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Princeton Warm-Bore Magnet

Eric Prebys

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Abstract

This note is a description of the warm bore superconducting magnet used by the Princeton HEP group. It is meant serve as an operating manual and also to summarize the most recent tests of the magnet.

Contents

1 General Specifications

This magnet is unusual in that it has a horizontal "warm bore" passing completely through the solenoidal coil, giving easy access to its peak field. There is a rumor that the peak field once went to 8 T. In our tests, we have not been able to go beyond about 6.5 T with a 45 A supply current. The measured ratio of the peak field to current is .146 T/A

The inner diameter of the bore is 3.6 cm and it has a full length of 41.7 cm. The longitudinal field has a FWHM of about 21 cm, and is flat to within 1% over about 9 cm.

See section 6 for a more detailed description of the field.

2 Principles of Operation

The cryostat has an intimidating number of feedthroughs, ports, and controls, but most of them have been provided for the service and telemetry of an optional sealed cold volume. In our warm bore configuration, most of these are not used, and the basic operation is quite simple.

A cross-sectional view of the cryostat is shown in Figure 1. The central liquid Helium reservoir is separated by vacuum from an intermediate Nitrogen reservoir, which is separated by another vacuum gap from the outer wall. The coil volume lies below the Helium reservoir. While there is no liquid Nitrogen between it and the outer wall or central bore, there is a stainless steel heat shield which is in thermal contact with the Nitrogen reservoir.

The magnet coil is shown schematically in Figure 2. It comprises a continuous loop of superconductor. In order to energize the coil, a small segment of the conductor is made resistive by means of a small heating coil. This arrangement is known as a "persistent switch". The power leads connect on either side of this switch. The heater is activated, the coil brought up to field, then the heat is shut off. When the segment cools, the coil becomes a closed superconducting loop, and the external power may be ramped down without reducing the field.

3 Preparation

This section assumes that the magnet is completely warm, and that the vacuum jacket is up to atmospheric pressure. Some steps may be skipped, depending on what state the magnet is actually in. For this and subsequent sections, refer to Figure 3 for the location of the important ports and controls. As mentioned before, there are a lot of unused controls. Sometimes, they are completely harmless. For example, the internal Helium valve has been capped off. On the other hand, the cold volume service lines open directly into the vacuum jacket and will spoil the vacuum if opened. Therefore, it's a good idea to not touch anything you don't need to.

The vacuum jacket is pumped out by connecting the bellows (Balzers) pump to the main pumpout port, opening the valve and pumping down. When warm, the system will eventually pump down to about 2×10^{-5} Torr. The leak rate is on the order of 1 mTorr/day, so in general the pump should remain attached and running while the system is in use. The exception is when the Helium volume is pumped out (described below).

If the Helium volume has been warm for a while or has been open to atmosphere, it's probably a good idea to pump and purge it before introducing any cryogens. It can be pumped out with the roughing pump by inserting the 3/8" Copper adapter tube into the He vent line. Make sure that the fill line is capped off and the backfill valve is closed at this point.

Note! The Helium volume is not designed to stand a 1 atmosphere overpressure, so *never* pump out the Helium volume unless the vacuum jacket has been pumped out first. Because the Balzers pump will vent if the power is shut off, it's probably a good idea to close the vacuum jacket pumpout valve whenever the Helium volume is being pumped out, particularly if it's being left unattended.

For reasons I don't understand, the Helium volume doesn't go to a very good vacuum, but pumping it to <400 mTorr should be more than adequate to get rid of any moisture. If it's been warm for a while, it's probably a good idea to purge it with Nitrogen or Helium via the backfill port, and pump it down again. Note that if one is pumping on Helium, the Convectron pressure gauge will read 999 Torr until the pressure is down to about 10 Torr. After that, it will be reasonably accurate.

After pumping and purging, the Helium volume should be backfilled up to a slight overpressure with Nitrogen or Helium. The vacuum jacket pumpout valve should then be reopened to maintain vacuum.

There is no practical way to pump out the Nitrogen reservoir, and it shouldn't really be necessary. If you think that there is moisture in the reservoir, it might be a good idea to run a dry Nitrogen purge through one of the fill ports for a while.

4 Cooldown and Liquid Fill

Fill the liquid Nitrogen reservoir by removing all three plug from the fill/vent ports, and putting the fill line in any one of them. The reservoir should be filled to the very top, until liquid begins to come out of one of the vent ports. Replace the vapor plugs. During operation, the Nitrogen reservoir needs to be filled *at least once per day.*

Because liquid Helium is expensive and doesn't have much heat capacity, it's economical to cool the magnet mass and Helium cryostat with liquid Nitrogen prior to introducing Helium. Loosen the knurled lock knobs on the Helium fill port and vent port, and remove both plugs. Insert a 1/2" Nitrogen fill as far as it will go into the liquid fill port and tighten the knob. Begin the liquid transfer. You'll need to go pretty slowly until the mass cools down. Fill the reservoir full of liquid Nitrogen, until liquid comes out of the vent line. If you remove the transfer line from the cryostat at this point, be sure to heat the port with a heat gun to prevent damage to the o-ring.

Leave the Nitrogen in the system for about a half hour to thoroughly cool the system, then all the liquid Nitrogen must be removed. This is done by inserting 1/2" drain line into the fill port (in practice, it may be the same as the fill line). The plug is inserted into the vent line. To force the liquid out of the system, a Helium bottle can be attached to the backfill port and set to about 2 psig. In order to maintain an overpressure, the Helium pressure relief flange must be clamped shut with C clamps. *This is potentially very dangerous.* It must not be done until the drain line is inserted, and they must be removed immediately after the Nitrogren is flushed out. After the relief flange has been clamped, the backfill valve can be opened to flush out the Nitrogen. It can be drained, for example, into a metal trash can and dumped outside. Once liquid stops coming out, shut off the backfill valve, remove the C clamps, remove the drain line (after heating the port), and reinsert the fill line plug.

There will still be residual Nitrogen in the system which must be pumped out. This is done by removing the vent line plug and inserting the 3/8" pumpout adapter. The system will pump down to 1.5 to 2.0 Torr and remain there until all liquid Nitrogen is gone. In practice, this may take several hours. It's perhaps a good idea to do this late in the day and let it pump overnight. As before, it's probably a good idea to close the vacuum jacket valve at this point, in case the Balzers pump shuts off.

When the Helium reservoir has been pumped to <400 mTorr, the pump valve should be shut off, and the system should be backfilled with Helium (not Nitrogem!) gas. The vacuum jacket pumpout valve should again be opened. The Helium pumpout line can be removed, and the vent plug reinserted. Now the system is now ready for liquid Helium.

The Helium transfer line is an expensive, fragile thing, so care must be taken when using it. After venting excess pressure from the Helium dewar, open the top and insert the transfer line as deep as it will go. Tighten the knob to form a pressure seal and close the vent line. The overpressure will begin to drive liquid through the line. Allow the line to cool until vapor is seen at the other end. At this point, quickly remove the liquid fill plug from the cryostat and insert the transfer line as deep as it will go. Remove the vent line plug. You will see vapor coming from the vent line. When it begins to slow down, you can speed things up somewhat by attaching a Helium bottle to the vent line of the Helium dewar and overpressuring it slightly. You don't want to go too fast as this wastes the enthalpy of the Helium. Ideally, there should be about a 1 m high vapor plume from the vent line of the cryostat. At this rate is should take about 1/2 hour to 1 hour to fill the cryostat. The level can be measured with the Helium depth gauge. Its use is hard to describe, so get an expert to show you how to use it. Fill the cryostat all the way to the top. The full depth should be about 44 cm. It will use up about 40 l of liquid from the dewar for the initial fill.

When the crostat is full, remove the fill line and reinsert the fill plug immediately. Also reinsert the vent plug after verifying that the pressure relief flange is not obstructed in any way. The system is now ready to go.

In operation, the liquid Helium should be topped off once a day. It will all boil away entirely in about two days.

5 Magnet Operation

Surprisingly, it doesn't take any extra time for the magnet to cool to superconducting temperatures. Once the cryostat is full, the magnet may be energized. To energize the magnet, the persistent switch must first be heated. This is done by putting about 0.5V accross the 10 Ω resistance of the persistent switch heater and waiting about 2 min. The current may then be ramped. The inductance of the coil is around 20 H, so a fairly low ramp rate of about .1 A/s should be used. If you don't observe a voltage consistent with this inductance, it's an indication that the persistent switch is not warm.

When one reaches the desired supply current, it will still take a while for the full current to go into the coil, as the inductive voltage drop will cause some of the current to be shunted through the resistive persistent switch. Monitor the supply *voltage* and wait for it to stabilize to the resistive drop of the supply lines, which are presently a total of about .035 Ω total. This can take several minutes. Don't try to go into persistent mode until the coil has settled to full current.

When the supply voltage is stable, you can, if you wish, go to persistent mode. This will among other things reduce the heat load on the liquid Helium. To do this, shut off the persistent switch heater and wait about two minutes. At this point, the current can be ramped down very quickly, as the supply no longer sees the inductance of the coil. At this point, the magnet will remain at full field indefinitely.

Care must be taken with going out of persistent mode, either to ramp down the magnet or to change the field. The supply current must be matched precisely to the current in the coil *before* heating the persistent switch. Failure to do so will result in the the excess coil energy being dissipated in the persistent switch and dumped into the Helium, having the same net effect as a quench. As before, while the switch is cold, the current may quickly be ramped to the desired value. Then the switch heat should be turned on, and after about 2 minutes, the coil current may be changed to zero or any other desired value.

In our tests, we have observed the magnet to quench at just over 45 A. When this happens, the coil goes resistive and the current is dumped through a diode to a capacitor, which dissipates it through a resistor into the Helium. The excess gas is vented through the Helium relief flange, which is pretty dramatic and it takes several minutes for the system to stabilize again. At this current, the energy in the coil is about 20 kJ, which is enough to boil away about a third of the total Helium supply.

Thus, with a full Helium reservoir, the system may quench twice and still have enough Helium to energize the magnet a third time. The third quench, however will leave basically no Helium in the system.

6 Magnet Characteristics

This section summarizes the tests of the magnet made on March 3, 1998. Fields were measured using a Bell axial probe with a Bell 620 gauss meter. The probe did not match the model number on the cable, so no specifications are known. We used an old cyclotron magnet to cross-calibrate it with a Bell 4048 gauss meter using a T-4048-001 tranverse probe. We found that *after multiplying the reading of the axial probe by an exact factor of 10*, it agreed with the 4048 to within the accuracy that we could read the scale (about 2%) in the range .1 to 1 T. This factor of 10 also gave us consistent measurements of the earth's field (about 5×10^{-5} T).

Figure 4 shows two complete longitudinal field profiles made at 5 A and 44 A. Positions are measured relative to *roughly* the geometric center of the warm bore. There is a systematic uncertainty of about 1cm as two where the probe is actually measuring. Also, the probe slipped slightly between these two sets of measurement, so the second measurement is shifted slightly relative to the first.

In Figure 5, the field values in each of these profiles have been normalized by the supply current. Also, the reported 44 A profile has been shifted by 1.25 cm to line up with the 5 A profile. Note that there appears to be a slight sag in the peak field, but the tails aggree perfectly. It is quite possible that this sag is due to a non-linearity of the probe/meter, since it was never calibrated for fields above 1T.

Peak field measurements were made for currents of 5, 10, 15, 20, 30, 40, and 44 A. These are plotted in Figure 6. Again the slight sag is apparent for the high points. A linearity factor of .146 T/A was obtained by fitting the first 5 points. The measured field at 44 A was 6.3 T. If we believe that the non-linearity is due to the probe, then the actual field was probably 6.42 T

We quenched the magnet three times in our attempt to go to the advertised 8 T field. On the first ramp, it quenched somewhere between 40 and 50 A. On the second ramp, it was unable to reach 45 A. On the third ramp, it could sustain a current of 45 A, but quenched when attempting to go to 46 A. At this point, we had used all of our Helium and the test was ended. If we believe our linearity factor, then a current of 45 A corresponds to a field of 6.57 T.

7 Warnings and Safety Tips

Here is a list of some important things to keep in mind while using the magnet, in order to prevent damage to the magnet itself and injury to users. Each of these is elaborated in the appropriate section of the document. They are listed in approximate order of imporance:

(1) While flushing the liquid Nitrogen out of the Helium volume, it will be necessary to clamp off the pressure relief port. *These clamps must be removed prior to introducing any liquid Helium into the system.* Failure to remove them could result in destructive pressures in the Helium reservoir. In particular, it could be extremely dangerous if the magnet were to quench with these clamps in place.

(2) Never pump on the Helium volume with the vacuum jacket at atmospheric pressure. The inner cryostat is not designed to withstand net external pressure a will be crushed if the vacuum jacket is not already pumped out. It's a good idea to close the vacuum jacket pumpout valve while pumping the Helium volume.

(3) If there is frost on either the Helium fill line or vent port, they should be warmed with a heat gun before manipulating them in any way (including removing any plugs or piping). This will prevent damage to the o-rings, which become brittle when cold.

(4) Never operate the persistent switch without first matching the supply current to the current in the magnet. Otherwise, the magnet's energy will be dumped into the Helium. More generally, remember that equal care must be taken to de-energizing the coil as to energizing it.

This list should be displayed on the magnet.

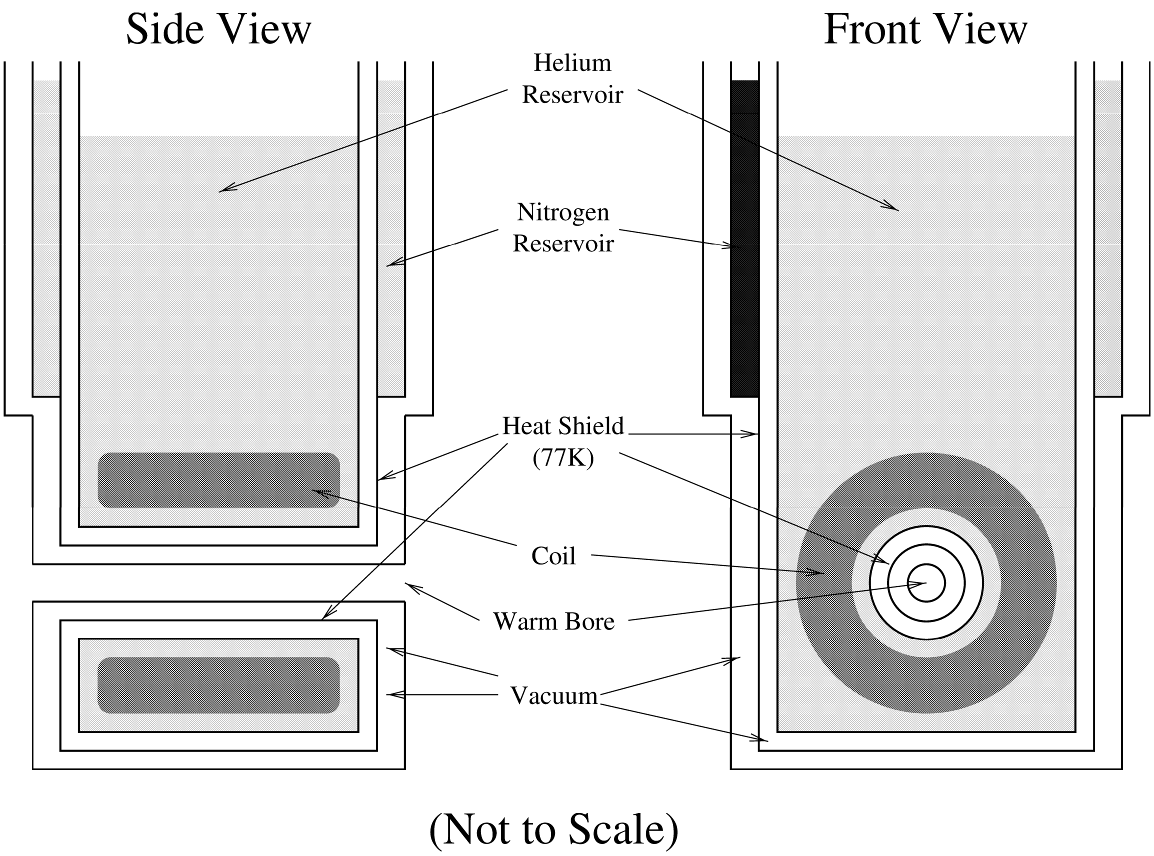

Figure 1: Cross-sectional conceptual view of magnet cryostat.

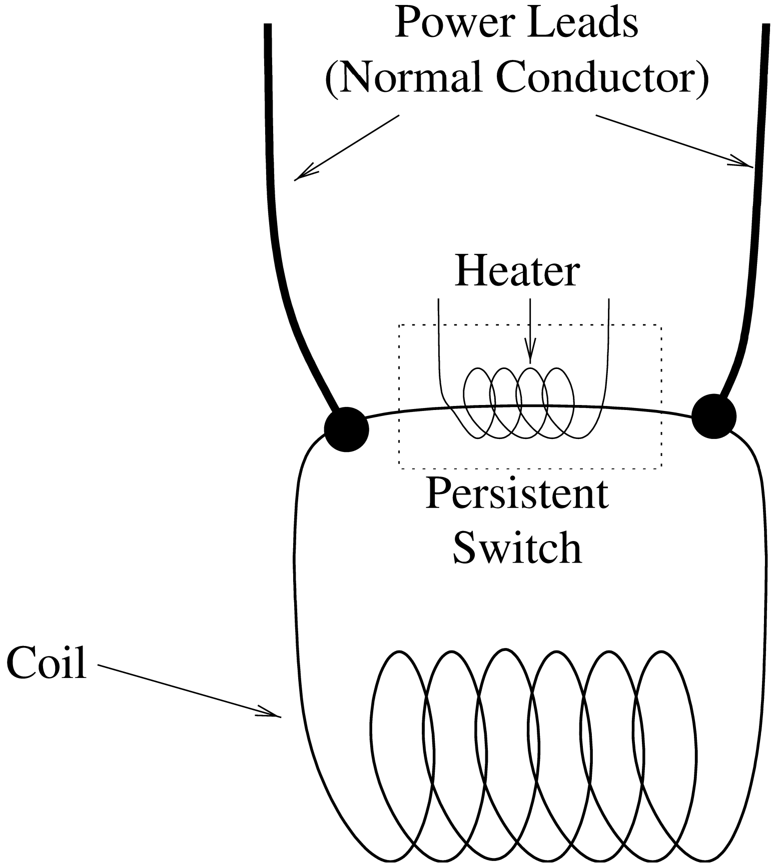

Figure 2: Schematic illustration of coil, showing persistent switch.

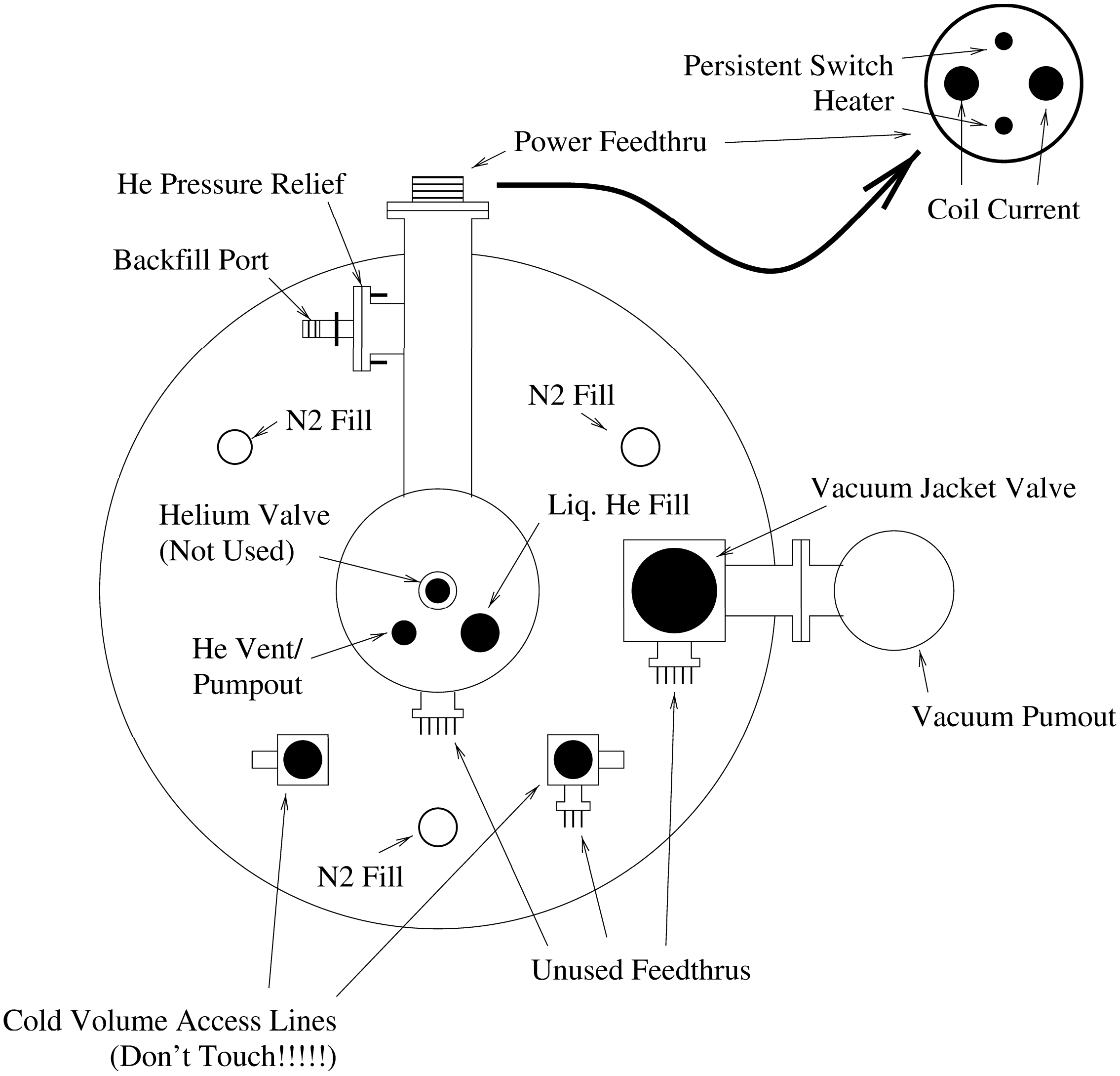

Figure 3: Top view of the cryostat. Note that many of the controls are for the service of a cold volume and are not used in our configuration.

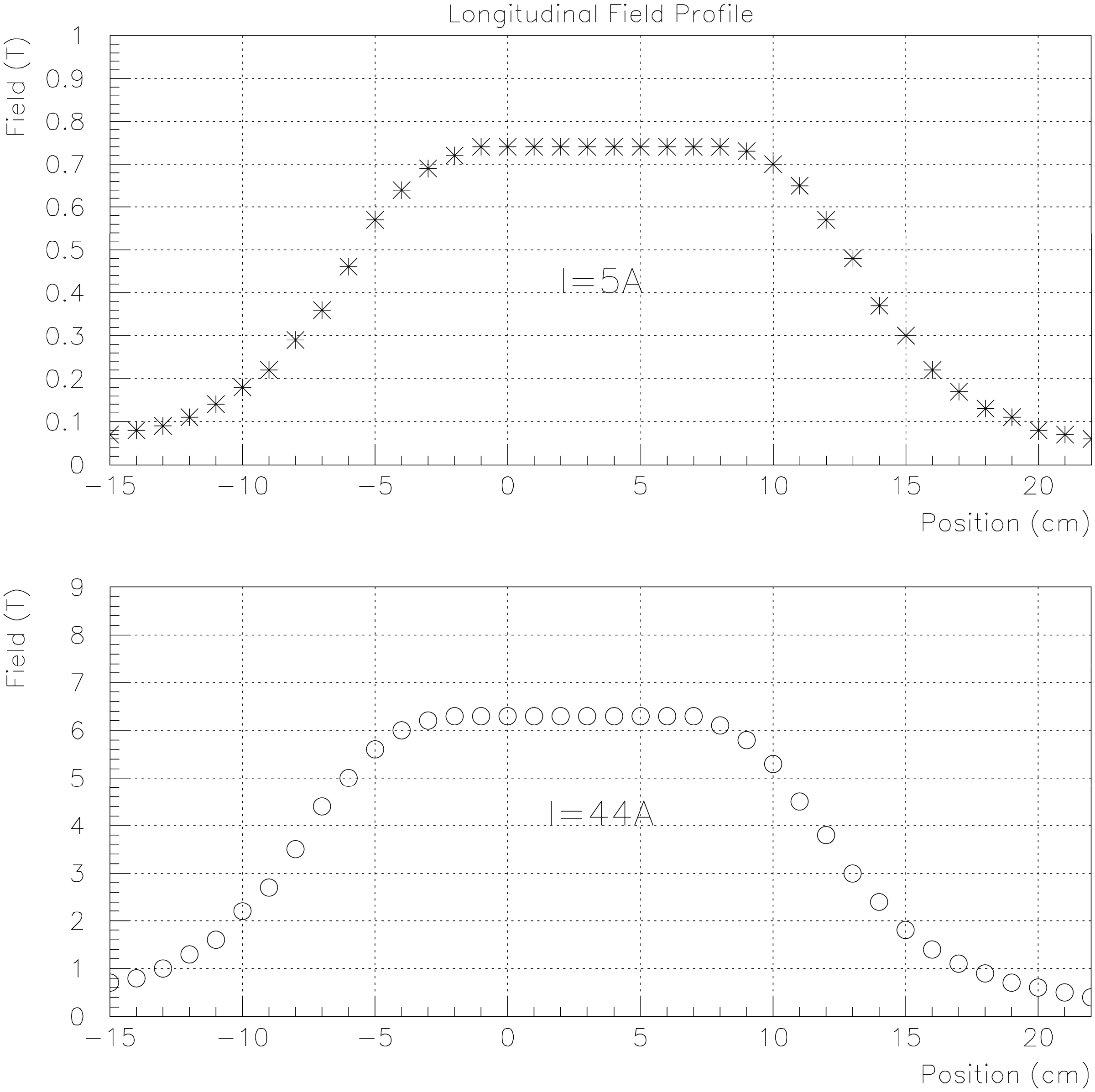

Figure 4: Longitudinal field profiles at 5 and 44 A. Position is measured from the approximate geometric center of the magnet.

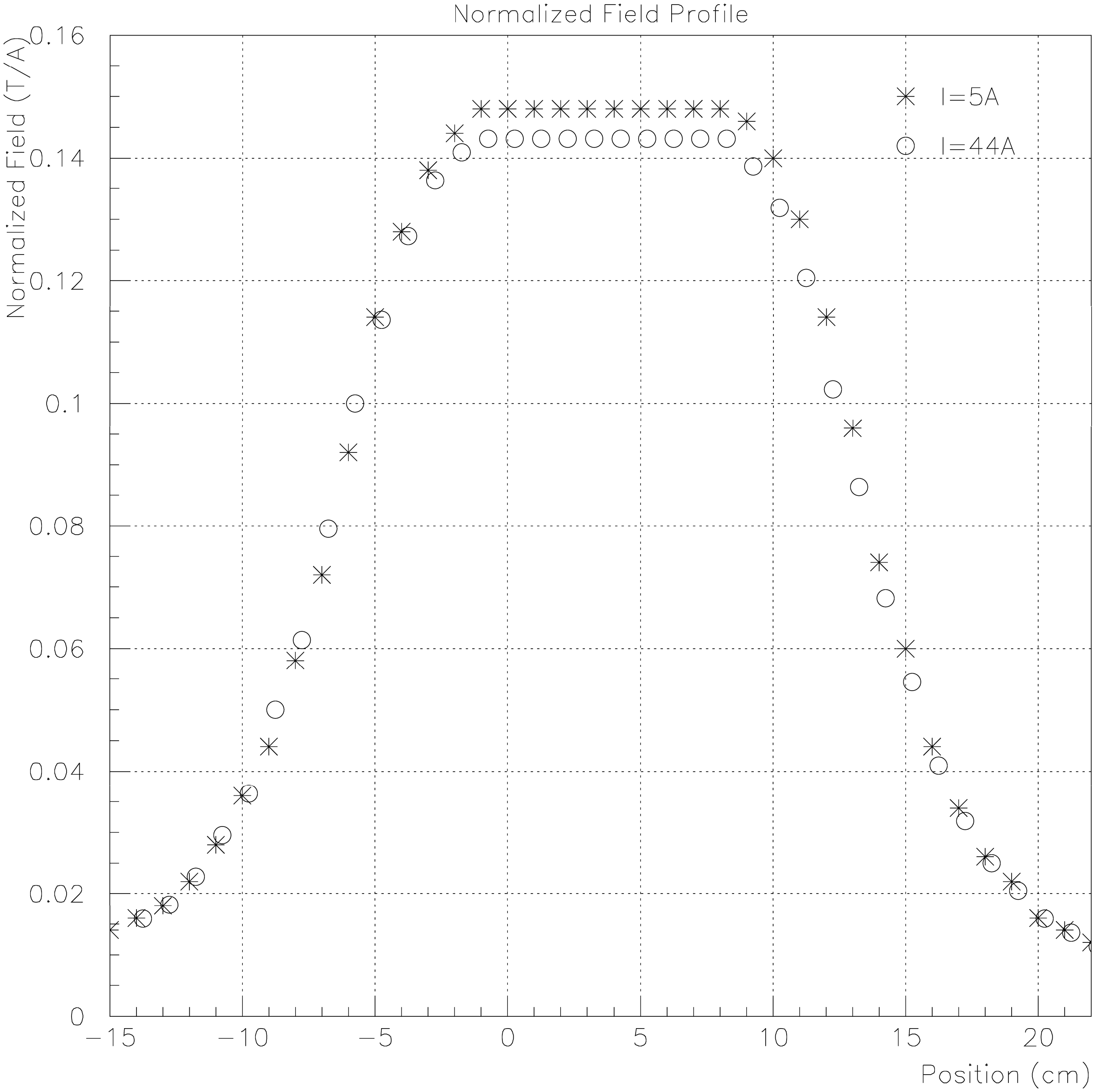

Figure 5: Normalized profiles (B/I) at 5 and 44 A. A systematic shift in position has been corrected for.

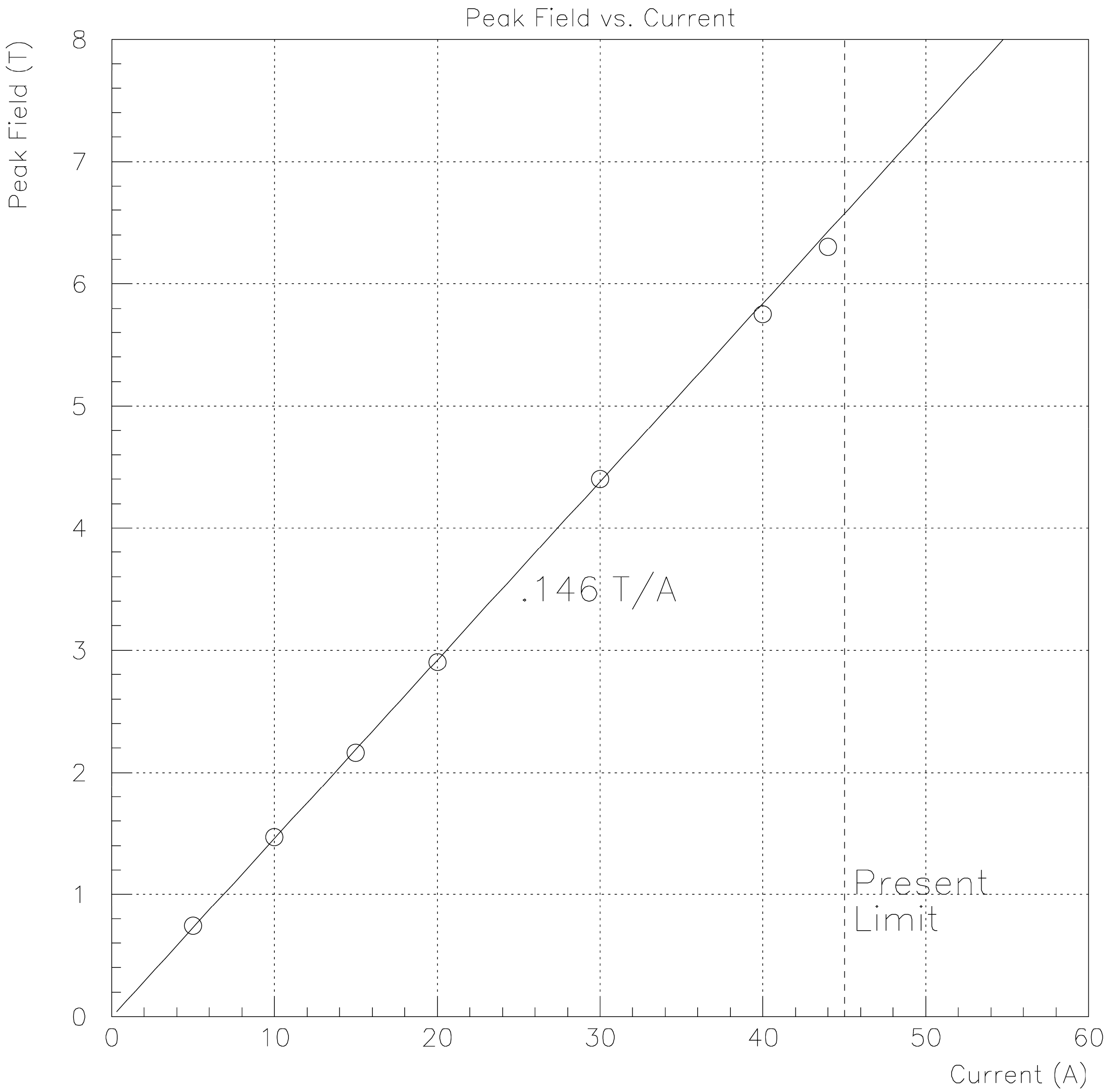

Figure 6: A plot of the measured peak field as a function of magnet current. The indicated slope is from a fit to the lower five points. Also shown is the highest sustained current to date (45 A).