Alignment in Circular Colliders and Specific Requirements for LHC

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IWAA 2004, CERN October 2004
Outline

• Closed orbit and tolerances
• Magnetic issues at LHC
• Aperture issues
  → Survey issues
• Conclusions
Closed orbit and tolerances
An issue for all machines: Closed Orbit errors

- Perfect machine, except for one QD mis-placed by $\Delta x = 1\text{mm}$ horizontally
- Without correction: $\sim \Delta x$ every 4th MQ with 1 MQ mis-placed
- With $N_{\text{MQ}} = 400$ and random moves
  \[ \Delta x = \sqrt{N} \] $\Delta x/4 = 5\text{mm r.m.s.}$
  \[ \rightarrow 10-15\text{mm peak} \]
- Larger ring: CO control more important (both good geometry and good correction system)

Mad model and correction algorithm, J. Wenninger
Residual after correction

- Usual case: no H-kicker at QD
  - Non-local correction:
    - Perturbation not eliminated, and expanding over \( \sim 7 \text{ MQ} \)
  - r.m.s \( \Delta x = 1 \text{ mm} \) over all MQ’s and BPM’s:
    - \( \Sigma_{\text{rms}} \Delta x = 1.5 \text{ mm} \)
  - This without BPM resolution, missing BPM’s, local coherent distortions, numeric matrix inversion errors …
  - \( \Delta_{\text{MQ}} < 1.5 \text{ mm} \), \( \Delta_{\text{BPM}} < 0.5 \text{ mm} \) (tol, total)

Mad model and correction algorithm, J. Wenninger
Experimental insertions

- High luminosity at LHC $\rightarrow$ beam size at crossing $\sigma = 17 \, \mu m$
- $\beta_{MQX} = 5000 \, m$ compared to $\beta_{arc} = 200m$
- Beam divergence $\sigma'_{MQX} = \sigma_{arc}/5$

- 2 opposite protons beams in the same tube: dipoles cannot do the job there
  $\rightarrow$ CO corrections must be made $\sim 2-300 \, m$ away

- Very critical, need MQX perfectly aligned with frequent remote checks and re-alignment
- See A. Herty et al. Tuesday
Magnetic issues
LHC basic parameters - I

• Goal: Allow to discover a H-boson up to $m_H = 400$ GeV (and more)
  → Proton-proton Collisions at $\sim 10$ TeV + 10 TeV
  → Luminosity $L = 10^{34}$ cm$^{-2}$s$^{-1}$ so: high stored current

• Fit in the LEP tunnel with arc curvature $\rho = 3606$ m

  With a filling factor of 0.8 (need focusing, correctors, etc):

  $\Rightarrow \rho_{mb} = 0.8 \rho = 2800$ m and $B = \frac{E}{0.3 \rho_{mb}} = \frac{10^4 \text{ GeV}}{0.3 \times 2800} = 12$T

• Classical ‘warm’ magnets: $B < 2$T
  → Need superconductor magnets
LHC basic parameters - II

- Best candidates NbTi, with in practice $B_{\text{best}} \approx 9$ T
- This even with superfluid helium
  \[(T_c = 2.8 \text{ K at } B=9T)\]

$\rightarrow$ Beam Energy in collision: $E_{\text{coll}} \approx 7$ TeV

- Finally: use existing injector: $E_{\text{inj}} = 0.45$ TeV
  $\rightarrow$ Fixes the r.m.s beam size $\sigma = 1.2$ mm
  $\rightarrow$ And the vacuum chamber size, see below
A super-conducting dipole field – basic theory

\[ \int_{\text{border}} \vec{B} \, d\vec{s} = \int_{\text{inside}} i \, dS \Rightarrow B(r) = \frac{\mu_0 i}{2} r \]

\[ \vec{B} = \frac{\mu_0 i}{2} (\vec{k} \wedge \vec{r}) \]

\[ \vec{B}_1 + \vec{B}_2 = \frac{\mu_0 i}{2} \left[ \vec{k} \wedge (\vec{r} + \epsilon \vec{i}) - \vec{k} \wedge (\vec{r} - \epsilon \vec{i}) \right] = \mu_0 i \epsilon \left[ \vec{k} \wedge \vec{i} \right] = \mu_0 i \epsilon \vec{j} \]

\[ \Rightarrow \text{A skin of current varying with } \cos \phi \]

produces a uniform dipole field

But: to be perfect, \( \epsilon \to 0, i \to \infty \)
The coils

- $\epsilon \approx 1$, not exactly $\epsilon \to 0$
- Cosine function not very close to textbook definition
- In spite of clever corrections, field map is not constant enough
  $\Rightarrow$ Need corrective elements

- $B = 9T \Rightarrow NI = 1MA$
  $\Rightarrow$ EM forces $\sim 2MN/m$
  $\Rightarrow$ High mechanical stiffness
A super-conducting dipole field – in practice

- 2 beam lines with opposite polarity
- Economical
- Twist control

Length $L = 15$ m
Weight $m = 27$ tons

Working point $T = 2$ K
(superfluid helium)
$\rightarrow$ Embedded in a cryostat

$\rightarrow$ CM hidden to Survey

Courtesy of F. Savary AT-MAS and F. Seyvet AT-CRI
Alignment in LHC, IWAA 04, BJ
Magnetic correction strategy

- Field map modify the tune, the chromaticity, etc.
- They can reduce the dynamic aperture (beam lifetime, losses)
- Corrections are needed
- Multipole coils running inside the main coils:
  - Strong dB/dt of main field $\Rightarrow$ strong inductive and persistent errors s.c. (non-resistive) in correcting coils (HERA)
- Rather: Autonomous correctors at the extremities
  - No inductive errors
  - But alignment issues

$\Rightarrow$ Transmutation of Magnetic problems into Survey issues! (see below)
### Field map errors expressed as multipole expansion in unit $10^{-4}$ with latest coil-shape

Use $z = x + iy$

$$B_y + iB_x = B_1 \sum_n (b_n + ia_n)(\frac{z}{17\text{ mm}})^{n-1}$$

Consider $b_5$, then misalign spool by $\delta$ along $y$:

$$(y + \delta)^4 - x^4 = \ldots = 4y^3\delta + 6y2\delta^3 + \ldots$$

$$\implies a_{4d} = \frac{4\delta}{R_r}b_5$$

The critical displacement $\delta_{cr}$ for $a_{4d} < a_4/2$ is:

$$\delta_{cr} < \frac{a_{4d}}{2b_5} \frac{R_r}{4} = 0.3 \text{ mm}$$

!! Much simplified, see S. Fartoukh LCC 2001-11 & FQWG March 2003 !!

<table>
<thead>
<tr>
<th>N-pole</th>
<th>Ap1 inj/top</th>
<th>Ap1 inj/top</th>
</tr>
</thead>
<tbody>
<tr>
<td>b2</td>
<td>$\sim 1.3$</td>
<td>$\sim -1.1$</td>
</tr>
<tr>
<td>b3</td>
<td>$\sim -4.5/3$</td>
<td>$\sim -4.5/3$</td>
</tr>
<tr>
<td>b4</td>
<td>$\sim 0/0.2$</td>
<td>$\sim 0/0.2$</td>
</tr>
<tr>
<td>b5</td>
<td>$\sim +1.0/0$</td>
<td>$\sim +1.0/0$</td>
</tr>
<tr>
<td>b6</td>
<td>$\sim 0$</td>
<td>$\sim 0$</td>
</tr>
<tr>
<td>b7</td>
<td>$\sim +0.3/+0.7$</td>
<td>$\sim +0.3/+0.7$</td>
</tr>
<tr>
<td>b8</td>
<td>$\sim 0$</td>
<td>$\sim 0$</td>
</tr>
<tr>
<td>b9</td>
<td>$\sim 0.8$</td>
<td>$\sim 0.8$</td>
</tr>
<tr>
<td>a2</td>
<td>$\sim -0.4$</td>
<td>$\sim -0.4$</td>
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<tr>
<td>a3</td>
<td>$\sim -0.26$</td>
<td>$\sim -0.23$</td>
</tr>
<tr>
<td>a4</td>
<td>$\sim +0.13$</td>
<td>$\sim +0.13$</td>
</tr>
<tr>
<td>a5</td>
<td>$\sim 0.03$</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td>a6</td>
<td>$\sim 0$</td>
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</tr>
<tr>
<td>a7</td>
<td>$\sim 0.04$</td>
<td>$\sim 0.04$</td>
</tr>
<tr>
<td>a8</td>
<td>$\sim 0$</td>
<td>$\sim 0$</td>
</tr>
<tr>
<td>a9</td>
<td>$\sim 0$</td>
<td>$\sim 0$</td>
</tr>
</tbody>
</table>
# Beam based specification for spool piece

<table>
<thead>
<tr>
<th>Beam Spec.</th>
<th>$\Delta x, \Delta z$</th>
<th>$\sigma(x), \sigma(y)$ w.r.t. tunnel</th>
<th>$\sigma(x), \sigma(y)$ w.r.t. cold mass *</th>
<th>$\sigma(\theta)$ w.r.t. tunnel **</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>[mm]</td>
<td>[mm]</td>
<td>[mm]</td>
<td>[mrad]</td>
</tr>
<tr>
<td>MCS</td>
<td>0.3</td>
<td>0.5</td>
<td>0.15</td>
<td>1.5</td>
</tr>
<tr>
<td>MCDO</td>
<td>0.3</td>
<td>0.5</td>
<td>0.15</td>
<td>2</td>
</tr>
</tbody>
</table>

*i.e. Magn. Axis w.r.t. cold mass mechanical mid-plane at ITP20*

**Not different from $\sigma(\theta)$ w.r.t. cold mid-plane**

Source: S. Fartoukh, LCC 2001-11 and FQWG 4th March 2003

Alignment in LHC, IWAA 04, BJ
Aperture issues
Beam Aperture - I

- Initially: cold bore with radius $R = 25$ mm (this after all the rest was fixed)
- Short bunch separation (25ns) and large population ($1.1 \times 10^{11}$ p):
  - Multipacting + e-cloud
  $\Rightarrow$ Need of a beam screen
- Ions finally trapped on the 2K cold bore
- But 3mm lost for aperture
- So please, Survey …

Courtesy of N. Kos AT-VAC
Beam Aperture - II

• High beam intensity $N = 3000 \times 10^{11}$ p
• With $\tau_{\text{beam}}=20h$, $\frac{dN}{dt_{\text{loss}}} = 4 \times 10^9$ p/s
• Quench with $\frac{dN}{dt_{\text{quench}}} = 10^7$ p/s/m
• With a margin factor $m=100$, need a collimation system with a capture efficiency $\sim 10^4$ (effective cascade absorption length $\sim 1$m)
• 2-stage collimation OK, but need pipe away by $4\sigma$ from collimator aperture
Beam Aperture - III

- \( n_1 \sigma + \delta \sigma = 1.1 \ (6+4) \sigma = 13 \text{ mm} \)
- \( a = CO + t + Ddp = 9 \text{ mm} \)
- Remains \( t \cong 2.5 \text{ mm} \)
- Let skip the bargains about splitting \( t \) between Cold mass, Assembly, Survey …

What remains for the finished cold mass →

silver (blue line) and a few golden ones
Survey issues

What is needed

1) An object with its inner shape controlled down to $\Delta x \times \Delta z \approx 1.5 \times 0.7 \text{ mm}^2$ over 15m inside its cryostat

2) Relative axis error MB/spool pieces $\Delta x < 0.3 \text{ mm with } \delta_{\text{r.m.s}} = 0.15 \text{ mm}$

3) Alignment of the object in the tunnel at the same level of precision – not discussed here, see J.P. Quesnel this afternoon.
Align the imperfect object

With which criteria?

- Fit to theoretical curve, averaging two beam tubes for best aperture
- What means best magnetic position of spool w.r.t. body?
Criteria and method

• It was shown that the axis which minimises forbidden n-poles (expected $b_n = 0$) coincides with best fit of cold bore center within 0.1mm residual (W.Scandale et al.)
• Then fully rely on geometry
• Perform full 3D image of both tubes & ends
  (J.P. Quesnel, M. Mayoud, D. Missiaen)
• Algorithm of minimisation by D. Missiaen, see Thursday
• Same procedure in industry for cold mass and at CERN for cold mass + cryostat
  (M. Bajko et al., see Thursday E. Wildner)
Results so far: 3D Laser-tracker data for > 100 MB

- This one a bit better than average, but not a rare case
- We get more ‘golden’ MB’s than strictly needed
  ➔ Helps much to play with not so easy magnetic sorting

Data from industry
M. Bajko et al.

Data from CERN after cold test, D. Missiaen

Data retrieved from MTF and MAS dBase

Alignment in LHC, IWAA 04, BJ
Survey and geometry of MB

• 3D internal MB data proved to be essential
  – We can fit the geometry well inside strict tolerances
  – It allowed to find a nasty mechanical instability, which deformed the magnet during cold testing

• Now the assembly is
  – Precise enough (aperture and magnetic)
  – Stable
  – Elastic

• ( MQ : adequate magnetic data need be obtained together with 3D geometry survey , see L. Bottura Thursday )
Conclusions

• Past machine (CERN at least)
  – Survey team was to install a ‘rigid and perfect object’ on a theoretical central orbit in a 3D absolute frame. More was not always really welcome

• LHC
  – Every cold assembly deserves precise internal 3D geometry data
  – Survey participation was essential in the design phase (not always adequately admitted)
  – LHC performance depends on a close interplay between hardware design, beam physics+operation and survey. This is new and will be true for any future big machines
  – It seems to be in a good way for LHC in that respect
  – but still more than two years of work in front of us