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Optimization of a 3x3 focusing array for heavy ion drivers

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Abstract— **A heavy ion driver for inertial fusion will accelerate an array of beams through common induction cores and then direct the beams onto the DT target. An array of quadrupole focusing magnets is used to prevent beam expansion from space charge forces. In the array, the magnet fields from the coils embracing the beams are coupled, which reduces the cost of superconductor and increases the focusing power. The challenges in designing such an array are meeting the strict requirements for the quadrupole field inside the beam pipes and preventing stray fields outside. We report our optimization effort on designing such an array and show that 3x3 or larger arrays are feasible and practical to build with flat racetrack coils.**

Index Terms— **Focusing, shielding, superconducting accelerator magnets.**

I. INTRODUCTION

HEAVY Ion Fusion is considered to be an attractive practical solution to commercial fusion. A focusing array is a critical element of the concept. Previously there was no feasible design of the array. This work is a logical continuation of the work [1], where it was shown that focusing arrays made with racetrack coils look promising in 2D analysis. The work [1] was inspired by paper [2], which formulated a general concept for termination coils but in [2] there was no practical solution for the termination coils. Note, in contrast to a single quadrupole, in the array cells, the other harmonics are present and needed to be analyzed and reduced.

It was shown in [1] that in the 2D geometry it is possible to create a quadrupole field with racetrack coils with a small error and with a low stray field. The Heavy Ion Fusion program needed to demonstrate the feasibility of the concept on a representative array, which was agreed to be a 3x3 array.

We needed to develop a 3x3 array, which would meet two major requirements:

1. Generate a high purity quadrupole field inside the bores of the array to eliminate particle loss.
2. Have no stray field outside the array, since some magnetic field sensitive elements are located in the vicinity of the focusing magnets.

The magnet design should be relevant to bigger arrays, like 5x5 or 10x10, since 3x3 array serves only as a proof of principle for larger HIF driver arrays.

TABLE I
QUAD ARRAY REQUIREMENTS

Parameter	Quantity	Units	Conditions
Number of channels:	9		fixed
Clear bore radius:	30	mm	fixed
Cell half-size:	40	mm	Opt.
Physical coil length:	600	mm	fixed
Total physical length:	700	mm	Opt.
Short sample gradient:	85	T/m	Opt.
Operating current:	0.7	I_{ss}	fixed
Operating temperature:	4.5	K	fixed
Copper current density:	1.5	kA/mm^2 @ I_{ss}	fixed
Magnetic length:	570	mm	Opt.
Harmonics ref. radius	20	mm	fixed
Field quality:	< 50	10^{-4} units @ I_{op}	Opt.

Iss- current of the conductor short sample at peak field at 4.5 K; Iop – operating current, Opt. – parameter guidance, subject to optimization

II. FIELD REQUIREMENTS AND DESIGN CHOICES

The preliminary set of requirements are given in Table I.

For our studies we adopted the following design choices:

1. Flat racetracks geometry of the coils
2. Cable used in previous R&D – bare 1.17x4.05mm^2, in insulation 1.35x4.4 mm^2, maximum current density in the winding pack at 5 T, 4.5 k is 500 A/mm^2
3. Minimum cable bend radius – 7.5 mm
4. 72x72 mm^2 cell size
5. Winding pack is at least 3 mm from the corner
6. Current density in the winding pack is 500 A/mm^2

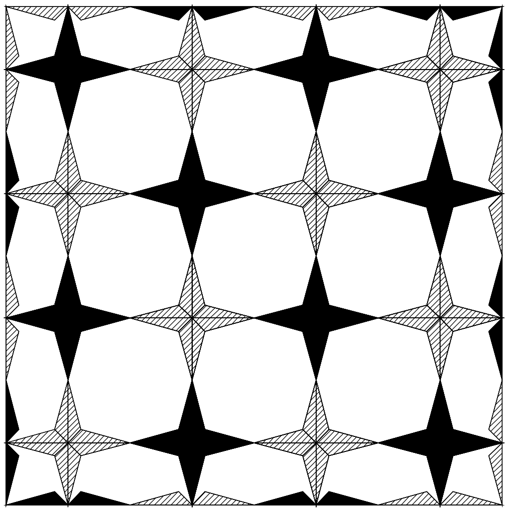

Fig. 1. Representation of analytical solution for ideal quadrupole array on the 3x3 array example.

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Nine apertures have a perfect quadrupole field. The perimeter windings outside the 3x3 array are called termination coils.

Fig. 1 illustrates that the current density changes in the cells linearly with the appropriate coordinate, but the ideal solution is valid only for infinitely thin current sheets; finite thickness blocks will introduce some error to the ideal quadruple field. From the practical stand point, it is very difficult to wind coils with the geometry like in Fig. 1 from a conductor with a constant cross section. Even more difficult will be to support such windings against huge electromagnetic forces. Therefore we will approximate this solution with a rectangular conductor and rectangular winding blocks and control the desired current density by spacers.

At this point the coils are represented in 2D by pairs of current sticks somehow connected into racetracks at the ends. At the next step we will modify the coils to make them practically feasible in the shape of racetrack coils, making sure that every current stick has a matching current stick with the opposite current that can be wound as a flat racetrack. Then we will try to simplify the terminating coils geometry until field quality both inside the cells and the stray field deteriorates below the requirements, thus we will find the simplest geometry which still meets the field quality specs. Then we will model the 3D coils and study end effects. Finally we will introduce ferromagnetic shields to suppress the stray field and will search for a shield geometry that does not deteriorate the field quality inside the array.

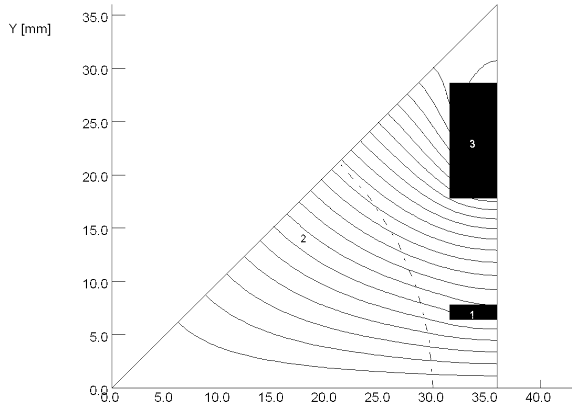

Fig. 2. Winding packs for the quadrupole field inside an infinite array.

IV. Infinite Array

Fig. 2 shows an optimized solution of the winding geometry for an infinite array. Due to the symmetry, only 1/8 of one cell is shown. Vector field lines are shown as well.

The space available for the structure supporting coils is outside the 30 mm radius circle, shown by a dashed line. The top edge coordinate of the winding pack labeled “3” is determined by condition 5 in section II. The gap between winding packs 1 and 3 was optimized to minimize the error field on the radius of 20 mm. The winding pack labeled “1” has only one turn. In the infinite array geometry, the non-zero harmonics are the quadrupole component b_2, and the error field components b_6, b_{10}, b_{14}… Since b_{14} and higher harmonics are negligible at the 20 mm reference radius, the figure of merit we chose to minimize was the $(b_6^2 + b_{10}^2)^{1/2}$. Table II shows the achieved error field components in the infinite array.

TABLE II
Harmonics in Infinite Array

Harmonics at R=20 mm	Value, T
b_2	-1.05
b_6	5.3e-4
b_{10}	1.9e-4
b_{14}	-6.5e-5

V. Finite Array Versions in 2D

On the basis of the infinite array solution we generate a finite array and the termination coils as described in [1]. The solution for coil geometry with dimensions is presented in Fig.3, where only one octant is shown. We call it version 1, it is obtained by reflections of Fig. 1 about appropriate mirror planes and by adding appropriate termination coils on the periphery. The solid blocks of the windings have one direction of the current; the lightly hatched blocks have the opposite direction. The circles represent the apertures of the cells with 72 mm diameter, the beam space is within 60 mm diameter circle. The dashed ellipses mark out termination coils 1 and 2. Obviously, the termination coil 1 is not a racetrack coil, we would like to convert it into a racetrack geometry. The termination coil 2 is a single layer racetrack with spacers, but we would like to simplify it also by merging the winding pack maintaining their center of gravity and number of turns the same.

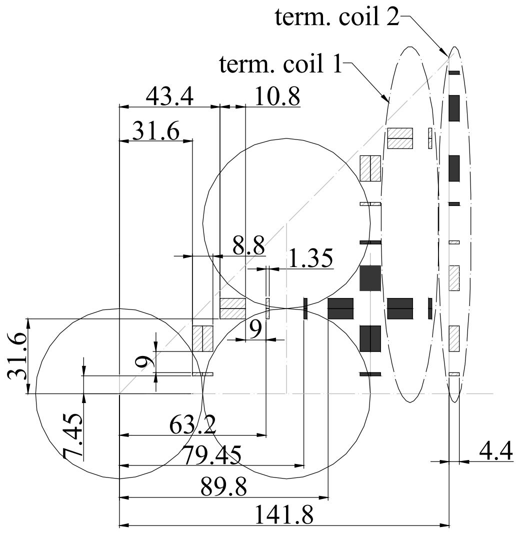

Fig.3. An octant of 3x3 array, iteration 1, dimensions are in mm.

Fig. 4 shows a series of modifications (from version 2 to version 6) towards a simpler geometry of the the termination coils, which were studied in this work. In ver. 2, the winding packs of the termination coil 1are rotated 90 degrees about the center of gravity to make them racetracks. In ver. 3, the winding packs of the termination coil 1 are merged, preserving the center of gravity of the winding packs. In ver. 4, the winding packs of the termination coils 2 are merged. In ver. 5 a next step of merging is done on the termination coils 2. In ver. 6 we added a ferromagnetic shield to see if we can eliminate the already small stray field and to see the shield effect on the field quality in the array.

VI. GRADIENT AND ERROR FIELD IN 2D MODELS

We will call the "right" cell the one with the center at x=72 mm, y=0, "diag" – the cell with the center at 72,72 and the "center" – the cell at 0,0. Obviously, in the 3x3 arrays there are one central cell and four of "right" and "diagonal" cells each. Fig. 5 presents gradient in the apertures of the array.

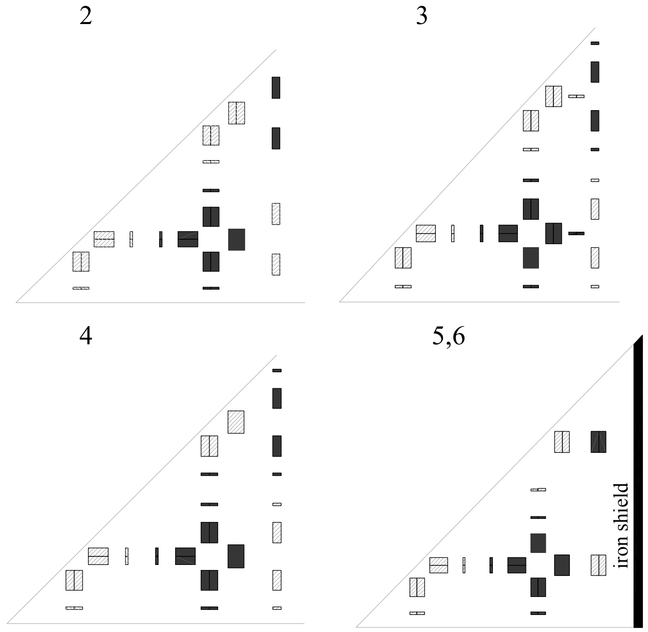

Fig. 4. 3x3 array termination coils studied in 2D geometry

As one can see, the gradient in all cells is practically identical in versions 1-4 and shows 2 % scatter in versions 5 and 6.

Now we will analyze the error fields. In the finite array, we shall expect more error harmonics than in the infinite array where due to symmetry many harmonics are absent.

Fig. 6 shows error field in the "diag" cell that has the highest error field. Some selected harmonics and an integrated error are shown. We define an integrated error as:

$$Interr = sqrt(b_3^2 + b_4^2 + b_5^2 + b_6^2 + b_{10}^2) \qquad (1)$$

This integral error does not include b_1 dipole component because it can be compensated separately. Other, higher harmonics are ignored because they are negligible. The skew a_n components (which are negligible in the center and in the "right" cells but are not small in the "diag" cell) are not included since we select integration in the diagonal cells in such a way that they are zero and b_n represent actually $c_n=(a_n^2+b_n^2)^{1/2}$.

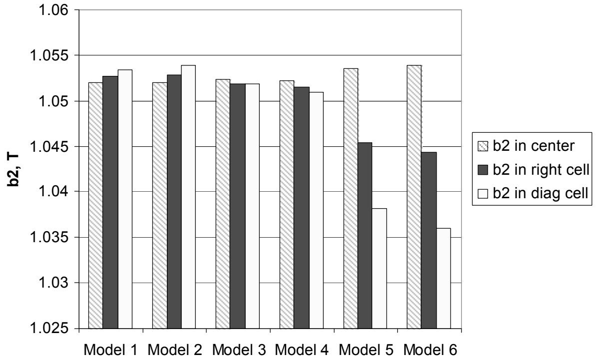

Fig. 5. Gradient in the 3x3 array versions

It is clear that the field quality remains well within the specs in first four versions; in the fifth the error field becomes high. Also, the stray field line of 20 Gauss went from R=200 mm to 280 mm in the version 5. Therefore we will use version 4 for our 3D studies as the simplest but with still a good quality field. Version 6 showed that an iron shield effectively eliminates the stray field without affecting the field inside the array.

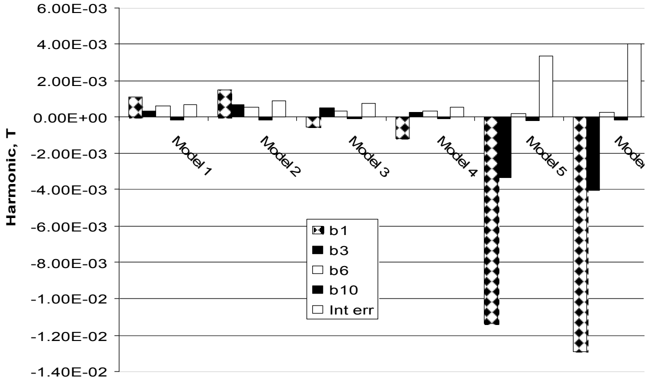

Fig. 6. Error field in the "right" cell (top) and "diag." cell (bottom)

VII. 3D MODEL

We used the version 4 and made a 3D model with flat racetracks and minimum radius of curvature of 7.5-8 mm. We computed the field for this 3D model without any iron shield and also with several configurations of the iron shield.

We expected that the coil ends will contribute to the error field, but our main concern was that the stray field will be unacceptably high especially near the ends.

When no shield was used, the stray field near the coil ends, was expectedly high. We tried a purely cylindrical 5 mm thick shield open from both ends, that did contained the stray field in the radial direction, but propagation of the stray field along the beam line was unacceptably high. The final model we built was almost a complete enclosure. We enclose the windings with a 4 mm thick steel shield at the radius of 226 mm. In the end region we put a 4-mm thick flange at z=315 mm (15 mm

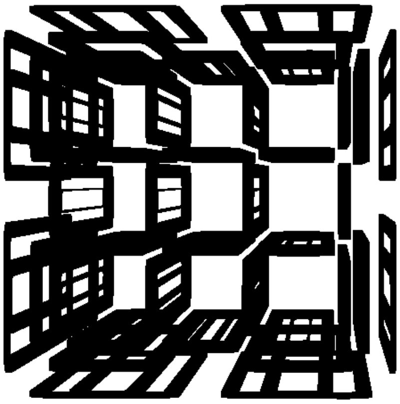

Fig. 7. 3x3 array windings with termination coils

away from the winding ends). The beam holes in the flange are 60 mm in diameter. The shield is shown in Fig. 8.

We computed the magnetic field in the array. The magnet length, defined as the integrated gradient divided by the gradient in the center was very high – about 97% of the coil length, which shows a very efficient design.

The worst field quality inside the array is the diagonal cell. The components of the error field are shown in Fig.9. The worst components by far are b_1 and b_3; the others being negligible. The dipole component b_1 is compensated by correction coils, therefore this component represents no danger for beam focusing. The component b_3 integrated value is about 11 units of 10^{-4}, which is well within the specifications. If necessary, it can be improved by modifying the ends geometry. The field quality in the “right” cells and especially “central“ cell are much better.

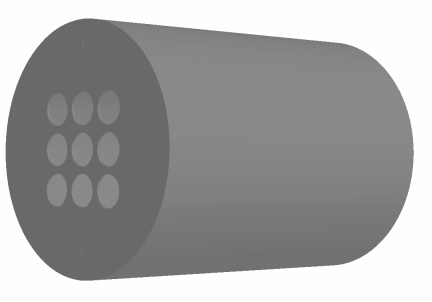

Fig.8. Shielded array, field module is shown on the shield surface

The iron shield did not significantly change the field quality in the array, but significantly reduced the stray field. The stray field reduced to below 20 Gauss 80 mm away from the shield, in axial direction and very small in the radial direction, which comfortably meets the specs. If necessary we can introduce an additional shield to suppress it even further.

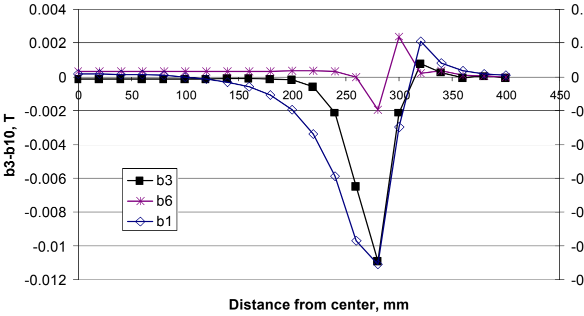

Fig. 9. Error field in the diagonal cell with complete iron shield

VIII. CONCLUSION

We developed a practical and feasible concept of the focusing array for HIF drivers on the basis of flat racetracks. The array has a high quality quadrupole field on the beam lines and low stray field outside. This principle is fully applicable to any arbitrary array without internal voids.

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