The impact of magnet field quality on machine performance

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Introduction

The design of a storage ring or a synchrotron starts by choosing the lattice, i.e. an optimum pattern of beam guiding elements. At this stage, ideal magnets are considered: all magnets are supposed identical and non-linearities are discarded. In practice, the ideal desired distribution of the magnetic field cannot be obtained, due to many reasons: truncation of poles, fringe and remanent fields, machining and assembly errors, environment, alignment, power supply fluctuations… Even if the figure of merit to quantify performances is different from one machine to the next (luminosity for a collider, brilliance for a light source, number of particles for a synchrotron…), achieving target performances requires very tight tolerances on the magnetic field. Most of the figures quoted in this talk will be related to light sources but the basic effects apply to all rings.

Magnet tolerances

Magnet tolerances are derived from their effects on beam dynamics, taking into consideration their feasibility and cost implications. They are generally balanced between the different contributions. Four classes of effects on the beam (closed orbit errors, focusing errors, coupling errors, non-linear behaviour) are driven by magnet imperfections. The main sources of errors are random errors in the integral of field in bending magnets, random errors in the integral of gradient of quadrupoles, horizontal or vertical mis-positioning of magnets (dipoles, quadrupoles, sextupoles), roll errors. Typical values for the tolerances are:

field integral	$\langle \Delta Bl/Bl \rangle \approx$ a few 10^{-4}
integral of gradient	$\langle \Delta Gl/Gl \rangle$, a few 10^{-4}
positioning of quadrupoles	$\langle \Delta x_Q \rangle$ and $\langle \Delta y_Q \rangle \approx 0.1$ mm
roll errors	0.1 – 0.2 mrad

Shimming, sorting, alignment are the classical cures used to minimise the impact of these errors.

Closed orbit errors

The bending field is matched to some ideal momentum for which one can define a reference trajectory that closes on itself. This trajectory is referred as the closed orbit. Imperfections in the guide field can distort this orbit. In most machines, the major source of closed orbit comes from quadrupole displacements since they generate a dipole kick, which in turn causes a closed orbit deflection.

On the machine side, closed orbit distortions are detrimental since they eat-up the available machine aperture, thus leading to uneconomical enlargement of the size of the vacuum chamber and magnet aperture. Since they cause the particles to pass off-centre through the sextupoles, a random quadrupole effect is induced. The orbit distortions also induce coupling errors, resulting in a blow-up of beam sizes and emittances. For an insertion device, the basic requirement is that, after passing through it, the beam should return to its nominal orbit. If this is not the case, a closed orbit will be set up, giving beam displacements around the machine and thus perturbing other beamlines.

Beam motion is also detrimental to beamline performance: time varying closed orbit errors displace the beam's centre of mass and the corresponding change in position or angle is equivalent to an enlargement of the beam emittance. For a light source, usual tolerances amount to 10 % of beam size and divergence, i.e. to the μm or μrad range.

Focusing errors

Parasitic focusing strengths are mainly induced by gradient errors in quadrupoles and horizontal mis-positioning of sextupoles. The main consequences are the excitation of random quadrupolar resonances. The excitation of these resonances creates stop-bands limiting the allowed region in the tune diagram. Any particle whose tune lies in the stop-band locks into resonance and is lost. For example, this limits the excursions in tune of Touschek scattered particles in a light source and degrades the lifetime; in a synchrotron, the number of injected particles might be reduced since space charge effects determine the zone occupied by the beam in the tune diagram.

Focusing errors also produce a modulation of β-functions that leads to a blow-up of beam sizes and a reduction of dynamic aperture, i.e. the boundary of stable motion in the $x - y$ plane. If the dynamic aperture is not large enough to accommodate the oscillations of the injected beam and of scattered particles, a poor injection efficiency and lifetime are induced.

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, generation of vertical emittance (ideally null) in an electron machine by dipole or quadrupole roll errors, closed orbit distortions, insertion device gap changes in a light source.

Multipolar errors

Multipolar field errors present in the guide field drive non-linear resonances. Since the width of the stop-bands directly depends on the strength of the error, the errors must be small enough to leave free space between the stop-bands. Otherwise, particles will be lost during acceleration or storage.

Conclusions

Magnet field quality is critical in most modern accelerators. Precise magnetic measurements are essential to check whether magnets are within accelerator tolerances, set fiducial marks for precise alignment, provide data for modelling the effects of errors on the beam and for defining adequate corrections.