A Superconducting Quadrupole Array for Transport of Multiple High Current Beams

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Abstract

We present a conceptual design of a superconducting quadrupole magnet array for the side-by-side transport of multiple high current particle beams in induction linear accelerators. The magnetic design uses a modified cosine 2θ current distribution inside a square cell boundary. Each interior magnet's neighbors serve as the return flux paths and the poles are placed as close as possible to each other to facilitate this. No iron is present in the basic 2-D magnetic design; it will work at any current level without correction windings. Special 1/8th quadrupoles are used along the transverse periphery of the array to contain and channel flux back into the array, making every channel look as part of an infinite array. This design provides a fixed dimension array boundary equal to the quadrupole radius that can be used for arrays of any number of quadrupole channels, at any field level. More importantly, the design provides magnetic field separation between the array and the induction cores which may be surrounding it. Flux linkage between these two components can seriously affect the operation of both of them.

1. DESIGN REQUIREMENTS

The proposed Heavy Ion Fusion Integrated Research Experiment (HIF/IRE) will be dedicated to studying and optimizing inertial confinement fusion for the first time on a driver scale. Quadrupole arrays are used to provide beam transport through most of the accelerator, and they may be located partially or fully within the induction core.

The design choices are to use quadrupole arrays within large induction cores, such as at low energies where short half periods are beneficial, and to use arrays which alternate with induction cores, such as at high energies, where beam transport is not limiting. In either case, the focussing quadrupoles are required to maintain a regular periodicity. The acceleration from any one induction module adds a relatively miniscule amount of energy to the beam, and consequently the accelerating gaps can be located along z in an irregular manner, accommodating pumps and diagnostic stations as required. Consequently, there is not a fixed relationship between the locations of the ferromagnetic cores and the focussing quadrupoles.

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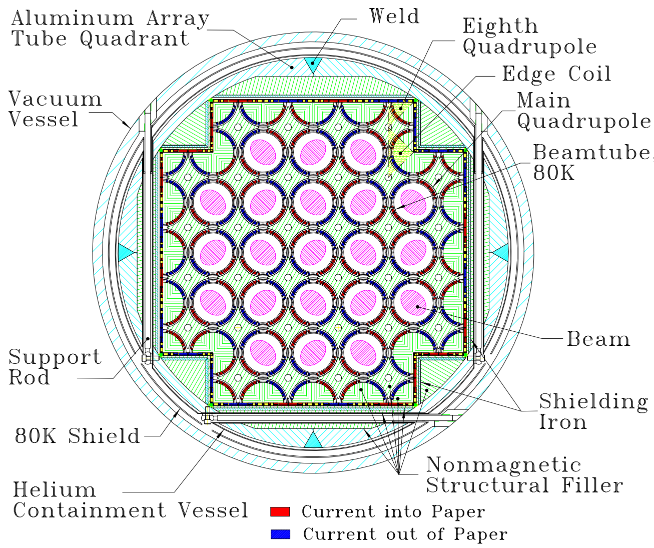


Fig. 1 Quadrupole Array Cross-Section

The only requirement is that neither one affects the other to an extent that beam quality is degraded. The interim criterion that we have adopted is that the focussing fields are within 0.1% of their correct values at the beam edge. The simplest solution for this requirement is to shield the cores from the quadrupoles and vice-versa, by choosing a shielded geometry which makes the quadrupole fields insensitive to what is outside the shield; in other words the quadrupole fields must be well contained within the package, with no significant stray fields that can reach the induction cores. Without such shielding, the quadrupole fields cannot be sensibly calculated without including the induction cores, and even then, because the induction cores are switched during and between every pulse, such a calculation would be challenging.

Superconducting quadrupole arrays are ultimately necessary to minimize energy costs for a powerplant scale driver, even though HIF/IRE will probably utilize pulsed conventionally conducting quadrupole arrays to minimize capital costs and development time. Prototypes of these pulsed quadrupoles have been successfully built and tested for approx. one year now. Superconducting magnet array development is planned concurrently for either an upgrade, or perhaps as original equipment, if the project is delayed. At this time, HIF/IRE will require approximately 250 arrays of 21 magnets each.

Minimizing transverse dimensions for these superconducting magnets results in smaller, more close-packed arrays, which reduces the size and costs of induction cores and their pulsed power supplies. Magnet fabrication and operating costs must be minimized to achieve the stiff requirements on plant efficiency that will make fusion power feasible.

Each successive lattice period in the beam transport section requires a slight increase in integrated field strength, and it is desired to use as few different magnet lengths as possible. Thus a wide range of operating current is desired.

2. DESIGN OVERVIEW

Fig. 1 shows a cross section of the array. Main quadrupoles are fabricated from either Rutherford style cable, as shown here, or from round cable, robotically placed and bonded in position[1]. They are encased in either aluminum alloy tubes, or filament wound with carbon or glass fiber with an epoxy binder matrix.

Edge coils are simply coils from main quadrupoles, arranged on a non-magnetic semicircular base. Eighth quadrupole coils are fabricated from round cable, though the figures here shows a Rutherford type cable of rectangular cross section for simplicity. Fig. 2 shows a detailed view of these coils.

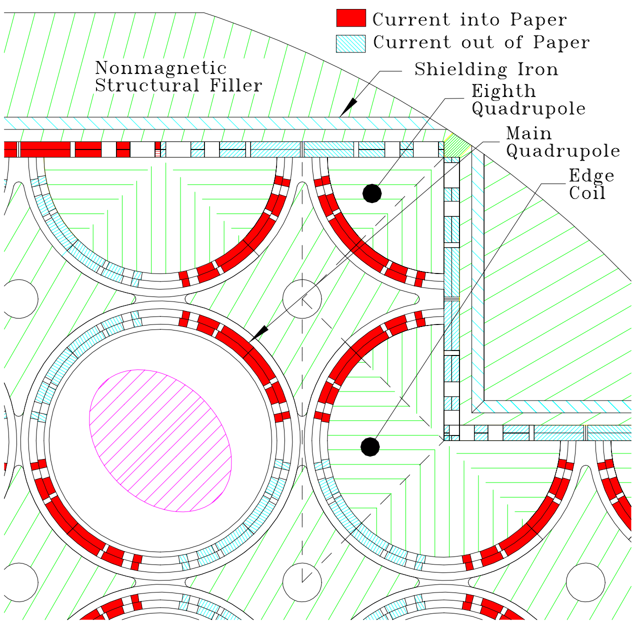


Fig. 2 Array Coil Detail

Nonmagnetic spacers are placed between the coils and around the entire coil package to align the coils and solidify the array. A thin iron sheet surrounds the array to shield it from small external fields. It is located a small distance away from the edge of the array and extends axially over the magnet ends by approximately one magnet radius to clamp any stray end fields. A set of aluminum alloy array tube quadrants are pressed onto this assembly and welded together to prestress the array in transverse compression for resistance to magnetic forces, and to prestress both the edge coils and the eighth quadrupoles in compression along both their planar and circular sides.

3. MAGNETIC DESIGN

The magnet array is a current dominated design, with conductors arranged in a circle inside a square magnetic flux normal boundary formed by each magnet's neighbors. Except for the shield around the array, no iron is present in the design; this allows the magnet to be used at different current levels without correction. For a current dominated design where conductors are arranged in a circular pattern in free space, or along the inside surface of a circular flux normal boundary, a pure cosine 2θ surface current distribution gives a perfect quadrupole. For a square flux normal boundary, a "perfect" quadrupole field distribution may be obtained by modifying the current distribution to eliminate the multipoles described by ref. 2 (subject to the usual constraints of using real, block type conductors). The design here is based on a design from Caspi[3], for a 4T maximum good field, using cable made from SSC superconducting wire.

Table 1. Magnet Parameters

Coil ID	12	cm
Coil OD	13.8	cm
Magnet tube OD	14.75	cm
Beam tube ID	11.5	cm
Magnet Transverse Pitch	14.4	cm
Array Vacuum Vessel OD	129	cm
Field Gradient, B' (max)	70	T/m
Bmax, Good Field Region	4.0	T
Bmax in conductor	5.26	T
Number of turns per coil	42	
Conductor Size	4.2x2.0	mm
Magnet Current, I	8064	A
Cu:Sc Ratio	1.3:1	

In any arbitrary infinite array of multipole channels, a closed subset of channels can properly be contained, or "terminated" by finding a suitable flux parallel surface (Dirichlet boundary) surrounding the channel subset, and imposing surface currents on the boundary equal to the magnetic field along the boundary. For quadrupole fields, Dirichlet boundaries lie on the axes of the poles. The magnetic field along these boundaries is proportional to the radius, requiring a corresponding linearly increasing surface current. By symmetry considerations, the total current requirement for the planar section is the same as for the arc shaped "half coil" facing it. Performing $\int H \bullet dl = NI$ along the Dirichlet boundary, just inside of it, facing the half coil section yields the amp-turns of the half coil. By symmetry, the same integral along a path mirrored about the boundary would yield the same number of amp-turns for a mirrored adjacent magnet cell (octant). This requires the total current on the planar surface current distribution replacing the adjacent magnet cell to have the same total current (in the opposite direction) as the half coil. Replacing the adjacent magnet cell with this planar current distribution, we can then perform $\int H \bullet dl = NI$ just outside the array, along the boundary. This yields zero total amp-turns and thus no magnetic field is present outside the array.

This equality of current distributions allows the "half coil" to be combined with the planar current distribution, making a real coil. The resulting coil represents a basic repeating unit cell of $1/8^{th}$ of a quadrupole. These $1/8^{th}$ quadrupoles are combined in various combinations, both with and without regular quadrupole coils, to form ¼, ½, and ¾ quadrupoles which can terminate all possible edge conditions of the array by providing the required flux turnaround. Fig. 3 shows a flux plot produced using the POISSON magnetic field computation program[4] demonstrating the effectiveness of this concept in

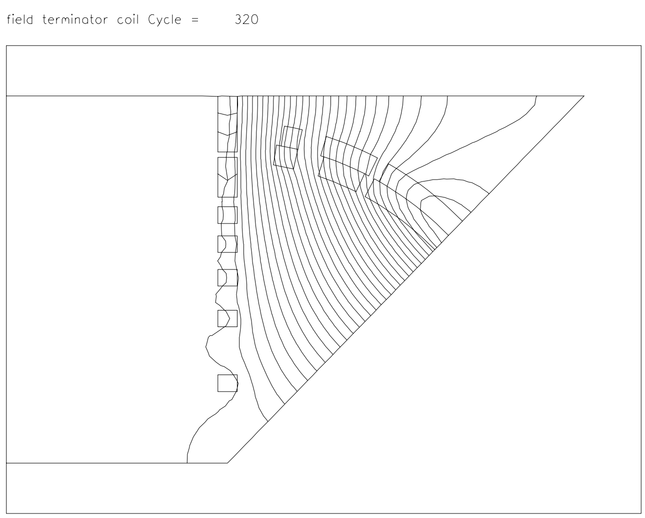


Fig. 3 Eighth Quadrupole Cross Section Flux Plot

containing the field. The same number of amp-turns present in the circular section is present in the planar section, of opposite sign. Field level to the left of the planar section of the coil was approx. 500G in (what is) a crude model of first iteration. The placement of a thin iron shell to the left is intended to take care of this small leakage.

The half coils are difficult, if not impossible to wind using Rutherford style cable. There is no beam tube over which the end turns must arc, however severe twists occur on the ends, and the cables may not stack in a compact fashion. Fig. 4a shows a possible cross section. The cable wants to bend along its easy axis which cannot be allowed coming out of the planar section. Restraining and compressing the ends would be very challenging. For keystoned cables, wedges under each cable run would be needed to produce the straight section. As such, a robotically placed round cable is proposed, as described in ref 1. A possible cross section is shown in Fig. 4b.

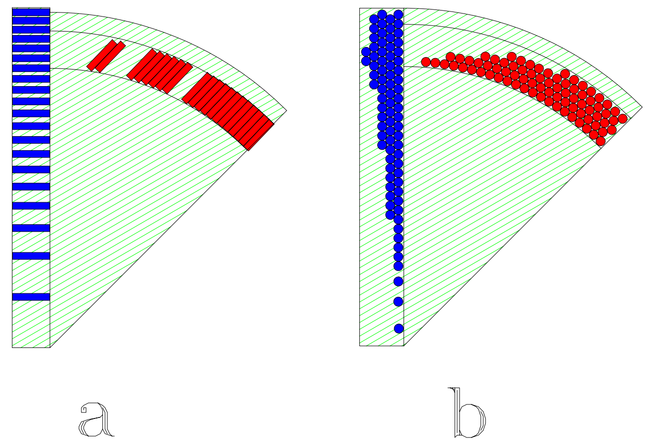


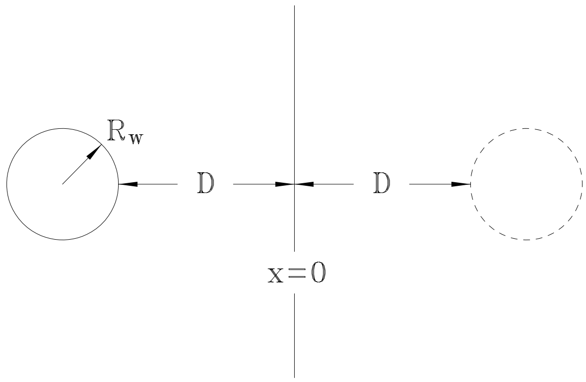
Fig. 4 Eighth Quadrupole Conceptual Cross Sections

Even winding this cable, which has no preferred bending direction, leads to long, unstable ends due to cable crossovers which tend to pile up at certain locations. Complex sculpted end forms may be necessary for winding. It remains to be verified whether a potted end, with or without end forms would be sufficiently stable against magnetic forces.

Upon inspection, one can see there are alternative schemes for providing the required edge current distributions, such as using various combinations of flat pancake coils, large "band" coils, "half circle quad coils", etc. However, these schemes, aside from requiring a large number of specialized coils specific to the size of the array, typically lead to "orphan" coil halves, unequal coil lengths, current cross-over problems from one side of the array to the other, and the concomitant difficulty of building and restraining these unusual and large coils from movement. In addition, the concept does not always scale to larger or smaller arrays, e.g., a 12 channel 4x4 array with the corner quads missing requires $3/4^{th}$ of the edge currents to be running in one direction. The proposed eighth quadrupole represents a single solution to all edge problems on any possible quadrupole array; only one coil design is necessary, in addition to the main quadrupole coils.

Other schemes for producing field turnaround have been proposed which reduce current requirements; this reduced current requirement can only come at the expense of large field turnaround areas. To keep the flux contained and close to the array boundary, thus minimizing the size of the array, high fields are required, necessitating large currents.

The importance of proper field containment can be illustrated by estimating the minimum allowable distance of nearby iron. Consider an isolated quadrupole near a magnetic planar boundary at x=0, either flux normal or parallel. If the quad has a radius R_w, thin windings, and a clearance D from the boundary, then there is an image quad at x=D+R_w:



The external field of a quad at a distance, R from the center is:

$$B = B_w \left(\frac{R_w}{R} \right)^3$$

We typically specify a field accuracy of 0.1%. For a single quad, where R_w; B_w are the radius and field at the windings:

$$\frac{\Delta B}{B} = \frac{B_w \left(\frac{R_w}{2D + R_w} \right)^3}{B_w} = .001 \ ; \ \frac{R_w}{2D + R_w} = .1 \ ;$$

$$10\, R_w = 2D + R_w \ ; \ D = 4.5 R_w \text{ is required}$$

For a planar array of quadrupoles, fields decay as:

$$B \propto B_w e^{-\frac{\pi x}{2R}}; \quad \pi \frac{2D}{2R} = 2.3 \log(1000) = 2.3(3)$$

$$D \cong 2.2R \text{ is required}$$

A corner quad is similar to a single quad and, unfortunately, is the quad closest to the induction core, so the larger clearance is required.

The magnetic centers and angular orientations must be very accurately aligned; absolute positional tolerances of the field may be less than 50 microns. It will probably not be possible to cost effectively build and align the array to the required tolerances. Therefore, to correct for misalignments, both magnet-to-magnet and array-to-array, beam steering magnets on individual beam channels will be needed, perhaps even on every array. Since each magnet channel is highly coupled with its neighbors, beam steering magnets for individual channels must be placed outside the main magnet array, as a separate array, using unsaturated iron for channel isolation[5]. These separate steering magnet arrays have substantially smaller field requirements and can be pulsed or, perhaps even superconducting. Each steering channel magnet set consists of two crossed dipoles, to correct translational misalignments, and one skew quadrupole to correct rotational misalignment. Magnet yaw and pitch errors are assumed to be translational errors, as integrated over the magnet length.

Coil connections and magnet lead connections require substantial overlap. Intramagnet coil connections are made around the inner magnet tube, and intermagnet lead connections are located in the space between the magnets.

4. MECHANICAL DESIGN

The design philosophy for the main quadrupoles is to use a tensile stressed tube around each quadrupole to prestress the coils in tangential compression, eliminating relative motion between components from magnetic forces for quench resistance, and to use spacers between the magnets in combination with a tensile stressed tube over the entire array to prestress the array, including the edge coils and 1/8th quads, in compression. For the magnets, the typical collar design of high field quadrupoles is not space efficient in the transverse dimensions. Fortunately, the field magnitude requirements are not severe and the required prestress is relatively low. Interior quadrupole coils are wound with Rutherford style cable, bifilar, in a 6 block design. They are assembled around a steel mandrel of a diameter equal to the final pre-stressed ID. The coils are prestressed by filament winding a carbon or glass fiber bundle (tow) at a tension near yield for the fibers, wetting them with epoxy as they wrap over the coils. If possible, only one full wrap is used for the hoop direction windings, which fully prestresses the coil in one wrapping pass. This method gives a very high efficiency of prestress for minimal OD buildout, as opposed to the method of winding successive wraps under tension, where each additional wrap tends to relieve initial tensile stress on previous wraps. To prestress the coil in the longitudinal direction, domed end pieces are placed over the magnet ends, and the assembly is then axially prestressed through the magnet bore using a hydraulic ram or leadscrew. While under compression, the assembly is overwrapped at a high helix angle with moderately high tension in a filament winding scheme similar to that used for winding pressure vessels. This operation lays tows at two angles symmetric to the longitudinal axis simultaneously. Leads protrude through these ends, so a locally nonuniform helix which avoids wrapping directly onto them may be necessary. Leads are coiled and rotated during the high helix wrapping operation to avoid wrapping over them. Fiber bundle ends are clamped off to maintain tension during an oven cure procedure. The magnet is then ground to final OD and a key for rotational alignment is bonded onto the OD in a precision fixture, before the mandrel is removed. After mandrel removal, the magnet is bonded to a stainless steel tube closely fitting the ID. This tube serves as part of the helium containment vessel at 4°K. Leads between coils are bent and twisted to lay flat when wrapped around this tube at one end of the magnet. This allows them to be lap soldered together within the radial confines of the coil.

An alternative method[6], by Caspi, et. al., of potting the coils inside an aluminum alloy tube with pressurized epoxy, is under development, and may prove suitable.

As mentioned earlier, the 1/8th quadrupoles will most likely be wound using round cable robotically placed and bonded onto a solid nonmagnetic form. To minimize the length of the ends, round multistrand cable, 2mm dia. is wound in a nested fashion on a sculptured form. This necessitates a tight radius bend in the high field region, disallowing the use of larger cable. 5 layers (8.6mm total radial width) are wound to account for the slightly lower packing factor of 91% relative to Rutherford style cable. The large number of individual conductors allows a high degree of current profile uniformity along the planar section, minimizing field excursions exterior to the coils. These 1/8th quadrupoles are potted after winding in a cryogenic compatible epoxy to minimize prestress requirements.

The diamond shaped intermagnet spacers will be made to high accuracy to minimize stackup tolerances. A non-brittle material with low thermal expansion is desired here, perhaps an epoxy or thermoplastic matrix highly filled with aluminum oxide or silica glass particles may prove suitable. Final assembly of the array is accomplished by pressing four aluminum alloy array tube quadrants over the magnet and spacer subassembly using a four direction press, and welding them together. Tabs on the quadrants provide stable bearing points for the press rams and are machined off after welding. Aluminum alloy, with its high thermal shrinkage rate provides additional prestress when cooled to cryogenic temperatures. Welding aluminum produces a reduced strength heat affected zone (HAZ), so the tube quadrants are made thicker at the weld to compensate. Using multipass welding (as many as ten passes per weld) minimizes the heat input into the array, and the extent of the HAZ, confining it to the thicker section.

5. ARRAY VACUUUM AND CRYOGENIC DESIGN

To minimize heat losses plus axial and radial space requirements, the beam tube serves as an 80K shield. The outer surface is polished and gold plated to minimize heat leak from the 4K magnet cryostat wall, polished and goldplated on its inner surface, without using multilayer insulation. The short beam tube length allows a very small gap between the beam tube and the magnet cryostat, providing more beam aperture. The 80K surface provides cryopumping and short magnet ends without the penalty of excessive heat leak at 4K.

The array is surrounded by a stainless steel helium containment vessel. This assembly is suspended in the cryostat on fiberglass rods which extend through holes in the spacers and array tube to reach the mounts of the array to the vessel, providing accurate and rigid positioning of the array within the cryostat, while minimizing transverse dimensions.

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