

Conventional Magnets for Accelerators

Neil Marks,
ASTeC, CCLRC
Cockcroft Institute
Daresbury Science and Innovation Park
Warrington WA4 4AD,
U.K.

Tel: (44) (0)1925 603191

Fax: (44) (0)1925 603192

E mail: n.marks@cockcroft.ac.uk

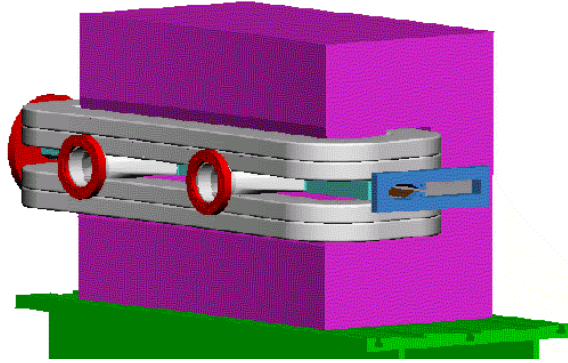
Contents

DC Magnets-design and construction:

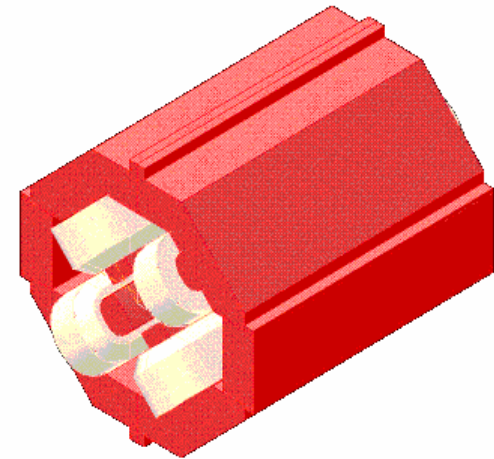
- Scalar potential solutions to Maxwell's magneto-static equations in 2D; 2D;
- Cylindrical harmonic in two dimensions (trigonometric formulation); formulation);
- Field lines and potential for dipole quadrupole, sextupole.
- Ideal pole shapes for dipole, quad and sextupole;
- Field harmonics-symmetry constraints and significance;
- Ampere-turns in dipole, quad and sextupole;
- Coil economic optimisation-capital/running costs;
- The magnetic circuit-steel requirements-permeability and coercivity; coercivity;
- Backleg and coil geometry- 'C', 'H' and 'window frame' designs;
- Magnet design: FEA techniques -OPERA 2D; TOSCA;
- Judgement of magnet suitability in design;
- Magnet ends-computation and design.

Magnets we know about:

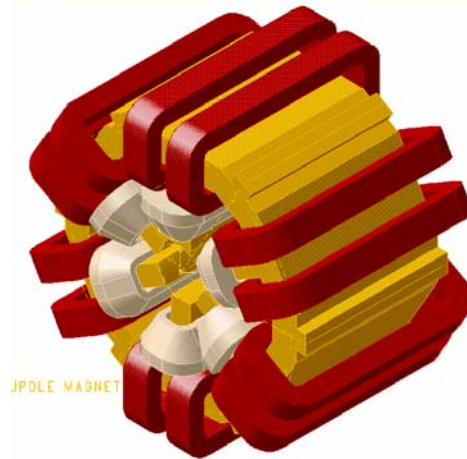
Dipoles to bend the beam:



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 $\underline{\mathbf{H}}$ (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 $\underline{\mathbf{B}}$ (as a vector);

units are Tesla (Webers/m² 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, no steel - Maxwell's equations in free free space:

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

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

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

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):

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

In practical situations:

The scalar potential simplifies to:

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

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

Giving components of flux density:

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

Significance

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

Distributions not given by above are not physically realisable.

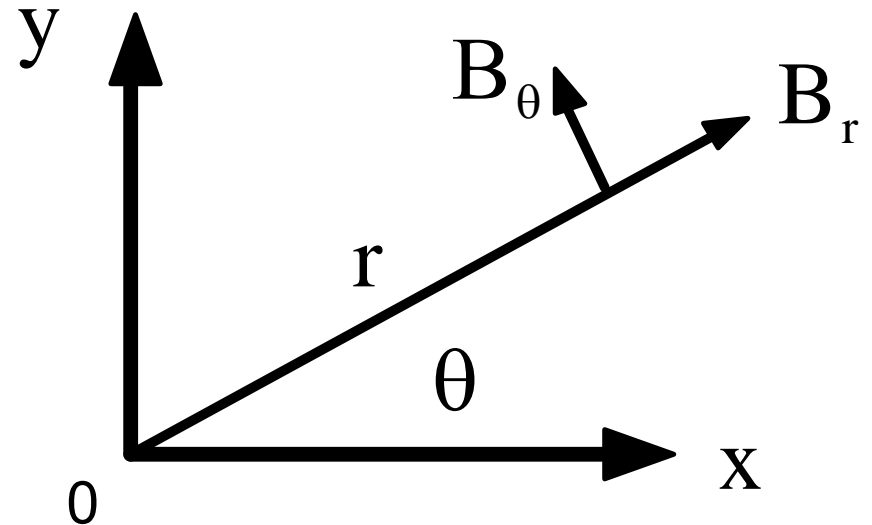
Coefficients J_n, K_n are determined by geometry (remote iron boundaries and current sources).

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:

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

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

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

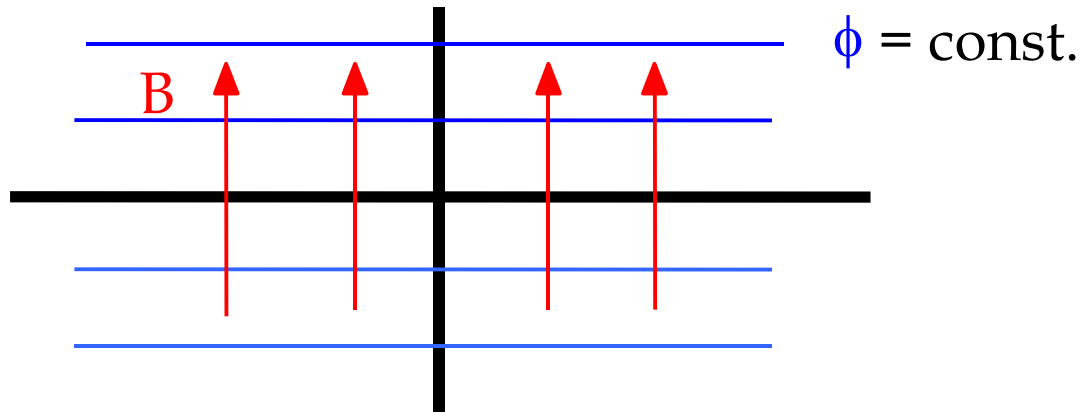
Cartesian:

$$B_x = J_1$$

$$B_y = K_1$$

$$\phi = J_1 x + K_1 y$$

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:

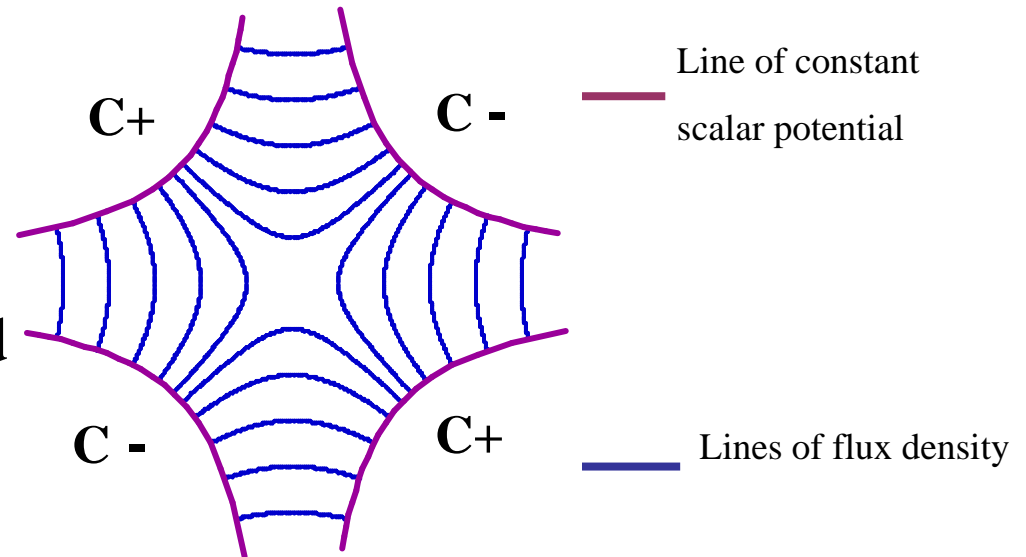
$$B_x = 2 (J_2 x + K_2 y)$$

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

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

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

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



Sextupole field: $n = 3$

Cylindrical;

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

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

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

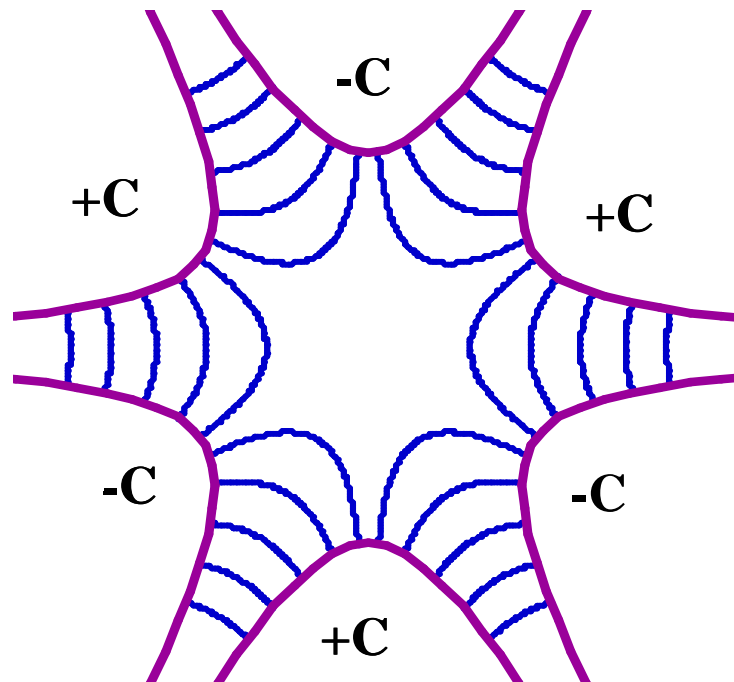
Cartesian:


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


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

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

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

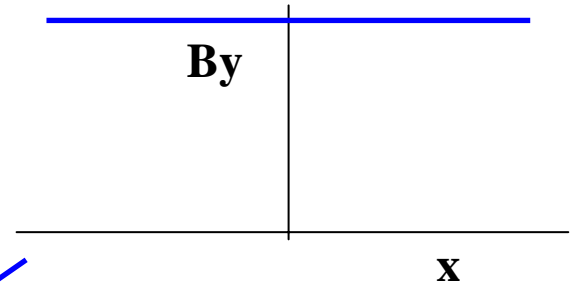


 **Line of constant scalar potential**

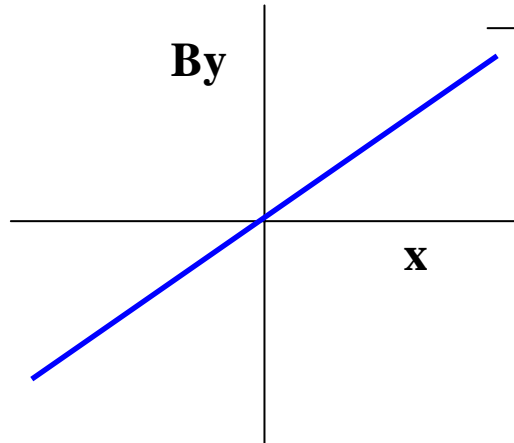
 **Lines of flux density**

Summary; variation of B_y on x axis

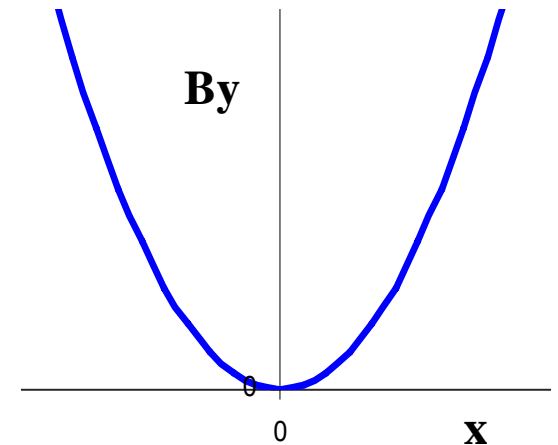
Dipole; constant field:



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.

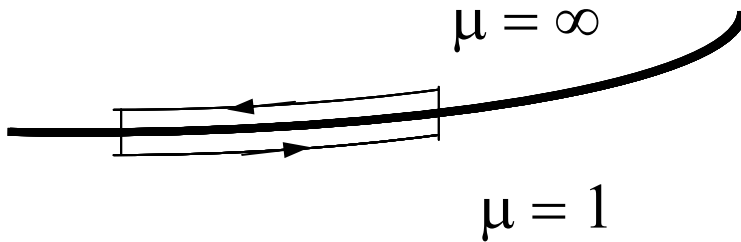
k has units:

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 :



$$\text{curl } \mathbf{H} = 0$$

$$\text{therefore } \int \mathbf{H} \cdot d\mathbf{s} = 0;$$

$$\text{in steel } \mathbf{H} = 0;$$

$$\text{therefore parallel } \mathbf{H} \text{ air} = 0$$

$$\text{therefore } \mathbf{B} \text{ is normal to surface.}$$

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

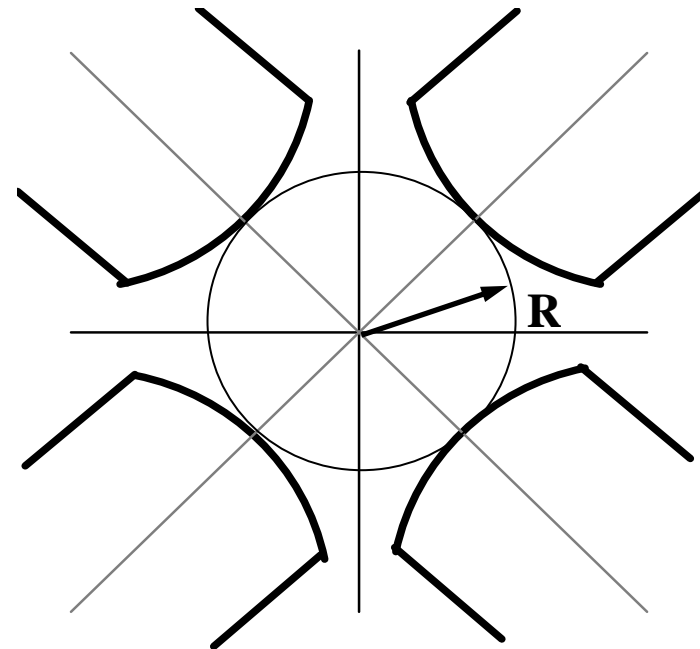
Quadrupole:

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

Sextupole:

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

R is the ‘inscribed radius’.

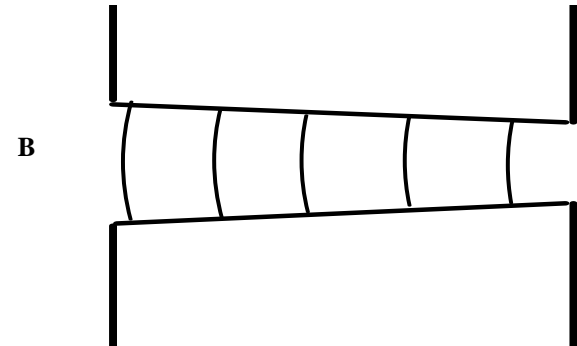


Combined function (c.f.) magnets

'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 !



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

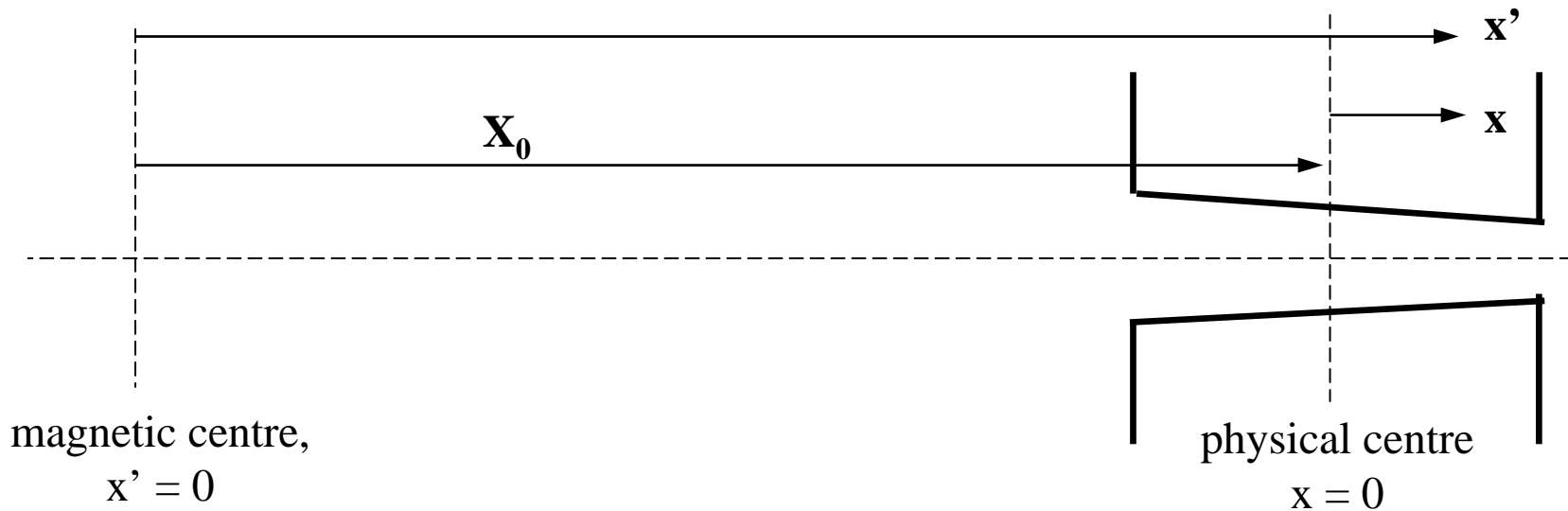
ρ is radius of curvature of the beam;

B_0 is central dipole field

Combined function geometry.

Combined function (dipole & quadrupole) magnet:

- beam is at physical centre
- flux density at beam = B_0 ;
- gradient at beam = $\partial B/\partial x$;
- magnetic centre is at $B = 0$.
- separation magnetic to physical centre = X_0



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

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

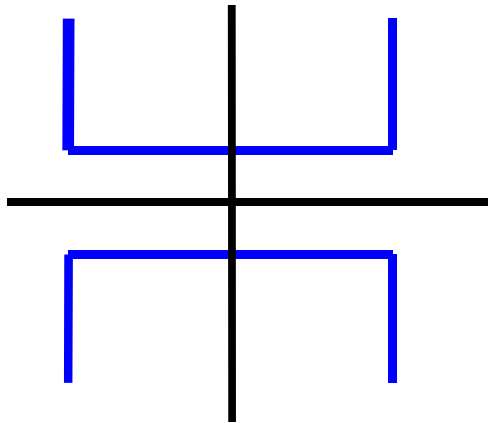
where g is the half gap at the physical centre of the magnet

The practical Pole

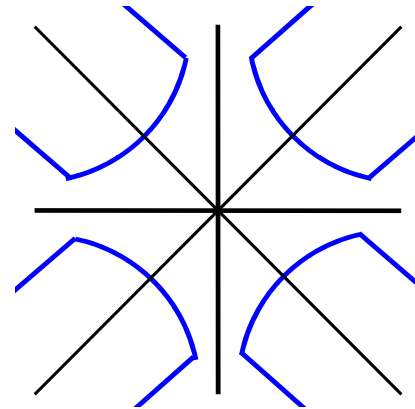
Practically, poles are finite, **introducing errors**; these appear as higher harmonics which degrade the field distribution.

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

Dipole:



Quadrupole:



Possible symmetries:

Lines of symmetry:

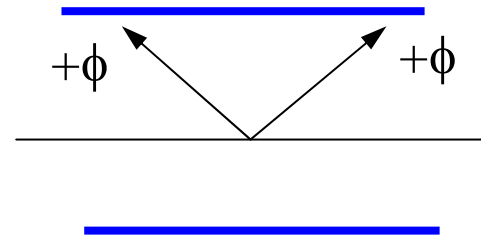
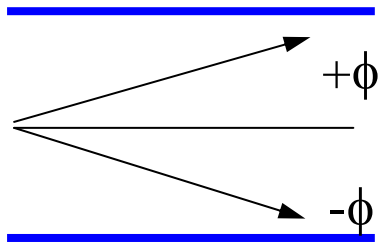
	Dipole:	Quad
Pole orientation determines whether pole is normal or skew.	$y = 0;$	$x = 0; y = 0$

Additional symmetry $x = 0;$ $y = \pm x$
imposed by pole edges.

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: $n = 1, 3, 5, \text{etc}$;



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: $n = 2, 6, 10, \text{ etc}$;

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: $n = 3, 9, 15, \text{etc.}$

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:

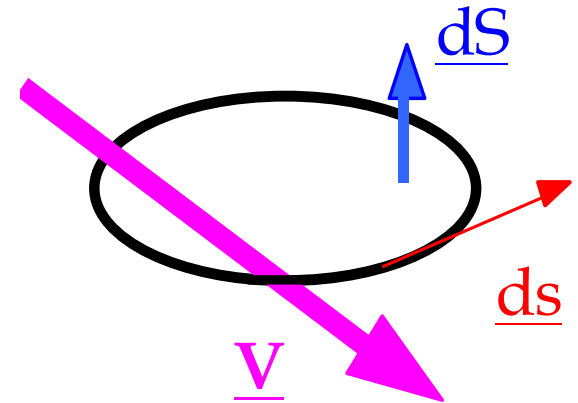
Fundamental geometry	'Allowed' harmonics
Dipole, $n = 1$	$n = 3, 5, 7, \dots$ (6 pole, 10 pole, etc.)
Quadrupole, $n = 2$	$n = 6, 10, 14, \dots$ (12 pole, 20 pole, etc.)
Sextupole, $n = 3$	$n = 9, 15, 21, \dots$ (18 pole, 30 pole, etc.)
Octupole, $n = 4$	$n = 12, 20, 28, \dots$ (24 pole, 40 pole, etc.)

Introduction of currents

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

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

$$\int \underline{V} \cdot \underline{ds} = \iint \text{curl } \underline{V} \cdot \underline{dS}$$



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

then in a magnetic circuit:

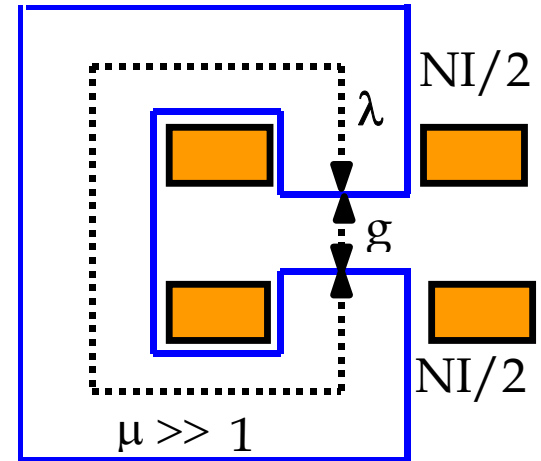
$$\int \underline{H} \cdot \underline{ds} = N I;$$

$N I$ (Ampere-turns) is total current cutting \underline{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, $\mu \gg 1$,
and $H_{\text{iron}} = H_{\text{air}} / \mu$;



So

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

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

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

$$NI = B g / \mu_0$$

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:**

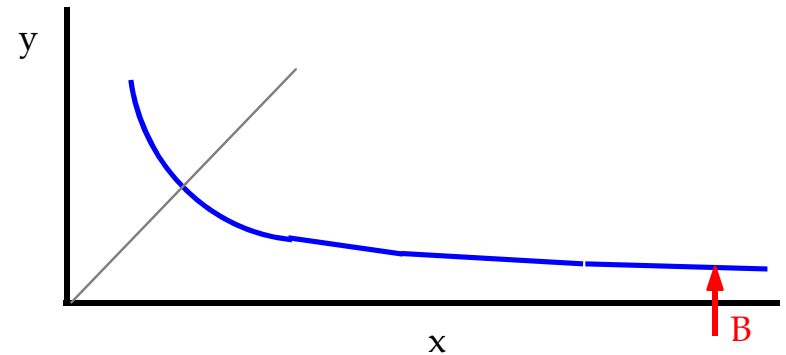
Pole equation: $xy = R^2 / 2$
On x axes $B_Y = gx$;
where g is gradient (T/m).

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!), $\mathbf{B} = \mu_0 \mathbf{H}$

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

Integrating over a limited path

(not circular) in air:

$$NI = (\phi_1 - \phi_2)/\mu_0$$

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:

$$\mu_0 NI$$

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

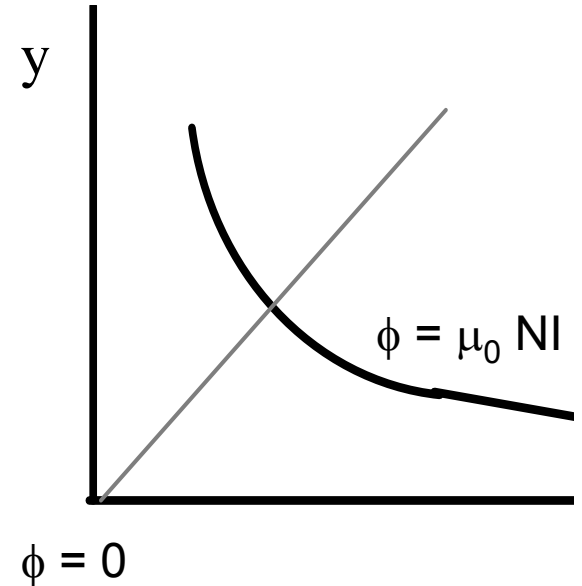
$$NI = (1/n) (1/\mu_0) \{B_r/R^{(n-1)}\} R^n$$

Where:

NI is excitation per pole;

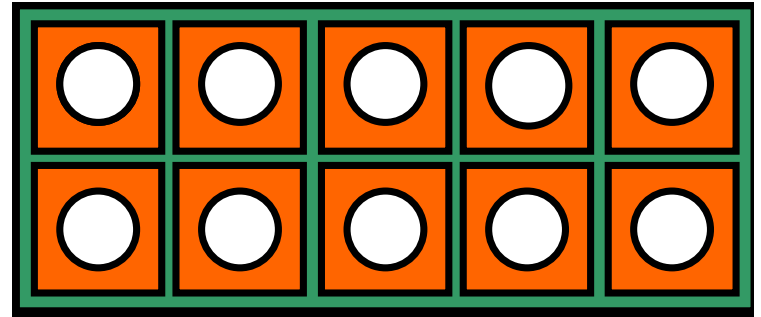
R is the inscribed radius (or half gap in a dipole);

term in brackets $\{\}$ is magnet strength in T/m⁽ⁿ⁻¹⁾.



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:
 $j = NI/A_{\text{copper}}$
Optimum j
determined from
economic criteria.

Current density - optimisation

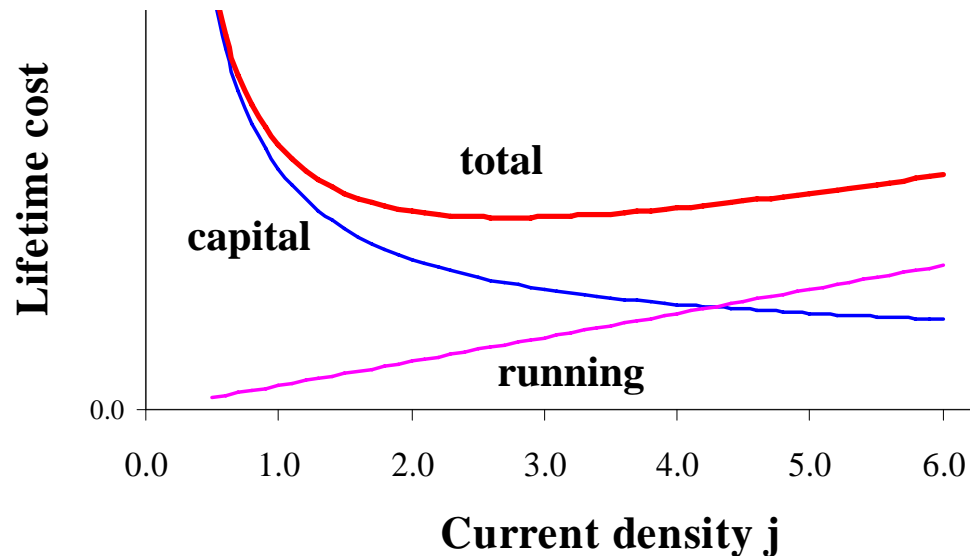
Advantages of low j :

- **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.



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, neat terminals.

Thin interconnections-hence low cost and flexible.

More insulation layers in coil, hence larger coil volume and increased assembly costs.

High voltage power supply
-safety problems.

Small N (high current)

Large, bulky terminals

Thick, expensive connections.

High percentage of copper in coil volume. More efficient use of space available

High current power supply.
-greater losses.

Examples of typical turns/current

From the Diamond 3 GeV synchrotron source:

Dipole:

N (per magnet):	40;	
I max	1500	A;
Volts (circuit):	500	V.

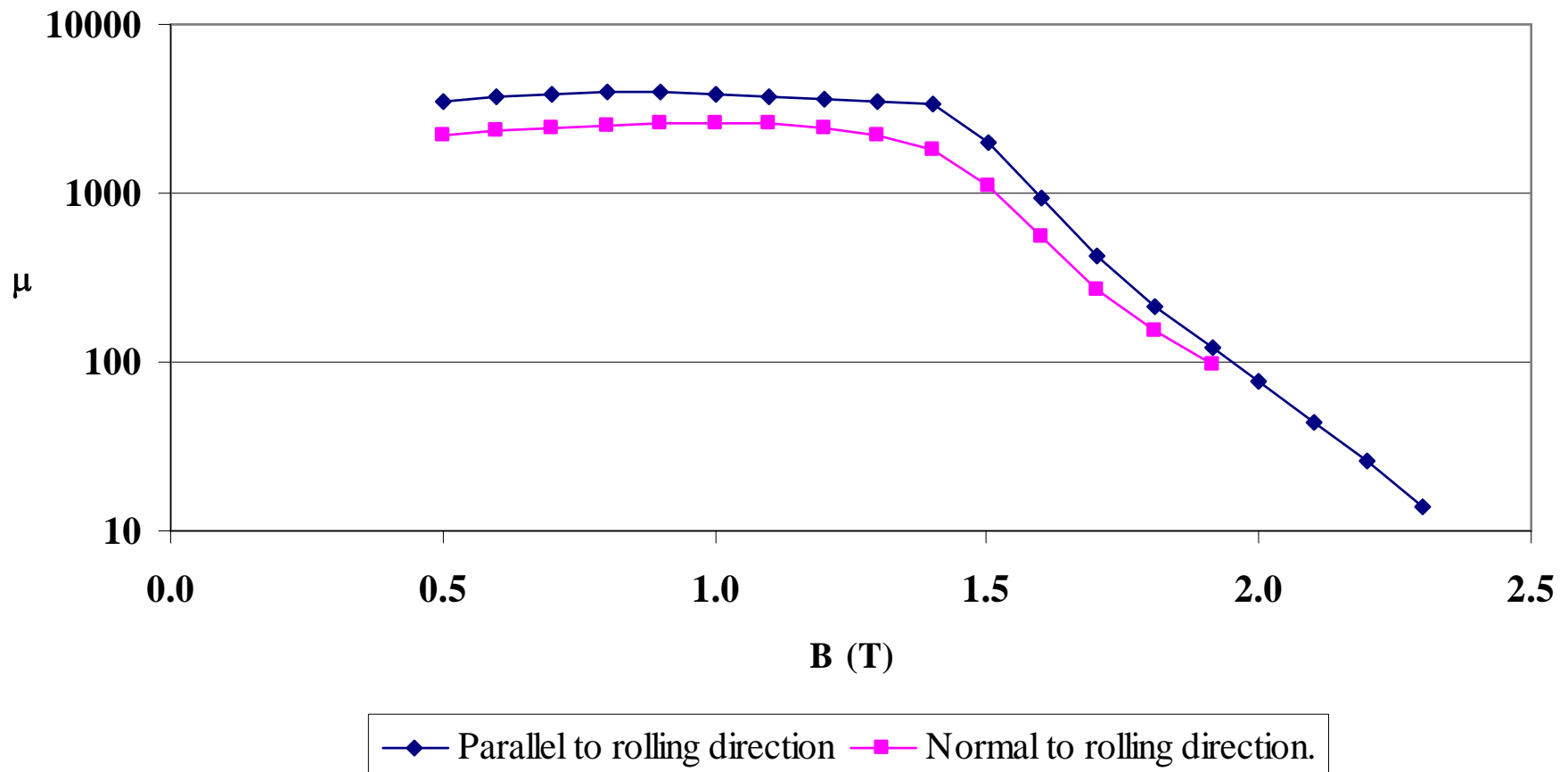
Quadrupole:

N (per pole)	54;	
I max	200	A;
Volts (per magnet):	25	V.

Sextupole:

N (per pole)	48;	
I max	100	A;
Volts (per magnet)	25	V.

Yoke - Permeability of low silicon steel



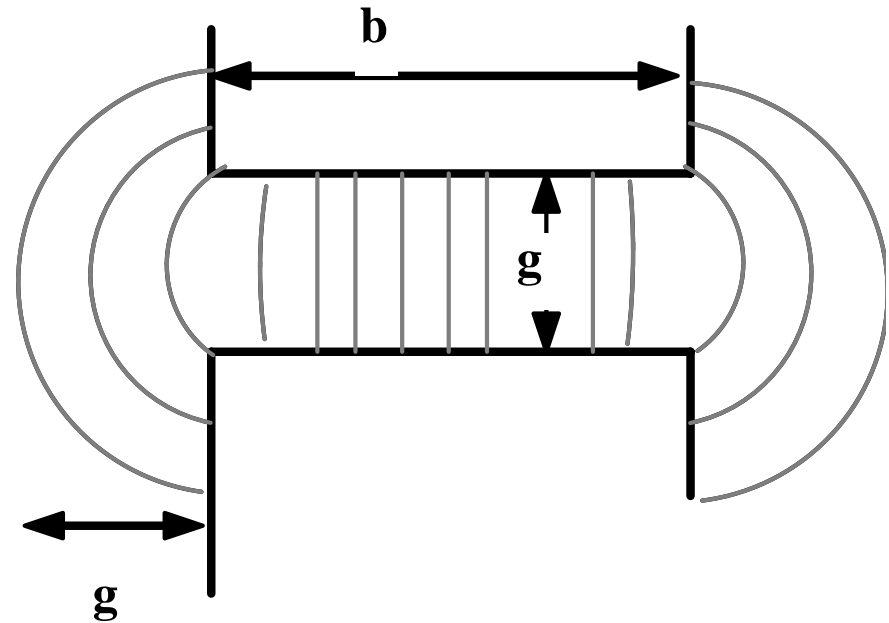
Iron Design/Geometry.

Flux in the yoke includes the gap flux and stray flux, which which extends (approx) one gap width on either side of the gap.
the gap.

Thus, to
calculate total flux in
the back-leg of magnet
length λ :

$$\Phi = B_{\text{gap}} (b + 2g) \lambda.$$

Width of backleg is chosen to
limit B_{yoke} and hence
maintain high μ .



'Residual' fields

Residual field - the flux density in a gap at $I = 0$;

Remnant field B_R - value of B at $H = 0$;

Coercive force H_C - negative value of field at $B = 0$;

$$I = 0: \quad \int H \cdot ds = 0;$$

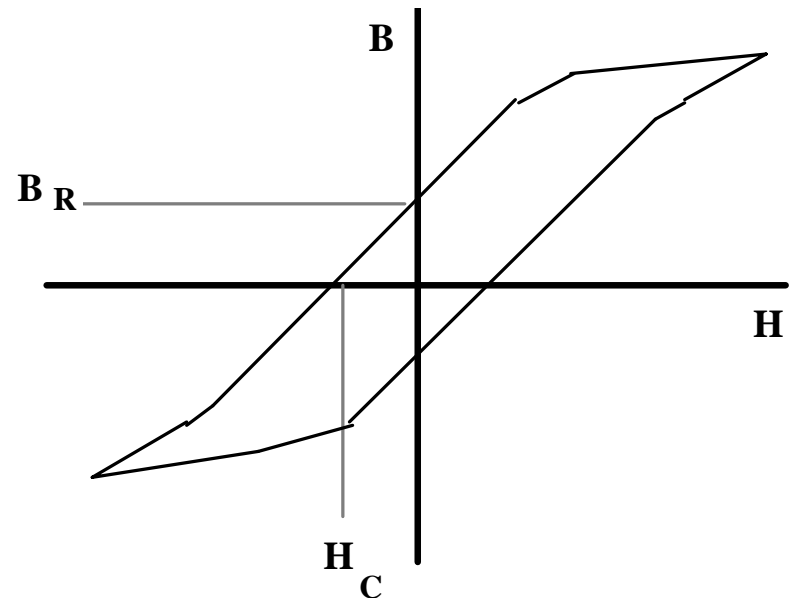
$$\text{So:} \quad (H_{\text{steel}}) \lambda + (H_{\text{gap}})g = 0;$$

$$B_{\text{gap}} = (\mu_0)(-H_{\text{steel}})(\lambda/g);$$

$$B_{\text{gap}} \approx (\mu_0) (H_C)(\lambda/g);$$

Where: λ is path length in steel;
 g is gap height.

Because of presence of gap, residual field is determined by coercive force H_C (A/m) and not remnant flux density B_R (Tesla).



Magnet geometry

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

"C" Core:

Advantages:

Easy access;

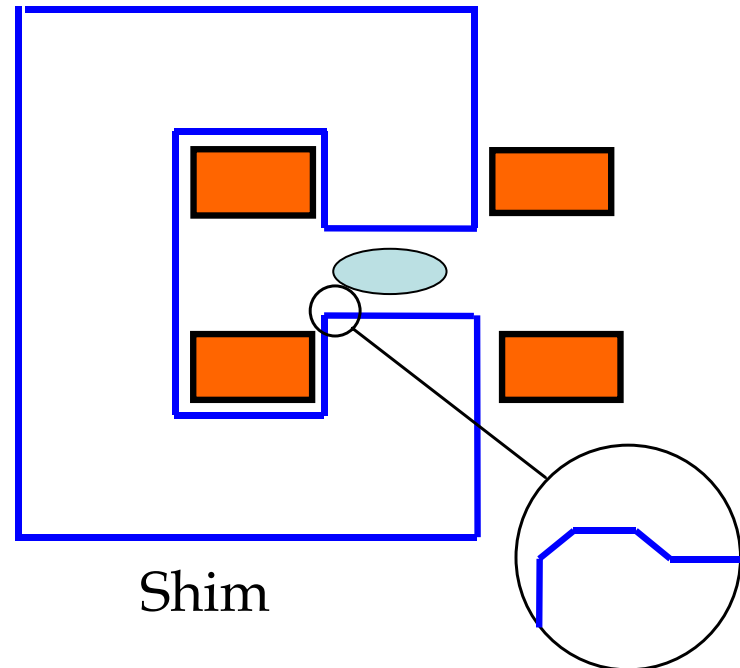
Classic design;

Disadvantages:

Pole shims needed;

Asymmetric (small);

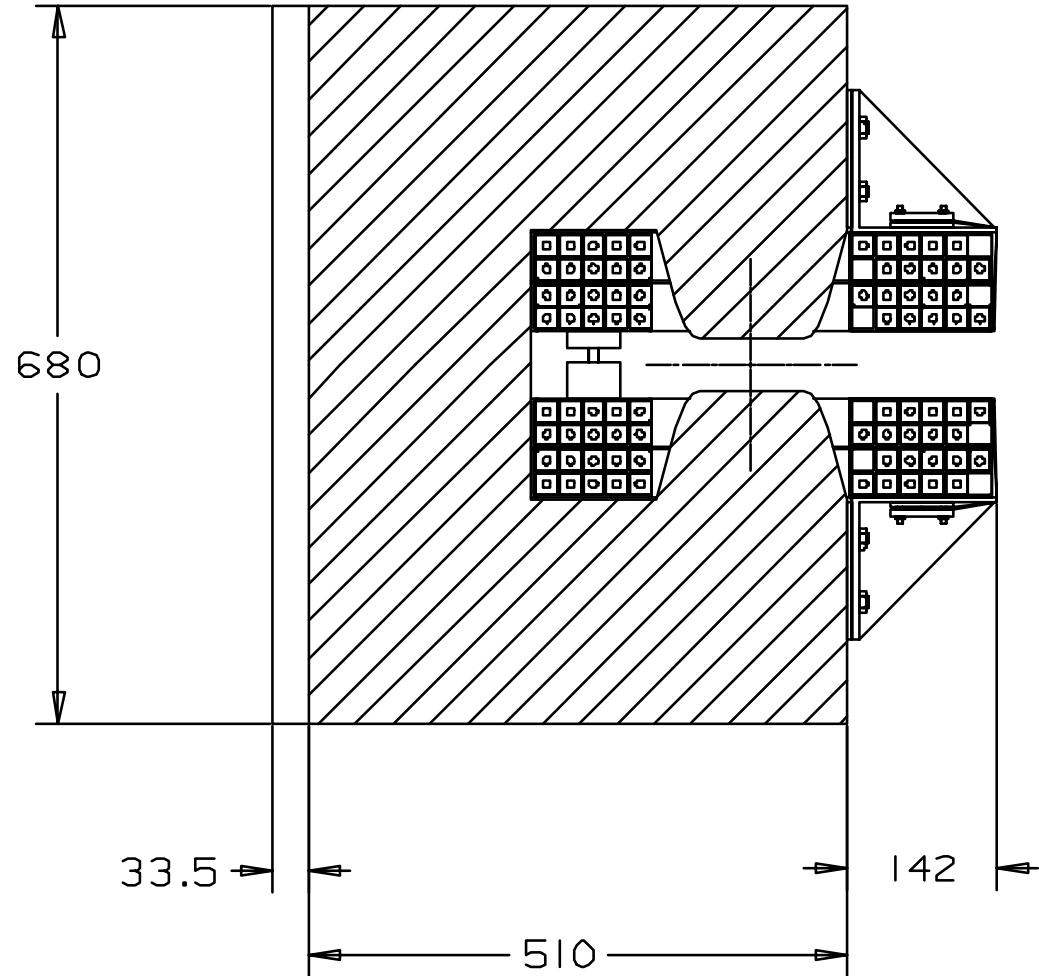
Less rigid;



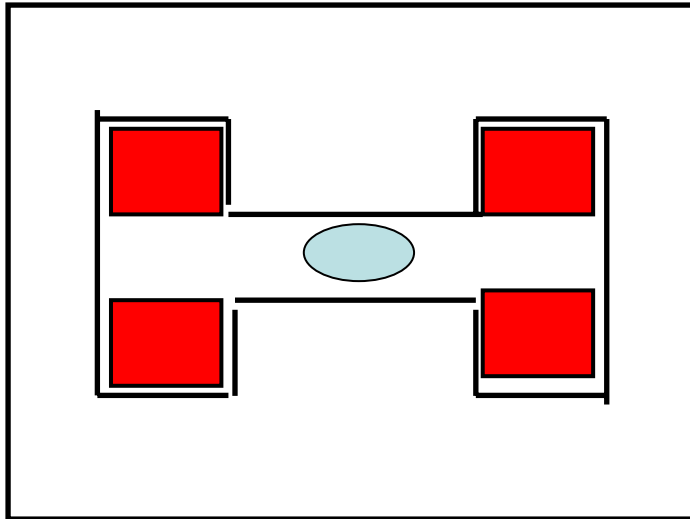
The 'shim' is a small, additional piece of ferro-magnetic material added on each side of the two poles – it compensates for the finite cut-off of the pole, and is optimised to reduce the 6, 10, 14..... pole error harmonics.

A typical 'C' cored Dipole

Cross section of the Diamond storage ring dipole.



H core and window-frame magnets



'H core':

Advantages:

Symmetric;

More rigid;

Disadvantages:

Still needs shims;

Access problems.

'Window Frame'

Advantages:

High quality field;

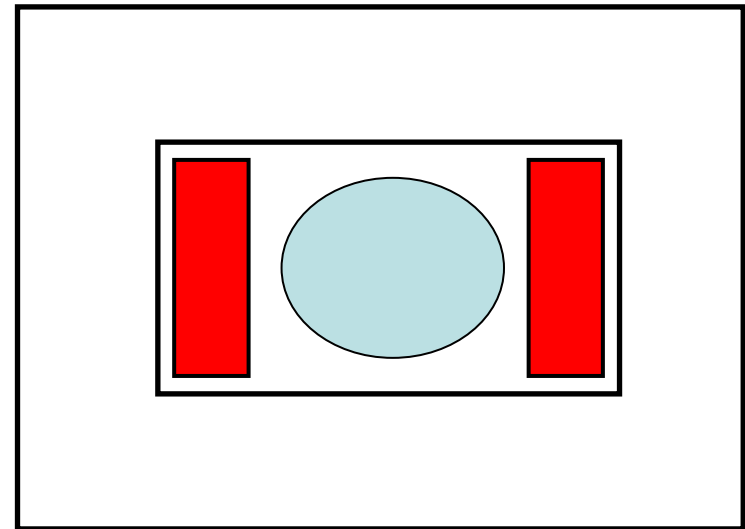
No pole shim;

Symmetric & rigid;

Disadvantages:

Major access problems;

Insulation thickness

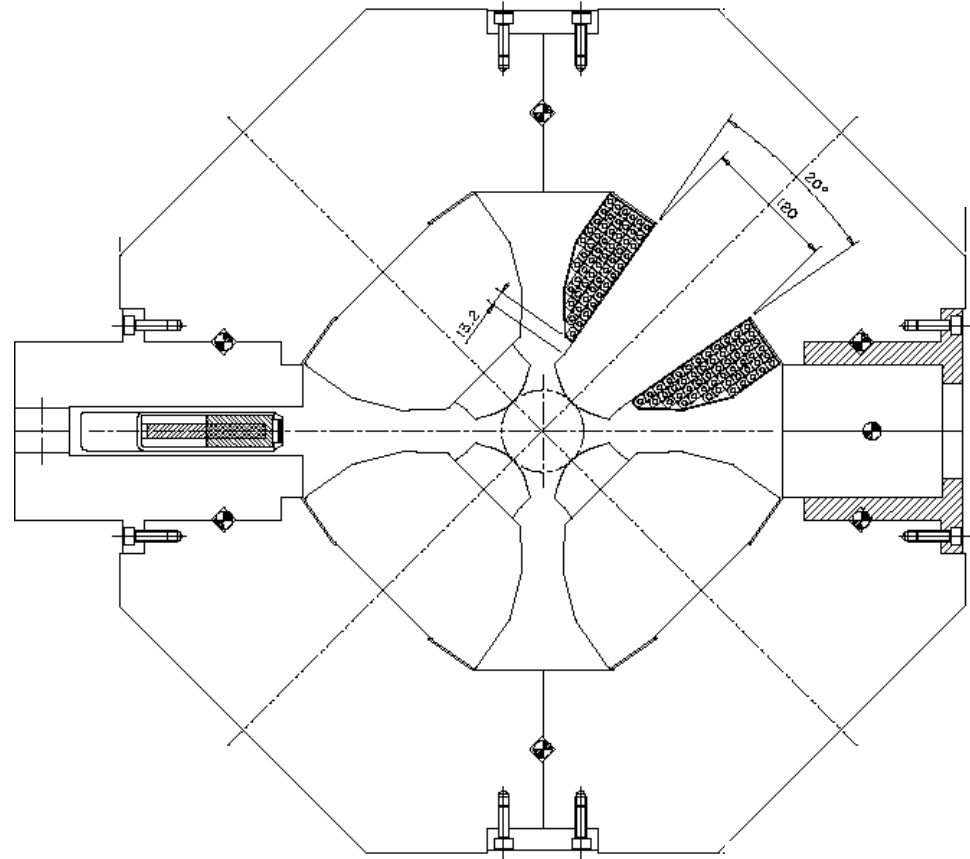


An open-sided Quadrupole.

‘Diamond’ storage ring quadrupole.

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

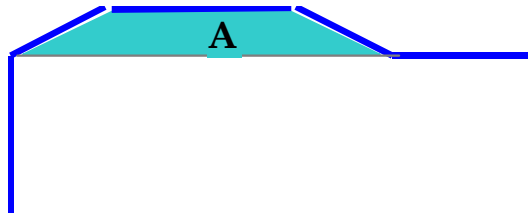
Error harmonics include $n = 4$ (octupole) a finite permeability error.



Typical pole designs

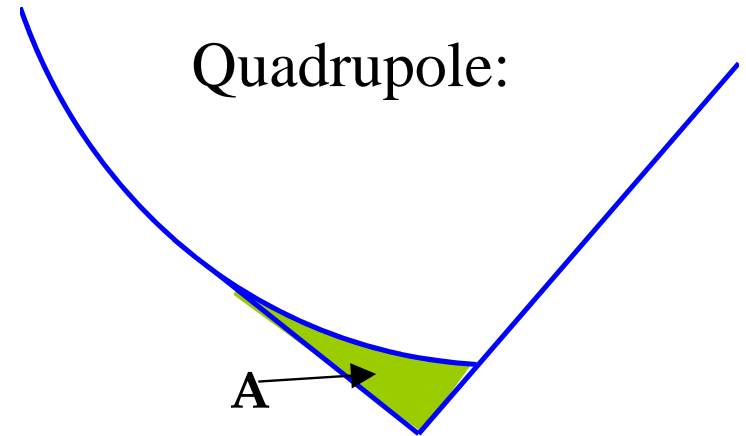
To compensate for the non-infinite pole, shims are added at the pole edges. The area and shape of the shims determine the amplitude of error harmonics which will be present.

Dipole:



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

Quadrupole:



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

Assessing pole design

A first assessment can be made by just examining $B_y(x)$ within within the required 'good field' region.

Note that the expansion of $B_y(x)_{y=0}$ is a Taylor series:

$$B_y(x) = \sum_{n=1}^{\infty} \{b_n x^{(n-1)}\}$$
$$= b_1 + b_2 x + b_3 x^2 + \dots$$

dipole quad sextupole

Also note:

$$\partial B_y(x) / \partial x = b_2 + 2 b_3 x + \dots$$

So quad gradient $g \equiv b_2 = \partial B_y(x) / \partial x$ in a quad

But sext. gradient $g_s \equiv b_3 = 2 \partial^2 B_y(x) / \partial x^2$ in a sext.

So coefficients are not equal to differentials for $n = 3$ etc.

Assessing an adequate design.

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:

$$\begin{aligned}\Delta B(x)/B(0) &\leq 0.01\% \\ \Delta g(x)/g(0) &\leq 0.1\% \\ \Delta g_2(x)/g_2(0) &\leq 1.0\%\end{aligned}$$

Design by computer codes.

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 iterative:

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

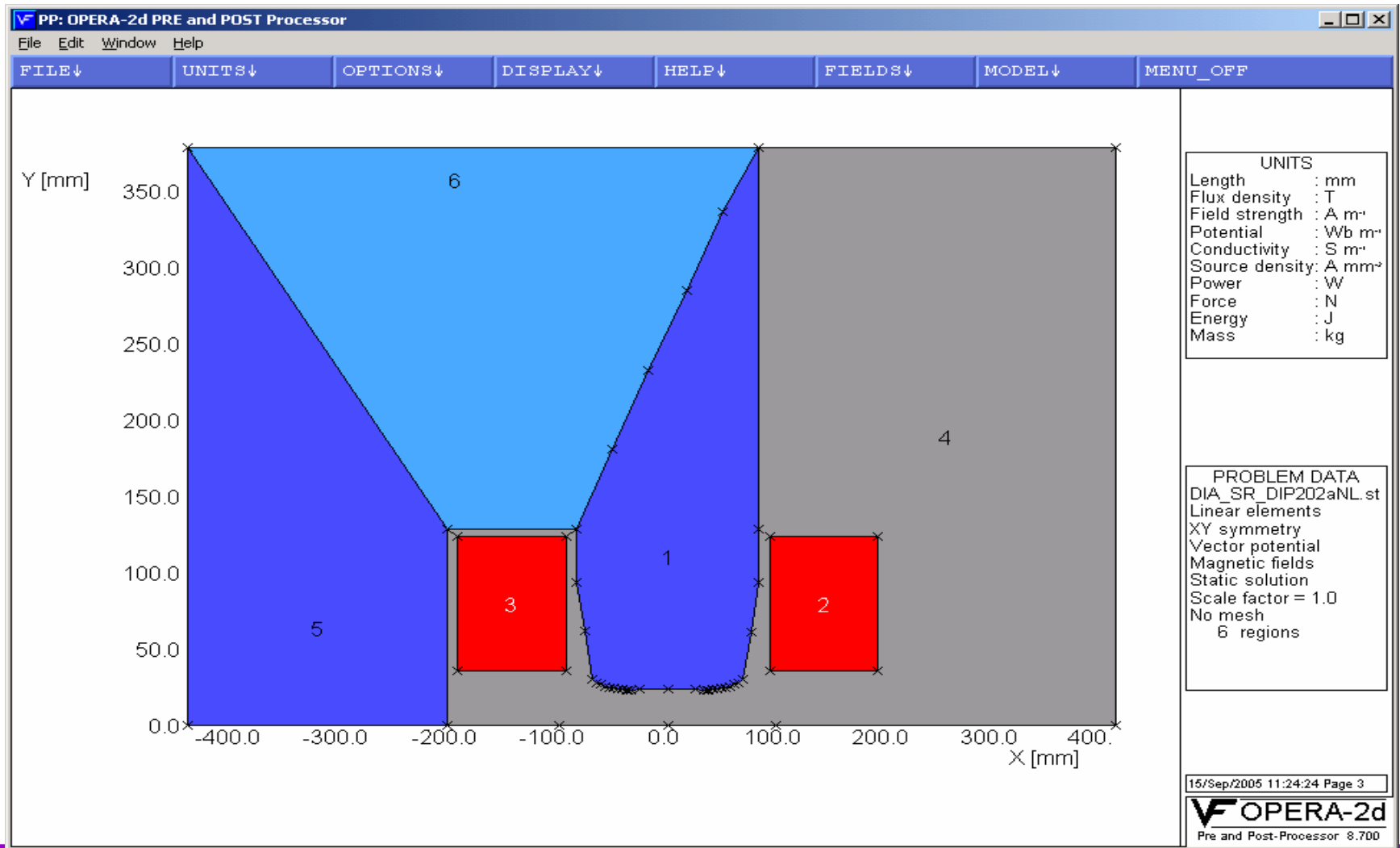
Design Procedures – OPERA 2D.

Pre-processor:

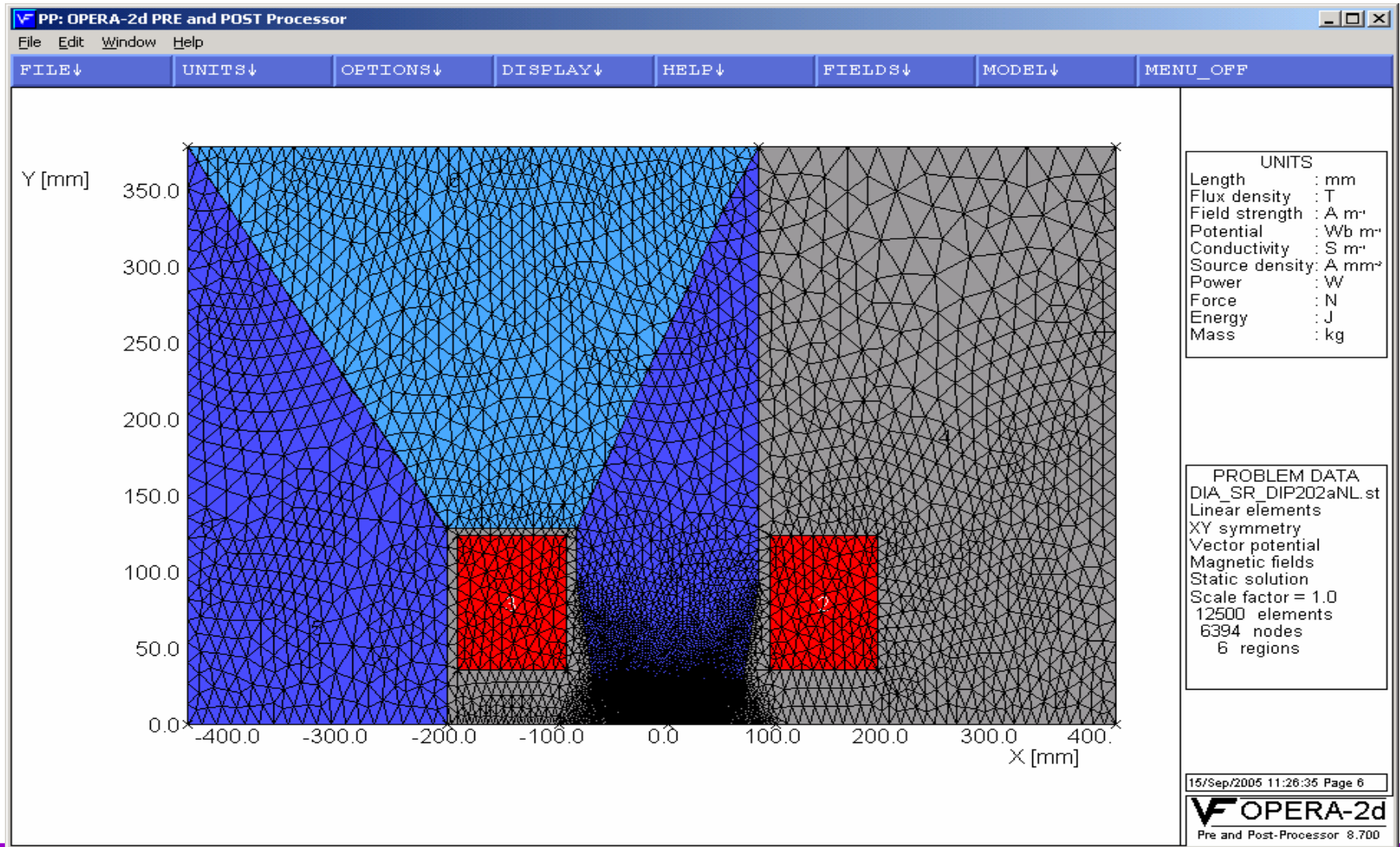
The model is set-up in 2D using a GUI (graphics user's user's interface) to define 'regions':

- 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

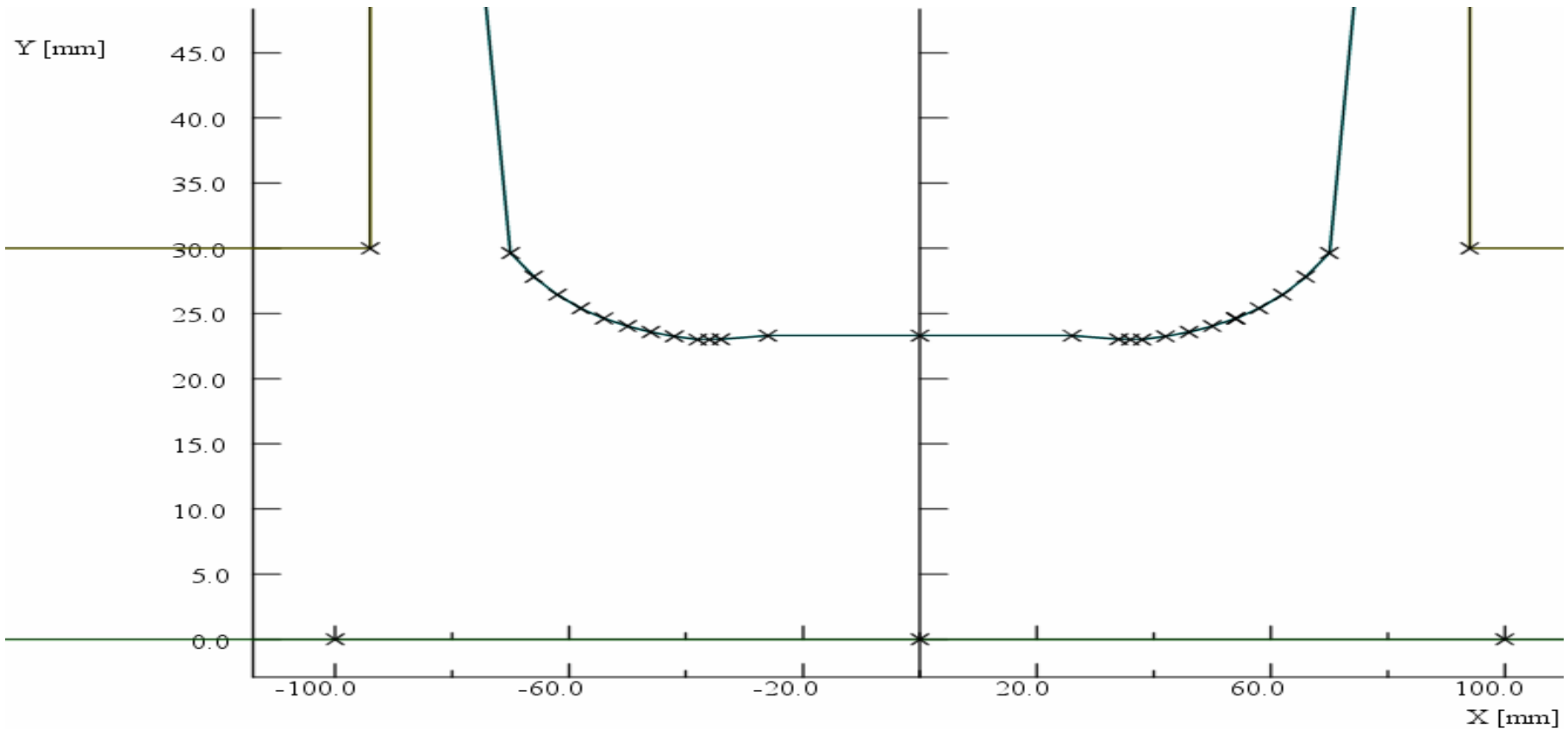


With mesh added

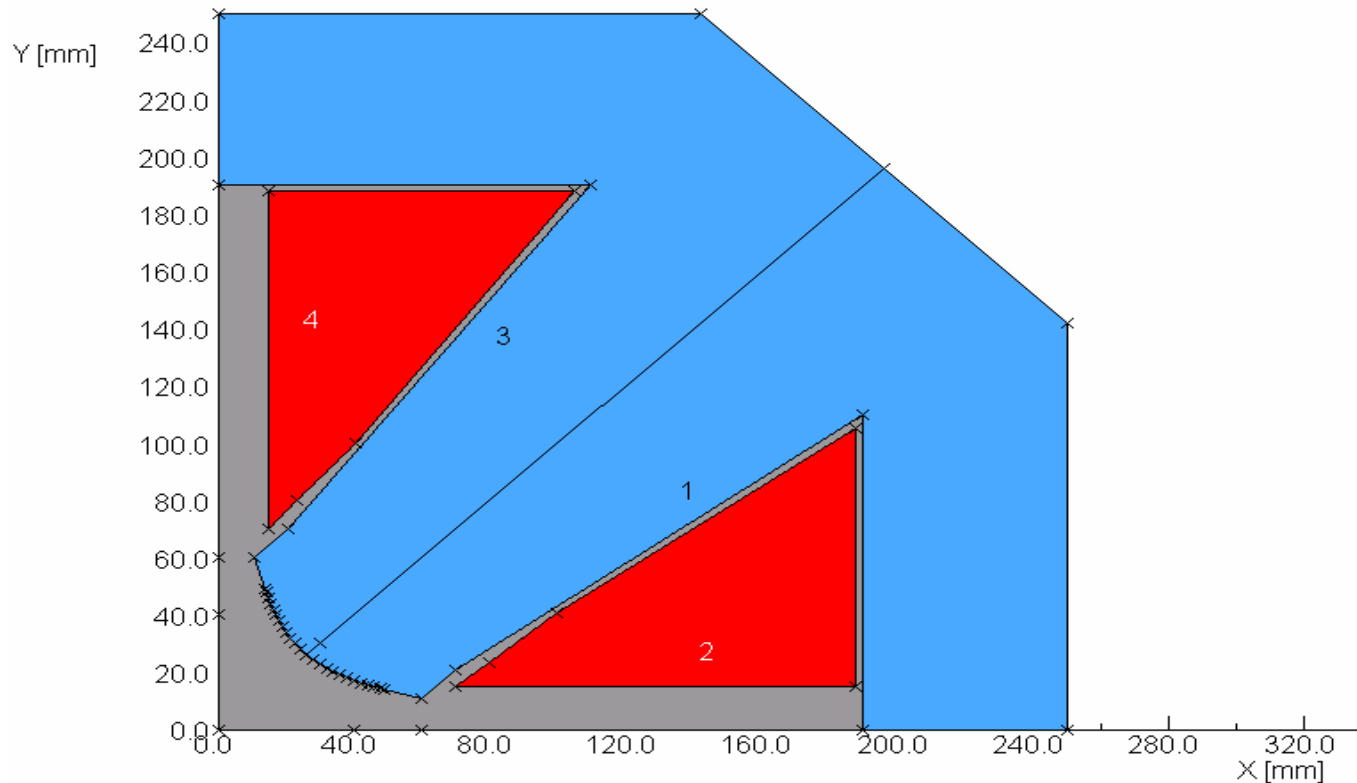


‘Close-up’ of pole region.

Pole profile, showing shim and Rogowski side 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 iterative with steel permeability set set according to B in steel calculated on previous iteration.

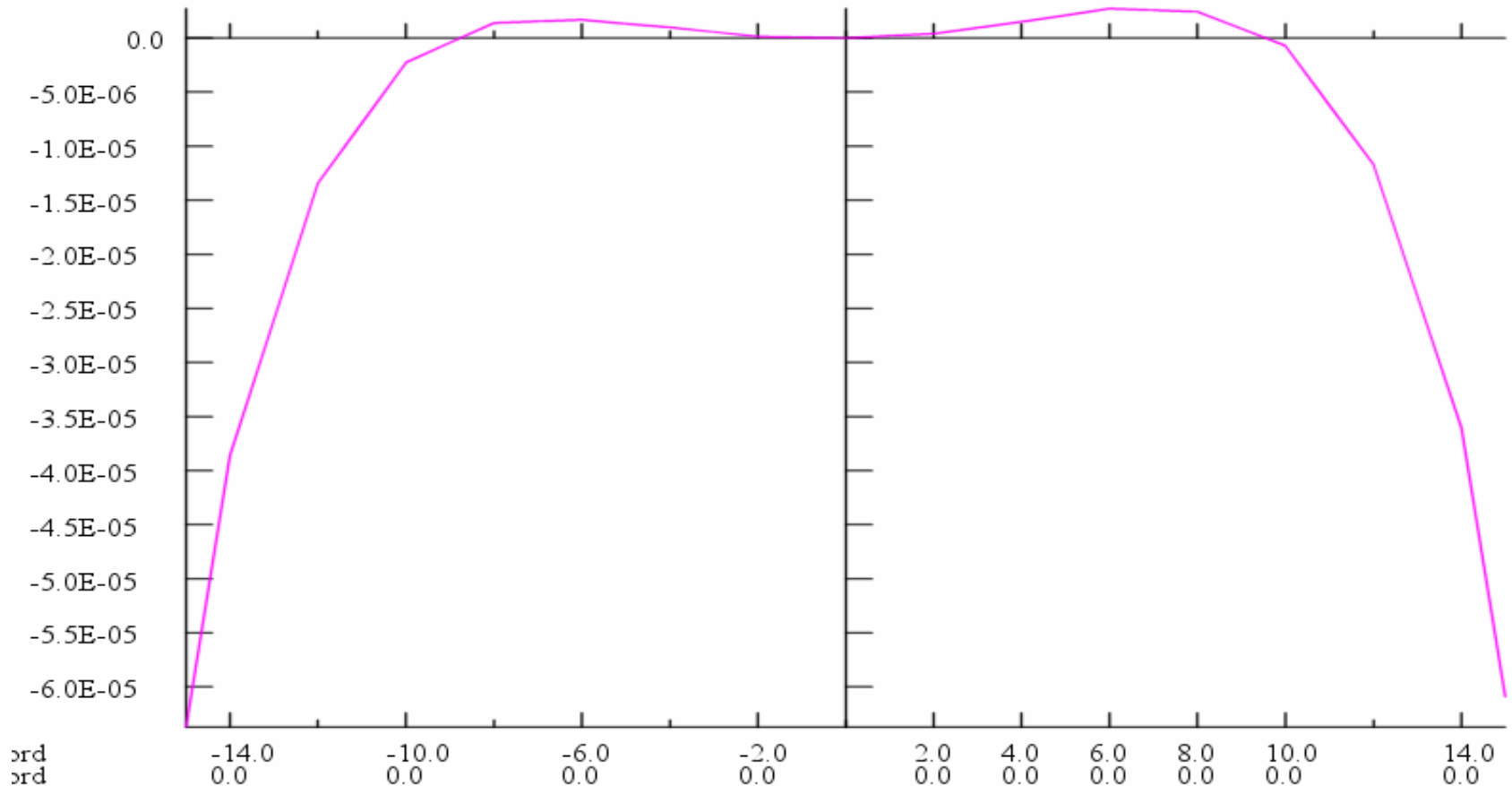
Data Display – OPERA 2D.

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).

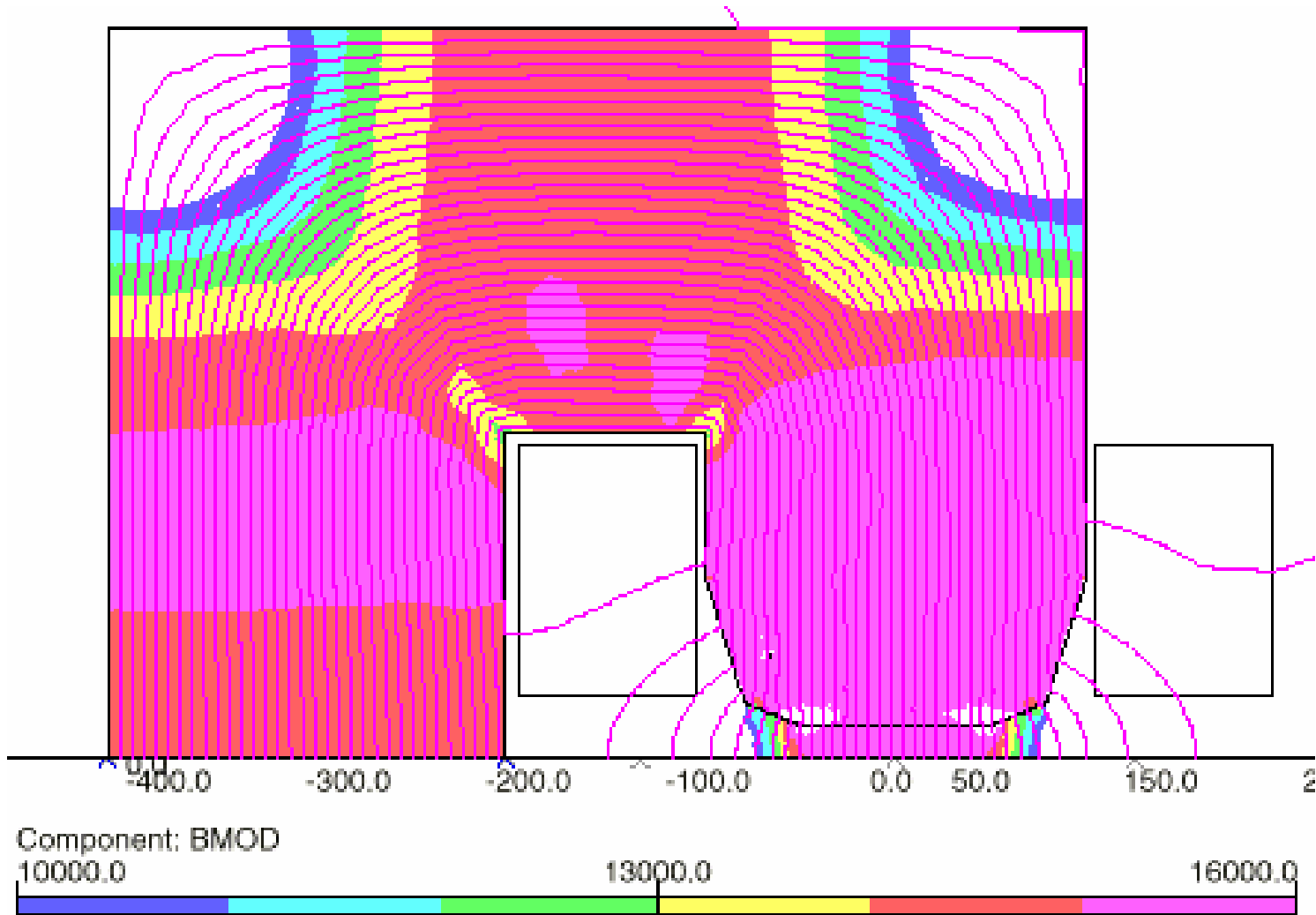
2 D Dipole field homogeneity on x axis



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

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

2 D Flux density distribution in a dipole.

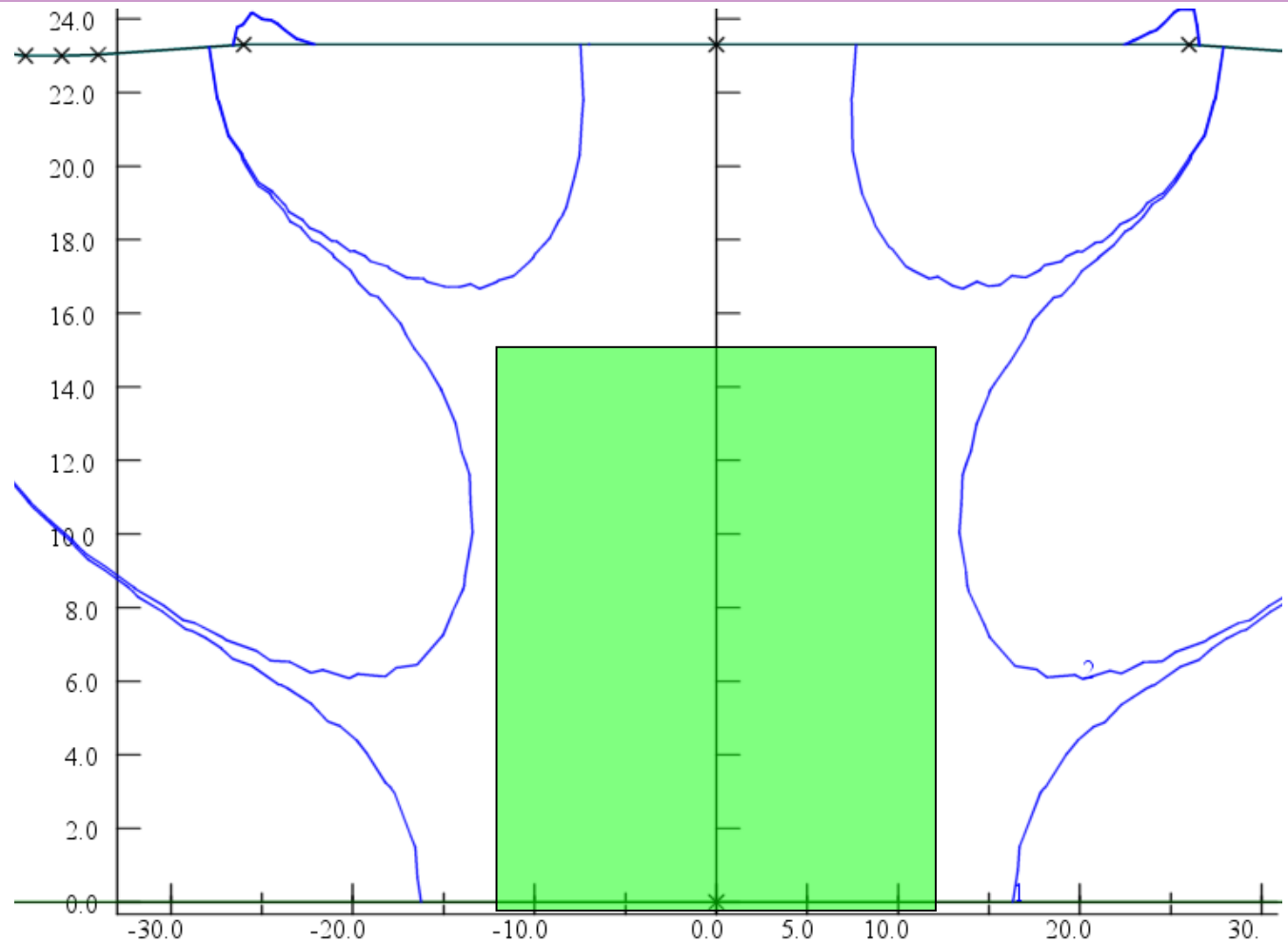


2 D Dipole field homogeneity in gap

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

contours are
 $\pm 0.01\%$

required good
field region:

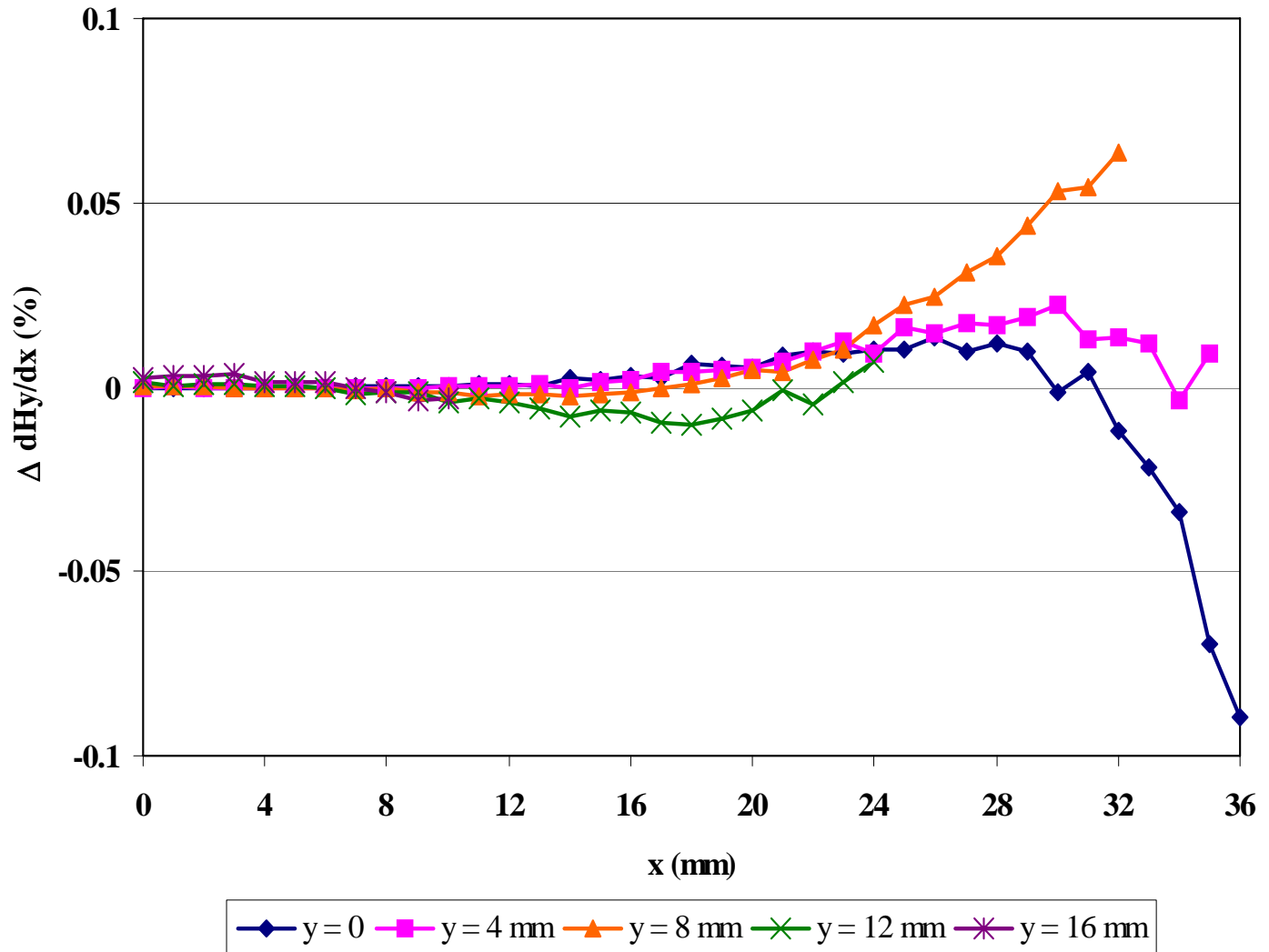


2 D Assessment of quadrupole gradient quality

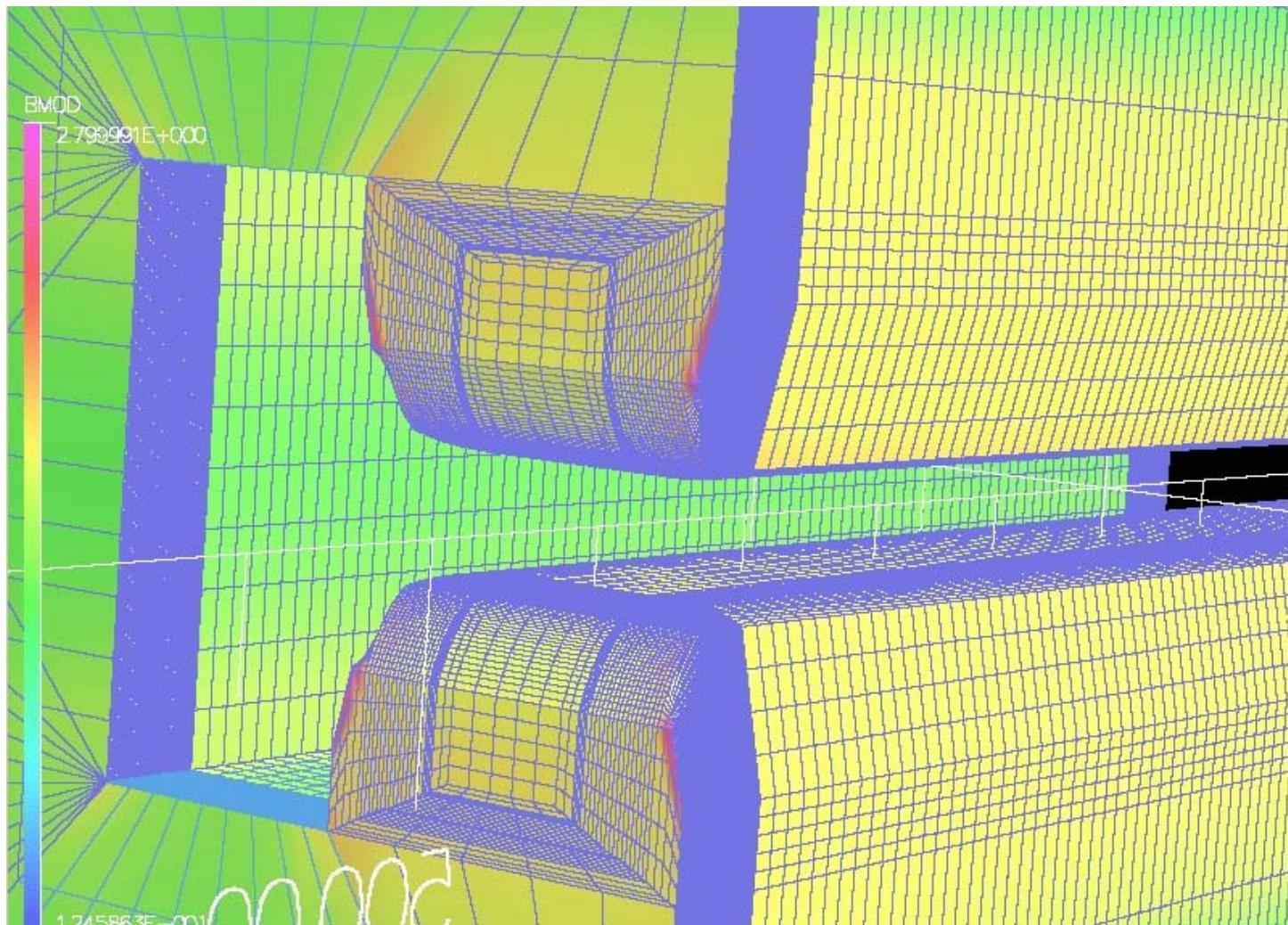
Diamond
WM
quadrupole:

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

Gradient
quality is to
be $\pm 0.1\%$ or
better to $x =$
36 mm.



OPERA 3D model of Diamond dipole.



Harmonics indicate magnet quality

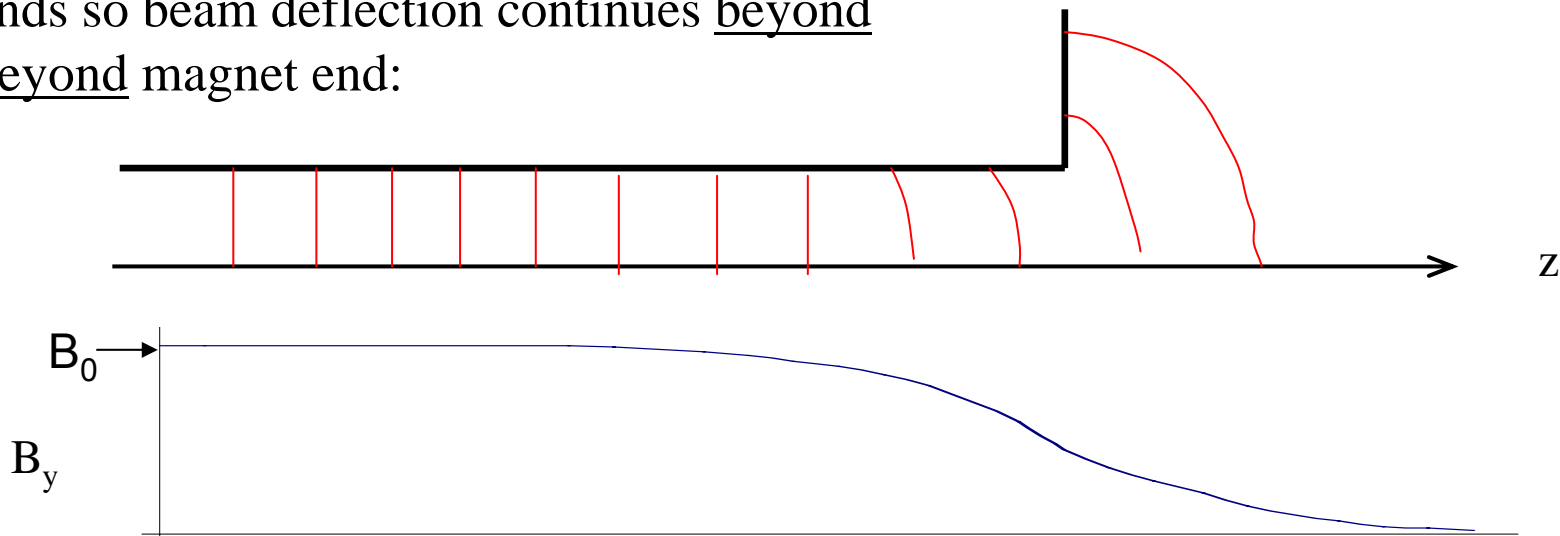
The amplitude and phase of the harmonic components components integrated through the length of a magnet magnet provide an assessment:

- 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.

And end fields matter!

The third dimension – magnet ends.

Fringe flux will be present at the magnet ends so beam deflection continues beyond beyond magnet end:



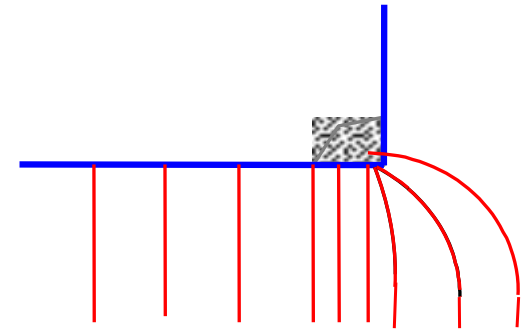
The magnet's strength is given by $\int B_y(z) dz$ along the magnet, the integration including the fringe field at each end;

The '**magnetic length**' is defined as $(1/B_0)(\int B_y(z) dz)$ over the same integration path, where B_0 is the field at the azimuthal centre.

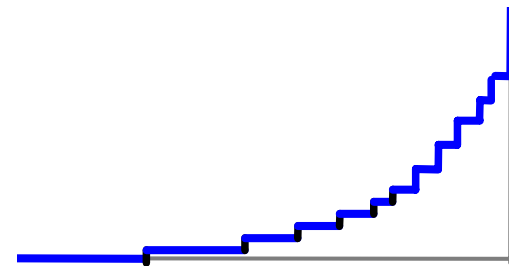
Magnet End Fields and Geometry.

It is necessary to terminate the magnet in a controlled way:

- to define the length (strength);
- to prevent saturation in a sharp corner (see diagram);
- to maintain length constant with x, y;
- to prevent flux entering normal to lamination (ac).



The end of the magnet is therefore 'chamfered' to give increasing gap (or inscribed radius) and lower fields as the end is approached



Classical end solution

The 'Rogowski' roll-off:

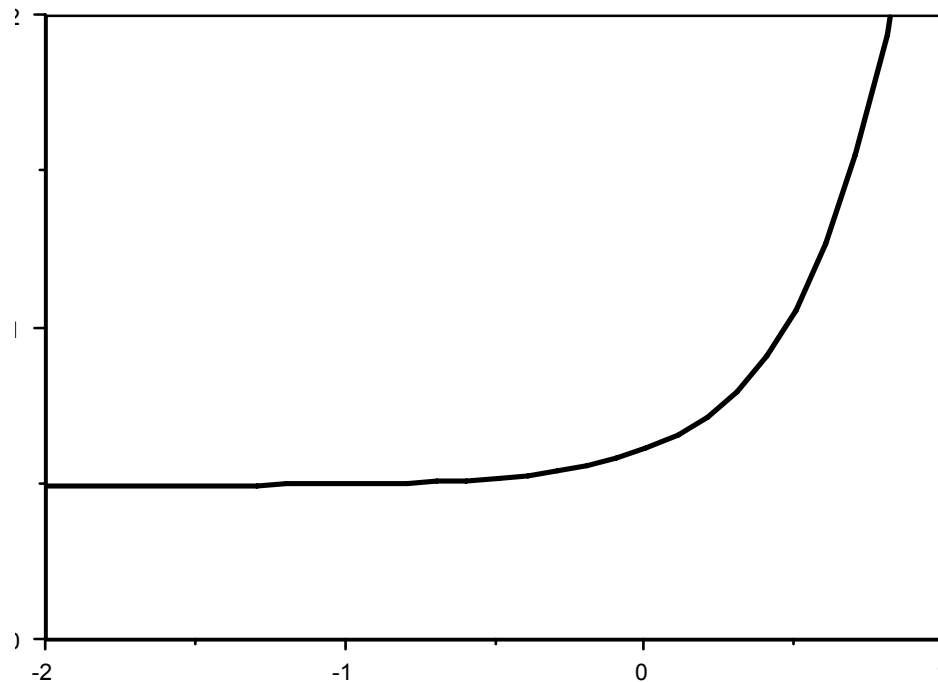
Equation:

$$y = g/2 + (g/\pi) \exp((\pi x/g) - 1);$$

$g/2$ is dipole half gap;

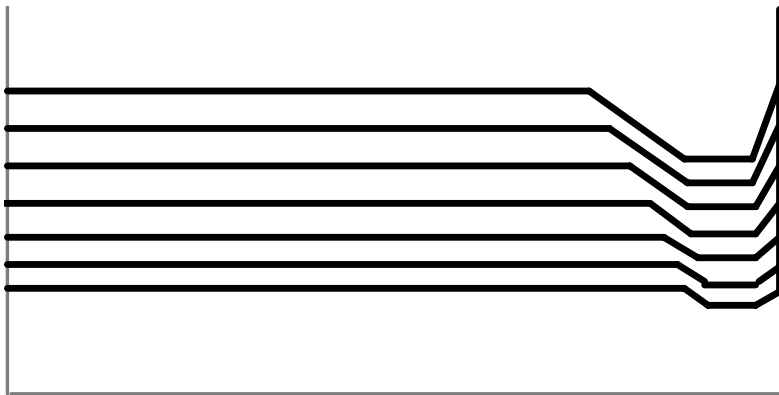
$y = 0$ is centre line of gap.

This profile provides the maximum rate of **increase** in gap with a monotonic **decrease** in flux density at the surface ie no saturation

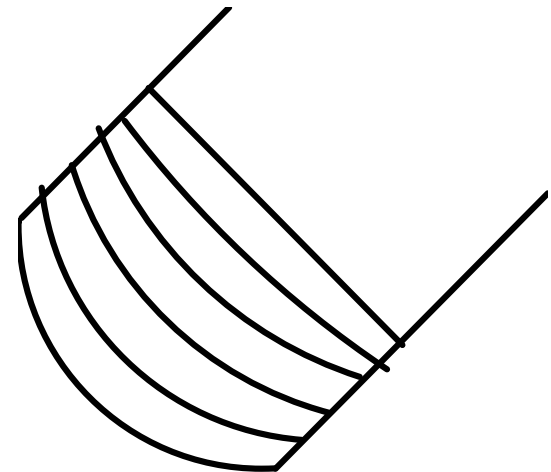


Pole profile adjustment

As the gap is increased, the size (area) of the shim is increased, to give *some* control of the field quality at the lower lower field. This is far from perfect!



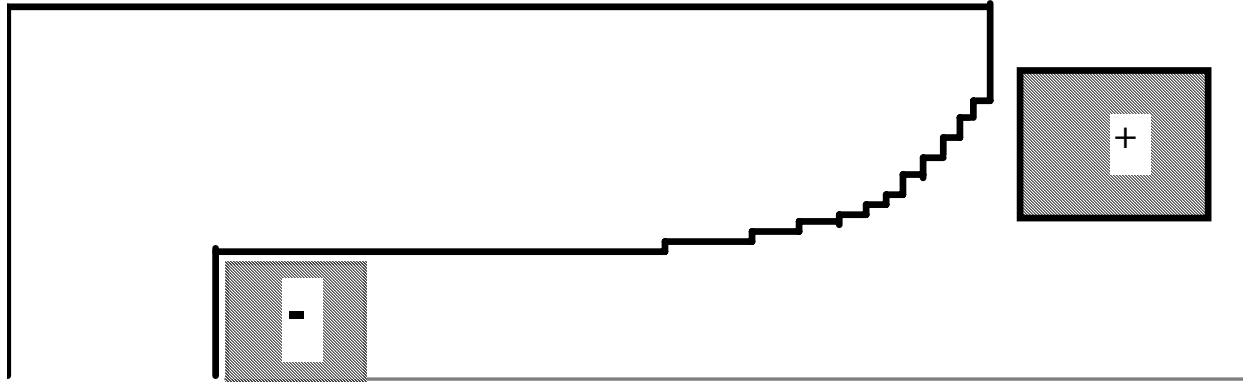
Transverse adjustment at end of dipole



Transverse adjustment at end of quadrupole

Calculation of end effects using 2D codes.

FEA model in longitudinal plane, with correct end geometry geometry (including coil), but 'idealised' return yoke:



This will establish the end distribution; a numerical integration will give the 'B' length.

Provided dBY/dz is not too large, single 'slices' in the transverse plane can be used to calculate the radial distribution as the gap increases. Again, numerical integration will give $\int B \cdot dl$ as a function of x .

This technique is less satisfactory with a quadrupole, but end effects are less critical with a quad.

End geometries - dipole

Simpler geometries can be used in some cases.

The Diamond dipoles have a Rogawski roll-off at the ends (as well as Rogawski roll-offs at each side of the pole).

See photographs to follow.

This give small negative sextupole field in the ends which will be compensated by adjustments of the strengths in adjacent adjacent sextupole magnets – this is possible because each sextupole will have int own individual power supply

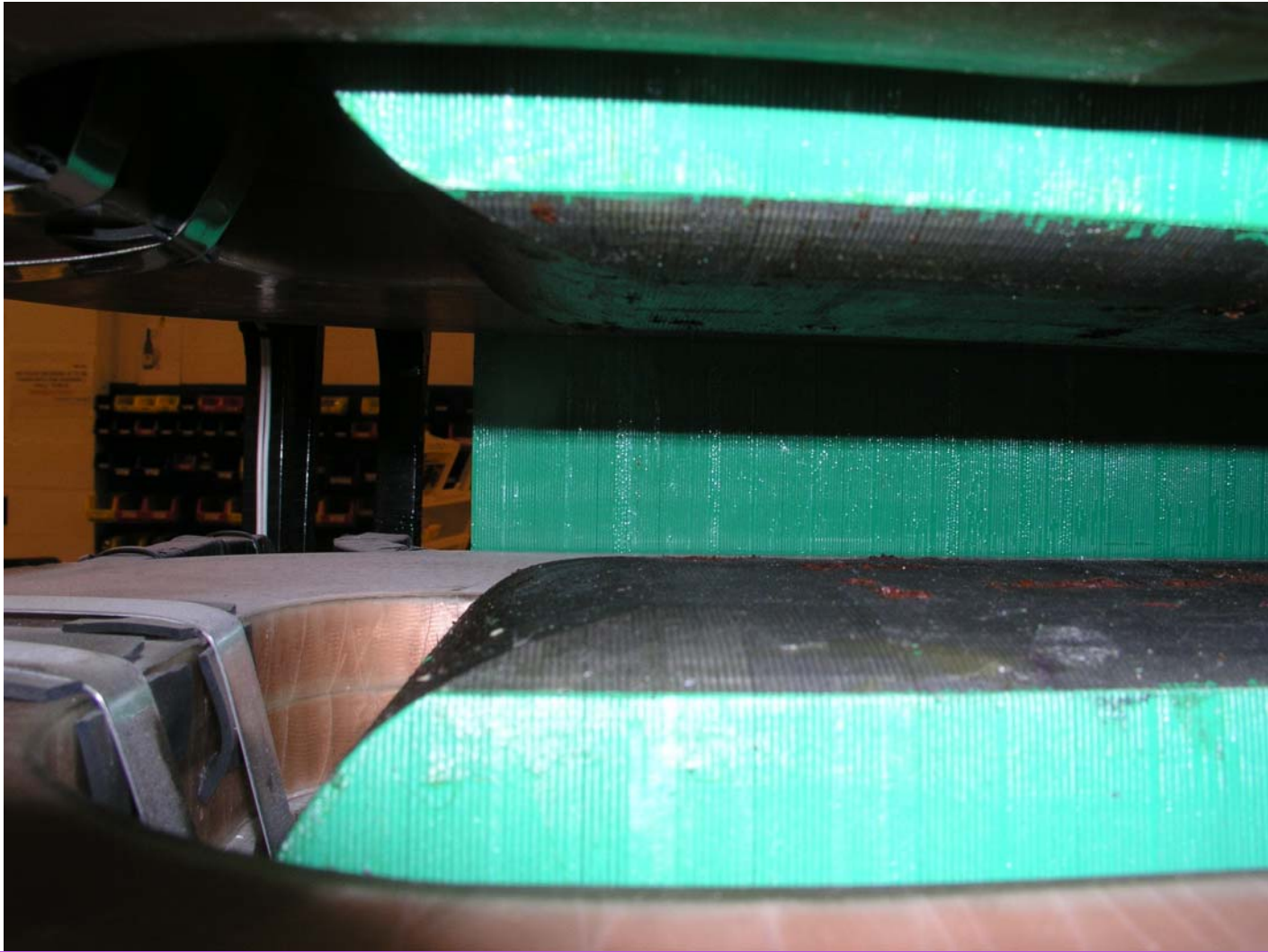
Diamond Dipole



Diamond dipole ends

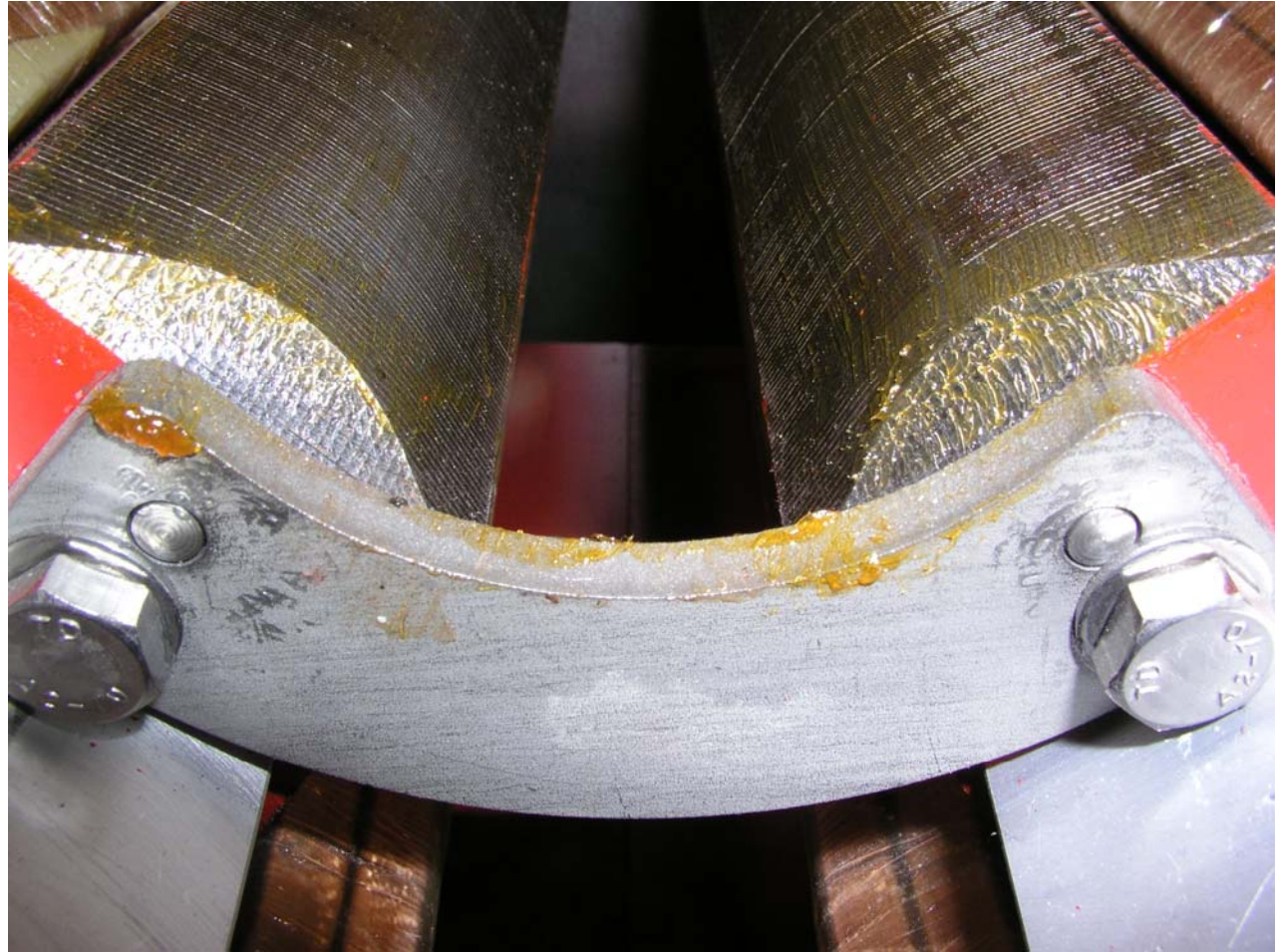


Diamond Dipole end

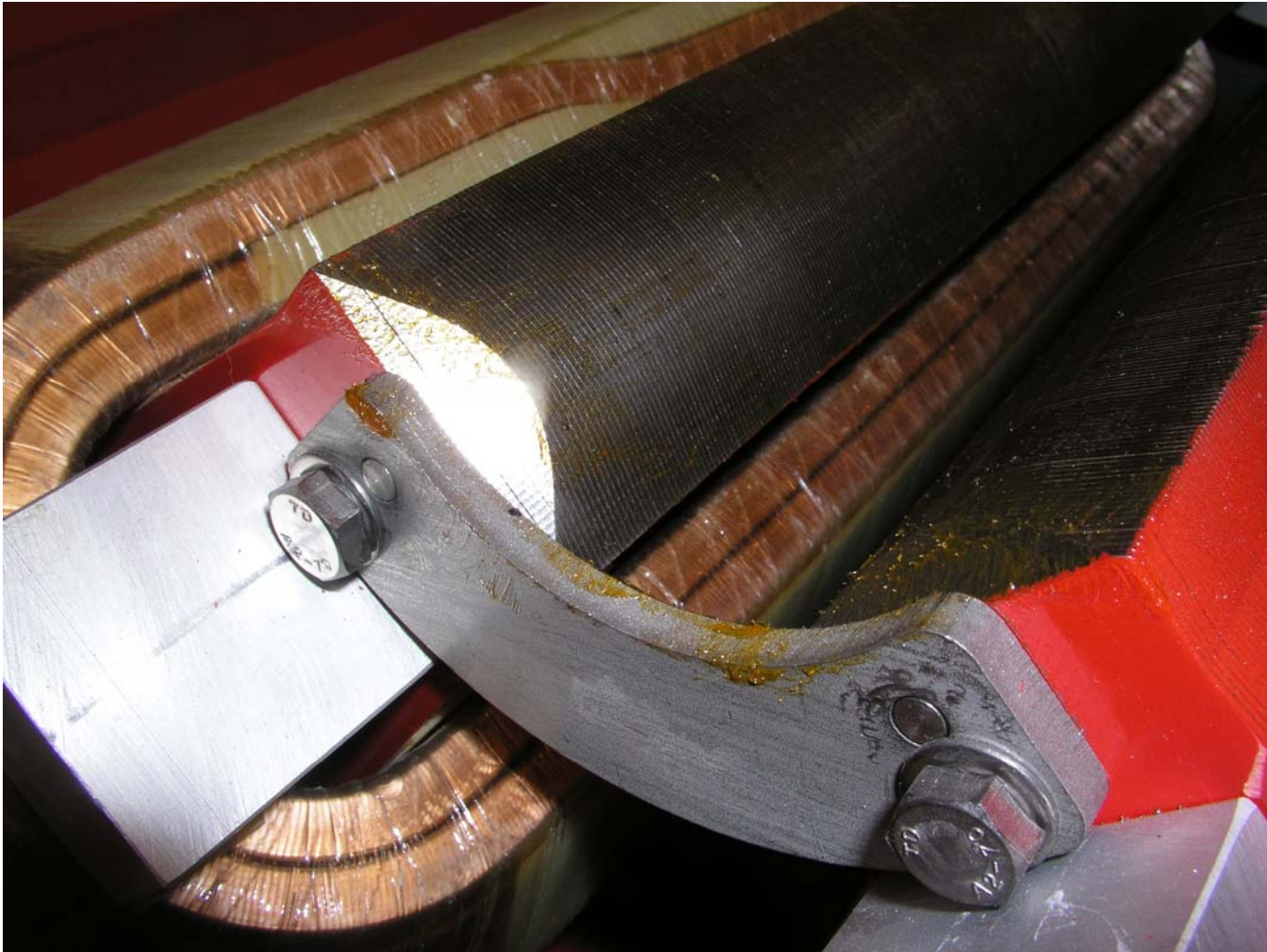


Simplified end geometries - quadrupole

Diamond quadrupoles have an angular cut at the end; depth depth and angle were adjusted using using 3D codes codes to give optimum integrated gradient.

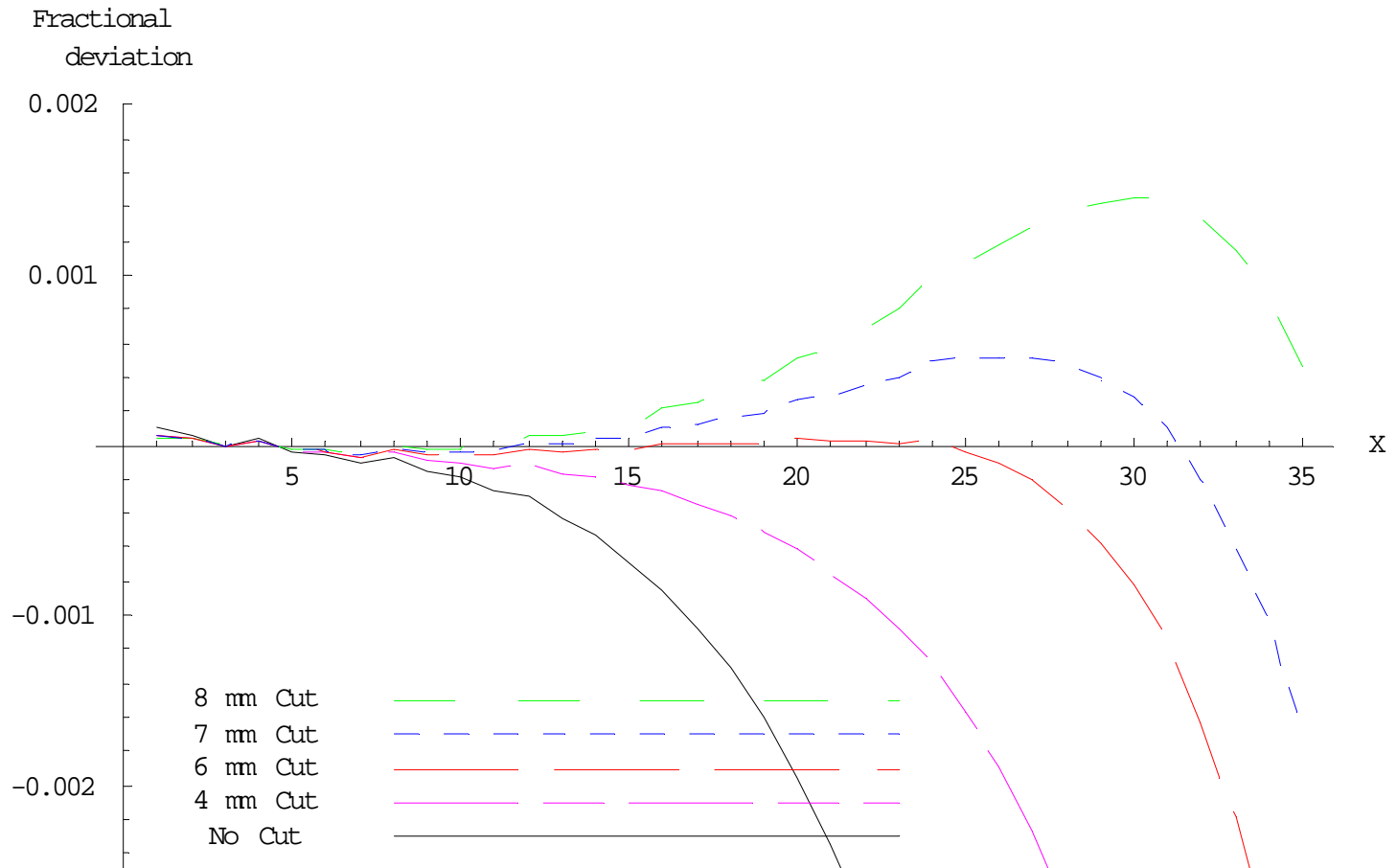


Diamond W quad end



End chamfering - Diamond 'W' quad

Tosca results - different depths 45° end chamfers on on $\Delta g/g_0$ integrated through magnet and end fringe field (0.4 m long WM quad). quad).



Thanks to Chris Bailey (DLS) who performed this working using OPERA 3D.

Sextupole ends

It is not usually necessary to chamfer sextupole ends (in a d.c. magnet).
Diamond sextupole end:

