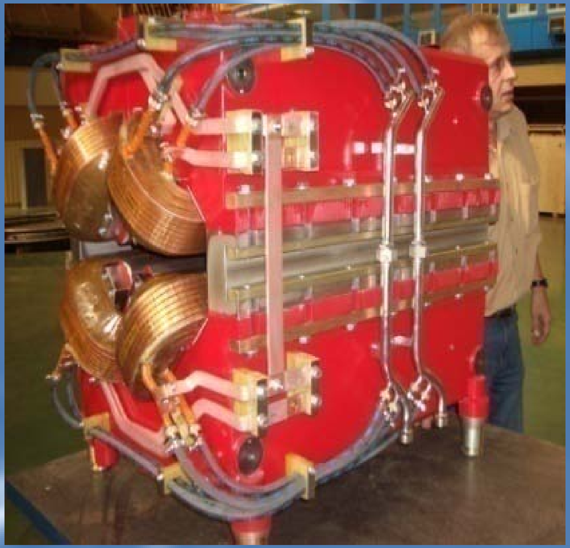
3rd ILSF Advanced School on Synchrotron Radiation and Its Applications

September 14-16, 2013

Electromagnets in Synchrotron Design and Fabrication



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ILSF

References

- S.Fatehi*, M.khabazi, "2nd ILSF school on synchrotron radiation and its applications" October2012.*
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- Jack Tanab, "Iron Dominated Electromagnets Design, Fabrication, Assembly and Measurements", January 6, 2005.
- G.E.Fisher,"Iron Dominated Magnets", Stanford Linear Accelerator Center, 1985.
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- H. Wiedemann, *Particle Accelerator Physics I*, Springer, 1999.
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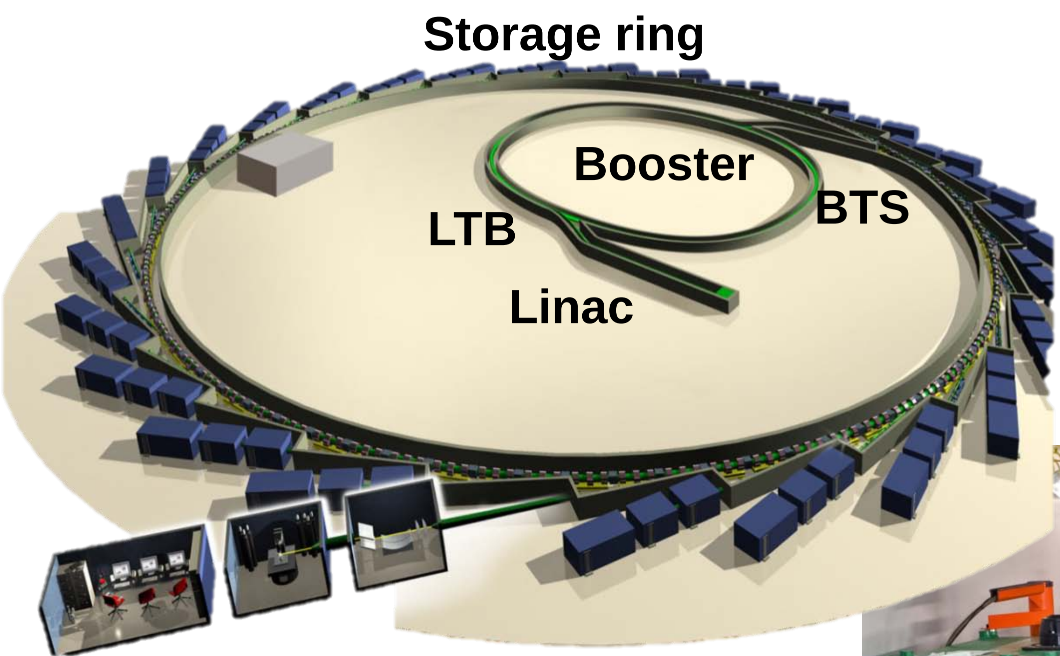
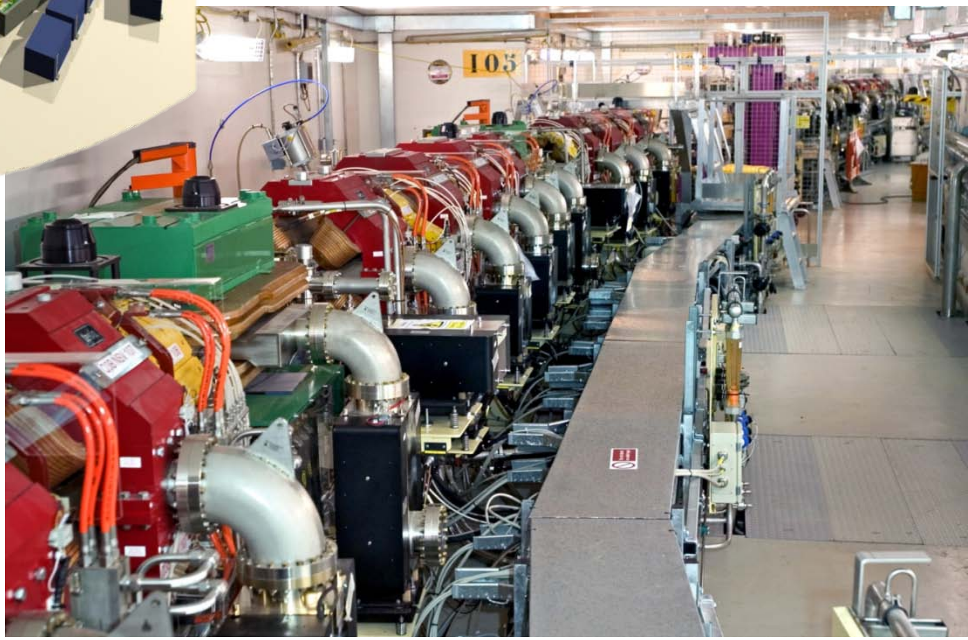
OutLine

- Light sources and magnets
- Magnet types
- Dipoles
- Quadrupoles
- Sextupoles
- Combined magnets
- Design Procedure
- ILSF Prototype magnets
- Fabrication Procedure

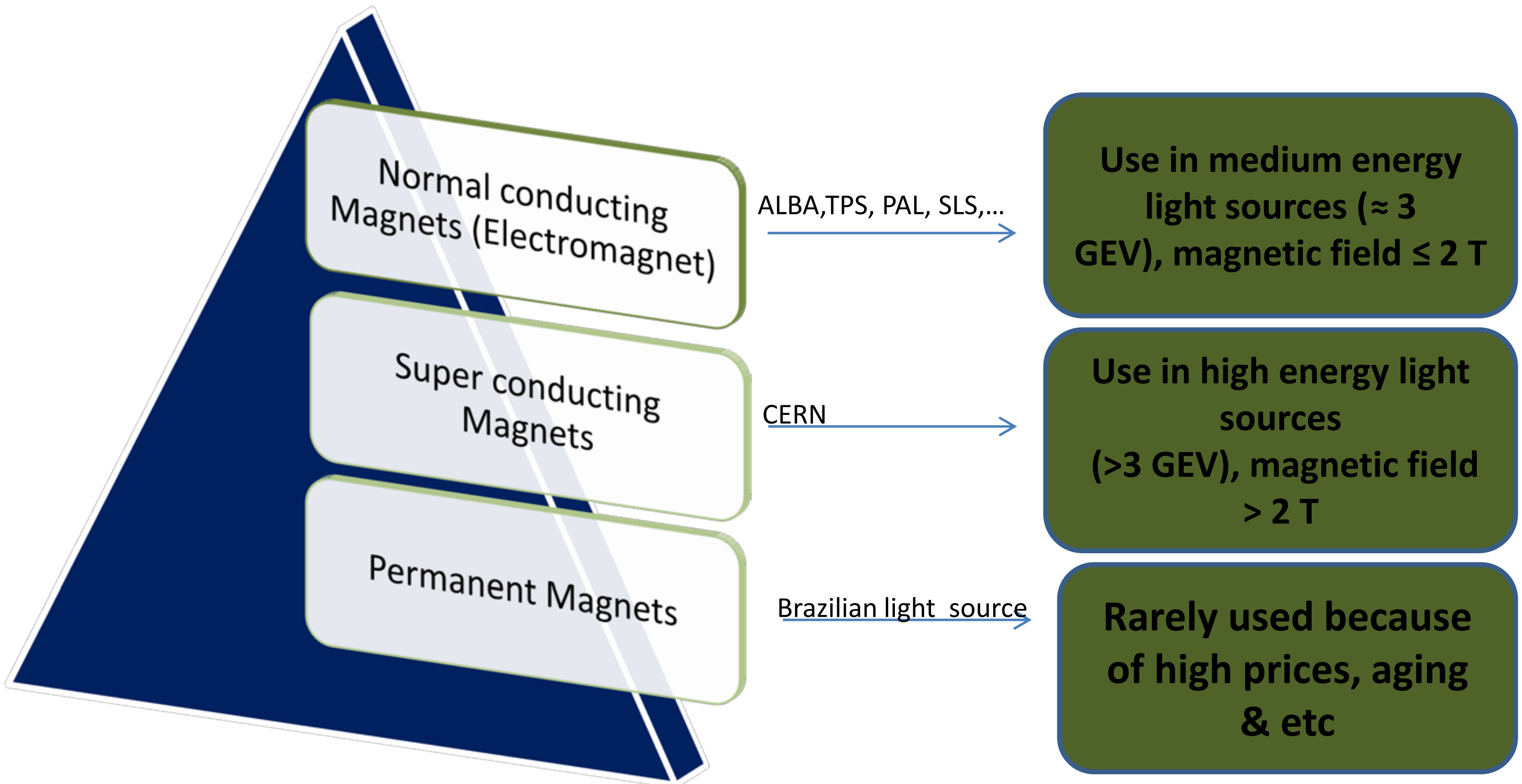
Light sources and magnets



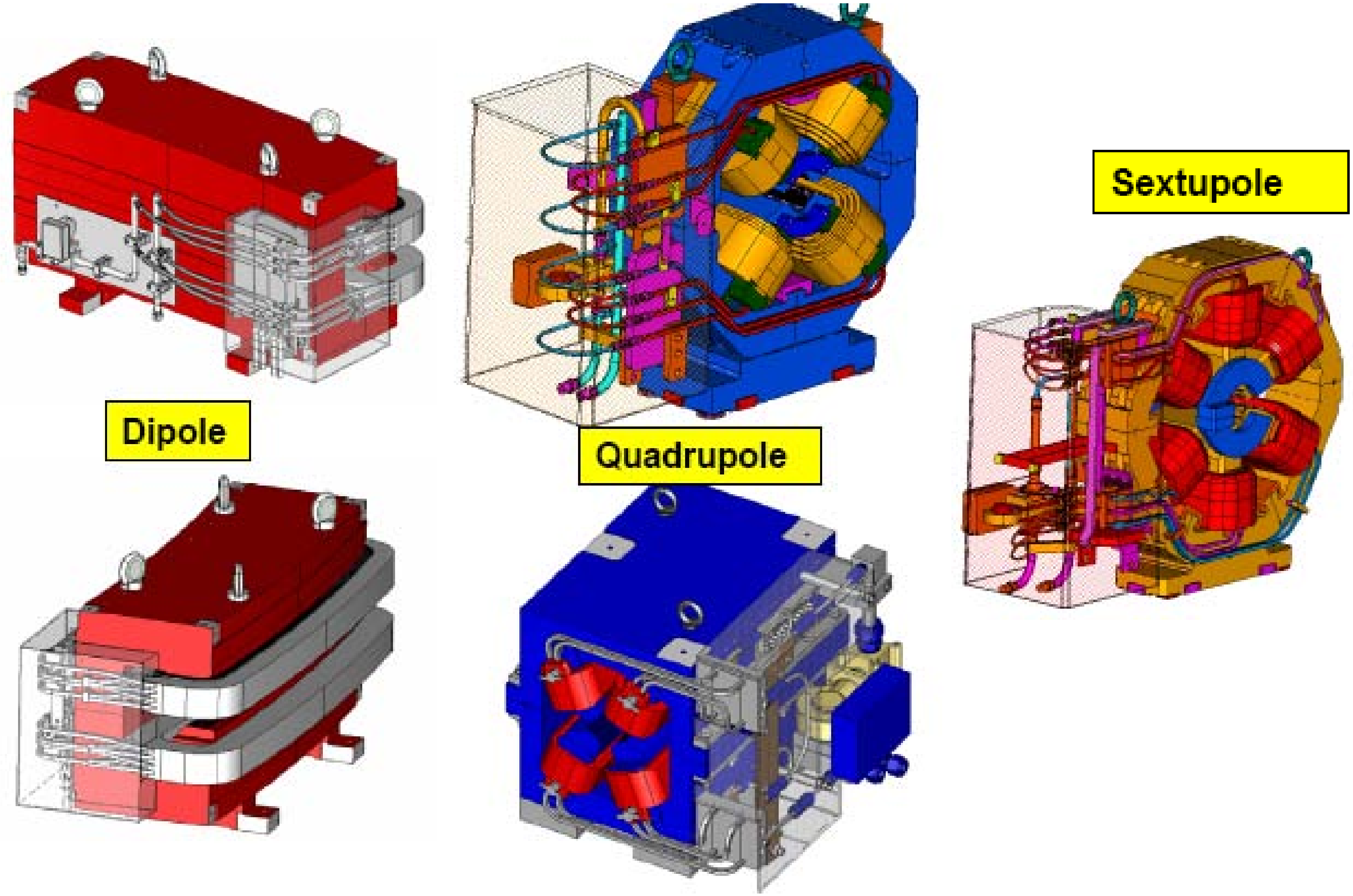
Diamond Accelerator Complex



Magnet types

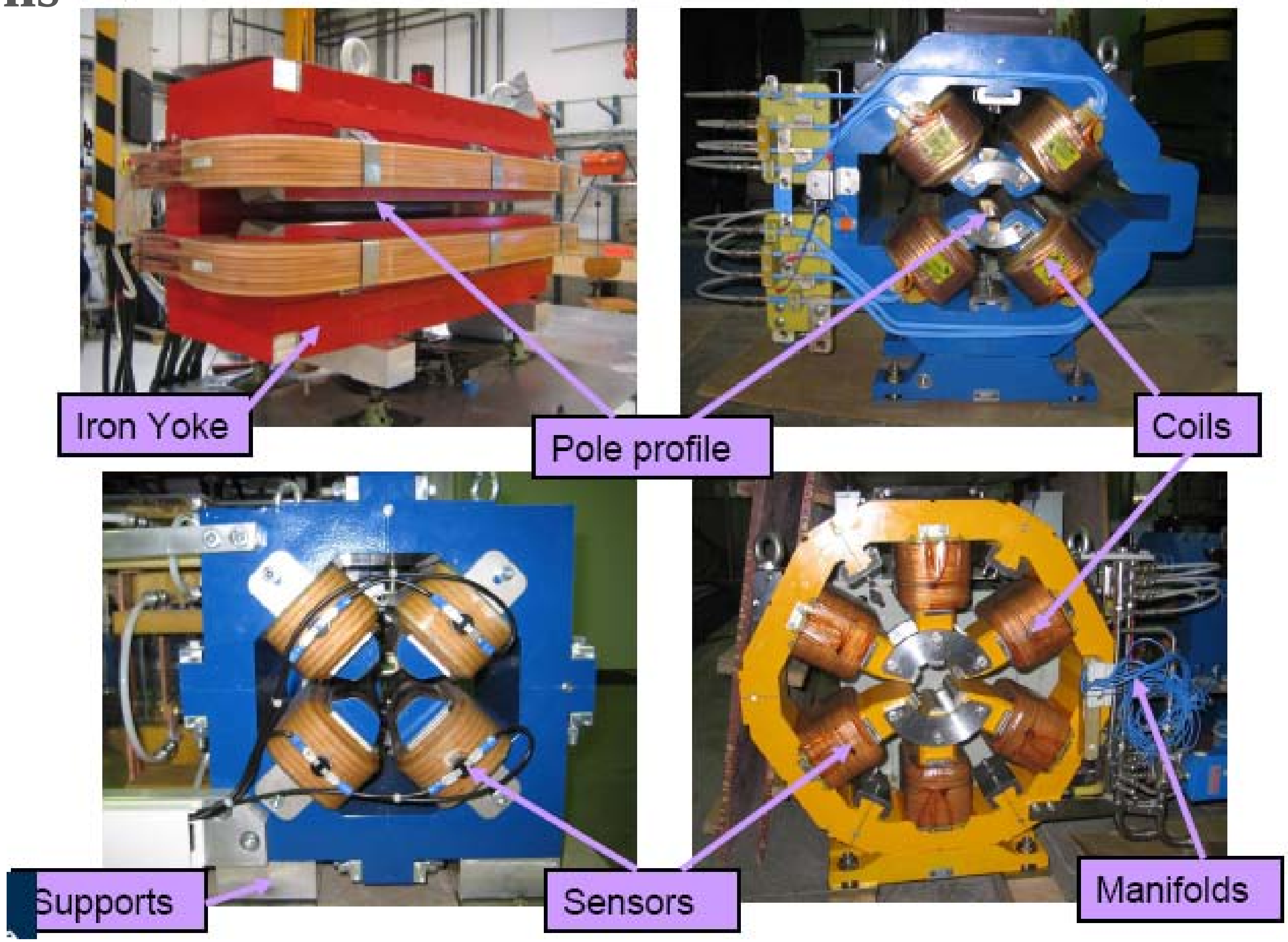


Electromagnet types



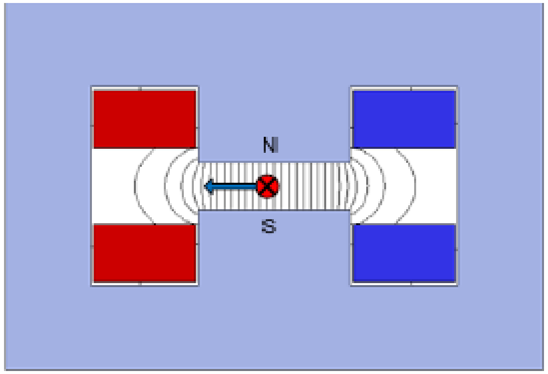
❖Each magnet has 2 main parts :

1. Iron yoke(includes back leg , pole root, pole ,…)
2. Coils



Dipole magnet(Bending magnet)

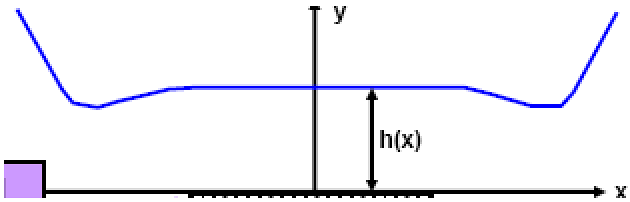
- Has 2 poles,2 coils
- Bends the electrons in a single curved trajectory.
- Injection of particles into the accelerator
- Extraction of particles from the accelerator
- Production of synchrotron radiation

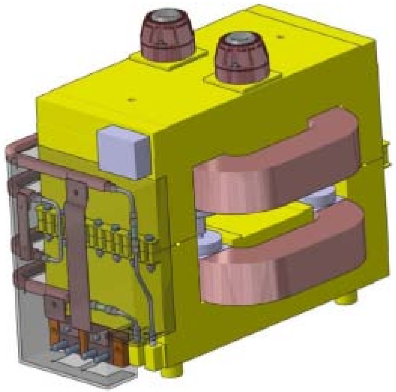


Pole profile eq.: y=h

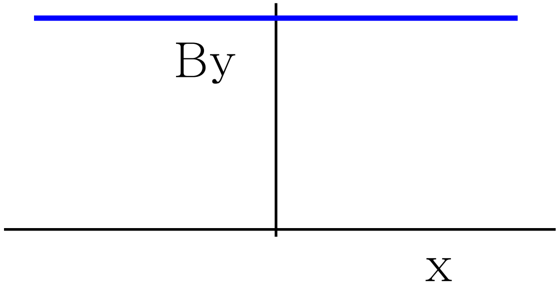
Dipole main parameters

- **B (magnetic field at center)**
- **L (length)**
- **h (half gap height)**
- **GFR (good field region),**

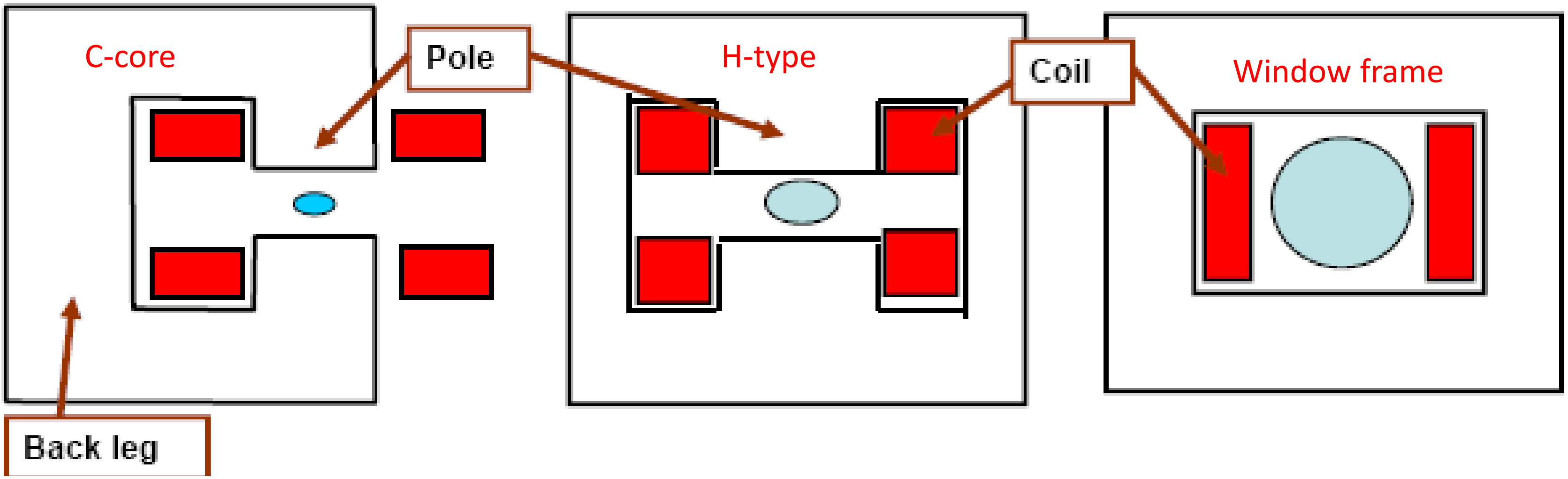




$$\boxed{B_y(x) = const}$$



Standard Dipole Geometries



	C-core	H-type	Window Frame
advantages	easy access		no pole shims
	classic design	symmetric	symmetric
		rigid	rigid
			compact
disadvantages	pole shims req.	pole shims req.	High ampere turn
	asymmetric	difficult access	difficult access
	less rigid		insulation thickness

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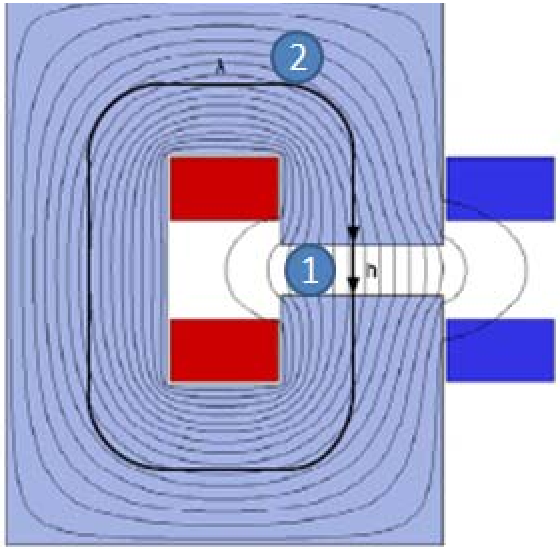
Normal Conducting Dipole Magnet



According to Maxwell it is:

$$\oint \overline{H} \bullet \overline{dl} = \oint_{Path1} \overline{H} \bullet \overline{dl} + \oint_{Path2} \overline{H} \bullet \overline{dl} = NI$$

Along Path 1 $\quad |H| = \dfrac{B}{\mu_0}$ and $H \| l$

Therefore: $\quad \oint_{Path1} \overline{H} \bullet \overline{dl} = \dfrac{Bh}{\mu_0}$

Along path 2, $\quad |H| = \dfrac{B}{\mu \mu_0}$ For iron: $\mu \approx 1000$

Therefore: $\quad \oint_{Path2} \overline{H} \bullet \overline{dl} = |H|_{iron}\, l_{iron} << \dfrac{Bh}{\mu_0} \approx 0$

Therefore: $\quad \overline{H} \bullet \overline{dl} = 0$

Finally: $\quad \oint \overline{H} \bullet \overline{dl} = \boxed{NI \approx \dfrac{Bh}{\mu_0}}$

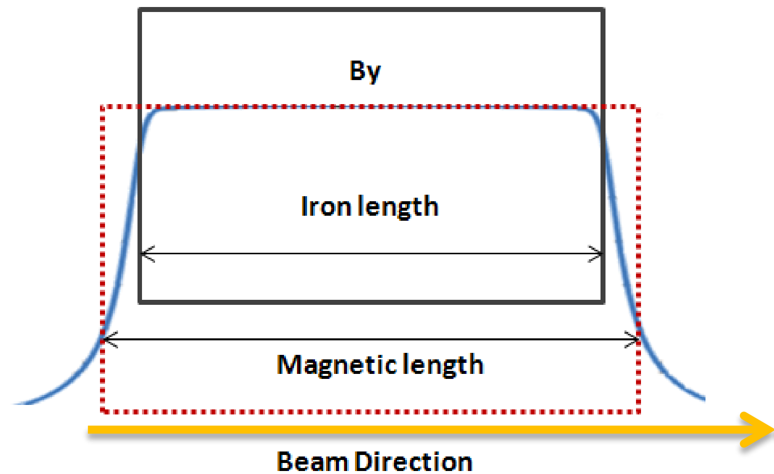
B magnetic flux
h (gap height)
μ_0 air permeability

Magnetic length

Coming from ∞, B increases towards the magnet center (stray flux)

'Magnetic' length > iron length

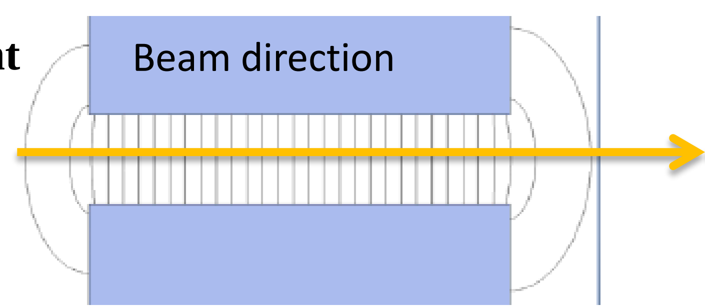
Magnetic length: $$L_{magnetic} = \int_{-\infty}^{+\infty} B\,dz \Big/ B_0$$



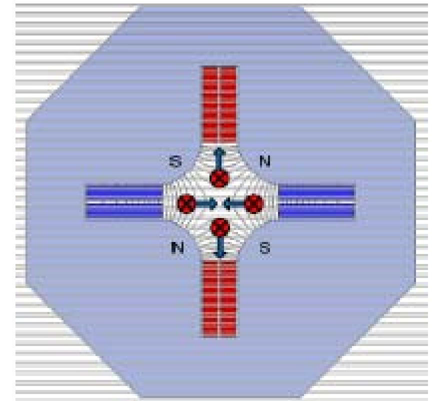
For a dipole: $$L_{magnetic} = L_{iron} + 2*(2h)*K$$

2h: gap height
k: geometry specific constant (≈ 0.56)

K gets smaller in case of:
- **Pole width < gap height**
- **Saturation**

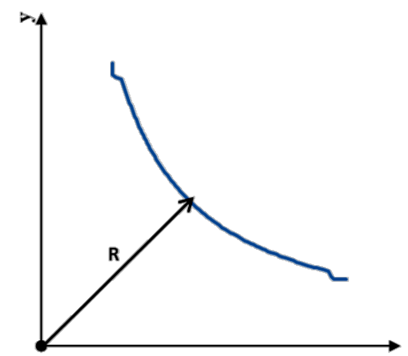


Quadrupole magnet



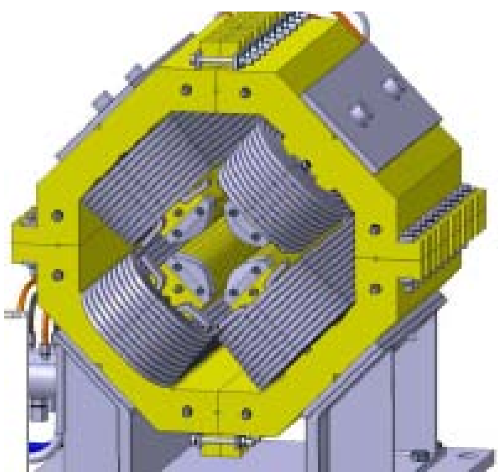
- 4 poles, 4 coils
- Focus the beam and prevent deviating
- Zero field in center
- Strong gradient *g (T/m)*
- Placed in straight sections between bending magnets

Pole profile eq.: $xy = \frac{R^2}{2}$

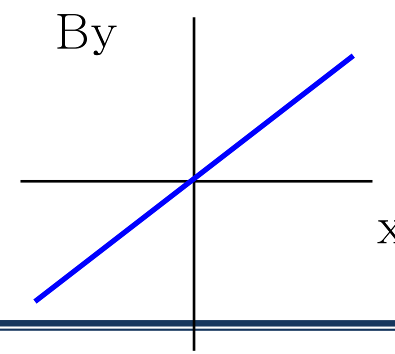


Quadrupole main parameters

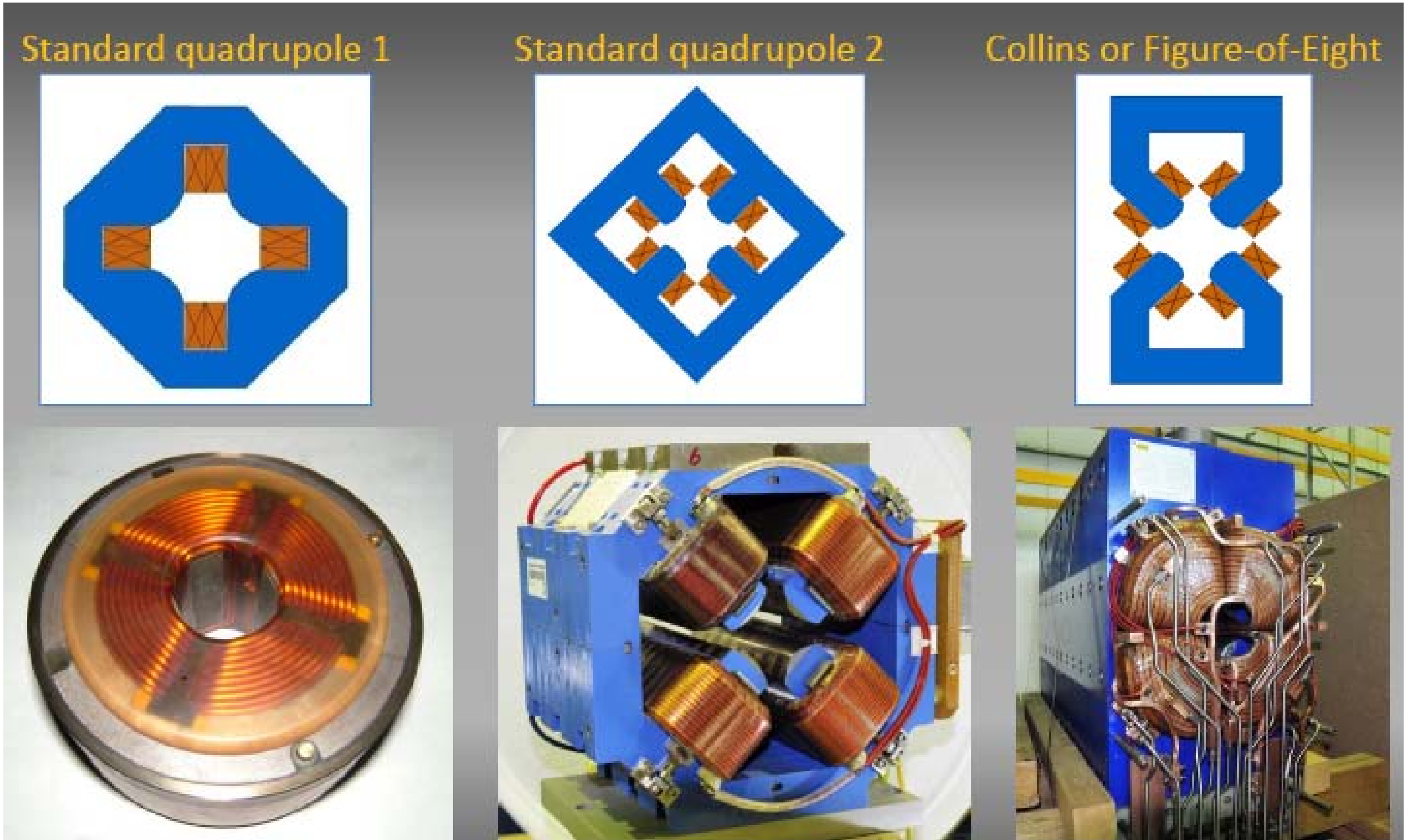
- **g (magnetic gradient field)**
- **L (length)**
- **R (Aperture)**
- **GFR (good field region)**



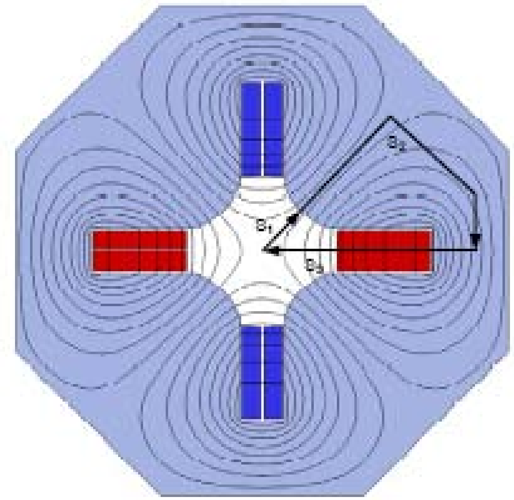
$$\boxed{B_y(x) = g\ x}$$



Standard Quadrupole Geometries



Normal Conducting Quadrupole Magnet



integration path split in 3 sections

$$\int_{\partial a} \mathbf{H} \cdot \mathbf{T} \, \mathrm{d}s = N\, I$$

$$\int_{s_1} \mathbf{H}_1 \cdot \mathbf{T}_1 \, \mathrm{d}s + \int_{s_2} \mathbf{H}_2 \cdot \mathbf{T}_2 \, \mathrm{d}s + \int_{s_3} \mathbf{H}_3 \cdot \mathbf{T}_3 \, \mathrm{d}s$$

field defined by gradient g

$B_x = gy$; $B_y = gx$

along s1: $$H = \frac{g}{\mu_0}\sqrt{x^2 + y^2} = \frac{g}{\mu_0} r.$$

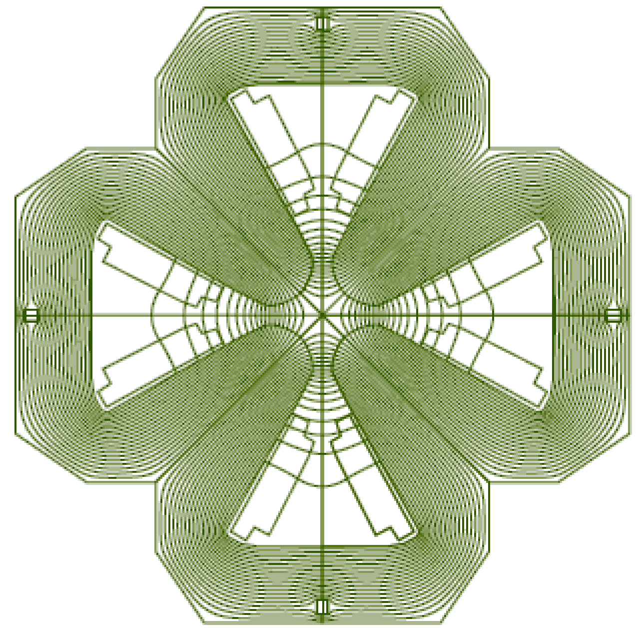
along s3: $$\mathbf{H} \cdot \mathbf{T} = 0.$$

along s2: & $\mu_{\mathrm{r}} \gg 1$

$$\int_0^{r_{\mathrm{a}}} H \mathrm{d}r = \frac{g}{\mu_0} \int_0^{r_{\mathrm{a}}} r \mathrm{d}r = \frac{g}{\mu_0} \frac{r_{\mathrm{a}}^2}{2} = N\, I \longrightarrow \boxed{g = \frac{2\mu_0 N I}{r_{\mathrm{a}}^2}}$$

g field gradient
ra Aperture
μ_0 air permeability

Magnetic length

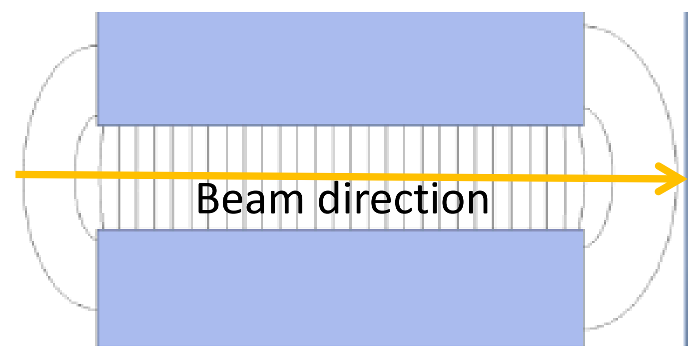


'Magnetic' length > iron length

Magnetic length For a Quadrupole:

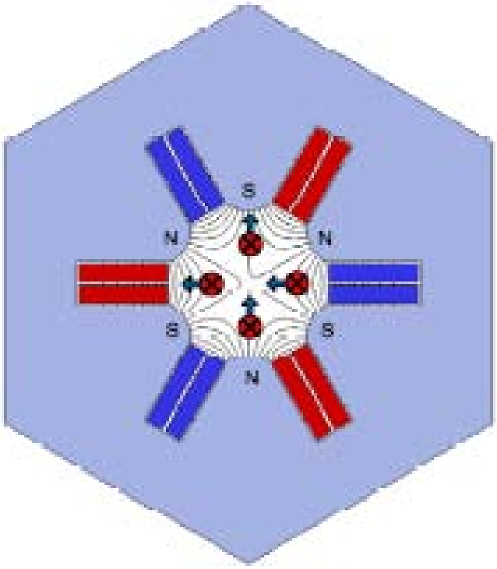
$$L_{magnetic} = L_{iron} + 2RK$$

R: Aperture
k: geometry specific constant (≈ 0.45)



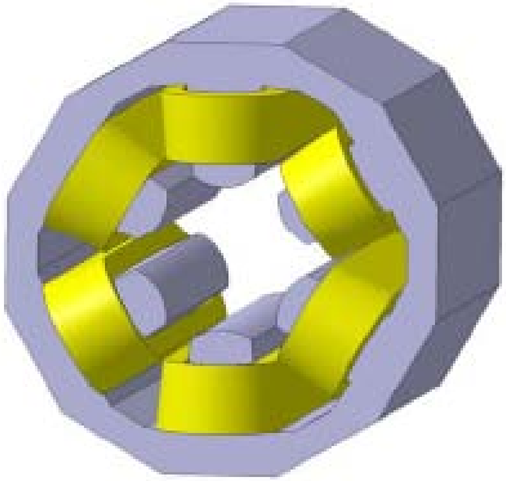
Sextupole magnet

- Sextupole magnet correct chromatic aberration due to focusing errors on particles with different energy



Sextupole main parameters

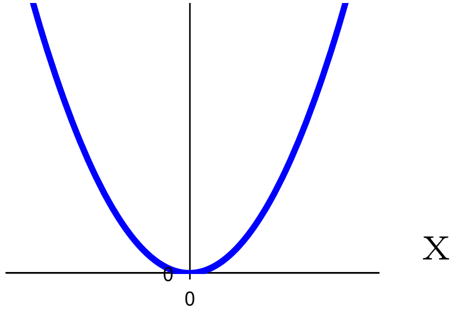
- **B'' (Sextupole component)**
- **L (length)**
- **R (Aperture)**
- **GFR (good field region)**



Pole profile:

$$3yx^2 - y^3 = R^3$$

$$\boxed{B_y(x) = \tfrac{1}{2} B'' x^2}$$



Normal Conducting Sextupole Magnet

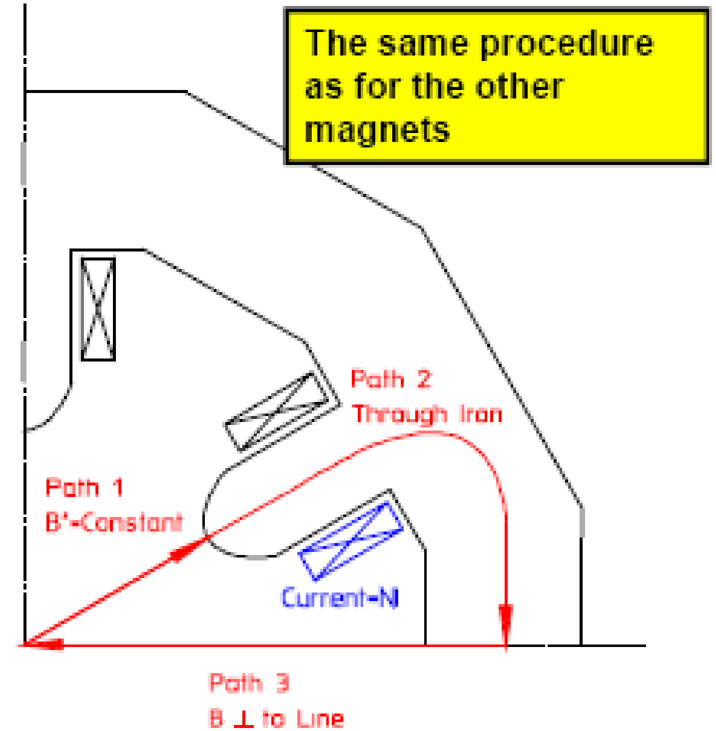
Along Path 1: $B'(r) = \int B''dr = B''r$

$$B(r) = \int B''rdr = \frac{B''r^2}{2}$$

$$H \| r \quad \text{and} \quad |H(r)| = \frac{B''r^2}{2\mu_0}$$

$$\oint_{Path1} \overline{H} \bullet \overline{dl} = \int_0^R \frac{B''r^2dr}{2\mu_0} = \frac{B''R^3}{6\mu_0}$$

Finally; $\oint \overline{H} \bullet \overline{dl} = \boxed{NI \approx \frac{B''R^3}{6\mu_0}}$

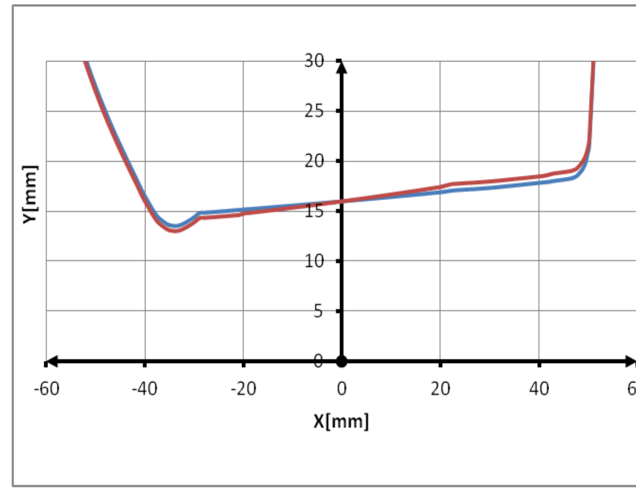


B´´ Sextupole component
R Aperture
µ0air permeability

Combined magnets

✓ Functions generated by pole shape (sum a scalar potentials): Amplitudes cannot be varied independently

- Dipole + quadrupole



$$y = \frac{h(O)}{1 + \frac{gx}{B_O}}$$

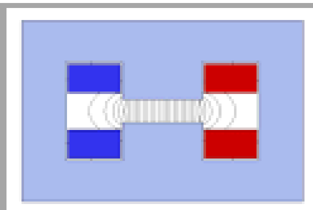
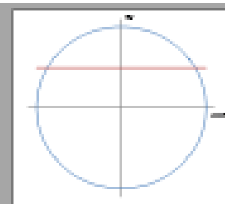
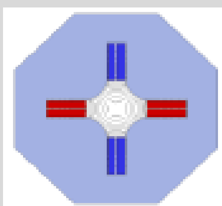
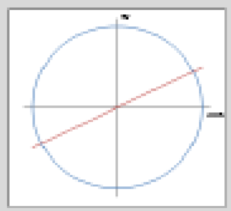
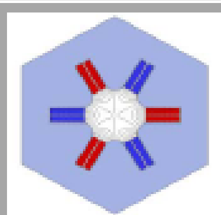
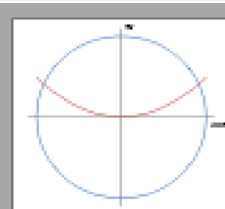
- Dipole + quadrupole + sextupole

$$y = \frac{h(O)}{1 + \frac{gx}{B_O} + \frac{B''x^2}{2B_O}}$$

- Quadrupole + sextupole

$$gxy + B''(x^2 y - \frac{y^3}{3}) = cte.$$

Summary

Pole shape	Field distribution	Pole equation	B_y on x-axis
		$y= \pm r$ Bend the electron beam	$B_y= a_1 = B_0 =$ const.
		$2xy= \pm r^2$ focuse the electron beam	$B_y= a_2 x$
		$3x^2y - y^3 = \pm r^3$ correct chromatic aberration	$B_y= a_3(x^2- y^2)$

Magnet Design

Magnet Design Procedure

Define Specifications (by beam dynamics)

↓

Perform computer design

- a) obtain the needed current from the defined parameters
- b) choosing material for the yoke
- c) profile designing and pole optimization
- d) Saturation test
- e) Checking field tolerances in the good field region

↓

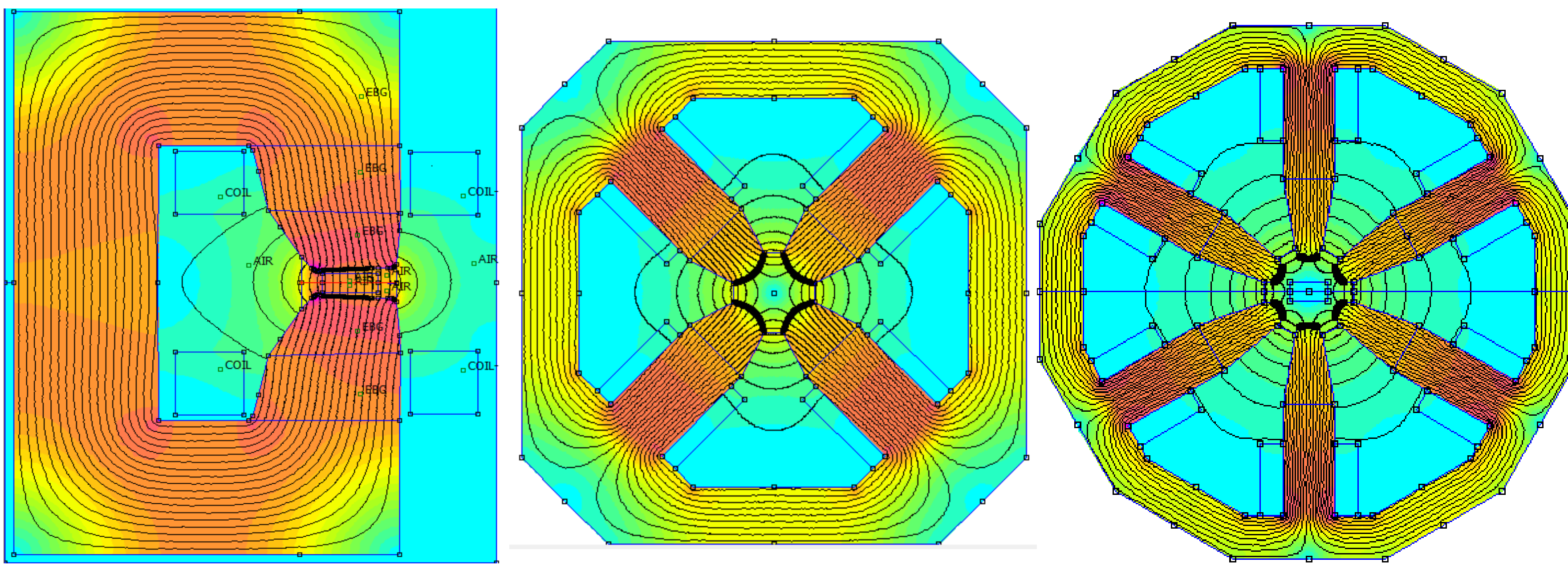
Electrical and Cooling Design

↓

Mechanical Design

2D design: (Poisson Superfish ,FEMM, Opera2D …)

- Use pre-processor or modeler to build geometry
- Profit from symmetries to reduce number of elements



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Yoke materials

Today's standard: cold rolled, non-oriented electro-steel sheets

- Massive iron only for dc magnets

•Magnetic and mechanical properties can be adjusted by final annealing in decarbonized atmosphere – the smaller carbon content results in better magnetic properties (Increase in permeability Decrease in hysteresis loss and aging)

- Magnetic properties (permeability, coercivity) should be within small tolerances .
- Homogeneity and reproducibility among the magnets of a series can be enhanced by selection, sorting or shuffling.
- Organic or inorganic coating for insulation and bonding.
- Material is usually cheaper, but laminated yokes are commonly used esp. in Booster rings. (Eddy current)
- Packing factor should be kept bellow 98%.

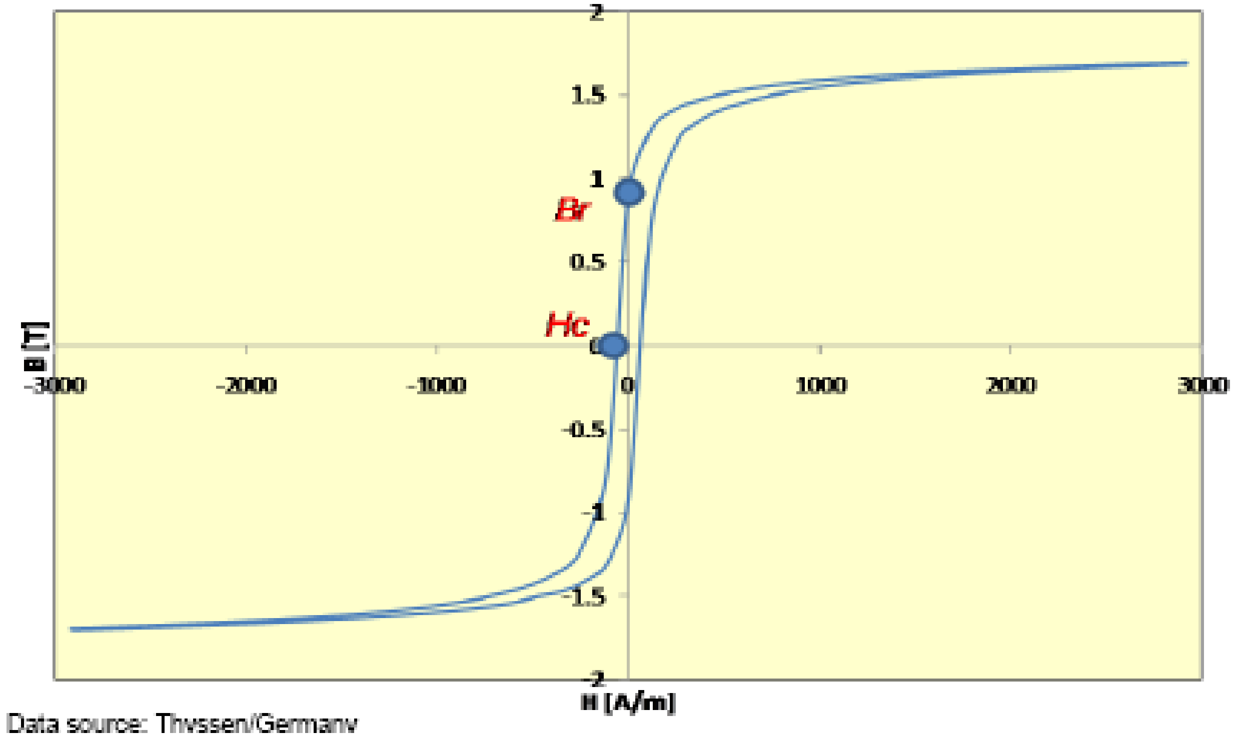
Common used materials:

• AISI1010 (max 0.1 % carbon content & max 0.3% silicon content)

•1200-100A(less than 0.003% carbon content & less than 1.3% silicon content)

•M400-50A(0.02% carbon content & 2.4 % silicon content)

•M800-50A(0.01% carbon content & 1.7 % silicon content)



- Sheet thickness: $0.3 \leq t \leq 1.5$ mm
- Specific weight: $7.60 \leq \delta \leq 7.85$ g/cm3
- Coercivity: Hc< 70 (±10) A/m
- Electrical resistivity @ 20°C: 0.16 (low Si) $\leq \rho \leq$ 0.61 μΩm (high Si)

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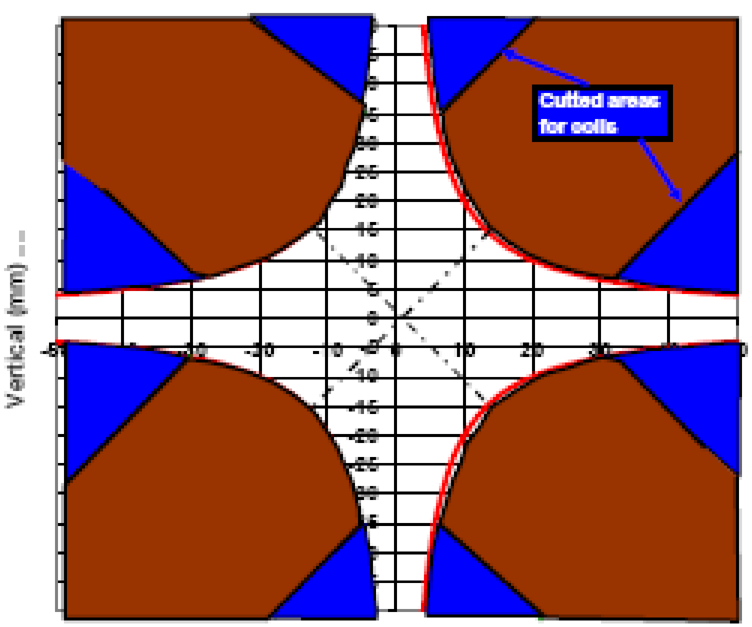
Pole Optimization



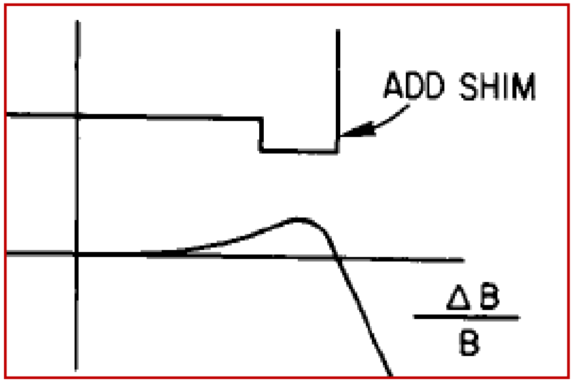
Summary of 'allowed harmonics' in fully symmetric magnets:

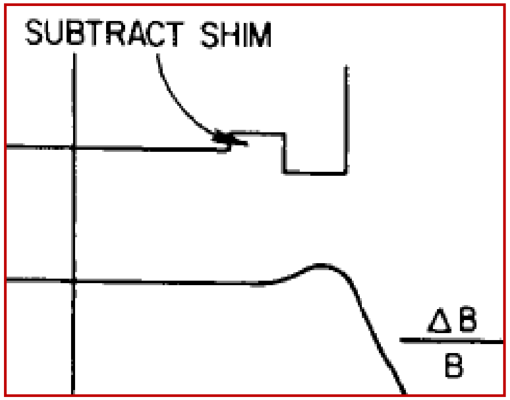
Fundamental geometry	'Allowed' harmonics
Dipole, n = 1	n = 3, 5, 7, ... (6 pole, 10 pole, etc.)
Quadrupole, n = 2	n = 6, 10, 14, ... (12 pole, 20 pole, etc.)
Sextupole, n = 3	n = 9, 15, 21, ... (18 pole, 30 pole, etc.)
Octupole, n = 4	n = 12, 20, 28, ... (24 pole, 40 pole, etc.)

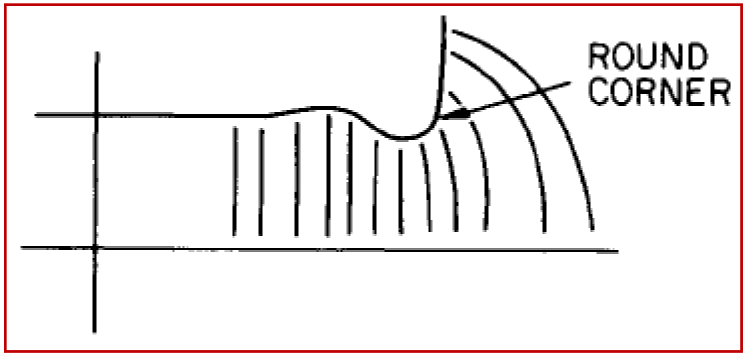
By cutting the pole profile in order to have space for the introduction of the coils the field distribution will be disturbed and higher multipoles will be introduced.

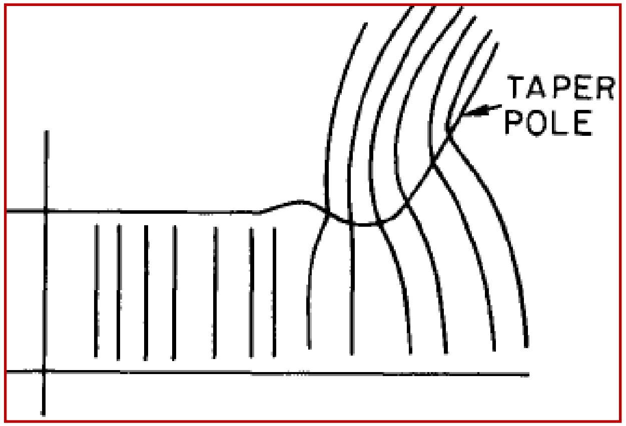
Rising the amount of these multipoles leads to BAD field quality i.e. more than 0.1% → SHIMMING is needed

Pole Optimization-Shimming process



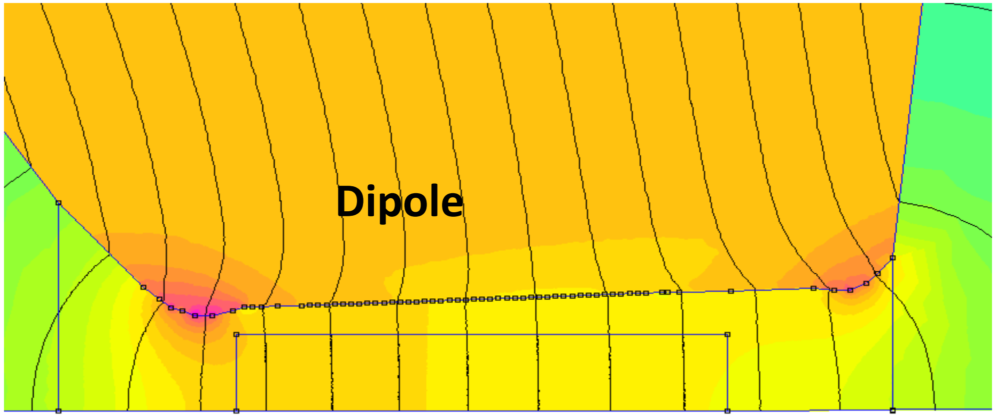


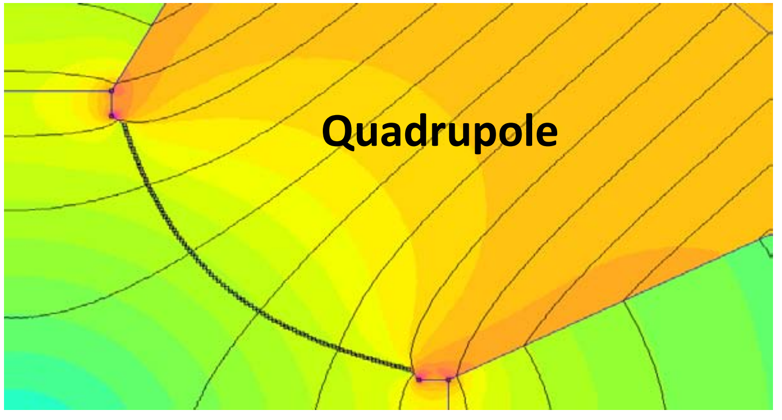


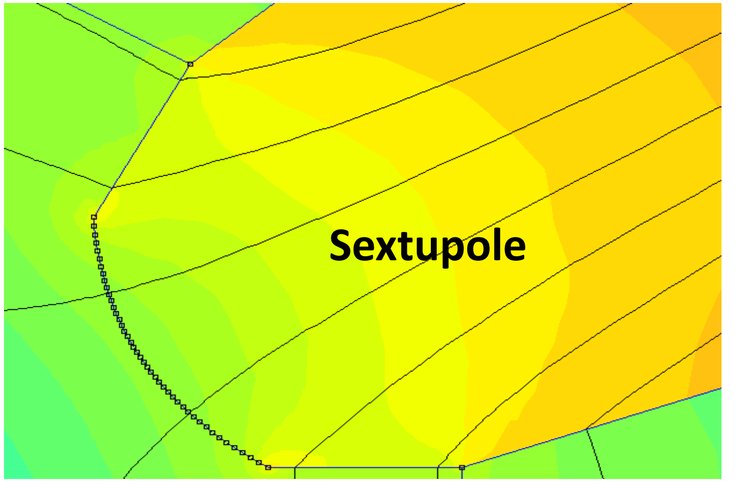


Pole Optimization is an iteration process & should be continued till one reaches the desire field quality i.e. < 10^{-4}

ILSF Dipole, Quadrupole & Sextupole shims







Field Quality Calculations

$$\Delta B = \frac{B - B_0}{B_0}$$

Dipole

$$B_0 = const\,central\ \ field$$

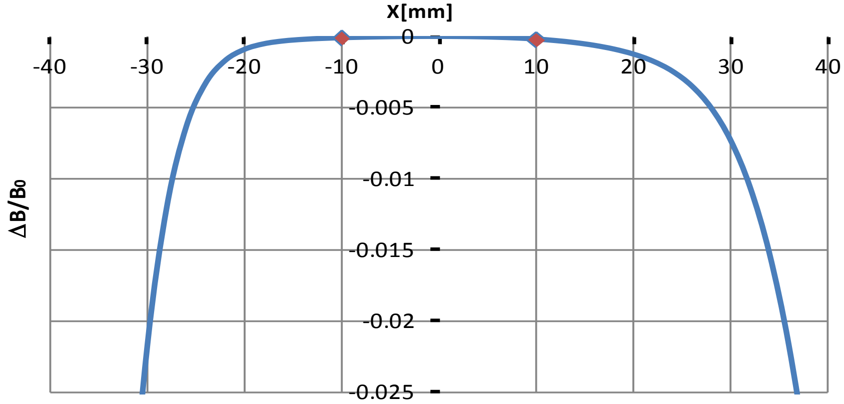
Quadrupole

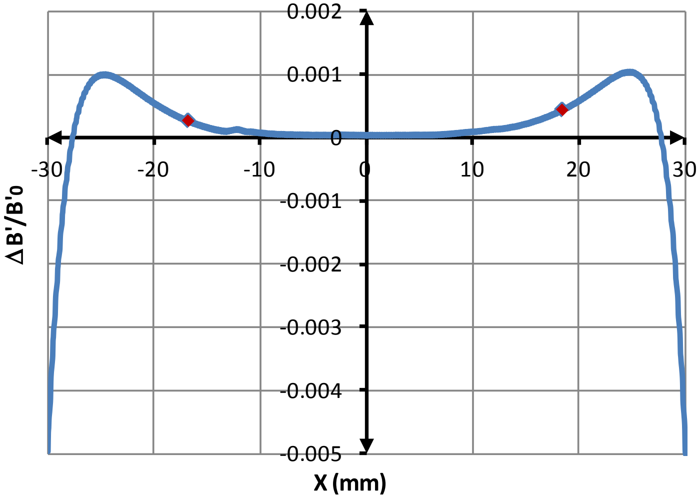
$$B_0 = g_0 x$$

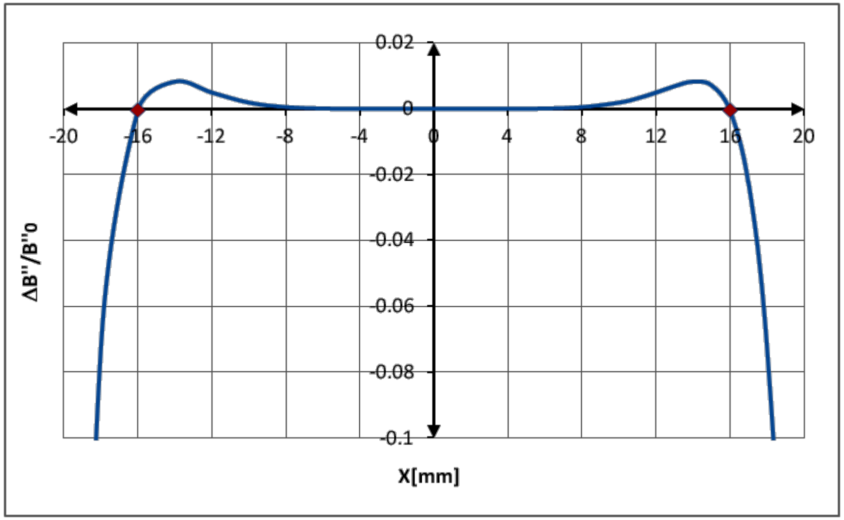
Sextupole

$$B_0 = \tfrac{1}{2} B_0'' x^2$$

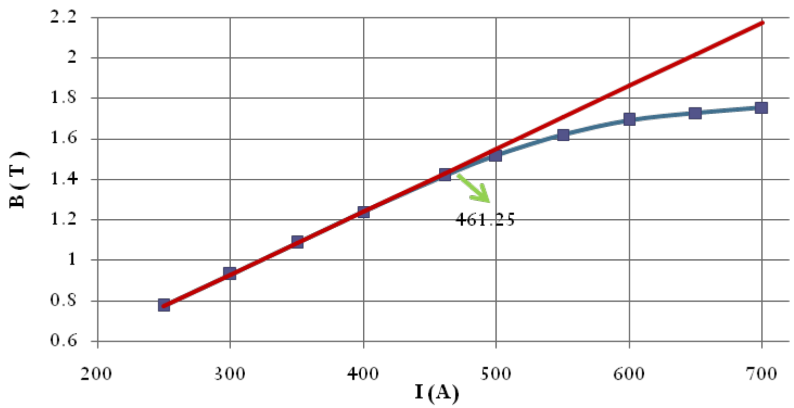
$B(x)$ Is the field at each point calculated by simulation

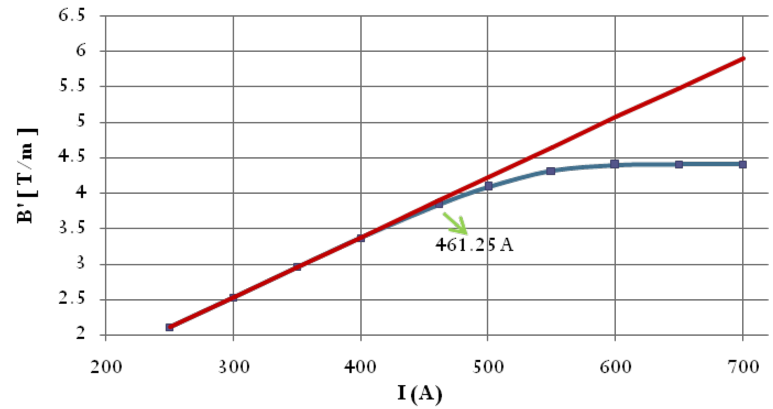

X[mm]
ΔB/B0
-40
-30
-20
-10
0
10
20
30
40
0
-0.005
-0.01
-0.015
-0.02
-0.025

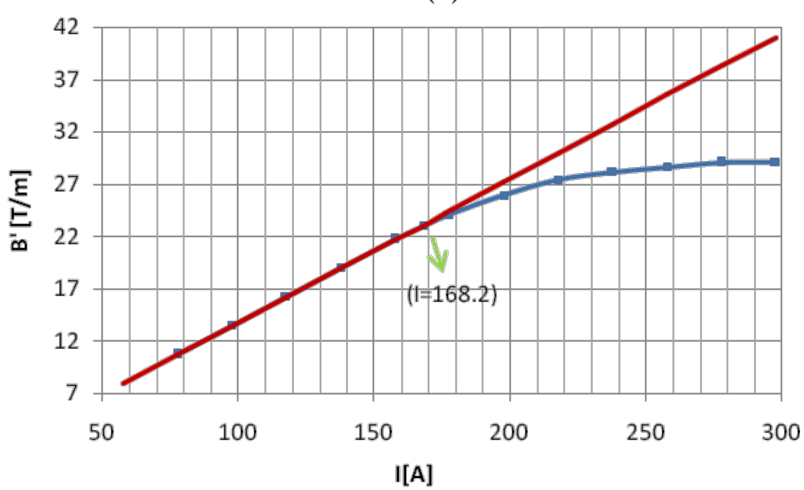

ΔB'/B'0
X (mm)
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-30
-20
-10
0
10
20
30

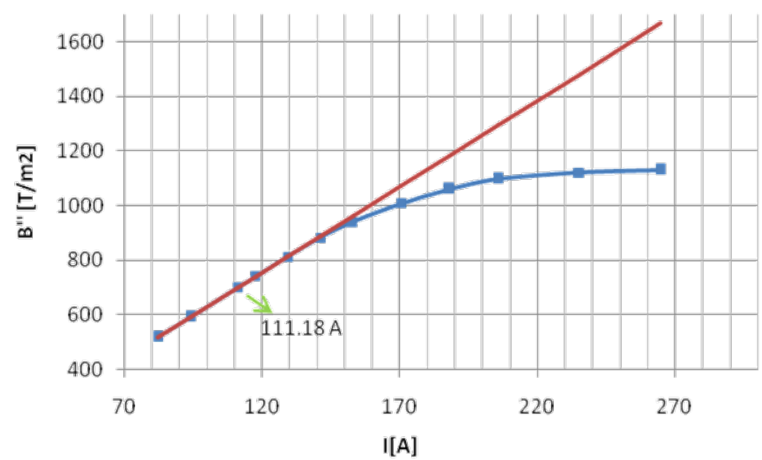

ΔB''/B''0
X[mm]
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-20
-16
-12
-8
-4
0
4
8
12
16
20

Saturation test

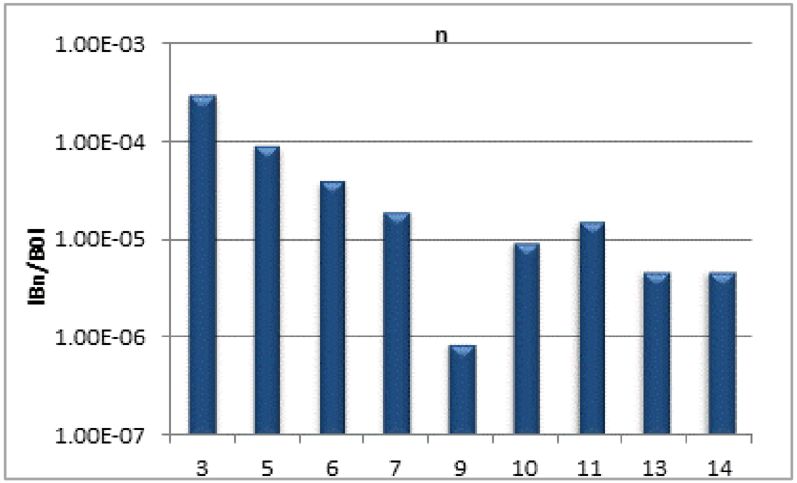


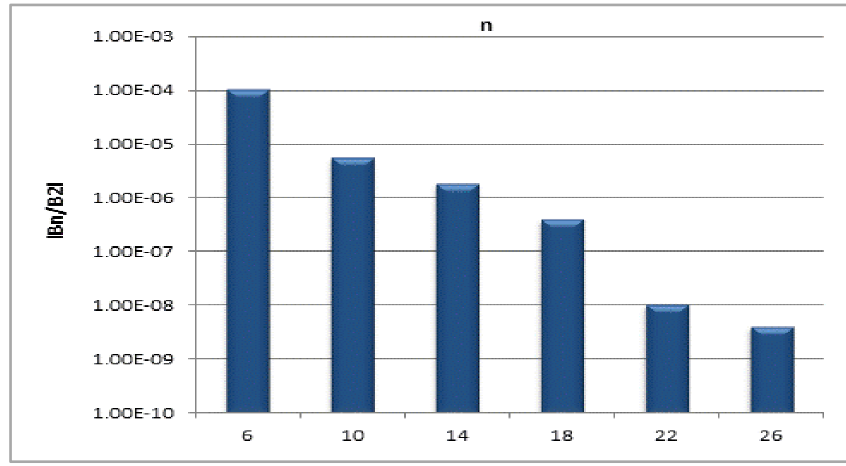


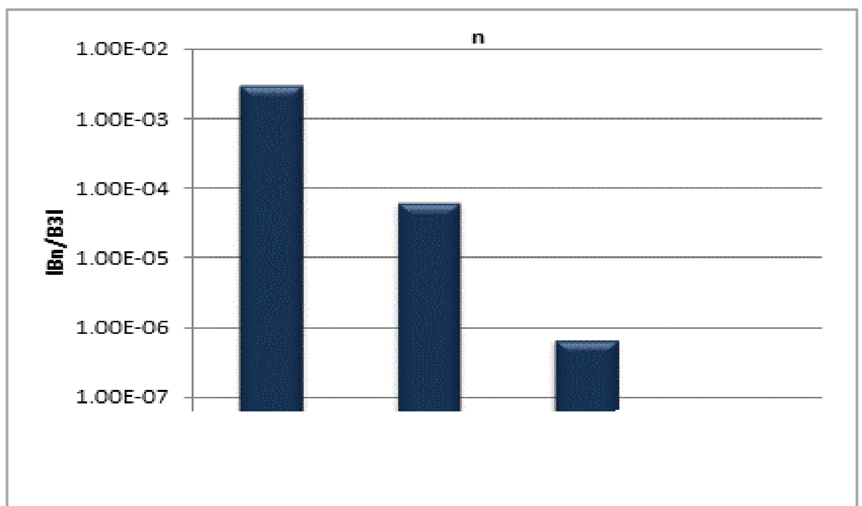




Harmonic analysis

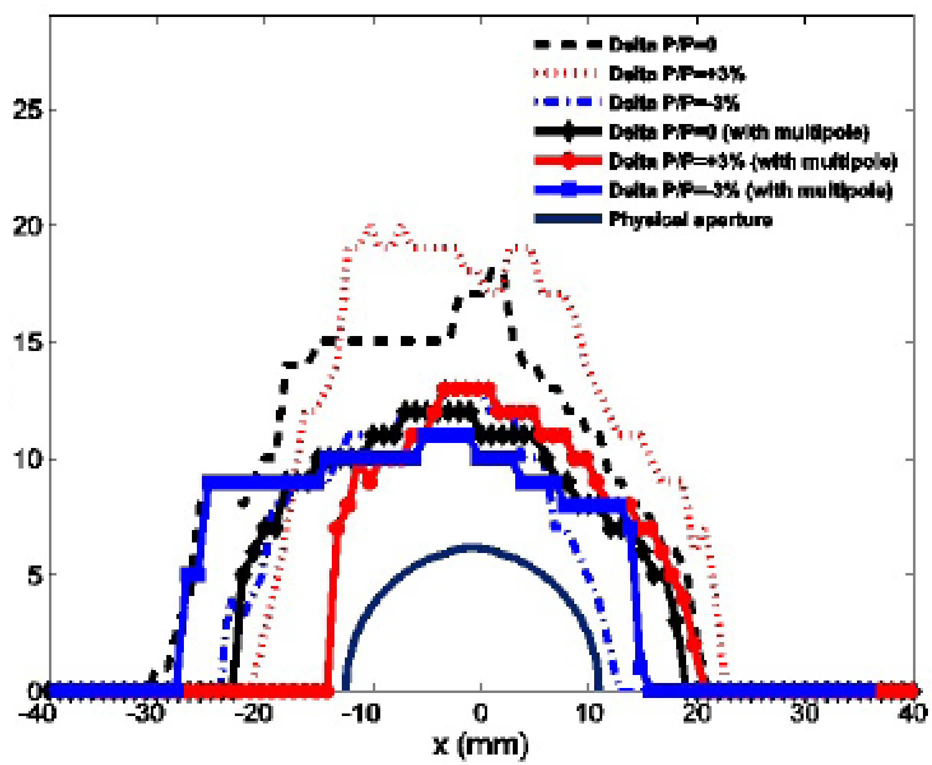






Harmonic analysis & Dynamic Aperture

Dipole			
	Field component	b_n	B_n/B_1[@12 mm]
n=1	Dipole	7.24E-01	1
n=3	Sextupole	5.46E-02	1.086E-05
n=5	10-pole	4.62E+02	1.322E-05
n=7	14-pole	-1.33E+04	-5.470E-08
n=9	18-pole	-1.67E+09	-9.934E-07
Quadrupole			
	Field component	b_n	B_n/B_2[@18 mm]
n=2	Quadrupole	2.50 E+1	1
n=6	12-pole	9.78 E+3	4.10 E-5
n=10	20-pole	-2.95 E+8	-1.30 E-7
n=14	28-pole	-1.23 E+16	-5.70 E-7
n=18	36-pole	-1.44 E+22	-7.03 E-8
Sextupole			
	Field component	b_n	B_n/B_3[@16 mm]
n=3	Sextupole	4.50 E+2	1
n=9	18-pole	-2.07 E+10	-7.71 E-4
n=15	30-pole	-6.76 E+18	-4.22 E-6
n=21	42-pole	1.13 E+27	1.18 E-8
n=27	54-pole	4.45 E+35	7.82 E-11

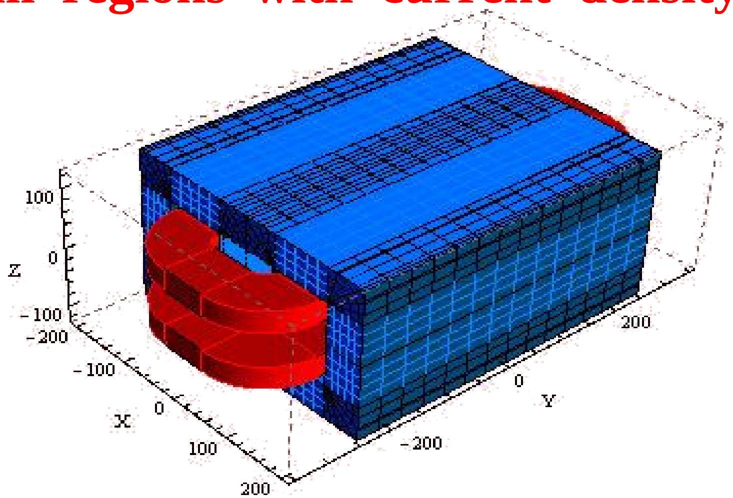


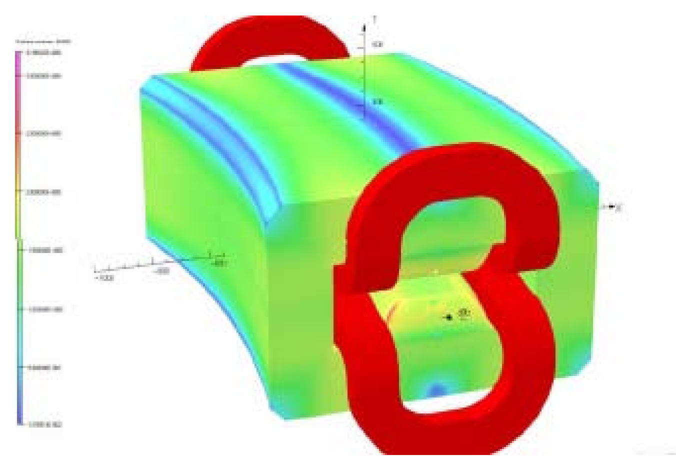
3D design:(Radia,Tosca,Mermaid,Flux3D…)

3D design is necessary to study :

- The longitudinal field distribution
- End effects in the yoke
- End effects from coils
- Magnets where the aperture is large compared to the length

Unlike 2D , in 3D:
all regions with current density have to be modeled completely

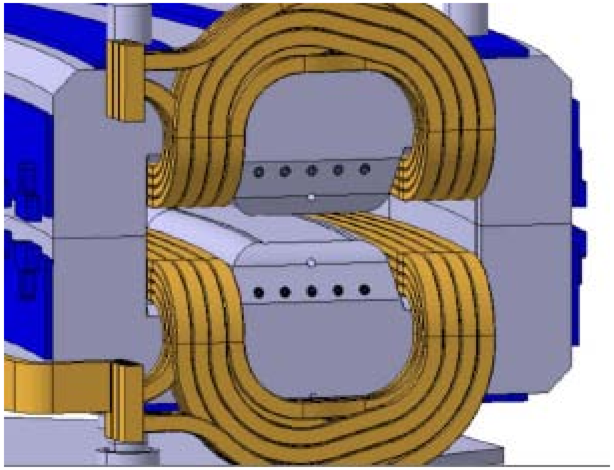




Longitudinal shimming (Chamfering)

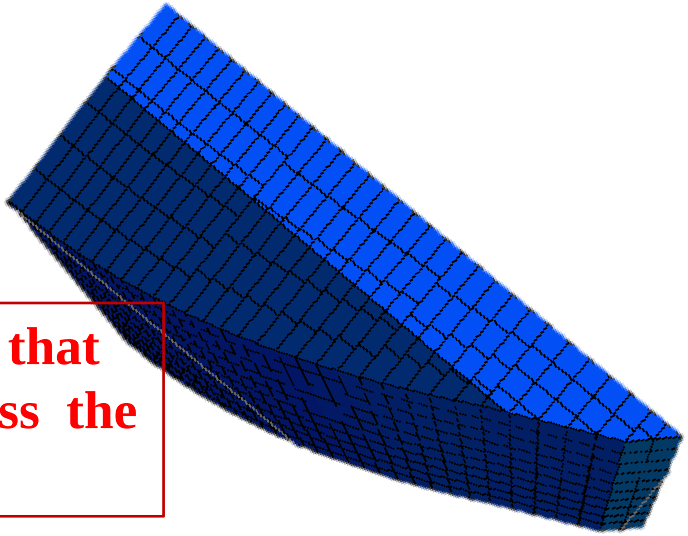
Dipoles:

•Rogowsky roll off or angular cut
•Depth and angle adjusted using 3D codes or measurements



Quadrupoles:
•Angular cut at the end

Sextupoles:
•Usually not chamfered

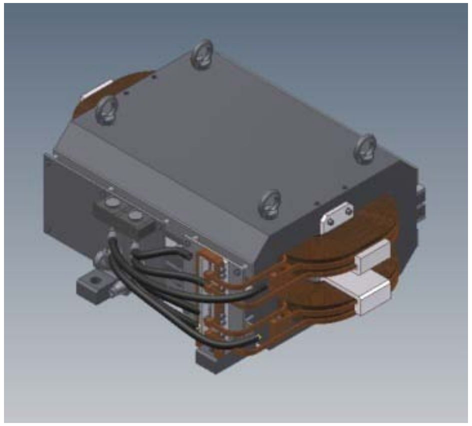


Chamfer should be chosen in such a way that maintain magnetic length constant across the good field region

ILSF Prototype Magnet I

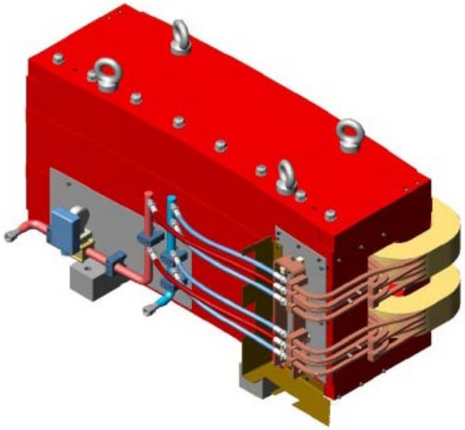
Parameter	Value
Field	0.5 T
Magnetic Length	50 cm
Gap height	34 mm
Good Field Region	±20mm

H-Type Dipole Magnet



Parameter	Value
Field	0.72 T
Magnetic Length	155 cm
Gap height	32 mm
Good Field Region	±18mm

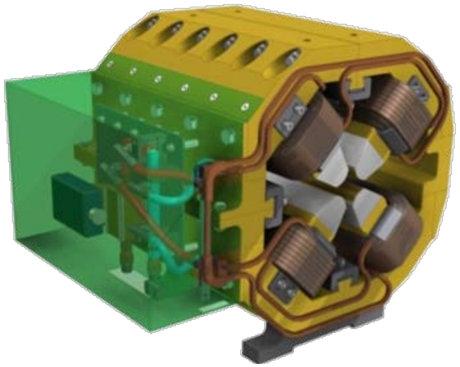
C-Type Dipole Magnet



ILSF Prototype Magnet II

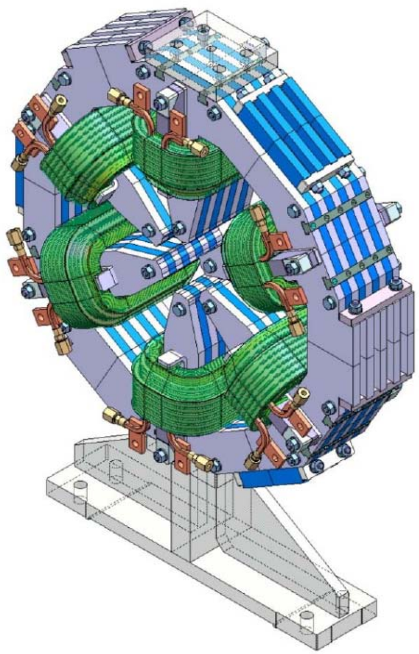
Parameter	Value
Field Gradient	23T/m
Magnetic Length	26 cm
Aperture radius	30 mm
Good Field Region	±18mm

Quadrupole Magnet



Parameter	Value
Sextupole Strength	750T/m2
Magnetic Length	24 cm
Aperture radius	36mm
Good Field Region	±21mm

Sextupole Magnet



Iranian Light Source Facility

prototype H-Type dipole magnet

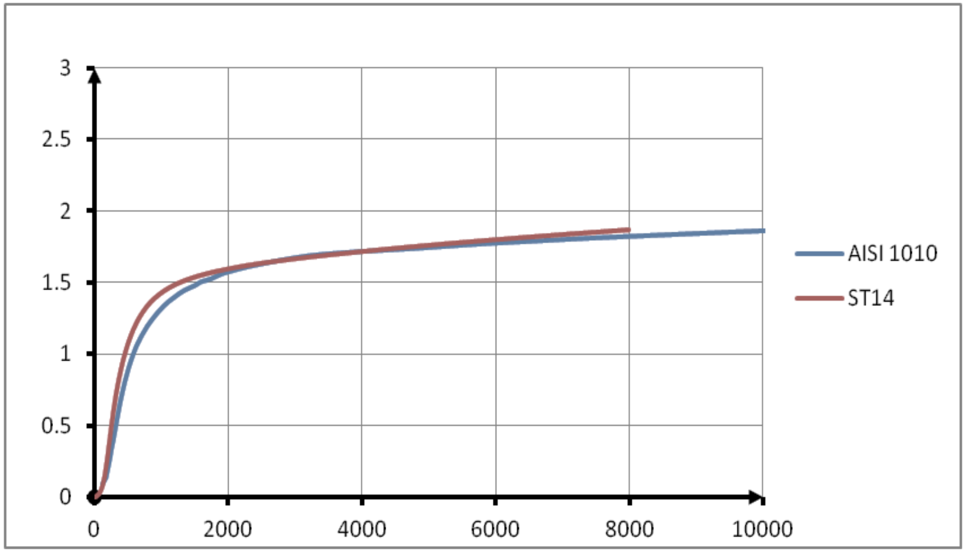
Main Objectives:

- To compare the measurement results with design data.
- To develop fabrication procedures and techniques.
- To find if the available low carbon steel is capable of using as magnetic steel.

Magnet specifications

Parameter	Unit	H. Prototype
Field-B_0	T	0.5
Gradient-B'	T/m	-
Gap	mm	34
Good Field Region	mm	±20
ΔB/B	-	$<1\times10^{-4}$
Mechanical Length	mm	500

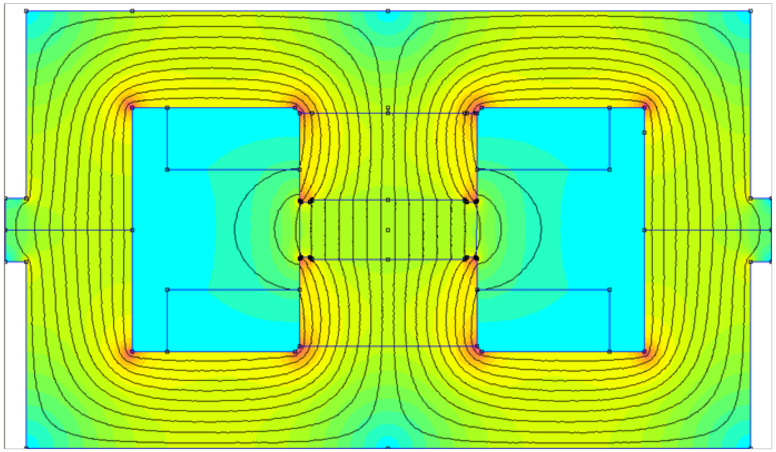
Magnetic specifications of material



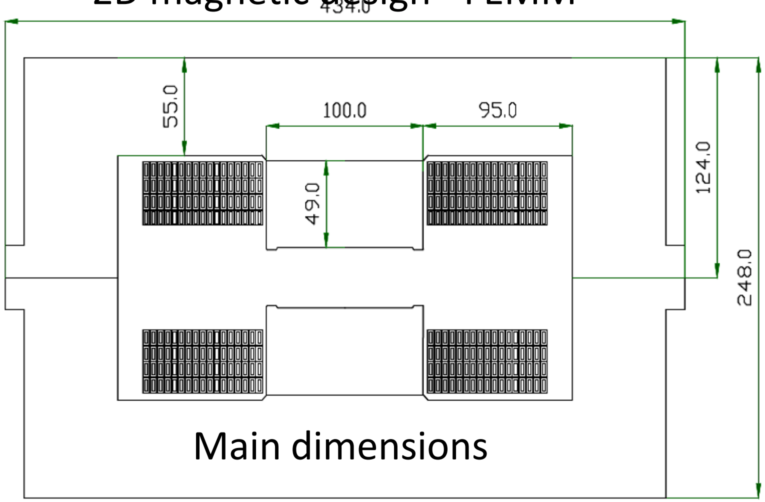
Chemical components of steel

C	Si	Mn	P	S
0.03 %	0.01 %	0.24 %	0.011 %	0.016 %

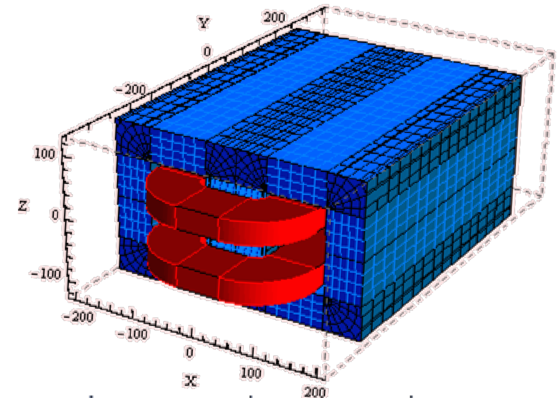
Physical design and main dimensions

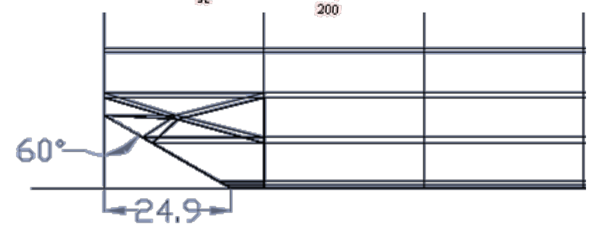


2D magnetic design - FEMM

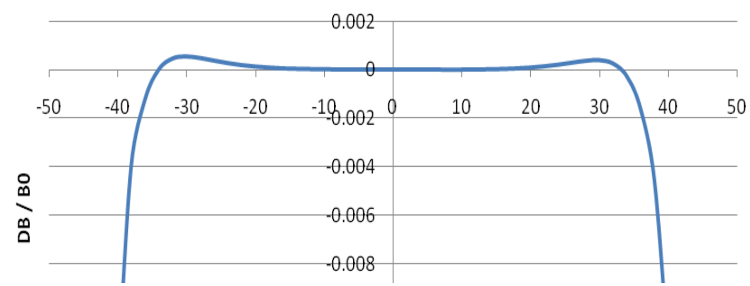


Main dimensions





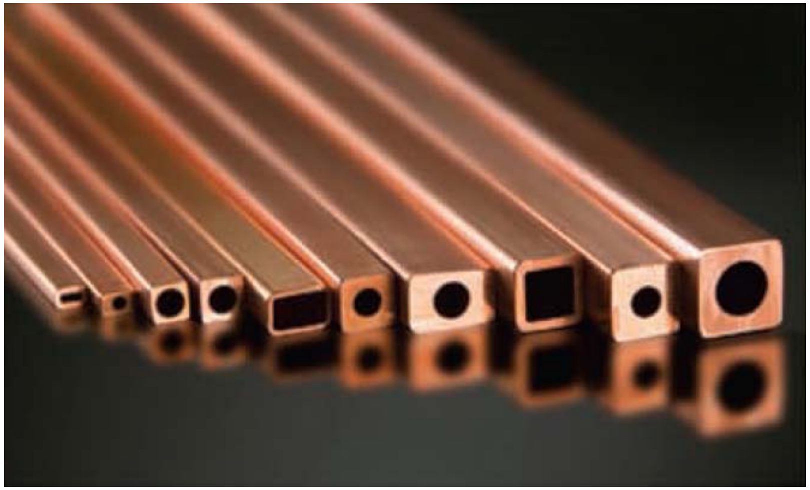
3D magnetic and chamfer design - RADIA

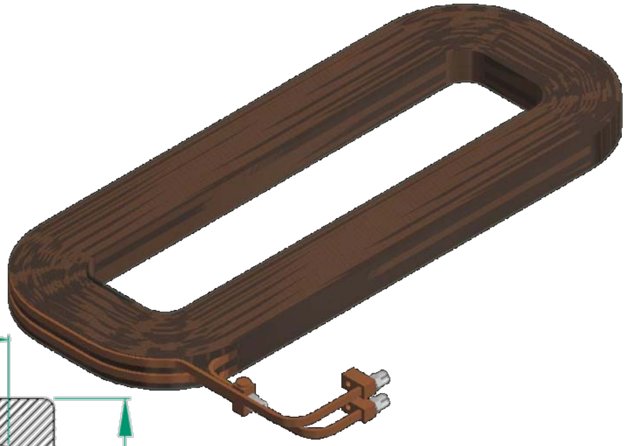


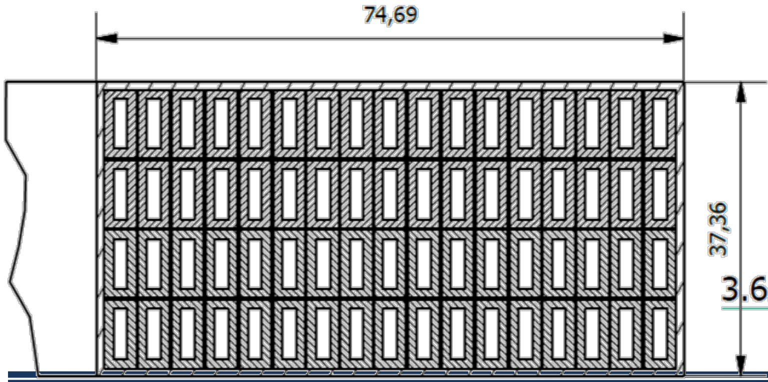
Field tolerances in GFR ≤ 1×10^{-4}

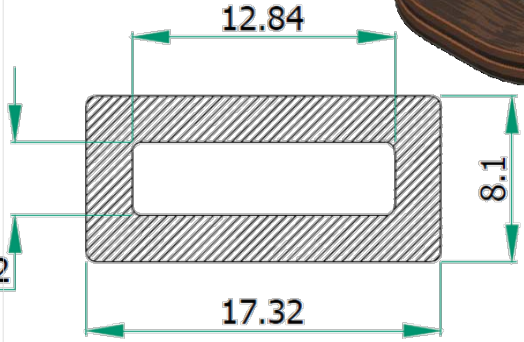
Electrical and cooling design

Parameter	Design Value	Unit
Total ampere-turns per coil	6900	A
Operating current	101	A
Number of turn per coil	68	-
Number of pancakes per coil	2	-
Number of turn per pancake	34	-
Conductor height	4.05	mm
Conductor width	8.66	mm
Cooling channel height	1.81	mm
Cooling channel width	6.42	mm
Copper area	23.45	mm^2
Specific resistance	0.018	Ohm×mm^2/m
Resistance per coil	0.08	Ohm
Current Density	4.33	A/mm^2
Voltage drop per coil	7.79	V
Power per coil	790.24	W
Number of water circuit per coil	2	-
Water temperature rise	8	C˚
Cooling water speed	1.02	m/s
Pressure drop per circuit	10	bar
Reynolds number	1776	-

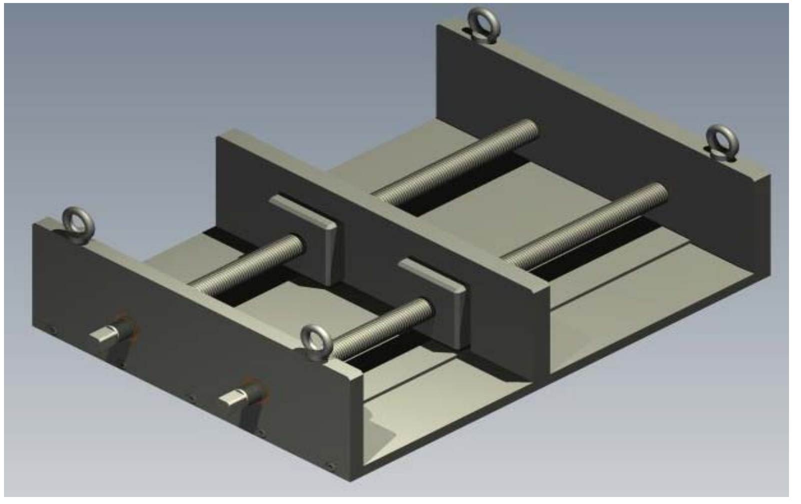








DESIGN AND FABRICATION OF FIXTURES



Stacking fixture

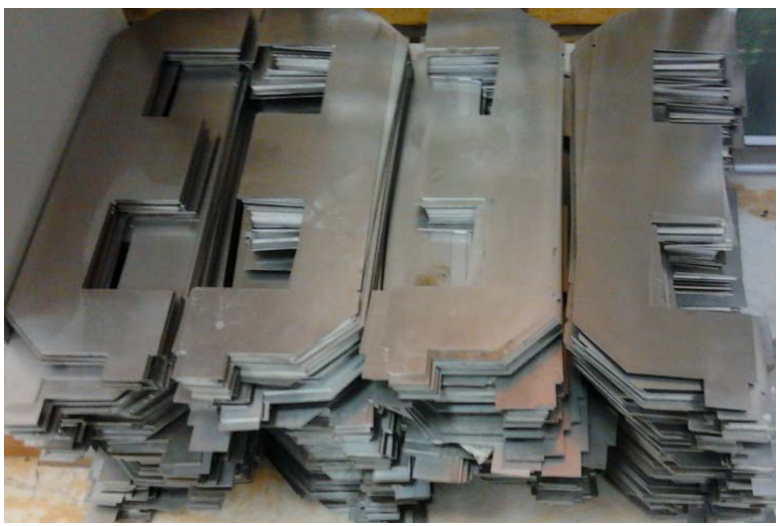
Winding fixture

Iranian Light Source Facility

FABRICATION PROCEDURE OF MAGNET

PREPARATION OF LAMINATIONS AND RESIN

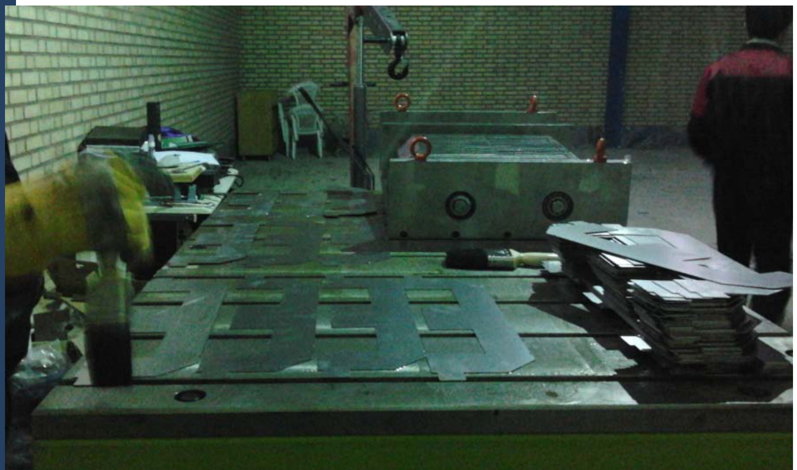
Laser cutting of laminations

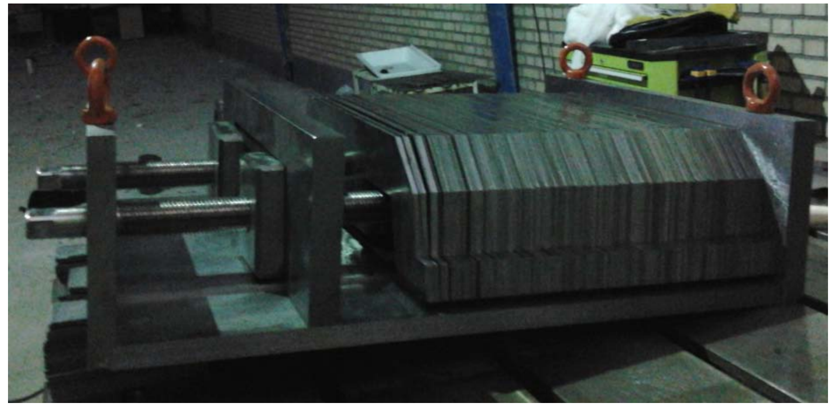


Washed and dried laminations

mixing the two components of resin

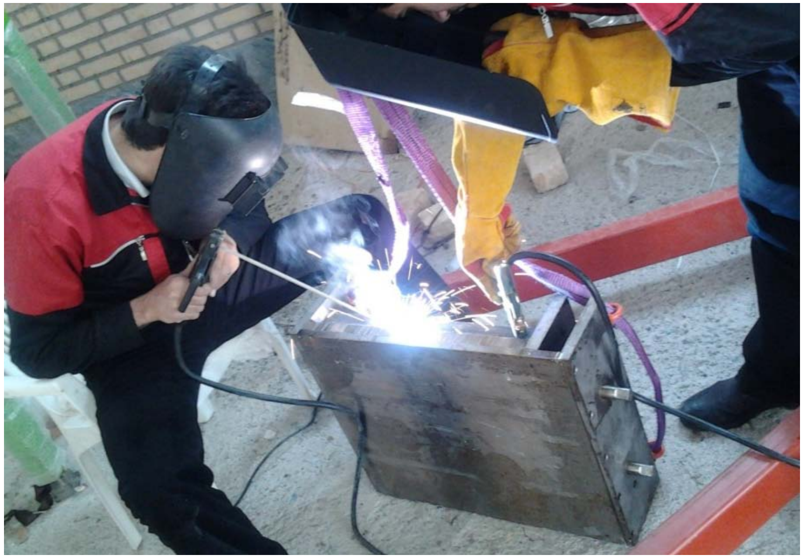
COATING AND STACKING OF LAMINATIONS





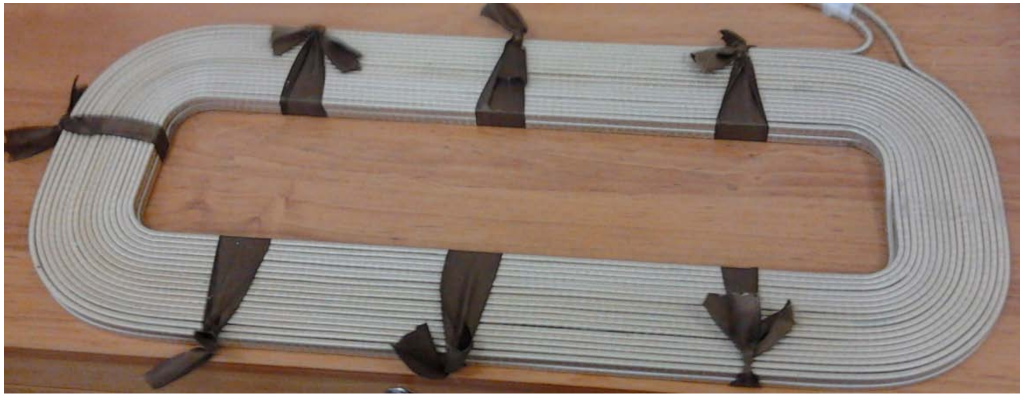
Coating procedure has been done by use of brush, and the packing factor is measured by measuring the length of packed laminations

CURING AND WELDING OF YOKE



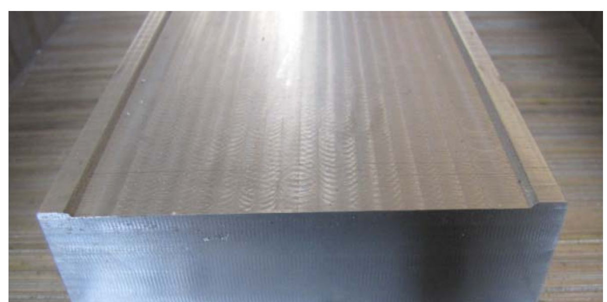
COIL WINDING

In order to have two ends of the coil in the outer side the coil should wind from the middle for each layers and we need to have even layers

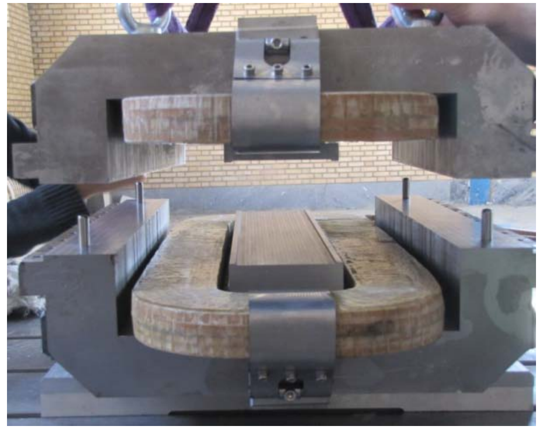
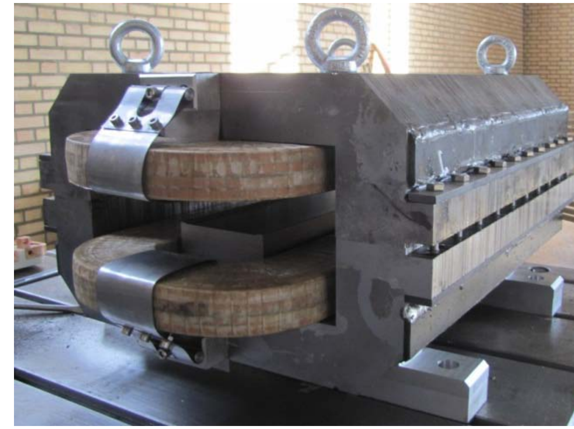


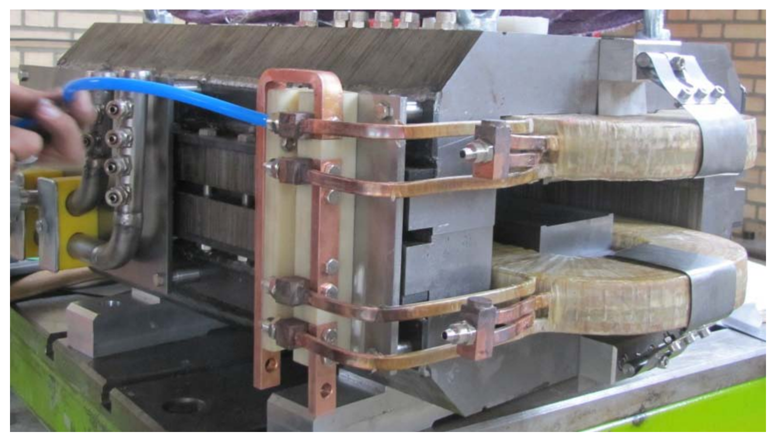
YOKE MACHINING

The machining procedure is done in a way to prevent delamination and to use the common reference point on both yokes to reach to defined tolerances

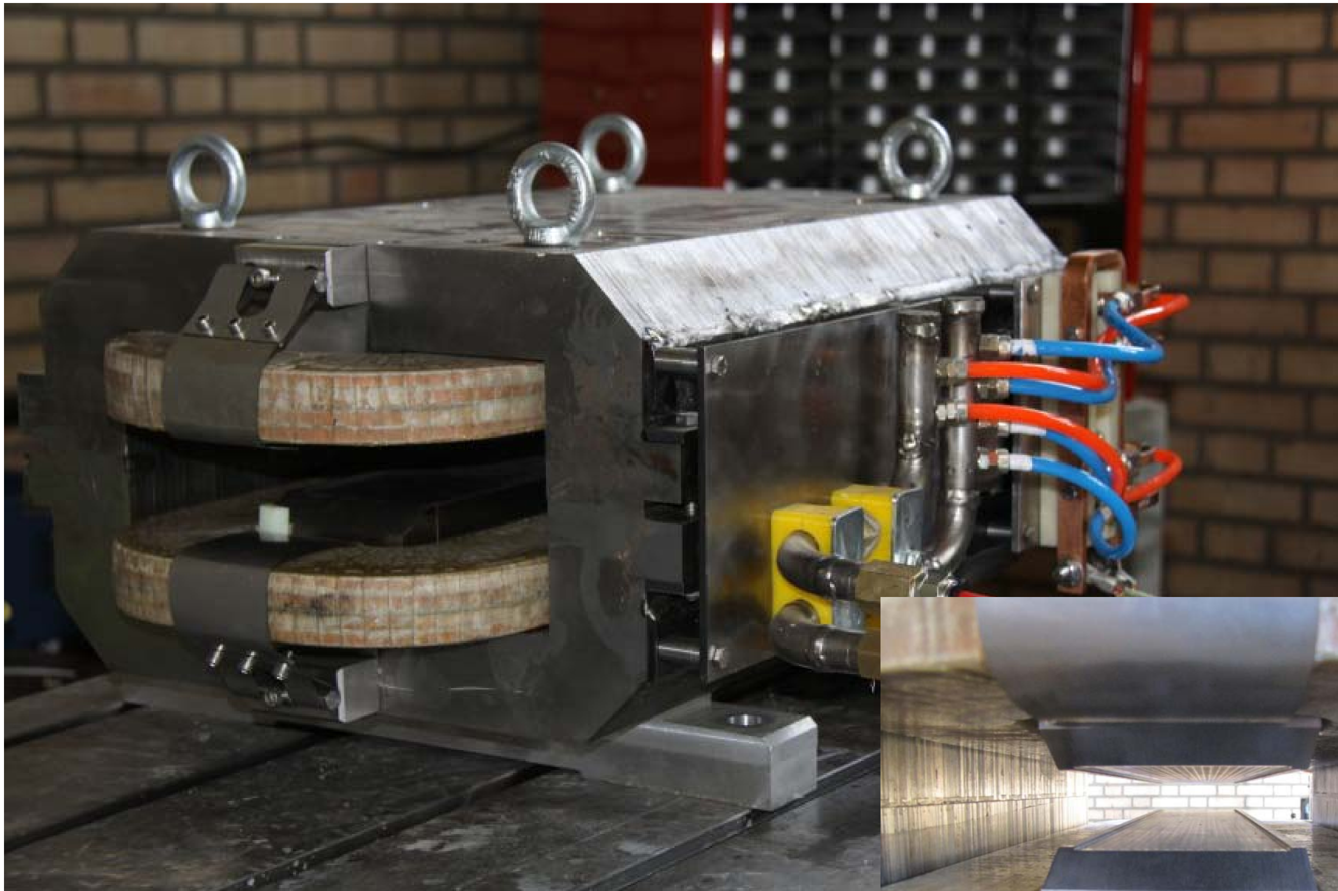


ASSEMBLING

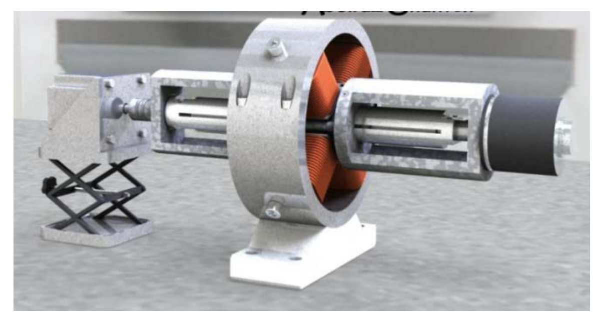






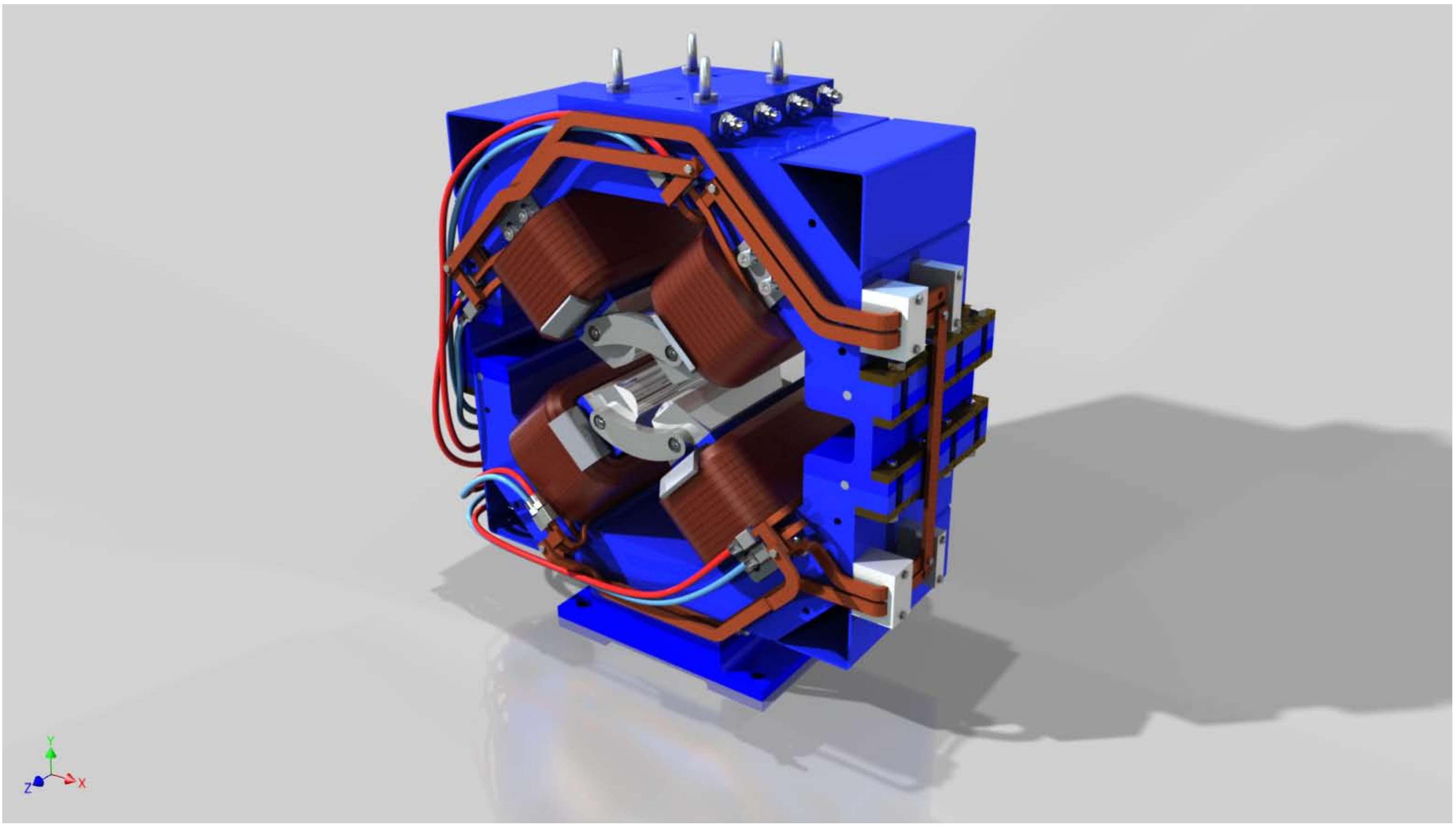
FINAL MAGNET



MAGNETIC MEASUREMENT



ILSF Prototype Quadrupole Magnet

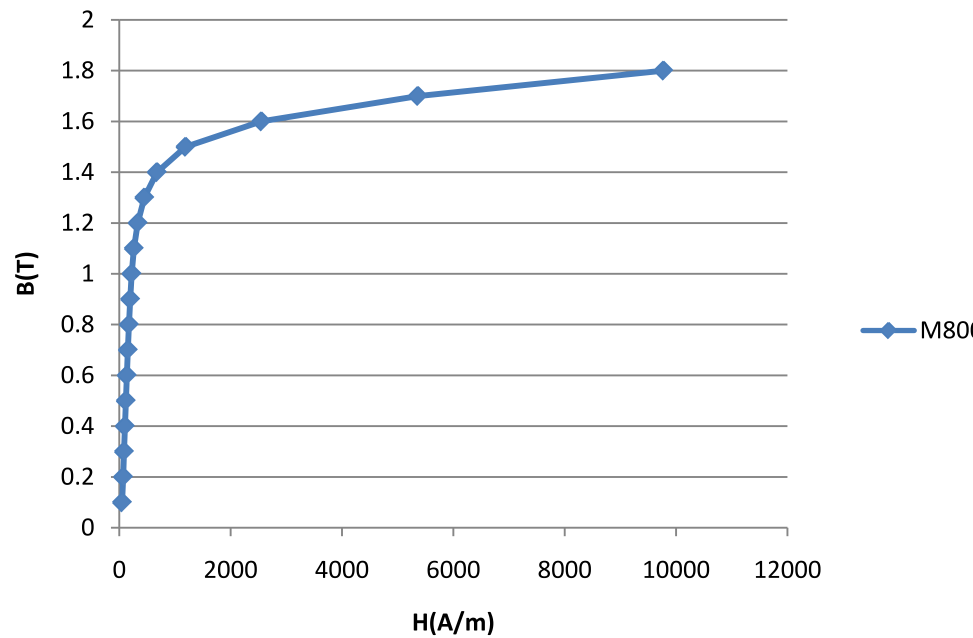


Specification of Quadrupole Magnet

Magnet specifications

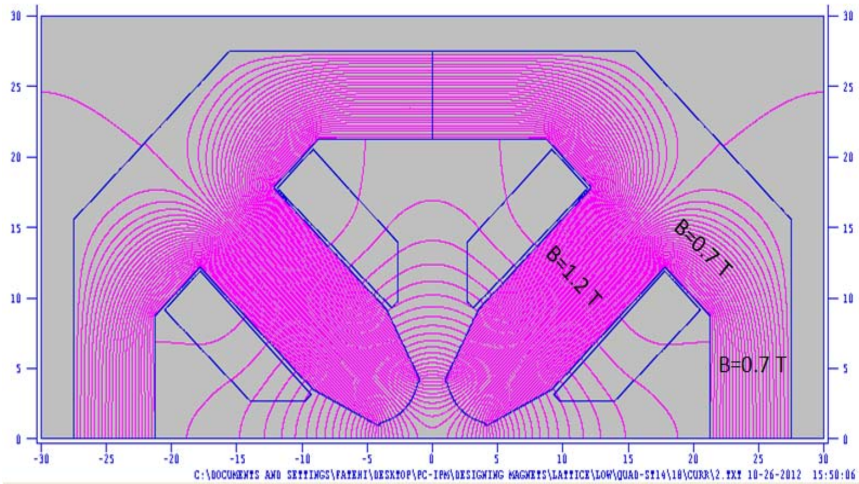
Parameter	Unit	H. Prototype
Gradient-B'	T/m	23
Aperture radius	mm	30
Good Field Region	mm	±18
Magnetic length	mm	260

Magnetic specifications of material

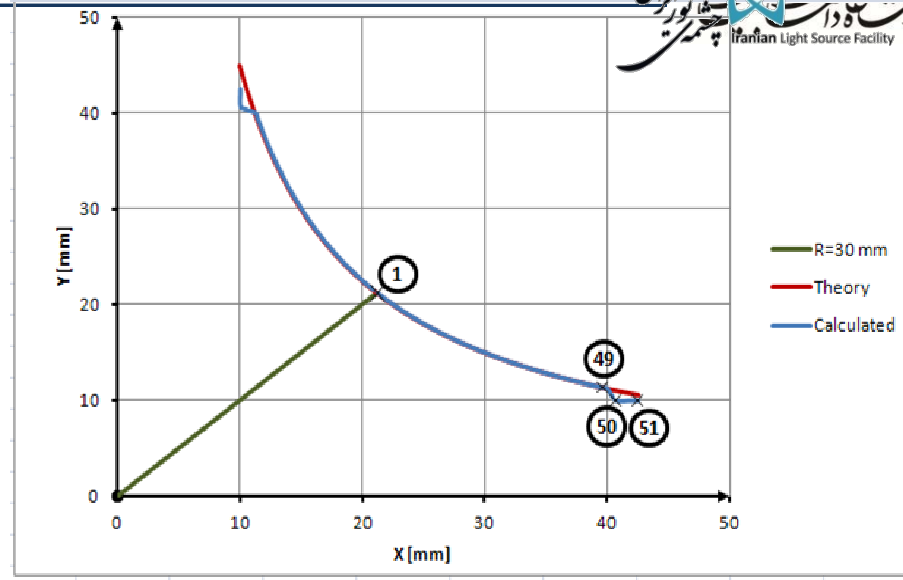


Chemical components of steel

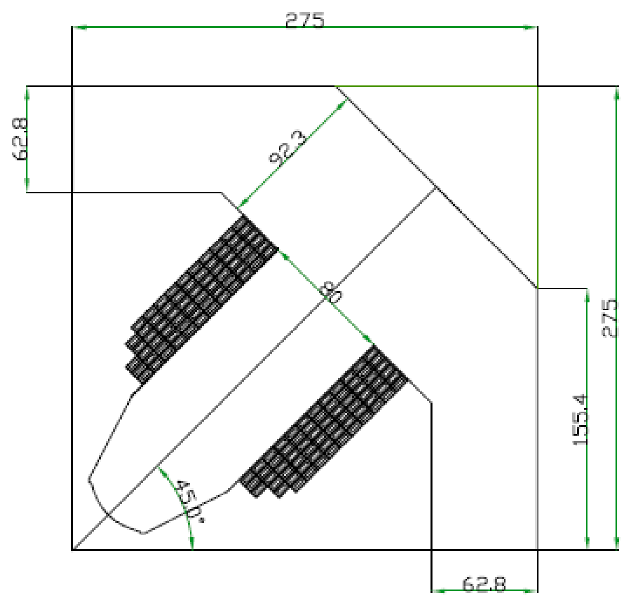
C	Si	Mn	P	S
0.01 %	1.7 %	0.24 %	0.037 %	-



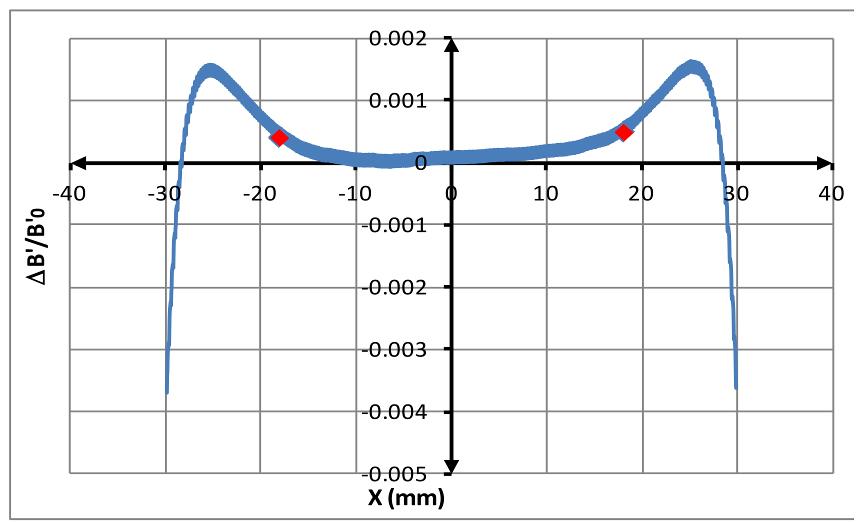
2D magnetic design - Poisson



Pole profile



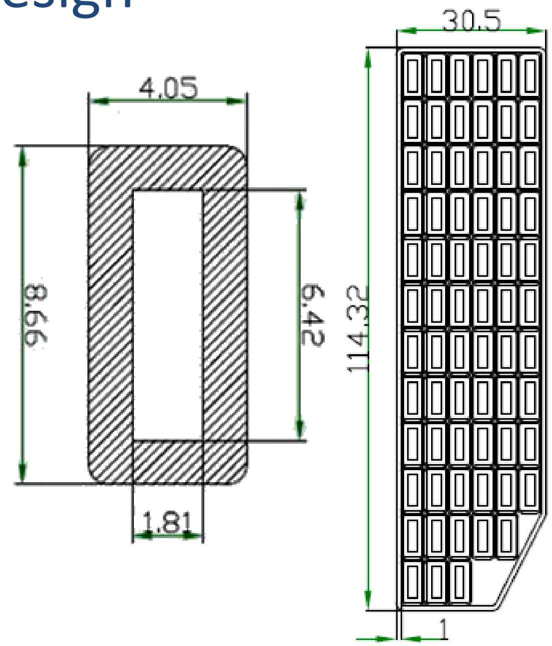
Main dimensions

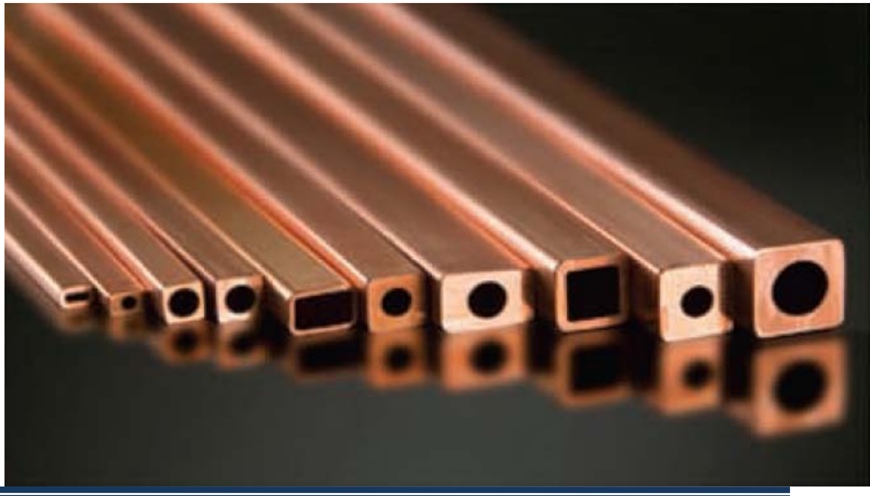


Field tolerances

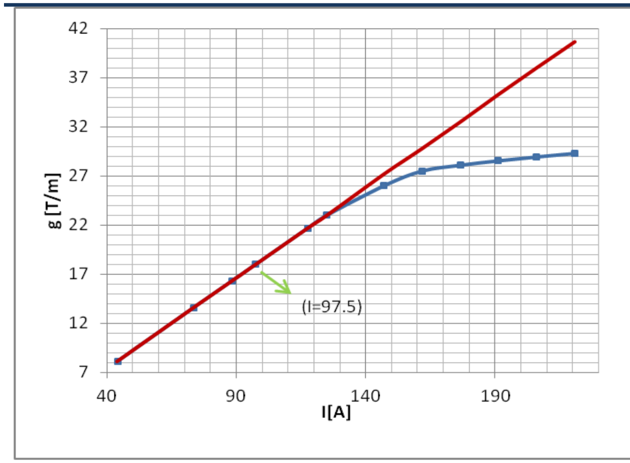
Electrical and cooling design

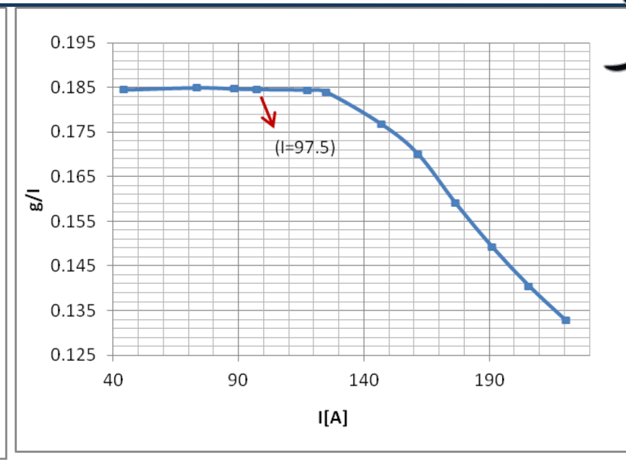
Parameter	Unit	value	Parameter	Unit	value
Mechanical length	m	.0233	Copper area	mm^2	23.45
Total Amp-turns per coil	At	6553	Current density	A/mm^2	4.16
Operating current	A	96.4	Voltage drop	V	25
Number of turns per coil	-	68	Power per magnet	KW	2.5
Number of pancakes per coil	-	No pancakes	Number of water circuits	-	4
Conductor height	mm	4.05	Water temperature rise	C	10.0°
Conductor width	mm	8.66	Cooling water speed	m/s	1.27
Cooling channel height	mm	1.81	Pressure drop	bar	6.7
Cooling channel width	mm	6.42	Reynolds number.	-	2441



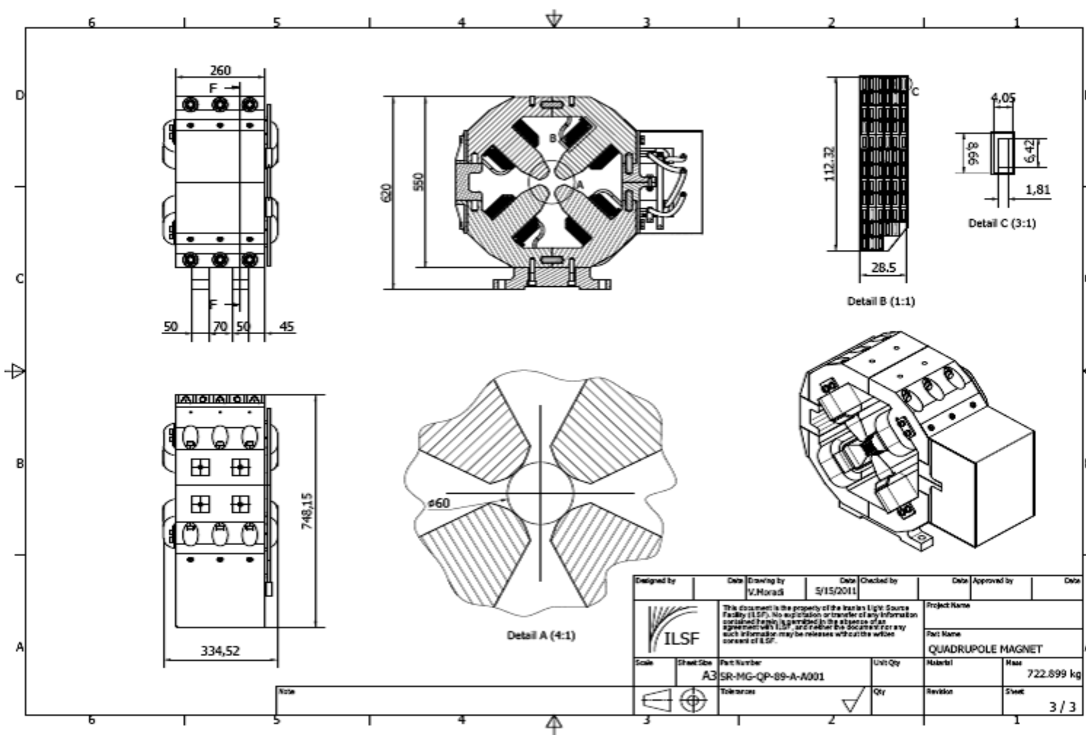


Saturation





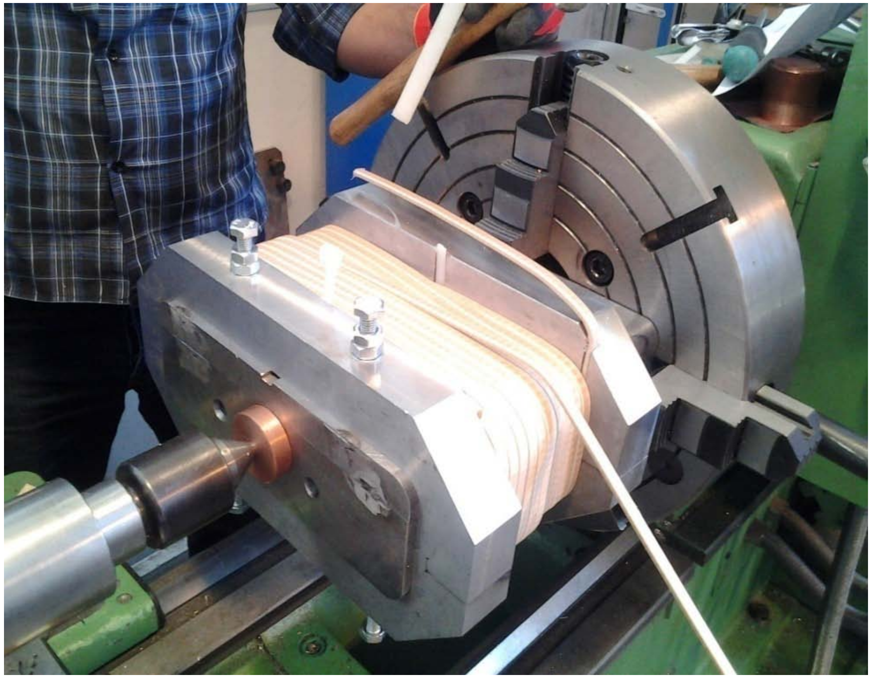
General Drawing



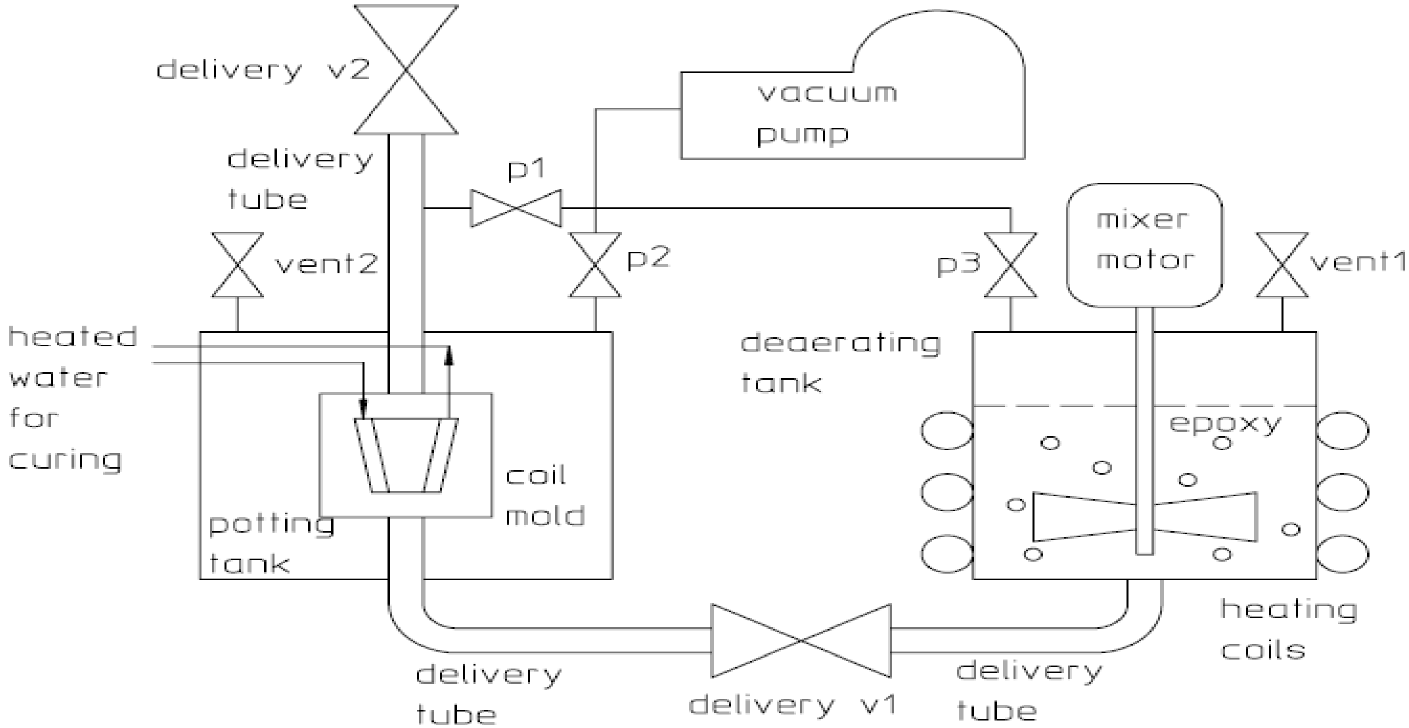
PREPARATION OF LAMINATIONS

Laser cutting of laminations
& wirecut

COIL WINDING



vacuum Presure impregnation (**VPI**)

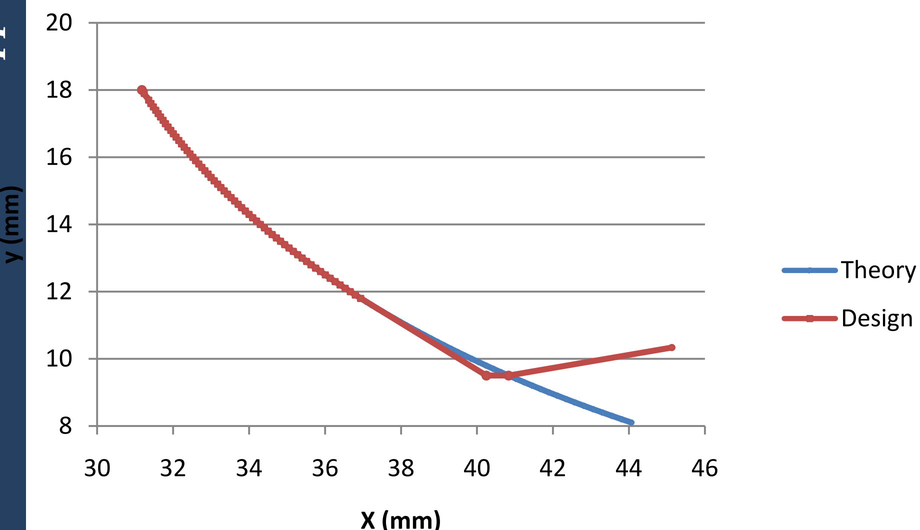


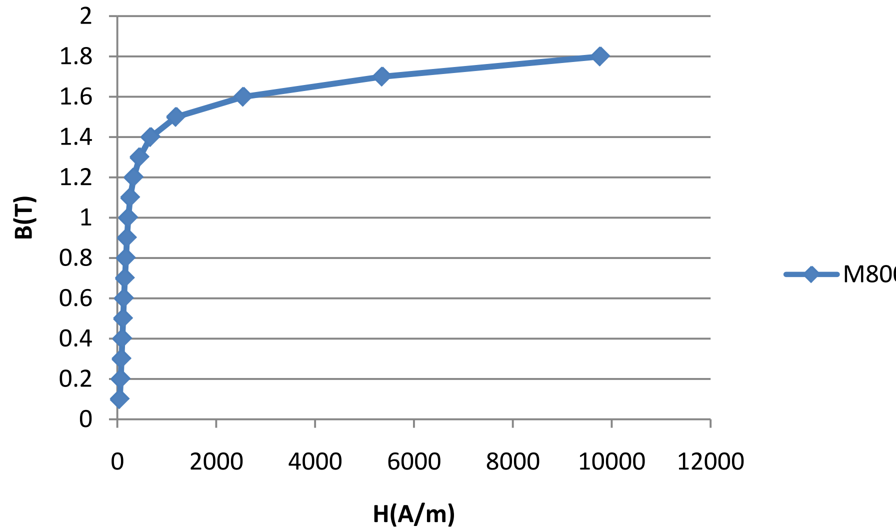
Yoke machining

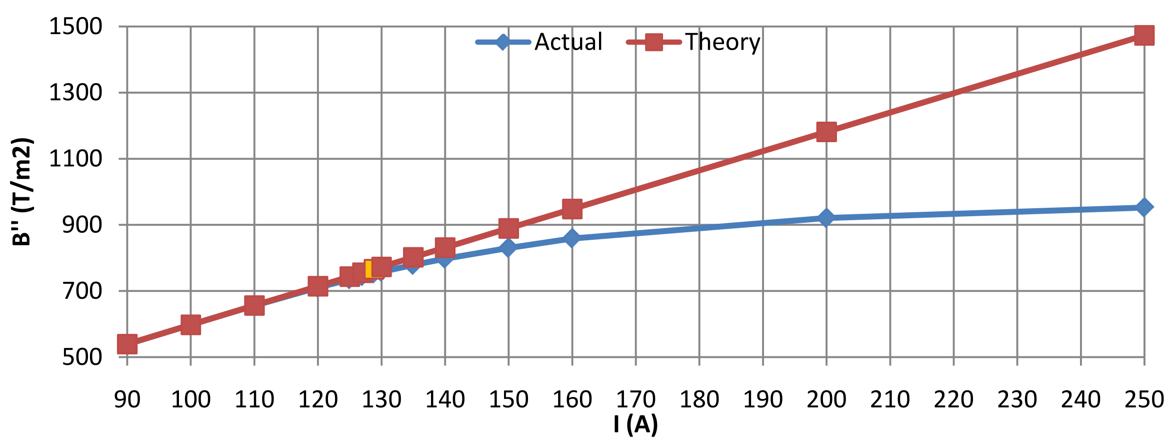
assembling

Magnetic Measurement

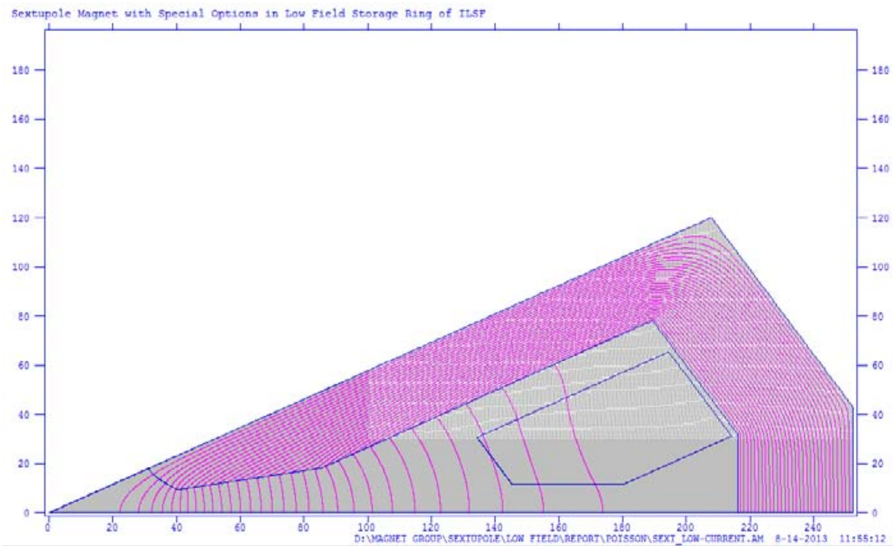
Sextupole Magnet Prototype

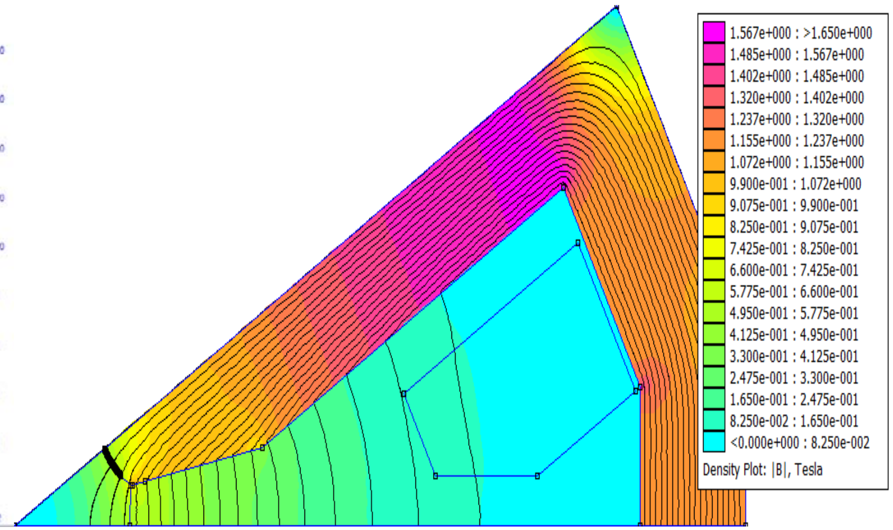


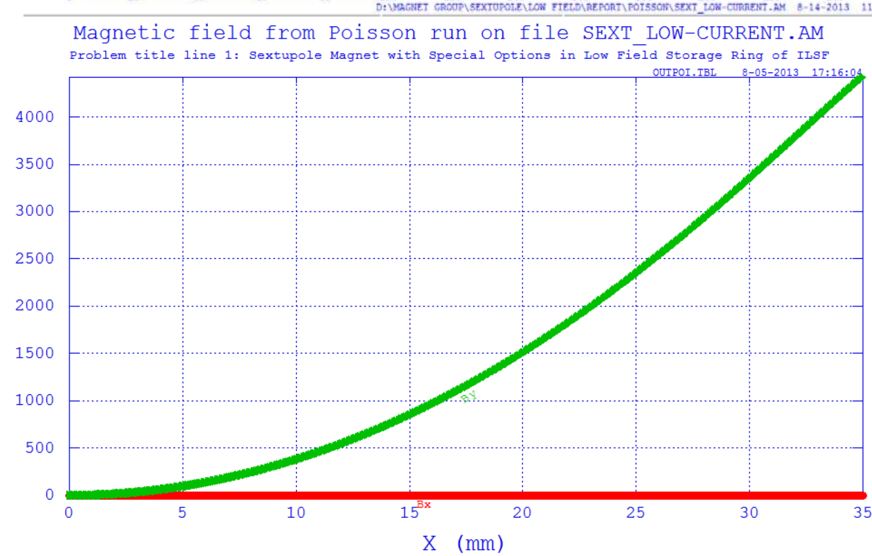


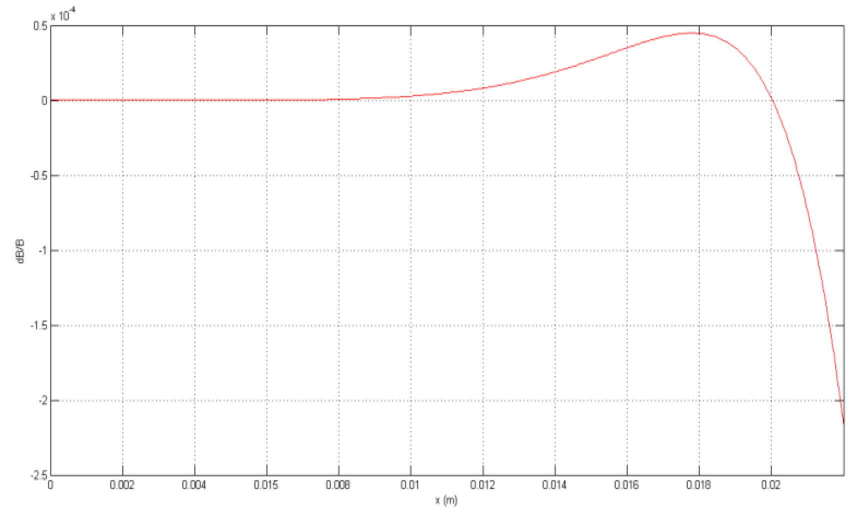


Sextupole Design



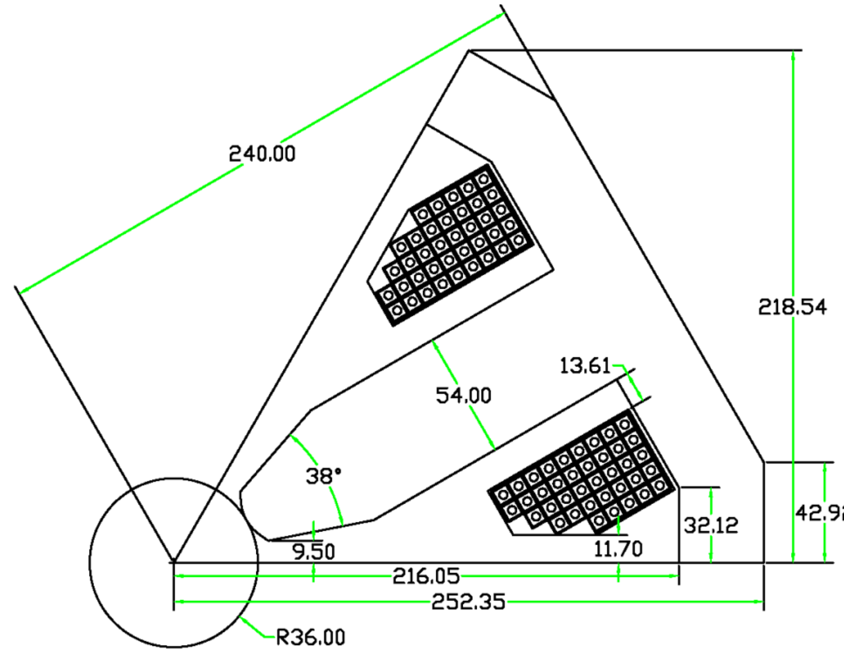


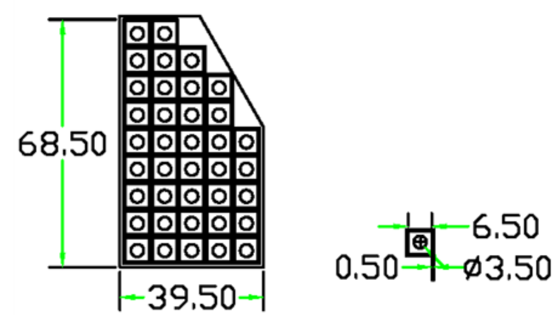




Electrical and cooling design

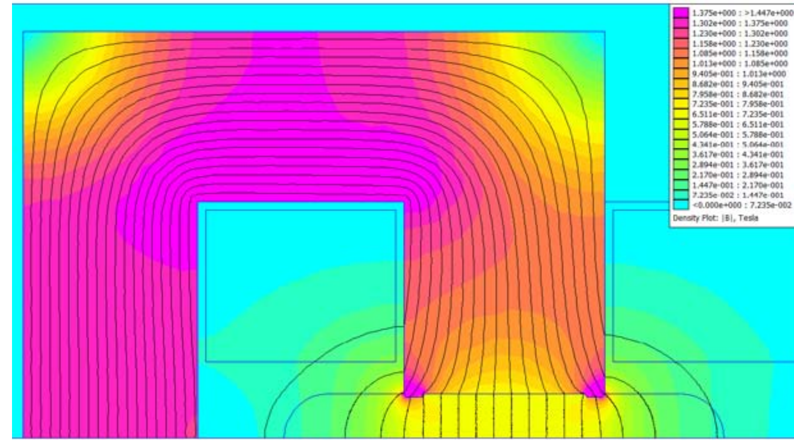
Parameter	Value
total Amp-turns per coil	4902 A
Operating current per coil	129 A
Number of turns per coil	38
Number of pancakes per coil	No pancakes
conductor dimensions	6.5 x 6.5 mm^2
Water cooling tube diameter	3.5 mm
Copper area	32.62 mm^2
Current density in copper	3.95 A/mm^2
Voltage drop per magnet	12.05 V
Power per magnet	1553.85 Watt
Number of water circuits per magnet	3
Water temperature rise	9.0° C
Cooling water speed	1.43 m/s
Pressure drop per coil	6.22 bar
Reynold No.(should be larger than 1160)	2500

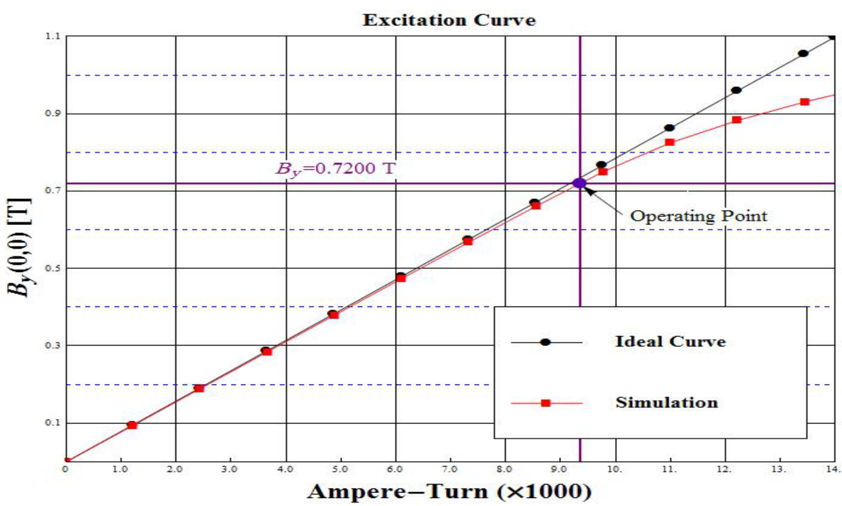


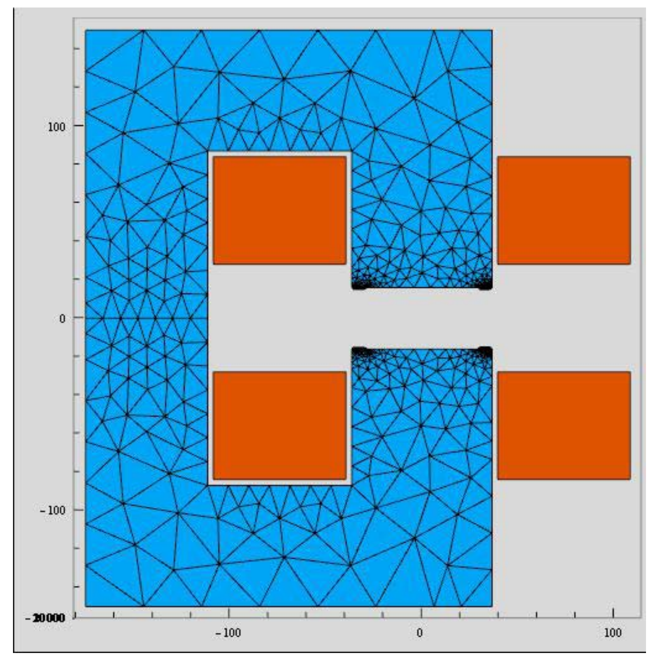


Bending Magnet Prototype

Parameter	Unit	BE1
Bending radius	m	14.01
Deflecting angle	Degree	6.429
Field	T	0.72
Gradient field	T/m	0
Gap Height	mm	32
Magnetic length	m	1.55
GFR	mm	±18







Thank you For your attention