Magnets (Warm)

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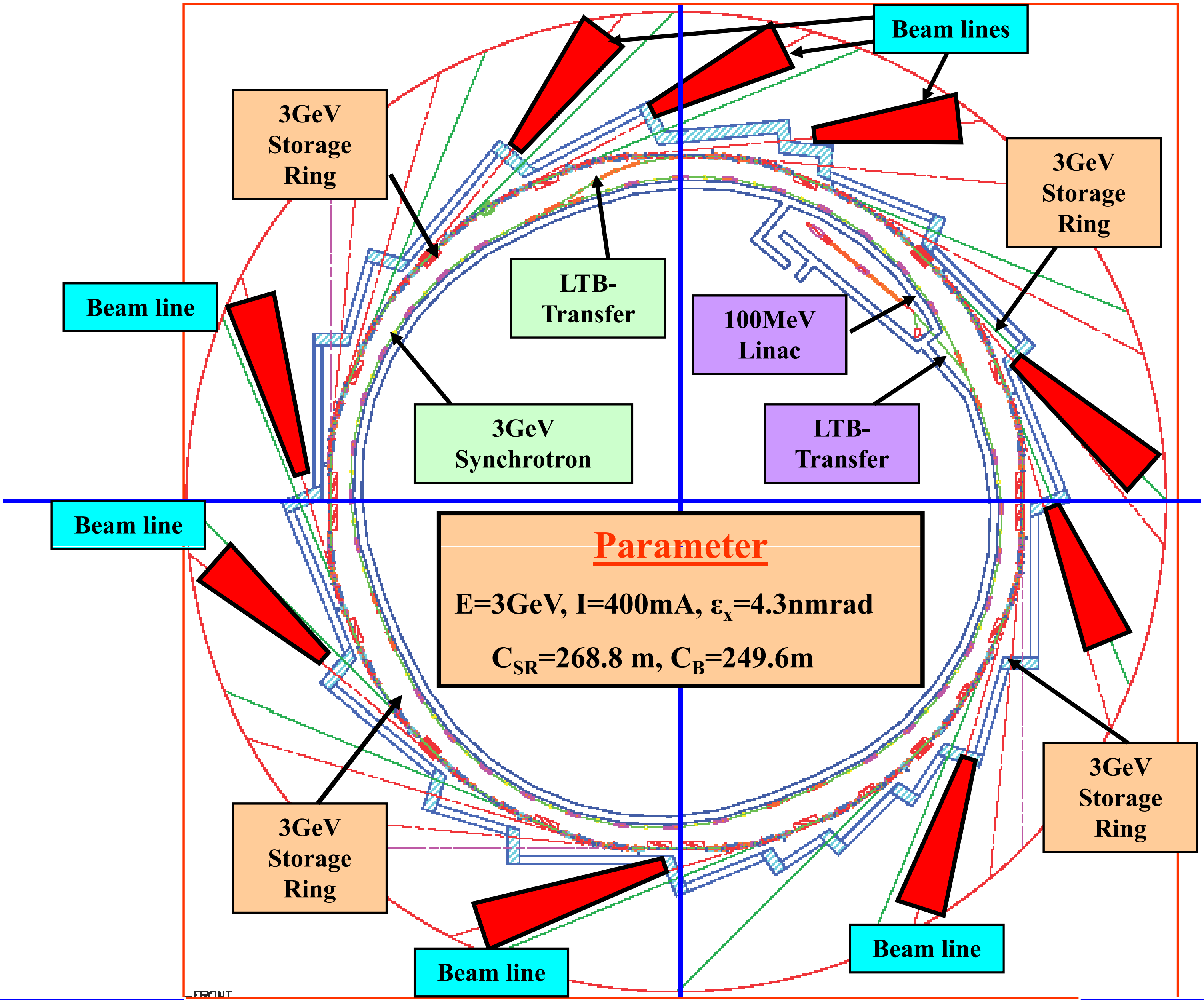
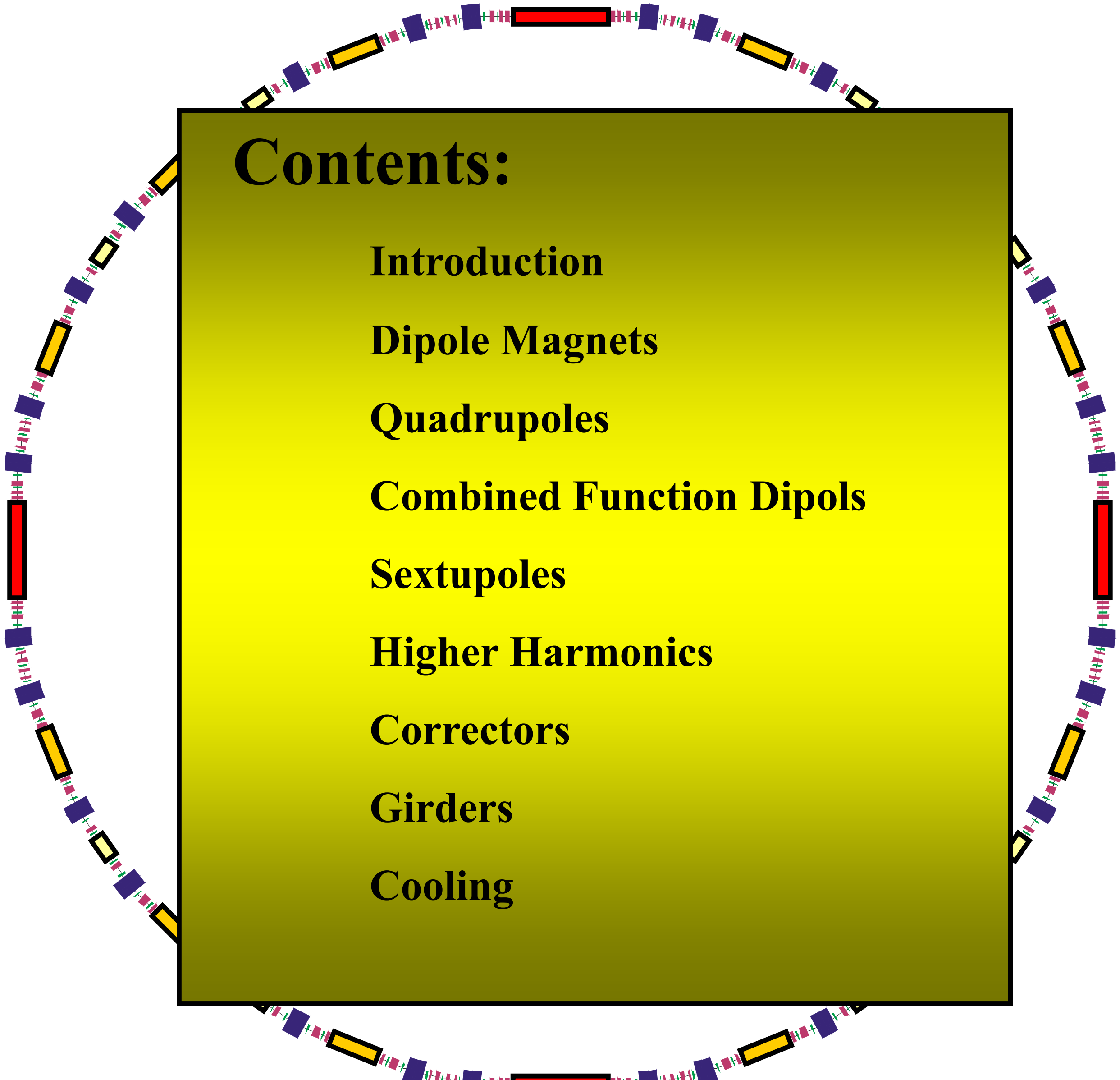
The Accelerator Complex of ALBA



Parameter

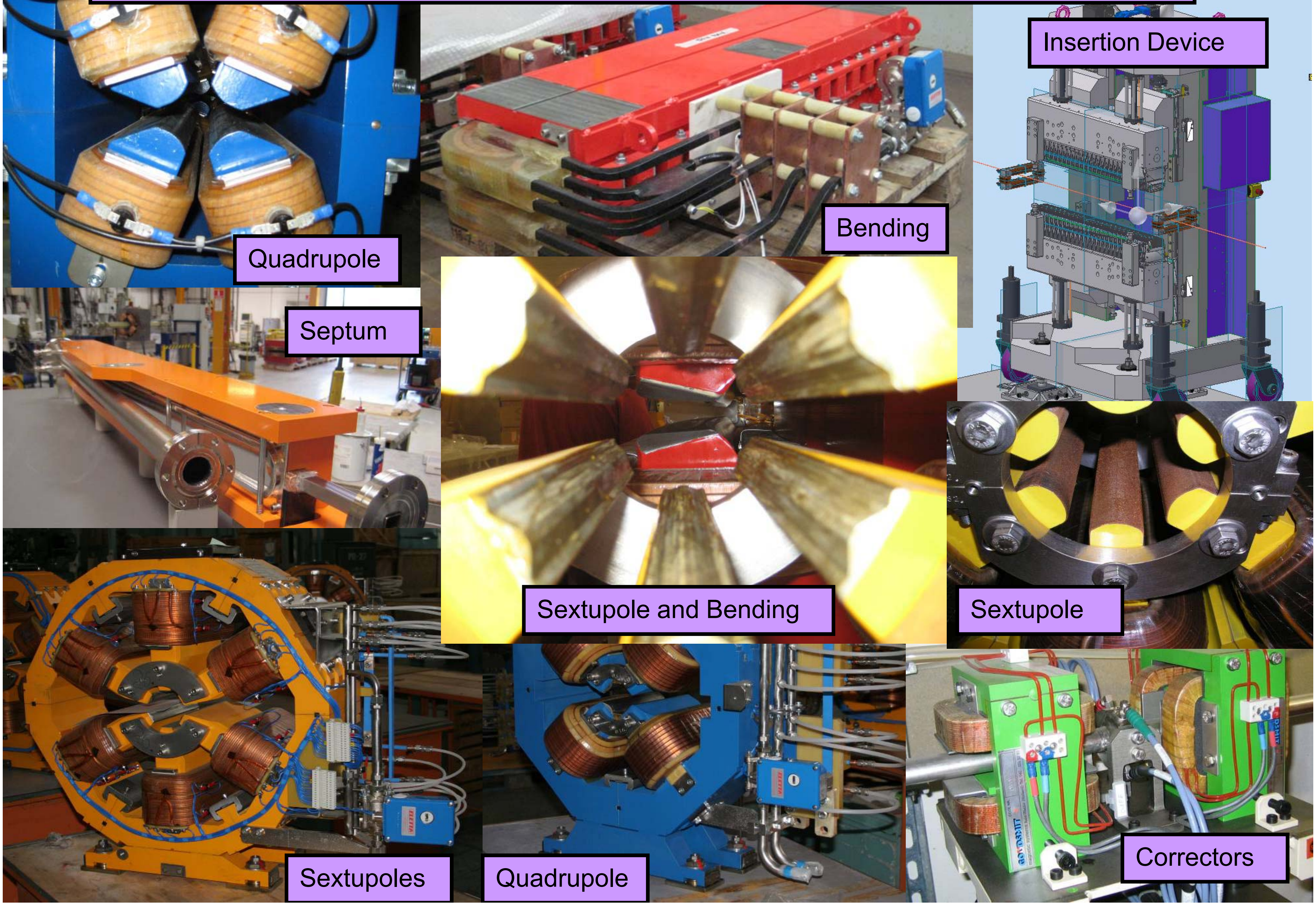
E=3GeV, I=400mA, ε_x=4.3nmrad

C_{SR}=268.8 m, C_B=249.6m



Contents:

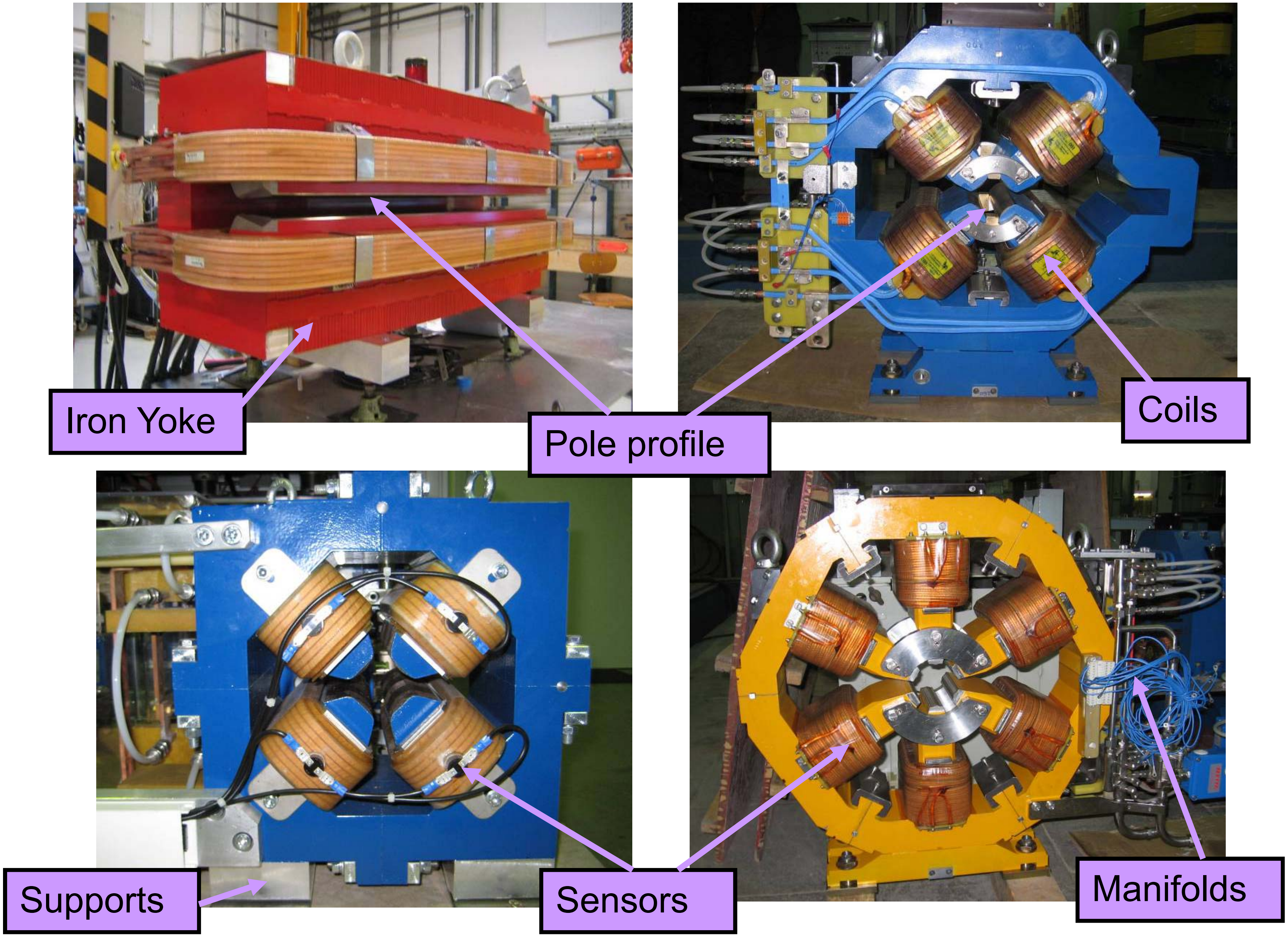
Magnets within an Accelerator Complex



Magnets within an Accelerator Complex

Bendings, Quadrupoles, Sextupoles and Correctors		Bendings, Quadrupoles and Correctors	
Storage Ring	**Boost. Synchr.**	**Transfer Lines**	**Linac**
Beam Optics	Beam Optics	Beam Optics	Beam Optics
Magnets	Magnets	Magnets	Gun
Vacuum Syst.	Vacuum Syst.	Vacuum Syst.	Bunching Section
Girders	Girders	Girders	Acceler.-Struct.
Alignment	Alignment	Alignment	Rad.-Freq.-Syst.
Power Supplies	Power Supplies	Power Supplies	Magnets
Diagnostics	Diagnostics	Diagnostic	Girders
Rad-Freq-Sytem	Rad-Freq-System	Control Syst.	Alignment
Pulsed Magnets	Pulsed Magnets	Shielding	Power Suppl.
Puls-Power-Suppl.	Puls-Power-Suppl.		Diagnostic
Timing	Timing		Timing
Control System	Control Syst.		Control Syst.
Insertion Devices	Shielding		Shielding
Shielding			

Main Components of a Magnet



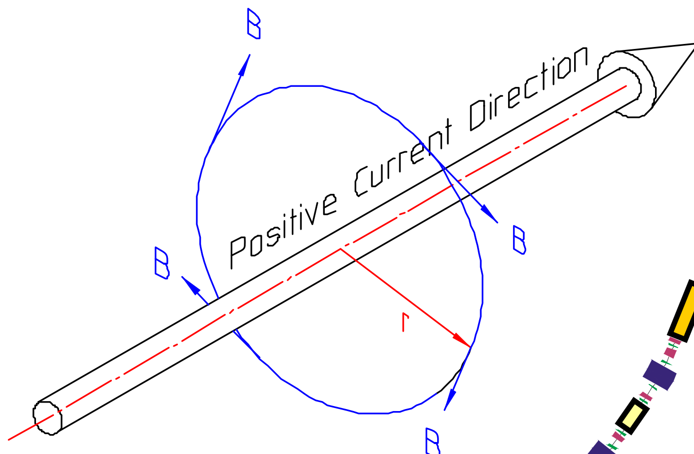
Principles of the Magnet Design

Bending, quadrupoles, sextupoles

correctors and combined magnets

$$I = \oint \vec{H} \bullet \vec{dl}$$

$$= \frac{B}{\mu_0} 2\pi r$$



Integral form of the Magnetic Field Equation

But first – nomenclature!

Magnetic Field: (the magneto-motive force produced by electric currents)

symbol is **H** (as a vector);

units are Amps/metre in S.I units;

Magnetic Induction or **Flux Density:** (the density of magnetic flux driven through a medium by the magnetic field)

symbol is **B** (as a vector);

units are Tesla (Webers/m^2)

Note: induction is frequently referred to as "Magnetic Field".

Permeability of free space:

symbol is μ_0 ; $\mu_0 = 4\pi*10^{-7}$

units are Henries/metre;

Permeability (abbreviation of **relative permeability**):

symbol is μ_r;

the quantity is dimensionless;

Calculation of the Magnetic Fields

Everything starts with the Maxwell Equations:

$$rot\,\vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \oint_L \vec{E}ds = -\frac{d\Phi}{dt} \text{....with....} \Phi = \oint_A \vec{B}dA$$

$$rot\,\vec{B} = \mu_0\,\vec{j} + \mu_0\varepsilon_0\frac{\partial \vec{E}}{\partial t} \qquad \boxed{\oint_L \vec{H}ds = I} + \frac{d\Psi}{dt} \text{....with....} \Psi = \oint_A \vec{D}dA$$

$$div\,\vec{E} = \frac{\rho}{\varepsilon_0} \qquad \oint_S \vec{D}dA = Q$$

$$div\,\vec{B} = 0 \qquad \boxed{\oint_S \vec{B}dA = 0}$$

With the following relations:

$$\vec{D} = \varepsilon_0\varepsilon_r\,\vec{E} \qquad \vec{B} = \mu_0\mu_r\,\vec{H}$$

Calculation of the Magnetic Fields

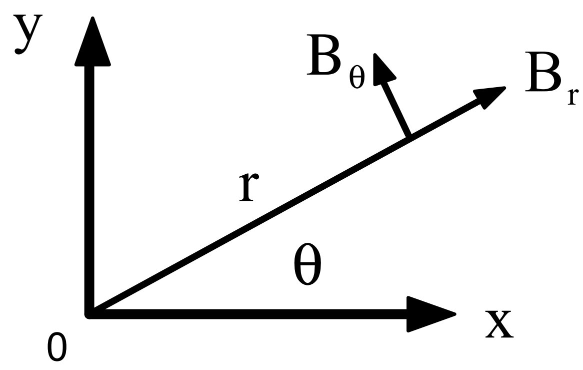
In a material free region the magnetic fields can be calculated by a potential function V(x,y,z), which is determined by the Laplace equation:

$$\Delta V = 0 = \frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r} + \frac{1}{r^2}\frac{\partial^2 V}{\partial \varphi^2} + \frac{\partial^2 V}{\partial z^2}$$

With some mathematical manipulations one gets the following field components:

$$B_r = -\sum_n (A_n r^{n-1} \cos n\Theta + B_n r^{n-1} \sin n\Theta)$$

$$B_\varphi = -\sum_n (-A_n r^{n-1} \sin n\Theta + B_n r^{n-1} \cos n\Theta)$$



B_n: are the normal components,

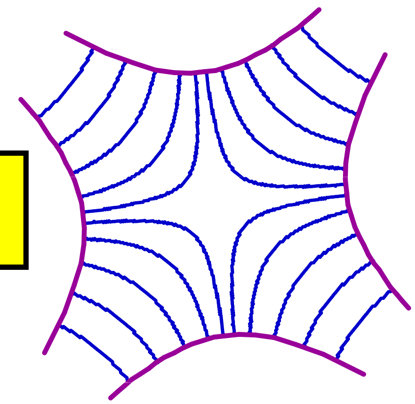
A_n: are the skew components,

$B_x = B_r \cos\theta - B_\theta \sin\theta$,
$B_y = B_r \sin\theta + B_\theta \cos\theta$,

Normal and Skew Magnets

Normal quadrupole

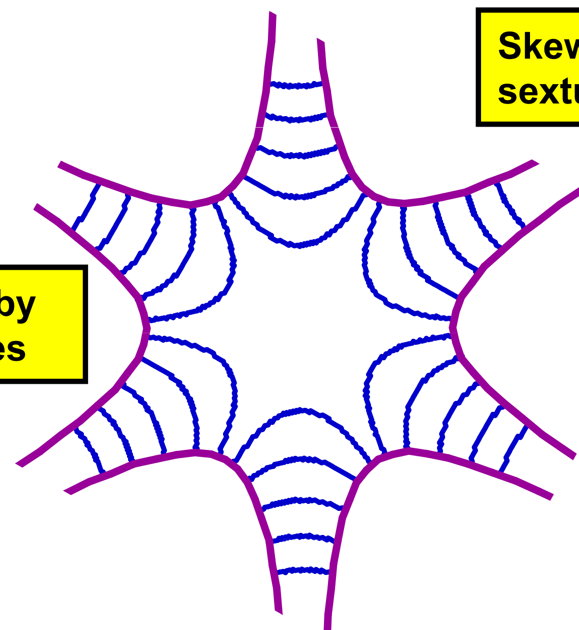
Rotation by 45 degrees



Skew quadrupole

Norma sextup

otation by) degrees



Skew sextupole

Description of a Magnetic Field

In general for the magnetic field one has the following description:

$$B = B_1 + B_2 * x + B_3 * x^2 + B_4 * x^3 + B_5 * x^4 + B_6 * x^5 + B_7 x^6 + B_8 * x^7 + B_9 * x^8 + B_{10} * x^9$$

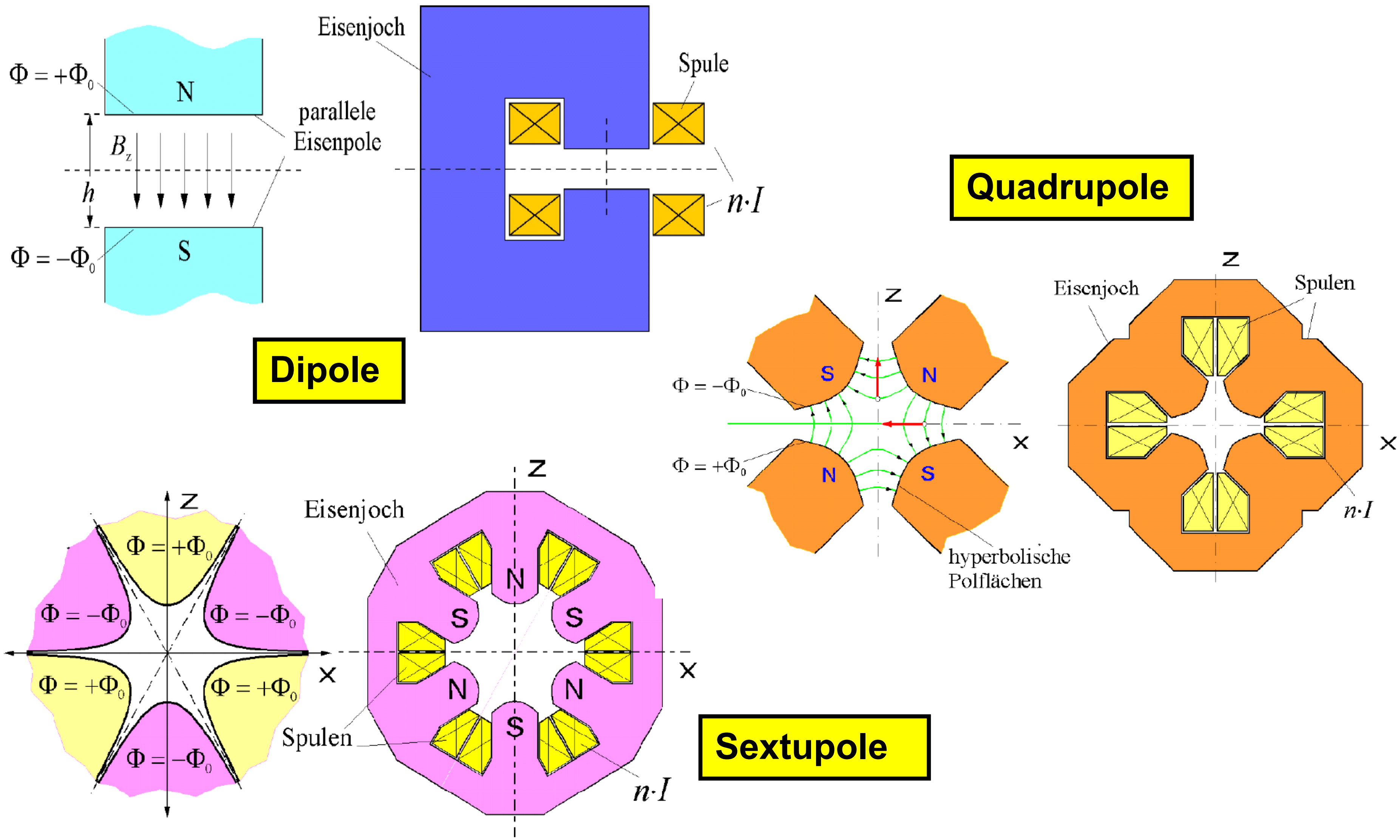
$$B = B_0 + \frac{1}{1!} \cdot \frac{dB}{dx} x + \frac{1}{2!} \cdot \frac{d^2 B}{dx^2} x^2 + \frac{1}{3!} \cdot \frac{d^3 B}{dx^3} x^3 + \frac{1}{4!} \cdot \frac{d^4 B}{dx^4} x^4 + \frac{1}{5!} \cdot \frac{d^5 B}{dx^5} x^5 + \frac{1}{6!} \cdot \frac{d^6 B}{dx^6} x^6 + etc$$

$$B = B_1 + B_2 \cdot x + \frac{1}{2} \cdot B^2 \cdot x^2 + \frac{1}{6} \cdot B^3 \cdot x^3 + \frac{1}{24} \cdot B^4 \cdot x^4 + \frac{1}{120} \cdot B^5 \cdot x^5 + \frac{1}{720} \cdot B^6 \cdot x^6 + etc$$

$$B = B_1 (2\,pole) + B_2 (4\,pole) + B_3 (6\,pole) + B_4 (8\,pole) + B_5 (10\,pole) + B_6 (12\,pole) + etc$$

Dipole	Quadrupole	Sextupole	Octupole	Decapole	Dodecapole

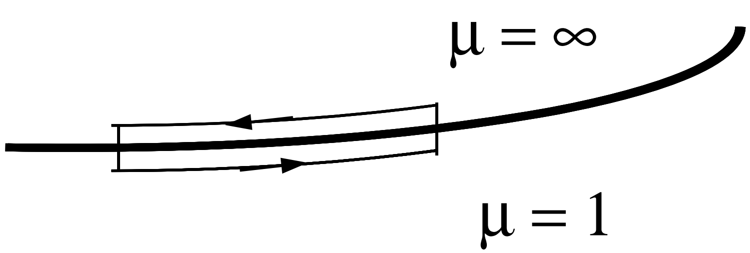
Dipole, Quadrupole and Sextupole



Introducing Iron Yokes

What is the ideal pole shape?

Flux is normal to a ferromagnetic surface with infinite μ:



curl H = 0

therefore $\int$ H.ds = 0;

in steel H = 0;

therefore parallel H air = 0

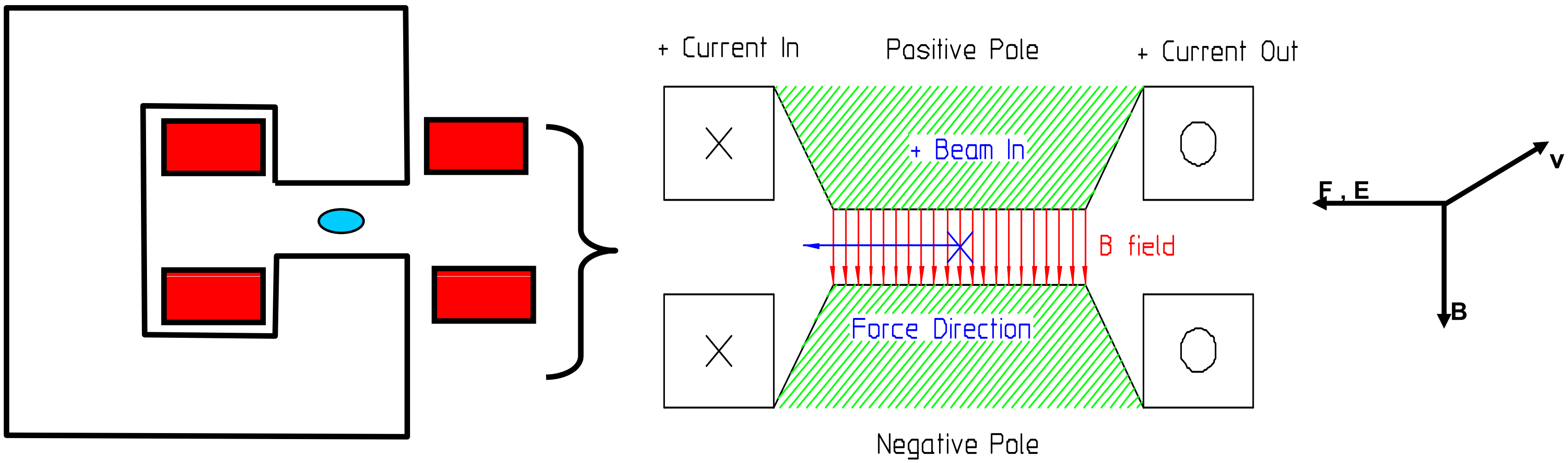
therefore B is normal to surface.

Flux is normal to lines of scalar potential, ($\underline{\mathbf{B}} = - \underline{\nabla}\phi$);

So the lines of scalar potential are the ideal pole shapes!

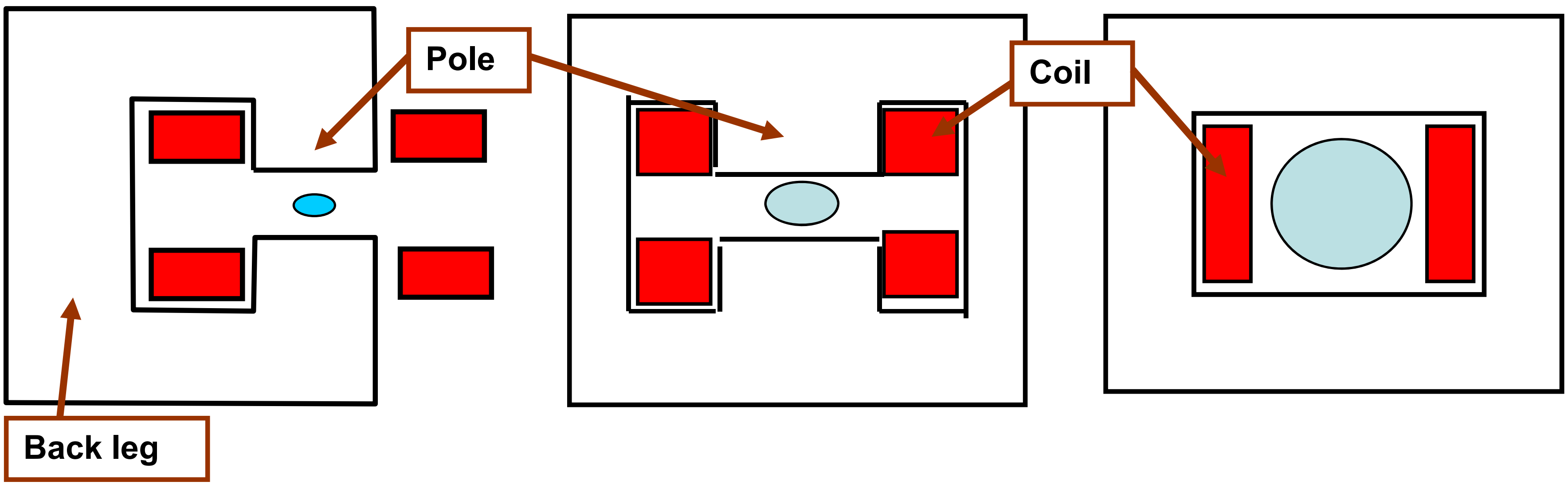
The Dipole Magnet

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. Using the right hand rule, the positive dipole steer the rotating beam toward the left.



The 'shim' is a small, additional piece of ferro-magnetic material added on each side of the two poles – it compensates for the finite cut-off of the pole, and is optimised to reduce the 6, 10, 14...... pole error harmonics.

Types of magnets



"C core":
Advantages:
- Easy access;
- Classic design;
- Low A-Turns;

Disadvantages:
- Less rigid;
- Still needs shims;
- Asymmetric.

"H core":
Advantages:
- Symmetric;
- More rigid;
- Low A-Turns

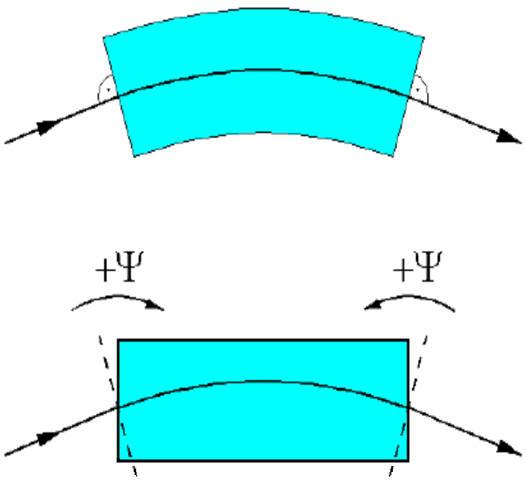
Disadvantages:
- Still needs shims;
- Access problems.

"Window Frame"
Advantages:
- High quality field;
- No pole shim;
- Symmetric & rigid;

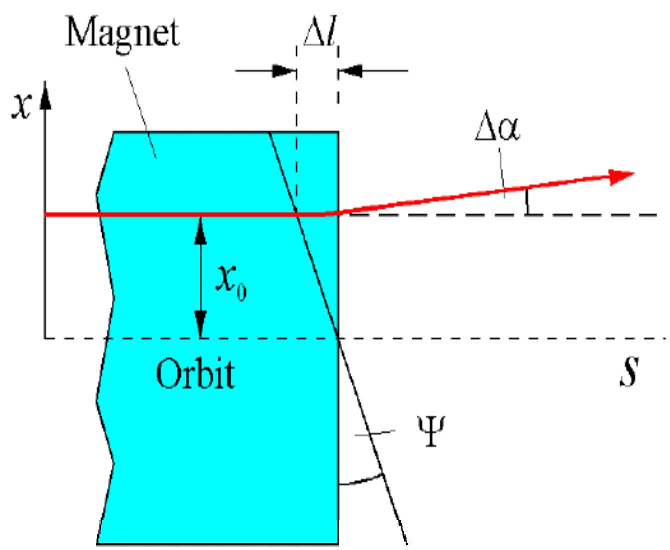
Disadvantages:
- High A-Turns
- Major access problems;
- Insulation thickness

More Types of Bending Magnets

Sector magnet



Rectangular magnet



Defocusing in a rectangular magnet

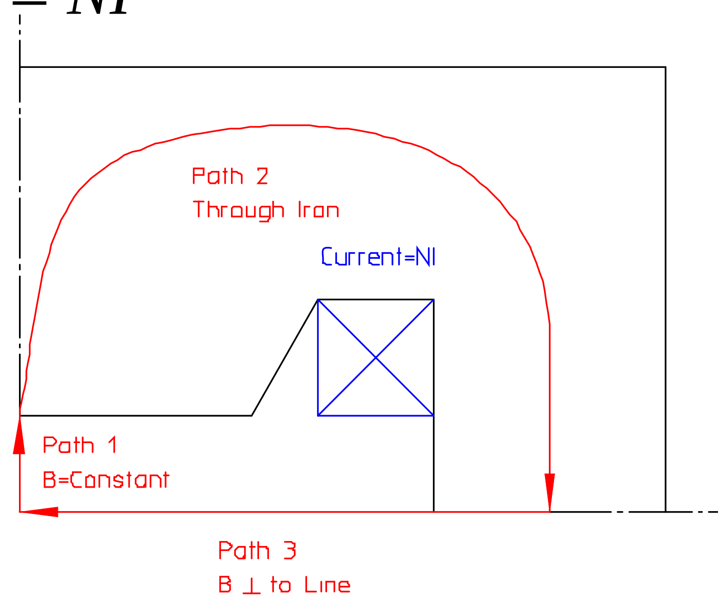
Within the sector bending magnet the trajectory length for positive x will be larger and therefore the sector magnet is a focussing one.

Within the rectangular bending magnet it is vice versa and it is a defocusing one.

Dipole Excitation

According to Maxwell it is:

$$\oint \overline{H} \bullet \overline{dl} = \oint_{Path1} \overline{H} \bullet \overline{dl} + \oint_{Path2} \overline{H} \bullet \overline{dl} + \oint_{Path3} \overline{H} \bullet \overline{dl} = NI$$



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, $\quad |H| = \dfrac{B}{\mu \mu_0}$ $\quad$ For iron; $\quad \mu \approx 1000$

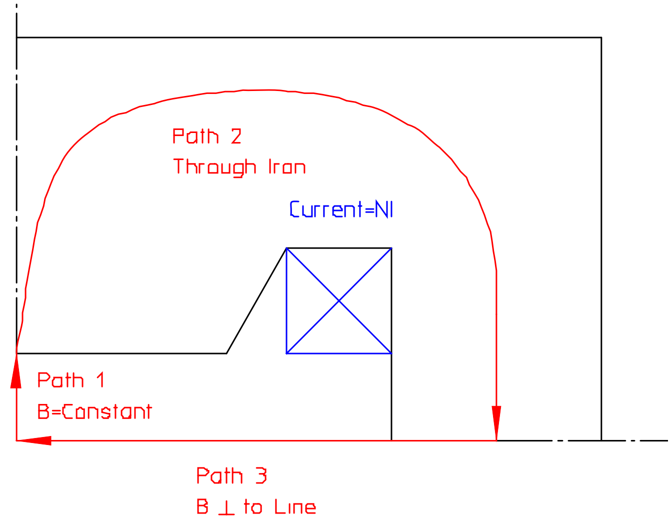
Therefore; $\quad \oint_{Path2} \overline{H} \bullet \overline{dl} = |H|_{iron} l_{iron} << \dfrac{Bh}{\mu_0} \approx 0$

Dipole Excitation

Along path 3: $\overline{H} \perp \overline{dl}$ and $\oint_{Path3} \overline{H} \bullet \overline{dl} = 0$

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

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

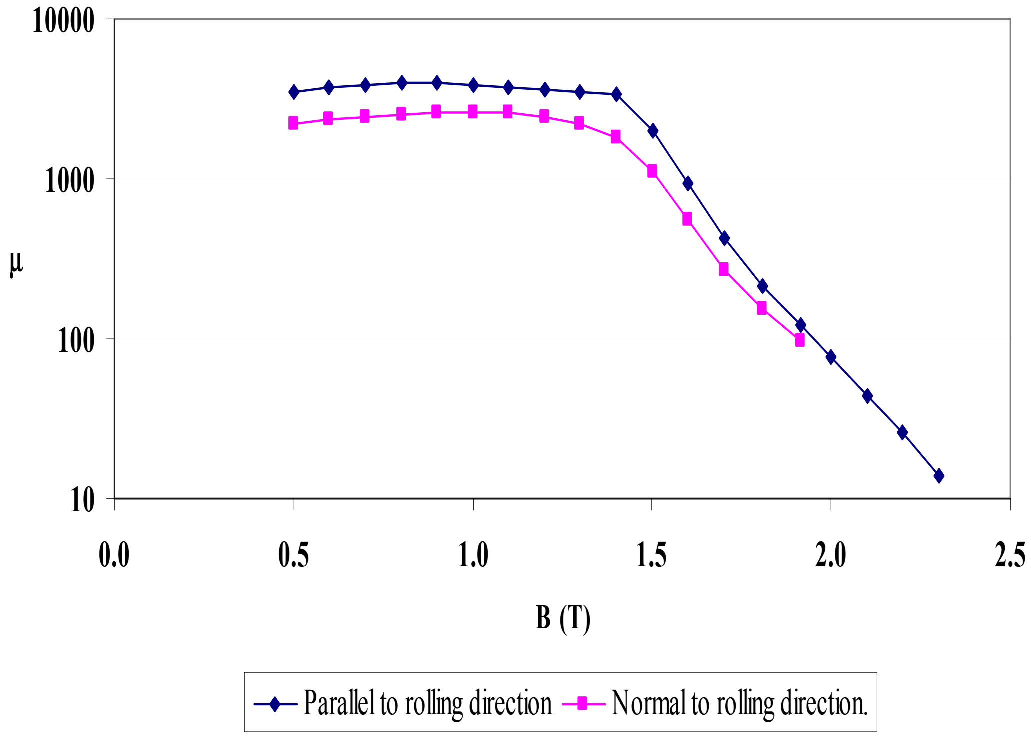


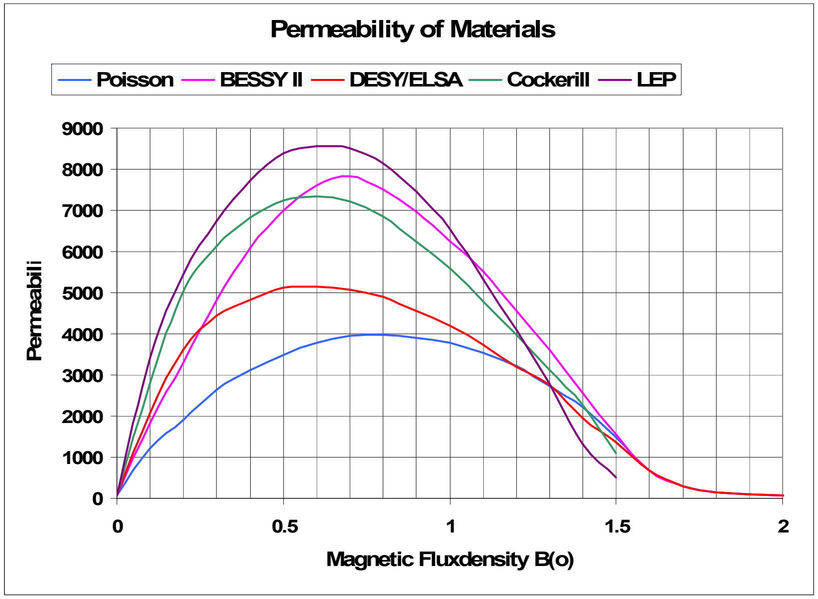
$B/I \approx \mu_0 N/h$ = constant

$B_{air} = \mu_0\ NI\ /\ (h + l_{iron}/\mu)$; is the exact solutions

The same procedure can be used for the calculation of the excitation for the quadrupoles, sextupoles and correctors

Yoke - Permeability of low silicon steel



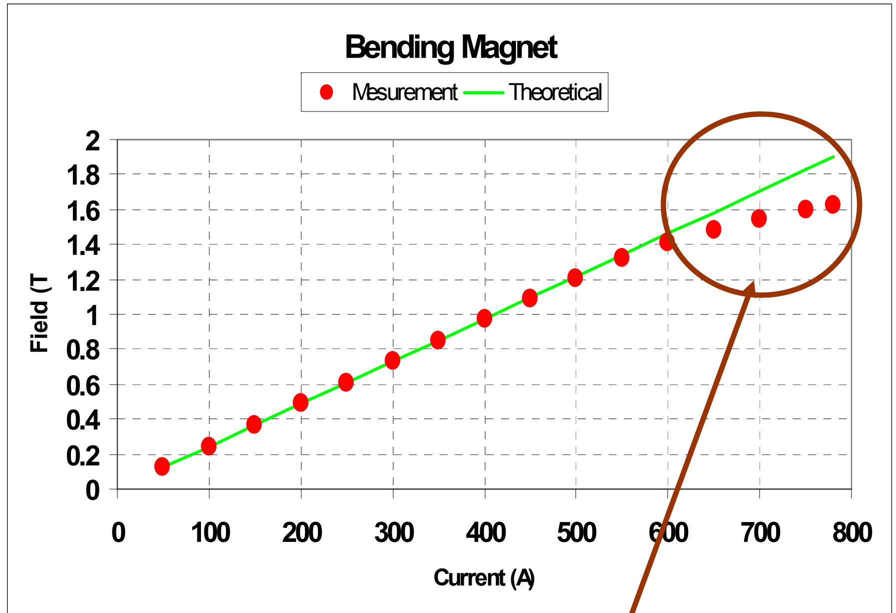


Without saturation the factor l_{iron}/μ should be much smaller as the half gap height h. For a synchrotron light bending magnet the length of the field line within half of the magnet is roughly 750 mm. At 1.5 T μ_r is roughly 1000, hence the factor l_{iron}/μ_r is roughly 1 mm, which makes roughly an saturation of 5 % to h=20 mm.

Excitation curve of the ANKA Bending magnet

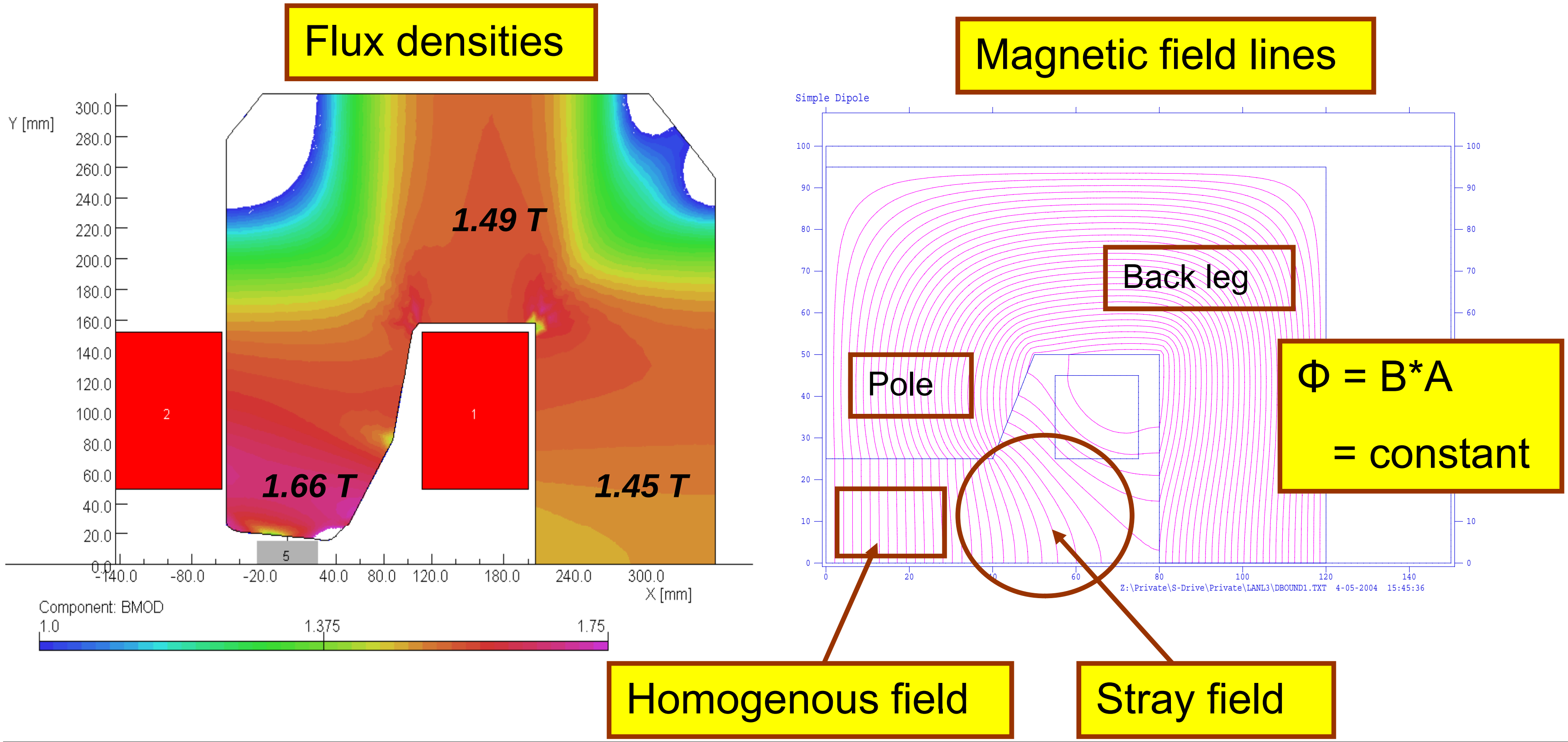
Flux density	1.40 T
Radius	5.956 m
Deflection Angle	22.5 degree
Magnetic length	2.340 m
Iron length	2.274 m
Total length	2.47 m

Strength	0.3411 m^{-2}
Gradient	2.84 T/m
Gap height	42 mm
Current	643 A
Turns	80
Conductor	13 * 13 mm^2



This is the region with some saturation, which means h (the gap height) is not any more much larger as the factor l_{iron}/μ.

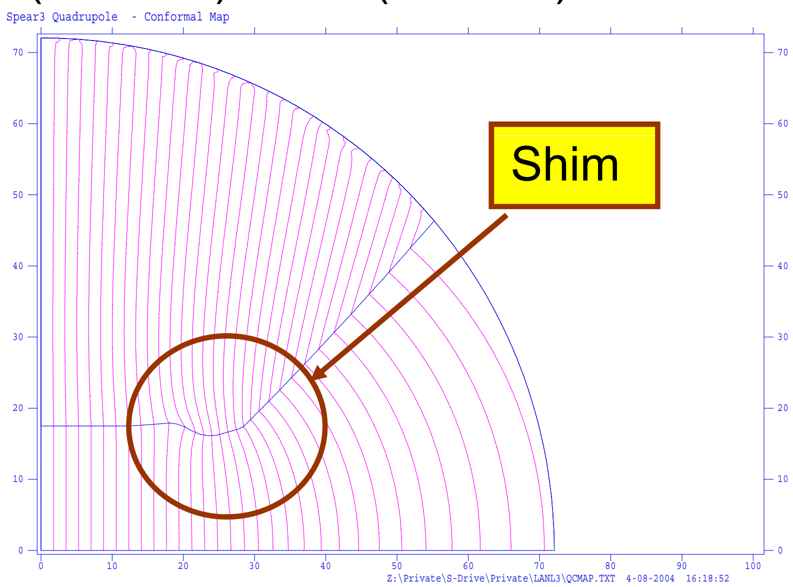
2 D Flux density distribution in the ALBA Dipole.



The flux of thestray field is roughly 30 % of the homogenous part. In order to have a constant flux density within the pole, the thickness of the pole has to be increase to the upper part. The thickness of the back leg must be the same or larger as the maximum width of the pole. If B<1 T an increase of the pole width is not needed.

Size of a Dipole.

The size of a dipole is given by the required so called “good field area” of the magnet. The good field area is given by the accelerator physicist. For example in a bending magnet for a synchrotron light source a good field area of roughly +/- 15 to 20 mm is required. In heavy ion - or other machines it can be completely different (much larger). To optimize the pole profile one uses to the end of the poles so called shims (as given below). The contour of the shims have to be determined with a 2D (Poisson) or 3D (TOSCA) code

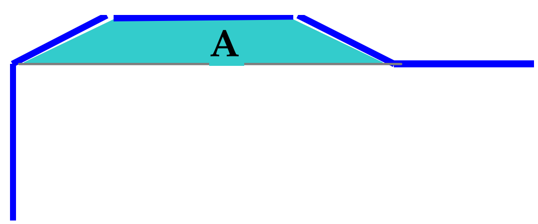


For accelerators operating with a fixed energy the flux density B can be up to 1.5 T or larger. For ramping machines the flux density should not be larger as roughly 1 T in order to avoid saturation effects.

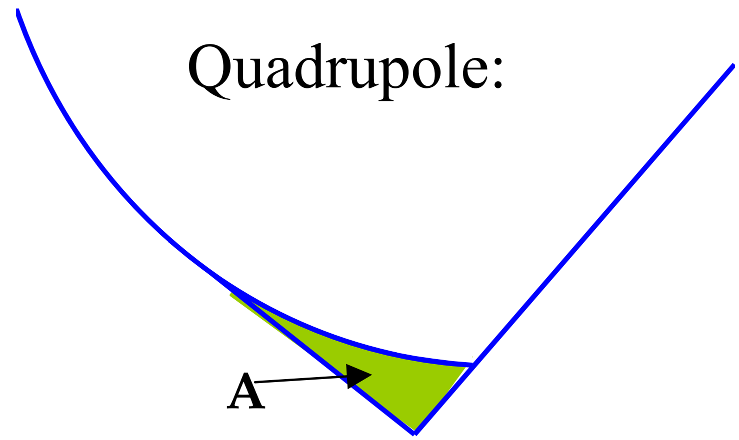
Shimming of Pole Profiles

To compensate for the non-infinite pole, shims are added at the pole edges. The area and shape of the shims determine the amplitude of error harmonics which will be present.

Dipole:



Quadrupole:

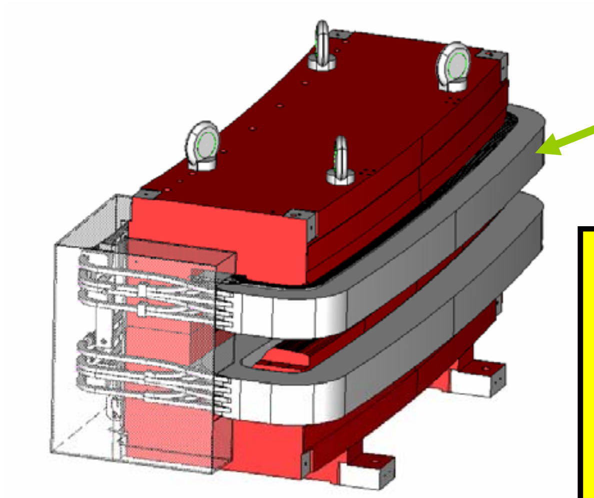


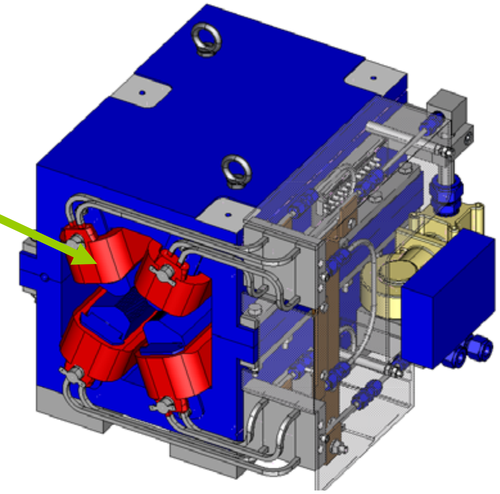
The designer optimises the pole by 'predicting' the field resulting from a given pole geometry and then adjusting it to give the required quality.

When high fields are present, chamfer angles must be small, and tapering of poles may be necessary

Size of Coils.

Coils





The currents and the windings of the coil have to make the excitation

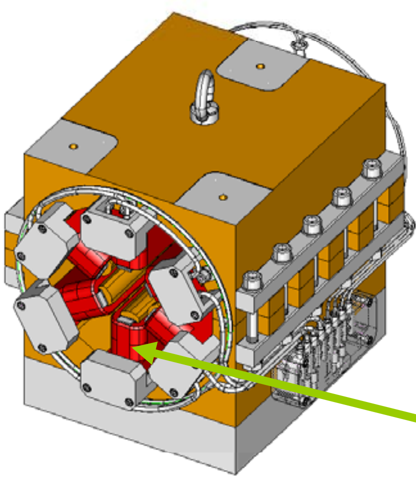
$$N*I = B_0(g+l_{Fe}/\mu_r)/\mu_0$$

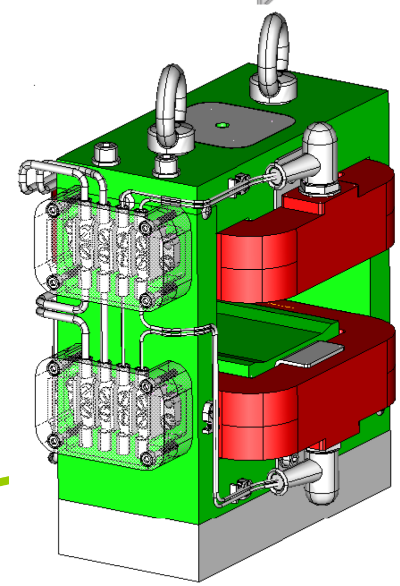
$$N*I \approx B_0 g/\mu_0$$

For the ALBA bending with a gap of 36 mm and a flux density of 1.42 T the excitation is:

$$N*I = 40680 \text{ A*Wdgs}$$

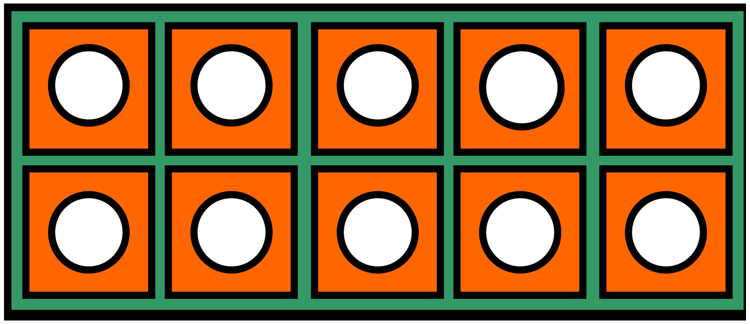
This can be done by a larger number of windings or a high current.





Coils

Coil Geometry



Standard design is rectangular copper (or aluminium) conductor, with cooling water tube. Insulation is glass cloth and epoxy resin.

Amp-turns (NI) are determined, but total copper area (A_{copper}) and number of turns (N) are two degrees of freedom and need to be decided.

Current density:
$j = NI/A_{copper}$
Optimum j determined from **economic** criteria.

Number of turns, N

The value of number of turns (N) is chosen to match power supply and interconnection impedances.

Factors determining choice of N:

Large N (low current)	Small N (high current)
Small, neat terminals.	Large, bulky terminals
Thin interconnections-hence low cost and flexible.	Thick, expensive connections.
More insulation layers in coil, hence larger coil volume and increased assembly costs.	High percentage of copper in coil volume. More efficient use of space available
High voltage power supply -safety problems.	High current power supply. -greater losses.

Current density - optimisation

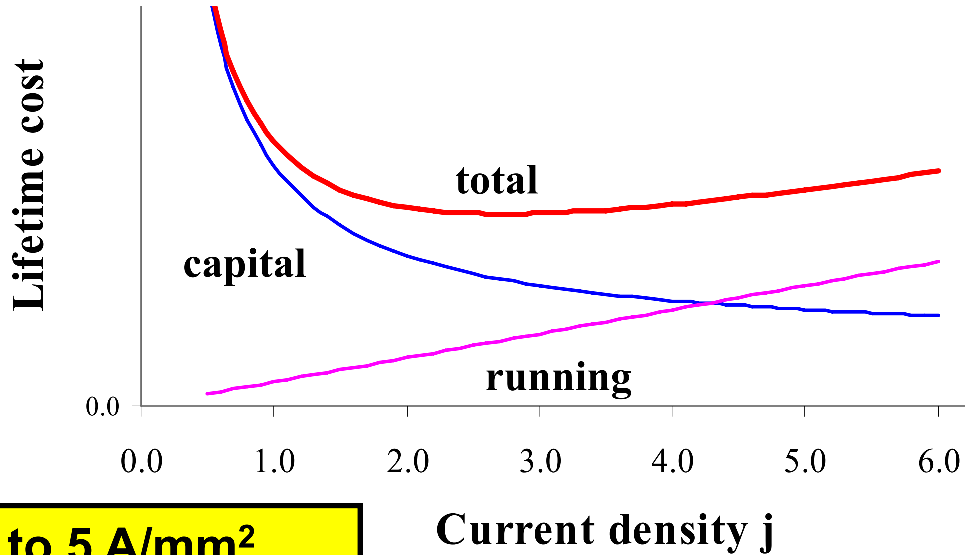
Advantages of low j:

- **lower power loss** – power bill is decreased;
- **lower power loss** – power converter size is decreased;
- **less heat** dissipated into magnet tunnel.

Advantages of high j:

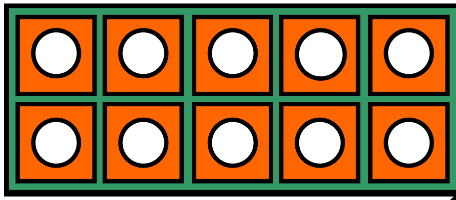
- **smaller coils;**
- **lower capital cost;**
- **smaller magnets.**

Chosen value of j is an optimisation of magnet capital against power costs



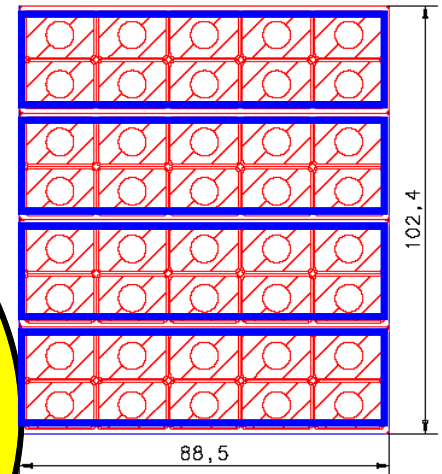
At ALBA we current densities of 3.5 to 5 A/mm²

Size of the Coil

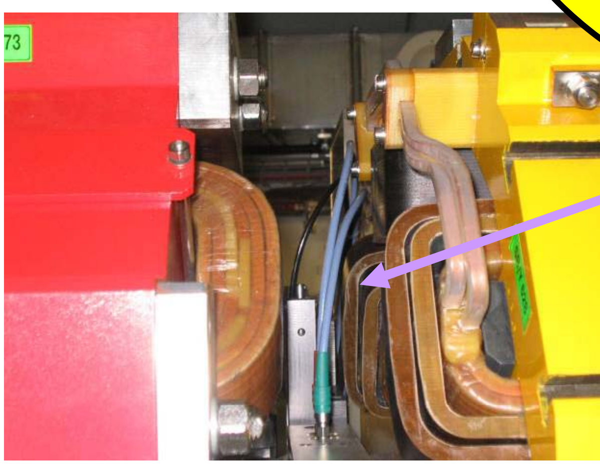


2 layers

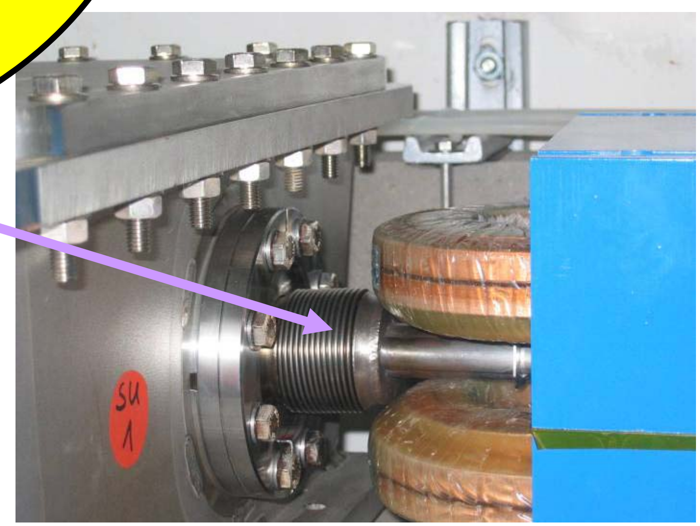
A small number of layers needs more space in the longitudinal directions. A high number of layers needs more space for the magnets in the vertical direction. For the number of layers one has to make a compromise and it depend upon the machine



4 layers/pancakes

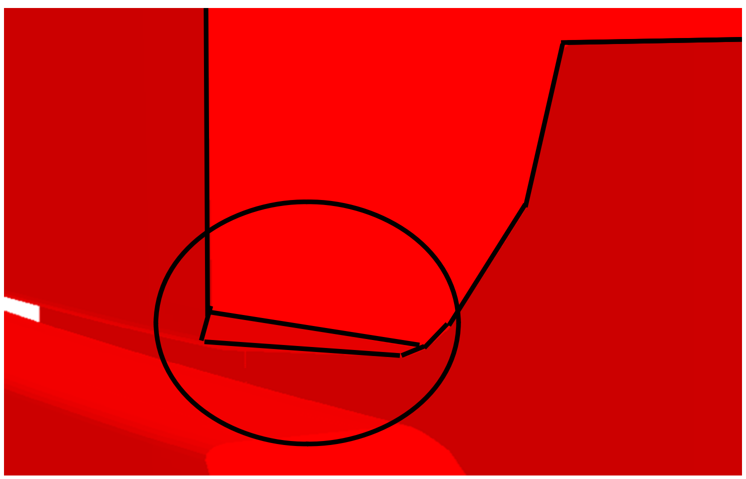


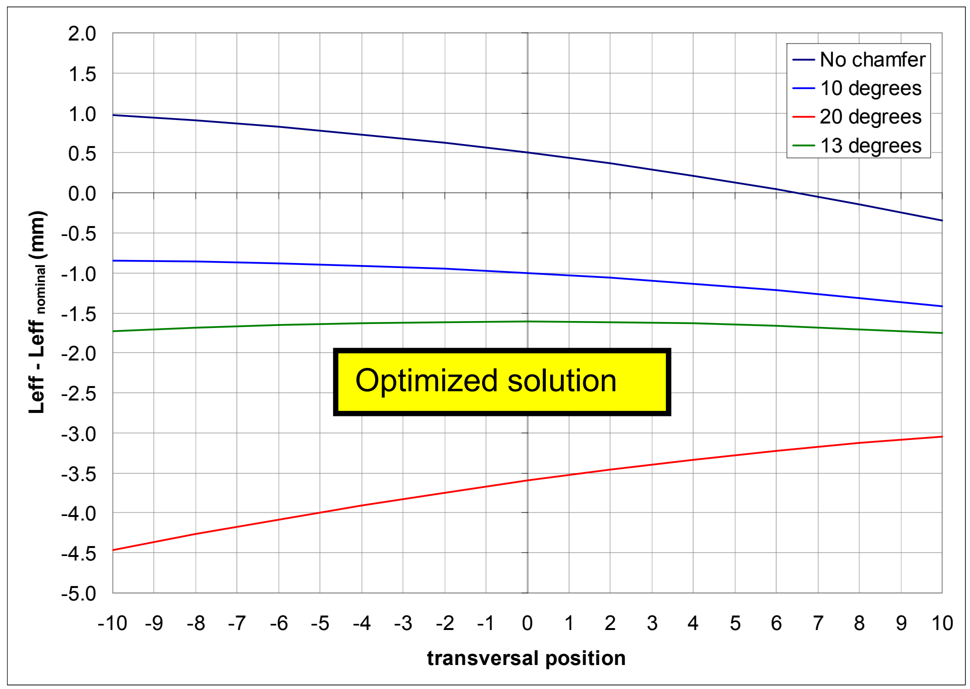
Space within the machine for the components should be as small as possible.



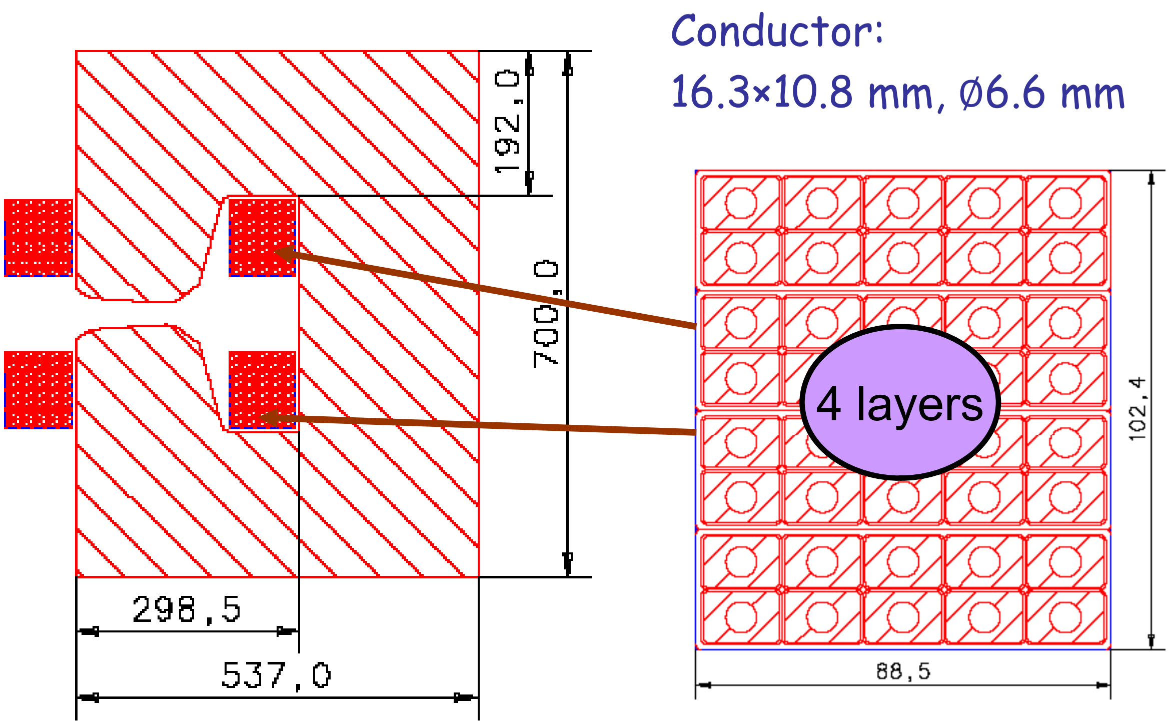
SR Dipole End Chamfer

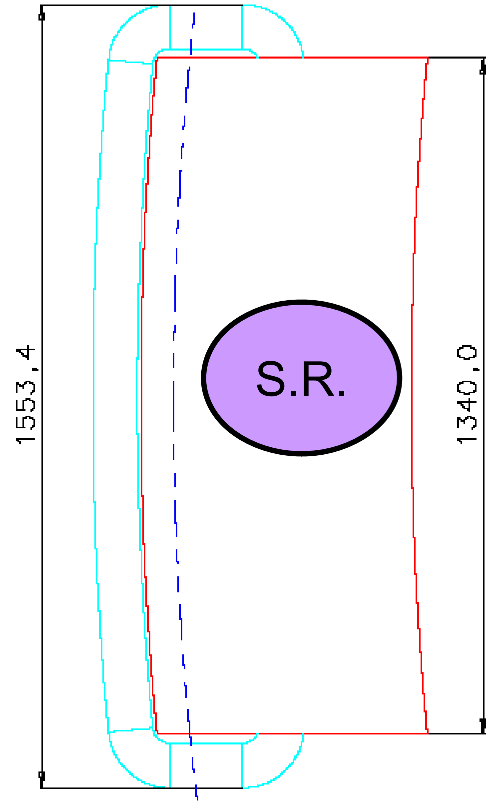
- Cut at 45º and then rotate the cut up to 20º
- Use OPERA-3D to model the magnet
- Calculate $B_y(s)$ at different transversal trajectories
- Beam Dynamics uses this field to do the machine simulation with a sliced magnet
- The best chamfer is that which makes the effective length constant along the transversal direction of the magnet.





Layout of the ALBA combined Bending Magnet



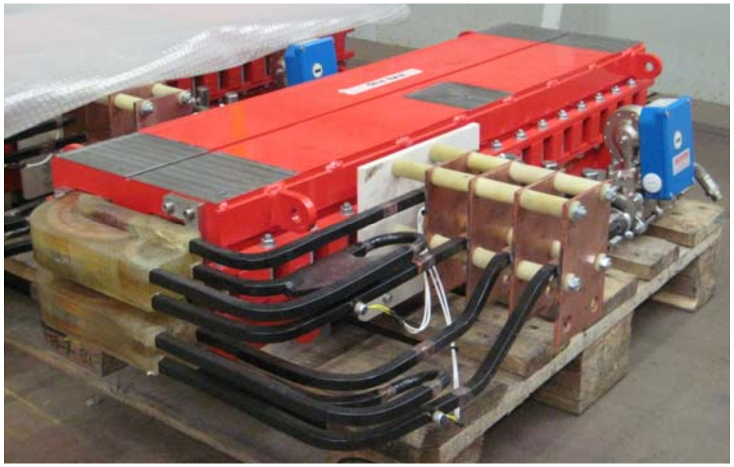


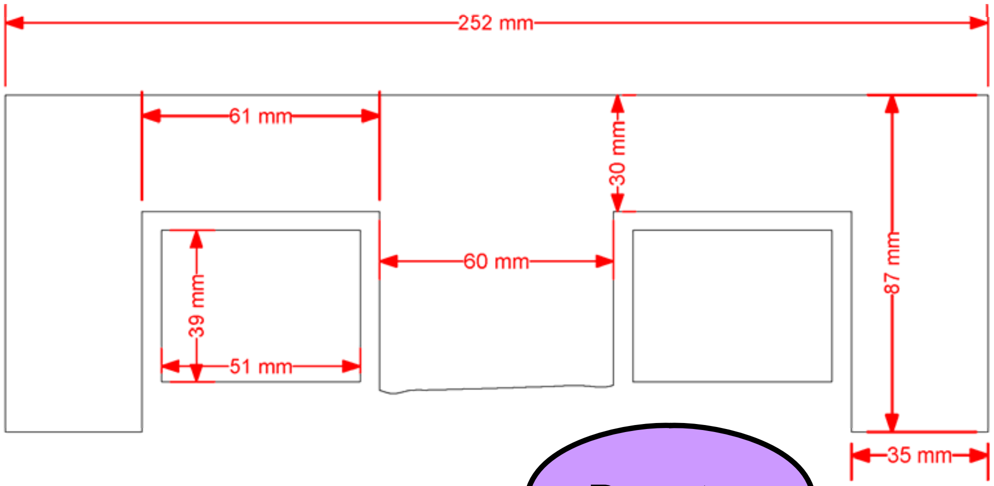
Bending angle	11.25°
Curvature radius	7.047
Central gap	36 mm
Central magnetic field	1.42 T
Gradient	5.65 T/m

2 coils

- 40 turns/coil (5 turns wide x 8 turns height)
- 4 pancakes/coil
- 2 hydraulic circuits/coil, ΔT=8.6 deg for ΔP=7 bars
- P=9.6 kW
- I=527 A

Dimensions of the ALBA combined Bending Magnet



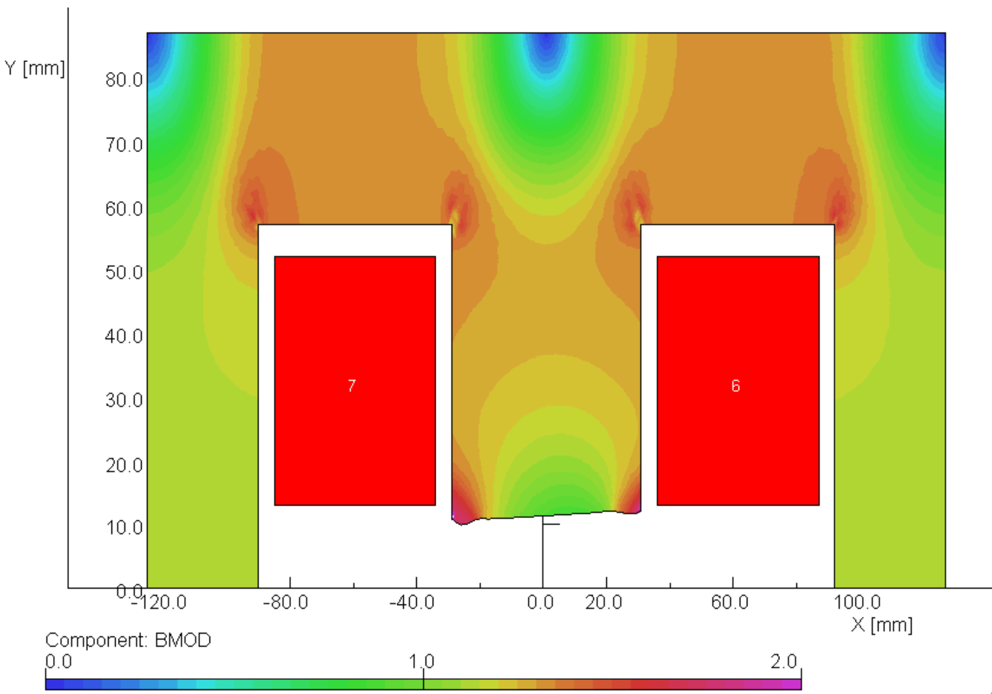


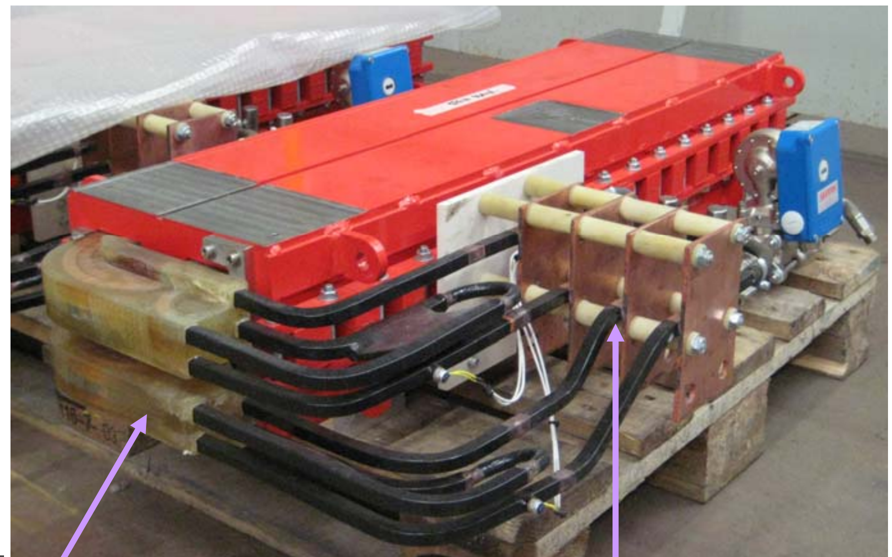
Booster

Number of magnets	8 / 32
Effective length (m)	1 / 2
Bending angles (°)	5 / 10
Curvature radius (m)	11.4592
Central gap (mm)	22.6
Central dipolar field (T)	0.873
Central Quadrupolar field (T/m)	-2.29
Central Sextupolar field (T/m^2)	-9.0

- 2 coils
  12 turns/coil
  (4 turns wide x 3 turns height)
- 1 / 2 hydraulic circuits/coil
  $\Delta T = 8^{o}C$, ΔP = 6 bars
- $P_{average}$ = 1.9 / 3.7 kW
- I_{peak} = 660 A

Booster Bending Dipoles (Opera – 2D models)

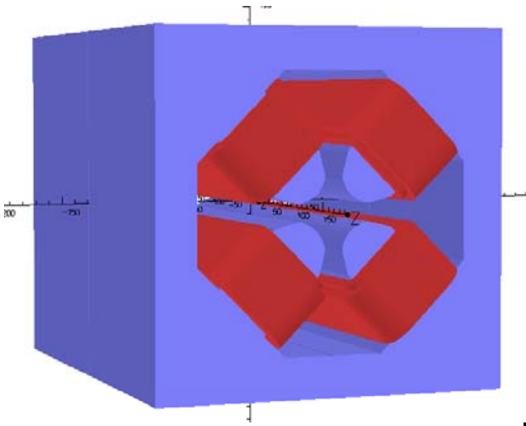




Coils with only two layers.

Space for the many fold and connectors

Quadrupole Design.

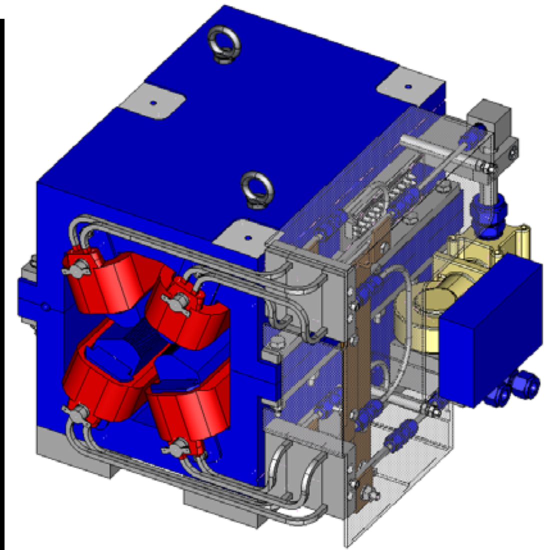


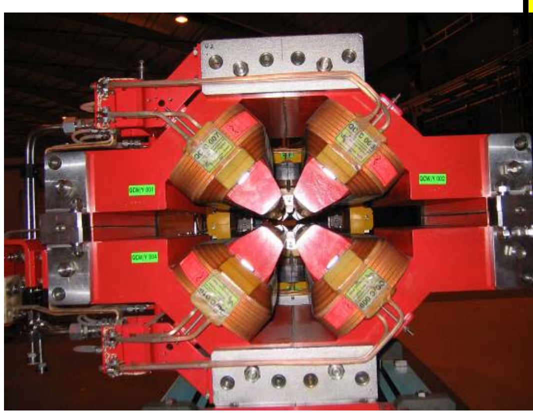
The Quadrupole Magnet has four poles. The field varies *linearly* with the the distance from the magnet center. It focuses the beam along one plane while defocusing the beam along the orthogonal plane. An *F* or focusing quadrupole focuses the particle beam along the *horizontal* plane.

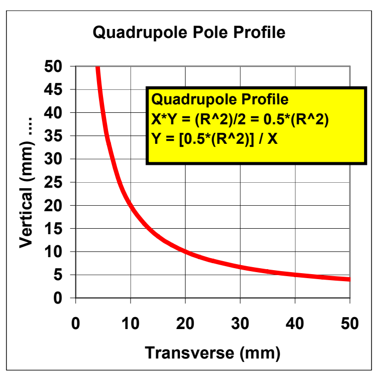
The field of the quadrupole has to be proportional to the distance from the centre (x or y). The excitation in general is given by:

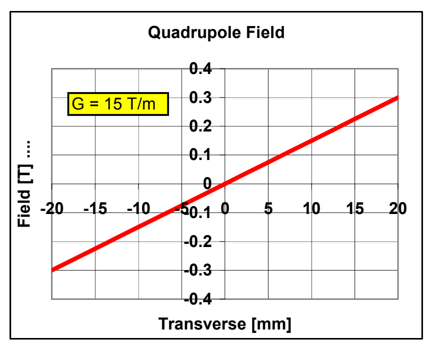
$$B_0 = \mu_0 N{*}I/g \text{ or } B(x) = \mu_0 N{*}I/x$$

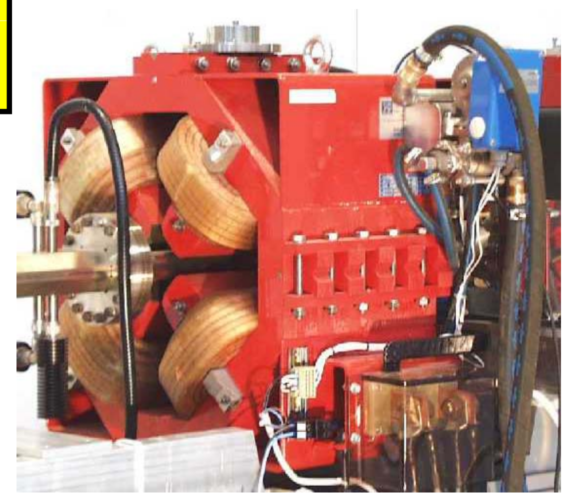
This means the pole profile of a quadrupole is a hyperbolic one.



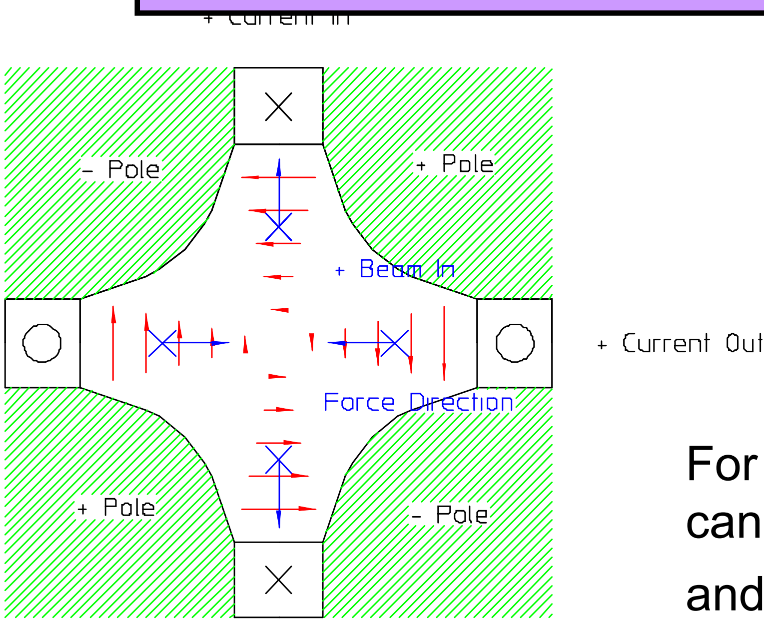


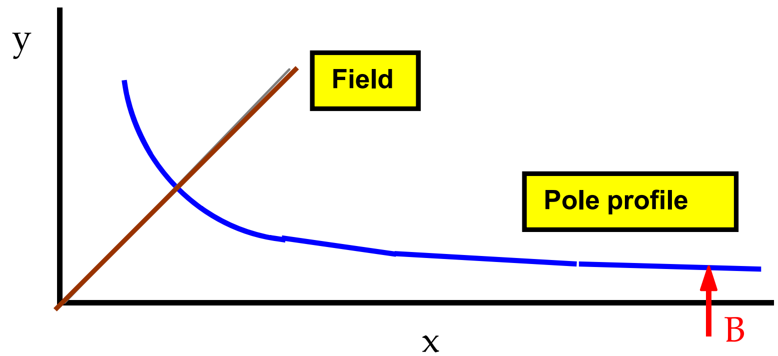






Excitation current in Quadrupole





For quadrupoles the required excitation can be calculated by considering fields and gap at large x. For example:

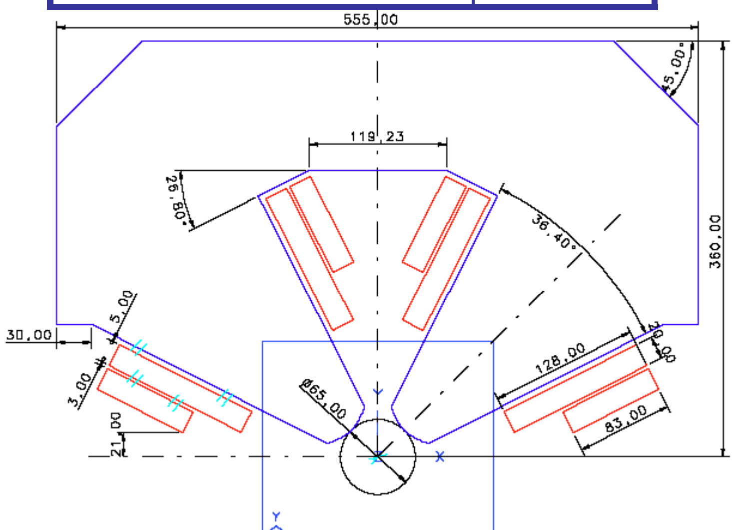
Pole equation: $x*y = R^2/2$; on x axes: $B_Y = g*x$; where g is gradient (T/m).

At large x (to give vertical lines at B): $N\,I = (g*x)\,(R^2/2x)/\mu_0$
or $N*I = g*R^2/2\,\mu_0$ (per pole).
The magnetic flux at the pole tip is given by: $B_{pole} = 2*\mu_0*N*I / R$.
The gradient is given by: $g = 2*\mu_0*N*I / R^2 = B_{pole} / R$ and $m = g/(\rho*B)$
With R = 35 mm and B_{pole} = 0.6 T the gradient is roughly 17 T/m.
Today one can go up with the gradient to 22 T/m

Dimensions of the ALBA Quadrupoles

Former Quadrupole Magnets

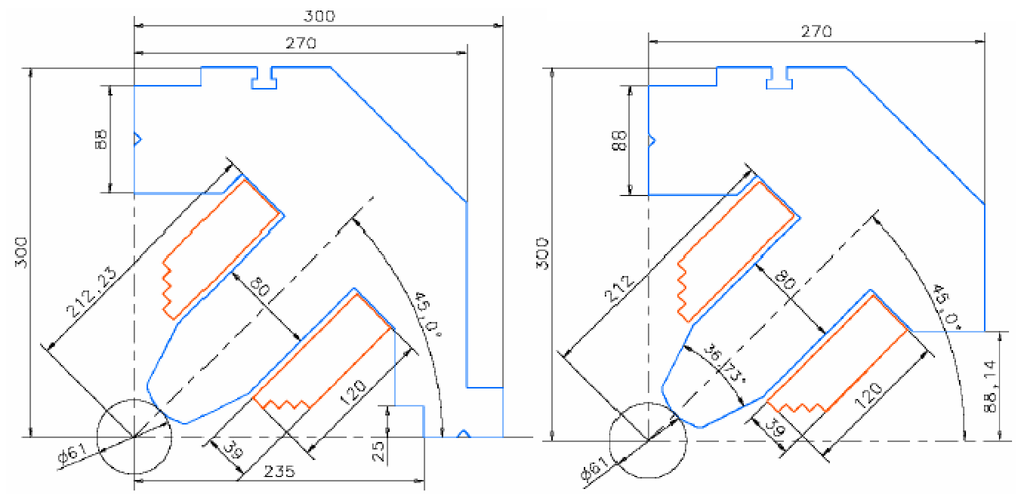
Number of magnets	112
Aperture	65 mm
Max. gradient	22 T/m
Max. current	200 A



- 1 type of lamination, 2 coil pancakes (56 turns, 8×8 mm, ∅4.5 mm)
- Mechanically made of 2 pieces
- All opened magnets with spacers
- Iron Overall dimensions are 550x720 mm

Present Quadrupole Magnets

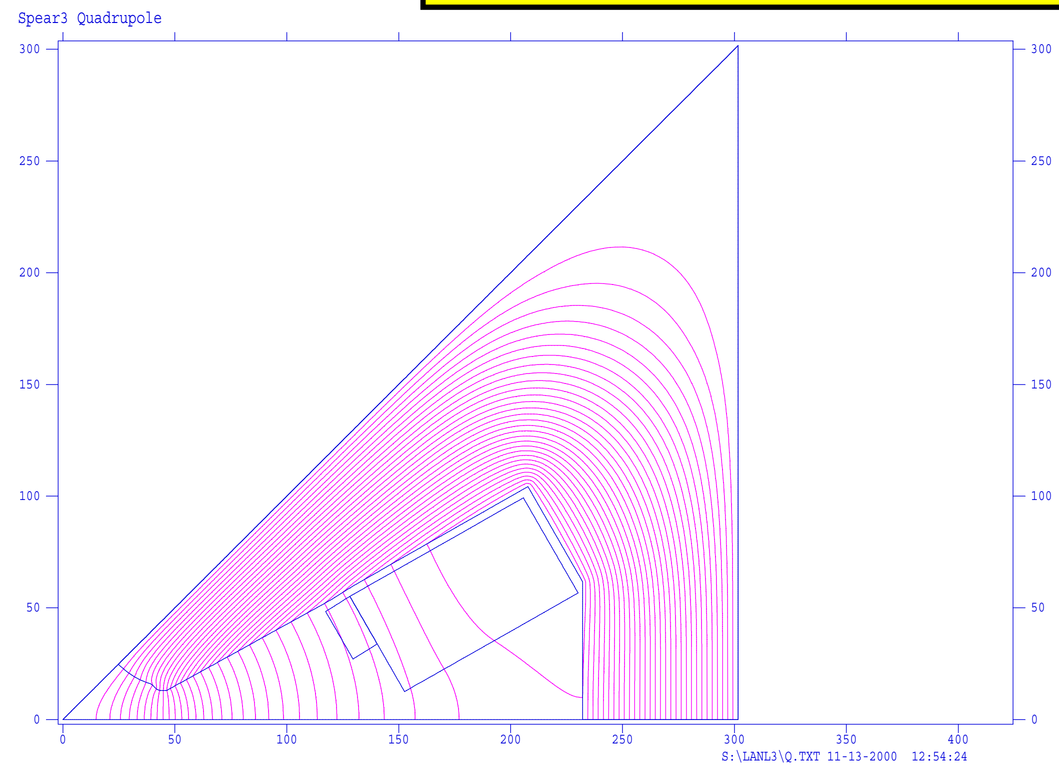
Number of magnets	112
Aperture	61 mm
Max. gradient	22.4 T/m
Max. current	185 A

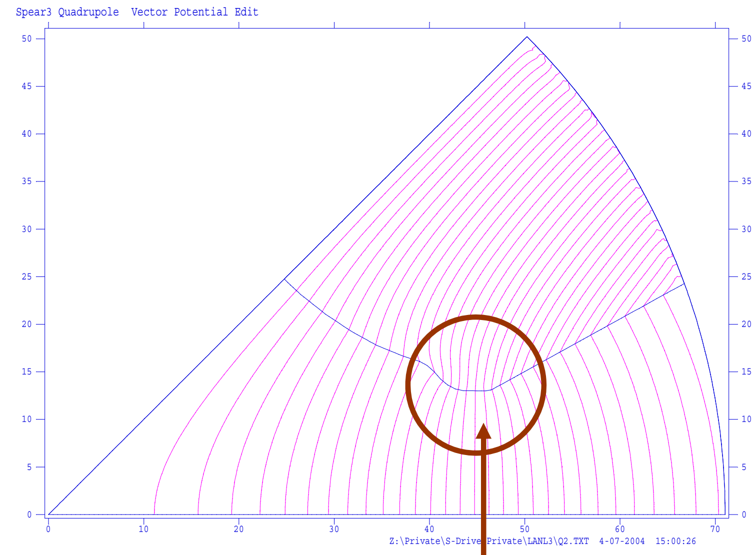


- 2 types of laminations, 1 coil (46 turns, 8×8 mm, ∅5 mm)
- Mechanically made of 4 pieces
- 100 closed magnets, 12 opened magnets
- Iron Overall dimensions are 600x600 mm

Symmetric Quadrupole

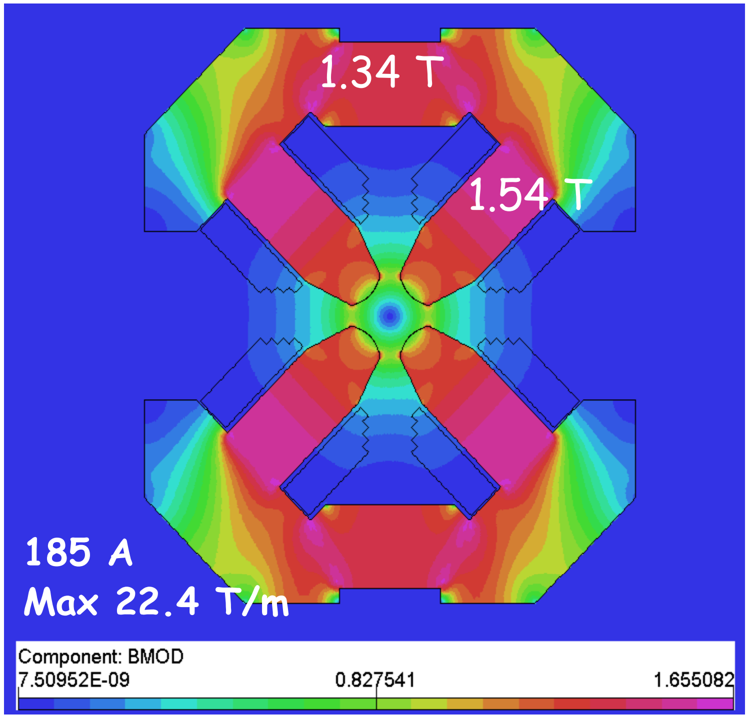
Magnetic field lines in a symmetric quadrupole

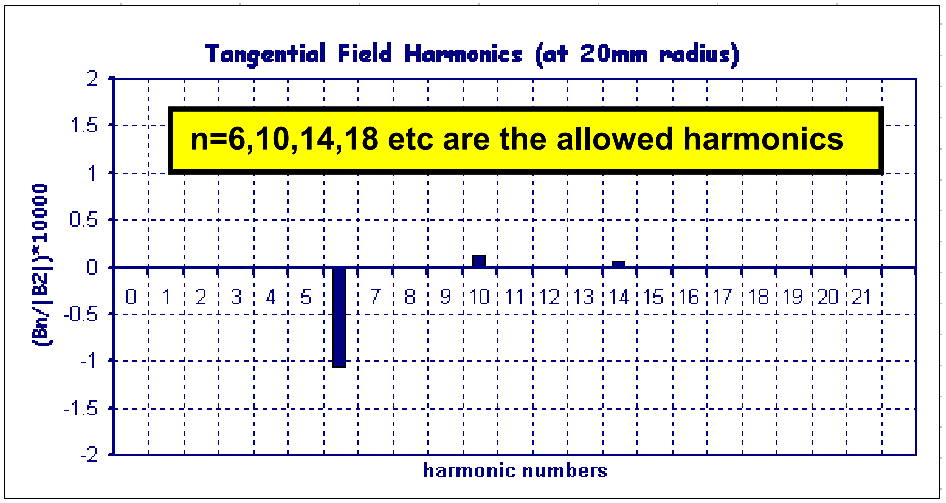


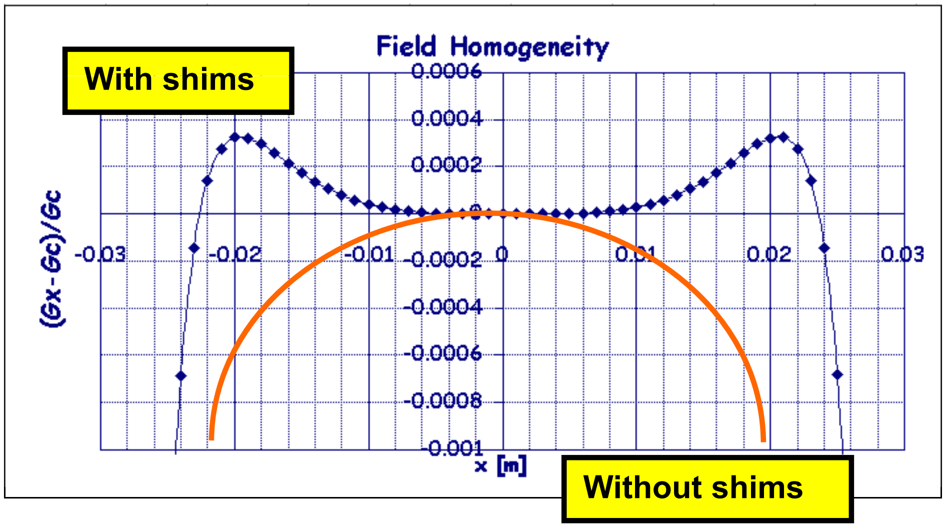


Introducing of a shim to increase the good field region

Quadrupole Magnets (2D-OPERA models)

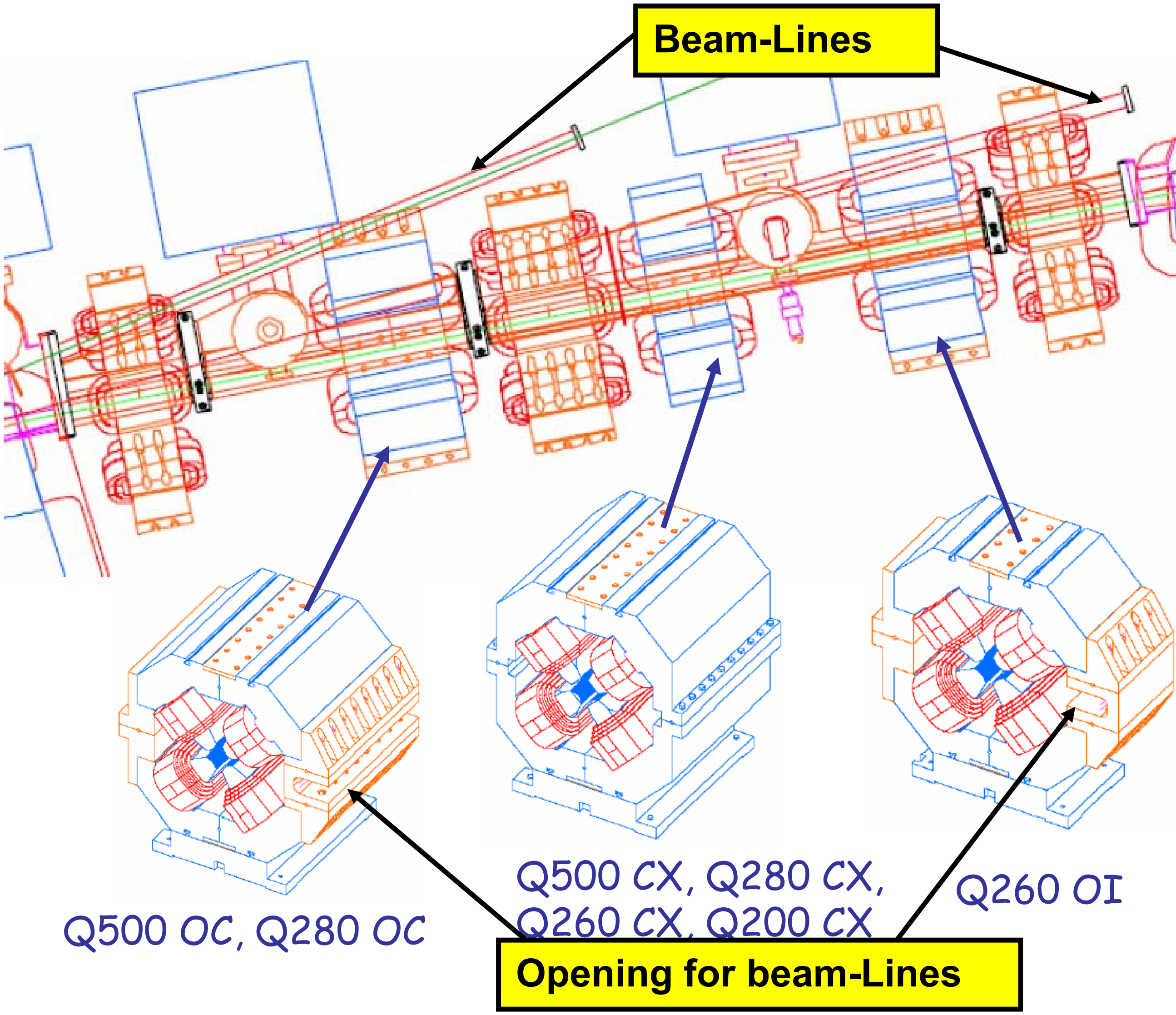




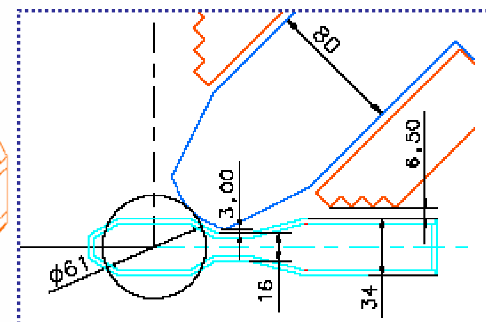


$$\frac{\Delta g}{g} \leq \pm 4 \cdot 10^{-4} \qquad |x| \leq 24.5 \text{ mm}$$

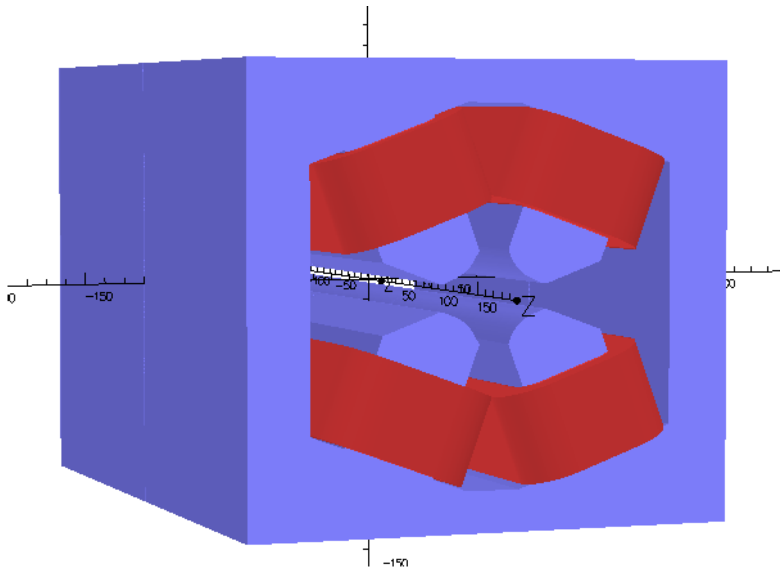
Quadrupole and Beam-Lines: Spacers

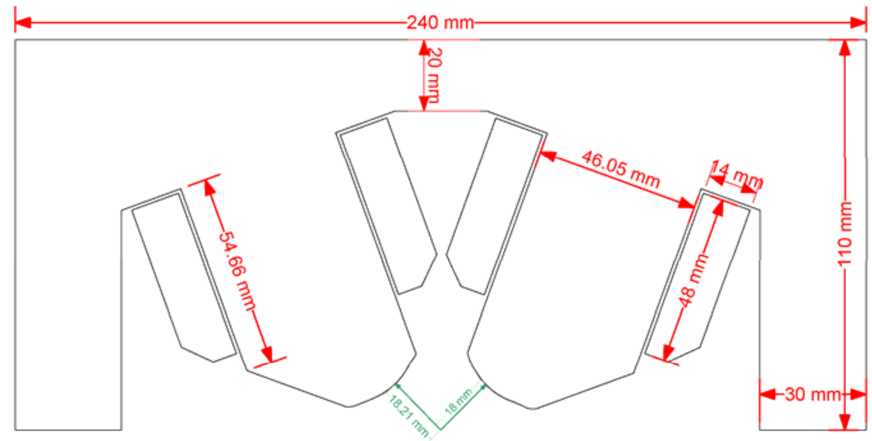


Type	Number
Q200CX	16+1
Q260CX	42+2
Q260OI	6+1
Q280CX	20+1
Q280OC	4+1
Q500CX	22+1
Q500OC	2+1

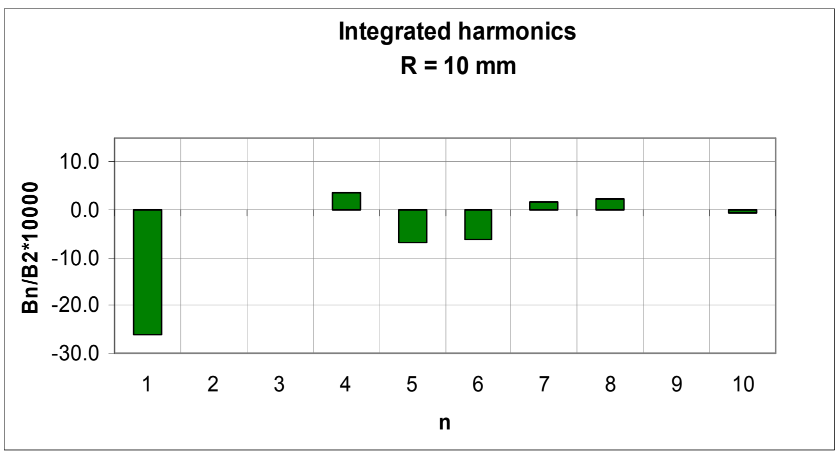


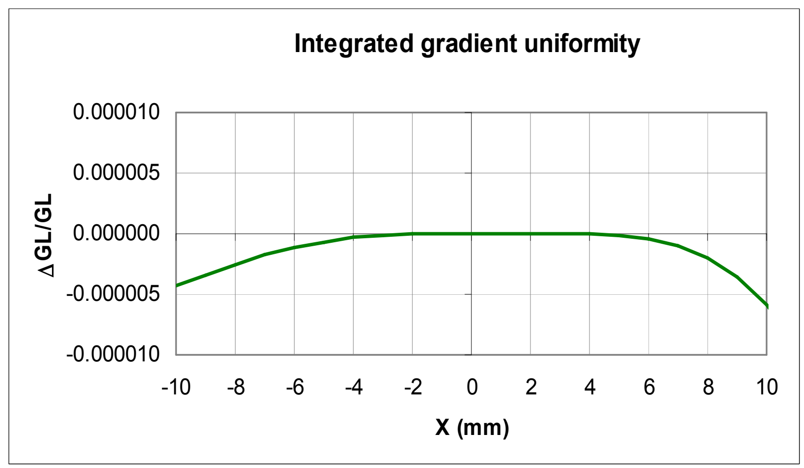
Combined Quadrupoles for the ALBA Booster





Introduction of a sextupole field

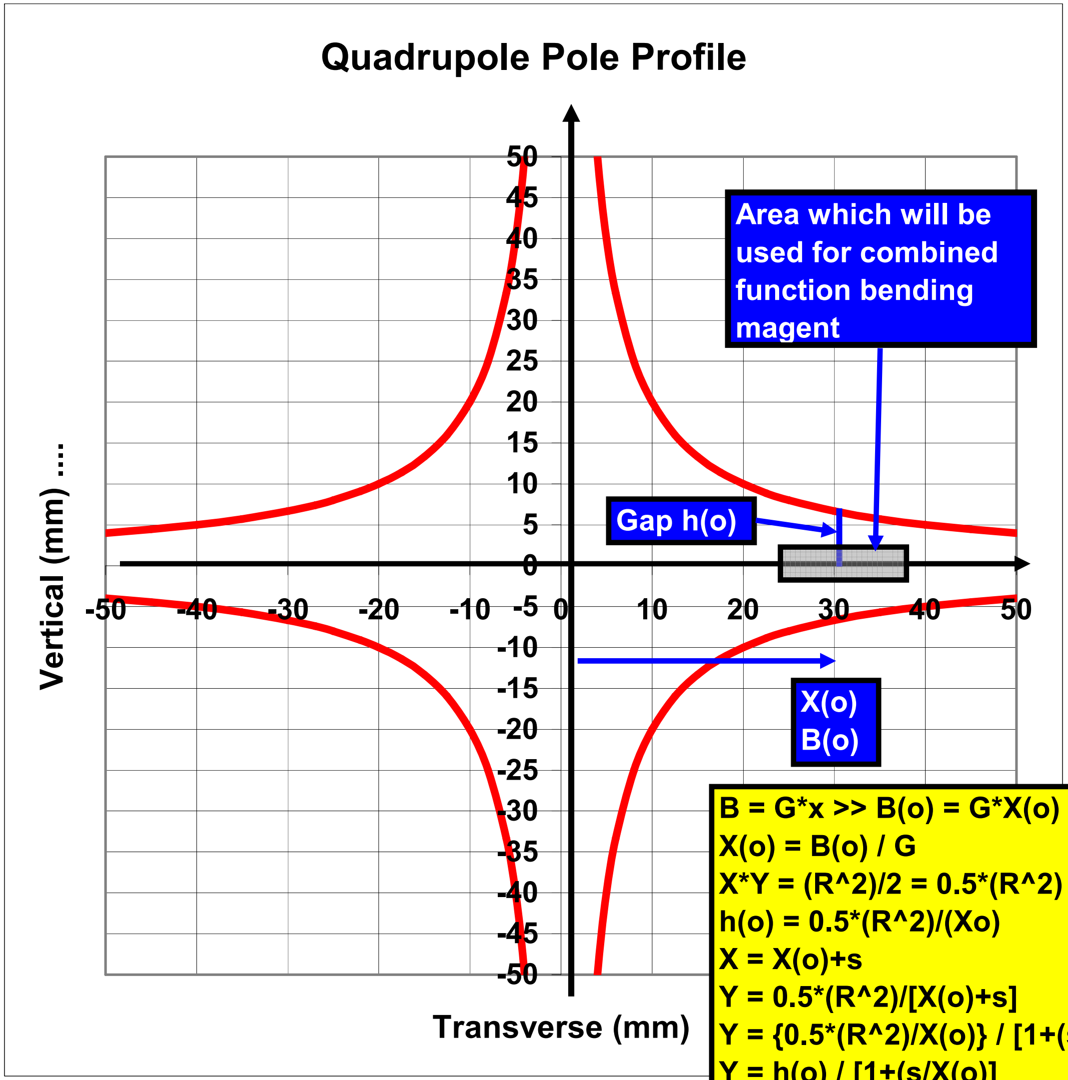




Combined function Bending Magnet.

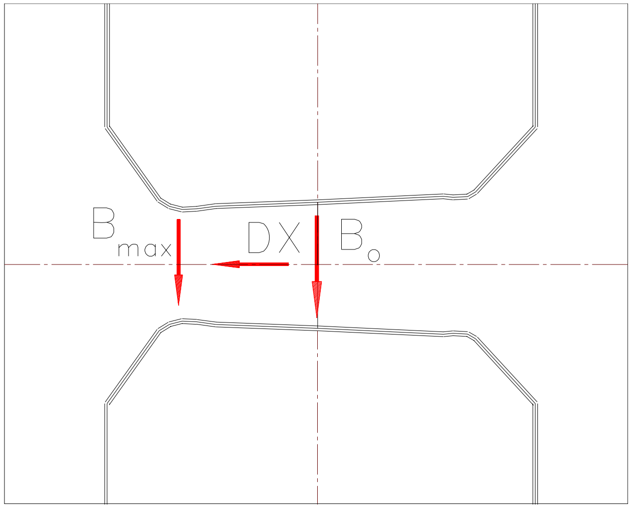
The combined function bending magnet combines the function of a bending magnet (bending a beam) and a quadrupole (focussing a beam) in one unit, the so called combined bending magnet. It is combined a “bending” in the horizontal direction with a “focussing” in the vertical direction. With combined direction. With combined bending magnet it is possible to build a compact machine, because some of the defocussing quadrupoles are not needed.

At Alba we used the combined bending magnet in the storage ring as well in the booster synchrotron.

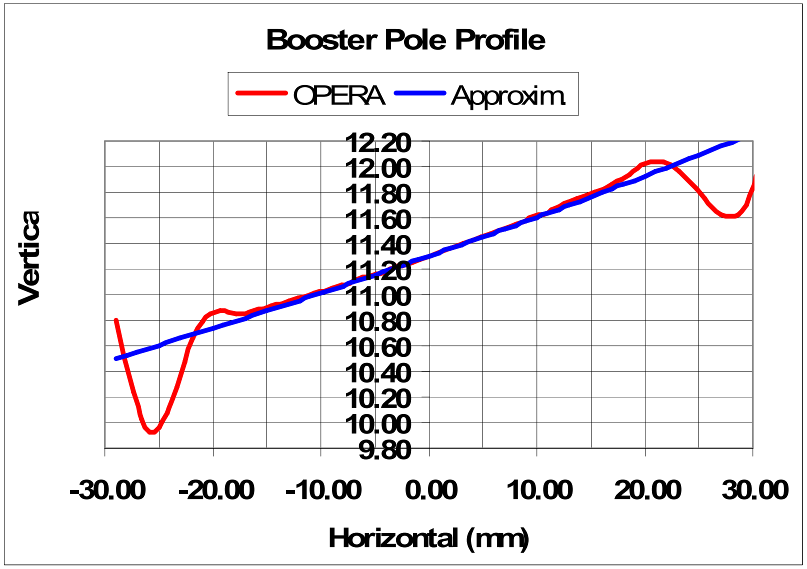


B = G*x >> B(o) = G*X(o)
X(o) = B(o) / G
X*Y = (R^2)/2 = 0.5*(R^2)
h(o) = 0.5*(R^2)/(Xo)
X = X(o)+s
Y = 0.5*(R^2)/[X(o)+s]
Y = {0.5*(R^2)/X(o)} / [1+(s/X(o)]
Y = h(o) / [1+(s/X(o)]
h(s) = h(o) / {1+[s/X(o)]}

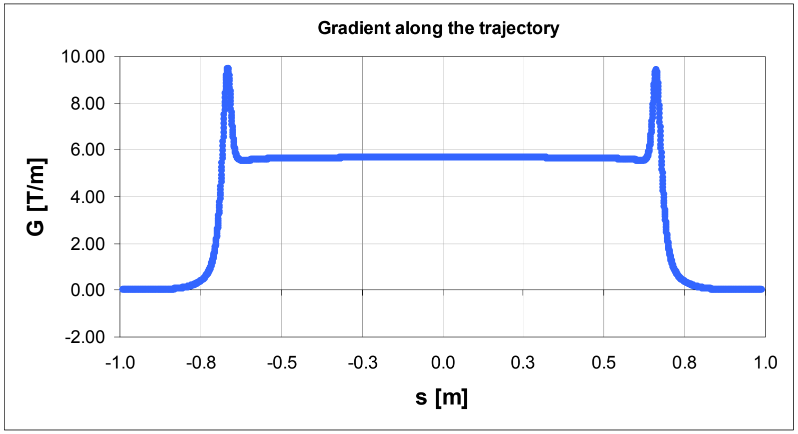
Combined function Bending Magnet.



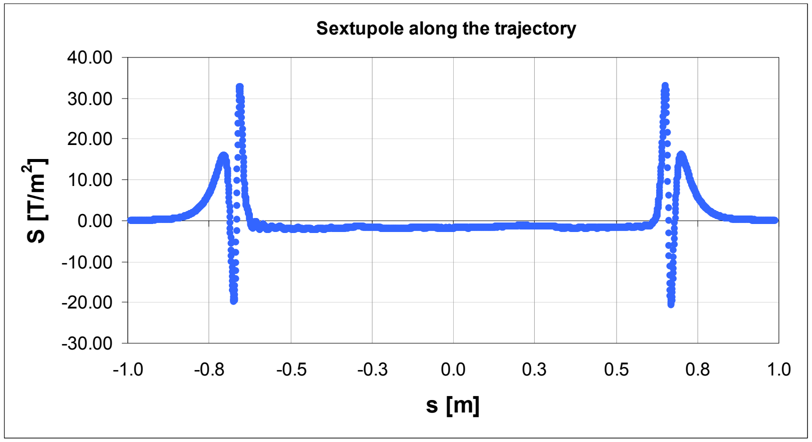
Source	Energy (GeV)	B_o (T)	G (T/m)	B_{max} (T)
ALS	1.9	1.279	5.133	1.58
Elettra	2.3	1.38	3.303	1.58
Boomerang	3.0	1.30	3.335	1.50
CLS	2.9	1.354	3.867	1.586
SPEAR III	3.3	1.4	3.60	1.62
ALBA	3.0	1.42	5.66	1.66



Longitudinal Field Distribution



Gradient: Focusing strength



Sextupole:

Change in chromaticity

Parameters of the ALBA Bending Magnets

Storage Ring Bending Magent		
Magnetic properties		
Beam Energy (E)	GeV	3
Central Field (Bo)	T	1.42
Field gradient (Go)	T/m	5.656
Sextupole component (B")	T/(m^2)	0
Effective length (Lo)	m	1.384
Mechanical properties		
Bending radius (Ro)	m	7.047
Bending angle (phi)	degrees	11.25
Central Gap (h)	mm	36
Length of Fe-yoke L(Fe)	mm	1340
Coil and conductor		
Number of coils		2
Number of pancakes per coil		4
Number of turns per pancake		10
Concductor size	mm^2	16.3*10.8
Cooling channel diameter (D)	mm	6.6
Number of ampere turns per coil	A-turns	21000
Current (I)	A	527
Current density (j)	A/mm^2	3.72
Resistance at 23 degrees	Ohm	
Inductivity	mH	
Voltage drop	V	
Power	kW	
Cooling		
Maximim DT	Celsius	8.6
Nominal input temperature	Celsius	23
Number of cooling circuits per coil		2
Maximum pressure drop per magnet	bar	7

Booster Bending Magents			
		5 Degr.	10 Degr.
Magnetic properties			
Beam Energy (E)	GeV	3	3
Central Field (Bo)	T	0.8733	0.8733
Field gradient (Go)	T/m	2.292	2.292
Sextupole component (B")	T/(m^2)	18	18
Effective length (Lo)	m	1	2
Mechanical properties			
Bending radius (Ro)	m	11.4592	11.4592
Bending angle (phi)	degrees	5	10
Central Gap (h)	mm	22.6	22.6
Length of Fe-yoke L(Fe)	mm	0.972	1.972
Coil and conductor			
Number of coils		2	2
Number of pancakes per coil		1	1
Number of turns per pancake		12	12
Concductor size	mm^2	12*12	12*12
Cooling channel diameter (D)	mm	5	5
Number of ampere turns per coil	A-turns	7906	7906
Current (I)	A	659	659
Current density (j)	A/mm^2	6.08	6.08
Resistance at 23 degrees	mOhm	9.2	18.2
Inductance	mH	1.3	2.6
Voltage drop	V	6.1	31.8
Power	kW	2	3.94
Cooling			
Maximim DT	Celsius	11	11
Nominal input temperature	Celsius		23
Number of cooling circuits per coil		1	2
Maximum pressure drop per magne	bar	7	7

Parameters of the ALBA Quadrupoles

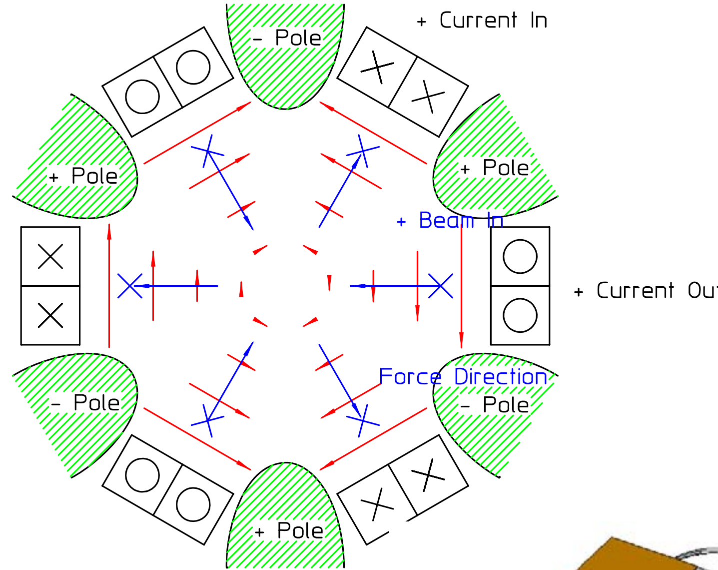
Storage Ring Quadrupole Magents					
		Q200	Q260	Q280	Q500
Magnetic properties					
Beam Energy (E)	GeV	3	3	3	3
Field gradient (Go)	T/m	19.8	21	21.4	21.9
Sextupole component (B")	T/(m^2)	0	0	0	0
Effective length (Lo)	m	0.23	0.29	0.31	0.53
Mechanical properties					
Aperture radius	mm	30.5	30.5	30.5	30.5
Length of Fe-yoke L(Fe)	m	0.2	0.26	0.28	0.5
Maximum length of magnet	m	0.298	0.358	0.378	0.598
Coil and conductor					
Number of coils		4	4	4	4
Number of turns per coil		46	46	46	46
Concductor size	mm^2	8*8	8*8	8*8	8*8
Cooling channel diameter (D)	mm	5	5	5	5
Number of ampere turns per coil	A-turns	7801	8274	8432	8629
Current (I)	A	167.8	178.7	199.6	187.4
Current density (j)	A/mm^2	3.78	4.02	4.5	4.22
Resistance at 23 degrees	mΩ				
Inductivity	mH				
Voltage drop	V				
Power	kW				
Cooling					
Maximim DT	Celsius	8	8	8	8
Nominal input temperature	Celsius	23	23	23	23
Number of cooling circuits per coil		4	4	4	4
Maximum pressure drop per magnet	bar	7	7	7	7

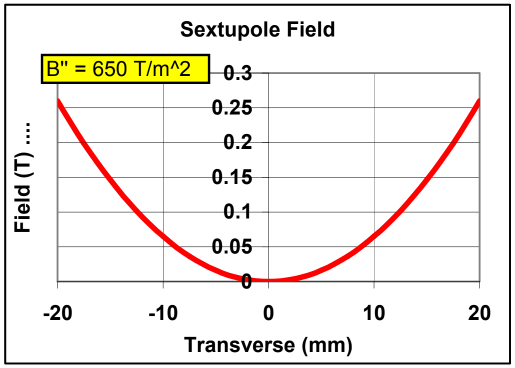
Booster Quadrupole Magents				
		QS180	QS340	QC340
Magnetic properties				
Beam Energy (E)	GeV	3	3	3
Field gradient (Go)	T/m	17.45	17.45	17.45
Sextupole component (B")	T/(m^2)	0	0	5
Effective length (Lo)	m	0.2	0.36	0.36
Mechanical properties				
Aperture radius	mm	18	18	18
Length of Fe-yoke L(Fe)	m	0.18	0.34	0.34
Maximum length of magnet	m	0.28	0.44	0.44
Coil and conductor				
Number of coils		4	4	4
Number of turns per coil		17	17	17
Concductor size	mm^2	5*5	5*5	5*5
Cooling channel diameter (D)	mm	3	3	3
Number of ampere turns per coil	A-turns	2250	2250	2250
Current (I)	A	132.4	132.4	132.4
Current density (j)	A/mm^2	3.78	4.02	4.22
Resistance at 23 degrees	mΩ	34.6	59	59
Inductivity	mH	3	6	6
Voltage drop (resistive)	V	4.6	7.8	7.8
Power	W	606	1034	1034
Cooling				
Maximim DT	Celsius	8	8	8
Nominal input temperature	Celsius	23	23	23
Number of cooling circuits per coil		1	1	1
Maximum pressure drop per magne	bar	7	7	7

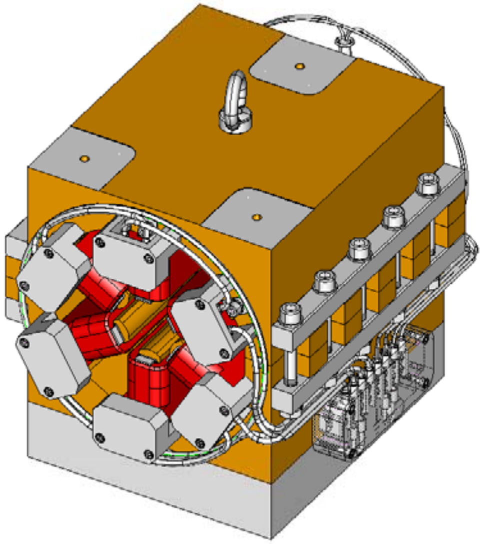
Sextupole Design.

The Sextupole Magnet has six poles. The field varies *quadratically* with the distance from the magnet center. It's purpose is to affect the beam at the edges, much like an optical lens which corrects chromatic aberration. Sextupole are needed for the compensation of the chromaticity to make in a small range the focusing of the machine energy independent. An *F* sextupole will steer the particle beam toward the center of the ring.

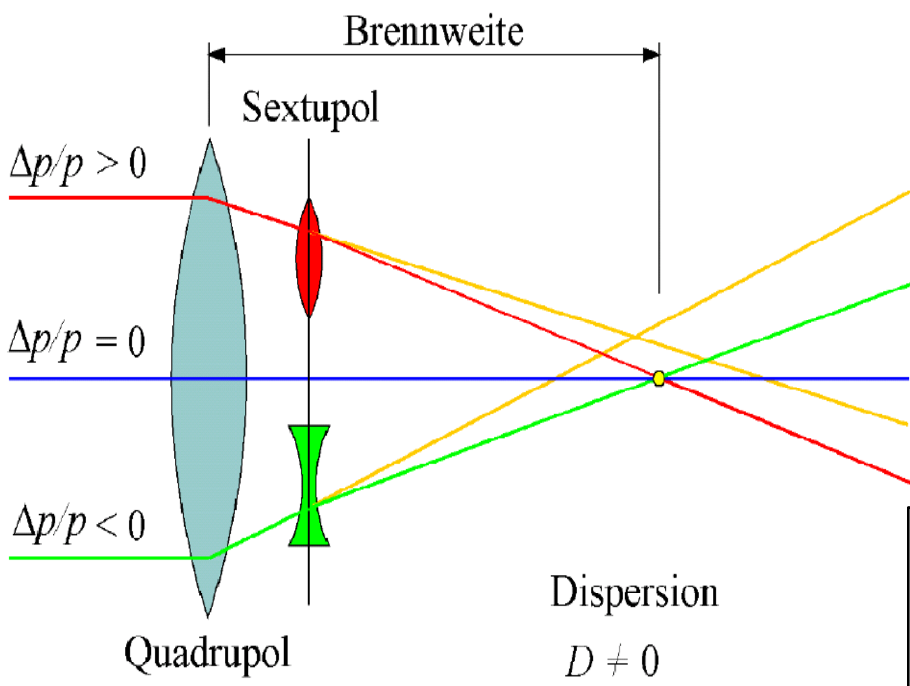
Note that the sextupole also steers along the 60 and 120 degree lines.

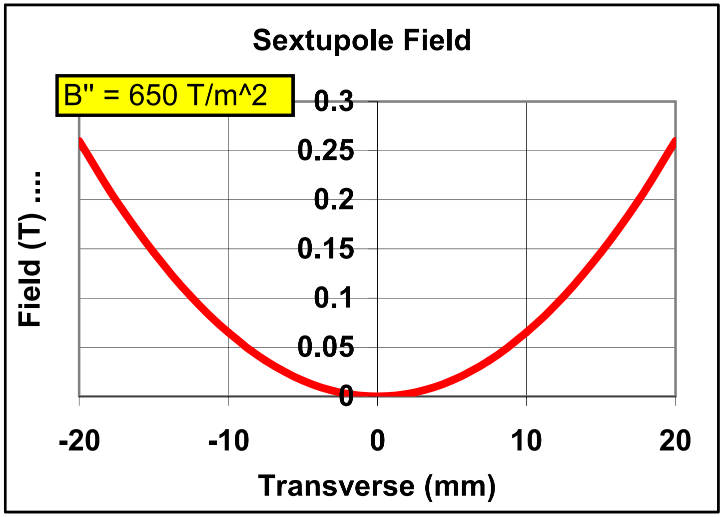






Sextupole Design.





Sextupole Excitation

Using arguments similar to those used for the dipole: $\oint_{Path2} \overline{H} \bullet \overline{dl} + \oint_{Path3} \overline{H} \bullet \overline{dl} \approx 0$

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

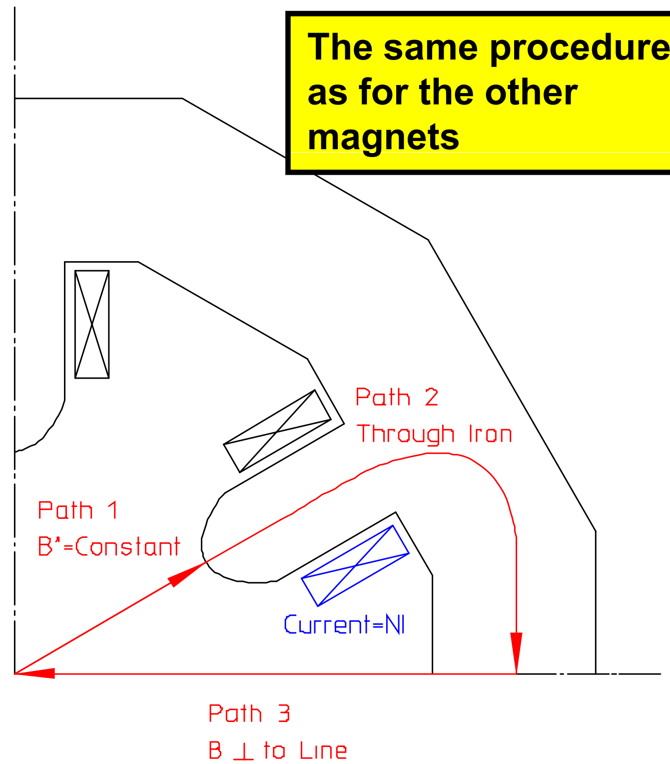
$$B(r) = \int B'' r dr = \frac{B'' r^2}{2}$$

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

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

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

The same procedure as for the other magnets



Excitation current in a Sextupole

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

$N*I = B''*R^3 / (6*\mu_0)$

$B_{Pole} = B''*R^2 / 2$ and $B'' = 2*B_{Pole} / R^2$

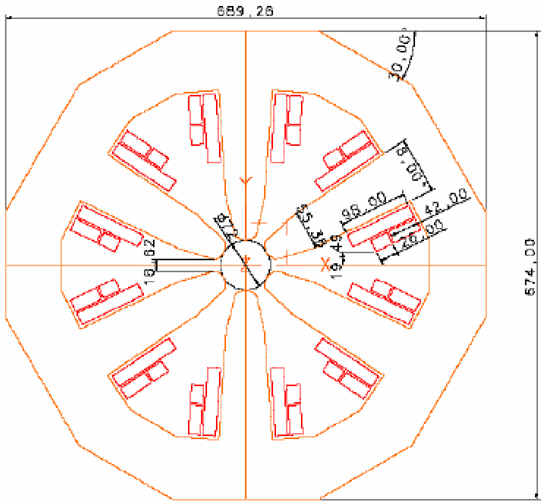
The magnetic flux at the pole tip is given by: $B_{pole} = 3*\mu_0*N*I / R$.
The differential gradient is given by: $B'' = 6*\mu_0*N*I / R^3 = 2*B_{pole} / R^2$
With R = 35 mm and B_{pole} = 0.4 T the differential gradient is roughly 653 T/m^2.

Today one can go up with the gradient to 750 T/m^2

Design of ALBA Sextupoles

Former Sextupole Magnets

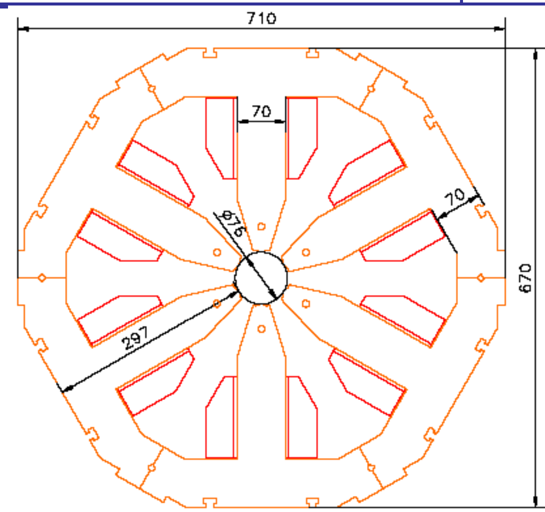
Number of magnets	120
Aperture	72 mm
Max. differential gradient	600 T/m2
Max. current	200 A



- 2 sextupole cross section needed.
- Sextupolar field: 1 coil per pole (28 turns, 7×7 mm, ∅3.5 mm).
- Correctors: 2 coils per pole (10 & 6 turns, 7×7 mm, ∅3.5 mm).

Present Sextupole Magnets

Number of magnets	120
Aperture	76 mm
Max. differential gradient	700 T/m^2
Max. current	200 A

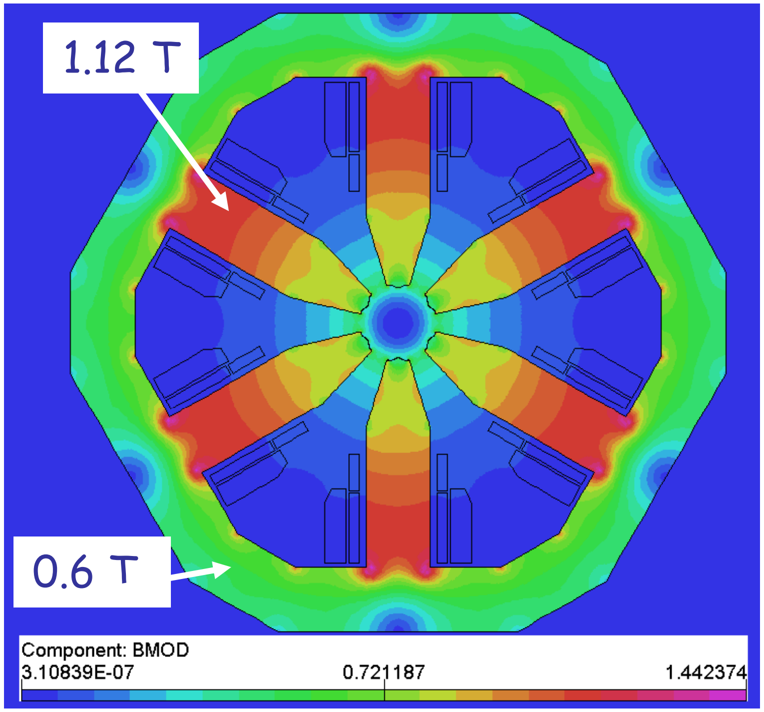


- 1 sextupole cross section.
- Sextupolar field: 1 coil per pole (28 turns, 7×7 mm, ∅3.5 mm).
- Correctors: 2 coils per pole (224 & 112 turns, 0.8×4.5mm solid conductor).

ALBA Sextupole Magnets (2D-OPERA models)

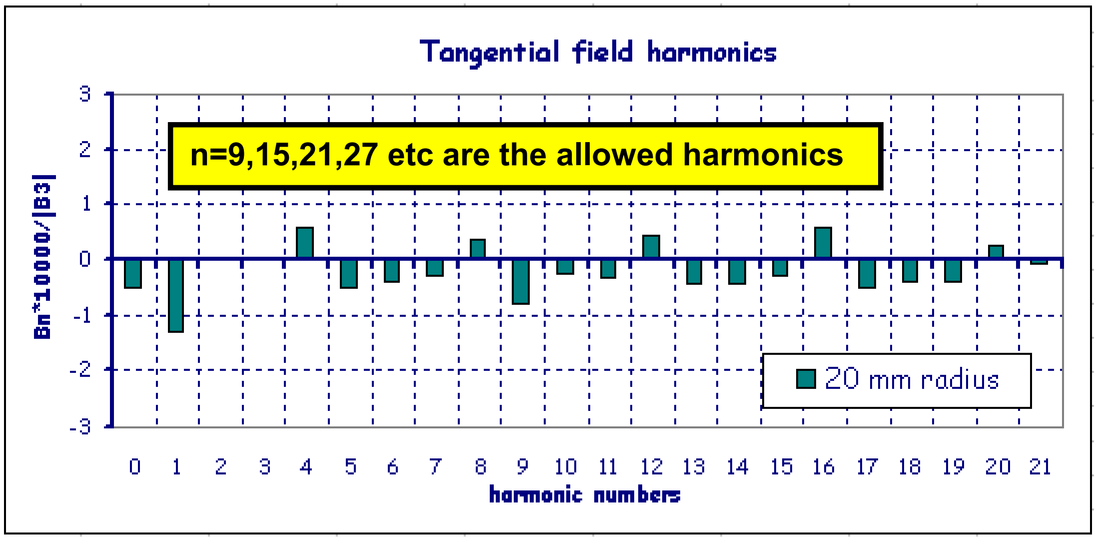
Sextupolar field:

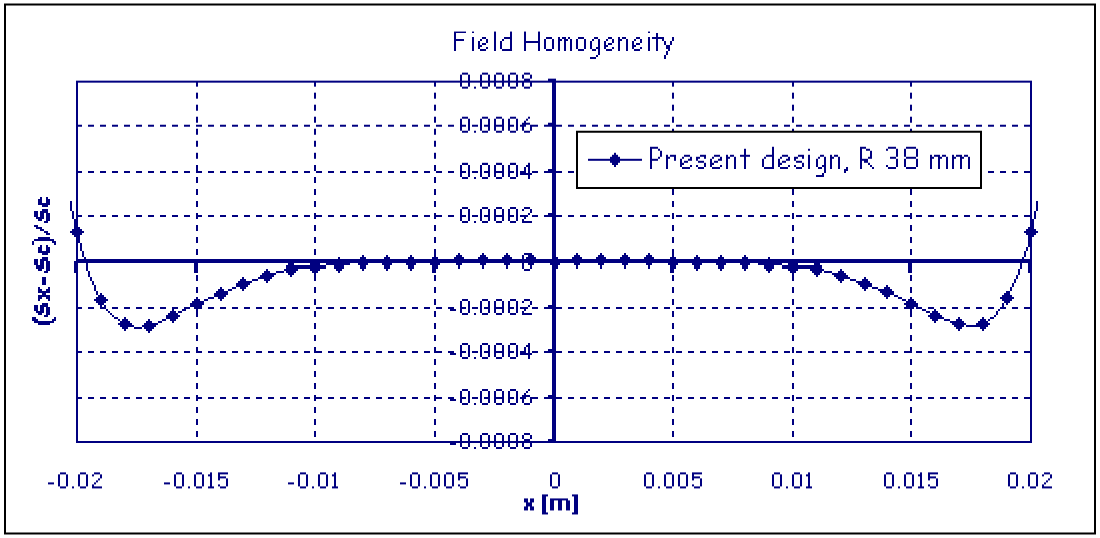
Max 4020 A-turns/coil
S = 532 T/m^2 (+5% included)



Required good field region

-20 ≤ x ≤ 20 mm $\frac{\Delta s}{s} \leq \pm 1 \cdot 10^{-3}$





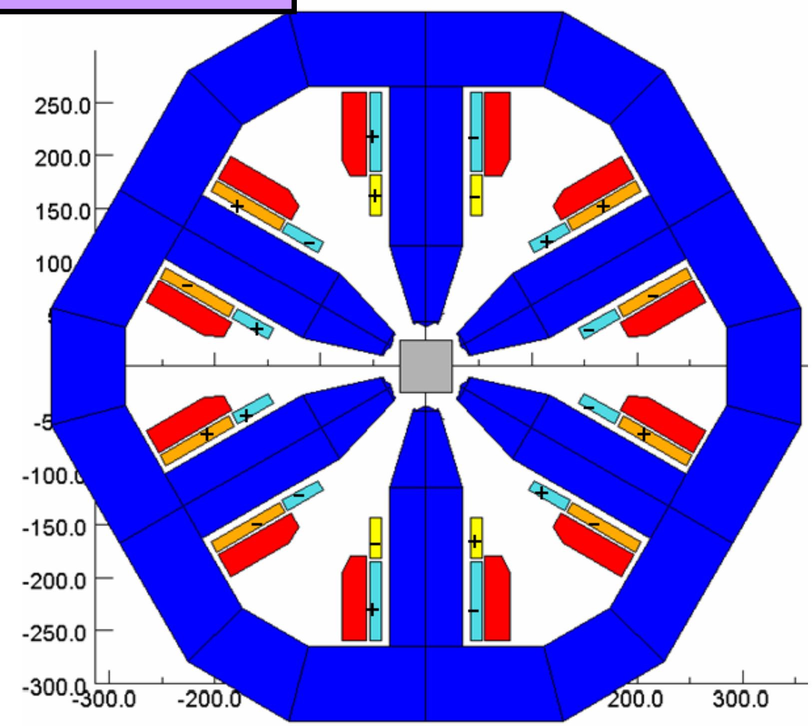
Steering (2D-models)

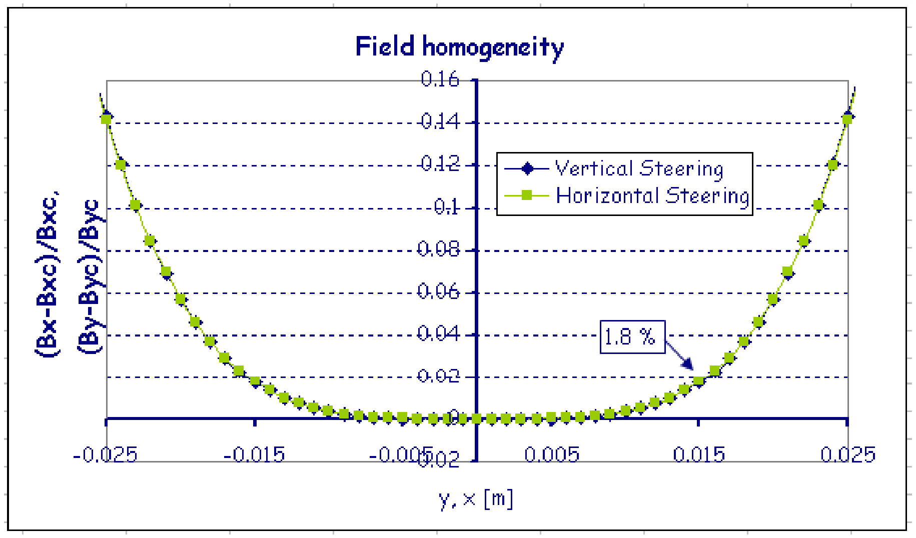
All sextupoles will be equipped with steering coils for:

Horizontal Steering 0.8 mrad
2 coil types (1806 A-turn, 903 A-turn)
By(x=0) = 0.0514 T

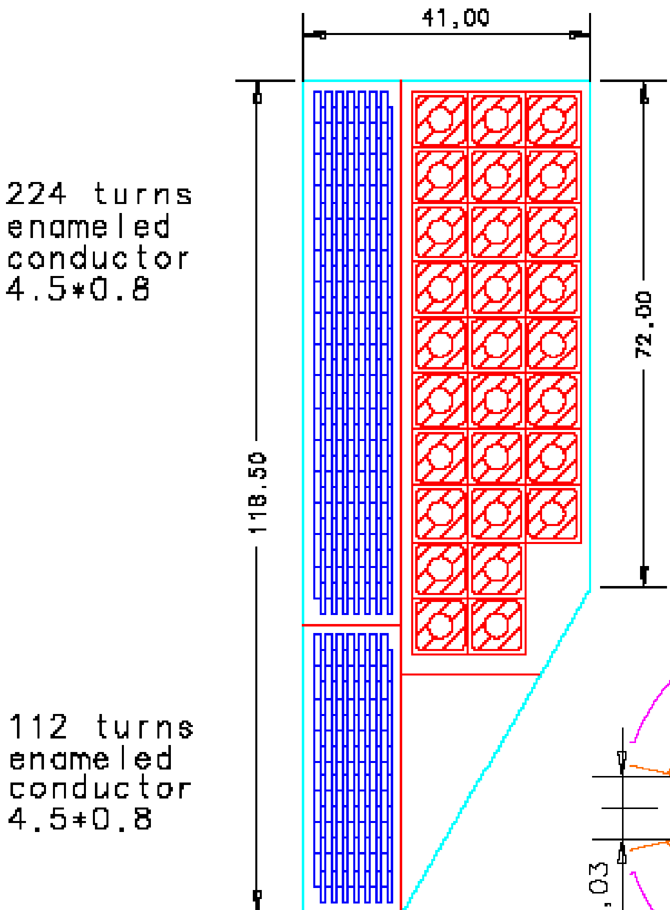
Vertical Steering 0.8 mrad
1 coil type (1520 A-turn)
Bx(y=0) = 0.0499 T

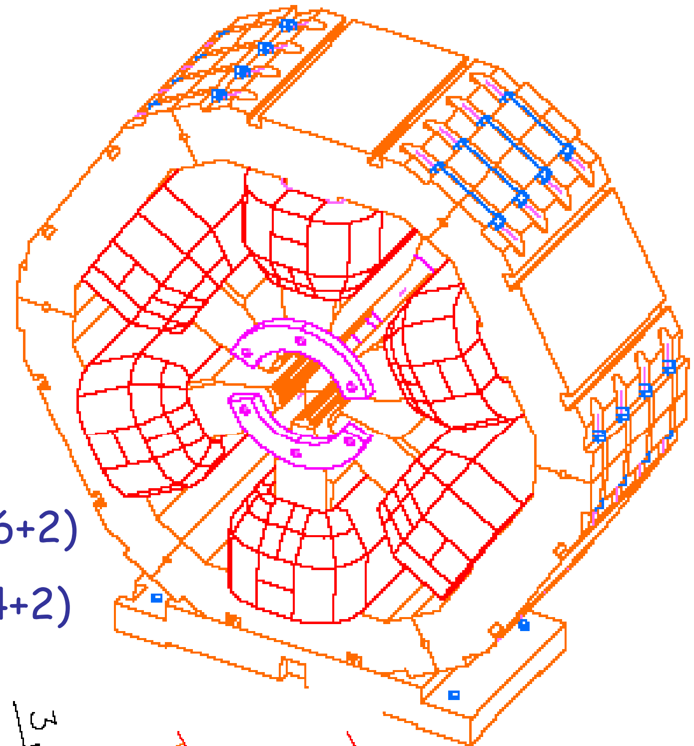
Skew Quadrupole gx=0.2 T/m
1 coil type (225 A-turn)





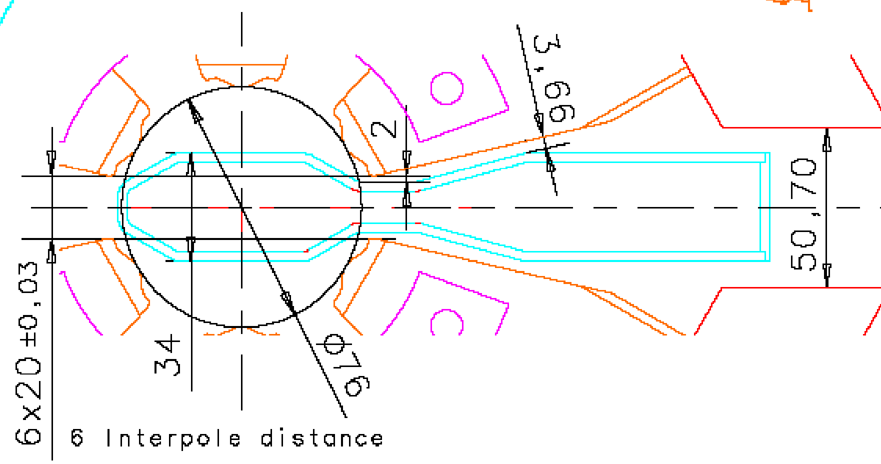
ALBA-Sextupoles: Mechanical design





S220 (56+2)

S150 (64+2)

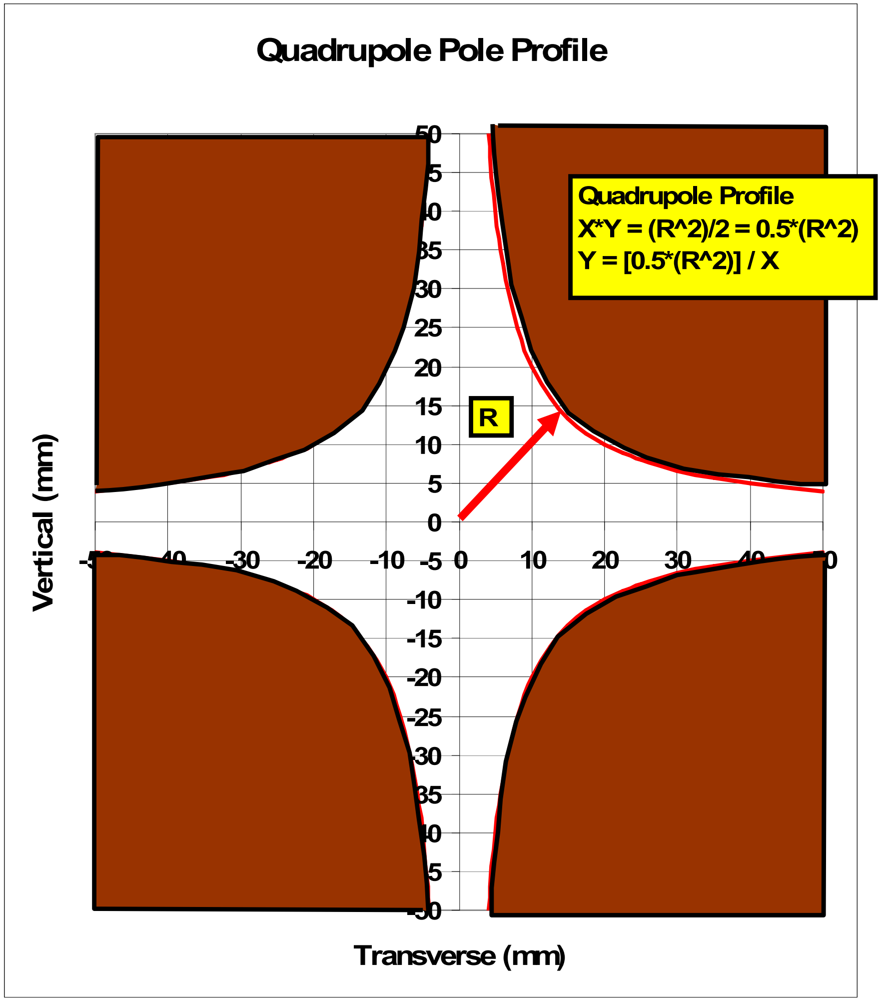


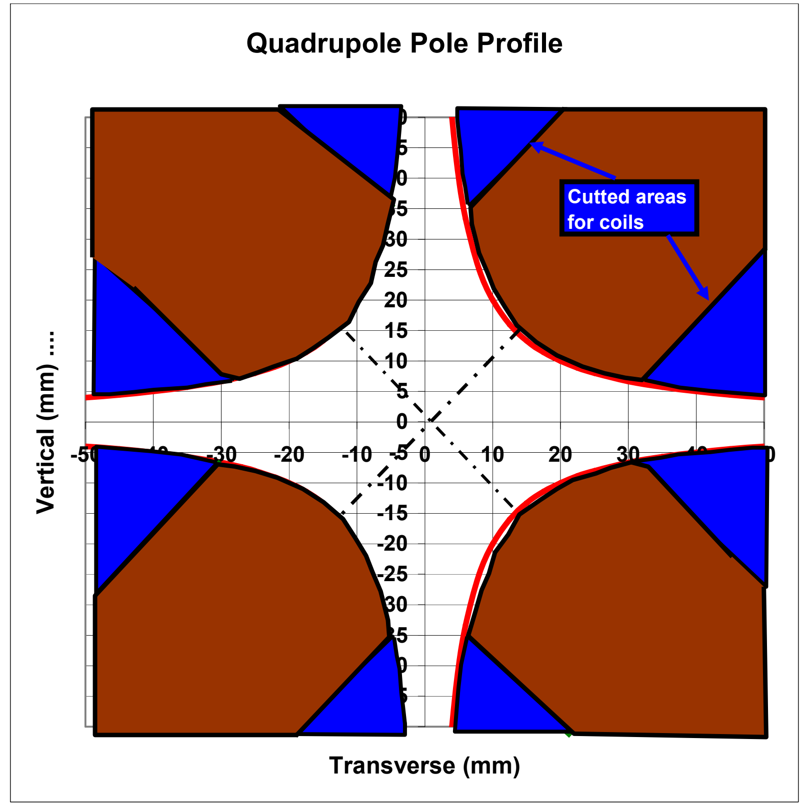
Parameters of the ALBA Sextupoles

Storage Ring Sextupole Magents			
		S-150	S-220
Magnetic properties			
Beam Energy (E)	GeV	3	3
Sextupole component (B")	T/(m^2)	700	700
Magnetic field at pole tip	T	0.51	0.51
Effective length (Lo)	m	0.175	0.245
Mechanical properties			
Aperture radius	mm	38	38
Length of Fe-yoke L(Fe)	m	0.15	0.22
Maximum length of magnet	m	0.252	0.322
Coil and conductor			
Number of coils		6	6
Number of turns per coil		28	28
Concductor size	mm^2	7*7	7*7
Cooling channel diameter (D)	mm	3.5	3.5
Number of ampere turns per coil	A-turns	5400	5400
Current (I)	A	192.9	192.9
Current density (j)	A/mm^2	4.9	4.9
Resistance at 23 degrees	mΩ		
Inductivity	mH		
Voltage drop	V		
Power	kW		
Cooling			
Maximim DT	Celsius	9	12
Nominal input temperature	Celsius	23	23
Number of cooling circuits per coil		3	3
Maximum pressure drop per magnet	bar	7	7

Booster Sextupole Magents		
		S-200
Magnetic properties		
Beam Energy (E)	GeV	3
Sextupole component (B")	T/(m^2)	400
Magnetic field at pole tip	T	0.065
Effective length (Lo)	m	0.2
Mechanical properties		
Aperture radius	mm	18
Length of Fe-yoke L(Fe)	m	0.2
Maximum length of magnet	m	0.3
Coil and conductor		
Number of coils		6
Number of turns per coil		50
Concductor size	mm^2	2.8*1
Cooling channel diameter (D)	mm	
Number of ampere turns per coil	A-turns	310
Current (I)	A	6.2
Current density (j)	A/mm^2	2.21
Resistance at 23 degrees	mΩ	886
Inductivity	mH	34
Voltage drop (resistive)	V	5.5
Power	W	33
Cooling		
Maximim DT	Celsius	
Nominal input temperature	Celsius	
Number of cooling circuits per coil		
Maximum pressure drop per magne	bar	

Explanation for higher Harmonics

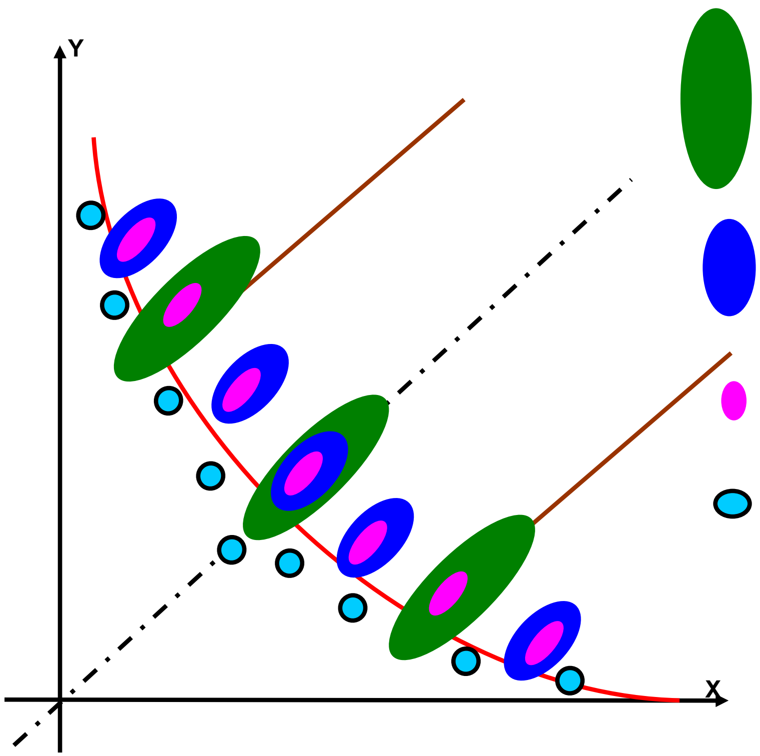




By cutting the pole profile in order to have space for the introduction of the coils the field distribution will be disturbed and higher multipoles will be introduced.

Higher Harmonics in Magnets

A dipole has overall 2 poles, which is n = 1
A quadrupole has overall 4 poles, which is n = 2
A sextupole has overall 6 poles, which is n = 3



Dipole: Introduction of 3 poles, that means overall 6 poles, which is n = 3
Quadrupole: Introduction of 3 poles, that means overall 12 poles, which is n = 6
Sextupole: Introduction of 3 poles, that means overall 18 poles, which is n = 9

Dipole: Introduction of 5 poles, that means overall 10 poles, which is n = 5
Quadrupole: Introduction of 5 poles, that means overall 20 poles, which is n = 10
Sextupole: Introduction of 5 poles, that means overall 30 poles, which is n = 15

Dipole: Introduction of 7 poles, that means overall 14 poles, which is n = 7
Quadrupole: Introduction of 7 poles, that means overall 28 poles, which is n = 14
Sextupole: Introduction of 7 poles, that means overall 42 poles, which is n = 21

Dipole: Introduction of 9 poles, that means overall 18 poles, which is n = 9
Quadrupole: Introduction of 9 poles, that means overall 36 poles, which is n = 18
Sextupole: Introduction of 9 poles, that means overall 54 poles, which is n = 27

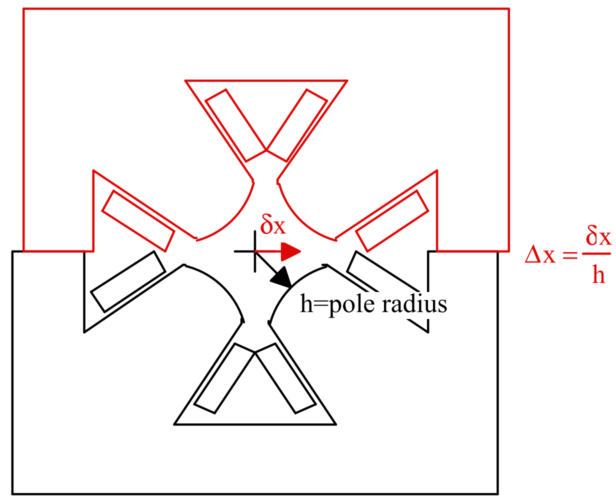
Summary - 'Allowed' Harmonics

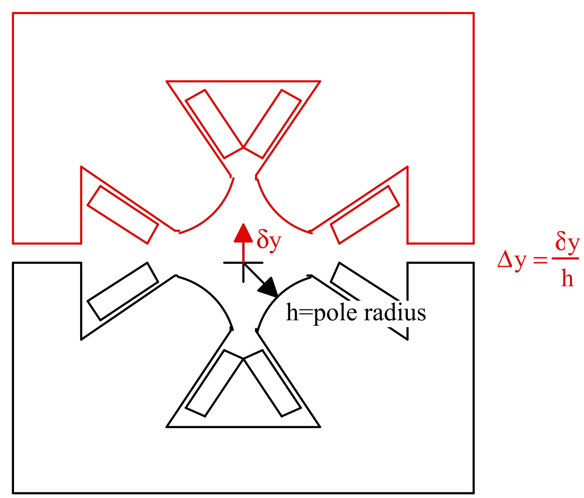
Summary of 'allowed harmonics' in fully symmetric magnets:

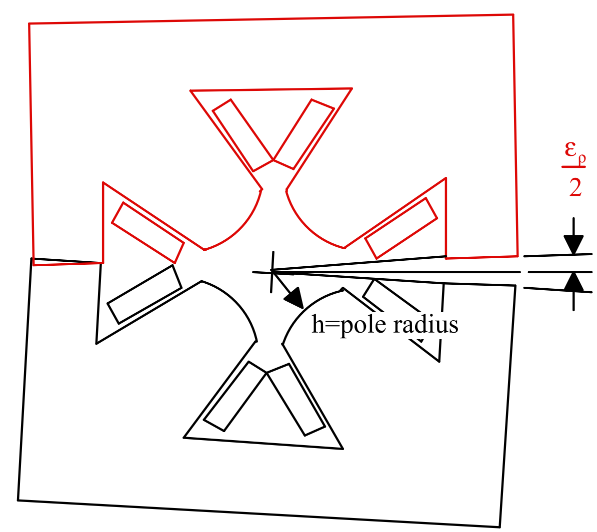
Fundamental geometry	'Allowed' harmonics
Dipole, n = 1	n = 3, 5, 7, ... (6 pole, 10 pole, etc.)
Quadrupole, n = 2	n = 6, 10, 14, ... (12 pole, 20 pole, etc.)
Sextupole, n = 3	n = 9, 15, 21, ... (18 pole, 30 pole, etc.)
Octupole, n = 4	n = 12, 20, 28, ... (24 pole, 40 pole, etc.)

Higher Harmonics in Magnets

Assembling errors introduce higher harmonics

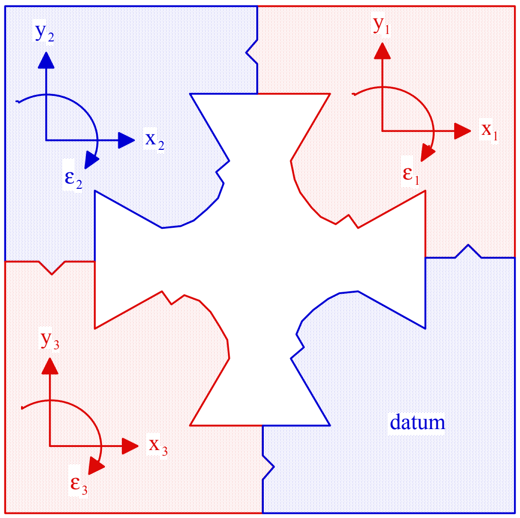




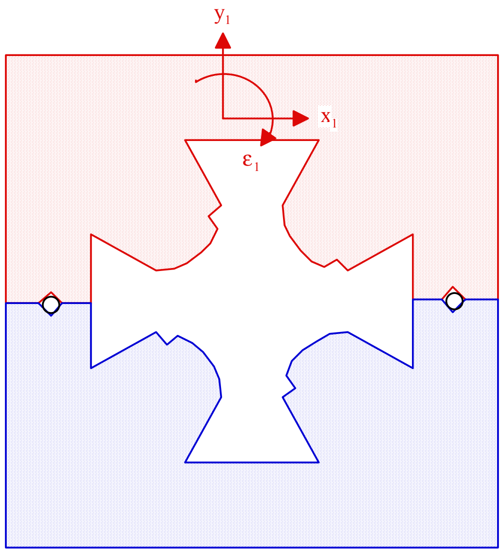


Assembling of Quadrupoles

Each segment can be assembled with errors with three kinematic motions, x, y and e (rotation). Thus, combining the possible errors of the three segments with respect to the datum segment, the core assembly can be assembled with errors with 3x3x3=27 degrees of freedom.



This assembly has the advantage that the two core halves can be assembled kinematically with *only* three degrees of freedom for assembly errors. Thus, assembly errors are more easily measured and controlled.



Higher Harmonics in Magnets

Typical results from a quadrupole

QUADROPOLE REGISTRATION CERTIFICATE OF Q500CX_021_180A_02

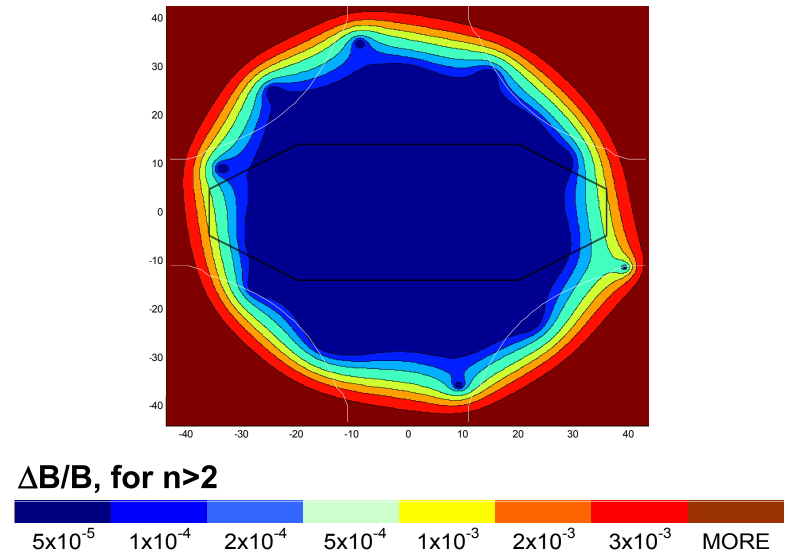
Date: 10:08:00 12.05.2008
Quadropole effective length (L): 50.00 cm. Coil radius (R): 2.65 cm. Horizontal shift:0.0094 mm.
Main current (I_M): 0.0000 A Vertical shift: 0.0131 mm.
Correction current: I = 0.0000 A Angle of slope:0.00001 rad.
D:\Measurements\--==ALBA==--04June\quadrupoles\Fourth\Q500\021\Q500CX_021_180A_02.lmf

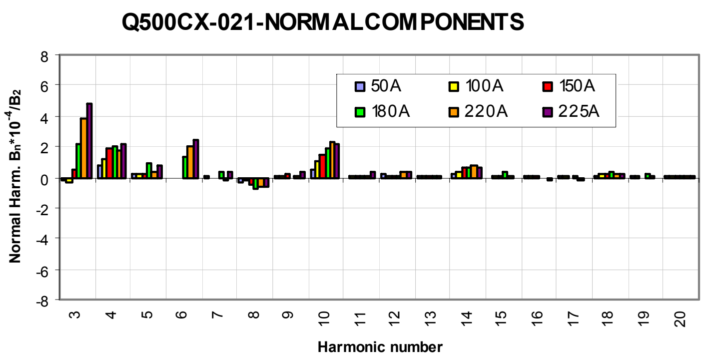
Harmonic (n)	Magnetic field amplitude at radius 1.00 cm.		Magnetic field amplitude at reference radius 2.500 cm.				Phase (rad.)
	$\sqrt{A_n^2+B_n^2}$ (Gs)	relative	B_n (Gs)	A_n (Gs)	$\sqrt{A_n^2+B_n^2}$ (Gs)	relative	
1	3.686146	0.001616	-2.15540	-2.99030	3.686146	0.000646	0.94624
2	2281.200	1.000000	-5703.00	-0.15592	5703.001	1.000000	0.00002
3	0.536546	0.000235	1.404338	3.045198	3.353416	0.000588	1.13869
4	0.084272	0.000037	1.312289	0.108339	1.316754	0.000231	0.08237
5	0.015485	0.000007	0.552235	0.246860	0.604900	0.000106	0.42037
6	0.009163	0.000004	0.890467	0.087789	0.894784	0.000157	0.09827
7	0.001125	0.000000	0.235104	-0.14181	0.274563	0.000048	-0.5427
8	0.001022	0.000000	-0.53130	0.326749	0.623742	0.000109	-0.5513
9	0.000060	0.000000	-0.07418	0.054630	0.092131	0.000016	-0.6347
10	0.000326	0.000000	1.230373	0.189723	1.244915	0.000218	0.15299
11	0.000038	0.000000	0.080772	0.351094	0.360266	0.000063	1.34467
12	0.000010	0.000000	0.066473	0.228560	0.238030	0.000042	1.28777
13	0.000006	0.000000	0.021216	0.380901	0.381491	0.000067	1.51515
14	0.000003	0.000000	0.390377	0.071631	0.396894	0.000070	0.18147
15	0.000001	0.000000	0.201315	0.075037	0.214845	0.000038	0.35678
16	0.000000	0.000000	-0.03192	0.144512	0.147997	0.000026	-1.3533
17	0.000000	0.000000	0.066092	0.200132	0.210763	0.000037	1.25183
18	0.000000	0.000000	0.186873	0.076697	0.202000	0.000035	0.38945
19	0.000000	0.000000	0.091177	0.083107	0.123369	0.000022	0.73913
20	0.000000	0.000000	0.063095	0.019988	0.066185	0.000012	0.30679

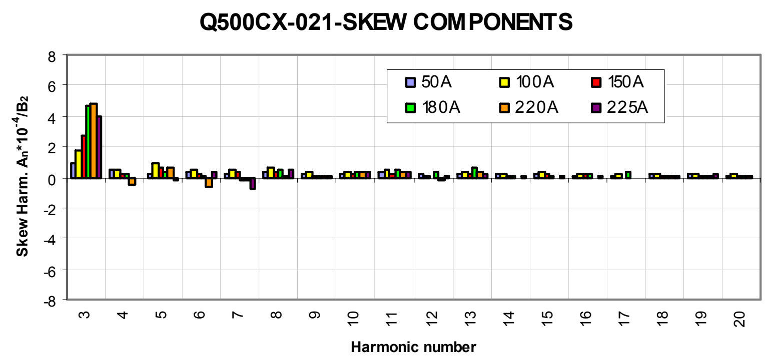
Operator: Blinov Semenov

Signature:

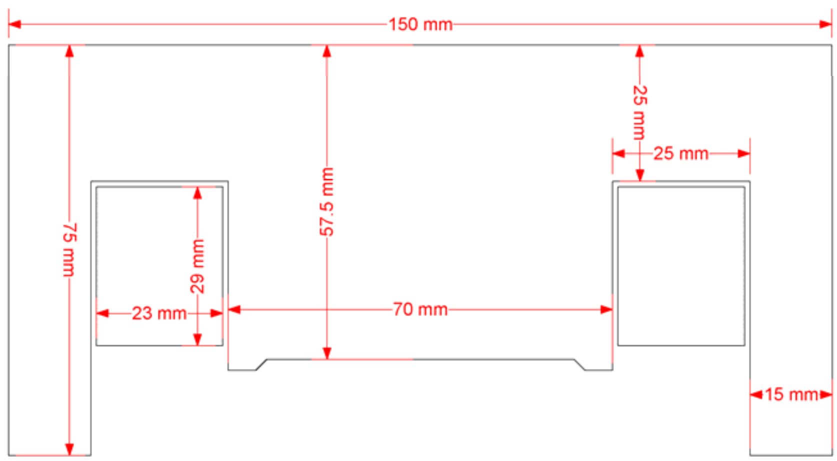
$$\frac{\int \vec{H}\,dl}{L} = \frac{\int \vec{H}_x\,dl}{L} + \frac{\int \vec{H}_y\,dl}{L}\text{; where}\quad \frac{\int H_x\,dl}{L} = \sum_n \left(\frac{r}{r_0}\right)^{n-1}(A_n\cos(n\varphi) - B_n\sin(n\varphi)) \quad \frac{\int H_y\,dl}{L} = \sum_n \left(\frac{r}{r_0}\right)^{n-1}(A_n\sin(n\varphi) + B_n\cos(n\varphi))$$



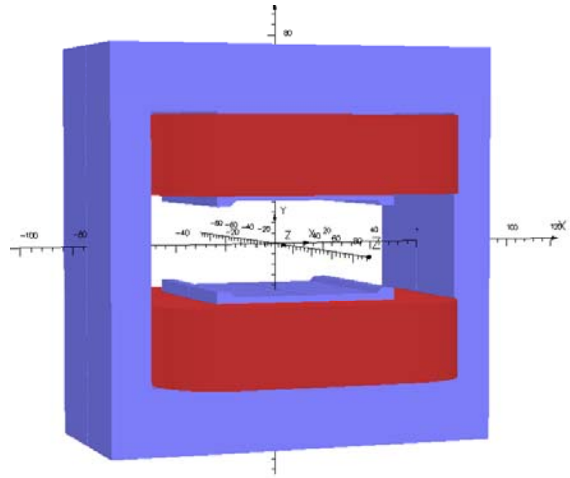


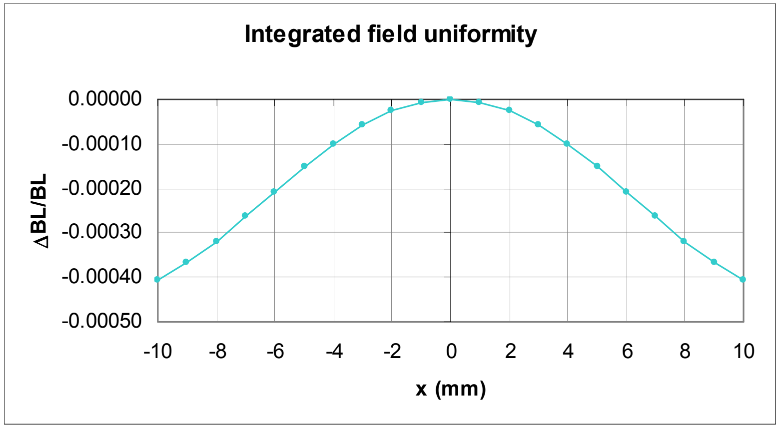


Correctors



Number of magnets	104
Physical length (mm)	70
Maximum field (T)	0.05
Max deflection @ 3 GeV (mrad)	0.5

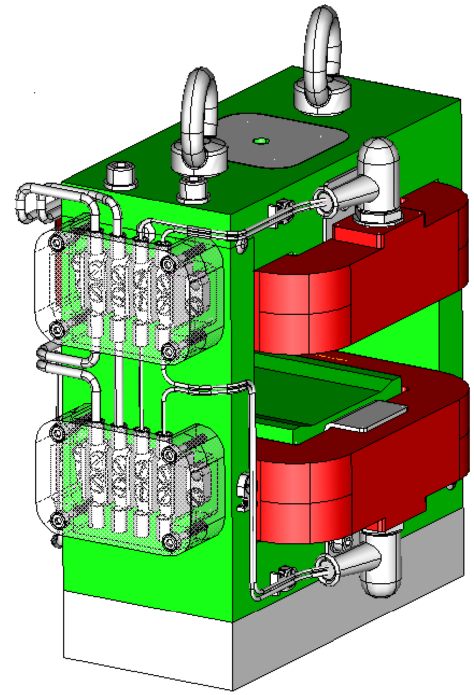


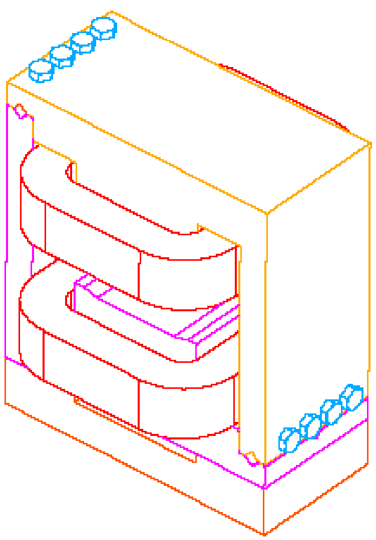


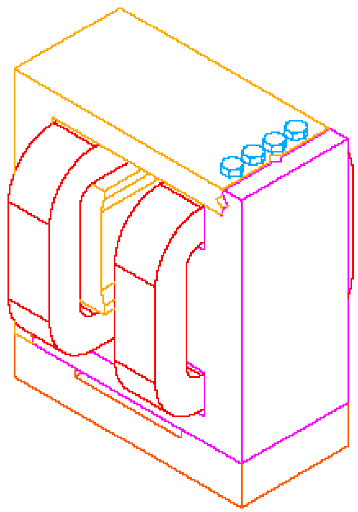
- 2 coils
  174 turns/coil (solid conductor)
- $P_{average}$= 8 W
- I_{max}= 4 A

ALBA-Booster-Correctors

Bending angle	mrad	1
Bending field	T	0.0503
Length of Fe yoke	mm	70
Gap	mm	35
Solid conductor size	mm²	2
Number of ampere turns	amp-turn/coil	700
Number of turns per coil		174
Current	A	4
Dissipated power	W	20

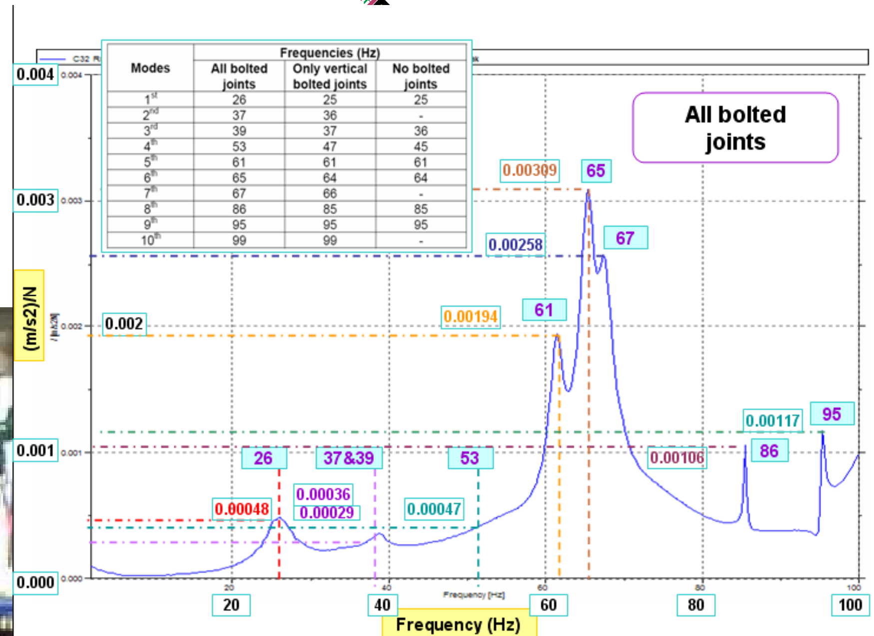






Girder System

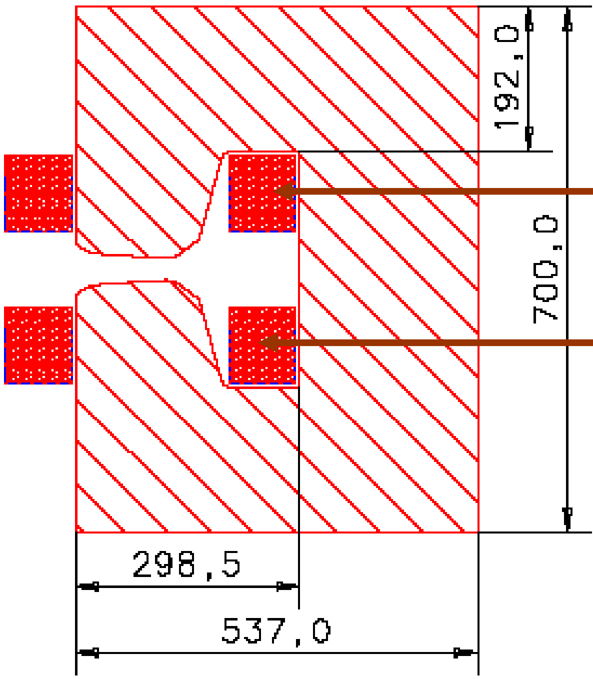
More or less it is the SLS design, but the number of feet's (pedestals) has been increased to six in order to move up the eigen-frequency



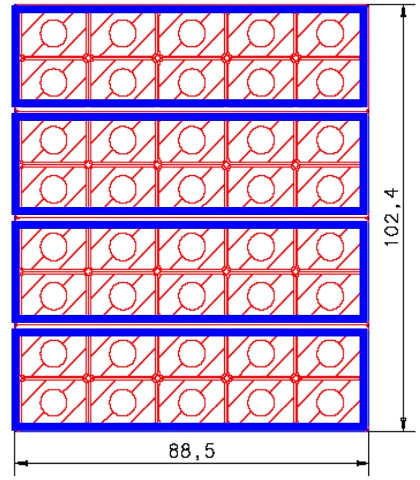
Modes	Frequencies (Hz)		
	All bolted joints	Only vertical bolted joints	No bolted joints
1st	26	25	25
2nd	37	36	-
3rd	39	37	36
4th	53	47	45
5th	61	61	61
6th	65	64	64
7th	67	66	-
8th	86	85	85
9th	95	95	95
10th	99	99	-

Additional Material for the Power and Cooling of Magnets

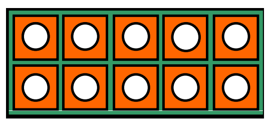
Calculation of the Power Consumption



This is the magnets with 2 coils and N total turns



This is the coil with 4 pancakes



This is a pancake with n turns

D is the diameter of the cooling pipe

A_{Cu} is the copper area

L_{Cu} = Average length of the conductor around the poles (m).

N = Total number of turns around the poles.

A_{Cu} = Copper area (mm)

D = Diameter of the cooling pipe within the conductor (mm)

ρ = Specific resistance of the conductor (Ω*mm^2/m)

Calculation of the Power Consumption

Θ = Excitation of the magnet ($\Theta = N*I = B*gap / \mu_0$).

I = Excitation-current ($I = \Theta / N$).

J = Current density in the conductor ($j = I/A_{Cu}$)

Φ = Magnetic flux of the magnet ($\Phi = B*A$).

L = Inductivity of the magnet ($L = N*\Phi/I$).

R_{Cu} = Resistance of the conductor ones around the poles ($R_{Cu} = \rho*L_{Cu}/A_{Cu}$)

R_M = Resistance of the coils around the poles ($R_M = N*R_{Cu}$)

V_{Cu} = Voltage drop for one turn around the poles ($V_{Cu} = I*R_{Cu}$)

V_M = Voltage drop for the magnet ($V_M = I*R_M = V_{Cu}*N = N*I*R_{Cu}$)

P_M = Power consumption of the magnet ($P_M = I*V_M = I^2 *R_M = N*I^2*R_{Cu}$)

$P_M = N*I^2*R_{Cu} = N*(j*A_{Cu})^2*R_{Cu} = N*j^2*A_{Cu}*\rho*L_{Cu} \approx N*j^2*A_{Cu}$

Calculation of the Power Consumption

P_M = Power consumption of the magnet ($P_M = I*V_M = I^2 *R_M = N*I^2*R_{Cu}$)

$P_M = N*I^2*R_{Cu} = N*(j*A_{Cu})^2*R_{Cu} = N*j^2*A_{Cu}*\rho*L_{Cu} \approx N*j^2*A_{Cu}$

We can write the power consumption also in an other way

$P_M = N*j^2*A_{Cu}*\rho*L_{Cu} = (N*I/A_{Cu})*j*A_{Cu}*L_{Cu} = (N*I)*j*L_{Cu}$

(N*I) is the required excitation of the magnet, hence the power consumption is proportional to the current density and the length of the magnet

The excitation currents are:

$$(N*I)_{dipole} = B*g / \mu_0$$

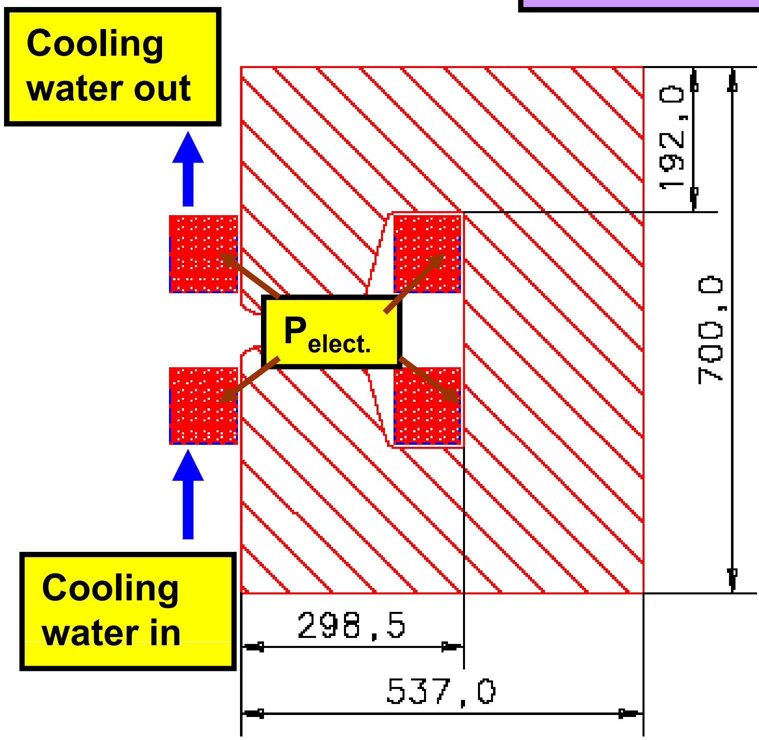
$$(N*I)_{quadrup.} = B'*R^2 / (2\mu_0)$$

$$(N*I)_{sextup.} = B''*R^3 / (6\mu_0)$$

Design criteria's: The inductivity should be low (N : small, I : high)

The power consumption should be low (g,R: small, R: small, and length: small)

Coil Cooling



Concerning the cooling we have the following definitions:

Q = Heat quantity

M = Mass [gr]

c = Specific heat capacity [cal / (gr*Kelvin)]

$\Delta\delta$ = Temperature change [Kelvin]

ρ = Specific gravity [gr / cm^3]

V = Volume [cm^3]

Caloric equivalent : 1cal = 4.186 VAs

$Q = M*c*\Delta\delta$ [cal] $= \rho*V*C*\Delta\delta$ [cal]

According to the conversation of energy it must be:

$$(dQ/dt) = P_{electr} = P_M \text{ / number of cooling circuits}$$

$$P_{electr.} = \rho*c*\Delta\delta*(\Delta V/dt)$$

Calculation of the Cooling

$$P_{electr.} = \rho * c * \Delta\delta * (\Delta V/\Delta t)$$

Or the required flow rate:

$$\Delta V/\Delta t = \{[P_{electr.}/W]/[\Delta\delta/K]\} * \{10^{-6}/4.186\}\ [m^3/s]$$

$$\Delta V/\Delta t = \{[Pelectr./W]/[\Delta\delta/K]\} * 0.2389 * 10^{-6}\ [m3/s]$$

$$\Delta V/\Delta t = \{[Pelectr./W]/[\Delta\delta/K]\} * 1.433 * 10^{-2}\ [l/min]$$

$$\Delta V/\Delta t = \{[Pelectr./W]/[\Delta\delta/K]\} * 0.86\ [l/h]$$

The corresponding flow velocity is:

$$v = (\Delta V/\Delta t) / A_{cool}\ ,$$

A_{cool} = cross section of the cooling pipe in the conductor.

$$v = \{(\Delta V/\Delta t)/10^{-6} m^3/s\} / \{A_{cool}/mm^2\}\ [m/s]\ ,$$

Calculation of the Cooling

For an optimized cooling we need turbulent flow within the cooling pipes of the copper conductor. Turbulent flow does exist if the Reynolds's number (Re) is larger as 1160:

$$Re > 1160$$

Calculation of the Reynolds number:

r = Radius in the cooling pipe of the conductor

ρ = Specific gravity (ρ from water = 1 gr/cm^3)

v = velocity (cm/s)

η = viscosity (η from water = 0.75 … 1 mPas)

Introducing all the numbers one get:

$$Re = [r/mm]*[v/(m/s)]*10^3$$

The corresponding critical velocity is:

$$v_c > 5.0 / (r/mm)\ [m/s]$$

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$$Re = [r/mm]*[v/(m/s)]*10^3$$

The corresponding critical velocity is:

$$v_c > 5.0\ /\ (r/mm)\ [m/s]$$

Calculation of the Pressure Drop

For a turbulent flow the pressure drop within a pipe is given by Blasius:

r = Radius in the cooling pipe of the conductor

ρ = Specific gravity (ρ from water = 1 gr/cm^3)

v = velocity (cm/s)

η = viscosity (η from water = 0.75 … 1 mPas)

Introducing all the numbers one get:

$$Re = [r/mm]*[v/(m/s)]*10^3$$

The corresponding critical velocity is:

$$v_c > 5.0 / (r/mm)\ [m/s]$$

Calculation of the Pressure Drop

According to the law of Blasius, the pressure drop in a pipe is the following:

$$\Delta P = \frac{0.1582}{2\sqrt[4]{2}} \bullet L \bullet \eta^{1/4} \bullet \rho^{3/4} \bullet \frac{v^{7/4}}{r^{5/4}}$$

$$\Delta P = 0.1582 \bullet L \bullet \eta^{1/4} \bullet \rho^{3/4} \bullet \frac{v^{7/4}}{(2r)^{5/4}}$$

$$\boxed{\Delta P = 5.0 \bullet 10^{-5} bar \bullet (L / m) \bullet [v / m / s)]^{1.75} \frac{1}{[2r / m]^{1.25}}}$$

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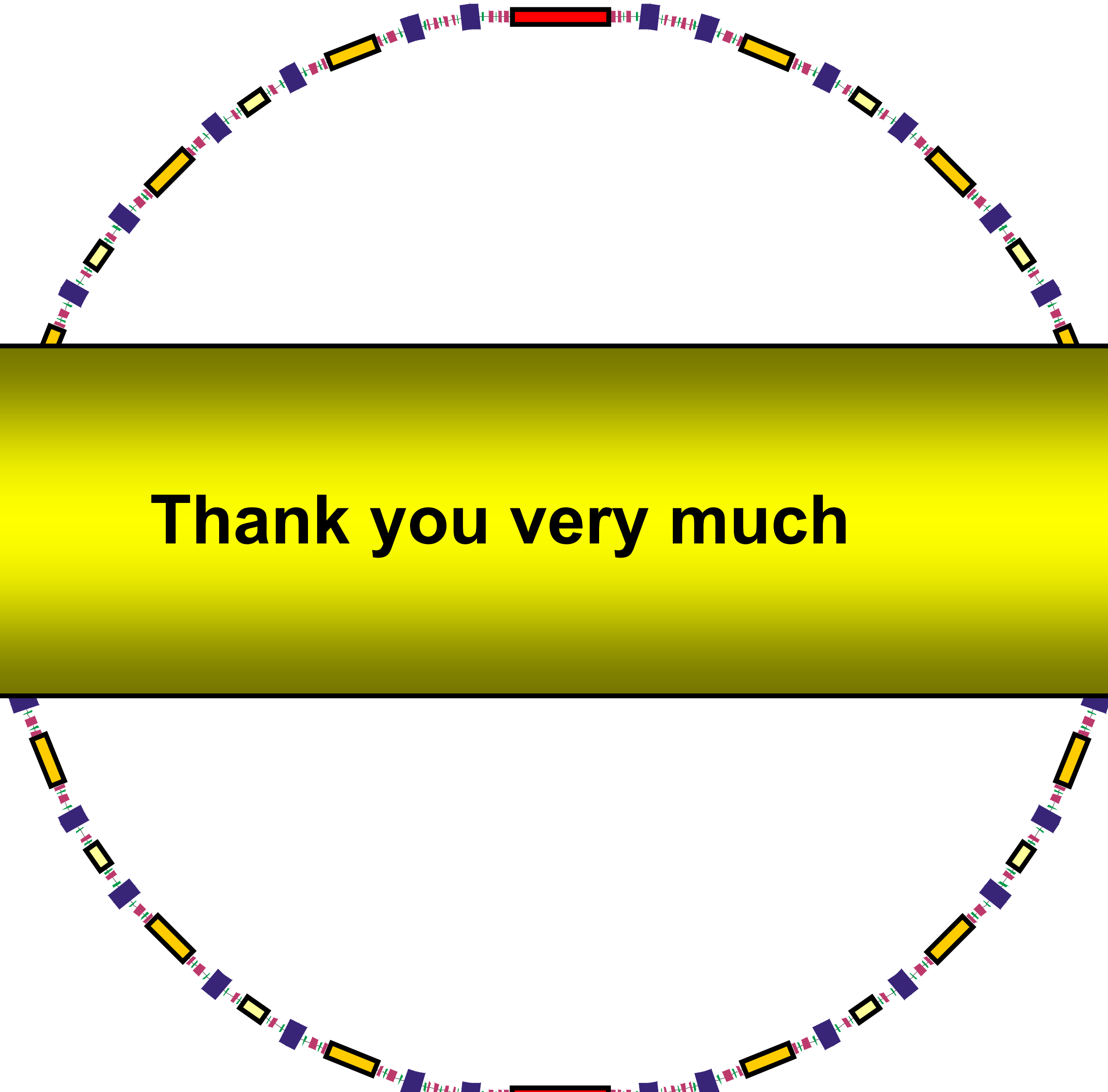

Thank you very much