# Warm (conventional) Magnets for Accelerators

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# Content.

- **The presentation deals with d.c. magnets only;**
- **It includes <u>some</u> material presented at the ‘introductory’ level CAS meetings;**
- **Additional material includes:**
    - **the significance of vector potential in magnet design;**
    - **using magnet measurements to judge magnetic quality of a design and subsequent manufacture.**

# 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 $(r,\theta)$:

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

# 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 $(r,\theta)$.

Distributions not given by above are not physically realisable.

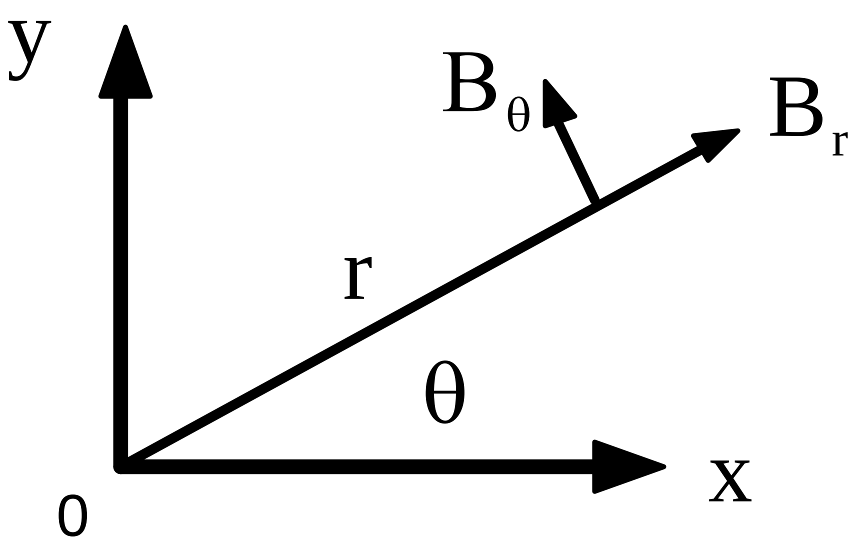
Coefficients $J_n$, $K_n$ are determined by geometry (iron boundaries or remote current sources).

# 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:**

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

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

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

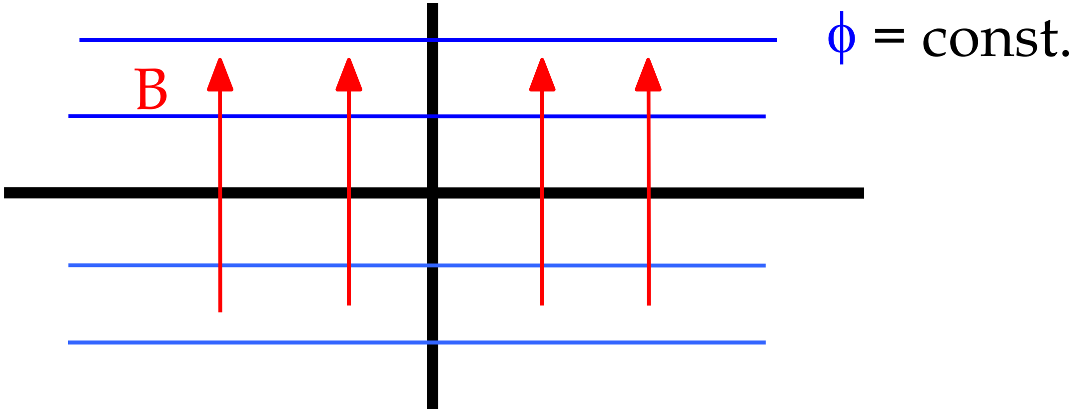
**Cartesian:**

$B_x = J_1$

$B_y = K_1$

$\phi = J_1 x + K_1 y$

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:**

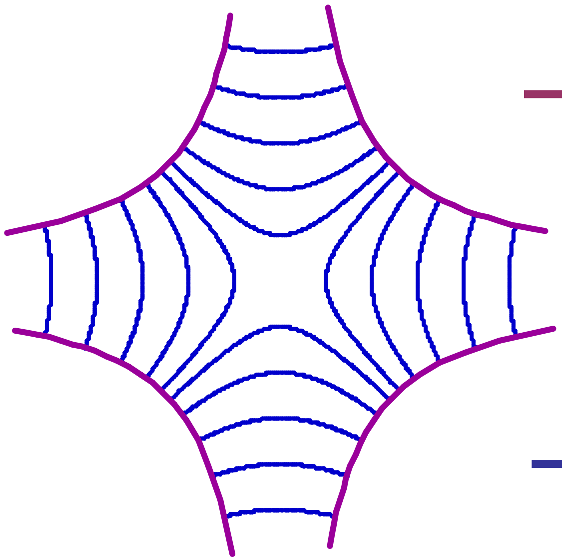
$Bx = 2 (J_2 x + K_2 y)$

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

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

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

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



Line of constant scalar potential

Lines of flux density density

# Sextupole field: n = 3

**Cylindrical;**

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

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

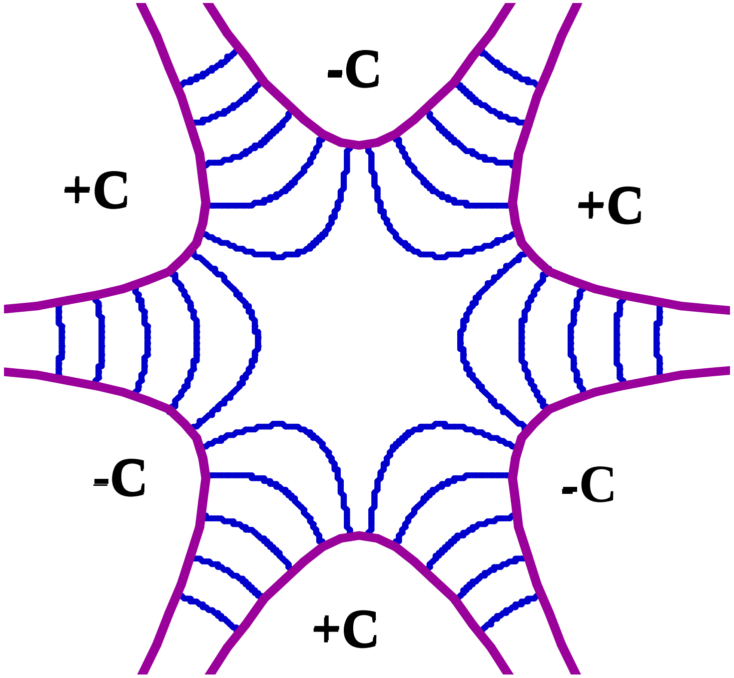
$\phi\ =\ J_3\, r^3 \cos 3\theta + K_3\, r^3 \sin 3\theta;$

**Cartesian:**

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

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

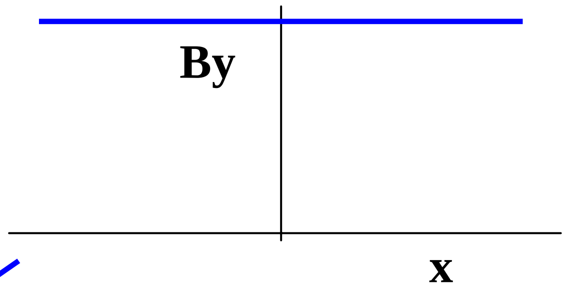
$\phi = J_3\,(x^3 - 3y^2x) + K_3(3yx^2 - y^3)$



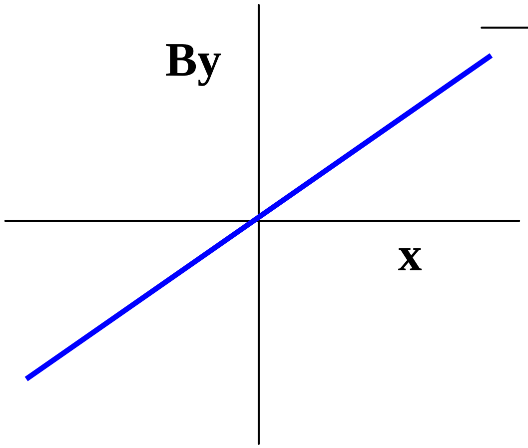

$J_3 = 0$ giving 'normal' or ‘right’ sextupole field.

# Summary; variation of $B_y$ on x axis

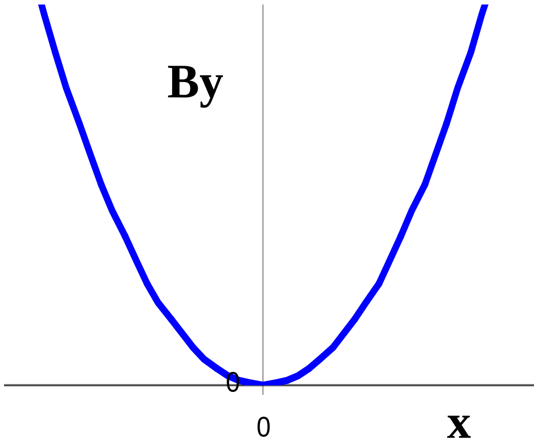
Dipole; constant field:




Quad; linear variation:




Sext.: quadratic variation:



# Vector potential in 2D.

We have: $\underline{\mathbf{B}} = \text{curl } \underline{\mathbf{A}}$ ($\underline{\mathbf{A}}$ is vector potential);

and $\text{div } \underline{\mathbf{A}} = 0$

Expanding: $\underline{\mathbf{B}} = \text{curl } \underline{\mathbf{A}} =$

$(\partial A_z/ \partial y - \partial A_y/ \partial z)\,\mathbf{i} + (\partial A_x/ \partial z - \partial A_z/ \partial x)\,\mathbf{j} + (\partial A_y/ \partial x - \partial A_x/ \partial y)\,\mathbf{k};$

where **i, j, k**, and unit vectors in x, y, z.

In 2 dimensions $B_z = 0$; $\partial / \partial z = 0$;

So $A_x = A_y = 0$;

and $\underline{\mathbf{B}} = (\partial A_z/ \partial y)\,\mathbf{i} - (\partial A_z/ \partial x)\,\mathbf{j}$

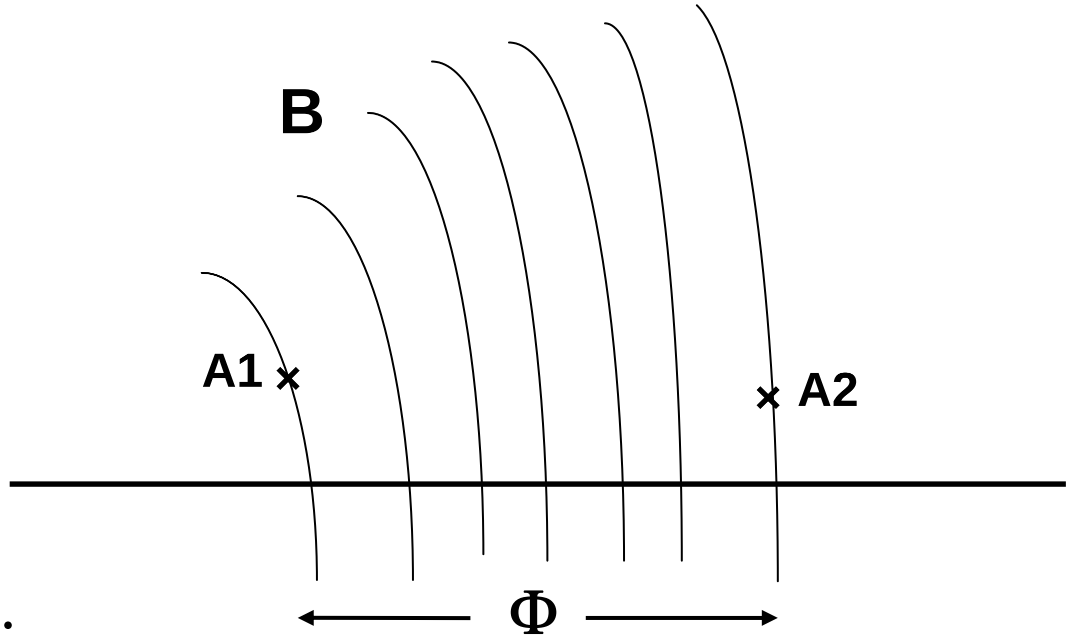
**$\underline{\mathbf{A}}$ is in the z direction, normal to the 2 D problem.**

Note: $\text{div } \underline{\mathbf{B}} = \partial^2 A_z/ \partial x \partial y - \partial^2 A_z/ \partial x \partial y = 0$;

# Total flux between two points ∝ ΔA

In a two dimensional problem the magnetic flux  between two between two points is proportional to the difference between between the vector potentials at those points.

$\Phi \propto (A2 - A1)$

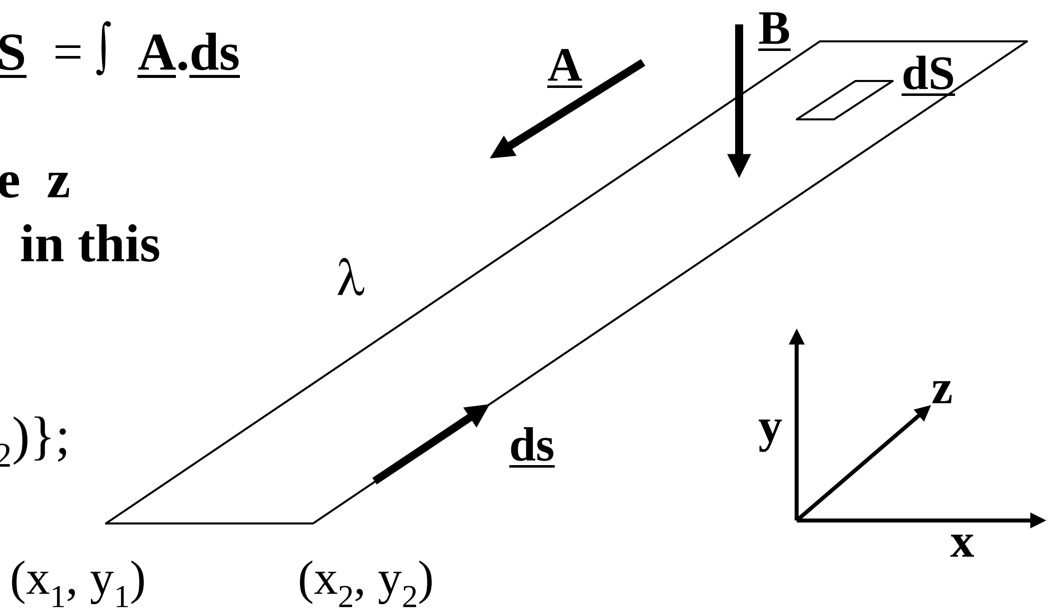



Proof on next slide.

# Proof.

Consider a rectangular closed path, length $\lambda$ in z direction at direction at $(x_1,y_1)$ and $(x_2,y_2)$; apply Stokes' theorem:

$\Phi = \int\int \underline{\mathbf{B}}.\underline{\mathbf{dS}} = \int\int (\text{curl } \underline{\mathbf{A}}).\underline{\mathbf{dS}} = \int \underline{\mathbf{A}}.\underline{\mathbf{ds}}$




**But A is exclusively in the z direction, and is constant in this direction.**

**So:**

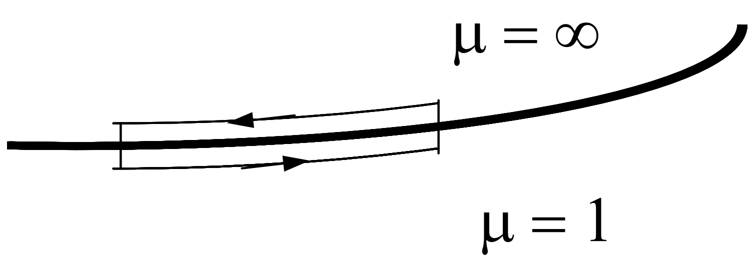
$\int \mathbf{A}.ds = l \{ A(x_1,y_1) - A(x_2,y_2)\};$

$$\Phi = \lambda \{ A(x_1,y_1) -$$

# Introducing Iron Yokes

What is the ideal pole shape?

•Flux is normal to a ferromagnetic surface with infinite μ:




curl H = 0

therefore ∫ 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:**

$$y = \pm g/2;$$

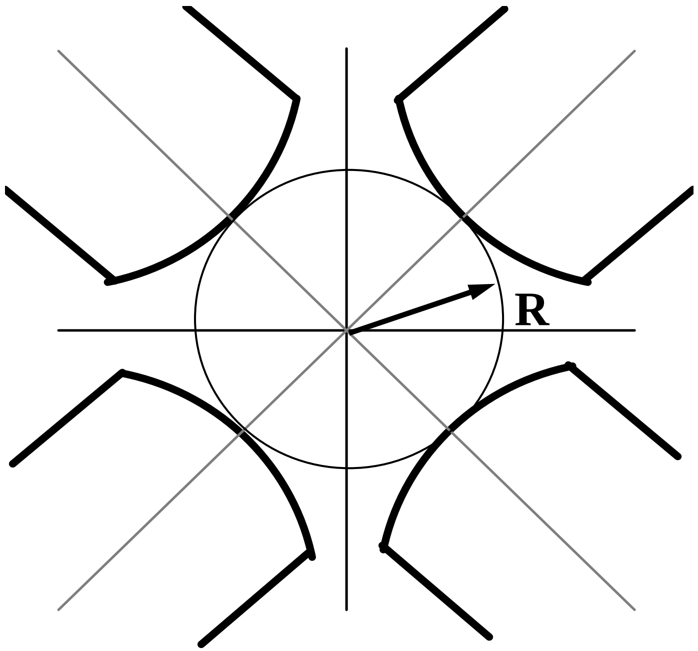
(g is interpole gap).

**Quadrupole:**

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

**Sextupole:**

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



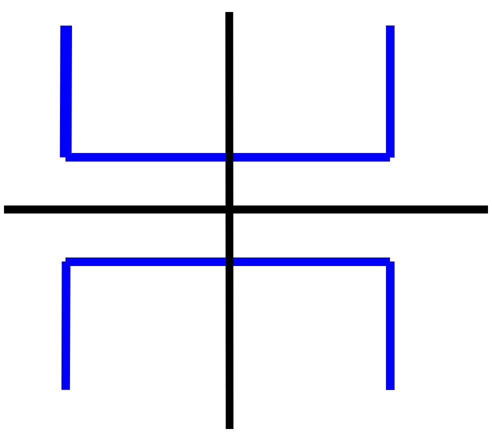
# The practical Pole

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

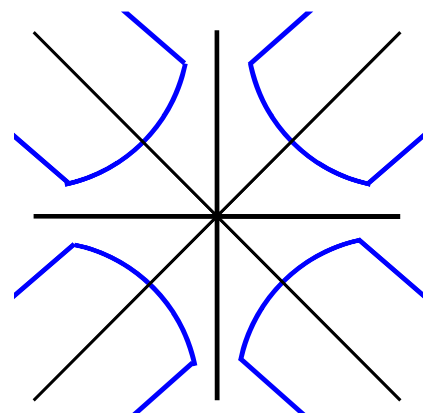
these appear as higher harmonics which degrade the field
field distribution.

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

Dipole:



Quadrupole:



# Possible symmetries:

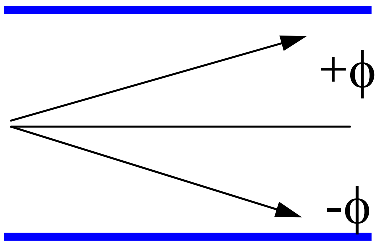
Lines of symmetry:

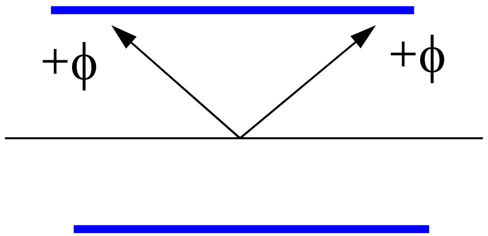
| | Dipole: | Quad |
|---|---|---|
| Pole orientation determines whether pole is normal or skew. | $y = 0$; | $x = 0$; $y = 0$ |
| Additional symmetry imposed by pole edges. | $x = 0$; | $y = \pm x$ |

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 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 pole errors can be present.

# Sextupole symmetries

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

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

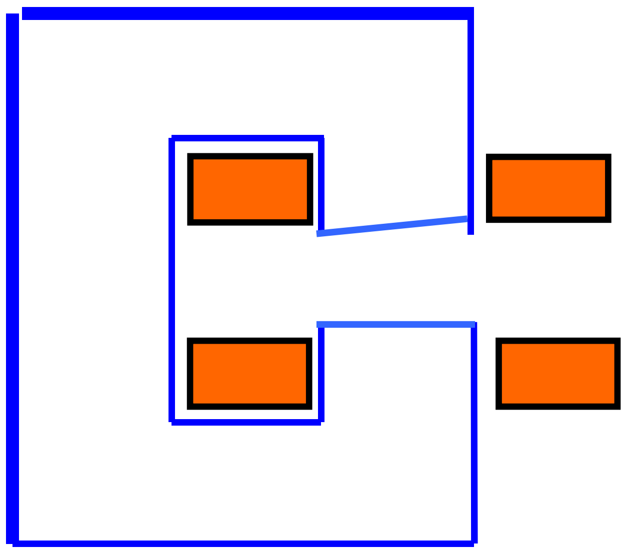
# Summary - 'Allowed' Harmonics

Summary of 'allowed harmonics' in fully symmetric magnets:
magnets:

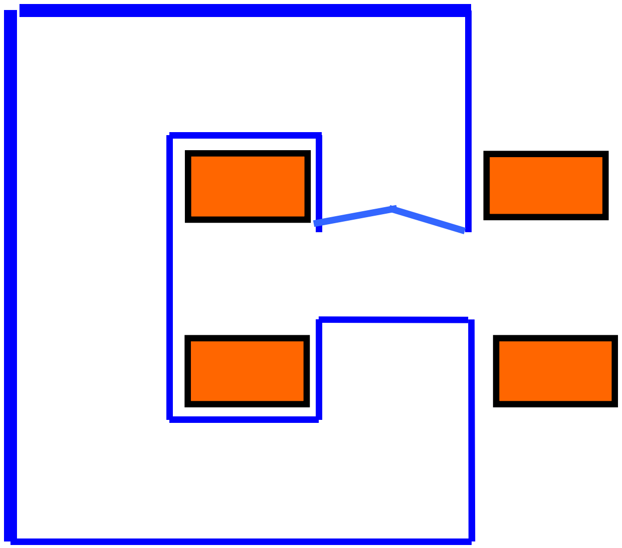
| Fundamental geometry | 'Allowed' harmonics |
|---|---|
| Dipole, n = 1 | n = 3, 5, 7, ...... ( 6 pole, 10 pole, etc.) |
| Quadrupole, n = 2 | n = 6, 10, 14, .... (12 pole, 20 pole, etc.) |
| Sextupole, n = 3 | n = 9, 15, 21, ... (18 pole, 30 pole, etc.) |
| Octupole, n = 4 | n = 12, 20, 28, .... (24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

# ‘Forbidden’ Harmonics in Dipoles

Asymmetries due to small manufacturing errors in dipoles:



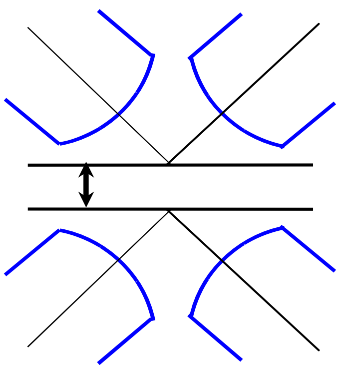
n = 2, 4, 6 etc.



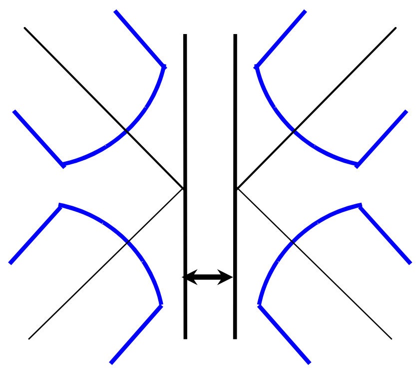
n = 3, 6, 9, etc.

# ‘Forbidden’ Harmonics in Quadrupoles

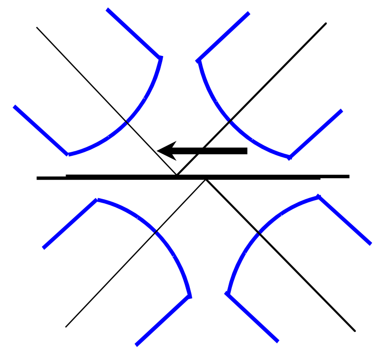
Asymmetries due to small manufacturing errors in quadrupoles:



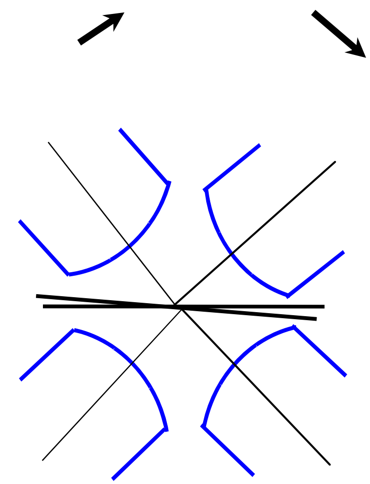
n = 4 - ve



n = 4 + ve



n = 3;



n = 2 (skew)

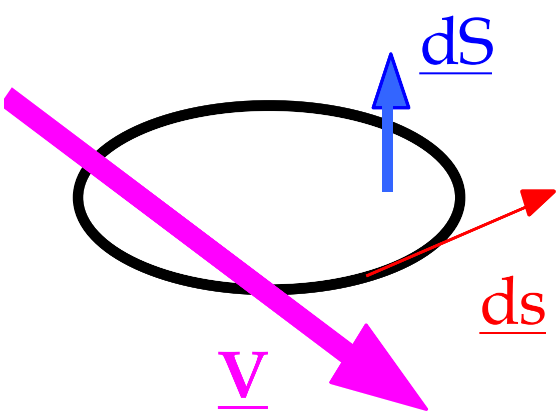
n = 3;

# Introduction of currents

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

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

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



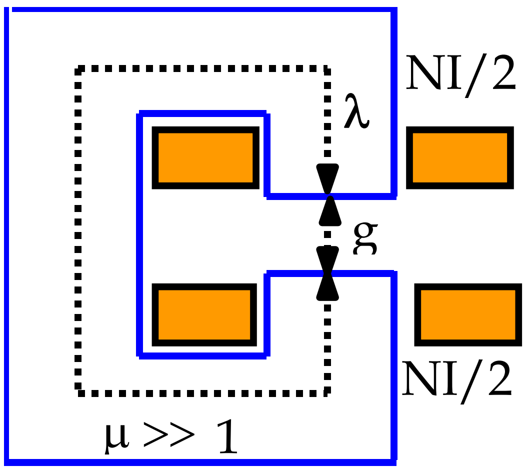

Apply this to: $\mathbf{curl\ H} = \underline{\mathbf{j}}$;

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

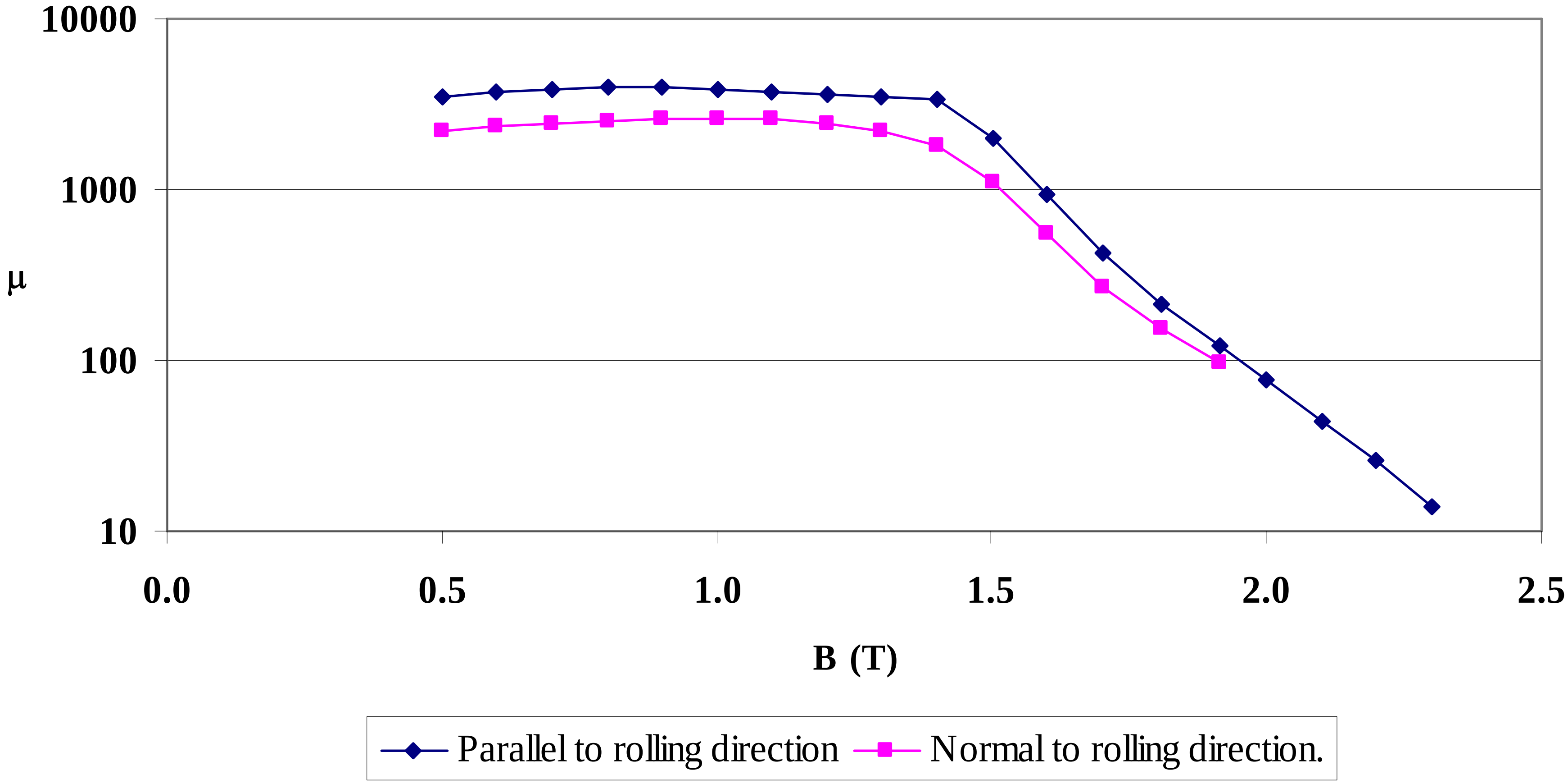
$$B_{air} = \mu_0 NI / (g + \lambda/\mu);$$

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

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

$$NI = B g / \mu_0$$

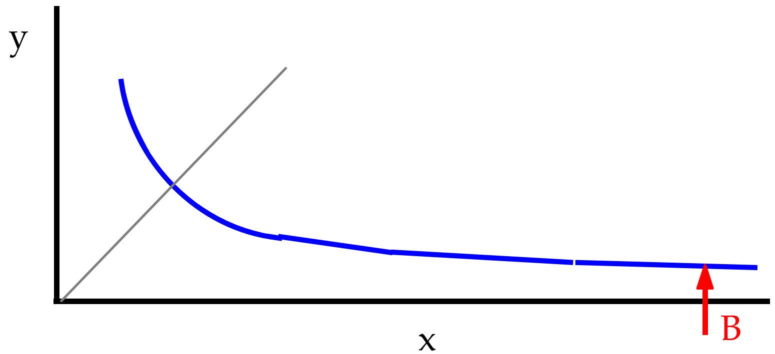
# Relative permeability of low silicon steel



# Excitation current in quad & sextupole

For quadrupoles and sextupoles, the required excitation can excitation can be calculated by considering fields and gap 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

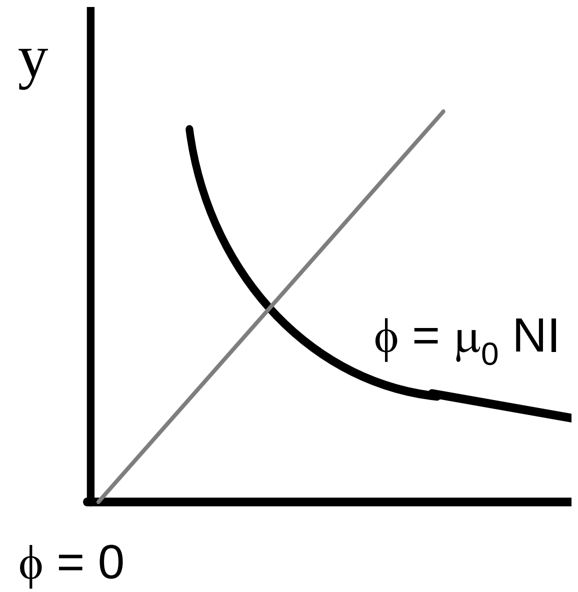
In air (remote currents! ), $\mathbf{B} = \mu_0 \mathbf{H}$

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

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

$\phi_1$, $\phi_2$ are the scalar potentials at two points in air.

Define $\phi = 0$ at magnet centre; then potential at the pole is: $\mu_o NI$




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;

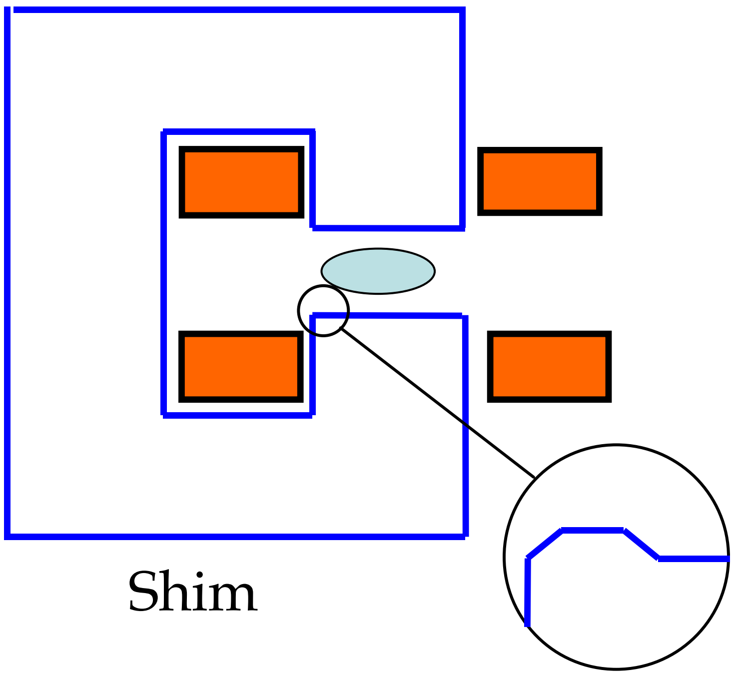
Classic design;

Disadvantages:

Pole shims needed;

Asymmetric (small);

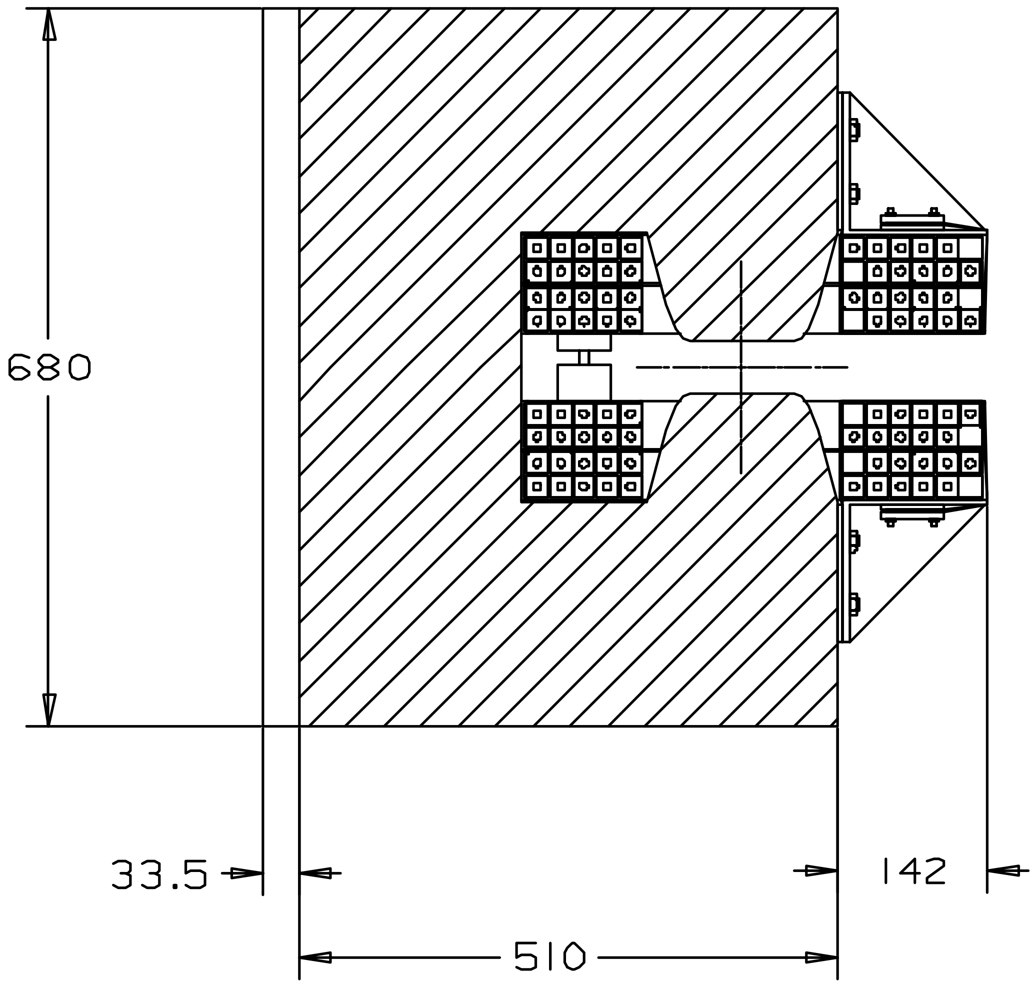
Less rigid;



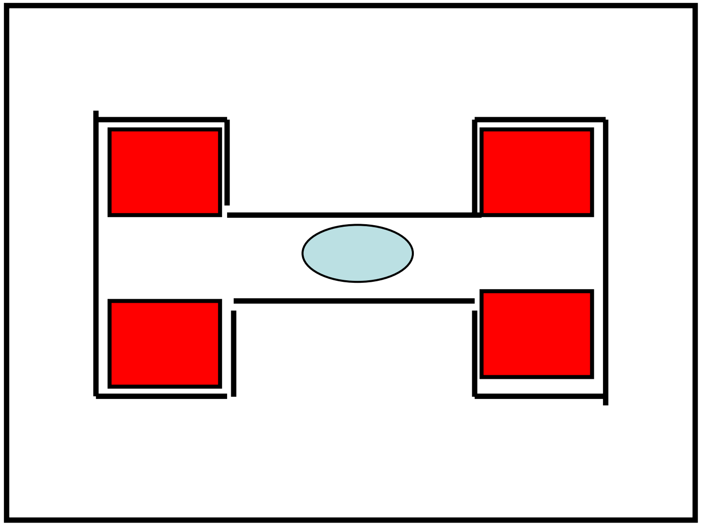

The ‘shim’ is a small, additional piece of ferro-magnetic material added on each side of the two poles – it compensates for the finite cut-off of the pole, and is optimised to reduce the 6, 10, 14...... pole error harmonics.

# 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

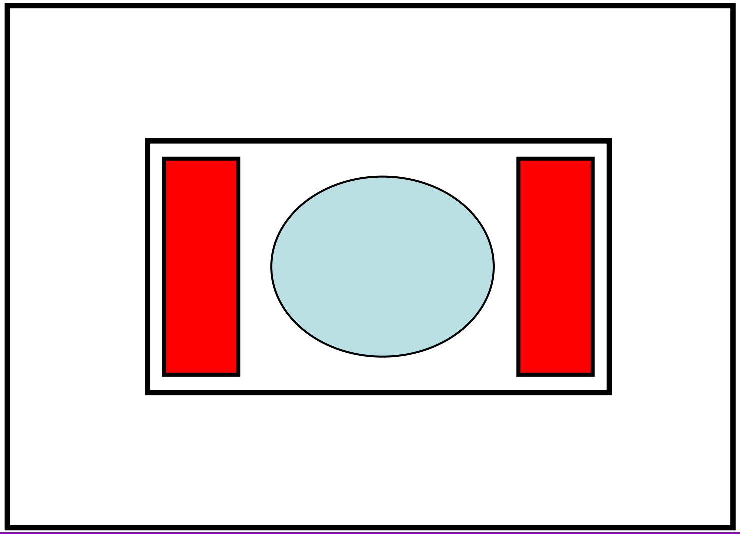
'H core':

Advantages:

- Symmetric;
- More rigid;

Disadvantages:

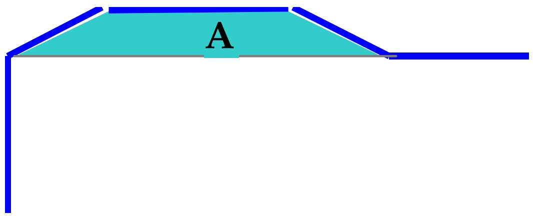
- Still needs shims;
- Access problems.



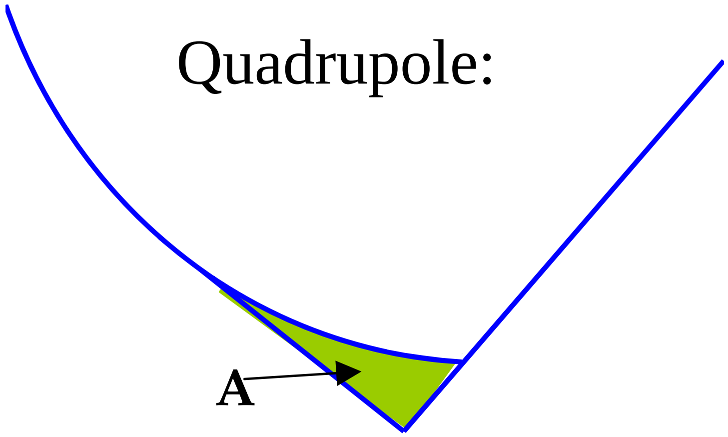
# Typical pole designs

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

Computer codes are now used to create a 'model' and and then predict the resulting field distribution;

eg the Vector 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 distribution of a defined geometry;
- adjust until required distribution is achieved.

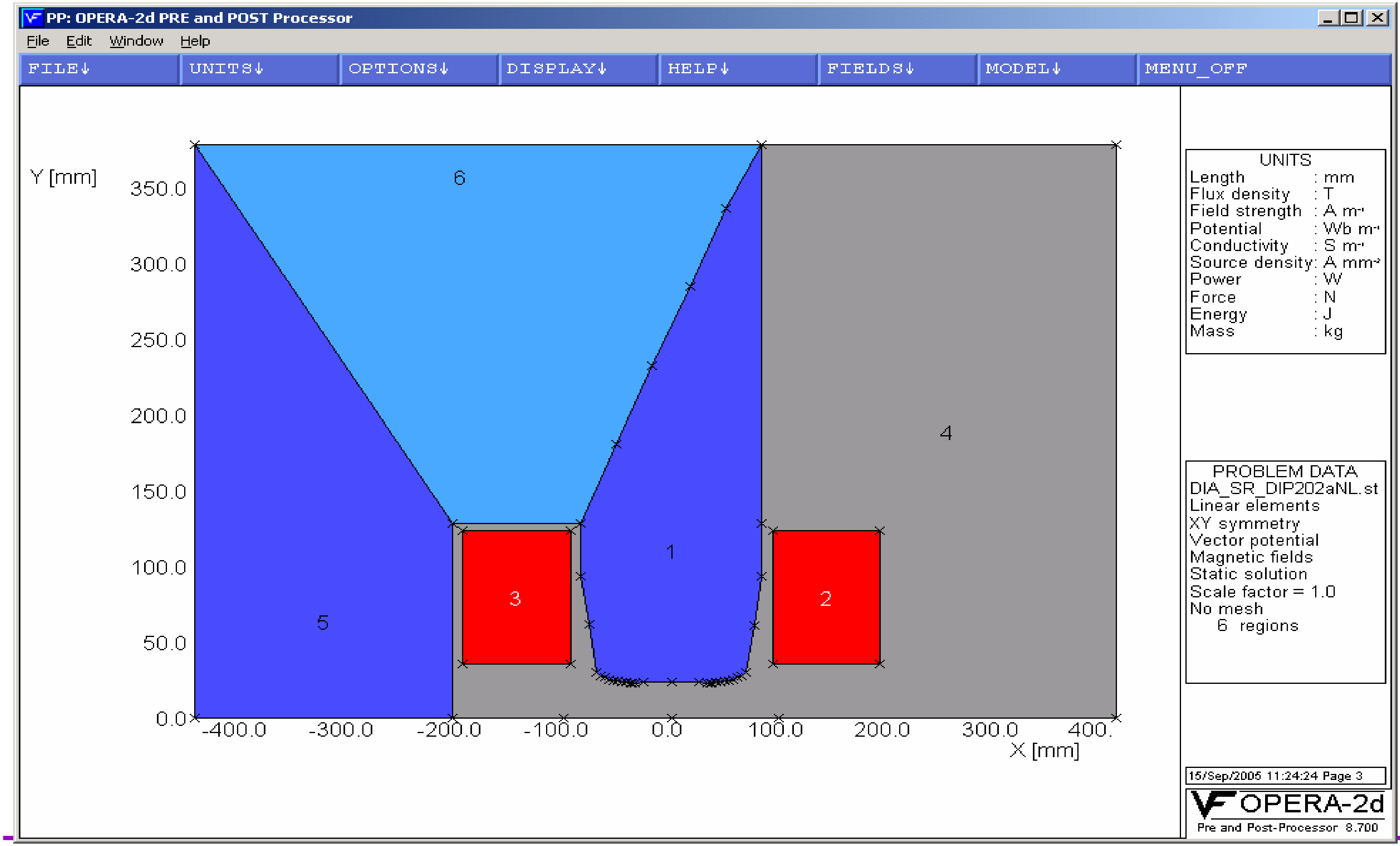
# Design Procedures – OPERA 2D.

## Pre-processor:

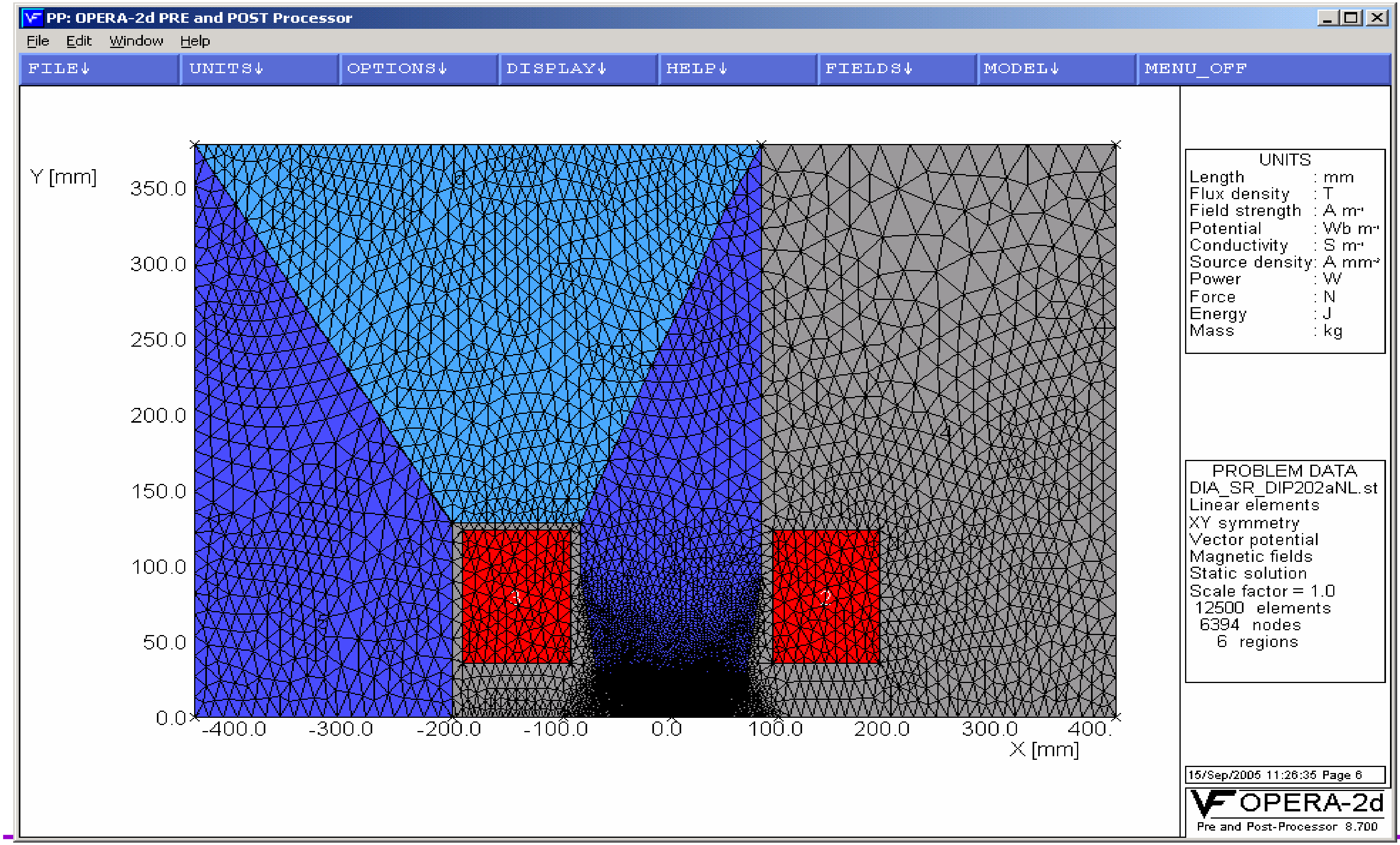
The model is set-up in 2D using a GUI (graphics user's user's interface) to define 'regions':

- 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

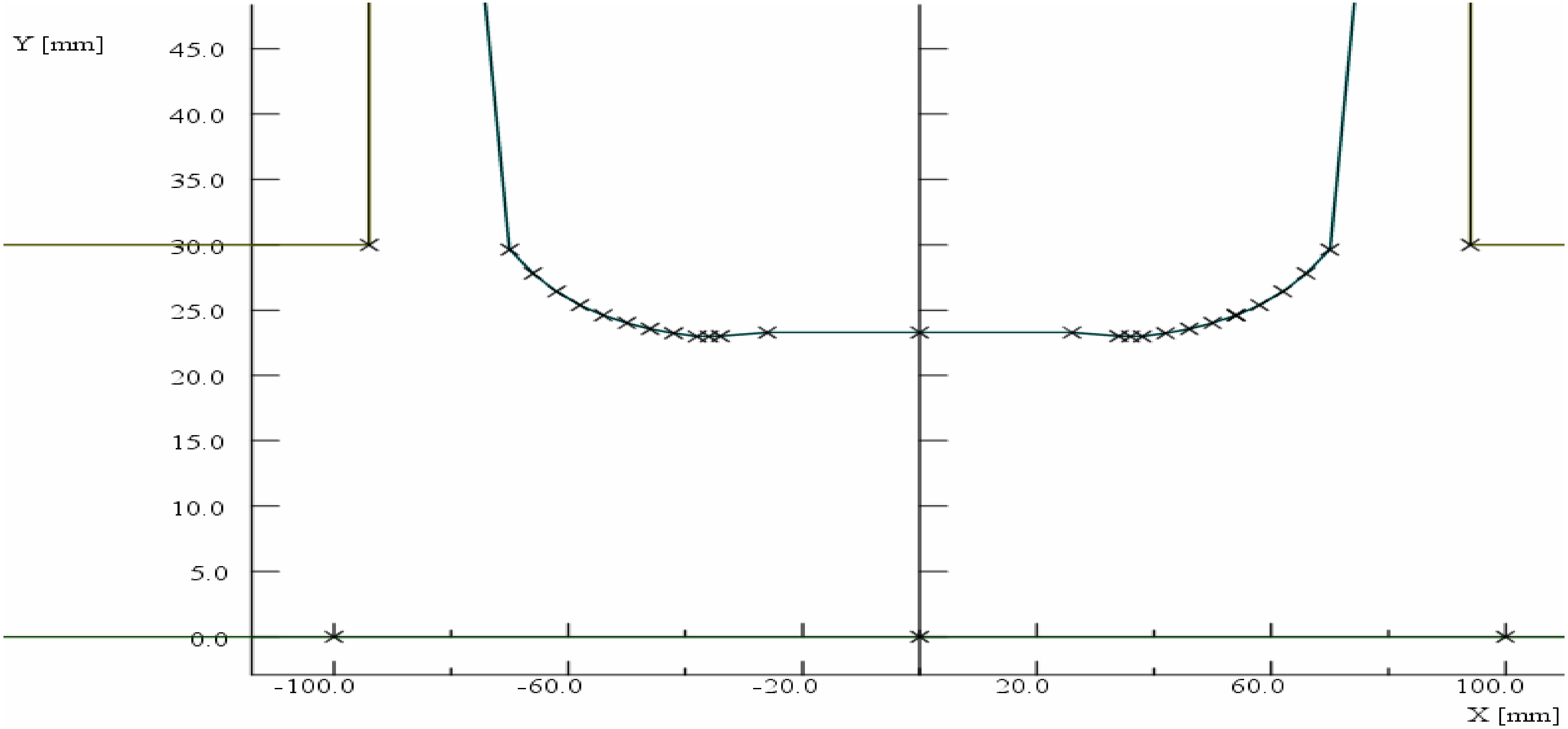


# With mesh added

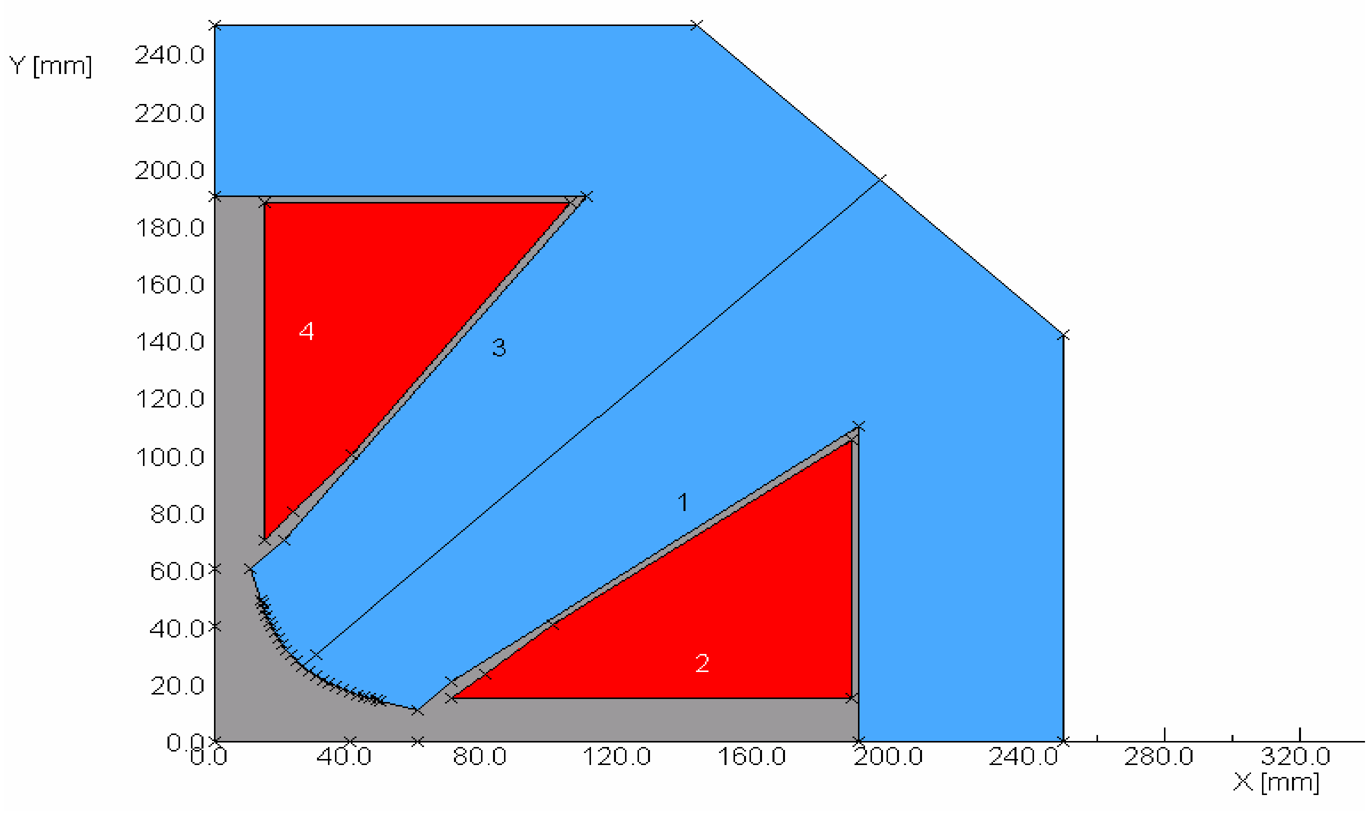


# ‘Close-up’ of pole region.

Pole profile, showing shim and edge roll-off for the 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 at each mesh point in steel, as calculated on
calculated on the previous iteration.

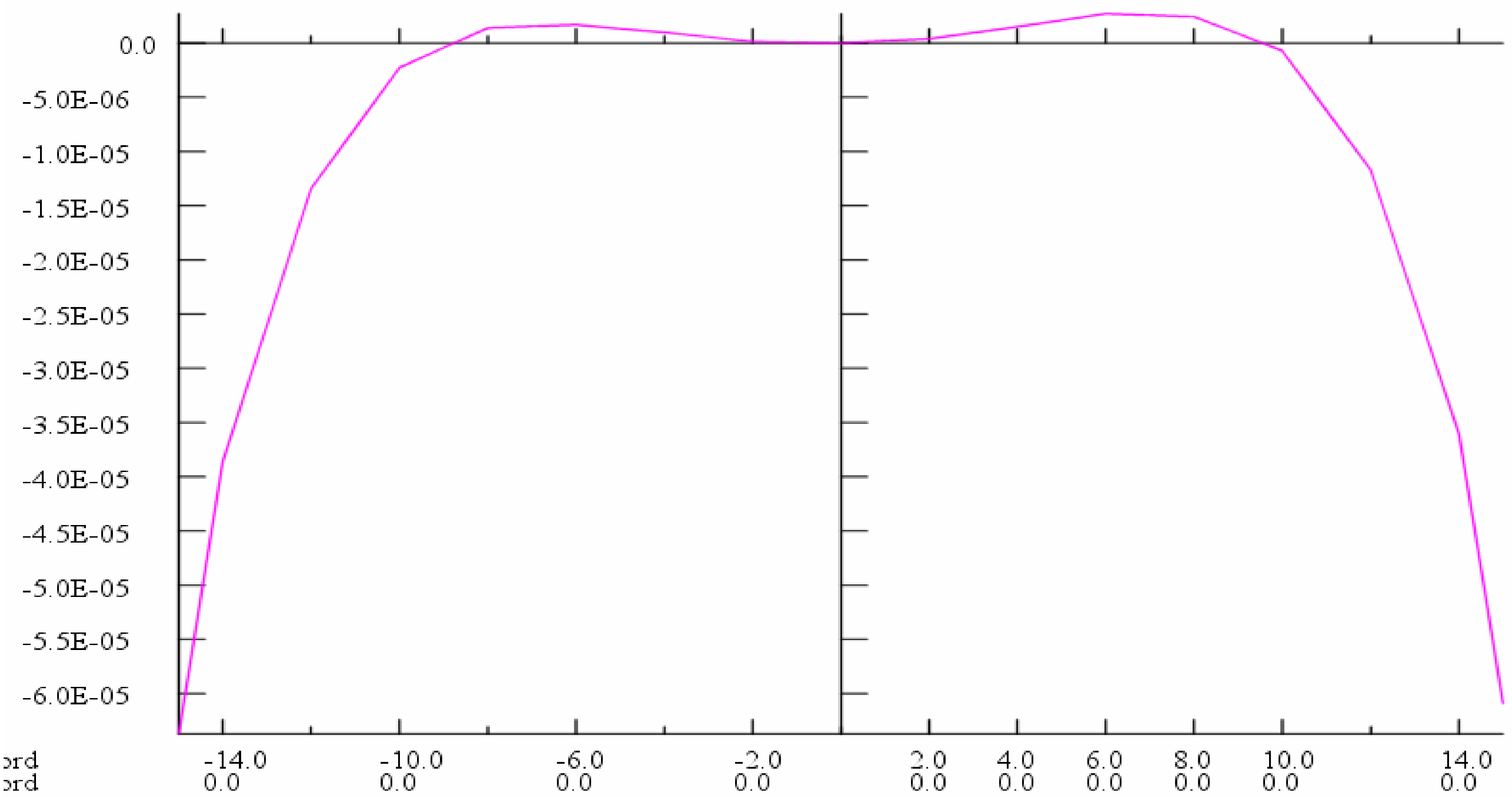
# Data Display – OPERA 2D.

Post-processor:

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

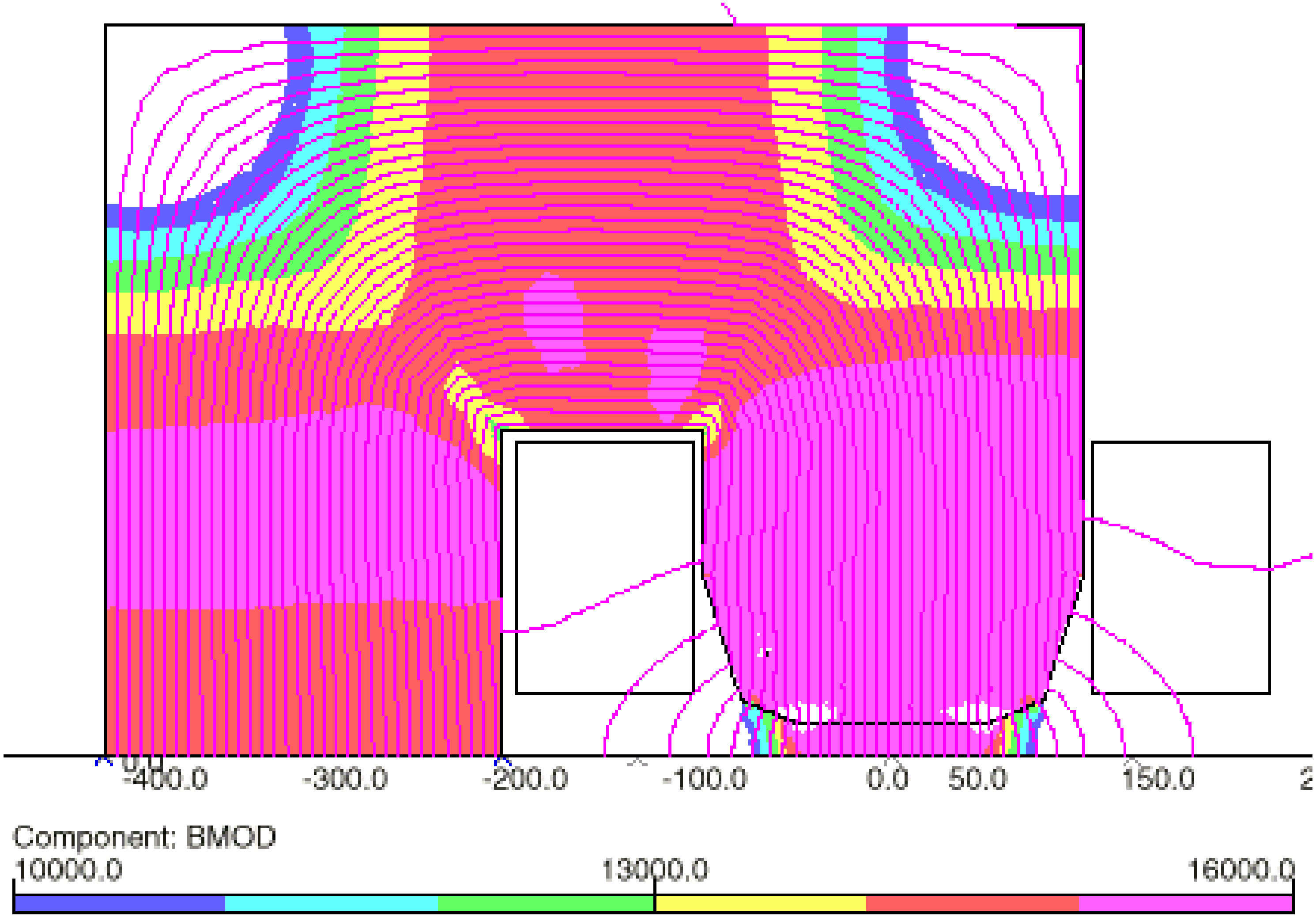
- field lines;
- graphs;
- contours;
- gradients;
- harmonics (from a Fourier analysis around a pre-defined defined circle).

# 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 $-12\text{mm} \leq x \leq +12$ mm..

# 2 D Flux density distribution in a dipole.

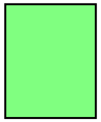


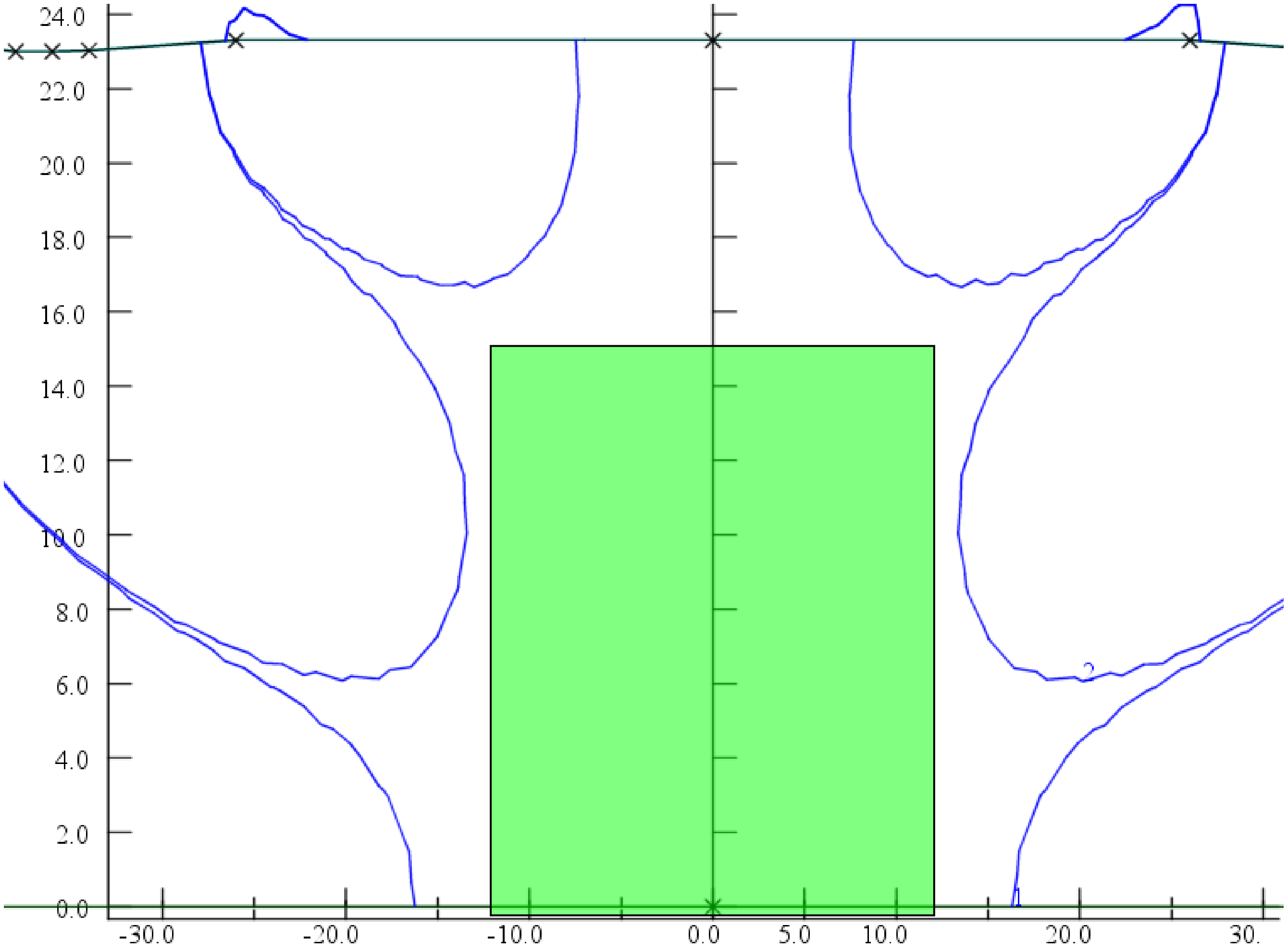
# 2 D Dipole field homogeneity in gap

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

contours are ±0.01%

required good field region:



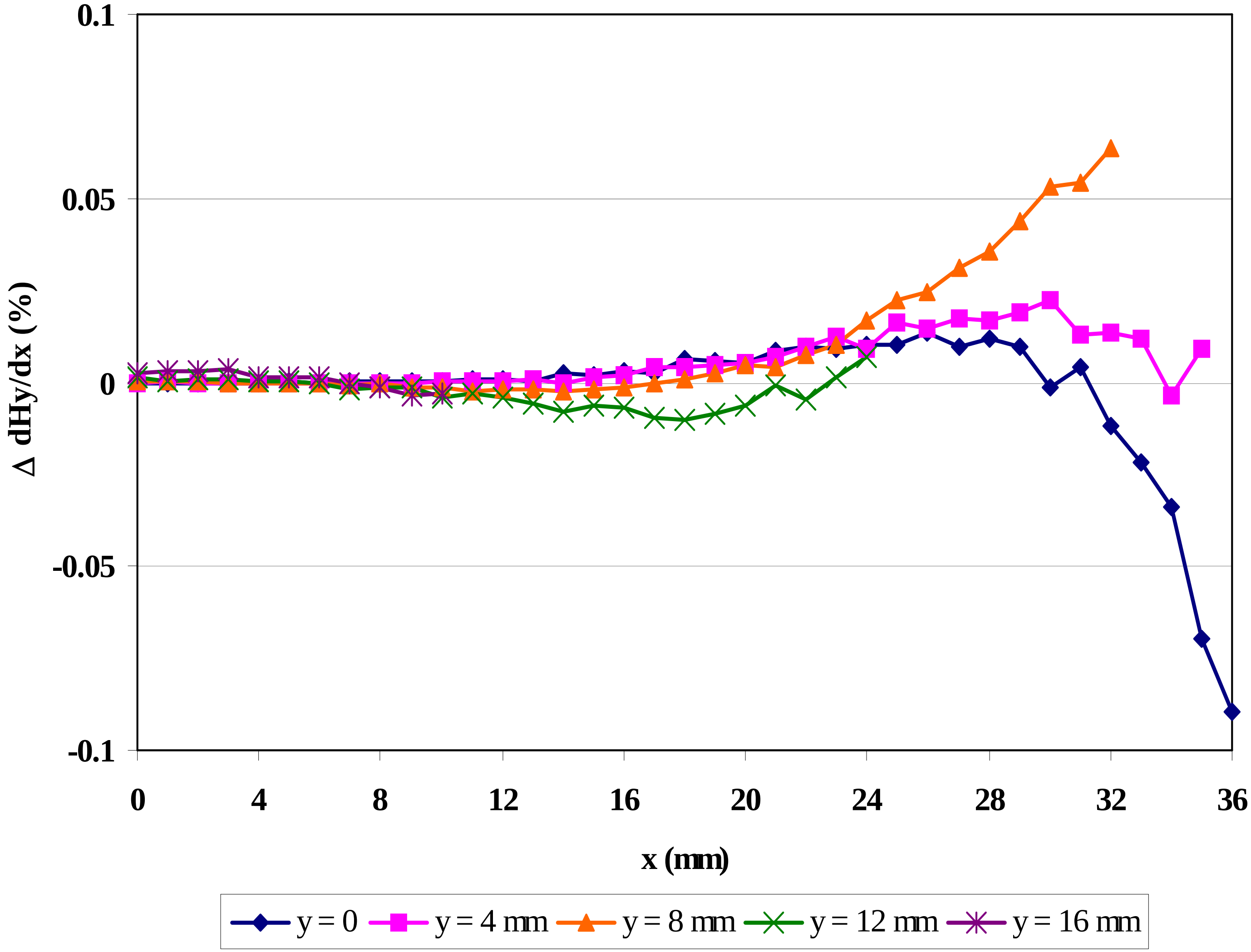


# 2 D Assessment of quadrupole gradient quality

**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.**



# Assessing results

A <u>simple</u> 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 behaviour in a lattice;
- when designs are judged for suitability;
- when the manufactured magnet is measured;
- to judge acceptability of a manufactured magnet.

Note that harmonic amplitude and phases are provide by many many modelling codes – and they relate directly to measurements.

# 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;

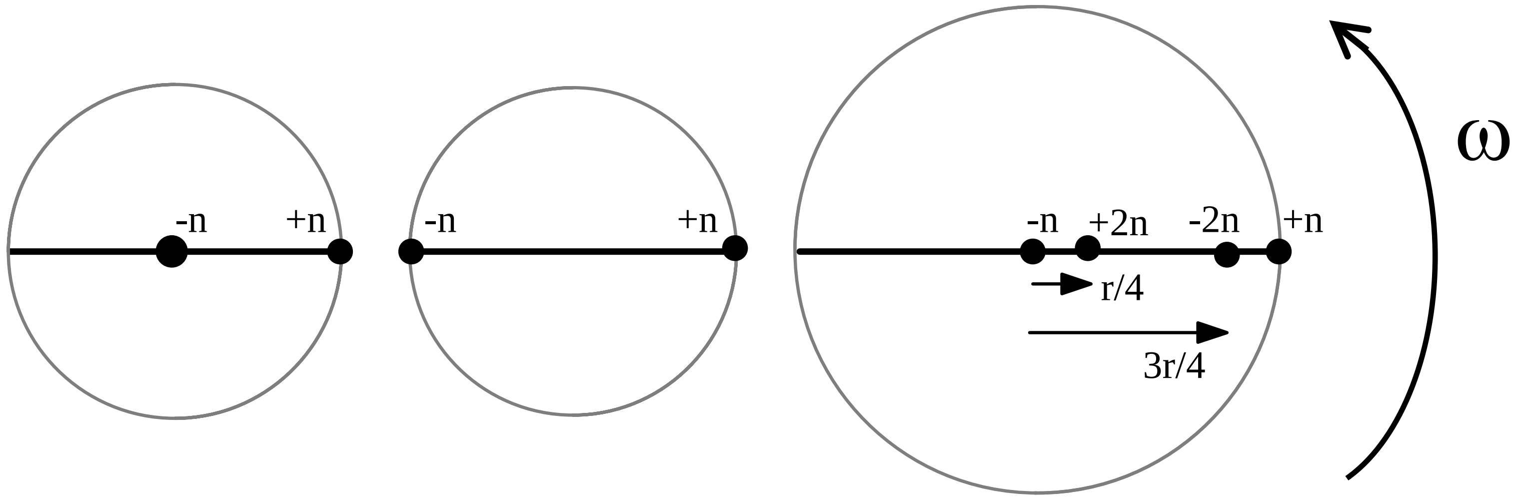
of each harmonic present, up to n ~ 30;

and:

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

# Rotating coil configurations

Multiple windings, rotating about the centre, with different radii radii (r) and numbers of turns (n) are combined to cancel out out some harmonics, - greater sensitivity to others:




Detects all harmonics

Detects all odd harmonics, 1,3,5 etc.

Dipole and quadrupole rejected.

# 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 | $\pm 3\text{x}10^{-4}$; |
| | angular phase accuracy | ±0.2 mrad; |
| | lateral positioning of magnet centre | ±0.03 mm; |
| | accuracy of multipole components | $\pm 3\text{x}10^{-4}$ |

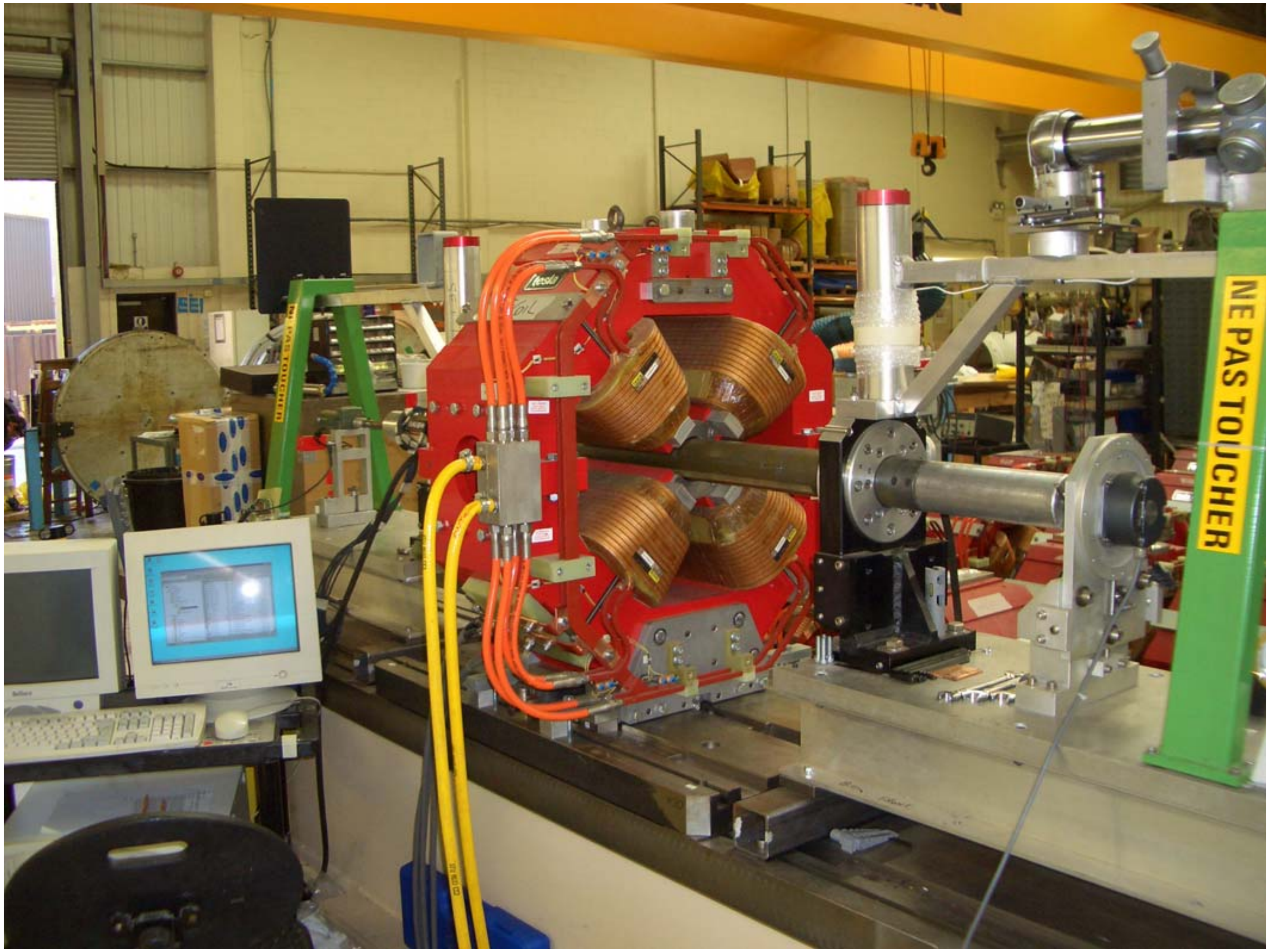
# Data output

Data output from the computer is a complete summary of magnet parameters:

- phase and amplitude of all harmonics;
- position of magnetic centre in both planes;
- angle error along the three axies of rotation;

Advanced systems (eg the CERN LEP measurement system) also automatically adjust the magnet positions and angles with respect to a base plate.

# Rotating coil system measuring Diamond Quad.



# Correction of DIAMOND Quadrupoles

This rapid and accurate measurement system allowed allowed the manufacturer to adjust the magnets to to substantially reduce the harmonics resulting from from assembly errors.

Meeting the requirements for quadrupole quality!

# 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 | | | | | | |