Magnet Power Converters and Accelerators

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Contents

The accelerator lattice.

Magnets:

- dipoles;
- quadrupole;
- sextupoles.

Magnet excitation requirements.

The magnet/power converter interface:

- number of turns in the coils;
- current density in the conductor;
- optimisation of magnet length and field strength.

Accelerator Magnets

The magnets control the direction and size of the beams of the circulating beam:

Dipoles - **bend** and **steer** the beams;

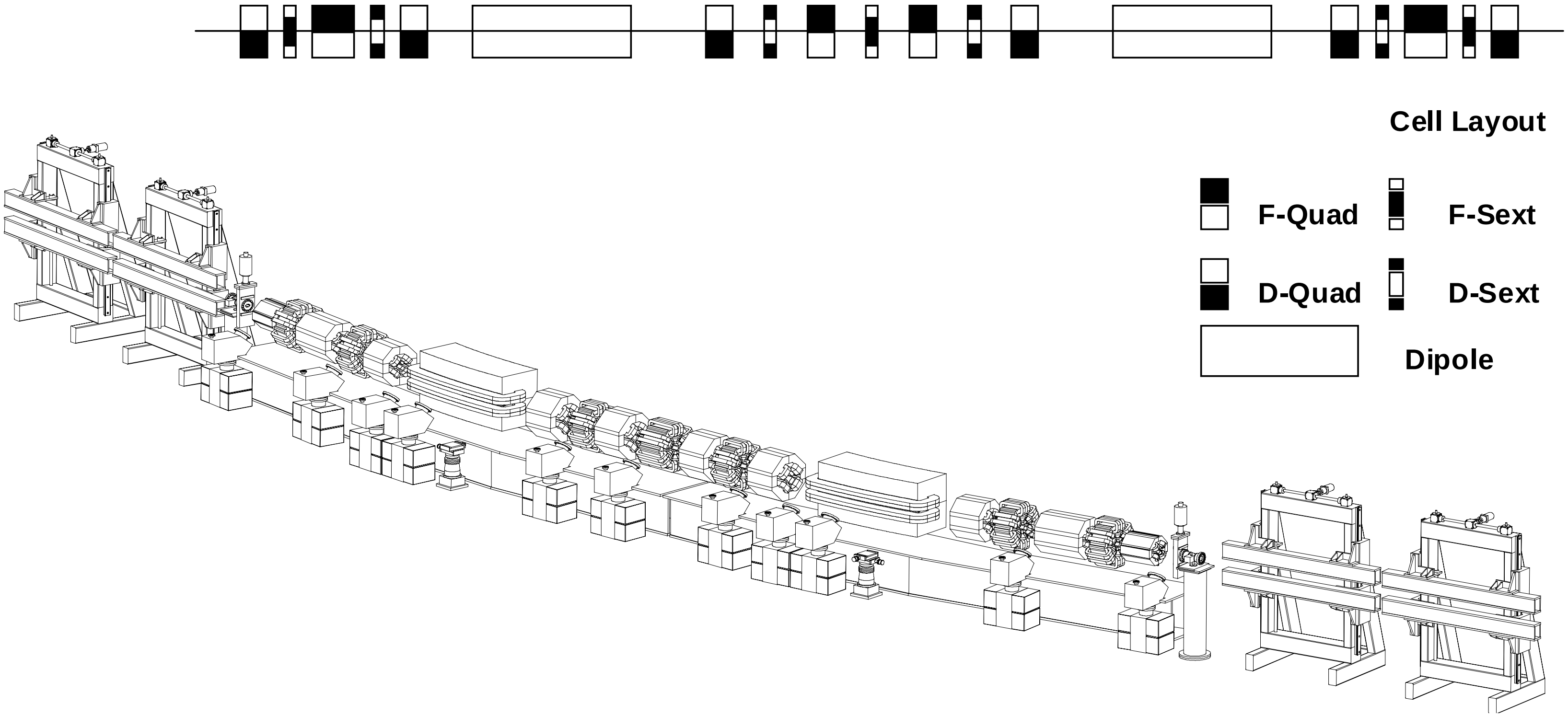
Quadrupoles - **focus** the beams;

Sextupoles - control the focusing of ‘off momentum’ particles (**chromaticity**);

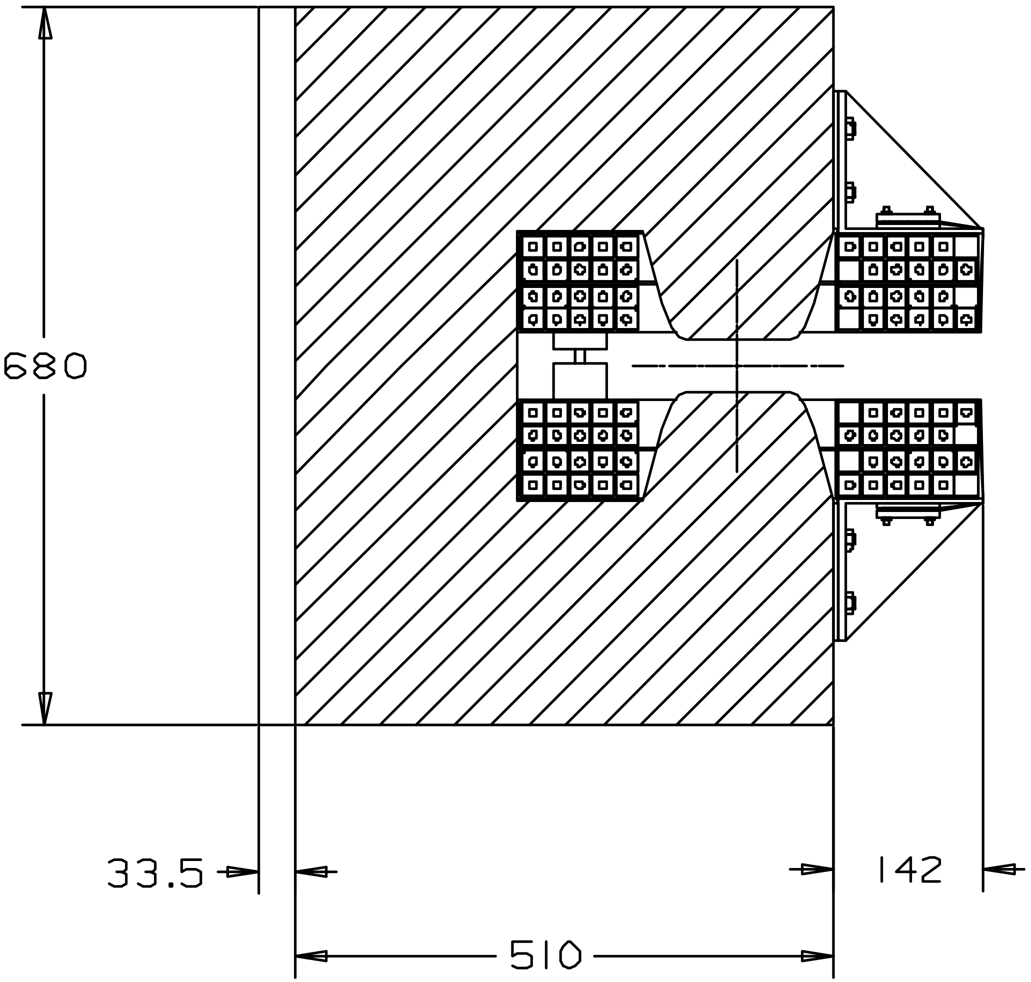
All together they make up the ‘**lattice**’.

A Cell in a Lattice

A **Separated Function** Lattice:



A typical ‘C’ cored Dipole



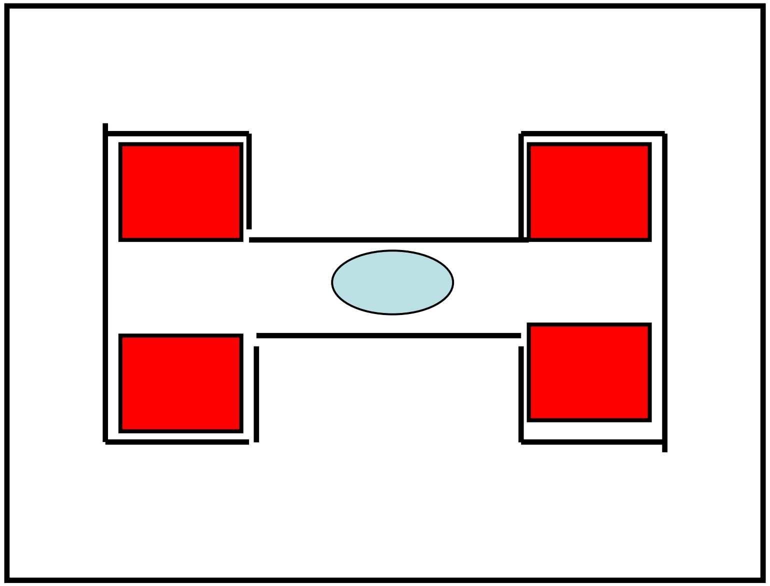
Other arrangements for dipoles:

‘H’ cores;

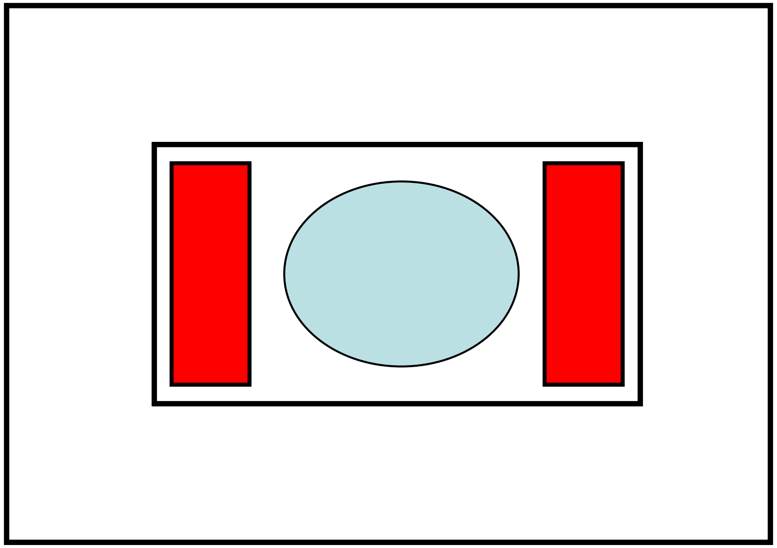
‘window frame’.

H core and window-frame magnets

‘H core’:



‘Window frame’:



Dipole requirements

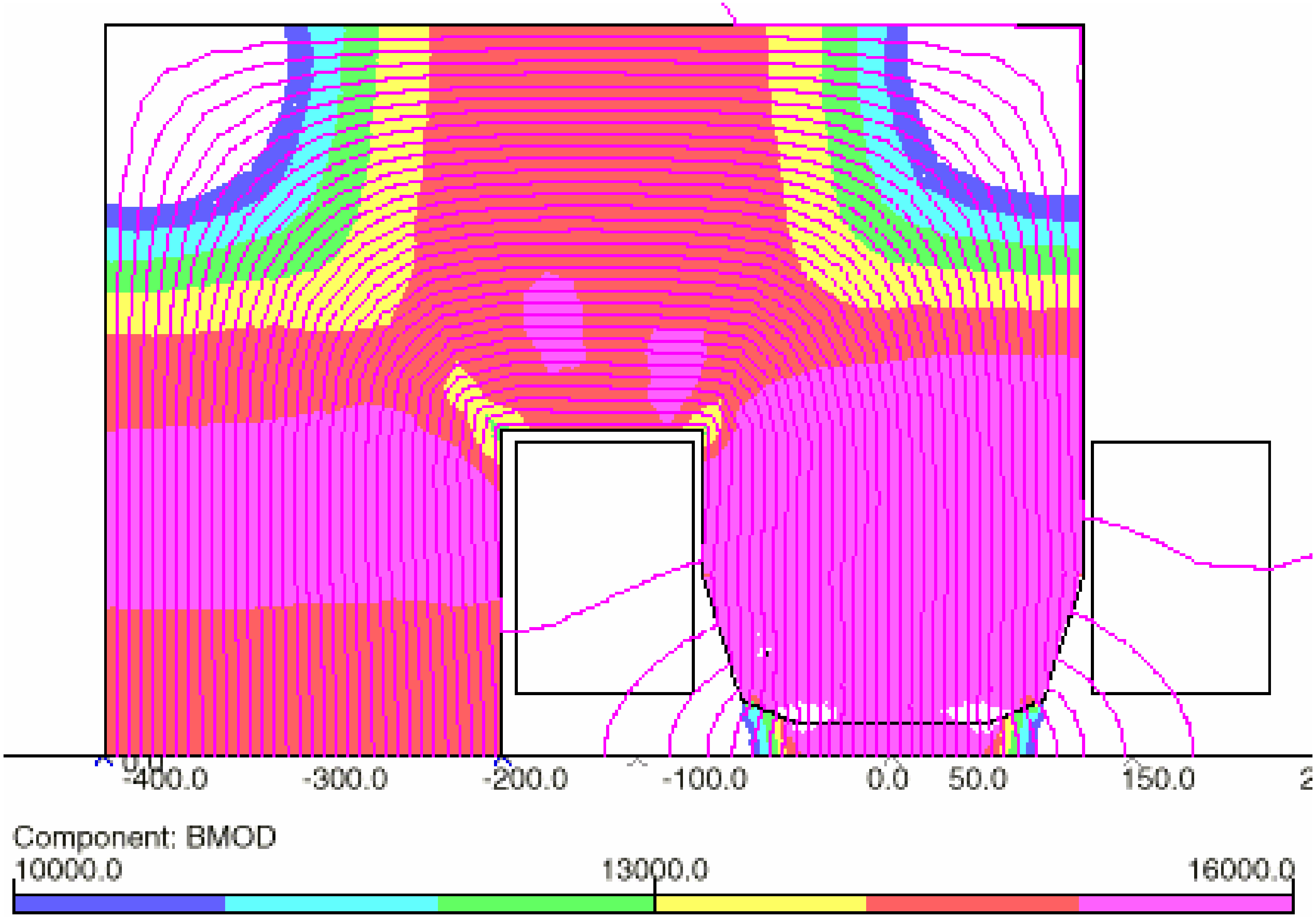
The dipole magnets need:

- high field homogeneity.

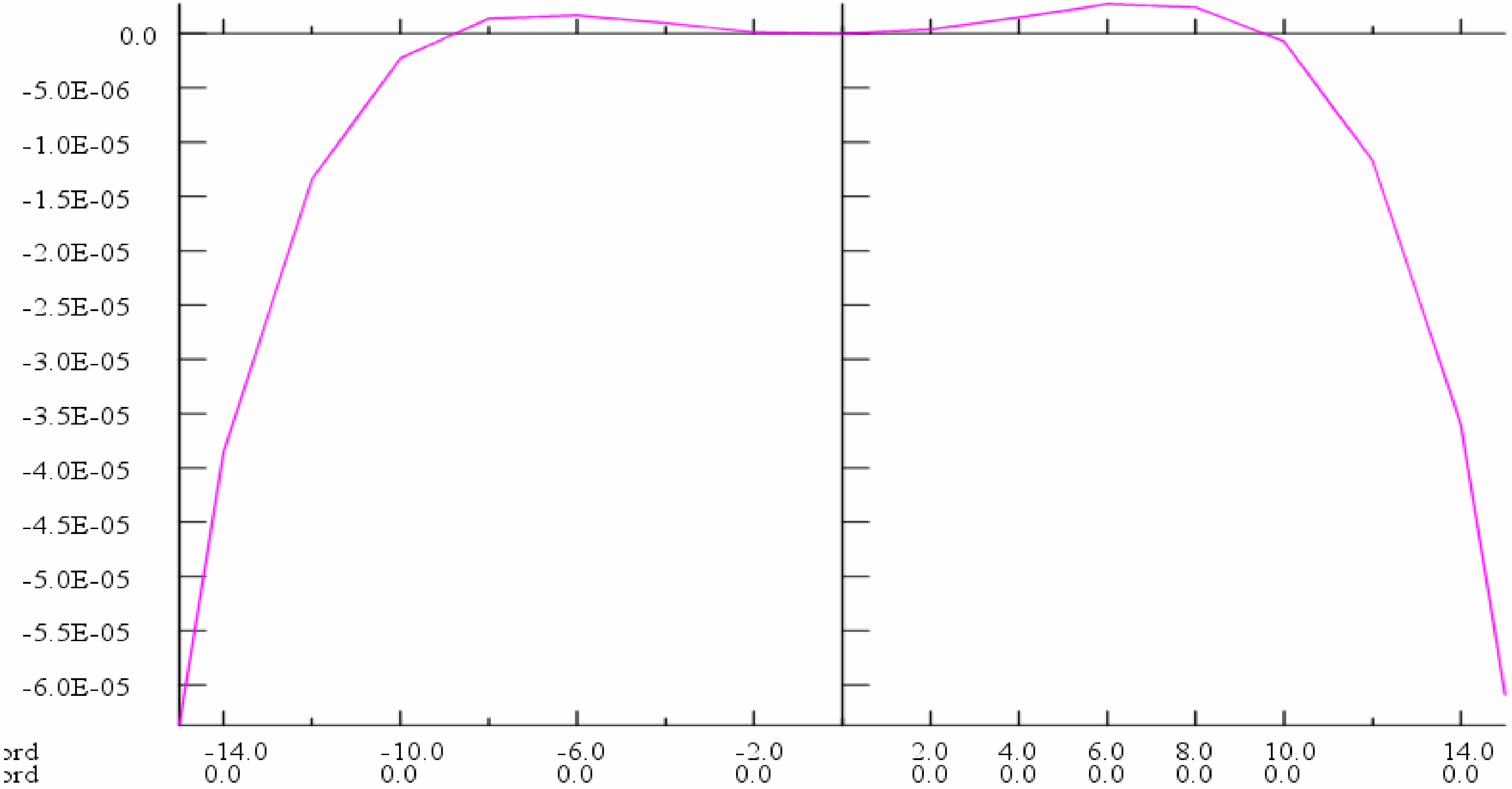
The dipole power circuit needs:

- stringent current continuity in the dipole circuit;
- high current stability;
- high current accuracy;
- low ripple;
- smooth current waveform (no discontinuities in I or dI/dt)

Flux density distribution in a dipole.



Dipole field homogeneity on beam axis

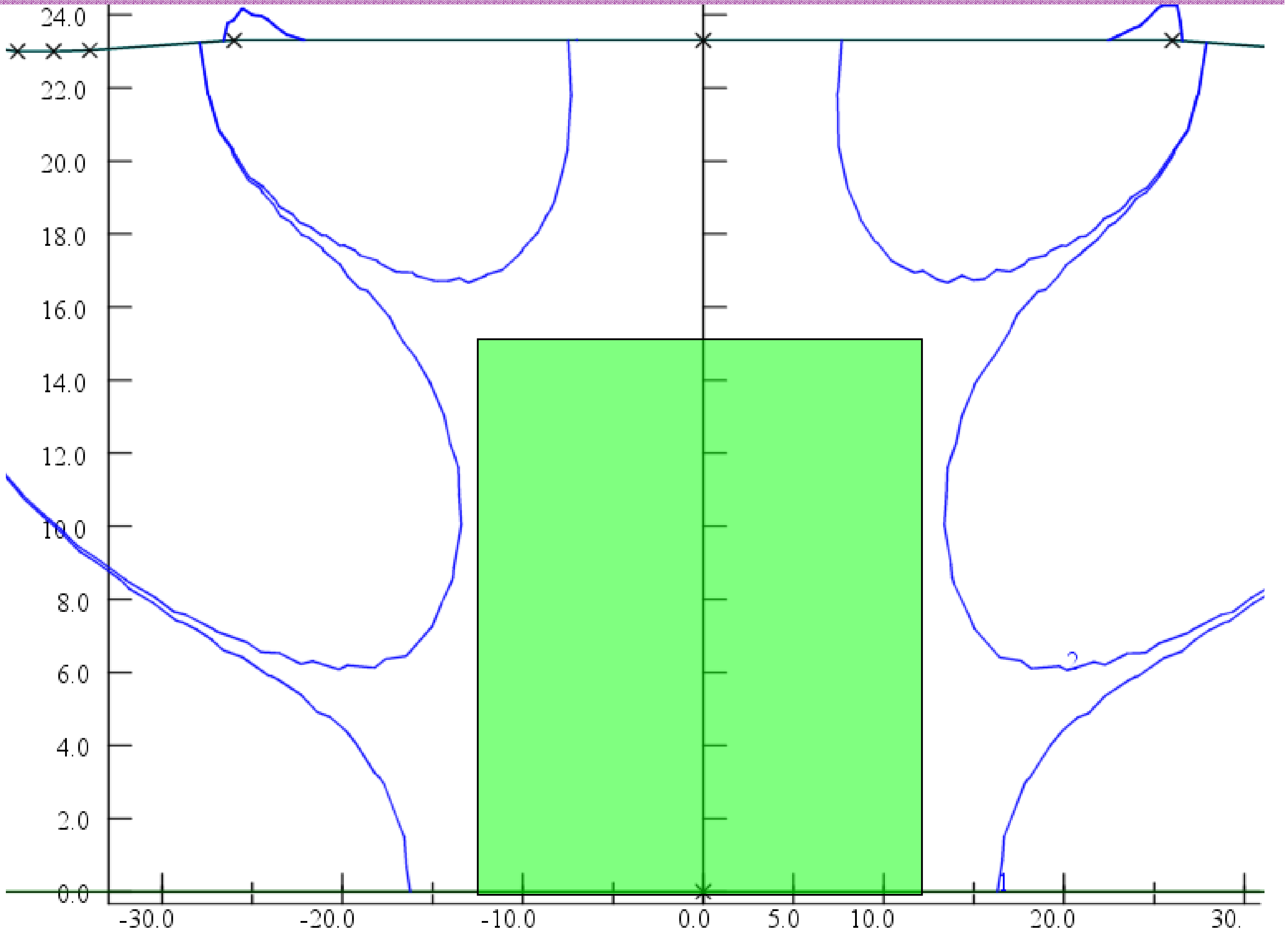


Homogeneity expressed as $\Delta B/B = \{B(x,y)-B(0,0)\}/B(0,0)$; typically ± $1:10^4$ within the 'good field region' defined by the beam transverse dimensions.

Dipole field homogeneity in gap

contours are ±0.01%

required good field region: 🟩



Field continuity between Dipoles

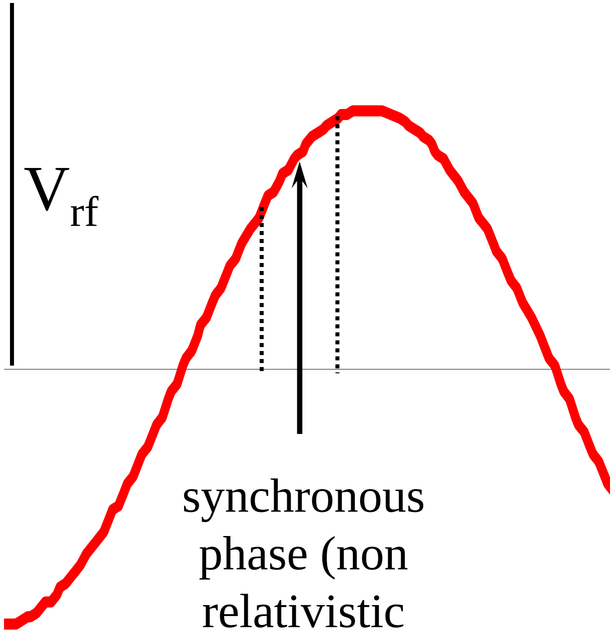
The dipoles in a lattice must have strong string current continuity (~ 1:10^4 or better):

- series connection (apart from very large accelerators – LHC for e.g.);
- low current leakage through cooling water and other parallel paths;
- low earth capacitance in a.c. accelerators (see presentation on ‘Cycling Accelerators’.

Dipole Current Stability

In a synchrotron:

- the particles are ‘trapped’ in a potential well around a point on the rising side of the r.f. waveform (non-relativistic beam);
- low energy particles arrive late - more r.f. volts – more acceleration (phase stability);
- **dipole field controls beam energy;**
- gradient discontinuities can disrupt phase stability.



synchronous phase (non relativistic particles).

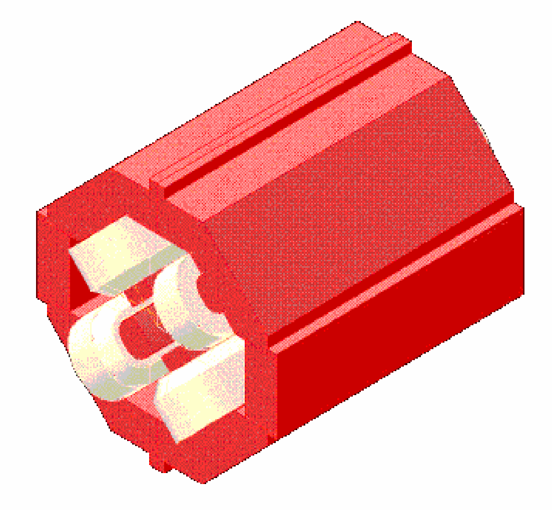
Quadrupole magnets

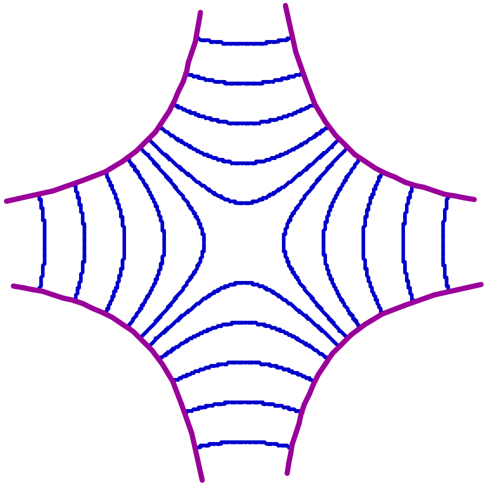
The quadrupoles focus the beam; there must be at least two types in the lattice:

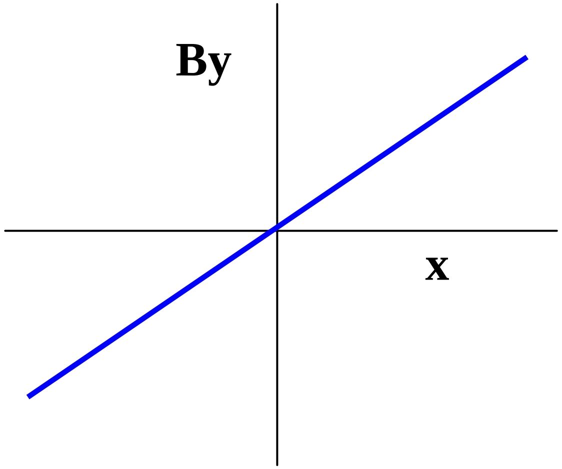
- **‘F’ types** which **focus horizontally**, defocus vertically;
- **‘D’ types** which defocus horizontally, **focus vertically**.

Quadrupoles have similar requirements as dipoles, with high stability power supplies; they must be very accurately aligned.

Quadrupole fields



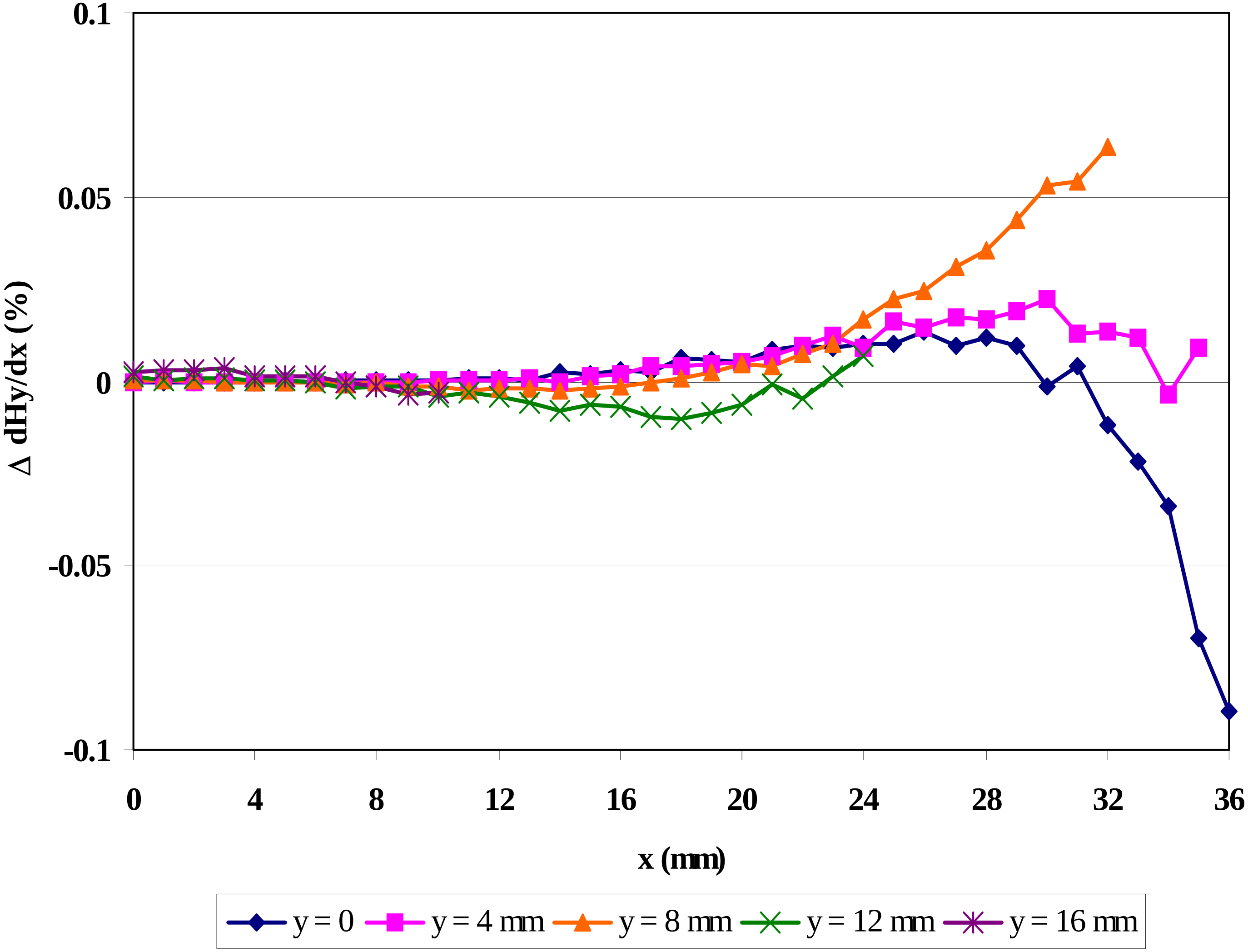


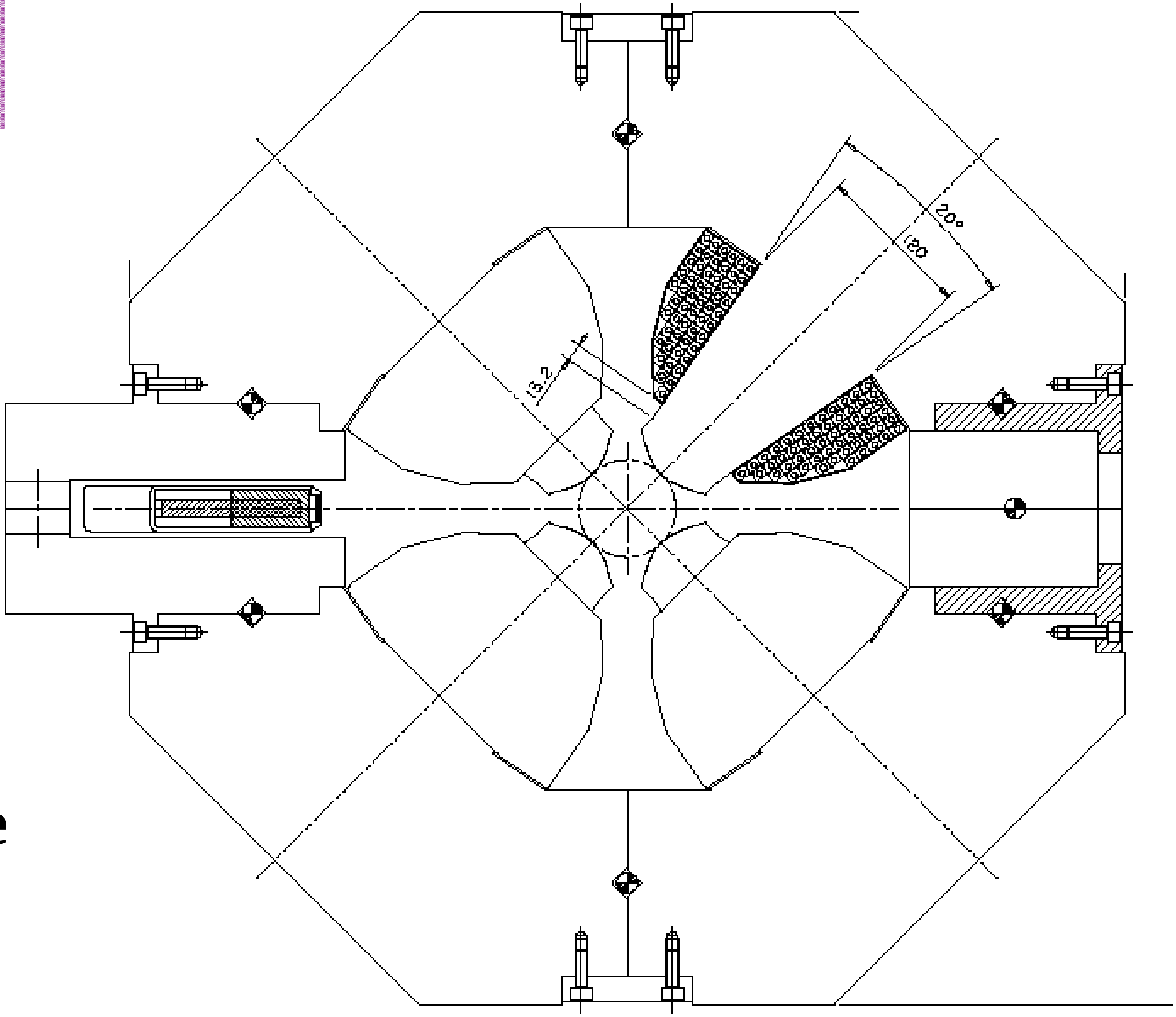


The field is zero at the centre and varies linearly with horizontal and vertical position. Off-centre particles are focused (or defocused); particles on the central orbit are undeviated (but misplacement of the magnetic centre results in horizontal or vertical beam bending).

Assessment of quadrupole gradient quality

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





‘Diamond’ quadrupole cross section.

Effect of current instabilities.

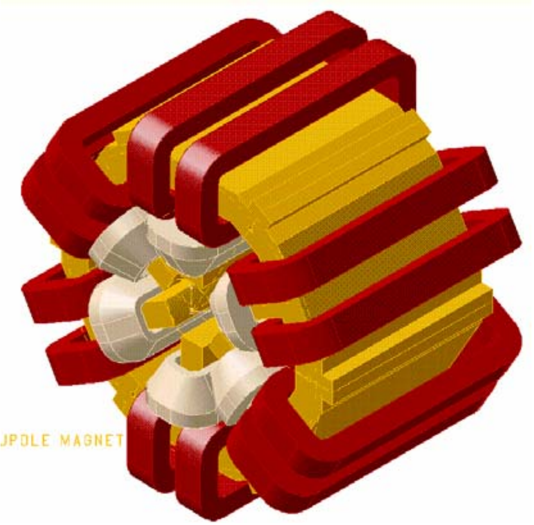
Quadrupoles must ‘track’ the dipoles (ie energy):

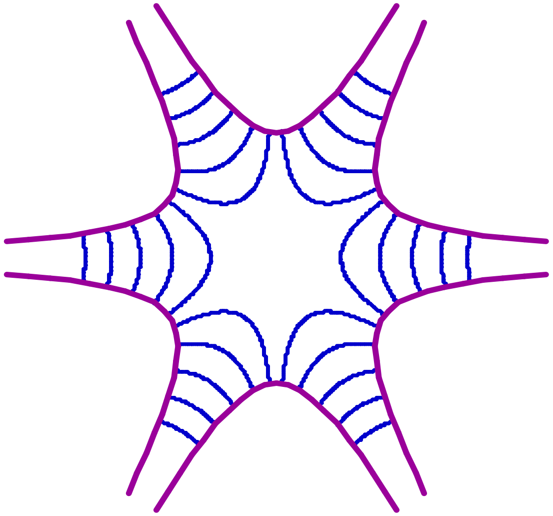
- they control the machine Q value - current variation could engage a resonance - beam loss - stabilities of the order of 1:10^4 are usually needed;
- they control the beta values in the lattice – current variation results in variation in beam size.

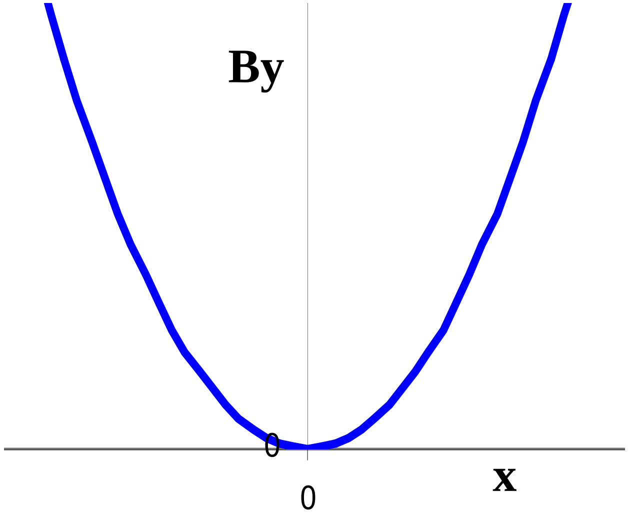
In many accelerators the quadrupoles are connected in series in ‘families’ (F and D for example).

In others (synchrotron sources for example) they are individually powered (separate power converters!) to give local control of beta values (beam size):

Sextupoles







The field and field gradient are zero at the centre; the field varies with a square law with horizontal and vertical position. Off-momentum (and therefore off-centre) particles see a gradient field and are therefore focused (or defocused); particles on the central orbit are undeviated and unfocused.

Sextupole functionality

Sextupoles are included in many lattices to control chromaticity:

- there are usually ‘H’ (controlling horizontal chromaticity) and ‘V’ type sextupoles in a lattice;
- the H and V are usually series connected in ‘families’.
- must also track the dipoles if field varies;
- but are often less critical than quadrupoles (depends on lattice configuration).

Are useful for including ‘correction’ dipole fields (and others) with auxiliary windings separately powered.

Combined function magnets

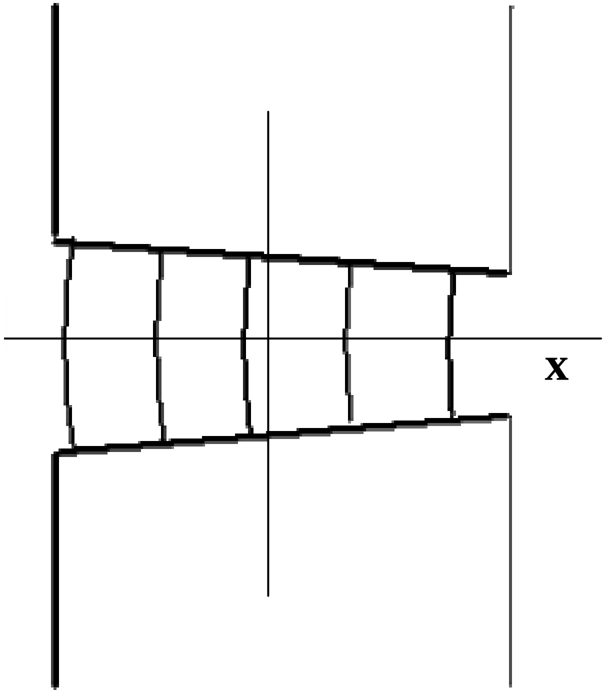
Some or all quadrupole field can be combined into dipoles-bending and focusing in the same magnet

(**but relative strengths cannot be adjusted!**).

Characterised by 'field index' n
(+ or – depending on gradient).

$$n = - \{\rho/B_0\}\{dB/dx\};$$

where ρ is radius of curvature or beam;
B_0 is central field in the magnet.



Magnet excitation - Dipoles

$$\text{curl } H = j;$$

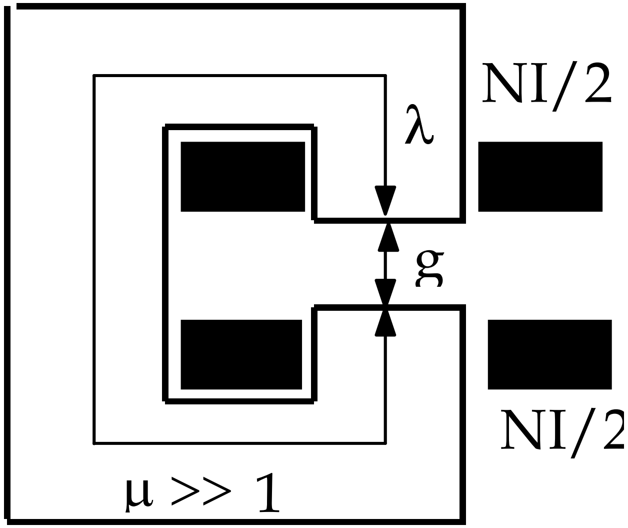
$$\int H.ds = NI;$$

$$(H_i)\lambda + (H_g)g = NI;$$

$$H_i = B/(\mu\mu_0) \quad \text{(small);}$$

$$Hg = B/\mu_0 \quad \text{(larger);}$$

$$B = \mu_0 NI/(g + \lambda/\mu);$$



Amp –turns:

$$\mathbf{NI = B (g + \lambda/\mu)/\mu_0 ;}$$

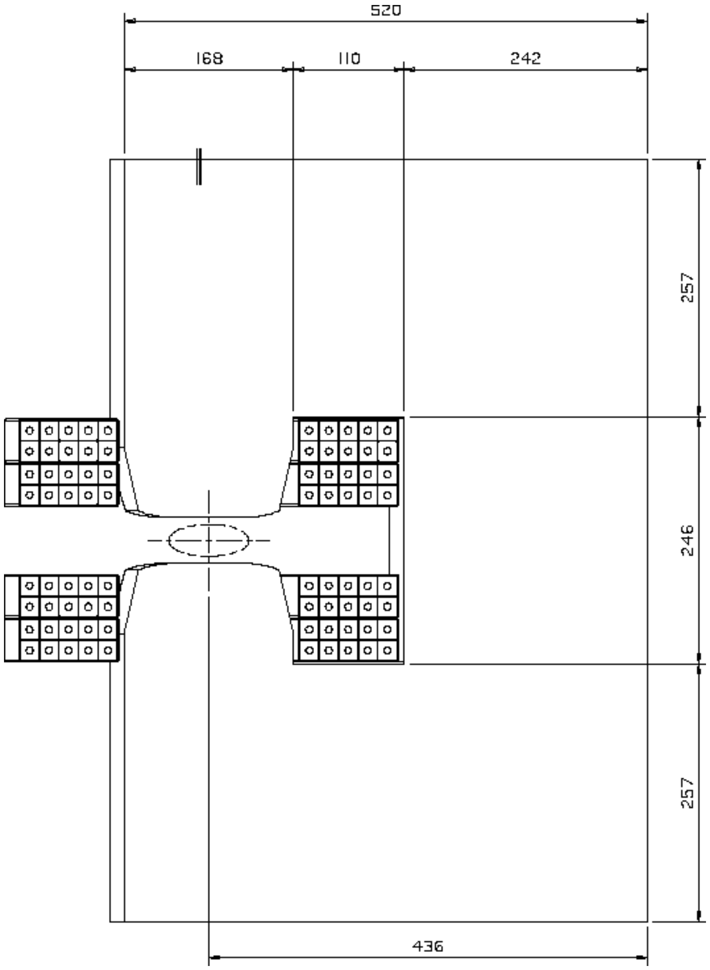
$$\mathbf{NI \approx B g / \mu_0 \qquad \mu >> 1.}$$

magnet gap:	g;	flux path in yoke:	λ;
steel permeability:	μ (>>1);	total turns in 2 coils:	N;
excitation current:	I;	field (A/m) in yoke:	Hi;
field (A/m) in gap:	Hg;	flux density in gap:	B (assumed constant)

Reluctance and low permeability.

$$NI = B\,(\underset{\text{gap `reluctance'}}{\underbrace{g}} + \underset{\text{yoke `reluctance'}}{\underbrace{\lambda/\mu}})/\,\mu_0$$

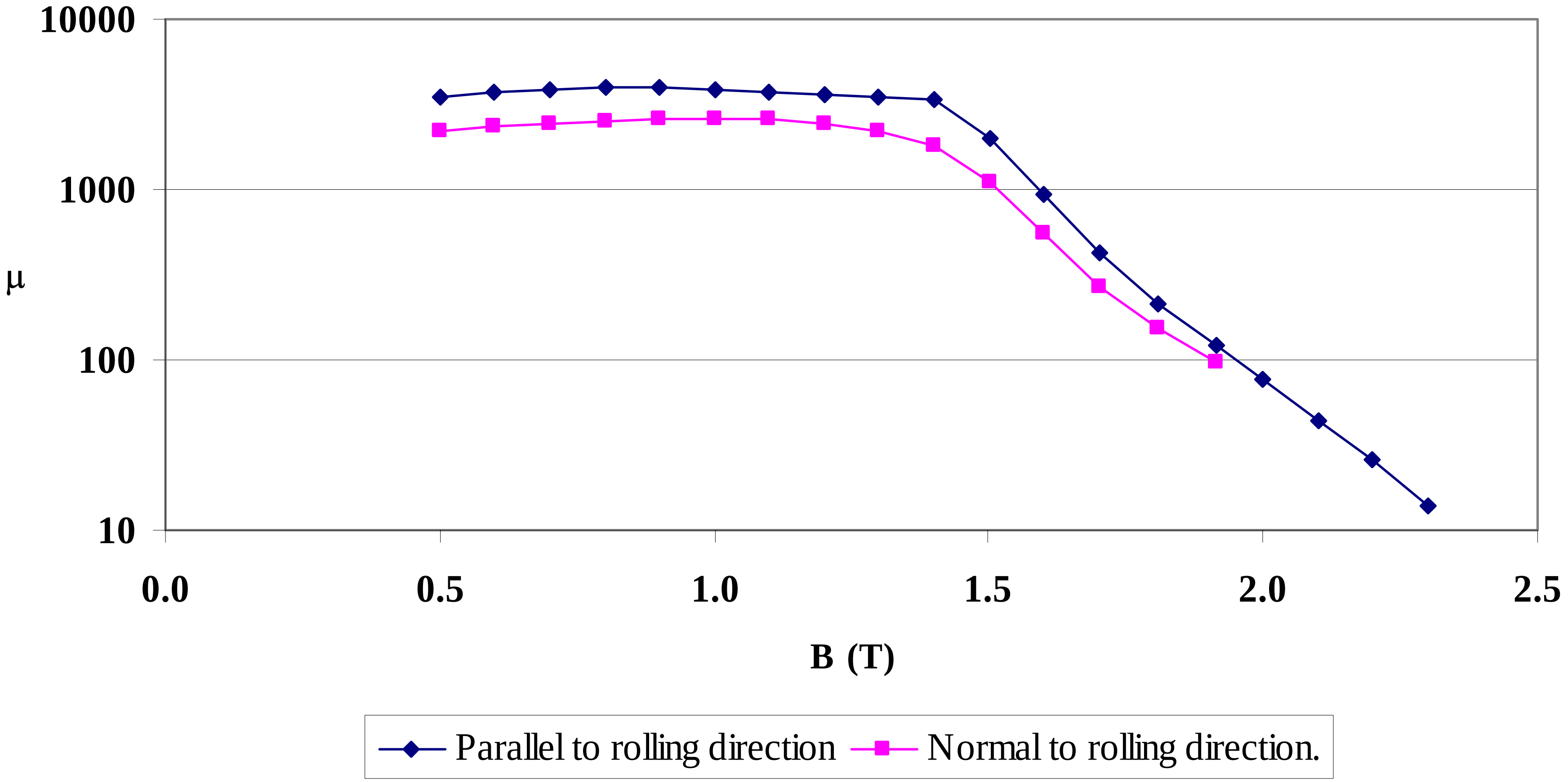
gap 'reluctance' yoke 'reluctance'



The magnet designed must limit the Amp-turns lost in the yoke by limiting the flux density in the steel:

- use wider top, bottom and back legs;
- diverge the pole if necessary.

Relative permeability of low silicon steel



Typical values of non-linearity.

In low and medium field (≤ 1.5 T) dipoles, the yoke reluctance should not exceed 2 ~ 3% of gap reluctance.

At values of B above 1.5 T, μ begins to fall rapidly; the magnet is becoming non-linear; current has to be increased to overcome the non-linearity.

Above 1.9 T, μ is typically less than 100 (depending on steel type); yoke reluctance will exceed 5%. The dipole is becoming saturated. The power converter will need to provide significant extra current and power.

Excitation in Quads and Sextupoles.

For inscribed radius R,
and ignoring yoke reluctance;

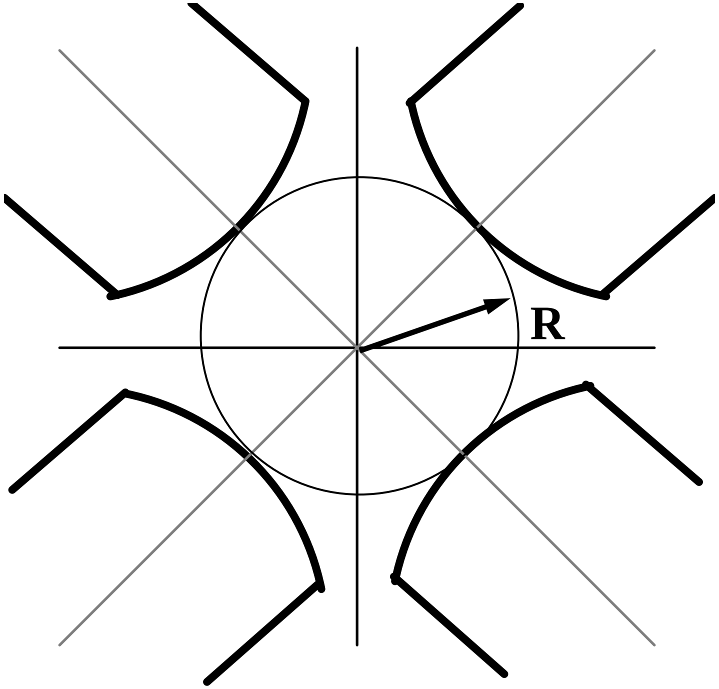
Amp – turns <u>per pole</u>:

Quadrupole:

NI = $G_q R^2/ 2 \mu_0$;

Sextupole:

NI = $G_s R^3/3 \mu_0$;



where: G_q is quadrupole gradient (T/m);
G_s is sextupole gradient (T/m^2).

The magnet/power converter interface.

Parameters to be chosen/optimised to ensure magnet/power converter compatibility:

- number of turns per magnet;
- current density in the conductor;
- length/field strength of the magnet.

In ‘conventional’ (not s.c.) magnets, these optima are determined by financial as well as technical issues. In s.c. magnets, the interface is technical (and financial!).

Number of turns - relationships

Fixed:

beam energy;

total Ampere-turns in coil: (NI);

conductor current density: j;

Therefore:

current $I \propto 1/N$;

cross section/turn: $A = I/j$;

$\propto 1/N$;

coil resistance: $R \propto N/A$;

$\propto N^2$;

power loss: $W = I^2 R$;

$\propto (1/N)^2 N^2$;

independent of N!

Number of turns - consequences

Advantages of large N:

- **lower** I – power converter current is decreased;
- **less loss** in transformers, rectifiers, cables.

Disadvantages of large N:

- **higher voltage** on converter, cables, magnets terminals;
- coil conductor content remains constant but inter-turn insulation increases – **coil becomes more larger** .

So, choice of N is a compromise between magnet design and power converter design.

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.

Current density (j) in conventional conductors.

Fixed:

beam energy;
number of turns N and current I.

Therefore:

cross section/turn: A $= I/j$;
coil resistance: R $\propto 1/A$;
$\propto j$;
power loss: W $= I^2 R$;
$\propto j$;
coil volume and weight $\propto 1/j$

Current density - consequences

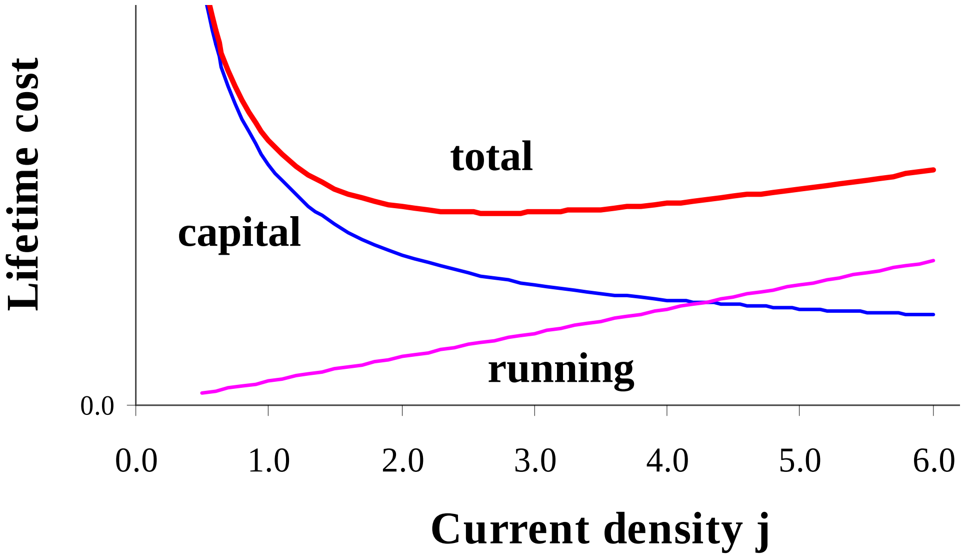
Advantages of low j:

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

Disadvantages:

- **higher capital cost;**
- **larger magnets.**

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

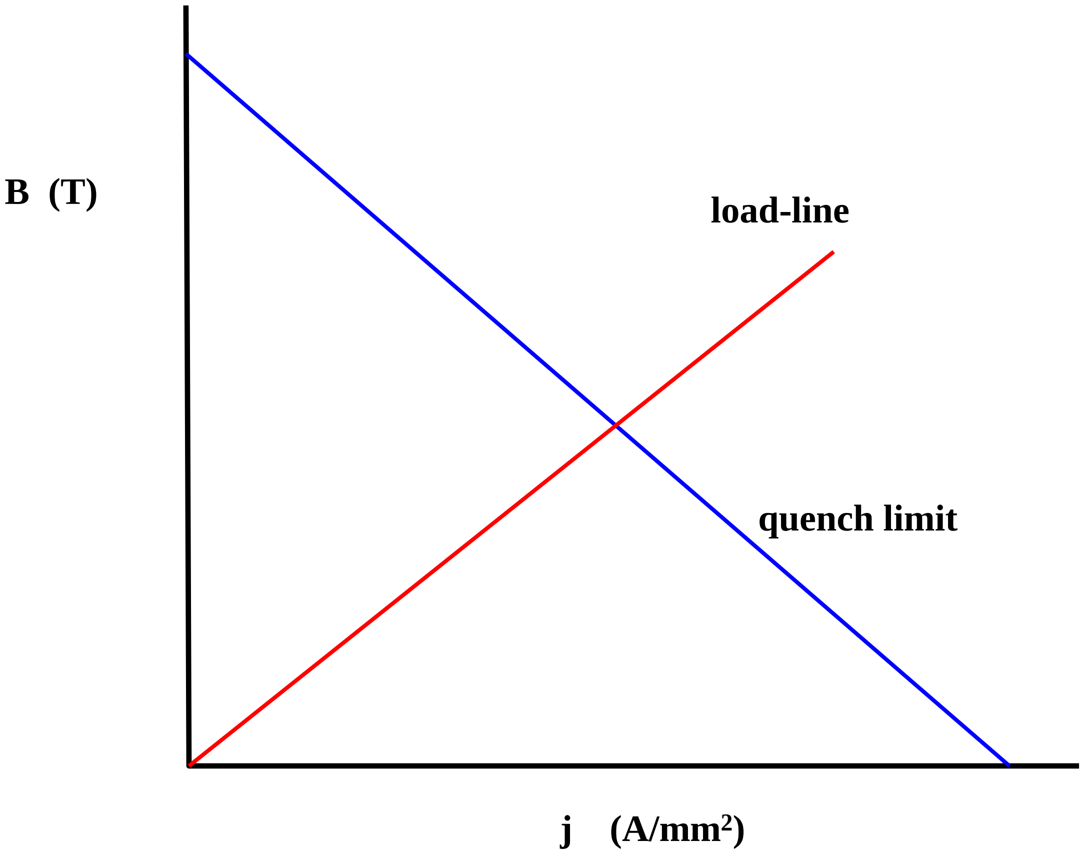


J and N in s.c. magnets

Specialised topic:

Current density chosen according to conductor B/j behaviour:

Number of turns determined by cable availability.



Length (ℓ)/Field (B) in d.c. magnets

Fixed: magnetic strength $B\ell$;
number of turns N;
j in conductor (but see below).

Then: field $B \propto 1/\ell$.
current $I \propto 1/\ell$;
resistance $R \sim \ell$;
power $W = I^2 R$;
$\propto 1/\ell$;

So longer magnets need less power – but more steel and conductor – this affects the optimisation of j !!

<u>But</u> if the conductor volume is kept constant (j varies):
cross section/turn $A \propto 1/\ell$;
resistance $R \sim \ell^2$;

Power is then independent of ℓ.

Length (ℓ)/Field (B) in a.c. magnets

Fixed: magnetic strength $B\ell$;
number of turns N;
j in conductor.

Then: field $B \propto 1/\ell$.
stored energy $E \propto B^2\ell$.
$\propto 1/\ell$.

A.C. power converter rating will strongly depend on stored energy (see presentation on cycling accelerators).

So: longer a.c. magnets have lower VA ratings irrespective of coil cross section or current density.

Length (ℓ)/Field (B) – conclusion.

Whilst magnet and power converter economics will play a role in determining the optimum B against ℓ, many other issues are also involved:

- building and infrastructure costs;
- r.f. power rating (particularly in electron accelerators);
- vacuum system costs;
- radiation spectra from bending magnets (in synchrotron sources);
- etc.