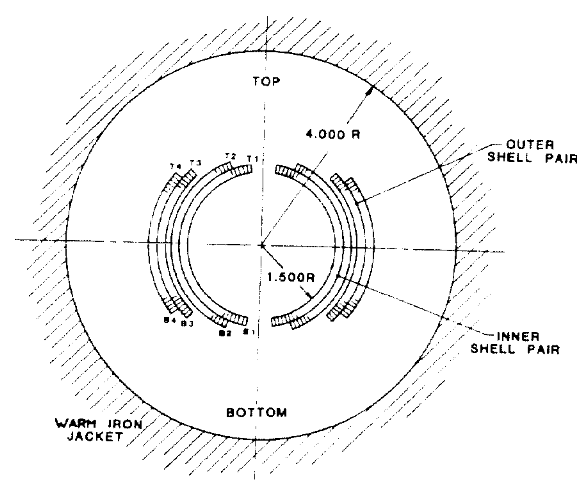

Fig. 3. A Cross Section of the Four Shell Reference Design for Energy Doubler Magnets.