

Experimental Magnets Commissioning

- Experiments Magnets Overview
- Commissioning, procedure
- Details, implementation

Ref.:
N. Catalan Lasheras, S. Fartoukh, J.P. Koutchouk, WPAB079, PAC’03
W. Herr, The effects of solenoids and dipole magnets of LHC experiments, Chamonix 2006

Acknowledgement: discussions with R. Bailey, W. Herr, S. Fartoukh, input from LPC, Alice solenoid data from A. Morsch, T. Risselada - Mad-X files and sample jobs; A. Koschik - remaining mismatch
Experiments Magnets Overview

IP1  Atlas   barrel and endcap toroids and  central solenoid  12 Tm  (6 m × 2 T)
IP2  Alice  dipole spectrometer internal angle y' = ±70 μrad and solenoid (L3) 6.05 Tm
(12.1 m × 0.5 T max, sometimes at lower field of 0.2 T)
IP5  CMS   central solenoid  52 Tm  (13 m × 4 T)
IP8  LHCb  dipole spectrometer 5 m from IP  4.2 Tm, x' = ±135 μrad

The spectrometer bumps are local, closed within Q1, adjust closure internally with using the calibration functions – then optics independent. Produce an internal crossing angle. Will be turned on here in commissioning phase A. Ramp at constant angle (LHCb spectrometer 5850A nominal, minimum 500 A requires an increase angle at 450 GeV) The additional external bumps to avoid parasitic collisions will only be needed later for 75 and 25 ns operation – not relevant for Phase A commissioning.

Toroids (Atlas): expect no effect on beam. To avoid any doubts: turn on together with solenoids - checks then apply to the combined system.

Solenoids: introduce coupling – minor effect for round beams. Once on, solenoids remain at fixed current such that solenoid coupling scales with 1/Energy.

General philosophy:
To avoid confusion and discussions (how small, what is negligible) : work in well defined order, with quantitative predictions and measurements. Prepare and use (linear, first order) corrections, calibrated with measurements.
### Commissioning Phases A

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<td>top energy, collisions (pilot physics)</td>
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<td>Reyes</td>
<td>Helmut</td>
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<td>A.12</td>
<td>Stefano</td>
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<tr>
<td>450 GeV, bring on experiments magnets</td>
<td>A. ?</td>
<td>D. Jacquet</td>
<td>Helmut ?</td>
<td></td>
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Adjustments at 450 GeV + short checks at 7 TeV. Could be done in steps - interleaved when convenient with top energy checks.

Phase A: no crossing angle. More checks needed in later phases with crossing angle.
Procedure

i) Alice and LHCb spectrometer dipole compensation
   • turn on bumps and check / adjust calibr. funct. for closure first at 450 GeV, both polarities
   check closure at 450 GeV with increased (~3 $\times$) angle
   • turn off in first ramp(s)
   • check again at 7 TeV, off and on both polarities. Then leave on in ramp at constant angle.

ii) Atlas, Alice, CMS solenoid compensation
commission at 450 GeV one by one (start with smallest and fasted - Alice) each time:
   • measure coupling and make sure it is well compensated
   • turn magnet on (measure during ramp-up)
   • measure coupling
   • turn on calculated compensation (globally, incremental adjust on skew quads)
   • measure coupling
   • scale/calibrate compensation if necessary
   • measure coupling - iterate if necessary (not expected)

solenoids + compensation: constant in field and current, reduced effect in strength at 7 TeV

solenoid coupling 7 TeV:
   • make sure LHC was well decoupled at 7 TeV before solenoids were turned on
   • check that this remains true after all solenoids were brought on with compensation as
     checked/adjusted at 450 GeV and scaled at constant current
Control - Knobs

i) spectrometer dipoles (calibration functions adjusted for perfect closure)
   - IR2 : Alice spectrometer. Knob to adjust internal crossing angle, ±70 μrad
   - IR8 : LHCb spectrometer. Knob to adjust internal crossing angle, ±135 μrad

ii) solenoids (with compensation adjusted to minimize global coupling)
   - IR1 : ATLAS solenoid. 0 – 1 (off to design current)
   - IR2 : ALICE solenoid. 0 – 1 (off to design current)
   - IR5 : CMS solenoid. 0 – 1 (off to design current)
More details

Spectrometer Bumps. Example IR8, horizontal, from W. Herr Chamonix ’06.

Nominal LHCb internal four magnet closed spectrometer bump. Closed within Q1, amplitude about ± 0.7 mm. Calibrate for perfect closure and always drive all 4 magnets together: then no optics dependence and perfectly decoupled from the rest of the machine.
small effect in LHC, see Koutchouk et al. CERN-SL-94-33, Part. Accel. 55 (1996) 183–191 (Montreux) smaller than uncorrected machine coupling of $c- \approx 0.17$ at injection before correction,

\[
c^T = - \frac{i}{4\pi} \frac{B_s l}{B\rho} \left( \sqrt{\frac{\beta_x^*}{\beta_y^*}} \pm \sqrt{\frac{\beta_x^*}{\beta_y^*}} \right)
\]

\[
c^- = - \frac{i}{2\pi} \frac{B_s l}{B\rho}
\]

\[
\theta = \frac{B_s l}{2B\rho}
\]

for round beams, the sum resonance is not excited, $c^+ = 0$

only the difference, $c-$ relevant

| $c-1$ measurable as closes tune approach

Why much weaker than in LEP? Two reasons:

• **strong LHC fields**
  
  LEP: L3 6 Tm, Aleph 10 Tm, Opal 2.6 Tm, Delphi 5 Tm
  
  LHC: Atlas 12 Tm, Alice 6 Tm, CMS 52 Tm or $5 \times$ stronger than LEP
  
  LEP inj. 22 GeV -> LHC inj. 450 GeV or $20 \times$ stronger than LEP

  relative importance of solenoids at injection $4 \times$ less in LEP

• **round beams** ($\beta_x^* = \beta_y^*$) Is this always guaranteed?ookie:

  $\beta^* x/y$ ratio, term in brackets $2$ for LEP, $6.3$ for LHC

  Together: solenoid fields (Aleph / CMS) at injection $12 \times$ stronger in LEP

  but also: LHC target tunes **much** ($3-10 \times$) closer to coupling resonance
Tunes can be measured very precisely based on SPS experience - impedance measurements, detuning with intensity even in the presence of several peaks, FFT with peak interpolation ~ 1/10 of bin width or $2 \times 10^{-5}$ for $2^{12} = 4096$ turns, often rather limited by machine stability; in SPS, well possible (even from cycle to cycle) to measure tunes to $<10^{-4}$

LHC design tunes, working point not far from coupling resonance

physics Q V-H 0.32 - 0.31 = 0.01 (LEP 1 Qx - Qy = 0.31 - 0.17 = 0.14)

injection Q V-H 0.31 - 0.28 = 0.03 required 1/10 of this or 0.003

LHC \( \rho = 2803.98 \text{ m} \)

450 GeV : \( B = 0.535324 \text{ T} \) \( B_\rho =1501.04 \text{ Tm} \)

7 TeV : \( B = 8.32727 \text{ T} \) \( B_\rho =23349.5 \text{ Tm} \)

<table>
<thead>
<tr>
<th></th>
<th>( B_s [T] )</th>
<th>( B_s L [\text{Tm}] )</th>
<th>c-, 450 GeV</th>
<th>c-, 7 TeV</th>
<th>( \theta ), mrad</th>
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<tbody>
<tr>
<td>IR1 Atlas</td>
<td>2</td>
<td>12</td>
<td>0.00127</td>
<td>0.00008</td>
<td>4.00</td>
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<td>IR2 Alice</td>
<td>0.5</td>
<td>6.05</td>
<td>0.00064</td>
<td>0.00004</td>
<td>2.02</td>
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<td>IR5 CMS</td>
<td>4</td>
<td>52</td>
<td>0.00551</td>
<td>0.00035</td>
<td>17.3</td>
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<td></td>
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<td>0.00743</td>
<td>0.00048</td>
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</table>
Implementation details, Mad-X files

**Numbers based on B×L,** internally using Bpeak and L such as to get correct B×L

V6.501 / V6.5.inj.str

Solenoid strength in mad convention $ks = eB/pc$; numerically with units $B[T] \times 0.299792458 / p [GeV]$ to avoid expressions and dependence on pbeam, madx strength files calculate currently $ks$ for 7 TeV as

- $abas := 12.00/6.0*clight/(7E12)*on.sol_atlas;$ ! Atlas solenoid 12.00 Tm
- $abls := 6.05/12.1*clight/(7E12)*on.sol_alice;$ ! Alice solenoid 6.05 Tm
- $abcs := 52.00/13.0*clight/(7E12)*on.sol_cms;$ ! CMS solenoid 52 Tm

V6.501 / V6.5.seq:

**REAL CONST l.MBAS = 6.0;** ! Atlas solenoid 12.00 Tm
**REAL CONST l.MBLS = 12.1;** ! Alice solenoid 6.05 Tm
**REAL CONST l.MBCS = 13.0;** ! CMS solenoid

mbas: solenoid, l:= l.mbas/2, ks:= abas;
mbls: solenoid, l:= l.mbls/2, ks:= abls;
mbcs: solenoid, l:= l.mbcs/2, ks:= abcs;

placed in two halves L/R of IP to allow for marker at IP

Knob on Mad-X level:
on_sol_atlas etc., see /afs/cern.ch/eng/lhc/optics/V6.501/job_solenoids.madx

also implemented in MadX with slicing by makethin for tracking, H.B. MadX meet 28/11/2005
still to be checked: signs, - solenoid field direction.
Coupling correction using skew quads is global (not local as in LEP), by increments in currents using the same skew quads as done for the machine coupling. Results in 0.1% $\beta$ and 0.2% dispersion beating.

Correction: 1st order, includes edge effects; checked that working well for both beams.
Global solenoid coupling correction, remaining mismatch

\[ \Delta \beta/\beta = 0.1 \% \text{ peak} \]

\[ \frac{\Delta D_x(s)}{\sqrt{\beta_x(s)}} / \frac{D_{x,\text{qf}}}{\sqrt{\beta_{x,\text{qf}}}} \text{ and } \frac{\Delta D_y(s)}{\sqrt{\beta_y(s)}} / \frac{D_{y,\text{qf}}}{\sqrt{\beta_{y,\text{qf}}}} \]

\[ D_{x,\text{qf}} = 2.1 \text{ m, } D_{y,\text{qf}} = 16 \text{ cm} \]

\[ \beta_{x,\text{qf}} = \beta_{y,\text{qf}} = 180 \text{ m} \]

Figure 3: Induced \( \beta \)- and dispersion-beating by the CMS solenoid in the LHC at 450 GeV.
Backup Slides
Entry conditions – both for 450 GeV part and 7 TeV parts:
No particular requirements on number of bunches / intensity – just safe and good accuracy for measurements. Standard LHC optics, single or separated beams, well corrected machine.
For solenoid coupling compensation: needs well corrected machine coupling. Single beam would be sufficient for coupling; bump closure is better checked for both beams.

Exit conditions:
solenoids on and LHC machine globally well decoupled
well closed spectrometer bumps for both polarities from 450 GeV to 7 TeV
Implementation, Solenoid Transfer Matrix

linear (thick, symplectic) transfer matrix used in Mad-X twiss, mad8, transport

where \[ k = \frac{eB_0}{2p_s} \quad C = \cos kL \quad S = \sin kL \]

\[
R_{\text{sol}} = \begin{pmatrix}
C^2 & \frac{SC}{k} & \frac{SC}{k} & \frac{S^2}{k} & 0 & 0 \\
-kSC & C^2 & -kS^2 & \frac{SC}{k} & 0 & 0 \\
-kSC & -\frac{S^2}{k} & C^2 & \frac{SC}{k} & 0 & 0 \\
kS^2 & -S & -kS & \frac{SC}{k} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & \frac{L}{\beta^2 \gamma^2}
\end{pmatrix}
\]

can be written as product of two matrices, rotation × matrix (looking like a quad focusing in two planes)

\[
R_{\text{sol}} = \begin{pmatrix}
C & 0 & -S & 0 & 0 & 0 \\
0 & C & 0 & -S & 0 & 0 \\
S & 0 & C & 0 & 0 & 0 \\
0 & S & 0 & C & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix} \begin{pmatrix}
C & \frac{S}{k} & 0 & 0 & 0 & 0 \\
-kS & \frac{C}{k} & 0 & 0 & 0 & 0 \\
0 & 0 & C & \frac{S}{k} & 0 & 0 \\
0 & 0 & -kS & \frac{C}{k} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & \frac{L}{\beta^2 \gamma^2}
\end{pmatrix}
\]

rotation by \( \phi = kL \) focusing matrix in both x and y
The thick solenoid matrix shown last time is symplectic and includes edge effects

\[ R_{\text{sol}} = \begin{pmatrix} \frac{SC}{K^2} & \frac{SC}{C^2} & \frac{SC}{C^2} & \frac{SC}{C^2} \\ -KS & -K^2 & -K^2 & -K^2 \\ -SC & -SC & -SC & -SC \\ K^2 & K^2 & K^2 & K^2 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -K & 0 \\ 0 & 0 & 1 & 0 \\ K & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{SC}{K} & 0 & \frac{S^2}{K} \\ 0 & C^2 - S^2 & 0 & 2CS \\ 0 & -S^2 & 1 & \frac{SC}{K} \\ 0 & -2CS & 0 & C^2 - S^2 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & K & 0 \\ 0 & 0 & 1 & 0 \\ -K & 0 & 0 & 1 \end{pmatrix} \]

where

\[ \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -K & 0 \\ 0 & 0 & 1 & 0 \\ K & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -K & 0 \\ 0 & 0 & 1 & 0 \\ -K & 0 & 0 & 1 \end{pmatrix} = 1 \] (no problem with edges when using several pieces)

Simple thin version: \( C \to 1, \ \sin KL \to KL, \ \frac{SC}{K} \to L \) (drift term), \( \frac{S^2}{K} \to 0 \)

\[ R_{\text{thinsol}} = \begin{pmatrix} 1 & 0 & KL & 0 \\ -K^2L & 1 & 0 & KL \\ -KL & 0 & 1 & 0 \\ 0 & -KL & K^2L & 1 \end{pmatrix} \]

verified, that inserting this between drifts of \( L/2 \) converges well with the numbers of slices \( n \), and \( L \to L/n \)

(for \( KL \ll l \) as generally the case, in particular for LHC)
LEP, description of L3 solenoid in mad8. Using 0.5 m slices.
Coupling introduced by solenoids can be compensated using skew quadrupoles.

In general 4 skew quadrupoles on each side of the solenoid are needed for the compensation to work.

Complex coupling coefficient

\[ c_{skew}^{\pm} = \frac{1}{2\pi} \sqrt{\beta_x \beta_y} \cdot k_s \cdot e^{i[\mu_x \pm \mu_y]} \]

4 linear equations have to be satisfied in order to decouple the machine:

\[
\sum_{m} c_{skew}^{+} = \sum_{m} \frac{1}{2\pi} \sqrt{\beta_x^m \beta_y^m} \cdot k_s^m \cdot e^{i[\mu_{x}^m \pm \mu_{y}^m]} = c_{sol}^+ \\
\text{for } m = 1, \ldots, 4
\]

\[
\sum_{m} c_{skew}^{-} = \sum_{m} \frac{1}{2\pi} \sqrt{\beta_x^m \beta_y^m} \cdot k_s^m \cdot e^{i[\mu_{x}^m - \mu_{y}^m]} = c_{sol}^-
\]