Alignment Issues for the 3 TeV Ring

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Traditionally, separate function accelerators have always included a system of individually tunable correction dipoles, one at each quadrupole, to correct for the errors in quadrupole alignment, roll angle of the dipoles, and variations in the integral field of the dipoles. This note examines the possibility of doing without the correction dipoles, in the interest of economy, and instead realigning the quadrupoles rather frequently, based on an analysis of the beam orbit. This technique was in fact used for the Fermilab Main Ring, in which the correction dipoles were too weak to center the beam at 200 GeV. This realignment could be done in the customary manner or more inventively with a robot (an idea provided by Bill Foster), which would allow adjustments while beam was circulating, or at least without an access to the ring. Data is also presented on the rate at which the quadrupoles of several existing accelerators became misaligned.

Following the analysis and notation of Ref. [1], the maximum (98% probability) closed orbit distortion has been evaluated for assumed rms values of the misalignments. The analysis of Ref. [1] is based on the derivations of N. M. King [2] for a separate function machine; it is assumed that it would apply to a combined function machine to within a factor of two.

Let ΔQ_{rms} = the rms misalignment of the "quadrupoles" (the magnets in this case)
$\Delta B/B_{rms}$ = the rms variation of dipole field from magnet to magnet
$\Delta \Phi_{rms}$ = the rms roll angle of the dipoles
$\langle X \rangle_Q$, $\langle Y \rangle_Q$, $\langle X \rangle_B$, $\langle Y \rangle_\Phi$ = the maximum closed orbit distortions resulting from each of these misalignments.

For the values of the parameters, it has been assumed that:
ΔQ_{rms} = 0.1 mm (this has been achieved at LEP)
$\Delta B/B_{rms} = 2 \times 10^{-4}$ (from Bill Foster, achievable with magnet sorting)
$\Delta \Phi_{rms}$ = 0.17 mrad.

Of these parameters, the last one is the most questionable. It is derived assuming that the elevation of the left side of the magnet can be set to within 25 microns of the right side of the magnet - and that the mean magnetic plane of the magnet can be known that well relative to external fiducials. This parameter will need some R&D.

The equations of Ref. [1] also need some parameters of the ring, which are taken to be:
cell length = 172 m
number of dipoles per cell = 12
tune of machine = 33.18
phase advance per cell = 60°.

The resulting values of the maximum closed orbit distortions are:
$\langle X \rangle_Q = \langle Y \rangle_Q$ = 15 mm
$\langle X \rangle_B$ = 16 mm
$\langle Y \rangle_\Phi$ = 14 mm

which can be compared with the half widths of the vacuum tube, 15 x 9 mm. The conclusion is that at startup of the machine, one would probably not achieve a full turn of the beam before hitting the vacuum pipe. Either a few corrector magnets in each plane would be needed, or the robot would have to make selected magnet realignments slightly upstream of the last place that the beam was lost. It appears very inefficient to send a crew into the ring to adjust magnets every time that the beam is lost at a new location.

It is also instructive to apply this same formalism to the Tevatron, where the misalignment parameters were well known at startup time and the initial tune-up is remembered The values of the parameters were:

$\Delta Q_{rmsH} = 0.56$ mm

$\Delta Q_{rmsV} = 0.30$ mm

$\Delta B/B_{rms} = 1 \times 10^{-3}$

$\Delta \Phi_{rms} = 0.28$ mrad.

The resulting values of the maximum closed orbit distortions are:

$<X>_Q = 44$ mm

$<Y>_Q = 23$ mm

$<X>_B = 32$ mm

$<Y>_\Phi = 9$ mm

which can be compared with the beam pipe radius of 32 mm. The following experiences are remembered from the first attempt to nurse the beam around the ring. After adjusting the first few correction dipoles in E-sector to compensate for injection errors, the beam went all the way from E15 to a beam dump at A0 (roughly one-third of the ring) without any correction dipoles. Later, when the rest of the ring had been installed and cooled, it took only a few correction dipoles to achieve the first complete turn.

In planning for how often it might be necessary to realign magnets, it is instructive to examine the rates at which the alignment of the SPS, the Tevatron, and LHC degenerated. In the SPS, which is the same size as the Main Ring but which is placed on bedrock (“molasse”), ΔQ_{rmsH} grew at the rate of 0.02 mm/yr over the course of 9 years, while ΔQ_{rmsV} grew at the rate of 0.05 mm/yr over a 4 year period. In the Tevatron, ΔQ_{rmsV} grew at the rate of 0.1 mm/yr in the first two years after the initial alignment, and then at a rate of 0.22 mm/yr in the next two years. The large difference between the SPS and Tevatron experience may be due to the fact that the Tevatron is placed on the glacial til (clay).

In LEP, which is also set in bedrock, but which crosses a fault line in Ferney-Voltaire and goes somewhat into the Jura mountains, ΔQ_{rmsV} grew at the rate of 0.14 mm/yr during the four years after initial alignment. This rms value is calculated after removing from the data two local “spikes” of 3 mm and 10 mm.

If the experience in the 3 TeV ring is comparable to that of LEP, and one wants to keep ΔQ_{rms} less than 0.025 mm relative to the initial beam-on alignment, then one would need to realign several times per year.

References:

1. C. Moore, C. T. Murphy, J. Norem, and M. Zisman, in "Accelerator Physics Issues for a Superconducting Super Collider", M. Tigner, ed. (Ann Arbor, 1983) 78.
2. N. M. King, in “Proceedings of the Second ICFA Workshop on Possibilities and Limitations of Accelerators and Detectors”, U. Amaldi, ed. (Les Diablerets, 1979).