ESS Engineering
- Magnets -

Zvonko Lazic
Mech. Engineer

www.europeanspallationsource.se
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Presenter

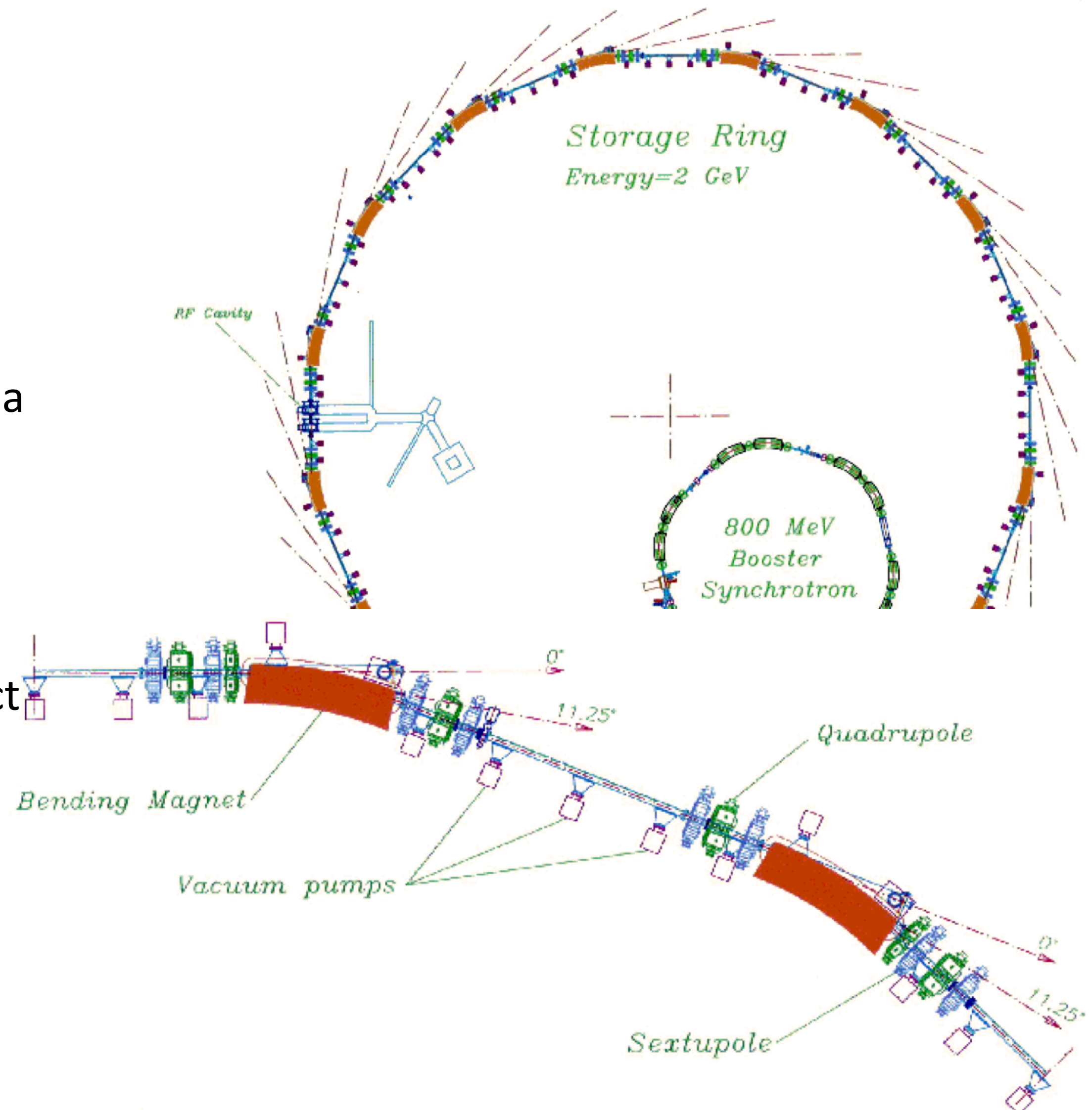
- Zvonko Lazic
- At ESS, section leader for mechanical design engineering – Design division.
- Background – Special purpose automation; magnetics.
- Magnetic FEA using Vector field.
  Permanent magnet modeling for ECPMDC rotating machines.
  Normal conducting magnets for ion implant lines and synchrotron labs.
  High temperature superconducting magnets for industry and physics labs.
- Engineering background helps designing magnetics that can be produced.

Overview

- Magnets as part of an accelerator; types and what do they do.
- Magnetic design in accelerator environment.
  - fundamentals
- Electrical design (of magnets).
- Mechanical design (of magnets).
- Manufacturability and errors/tolerances.
- Verification and measurement of magnets (for accelerators).

Accelerator magnets

- There are a few accelerator types. Consider a storage ring.
- Storage ring (synchrotron) accepts particles (from a linac or a booster ring), keeps them stored and recirculate in order to produce a synchrotron light.
- Particles are 'stored' by utilising magnetic field (they are contained in a magnetic field).
- For this to work, several types of (electro)magnets are required.
- Something to make the beam bend into a circle, something to keep the beam contained, something to extract the beam, something to use in a sample environment, etc…



Accelerator magnets

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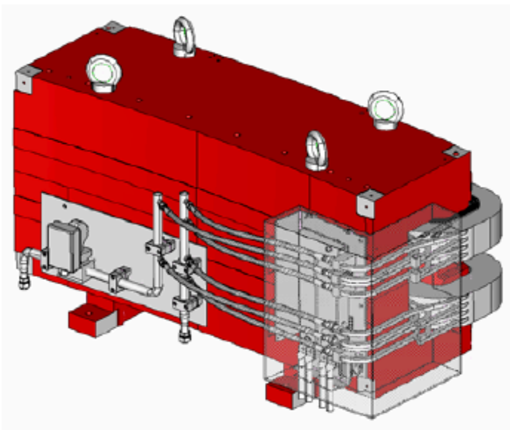
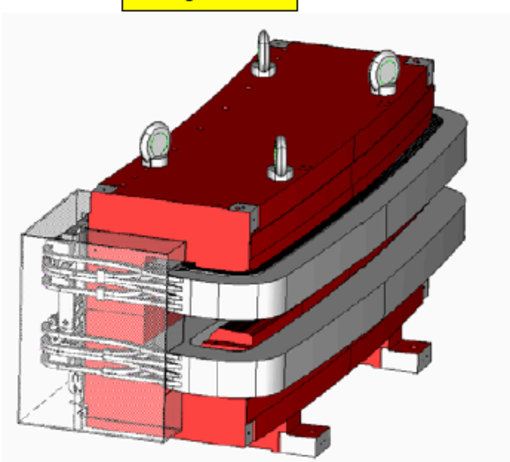
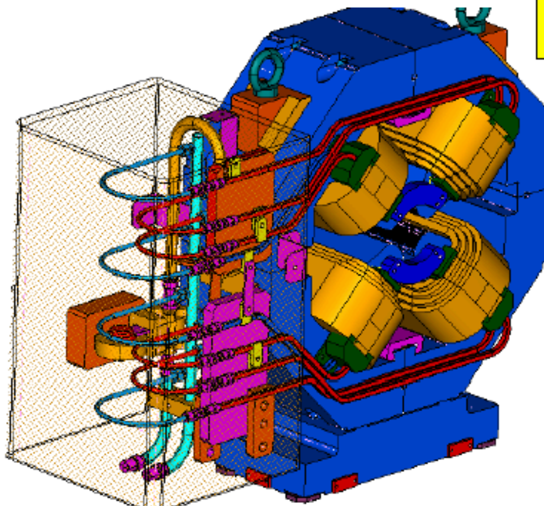
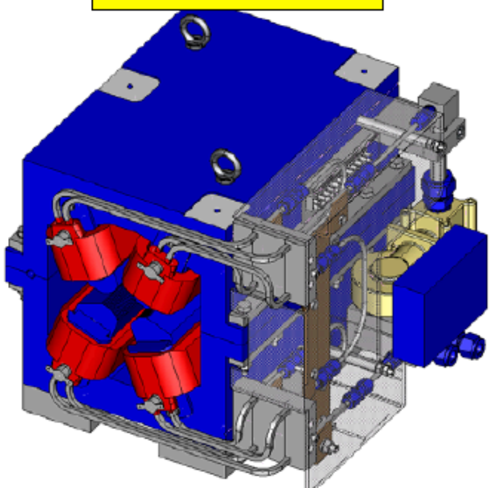


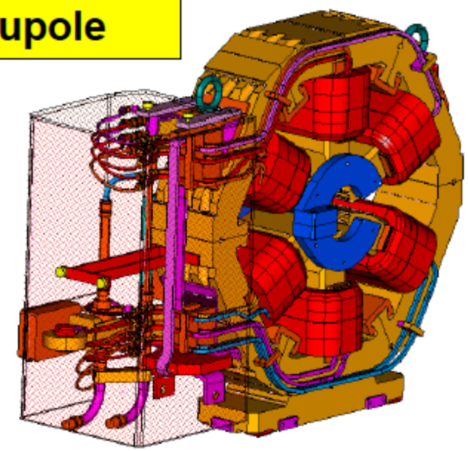


Dipole

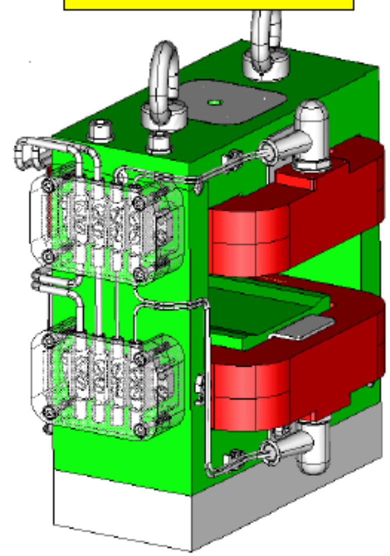




Quadrupole



Sextupole



Corrector

Credit: D. Einfeld & M. Pont_CELLS/ALBA

Main components of a Magnet system

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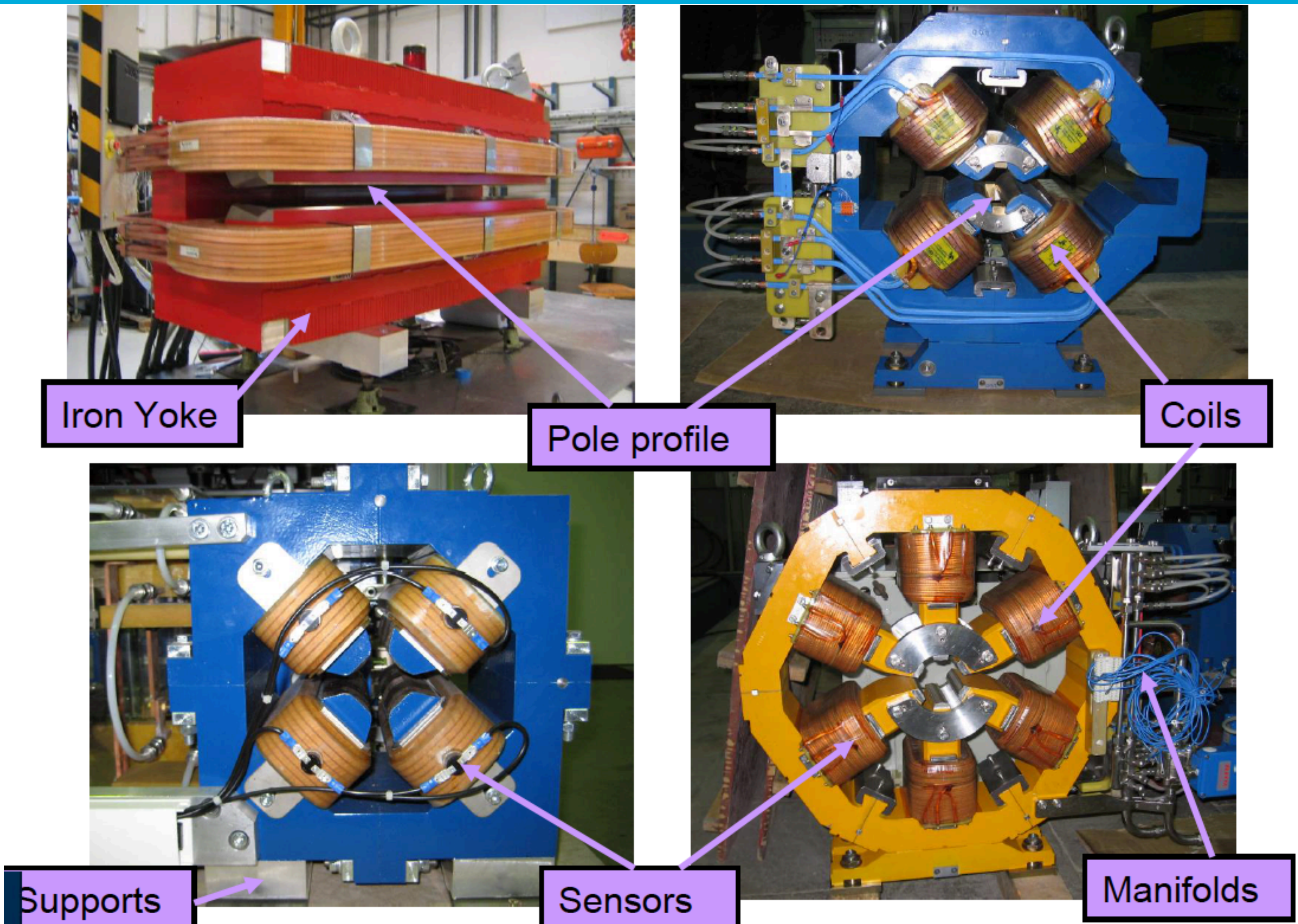

Credit: D. Einfeld & M. Pont_CELLS/ALBA

Generic sequence of a magnet production

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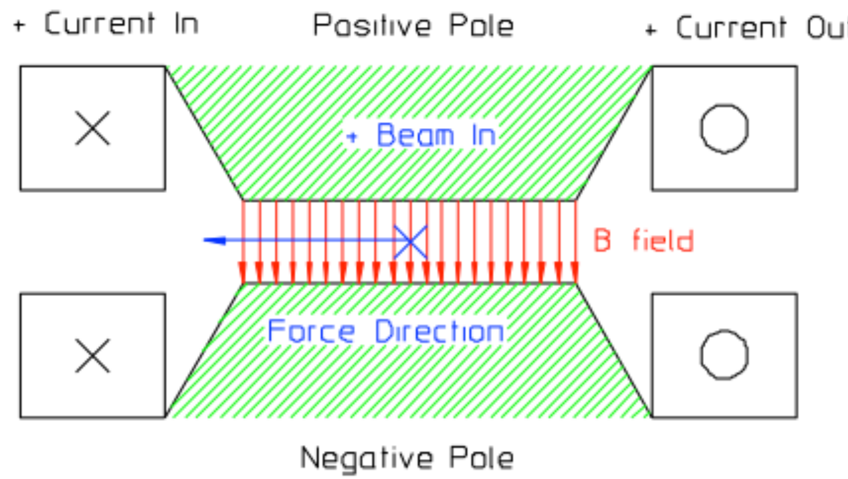
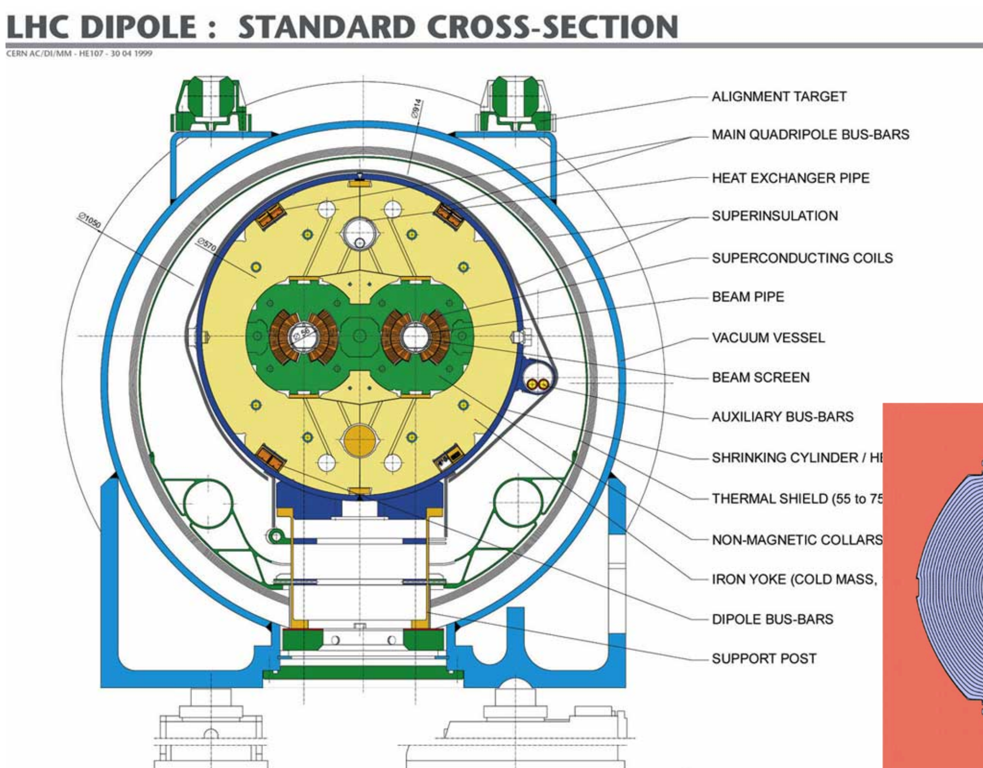
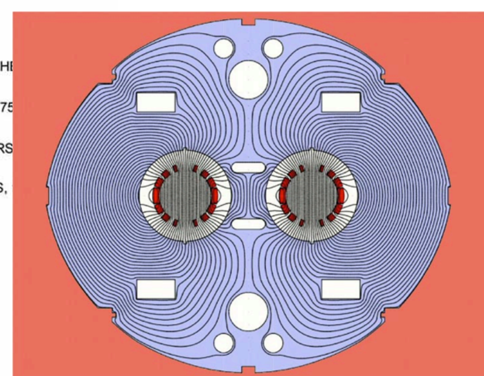
1) Magnet requirements (magentic specs – field, magnetic length, good field quality and specifications, etc;
2) Basic/initial (magnetic) design is usually presented by the magnet group, or beam Dynamics group;
3) The steps 1. and 2. have to be made in accordance with space requirements, vacuum, diagnostics, facility preference regarding power supplies and water cooling;
4) Publish tender
5) Manufacturer selected, contracts signed;
6) Detailed design done by manufacturer;
7) Acceptance of the detailed design;
8) Production of manufacturing drawings (detailing);
9) Production of any tooling;
10) Materials procurement (steel, copper,…);
11) Acceptance of material tests (laminations, copper);
12) Production of prototype (or pre-series);
13) Magnetic measurement of prototypes;
14) Determination of end chamfer;
15) Serial production (production of full quantity of magnets);
16) Mechanical testing of the yokes;
17) Magnetic and electrical tests of the coils;
18) Magnetic measurement of the magnet;
19) Acceptance…

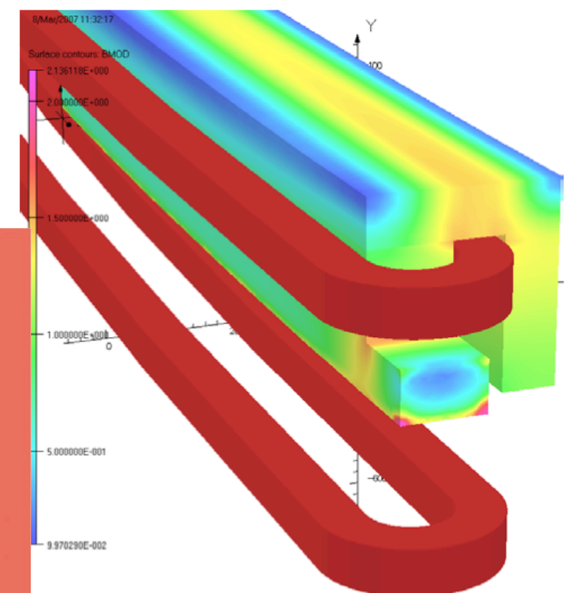
Dipoles

- Dipoles serve to steer the beam, to ‘bend it’ and ensure circular trajectory of the particle bunch.
- Synchrotron dipoles can have different configurations; main layouts, an H, a C, gradient dipoles, etc.



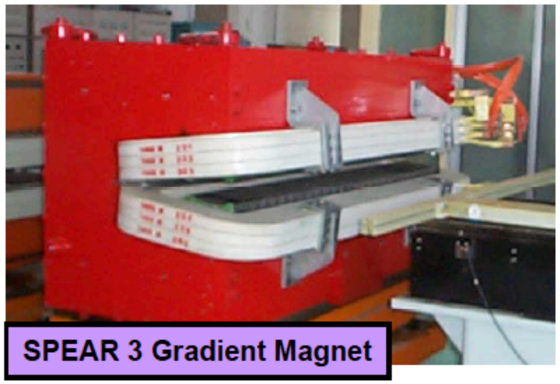


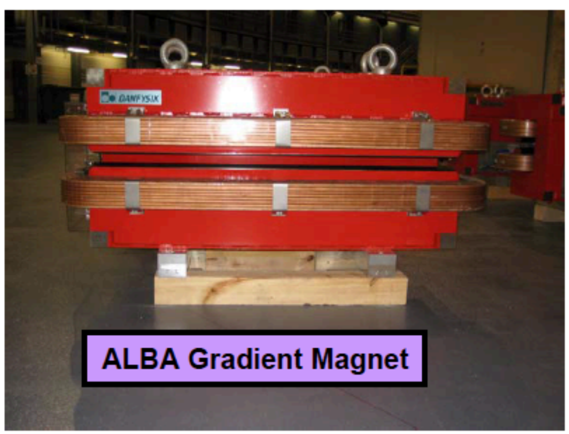




Dipoles

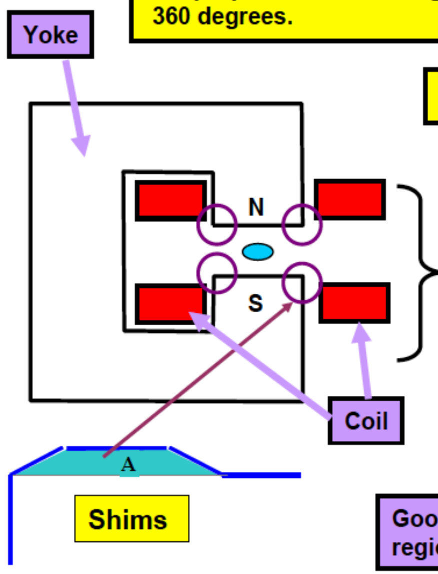
- We use mks system of units on the vector equation;
- The right hand rule is used for vector directions.





Credit: D. Einfeld & M. Pont_CELLS/ALBA
J. Tanabe _ “Magnet design”

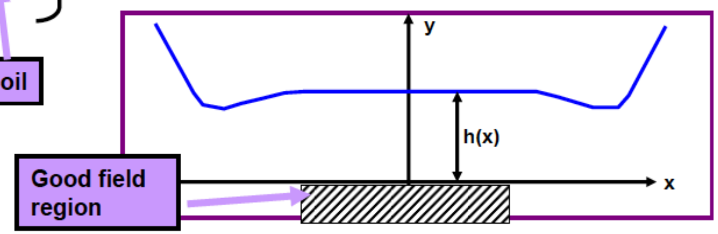
The dipole magnet has two poles, a constant field and steers a particle beam. The purpose of all bending magnets in a ring is to bend the beam by exactly 360 degrees.



The gap (g = 2*h) in a normal bending magnet is constant:

$$h(x) = const. = gap/2$$

To the ends of the pole there are shims introduced to optimize the “good field region area”



$$\vec{F} = e\vec{B} \times \vec{v}$$

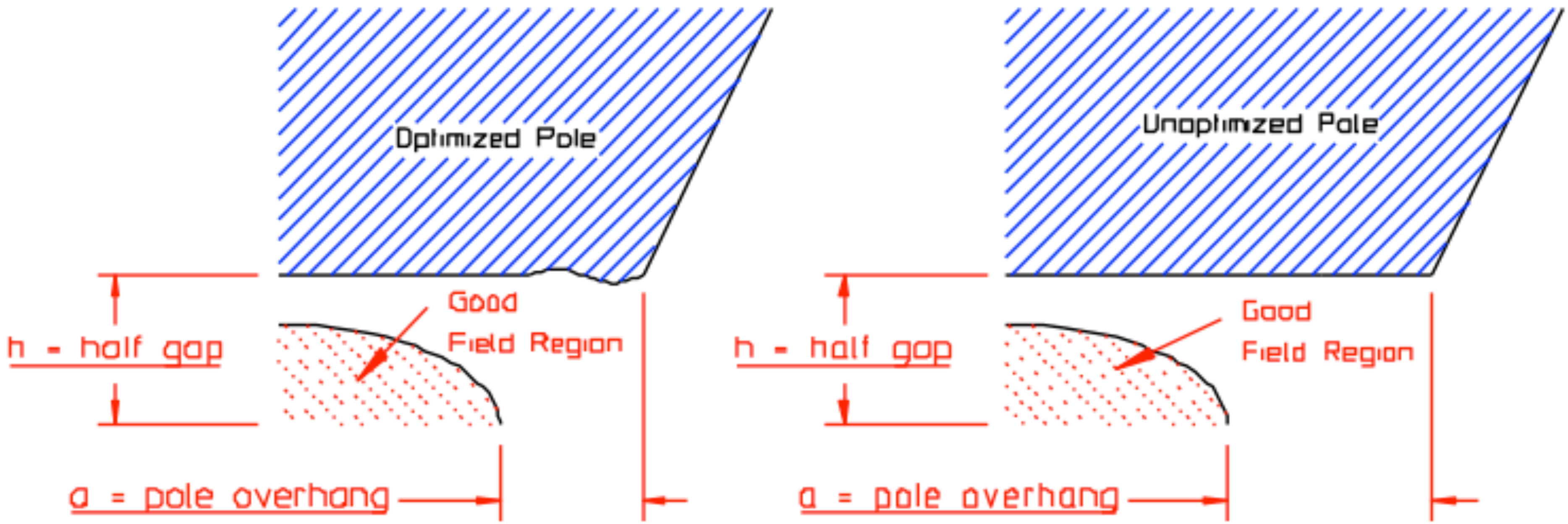
$$\vec{F} = coulombs \times Tesla \times \frac{m}{\sec} = coulombs \times \frac{Webers}{m^2} \times \frac{m}{\sec}$$

$$= \frac{V-\sec}{m} \times \frac{coulomb}{\sec} = \frac{V-Amp-\sec}{m} = \frac{Watt-\sec}{m}$$

$$= \frac{joules}{m} = \frac{Newton-m}{m} = Newton(force)$$

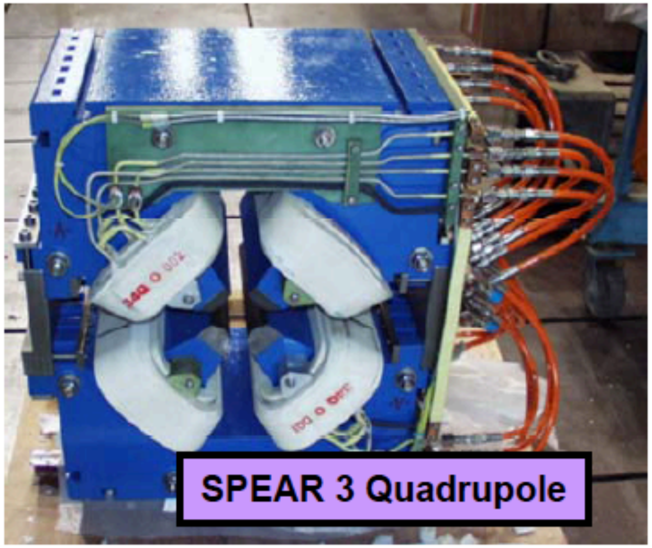
Dipoles _ Specification

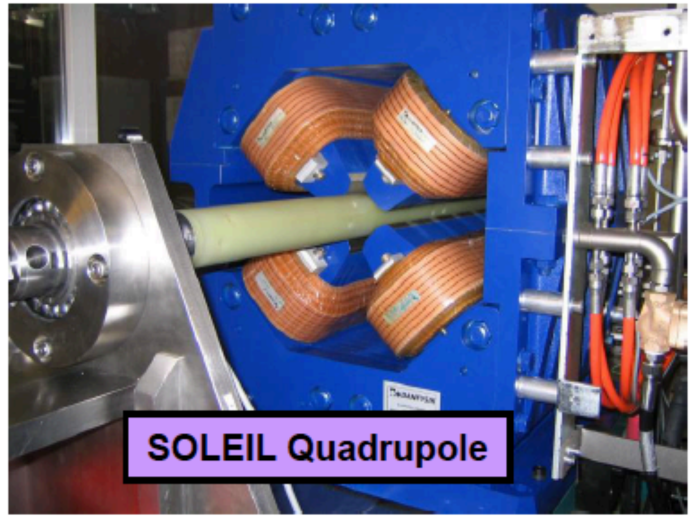
- The size of a dipole is given by the required good field region, the required bending radius, the beam energy and the field that can be achieved in the good field region.
- To achieve required field uniformity in the good field region, several design/manufacturing practices are involved.
- Dipoles are designed with 'shims'. These are special profiles designed into the magnet poles to facilitate the field uniformity within the good field region. This shim design allows for lower magnet footprint and for optimised field profile.



Credit: D. Einfeld & M. Pont_CELLS/ALBA
J. Tanabe _ "Magnet design"

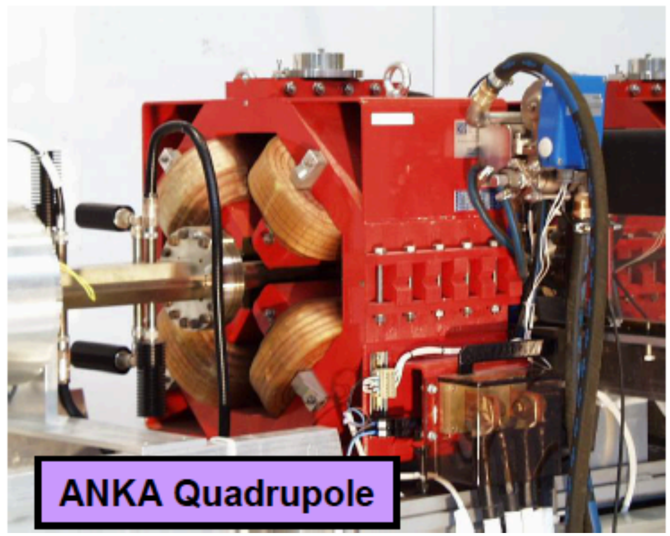
Quadripole Magnets

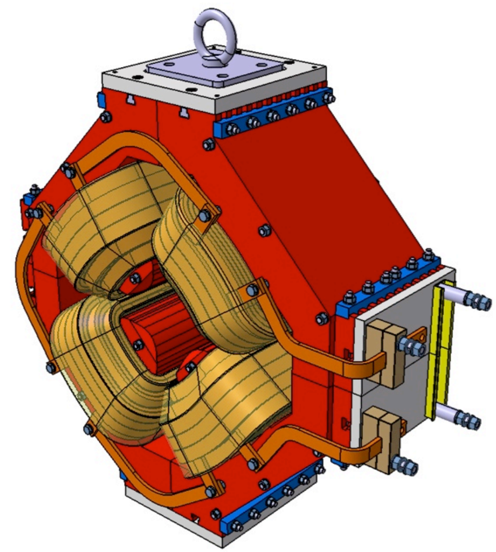

SPEAR 3 Quadrupole


SOLEIL Quadrupole

Credit: D. Einfeld & M. Pont_CELLS/ALBA
J. Tanabe _ "Magnet design"


ALBA Quadrupole


ANKA Quadrupole


ESS Quadripole

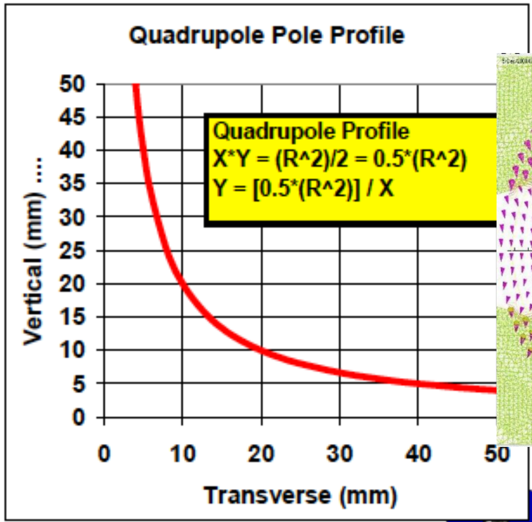
Quadripole Magnets

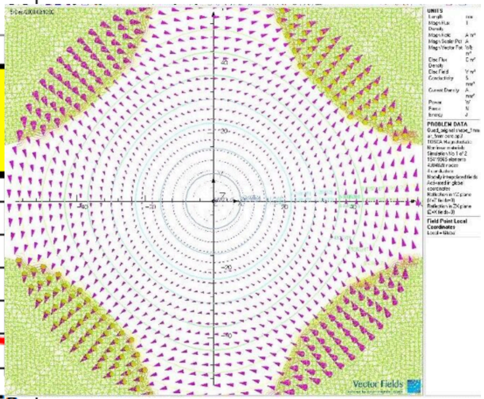
The Quadrupole Magnet has four poles. The field varies *linearly* with the distance from the magnet center. It focuses the beam along one plane while defocusing the beam along the orthogonal plane.

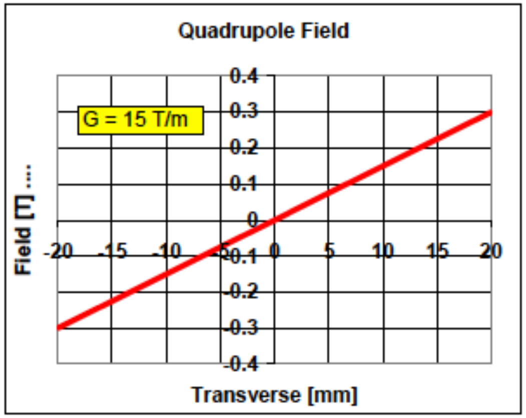
The field of the quadrupole has to be proportional to the distance from the centre (x or y). The excitation in general is given by:

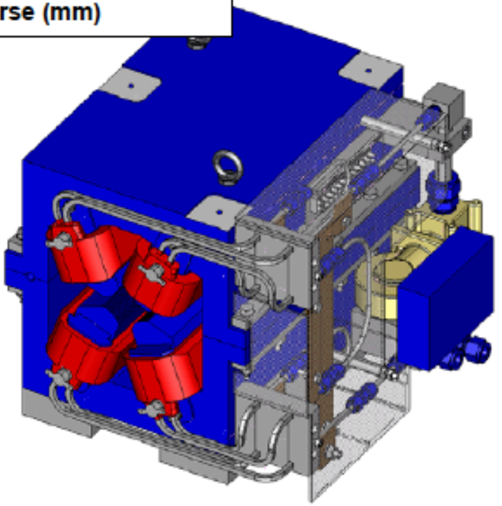
$$B_0 = \mu_0 N{*}I/g \text{ or } B(x) = \mu_0 N{*}I/x$$

This means the pole profile of a quadrupole has to be a hyperbolic one.









Credit: D. Einfeld & M. Pont_CELLS/ALBA
J. Tanabe _ "Magnet design"

Harmonics and Fourier transforms - intro

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Some definitions include (but are not limited to..) :

In acoustics and telecommunication, a harmonic of a wave is a component frequency of the signal that is an integer multiple of the fundamental frequency. For example, if the fundamental frequency is f, the harmonics have frequencies f, 2f, 3f, 4f, etc. ...

Harmonic - In mathematics, a number of concepts employ the word harmonic. The similarity of this terminology to that of music is not accidental: the equations of motion of vibrating strings, drums and columns of air are given by formulas involving Laplacians; the solutions to which are given by eigenvalues ...

Harmonics are electric voltages and currents that appear on the electric power system as a result of certain kinds of electric loads. Harmonic frequencies in the power grid are a frequent cause of power quality problems.

- harmonic - of or relating to harmony as distinct from melody and rhythm; "subtleties of harmonic change and tonality"- Ralph Hill
- harmonic - of or relating to the branch of acoustics that studies the composition of musical sounds; "the sound of the resonating cavity cannot be the only determinant of the harmonic response"
- harmonic - a tone that is a component of a complex sound
- harmonic - relating to vibrations that occur as a result of vibrations in a nearby body; "sympathetic vibration"

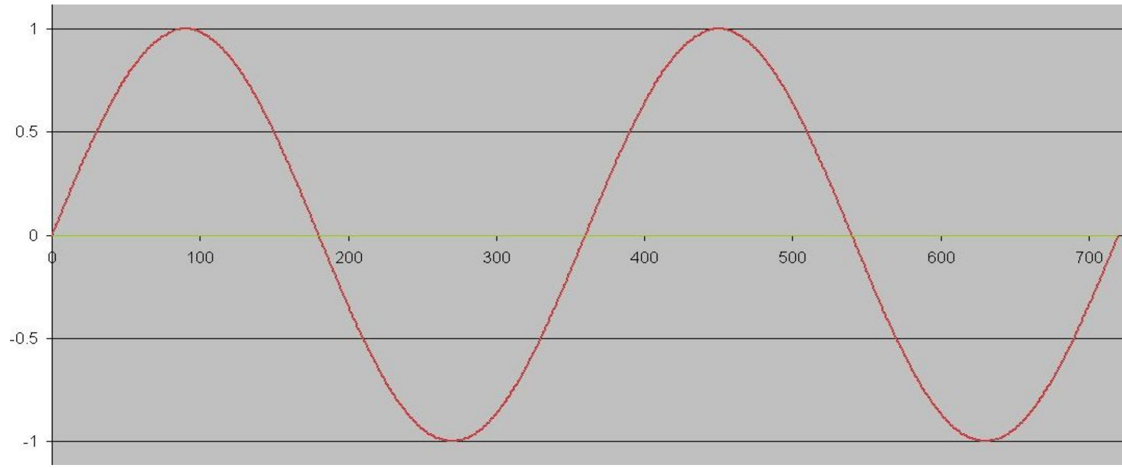
Many different ways to explain it… The term (harmonics/harmonic) is used a lot across math, music, physics…

To make things simpler, let us draw..

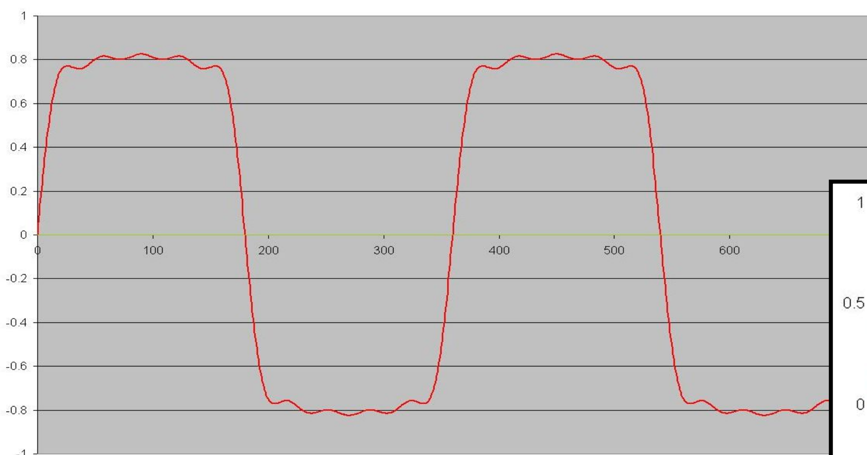
Harmonics and Fourier transforms - intro

Consider a SINE WAVE…

A Sine Wave falls under a 'pretty' category. It is very pretty, and reasonably hard to 'produce'. (for example, some people spend lots of time trying to make newly developed electro-motors to produce a Sine Wave BEMF)… Things wouldn't be interesting if everything was so simple…



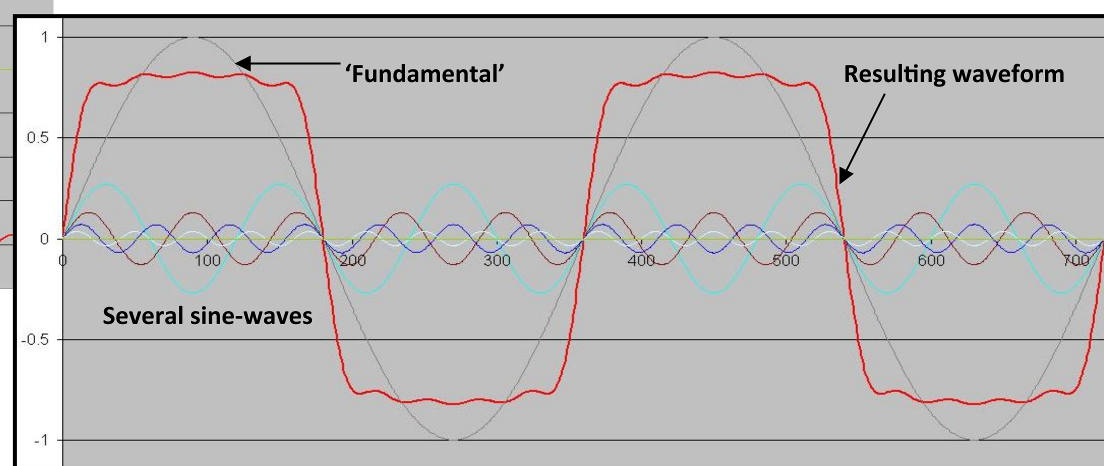
Consider another wave form…



Not-so-sine-wave

And here we are…

All sine waves making up the resulting waveform (when added up) are HARMONICS of that waveform



Harmonics and Fourier transforms - intro

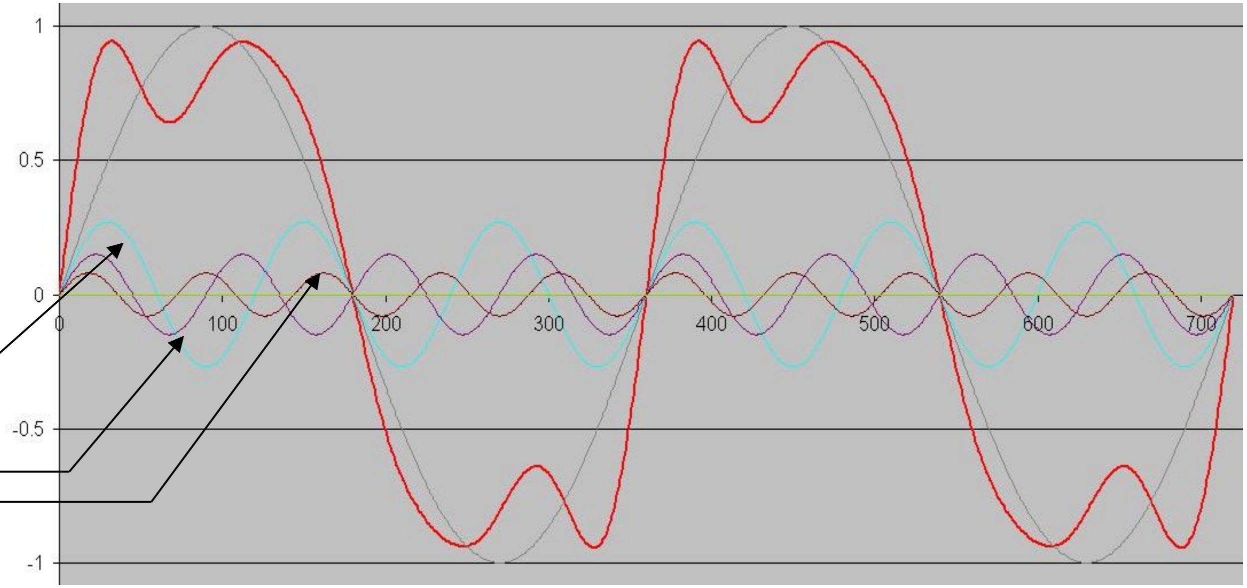
All sine waves making up the resulting waveform (when added up) are HARMONICS of that waveform

Counting how many times does 'harmonics sine wave' oscillate inside one oscillation of the fundamental, will give you the 'harmonics order'…

For example, 3rd order harmonics of a fundamental is the sine waveform that is got 3 times the frequency of the fundamental…

4th order 4 times,

5th order 5 times and so on…



What this all mean to us?

Well, magnetic field quality is often (more appropriate word here is ALWAYS) described as allowed HARMONICS to the fundamental…

Let us DRAW some more…

Harmonics and Fourier transforms - intro

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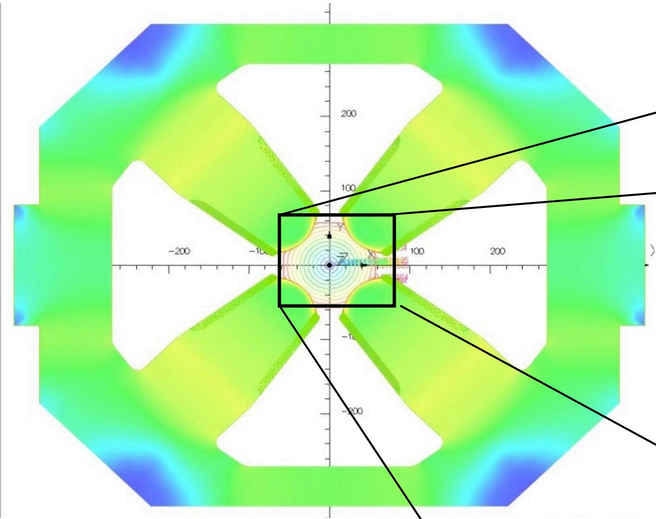
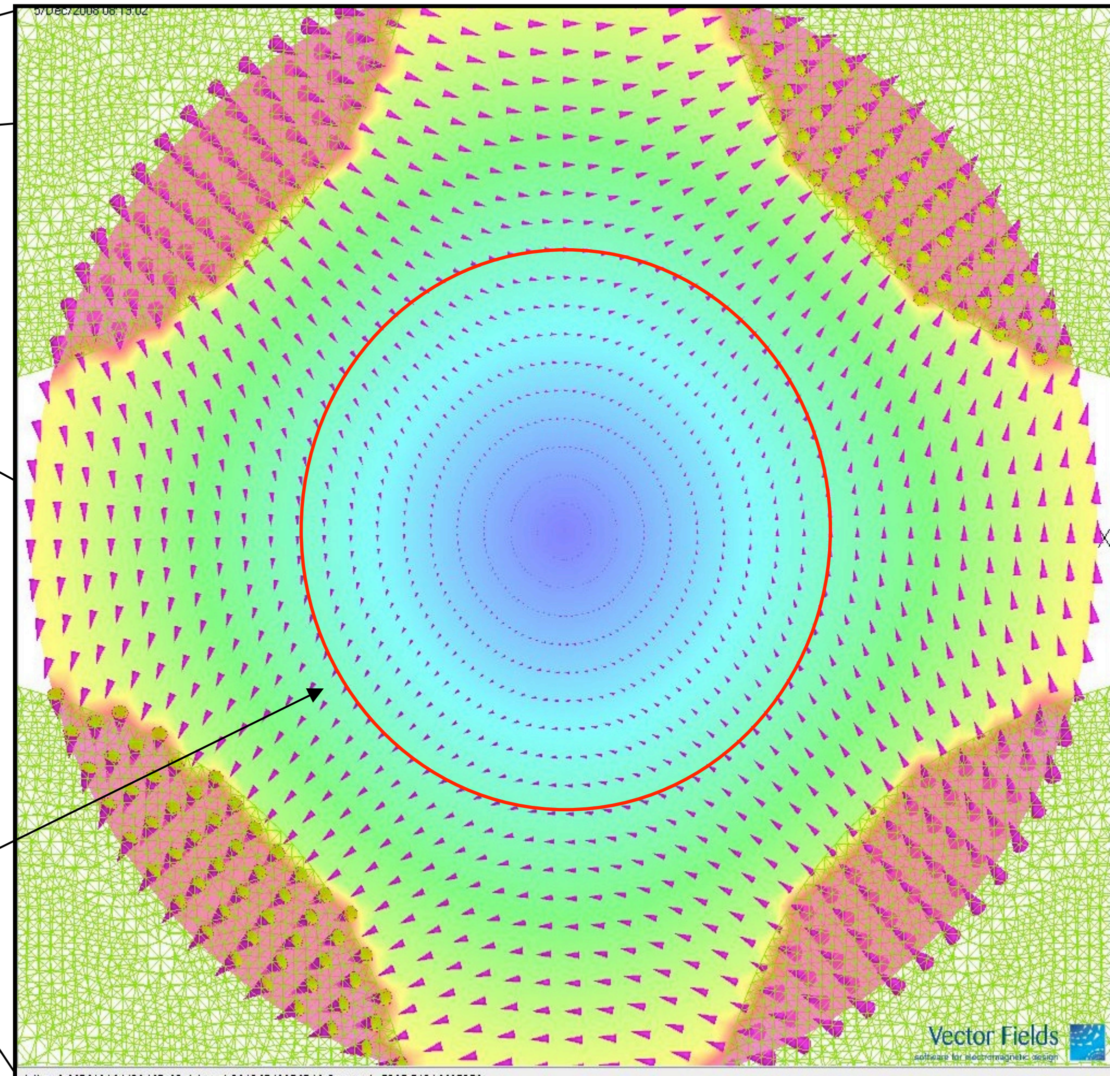
For example, take a BNL Quadripole magnet…





When a physicists talk about their quadripole field, there is always a radius at which this field is specified.

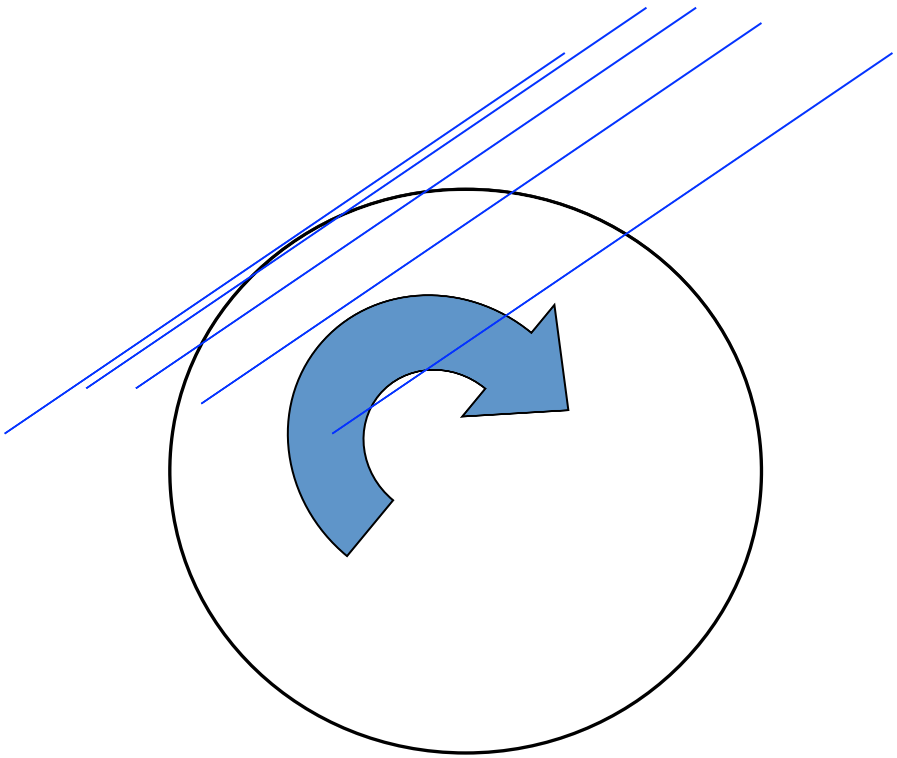
Harmonics and Fourier transforms - intro

The way measurements are made goes roughly like this:

- imagine a straight line positioned on the specified radius inside that quad magnet.
- than magnetic field density is measured for that line
- the line is stepped around the circle (lots of steps, more to better)
- for every step, there is a magnetic field density value…
- plotting all the values going around the circle will give something very close to the sine-wave

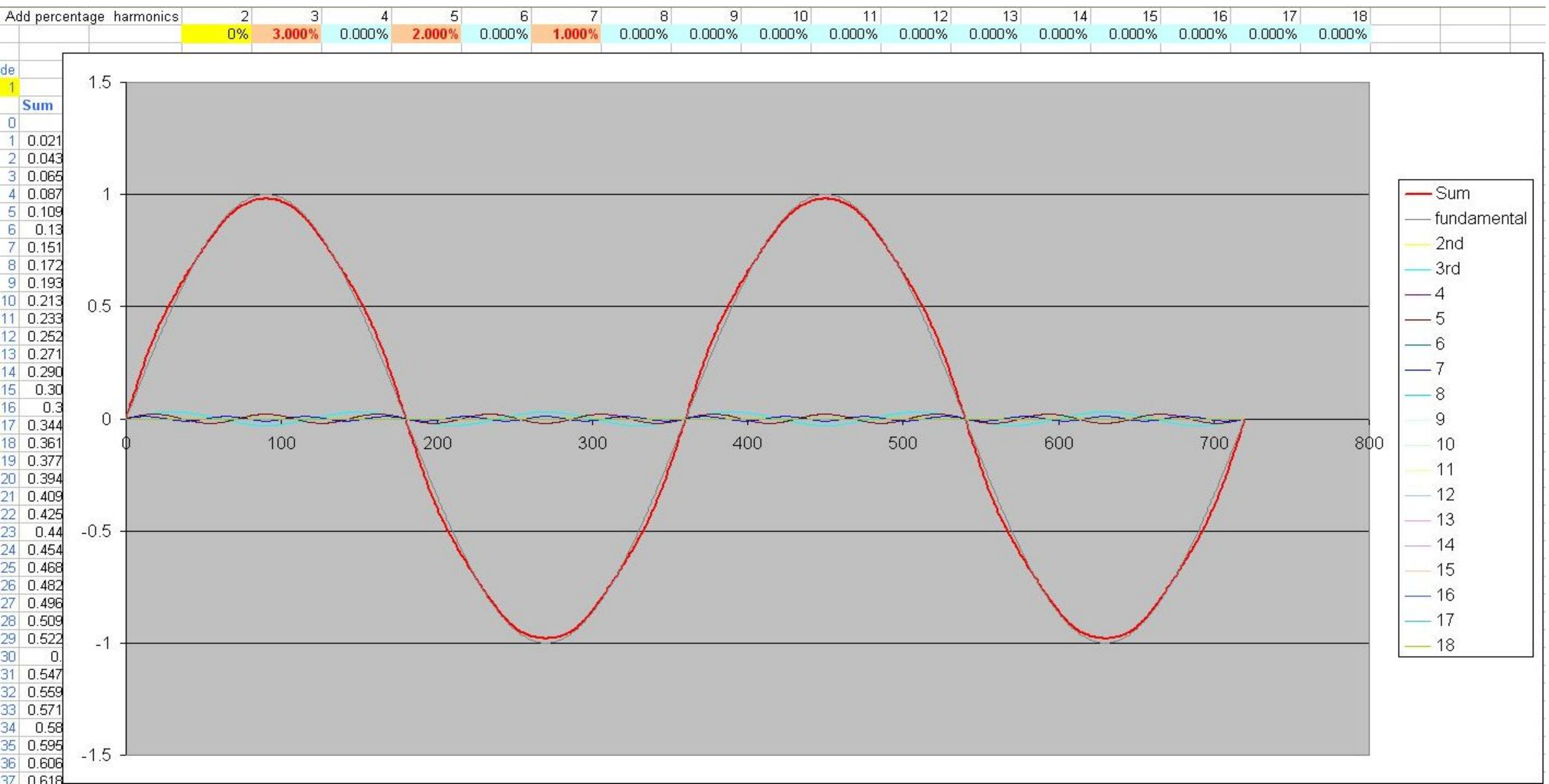
- however, there are ALWAYS deviations from the perfect sine wave. Those deviations are what is specified as 'allowed harmonics' of the field

- So, 'allowed harmonics' are the wave components that describe deviations from the 'fundamental'.



Harmonics and Fourier transforms - intro

The image bellow shows a few percents of 3rd, 5th and 7th added to the fundamental. With quad/sext magnets we produce, what we are required to 'chase' is a few hundredths or thousandths of a **percent** of harmonics ranging in order from 3 to 20 and higher.



Basic magnetics - MFEA

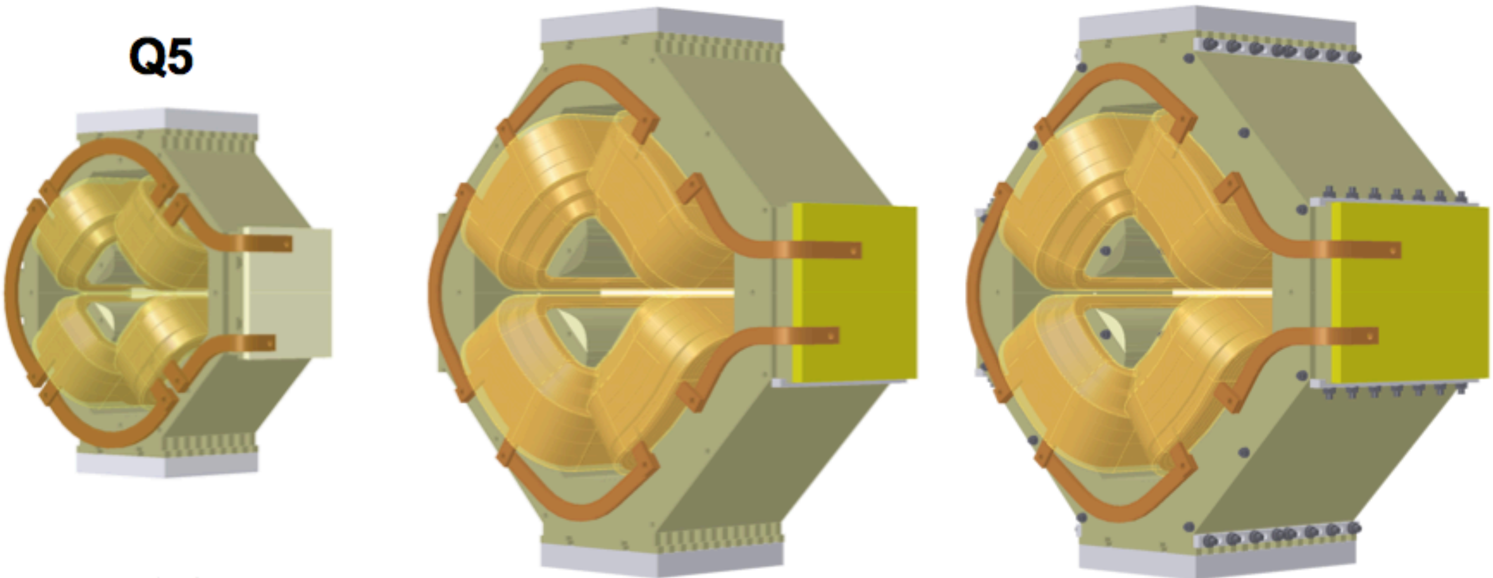
Real basic parameters (and last requirements)

Parameters		**Q5**	**Q6**	**Q7**	unit
Number of required quads	n	**25**	**95**	**12**	#
Bore diameter	Ø	**68** (≥ 67)	**112** (≥ 112)	**112** (≥ 112)	mm
Maximum integrated gradient	$IntG_{Max}$	**2.21** (≥ 1.9)	**2.45** (≥ 2.3)	**2.98** (≥ 2.9)	T
Range of integrated gradient	$IntG_{range}$	**1.05 - 1.8**	**1.20 - 2.20**	**0.85 - 2.70**	T
Magnetic length	L_{eff}	**200** (≥ 150)	**276** (≥ 250)	**335** (≥ 250)	mm
Overall length	$L_{Overall}$	**240** (≤ 250)	**335** (≤ 350)	**390** (≤ 400)	mm

Q6 and Q7 have been designed with the same laminations, the same ampere-turns and different yoke and magnetic length in order to cover the different nominal ranges.

Q5 is smaller, has simpler coil and pole extension geometry and has been designed for last.

ESS Quadripole



Q5

L_{Yoke} = 170 mm
WH_{Yoke}= 430 mm
Turns = 13

Q6

L_{Yoke} = 230 mm
WH_{Yoke}= 650 mm
Turns = 28

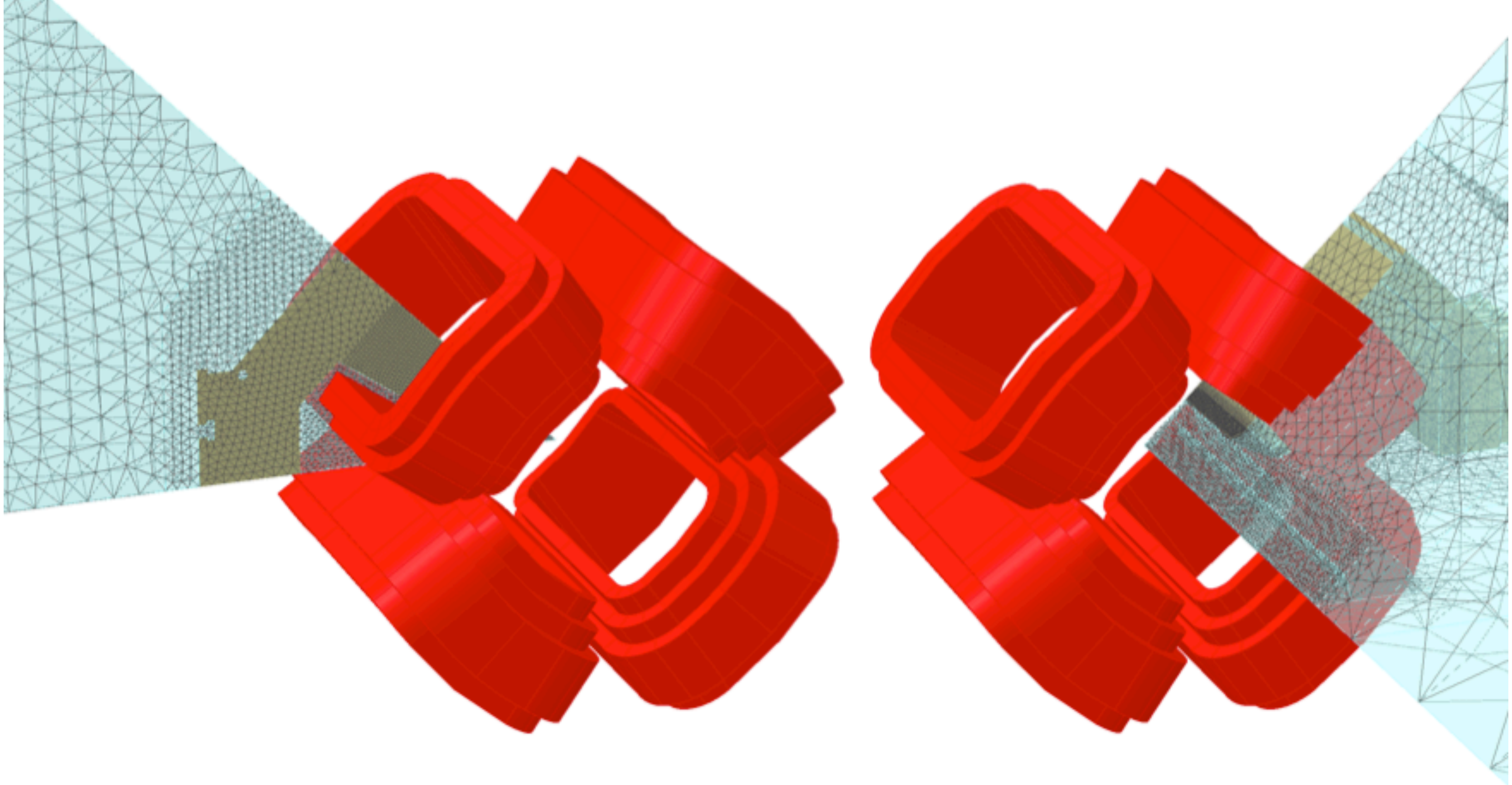
Q7

L_{Yoke} = 290 mm
WH_{Yoke}= 650 mm
Turns = 28

These ESS magnets are located at different positions along the linear accelerator. They are PULSED, operating at the beam frequency of 14Hz.
This allows for lower duty cycle of the magnet, lower thermal load on the coils, and easier manageable power supplies.

ESS Quadripole

Q6 Opera model for Tosca and Elektra simulations



Single lamination model (2.5D)   3D model

Being AC magnets, transient simulations need to be performed

ESS Quadripole

Q5

Int.Gradient (at x = 35mm) at 400A; -0.97%		
GN	|G|	G/G2 [%]
G2 [T/m]	2.2075	100.00
G4 [T/m⁴]	0.0001	0.0048
G6 [T/m⁶]	0.0001	0.0041
G8 [T/m⁸]	0.0002	0.0069
G10 [T/m¹⁰]	0.0001	0.0024

Int.Gradient (at x = 35mm) at 200A: -0.05%		
GN	|G|	G/G2 [%]
G2 [T/m]	1.1141	100.00
G4 [T/m⁴]	0.0000	0.0044
G6 [T/m⁶]	0.0001	0.0093
G8 [T/m⁸]	0.0001	0.0071
G10 [T/m¹⁰]	0.0000	0.0026

Int.Gradient (at x = 35mm) at 100A; 0.00%		
GN	|G|	G/G2 [%]
G2 [T/m]	0.5573	100.00
G4 [T/m⁴]	0.0000	0.0044
G6 [T/m⁶]	0.0001	0.0104
G8 [T/m⁸]	0.0000	0.0071
G10 [T/m¹⁰]	0.0000	0.0026

Q6

Int.Gradient (at x = 35mm) at 400A; -1,32%		
GN	|G|	G/G2 [%]
G2 [T/m]	2.4517	100.00
G4 [T/m⁴]	0.0001	0.0028
G6 [T/m⁶]	0.0001	0.0029
G8 [T/m⁸]	0.0000	0.0001
G10 [T/m¹⁰]	0.0000	0.0010

Int.Gradient (at x = 35mm) at 200A; -0.13%		
GN	|G|	G/G2 [%]
G2 [T/m]	1.2406	100.00
G4 [T/m⁴]	0.0001	0.0029
G6 [T/m⁶]	0.0001	0.0040
G8 [T/m⁸]	0.0000	0.0000
G10 [T/m¹⁰]	0.0000	0.0009

Int.Gradient (at x = 35mm) at 100A; 0.00%		
GN	|G|	G/G2 [%]
G2 [T/m]	0.6211	100.00
G4 [T/m⁴]	0.0000	0.0020
G6 [T/m⁶]	0.0000	0.0056
G8 [T/m⁸]	0.0000	0.0000
G10 [T/m¹⁰]	0.0000	0.0009

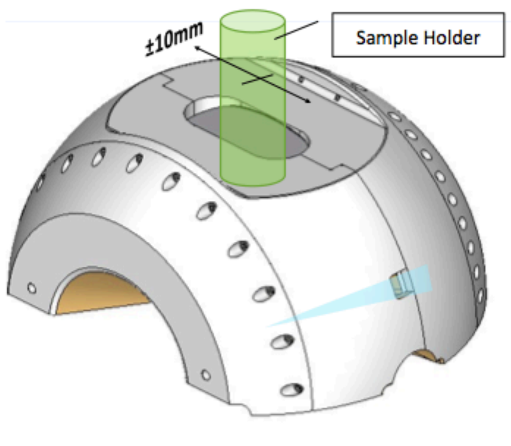
Q7

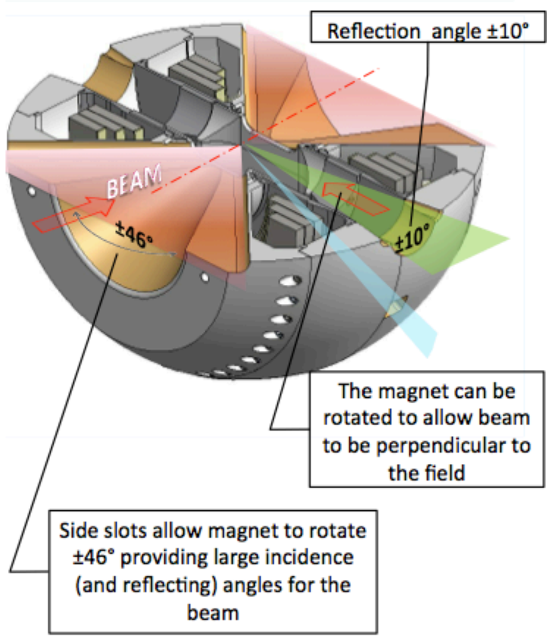
Int.Gradient (at x = 35mm) at 400A; -1.22%		
GN	|G|	G/G2 [%]
G2 [T/m]	2.9813	100.00
G4 [T/m⁴]	0.0002	0.0041
G6 [T/m⁶]	0.0002	0.0028
G8 [T/m⁸]	0.0001	0.0029
G10 [T/m¹⁰]	0.0001	0.0012

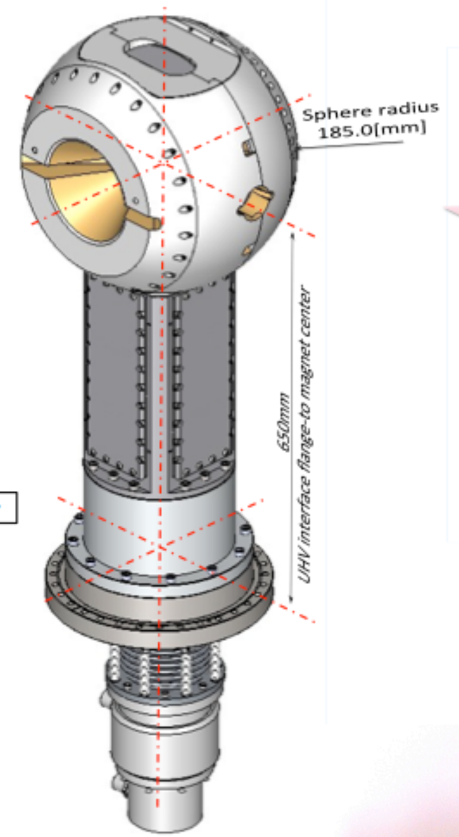
Int.Gradient (at x = 35mm) at 200A; -0,10%		
GN	|G|	G/G2 [%]
G2 [T/m]	1.5076	100.00
G4 [T/m⁴]	0.0002	0.0044
G6 [T/m⁶]	0.0002	0.0060
G8 [T/m⁸]	0.0001	0.0031
G10 [T/m¹⁰]	0.0000	0.0011

Int.Gradient (at x = 35mm) at 100A; 0.00%		
GN	|G|	G/G2 [%]
G2 [T/m]	0.7546	100.00
G4 [T/m⁴]	0.0001	0.0044
G6 [T/m⁶]	0.0001	0.0095
G8 [T/m⁸]	0.0000	0.0031
G10 [T/m¹⁰]	0.0000	0.0011

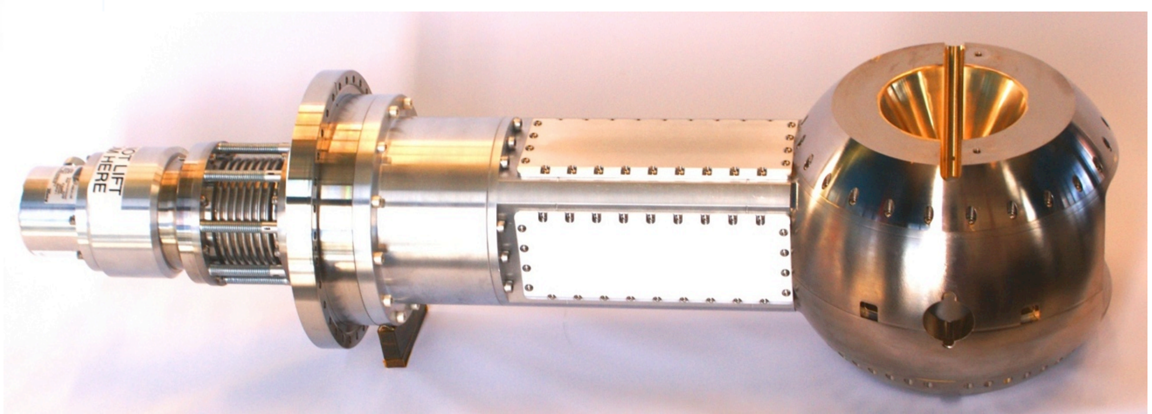
Sample environment magnets



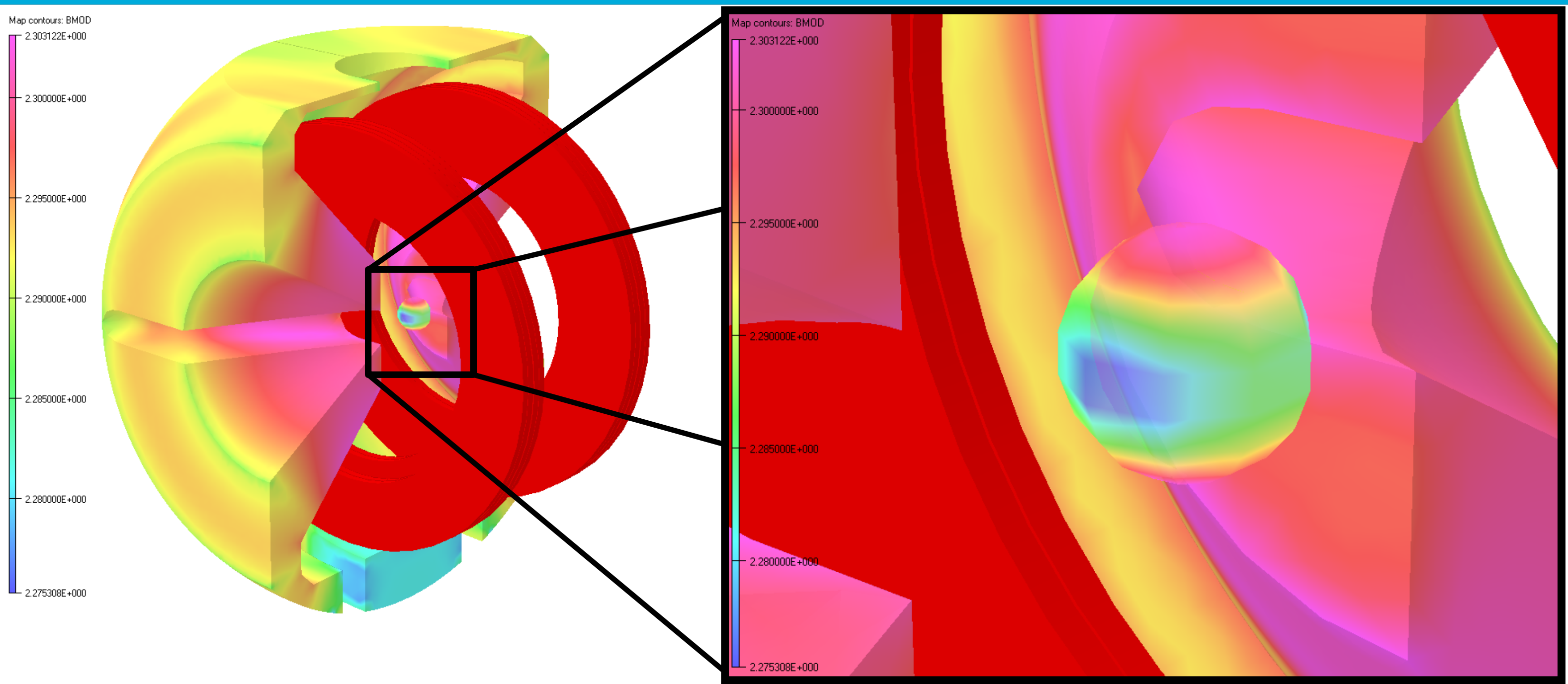




- As the name says, these magnets are used in the sample environment. Their purpose is to apply magnetic field at/around the sample area subjecting it to the required field.
- The technical requirements for these magnets are very different from case to case. Depending on the experiment that needs to be performed.
- Sometimes a super high field is required (over 20T) when superconducting magnets needs to be deployed. Sometimes just a steel saturation field is required (~1,5T) when conventional room-temperature conductor



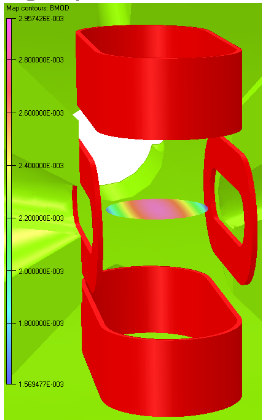
Sample environment magnets

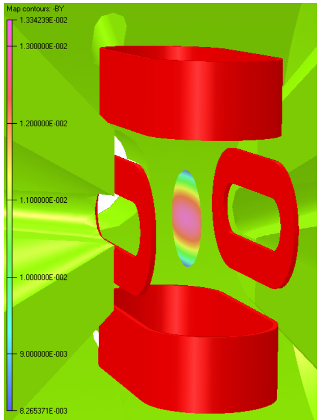


Main coils produce required 2T with allowed 10% margin (modeled 2.2T)

- Magnetic and thermal design of the system is performed using Opera TOSCA® software.

Magnet system performance (magnetic and thermal) is modeled applying set requirements and limits. The FEA shows that the requirements can be met. Additional (ambient temperature) coils have been designed to provide superimposing DC and AC field over the sample area.





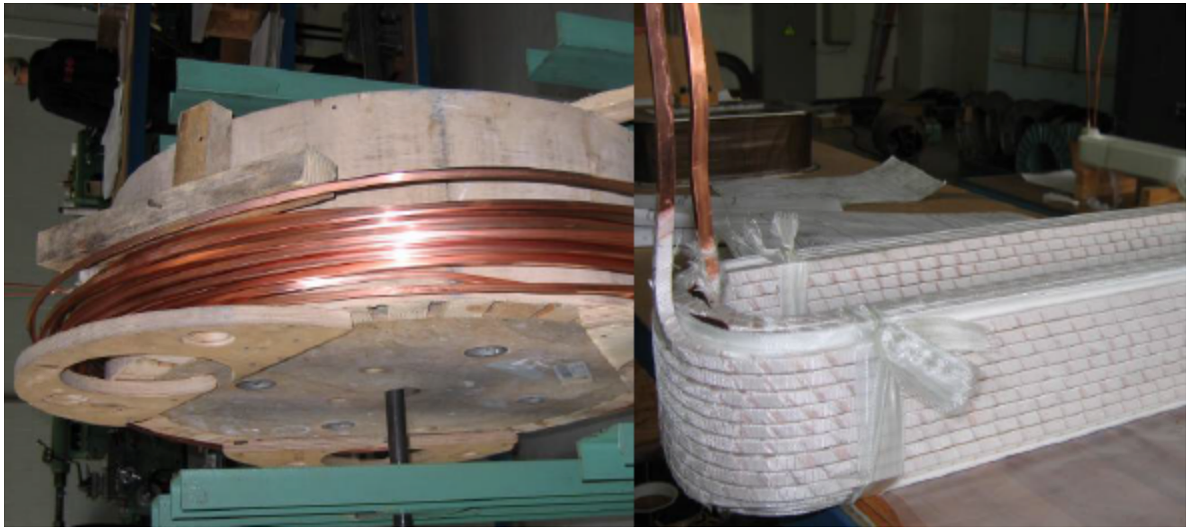
Modeled performance of ambient temperature Cu (superimposing) coils.

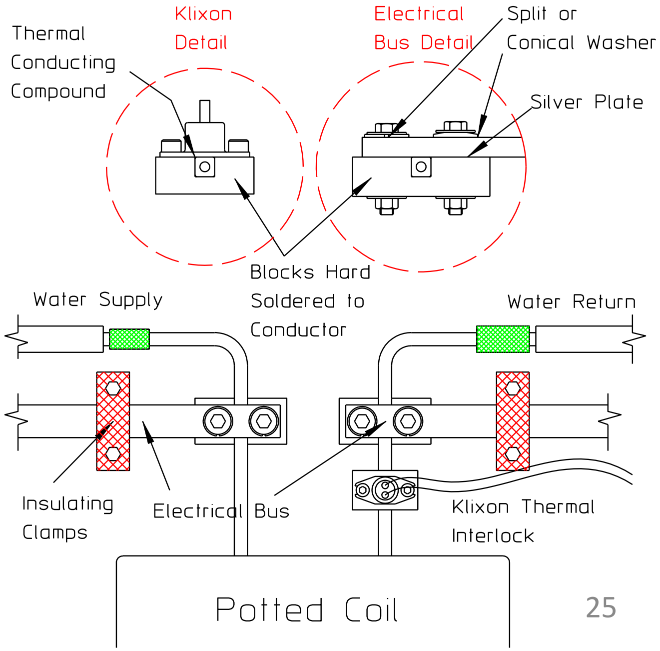
Vertical coils produce 30 Gauss and Horizontal 133 Gauss of superimposing field.

Electrical design

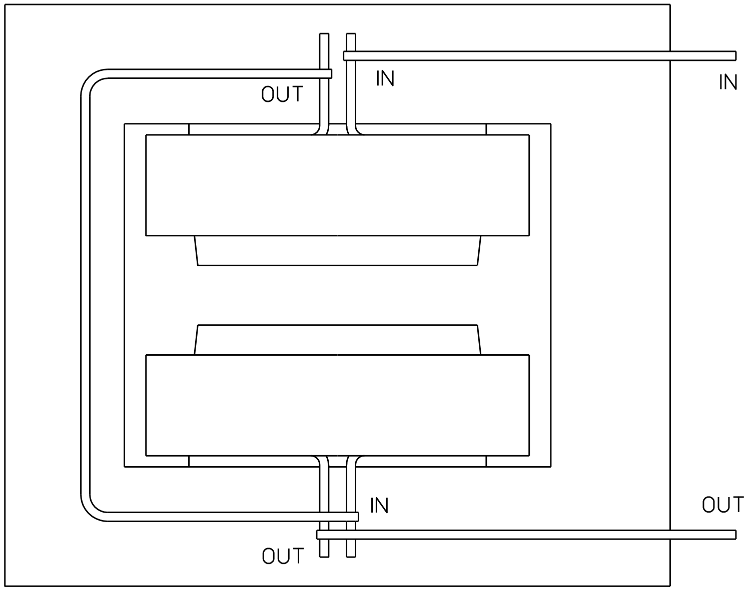
- Magnet design starts with the magnet(ic) requirements.
- To achieve certain field and field quality, the magnet is designed with the maximum available current in mind (this is usually driven by the cost and availability of power supplies.
- The maximum available current, coupled with selected conductors, translates into an “Engineering Current Density”.
- This is the current density [A/mm^2] of the conductor cross section as it appears in a drawing. This means that the conductor includes insulation, any cooling channels, any required spacing etc…
- With setting up the current, we have to worry about the cooling.
- As a rule of thumb, we say that for air-cooled coils we don’t put in more than 1A/mm^2 (but can push it to 3). For water cooled we don’t go more than 10A/mm^2 but this can be pushed further, depending on available cooling water pressure.

- Out of the above, some conflicting boundaries are set for magnet design:
- - magnetic design usually requires tight tolerances, as much steel as possible
- - electrical design usually requires fine balancing between the current density, cooling capacities and available power supplies
- - designing magnet coils require careful consideration of electrical and thermal loads on the system, all the while maintaining required field strength and quality.
- In the case of the ESS, quad magnets presented here are pulsed. They operate at beam frequency of 14 Hz therefore the electrical duty cycle is reduced, therefore the demand on cooling is low. This resulted in simpler magnet design.



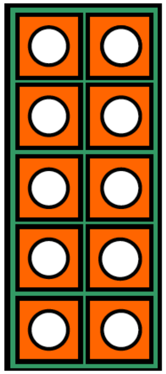


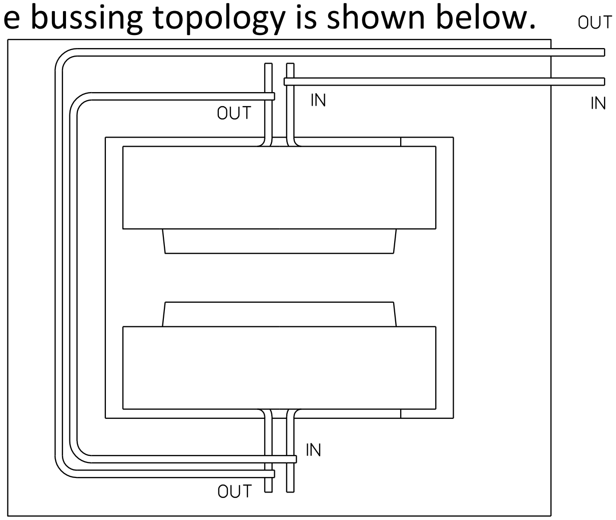
Electrical design



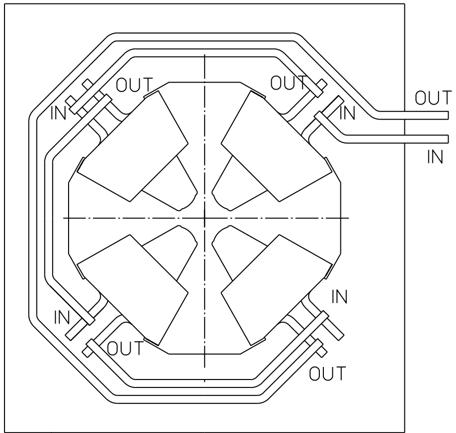
- What is wrong with this picture?

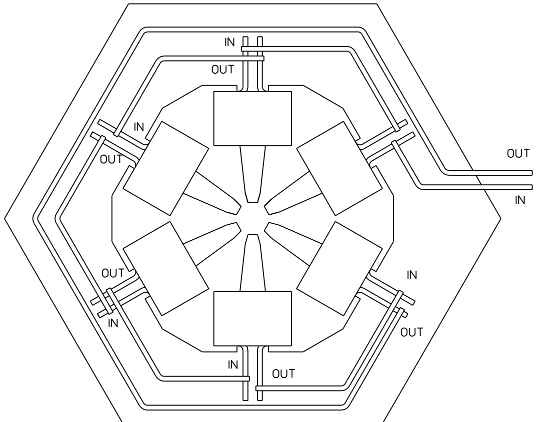
- The electrical bussing connection creates a loop around the beam line, resulting in a small solenoidal field. This longitudinal field can rotate the beam.
- The correct dipole bussing topology is shown below.





- The correct quadrupole and sextupole bussing scheme is shown. Again, it is recommended that the conductors be placed close to each other.





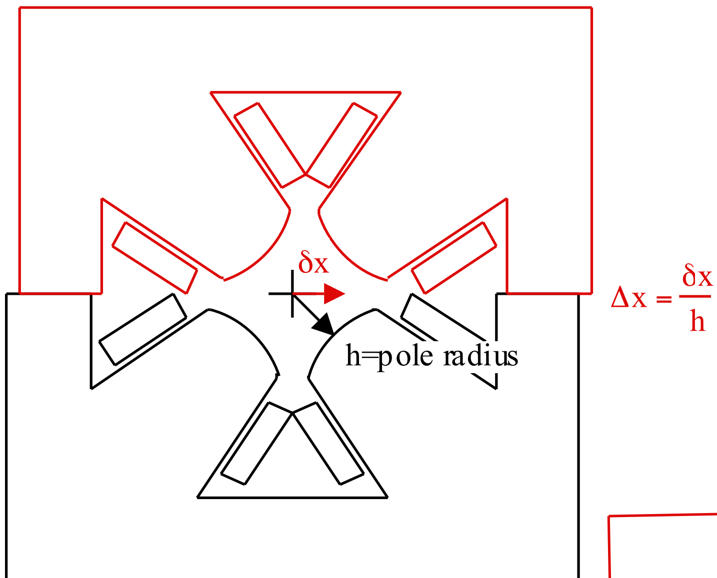
Credit: D. Einfeld & M. Pont_CELLS/ALBA
J. Tanabe _ “Magnet design”

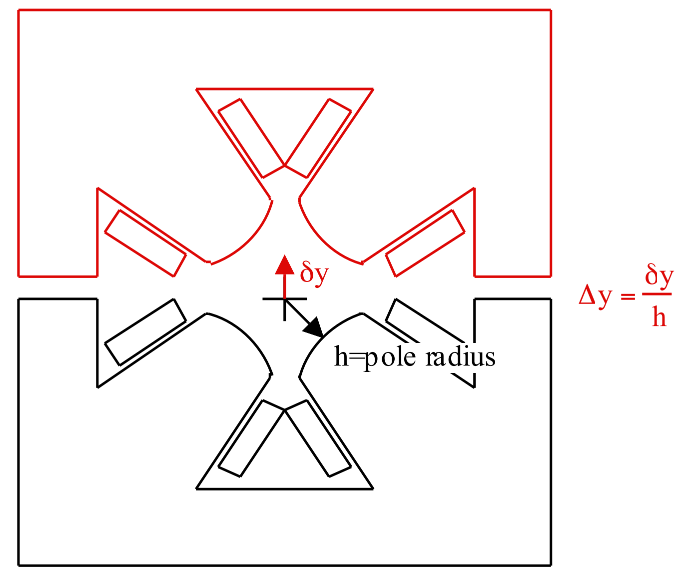
Mechanical design

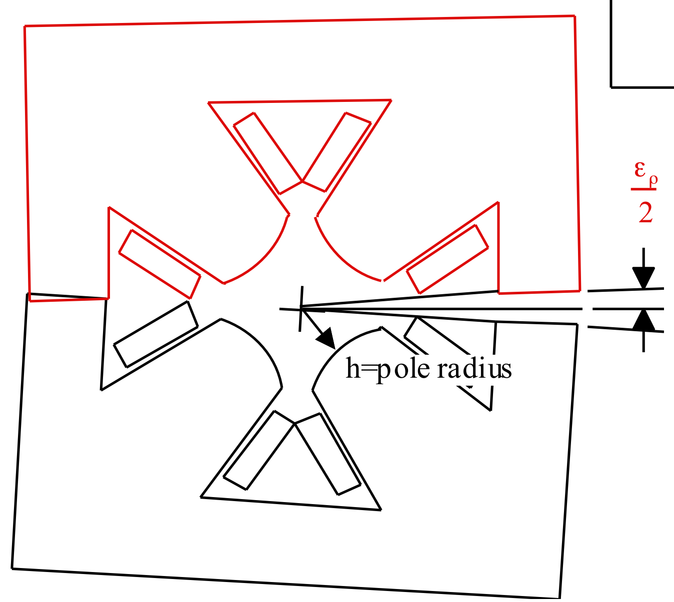
- The mechanical design of the magnet is performed after the magnetic optimisation (usually 3D MFEA). Following the mechanical design, another round of MFEA is required to implement any magnet geometry changes that are driven by manufacturability requirements.
- Some guidelines when performing the mechanical design of an accelerator magnet:
  - know materials restrictions (it is irradiated environment, some materials do not survive to well in this),
  - manufacturability is the key. Often accelerator magnets are ordered in good quantities (10s, 100s,…). During the mechanical design and implementation of magnet geometries as dictated by the MFEA, apply robust design practices. How are things produced, assembled, verified,…
  - have a good verification plan. This means measurement of key geometry features of the magnet (in our case, this are magnet poles geometry)…
  - be aware of manufacturing errors (and they always happen) influence on field quality (allowed and non-allowed harmonics).
    - The shear motion of the top half of the magnet with respect to the bottom introduces skew even multipole errors.
    - The vertical motion introduces real even multipole errors.
    - The rotational motion introduces real odd multipole errors.

Credit: D. Einfeld & M. Pont_CELLS/ALBA
J. Tanabe _ "Magnet design"

Manufacturing errors





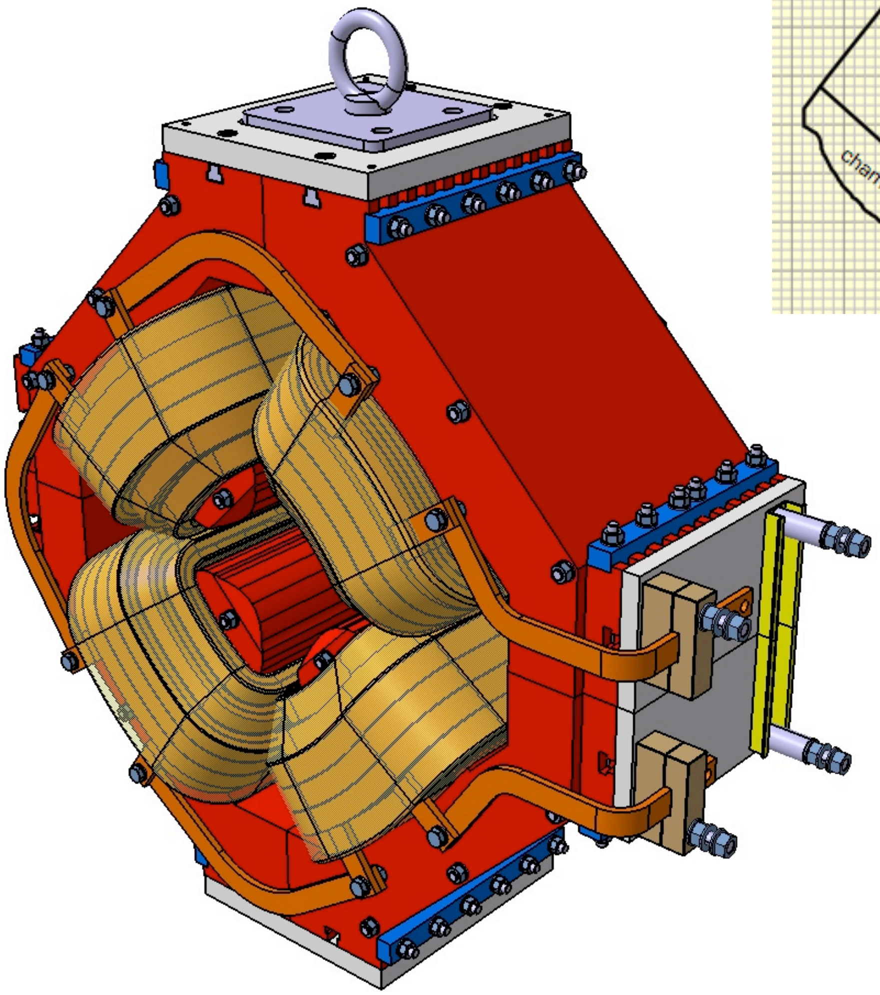


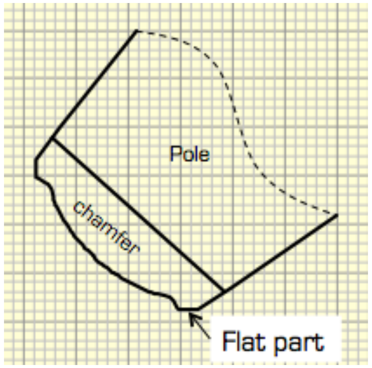
Credit: J. Tanabe _ "Magnet design"

Testing

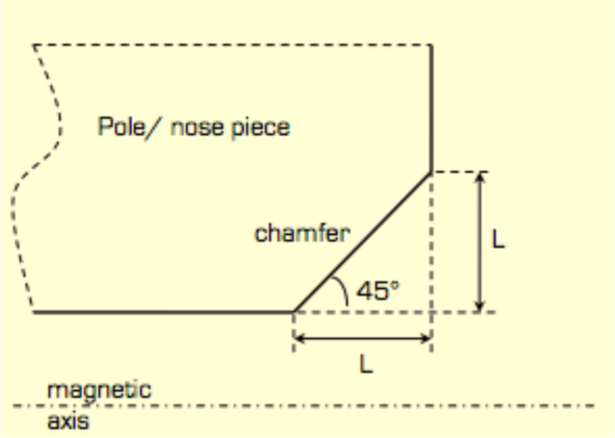
- Testing is planned throughout the magnet manufacturing cycle.
- Core is tested for magnetic properties before and after it has been assembled into a yoke. Yokes are tested for uniformity of the material spread.
- Coils are tested for all electrical properties (insulation between turns, capacity to carry prescribed current.
- Cooling system (designed cooling channels) are tested for thermal performance during full load.
- Full CMM measurements are logged and presented (to relate any magnetic anomalies to the mechanical ones).
- Magnetic testing is done
  * magnetic field mapping using x/y/z hall probe mapping table,
  * rotating coil for multipoles or stretched wire for dipoles tests,
  * the above tests results are compiled, from these actual field quality is noted, harmonics are analysed and corrected when needed,
  * pole tips add-ons are referenced to field measurements and adjusted if needed,
- Acceptance report produced to accompany delivery of the magnet system.

Questions...

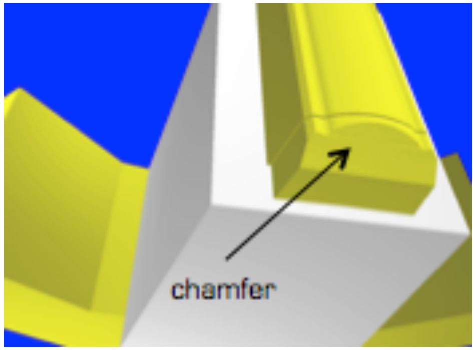




Pole
chamfer
Flat part



Pole/ nose piece
chamfer
45°
L
L
magnetic
axis



chamfer

What did we miss…

- Yoke manufacturing – wire or laser cutting? Shuffling? Stacking and gluing?
- Yoke manufacturing – final machining on assembly; stress relieveing; de-burring; chamfering.
- Coil manufacturing – range of tests (Hi-pot, continuity, capacity).
- Coil manufacturing – calculations background; hollow or flat conductor.
- Final assembly – ability to take magnet apart and put it back together without errors; ability to connect power and cooling without difficulties.
- Testing methods – rotating coil details.
- MFEA – taking note of meshing restrictions and effects; modelling transients.
- 'On-beamline' performance and testing.
- Touch on superconducting (LTS and HTS).
- Common modes of failure.