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Development of Superconducting Magnet Systems for HIF Experiments*

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Abstract— The U.S. Heavy Ion Fusion program is developing superconducting focusing quadrupoles for near-term experiments and future driver accelerators. Following the fabrication and testing of several models, a baseline quadrupole design was selected and further optimized. The first prototype of the optimized design achieved a conductor-limited gradient of 132 T/m in a 70 mm bore, with measured field harmonics within 10 parts in 10^4. In parallel, a compact focusing doublet was fabricated and tested using two of the first-generation quadrupoles. After assembly in the cryostat, both magnets reached their conductor-limited quench current. Further optimization steps are currently underway to improve the performance of the magnet system and reduce its cost. They include the fabrication and testing of a new prototype quadrupole with reduced field errors as well as improvements of the cryostat design for the focusing doublet. The prototype units will be installed in the HCX beamline at LBNL, to perform accelerator physics experiments and gain operational experience. Successful results in the present phase will make superconducting magnets a viable option for the next generation of integrated beam experiments.

1. Introduction

The U.S. Heavy Ion Fusion (HIF) program is progressing through a series of physics and technology demonstrations leading to an Inertial Fusion Energy (IFE) power plant [1]. Experiments with high current beams are currently underway in the areas of injection, transport and final focus. The next step involves source-to-target experiments to demonstrate that all beam manipulations required by the fusion driver can be carried out in an integrated manner, thus setting the basis for a IFE demonstration facility.

Efficiency requirements for the driver accelerator lead to the choice of superconducting technology for beam transport [2]. Superconducting magnets are also preferred for near term experiments, to better simulate the beam environment in a fusion driver and gain operational experience. A collaboration of Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), MIT Plasma Science and Fusion Center, and Advanced Magnet Lab (AML) is developing superconducting quadrupoles for HIF and their associated cryostats. Several design concepts have been explored, and prototype cells have been fabricated and tested. These cells are suitable for use in single-beam channels as well as modules in multi-beam arrays. Following a design selection aimed at focusing the available resources on a single development path, present activities involve optimization of the module cell and fabrication of cryostated focusing doublets. These units will be tested with beam in the High Current Experiment (HCX), currently underway at LBNL [3].

2. Magnet Parameters

The design parameters of the prototype superconducting quadrupoles were defined based on the requirements of the HCX. Magnetic transport experiments in HCX are primarily directed to study the effects due to electrons trapped in the potential well of an intense ion beam. The lattice period is 45 cm and the nominal quadrupole gradient is 84.2 T/m over a magnetic length of 10.1 cm. The coil aperture is 70 mm. The field quality is specified in terms of axial integrals of the magnetic field components. For any longitudinal field integral calculated at 25 mm radius and $0<\theta<2\pi$, a maximum deviation of 0.5% from the ideal quadrupole field at that location is allowed. Detailed specifications of the magnet parameters are given in Ref. [4].

The HCX, along with other experiments presently underway, will lead to the Integrated Beam Experiment (IBX), which is expected to perform all of the beam manipulations required in a fusion driver, including injection, acceleration, compression, bending and final focus. The machine design is in progress [5]. The magnet parameter range considered is: clear bore 40-80 mm, operating gradient 40-120 T/m, magnetic length 8-14 cm. For a given integrated strength, high gradients over a short magnet length are preferred, to increase the space for accelerating gaps, cryostat terminations and beam diagnostics. The magnet design must accommodate dipole steering coils and may include a cold beam pipe (at 4.5 K) with a 77 K baffle-like beam screen [6].

After completion of the IBX, experiments with multiple beams will be performed, to study magnetic coupling effects at high energy and provide the basis for an Engineering Test Facility (ETF). Superconducting quadrupole arrays must be developed for this application. Since a large number of arrays will be required in a fusion driver, economy of fabrication is a primary consideration. Other design objectives include minimization of the transverse size (to limit the size and cost of the induction accelerator cores) and implementation of special edge coils to adjust the field in outer cells and terminate the magnetic flux.

3. Magnet Design

The special requirements of HIF lead to different magnet optimization strategies with respect to quadrupoles designed for high energy physics accelerators [7]. The development of focusing cells for beam physics experiments provides an opportunity to address key magnet design issues like maximum achievable gradient, simplicity, cost effectiveness, optimization of the conductor parameters, field quality, modularity, and compact cryostats. At the same time, the design of these focusing cells must take into account the long-term requirements for application to a fusion driver, including efficiency and compacteness in multi-beam arrangements, and the complexity of the termination scheme required to adjust the field in the boundary cells and return the magnetic flux.

Both shell-type (cos2θ) and block-type coils can be considered for this application. A shell-type configuration using keystoned Rutherford cables has the advantage of a self-supporting Roman-arch structure, and provides good magnetic efficiency. However, it features a complex geometry and requires expensive, inflexible tooling and parts for coil fabrication. Conversely, accelerator magnets based on block-coils have received considerable attention in recent years due to their simplicity and cost-effectiveness [8]. Double-layer racetrack coils are of particular interest. The advantages of block-type coils for HIF near-term applications include: inexpensive tooling; flexibility in adjusting key design parameters (aperture, gradient, length) to the experiment requirements; longitudinal compactness at the magnet ends, as required to achieve short lattice periods for low-energy transport. In addition, block-coils easily conform to the square cell layout of the array. They can be arranged back-to-back improving flux sharing, and facilitate the support structure design since the outwards components of the magnetic force are balanced between cells. Neighboring coils can in fact be combined using a wider cable, with significant reduction of the number of parts, conductor joints, and inductance. Finally, racetrack coils are compatible with brittle superconductors, due to the use of flat cables with low cabling degradation, and a planar coil geometry [9]. Although the properties of conventional NbTi are adequate to meet the requirements of present experiments, the high critical currents and temperature margins of advanced conductors like Nb_3Sn and HTS may significantly improve the performance and cost-effectiveness of the fusion driver.

Based on these considerations, and following the successful testing of a prototype pre-series, a racetrack quadrupole design developed by LLNL [10] was selected as the baseline [11]. It features two layers of double-pancake coils, wound around iron cores and preloaded using stainless steel holders and keystoned wedges. The inner and outer coils of each quadrant are vacuum impregnated with epoxy to form four monolithic sub-assemblies which are aligned at their mitered corners. Joints are used to connect the coils in series. A 4-piece iron yoke surrounds the coils and a welded stainless steel outer shell provides additional support against Lorentz forces.

Two pre-series models of this design were fabricated and tested. Both reached their conductor-limited gradient with very few training quenches. Following these tests, a first design iteration was performed by LLNL to further improve the performance and reduce cost [12]. The coil ends were modified from continuous arcs to tight bends followed by straight segments to increase the integrated gradient and improve the field quality (Fig. 1). A change of the coil holder material from stainless steel to a less expensive, high strength aluminum alloy was incorporated. The structural tube used in the bore of previous prototypes to provide internal support to the coils was removed. The superconducting strand was changed from SSC-outer to SSC-inner type, with lower copper fraction. The strand was redrawn from 0.808 mm to 0.648 mm to match the baseline cable design. A prototype of the optimized design (HCX-C) was fabricated by AML and tested at LBNL [12]. The magnet reached its conductor-limited gradient of 132 T/m in two training quenches, without retraining after a thermal cycle, and with a low ramp-rate sensitivity. These results confirmed the effectiveness of the design improvements implemented in HCX-C. Magnetic measurements were also performed on this prototype to check the field quality. The relative field errors are at the 0.1% level, a good result for a first iteration, but only marginally acceptable for beam transport. The analysis of HCX-C prompted several modifications of the magnet design and the coil fabrication procedures, in order to improve the field quality and further reduce cost.

4. Field Quality and Cost Optimization

Tables I and II show a comparison of calculated and measured field harmonics for the HCX-C prototype. The field is represented in terms of harmonic coefficients defined by the power series expansion:

$$B_y + iB_x = B_2 10^{-4} \sum_{n=1}^{\infty} \bar{c}_n \left(\frac{x + iy}{r_0} \right)^{n-1}$$

where B_x and B_y are the transverse field components, B_2 is the quadrupole field, and $\bar{c}_n = b_n + i\,a_n$ are the multipole coefficients, expressed in 10^{-4} "units" of the quadrupole component. Only the harmonic components b_{2n+4} are allowed by the quadrupole symmetry. The other harmonics appear due to departures from perfect quadrupole symmetry, which may originate from either the magnet design or the fabrication tolerances. The magnetic midplanes of the quadrupole field lie along the x and y-axes, and the z-axis is directed from the return end towards the lead end. Both measurements and calculations are longitudinally integrated over the length of the measurement coil. A reference radius r_0 of 22 mm was defined for these measurements, to match the radius of the rotating probe.

The allowed harmonics (Table I) are in good agreement with calculations. The main contributions to the field error are due to the 12-pole (b_6) and 20-pole (b_{10}) components, with required corrections of 8.1 units and 8.7 units, respectively. After considering several possibilities, the following design modifications were implemented to provide such corrections:

- two rectangular pockets were introduced in the iron pole of the inner coils, on the surface facing the bore. The pockets are 2.95 mm deep, 12 mm wide and 100 mm long;
- three turns (per layer) were eliminated from the inner coil, and one turn (per layer) was eliminated from the outer coil. For both coils, the position of the midplane turns is unchanged: the turns are removed at the pole;
- the outer perimeters of the pole-islands were modified to fit the new profile of the coils;
- at the same time, the end radii for both coils were increased from 6 mm to 9 mm to facilitate coil winding.

Although the b_6 and b_{10} components representent the main systematic contributions to the error field in HCX-C, close attention needs to be paid to the b_{14} component. The baseline design has an integrated b_{14} of -0.66 units at 22 mm. Since b_{14} rapidly increases with radius, it can become the dominant error for beams with high aperture filling factor. In fact, the position of the iron pocket which would be the most favorable to correct b_6 and b_{10} is not accessible, since it would make b_{14} significantly higher. The requirement to limit the b_{14} component constrains the shape and position of the iron cut-out, leading to more pronounced modifications of the coil geometry than were originally anticipated.

With the new design, the calculated b_6 and b_{10} harmonics at the reference current of 2.5 kA and the reference radius of 22 mm are reduced from 8-9 units to less than a unit. A small improvement of the b_{14} harmonic is also obtained. Saturation effects are comparable with the previous design: b_{14} essentially does not depend on current; b_{10} is in the range of -0.8 to 0.0 units between 2 kA and 3kA. b_6 is in the range of -5 to +5 units between 2 kA and 3 kA. This effect is mainly due to the saturation of the iron poles (inner and outer) and as such is difficult to correct. However, it is possible to tune the b_6 to essentially zero at any given operating current of choice with a small change of the depth of the iron pole cut-out. The other harmonics are not significantly affected by this change.

The transfer function (integrated gradient vs. current) decreases by about 9%, due to the decrease in the number of turns, the increase of the minimum bending radius, and the cut-out in the iron pole. However, the peak field (still located in the outer coil) also decreases by a similar amount. In addition, the peak field is better balanced between the inner and the outer coils (the difference in peak field is reduced from 9% to 5%). As a result, the quad focusing power does not decrease in a significant way (-3%). The conductor volume is reduced by 12%. The 50% increase of the minimum bending radius significantly facilitates coil winding.

The non-allowed harmonics can be correlated to random field errors due to manufacturing tolerances. The calculated standard deviations from Monte Carlo simulations, assuming conductor displacements uniformly distributed in the range of

±100 μm from the design positions, are shown in Table II. The measured harmonics for n=3,4,7 are consistent with these random error estimates. The n=8 component corresponds to about 3 sigma, while the errors observed for the n=5 and n=9 components are significantly larger than expected. In order to better control the geometrical tolerances, and at the same time reduce the magnet cost, a new coil fabrication procedure was proposed [13]. With this method, the coils are wound around a monolithic pole-island, and vacuum impregnated in a precise mold to obtain an accurate and reproducible geometry. The impregnated coils are later inserted in aluminum holders, which are pre-heated to a temperature of 200 C to obtain sufficient clearance for coil insertion. At room temperature, there is a small interference between the coil and holder dimensions, resulting in a tight fit with no gaps. As for the previous design, the differential contraction coefficient between the coil and its holder provides additional pre-load after cool-down to 4.2 K. The new procedure results in fewer parts, simpler fabrication steps and a more precise coil geometry. However, the coil pre-load previously obtained at the assembly stage using a segmented pole-island with wedges (Fig. 1) is lost. Experimental verification of the quench performance with the new procedure is therefore required. A new prototype (HCX-D) has been fabricated by AML using the new coil design and fabrication procedures (Fig. 2). The magnet is now undegoing the final assembly steps, followed by testing in a vertical dewar at LBNL.

Additional control of the non-allowed harmonics may be obtained by implementing a magnetic shim correction scheme similar to those developed for the Interaction Region Quadrupoles of high-energy colliders [14-15]. The rectangular pockets introduced in the inner pole-island for control of the systematic harmonics (Fig. 2) are also suitable for housing the magnetic shims.

5. Cryostat Development

The development of a first cryostated focusing doublet has been successfully completed by MIT, based on a design provided by LLNL. The unit was fabricated by CVIP, Inc. under MIT supervision. It is compatible with the HCX lattice requirements as well as the use of induction cores for acceleration. Details of the design are shown in Fig. 3. The pre-series prototypes of the HCX design were used for this doublet. The current leads and cryogenic supplies are routed through a shielded vertical chimney, to maximize the space available for induction acceleration cores surrounding the transport line. In order to minimize the radial space between the beam pipe and the LHe vessel in the magnet bore, special low-emissivity aluminized stainless steel foils (ε=0.002) are used for radiation shields, with no active thermal shields [16].

The unit was tested at MIT in November 2003 and January 2004. During the first test, a thermal short was discovered in the beam tube region, resulting in unacceptably high heat loads for operation in a beamline. Nevertheless, both magnets could be charged to their conductor-limited quench current with essentially no training. After repairing the thermal short, the test was repeated and heat loads between 0.85 W and 1.1 W were measured in the quadrupole/chimney sub-assembly. A detailed report of the cryostat test results is in preparation [17]. At the same time, the design of a second doublet optimized for operation in the HCX beamline has started. The HCX-C and HCX-D prototypes will be installed in this second focusing unit.

6. Cost Analysis

The cost of a series production of HCX quadrupoles can be estimated based on experience with prototype fabrication, the cost of parts procured for these prototypes, and quotes obtained by different suppliers for fabrication of larger sets of parts [18]. The initial HCX plan (Phase II) called for installation of 100 magnetic quadrupoles. This number will be used as a reference, although the HCX Phase II has now been replaced by the IBX. It is assumed that the conductor is procured by the project and delivered to the magnet manufacturer, an approach adopted by most accelerators. The other parts are procured by the manufacturer. The company overhead and fees are estimated at 40% of the cost of materials (excluding conductor) and labor. The cost estimate does not include magnet prototyping and technology transfer. The project costs (EDIA, installation, project management, contingency and escalation) are also not included in the figures.

The main magnet components are: conductor, insulation, coil support structure, yoke and support shell. The baseline conductor is a Rutherford cable made of 13 SSC-type strands. Two options were demonstrated in the prototypes: SSC outer strand (0.648 mm diameter) and SSC inner strand with lower copper fraction (redrawn from 0.808 mm to 0.648 mm). The second option is presently preferred, since it provides higher field gradients. The required cable length is 9 m for each inner coil, 15 m for each outer coil, resulting in 96 m of cable for one magnet (3.3 kg). Based on a recent purchase of several billets of SSC-type conductor for the LHC IR Quadrupole program [19], the conductor cost is 500$ for one magnet. The cost of fabricating a small Rutherford cable can be estimated at 30% of the cost of the wire for a length of 10 km (100 magnets). All prototypes to date used a glass fiber insulation braided on the cable. The use of kapton insulation may be explored as a more cost-effective option, but it is less suitable for epoxy impregnation.

The cost of parts was estimated by a US vendor on the basis of production of 100 magnets. The labor requirements were estimated in collaboration with the companies that fabricated the prototypes. The figures reflect the use of improved tooling (a 50 k$ investment) and increased experience with the process with respect to the first prototypes. However, a production run of 100 units may be significantly affected by the initial process optimization, so that the cost savings typical of large series productions cannot be fully realized.

On this basis, the unit cost of one HCX magnet was estimated at 9 k$ (with aluminum holders). This cost includes overhead and fees, assuming a production run of 100 quadrupoles.

The first prototype focusing unit consists of two major components: the quadrupole doublet cryostat, and a feedbox containing the vapor cooled leads and cryogen supply. Based on experience with fabrication of the first unit, CVIP has estimated the cost of a series production of 50 quadrupole cryostats at 35 k$ each, in the absence of significant design changes. It is reasonable to expect that several design improvements identified during fabrication of the first prototype will result in significant cost reductions with respect to the above estimate. A second prototype unit is being developed to address these issues. The magnets will be operated as a string from a single feedbox. The feedbox, end box and transfer lines contribute an additional 20% to the cost of the quadrupole cryostats. The static heat load for the HCX machine was estimated at 180 W at 4.2 K for 100 quads [21].

Cold testing of all cold masses before assembly in the cryostat would be expensive, and is not required based on the test results of the prototypes. In order to monitor the quality of magnet production, the first 10% of the units, and another 10% randomly distributed during the rest of the production, could be cold tested before installation.

The HCX racetrack quadrupole is well matched to IBX requirements with simple modifications. Two design options are being explored for IBX. The first option requires magnet parameters similar to the HCX, which could be obtained with a two-layer design at a cost close to the figure quoted for HCX. The second option has a larger aperture and a lower gradient. It can be implemented with a design based on a single coil layer, allowing significant cost savings with respect to the HCX. The basic coil parameters are very similar to the HCX outer coils. The HCX cost estimates can then be adjusted to IBX to give a total cost per quad of 6 k$.

It is useful to compare the IBX cost distributions with available data for the RHIC dipoles (Table III). The larger labor fraction in IBX corresponds to the smaller scale of the production, in particular the higher labor requirements of the first 20-50 magnets (Fig. 3), and a smaller investment in tooling. The lower fraction of project-procured material in IBX reflects the fact that the iron yoke steel for the RHIC dipole was procured by BNL, while for IBX it is assumed that it will be procured by the magnet vendor. In addition, the yoke represents a higher fraction of the cost in IBX than in RHIC.

While the racetrack design appears well suited to IBX, other approaches may be considered. Possible alternatives include a single-layer shell-type (cos2θ) design similar to the RHIC arc quadrupole [15]. A significant difference in magnetic efficiency between shell and racetrack coils is not expected for very short magnets, but shell-type coils are radially more compact in a single-channel configuration. A radially compact magnet leads to a more effective acceleration system. The RHIC arc quadrupole is close to the IBX aperture and gradient specifications, and is already optimized for low cost and robust performance. However, contrary to IBX, no strong constraints on the coil end design were present in RHIC (1.1 m magnetic length). In order to obtain very compact ends and meet the gradient specifications, the magnets would have to be redesigned. The development of a new shell-type design requires expensive tooling and experimental verification of the magnet performance by fabrication and test of several prototypes. For a small production like IBX, the cost of the R&D required to develop and optimize a new shell-type design may be prohibitive.

7. Conclusions

The U.S. Heavy Ion Fusion program is developing superconducting focusing quadrupoles for near-term experiments and future driver accelerators. Several prototype magnets and one cryostated focusing unit have been tested with excellent results. Further optimization steps are currently underway to improve the magnet system performance and reduce its cost. Detailed cost estimates for magnet production have also been generated, to support the design of the next generation of integrated beam experiments for HIF.

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FIGURES AND TABLES

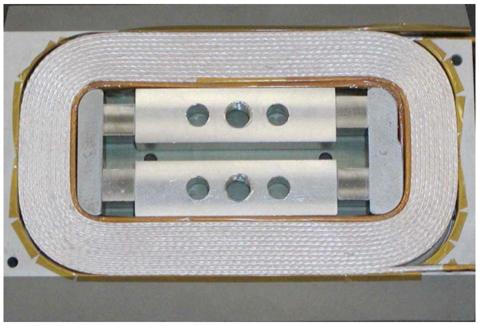

Fig. 1: HCX-C prototype coil module

TABLE I
INTEGRATED HARMONICS

Current (A)	Temp (K)	Data type	Gradient B_2/r_0 (T)	12-pole $\lvert c_6 \rvert$ (units)	20-pole $\lvert c_{10} \rvert$ (units)
9.5	300	Meas. (*)	0.0674	109	15.5
9.5	-	Calc.	0.0726	121	19.1
2500	4.2	Meas.	11.03	5.8	8.5
2500	-	Calc.	11.63	8.1	8.7

(*) Averages for ± 9.5 A current and clock/counterclockwise probe rotation

TABLE II
NON-ALLOWED HARMONICS VS RANDOM ERRORS (1 SIGMA)

Order *n*	Measured $\lvert c_n \rvert$ (units)	Random- Block $\lvert c_n \rvert$ (units)	Random-Quadr. $\lvert c_n \rvert$ (units)
3	5.3	2.7	6.5
4	2.5	1.8	1.8
5	7.0	0.8	0.3
7	0.6	0.2	0.5
8	1.0	0.1	0.3
9	2.8	0.05	0.1

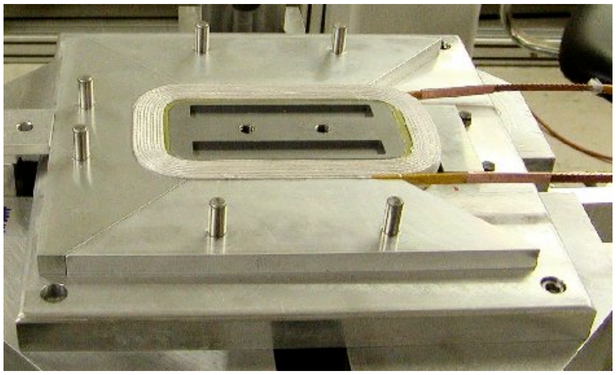

Fig. 2: HCX-D coil fabrication. Impregnation mold, iron cut-outs.

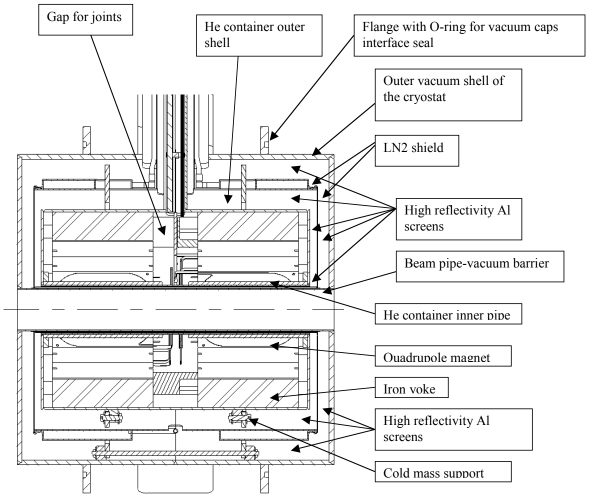

Fig. 3: Cryostat design for prototype doublet.

TABLE III
IBX VS. RHIC MAGNET COST DISTRIBUTIONS [18]-[22]

Category	IBX [%]	RHIC [%]
Materials (project)	10	22
Materials (vendor)	38	38
Labor	24	11
Overhead/fees	28	29