Invited Article: Development of high-field superconducting Ioffe magnetic traps


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We describe the design, construction, and performance of three generations of superconducting Ioffe magnetic traps. The first two are low current traps, built from four racetrack shaped quadrupole coils and two solenoid assemblies. Coils are wet wound with multifilament NbTi superconducting wires embedded in epoxy matrices. The magnet bore diameters are 51 and 105 mm with identical trap depths of 1.0 T at their operating currents and at 4.2 K. A third trap uses a high current accelerator-type quadrupole magnet and two low current solenoids. This trap has a bore diameter of 140 mm and tested trap depth of 2.8 T. Both low current traps show signs of excessive training. The high current hybrid trap, on the other hand, exhibits good training behavior and is amenable to quench protection. © 2008 American Institute of Physics. [DOI: 10.1063/1.2897133]

I. INTRODUCTION

Magnetic traps can confine electrically neutral particles with non-zero magnetic moments; they have been used to trap atoms, molecules, and neutrons. A magnetic moment in a magnetic field undergoes the Larmor precession around the direction of the local field. When the magnetic field is changing slowly compared to the Larmor precession frequency, the so-called adiabatic condition, the orientation of the magnetic moment with respect to the field is preserved and the energy of the moment may be expressed as \( E = E_{\text{kin}} + \mu_B B \), where \( E_{\text{kin}} \) is the kinetic energy and \( \mu_B \) is the magnetic moment in the direction of the magnetic field. Thus, an inhomogeneous magnetic field with a local minimum in magnitude can form a trap for “low-field seeking” particles with \( \mu_B > 0 \).

In most cases, it is advantageous to have the highest possible trap depth, defined as the difference between the minimum magnitude of the magnetic field on the edge of the trapping volume and the minimum of the magnetic field inside the trap. In addition to the trap depth, important characteristics to consider are trapping volume and the specific magnetic field profile inside the trap. These affect the density, number, and energy spectrum of the trapped species.

An Ioffe-type magnetic trap consists of a quadrupole assembly for radial confinement and two solenoid assemblies in the same current sense for axial confinement. Such a configuration eliminates zero field regions inside the trap, thereby suppressing the spin-flip probability of trapped particles. Ioffe traps are commonly used in atomic and particle physics experiments. Ioffe traps described in this paper are developed for the ultracold neutron lifetime experiment currently being conducted at the National Institute of Standards and Technology Center for Neutron Research. Two primary design considerations are important for the experiment: neutron loss due to spin flip which represents a systematic error that should be minimized, and maximizing the number of neutrons trapped, which approximately scales with \( B^2 V_T \), where \( B_T \) is the trap depth and \( V_T \) is the trapping volume.

Three generations of Ioffe traps have been developed for this work. Mark I and II traps are constructed from low current (several hundred amperes) superconducting coils. Mark I trap has a bore diameter of 51 mm and a trap depth of 1 T. It was used for the initial demonstration of neutron trapping. Mark II trap has a similar trap depth, but a larger bore size, resulting in a factor of 6 increase in the number of trapped neutrons. The larger bore size also allows one to design a detection system with a higher detection efficiency. With this trap, we were able to reach a statistical relative standard uncertainty of 5% for the neutron lifetime measurement. However, excessive training behavior and low quench protection efficiency of this trap suggested that additional increase in trap depth and volume required a new approach. Mark III trap combines a high current (several thousand amperes) quadrupole assembly and two low current solenoids. This high current trap has a designed trap depth of 3.2 T, and can increase the number of trapped neutrons by a factor of 20. This new trap will enable us to reach a statistical relative standard uncertainty of better than 0.5% for the...
TABLE I. Design and operation parameters of the Ioffe traps (the operating parameters of mark III trap are design values, initial test values can be found in Table II).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mark I</th>
<th>Mark II</th>
<th>Mark III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet bore diameter (mm)</td>
<td>51</td>
<td>105</td>
<td>140</td>
</tr>
<tr>
<td>Magnet length (cm)</td>
<td>69</td>
<td>80</td>
<td>110</td>
</tr>
<tr>
<td>Trap radius (mm)</td>
<td>15</td>
<td>42</td>
<td>56</td>
</tr>
<tr>
<td>Trap length (cm)</td>
<td>40</td>
<td>42</td>
<td>75</td>
</tr>
<tr>
<td>Short sample limit (A)</td>
<td>400</td>
<td>320</td>
<td>3750 (quadrupole)</td>
</tr>
<tr>
<td>Operating current (A)</td>
<td>180</td>
<td>170</td>
<td>3400 (quadrupole)</td>
</tr>
<tr>
<td>Trap depth (T)</td>
<td>1.0</td>
<td>1.0</td>
<td>3.2</td>
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The field profiles of the traps are calculated by a magnetic field modeling software “Biot–Savart,” which numerically integrates the field using Biot–Savart law. Figure 2(a) shows the field along a line parallel to the axis of the trap and passing through the turnaround region of the race-track coil for mark II trap. Located on this line is the maximum field on the race-track coil. This field determines the maximum current theoretically possible while still maintaining superconductivity. Figure 2(b) shows the field along a line defined by the inner surface of mark II trap cell used in the neutron trapping experiment (r=42 mm). The minimum field on this line determines the upper limit of the magnetic trap depth. The asymmetric dip in the field is a result of the partial cancelation of the trapping field by the divergent field produced by the pinch coils. The key parameters in the magnet design are the length, width, and cross-sectional area of the race-track coils, the diameter and length of the solenoid assembly, and the diameter and copper to superconductor ratio of the wire. The size of mark I trap was limited by the commercially available race-track coils at the time. Mark II trap was designed to be the largest trap that could fit in the cryogenic vessel used for mark I trap.

The major design difference between mark I and II traps lies in their different prestressing techniques for the quadrupole assembly. The reason for holding the race-track coils under tension is to minimize any movement of these coils due to current-induced forces when the magnet is energized. Even tiny coil movements can lead to undesirable magnet quenching.

In mark I trap, the race-track coils are held onto a titanium form and aluminum spacers are added to the assembly to make it cylindrical (see Fig. 3). Prestressing of the coils is done by wrapping the assembly with 20 layers of Kevlar under \(67N\) of tension. The Kevlar wrapping is protected from abrasion by a layer of Tedlar on the inside and by a layer of epoxy impregnated fiberglass on the outside. Unfortunately, we found out that the Kevlar wrapping might not have provided enough compression. On one occasion the Kevlar-fiberglass assembly shifted between cooldowns. Kevlar’s properties of creeping over time and negative index of thermal expansion at low temperature \(^{11,12}\) may have contributed to a lack of compression at low temperature.

The field profiles of the traps are calculated by a magnetic field modeling software “Biot–Savart,” which numerically integrates the field using Biot–Savart law. Figure 2(a) shows the field along a line parallel to the axis of the trap and passing through the turnaround region of the race-track coil for mark II trap. Located on this line is the maximum field on the race-track coil. This field determines the maximum current theoretically possible while still maintaining superconductivity. Figure 2(b) shows the field along a line defined by the inner surface of mark II trap cell used in the neutron trapping experiment (r=42 mm). The minimum field on this line determines the upper limit of the magnetic trap depth. The asymmetric dip in the field is a result of the partial cancelation of the trapping field by the divergent field produced by the pinch coils. The key parameters in the magnet design are the length, width, and cross-sectional area of the race-track coils, the diameter and length of the solenoid assembly, and the diameter and copper to superconductor ratio of the wire. The size of mark I trap was limited by the commercially available race-track coils at the time. Mark II trap was designed to be the largest trap that could fit in the cryogenic vessel used for mark I trap.

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In mark II trap, aluminum tubes instead of Kevlar are used to compress the assembly (see Fig. 3). Most of the assembly is built from grade 2 commercially pure titanium (CPT). CPT shrinks 0.141% as it is cooled from 300 to 4 K. Aluminum alloy 6061, used for the construction of the compression tubes, shrinks 0.41% between 300 and 4 K. The aluminum tubes, placed over the magnet assembly, shrink more than the titanium when cooled, compressing the assembly with a pressure $p = \frac{(2Et \partial l)}{d^2} = 12.1$ MPa, where $E = 78.4$ GPa is Young’s modulus of the aluminum alloy at low temperature, $t = 12$ mm is the thickness of the aluminum tubes and $\partial l = 240$ $\mu$m is the thermal differential contraction between the aluminum tubes and the titanium form. The compression pressure exceeds the 11.2 MPa of outward pressure exerted by the coils when fully energized. Since the stress in the aluminum tube, $E \partial l / d \approx 100$ MPa, is well below the yield strength of 6061 aluminum alloy [370 MPa at 4 K (Ref. 14)], the tube is expected to remain in the elastic regime and retain its shape even after repeated thermal cycles. This allows the assembly to be taken apart and coils replaced with a minimum of effort.

B. Magnet construction

All coils in mark I and II traps are wound with multiple turns of a single long strand of composite superconducting wire, multifilament niobium titanium (NbTi) in a copper matrix. The wires are bonded in an epoxy matrix to prevent movement under the Lorentz force when the magnet is energized; even an imperceptible movement of a wire can cause sufficient frictional heating that quenches the magnet. The characteristics of a good superconducting coil are high wire packing density and low epoxy rich or void regions. Racetrack coils are more difficult to wind than solenoids. In a solenoid, wire tension during winding naturally translates into a compression force on previous layers that helps to increase wire packing and reduce epoxy rich regions. In a racetrack coil, wires in the straight sections of the coil are not under compression during winding, and have to be compressed after winding, which often leads to more epoxy rich regions and hence premature quenching of the coils.

The racetrack coils in mark I trap were wound commercially, and the solenoid assembly was wound by the authors. The Kevlar wrapping for the quadrupole assembly was done by the National High Magnetic Field Laboratory in Tallahassee, Florida. For mark II trap, we could not identify a company to wind the larger size racetrack coils in an affordable way. All coils were wound by the authors using a magnet winding machine located at Harvard University. The magnet form pieces were machined by the Boston University and Harvard University shops.

Here, we describe the coil winding and assembly construction of mark II trap in more detail. A schematic showing the basic construction of a mark II racetrack coil is shown in Fig. 4. Each coil has an overall length of $L = 80$ cm, with a distance between turnaround centers of $l = 70$ cm, a distance between the centers of the current bars of $a = 7$ cm, and a $2.5 \times 2.5$ cm$^2$ cross section. The coils are wound using Formvar insulated NbTi wires with a 0.74 mm diameter and
a copper to superconductor ratio of 2:1. Previous work by others\textsuperscript{17} indicated that racetrack shaped coils wound with Kapton-insulated wire exhibit improved training behavior. It is generally thought that the Kapton design allows the wires to move slightly within the Kapton sleeve as the magnet is energized. As the wire is not bonded to the epoxy in this case, the probability of quench-inducing epoxy cracks is reduced. We, however, see little difference between the Kapton and Formvar-insulated coils and Formvar was chosen due to its lower cost.

The racetrack shaped coils were wet wound onto a solid aluminum bar with rounded ends and two side supporting plates. A Teflon based epoxy release agent was sprayed onto the winding form to facilitate the release of the coils from the aluminum forms. All sides were enclosed by 1 mm thick G-10 (fiberglass and epoxy composite) sheets that had been machined beforehand. A channel was machined in one of the sheets in order to bring out the wire from the innermost layer. The G-10 sheets provided a flat surface that could be compressed evenly, and served to protect the coils as well. Epoxy\textsuperscript{18} was applied after each layer of winding. Although the curing time of the epoxy was 24 h, it became more viscous with time, so a new batch was mixed every 2–3 h during winding. Each of the 28 layers took approximately 30 min. to wind. The layers of wire were separated by a sheet of 0.5 mm thick fiberglass cloth, as shown in Fig. 4, to minimize crack propagation in epoxy rich regions. As the epoxy cured overnight after winding, the two straight sections of the coil were compressed by aluminum bars to help minimize epoxy rich regions. After the epoxy was cured, the current leads of the coil were strengthened by adding an additional superconducting wire soldered onto them.

The racetrack shaped coils were first tested individually on their winding forms (see Sec. II D). They were then taken off the winding forms, placed on the titanium form, and compression pieces (see Fig. 3) were bolted to the form. Then, the entire assembly was put on a lathe and machined to a diameter of 193 mm. Sections of aluminum tubing were machined to slide over the magnet assembly. Seven tubes were machined, each with a thickness of 12 mm. It was found that the titanium magnet assembly could not be easily machined to a uniform diameter. The diameter varied about 100 $\mu$m over its length. Therefore, in order for the aluminum tubes to slide on with the required tolerance ($<25 \mu$m on the radius), the tubes were machined to each fit over a specified section of the magnet assembly.

Surrounding the quadrupole assembly are two solenoid assemblies. Each assembly has an inner diameter of 21.4 cm and an outer diameter of 24.6 cm. These dimensions were chosen to maximize the size of the trap, while ensuring that the entire assembly could fit into the existing helium vessel of the cryostat with 7 mm clearance. The solenoids were wet wound on an aluminum form. Because the wire packing density is high for solenoids due to winding tension, fiberglass is often not needed between layers. The coil windings were separated from the form by a layer of 0.25 mm thick Kapton film and epoxy release agent sprayed onto the form before winding. Solenoids, in general, perform better when the windings are not directly bonded to the form. After winding, each solenoid assembly was slid on the outside of the quadrupole assembly and electrically connected to the quadrupole in series.

### C. Quench protection system

Despite careful design and construction of a superconducting magnet, quenching may still occur. A magnet quench occurs when some event heats part of the superconducting wire above certain temperature and it becomes normal. Dissipation of the magnet’s stored energy through resistive heating of the normal portion of the magnet produces additional heat that is conducted along the magnet wire, driving more of the magnet normal and propagating the quench. In less than a second, it is possible for the entire stored energy of the magnet to be dissipated. If the stored energy is high and the quench propagation is slow compared to the energy dissipation time, a small length of wire can be vaporized by the heat, destroying the continuity of the magnet. The probability of such a catastrophic event depends on the quench location within the magnet and details of the quench dynamics.

Smalloffee magnetic traps, such as mark I trap, typically do not require quench protection. The stored energies are small enough that the probability of a catastrophic quench is very low. Mark II trap, due to its greater stored energy, proved to be much more susceptible to catastrophic quenches. For example, one of the racetrack coils was damaged during such a quench. As a result, an active quench protection system was developed which could quickly detect a quench and dissipate the stored energy externally. An active quench protection system typically consists of quench detection and quench protection (energy dissipation) circuits. A schematic of the protection system used for mark II trap is shown in Fig. 5.

A magnet quench can be detected by observing the voltage imbalance signal between matching pairs of coils. Voltages across individual coils in the trap are measured from installed voltage taps using unity gain difference amplifiers.\textsuperscript{19} Each voltage consists of both a resistive component and an inductive component. While the resistive component is nonzero only during a quench, the inductive component is nonzero while charging or discharging the magnetic field. Because the inductive voltages of two coils opposite to each other in the quadrupole or in different solenoid assemblies (a matching pair) are almost the same due to
similar amounts of magnetic flux penetration, they cancel each other to first order in the voltage difference (with some coefficients compensating for small geometric differences). The sum of the voltage differences from matching pairs of coils thus forms a voltage imbalance signal, which stays zero for stable operation as well as magnet ramps. A nonzero imbalance signal therefore can only arise from resistive voltage which is a strong indication of a quench.

Mark II trap consists of ten coils connected in series; four racetrack shaped coils, two solenoid pinch coils, and four bucking solenoid coils. Since the connections between each set of three coils in the two solenoid assemblies are made without the use of lugs or voltage taps, we consider each solenoid assembly to be one coil for the purposes of quench detection. Together with four racetrack coils, they form three matching pairs. The voltage imbalance signal from these matching pairs is sent into a threshold detection circuit. When the absolute value of the imbalance signal exceeds 1 V, the trigger circuit is set to initiate the protection circuit. An optoisolator is used in the trigger circuit to isolate the detection circuit from the high voltages generated in the protection circuit.

The quench protection circuit shown in Fig. 5 is a modified version of the system developed by Fermi National Laboratory (see Ref. 20). The basic idea is to quickly connect a resistor in series with the magnet when a quench is detected so that the stored energy can be dumped externally. This is accomplished by using silicon controlled rectifiers (SCRs) as fast switches. When the magnet is energized, almost all of the current flows through the run SCR, \( S_R \), and through the magnet (see Fig. 5). \( S_R \) is initially put into conduction by briefly connecting a 5 V floating power supply to the gate. When a quench is detected, the trigger circuit sends out a 200 mA, 75 ms pulse that opens the dump SCR, \( S_D \). The dump capacitor then discharges which temporarily stops the current flow in the run SCR, thus turning it into the nonconducting state. After the capacitor is completely discharged, the dump SCR, \( S_D \), also stops conducting current in a few milliseconds. The magnet with an inductance \( L \) and the dump resistor \( R_D \) then form a circuit with a \( L/R_D \) time constant of about 0.5 s. The capacitor is recharged to its original voltage through a charging resistor \( R_C \) (several kilo-ohms) by a separate power supply. The diode \( D \) prevents the capacitor from discharging through the dump resistor. The dump resistor (1.86 \( \Omega \)) is made from a 44 m long, 2 mm diameter soft steel wire. The resistance of the dump resistor is chosen to limit the maximum voltage during a quench to below 500 V. the heat capacity of the wire limits its temperature rise to 50 K even if all of the magnet stored energy is dissipated in the resistor.

### D. Magnet training

Both mark I and II traps only reached \( \sim 50\% \) of the theoretical short sample limit and exhibited excessive training behaviors. Here, we detail the training results of mark II trap.

The racetrack shaped coils from mark II trap were tested individually after winding. During these tests, they were left on the winding forms, with additional aluminum side plates providing structural support and compression. All coils reached within 15% of the 320 A short sample limit. The
The training behavior of the individual coils is shown in Fig. 6. The solenoid assemblies were tested together in series. They reached 70% of the short sample limit after a dozen or so quenches, showing signs of excessive training.

During initial tests of the trap assembly, a spontaneous quench resulted in a catastrophic failure of the magnet. The quench apparently started in a part of the lead connecting two racetrack coils, since a section of lead was vaporized, as were several layers of wire in one of the racetrack coils where the lead entered the coil. Although the lead entrance point into the racetrack coils was identified as a weak point, and an additional wire was soldered to the lead for reinforcement, it proved to be an insufficient protection measure.

After replacing the racetrack coil, a quench protection system (see Sec. II C) was installed to reduce the risk of a catastrophic quench. The energies dissipated in the magnet and the dump resistor during each quench were monitored by measuring liquid helium boiloff, temperature increase in the dump resistor and the voltage decay curve across the dump resistor. All three methods were consistent with each other, with the voltage measurement giving the best precision. Our data show that the efficiency of the protection circuit, which is the fraction of the magnet’s stored energy dissipated in the dump resistor, decreases linearly with current as shown in Fig. 7. The decrease probably results from a faster rise of the magnet’s resistance during a quench at a higher current.

The entire trap was first trained in a vertical test dewar. Its training profile is shown in Fig. 8. In general, the maximum current increased from quench to quench, but the slow rate of increase was a sign of excessive training. After 15 quenches, the magnet reached 181.4 A, 53% of the short sample limit. At this current, the measured energy dissipation in the magnet was already comparable to the amount of energy dissipated in the magnet during the catastrophic quench. Hence, it was determined that the magnet should be operated at a current no higher than 180 A, simply to minimize the risk of catastrophic failures.

When the trap was cooled in the trapping apparatus, following the above training, additional training was required in order to achieve an operating current of >170 A. The training curve of the quadrupole trap in the main apparatus is also shown in Fig. 8. Since the current seemed not to increase much beyond 170 A after numerous quenches, a running current of 170 A was selected for mark II trap.

E. Discussion

In mark II trap, each of the racetrack coils reached over 85% of the short sample limit within five to six quenches; however, the quadrupole assembly and the solenoid assemblies only reached 50% and 70% of the short sample limit, respectively, and showed signs of excessive training. This premature quenching behavior suggests problems with the compression scheme, the winding technique, or a combination of the two. An improvement in the quadrupole design could be to incorporate the racetrack coil winding form as a part of the magnet assembly, thus reducing gaps between the coil and the form and, perhaps, ensuring better compression. Such a change, however, may also have the undesirable ef-
fect of increasing in-coil stresses. Further studies are warranted in this regard. An improvement in the solenoid form design can be to add outer support pieces to reduce form deformation under the repulsive force between the pinch and bucking coils, and the additional Lorentz force caused by the field from the quadrupole (see Sec. III C).

Although it is possible to improve the performance of the low current traps with better winding and compression techniques, the low quench protection efficiency for these traps becomes a big concern for designs of a deeper and larger trap. Our mark II trap test shows that the efficiency of the active protection circuit implemented decreases rapidly with increasing current, and cannot provide adequate protection at much higher current. One way to better protect the magnet would be to incorporate heaters in the coil windings, then when a quench is detected, the heaters drive a large fraction of the magnet to normal to avoid the deposition of energy in a small region. Such a method would require us to experiment with modifications in our coil winding and assembly techniques. In addition, the high quench voltages and intrinsically low quench propagation speed of the small diameter wire may still pose problems.

Another approach for better quench protection is to use high current and lower inductance magnets. In this case, energy dissipation may be performed faster and without an undesirable increase in the maximum voltage on the external resistor. Using larger diameter wire for the construction of the lower inductance magnet can also reduce the chance of a quench because of the decreased contact surface area between the wire and the epoxy. Larger wire diameter also provides faster heat dissipation through the wire, so that local heating of the wire may not result in a quench.

III. HIGH CURRENT IOFFE TRAP (MARK III)

Due to the difficulty in manufacturing a high quality quadrupole assembly and in quench protecting low current Ioffe traps, we explored the possibility of using low inductance and high current magnets developed in the accelerator community for mark III trap. Because the cost of custom-built, high current magnets is very high, we use a combination of a high current quadrupole (on loan from the KEK laboratory in Japan) and two low current solenoids for the new trap. In the following section, we describe the design consideration, quench protection, and testing of mark III trap.

A. The KEK quadrupole magnet

The high current quadrupole magnet we obtained was originally used for electron beam focusing at the TRISTAN accelerator at the High Energy Accelerator Research Organization in Japan (KEK). Since these magnets were not in use, the group at KEK generously loaned one magnet to us. The KEK magnet has an effective field length of 1.14 m, a bore size of 14 cm, and a nominal outer diameter of 28 cm. It consists of 16 racetrack shaped coils, forming four concentric layers. The magnet is designed to operate at 3405 A (at 4.2 K) for a field gradient of 70 T/m with a maximum field of 4.9 T inside the magnet bore. The coils are prestressed by 30 mm thick 316LN stainless steel\textsuperscript{13} collars on the outside with typical radial forces of 6.9 \times 10^5 N. A cross section of the quadrupole magnet is shown in Fig. 9.

The KEK magnet is wound with a keystoned cable with mean thickness of 1.27 mm, width of 9.09 mm, and composed of 27 strand wires with a diameter of 0.68 mm. Each wire is made of approximately 2200 twisted NbTi filaments embedded in a copper matrix having a copper to superconductor ratio of 1.8. The wire strand packing factor is 0.89, which means 11% of the cable is expected to be filled with liquid helium. The direct contact of the superconductor with liquid helium provides added stability. The maximum field in the KEK magnet is at the racetrack coil turnaround regions. At 4.2 K, the critical current of the KEK magnet is about 4100 A. The critical current can be increased by roughly 30%, if the magnet operates in superfluid helium at 1.8 K.

During the initial training after its production, the KEK magnet successfully reached 4000 A after several quenches. In later test runs, the magnet was operated at 3405 A, about 85% of the short sample limit. No natural quenches occurred. Further details on the characteristics and production of the KEK quadrupole magnet can be found in Ref. 22.

B. Solenoid design

Given the 14 cm diameter bore size of the KEK magnet and an estimate of the space needed for implementing an experimental cell, we can expect to have an effective trapping diameter of roughly 11.0 cm. At its operating current, the KEK magnet can provide a 3.85 T radial trapping field. Generally, the pinch solenoids are designed to produce about the same axial trapping field as the radial field. The parameters of the solenoids can be adjusted to maximize the effective trapping volume, \( \int (B_{\text{trap}} - B)^{3/2} dV \). The magnetic field \( B \) in the trap is calculated using the Biot–Savart program. \( B_{\text{trap}} \) is defined as the lowest field at which neutrons can escape from the trap. This escape point is typically near the trap wall where the fringing field from a solenoid reduces the field from the quadrupole. The volume integral integrates the vol-

![FIG. 9. A cross-section view of the KEK quadrupole magnet (Ref. 22).](http://rsi.aip.org/rsi/copyright.jsp)
ume inside the equipotential surface of $B_{\text{trap}}$. An additional consideration in the design is to limit the maximum field on the KEK windings to below 7 T so that the quadrupole magnet can operate at approximately 90% of the short sample limit.

In the low current Ioffe traps, bucking coils are added to each side of the pinch solenoids to increase effective trap length and reduce peak field at the turnaround region of the racetrack coils. We find that with mark III trap, the signal gain from adding bucking coils to the solenoids is only 15% due to the longer trap length. In addition, adding bucking coils would certainly increase the complexity and cost of the solenoids. There is also a concern that the large repulsive Lorentz force between the pinch solenoid and the bucking coils could be a source of premature quenching unless a very sturdy magnet form is designed to counter this force. Given these considerations, the no-bucking coil design is chosen for its simplicity and reliability, despite the estimated 15% loss in signal.

The cost of winding high current solenoids can be significantly higher than low current epoxy bond solenoids. However, as discussed before, low current solenoids are not well suited for effective quench protection. In order to lower cost but reduce the probability of a catastrophic quench, the solenoids are designed to operate at low current and 25% below the short sample limit. In the final design, each solenoid has an inner diameter of 29.5 cm, an outer diameter of 36.1 cm, and a length of 18 cm.

**C. Solenoid form design**

By studying the force interactions between the solenoids and the quadrupole magnet, we find that the magnetic field from the solenoids only changes the distribution of the radially outward Lorentz force on the quadrupole magnet and not the direction. Simulations indicated that the existing stainless compression collars outside the quadrupole assembly were sufficient to counteract this modified Lorentz force. On the other hand, the magnetic field from the quadrupole exerts a Lorentz force axially on the solenoids. Such forces are not supported by typical solenoid forms. Although it is not certain that this additional force would cause the solenoids to quench prematurely, a cautionary approach is taken to design a form that will minimize wire movement under such force.

When a stand-alone superconducting solenoid is energized, the Lorentz force pushes the wires toward each other and the solenoid as a whole radially outward. Because the solenoid form only needs to withstand the prestressing from the winding in stand-alone operation, the form is typically made from aluminum with thin end flanges. However, in an Ioffe trap, the Lorentz forces are different. The field from the KEK magnet at the solenoid has a magnitude of 1 T. The direction of the field is shown in Fig. 10. The tangential component of the field is greater than in the same direction as the solenoid current exerts no Lorentz force. However, the radial component of the field induces Lorentz forces that push the coil toward the end flanges of the magnet form. The total force on the flanges is approximately $7.9 \times 10^4$ N. Because the radial component of the field changes direction for every $90^\circ$ increment in azimuthal angle, the Lorentz force also reverses its direction every $90^\circ$. The net effect is to try to twist the coil into a saddle shape.

Several magnet form designs were considered with the aim to minimize the solenoid coil movement. The form deformation and stress concentration are calculated using a finite element program ANSYS. Results show that adding a supporting sheath outside the magnet form can reduce the maximal stress concentration (500 MPa) and form displacement (500 $\mu$m) by a factor of close to 10, leading to 72 MPa and 42 $\mu$m, respectively. This form design is shown in Fig. 10. The sheath is connected to the form by close fitting supporting pegs. Due to the large stress concentrations in the form, especially at the pegs, aluminum 2219-T87, which has a yield strength of 440 MPa, significantly higher than the 66 MPa yield strength of common alloys such as 6061, is chosen as the form material. Although other structural materials such as titanium have larger Young’s modulus which could reduce form deformation, aluminum has a thermal expansion coefficient better matched to the copper clad wire, thus minimizing any undesirable gap between the winding and the magnet form as the magnet is cooled to liquid helium temperature.

The magnet bobbins and supporting sheaths were machined at the machine shop of North Carolina State University. The bobbins were then shipped to American Magnetics, Inc. for coil winding. After winding, the supporting sheaths were added and the support pegs were machined to fit in the
side holes with 15 μm tolerance. Similar construction techniques are used in anti-Helmholtz traps.24

D. Quench protection

The KEK quadrupole magnet has a stored energy of 336 kJ at its designed operating current. It is protected by an active system similar to that used with mark II trap (see Sec. II C). Eight two-layer racetrack coils form four matching pairs. The protection circuit is set to trigger when the absolute value of the voltage imbalance signal exceeds 400 mV for 1 ms. This new threshold detection circuit avoids the occasional false trigger from voltage spikes, as seen in mark II system. The operation principle of the protection circuit can be found in Sec. II C. The main difference is that major components in this circuit are scaled up to accommodate the 20-fold increase in operation current. Instead of a single Hewlett-Packard 6681A (875 A, 5 V) supply running in autoparallel mode, four Hewlett-Packard 6880A (875 A, 5 V) supplies running in autoparallel mode are used for the KEK quadrupole. In addition, the single run SCR (see Fig. 5) is replaced by four SCRs running in parallel. Because the voltage drop across each SCR is slightly different and SCRs have exponential I-V curves, four resistors are put in series with the run SCRs to evenly split the current between them. Each resistor (0.6 mΩ) is made of a 17.8 cm long CuNi tube with a 1.3 cm inner diameter that enables water cooling to flow through its center. The dump resistor is also much larger. It is made from 1.6 cm thick 316 stainless steel plate with a 100 mΩ resistance and 15 kg of weight.

Each solenoid has a stored energy of 180 kJ at its designed operating current. Due to its high inductance (7 H), the stored energy cannot be effectively dumped externally using a similar active protection circuit. Instead, each solenoid is protected passively by diodes across four subdivisions of the solenoid. During a quench, when the voltage across a subdivision goes above a certain value (2 V), the corresponding diode goes into conduction, letting some current bypass the subdivision, therefore reducing its current density and heating. Since the diodes can only dissipate a small amount of energy, they provide very limited protection to the solenoids. To further reduce the probability of catastrophic failure, the solenoids are intended to operate at a current well below the short sample limit.

E. Magnet tests

The KEK magnet and the solenoids were first tested separately. During the KEK magnet test, no natural quench of the KEK magnet was observed with currents up to 2900 A. Quenches were induced using four 5 Ω resistive heaters attached to the four inner coils. 20 W of input power into a single heater can initiate a quench. The quench protection efficiency can be calculated from measured liquid helium boiloff, the temperature rise in the dump resistor or the voltage decay curve across the dump resistor. As shown in Fig. 11, the efficiency of the protection circuit remains high at different operating currents with an average value of 95%. The solenoids were tested by American Magnetics, Inc. after initial winding up to 235 A with no natural quenches.

Mark III trap assembly was tested in a vertical test dewar. Two separate pairs of vapor cooled current leads supplied currents to the quadrupole and solenoids, respectively. The quadrupole magnet was designed to operate at 90% of its short sample limit, and the solenoids at 75% of their short sample limit. During the trap test, two quenches were observed: the first one at about 80% of the design current and the second one at about 90% of the design current. Because the KEK magnet and the solenoids were controlled by separate power supplies, their ramping rate did not exactly match each other. The exact parameters of the quenches are shown in Table II. After the first quench, the voltage imbalance signal from the KEK magnet and the voltages across the solenoids were monitored by an oscilloscope. Based on the registered traces, it could be determined that the second quench originated in the KEK magnet. Though the majority of the stored energy in the KEK magnet was dumped in the external dump resistor, all stored energy in the solenoids was dumped in the cryogenic environment, enough to boil off 100–1201 of liquid helium. After an initial explosive boiloff, increased liquid helium boiloff was observed for ten to 15 min. Because the current leads for the KEK magnet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quench 1</th>
<th>Quench 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrupole current (A, % of design value)</td>
<td>2700 (79%)</td>
<td>2950 (87%)</td>
</tr>
<tr>
<td>Solenoid current (A, % of design value)</td>
<td>190 (84%)</td>
<td>210 (93%)</td>
</tr>
<tr>
<td>Trap depth (T)</td>
<td>2.5</td>
<td>2.8</td>
</tr>
<tr>
<td>Quench initiation place</td>
<td>N/A</td>
<td>KEK</td>
</tr>
</tbody>
</table>

FIG. 11. The graph shows the measured quench protection efficiency at various currents of the KEK quadrupole magnet. On average, the protection circuit has an efficiency of 95%.
were rated for 3000 A and one lead, in particular, heated up quickly at 2950 A, we did not attempt to go to higher current after the second quench. This limitation can be easily overcome in future tests with the use of higher rated current leads, either vapor cooled or high temperature superconducting leads.

**F. Discussion**

Compared with the low current traps, mark III trap exhibits much better training and quench protection behaviors. In two quenches, the quadrupole reached 78% of the short sample limit, the solenoids reached 70% of the short sample limit and the whole trap reached a trap depth of 2.8 T. This improvement in performance can most likely be attributed to better production as well as a stronger mechanical support of the magnet form.

We expect that the performance of the trap at 4.2 K will be limited by the KEK magnet, because, in the trap design, the KEK magnet is pushed closer to its short sample limit (90%) than the solenoids (75%). This situation makes the option of running the trap in superfluid helium very attractive. The performance of the KEK magnet is expected to increase by 30% at 1.8 K. Superfluid helium in direct contact with the superconducting cables can help stabilize the magnet against quenches. The performance of the solenoid is also expected to increase by 30% at 1.8 K. However, because most of solenoid wire is not in direct contact with superfluid helium, the increase in current density would make the solenoids more prone to quenches. Furthermore, without an effective quench protection, an increase in stored energy also increases the probability of permanent damage to the solenoids in a quench. These concerns will likely be the limiting factors of the trap performance at 1.8 K.

**IV. CONCLUSIONS AND FUTURE DIRECTIONS**

In the development of the three generations of Ioffe traps, we have progressively increased the trap volume and trap depth. The low current mark I and II traps are modular and represent a fairly inexpensive way to build a large three-dimensional high-field magnetic trap. The high-current mark III trap, although more complex, has overcome the limitations in production and quench protection presented with the low current, high inductance traps. Mark III trap has already reached a trap depth of 2.8 T and can potentially perform even better if operated in superfluid helium.

Further increase in the Ioffe trap depth and volume will require a larger and deeper high current quadrupole assembly. The development of such a magnet is beyond our technical capability, and would need to rely on the accelerator community. In anticipation of the construction of the proposed very large hadron collider (VLHC), several groups are currently developing accelerator magnets using high temperature superconductor (HTS) material. HTS has a much higher critical current density and less susceptible to frictional heating induced quenches. However, it is very brittle and difficult to make into wire or cable. The most promising avenue for achieving the highest field is a hybrid design, which makes the inner coils from HTS material where the field is the highest and outer coils from LTS material Nb₃Sn where the field is somewhat lower. With the rapid development of second generation HTS materials and accelerator magnet manufacturing technology, a quadrupole magnet with a 10 T radial trap depth may become available, and building an Ioffe trap with a trap depth above 9 T will be possible.

**ACKNOWLEDGMENTS**

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9. When first energized, a superconducting magnet often becomes resistive (quench) at a current below its critical current. For subsequent times, the magnet usually quenches at successively higher currents until it reaches the critical current. This process is known as training. Excessive training means that a magnet repeatedly quenches at a current below the critical current, and further training can no longer improve its performance.
10. Any mention of commercial products or reference to commercial organizations is for information only; it does not imply recommendation or endorsement by NIST nor does it imply that the products mentioned are necessarily the best available for the purpose. Ripplon Software Inc., Burnaby, BC, Canada.
16. Because the thermal expansion coefficient of unreinforced epoxy is usually three to five times higher than the superconductor, even an epoxy rich region with a thickness of 0.5 mm can lead to cracking and magnet quench at low temperatures (Ref. 15).
17. W. B. Sampson (private communication).
18. Shell Resin 815C with 3140 hardener, at a mass ratio of 1:1.
19. Burr-Brown INA117. These difference amplifiers were selected because they are rated to withstand ±500 V on the inputs, with respect to ground.
21. A SCR is a three terminal (gate, anode, and cathode) solid state device similar to a transistor. The connection between anode and cathode is normally nonconducting, but can be made conducting by applying a positive bias voltage between the gate and the cathode. The anode-cathode voltage
drop of the SCRs used is approximately 1.2 V. Once in the conductive state, the SCR remains conducting until the gate-cathode bias voltage is removed and the anode-cathode current stops flowing for longer than $t_q$ (15 $\mu$s in our case). The run SCR is water cooled since it dissipates large amount of power.


23 A finite element analysis program by ANSYS, Inc., Canonsburg, PA.


25 Electronic Proceedings Of Workshops on VLHC (http://vlhc.org/).
