**Title**

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# A Superconducting Quadrupole Magnet Array for A Heavy Ion Fusion Driver

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*Abstract*— **A multi-channel quadrupole array has been proposed to increase beam intensity and reduce space charge effects in a Heavy Ion Fusion Driver. A single array unit composed of several quadrupole magnets, each with its own beam line, will be placed within a ferromagnetic accelerating core whose cost is directly affected by the array size. A large number of focusing arrays will be needed along the accelerating path. The use of a superconducting quadrupole magnet array will increase the field and reduce overall cost.**

**We report here on the design of a compact 3x3 superconducting quadrupole magnet array. The overall array diameter and length including the cryostat is 900x700 mm. Each of the 9 quadrupole magnets has a 78 mm warm bore and an operating gradient of 50 T/m over an effective magnetic length of 320 mm.**

## I. INTRODUCTION

It has been proposed that commercial electricity can be generated economically from thermonuclear microexplosives[1]. Central to this concept is the driver, which ignites fusion targets at a high repetition rate (~5 Hz) with high power pulses of energy ( ~5 MJ, 500 TW). A leading driver candidate is a high energy, high current heavy ion accelerator. This approach is an attractive one due to the short range of heavy ions in the target, durability, and efficiency of appropriate accelerator systems. To achieve high currents it is generally desirable to accelerate multiple beams in parallel through a low impedance accelerating structure; a long pulse induction linac can be designed to do this. Current is increased to ~44 kA/beam by drift compression following acceleration, to reach the required 500 TW for high gain microexplosives. At lower kinetic energy, current per beam increases steadily from an initial 1.0 A at the source by the combined operation of spatial compression and increased velocity from acceleration. Efficient transport of beam current in the multibeam accelerator would be accomplished with multiple channel superconducting quadrupole magnets operating in a DC mode with warm bore. The low power expenditure of such magnets is essential for accelerator efficiency, and their large magnetic gradient (~50 T/m) permits this transport of high ion currents. These considerations guide the design described in this paper.

## II. MAGNET DESIGN

### A. Magnet design

A superconducting quadrupole array (Fig. 1) is an assembly of individual quadrupoles, each consisting of a coil package and a structural collar (Fig. 2). Between individual magnets Supporting Blocks (SB) are placed and; in a finite array; additional coils are placed along the boundary. The array size depends on the size of its unit cell (pitch). An overall figure-of-merit for the array can be viewed as the beam current density, in amp per square meter, averaged over the entire lattice. Trying to avoid issues such as beam location and size we have introduced a figure-of-merit that is proportional to the gradient divided by the pitch square ($\frac{G}{p^2}$), and used it to determine the size and diameter of the coil. From that analysis, using actual size of cable and coil, we have picked an inner coil diameter of 120 mm and an average coil width of 8 mm.

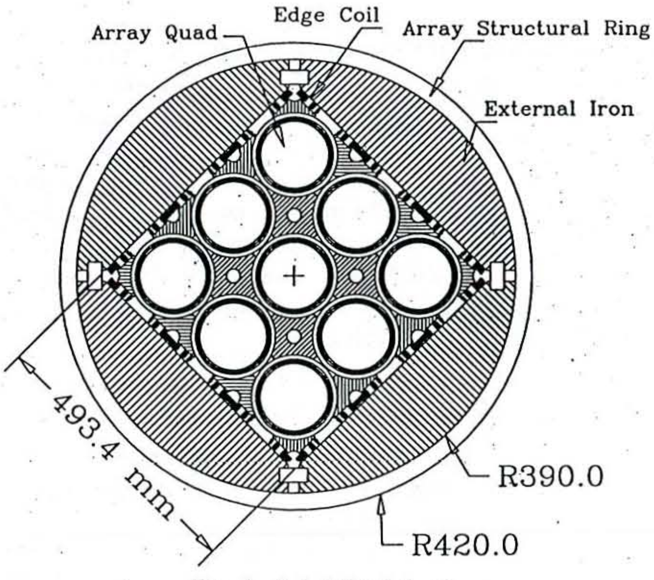

Fig. 1. A 3x3 Quad Array.

Based on the immediate availability of a "SSC outer" strand wire, we decided to use a 12 strand superconducting cable. A two layer coil with two wedges per layer was optimized for field quality while the pole angle between layers was displaced azimuthally by one turn to simplify a layer to layer ramp. The four coil assembly will be placed within a 6.5 mm thick aluminum tube and prestressed using high pressure epoxy impregnation. The choice of using the same cable in both layers was made strictly to avoid a high field joint.

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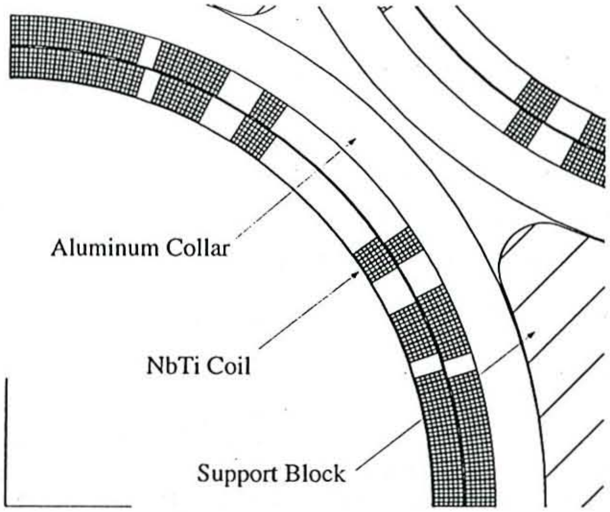

Fig. 2. Coil cross section

Table I Magnet radial build up

| | Radial (mm) |
|---|---|
| warm bore radius (mm) | 39.5 |
| cold bore radius (mm) | 60.0 |
| layer 1 inner radius (mm) | 60.125 |
| layer 1 outer radius (mm) | 64.356 |
| layer 2 inner radius (mm) | 64.61 |
| layer 2 outer radius (mm) | 68.84 |
| collar inner radius (mm) | 69.35 |
| collar outer radius (mm) | 75..85 |
| outer most radius (mm) | 77.0 |

The pitch length of the unit cell is 154.0 mm (2x77.0). The short sample current density, at 4.35 K, for a two dimensional infinite array is 2348 A/mm$^2$, corresponding to a gradient of 77.7 (T/m), a current of 3315 (A), and a maximum field of 5.49 (T). Additional 3D calculations have shown that the short sample limit is located at the magnet end. Based on the field rise in the "end" and the need for margin, we propose an operating current of 2153 (A), a gradient of 50 (T/m) and a maximum field of 3.74 (T). Detailed magnet geometry and parameters are listed in Tables I and II

### B. *The choice of materials for Support Blocks*

Superconducting magnets in accelerators have always included iron. Ferromagnetic material is used to raise the field, return the flux and provide inexpensive structural support. Superconducting magnets are high field and the iron does saturate; having a small and manageable affect on field quality. In contrast, the field in conventional electromagnets is shaped by the iron and is therefore quite sensitive to saturation. The question whether iron should or should not be used for the internal Support Blocks has two possible answers.

It is quite possible to design a finite size array that includes both beam and edge coils that produces good field quality throughout. An example of such a design may be a "cos2$\theta$" coil with wedges optimized to take care of harmonics generated by neighboring coils[2].

Table II Magnet parameters

| | LAYER 1 / 2 |
|---|---|
| Conductor type | NbTi |
| Strand diameter, SSC outer (mm) | 0.6477 |
| Strand per cable | 2x6 |
| Cable thickness, bare (mm) | 1.0307/1.1112 |
| Cable width, bare (mm) | 4.043 |
| Nominal keystone angle° | 1.14 |
| Cu to SC ratio | 1.8:1 |
| Insulation thickness (mm) | 0.094 |
| Insulated cable thickness (mm) | 1.2187/1.2992 |
| Insulated cable width (mm) | 4.2308 |
| Turns per layer 1 / 2 | 25 / 26 |
| SC/turn (mm$^2$) | 1.41 |
| Cu/turn (mm$^2$) | 2.54 |
| $J_c$ 5T, 4.2K (A/mm$^2$) | 2750 |
| 2D | |
| $J_{ss}$ short sample, 4.35K (A/mm$^2$) | 2348 |
| $I_{ss}$ short sample, 4.35K (A) | 3315 |
| Short sample Gradient (T/m) | 77.7 |
| Max. short sample field layer 1 (T) | 5.49 |
| Max. field layer 2 (T) | 5.2 |
| 3D | |
| $J_{ss}$ short sample, 4.35K (A/mm$^2$) | 2290 |
| $I_{ss}$ short sample, 4.35K (A) | 3230 |
| Short sample Gradient at z=0 (T/m) | 74.0 |
| Max. field layer 1, return end (T) | 5.61 |
| Max. field layer 2, ends (T) | 5.23 |
| Magnetic Length (mm) | 320.0 |
| Inductance (single coil $\mu = \infty$) (mH) | 3.878 |
| Inductance, array, (mH) | 58.1 |
| Stored Energy, single quad (kJ) | 20.23 |
| Stored Energy, full array, (kJ) | 303.1 |
| Operating | |
| $J_o$ operating, 4.35K (A/mm$^2$) | 1527 |
| $I_o$ operating, 4.35K (A) | 2153 |
| Operating Gradient (T/m) | 50 |
| Max. operating field layer 1, end (T) | 3.74 |
| Max. operating field layer 2, end (T) | 3.48 |
| Stored Energy, single quad (kJ) | 9.0 |
| Stored Energy, full array (kJ) | 134.6 |

Whereas in a single magnet with pure "cos2$\theta$" current distribution, the quadrupole field is harmonics free, in an infinite array of such quadrupoles the current distribution will produce a **none pure** quadrupole field. In addition the field will depend not only on the coil radius but on the distance between coils and pole orientation[3],[4],[5]. Placing the coils in such a way that all identical poles face each other, produces the highest gradient with the lowest induction. In a two dimensional infinite array with a thin $J_0 \cos 2\theta$ current density at r=R and a coil to coil distance S, the field within the windings normalized to a radius $\rho$ can be expanded as

($R = 64.35$ mm , $S = 77$ mm , $\rho = 40$ mm),

$$\left\{\begin{matrix} B_r \\ B_\theta \end{matrix}\right\} = B_0\left(\frac{r}{4}\right)\left\{\begin{matrix} \left\{\begin{matrix} \sin 2\theta \\ \cos 2\theta \end{matrix}\right\} + \\ b_6\left(\frac{r}{4}\right)^4\left\{\begin{matrix} \sin 6\theta \\ \cos 6\theta \end{matrix}\right\} + \\ b_{10}\left(\frac{r}{4}\right)^8\left\{\begin{matrix} \sin 10\theta \\ \cos 10\theta \end{matrix}\right\} + \ldots \end{matrix}\right\}$$

$$\left\{\begin{matrix} b_6 \\ b_{10} \end{matrix}\right\} = \left\{\begin{matrix} -\frac{0.30546}{1+0.8863\left(\frac{R}{S}\right)^4}\left(\frac{\rho R}{S^2}\right)^4 \\ \frac{0.054542}{1+0.8863\left(\frac{R}{S}\right)^4}\left(\frac{\rho^2 R}{S^3}\right)^4 \end{matrix}\right\} = \left\{\begin{matrix} -75.75 \text{ units} \\ 0.98 \text{ units} \end{matrix}\right\}$$

Based on 3D calculations using 9 coils, the field and harmonics at a radius of $\rho = 40$ mm are;$B_0 = -3.0210$ tesla , $b_6 = -74.94$ units , $b_{10} = 0.78$ units, in good agreement with the above expected values.

The dependency of the fundamental term and higher harmonics on the distance between neighboring coils S is evident.

In a single optimized coil, harmonics such as $b_6$ and $b_{10}$ can be taken care of by wedges; a fact that depends only on cable size and location. In an array, the size and location of wedges will also depend on the location of neighboring coils. Therefore, tolerance size, construction errors and assembly will affect the field quality. It is also evident that any design changes introduced to the distance between coils, will require the coil cross section to be modified (e.g. changing wedge sizes).

Choosing a ferromagnetic material for the Support Blocks does not affect the gradient but will have a pronounced effect on all higher harmonics. The iron acts as an harmonic filter capable of reducing the influence of neighboring coils on the local dodecapole by an order of magnitude. It may serve, therefore, as a mean, to reduce coil-to-coil "cross-talk", thereby relaxing tolerances, reducing the effect of construction error and maintaining a degree of flexibility in future design changes. The effect of iron saturation on field quality can easily be maintained in the same fashion as its done in many other superconducting magnets.

### III. 3D

To carry out 3D field calculations and determined end spacers geometry, we have generated the coil windings of the entire magnet; including return end, lead end and layer to layer transition (Fig. 3). The end blocks were spaced in such a way that reduces integrated harmonics and lowers the field rise in the end. Geometrical data of 9 coils were submitted to the NERSC parallel—processor T3E computer, and the resulting field reduced to normal and skew harmonics. Additional detailed calculations were made to determine the field at the conductor. The maximum field was found to be located in the return end with a field rise (with respect to the straight section, z=0) of 0.2 T (Fig.4) in strand number 5 (located near the outer edge of layer 1 pole).

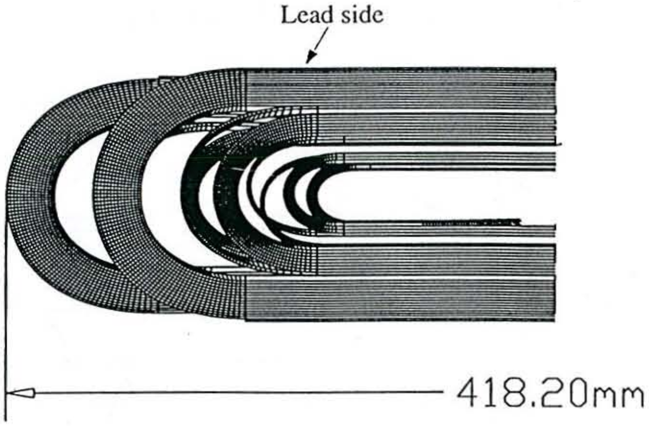

Fig. 3. Top view of a single two layer quad windings (lead end).

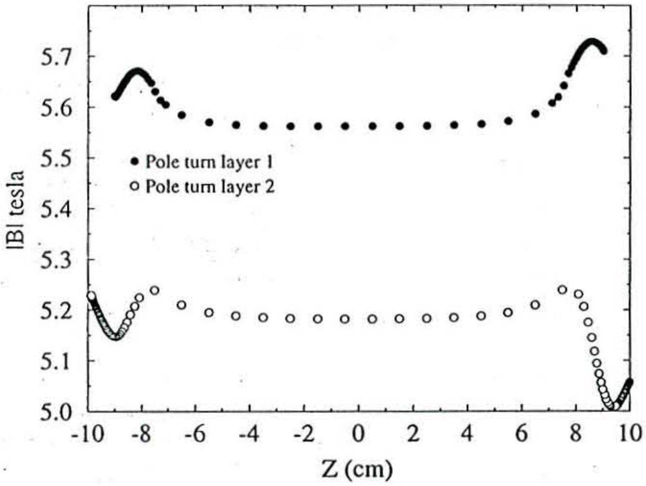

Fig. 4. Field magnitude around a pole turn in 3x3 array.

It is appropriate to consider a 3D expansion for magnet with large bore size and the short coil length. We have computed both the normal and skew A(z) functions (Fig. 5,6) associated with the following expression,

$$B_r = \begin{matrix} \left[-2A_2(z) + \frac{1}{3}A_2''(z)r^2 \cdots\right] r \sin 2\theta + \\ \left[-6A_6(z) + \frac{2}{7}A_6''(z)r^2 \cdots\right] r^5 \sin 6\theta + \\ \left[-10A_{10}(z) + \frac{3}{11}A_{10}''(z)r^2 \cdots\right] r^9 \sin 10\theta + \end{matrix}$$

$$B_\theta = \begin{matrix} \left[-2A_2(z) + \frac{1}{6}A_2''(z)r^2 \cdots\right] r \cos 2\theta + \\ \left[-6A_6(z) + \frac{3}{14}A_6''(z)r^2 \cdots\right] r^5 \cos 6\theta + \\ \left[-10A_{10}(z) + \frac{5}{22}A_{10}''(z)r^2 \cdots\right] r^9 \cos 10\theta + \end{matrix}$$

$$B_z = \begin{matrix} \left[-A_2'(z)+\cdots\right] r^2 \sin 2\theta + \\ \left[-A_6'(z)+\cdots\right] r^6 \sin 6\theta + \\ \left[-A_{10}'(z)+\cdots\right] r^{10} \sin 10\theta + \end{matrix}$$

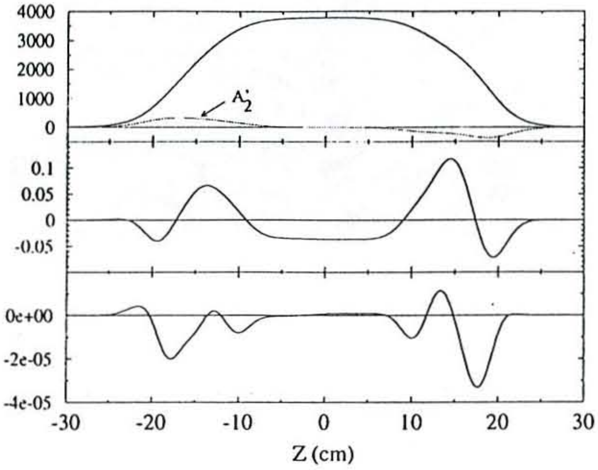

Fig. 5. Normal A's

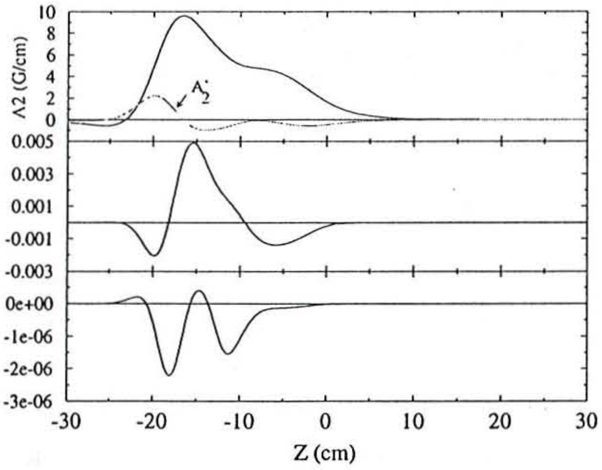

Fig. 6. Skew A's

## IV. FORCE AND STRESS

High field superconducting (SC) magnets generate substantial Lorentz forces and require a robust structural support system. The support structure for the quad array will have to provide a controlled measure of stress during cool down and ensure safe operation at 4.2 K. To reduce stick-slip conditions within the conductor and "improve" its mechanical properties, prestress will have to be applied directly to the coils. Whereas in many SC magnets prestress is applied during assembly by interlocking collars, lack of space in the array requires we use a thin Aluminum shell and consider an alternative method for assembly.

The midplane Lorentz stress in a single quad within the array is 47 MPa at 3300 A. The corresponding maximum radial pressure is 6.3 MPa. To provide coil prestress that corresponds to such values, a 6.5 mm thick Aluminum shell will have to be placed over the coils and put under 70 MPa azimuthal tension (assuming axisymmetry conditions, e.g. no bending). Since the required prestress in the coil is only about half of the maximum Lorentz force (47.0/2 MPa), we have allowed a 50% loss in prestress during assembly or cool down.

To ensure no bending, of the Aluminum shell the collared coil will have to be firmly supported by four Support Blocks. Although the maximum side force produced by a single quad, $F_{ss}$, is equal to 670 kN/m at 3300 A, the net force on each Block is zero. The accumulated forces will have to be reacted along the array sides with a maximum force equal to $3\sqrt{2}F_{ss}$ or 2842 kN/m. Such a force will produce an average outward pressure of 4.64 MPa on the inner surface (R=390 mm) of the Array Structural Ring (ASR). Since each coil is prestressed individually the main function of the ASR is to assure that Support Blocks and the coils Al shells maintain good contact after cool down. Due to thermal contraction the ASR radius will change by about 1.5 mm when the temperature is lowered to 4.2 K. A 30 mm thick stainless steel ASR that is prestressed azimuthally to 180 MPa at room temperature will cause the coil array to be compressed to 15 MPa. After cool down the tension in the ASR will drop to 8 MPA while the array will reduce its external pressure to zero. Powering the coils to short sample will put the ASR under 5 MPa of radial stress and increase the azimuthal tension to 70 MPa. Under such conditions radial displacements will be less than the order of 0.15 mm. The axial force generated by the "end" of each quad is 83 kN. The total axial force on a 3x3 array (including edge coils) is 1230 kN and the corresponding axial magnetic pressure within the ASR is 2.6 MPa.

## V. CONCLUSION

We have completed a conceptual design of a 3x3 quadrupole array for a Heavy Ion Fusion Driver. The operating quadrupole field is 50 T/m across a 78 mm warm bore and the magnetic length is 0.32 m. The overall array size including its cryostat is 900 mm in diameter and 700 mm long.

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