# MULTI-CYLINDER QUADRUPOLES WITH SQUARE CROSS SECTION*

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## *Abstract*

Compact superconducting quadrupole magnets with a total length of 150 mm, an integrated gradient of about 13 T, and good field quality are needed for the High Current Transport Experiment (HCX) at Lawrence Berkeley National Laboratory. The Advanced Magnet Lab, Inc. has developed a novel concept, called multi-cylinder coils, which is ideally suited for this application. In this concept a round mini-cable is placed in grooves, which are precisely machined in flat support plates. The plates are stacked on top of each other to build up multilayer coils. The grooves guarantee precise placement of the conductor with high design flexibility, giving unique control over random and systematic field errors and management of mechanical stress. The designed quadrupole consists of four subcoils, which form the four sides of a square cross section box. Each subcoil is built up from 6 plates, accommodating 6 layers of conductor. The complete quadrupole is wound from a continuous conductor with no internal splices. Test results from the first prototype magnet are presented.

## 1 INTRODUCTION

Lawrence Berkeley, Lawrence Livermore National Laboratories and Princeton Plasma Physics Laboratory are preparing a beam transport experiment, the HCX [1], to study low energy, high current ion beam transport. The HCX beam studies will enable design and construction of a multi-beam induction linac driver for Heavy-Ion Fusion, the Integrated Research Experiment (IRE). Compact superconducting quadrupole magnets are needed for single beam focusing in the HCX. It is highly desirable that the design of these magnets is applicable to the focusing arrays for the IRE, where 20 or more quadrupoles are arranged parallel to each other in one cryostat. Highest reliability and cost effectiveness of the quadrupole magnets are of utmost importance for this application.

## 2 QUADRUPOLE DESIGN

The requirements and key parameters of the superconducting quadrupole magnets for the HCX are listed in Table 1.

Table 1: Magnet design requirements and parameters

| Parameter | Unit | Value |
|---|---|---|
| Integrated gradient | Tesla | 13 |
| Field margin | % | <15 |
| Coil length | mm | 150 |
| Slot length | mm | 170 |
| Coil aperture | mm | 62 |
| Beam tube aperture | mm | 50 |
| Nominal current | A | 2080 |
| Operational temperature | K | 4.25 |

### *2.1 Superconductor*

Given the short coil and slot lengths of the HCX quadrupole magnets, it is advantageous to use a conductor of modest dimensions. For this reason a round mini-cable with a 6-around-1 strand configuration was chosen. A round mini-cable has no preferred bending direction, and interconnections between subcoils within a magnet and adjacent magnets in a beamline can be accommodated within short distances. For the IRE focusing arrays, where 30 or more magnets have to be connected within a distance of a few centimeters, the round mini-cable has particular advantages over flat Rutherford type cables, which are conventionally used for accelerator magnets. A round cable is also less costly than a Rutherford type conductor and has a smaller degradation in critical current density from the cabling process. The parameters of mini-cable used are listed in Table 2.

Table 2: Cable Parameters

| **Parameter** | **Unit** | **Value** |
|---|---|---|
| Cable diameter | mm | 1.95 |
| Configuration | | 6-around-1 |
| Twist pitch | mm | 25 |
| Number of strands | | 7 |
| Strand diameter | mm | 0.65 |
| Cu/SC ratio | | 1.8:1 |
| Ic(strand), 5T, 4.2 K | A | 325 |
| J(Cu) at nominal current | A/mm$^2$ | ~1400 |

The critical current of the cable is estimated from the strand measurements given in Table 2. Assuming perfect current sharing between all 7 strands and no

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degradation due to cabling and handling of the conductor in the coil winding process, the critical current $I_{SS}$ of the magnet is estimated as 2450 A at 4.2 K with a peak field of 4.7 T. The nominal current, defined as $0.85\times I_{SS}$, is thus 2080 A. It is interesting to point out that the nominal current density in copper is almost 1400 A/mm$^2$, significantly larger than in typical accelerator magnets.

### *2.2 Coil Design*

Standard accelerator magnets, made with Rutherford type cable, use spacers in the coils to suppress higher-order multipole components and to reduce peak fields in the coil ends. The insertion of such spacers requires great care to prevent any voids in the coils, which can be the origin of premature quenching. Due to the short length of the HCX quadrupole coils, their fields are largely dominated by the influence of the coil ends, and numerous complex spacers would be necessary to achieve good field quality and to reduce peak fields.

To improve reliability and to reduce cost, a novel concept, called multi-cylinder technology, has been developed for the HCX magnets. No spacers of any kind are needed in this technology. The conductors are placed into grooves, which are precisely machined in flat support plates, made from aluminum or a composite material like G-11 as shown in Figure 1. Several plates are stacked on top of each other to build up a multi-layer coil.

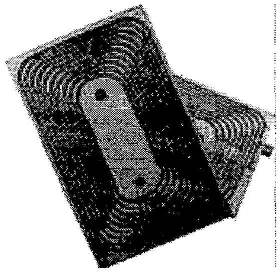

Figure 1: Support plates with inserted mini-cable

The novel concept offers precise conductor placement with highest design flexibility for the conductor arrangement. The spacing between any two conductors can be varied to achieve a desired field configuration without increasing the complexity of the coil manufacturing process. Furthermore, the conductors are supported in individual grooves, and build-up of mechanical stress in the coil under the influence of Lorentz forces is avoided.

For a quadrupole magnet the conductor support plates are arranged at the four sides of a box with square cross section. The resulting coil cross section is shown in Figure 2.

As indicated in Figure 2, the coil has 6 layers. The resulting gradient and field quality are indicated in Table 1. The complete coil is wound with one continuous length of conductor without any splices. The conductor is routed from plate to plate within the subcoils stacks and then from one subcoil to the next.

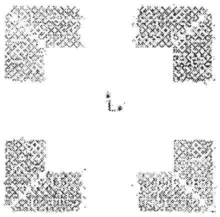

Figure 2: Cross section to HCX coil

A preliminary field optimization for the HCX quadrupole has been performed using a 3D ANSYS model of the magnet. As indicated in Figure 2, the turn-count and turn-pitch were optimized to produce the highest field gradient with the lowest 6th and 10th harmonic coefficients. The critical current gradient is 110 T/m with a peak field at the conductor of 4.7 T. The stress analysis performed by ANSYS shows that the maximum stress in the coil is well below the strength of the G-11 support plates.

### *2.3 Magnet Design and Manufacturing*

The design of the complete magnet is schematically shown in Figure 3. The support plates for the HCX magnet are 3mm thick. The plate stacks are glued together and joined with 45-degree miters (see Figure 3). A laminated iron yoke surrounds the resulting assembly. Each layer of these laminations consists of 4 pieces. The complete iron yoke is surround by an aluminum box, which compresses the iron yoke at operational temperature and closes small gaps between the four pieces of each lamination layer. The pressure is transmitted onto the cable support plates and puts a compressive force on the assembled coil.

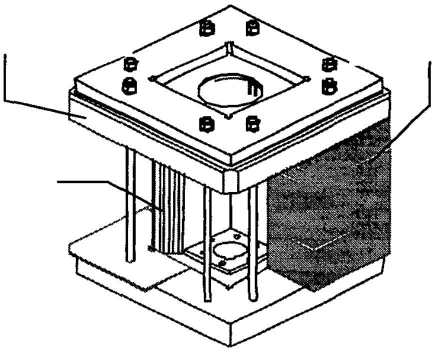

Figure 3: Isometric view of HCX coil with part of the iron yoke

In the axial direction the coil is contained between two flanges, which are held together by rods passing through the iron yoke. The conductor interconnections between the four subcoils are inserted and stabilized in the top flange.

## 3 MAGNET TESTING

The HCX prototype has been tested in a liquid helium bath cryostat at MIT. The main purpose of the cold test was to evaluate the number of quenches for the magnet to be fully trained to the nominal current. After a warm-up to room temperature, the magnet was cooled down again and its current ramp rate sensitivity was studied. In a final test the bath cryostat was slightly pressurized to increase the helium temperature and the operational temperature of the magnet. The dependence of quench current on temperature should indicate if the critical current of the magnet is limited by the conductor or the mechanical strength of the magnet.

The first cold test focused on training the magnet at a slow current ramp rate of 2 A/s. As shown in Figure 4, the first quench occurred at $I_Q = 1900$ A. The nominal current $I_{OP}$ of 2080 A was exceeded after 4 training quenches and the magnet never quenched below $I_{OP}$ again unless the current ramp rate exceeded 1000 A/s in the later cold test. The low quench current in quench number 11 was caused by a lack of liquid helium in the bath cryostat.

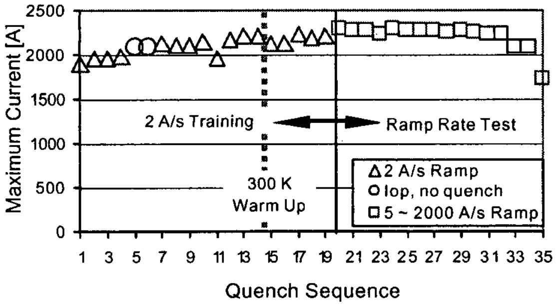

Figure 4: Quench history of HCX prototype tested in liquid helium at 4.25 K.

The quench current saturated at 2200 A in the first test series, which is 92% of the strand critical current. During this training process, quenches were observed in all four subcoils.

The magnet was warmed up to 300 K and the cold test was repeated to check if the magnet shows any retraining after a thermal cycle. The results are shown in Figure 4 (#15-19). The first quench occurred at 2125 A, i.e., about 3% lower than in the maximum quench current reached in the first cold test, but well above the nominal current.

During the second cold test, a ramp rate sensitivity study (shots #20-35) was performed with current ramps rate varied between 5 A/s and 2000 A/s. For ramp rates below 100 A/s, the quench currents increased to 2300 A (~97% of $I_{SS}$ at 4.25 K). Although the most likely effect of this increase is a further training of the coil, a more effective current sharing between the strands in the 6-around-1 cable can currently not be ruled out. For ramp rates in excess of 400 A/s a significant decrease in the magnet critical current is observed (quench #32-35). This ramp rate sensitivity is, however, irrelevant for the HCX and IRE applications, where the focusing quadrupoles will be operated at their nominal steady state current.

In a third test series the sensitivity of the quench current on the operational temperature was measured between 4.25 K and 4.5 K with a fixed current ramp rate of 10 A/s. As expected, the quench current shows a slight decrease with increasing temperature, which is well described by the calculated decrease in critical current density of the conductor.

## 4 CONCLUSIONS

A novel concept, called multi-cylinder coils, has been developed for the manufacturing of superconducting accelerator magnets. The conductor is placed in grooves precisely machined in support plates. The concept combines high flexibility for the conductor arrangement with outstanding placement accuracy. Systematic and random field errors can be minimized without cost penalty. The support plates being used also provide a reliable management of mechanical stress. Quadrupole magnets can be manufactured without internal splices, which is of particular interest for applications like the IRE, where arrays of 30 or more quadrupoles occupy one cryostat.

A first HCX prototype has been built and tested. The magnet exceeded the nominal current after 4 training quenches and reached 97% of the strand critical current. The calculated current density in copper is about 1400 A, which significantly exceeds the values typically used for accelerator magnets. A second prototype with an improved iron yoke configuration and some mechanical improvements is currently being built.

## 5 REFERENCES

[1] P. Seidel et. al., "Overview of the Scientific Objectives of the High Current Experiment for Heavy-Ion Fusion", submitted to PAC2001, Chicago, June 2001.