Title

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PROGRESS IN THE DEVELOPMENT OF SUPERCONDUCTING QUADRUPOLES FOR HEAVY ION FUSION[1]

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Abstract

The Heavy Ion Fusion program is developing single aperture superconducting quadrupoles based on NbTi conductor, for use in the High Current Experiment at Lawrence Berkeley National Laboratory. Following the fabrication and testing of prototypes using two different approaches, a baseline design has been selected and further optimized. A prototype cryostat for a quadrupole doublet, with features to accommodate induction acceleration modules, is being fabricated. The single aperture magnet was derived from a conceptual design of a quadrupole array magnet for multi-beam transport. Progress on the development of superconducting quadrupole arrays for future experiments is also reported.

1. INTRODUCTION

The High Current Experiment (HCX) at Lawrence Berkeley National Lab is designed to explore the physics of intense beams with line-charge density (0.2 μC/m) and pulse duration (τ≥4 μs) close to the values of interest for a fusion driver [1]. Experiments are performed near injection energy (1-1.8 MeV). HCX beam transport is mainly based on electrostatic quadrupoles, which provide the most efficient option at this energy. However, magnetic transport experiments will also be performed, to gain operational experience and to explore limitations associated with magnetic focusing, in particular the onset of instabilities due to electrons trapped in the potential well of the ion beam. Magnetic quadrupoles lack the strong sweeping fields associated with electric focusing. Both pulsed and superconducting magnets will be installed in HCX. Pulsed magnets provide a more flexible alternative for initial experiments. Superconducting technology is the most attractive in view the ultimate fusion driver application.

Superconducting magnet development for HCX and future experiments is carried out by a collaboration of Lawrence Berkeley National Lab (LBNL), Lawrence Livermore National Lab (LLNL), MIT Plasma Science and Fusion Center, and Advanced Magnet Lab (AML).

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2. FIRST PROTOTYPE SERIES

A minimum quadrupole gradient of 84.2T/m over a magnetic length l_q=10.1cm is required for HCX. The nominal coil aperture is 70 mm (resulting in 59 mm vacuum chamber aperture). Magnet field quality is specified in terms of axial integrals of the 3D 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. Details of the magnet specification are given in Ref. [2].

Two design concepts were proposed by LLNL and AML in 2000. The LLNL approach uses double-pancake coils wound around iron cores and preloaded using stainless steel holders and keystoned wedges (Fig. 1, left). Accelerator magnets based on double-pancake coils have received considerable attention in recent years, due to their simplicity and cost-effectiveness. In the LLNL design, the inner and outer layer coils of each quadrant are vacuum pressure impregnated to form four monolithic sub-assemblies. Soldered lap joints connect the coils in series. A 4-piece iron yoke surrounds the coils and a welded stainless steel outer shell provides mechanical support.

In the AML approach, grooved plates support a round 7-strand (6x1) cable (Fig. 1, right). The plates are painted with adhesive and each stack of 6 plates is cured under pressure to form a monolithic subcoil. The magnet consists of four subcoils arranged in a square geometry, surrounded by a iron yoke, with a square aluminum frame providing preload against Lorentz forces. Transition inserts at each plate and a special interconnection flange allow continuous winding of the magnet without joints.

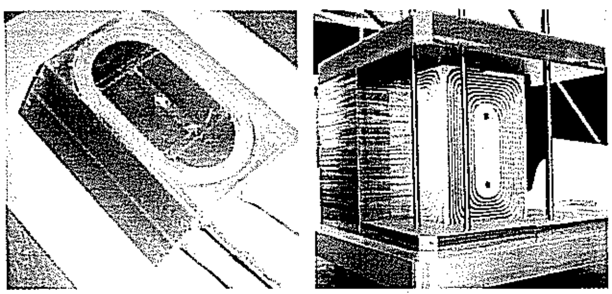

Fig. 1: Coil layout. LLNL (left), AML (right).

Two prototypes of each design were fabricated and tested in 2001. The LLNL prototypes were tested at LBNL, while the AML prototypes were tested at MIT.

Different conductors are used in the two LLNL prototypes. The first prototype uses a monolith with low Cu/Sc ratio (1:1) fabricated using the Artificial Pinning Centers (APC) process [3]. The second prototype uses a Rutherford cable with 13 SSC outer strands and Cu/Sc ratio of 1.8:1. A design change was also implemented for the AML round cable. The central superconducting strand was replaced with a pure copper wire in the second prototype to improve conductor stability. In addition, the second prototype incorporated iron cores within the racetracks, similar to the LLNL design, to increase the quadrupole field while decreasing the peak field in the conductor, and a central stainless steel tube to improve the coil mechanical support.

Table 1 shows a summary of the training performance for the four prototypes. All magnets surpassed the nominal operating current (I_{op}), defined as 85% of the short sample limit. The first LLNL prototype had relatively low initial quenches but rapidly trained to short sample. The second prototype showed essentially no training, with a first quench at 98% of short sample. The AML prototypes showed slower training, and the maximum current achieved by the first prototype was a few percent below the expected short sample limit.

Prototype	1st Quench $I_q^{(1)} / I_{ss}$	Mx. current $I_q^{(max)} / I_{ss}$	No. quench to reach I_{op}
LLNL#1	0.75	1.0	3
LLNL#2	0.98	1.0	0
AML#1	0.78	0.97	4
AML#2	0.65	1.0	12

Table 1: HCX prototype training performance

No significant retraining after a thermal cycle was observed in all prototypes. Ramp rate dependence was well within the HCX operational requirements. Further details on prototype design, fabrication and testing are reported in Refs. [4, 5].

3. DESIGN SELECTION

The results of prototype design, fabrication and testing formed the basis for a design selection aimed at focusing the available resources on a single development path. The designs were evaluated and compared based on performance requirements in Ref. [2]. A rating system was developed to take into account all aspects of magnet design, fabrication and testing, including projected cost and the relevance of the proposed designs to future array applications.

Both designs meet the minimum gradient specification for HCX. The LLNL approach can achieve higher gradient in a given physical envelope, due to the rectangular conductor geometry without individual turn support, leading to higher conductor packing. The LLNL prototypes also showed faster training. The AML design allows more freedom of conductor placement and has a potential for achieving better design field quality. However, both approaches can achieve good integrated field quality using body-end error compensation, which was proven acceptable in Particle-in-Cell simulations of the beam dynamics. Cost considerations did not give a considerable advantage to either design. With respect to quadrupole array applications, both designs rely on a racetrack coil geometry and have similar properties in terms of multiple aperture stacking, edge coil design, and flux termination. However, higher field enhancement among neighboring coils is expected in the LLNL design, due to higher conductor packing.

Based on these considerations, the LLNL approach using double pancake racetrack coils was selected by a 7-member board as the baseline for further development and optimization.

4. MAGNET OPTIMIZATION

The optimized HCX quadrupole is expected to achieve significant improvements in integrated gradient, field quality, coil mechanical support and cost with respect to the first prototype series [6-7]. Figure 2 shows the new coil geometry. The coil ends have been modified from continuous arcs (Fig. 1, left) to tight bends followed by straight segments, similar to the AML geometry (Fig. 1, right). This results in a longer magnetic length for the same coil length, and better end field quality. In addition, independent optimization of the field quality in the body and ends results in a more efficient cross-section. These combined advantages lead to a 20% increase of the integrated gradient for the same conductor properties.

A Rutherford cable will be used in the optimized quadrupole. The Rutherford cable offers a more flexible design based on available wire, an important advantage during magnet R&D. The option of using a monolithic conductor will be reconsidered for series production. SSC inner strand with Cu/Sc ratio of 1.3:1, redrawn to 0.648 mm diameter, will be used in the optimized prototype. The expected short sample gradient is 132 T/m, with an effective magnetic length of 105.4 mm. The integrated harmonics (in 10^{-4} "units" of the quadrupole component at 25 mm reference radius) are b_6=-7.3, b_{10}=-19.8.

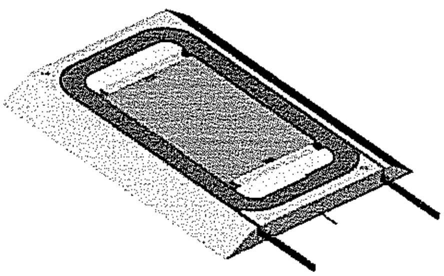

Fig. 2: Optimized HCX coil module

A change of the coil holder material from stainless steel to aluminum is also incorporated in the optimized quadrupole. The thermal contraction coefficient for aluminum is closer to that of the winding pack, allowing the achievement of higher preload and a decrease of shear stress in the insulation with repect to stainless steel. In addition, the projected cost of Al holders in production is lower by a factor of three with respect to stainless steel. Procurement of conductor and parts for the optimized prototype is underway. The magnet will be tested at LBNL in the fall of 2002. The test will include magnetic measurements to confirm that the prototype meets field quality specifications.

5. CRYOSTAT DEVELOPMENT

Due to the low beam energy, the HCX lattice has a short lattice period (FODO) of 45cm. Gaps are needed between cryostat tanks to allow axial space for induction acceleration, diagnostics and pumping ports, leading to a challenging packing. Lattice syncopation is used to gain sufficient axial space for cryostat terminations in the long drift section of each focusing period. A cryostat design with two quadrupoles was developed, allowing an 8 cm inter-cell warm gap [8]. However, some modifications were necessary for the first prototype unit, in order to utilize the existing LLNL quadrupoles with minimal rework of the current leads, inter-coil joints, and bore support tube. As a result, the total length of the cryostat increases from 37 cm to 42.8 cm, and the clear bore diameter decreases from 59 mm to 53.6 mm. In addition, the focusing strengths of the two quadrupoles powered in series differ by about 10% due to different conductor geometry. These changes do not compromise the capability to carry out the desired experiments with the prototype doublet. The nominal cryostat geometry will be recovered in future units based on optimized quadrupoles.

Details of the cryostat design are shown in Fig. 3 [9]. The unit contains two quadrupole magnets mounted on an alignment tubing, the 4 K cold mass container, LN2 thermal shields and radiation shields, a vacuum vessel and a shielded straight chimney enclosing a pair of Nb_3Sn bus bars connected to the coil leads. The chimney is needed to maximize the space available for induction acceleration cores surrounding the transport line. A transition box at the top of the chimney provides interconnection between the quadrupole cryostat and an upper cryostat housing a pair of 3 kA vapor cooled leads (VCL), transfer lines and diagnostics connections. In order to minimize the radial spacing between the beam pipe and the LHe vessel in the magnet bore, special low-emissivity aluminized stainless steel foils (ε=0.002) will be used as radiation shields, without active thermal shields [10].

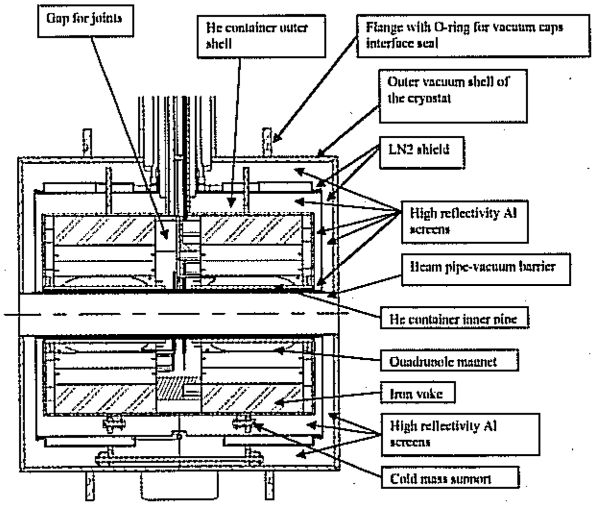

Fig. 3: HCX cryostat design.

6. QUADRUPOLE ARRAYS

Accelerators for fusion energy production will require arrays of quadrupoles to transport multiple beams through a sequence of induction acceleration cells. The number of parallel beams in a fusion driver is expected to be of the order of 100. However, most design issues can be addressed with smaller scale prototypes. Near-term experiments like the Integrated Beam Experiment (IBX) and the Integrated Research Experiment (IRE) will also require a limited number of beams [11]. The IBX will start with a single beam, and will be upgraded to 4 beams, with magnet specifications similar to those of HCX.

The main design issues are compactness to minimize the size and cost of the induction cores, design of edge coils to adjust the field in boundary cells and terminate the flux, minimization of the number of joints, alignment, and achieving high vacuum in the presence of high currents. More details on array development issues are reported in another paper at this conference [12].

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