The impact of magnet field quality on machine performance

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Outline

- Introduction
- Magnet tolerances / beam parameters
- Closed orbit distortions
- Focusing errors
- Emittances and beam sizes
- Multipolar errors

Introduction

First step in designing a synchrotron or storage ring: choose the lattice, i.e. an optimum pattern of beam guiding elements

At this stage, ideal magnets are considered:

- Identity between magnets
- Non-linearities are ignored

In practice, the ideal desired distribution of the magnetic field cannot be obtained (pole truncation, fringe and remanent fields, machining and assembly errors, environment, alignment, power supply fluctuations,….)

Achieving target performances

- luminosity for a collider
- brilliance for a light source
- number of particles for a synchrotron

requires very tight tolerances on the magnetic field

Magnet tolerances

Magnet tolerances are derived from their effects on beam dynamics, taking into consideration their feasibility and cost implication

Machine	Magnet imperfection s			Cures	
parameters	dipoles	quadrupoles	sextupoles	dipoles	quadrupoles
Closed orbit errors $< \Delta x >$	$<\Delta BL/BL>$ $<\Delta s_D>$	$<\Delta x_Q>$		shimming sorting	alignment
$< \Delta y >$	$<\Delta z_D>$ $<\Delta \varphi_s>$	$<\Delta z_Q>$		alignment	alignment
Focusing errors	$<\Delta n>$	$<\Delta GL/GL>$ $<\Delta s_Q>$	$<\Delta x_S>$		sorting alignment
Coupling errors	$<\Delta z_D>$ $<\Delta \varphi_s>$	$<\Delta z_Q>$ $<\Delta \varphi_s>$	$<\Delta z_S>$	alignment	alignment
Non-linear behaviour	systematic and random multipoles				

A few examples of tolerances

Generally balanced between the different contributions, unless one is dominating

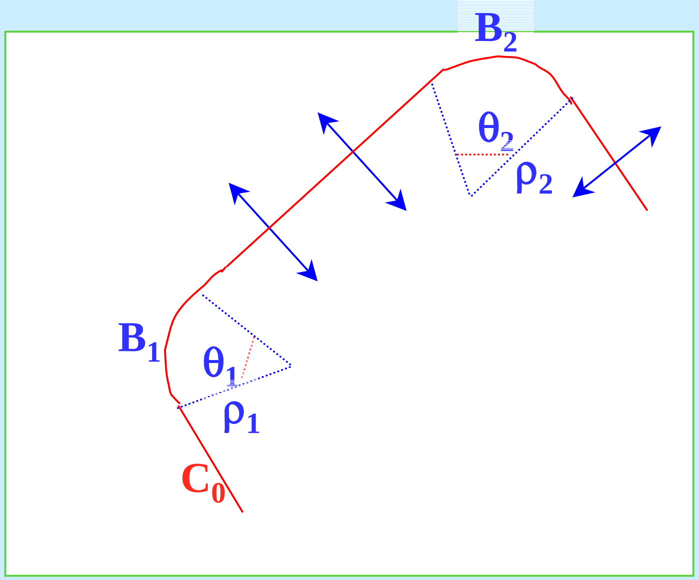
	ESRF	LEP	MIMAS
Field			
$\langle \Delta BL/BL \rangle$	5 10^{-4}	5 10^{-4}	5. 10^{-4}
sextupole	5 10^{-3}@25 mm	2/-5 10^{-4}@59 mm	
decapole	2 10^{-3}@25 mm	1.3 10^{-4}@59 mm	0.3 mrad
$\langle \Delta GL/GL \rangle$	1.0 10^{-3}	1.3 10^{-4}@59 mm	5.0 10^{-4}
octupole	5 10^{-3}@32 mm	5 10^{-4}@59 mm	
dodecapole	5 10^{-3}@32 mm	1 10^{-3}@59 mm	
Alignment			
$\langle \Delta x_Q \rangle$ / $\langle \Delta z_Q \rangle$	0.1 / 0.1mm	0.1 / 0.1mm	1.2 / 0.6 mm
$\langle \Delta \varphi_s \rangle$	0.2 mrad	0.1 mrad	0.3 mrad

Closed orbit distortions

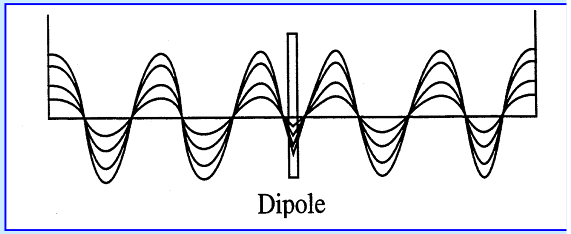
Bending field matched to some ideal momentum p_0

↓

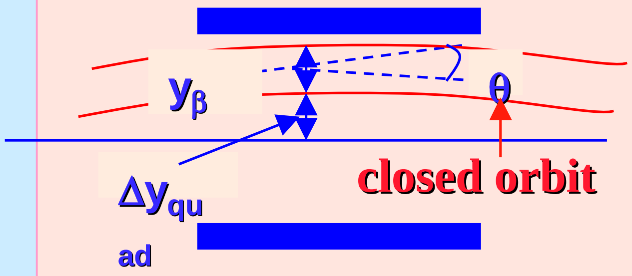
Reference trajectory C_0 which closes on itself



Imperfections in the guide field can distort this orbit



Quadrupole displacements



quadrupole of strength k and length l

$$\boxed{\begin{aligned}\theta_y &= kly = kl\left(\Delta y_{quad} + y_\beta\right)\\ &= kl\Delta y_{quad} + kly_\beta\end{aligned}}$$

↑

dipole kick

Amplification factor: $\boxed{A = \frac{\sigma_{co}}{\sigma_{quad}}}$

A~100 ⇨ σ_{co} = 10 mm for σ_{quad} = 0.1 mm

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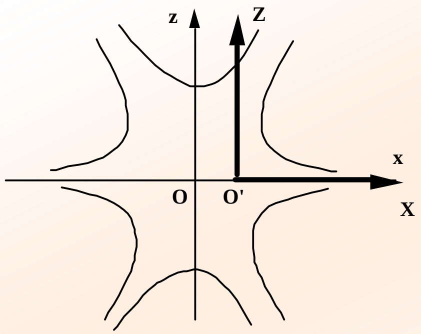
Closed orbit distortions (cont')

Machine side

- **Eats up available machine aperture**

  The size of the vacuum chamber and magnet aperture could become uneconomically large if large distortions are allowed

- **Cause the particles to pass off-centre through the sextupoles**



$B_x = 2Hxz$

$B_z = H(x^2 - z^2)$

from $x = x_O + X \;,\; z = Z$

$B_x = \quad 2Hx_{O'}z + 2Hxz$

$B_z = Hx_{O'}^2 + 2Hx_{O'}x + H(x^2 - z^2)$

☯ ☯ ☯

dipole quadrupole hexapole

c.o in multipole of order n generates multipolar errors of order < n

Orbit distortion

+

Random quadrupole effect

- **Generates coupling errors**

Beam size and emittance blow-up

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Closed orbit distortions (cont')

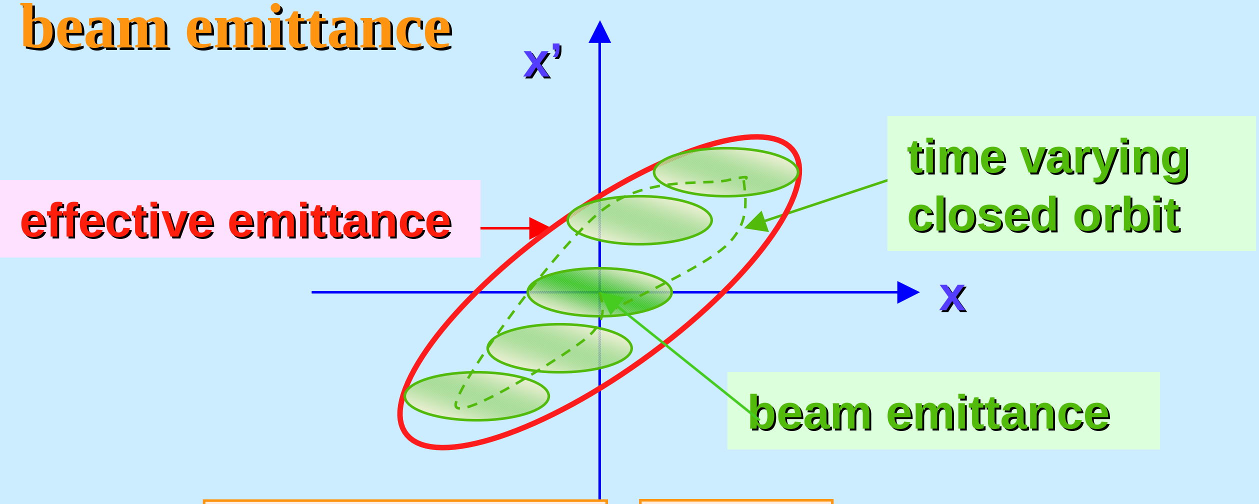
User side

Beam motion is detrimental to beamline performance

- Intensity changes degrade measurement resolution
- Mis-steering can miss sample

Time varying closed orbit errors displace the beam's centre of mass

The change in position or angle is equivalent to an enlargement of the beam emittance



effective emittance

time varying closed orbit

beam emittance

$$\sigma^2_{eff} = \sigma^2_{\beta} + \sigma^2_{co}$$

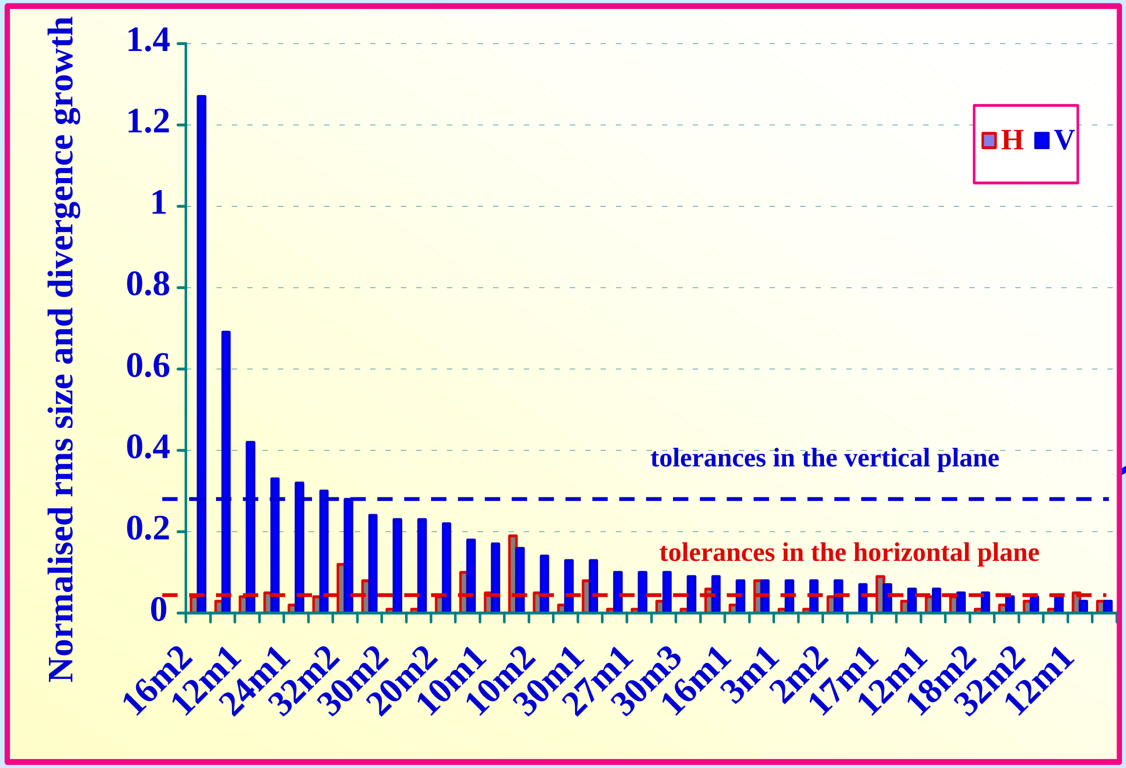
$$\rightarrow \varepsilon_{ff}$$

Usual tolerances:

10 % of beam size and divergence

Effects of Insertion Devices

Basic specification: after passing through an ID, the beam should return to its nominal orbit ⇨ $\int B ds = 0$



→

0.12 ± 0.08 G.m

0.40 ± 0.2 Gm^2

→

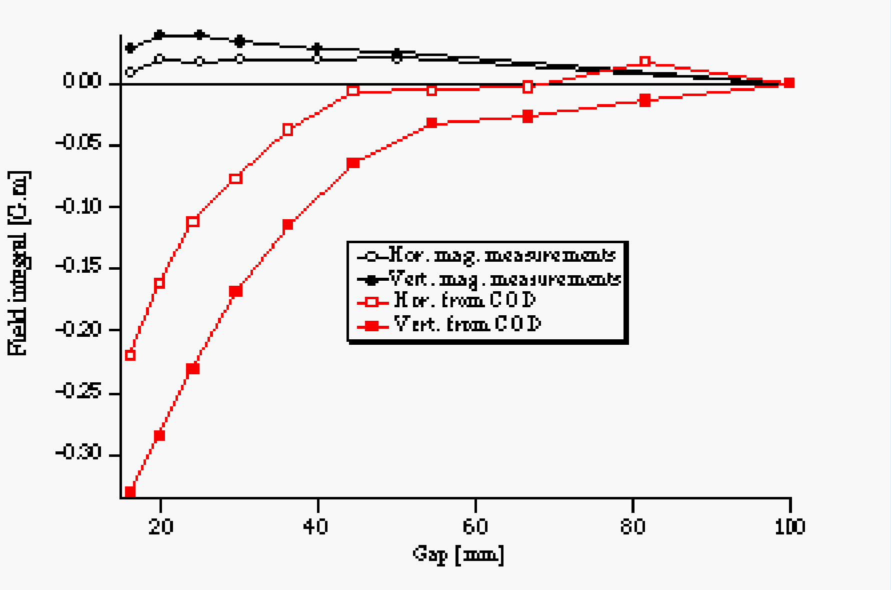
0.15 ± 0.1 G.m

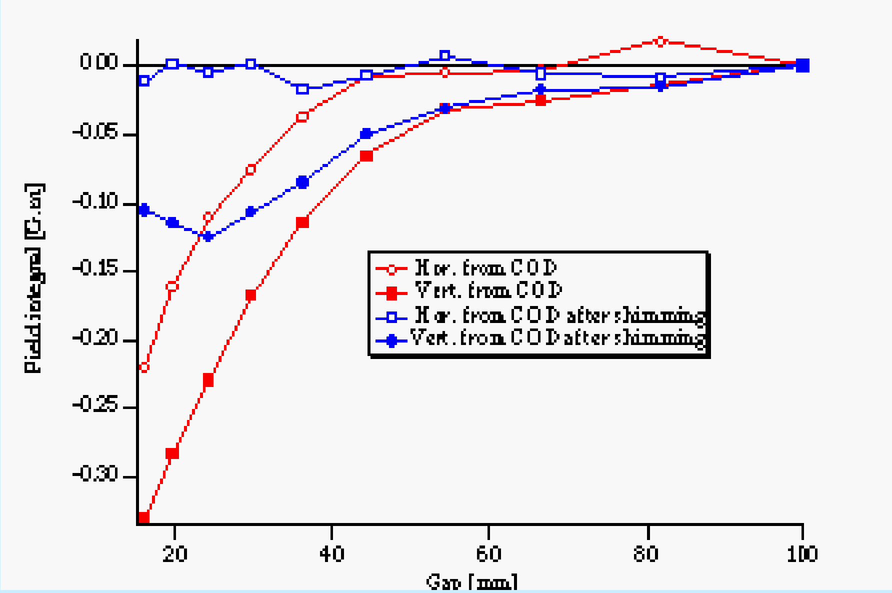
0.60 ± 0.3 Gm^2

Courtesy of J. Chavanne (ESRF)

Effects of Insertion Devices (cont')

Example of in-situ shimming to correct field integrals





Courtesy of J. Chavanne (ESRF)

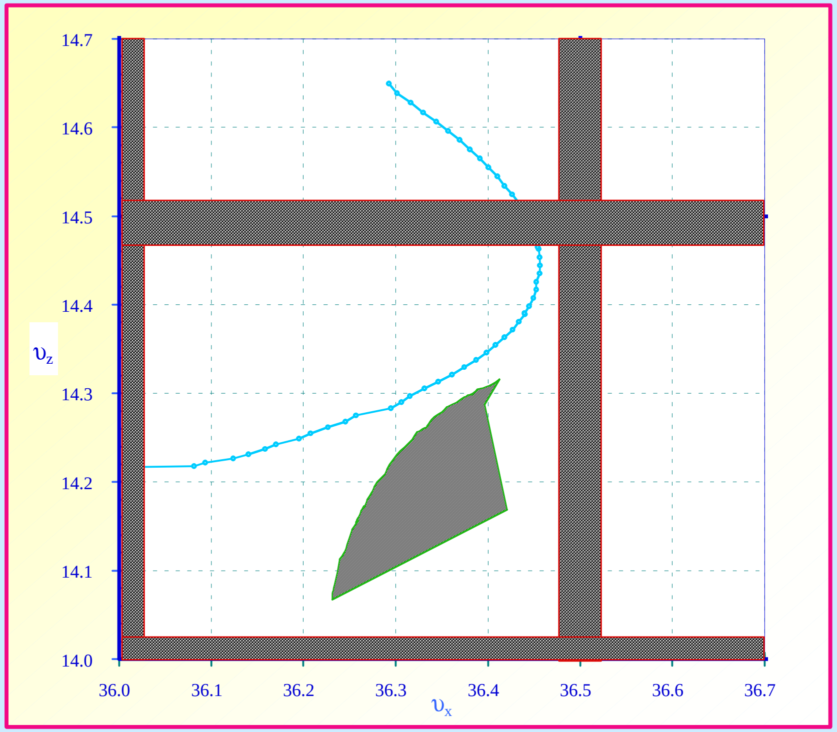
Focusing errors

Parasitic focusing strengths are mainly induced by gradient errors in quadrupoles and horizontal mis-positioning of sextupoles

- **Excitation of resonances and stop-bands limiting the allowed region in the tune diagram**

Stop-band width $$\Delta\upsilon \approx \left< \frac{\Delta Gl}{Gl} \right>$$

Any particle whose tune lies in the stop-band locks into resonance and is lost



Focusing errors (cont')

- **Modulation of β-functions** ⇨ **blow-up of beam sizes**
  reduction of dynamic aperture

Dynamic aperture = boundary of stable motion in the x-y plane

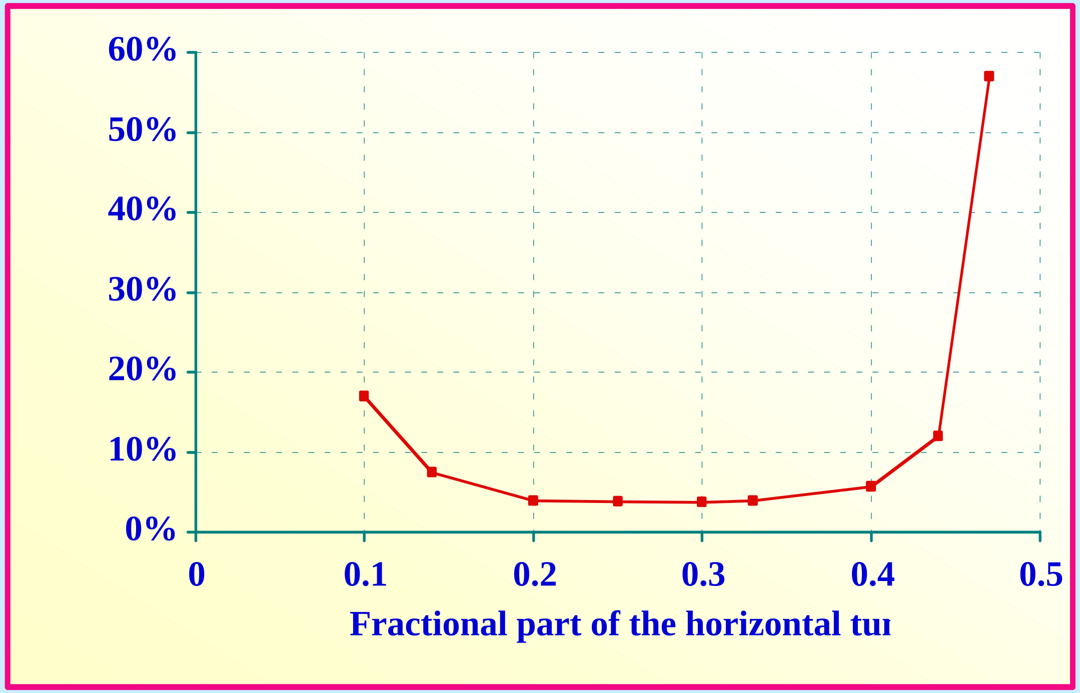
Must be large enough to accommodate the oscillations of the injected beam and Coulomb or Touschek scattered particles

Otherwise poor injection efficiency
short lifetime

Emittances and beam sizes

Achieving design emittances and beam sizes is a key issue for a number of machines. This can be spoilt by many factors .

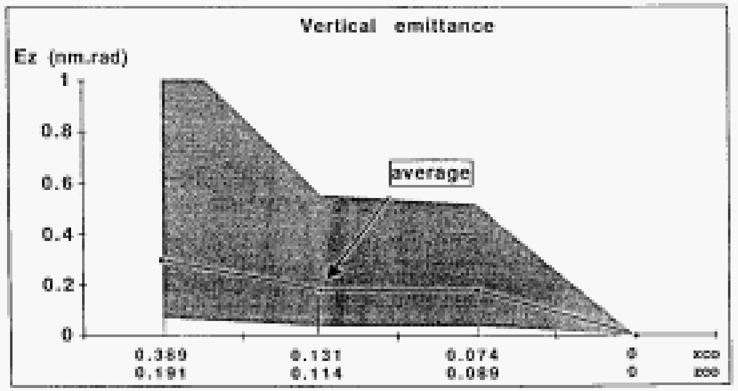
Blow-up of the horizontal emittance due to the proximity of quadrupolar errors and / or an imperfect closed orbit

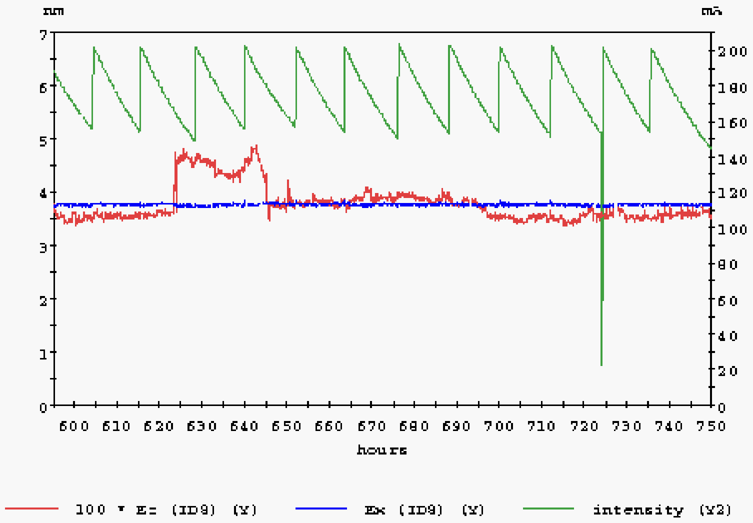


Emittances and beam sizes (cont')

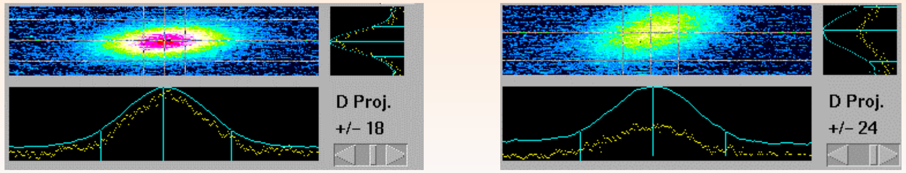
The vertical emittance, which is null in a perfect e^- machine, is generated by several sources of imperfections:

- **dipole or quadrupole rotation errors**
- **closed orbit distortions**





Beam spot measured by a pinhole camera



gap = 20 mm

gap = 2.25 mm

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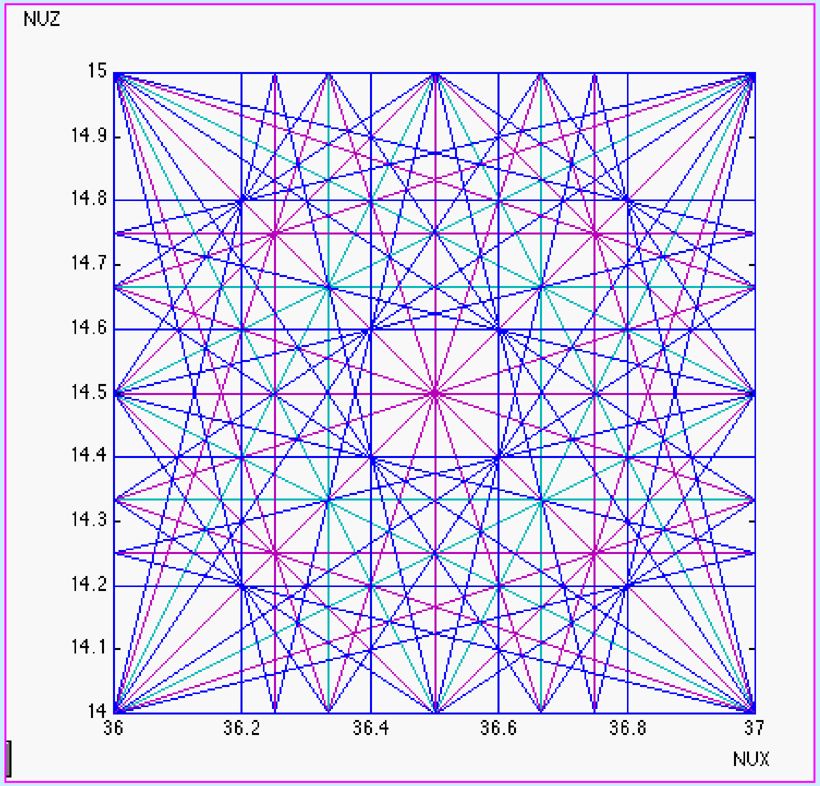
Multipolar errors

Multipolar field errors present in the guide field drive resonances

The order of the resonance is related to the order of the multipole
The width of the stop-band depends directly on the strength of the error

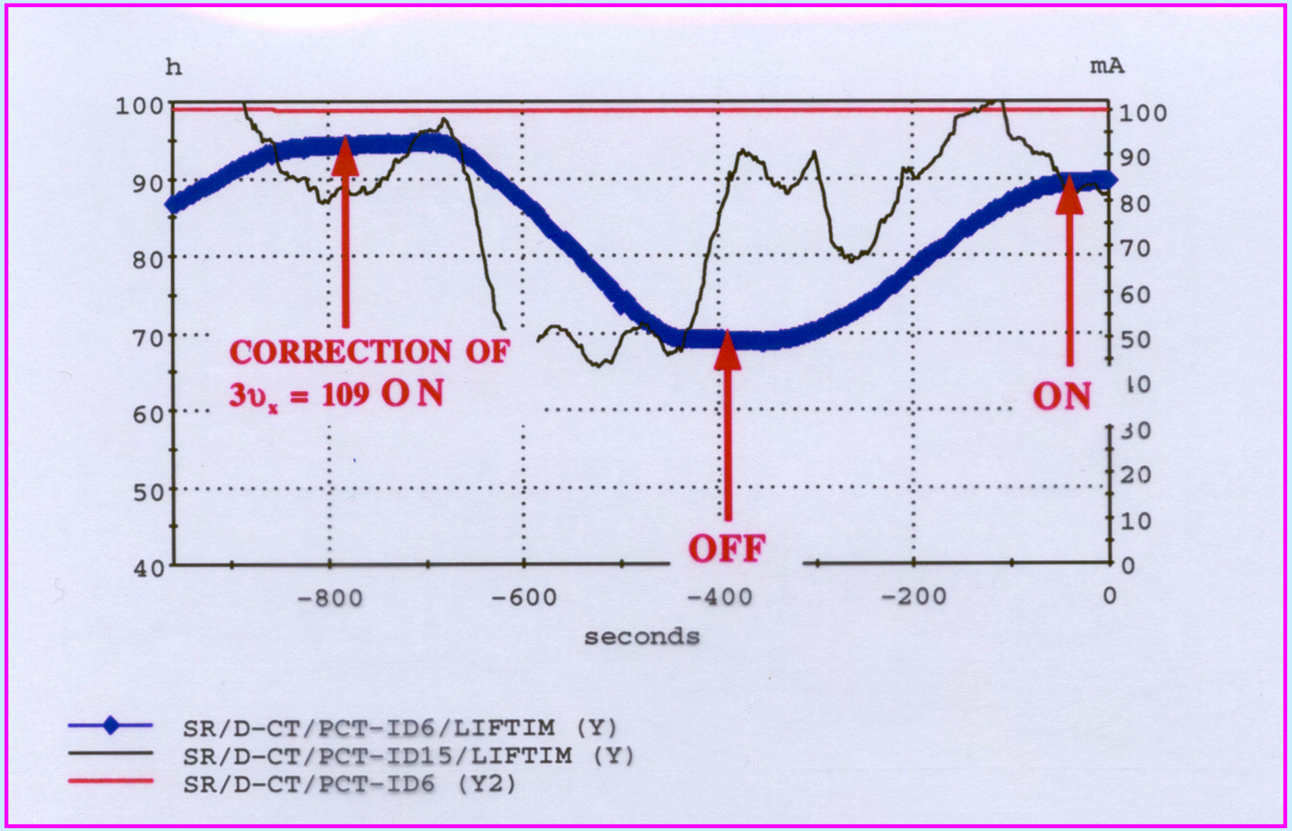
The errors must be small enough to leave clear space between the stop-bands

Otherwise particles will be lost during acceleration or storage



Multipolar errors (cont')

Effect of the correction of a third-order resonance driven by sextupoles



CORRECTION OF $3\upsilon_x = 109$ ON

OFF

ON

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Conclusion

Magnet field quality is critical in most modern accelerators

Precise magnetic measurements are essential to

Check whether magnets are within accelerator tolerances

Provide data for modelling the effects of errors on the beam and defining corrections

Set fiducial marks for precise alignment