Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

IOTA octupoles

Supervisors: A. Valishev, K. Carlson
Collaborators: S. Antipov, W. Johnson, J. Di Marco, A. Romanov

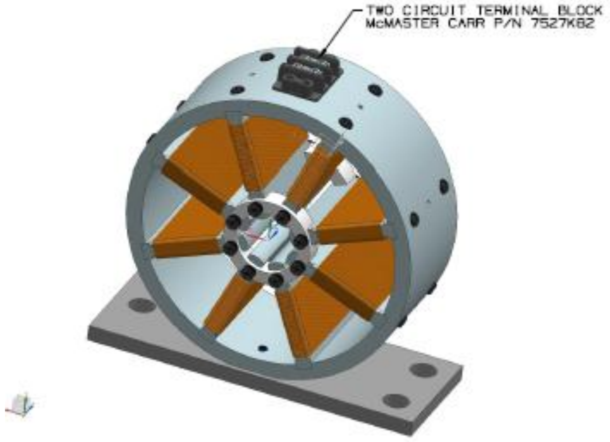
Riccardo Castellotti
Final relation
9/23/2015

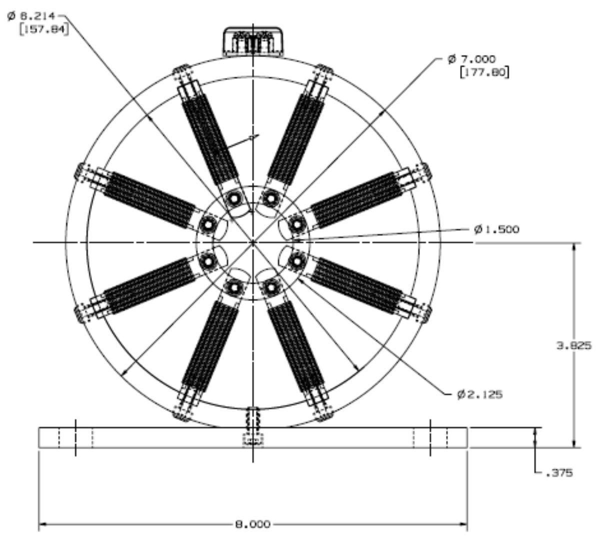
What is IOTA?

- IOTA stands for Integrable Optics Test Accelerator and is being built at New Muon Lab at Fermilab.
- The planned experiments for this accelerator are:
  - study the stability of single particle motion in nonlinear integrable lattices,
  - Test nonlinear integrable optics with space charge
  - Study space charge compensation with:
    - Electron lens
    - Self-generated electrons columns
  - Proof-of-principle studies on optical stochastic cooling

My task

- My task consists in the development of the octupoles magnets to be installed in IOTA, including computer simulation and prototype tests.





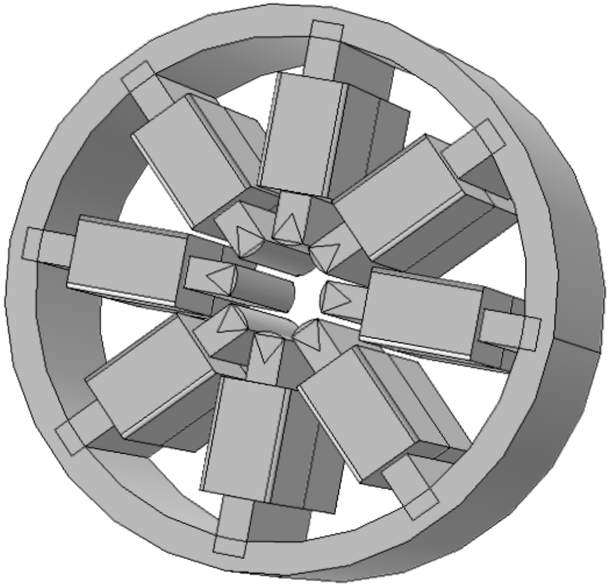
- I chose the wire needed for achieving the expected current density, weight and volume values. 14 AWG square copper wire has been used.

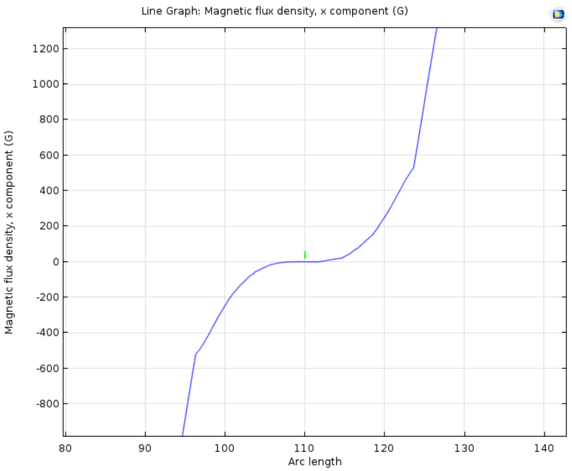
- For the prototype, the magnetic field is so low that a non-magnetic steel can be used with advantages in both time and costs. The chosen steel alloy for prototyping is 1026, while the final magnets will be produced in 1010 low carbon alloy.

COMSOL simulation

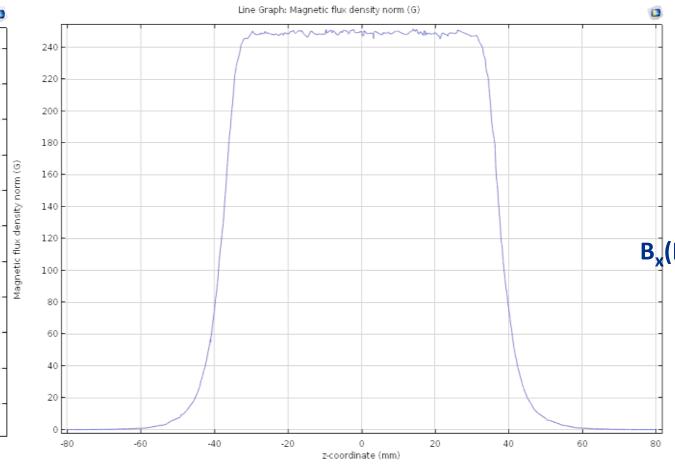
I have been given the drawings of the magnet and had to simulate the magnetic field.

The purpose of the simulation was calculating the field quality and the magnetic length of the octupole.

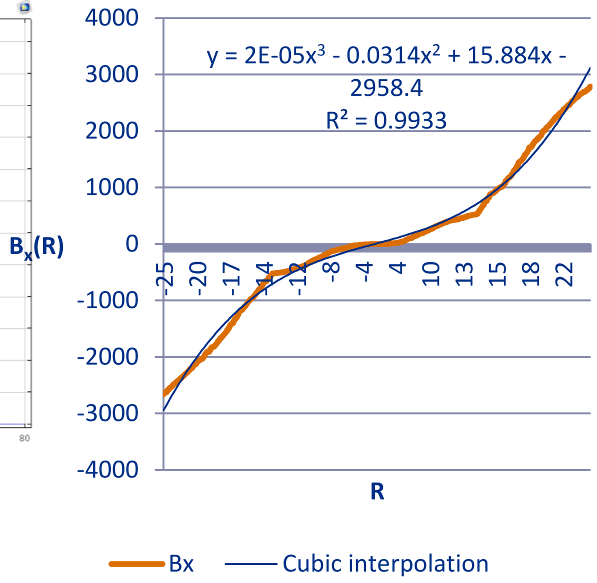




Plot used for field quality evaluation



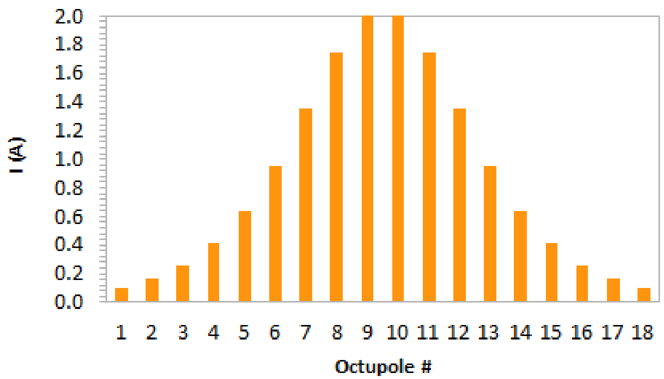
Plot used for magnetic length evaluation



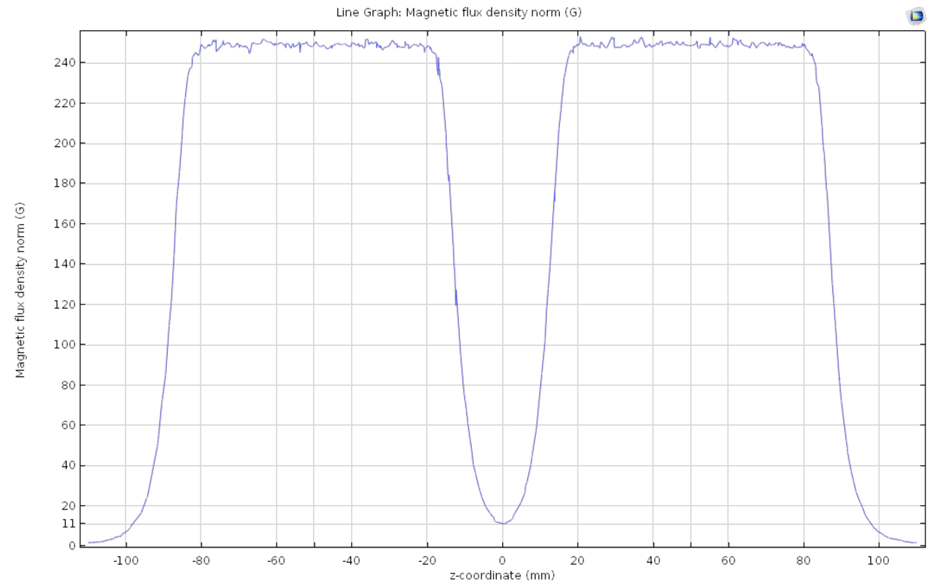
COMSOL exports and MS Excel chart used for calculations.

The yoke length is 70 mm and the magnetic length 77.5 mm.

The field in the octupole should vary on a cubic dependence from the radial distance. For this octupole, the cubic interpolation has a correlation factor of 0.9933, as shown in the chart.



Octupoles' current



Plot showing magnetic field in case of two magnets 100 mm far from each other

IOTA ring will use a tunnel made up of 18 octupoles , running at different currents and thus generating different fields' magnitudes. I estimated the effect of the two central magnet's (where the effect is stronger) fields on each other. The field at 50mm from the center is 7G considering just one and 11G considering the superposition of the effects.

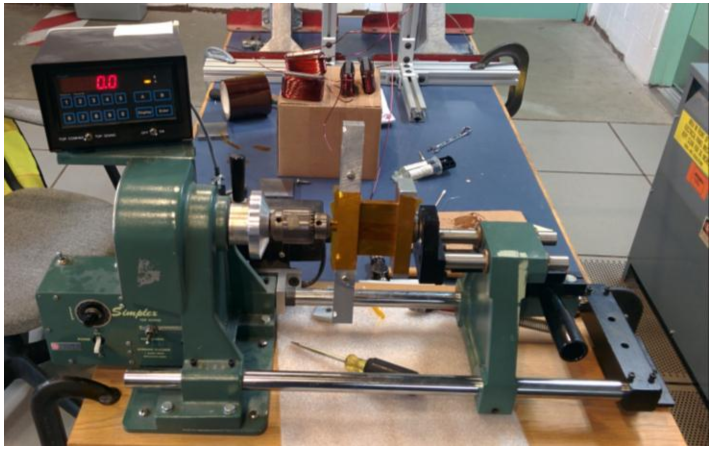
Assemblying the prototype

Yoke and poles machining has been outsourced.

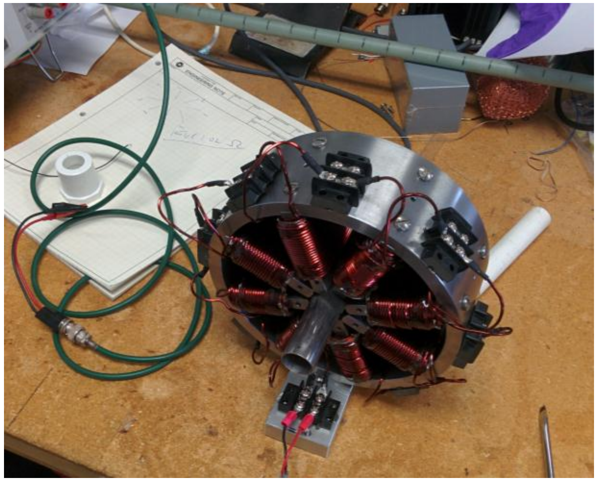
I have wound the wire with a winding machine for all the poles, then screwed them in the yoke.

I soldered the coil wires together and glued circuit terminal blocks to the yoke.

Poles alignment was ensured by an aluminum crown: I screwed all the poles to it after aligning using feeler gauge.



The winding setup

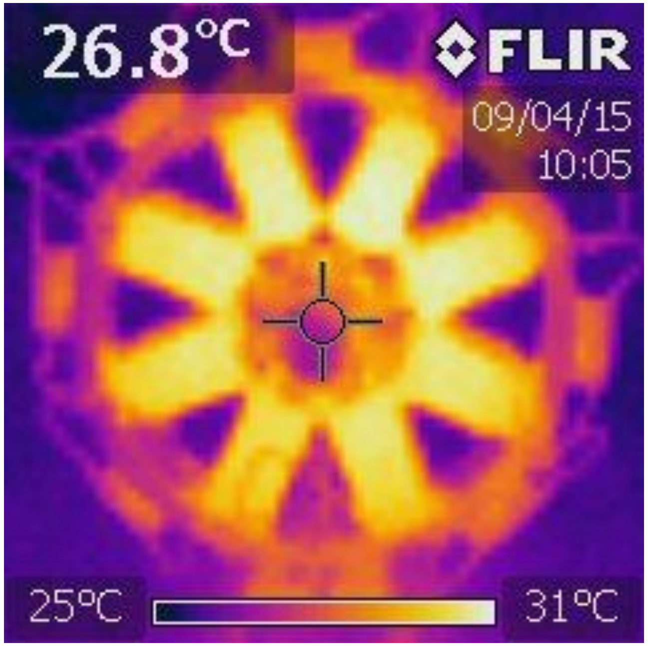


The almost-finsihed prototype on the bench for thermal tests.

Thermal measurement

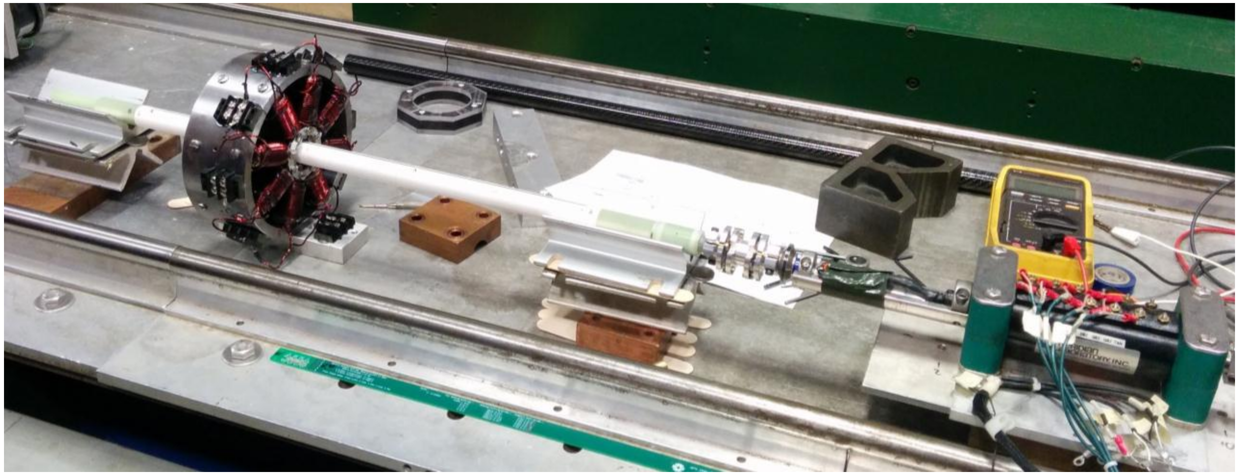
The octupole was installed on a bench and let reach thermal equilibrium overnight. Then temperature was measured with the thermal cam. As shown in the picture, temperature reaches nowhere temperatures higher than 31 ˚C.

Measuring temperature indirectly by increase in resistance led to inaccurate results due to very low increase in temperature.



Thermal cam photo

Magnetic field measurement



The rotating wire strumentation: the rotating coil is inside the white probe. On the right is the rotating engine and the links to the PLC and the recording computer. Close to the octupole is the permanent quadrupole used for calibration.

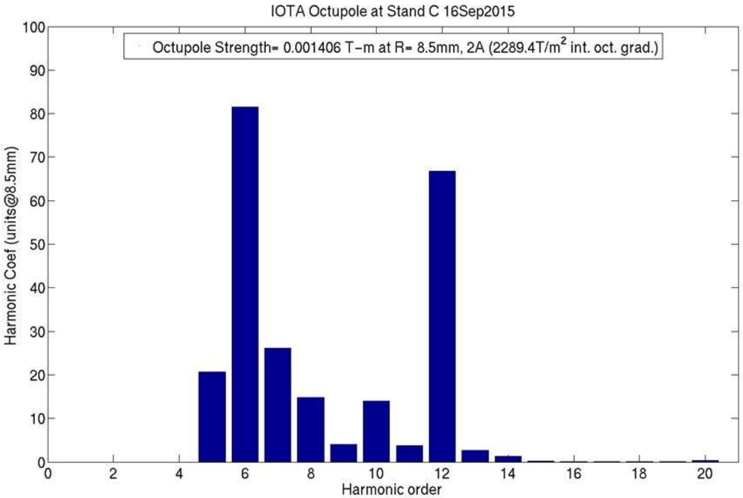
Thermal measurements could be easily performed using a thermal cam or an ohmmeter, but magnetic fields need much more instrumentation and processing.

The magnet had to be measured at Magnet Test Facility.

Harmonics

The harmonics analysis showed that all the harmonics are below 1% (100 units = 1%) of the total field.

The most relevant harmonics are the 6^{th} (12pole, the first allowed of the quadrupole) and the 12^{th} (24pole, the first allowed for the octupole).

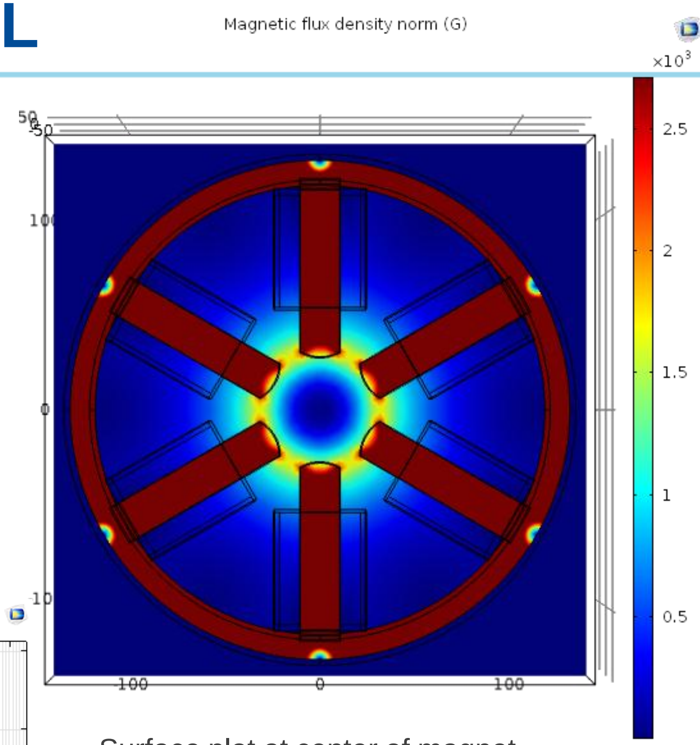


Measurement results showing harmonics

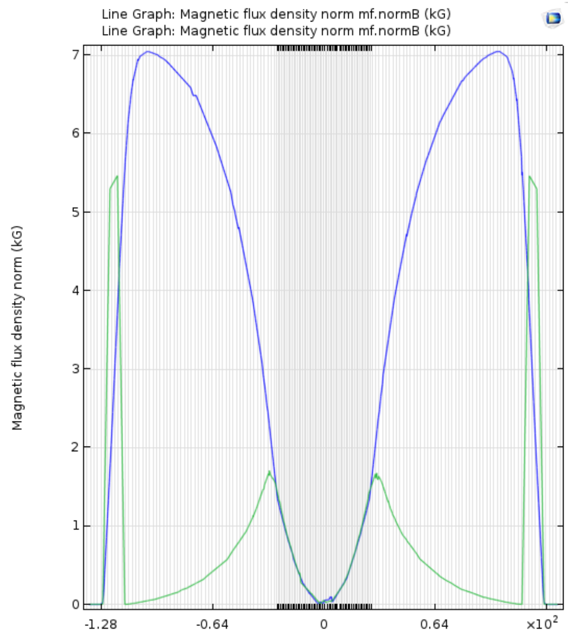
The sextupole simulation _ COMSOL

For the sextupole, the main interest was in knowing whether 1010 steel would saturate or not.

The maximum B value is about 7 kG, which is acceptable for this type of steel.

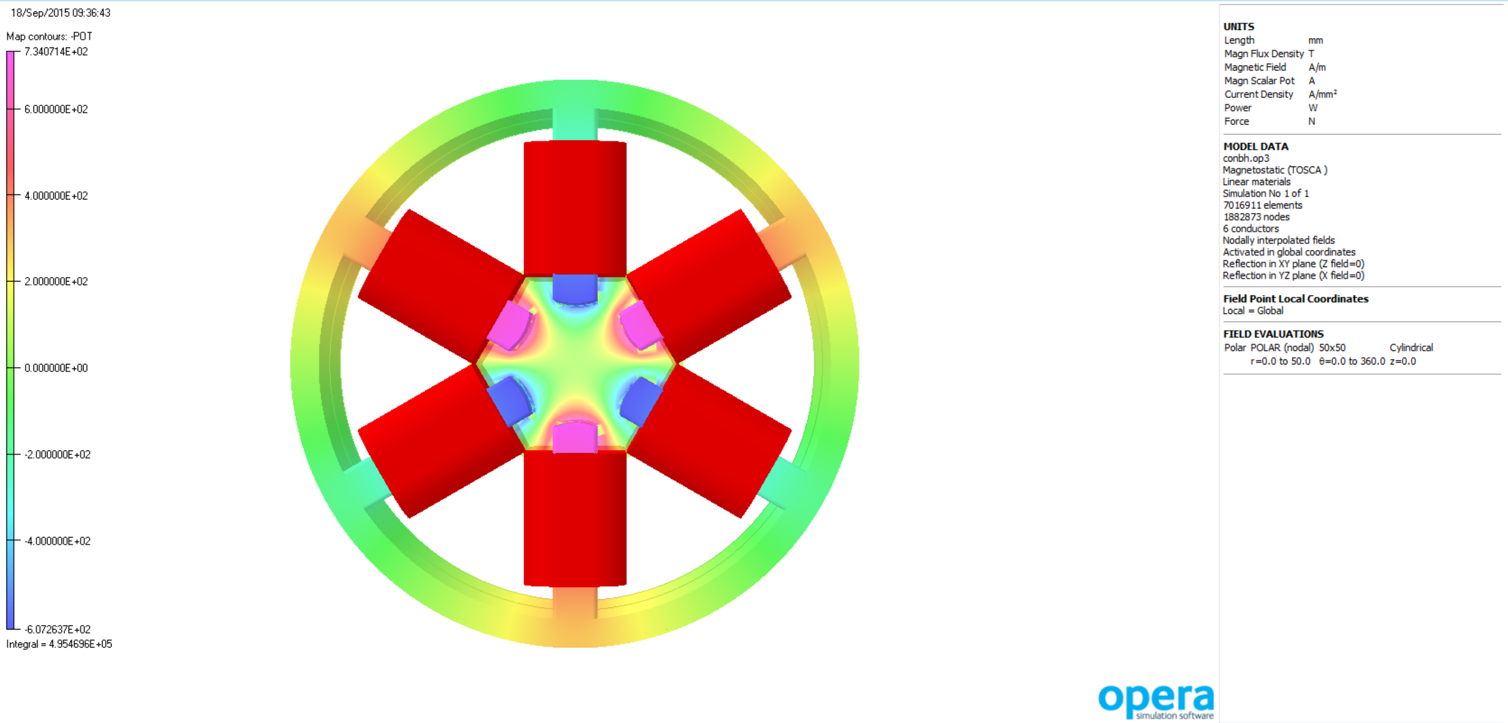


Surface plot at center of magnet (COMSOL)



Magnetic flux density on pole axis (blue) and axis between poles (green)

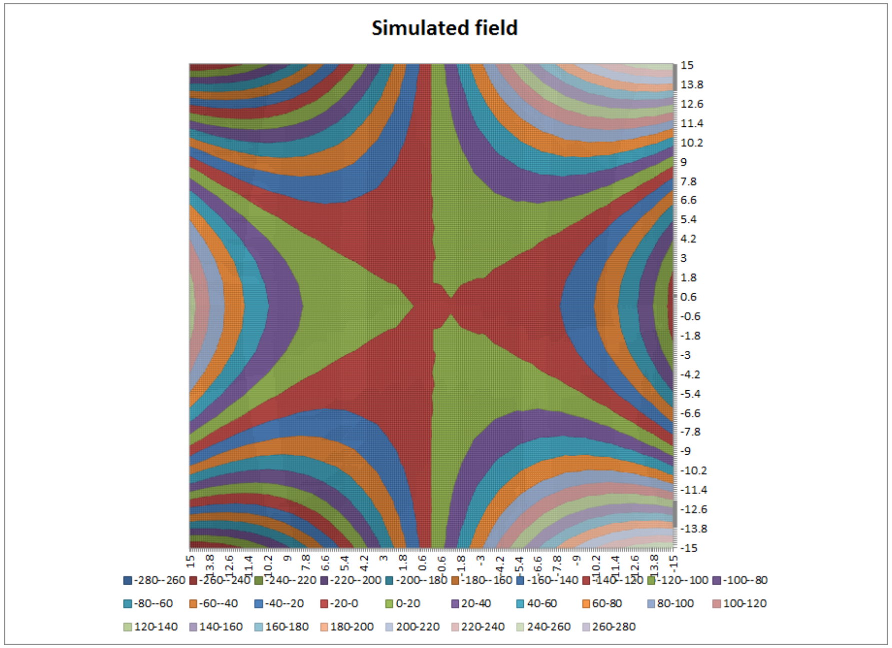
The sextupole simulation _ OPERA-3D

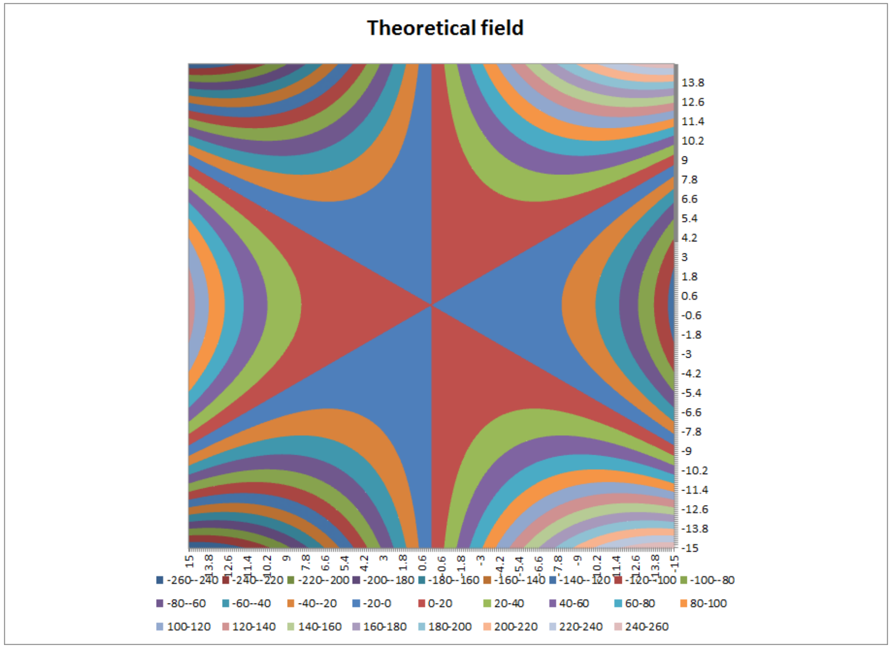


Potential in sextupole OPERA

- A model was built and simulated with Opera-3d, a FEA software specifically designed for electromagnetism.
- Field in the center was evaluated for harmonics and for geometrical discrepancies from theoretical model.

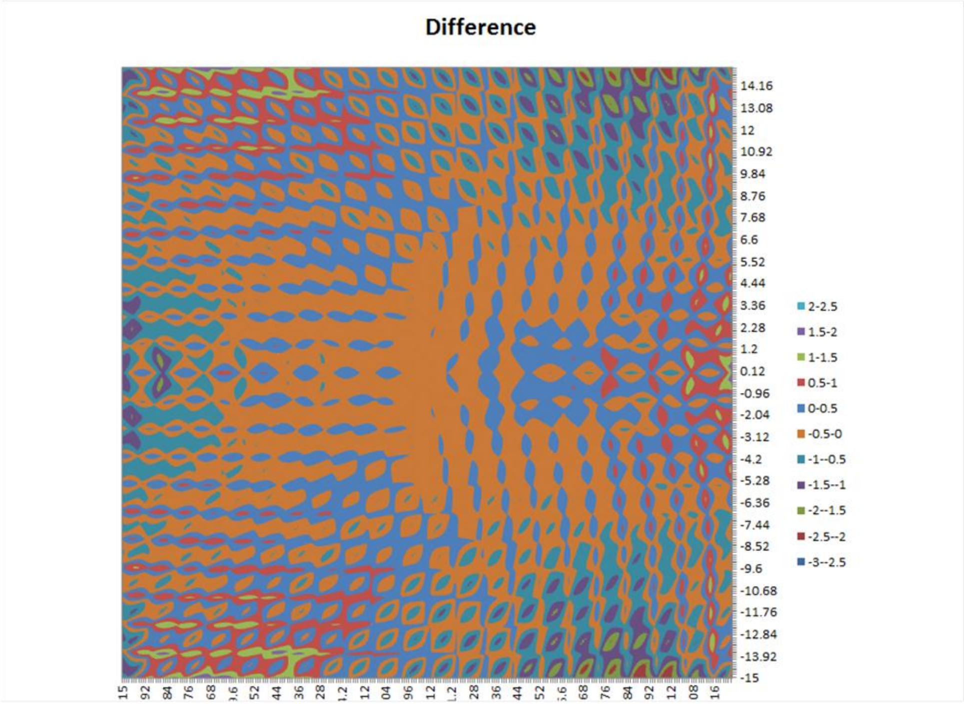
Fermilab





Plot exported from Opera and elaborated with MS Excel

Plot of $\Phi=K(3yx^2-y^3)$, theoretical potential in perfect sextupole magnet



Difference between theoretical and simulated potential due to higher harmonics.

Order	Sine term	Cosine term	Amplitude	Phase
n	A_n	B_n		
1	0.067303376	2.86E-14	0.067303376	-90
2	1.54E-14	0.078339839	0.078339839	-1.13E-11
3	**-207.005911**	**5.61E-14**	**207.0059105**	**90**
4	-3.16E-14	0.130630841	0.130630841	1.39E-11
5	-0.01431437	3.66E-14	0.014314375	90
6	-2.39E-14	0.103558898	0.103558898	1.32E-11
7	0.04385499	-1.39E-14	0.04385499	-90
8	-2.14E-15	0.163737987	0.163737987	7.48E-13
9	-0.51001517	6.86E-15	0.510015174	90
10	-1.75E-15	0.044817399	0.044817399	2.24E-12
11	-0.03092109	-2.08E-14	0.03092109	90
12	-2.89E-15	0.077767123	0.077767123	2.13E-12
13	-0.01470777	-5.17E-15	0.014707773	90
14	-2.79E-14	0.132423179	0.132423179	1.21E-11
15	0.073368084	4.33E-14	0.073368084	-90
16	-1.30E-14	0.10998031	0.10998031	6.76E-12
17	0.030763396	2.12E-14	0.030763396	-90
18	1.02E-14	0.072507086	0.072507086	-8.05E-12
19	-0.01699336	1.53E-14	0.01699336	90

Harmonics of potential at 18 mm from the center (the 3rd one is the most relevant)

Thank you for the attention!

Questions?