IOTA octupoles design

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Contents

The task

The task during the summer student program has been to simulate, to prototype and to measure an octupole that will be installed in IOTA accelerator. I have also worked on the sextupoles for the same accelerator.

IOTA (Integrable Optics Test Accelerator) is an accelerator that is being built at New Muon Lab facility, in Fermilab. This accelerator will be used in many accelerator physics experiments [1].

These will be the study of the motion of single particles and of space charge in nonlinear integrable lattices, study of space charge compensation with both electron lens and self-generated electrons columns. Optical stochastic cooling will also be studied.

The most important magnets in the accelerator will be the nonlinear ones, but many other higher order magnet will be needed for beam focusing and correction.

A total of 18 octupoles will be installed in the ring. They will form a tunnel and will be powered with a current which varies with a distribution depending on the beta function[1] β(s).

The current varies as $I = \frac{1}{\beta(s)^3}$ where $\beta(s) = \beta_0 + \frac{s^2}{\beta_0}$. β_0 is the value in the center of the 180cm-long channel and s is the distance between the center of each octupole and the center of the channel; β_0 is about 65 cm.

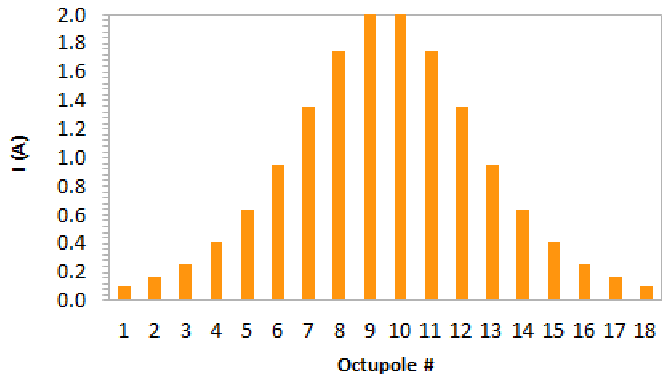

Figure 1 Currents for magnets in the tunnel

[1] The **beta function** in accelerator physics is a function related to the transverse size of the particle beam along the nominal beam trajectory

My task was to finish the development of the magnet, run a simulation of its behavior and to choose the correct materials for the prototype. After this, I assembled one prototype and performed the necessary measurements to ensure the quality of the project.

Yoke length	70 mm
Pipe diameter	177.8 mm
Beam pipe diameter	25 mm
Wire turns per pole	88
Wire current	2 A
Wire used	14 AWG
Magnet weight	8.74 kg
Field intensity at 10 mm	258 G
Magnetic length	77.5 mm
Number of octupoles installed	18
Distance between magnets	100 cm

Table 1 Some of the octupole specifications

The sextupole

IOTA ring will use sextupoles in order to correct beam chromaticity[2]. I have collaborated in the development of these magnets evaluating the maximum field intensity in the steel structure and the field harmonics in the beam pipe area through computer simulations.

[2] Chromaticity is the change of parameters of transverse motion of a single particle due to a change of beam energy.

The design

The development is a multiphase one: it begins with the definition of the field strength and the magnet size, followed by the physical structure's design. I have been involved in the choice of both the structure's alloy and the correct size for the wire needed for the coils. The preferred steel alloy would have been 1010 low carbon which is the one commonly used at Fermilab for magnets of this size. However, due to cost and time savings, 1026 alloy has been used (only for the prototype, the definitive magnets will be in 1010). Therefore, for the production magnets we should only expect very small increases in field strength since the field calculated within the COMSOL simulation is below the saturation values for both 1026 and 1010.

The choice for the wire section area is more important than the steel's one because it both defines the total coil resistance (the power supplies used can supply a maximum of 20V and each of them will power two magnets in series) and the current density in the wire which has to be below 2 A/mm^2 [2] to allow air cooling.

The wire I chose was 14 AWG square copper wire with a HAPT 200 coating, which is rated for use at 200˚C and which was twice as cheap as the 15 AWG[3], which could also have been used. This wire resulted in being more difficult at winding than a rectangular wire of the same section area, since during the winding it inevitably began to turn around itself, thus increasing the coil thickness. However, this fact did not lead to major issues because the coils were only 4 layers thick.

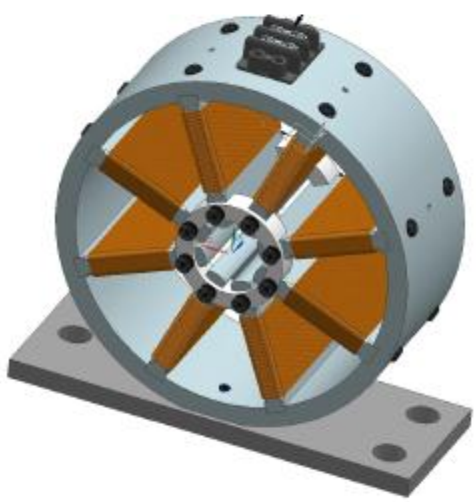

Figure 2 The 3D model of the magnet with its stand

[3] AWG (American Wire Gauge) is a unit of measure where increasing gauge numbers denote decreasing wire diameters (this is due to the fact that for a thinner wire requires more passes in the drawer machine)

The simulation

The magnetic field simulation was performed using COMSOL, a finite element analysis software. The software is able to solve general PDEs through FEM method. It also has many predefined physics studies, among which magnets and electrical coils, included in AC/DC Module, which I used.

The model

I produced the 3D geometry from the initial drawings, added the coils to the model and set the correct properties for the materials. I decided to use linear models for the materials, due to increased computational complexity of nonlinear ones. My choice is justified by the small field values because this fact implies constant relative permeability.

The physical model used is described by the Ampere's Law:

$$\nabla \times \frac{\boldsymbol{B}}{\mu_0 \mu_r} - \sigma \boldsymbol{v} \times \boldsymbol{B} = \boldsymbol{J_e}$$

$$\boldsymbol{B} = \nabla \times \boldsymbol{A}$$

Where **B** is the magnetic flux density, **A** the magnetic vector potential, **v** the velocity (0 in this case), $\mathbf{J_e}$ the current density.

For the multi turn coil, the current density is defined by the following:

$$\boldsymbol{J_e} = \frac{N \boldsymbol{I_{coil}}}{A}$$

Where $\mathbf{I_{coil}}$ is the excitation current for the coil, A the section area and N the number of turns [3].

Boundary conditions for this simulation were no tangential flux component on the boundary, which was a parallelepiped filled with air 220 x 220 x 160 mm wide. The coil were modeled with a built-in COMSOL function, which allows to define wire current, wire size and current direction. Meshing was refined until the quality did not show further improvement. Also the poles' tips were specially refined since their surface plays a very important role in defining the field in the central region.

Simulation results

During the post processing of the result, I was able to carry out some information about the field, evaluating both the magnetic length and the quality of the field.

Magnetic length

Magnetic length, defined as the ratio between the integral of the magnetic field along a longitudinal line and the field on that line at the center of the yoke was measured by applying this definition to the COMSOL results.

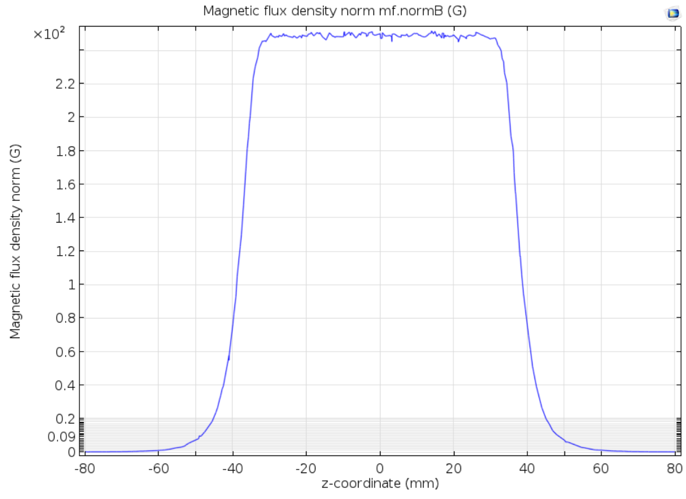

Figure 3 Comsol plot showing B magnitude along z-axis at 10 mm from the center

The field intensity at 10 mm from the center was 258G and magnetic length resulted in being 77.5 mm, 10% more than the yoke length.

Another measurement I carried out on the z-axis was the effect of the near magnets to the field intensity. Due to the distribution of currents, the maximum effect was between the two middle magnets. The flux density norm in the middle of the two (at 50 mm from the centers) results to be 11G, while on the other side it is 7G.

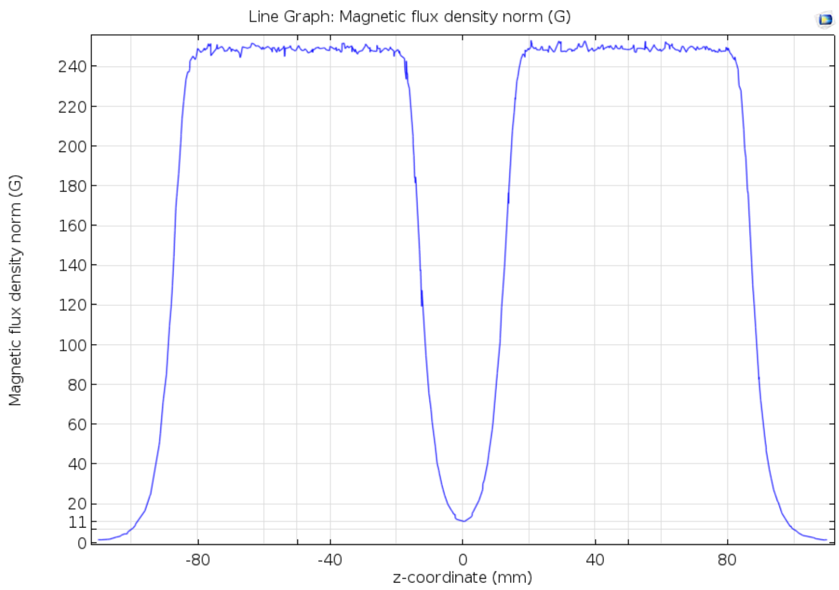

Figure 4 Comsol plot showing B magnitude along z-axis at 10 mm from the center for two magnets both powered at 2A

Field quality

Another measurement was about field quality: the dependence between the radial distance from the center and the field strength is supposed to be cubic, so I evaluated the precision of the interpolation.

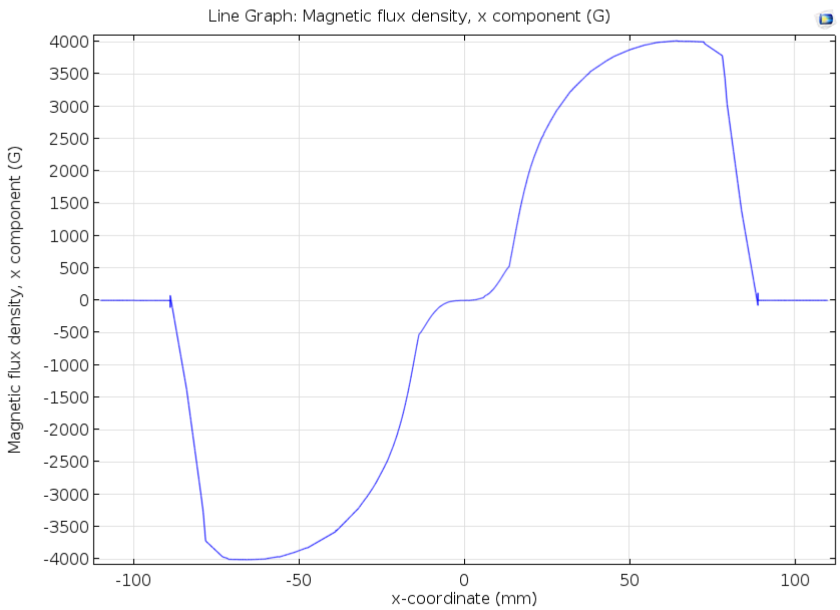

Figure 5 Comsol plot showing flux norm along x axis

The correlation factor between the field strength and its cubic interpolation resulted in being 0.9933. This measurement allows for the observation of the effect of all the harmonics combined together.

The differences with a perfect cubic line are due to the higher order harmonics which could be later measured on the prototype.

Assembling

While finishing the simulation, I got the 14 AWG square cooper wire, the poles and the yoke for the construction. Errors allowed during manufacturing production were 0.5 mm. In order to wind the wire around the poles, I had to adjust the winding machine to my pole's shape by building aluminum frames for both the tip and the back. Also a tensioner was needed for the wire to wind it firmly around the pole. I wound 8 poles with the wire and then screwed all the poles to the yoke, linked the coils together, put the magnet on the measurement bench.

Since the crown needed to align the poles didn't arrive on time, the thermal measurements were taken without it. Later on, semi-finished crowns arrived and I needed to use a feeler gauge to align the poles before screwing them. The magnet was then ready for testing.

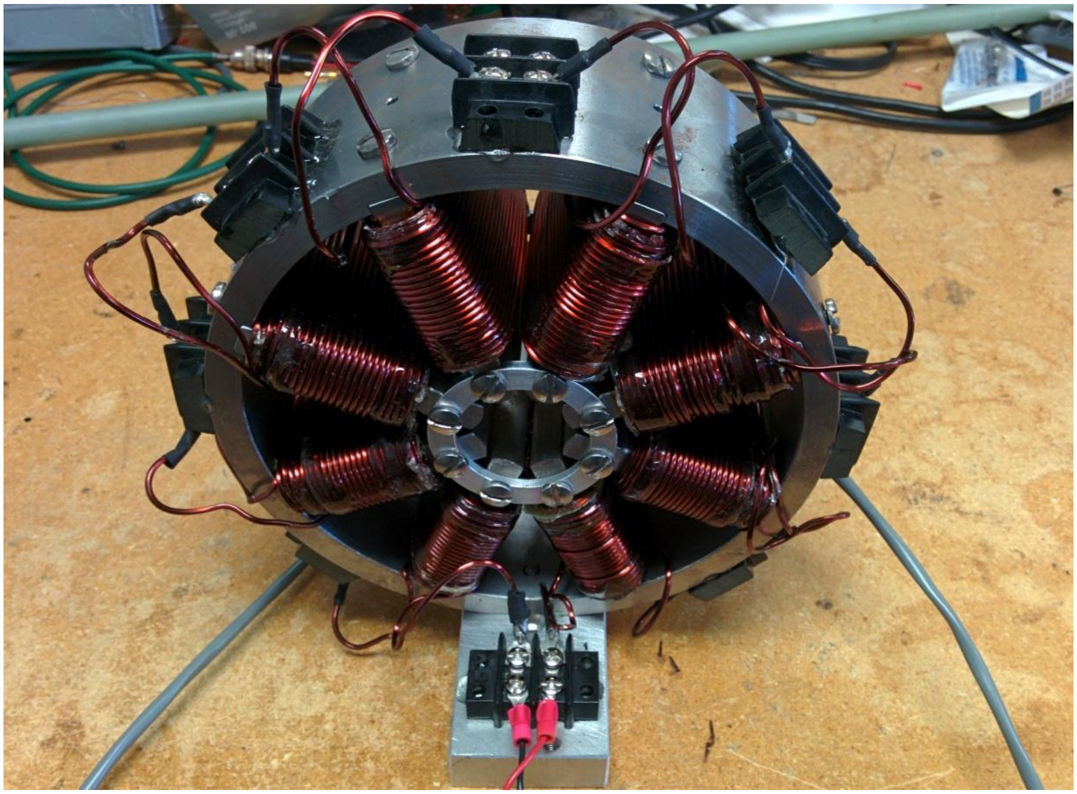

Figure 6 The prototype ready for magnetic measurements

Measurements

Thermal measurements

Once the prototype was assembled it could be tested to find out the working temperature. I did not expect any issue, since the total coil power is below 4W and dissipation was ensured by 6.2 kg of steel. I let the magnet work with a 2A current in the coils, which is the maximum design current for these magnets, all night long. The measurement was performed using a thermal cam the next morning

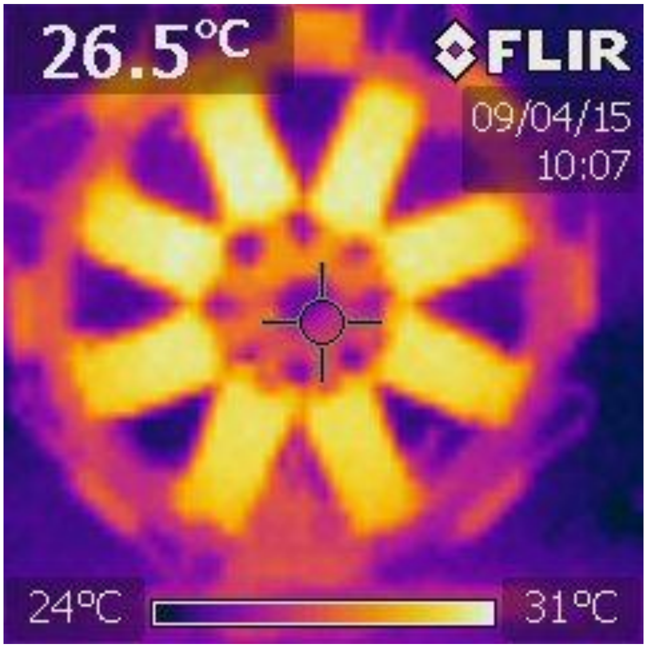

Figure 7 Thermal cam picture @2A

Another way to measure the temperature of the wire is measuring the increase in resistance of the wire used for the coils[4]. Due to the low resistance, 4-wire method has been used. The resistance of the 8 coils was about 900 mΩ at room temperature and the increase was so little that this attempt didn't result in an accurate measurement.

Magnetic field measurements

For magnetic fields, many different types of measurements can be performed. For the octupole we chose to measure the integral field (which is the integral of the field over the z axis at a certain radius). The method we used is called Rotating Coil and consists of a rectangular coil that spins with one side aligned along the axis of the magnet and the voltage induced in the coil is evaluated.

[4] This method is often used in water-cooled copper magnets, where temperatures are higher and coils are thicker. Measuring temperature of water at the exit from the coil implies relevant errors due to heat transfer from water to external environment.

After the measurement takes place, the data need to be analyzed in a process that allows assessing the offset of the magnetic center from the physical one and remove the noise due to the fact that the probe vibrates during operation. Subsequently, the refined input is Fourier-analyzed and harmonics coefficients are given as output.

Harmonics[5]

For the octupole, the main harmonic is the 4th and the allowed ones are: 12, 20, 28…

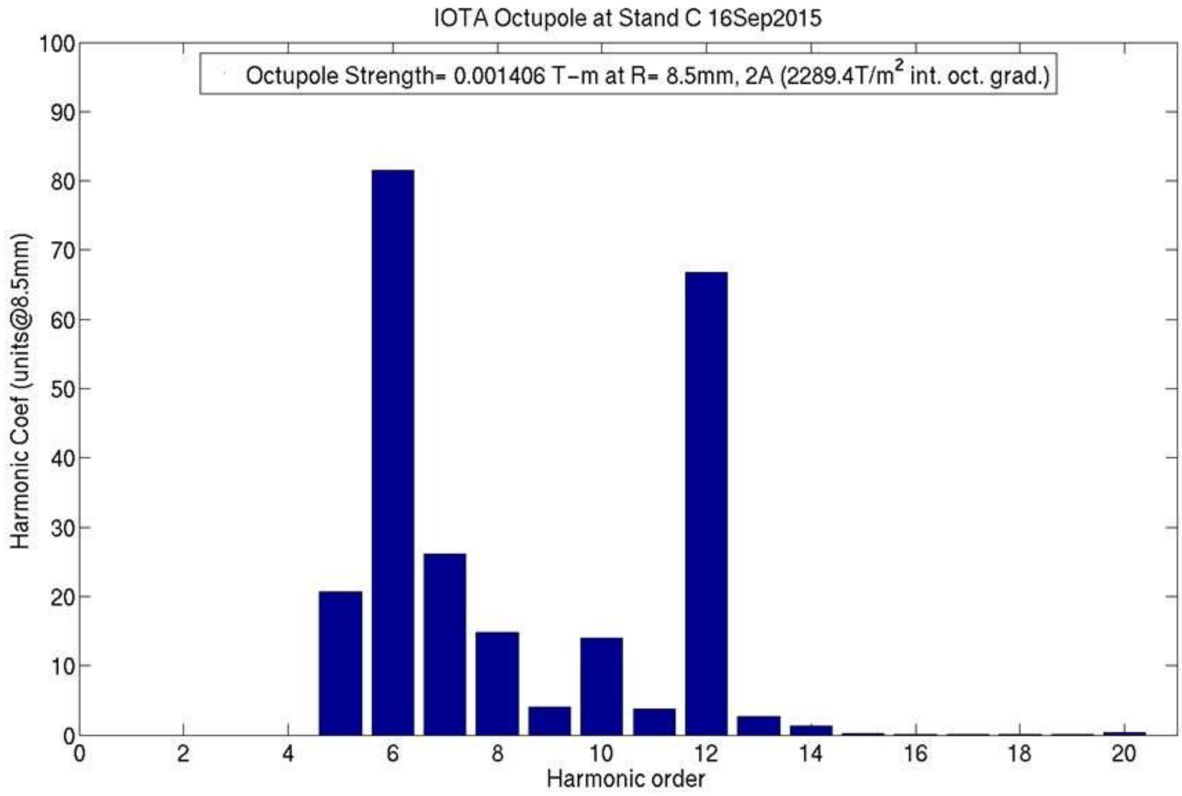

Figure 8 The harmonics of the octupole field at 8.5 mm from the magnetic center

The harmonic coefficients are less than 1% (100 units) for all orders, with the largest terms being n=6 (i.e. 12-pole - first allowed harmonic of quadrupole symmetric magnet) and n=12 (the 24 pole - first allowed term of an octupole magnet). The n=10 and n=20 are also visible as local peaks, being the next allowed harmonics of quad and octupole magnets, respectively.

[5] Harmonics in magnetic fields are the coefficients of the polynomial expansion so that the n-th harmonics is coefficient of the (n-1)th term

The sextupole simulation

As a secondary task for my internship, I worked on 3d-modeling and simulating IOTA sextupoles. This magnet differs from the octupoles in having much stronger fields (due to the 1000 A coil current[6]) and we needed to be sure the iron wouldn't saturate.

Iron saturation

For estimating the magnetic field values I used COMSOL, with a very similar model to the octupole's one. This time, however, I chose to use the nonlinear model provided by COMSOL for 1010 steel. It proved to be necessary due to the higher field intensity. Magnetic permeability was therefore set to values derived from the B-H curve. This curve relates the magnetic flux density B to the magnetic field intensity H. This curve is not a straight line for strong fields: actually this brings to saturation of the maximum flux density achievable.

In the sextupole, the field in the iron reaches 7 kG, which is below the maximum values measured in some already functioning sextupoles.

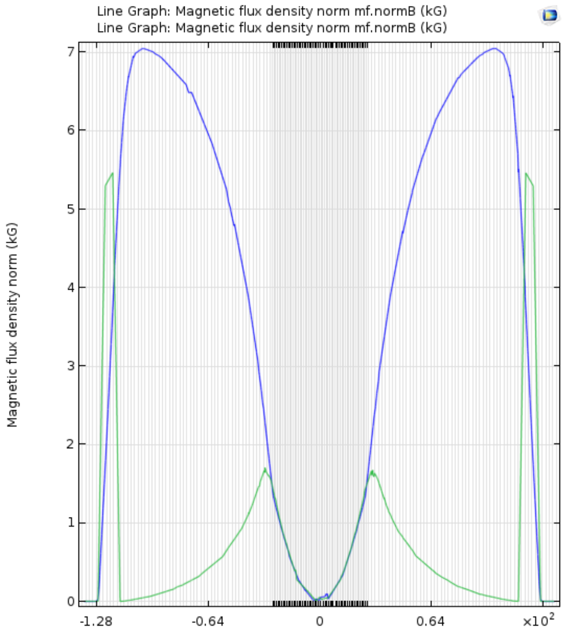

Figure 9 COMSOL plot showing the flux norm along the pole axis (blue line) and a perpendicular axis (green line)

[6] Coil current is defined as the wire current times coil turns.

Field quality

Opera3d is a Finite Element Analysis software developed specifically for magnetic applications. Therefore, it has built-in functions that allow harmonics analysis and field accuracy evaluation. After the model preparation, the conductors were set as racetracks and the simulation took place.

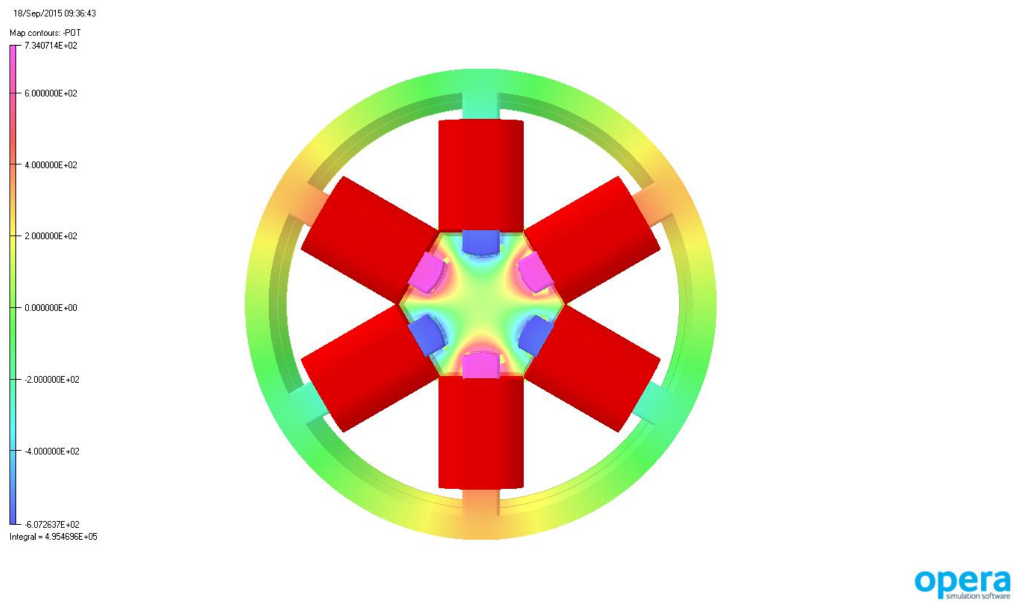

Figure 10 OPERA model showing magnetic potential

Evaluating potential harmonics was straightforward thanks to an Opera built-in function which allows to evaluate the Fourier expansion of the magnetic potential along a circle. As can be seen from Table 2, the most relevant harmonic is the 3, as expected from a sextupole magnet.

Order	Sine term (An)	Cosine term (Bn)	Amplitude	Phase
1	0.067001022	-1.69E-14	0.067001022	-90
2	3.20E-14	0.078150838	0.078150838	-2.35E-11
3	-207.0059495	5.87E-15	207.0059495	90
4	-4.58E-14	0.130259172	0.130259172	2.02E-11
5	-0.013707102	2.41E-14	0.013707102	90
6	-1.96E-14	0.103590441	0.103590441	1.09E-11
7	0.043242222	-5.47E-15	0.043242222	-90
8	-1.57E-14	0.163678842	0.163678842	5.50E-12
9	-0.509806674	7.18E-14	0.509806674	90

Table 2 Coefficients of Fourier expansion for magnetic potential

In order to show the areas where differences between the simulated potential values and the theoretical ones were higher, I processed data with Excel.

In a normal[7] sextupole the potential is described (in a Cartesian coordinate system centered in the magnet center) by the expression:

$$\Phi = K(3yx^2 - y^3)$$

Where K is a normalization coefficient. [4] For my evaluation, I normalized the field so that the average of the values on the border could match.

I exported the potential values from Opera results to Excel and then plotted them together with the absolute value of the difference of the two.

As can be easily seen from the last plot, the difference is below 1 G almost everywhere.

[7] A normal sextupole is one that has two poles aligned along y axis, a skew one has two poles aligned along x.

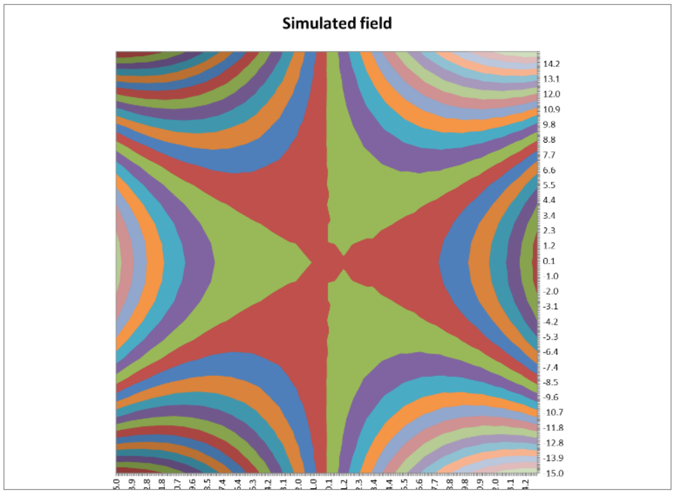

Figure 11 Data reconstructed from Opera

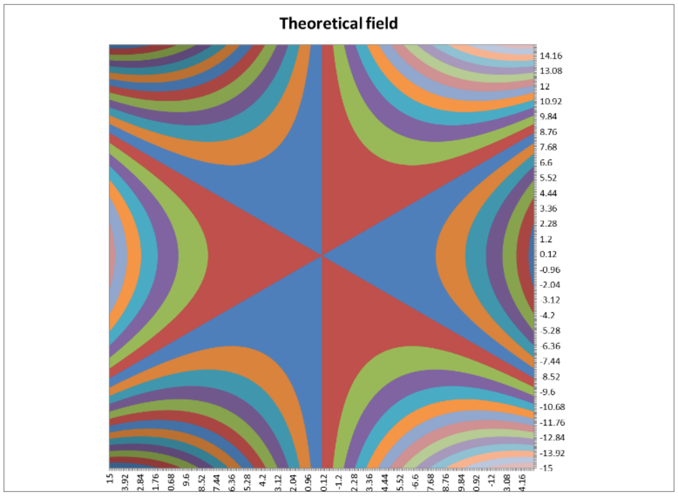

Figure 12 Theoretical trend

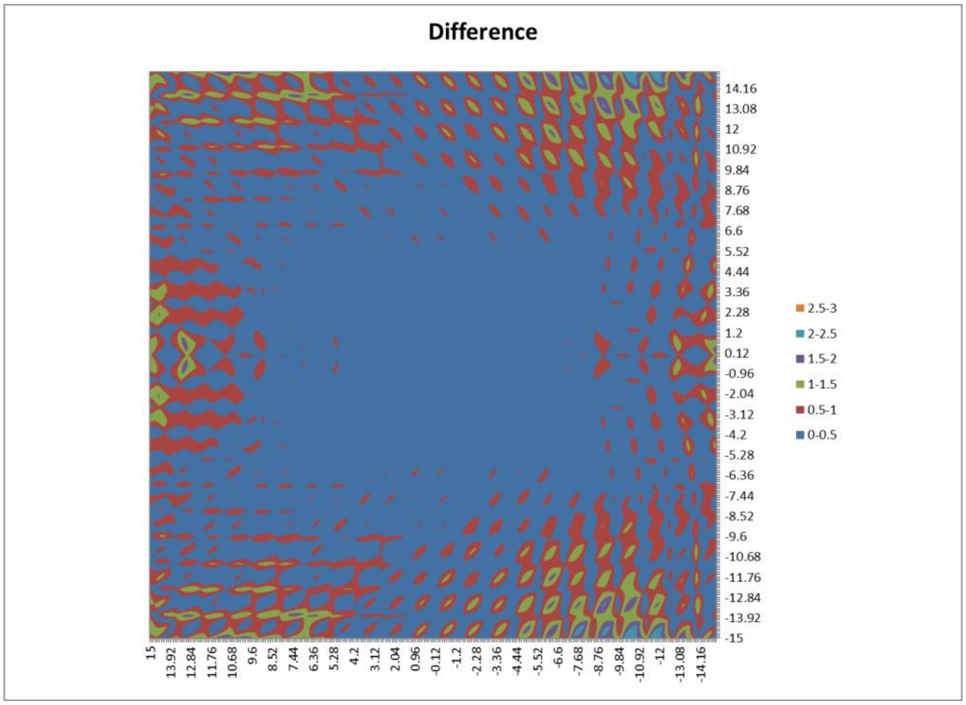

Figure 13 Absolute value of the difference betwewn theorical and simulated trends. Difference is below 1 G almost everywhere

Conclusions and future work

In this paper I have described the different development phases of the magnet from the concept stage to the realization of a completely working, “ready to use” accelerator part.

Further development is needed to install the tunnel in the ring: all eighteen magnets will have to be produced and measured to know their exact properties. Final alignment will be a critical phase in order to define the working quality.

First beams will begin to circulate in IOTA ring in 2017.

Bibliography

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[5] Field Precision LLC, "Properties of soft magnetic materials," [Online]. Available: http://www.fieldp.com/magneticproperties.html. [Accessed 12 August 2015].