Fermilab

TM-845
1600.000

APPLICATION OF SUPERCONDUCTING TECHNOLOGY TO BIG ACCELERATORS

R. Yamada
Fermi National Accelerator Laboratory

I. Superconducting Technology Applied to High Energy Physics

Superconducting technology has been in use in high energy physics since 1966 when a small bubble chamber was made with superconducting wire. Since then a lot of DC superconducting magnets have been made. Bigger and bigger the magnets were made in size and more and more different kinds. The usefulness of superconducting technique has been established. The following is a categorical list of DC magnets which are being used successfully in many different high energy laboratories.

1. Big bubble chambers
2. Analyzing magnets for experiments
3. Big solenoids for colliding and fixed target experiments
4. Beam line magnets
5. Magnets for polarized targets

and the following are now being developed and will be used in the near future.

6. R.F. cavities
7. Pulsed synchrotron and storage ring magnets.

The two main reasons to apply superconducting techniques in wide ranges of high energy physics and its accelerators are:

1. Attain higher field above 20 kG.
2. Save energy by reducing the electrical resistance.

The big bubble chamber magnets in use are a 15' magnet at Fermilab and BEBC at CERN. The Fermilab 15' magnet goes up to 30 kG without an iron yoke. This is one of the great advantages of the superconducting magnet. They have been in use for over four years. The 12' magnet at Argonne has been in use over several years and is now being modified to be used at PEP as an analyzing magnet. The Argonne and CERN magnets use iron as yokes and their maximum fields are 18 and 35 kG respectively; they save power tremendously.

Many analyzing magnets have been made and are in use at many laboratories. At Fermilab there are five analyzing magnets, which are called Hertz, Avis, Delta, and MPS. They use a rather thin wire with a current carrying capacity of about 200 A. The ratio of copper to superconductor is 4 to 1 or 10 to 1. The maximum field of these magnets is less than 20 kG and iron is used for the yoke. They are called superferric magnets, and the field shape is defined mainly by a steel shape as in the conventional magnets. They are made to save electrical power. These magnets are filled with liquid helium once a week or once a day and stay operational. Their usefulness and their easy operation have been appreciated and many other old conventional magnets are now being modified to use superconducting wire. The old Chicago Synchrocyclotron magnet, which is being used as an analyzing manget, and the 30" bubble chamber magnet are being converted to superferric magnets at Fermilab to save power.

Big solenoidal magnets with a diameter larger than 1 meter and with a field strength over 1.5 Teslas have been in use at colliding beam areas at ISR of CERN and at Doris of DESY. Bigger solenoidal magnets are being made: one for PETRA and the other for PEP. A solenoid of 3 meters in diameter, 5 meters in length and 1.5 Teslas is being designed at Fermilab. Some of the solenoidal magnets for colliding experiments have another condition to reduce radiation length of the conductor to the smallest amount possible. In their case a special structure is incorporated in the magnet--for example, using a pure aluminum layer as an energy absorber. Solenoidal magnets are also being used as analysing magnets, such as LASS at SLAC and two at CERN's SPS.

All of these big bubble chamber magnets, analyzing magnets, and solenoidal magnets are DC magnets and use cryostabilized superconducting wire.

The beam line magnets are another area where superconducting magnets have been used recently. At BNL a series of HEUB magnets have been in use for over two years. They are scaled up versions of the ISABELLE model magnets and have a bigger aperture than the latter. At Argonne another series of beam line magnets have been in use for over two years with polarized target experiments. These two series of superconducting magnets were originally made partially to test the radiation effect on the superconducting storage ring magnets. At Fermilab there are several projects which are going on to replace conventional beam line magnets with superconducting magnets, either with Energy Doubler magnets or bigger aperture magnets. A polarized target with a superconducting magnet which goes up to 25 kG was developed at Argonne and has been in use for over two years.

Another area in high energy physics, where superconductivity is used, is in an RF cavity. Now RF cavities are being used at CERN to separate secondary beams. With high Q cavities of superconducting material RF cavities can get higher voltage and tremendously reduce wall power loss. RF cavities are also being developed for large electron synchrotrons, namely at Cornell and at Karlsruhe for PETRA. At KEK, RF cavities are being studied. At Stanford an L-band superconducting linac has been made and is now being tested.

II. Superconducting Technology Applied to Big Accelerators

In all of the above fields superconducting technology has been successfully used, but the application of superconducting technology to big accelerators has been a big problem over the past decade. In many laboratories throughout Europe and the United States, many attempts have been made. It seems now that the major problems related to big accelerators have been solved for superconducting magnets with fields up to 45-50 kG, by using Niobium Titanium conductors. At Fermilab we have started production of superconducting magnets for the Energy Doubler (i.e., Super Ring). A brief history is given in this section and technical details are provided in the following section.

Rutherford Laboratory has contributed greatly in the development of superconducting wire for the application to synchrotron magnets in the late 1960's. The Rutherford group worked on the theory of wire and did model magnet tests. Before CERN decided to make 400 GeV SPS magnets five years ago, they were seriously considering using superconducting magnets. They had asked Rutherford, Saclay and Karlsruhe to make prototype bending magnets at each institute. Unfortunately, they could not make successful magnets in time with satisfactory precision and easiness, thus dropping the project in Europe.

Brookhaven has spent ten years already for the development of superconducting magnets for the ISABELLE project.[1] They started from developing superconducting wire itself. They have been doing this project with several physicists during the first several years. By now they have built over a dozen model magnets. They have quite a big number of people, over 100, involved in this project. They think they have made enough progress so that the quality of their superconducting magnet is good enough for their storage ring. In the next fiscal year they are going to build a full cell, consisting of six dipole magnets and two quadrupole magnets.

ESCAR at LBL was started in 1974, but it took many years for the development, and now the project has been terminated.[2] They should have finished the project quite some time ago, but they went through quite a long series of problems. At the end they made a string of magnets consisting of twelve dipole magnets. They did excite a string of six magnets up to 39 kG level at the end and concluded the project.

At Fermilab the application of superconducting magnets was considered before we started building the existing 500 GeV Main Ring magnets. At that time, about ten years ago, the technology of superconductivity was not mature enough for building a synchrotron. Since then the technology has gradually developed in Europe and the U.S.A.

After the achievement of 200 GeV beam in the Main Ring in 1972, a small group was formed and construction of model magnets for the Energy Doubler was started. In the past several years many model magnets in lengths of 1, 5, 10, and 22 feet have been made. Their characteristics were studied and many different technical difficulties solved.[3] At the same time the Energy Doubler group and its related groups were gradually expanded.

At the beginning of this year we started production of the Energy Doubler magnets. We have built 60 production magnets up to now (August, 1978). Meanwhile, over 100 coils of 22 foot length were produced, including many experimental ones.

By now we have solved all major technical problems related to superconducting magnets, and they are listed as follows:

1. Superconducting wire development
2. Achieving 45 kG at the central field
3. Good magnetic field quality

4. Mass production procedure of the coil and the cryostat
5. Test facility and procedure of production magnets
6. Installation procedure in the tunnel
7. Refrigeration system

The details of these technical problems are described in the next section.

Now UNK project at Serpukhov in the USSR is trying to develop prototype magnets for a 3 TeV proton synchrotron. They have made a first model magnet which is 90 cm long. They tested it without iron lamination and achieved 39 kG. They are going to test it with a cryostat in a month. They also asked the Saclay group and the Leningrad group to make two short model magnets each, which will be delivered to Serpukhov by the end of this year and will be tested. It seems they have about 50 to 100 people working on this project now and are preparing for a big building and other components.

III. Technical Achievements in Superconducting Technology Applied to Energy Doubler

In this section we will describe mainly the recent achievements in superconducting technology as applied to Energy Doubler magnets.

III.1 Superconducting Wire

At present Niobium Titanium is the most commonly-used superconducting material for synchrotrons and will be used at least for the next several years. Current density is about 200 kA/cm^2 at 5 Tesla in superconducting filament and it can be obtained commercially. Wires with Niobium Tin are being developed now but it will require a few more years of study for full development. Niobium Tin has a higher current density at higher field but it is hard to make a coil.

In the last few years the wire with Niobium Titanium, which carries the field range up to 50 kG, has been developed very extensively. There are two main types of wire for synchrotron application. One wire, developed at BNL, is braided and uses very fine strands. The other one is a cabled wire originally developed at Rutherford. The wire which is being used for the

Energy Doubler is a 23 strand cabled and fully keystoned wire. The outside dimensions are 300 mils wide, and 44 mils and 55 mils thick at both ends. The short sample data of the fully keystoned cable is typically 5500 amp at 5 Tesla. The single strand is about 27 mils in diameter and has a current carrying capacity of 300 amp at 5 Tesla. It has typically 2,200 filaments of 8μ in diameter, and is twisted twice per inch to reduce the coupling loss between the filaments. The ratio of copper to superconductor is 1.8 to 1.

During the years of development of superconducting wire, several companies in the world have contributed and the current density has been increased steadily to the above value. It is very important that the above current density has been achieved commercially--not only at experimental run.

The cabled wire was soldered together originally to increase mechanical strength of the coil. Soldering increased the ac loss of the coil by an order of magnitude and was abandoned. The surface of the single strands had been coated with Staybrite (5% Ag and Tin) to increase contact resistance between strands. It had enough electrical resistance in old prototype magnets, when the wire was not fully keystoned. Recently the wire had been fully keystoned as mentioned before, and the contact resistance between the strands with Staybrite was reduced beyond tolerance, increasing ac loss. Now the strands are chemically treated with Ebanol to make oxidized surfaces, reducing the coupling loss between strands. Presently we are using unsoldered, but fully keystoned cable. By fully keystoning cabled wire each strand is interlocked into its place by slight deformation, thus increasing mechanical stability.

The cabled wire is wrapped with 1 mil mylar tape overlapping half width. Over that a 5 mil B-stage epoxied glass tape is wrapped leaving open space between successive turns. This guarantees full penetration of liquid helium into the inside of cabled wire.

The aspect ratio of the bare cable is about 6 and with its insulation it goes down roughly to 5. This small aspect ratio is essential for a bigger packing factor of about 80% including insulation, and results in a compact size magnet. On the other hand, a braided conductor has porosity of about 70% and its aspect ratio is much bigger. Therefore, its overall packing factor is estimated at about 55% with insulation material.

III.2 Structure of Energy Doubler Magnet

The cross section of a bending magnet is shown in Fig. 1. It has a warm iron shield and a cold beam bore. The coil is held by collars, which are in turn supported by thermal insulating G-10 supporters from the iron shield. The space between the collar and the iron shield constitutes a part of the cryostat. The outside dimensions of the shield are 10" high and 15" wide. The coil is composed of two layers. The inner layer has 35 x 2 turns and the outside layer has 21 x 2 turns. Usually the field strength at the end of the innermost turn of a coil will be maximum, unless the conductors are spread out. In our case, the inner layer coil is spread out at the inside of the end section. The integrated field components over the end section were measured first and these data were used to design the cross section of the coil at the central region. Especially the extended angles of both layers relative to the median plane, thus turn numbers of both layers were determined to reduce the integrated sextupole and octuple components. At the same time the sum up to 30th harmonic components at one inch radius was minimized.

The magnetic force to the coil at 45 kG is shown in Fig. 2. An individual conductor has different vertical and horizontal components. Typical values are shown in that figure. In a coil assembly, the vertical components cancel due to up and down symmetry. The resultant force is outwards and 2.68 tons/linear inch of a magnet. The total horizontal force to a magnet is 677 tons toward both sides. The coil is at a stable point if it is exactly centered relative to the core. The more it is off-centered, the stronger the force toward the core. The force is 11 lb/inch for a 10 mil displacement and proportional to the amount of displacement.

It is necessary to design the structure of the magnet so that such magnetic force is confined inside the magnet. A series of collars was designed, which holds conductors in place. The present one is called Mark V, which is made of stainless steel plate 60 mil thick. The collar module of this type was tested mechanically ten million times without a failure.

III.3 Assembly of Magnet

We have to make about 1000 magnets in two years. It was imperative for us to design the magnet so that it could be easily assembled, in a very economical way. Therefore, we made a lot of innovations and improvements in the design of the magnet. The inner layer of the coil is wound in pancake shape using iron sheets with winding tension of 38 lbs. The coil can be wound within several hours by a pair of unskilled persons. Then this layer is pressed into a saddle shape using a long hydrostatic press of 1450 tons. The wire is fully keystoned so that every turn nestles each other when pressed. Under the pressure the coil is cured at 250°F for one hour with heated oil. The second layer of the coil is wound on top of the first layer, using regular rocking winding technique. After pressing and curing again for two hours using a second press of 2200 tons, the assembled coil is checked in its dimensions at a dozen points along the length of the coil.

Then the coil is put into a third press of 3250 tons and assembled and preloaded with half collars. These collars are preassembled into blocks of four inches, which look like a comb. While pressing the collars into the exact dimensions at room temperature, the outside of the collars are welded with automatic welding machines.

III.4 Preloading of Coil

The coil is preloaded with collars in the azimuthal direction. The inner and outer layers are preloaded at 3000 and 2000 lb/in at room temperature. When cooled down to liquid helium temperature, these loading values are reduced by half into 1500 and 1000 lb/in respectively due to the difference of expansion co-efficients. This preloading is such that under the extreme excitation of 50 kG, it will be canceled by the magnetic force. Therefore at 45 kG there is still preloading left and the coil is kept rigid.

By fully keystoning the cabled wire and preloading the coil, the coil is made rigid enough to prevent the wire movement. Therefore, the Energy Doubler magnet shows very minimal training effect. Usually the coil reaches the 100% point of short sample data after two or three quenches. Also the ac loss curve of a magnet at constant ramp rate shows no increase in energy loss due to wire movement nor due to coil deformation, while a superconducting magnet without such consideration shows a great deal of training ranging up to 50 to 100 quenches. Sometimes, training is attributed to cracking of epoxy with the case of an impregnated coil.

III.5 Mechanical Accuracy

It is preferable to make all of the Energy Doubler magnets with the accuracy of 10^{-4} in the integrated magnetic length of the bending magnets. The variation of 10^{-3} in that value leads to the orbit distortion of 15 mm. We have achieved the accuracy of better than 10^{-3} and we think we can go down to a couple of 10^{-4}.

The inside magnetic field value of a magnet is inversely proportional to the radius of the coil. Therefore, the error of 0.075 mm (= 3 mils) in the diameter of 3 inches corresponds to 10^{-3}. The field variation along the length of the magnet RAD-99 is shown in Fig. 3. The ordinate gives the ratio of a magnetic field strength in Gauss over a current in Amp. It shows the variation along the length of the magnet is well within 0.1%.

The coil jigs and assembly jigs should be made with an accuracy better than 1 mils. To achieve this, all of the jigs are made of laminated steel plates, instead of machined steel blocks. It is not easy nor economical to machine accurate block jigs for such accuracy and for this length of 22 feet. We can make accurate laminations using a precision die and easily assembling them to make an accurate jig. If a modification is needed we can easily change the die and make a new jig. By using jigs of this kind, we can make the magnet coils of the necessary accuracy.

III.6 Field Quality of Energy Doubler Magnets

The harmonic components for the magnet RAD-99 were measured at 40 kG (4000A) up to the 30th pole at the central region. The reconstructed field shape is shown in Fig. 4 together with a designed curve. The difference is about 0.05% at one inch radius. It comes mainly from the extra big decapole component which can be easily corrected by correcting a shim or the die. Otherwise the agreement between them is very good and we think we can make a consistently good magnet for the Energy Doubler.

The field distributions similarly measured and reconstructed, are shown in Fig. 5 for 5, 10, 20 and 40 kG. Also the distributions at 10 and 5 kG for ramping down are shown in Fig. 5. It clearly shows the effect of magnetization at 5 kG. This effect is roughly inversely proportional to the value of magnetic field, and this is the reason why the injection field is selected near 5 kG. Even at 5 kG we need correction magnets, mainly sextupole magnets. The remanent field is roughly 10 Gauss at center. The iron yoke contributes about 2 Gauss and the remaining is coming from the magnetization effect of superconducting wire. The amplitude of the remanent field components at 1 cm versus the maximum excitation current is shown in Fig. 6. It also shows the relatively large sextupole component. The quadrupole component is due to the imperfect asymmetrical construction of this magnet PAB-59.

III.7 AC Loss

The ac loss of a magnet with fully keystoned Ebonol wire is about 500 J/cycle for a cycling operation of 60 seconds, corresponding to 20 seconds up, 20 seconds flat top at 43 kG, and 20 seconds down. This value was about 600 J/cycle for a magnet with partly keystoned Staybrite wire. But, this value was increased to 1500 to 2000 J/cycle for a magnet with fully keystoned Staybrite wire, when we preloaded and compacted the coil to reduce the wire movement, thus increasing the coupling loss between strands. Therefore, we abandoned Staybrite and adopted Ebonol to increase the resistance between the strands.

The ac loss includes the hysteresis loss which is about 200 J/cycle and the eddy current loss which is about 300 J/cycle. Out of 300 J/cycle, the coupling loss between filaments within a strand may be 100 J/cycle and the coupling loss between strands may be 200 J/cycle.

III.8 Damaging Magnet

During the early stage of development and test run of Energy Doubler magnets, we unintentionally damaged about a half dozen magnets due to many different reasons.

Superconducting magnets for big accelerators are a new technology and designed with a much smaller safety factor in it. Therefore, we had to device new techniques to prevent any further similar damages. We learned a lot about the magnets and their safety systems from their operation and failure.

At Escar they damaged six out of 12 dipole magnets during a string test. At BNL they also damaged several full-scale magnets. In all cases, the problems were the failure of safety circuits, shorting between turns or to ground due to poor insulation, bursting liquid helium into vacuum systems and so on. We may not have exhausted all possible cases, and we should be really careful for the design, construction, and operation of safety circuits.

III.9 Economics of Production Magnets

For large accelerators like the Energy Doubler and the ISABELLE we have to make about 1000 magnets. This means we have to make a magnet at a unit cost of 30 to 50 thousand dollars. Therefore, it is imperative to design the coil, core and cryostat as simply and economically as possible to save the total construction money. We went through many changes of these parts, and now they are made much simpler in their design and construction methods. Therefore we can now buy preassembled cryostats for the Energy Doubler magnets.

IV. Conclusion

The superconducting magnet technique for a large accelerator and a storage ring are now well established. At Fermilab we started the production of production magnets for Energy Doubler magnets. The major problems of achieving 45 kG at center, good field quality, establishing mass production procedure of coils and cryostats, construction of a test facility and establishing the procedure of a production test, have been successfully solved. We should be seeing the operation of an accelerator with superconducting magnets in a few years.

The questions for the immediate starting of the development on pulsed superconducting magnets in Japan are listed in the appendix and also a comparison list of ISABELLE magnets and Energy Doubler magnets is added.

References

1. "ISABELLE, A Proton-Proton Colliding Beam Facility", BNL Report, 50648(1977).

2. T. Elioff, et al., ESCAR Mid-Term Report. IEEE Trans. Mag. Vol. MAG-13, No. 1, Jan., 1977. (LBL-4818).

3. "The Energy Doubler", Fermilab Report, Oct., 1976;
"The Tevatron", R. R. Wilson, Physics Today, Oct., 1977,23;
"The Energy Saver", Fermilab Report, Jan., 1978;

"Tevatron", R. Yamada, to be published in the Proceedings of International Symposium on Perspective and Future Projects in High Energy Physics, Tokyo, August, 1978.

Appendix I

Is it possible to start development on pulsed Superconducting Magnets in Japan now?

Questions		Answers
1.	S.C. Wire (NbTi)	Equivalent wire is being made in Japan
2.	Winding Precision Coil	Commercially capable
3.	Training and Achieving Max. Field	All mechanisms are now understood, possible.
4.	Maximum Field	40-50 kG possible
5.	Magnetic Field Quality	Storage ring quality can be achieved
6.	Cryostat	Weak now, but can be made because it is simple job. Good welders are needed.
7.	Large LHe Refrigerator	Weak, but can be improved or, bought from USA
8.	He Gas	Buy from USA
9.	Manpower	?
10.	Budget	?

Appendix II

Comparison between ISABELLE Dipole Magnets and Energy Doubler Dipole Magnets

	ISABELLE	Energy Doubler
B_{max}	50 kG	42.3 kG (45 kG)
Injection	3.7 kG	4.2 kG
Conductor	Braided	Cabled
Filling Factor with Insulation	~ 0.55	~ 0.8
AC Loss	Big	Moderate
Ramp Up	240 sec.	20 sec.
Temp.	3.8K (super critical)	4.5K (subcooled liq.)
Beam Bore	Warm	Cold
Bore Size	8.8 cm dia.	7.5 cm
Iron	Cold	Warm
Saturation of Iron	Yes	No
Rough Outside Dim.	30" x 40"	15" x 10"
Cooldown Time	15 days	3-4 days
Assembly	Hard	Moderate
Handling and Shipping	Fragile	Easy
Weight	7 tons	4 tons
Overall (Magnetic) Length	5.65 (4.75) m	6.7 (6.4) m

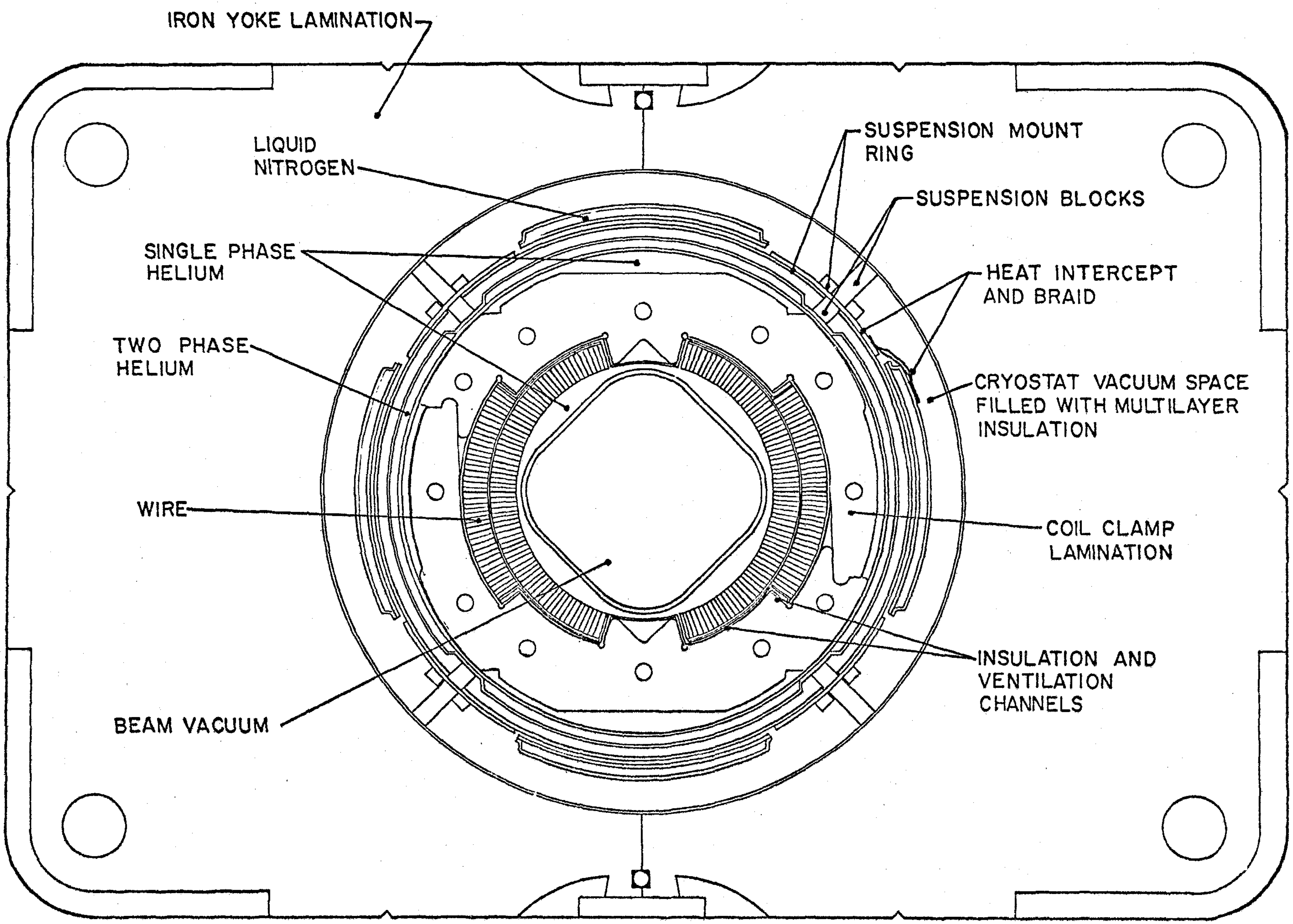

Fig. 1. Cross Section of Energy Doubler Dipole Magnet.

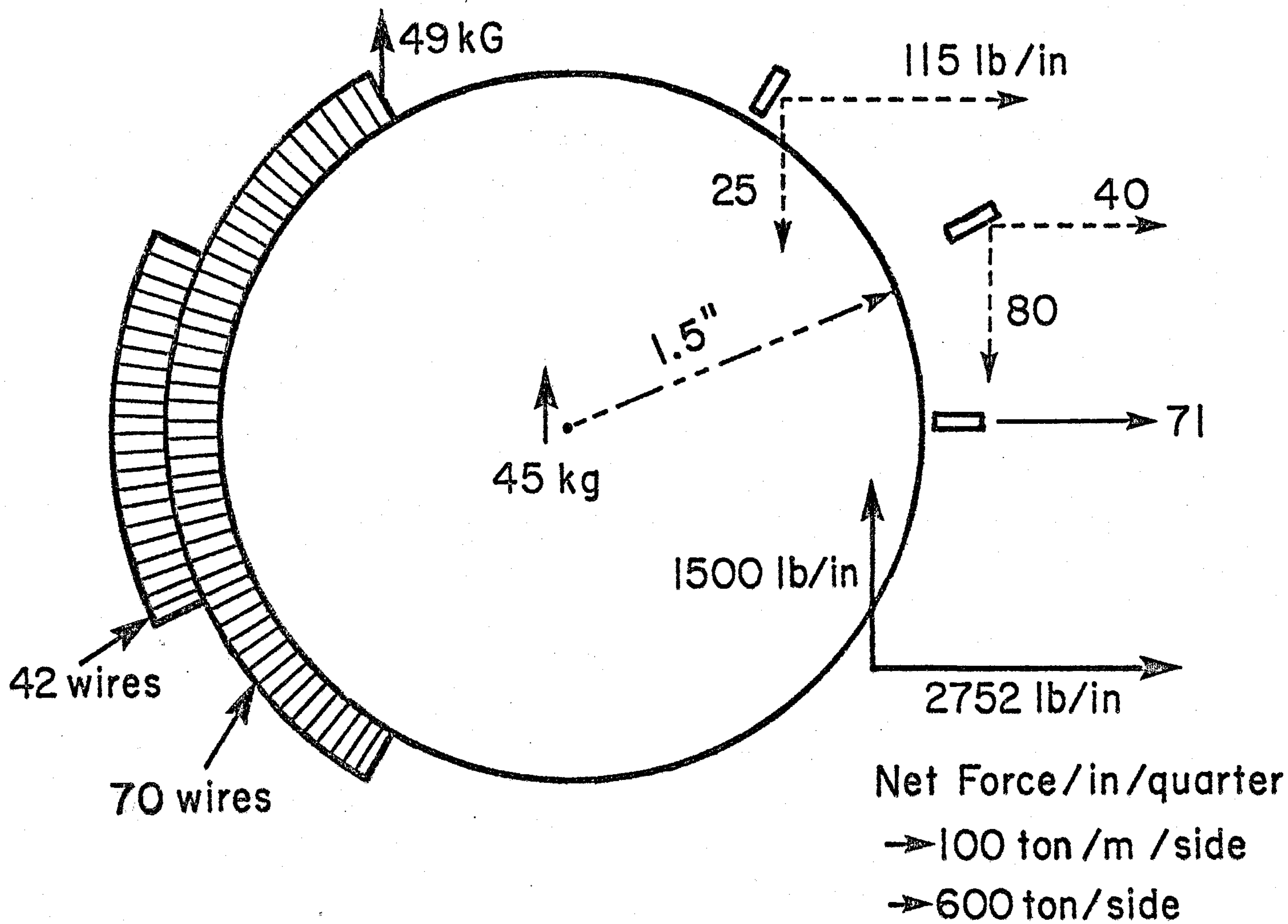

Fig. 2. Magnetic Force to Coil at 45 kG.

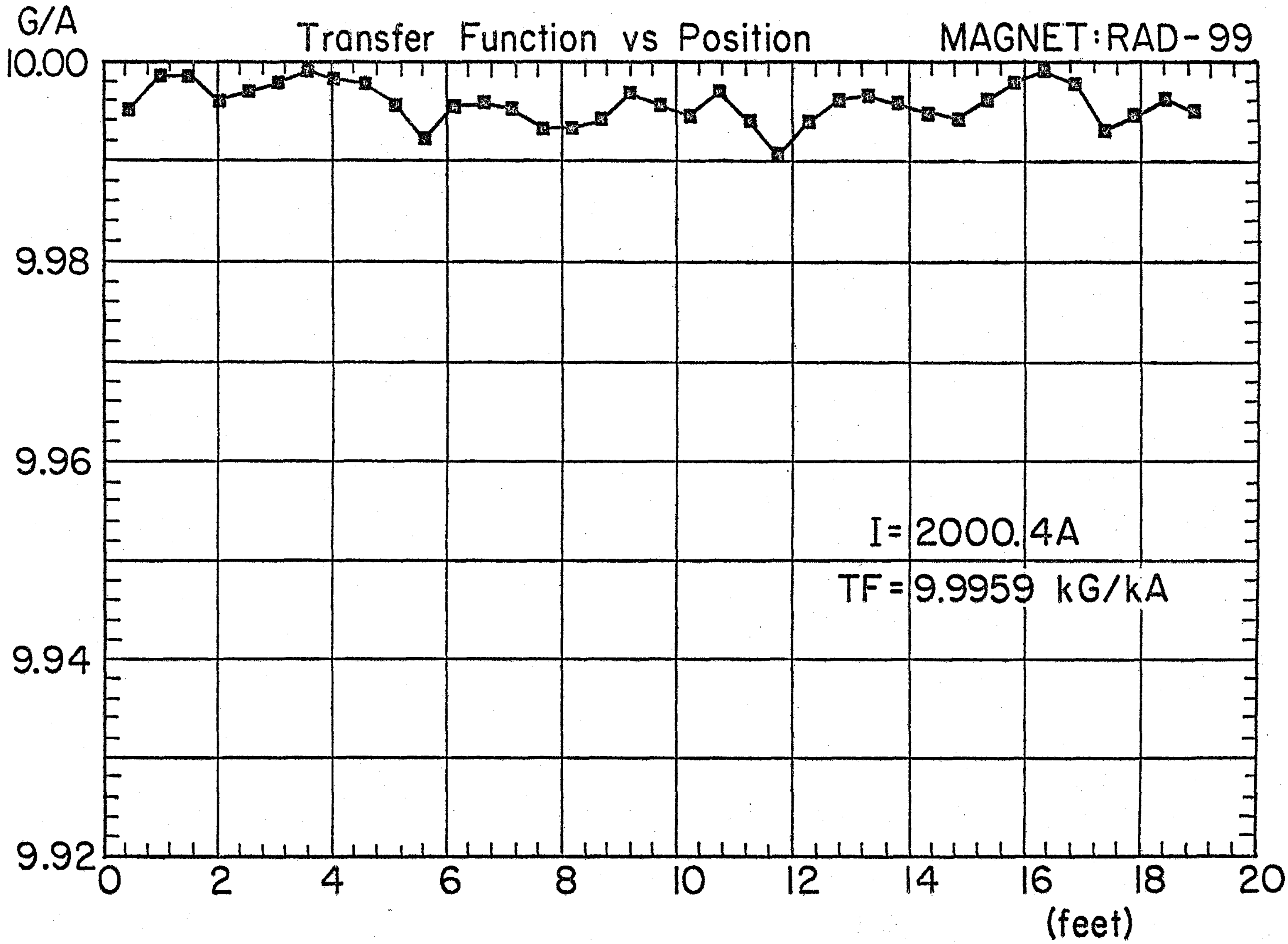

Fig. 3. Central Field Variation along Length of Magnet RAD-99.

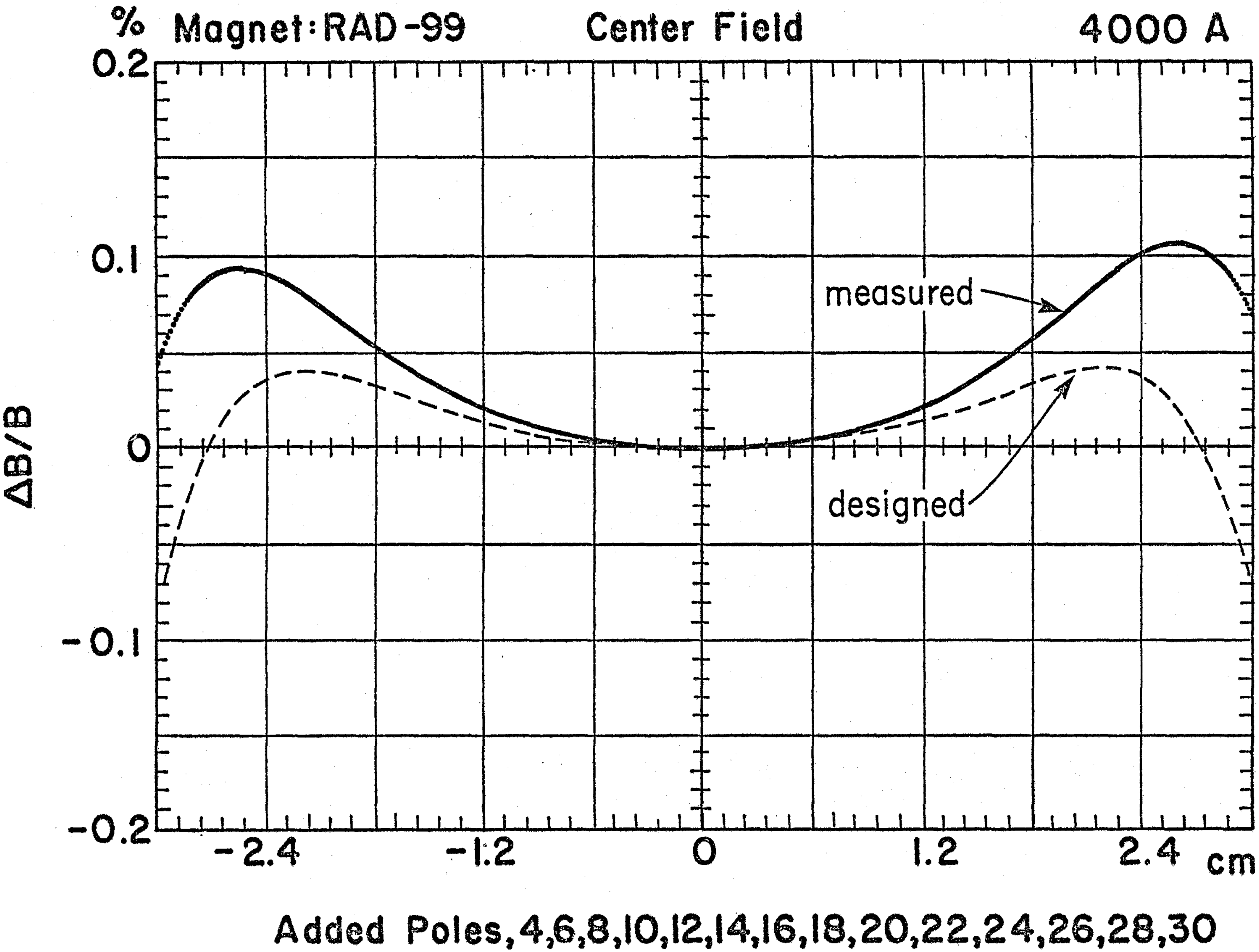

Fig. 4. Reconstructed Field Shapes of Magnet RAD-99 at 40 kG.

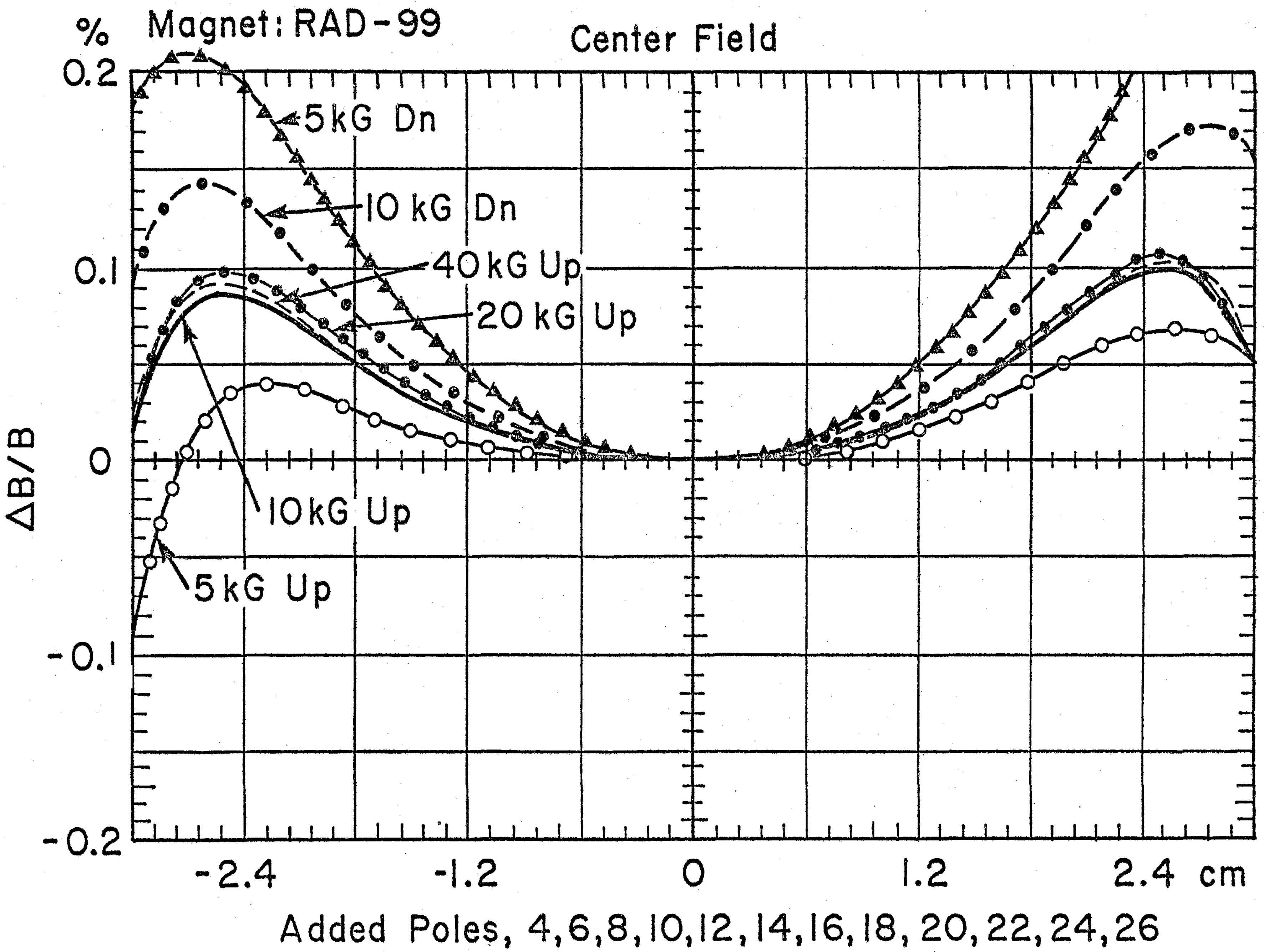

Fig. 5. Reconstructed Field Shapes at Different Excitation.

TM-845
1600.000

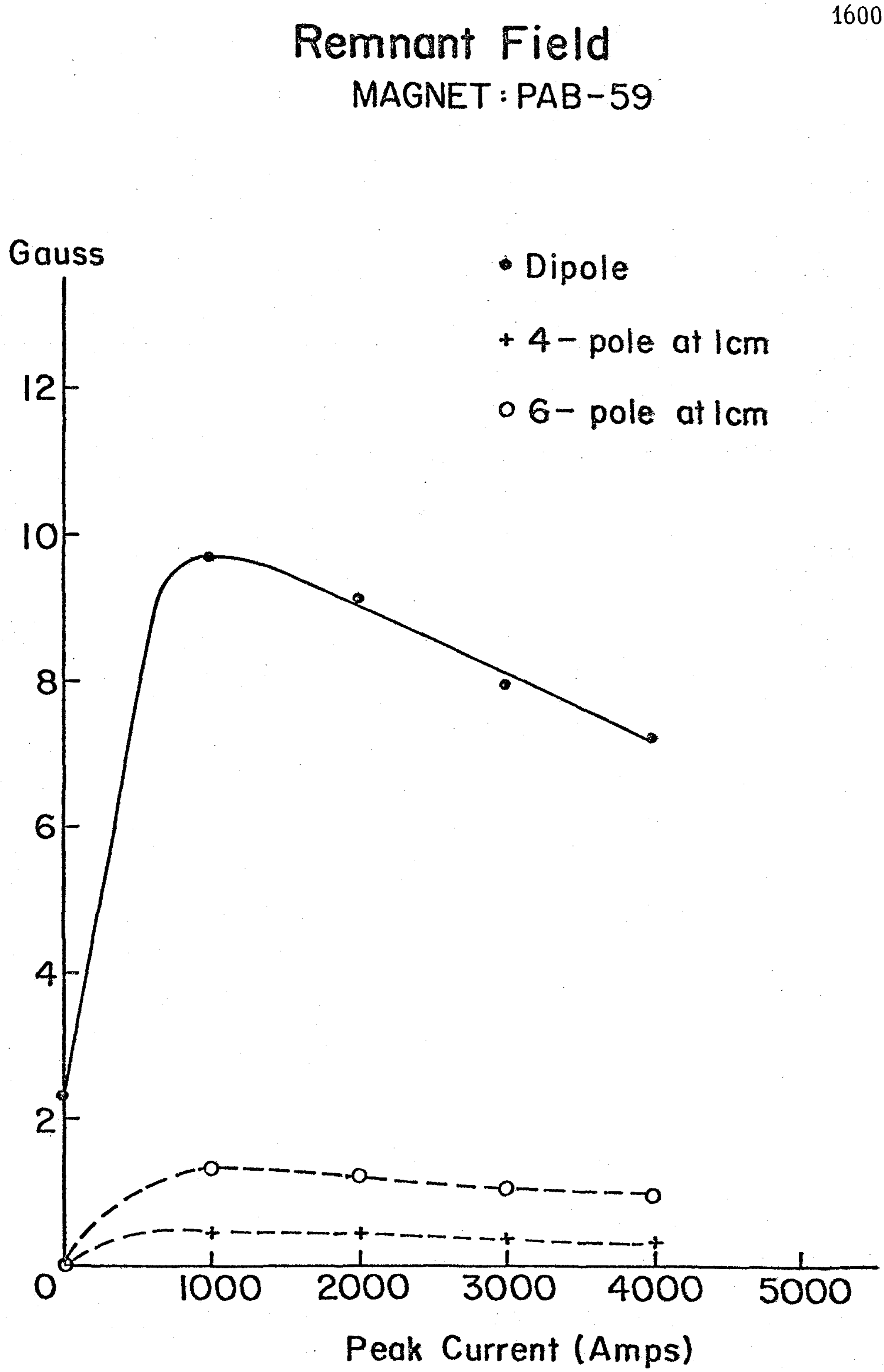

Fig. 6. Amplitude of Harmonic Components for Remanent Field vs. Peak Excitation Currents.