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PROGRESS REPORT ON THE NAL ENERGY DOUBLER DESIGN STUDY

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Summary

For close to a year and a half, a study has been in progress at NAL to examine the feasibility of constructing the "Energy Doubler" - an accelerator employing superconducting magnets which would increase the energy of protons available at the Laboratory substantially above that provided by the present accelerator system and possibly to 1000 GeV. In this paper, we report on the progress to date and on plans for continuing the study in the immediate future.

The Energy Doubler Concept

The design parameters of the NAL accelerator were set primarily by the funds available for construction. There was no sharp guideline of an energy threshold at which some crucial physics hypothesis could be tested, nor did accelerator technology dictate a limit to the energy that could be achieved. Thus, there was considerable incentive to build a potential for higher energies and to conserve funds so that this potential could be realized within the initial $250 million construction authorization for the Laboratory.

The NAL proton synchrotron was initially intended to be a 200 GeV machine. It now regularly operates at 300 GeV and has occasionally produced protons at 400 GeV. In the near future, tests at energies up to 500 GeV are planned.

It was recognized early in the project that an even higher energy or an improved duty cycle was conceivable if a ring of superconducting magnets were to be installed in the same enclosure as the present main accelerator, which would then act as the proton source for the superconducting ring. Space in the tunnel and in the service buildings has been saved for just such a possibility. Because superconducting bending magnets might be expected to reach 45 kG, twice the field of the conventional magnet ring at 500 GeV, the superconducting ring has been designated an "Energy Doubler."

Origin of The Design Study

After the accelerator came into operation in 1972 and high energy physics experiments got underway, it was not only possible to devote some attention to the Doubler idea but it was also timely. 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 a reasonable state of completion and some $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 authorization. The design effort to date represents a first step in the exploration of this possibility.

Though the next section offers comments on the various roles that the Doubler might play at the Laboratory, the purpose of those remarks is intended only to provide a context within which to view the subsequent discussion, since the emphasis of the work thus far has been on magnets and refrigeration. There are many other accelerator-related topics that deserve study, but given the limited resources that could appropriately be diverted from far higher priority activities associated with bringing the accelerator performance up 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.[1]

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

- the Doubler cycle time will not exceed 100 seconds but in order that thermal loads originating from time varying currents not be the major factor in determining refrigeration system capacity and cost, shorter cycle times are not essential.
- 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 non-saturating, two criteria intended to provide magnets whose fields are linear with excitation and within the smallest possible total cross-section, including dewars and to reduce the refrigeration requirements for reasonable cool down times.
- the superconducting material will be NbTi since this is the only material which industry presently is able to provide in a filamentary configuration in large quantity.
- 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.

The discussion below will summarize the work thus far in developing cryogenic systems and magnets consistent with the above.

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. Only limited variations from the disposition of magnets in the present accelerator is possible for the doubler lattice, having selected the enclosure. For

* Operated by Universities Research Association, Inc. under contract with the U. S. Atomic Energy Commission.

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, but for the purpose of this discussion it is sufficient to think that the Doubler replicates the main accelerator bend-for-bend and quadrupole-for-quadrupole.

We have adopted a length of 20 feet for our superconducting dipole prototypes - the same length as the conventional dipoles in the main accelerator. A total of 744 such magnets would be required. A duplication of the main ring lattice implies 192 normal cell quadrupoles and 48 long straight section matching quadrupoles. If the tune of the Doubler is to be the same as that of the main ring, then $B'l$ for the normal cell would be 1260 kG-m at 1000 GeV, and just over 60% of that figure for the matching quads. Thus a total of 1014 superconducting magnets are needed for the Energy Doubler.

Uses for the Doubler

As a Conventional Accelerator. In its basic form, the Energy Doubler idea is that of a slow-cycling machine with a period of 100 seconds or less at 1000 GeV, but not an order of magnitude less. Today the typical operating intensity of the NAL accelerator is 8×10^{12} protons per pulse with a 6 second cycle at 300 GeV. If, by the time the Doubler is functioning, the accelerator has achieved its design goal of 5×10^{13} protons per pulse and if this charge can be conveyed to, accelerated in, and extracted from the Doubler without significant loss, then a 60 second cycle time Doubler would deliver to the external beam lines approximately the same average intensity as the accelerator produces at present. Of course, for internal target experiments causing negligible diminution of the circulating beam current, the effective intensity is independent of cycle time. Fig. 2 shows how the accelerators might operate in this mode. In this and the following examples let's assume that the Doubler ramp rate is limited to 20 GeV/sec. One out of every ten 300 GeV main ring pulses is injected into the Doubler; the remaining nine are extracted and used as at present. The Doubler accelerates to 800 GeV at which energy the beam is extracted. Higher energies would imply longer Doubler cycle times.

As an Energy Saver. The present accelerator system, operating at 300 GeV with a 6 second repetition rate and a 1 second flat-top, requires an average power of somewhat over 40 MW. This already substantial demand increases rapidly with higher energy or duty factor. It is easy to think of ways in which a superconducting ring may help in this situation. Fig. 3 illustrates two approaches to a 12 second 400 GeV cycle each having a duty factor of ~ 1/6. The dotted line represents the main accelerator going to 400 GeV with a 2 second flat-top. The average power required is 60 MW. In contrast, the solid lines depict an acceleration in the main ring to 300 GeV, fast transfer to the Doubler, acceleration in the Doubler to 400 GeV, and subsequent extraction using a 2 second flat-top. We estimate the average power required in this case to be 22 MW, almost a factor of three less than that associated with the present accelerator system alone.

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 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 NAL Long Range Advisory Committee has recently 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 accomodate 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 thereby simplifying their construction.

Dynamical Questions

Since the Energy Doubler as pictured here closely resembles the main accelerator in number and disposition of magnets, many of the aperture arguments are the same for the two machines and need not be detailed here. Finding and improving a closed orbit, provided a suitable beam position monitoring system is available, is a well-understood problem. Given reasonable magnetic measurement data, a careful survey, and a means for beam steering, it is likely that a circulating beam can be obtained without unusual difficulty insofar as magnetic length and placement effects are concerned.

Efficient extraction imposes a more severe aperture requirement. In a resonant extraction scheme the aperture has to be large enough in the extraction plane to permit a betatron oscillation of sufficient amplitude to develop so that the amplitude-dependent step size becomes sufficient to jump an extraction septum with high efficiency. A measurement made at 300 BeV in February of this year indicated that the extraction system of the main accelerator uses 1.3 inches of aperture in which the unstable betatron oscillation builds up. To this we add twice the septum channel width of 0.4 inch, and arrive at an aperture requirement of 2.1 inches. At present, the extraction efficiency is typically 96% and is limited by effective septum thickness.

The full scale Doubler prototype dipoles discussed below have a geometrical (in contrast to good-field) aperture in the horizontal plane of just under 2.2 in. Though the fundamental guide line in the doubler proposition is the acceleration of protons to the 1000 GeV range at minimum cost, clearly their effective delivery to external experimental areas is a most desirable feature, and it remains a subject for further study to determine whether or not improvements in the extraction scheme or in the good field width of the magnets can be made to compensate for the aperture constraints considered here. As the design progresses it may also be necessary to make the magnets slightly wider in order to accomplish high efficiency slow extraction from the Doubler.

The second principal accelerator related question associated with the Doubler magnet design concerns non-linear effects. Interpretation and correction of non-linear resonances in the main accelerator has proved to be a difficult and time-consuming process. Measurements on field quality of the superconducting

magnet prototypes produced thus far give cause for concern. The cost trade-off between increasing the coil aperture to improve field quality versus an elaborate correction system remains to be assessed.

Refrigeration System

The design principles upon which the magnet cooling system is based were reported at the 1973 Particle Accelerator Conference in San Francisco.[2] Very briefly, the idea is that subcooled liquid helium will be pumped from 12 (or 24) refrigeration stations, located at 12 (or 24) main accelerator service buildings into the coil colume of magnets situated upstream and downstream of each such station. At the point halfway to the next refrigeration station, the coolant will pass through a Joule-Thompson pressure reduction valve, and flow back toward the refrigerator as boiling liquid in an annular space surrounding the subcooled liquid helium coming from the refrigerator. One of the 12 (or 24) modules of the system is sketched in Fig. 4. The realization of this scheme with the magnets is discussed under Magnet Development below. In this section we report on experimental work on the pumped helium feature and on progress toward a refrigerator specification.

Liquid Helium Pump Loop

Large pumped helium systems of the sort required for the Energy Doubler have not been built. Accordingly, a significant effort in the design study is the construction and testing of a liquid helium pump loop on a scale large enough to provide experimental verification of Energy Doubler refrigeration concepts. A detailed report on the pump loop will be published shortly;[3] here we summarize this activity.

The basic pump loop system is sketched in Fig. 5. Refrigeration is provided by a 150-200 ℓ/hr helium liquefier (equivalent to ~ 600 W of refrigeration at 4.5°K) purchased from Gardner Cryogenics, Inc., which makes liquid into a reservoir. The reservoir contains a liquid helium pump which circulates liquid helium through the pump loop. In addition to the liquid helium pump, the reservoir contains a heat exchanger, which (together with a vacuum pump) will make it possible to operate the loop at temperatures as low as 3.6°K.

The loop itself consists of 2 lengths of 200 feet of coaxial pipe forming a total length of 400 feet (space constraints required that the line double back on itself). The helium pump forces liquid through the inner tube. At the end of the 400 feet, the liquid is expanded through a Joule-Thompson valve and low pressure liquid helium returns through the outer annulus to the reservoir. Typical temperatures of the subcooled supply and low pressure return streams are 4.6°K and 4.4°K respectively. The pressure difference between the two streams lies in the range of 5-15 lb/in^2. The loop is equipped with temperature, pressure and flow monitors, heaters that simulate the thermal loads of magnets, and valves to simulate the pressure drops of the magnets.

It is intended that Energy Doubler magnets will be inserted in the loop by removing sections of pipe and replacing them with magnets. Even without magnets, however, an interesting and useful test program has carried out.

The system has been operated for three runs of 109, 70 and 106 hours duration. These tests were vary valuable in giving experience in the operation of a cryogenic system on this scale. As noted above, discussion of the results will appear elsewhere;[3] we only enumerate some of the subjects of study here.

Pump Characteristics. The liquid helium pump was purchased from Sunstrand Aviation and was developed for this applicatio based on their experience with liquid hydrogen pumps. Measurements of flow rate versus developed head are in agreement with predictions of the manufacturer. To illustrate a typical operating condition, a flow of 215 lbs/hr corresponds to a pressure rise of 10.4 lbs/in^2 across the pump.

The electrical power measurements compare favorably to the power measured by the fluid properties. Heat input to the liquid for the aforementioned condition is approximately 61 watts.

Pressure Drops. Under all flow conditions, as expected, pressure drops were quite low. Measured psi drop on the liquid line as measured by the pressure gauges for the 400 foot loop are in the region of 20" of H_2O.

The pressure drop as measured on the 2 phase return line, with an unknown quality, is approximately 42" of H_2O.

Precise measurements will be made with the installation of improved instrumentation.

Heat Transfer. By energizing heaters in the subcooled helium pipe and observing temperatures in the two streams, the heat transfer coefficients between the subcooled and two-phase regions can be determined. The measurements are in agreement with calculations, the principle uncertainty being in the quality of the two-phase flow.

Thermal Oscillations. In the first run, thermal oscillations, sometimes of magnitude sufficient to cause visible motion of the entire pump loop, were frequently observed. Modifications - principally the conversion to cold check valves - eliminated these oscillations at design flow parameters by the time of the third run.

Magnet Development

Superconducting Wire

For our first full scale prototype magnets, we settled on a multi-filament NbTi wire, consisting of about 2300 filaments 35 μm in diameter embedded in a Cu matrix, with outside dimensions of 0.075 inch x 0.150 inch including a 0.002 inch layer of polyvinyl and formvar insulation. The short sample test requirement was specified to be 3100 A in a 50 kG field at 4.2°K. This configuration offered the high current and high current density desired for our magnets (2815 A and 43.6 kA/cm^2 at 45 kG) yet was also felt to be achievable with present technology.

Since we are interested in developing magnets with coils that can be wound by more or less conventional techniques in industry, the conductor should resemble a "stiff" copper wire. Initially, this presented some

problems at the current densities desired since most conductors offered when this project began optimized the critical current density by cold working the wire. In response to our invitations for proposals, Magnetic Corporation of American recommended the use of superconducting alloys that would optimize the critical current by the solid state precipitation of submicroscopic normal particles within the filaments. An order was placed with this vendor, and the conductor that they have supplied has met our specification with regard to critical current. With few exceptions, the "windability" of this material has been excellent.

With its relatively large filament size and low-resistivity matrix, this conductor is not suited to high repetition rates. Calculations indicate that hysteresis losses dominate at a 100 second repetition rate and it is not until cycle times shorten to about 10 seconds that hysteresis and coupling losses become comparable.[4] Insofar as the initial conductor order was concerned, we felt that the more important goal was to establish that a high current density wire could be made and that later industry could develop a similar wire but with smaller filaments. We also have on order a quantity of cable conductor sufficient for the fabrication of two full scale dipole prototypes; this cable is to be made of seven wires each containing filaments less than 20 μm in diameter and separated one from another by a high resistivity material (cupro-nickel).

The Energy Doubler would require 6 million feet of superconducting wire. An order of this size would have considerable impact on the industry. We expect that for these lengths, the cost per foot would come down to an asymptotic level approaching less than half of present costs. Additionally, the cost difference between a relatively sophisticated small filament cable and a larger filament wire may be small. Fig. 6 shows our estimate of cost per foot as a function of total length.

Magnet Design and Fabrication

Here we will only summarize work on dipole magnets. A full-scale quadrupole prototype is nearing completion; however, the emphasis so far has been on dipoles. Fig. 7 shows a transverse section through a magnet.

The Bore Tube. The bore tube forms both the vacuum chamber and the locating surface for mounting the coils. In cross-section, the tube geometry consists of two semi-circles joined by flat portions top and bottom to provide a proton beam aperture measuring 2.2 inches horizontally by 1.4 inches vertically. The bore tube is a composite of an inner 0.032 inch stainless steel pipe with a molded epoxy-fiberglass coating to provide a reproducible insulating base for the coils.

Coils. The coils are wound as three concentric shell-like layers, with conductor placement calculated to provide a field uniform to 0.1% within a region similar in shape to the inner surface of the coils but 25% to 30% smaller in linear dimensions. The conductor is graded in size for economy; a smaller cross section wire (0.050 inch x 0.150 inch) formed by an additional drawing of the basic conductor is used in regions of sufficiently lower field. Prior to winding, the wire is keystoned so that it may be close-packed into the shell configuration. Winding is performed on a specially designed fixture in which the mandrel oscillates about its longitudinal axis while the conductor supply reel "walks" at a programmed speed around the table in which the mandrel is mounted.

Coil Cooling Passages. Liquid helium flows along the length of the magnet in the spaces above and below the coil. The conductors are to be cooled by vertical convection through passages between the innermost coil and the bore tube, between the inner shell and the second shell, and between the third shell and the wall of the vessel. It is intended that at least 40% of one edge of every conductor be exposed to the convective flow, that fraction representing a compromise between the demands for cooling on one hand and for adequate rigidity of the structure to withstand the magnetic forces on the other. The passages are formed by circumferential grooves on the bore tube, by G-10 spacers between the first and second coil shell, and by the banding on the outer coil bundle as described below. In the present design the passages extend 0.25 inch in the dimension parallel to the axis of the magnet. The two inner passages are 0.062 inch in depth.

Coil Banding. The coils are held against the beam tube by prestressed bands, with a periodicity and width determined by the cooling passage requirements mentioned above. Until recently, a thin high strength mylar was used as the banding material, applied at a tension of ~ 80% of its breaking strength. As this material was available in a thickness of only .00075 inch, 210 layers were needed to produce the required strength resulting in an overly costly and time-consuming stage in magnet fabrication. At present, we are using stainless steel as the banding material.

Cryostat. The helium vessels are formed by two concentric stainless steel cylinders, separated by a corrugated structure to transfer electromagnetic forces on the magnet to the suspension members. These, containing the coil, form the 4-5°K volume of the magnet. A precisely centered energized coil is in unstable equilibrium with respect to the shield; at 45 kG, the "negative spring constant" is ~ 750 lb/in. Thus a strong, low heat loss suspension must be interposed between the inner chambers and the outer cryostat jacket. The use of an intermediate temperature (15-20°K of gaseous helium) shield makes this problem more tractable and is now being incorporated in prototype magnets. Prototypes completed to date have, for simplicity, not included a heat shield, and although considerable effort has gone into the development of a suspension which would be adequate for use without the shield, the results have not been encouraging.

Iron Shield. The iron enhancement shields consist of two laminated half cores stacked in one of the original main ring magnet fixtures with a precamber to compensate for the subsequent deflection under gravity. The laminations are first roller coated with a room-cure epoxy and stacking of a 20 foot half-core is then easily accomplished within the three hour pot life of the resin.

Ends and Interconnections. In a sense, the transverse section described above is the simple part of the magnet. Space does not permit us to describe present designs for ends and interconnections, which

may be fortunate, since ideas concerning these aspects of the magnets are changing daily.

Magnet Tests

Prior to the construction of the first full scale prototype dipole, seven short magnets (6 dipoles and 1 quadrupole with lengths ranging from 12 inches to 40 inches) were built. The first five were in a sense fabrication studies.[5] Two coil geometries were in competition - the shell configuration described above and a pancake style. Tests in both vertical and horizontal dewars suggested that the shell offered a geometry more appropriate to effective cooling. As a result, the shell coil was adopted for further development.

The last two of this seven magnet series were a pair of 30 inch long dipoles intended to be identical. Comparative measurements of magnetic length and field quality were made in order to determine whether or not the magnets were indeed identical insofar as the design goals established for them were concerned. Their magnetic lengths did in fact agree at the 0.1% level, however a significant quadrupole component in both magnets (~ 0.4%/inch) indicated that some symmetry had been lost in construction.[6]

In general, results on this set of short prototype magnets were quite encouraging. The superconducting wire procured for the full scale magnets was not yet available, so the coils of these magnets were wound from a variety of conductors available at the time. These conductors did not permit excitation to the 45 kG level demanded of the Doubler, however, in all cases, these short prototypes were capable of excitation at ~ 90% of the short sample current for the materials used in their fabrication. In all cases, magnets were tested in pool-boiling helium.

In February of this year, a full scale, 20 foot long prototype was ready for test. This was the first magnet wound from the wire intended for use at 45 kG. Also, it was the first magnet incorporating the complete counter flow cooling scheme proposed for the Doubler. Thus far, the performance of this magnet has been, in general, unsatisfactory. It has quenched repeatedly at low current levels - less than 50% of design current. Though the current at quench has been increasing gradually, whether or not the magnet would eventually reach its design current is an academic question, for the processing of a large number of magnets in this way is impractical. Nevertheless, the construction of a full scale magnet at the earliest possible time in our program was very valuable in suggesting improvements in fabrication methods.

In order to isolate and identify the source, or sources, of difficulty in the full scale magnet we are now engaged in a program of testing 30 inch long dipoles. These magnets have geometrical cross sections similar to the 20 foot doubler magnet but allow us to make changes in magnet construction in a known and controlled way - for example, operating with one, two or three shells. To date, a three shell version identical to the 20 foot magnet except for length and stainless steel vice mylar banding has exhibited behavior similar to the 20 foot magnet and a single, inner shell version impregnated with epoxy and banded with stainless steel has gone to the short sample limit, 4500 A at 23 kG, in a vertical dewar. This program is continuing in full force and is expected to shortly provide the engineering data that will allow us to resume construction of the 20 foot magnets.

Plans for the Near Future

As the discussion of the preceeding paragraphs would imply, our immediate goal is the production of full scale dipole magnets capable of excitation to fields in the neighborhood of 45 kG without excessive processing.

The next phase will bring the magnet and refrigeration systems programs together by installation of a series of magnets in the pump loop. Actually, a step in this direction is already underway, for the second full scale prototype is being readied for insertion in the loop. This magnet does differ significantly from the first, so its excitation characteristics are likely to be the same, however, useful experience will be gained in the loop system by this exercise. Completion of this phase will be marked by the insertion in the loop of a complete basic lattice period of the Doubler - 8 dipoles and 2 quadrupoles.

As indicated earlier, the design effort to date has been highly concentrated on the magnet and refrigeration system for the Doubler in order to establish their feasibility for a cost of something like $20 million. So far, in order of descending confidence, we have had industrial estimates made on the refrigerator, the superconducting wire and the magnets. On this preliminary basis, it appears hardly possible to talk about these items being accomplished for the period we have allowed. We have a long way to go, however, in completing the design and building satisfactory prototypes and production models before we can say something in more definite. We, like everyone else, are also experiencing shortages and higher costs for raw materials, and the current state of uncertainty in the economy will no doubt play an as yet unknown role in the final estimate for the doubler, particularly in view of the instability of the superconducting wire business.

Acknowledgements

Many more members of the Laboratory staff have contributed to this effort than is reflected in the authorship of this particular paper. Magnet design and fabrication has been carried out by Technical Services headed by H. Hinterberger; G. Biallas, R. Brocker, and W. Hanson have devoted much of their time to this activity during the past year. S. Snowden of the Accelerator Theory Group has performed a number of the more difficult calculations relating to the magnets. We are indebted to R. R. Wilson for his support, guidance, and welcome participation.

References

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2. P. C. Vander Arend and W. B. Fowler, IEEE Transactions on Nuclear Science, Volume NS20, No. 3, 119 (1973).
3. To be presented at the 1974 Applied Superconductivity Conference, September 30, 1974.
4. W. Gilbert, LBL, Private Communication.

5. Tests on the first two magnets of this series were reported by P. J. Reardon et al, IEEE Transactions on Nuclear Science, Volume NS20, No. 3, 744 (1973).
6. NAL Technical Memorandum TM-456-0428, by B. P. Strauss and D. F. Sutter, "Evaluation of Matched Superconducting Dipoles."

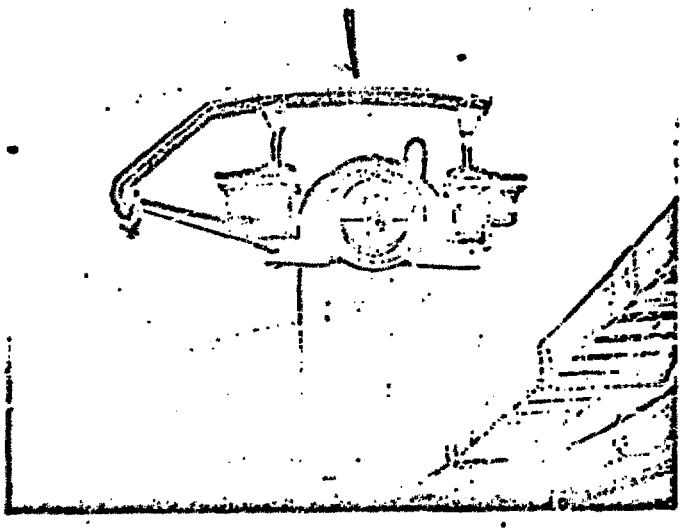

Fig. 1. A model magnet and suspension system hung in the present NAL Main Ring.

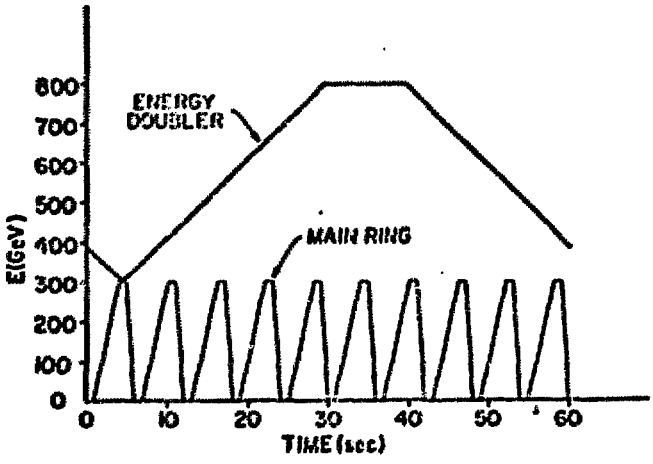

Fig. 2. The proposed Energy Doubler cycle superimposed on the present Main Ring cycle.

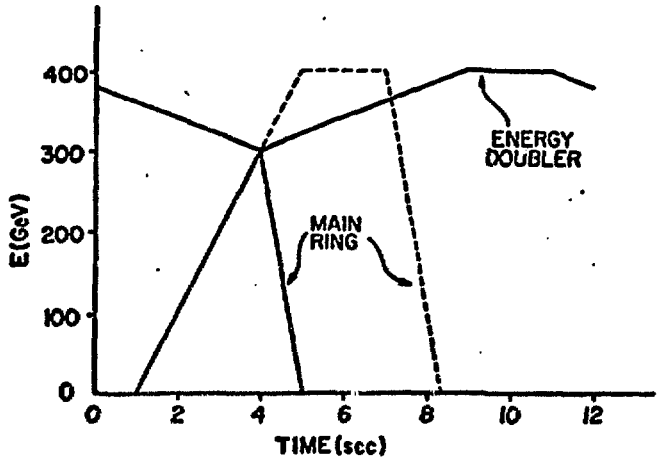

Fig. 3. The proposed energy saver cycle. Here the Energy Doubler is used to accelerate protons from 300 to 400 GeV and provide an extended flat-top.

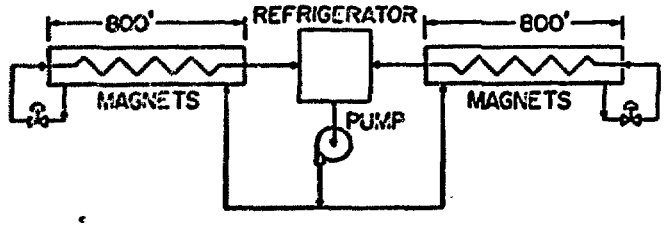

Fig. 4. Schematic diagram of the pump loop showing one refrigerator servicing the magnets between two service buildings. Note the main features of the pump and the Joule-Thompson expansion valves at the end of each string of magnets.

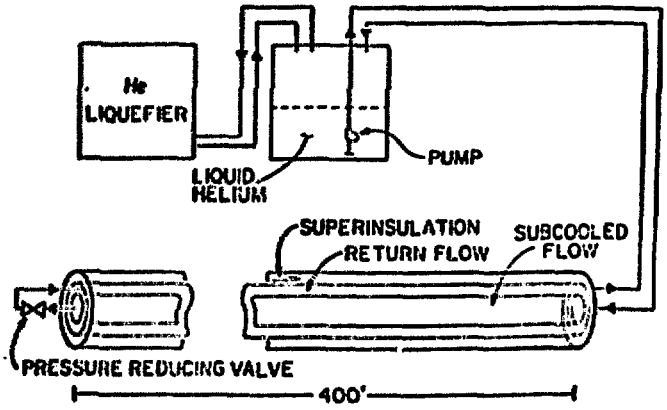

Fig. 5. Schematic diagram of the pump loop presently installed in a prototype tunnel at the NAL Village. This is basically the same system shown in Fig. 4 except for the elimination of the magnets.

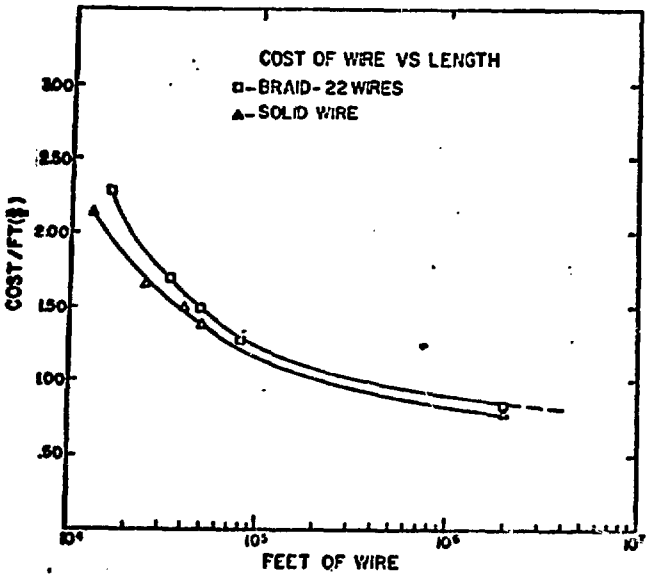

Fig. 6. The estimated cost of the present conductor for the Energy Doubler as a function of the total order is shown. It is assumed that at high quantities sufficient economies of scale will bring the price down to less than half of the present cost.

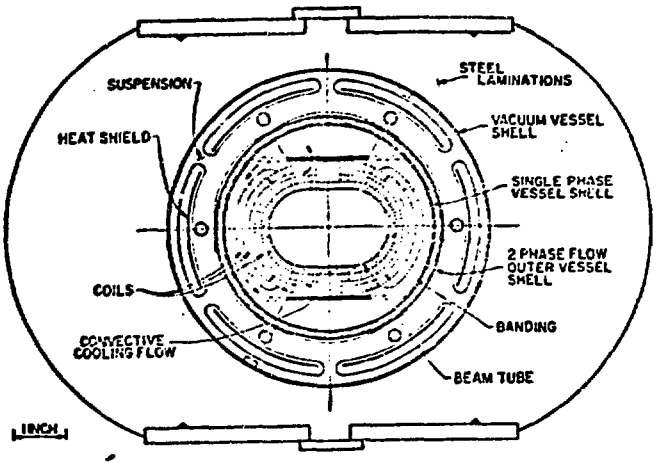

Fig. 7. Transverse section through the latest version of the Energy Doubler dipoles. This shows a fully shielded magnet. Note the features of warm iron, counter flow dewar, heat shield and low loss suspension.

NOTICE

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