ITERATIVE KAPPA MAGNET POLE SHAPE OPTIMIZATION FOR MA CORE ANNEALING

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Abstract

The accelerator cavities of J-PARC synchrotrons RCS and MR are loaded with FineMet FT3M cores. The performance of such MA (Magnetic alloy) cores can be improved with an external B-field during annealing. Such small size cores are available as FT3L. As the maker has no suitable magnet to operate while annealing large cores, we reused a magnet in the J-PARC Hadron hall for the trial production of large size cores similar to FT3L. This magnet was returned to the experiment group.

The next setup uses the so-called Kappa magnet for a mass production scenario. The pole distance of the Kappa magnet is matched to the oven used for annealing. The pole surfaces are extended to reduce the current that gives the required B-field where the MA core is located in the oven.

We describe a procedure, where the 2D magnet pole geometry is defined in Excel. An Excel macro calls the static field solver. The simulation results are processed and read back. This allows geometry studies, while keeping simulation results of magnet current and field distribution along the MA core consistent, although the magnet yoke is non-linear and several iterations are needed to find the current for the required B-field.

INTRODUCTION

In 2011, we succeeded in annealing, e.g. heat treatment of MA cores under the influence of an external dipole field [1]. The setup, which is shown in Fig. 1, used a large dipole magnet in the J-PARC Hadron hall that had to be returned to the experimental group in summer 2011 after the first set of cores had been processed.

In order to continue to be able to process MA cores with large dimensions of up to 850 mm diameter as required for J-PARC RCS and 800 mm for Main Ring cavities, we had to look for another magnet.

The requirement is that the B-field at the positions, where the core to be annealed is located, should be at least 0.3 T. For smaller size cores up to approximately 30 cm diameter, the original manufacturer uses a solenoid structure to generate the required field during the annealing procedure for FT3L.

We were able to obtain a used dipole, called by the nickname "Kappa magnet". We wanted to reuse the oven, which had performed quite well in the Hadron Hall setup. This resulted in the requirement that the oven has to fit into the available gap space of the magnet. As the dimensions of the magnet yoke needed modification, we had a chance to optimize the pole shape to reduce the required power supply current.

Fig. 1: MA core annealing setup in J-PARC Hadron hall.

GEOMETRY AND MATERIAL DEFINITION

The original "Kappa" magnet had 400 mm gap distance. It has 2 upper and 2 lower coils each with 50 turns, which are electrically in series. In the Superfish [2] magneto-static simulation each 50 turn coil is modeled by a 1 turn coil for simplicity. With a magnet current in the order of 510 A the desired field of 0.3 T is obtained at the magnet centre, which is at x=150 cm distance from the left edge of the yoke. A FineMet core with 850 mm diameter located horizontally in the centre of the magnet will extend from 107.5 to 192.5 cm. Assuming the core can be treated as μ_r=1 (for example when the material is above the curie temperature), the B-field at the left edge of the core is only 65% of the centre value and the B-field at the right edge of the core is 68% of the centre value. Thus a higher magnet current of 784 A is necessary to fulfill the condition that the B field should be at least 0.3 T at the core position. The geometry of the Kappa magnet with a FineMet core modeled as μ_r=1 is shown in Fig. 2. In the simulation the 1-turn coil current is 39.2 kA. However, a gap distance of 40 cm is not enough to put an oven for annealing inside. When the gap is increased from 40 cm to 65 cm, according to simulation the necessary magnet current becomes 1304 A. The B_y components at the centre position of the core for both 40 and 65 cm gap are plotted in Fig. 3.

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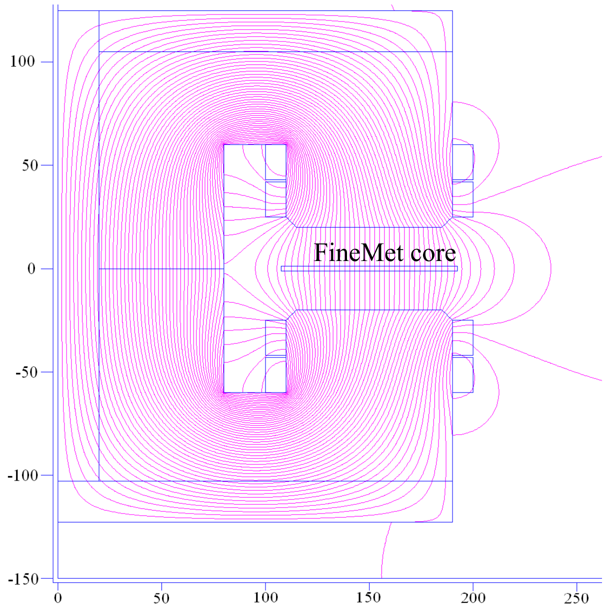

Fig. 2: Simplified Kappa magnet with 40 cm dipole gap at 784 A current. The FineMet core is modeled with μ_r=1. The dimensions are given in [cm].

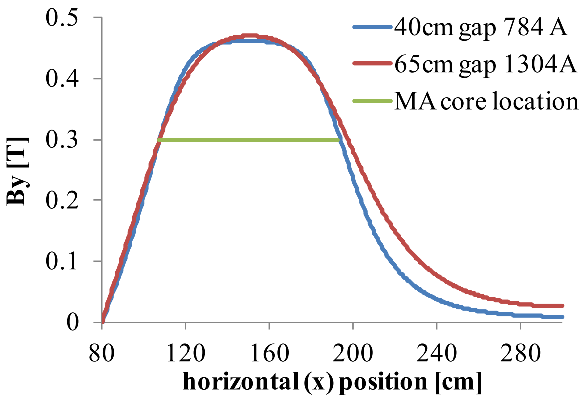

Fig. 3: The B_y component at the location of the FineMet core for both 40 cm and 65 cm magnet gap.

These Superfish simulation results were obtained under the assumption that the iron material of the magnet yoke is linear and can be treated with the standard setting for material 2 (Iron), e.g. μ_r=250. The 40 cm gap case needed 13 s for 1450 iterations and the 65 cm gap case required only 8 s for 1010 iterations with the Poisson solver.

While this is a reasonable approach to get started, in reality the material characteristics are different, and we have to take non-linearity into account. The magnet yoke material is described as “pure iron”. In a booklet from VAC [3] the properties of the material VACOFER S1 can be found, which is equivalent to “pure iron”. The material properties were approximated by a set of six 5th order polynomials. Then a material table suitable for Superfish analysis was created. Fig. 4 compares the built-in 1010 steel to VACOFER S1. Using such non-linear materials, the simulation CPU time increases.

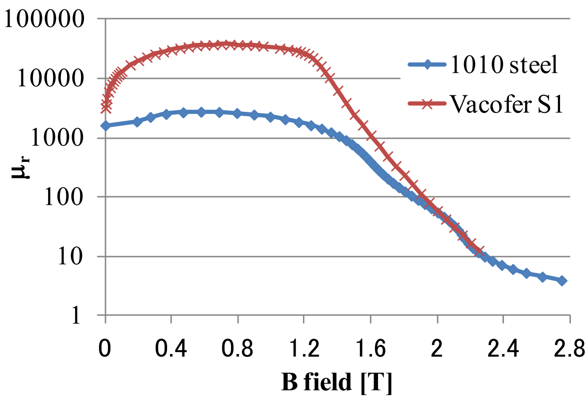

Fig. 4: Permeability of 1010 steel and Vacofer S1.

COMPUTING ENVIRONMENT

For Superfish/Poisson calculations, the geometry information is stored in a readable text file, processed by the Automesh program. As the geometry and the magnet current will be changed quite often to find an optimum, manual editing has the risk of errors and inconsistencies. Therefore the information is split in two parts. One file contains the information considered fixed. Another text file contains the information how the pole shape of the magnet, the magnet current and the yoke material are modified. The two files are combined, and then according to the flowchart in Fig. 5 the simulation proceeds.

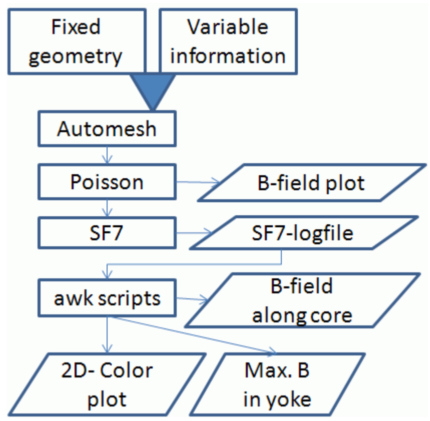

Fig. 5: Simulation flowchart

The specified geometry is processed by Automesh. Poisson is used as solver, and finally SF7 interpolates the B-field along given curves, here the centre plane of the magnet, where the FineMet core will be positioned.

Three awk scripts analyze the log-file content of SF7. This way the whole calculation process can be performed without user action in between. This simplifies parametric studies with the geometry.

The process is run as a batch-file, which can be started from within an Excel-Worksheet to keep geometry information and simulation results consistent, even if a large number of modifications are performed.

Within the Excel worksheet the information about the pole-shape modification is given as a set of numbers in two columns, which is also displayed in a scatter graph, so that the user gets an impression of pole shape. On the Excel sheet the coordinates are changed into the format that is required by Automesh.

A button on the Excel-sheet calls a Macro that writes the actual pole shape and current parameters to the “variable information file” mentioned before and starts the calculation by executing the batch file.

After the Superfish calculation has finished another macro imports the file that contains the B_y component of the B-field along the magnet centre plane, where the FineMet core is to be placed. Also it imports the maximum absolute value of the B-field. These data can be further processed by Excel to calculate the average field along the FineMet core position, the maximum and minimum, and the field at the edges. Finally the geometry is qualified by:

- The current to reach B_y=0.3 T at all core positions
- The ratio of minimum/maximum B_y-field along the core position
- The maximum B-field in the yoke geometry

The B_y-field distribution along the core is shown in the graph that contains the pole shape geometry to give a hint for the next optimization step. Once a geometry parameter for optimization has been exhausted, one can try with another parameter on a new sheet. Finally, one can make a summary worksheet, to see how the geometry has evolved.

INITIAL SIMULATION RESULTS

A simplified intermediate geometry of the magnet (as of 2011/8/24) is shown in Fig. 6. The effect of modifying the horizontal dimension of the blue colored pole extension plates with t=30 mm thickness between magnet poles and oven is analyzed in the following.

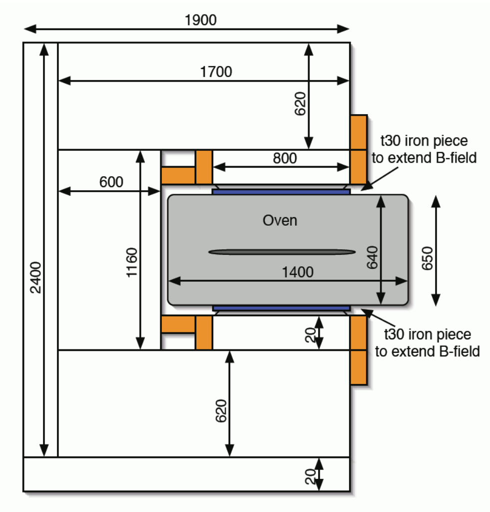

Fig. 6: Simplified magnet geometry for optimization

The related simulation results are shown as overview in Fig. 7. At optimization step 0, the iron extension piece is treated as material air (with μ_r=1), therefore it has no effect on the magnet field distribution. This can be regarded as a reference. As seen in Fig. 7, the necessary magnet current is highest in this case, and the B-field flatness, expressed as B_{min}/B_{max} along the core is low. The maximum B-field in the geometry is less than 1 T, indicating that the iron yoke is far enough from saturation.

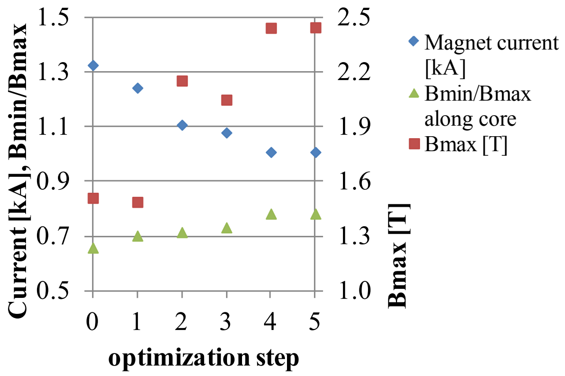

Fig. 7: Optimizing results of t=30mm pole extension

At step 1, the extension piece is still air, but the core is moved 2.5 cm outside to the right. The optimum FineMet core position differs from the geometrical centre of the magnet poles.

At step 2, the extension piece with 80 cm length matched to the pole dimension inside the coils is treated as iron like the yoke. The optimum place for the core is shifted 2 cm to the right from the geometry centre. The necessary magnet current is reduced and the field flatness along the core is improved. The maximum B field in the geometry is getting up.

At step 3, compared to step 2, the iron piece is extended to the left and right by 1.5 cm, so that the maximum field is reduced to 2.05 T.

At step 4, compared to step 3, the iron piece is extended to the right by 16 cm. Also the pole edge is covered, which partially increases the extension thickness from 30 to 50 mm. The optimum core position is shifted 5 cm to the right from the geometrical centre.

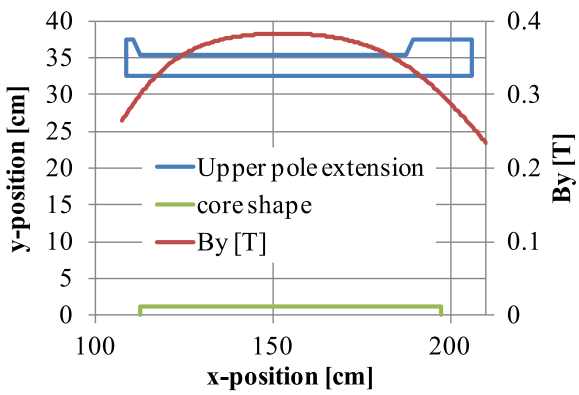

Fig. 8: The pole extension shape at optimization step 4.

At step 5, compared to step 4, the right side edges of the pole extensions are cut by 2·2 cm, but this did not improve B_{max}, or the magnet current. Here the optimum is obtained in step 4. In Fig. 8 the pole extension for this case is shown together with the B_y-field along the core, which is also indicated. Fig. 9 shows, how necessary magnet current and field flatness change as function of pole piece extension to the right side. The chosen optimum for the extension is 16 cm. Fig. 10 shows that the optimum position of the core is 5 cm to the right of the magnet geometrical centre. This means that the oven can be moved a little to the right, giving more space between the right side of the 60 cm thick yoke and the oven.

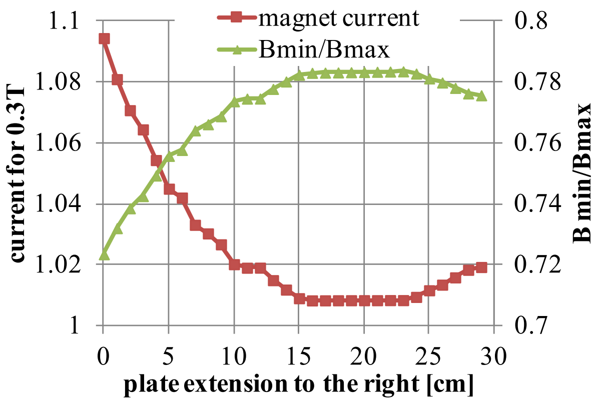

Fig. 9: The intermediate simulation conditions.

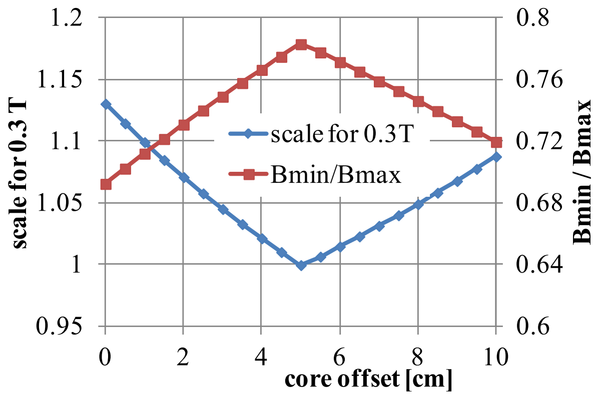

Fig. 10: Optimum core offset for minimum current and good field flatness.

USING NON-LINEAR MATERIAL

The simulation results with linear material indicated that the extension pole piece can saturate. Then it is necessary to repeat the simulation process with non-linear material tables.

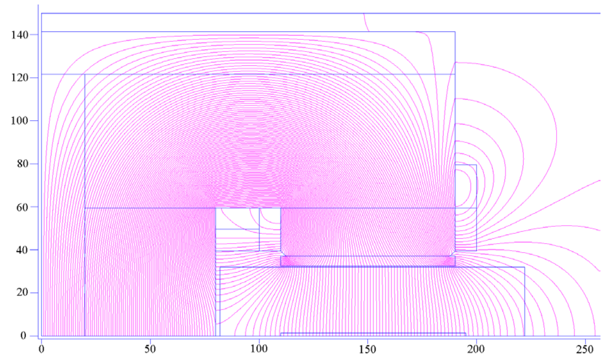

Fig. 11: B-field lines for scenario S3. Dimensions in [cm].

The pole extension thickness was increased to 45 mm to reduce the expected saturation, and the magnet geometry was modified accordingly. The scenarios are described in Table 1 and the results in Table 2. One simulation could require more than 500 s CPU time. For case S3, where both magnet and extension are treated as pure iron, the B-field lines are shown in Fig. 11 and the color graded plot of |B| in [T] is shown in Fig. 12. Dimensions are in [cm].

Table 1: Scenarios with non-linear material

Step	Core offset	Comment
start	0.0 cm	Extension piece as air
S1	2.5 cm	Extension piece air, FineMet core position adjusted
S2	2.5 cm	80 cm t45 extension as 1010 steel
S3	2.5 cm	80 cm t45 extension as Vacofer S1
S5	4.5 cm	fill pole edge, 2 side extension 14 cm Vacofer S1
S9	3 cm	Vacofer S1 left 5 cm, right 13 cm, with outer shield

Table 2: Simulation results with non-linear material

Step	Current [kA]	B_{min} / B_{max} along core	B_{max} in yoke [T]
start	1.393	0.6543	1.636
S1	1.299	0.7015	1.526
S2	1.096	0.7202	2.108
S3	1.096	0.7205	2.132
S5	0.954	0.8213	2.462
S9	1.012	0.7760	2.415

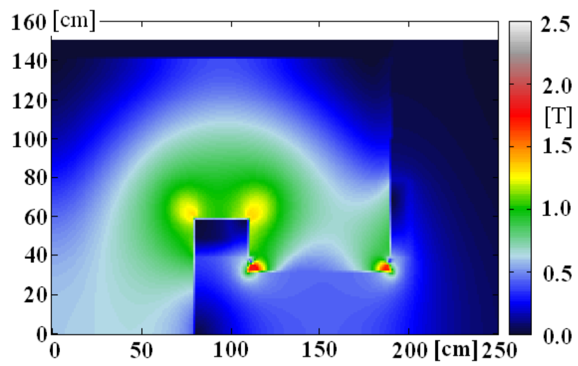

Fig. 12: Color graded absolute B-field [T] for scenario S3.

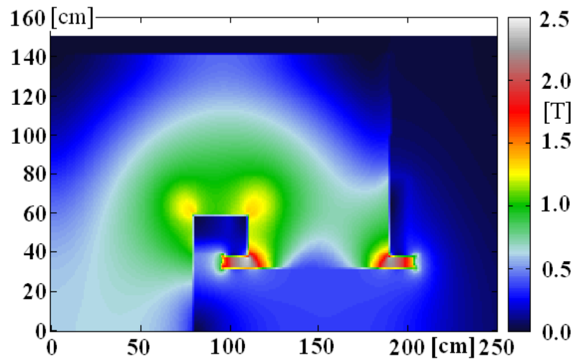

Fig. 13: Color graded absolute B-field [T] for scenario S5.

In case S5 the pole extension is extended from the original 80 cm by 14 cm to the left and right. Outside the pole region is more space, there the extension is 65 mm thick. The color graded plot of the absolute B-field is shown in fig. 13. For safety reasons it was decided that the former outer magnet shield should be included again. In such case, an asymmetric pole extension (5cm left of the pole and 13 cm right to the pole) was the optimum. The color graded plot of the absolute B-field of this scenario (S9) is shown in Fig. 14. The highest field is marked by a red arrow.

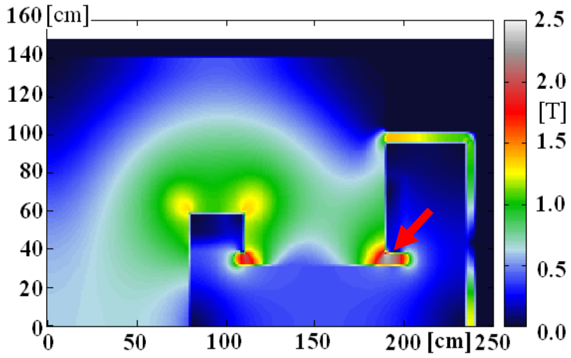

Fig. 14: Color graded absolute B-field [T] for scenario S9.

FINALIZING THE GEOMETRY

The maximum B-field in the geometry, indicated by a red arrow in Fig. 14, was regarded as too high. Additional simulations showed that if for example the pole extension plate thickness could be increased to 12 cm, then the maximum field would be less than 2 T. However there is a limit in manufacturing the iron block dimensions for increasing the yoke height. The yoke extension parts were decided as 4 pieces of 15 cm·60 cm·150 cm. This allowed a compromise for the extension piece thickness of 80 mm at the pole, and adding another 25 mm on the right side outside the pole. On the side of the pole extension facing the oven, C10 corners were cut, and on the other sharp edges, C20 corners. An enlarged view of the field between pole and core is shown in Fig. 15, and |B| is shown in Fig. 16. The magnet current is 992 A, the ratio of B_{min}/B_{max} along the core is 0.79 and the maximum value of the B-field in the extension is 2.38 T. An intermediate installation stage of the magnet is shown in Fig. 17, where the two pole extension pieces are visible.

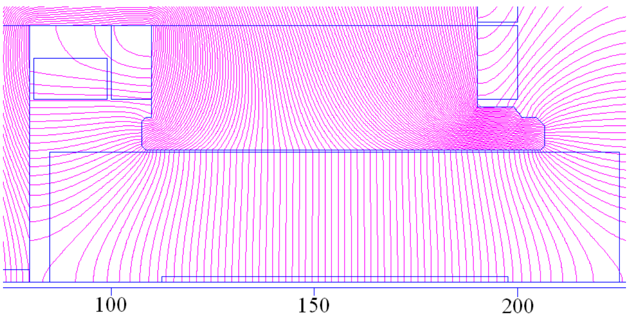

Fig. 15: B-field region between core and upper magnet pole with 80 mm thick extension. The axis unit is [cm].

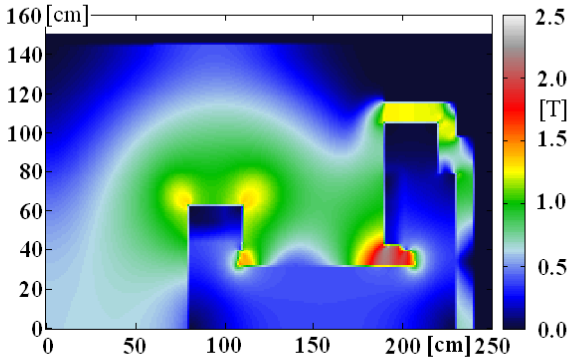

Fig. 16: Color graded absolute B-field of the production version.

Fig. 17: The Kappa magnet with pole extensions during installation in the NU1 building.

SUMMARY AND OUTLOOK

The 2D simulation results show that the required field of 0.3 T can be obtained with a magnet current in the order of 1000 A. The manufacturing process for the parts to modify the "Kappa" magnet yoke was started.

We plan that the modified magnet, currently installed in the NU1 building of J-PARC, will become available this year in summer for high impedance core annealing. Then we can run performance test with these high impedance cores, which are intended to support the J-PARC intensity upgrade in the future [4].

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