Magnetic Measurements

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Philosophy

•To cover the possible methods of measuring flux density but concentrating on the most frequently used methods.

•Note that magnetic field H is a measure of the excitation (creation) of the magnetic phenomenon; all measurable effects are driven by the flux density B.

•Note that measurement 'accuracy' involves three different facets:

- resolution;
- stability and repeatability;
- absolute calibration.

Contents:

1. Physical effects available for measurement:

a) force on a current carrying conductor;
b) electromagnetic induction;
c) Hall effect (special case of (a));
d) nuclear magnetic resonance.

2. Practical applications:
a) point-by-point measurements;
b) rotating coil methods;
c) traversing coils.

Force on a current carrying conductor

$$F = B\,I$$

where: F is force per unit length;

B is flux density;

I is current.

<u>Advantages:</u>

integrates along wire;

I can be accurately controlled and measured.

<u>Disadvantages:</u>

not suitable for an absolute measurement;

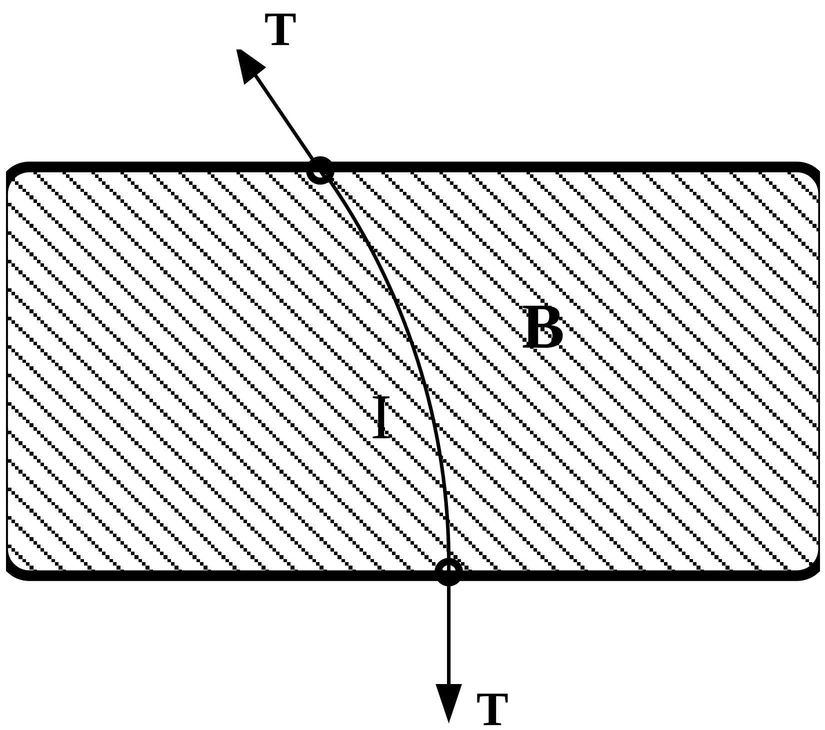
measurement of F is not very highly accurate;

therefore not suitable for general measurements.

Use in spectrometry

specialised trajectory tracing in experimental magnets:

'Floating wire' technique - wire is kept under constant tension T and exit point is measured for different entry points.



Electromagnetic induction

$\text{curl } \mathbf{E} = - \partial \mathbf{B} / \partial t$; $V = B\,An \sin \omega t$.

(V is induced voltage; B is flux density; A is coil area; n is coil turns.

Advantages:

V can be accurately measured;

Gives B integrated over the coil area.

Disadvantages:

$\partial / \partial t$ must be constant (but see later);

absolute accuracy limited by error in value of A;

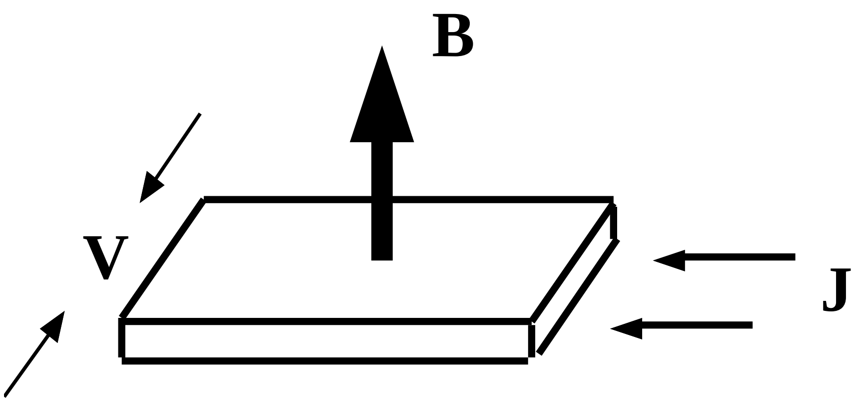
Can be sufficiently accurate to give absolute measurements but best for relative measurements.

Used:

standard measurements of accelerator magnets;

transfer standards;

Hall effect



Special case of force on a moving charge; a metal (or semiconductor) with a current flowing at right angles to the field develops a voltage in the third plane:

$$\mathbf{V} = -R\,(\mathbf{J} \times \mathbf{B})\,a$$

where: V is induced voltage; B is field;

J is current density in material;

a is width in direction of V

R is the 'Hall Coefficient' (fn of temperature):

R = fn (α, θ)**;**

θ is temperature; α is temperature coefficient.

The Cockcroft Institute of Accelerator Science and Technology

Hall effect (cont.)

Advantages:

small light probe;

easily portable/moved;

J, V accurately measurable – good resolution, repeatability;

covers a very broad range of B;

works in non-uniform field.

Disadvantages:

θ must be controlled measured/compensated;

R and a must be known accurately.

Used:

commercial portable magnetometers;

point-by-point measurements;

Nuclear magnetic resonance.

In an external magnetic field, nuclei with a magnetic moment precess around the field at the Larmor precession frequency:

$$\nu \propto (\gamma /2 \pi) B;$$

where: ν is the precession frequency;

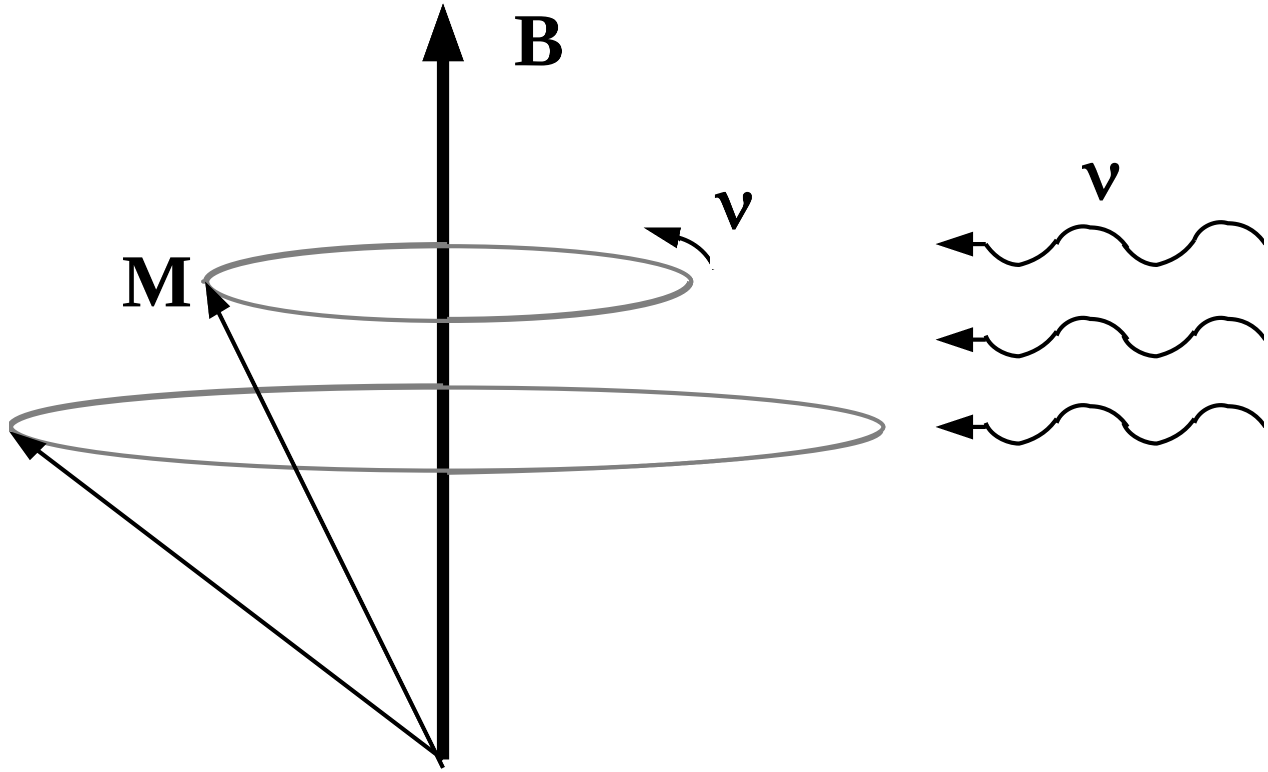
γ is the gyro-magnetic ratio of the nucleus;

B is external field.

A radio-frequency e-m field applied to the material at this frequency will produce a change in the orientation of the spin angular momentum of the nucleus, which will ‘flip’, absorbing a quantum of energy. This can be detected and the r.f. frequency measured to give the precession frequency and hence measure the field.

Spin transition.

The 'spin flip' in a nucleus:



Example:

for the proton (H nucleus):
with B = 1 T;
ν = 42.6 MHz.

N.M.R. (cont.)

Advantages:

- only dependent on nuclear phenomena - not influenced by external conditions;
- very sharp resonance;
- frequency is measured to very high accuracy ($1:10^6$);
- used at high/very high B.

Disadvantages:

- probe is large size (~ 1cm);
- resonance only detectable in highly homogeneous B;
- apparatus works over limited B range, (frequency ν is too low at low B);
- equipment is expensive;

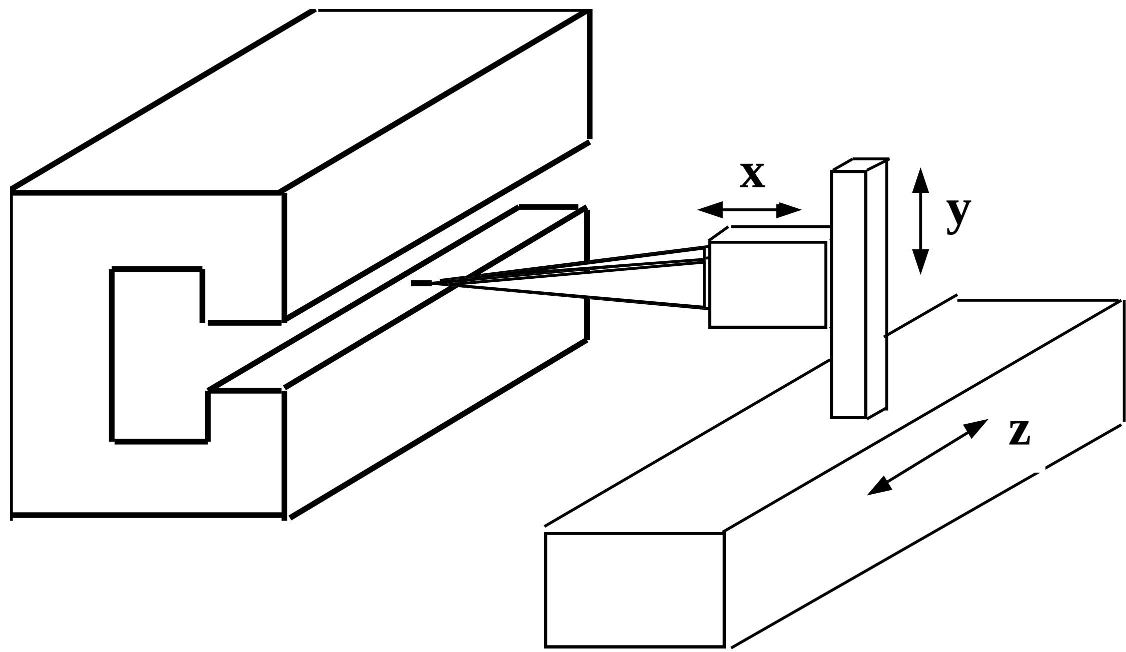
Use:

- most accurate measurement system available;
- commercially available;
- absolute measurement of fields;
- calibration of other equipment.

Practical Applications – Point by point

A probe is traversed in 2 or 3 planes with B measured by a Hall plate at each point to build up a 2/3 dimensional map.

Superseded by rotating coils for multi-poles, but still the method of choice for a <u>small number</u> of high quality dipoles. (It is too slow for a production series)



Modern Hall-probe Bench used at DL for insertion magnets.

Hall Probe	MPT-141-3m	(Group 3);
Teslameter	DTM-141-DG	“
Longitudinal Range	1400	mm
Horizontal Range	200	mm
Vertical Range	100	mm
Longitudinal Resolution (z)	1	µm
Horizontal Resolution (x)	0.5	µm
Vertical Resolution (y)	0.5	µm
Nominal Longitudinal Velocity	1	mm/s
Maximum Calibrated Field	2.2	T
Hall Probe Precision	± 0.01 %	
Hall Probe Resolution	0.05	mT
Temperature Stability	± 10	ppm/°C

Rotating Coil systems.

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

This technique provides the capability of measuring:

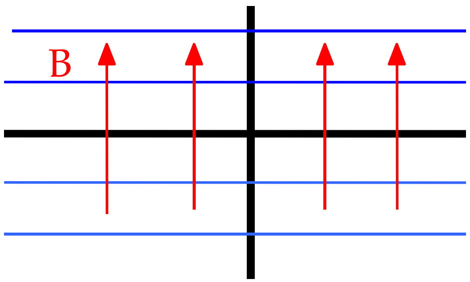
- amplitude;
- phase;

  integrated through the magnet (inc end fringe fields) of each harmonic present, up to n ~ 30 or higher;

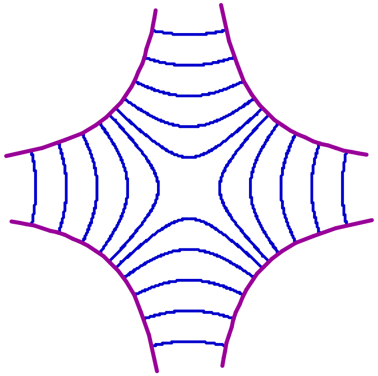
  and:
- magnetic centre (x and y);
- angular alignment (roll, pitch and yaw)

The Rotating Coil

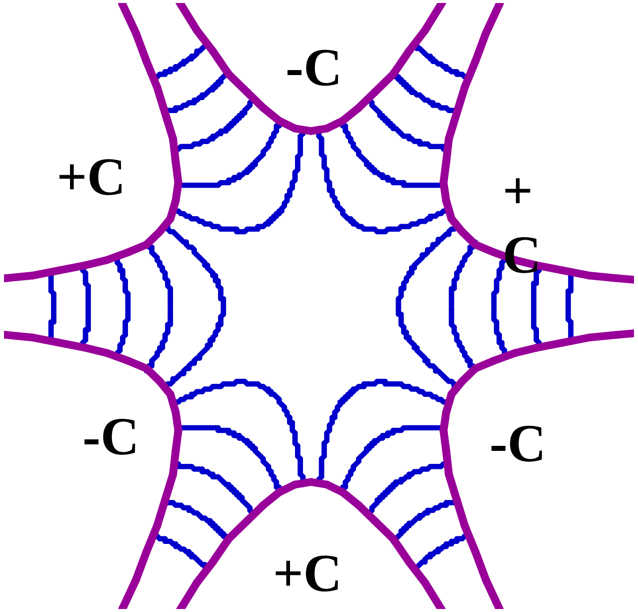
A coil continuously rotating (frequency ω) would cut the radial field and generate a voltage the sum of all the harmonics present in the magnet:



dipole: V = sin ωt



quad: V = sin 2 ωt

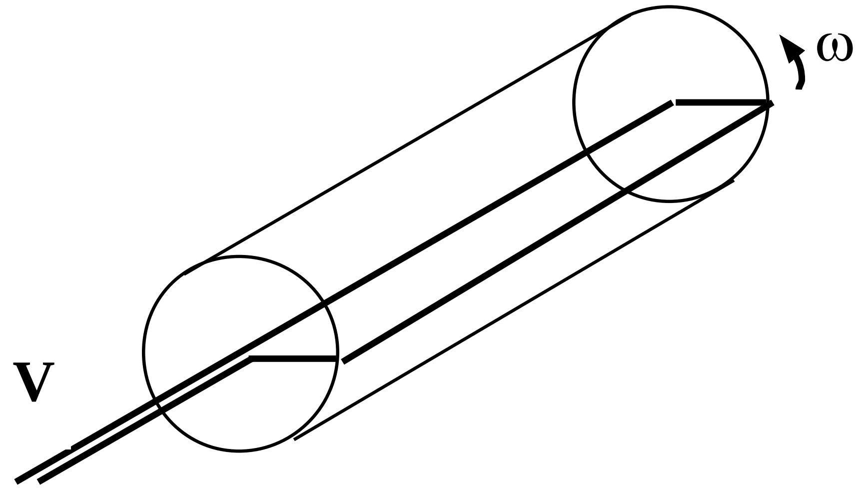


etc.

sextupole: V = sin 3 ωt

Continuous rotation

The coil (as shown) is rotated rapidly in the magnetic field; the induced voltage is analysed with a harmonic analyser.



Induced voltage :

$$V = \partial\Phi/\ \partial t = N_{coil} A_{coil}\ \partial B_r/\ \partial t;$$

$$= N_{coil} A_{coil} \sum_{n=1}^{\infty} \left\{ n^2 r^{n-1} (A_n \sin n\theta + B_n \cos n\theta)(\partial\theta/\ \partial t) \right\}$$

Continuous rotation is now regarded as a primitive method!

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.

Solution:

Rotation and data processing:

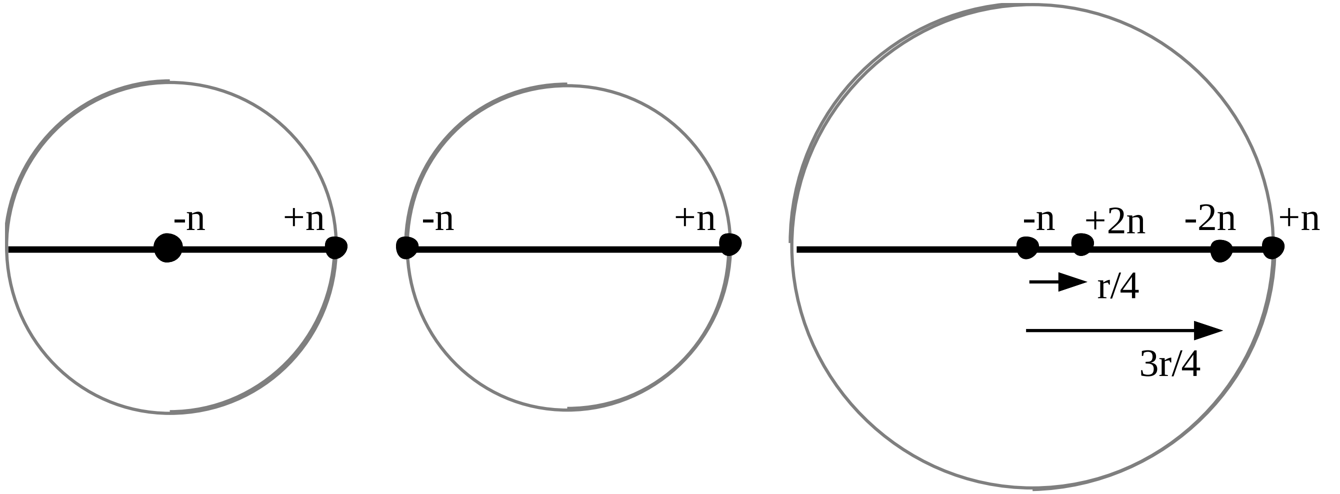
- coil cylinder make < 2 revolutions in total;
- windings are hard wired to detection equipment;
- an angular encoder is mounted on the rotation shaft;
- the output voltage is converted to frequency and integrated w.r.t. angle, so eliminating any $\partial/\partial t$ effects;
- integrated signal is 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 multi-pole 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:

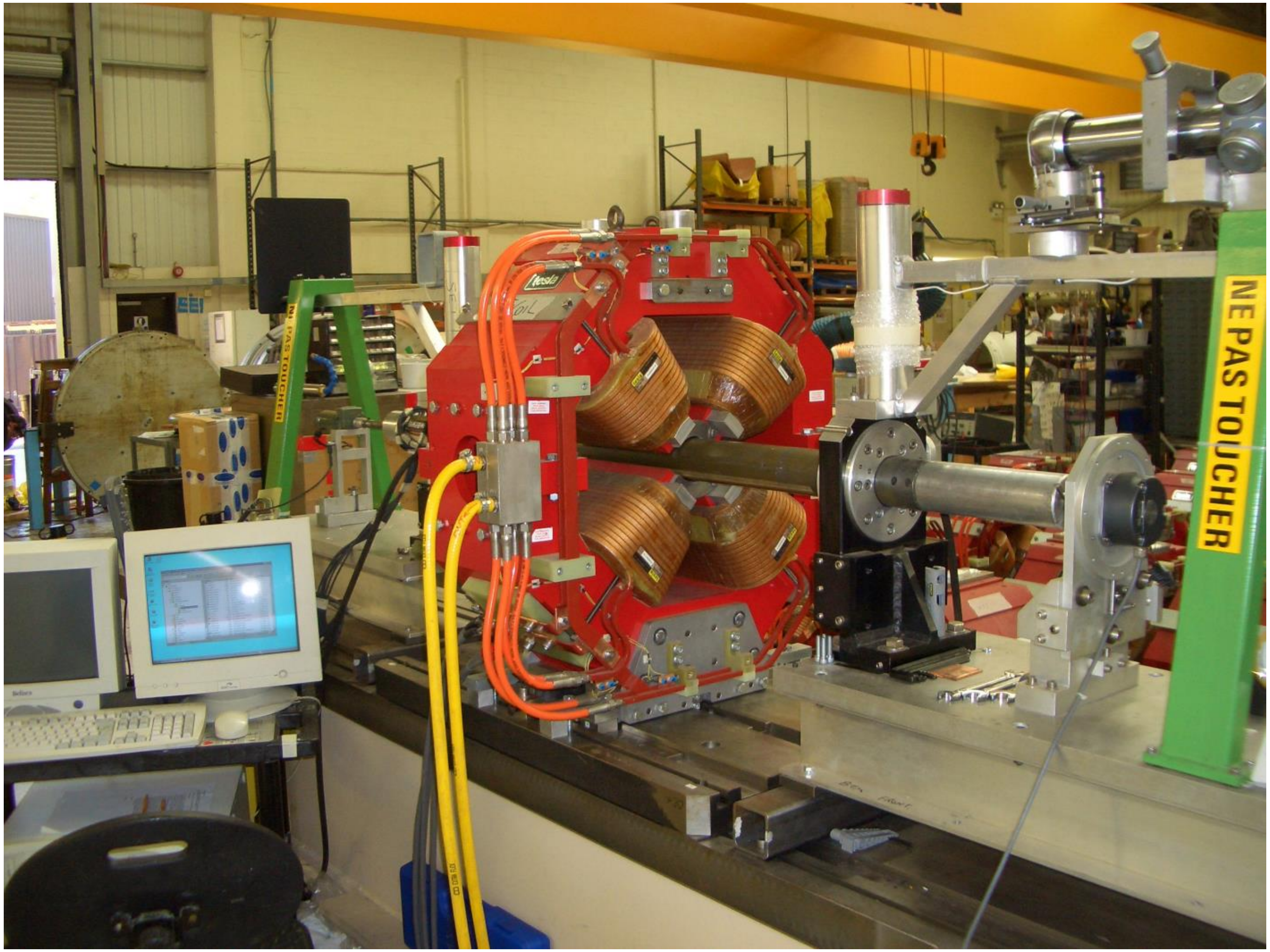


All harmonics

All odd harmonics, 1,3,5 etc.

Dipole and quadrupole rejected.

A rotating coil magnetometer.



Test data used to judge Diamond quads

(acknowledgement to Tesla Engineering for spread-sheet developed for Quad measurement)

Validity	This template is current		Midplane	adjustment	Next actions (Refer first):	
Iteration No.	1			(+ to open)	DLS referral done? (Yes/No/NA)	yes
Magnet type identifier	WM		East (um):	240	Reject/Hold for refer? (S4, C6+)	
Magnet serial	WMZ086		West (um):	80	Adjust vertical split (S3)?	Yes
			Top (um):	80	Adjust midplane (C3/C4)?	Yes
			Bottom (um:)	0	Full align?	
Date of test	12/07/2005		C3 switch	1	Adjust dx only?	
Tester	Darren Cox		S3 switch	1	Accept magnet?	
Comments:	180A preliminary		C4 switch	1		
DLS comments:	Please insert comments here		S4++ switch	1		
Dipole+NS007 reference angle	137.89068	(update fortnightly)	Full switch	1		
Adjusted dipole reference angle	137.90085		dx switch	1		

Field quality data			DLS OK? ?Yes/No?	Post-shim prediction	Alignment data [good pass/pass]	Value	Outcome
R(ref) (mm)	35.00				dx [0.025/0.05]mm	-0.089	Fail
Current (A)	180.00				dy [0.025/0.05]mm	-0.059	Fail
Central strength (T/m)	17.6328				dz [2.5/5.0]mm	2.414	Good pass
L(eff) (mm)	407.253				Roll [0.1/0.2]mrad	0.052	Good pass
C3 (4-8)	-0.49	Pass	No	-0.49	Yaw [0.15/0.3]mrad	-0.048	Good pass
S3 (6-12)	-10.88	Refer, or shim vertical	No	-2.33	Pitch [0.15/0.3]mrad	-0.085	Good pass
C4 (4-7)	6.90	Refer, or shim horizontal	No	-2.64			
S4 (1-4)	0.80	Pass	No	-0.04		Adjust X alone?	
C6 (2.5-10)	7.97	Refer to DLS	yes			Alignment OK?	
|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				

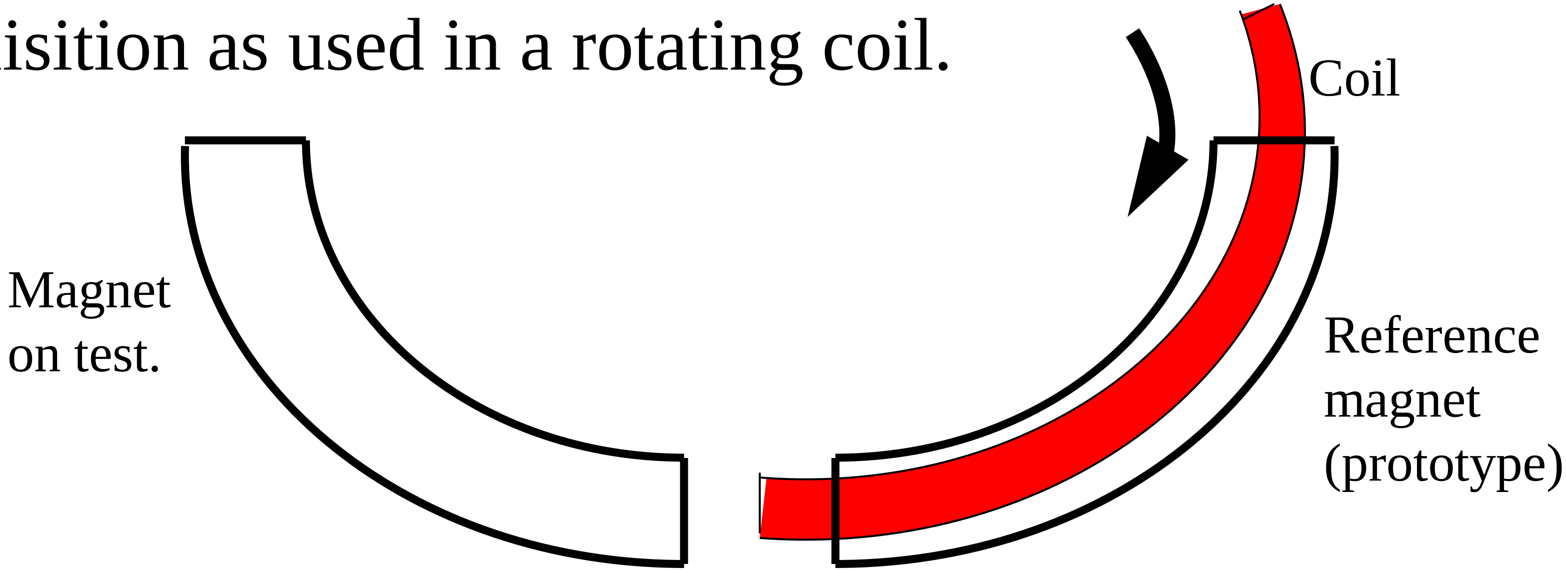
Keys to use	N key	S key	NW foot	NE foot	SW foot	SE foot
Next shims to use (rounded)	N/A	N/A	N/A	N/A	N/A	N/A

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						

Traversing coils

Used in curved dipoles -similar method of data acquisition as used in a rotating coil.



The coil (with multiple radial windings) is traversed from the reference to the test magnet; voltage from each winding is integrated; variation from zero in the integrated volts, after the traversal, indicates variations from the reference magnet total flux vs radius values, which are known.