Experimental Magnets Commissioning

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

Ref.:

J.P. Koutchouk et al. CERN-SL-94-33, Part. Accel. 55 (1996) 183–191 (Montreux)

N. Catalan Lasheras, S. Fartoukh, J.P. Koutchouk, WPAB079, PAC'03

S. Fartoukh, J.P. Koutchouk, *Tune Meas. Func. Spec.*, 7/2004, EDMS LHC-B-ES-000910-00

W. Herr, *The effects of solenoids and dipole magnets of LHC experiments*, Chamonix 2006

A. Koschik, H.B., T. Risselada, F.Schmidt, *On the implementation of experimental solenoids in MAD-X and their effect on coupling in the LHC*", Proc EPAC 2006 WEPCH043

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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

Phase	Phase	Procedures	LTC Presenter	Date
injection and first turn	A.1	Magali	Brennan	7.03
circulating beam, RF capture	A.2	Magali	Gianluigi	14.03
450 GeV, intial commissioning	A.3	Verena	Rhodri	28.03
450 GeV, optics meas	A.4	Stefano	Frank	11.04
450 GeV, increase intensity	A.5	Laurette	Jan	25.04
450 GeV, two beam operation	A.6	Walter/Verena	Ralph	4.07
450GeV, collisions	A.7	Magali	Helmut	10.10
snapback and ramp	A.8	Reyes	Mike	9.05
top energy checks with beam	A.9	Walter	Frank	6.06
top energy, collisions (pilot physics)	A.10	Reyes	Helmut	20.06
squeeze	A.11	Stefano	Massimo	23.05
top energy, physics runs	A.12			
450 GeV, bring on experiments magnets	A. ?	D. Jacquet ?	Helmut ?	?

?

+

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 ×) 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)

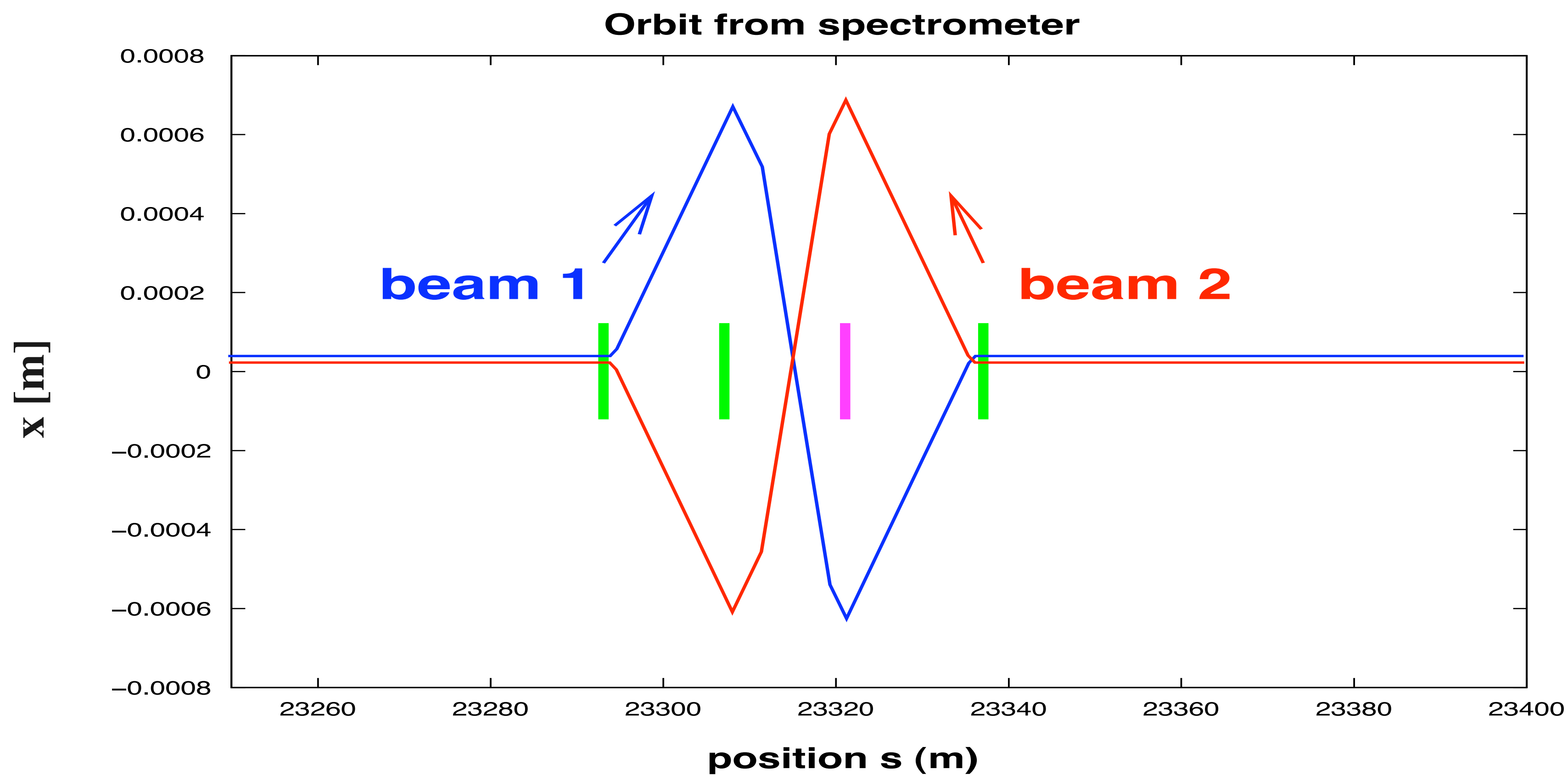
IR1 : ATLAS solenoid. 0 – 1 (off to design current)

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.

Solenoid Coupling

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- ≈ 0.17 at injection before correction,

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

for $\beta_x = \beta_y$:
0 for c^+ and 2 for c^-
$\sqrt{40} = 6.3$ for LEP

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

for round beams, the sum resonance
is not excited, c+ = 0
only the difference, c- relevant
| c- | measurable as closes tune approach

$$\theta = \frac{B_s l}{2B\rho}$$

Rotation

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 × stronger than LEP
  LEP inj. 22 GeV -> LHC inj. 450 GeV or 20 × stronger than LEP
  relative importance of solenoids at injection 4 × less in LEP
- **round beams** ($\beta^*_x = \beta^*_y$ Is this always guaranteed ?)
  β^* x/y ratio, term in brackets 2 for LEP, 6.3 for LHC

Together : solenoid fields (Aleph / CMS) at injection 12 × stronger in LEP
but also : LHC target tunes much (3-10 ×) closer to coupling resonance

Precision : possible and required

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 2×10^{-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

S. Fartoukh, J.P. Koutchouk, *Tune Meas. Func. Spec.*, 7/2004, EDMS LHC-B-ES-000910-00

LHC, Solenoid Coupling ; Parameters

LHC ϱ = 2803.98 m

450 GeV : B = 0.535324 T $B\varrho$ =1501.04 Tm

7 TeV : B = 8.32727 T $B\varrho$ =23349.5 Tm

450 GeV

	B_s [T]	B_s L [Tm]	c-, 450 GeV	c-, 7 TeV	θ, mrad
IR1 Atlas	2	12	0.00127	0.00008	4.00
IR2 Alice	0.5	6.05	0.00064	0.00004	2.02
IR5 CMS	4	52	0.00551	0.00035	17.3
			0.00743	0.00048	

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] × 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

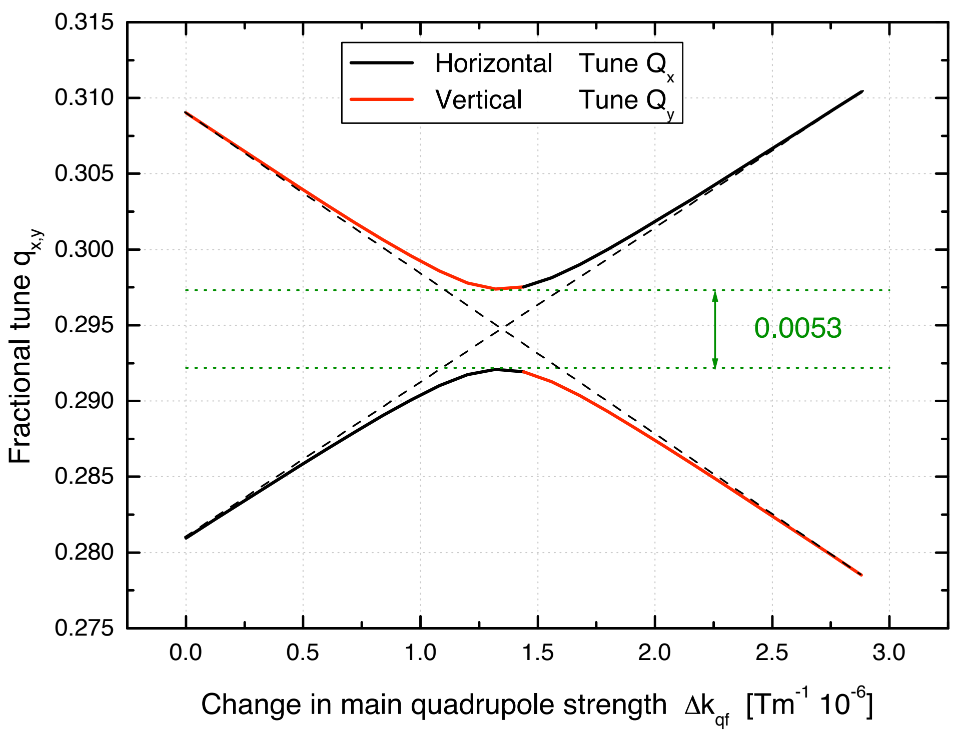
also implemented in MadX with slicing by makethin for tracking, H.B. MadX meet 28/11/2005

still to be checked : signs, - solenoid field direction.

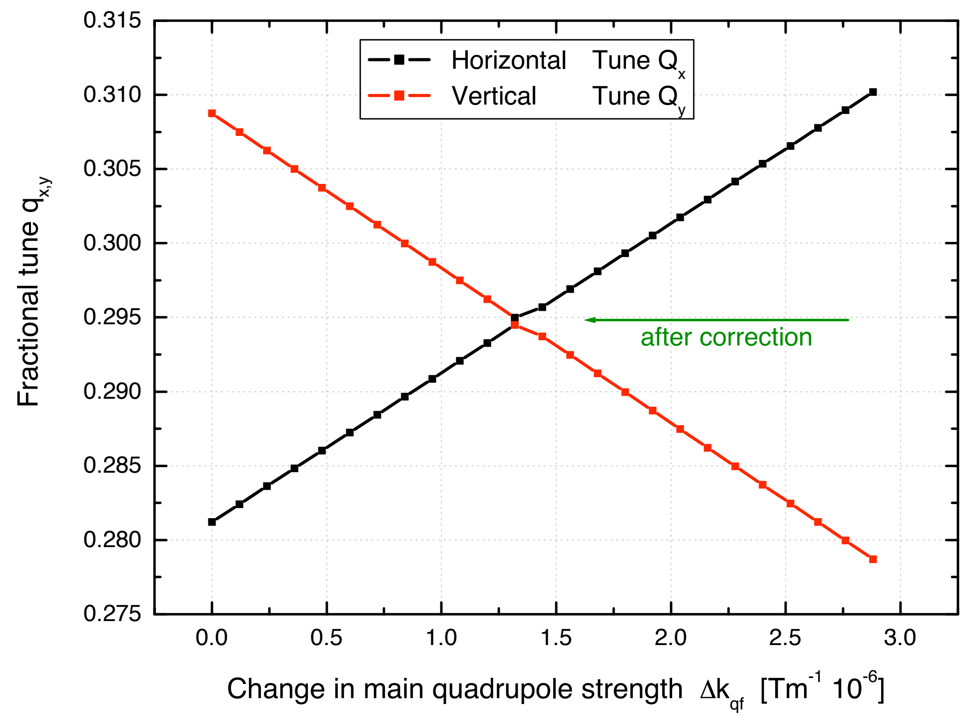
Coupling Compensation

MAD-X predictions

CMS solenoid On
no compensation



CMS solenoid On
with compensation

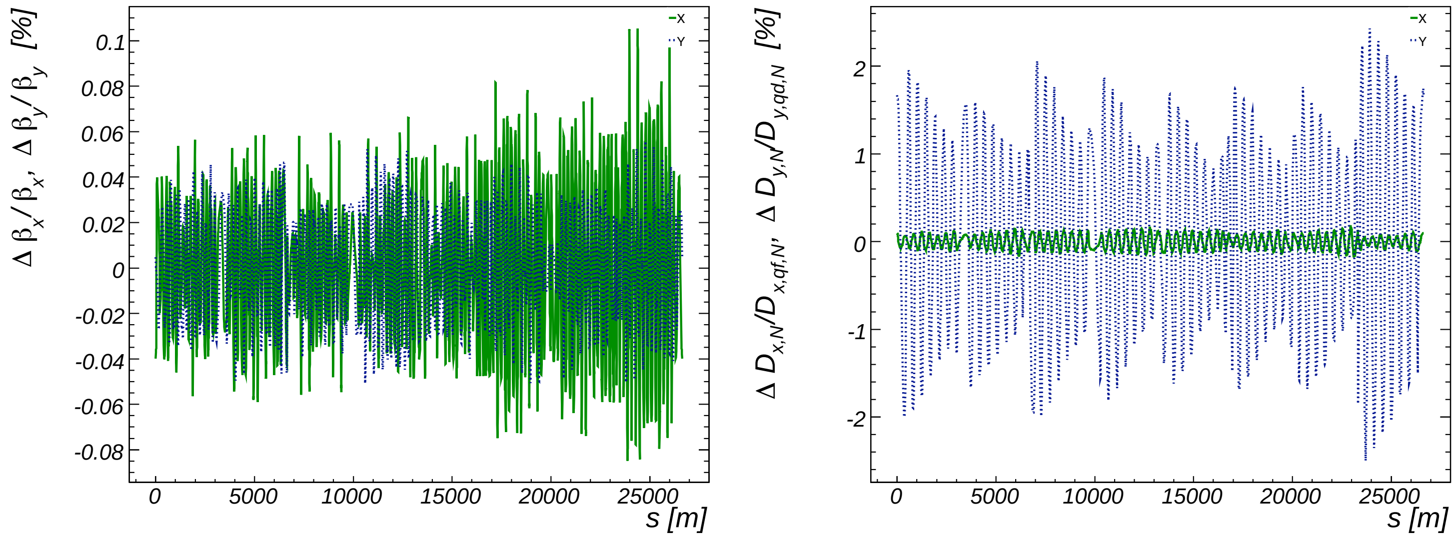


Coupling correction using skew quads is global (not local as in LEP), by increments in currents using the same skew quads as done for the machine coupling.
Results in 0.1% β and 0.2 % dispersion beating.

Correction : 1 st order, includes edge effects ; checked that working well for both beams

Global solenoid coupling correction, remaining mismatch

β - beat **dispersion mismatch**



blue y
green x

Figure 3: Induced β- and dispersion-beating by the CMS solenoid in the LHC at 450 GeV.

induced beta beat : **Δβ/β = 0.1 % peak**

relative dispersion beating : 0.2 % in x 2.5 % in y

$$\frac{\Delta D_x(s)}{\sqrt{\beta_x(s)}} \Big/ \frac{D_{x,\mathrm{qf}}}{\sqrt{\beta_{x,\mathrm{qf}}}} \quad \text{and} \quad \frac{\Delta D_y(s)}{\sqrt{\beta_y(s)}} \Big/ \frac{D_{y,\mathrm{qd}}}{\sqrt{\beta_{y,\mathrm{qd}}}}$$

$$D_{x,\mathrm{qf}} = 2.1\,\mathrm{m}, \quad D_{y,\mathrm{qd}} = 16\,\mathrm{cm}$$

$$\beta_{x,\mathrm{qf}} = \beta_{y,\mathrm{qd}} = 180\,\mathrm{m}$$

Backup Slides

Conditions

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 $k = \frac{eB_0}{2p_s}$ $C = \cos kL$ $S = \sin kL$

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

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

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

rotation by $\phi = kL$ focusing matrix in both x and y

More on Solenoids

The thick solenoid matrix shown last time is symplectic and includes edge effects

$$R_{\rm sol} = \begin{pmatrix} C^2 & \frac{SC}{K} & SC & \frac{S^2}{K} \\ -KSC & C^2 & -KS^2 & SC \\ -SC & -\frac{S^2}{K} & C^2 & \frac{SC}{K} \\ KS^2 & -SC & -KSC & C^2 \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -K & 0 \\ 0 & 0 & 1 & 0 \\ K & 0 & 0 & 1 \end{pmatrix}}_{\rm edge1} \underbrace{\begin{pmatrix} 1 & \frac{SC}{K} & 0 & \frac{S^2}{K} \\ 0 & C^2-S^2 & 0 & 2CS \\ 0 & -\frac{S^2}{K} & 1 & \frac{SC}{K} \\ 0 & -2CS & 0 & C^2-S^2 \end{pmatrix}}_{\rm solenoid\ body} \underbrace{\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & K & 0 \\ 0 & 0 & 1 & 0 \\ -K & 0 & 0 & 1 \end{pmatrix}}_{\rm edge2}$$

where $\underbrace{\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -K & 0 \\ 0 & 0 & 1 & 0 \\ K & 0 & 0 & 1 \end{pmatrix}}_{\rm edge1} \underbrace{\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & K & 0 \\ 0 & 0 & 1 & 0 \\ -K & 0 & 0 & 1 \end{pmatrix}}_{\rm edge2} = \mathbf{1}$ (no problem with edges when using several pieces)

Simple thin version : C → 1, sin KL → KL , SC/K → L (drift term), $S^2/K \to 0$

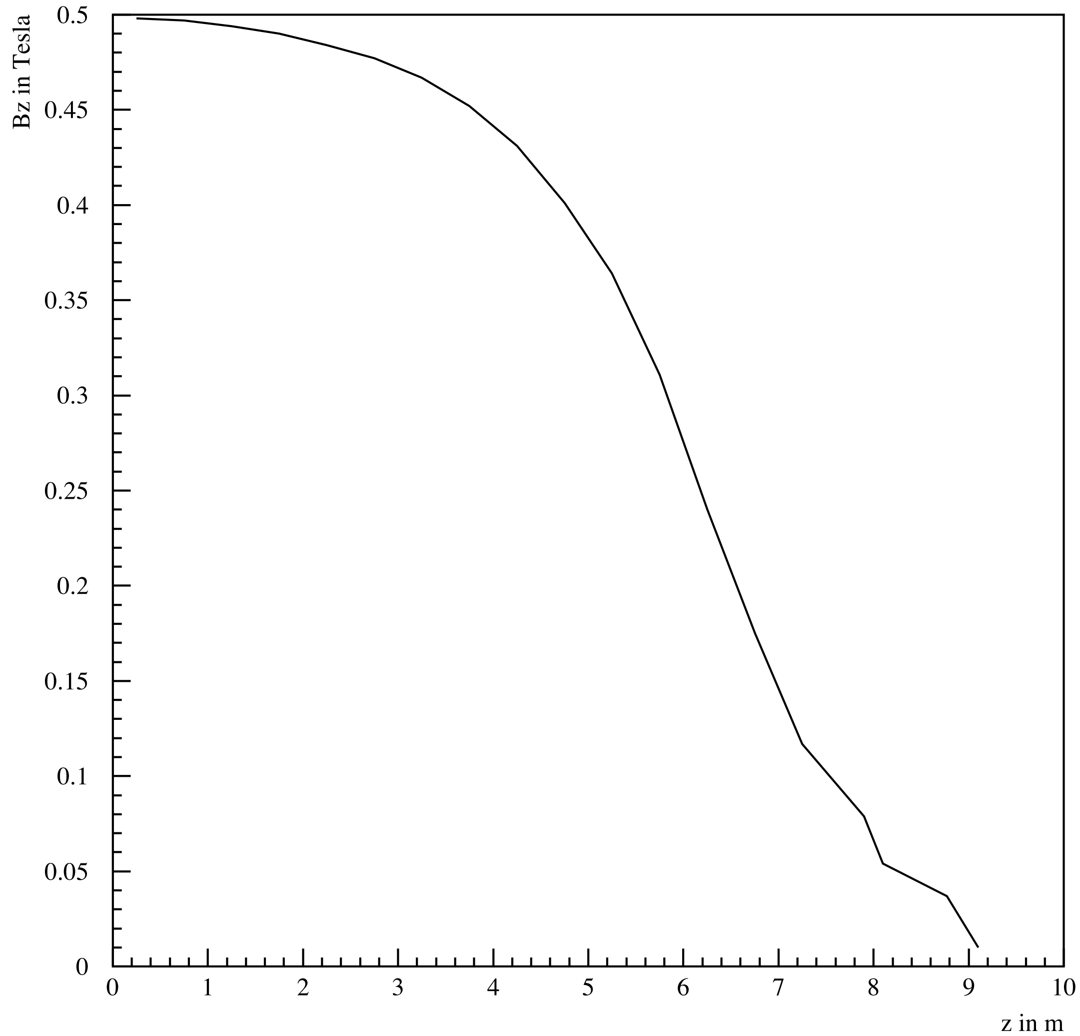
$$R_{\rm thinsol} = \begin{pmatrix} 1 & 0 & KL & 0 \\ -K^2L & 1 & 0 & KL \\ -KL & 0 & 1 & 0 \\ 0 & -KL & K^2L & 1 \end{pmatrix}$$

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

(for $KL \ll 1$ as generally the case, in particular for LHC)

LocMeet08-11-2005.pdf

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

$$c^{\pm}_{skew} = \frac{1}{2\pi}\sqrt{\beta_x\beta_y}\cdot k_s \cdot e^{i\left[\mu_x \pm \mu_y\right]}$$

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

$$\sum_m c^{+}_{skew} = \sum_m \frac{1}{2\pi}\sqrt{\beta^m_x\beta^m_y}\cdot k^m_s \cdot e^{i\left[\mu^m_x + \mu^m_y\right]} = c^{+}_{sol}$$

$$m = 1, \dots, 4$$

$$\sum_m c^{-}_{skew} = \sum_m \frac{1}{2\pi}\sqrt{\beta^m_x\beta^m_y}\cdot k^m_s \cdot e^{i\left[\mu^m_x - \mu^m_y\right]} = c^{-}_{sol}$$

A. Koschik, LOC 31/07/2006