Alignment in Circular Colliders and Specific Requirements for LHC

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Outline

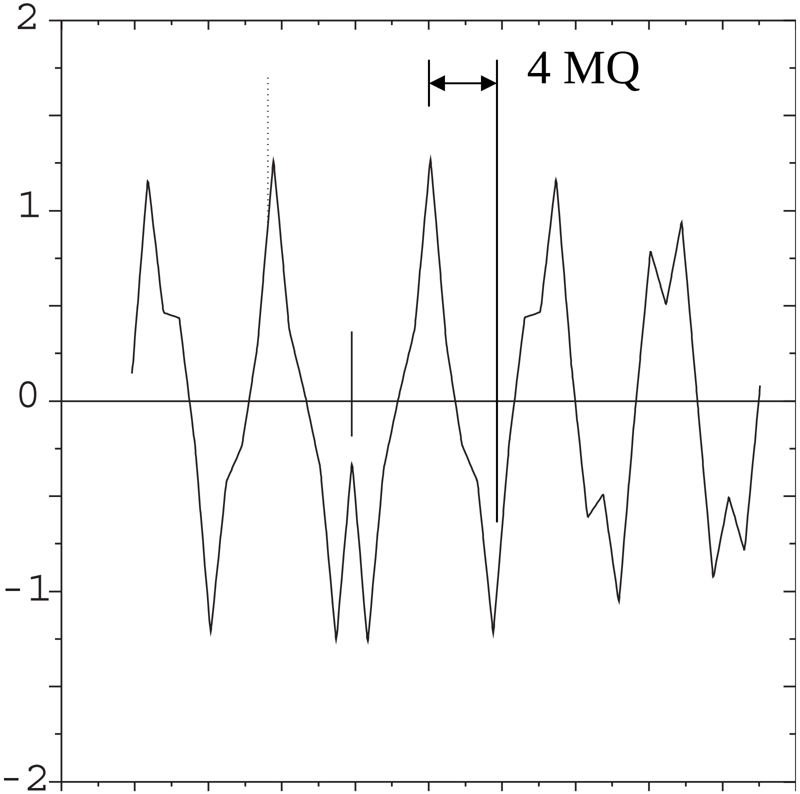
- Closed orbit and tolerances
- Magnetic issues at LHC
- Aperture issues

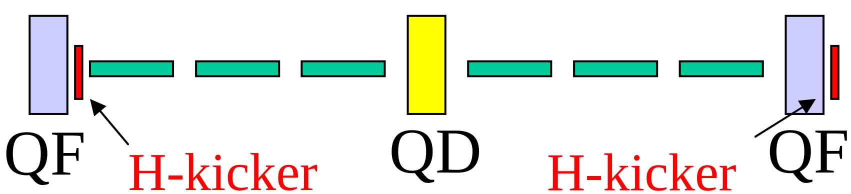
→ Survey issues

- Conclusions

Closed orbit and tolerances

An issue for all machines : Closed Orbit errors





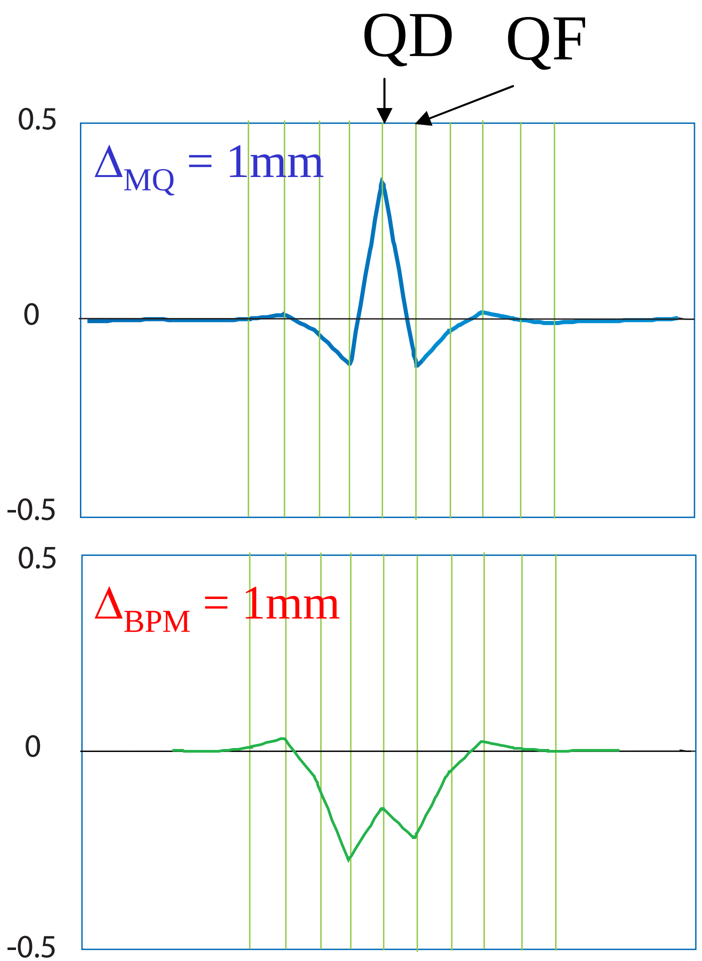
- Perfect machine, except for one QD mis-placed by Δx = 1mm horizontally
- Without correction: ~Δx every 4th MQ with 1 MQ mis-placed
- With N_{MQ}=400 and random moves

→ Δx = root (N) Δx/4 = 5mm r.m.s.
→ 10-15mm 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 ~7 MQ

- r.m.s Δx= 1mm over all MQ's and BPM's :

→ Σ_{rms} Δx = 1.5 mm

- This without BPM resolution, missing BPM's, local coherent distortions, numeric matrix inversion errors …
- Δ_{MQ} < 1.5mm , Δ_{BPM} < 0.5mm (tol, total)

Mad model and correction algorithm, J. Wenninger

Experimental insertions

- High luminosity at LHC → beam size at crossing σ=17 μm
- β_{MQX} = 5000 m compared to β_{arc} = 200m
- Beam divergence $\sigma'_{MQX} = \sigma_{arc}/5$

- 2 opposite protons beams in the same tube : dipoles cannot do the job there

→ CO corrections must be made ~2-300 m away

- Very critical, need MQX perfectly aligned with frequent remote checks and re-alignmnet
- 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 ~ 10 TeV + 10 TeV

  → Luminosity L = 10^{34} $cm^{-2}s^{-1}$ so : high stored current

- Fit in the LEP tunnel with arc curvature ρ = 3606 m

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

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

- Classical 'warm' magnets : B < 2T

→ Need superconductor magnets

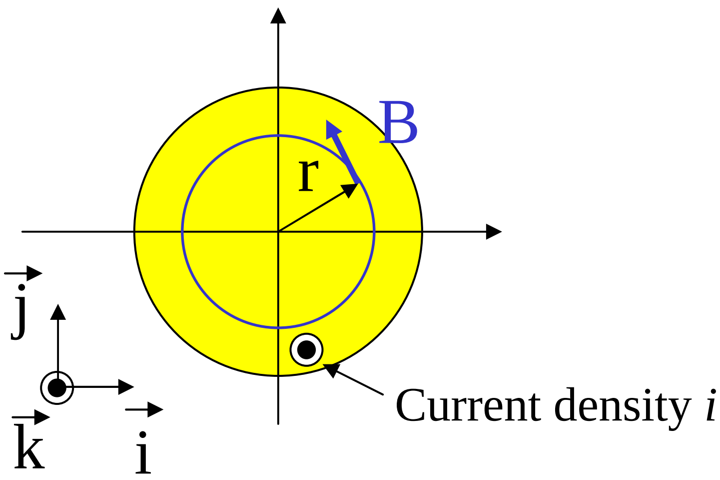
LHC basic parameters - II

- Best candidates NbTi , with in practice $B_{best} \cong 9$ T
- This even with superfliud helium
  (Tc = 2.8 K at B=9T)

→Beam Energy in collision : $E_{coll} \cong 7$ TeV

- Finally: use existing injector : E_{inj} = 0.45 TeV
  → Fixes the r.m.s beam size $\sigma = 1.2$ mm
  → And the vacuum chamber size, see below

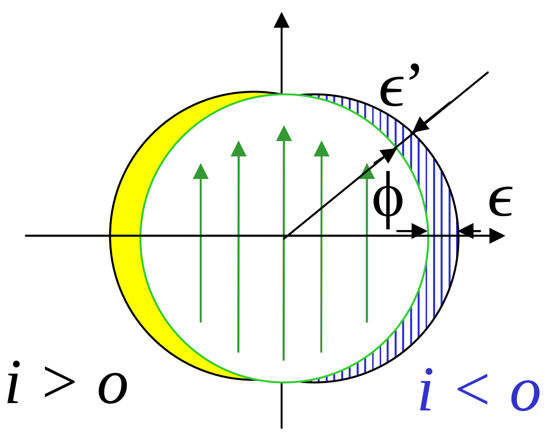
A super-conducting dipole field – basic theory



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

→ $$\vec{B} = \frac{\mu_0 i}{2}(\vec{k} \wedge \vec{r})$$

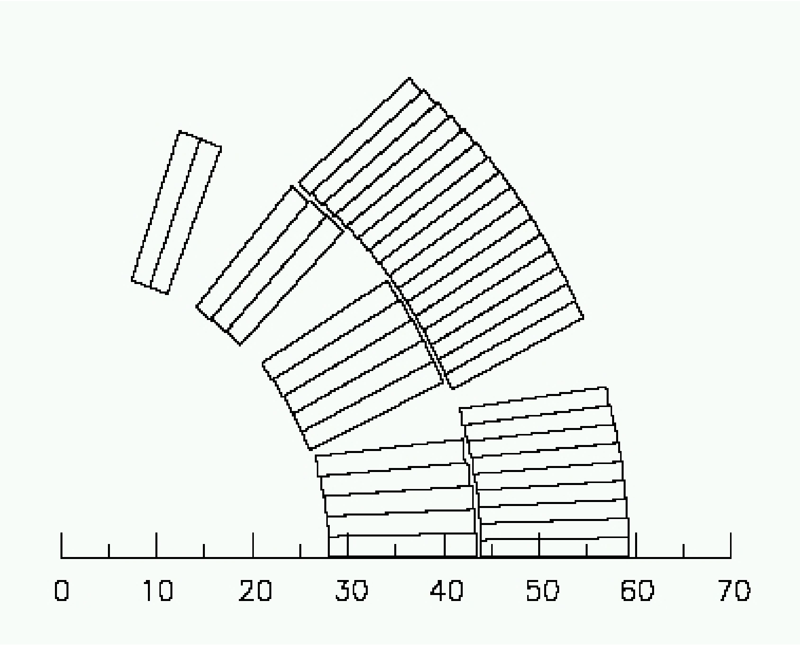
$$\vec{B}_1 + \vec{B}_2 = \frac{\mu_0 i}{2}[\, \vec{k} \wedge (\vec{r} + \epsilon\vec{i}) - \vec{k} \wedge (\vec{r} - \epsilon\vec{i})\,] = \mu_0 i \epsilon [\, \vec{k} \wedge \vec{i}\,] = \mu_0 i \epsilon \vec{j}$$



→A skin of current varying with *cos* ϕ produces a uniform dipole field

But : to be perfect, ϵ → 0, *i* → infinity

The coils



- $\epsilon \cong 1$, not exactly $\epsilon \rightarrow 0$
- Cosine function not very close to textbook definition
- In spite of clever corrections, field map is not constant enough

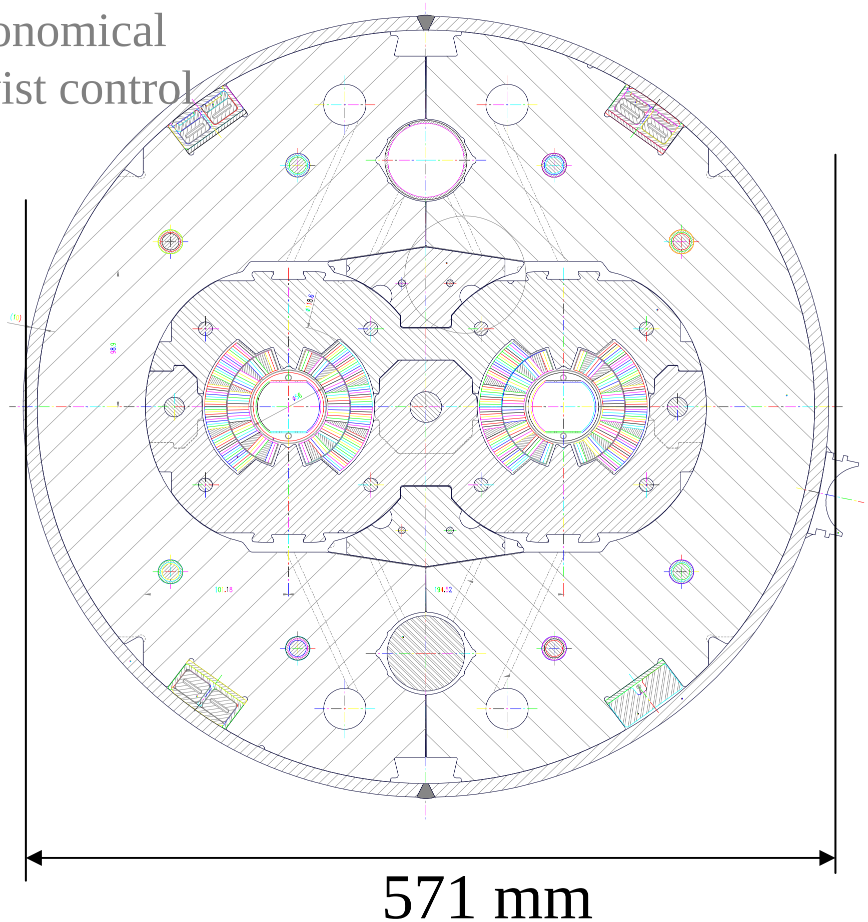
→ Need corrective elements

- B = 9T → NI = 1MA
  → EM forces ~ 2MN/m

→ High mechanical stiffness

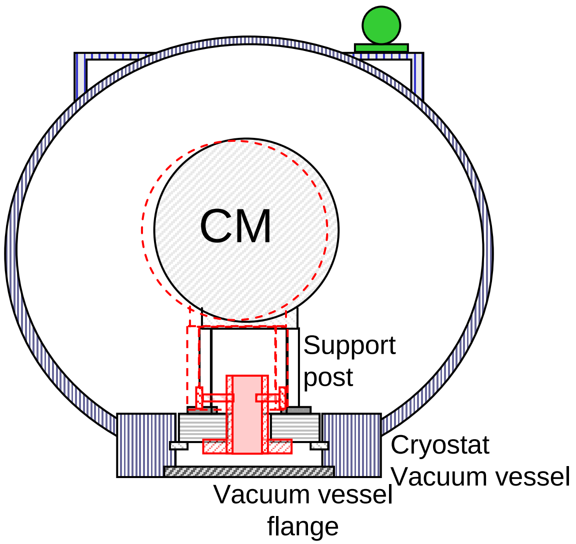
A super-conducting dipole field – in practice

2 beam lines with opposite polarity
- Economical
- Twist control



Length L = 15 m
Weight m = 27 tons

Working point T = 2 K
(superfluid helium)
→Embedded in a cryostat



→ CM hidden to Survey

Courtesy of F. Savary AT-MAS and F. Seyvet AT-CRI

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 → strong inductive and persistant errors s.c. (non-resistive) in correcting coils (HERA)
- Rather: Autonomous correctors at the extremities
  - No inductive errors
  - But alignment issues

→ Transmutation of Magnetic problems into Survey issues! (see below)

Field map errors expressed as multipole expansion in unit 10^{-4} with latest coil-shape

N-pole	Ap1 inj/top	Ap1 inj/top
b2	~ 1.3	~ -1.1
b3	~ -4.5 / 3	~ -4.5 / 3
b4	~ 0 / 0.2	~ 0 / 0.2
b5	~ +1.0 / 0	~ +1.0 / 0
b6	~ 0	~ 0
b7	~ +0.3 /+0.7	~ +0.3 /+0.7
b8	~ 0	~ 0
b9	~ 0.8	~ 0.8
a2	~ -0.4	~ -0.4
a3	~ -0.26	~ -0.23
a4	~ +-0.13	~ +-0.13
a5	~ +0.03	~ +0.02
a6	~ 0	~ 0
a7	~ +0.04	~ +0.04
a8	~ 0	~ 0
a9	~ 0	~ 0

Use z = x + iy

$$B_y + iB_x = B_1 \sum_n (b_n + i a_n)\left(\frac{z}{17\,\mathrm{mm}}\right)^{n-1}$$

Consider b_5, then misalign spool by δ along y:

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

$$\Longrightarrow \quad a_4^{\mathrm{fd}} = \frac{4\delta}{R_r} b_5$$

The critical displacement δ_{cr} for $a_4^{fd} < a_4/2$ is :

$$\delta_{\mathrm{cr}} < \frac{a_4^{\mathrm{fd}}}{2b_5}\frac{R_r}{4} = 0.3\ \mathrm{mm}$$

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

Beam based specification for spool piece

Beam Spec.	Δx, Δz	$\sigma(x)$, $\sigma(y)$ w.r.t. tunnel	$\sigma(x)$, $\sigma(y)$ w.r.t. cold mass *	$\sigma(\theta)$ w.r.t. tunnel **
Unit	[mm]	[mm]	[mm]	[mrad]
MCS	0.3	0.5	0.15	1.5
MCDO	0.3	0.5	0.15	2

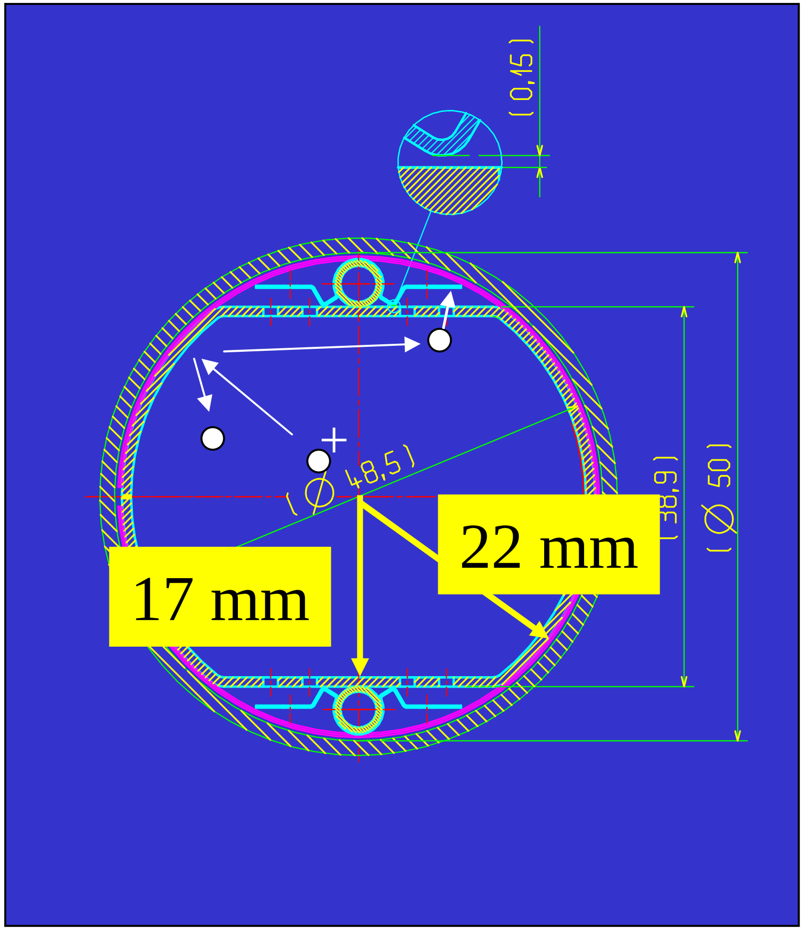
*i.e. Magn. Axis w.r.t. cold mass mechanical mid-plane at ITP20

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

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

Aperture issues

Beam Aperture - I



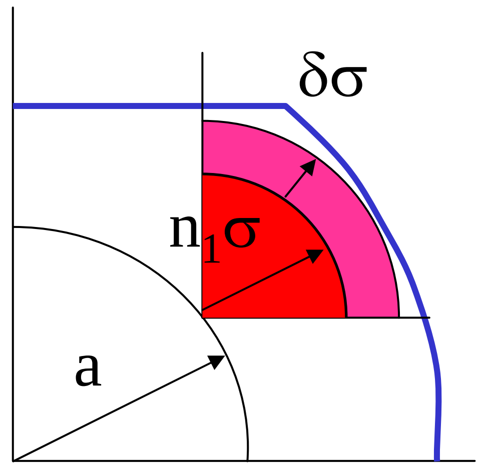
Courtesy of N. Kos AT-VAC

- Initially : cold bore with radius R= 25 mm (this after all the rest was fixed)
- Short bunch separation (25ns) and large population (1.1x10^{11} p):
  - Multipacting + e-cloud
  - → Need of a beam screen
- Ions finally trapped on the 2K cold bore
- But 3mm lost for aperture
- So please, Survey …

Beam Aperture - II

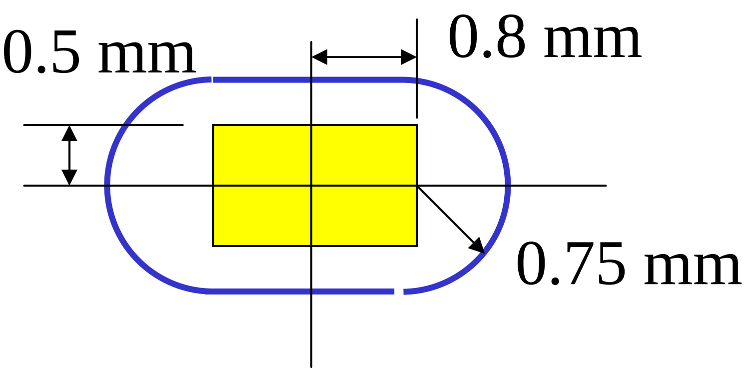
- High beam intensity N = 3000 x 10^{11} p
- With τ_{beam}=20h , dN/dt_{loss} = 4 x 10^9 p/s
- Quench with dN/dt_{quench} = 10^7 p/s/m
- With a margin factor m=100, need a collimation system with a capture efficiency ~ 10^4 (effective cascade absorbtion length ~1m)
- 2-stage collimation OK, but need pipe away by 4σ from collimator aperture

Beam Aperture - III



- $n_1\sigma + \delta\sigma = 1.1\ (6+4)\sigma = 13$ mm
- a = CO + t + Ddp = 9 mm
- Remains t ≅ 2.5 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

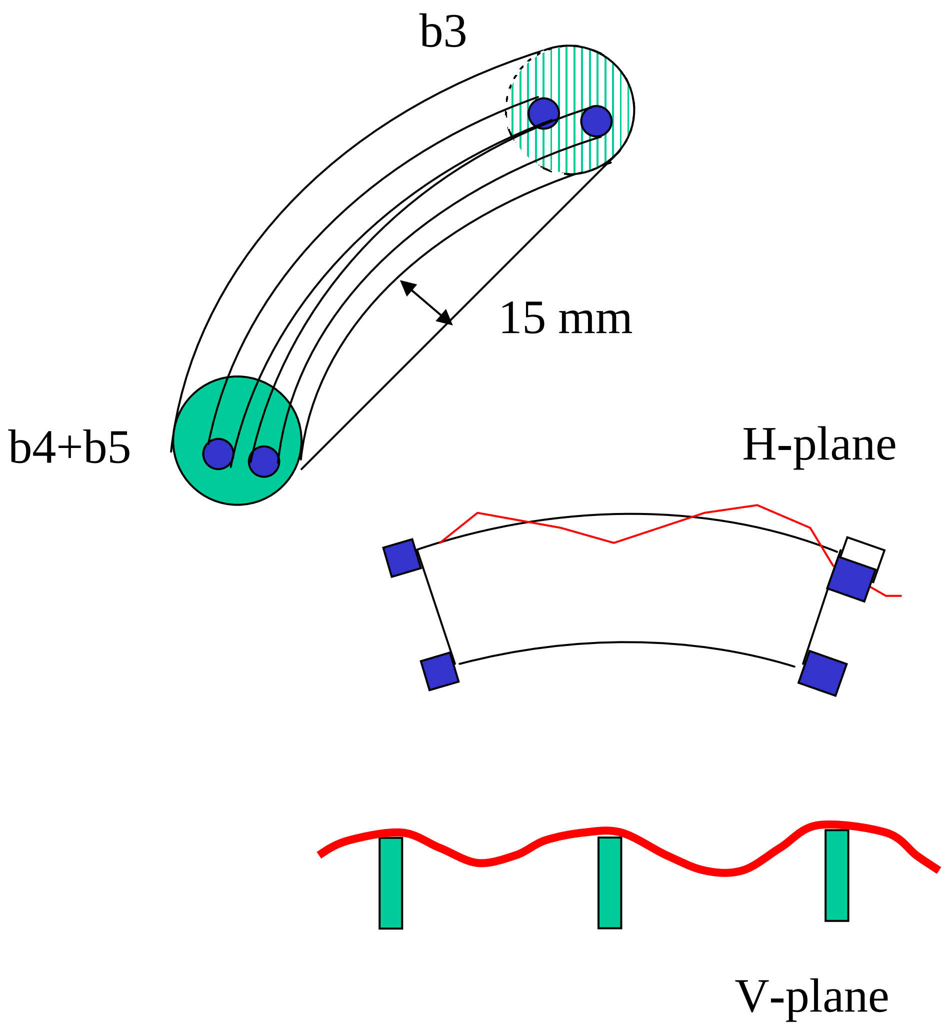
What is needed

1) An object with its inner shape controlled down to $\Delta x \times \Delta z \cong 1.5 \times 0.7\ mm^2$ over 15m inside its cryostat
2) Relative axis error MB/spool pieces $\Delta x < 0.3$ mm with $\delta_{r.m.s} = 0.15$ 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 theoritical curve, averaging two beam tubes for best aperture
- What means best magnetic position of spool w.r.t. body ?



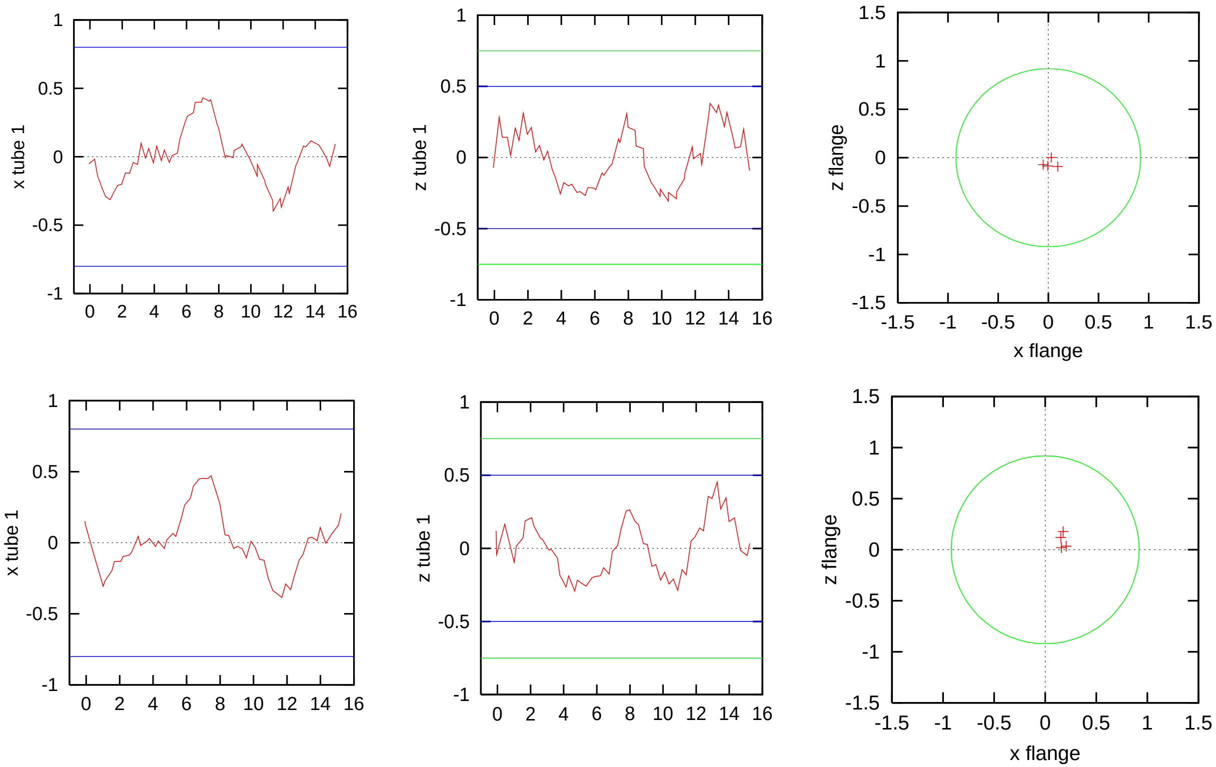
Criteria and method

- 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



←Data from industry
M. Bajko et al.

←Data from CERN after
cold test, D. Missiaen

Data retrieved from
MTF and MAS dBase

- This one a bit better than average, but not a rare case
- We get more ‘golden’ MB’s than stricktly needed

→ Helps much to play with not so easy magnetic sorting

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