SUPERFERRIC MAGNETS FOR 20 TeV

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Whether the next large proton accelerator (20 TeV ?) is built on a national basis or as an international effort, to be affordable, innovations in construction must be made. The design of a superferric magnet ring buried in a pipe in the ground is explored here to see what reductions in cost might result. Rather detailed attention will be given to the possibility of construction of such a magnet ring while the more important questions of injector, lattice, instabilities, etc. will be ignored.

Superferric magnets (an old idea) use iron to shape the field and superconductors to excite the field. Although in principle constrained to lower magnetic fields than can be reached in purely superconducting magnets,* superferric magnets have the advantage of simplicity, of being more sparing in the use of superconductor, less sensitive to the position of the superconductor, easier to construct, and perhaps more reliable to use.

A nominal 2.5T superferric bending (dipole) magnet of aperture (1 in. × 2 in.) is shown in Fig. 1 and a 100 T/m focusing (quadrupole) magnet of the same aperture is shown in Fig. 2. The conductors could be four straight bars of NB_3Sn. Each dipole magnet might be about 500 ft long (probably made up of shorter sections) and each quadrupole magnet might be about 20 ft long.** The dipole might be contained in a culvert pipe 3 feet in diameter buried 6 to 8 feet underground as indicated in Fig. 3. For a field of 2.5 Tesla in the dipole, a 20-TeV proton would require a ring approximately 30 km in radius (~120 miles around). The culvert would extend underground along the proton orbit from one manhole to the next, the manholes occurring every 600 feet or so. At each manhole the culvert would be increased in size to become a tunnel about 8 ft in diameter, the tunnel extending for about 20 ft to give access to one end of the dipole, to one end of the quadrupole, and to the complete length of the free section which would contain leads, metal bellows, beam sensors, correction magnets, etc. The dipole and quadrupole would be joined together within the 8 in. vacuum pipe back in the culvert.

The culvert would also serve to pick up vented He. It would continue (with a removeable top) through the 8 ft access tunnel--the leads, etc., coming out through the wall of the pipe. An important ingredient of the inaccessible buried pipe is the robot (or army of robots) suggested by R. Lundy. A robot is shown schematically in Fig. 3 where it can be seen to roll along rails fastened to the sides of the pipe. The robots should be able to adjust the positions of the dipoles and quadrupoles even with the beam on by turning the adjusting screws indicated schematically in Fig. 3. Each robot would carry a precision level and by fastening itself to indexing points on the magnets should be able to maintain the verticality of the field direction. The robots would be able to lock onto a laser beam which would shine from one manhole to the next, the laser first having been set up by another robot. There are other chores that robots could accomplish: sensing temperatures, magnet positions, beam positions, etc., not to mention fetching and carrying.

Let us return to the superferric magnets. A model of the magnet shown in Fig. 1 designed to reach 2T but with a 1.5 in. gap was made by J. Heim, H. Hinterberger, and J. Jagger[2] of ordinary mild steel using standard Tevatron NbTi superconductor. It was tested by A. D. McInturff[3] in a boiling helium cryostat. It speaks mostly for the skill of the men involved with the work that within one week they had built and tested the 1 ft long model. Perhaps it also says something about the simplicity and forgivingness of a superferric magnet compared to a straight superconducting magnet.

The measured value of the magnet field as a function of current is shown in Fig. 4. The curve is linear to 2T and reached 3T with a saturation of 25%. The return path of the flux as shown in Fig. 1 has been nearly doubled over that of the model in the hope of considerably decreasing the saturation at 3T. K. Ishibashi[4] calculated the curve of Fig. 4 (solid line) including the effect of saturation of the iron. The fit is remarkable. Figure 4 also shows his computation (dashed curve) of the sextupole component of the field. It takes off at 2T as it should for a magnet designed only to reach that field. However, the question is raised as to how high a field with accelerator quality can be reached with better steel and with increased yoke thickness.

There are a number of tricks for reducing the sextupole field by placing holes in the iron at appropriate places. The sextupole moment can also be compensated by inserting specially shaped laminations (as indicated by the dotted lines in Fig. 1) every few inches. At low field these would have no effect, but as the iron at the gap would begin to saturate, the effect of the shape would tend to compensate for the effect of saturation. An experimental program should be instituted to find to what field superferric magnets can reach. On the basis of the model test, it is assumed here that 2.5T is feasible, but perhaps 3T or even higher can be obtained.

Let us now make some remarks about burying the magnet and then return to the problem of assembling it. The ditch for the culvert would first be dug to a depth of 6 to 8 ft for a few thousand feet ahead of the emplacement of the magnets and following the carefully surveyed line of the proton orbit. The culvert would be divided into a lower half and upper half. The lower half would be installed immediately behind the ditch digger so as to be supported in a short bed of concrete at the bottom of the ditch every 10 ft or so. The support screws for the magnets could then be welded in place at the concreted positions. An accuracy of placement of about 1/4 in., following an even more accurate survey, should be attained.

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*Gordon Danby, who has been an early proponent and designer of superferric magnets, would probably dispute this statement.[1]

**These lengths are nominal: they could change by a factor of two, depending on the accuracy of magnet construction compared to the accuracy of magnet placement.

Although the ideal would be to squeeze magnet into the culvert like toothpaste, and one can think of approximations to this, let us assume instead that 100 ft lengths of magnet are assembled in a portable factory that can be moved so as to be not farther than about 10 miles from the places where the magnets were being inserted into the culvert. Magnets could be being made in parallel in the factory for insertion at different places around the ring. Helicopters are indicated for transport, although trucks could be used as well.

Let us discuss the installation of magnet units in the culvert: we pick up the story after several units have already been installed. The unit would be made such that about 6 in. of the inner magnet (the iron part) would protrude beyond the enveloping nitrogen shield and outer 8 in. o.d. vacuum tube. The magnet unit being inserted would be brought up next to the already inserted magnet and connections would be made in the vacuum pipes and superconducting cables. The separation between magnets then might be about 6 in. and no relative expansion or contraction would be allowed for--the joint being made very firm. The approximately 10 in. of contraction in length that would occur at each end of a whole dipole magnet as it cooled to liquid He temperature would be taken up by the rollers and would be taken care of with metal bellows and loops of superconductor in the enlarged section of tunnel at the manholes. This is where trouble (god forbid!) is likely to occur.

Of course attention would be paid to the problem of differential contraction between the different materials of the inner magnet: the iron, the donut, and the superconductor. These would be matched as well as possible and then the whole structure would be clamped together firmly so that the elasticity of the different materials would take up the stress. Appropriate prestressing is indicated. The superconducting bars could be made up of strands of wire twisted together and passed through a die. This cable, because of its approximately helical form, would expand or contract rather easily.

Next, the nitrogen jacket would be rolled in place and connections made, and then the outer tube could be rolled in place and welded. The whole magnet unit could now be fastened to its adjustable bolts and very carefully positioned, leak checked, etc., etc. The top of the culvert would now be bolted or welded on and the trench filled. If trouble subsequently developed in a magnet unit, the culvert would be exposed using a back hoe, the top removed, and a new 100 ft magnet inserted--probably taking one or a few days.

It has probably been noticed in Fig. 3 that room has been allowed to have two magnet rings within the 3 ft pipe. This would allow for the possibility of pp as well as the $\bar{p}p$ collisions provided by one ring. It also might allow for higher luminosity $\bar{p}p$ than would only one ring. There would also be the possibility of redundancy in the use of one ring: in case of trouble, the beam could be switched from one ring to the next.

How about assembling the 100 ft long unit magnets? The magnets would be made straight and then curved by the position adjustments in the culvert--the displacement being only about 0.01 in. in 10 ft, about 1 in. in 100 ft. The 6 in. o.d. iron pipe which would contain the 1/8 in. thick magnet stampings would be fabricated of four lateral sectors, each 100 ft long. One of these sectors, the bottom one, would be placed on a roller bed and held in a straight position. Then the wedge-shaped key (100 ft long) would be tacked in place in the bottom of the sector by an automatic device which would follow a laser beam from one end to the other. The bottom halves of the laminations would then be loosely stacked on the key--alternating their sense, so the opening of the magnet would be formed but without the top half yet in place.

The four bars of electrically insulated superconductor and the donut would then be dropped in place--the top and bottom walls of the donut would be bowed so that, as the top laminations were pressed into position, the vertical sides of the donut would press out firmly against the superconductor. The magnetic force would also press the bars against the iron walls of aperture. It should not be necessary to have to cement the coils together as is done in Tevatron magnets.

The top laminations would then be dropped in place so as to interleave with the bottom laminations--a jig being contrived so that several feet of laminations could be handled at a time. Another device would then compress all the laminations to a preset mark which would give a uniform mass of steel per unit length, thus insuring uniform saturation properties.

Eventually the top quadrant of the magnet vacuum pipe, with its key already tacked in place, would be lowered into the magnet and the two side quadrants could be put in place. The magnet would then be rolled in steps through a press where four welds would be simultaneously made as the iron pipe and its contained laminations was accurately compacted together. The magnet would then be straightened along its length as much as possible and the top and bottom tracks, in which the thermally insulating rollers would move, would be tacked in place to correspond accurately to the top and bottom keys on the inside of the pipe--no doubt by means of X rays. Of course, the vacuum welds would also be X-rayed and tested before the inner magnet was rolled onto the rollers already in place in the nitrogen shield which would have previously been rolled into the outer vacuum pipe. The completed magnet unit could then be attached to a steel I-beam for handling and for any preliminary measurements that might be made before being transported for insertion in the culvert.

It is not difficult to imagine a "mole" that could be drawn through the magnetic aperture by which means the magnetic field could be accurately measured and by which register points could be transferred to the magnet support bars to correspond accurately to the vertical direction of the magnetic field.* An x-raying device is indicated for determining the position of the mole.

By no means have all the problems of construction been here considered. Most problems would be encountered and hopefully solved by

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*"MULTIVAC was self-adjusting and self-correcting. It had to be, for nothing human could adjust and correct it quickly enough or even adequately enough." (Thanks to C. Ankenbrandt)--Isaac Asimov, "The Last Question," Science Fiction Quarterly, 1956.

actually making magnet units and installing them in a culvert in a test unit about 1000 ft long.

Once the magnet ring was in place and the magnets positioned by the robots as accurately as possible--perhaps to ±0.1 mm--then the beam itself would be used for the really precision alignment. At each manhole would be a beam position monitor and the appropriate correction magnets to lead the beam exactly on center from manhole to manhole--the robots, informing and informed by the computer, heroically and automatically doing the job. Changes in the supporting earth would be compensated in this way as well as the adjustment of the magnets.

The correction magnets presumably would look in cross section like the dipoles or quadrupoles already described with the exception that they would be much shorter and that the coils would be made of many turns of fine superconducting wire in order to reduce the heat leakage of the electrical leads and to be able to use more conventional power supplies. If it should be necessary to conserve space along the beam, there would be no reason not to use much higher fields for the correction magnets. Thus, if necessary to follow an undulating contour of the ground, even 10T might be used.

It has been assumed that the injector would be the usual concatenation of accelerators, each taking the energy up by a factor of about 20. It is also assumed that the initial injector--presumably a linac--would be much superior in beam quality than the present linac injectors so that the beam at injection into the big ring would be considerably less than 1 mm in thickness.

The cluster of injectors and the experimental areas might all be located at one point of the ring in an area say 10 km long by 5 km wide. The straight sections being created in series and parallel by use of 10T magnets.

Once installed the ring ought to be as passive as possible--the action occurring in the laboratory sector. A good ring road about 100 ft inside of the magnet ring would provide access to the manholes and to the utility buildings which would be located about a mile apart. A fence on either side of the magnet ring at an appropriate distance (500 ft) would provide protection against a one-pulse beam accident. The robots, of course, would have full access everywhere, carrying only a sentimental, if atavistic, film badge made of blank paper.

The philosophy has been to consider the ring or rings as a collider only. One would then calculate how fast it could be ramped to provide an external beam and what additional costs would then yield additional beam intensity. Presumably, electron rings would be made on the central site, and eventually in a huge ring that would parallel the large magnet ring to give an electron collider of 100-GeV electrons on 20-TeV protons.

The costs of such a superferric magnet ring will be taken up by R. Lundy and P. Mantsch in the following presentation. Many of the concepts should also apply to superconducting magnets of higher field intensity if, and insofar as, they can be manufactured reliably and economically. It behooves us to strive to demonstrate such magnets by actual actually constructing them for that could make a substantial reduction in the cost of a 20-TeV accelerator.

May I express my thanks to L. Lederman for suggesting that I consider this problem, to R. Lundy and R. Huson for many suggestions, and to the people already referred to who built and tested the superferric test magnet. My attention has been drawn to an abstract of an article by I. A. Shelaev et al., of the Joint Institute of Nuclear Research, Dubna, USSR, who appear to have done much of the work reported here at an earlier time.

References

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3. A. D. McInturff, Fermi National Accelerator Laboratory Internal Report TM-1121.
4. K. Ishibashi, Fermi National Accelerator Laboratory Internal Report TM-1123.

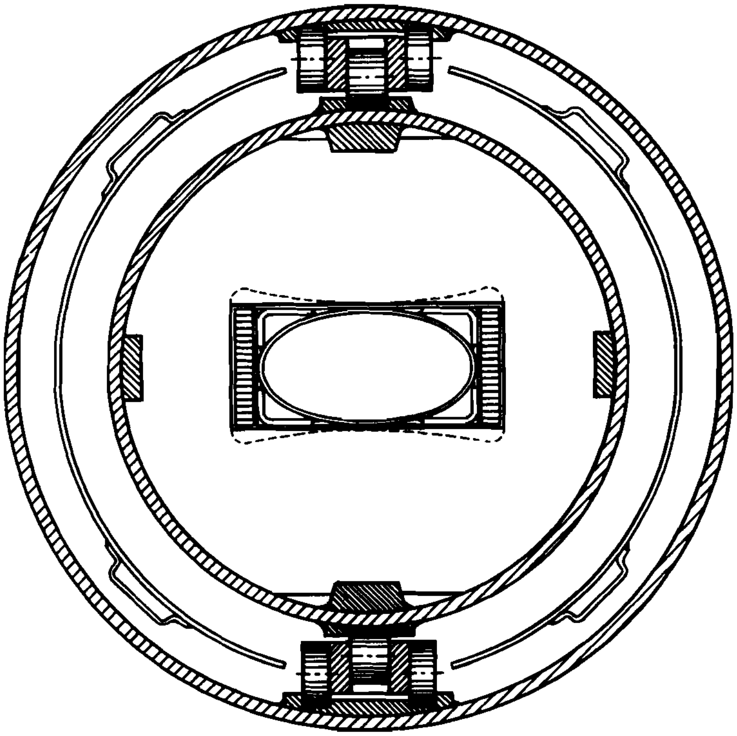

Fig. 1. Superferric 2.5 Tesla dipole magnet.

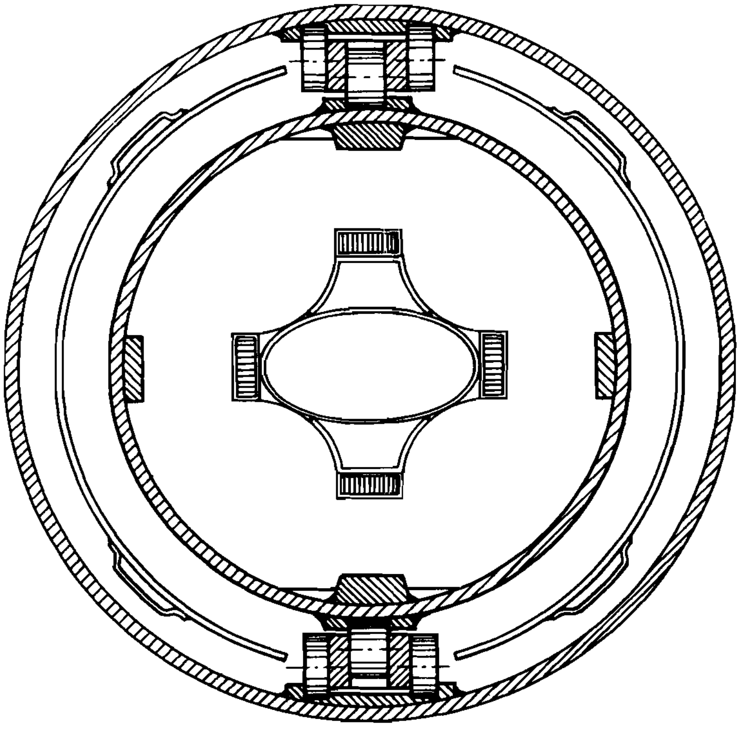

Fig. 2. Superferric 100 T/m quadrupole magnet.

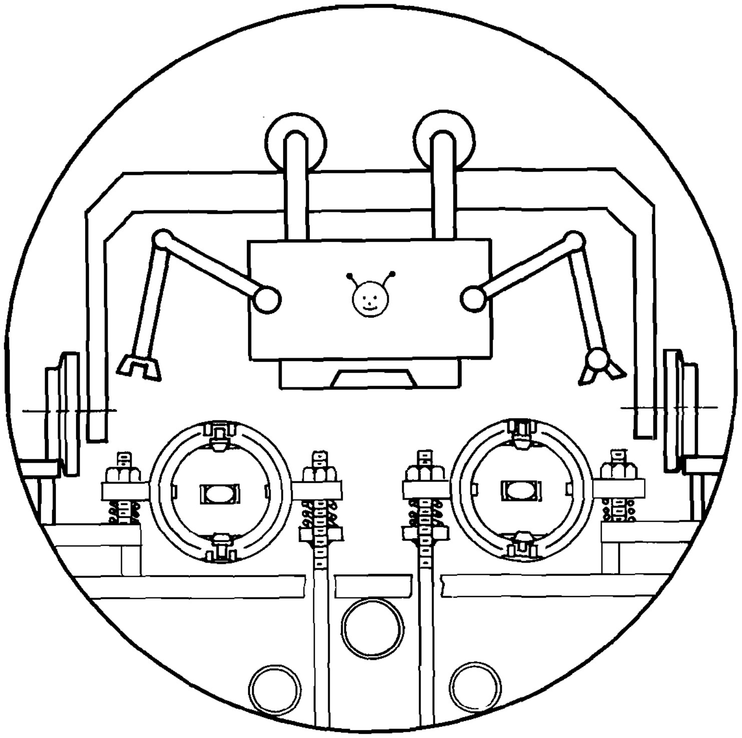

Fig. 3. Cross section of the 3-foot "tunnel" and magnets with an artist's conception of a robot.

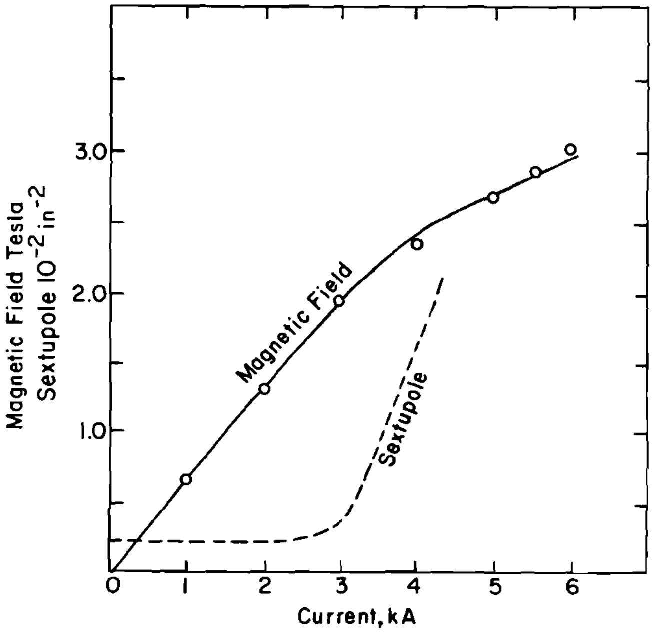

Fig. 4. Dipole and sextupole field for a 1-foot model magnet. Circles are data points; curves are calculated.