Conventional Magnets for Accelerators

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Objectives.

- **The presentation deals with d.c. magnets only.**

- **It includes some material presented at the ‘introductory’ level CAS meetings.**

- **However, additional material emphasises the judgement of magnetic quality in design and manufacture.**

Contents:

i) No current or steel:

- Laplace's equation with scalar potential;
- Cylindrical harmonic solutions in two dimensions;

ii) Introduce steel yoke:

- Ideal pole shapes for dipole, quad and sextupole;
- Field harmonics-symmetry restraints and significance;

iii) Introduce current:

- Ampere-turns in dipole, quad and sextupole;

Contents (cont.)

iv) Magnet geometry:

- Yoke and coil geometry- 'C', 'H' and 'window frame' designs; designs;

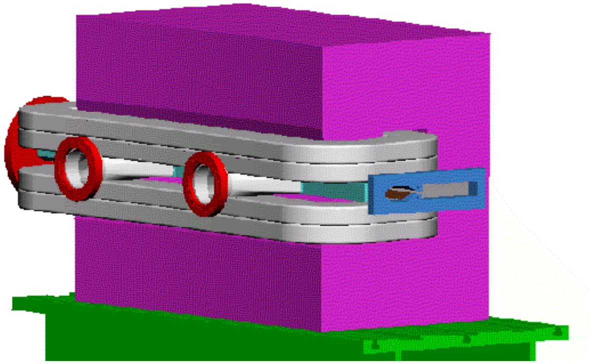
v) Field computation and pole optimisation:

- Field computation techniques;
- Design of pole geometry for dipole, quad and sextupole;

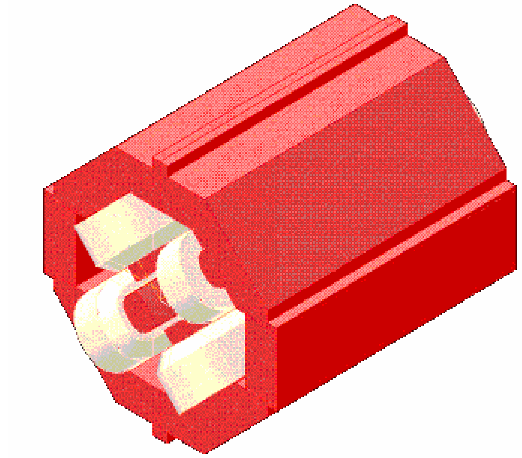
v) Judgement of field quality during design and after manufacture.

Magnets we know about:

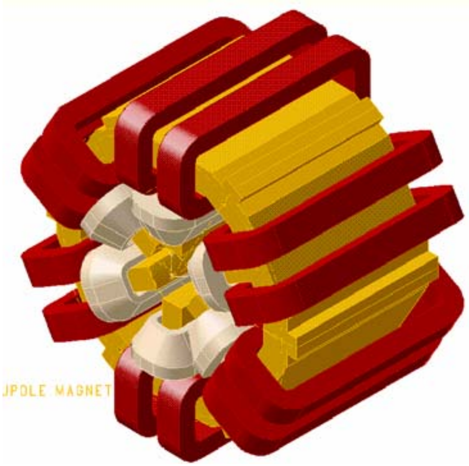
Dipoles to bend the beam:



Quadrupoles to focus it:



Sextupoles to correct chromaticity:
chromaticity:



We need to establish a formal approach to describing these magnets.

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 (Oersteds in cgs);

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 in mks, Gauss in cgs);

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

Permeability of free space:

symbol is μ_0 ;

units are Henries/metre;

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

symbol is μ;

the quantity is dimensionless;

No Currents - Maxwell's equations:

$$\underline{\nabla}.\underline{\mathbf{B}} = 0 \;;$$

$$\underline{\nabla}\ \underline{\mathbf{H}} = \underline{\mathbf{j}} \;;$$

In the absence of currents: $\mathbf{j} = 0.$

Then we can put: $\underline{\mathbf{B}} = -\,\underline{\nabla}\phi$

So that: $\underline{\nabla}^2\phi = 0$ (Laplace's equation).

Taking the two dimensional case (ie constant in the z direction) and solving for cylindrical coordinates (r,θ):

$$\phi = (E+F\,\theta)(G+H\ln r) + \Sigma_{n=1}^{\infty}\,(J_n\, r^{\,n} \cos n\theta + K_n\, r^{\,n} \sin n\theta$$
$$+ L_n\, r^{\,-n} \cos n\,\theta + M_n\, r^{\,-n} \sin n\,\theta\,)$$

In practical situations:

The scalar potential simplifies to:

$$\phi = \Sigma_n (J_n r^n \cos n\theta + K_n r^n \sin n\theta),$$

with n integral and J_n, K_n a function of geometry.

Giving components of flux density:

$$B_r = - \Sigma_n (n J_n r^{n-1} \cos n\theta + nK_n r^{n-1} \sin n\theta)$$
$$B_\theta = - \Sigma_n (-n J_n r^{n-1} \sin n\theta + nK_n r^{n-1} \cos n\theta)$$

Significance

This is an infinite series of cylindrical harmonics; they they define the allowed distributions of **B** in 2 dimensions in the absence of currents within the domain domain of (r,θ).

Distributions not given by above are not physically realisable.

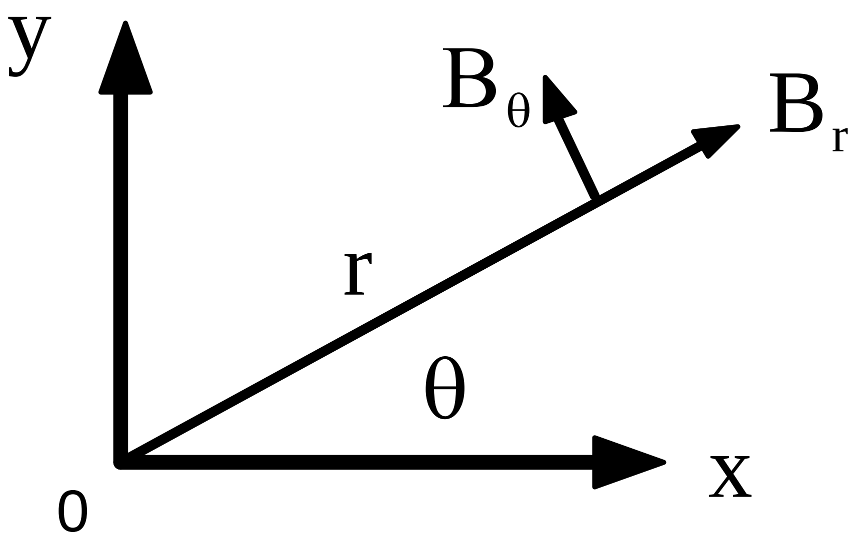
Coefficients J_n, K_n are determined by geometry (iron boundaries or remote current sources).

Cartesian Coordinates

In Cartesian coordinates, the components are given by:

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

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



Dipole field: n = 1

Cylindrical:

$B_r = J_1 \cos\theta + K_1 \sin\theta;$

$B_\theta = -J_1 \sin\theta + K_1 \cos\theta;$

$\phi = J_1 r \cos\theta + K_1 r \sin\theta.$

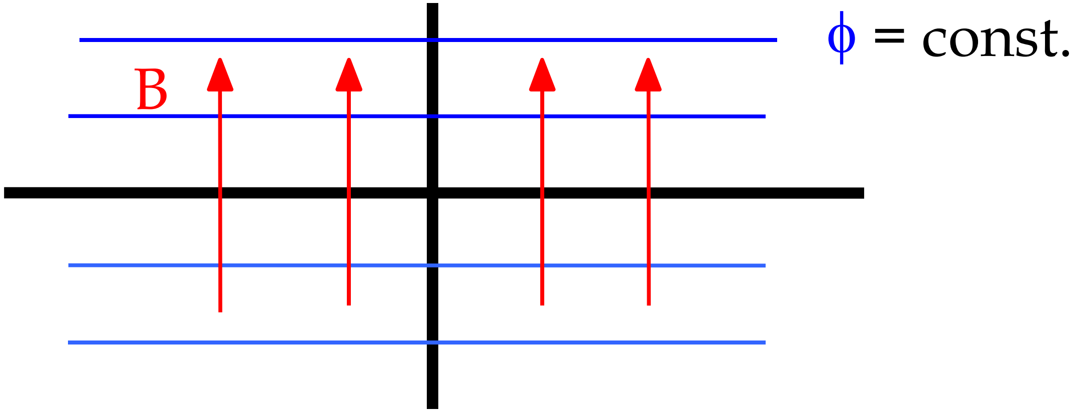
Cartesian:

$B_x = J_1$

$B_y = K_1$

$\phi = J_1 x + K_1 y$

So, $J_1 = 0$ gives vertical dipole field:



$K_1 = 0$ gives horizontal dipole field.

Quadrupole field: n = 2

Cylindrical:

$B_r = 2 J_2 r \cos 2\theta + 2K_2 r \sin 2\theta;$

$B_\theta = -2J_2 r \sin 2\theta + 2K_2 r \cos 2\theta;$

$\phi = J_2 r^2 \cos 2\theta + K_2 r^2 \sin 2\theta;$

Cartesian:

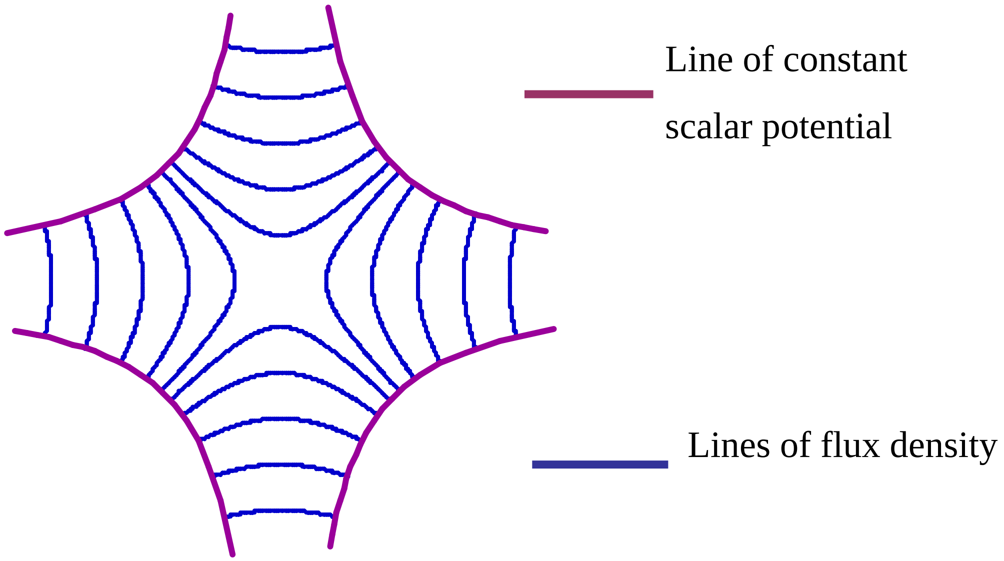
$Bx = 2 (J_2 x + K_2 y)$

$B_y = 2 (-J_2 y + K_2 x)$

$\phi = J_2 (x^2 - y^2) + 2K_2 xy$

$J_2 = 0$ gives 'normal' or 'right' quadrupole field.

$K_2 = 0$ gives 'skew' quad fields (above rotated by $\pi/4$).



Sextupole field: n = 3

Cylindrical;

$B_r = 3\, J_3 r^2 \cos 3\theta + 3K_3 r^2 \sin 3\theta;$

$B_\theta = -3J_3\, r^2 \sin 3\theta + 3K_3\, r^2 \cos 3\theta;$

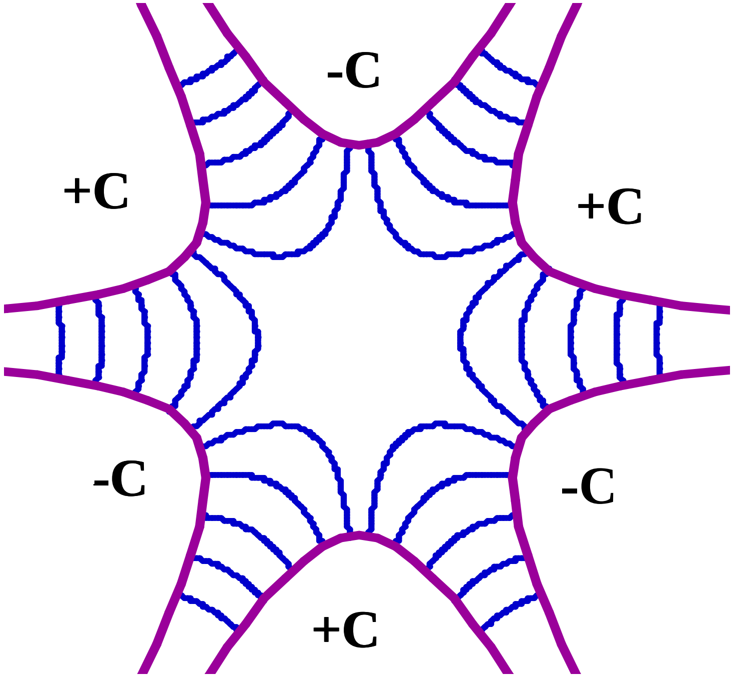
$\phi = J_3\, r^3 \cos 3\theta + K_3\, r^3 \sin 3\theta;$

Cartesian:

$B_x = 3\{J_3\,(x^2 - y^2) + 2K_3 yx\}$

$B_y = 3\{-2\, J_3\, xy + K_3(x^2 - y^2)\}$

$\phi = J_3\,(x^3 - 3y^2x) + K_3(3yx^2 - y^3)$



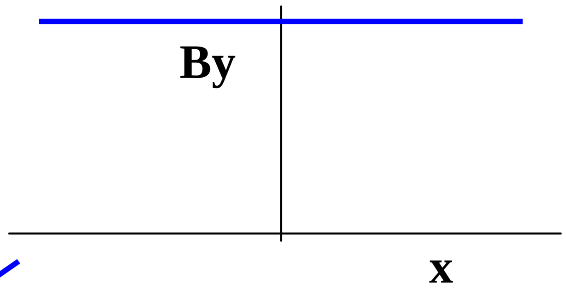
$J_3 = 0$ giving 'normal' or 'right' sextupole field.

Line of constant scalar potential

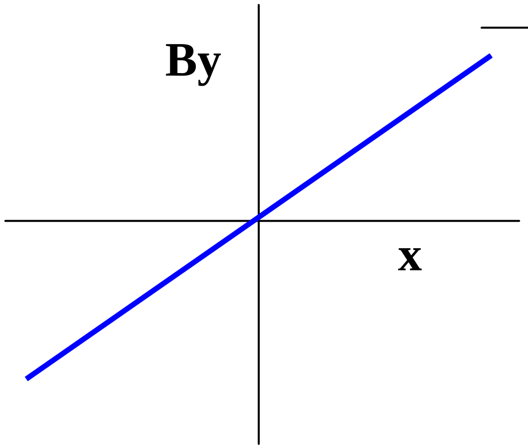
Lines of flux density

Summary; variation of B_y on x axis

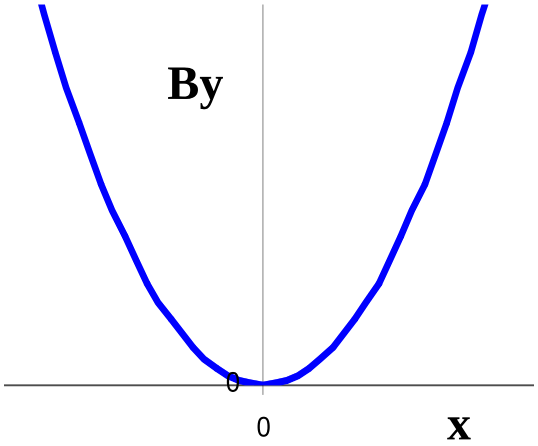
Dipole; constant field:



Quad; linear variation:



Sext.: quadratic variation:



Alternative notification (USA)

$$B(x) = B\rho \sum_{n=0}^{\infty} \frac{k_n \, x^n}{n!}$$

magnet strengths are specified by the value of k_n;
(normalised to the beam rigidity);

order n of k is different to the 'standard' notation:

dipole is	$n = 0$;	
quad is	$n = 1$;	etc.

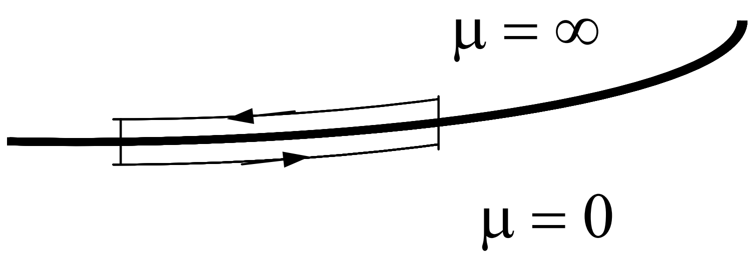
k has units:

k_0 (dipole)	m^{-1};	
k_1 (quadrupole)	m^{-2};	etc.

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, ($\mathbf{\underline{B}} = - \underline{\nabla}\phi$);
- So the lines of scalar potential are the ideal pole shapes!

(but these are infinitely long!)

Equations for the ideal pole

Equations for Ideal (infinite) poles;

(J_n = 0) for **normal** (ie not skew) fields:

Dipole:

$y = \pm g/2;$

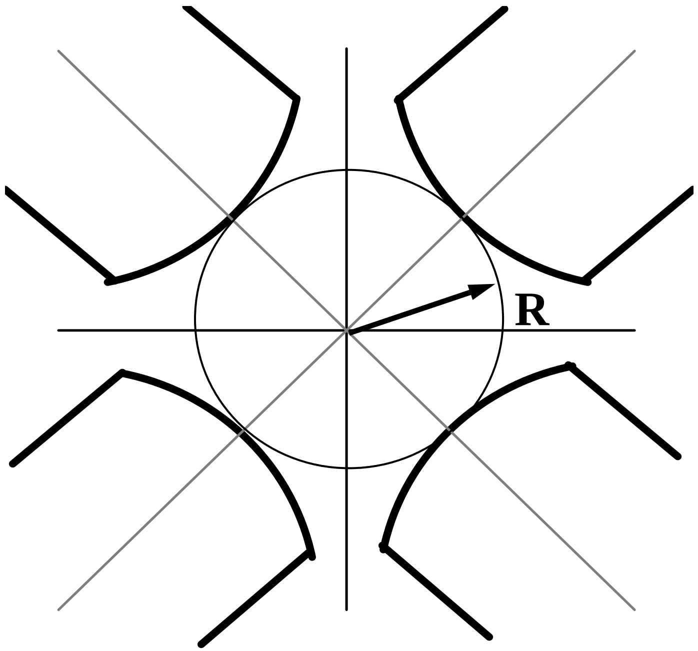
(g is interpole gap).

Quadrupole:

$xy = \pm R^2/2;$

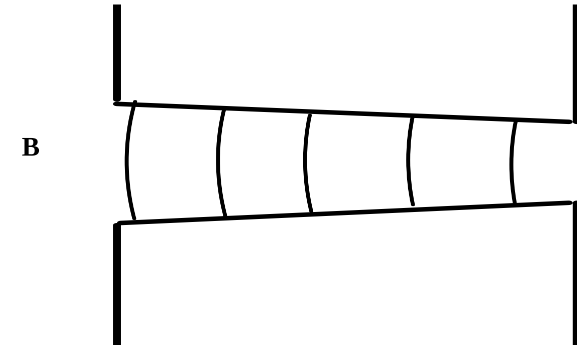
Sextupole:

$3x^2y - y^3 = \pm R^3;$



Combined function (c.f.) magnets

'Combined Function Magnets' - often dipole and quadrupole field quadrupole field combined (but see next-but-one slide):



A quadrupole magnet with physical centre shifted from magnetic centre.

Characterised by 'field index' n, +ve or -ve depending on direction of gradient; do not confuse with harmonic n!

$$n = -\left(\frac{\rho}{B_0}\right)\left(\frac{\partial B}{\partial x}\right),$$

ρ is radius of curvature of the beam;

B_o is central dipole field

Pole of a c.f. dip.& quad. magnet

If physical and magnetic centres are separated by X_0

Then $$B_0 = \left(\frac{\partial B}{\partial x}\right) X_0;$$

therefore $$X_0 = -\rho / n;$$

in a quadrupole $$x' y = \pm R^2 / 2$$

where x' is measured from the true quad centre;

Put $$x' = x + X_0$$

So pole equation is $$y = \pm \frac{R^2}{2} \frac{n}{\rho} \left(1 - \frac{nx}{\rho}\right)^{-1}$$

or $$\boxed{y = \pm g \left(1 - \frac{nx}{\rho}\right)^{-1}}$$

where g is the half gap at the physical centre of the magnet

Other combined function magnets.

Other combinations:

- dipole, quadrupole and sextupole;
- dipole & sextupole (for chromaticity control);
- dipole, skew quad, sextupole, octupole (at DL)

Generated by

- pole shapes given by sum of correct scalar potentials

  - amplitudes built into pole geometry – not variable.

- multiple coils mounted on the yoke

  - amplitudes independently varied by coil currents.

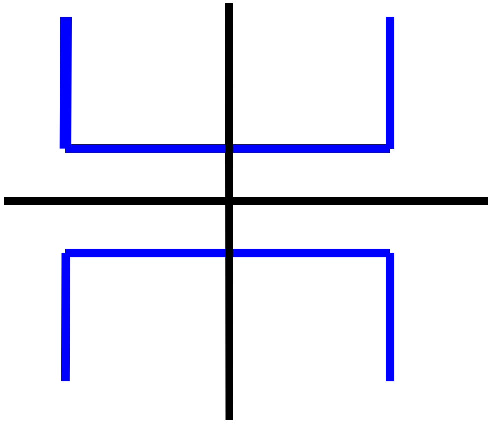
The practical Pole

Practically, poles are finite, **introducing errors**;

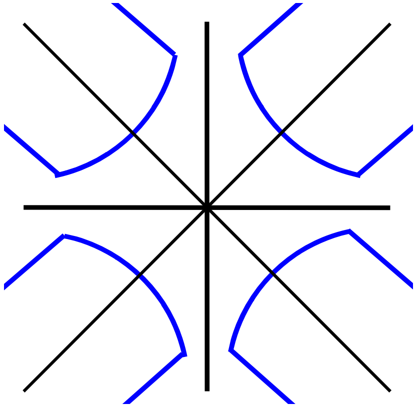
these appear as higher harmonics which degrade the field field distribution.

However, the iron geometries have certain symmetries symmetries that **restrict** the nature of these errors.

Dipole:



Quadrupole:



Possible symmetries:

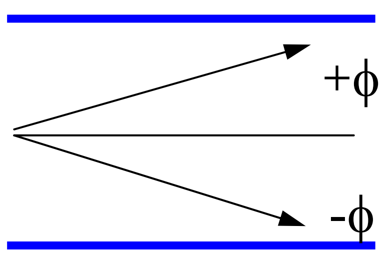
Lines of symmetry:

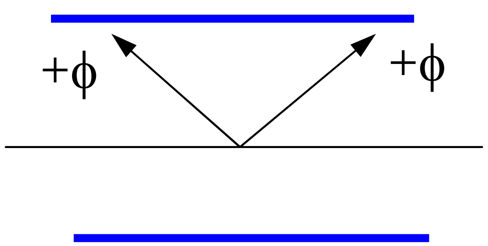
	Dipole:	Quad
Pole orientation determines whether pole is normal or skew.	$y = 0$;	$x = 0$; $y = 0$
Additional symmetry imposed by pole edges.	$x = 0$;	$y = \pm x$

The additional constraints imposed by the symmetrical pole pole edges limits the values of n that have non zero coefficients

Dipole symmetries

Type	**Symmetry**	**Constraint**
Pole orientation	$\phi(\theta) = -\phi(-\theta)$	all $J_n = 0$;
Pole edges	$\phi(\theta) = \phi(\pi - \theta)$	K_n non-zero only for: $n = 1, 3, 5$, etc;





So, for a fully symmetric dipole, only 6, 10, 14 etc pole errors can be present.

Quadrupole symmetries

Type	Symmetry	Constraint
Pole orientation	$\phi(\theta) = -\phi(-\theta)$	All $J_n = 0$;
	$\phi(\theta) = -\phi(\pi - \theta)$	$K_n = 0$ all odd n;
Pole edges	$\phi(\theta) = \phi(\pi/2 - \theta)$	K_n non-zero only for: n = 2, 6, 10, etc;

So, a fully symmetric quadrupole, only 12, 20, 28 etc pole errors can be present.

Sextupole symmetries

Type	Symmetry	Constraint
Pole orientation	$\phi(\theta) = -\phi(-\theta)$ $\phi(\theta) = -\phi(2\pi/3 - \theta)$ $\phi(\theta) = -\phi(4\pi/3 - \theta)$	All $J_n = 0$; $K_n = 0$ for all n not multiples of 3;
Pole edges	$\phi(\theta) = \phi(\pi/3 - \theta)$	K_n non-zero only for: n = 3, 9, 15, etc.

So, a fully symmetric sextupole, only 18, 30, 42 etc pole errors can be present.

Summary - ‘Allowed’ Harmonics

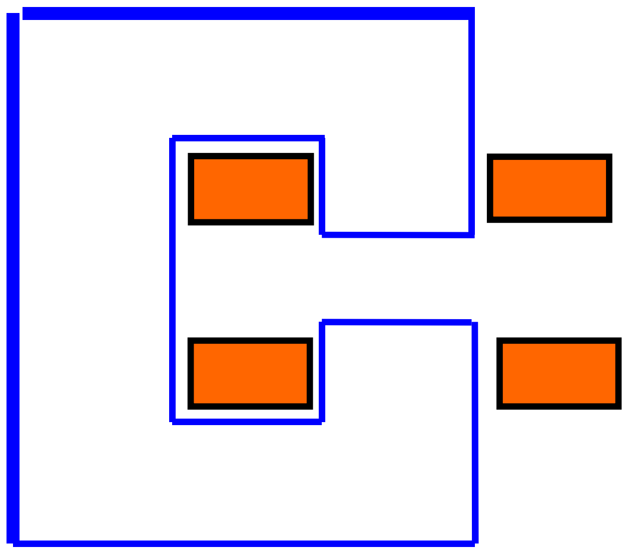
Summary of ‘allowed harmonics’ in fully symmetric magnets:
magnets:

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.)

Asymmetries generating harmonics (i).

Two sources of asymmetry generate 'forbidden' harmonics:

i) yoke asymmetries only significant with low permeability:

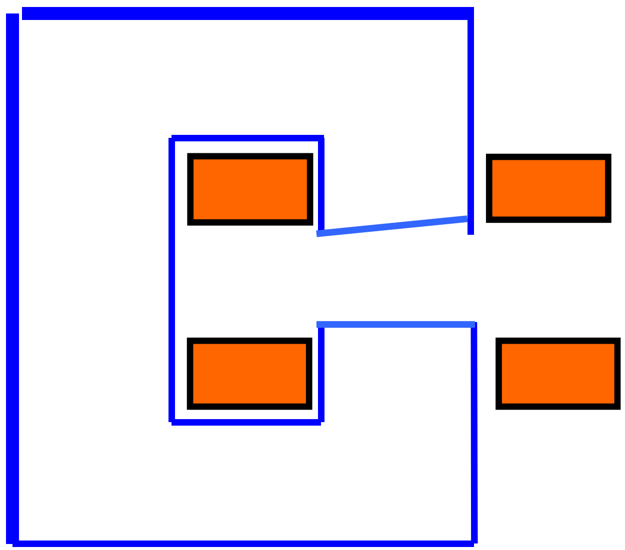


eg, C core dipole not completely symmetrical about pole centre, but negligible effect with high permeability.

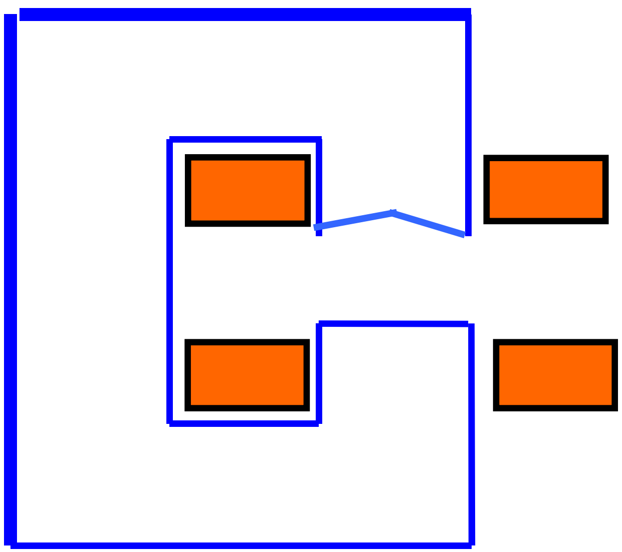
Generates n = 2,4,6, etc.

Asymmetries generating harmonics (ii)

ii) asymmetries due to small manufacturing errors in dipoles:
dipoles:



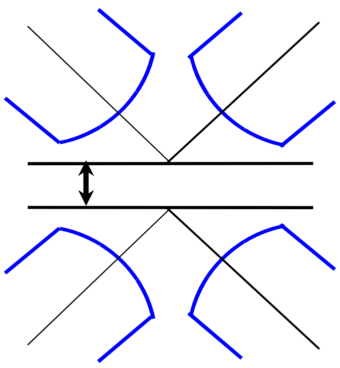
n = 2, 4, 6 etc.



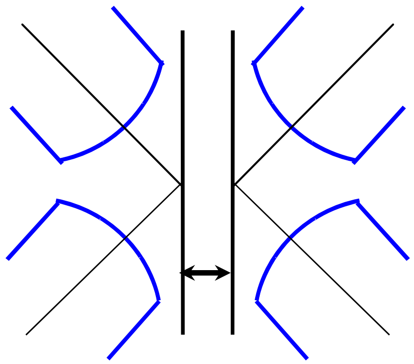
n = 3, 6, 9, etc.

Asymmetries generating harmonics (iii)

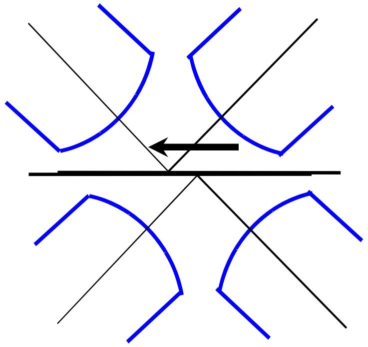
ii) asymmetries due to small manufacturing errors in quadrupoles:
quadrupoles:



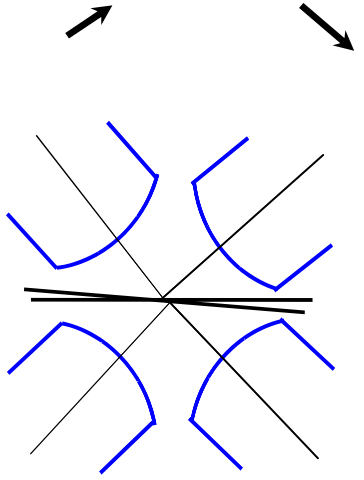
n = 4 - ve



n = 4 + ve



n = 3;



n = 2 (skew)

n = 3;

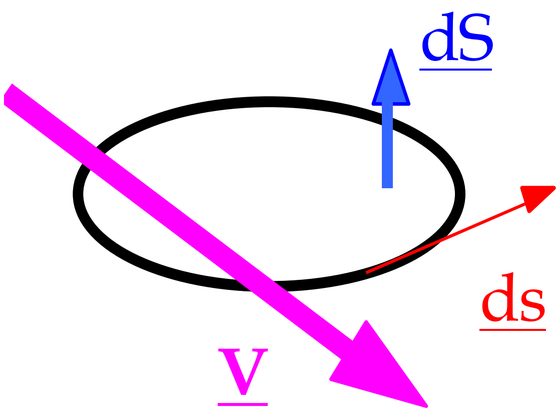
These errors are bigger than the finite μ type, can seriously affect machine behaviour and must be controlled.

Introduction of currents

Now for $\underline{j} \neq 0$ $\qquad \underline{\nabla}\,\underline{\mathbf{H}} = \underline{\mathbf{j}}$;

To expand, use Stoke's Theorum:
for any vector $\underline{\mathbf{V}}$ and a closed curve s :

$$\int \underline{\mathbf{V}}.\underline{\mathbf{ds}} = \iint \mathbf{curl}\ \underline{\mathbf{V}}.\underline{\mathbf{dS}}$$



Apply this to: $\quad \mathbf{curl}\ \mathbf{H} = \underline{\mathbf{j}}$;

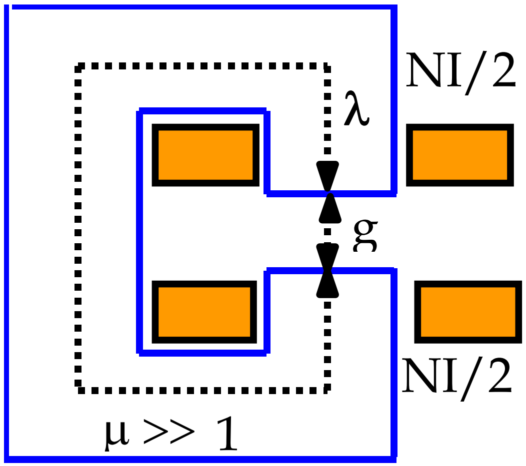
then in a magnetic circuit:

$$\int \underline{\mathbf{H}}.\underline{\mathbf{ds}} = N\ I;$$

N I (Ampere-turns) is total current cutting $\underline{\mathbf{S}}$

Excitation current in a dipole

B is approx constant round the loop made up of λ and g, (but see below);



But in iron, $\mu >> 1$,
and $H_{iron} = H_{air} / \mu$;

So

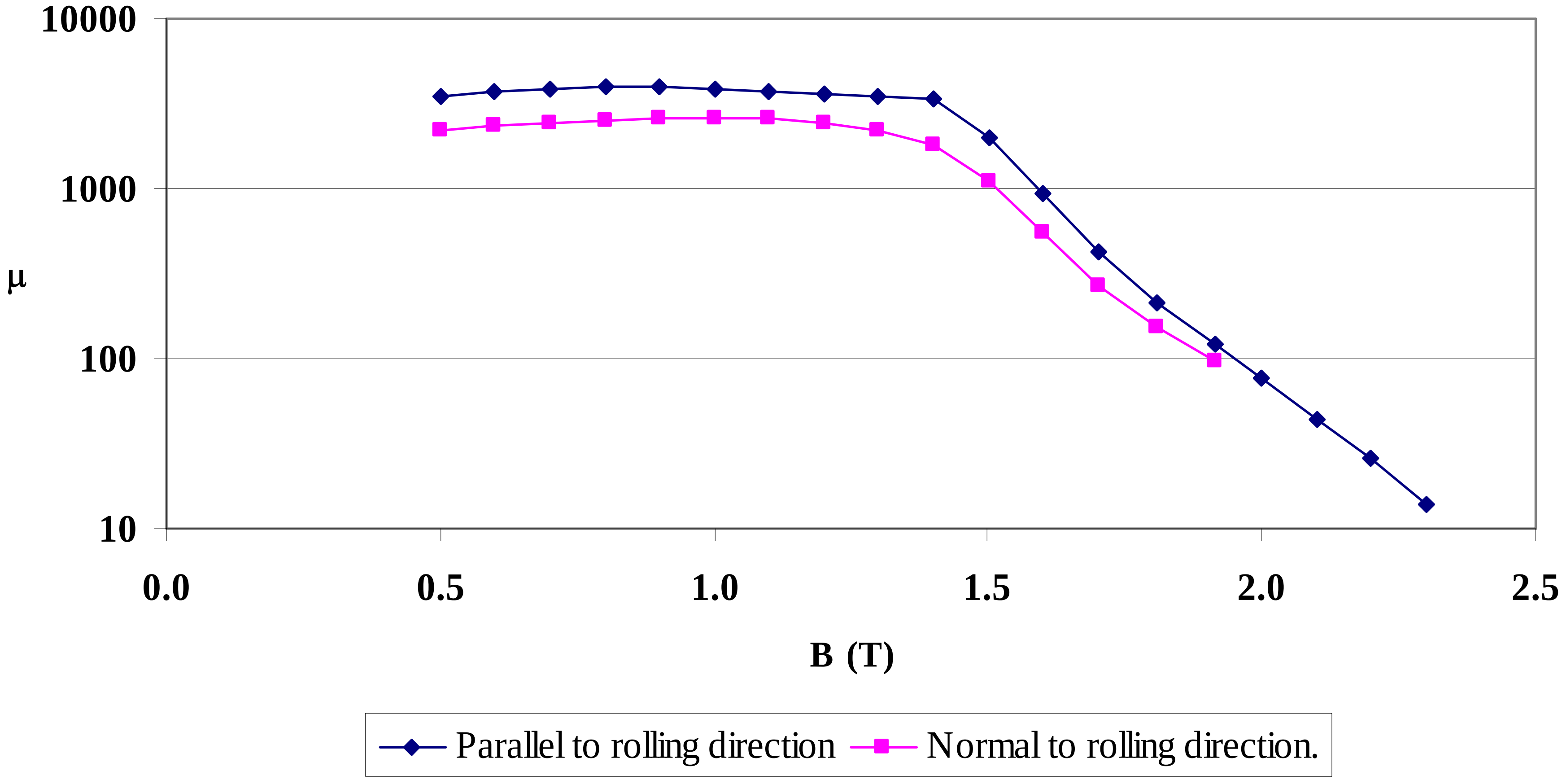
$$B_{air} = \mu_0 NI / (g + \lambda/\mu);$$

g, and λ/μ are the 'reluctance' of the gap and iron.

Approximation ignoring iron reluctance ($\lambda/\mu << g$):

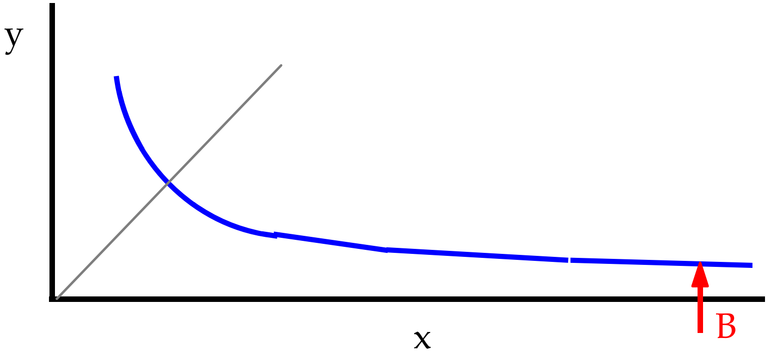
$$NI = B g / \mu_0$$

Relative permeability of low silicon steel



Excitation current in quad & sextupole

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



Pole equation: $xy = R^2/2$

On x axes $B_Y = gx$;

where g is gradient (T/m).

At large x (to give vertical lines of B):

$$N\,I = (gx)\,(R^2/2x)/\mu_0$$

ie

$$N\,I = g\,R^2/2\,\mu_0 \text{ (per pole).}$$

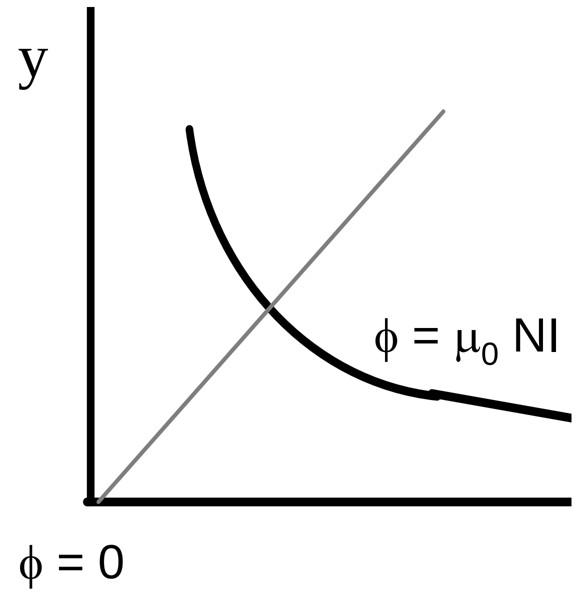
The same method for a **Sextupole**, (coefficient g_S,), gives:

$$N\,I = g_S\,R^3/3\,\mu_0 \text{ (per pole)}$$

General solution for magnets order n

In air (remote currents!), $\mathbf{B} = \mu_0 \mathbf{H}$

$\underline{\mathbf{B}} = - \underline{\nabla}\phi$



Integrating over a limited path
(not circular) in air: $N I = (\phi_1 - \phi_2)/\mu_o$

ϕ_1, ϕ_2 are the scalar potentials at two points in air.
Define $\phi = 0$ at magnet centre;
then potential at the pole is:

μ_o NI

Apply the general equations for magnetic field harmonic order n for non-skew magnets (all Jn = 0) giving:

$$N I = (1/n)\,(1/\mu_0)\,\{B_r/R^{(n-1)}\}\,R^n$$

Where:

NI is excitation per pole;
R is the inscribed radius (or half gap in a dipole);
term in brackets {} is magnet strength in $T/m^{(n-1)}$.

Magnet geometry

Dipoles can be 'C core' 'H core' or 'Window frame'

''C' Core:

Advantages:

Easy access;

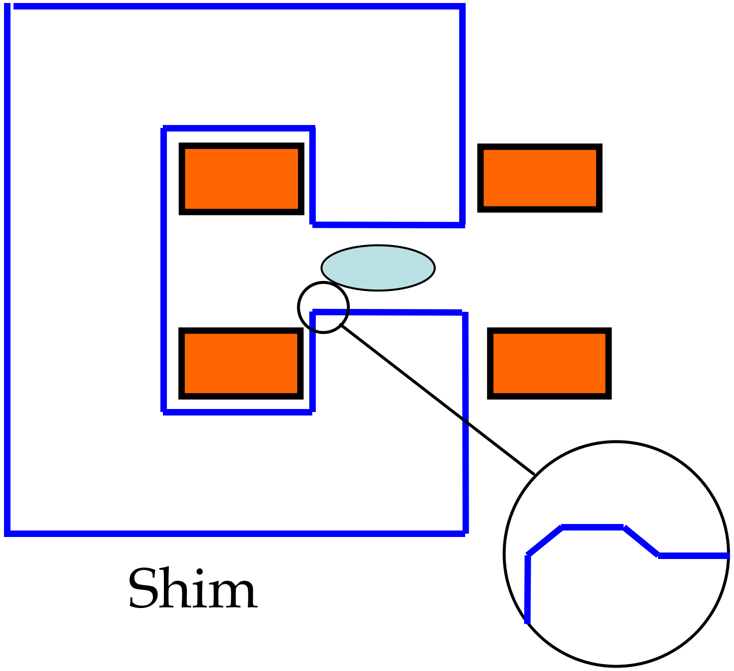
Classic design;

Disadvantages:

Pole shims needed;

Asymmetric (small);

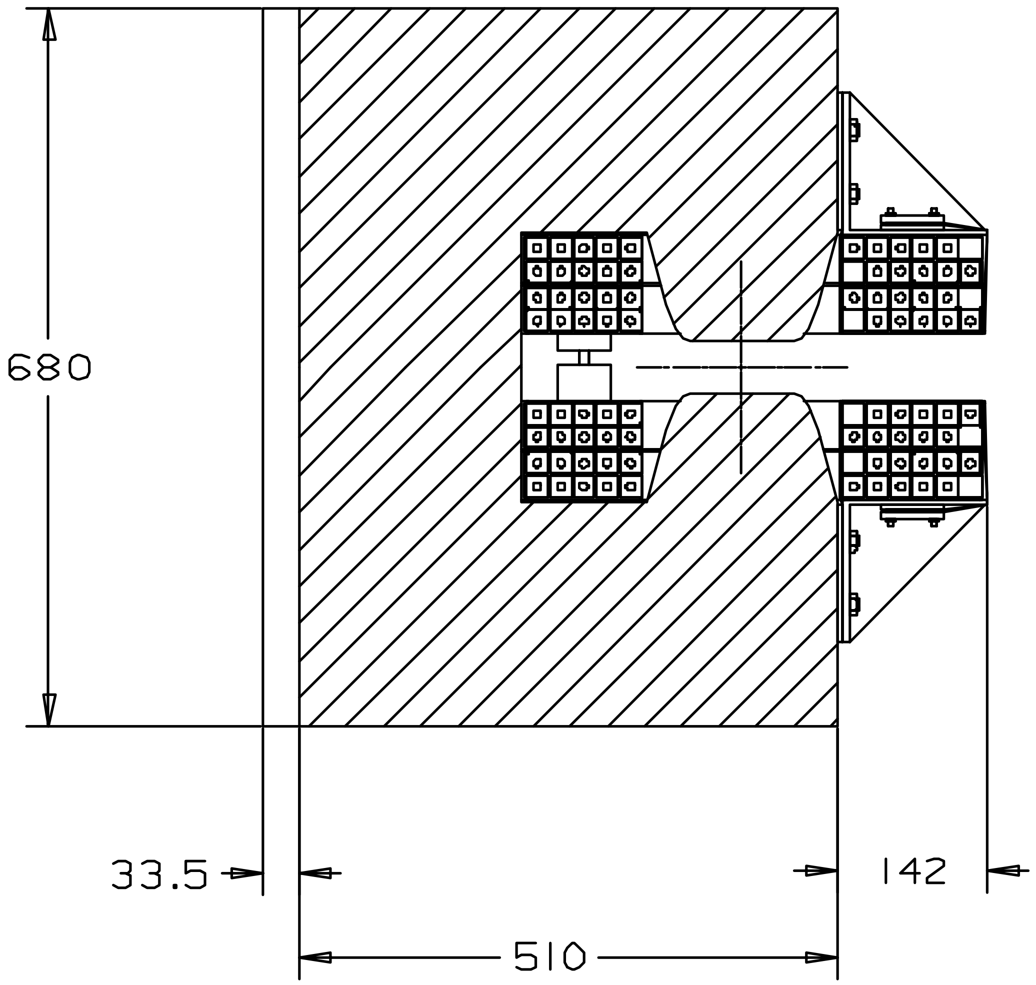
Less rigid;



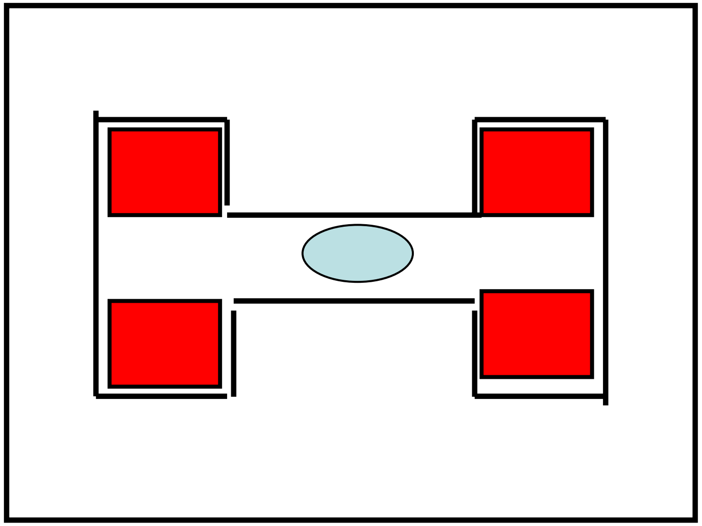
The 'shim' is a small, additional piece of ferro-magnetic material added on each side of the two poles – it compensates for the finite cut-off of the pole, and is optimised to reduce the 6, 10, 14...... pole error harmonics.

A typical 'C' cored Dipole

Cross section of the Diamond storage ring dipole.



H core and window-frame magnets



"Window Frame'

Advantages:

High quality field;

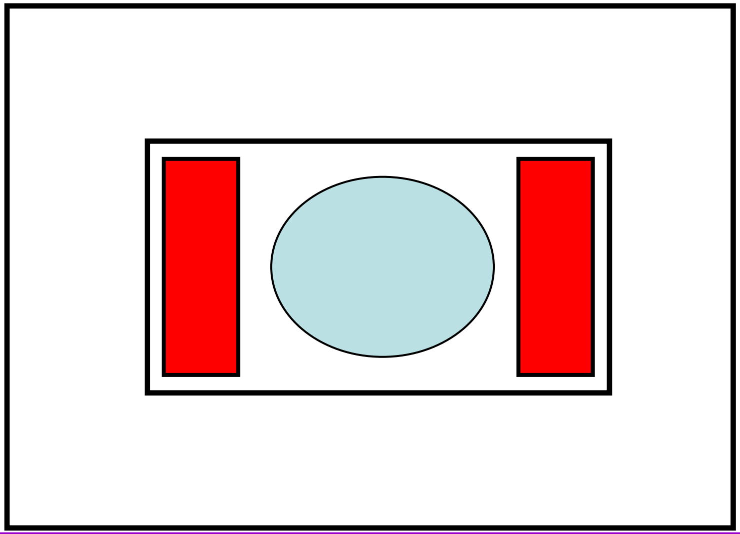
No pole shim;

Symmetric & rigid;

Disadvantages:

Major access problems;

Insulation thickness



'H core':

Advantages:

Symmetric;

More rigid;

Disadvantages:

Still needs shims;

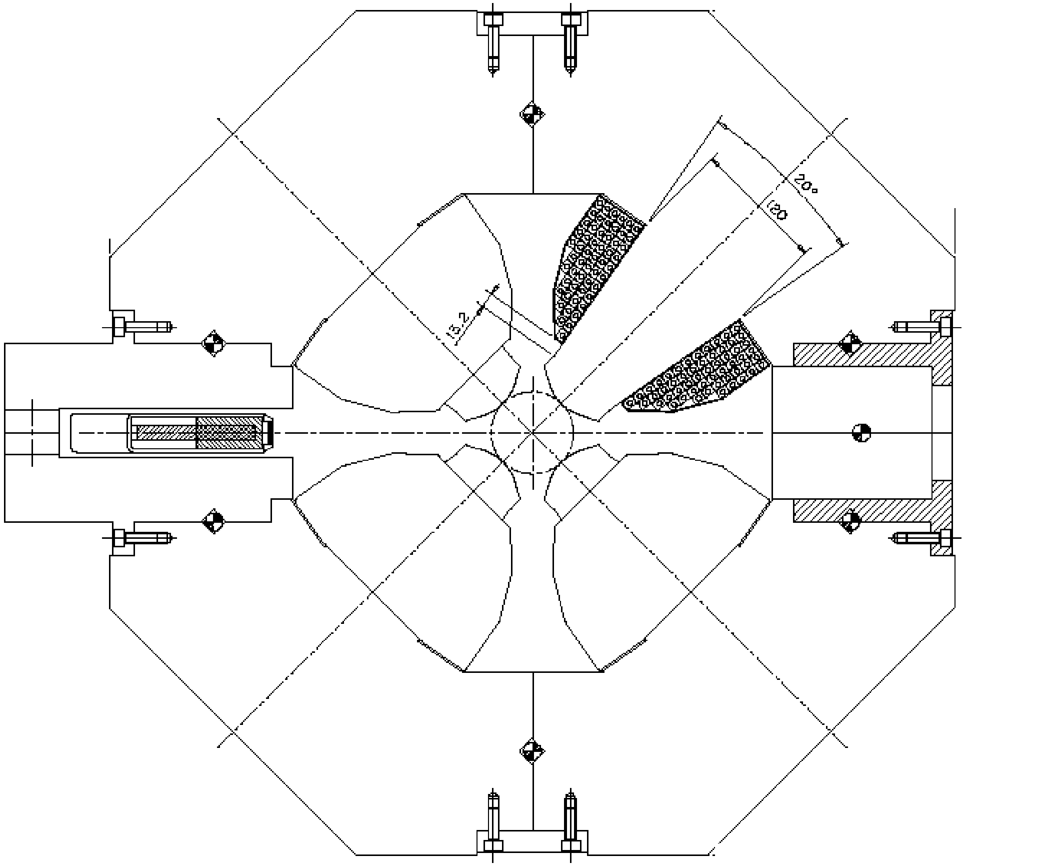
Access problems.

An open-sided Quadrupole.

‘Diamond’ storage ring quadrupole.

The yoke support pieces in the horizontal plane need to provide space for beam-lines and are not ferro-magnetic.

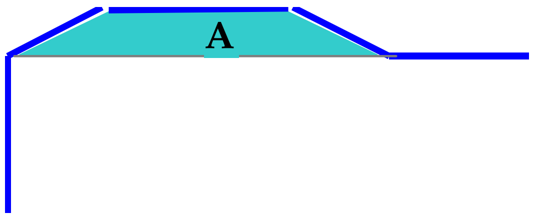
Error harmonics include n = 4 (octupole) a finite permeability error.



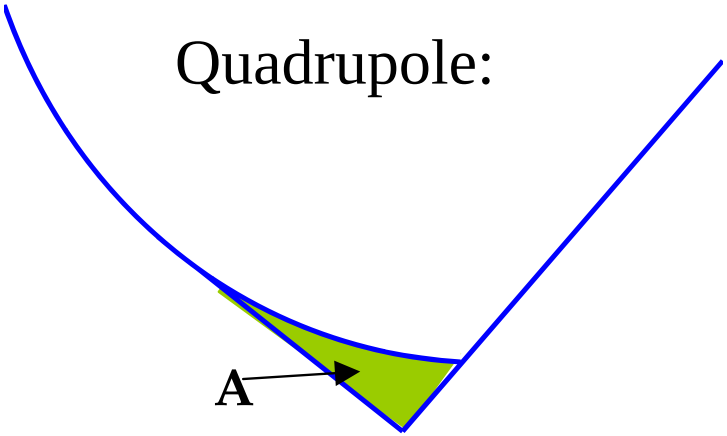
Typical pole designs

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:



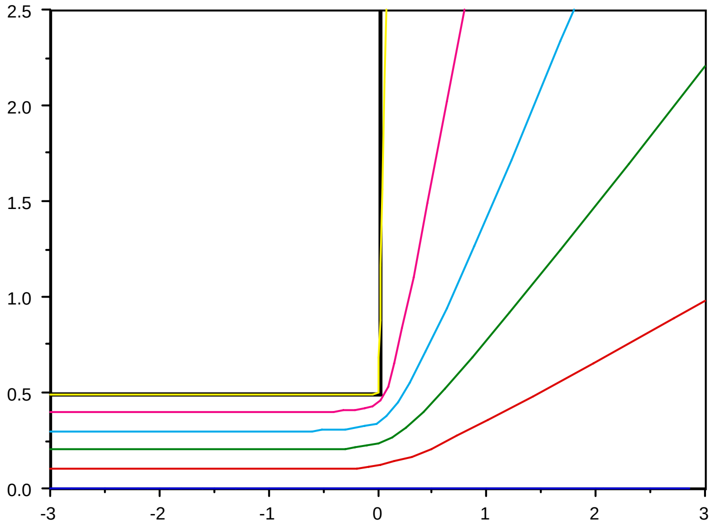
The designer optimises the pole by ‘predicting’ the field resulting from a given pole geometry and then adjusting it to give the required quality.

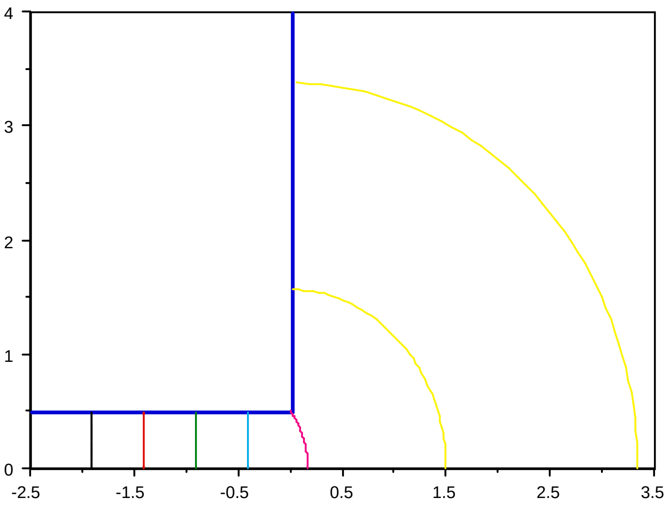
When high fields are present, chamfer angles must be small, and tapering of poles may be necessary

Design (i).

Pre computers, numerical methods and other maths methods were used to predict field distributions.

Still used - 'conformal transformations'; mapping between complex planes representing the magnet geometry and a configuration that is analytic. Examples below are for lines of i) constant scalar potential; ii) flux on a square end of a magnet pole.





Design (ii)

Computer codes are now used; eg the Vector Fields
Fields codes -'OPERA 2D' and 'TOSCA' (3D).

These have:

- finite elements with variable triangular mesh;
- multiple iterations to simulate steel non-linearity;
- extensive pre and post processors;
- compatibility with many platforms and P.C. o.s.

Technique is itterative:

- calculate flux generated by a defined geometry;
- adjust the geometry until required distribution is acheived.
acheived.

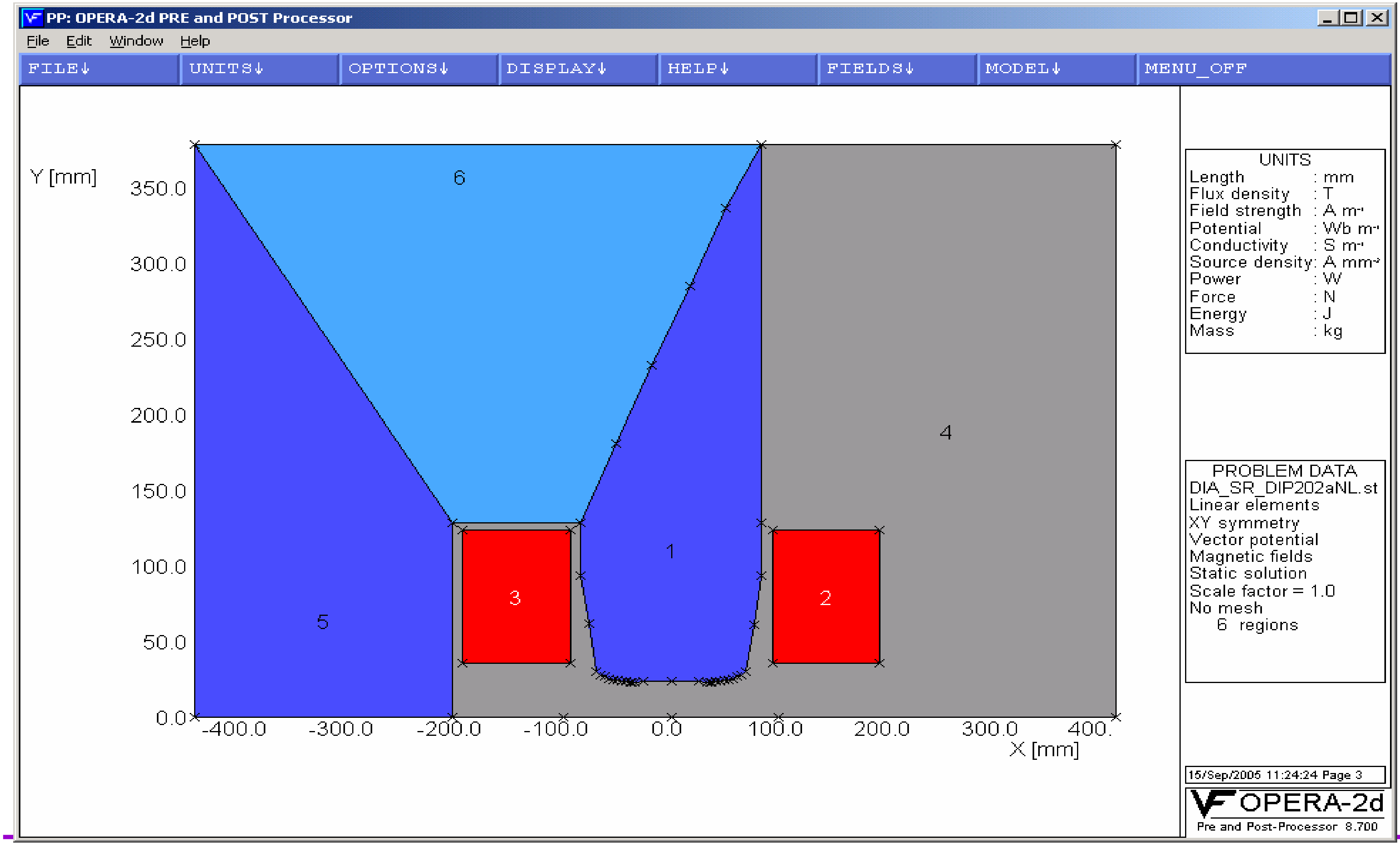
Design Procedures – OPERA 2D.

Pre-processor:

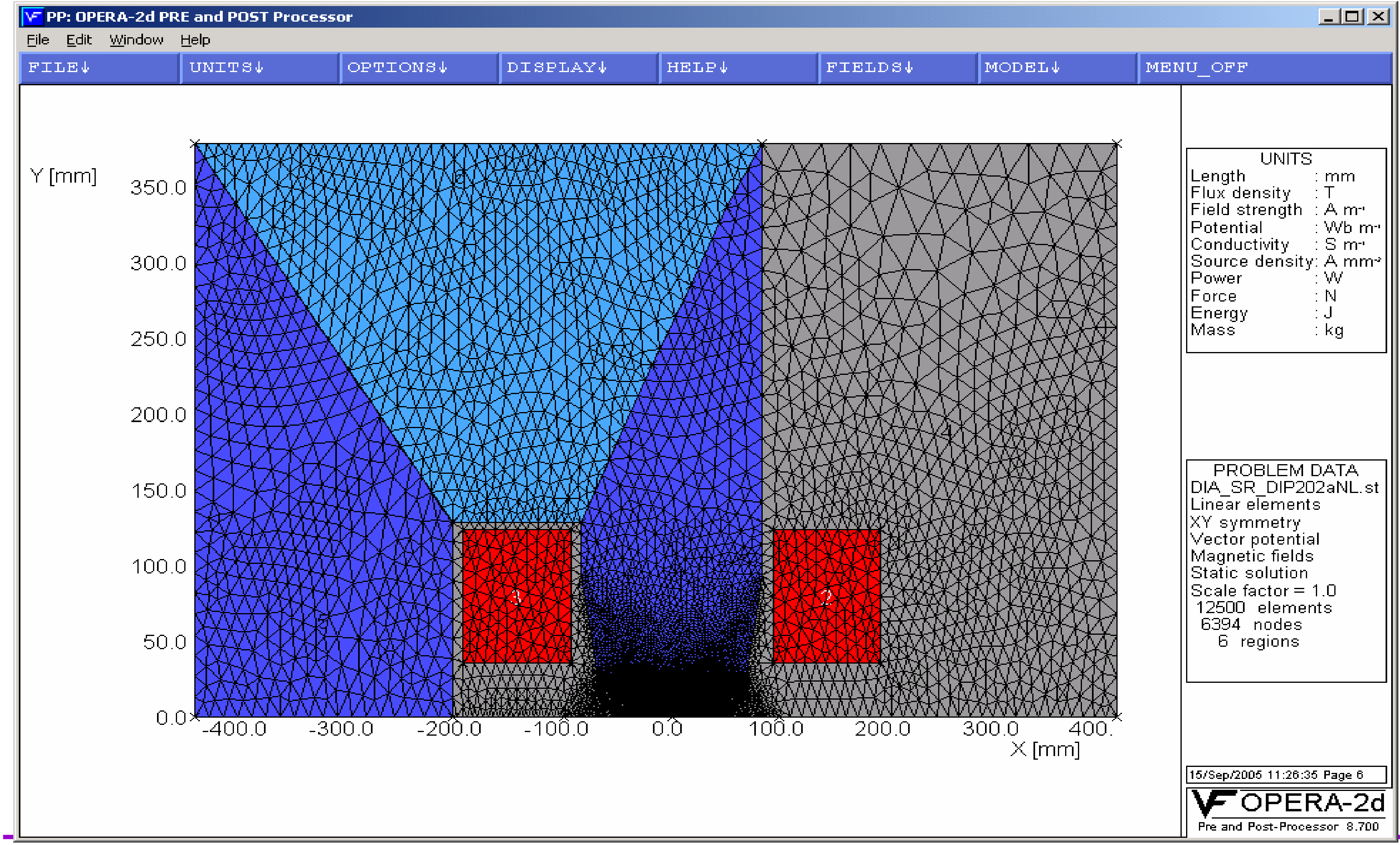
The model is set-up in 2D using a GUI (graphics user's user's interface) to define 'regions':

- steel regions;
- coils (including current density);
- a 'background' region which defines the physical physical extent of the model;
- the symmetry constraints on the boundaries;
- the permeability for the steel (or use the pre-programmed curve);
- mesh is generated and data saved.

Model of Diamond s.r. dipole

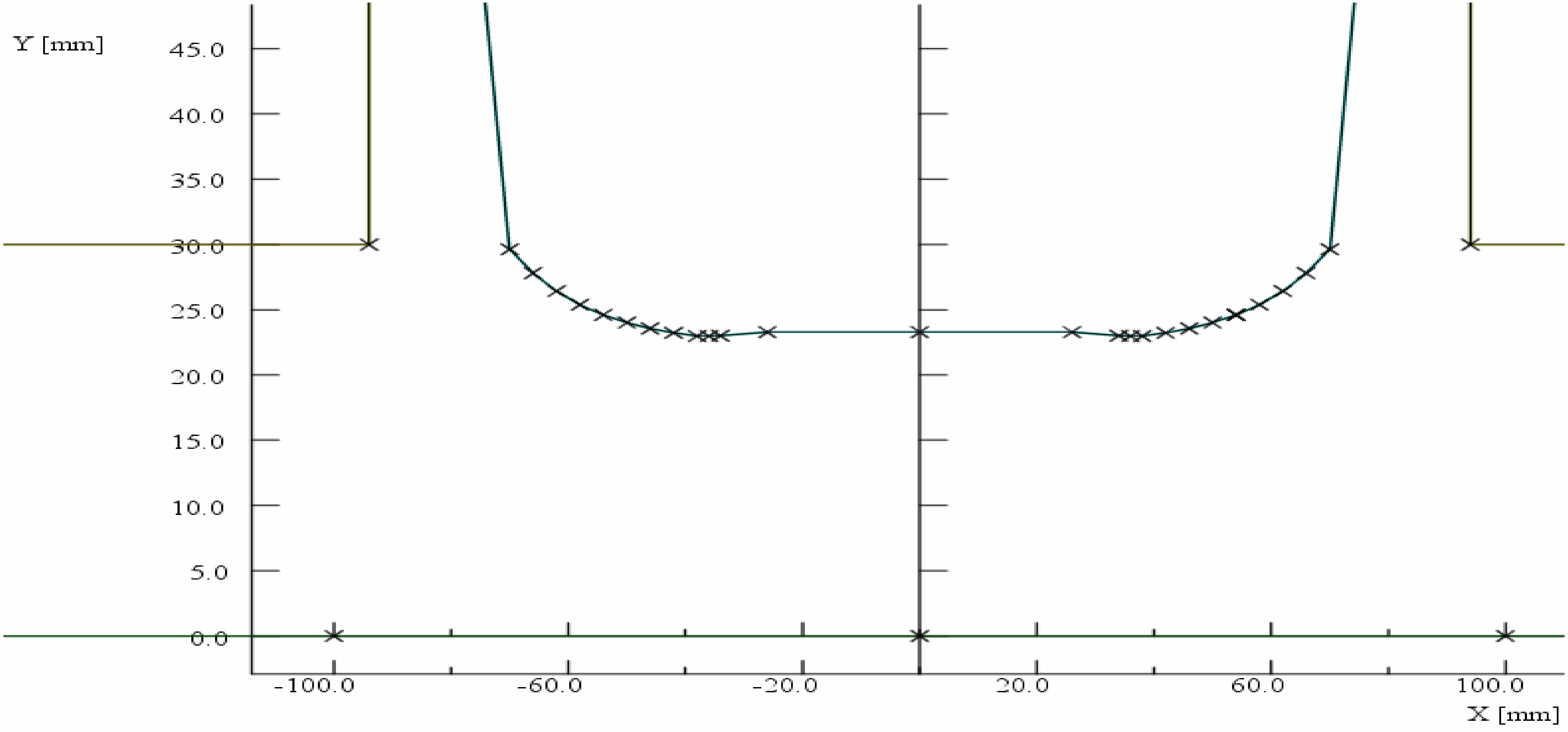


With mesh added

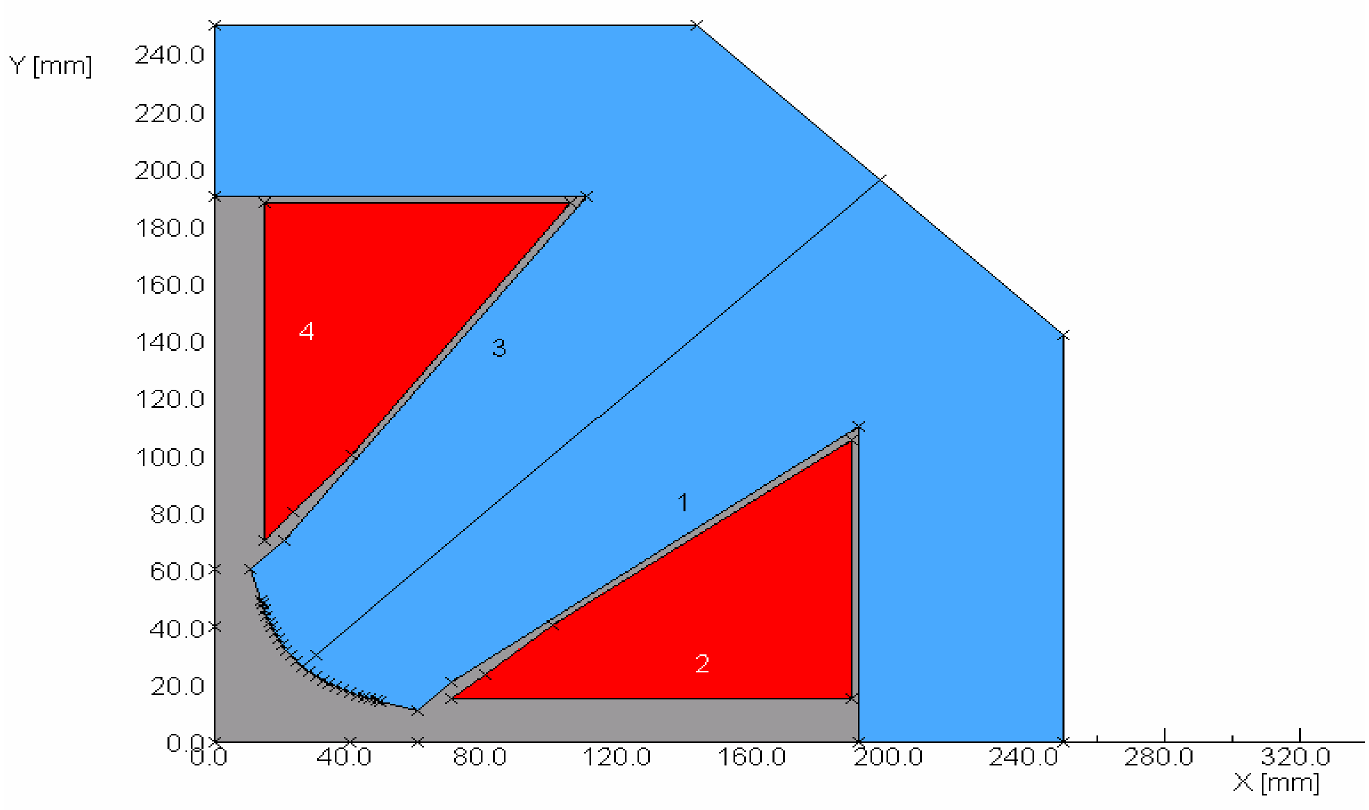


‘Close-up’ of pole region.

Pole profile, showing shim and Rogowski roll-off for Diamond 1.4 T dipole.:



Diamond quadrupole model



Note – one eighth of quadrupole could be used with opposite symmetries defined on horizontal and y = x axis.

Calculation.

Data Processor:

either:

- linear which uses a predefined constant permeability for a for a single calculation, or

- non-linear, which is itterative with steel permeability set set according to B in steel calculated on previous iteration.

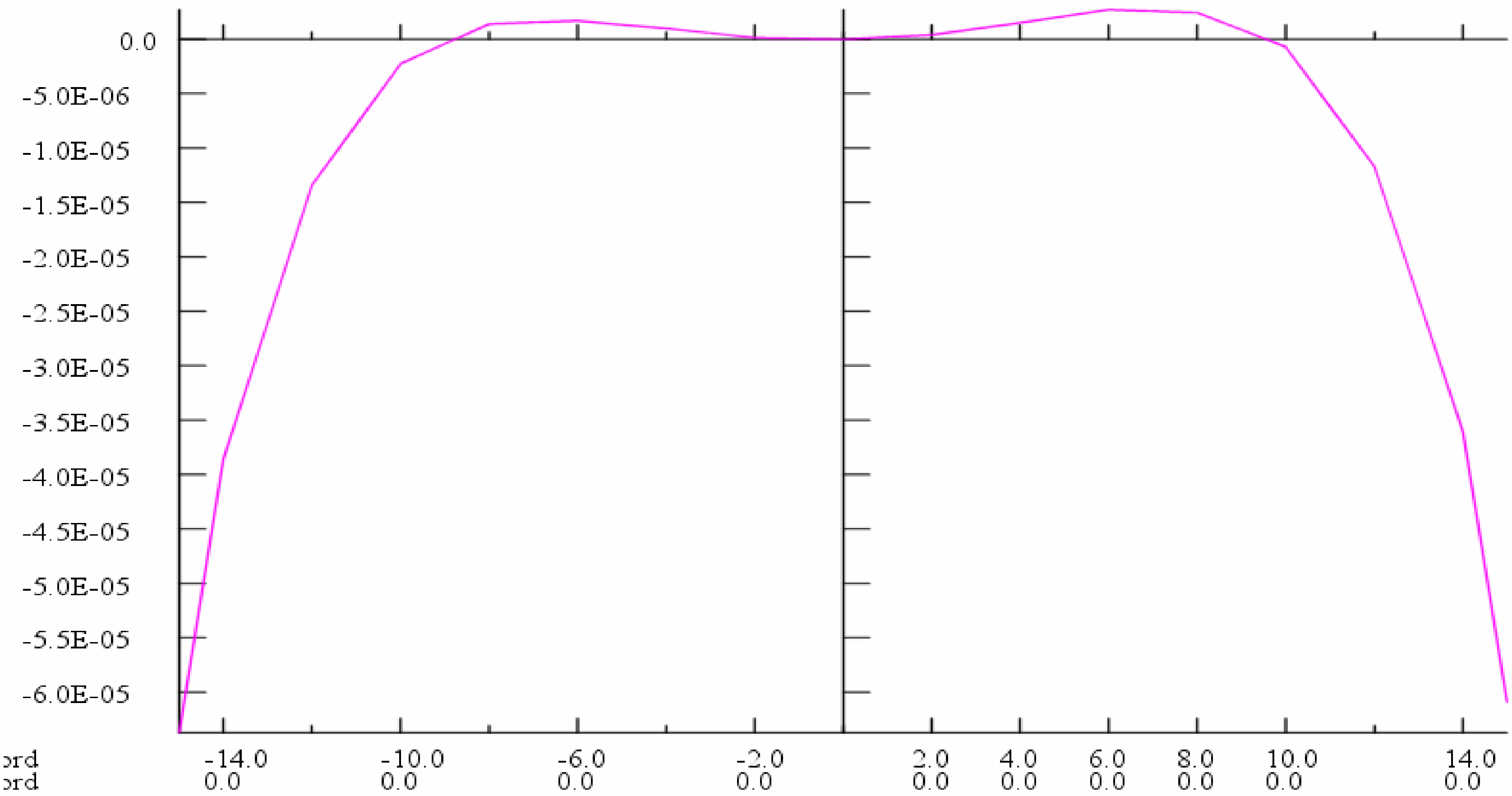
Data Display – OPERA 2D.

Post-processor:

uses pre-processor model for many options for displaying field amplitude and quality:

- field lines;
- graphs;
- contours;
- gradients;
- harmonics (from a Fourier analysis around a pre-defined defined circle).

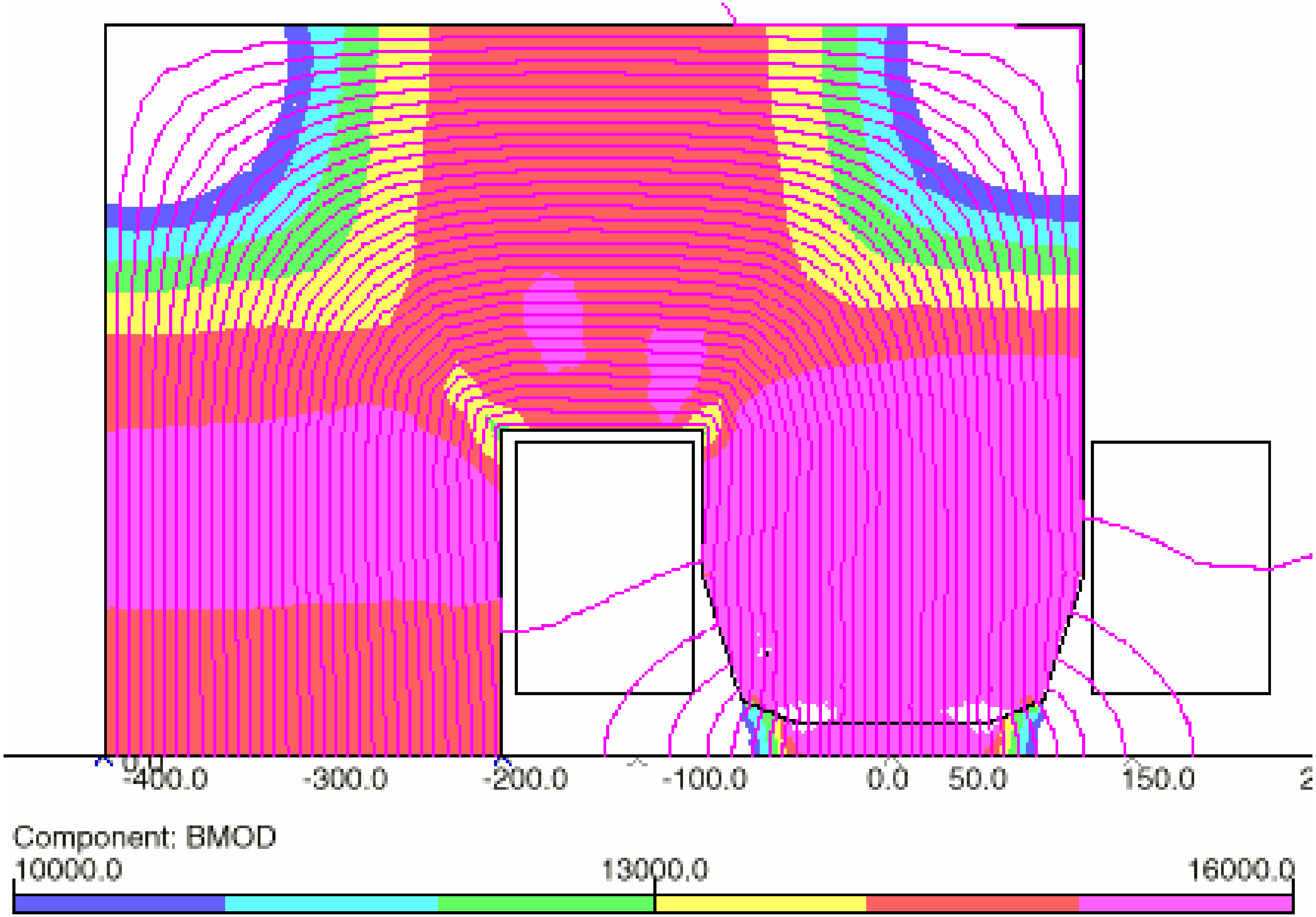
2 D Dipole field homogeneity on x axis



Diamond s.r. dipole: $\Delta B/B = \{By(x)- B(0,0)\}/B(0,0)$;

typically $\pm$ 1:10^4 within the 'good field region' of -12mm $\leq x \leq$ +12 mm..

2 D Flux density distribution in a dipole.

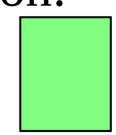


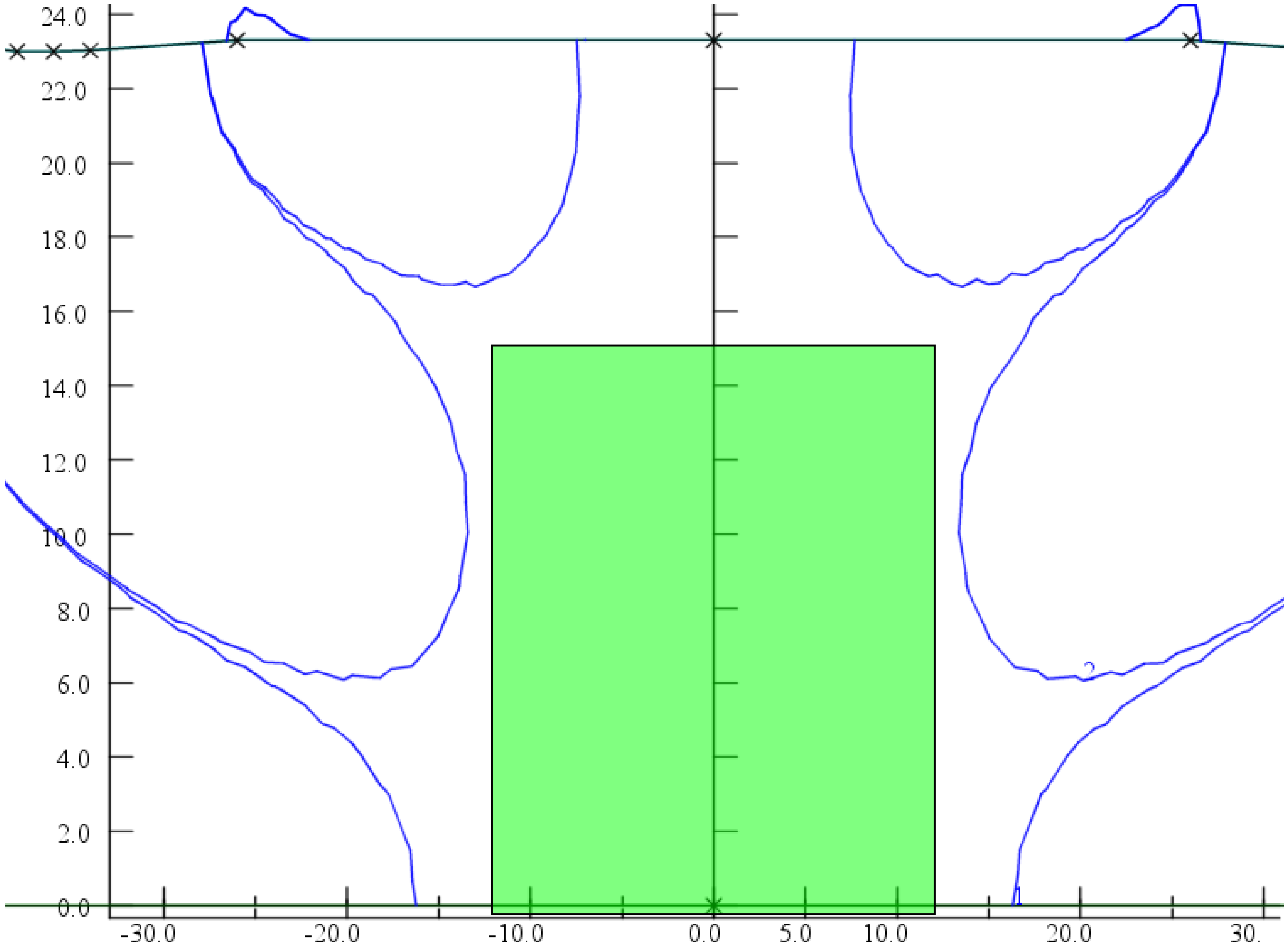
2 D Dipole field homogeneity in gap

Transverse (x,y) plane in Diamond s.r. dipole;

contours are ±0.01%

required good field region:



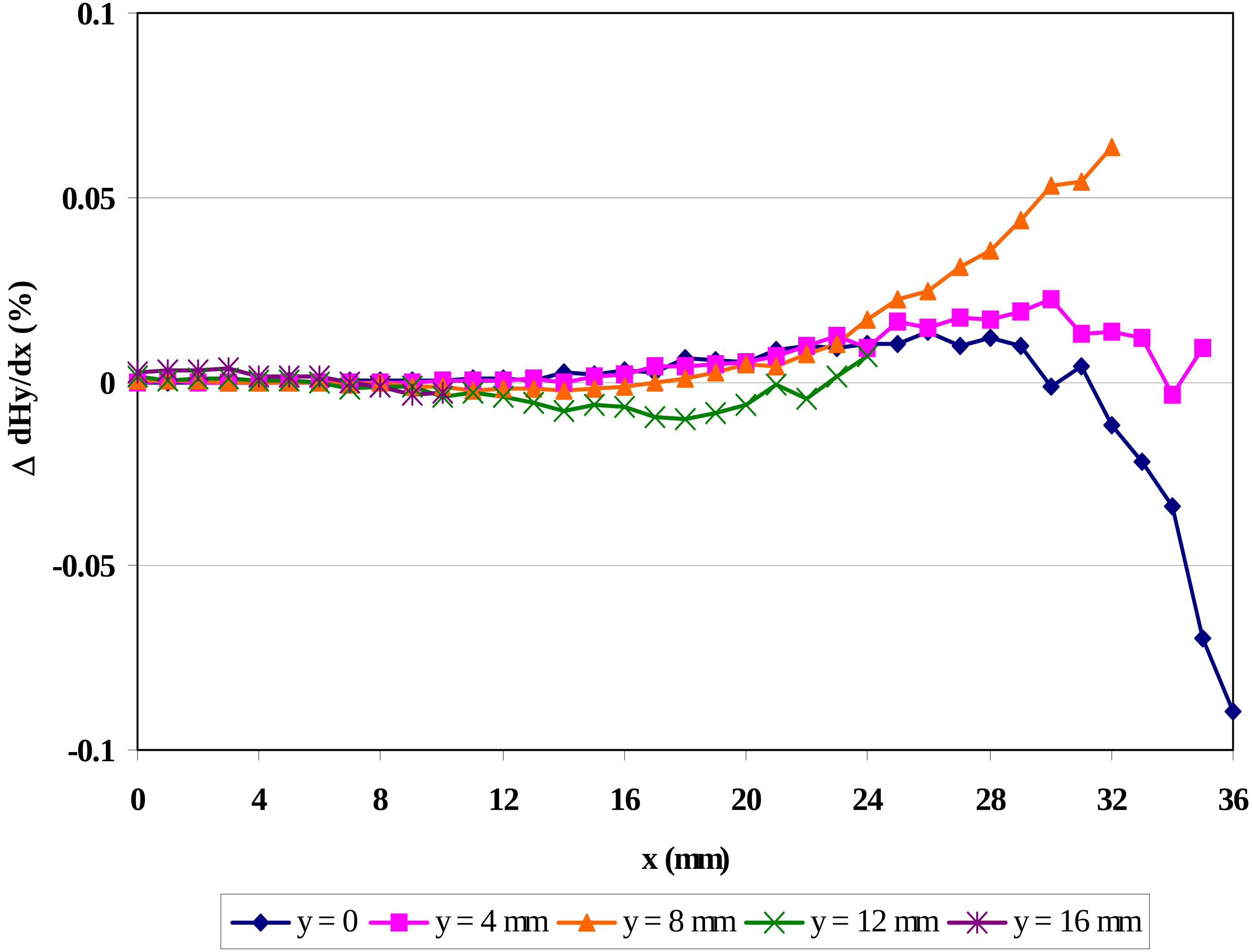


2 D Assessment of quadrupole gradient quality

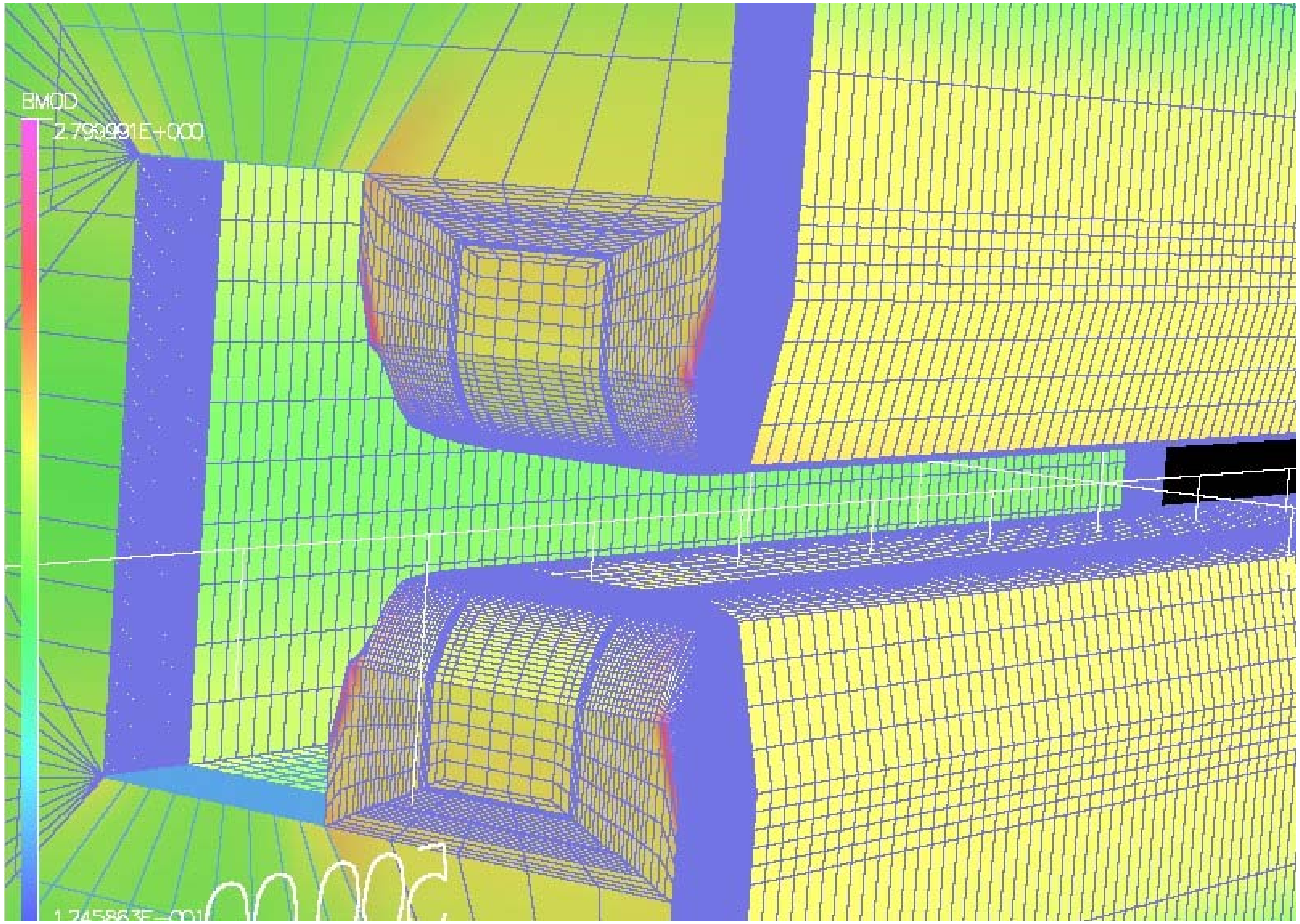
Diamond WM quadrupole:

graph is <u>percentage</u> variation in dBy/dx vs x at different values of y.

Gradient quality is to be ± 0.1 % or better to x = 36 mm.



OPERA 3D model of Diamond dipole.



Assessing results

A simple judgement of field quality is given by plotting:

•**Dipole:**	$\{B_y (x) - B_y (0)\}/B_Y (0)$	$(\Delta B(x)/B(0))$
•**Quad:**	$dB_y (x)/dx$	$(\Delta g(x)/g(0))$
•**6poles:**	$d^2B_y(x)/dx^2$	$(\Delta g_2(x)/g_2(0))$

'Typical' acceptable variation inside 'good field' region:

$$\Delta B(x)/B(0) \leq 0.01\%$$
$$\Delta g(x)/g(0) \leq 0.1\%$$
$$\Delta g_2(x)/g_2(0) \leq 1.0\%$$

Harmonics indicate magnet quality

The amplitude and phase of the harmonic components components in a magnet provide an assessment:

- when accelerator physicists are calculating beam behaviour in a lattice;
- when designs are judged for suitability;
- when the manufactured magnet is measured;
- to judge acceptability of a manufactured magnet.

Modern measurement techniques.

Magnets are now measured using rotating coil systems; systems; suitable for straight dipoles and multi-poles poles (quadrupoles and sextupoles).

This equipment and technique provides:

- amplitude;
- phase;

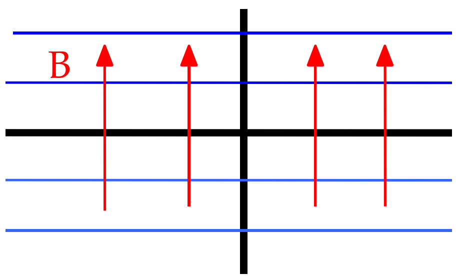
of each harmonic present, up to n ~ 20;

and:

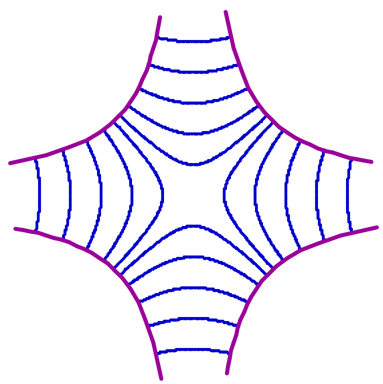
- magnetic centre (x and y);
- angular alignment (roll, pitch and yaw).

The Rotating Coil

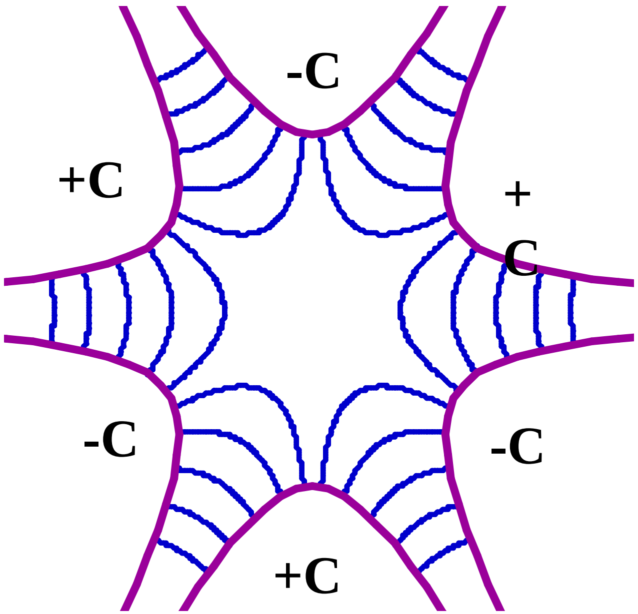
A coil continuously rotating (frequency ω) would cut the radial field and generate a voltage the sum of all the harmonics present in the magnet:



dipole: V = sin ωt



quad: V = sin 2 ωt



Etc.

sextupole: V = sin 3 ωt

Problems with continuous rotation

Sliding contacts: generate noise – obscures small higher order harmonics;

Irregular rotation: (wow) generates spurious harmonic signals;

Transverse oscillation of coil: (whip-lash) generates noise and spurious harmonics.

Solution developed at CERN to measure the LEP multi-pole magnets.

Mode of operation

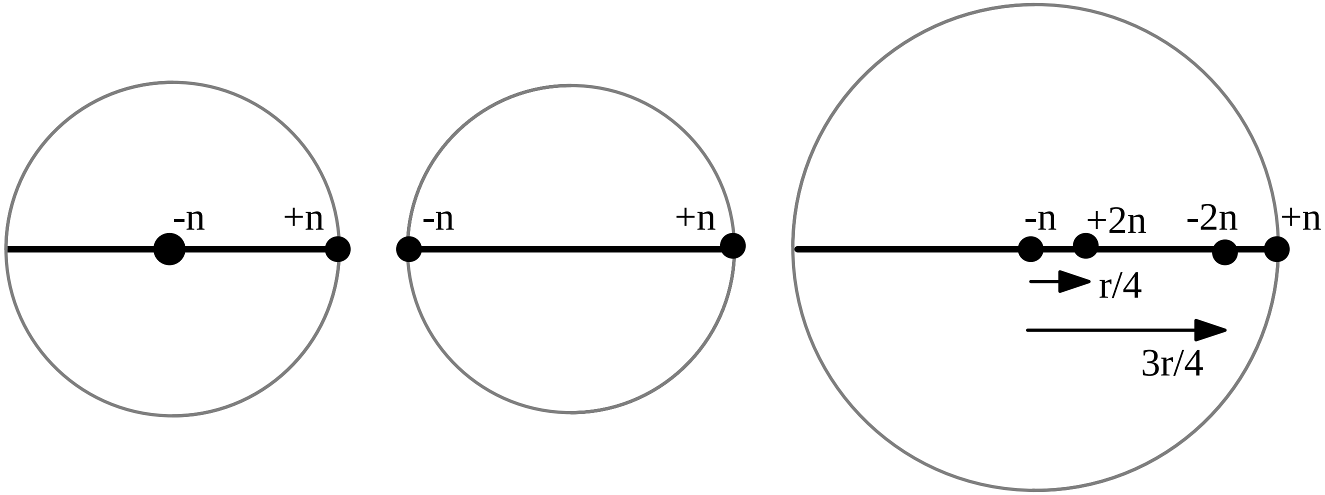
Rotation and data processing:

- windings are hard wired to detection equipment and cylinders cylinders will make ~2 revolutions in total;
- an angular encoder is mounted on the rotation shaft;
- the output voltage is converted to frequency and integrated integrated w.r.t. angle, so eliminating any ∂/∂t effects;
- integrated signal is Fourier analysed digitally, giving harmonic amplitudes and phases.

Specification:	relative accuracy of integrated field	$\pm 3\times10^{-4}$;
	angular phase accuracy	±0.2 mrad;
	lateral positioning of magnet centre	±0.03 mm;
	accuracy of multipole components	$\pm 3\times10^{-4}$

Rotating coil configurations

Multiple windings at different radii (r) and with different numbers of turns (n) are combined to cancel out harmonics, providing greater sensitivity to others:

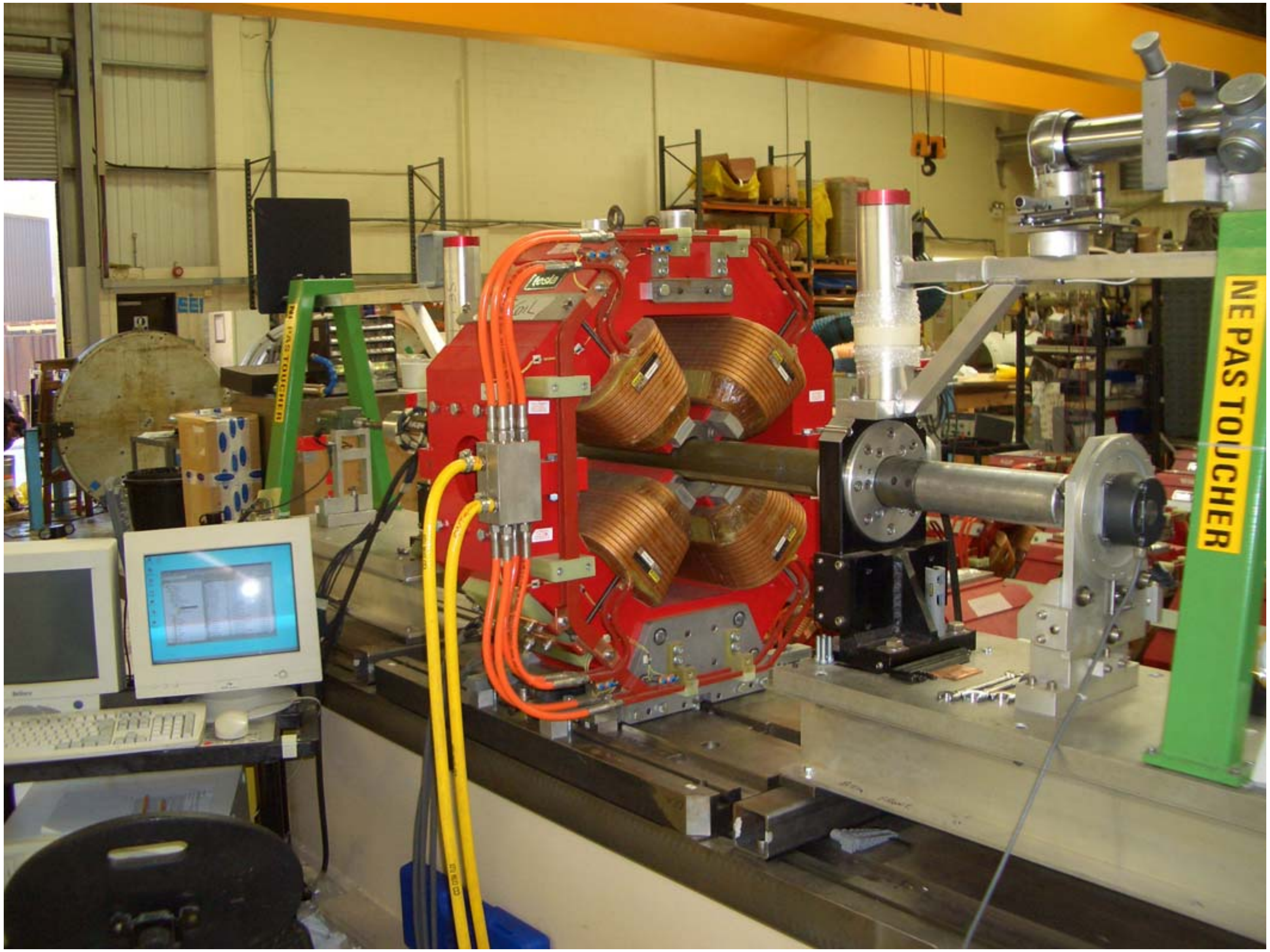


All harmonics

All odd harmonics, 1,3,5 etc.

Dipole and quadrupole rejected.

A rotating coil magnetometer.



Test data used to judge Diamond quads.

Validity	**This template is current**
Iteration No.	**1**
Magnet type identifier	**WM**
Magnet serial	**WMZ086**
Date of test	**12/07/2005**
Tester	**Darren Cox**
Comments:	**180A preliminary**
DLS comments:	**Please insert comments here**
Dipole+NS007 reference angle	**137.89068** (update fortnightly)
Adjusted dipole reference angle	**137.90085**

Midplane	**adjustment**	**Next actions (Refer first):**	
	(+ to open)	**DLS referral done? (Yes/No/NA)**	**yes**
East (um):	**240**	**Reject/Hold for refer? (S4, C6+)**	
West (um):	**80**	**Adjust vertical split (S3)?**	**Yes**
Top (um):	**80**	**Adjust midplane (C3/C4)?**	**Yes**
Bottom (um:)	**0**	**Full align?**	
C3 switch	1	**Adjust dx only?**	
S3 switch	1	**Accept magnet?**	
C4 switch	1		
S4++ switch	1		
Full switch	1		
dx switch	1		

Field quality data			**DLS OK? ?Yes/No?**	**Post-shim prediction**
R(ref) (mm)	35.00			
Current (A)	180.00			
Central strength (T/m)	17.6328			
L(eff) (mm)	407.253			
C3 (4-8)	-0.49	**Pass**	**No**	**-0.49**
S3 (6-12)	-10.88	**Refer, or shim vertical**	**No**	**-2.33**
C4 (4-7)	6.90	**Refer, or shim horizontal**	**No**	**-2.64**
S4 (1-4)	0.80	**Pass**	**No**	**-0.04**
C6 (2.5-10)	7.97	**Refer to DLS**	**yes**	
|C10,S10|: (N:3-5, W:6-8)	5.16	**Pass**	**No**	
All other terms up to 20 (2.5-5)	4.98	**Refer to DLS**	**yes**	

Alignment data [good pass/pass]	**Value**	**Outcome**
dx [0.025/0.05]mm	-0.089	**Fail**
dy [0.025/0.05]mm	-0.059	**Fail**
dz [2.5/5.0]mm	2.414	**Good pass**
Roll [0.1/0.2]mrad	0.052	**Good pass**
Yaw [0.15/0.3]mrad	-0.048	**Good pass**
Pitch [0.15/0.3]mrad	-0.085	**Good pass**
	Adjust X alone?	
	Alignment OK?	

Keys to use	**N key**	**S key**	**NW foot**	**NE foot**	**SW foot**	**SE foot**
Next shims to use (rounded)	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**

Shimming History

Iteration#	**N key**	**S key**	**NW foot**	**NE foot**	**SW foot**	**SE foot**
Shims in use	**32.010**	**32.012**	**19.011**	**19.020**	**19.004**	**19.015**
Next shims (measured)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
3	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
4	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
5	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
Rounding errors	0.000	0.000	0.000	0.000	0.000	0.000
Warnings						