Orbit feedback for collimation

J. Wenninger AB Operation / SPS

- Requirements on orbit stability
- Expected orbit perturbations
- Feedback architecture
- Feedback tests at the SPS
- Collimation setup issues
- Summary

Acknowledgements :
R. Assmann, R. Jones, M. Lamont, R. Schmidt, R. Steinhagen

The core team

AB operations group : **accelerator physics, architecture, prototype tests**

Jorg Wenninger 10-20%

Ralph Steinhagen (doct. student) ~100%

AB beam diagnostics group : **BPM system**

Rhodri Jones

Lars Jensen

AB controls group : **architecture, control issues**

Jens Andersson (fellow) *has left CERN*

+ colleagues of AB and AT department, collimation and machine protection WG.

The role of the orbit feedback

Two distinct steps for orbit correction & stabilization

1. Establish a reference orbit
   - More or less manual corrections to define a reference orbit.
   - Established by the operation crews using applications embedded in the LHC controls system (LSA, presentation by M. Lamont). Responsible for steering application is J. Wenninger.
2. Stabilize the orbit
   - Stabilize the orbit around the pre-defined reference.
   - This is the role of the orbit feedback.

Collimation requirements

Total tolerance on separation of primary & secondary jaw :

→ 0.6σ from simulation of beta-beat effect.

Split up among :

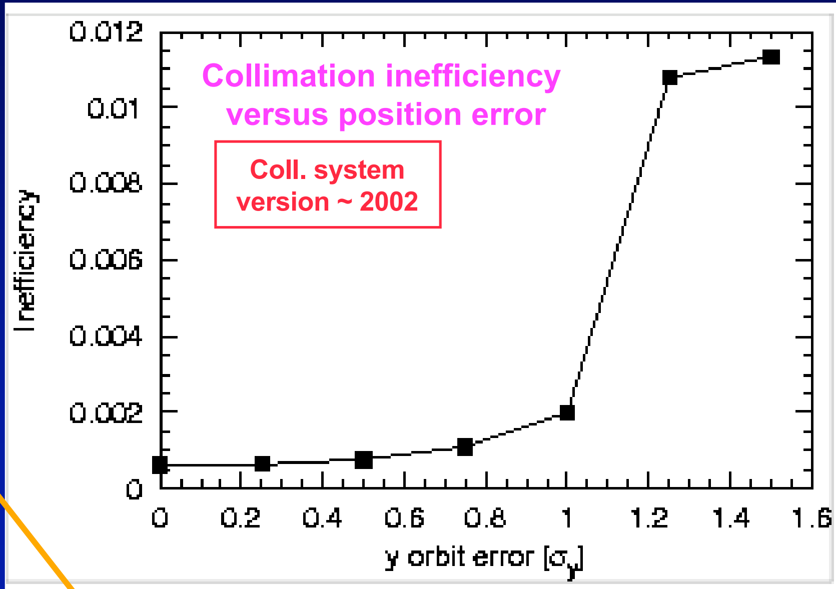
- Mechanical tolerance of jaws ~ 40 μm.
- Setting up tolerance
- β-beat
- Orbit

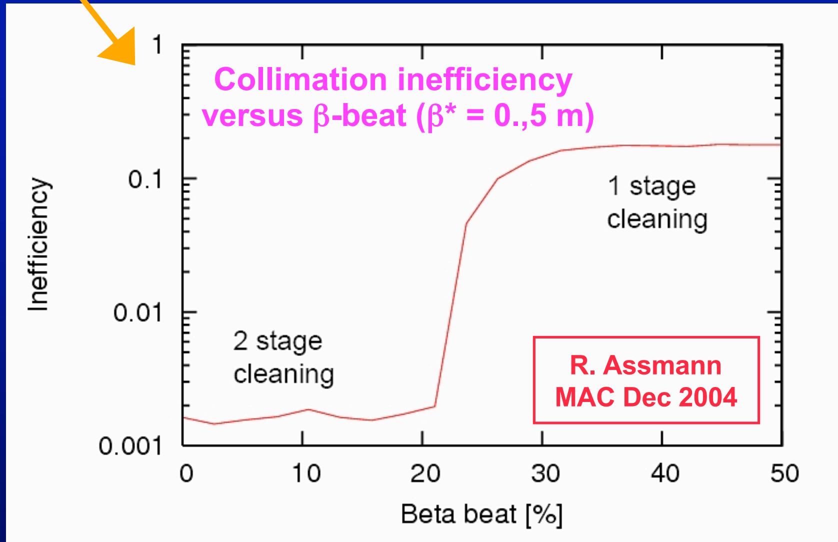
dynamic ↔ reproducibility (fill-to-fill, inside fill)

Example of *tolerance sharing* at 7 TeV :

Mech. tol	40 μm
Setup	50 μm
Orbit	50 μm
β-beat	5 %
Total 0.6σ	160 μm (β = 150 m)

'Conservative' : errors added linearly!





Local stability requirements

Absorbers & protection devices :

▪ TCDQ (prot. asynchronous beam dumps)	$<0.5\sigma$	IR6
▪ Injection collimators & absorbers	$\sim 0.3\sigma$	IR2,IR8
▪ Tertiary collimators for collisions	$\sim 0.2\sigma$	IR1,IR5
→ absolute numbers are in the range :	~100-200 μm	

Active systems :

▪ Transverse damper	~200 μm	IR4
▪ Q-meter / PLL BPM	~200 μm	IR4

Performance :

▪ Collision points stability	minimize drifts	IR1,2,5,8
▪ TOTEM / ATLAS Lumi Roman Pots	~20 μm	IR1,IR5

Global stability requirements

Injection protection :

- Arc aperture wrt protection devices <0.5σ ~ 0.5 mm

Feed-down of multipoles (injection/ snapback) :

- Reduce perturbations from feed-downs <0.5 mm

Electron cloud :

- Maintain beam on cleaned surface <1 mm (?)

<u>In summary :</u>

- Many tight local requirements
- Looser global requirements
- Collimation is the driving constraint behind the feedback system.
- Collimation constraints of ~ 50 μm may become tighter if the β-beat changes are larger than 5% !

Sources of orbit perturbations

Ground motion :

- LEP experience predicts slow drifts ~ 200-500 μm / store.
- No problems expected at frequencies > 0.5 Hz.

Dynamic effects from superconducting magnets (injection, ramp start) :

- Induce few mm rms drifts, dominated by random b1.

Beta squeeze :

- Most critical source of perturbations, amplitudes of up to 20 mm !
- Depends critically on orbit quality in insertions and alignment.
- Use feed-forward from cycle to cycle to reduce effects.

Other sources :

- Ramp…

Orbit feedback and operation

For nominal performance the orbit tolerances are very tight.

The relative position of collimators, absorbers.. must be maintained throughout the LHC cycle.

➔ The orbit is not a 'play-parameter' for operation, except at low intensity.

'Playing' with the orbit will result in quasi-immediate quench at high intensity.

At the LHC the orbit must always be very well controlled, but perturbations during various phases (snapback, ramp, squeeze) can be large and fast.

➔ *Stabilization by a <u>real-time orbit feedback</u> system was foreseen already at an early stage.*

BPM system overview

- 528 BPMs/ring provide horizontal and vertical position measurements.
- Orbit sampling :
  - One BPM at each quadrupole
  - In the collimation sections, there is one BPM on each side of the quadrupole.
  - In the arcs the phase advance between BPMs is 45˚ - sampling is good.
- BPMs are grouped into 64 acquisition crates.
  - 8 crates / IR.
- Acquisition based on ‘Wide Band Time Normalizer’ principle (CERN design) :
  - Position information is transformed into time duration.
  - Full bunch-by-bunch acquisition (40 MHz system).
  - RT orbit sampling at 10 Hz nominal frequency, possibly up to 25 Hz.
  - Orbit resolution < 5 μm for nominal intensity.

Steering magnets

- There are ~280 orbit corrector magnets per ring and per plane.
- Most of the correctors are superconducting magnets :
  - Circuit time constants $\tau = L/R \cong 10$ to 200 s → slow !!!
  - EVEN for SMALL signals, the PC bandwidth is ~1 Hz.

    At 7 TeV : ~ 20 μm oscillation / corrector @ 1 Hz.
- Much faster normal-conducting correctors are installed in IR3 and IR7.
  - Not usable for fast FB because they are too few of them.
- The PCs are connected over a real-time field-bus (WorldFip) to the gateways that control them – the bus operation is limited to <u>50 Hz</u>.

<u>Consequence of BPM and PC system parameters</u> :

The orbit FB could operate at up to 50 Hz - more likely at 10-25 Hz.

But this sampling rate is adequate given the expected perturbations !

Feedback architecture / 1

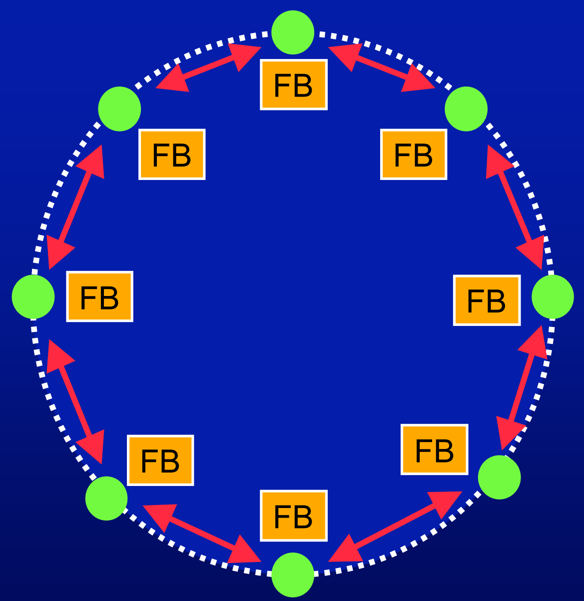
Local

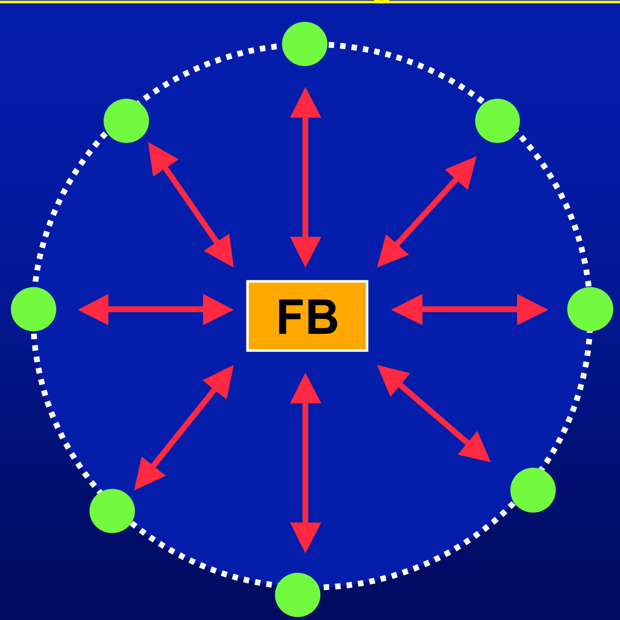
- ✓ reduced # of connections.
- ✓ numerical processing simpler.
- ✓ …
- × less flexibility.
- × not ideal for global corrections.
- × coupling between loops is an issue.
- × problems to ensure closure.
- × …

Central

- ✓ entire information available.
- ✓ all options possible.
- ✓ can be easily configured and adapted.
- ✓ …
- × communication more critical – DELAYS !
- × large # of connections.
- × …

<u>All light sources are moving into this direction</u>





Feedback architecture / 2

Present baseline : <u>central architecture</u>

- Fully digital feedback.
- Centralized control with high performance (multi-processor) PCs running Lynx / Linux real-time operating systems.
- Correction based on a super-position of global and local corrections.

    Global orbit correction using Singular Value Decomposition.

    Local orbit corrections applied on top of the predicted global correction residual.

    → both can be combined into a single matrix multiplication.

- Max. operation frequency is estimated to be ~ 25 Hz – adequate.
- Combined stabilization of both rings possible.

Remark :

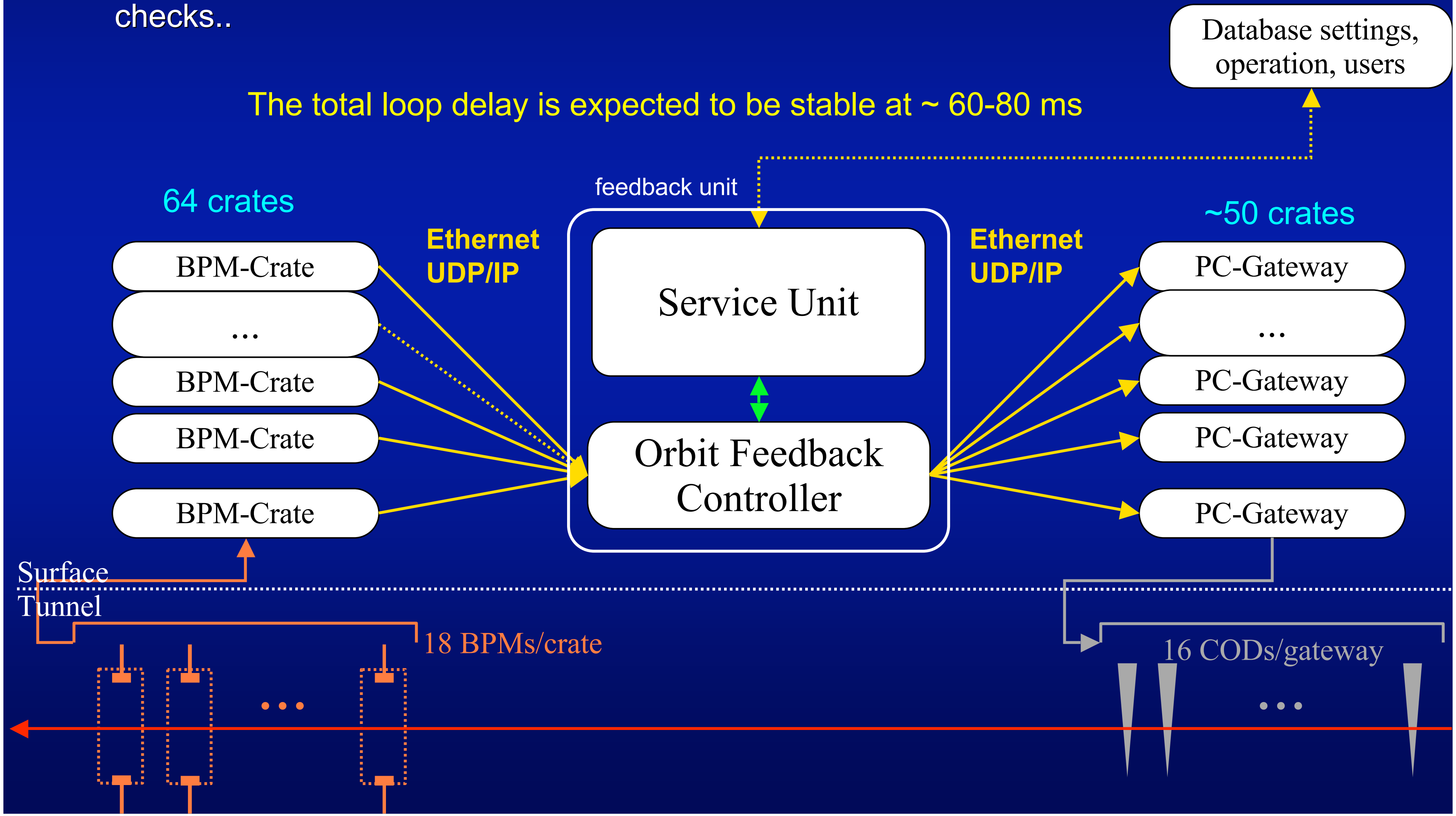
- Because this design is flexible, it is possible to build fast local systems in selected IRs combined with a slow global loop → but this raises loop coupling issues.

Feedback Control Layout

Central FB unit has 2 functional parts

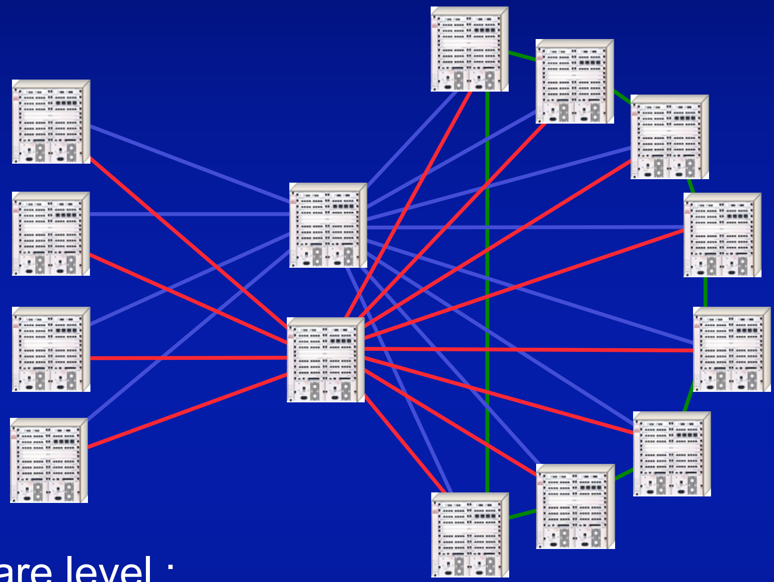
- Time-critical controller unit to compute the corrections (hard real-time).
- A Service Unit for DB and user interfaces, matrix operations, sanity checks..

The total loop delay is expected to be stable at ~ 60-80 ms



Technical network

The feedback will use the CERN Technical Network for data communication :



- Switched network
  - *no data collisions*
  - *no data loss*
- Very fast switches (delay ~ 3 μs)
- Double (triple) redundancy
- Transmission delays ~ 300 μs
  - *20% due to routers/switches*
  - *80% propagation speed in optical fibres*
- Provides QoS (Quality of Service) at the hardware level :
  - *Feedback packets will have higher priority than other users.*
  - *'Nearly' deterministic response – delays negligible on FB time scale.*
- We have performed numerous network tests for the FB, and they all showed that the network itself is not a problem. Network delays are smaller than 1 ms.

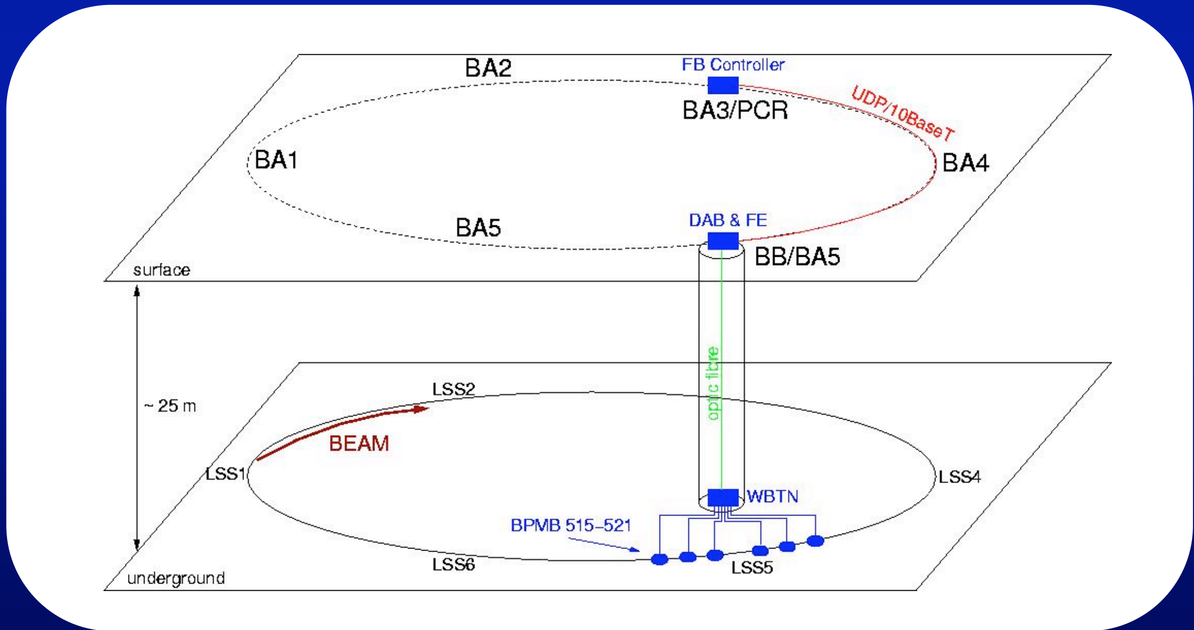
SPS prototyping

A feedback loop was sent up at the SPS and tested in 2003/2004 :

- 6 dedicated BPMs equipped with standard LHC electronics.
- Standard SPS CODs used as steering magnets (~14 Hz bandwidth).
- Data transport to the control room and back using the CERN technical network.

Between 2003 and 2004 the SPS network was upgraded to the same hardware that is used for the LHC.

→ test LHC architecture and components

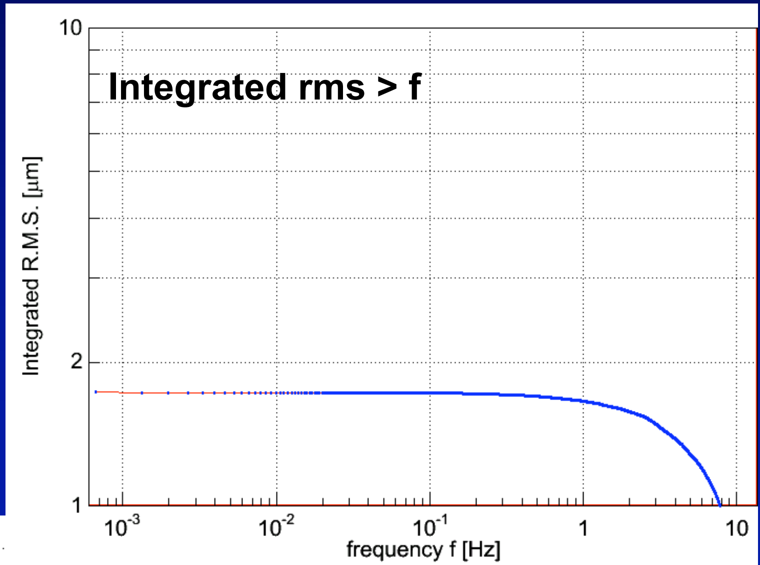


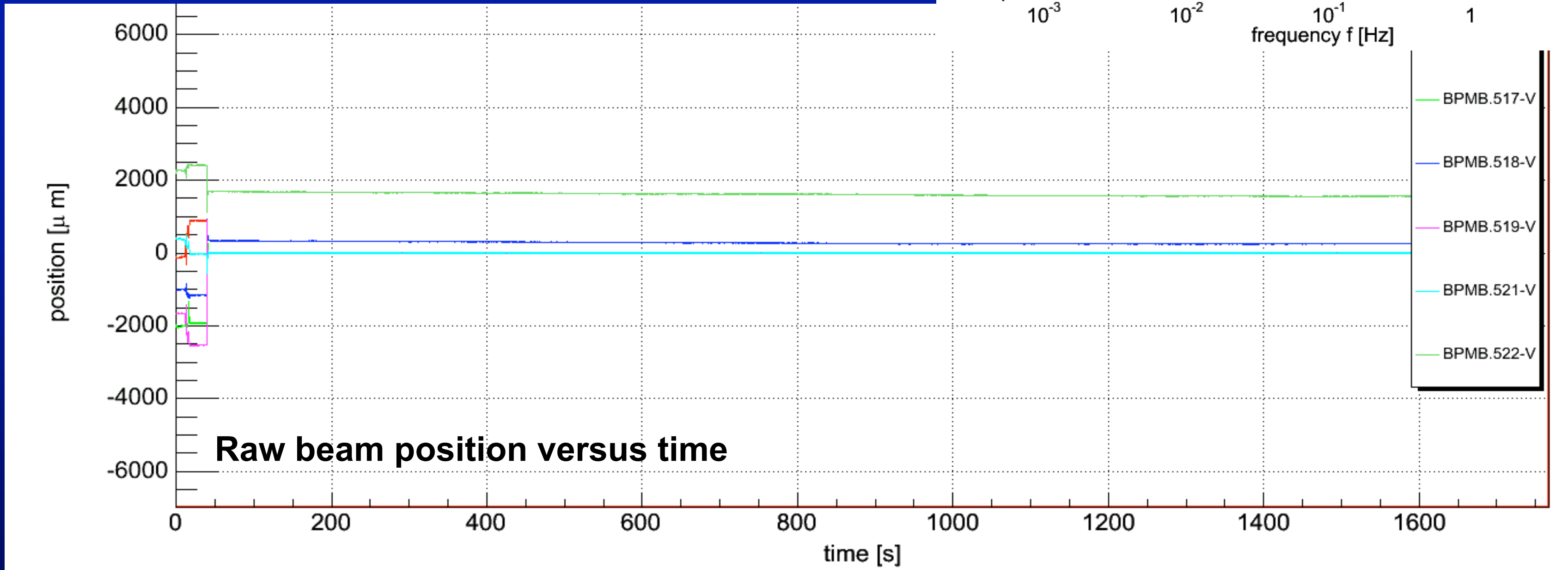
Prototype results / 2004

Running conditions for SPS tests :

- 270 GeV stored proton beam
- 72 bunches, ~10^{11} protons each
- β_v ~ 100 m
- 25 Hz sampling rate

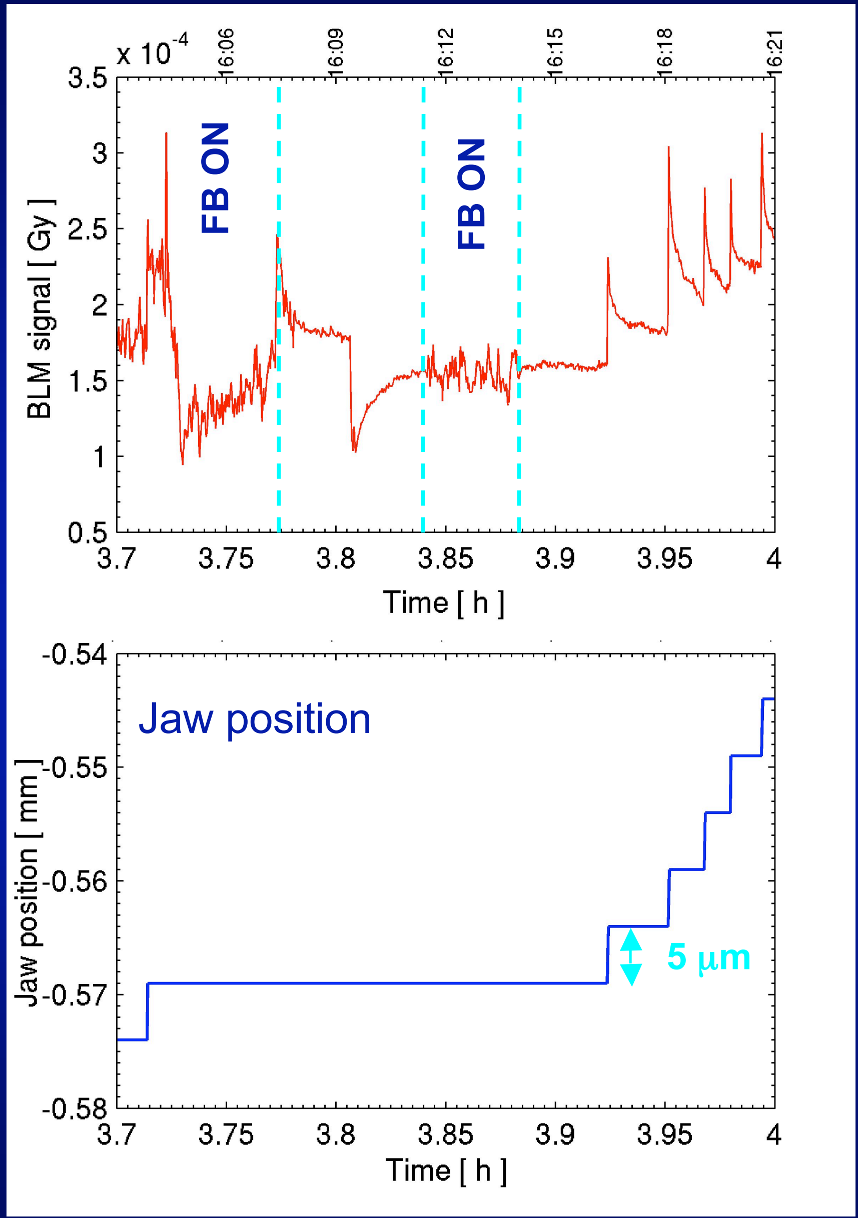
→ rms stability ~ 2-10 μm over few hours





SPS collimator tests

- Scraping of up to 5_10^{12} p at 270 GeV.
  - No effect observed on downstream BPMs and overall orbit feedback – but no clear conclusion since the expected amount of beam loss is not known.
- Beam loss rates with orbit FB ON and OFF :
  - Increased noise observed on BLM signal, equivalent to noise of few μm jaw steps.
  - Consistent with BPM noise.
  - Confirms ~ sub-micron stability of SPS beam at 270 GeV on time scale of seconds to minutes as expected from ground motion measurements.



Orbit stabilization for collimation / 1

The SPS tests and simulations gives us confidence that

- The baseline feedback architecture works,
- The stabilization requirements can be met,
- In particular stabilization better than 50 μm can be achieved in IR3 and IR7 for '*perfect' BPMs*,

but it is clear that the BPM data quality is absolutely essential to fulfil the local collimation requirements !

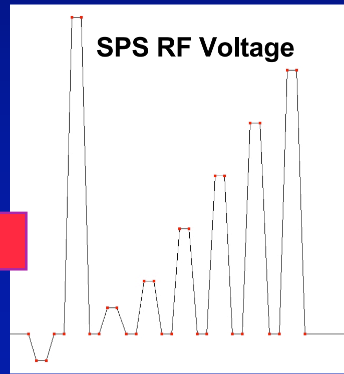
BPM bunch length dependence

Some residual bunch length effects are expected from the design.

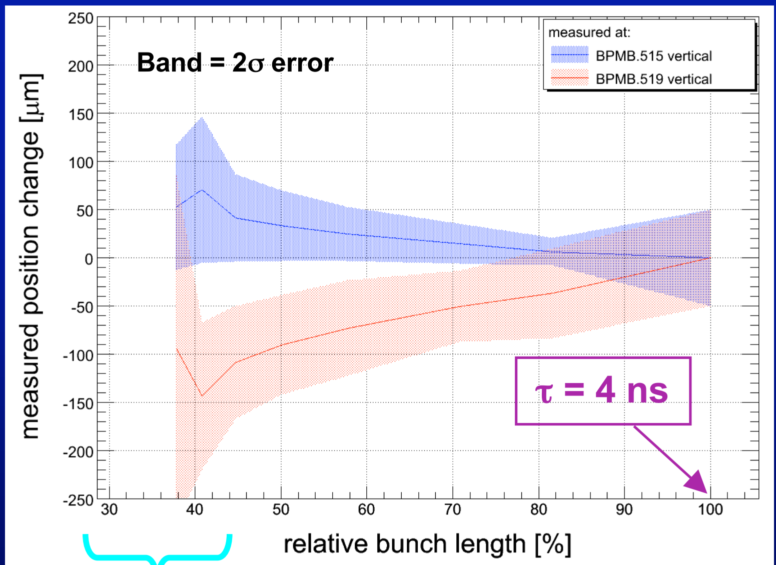
- SPS tests demonstrate the effect – up to ~ 200 μm.
- Effect expected to be significantly reduced at the LHC.

  Filters are optimized for shorter bunch lengths

- Mostly a problem to compare injection & collision settings.
- BPM-to-BPM spread.
- Possibility to measure and correct if it is required…?

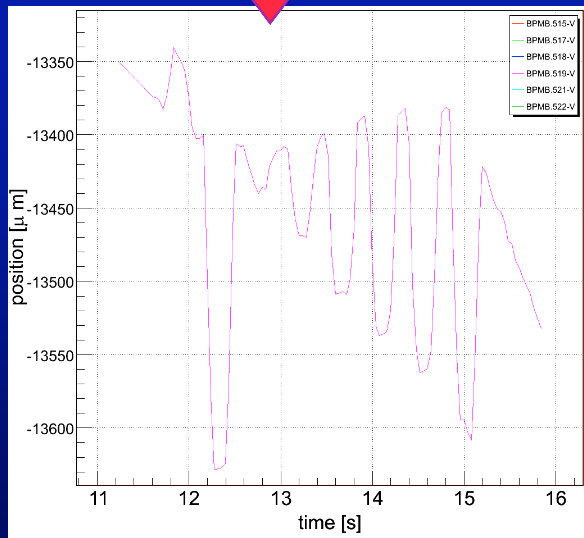


SPS tests at 26 GeV/c



LHC range

τ = 4σ bunch length

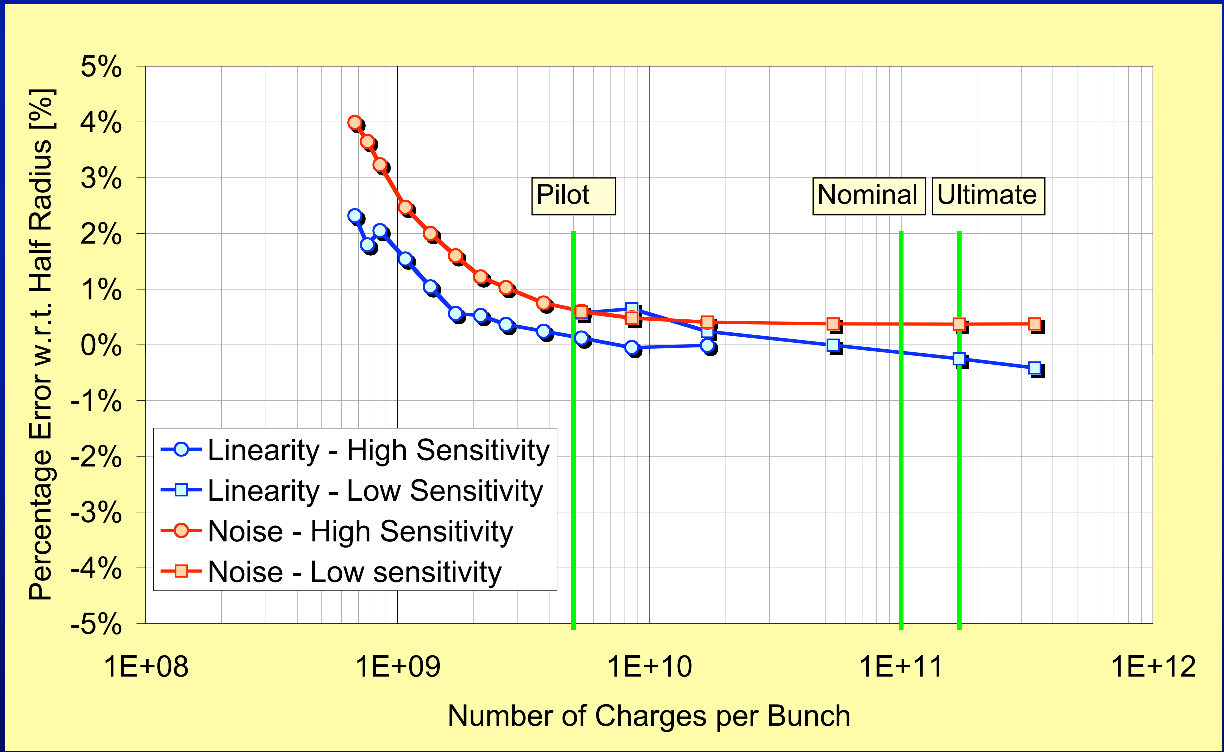


200 μm

BPM intensity dependence

The LHC BPM electronics is only sensitive to the *bunch intensity*, but not to the total beam intensity or bunch pattern because it is intrinsically working on a bunch-by-bunch basis.

- Collimator setting up may be done with a few bunches, provided the bunch intensity is the same as for nominal fill.
- We have to expect some systematic effects as the intensity decreases.



12 mm _ radius :

0.5% → 60 μm error

Courtesy R. Jones

Collimation setup

- Step 1 :
  - Optimize collimators with a few bunches, but with the same bunch population as for normal fills (within ~10-20%).
  - Record the orbit and define this orbit as reference.
- Step 2 :
  - Restore collimator positions and reference orbit (with FB) around the collimators for subsequent physics fills, making sure the bunch intensity is the same.

  → Based on the SPS experience, this procedure should provide a reproducibility of better than 50 μm.

- Remark :

  Detailed setup procedures are studied in the collimation project.

- Issues :
  - Systematic effect due to intensity decrease in physics – requires some learning.
  - Long(er) term stability of the reference positions (orbit & collimators).

Summary

- The design of the LHC orbit FB is well advanced, including control aspects.
  - Implementation of the system to begin soon !
- Feedback tests have been performed in 2003 and 2004 at the SPS using BPMs equipped with LHC electronics.
  - The performance results exceeded our initial expectations, stabilization < 10 μm achieved.
  - The new CERN networks for the SPS/LHC proved very reliable.
  - BPM reproducibility ~ 20-50 μm over 1-2 days.
- Orbit reproducibility in the collimation region of better than 50 μm can be expected provided care is taken to ensure consistent bunch intensities.
  - Some systematic intensity dependent effects still need to be evaluated.
- (Possible) future SPS beam tests :
  - Reproducibility tests (BPMs – collimator) – time consuming !
  - BPM systematic effects.
- Impact of BPM/COD failures on FB : evaluation in progress…

Reserve slides

Machine apertures at injection

Mech. aperture of LHC ring defines the scale $a_{ring} \approx 8\sigma$

➔ *tight aperture*

Protection devices protect ring aperture $a_{prot} < a_{ring}$

➔ *protect against injected beam*

Secondary collimators tighter than protection $a_{sec} < a_{prot}$

➔ *limit the amount of halo hitting protection devices*

Primary collimators tighter than secondary $a_{prim} \approx 5\text{-}6\sigma < a_{sec}$

➔ *primary collimators define the aperture bottleneck in the LHC for cleaning of the circulating beam!*

- These conditions must always be fulfilled :

  ➔ *orbit tolerances are at the level of 0.1-0.5$\sigma \approx$ 100-500 μm.*

  ! long distance correlations : some objects are separated by kms !
- The aperture definition includes tolerances for beta-beat (20%), orbit (4 mm), energy offsets, spurious dispersion…

Machine aperture at 7 TeV

Settings at 7 TeV for fully squeezed beams (β^* = 0.5 m IR1/5)

Low-beta triplet aperture defines the scale $a_{triplet} \approx 9\sigma$

Protection devices must protect aperture $a_{prot} < a_{triplet}$

➔ *protect against asynchronous beam dump*

Secondary collimators tighter than protection $a_{sec} < a_{prot}$

➔ *minimize halo hitting protection devices*

Primary collimators tighter than secondary $a_{prim} \approx 5\text{-}6\sigma < a_{sec}$

➔ *primary collimators define the aperture!*

- Operation at nominal intensity requires excellent beam cleaning.
  - ➔ *orbit tolerance around collimators is in the range $\sigma/3$ ~ 50 μm.*

Ground motion

The LHC tunnel is a fortunately a quiet place…

orbit rms ≈ κ × ground movement

→ Uncorrelated motion : κ ≈ 35

→ Ground waves :

f < 5 Hz **κ ≈ 0 – coherent motion**

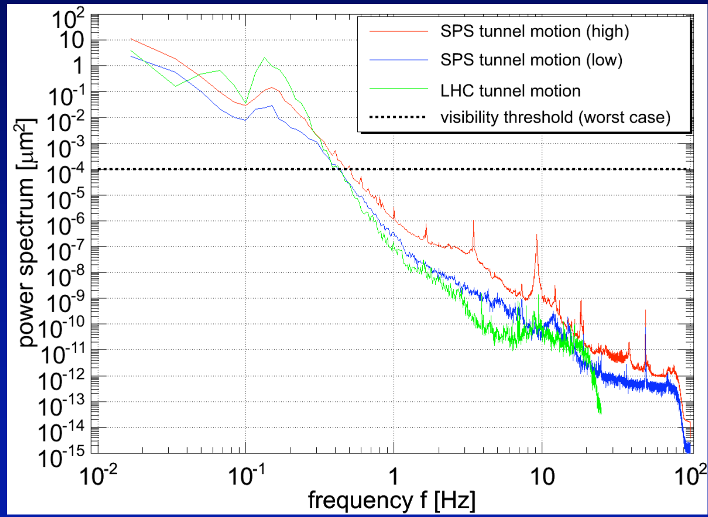
f > 5 Hz **1 < κ < 100**

orbits movements at f > 0.1 Hz
are expected to be ≤ 20 μm !

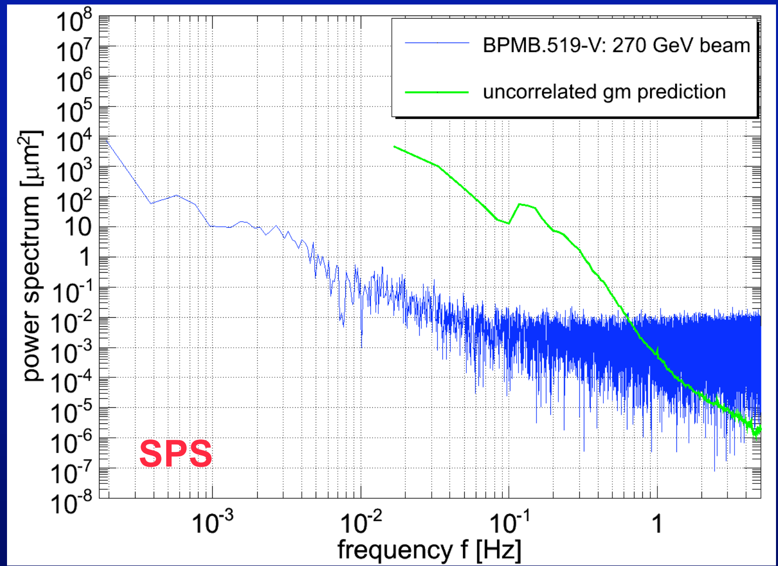
Long term orbit drifts (LEP) :
~ 200-500 μm rms over a few hours
~ 20-50 μm rms over ~ minute(s)

→ a priori we expect similar figures for the LHC !

Ground motion data



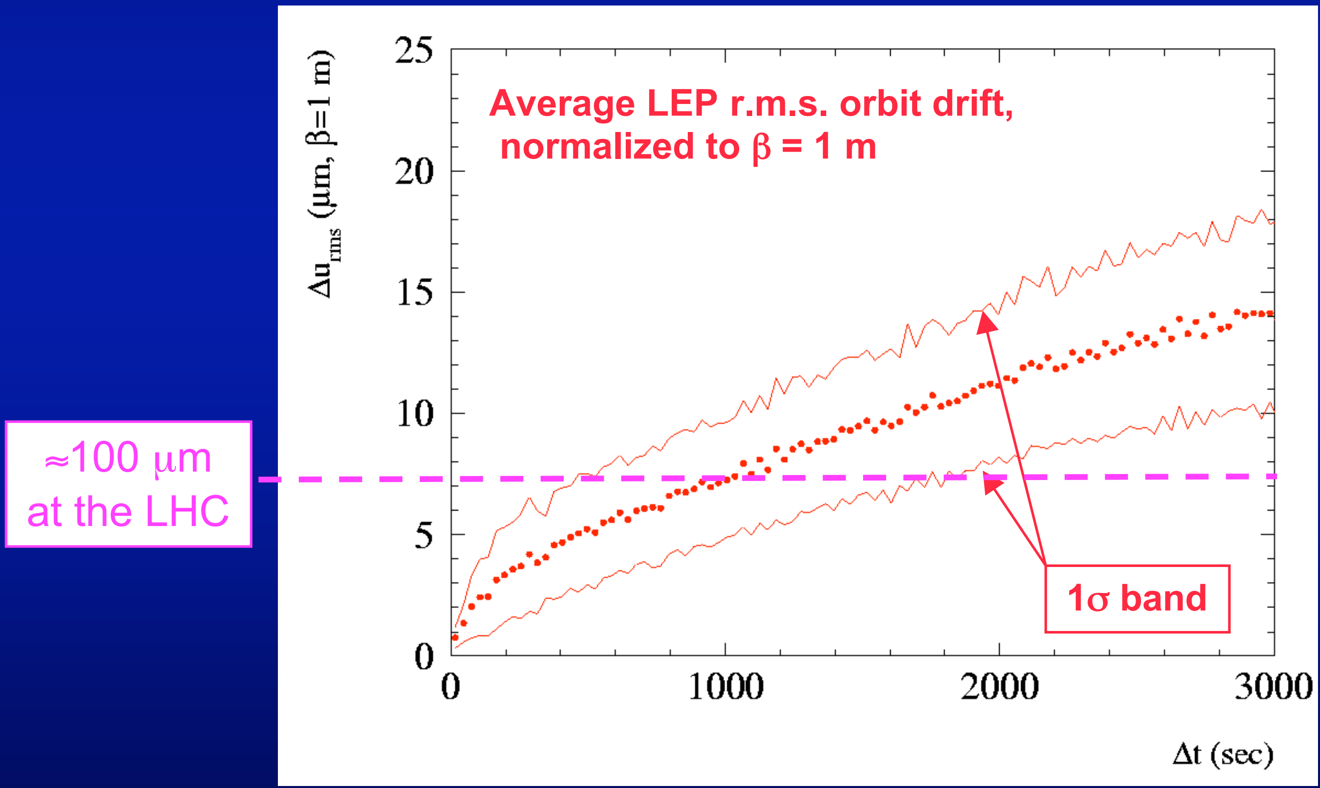
Beam data



LEP slow orbit drifts

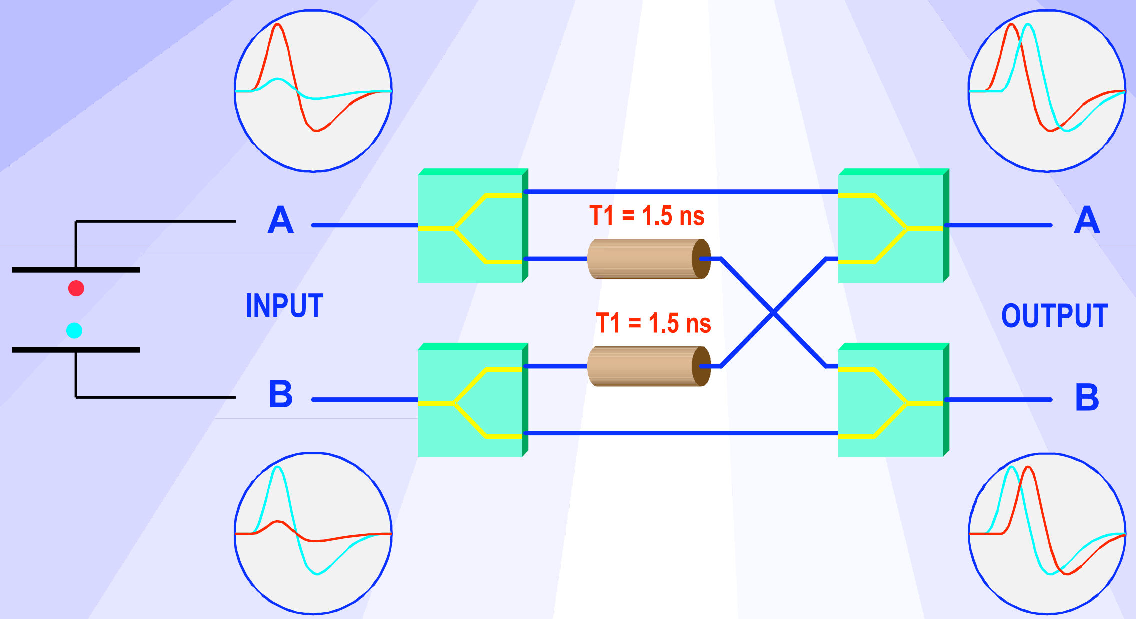
The measured slow LEP orbit drifts should give a good indication of what to expected at the LHC

→ no problem for a FB running at ≥ 0.5 Hz



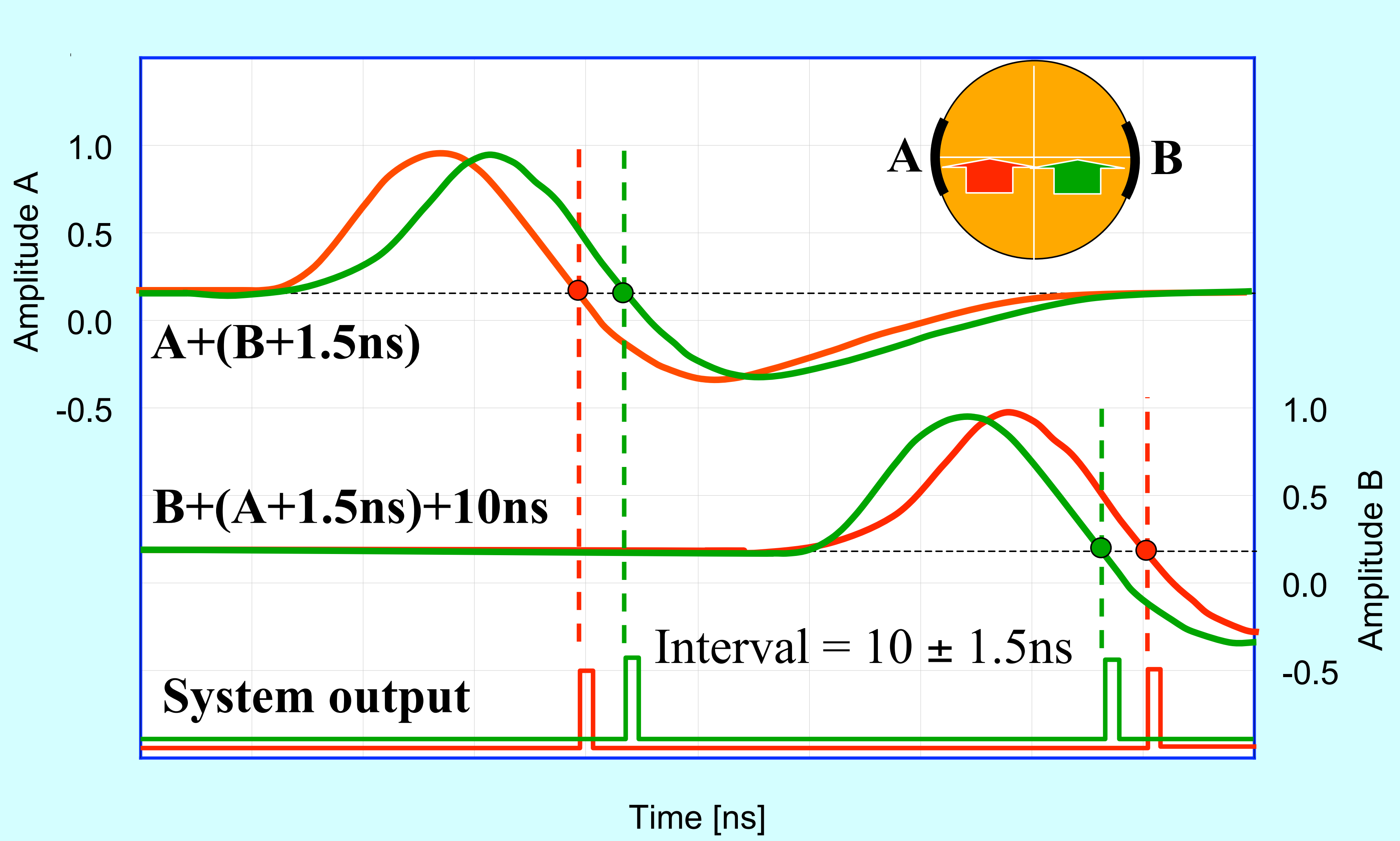
LHC Amplitude to Time Normaliser Principle

WIDE BAND TIME NORMALISER PRINCIPLE (WBTN)



Position difference is translated into a time difference of signals

Wide Band Time Normalizer



Beam Position Data Rates

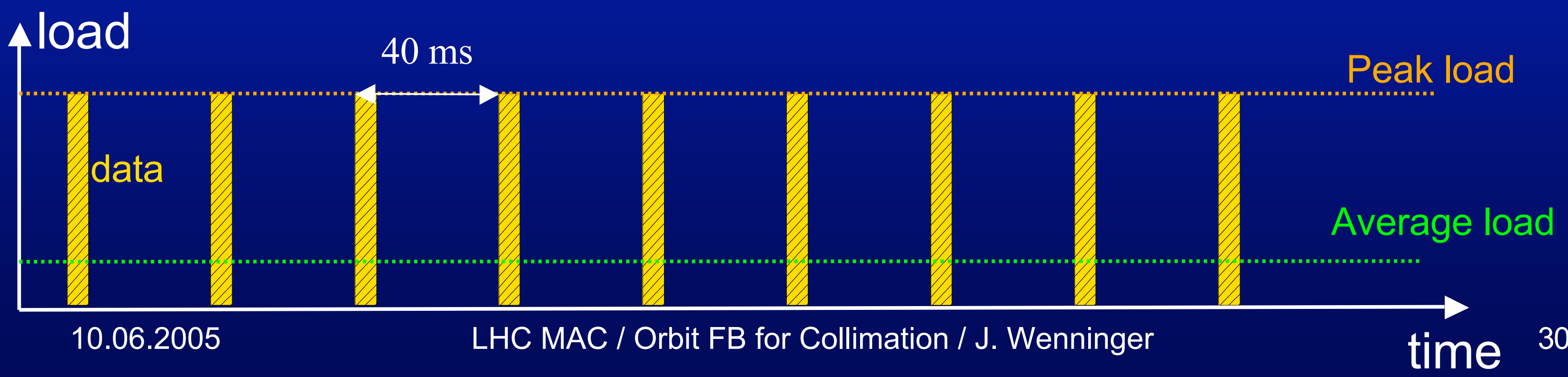
- Both rings covered by 1056 BPMs
- Measurement for both planes (2112 readings)
- BPM are organised in front-end crates (PowerPC/VME) in surface buildings
  - 18 BPMs (hor & vert) → *36 positions / VME crate*
  - *64 crates in total, 8 crates /IR*

Data stream:

- *Average data rates :*

18 BPMs x 20 bytes	*~ 400*	*bytes*	*/ sample / crate*
1056 BPMs x 20 bytes	*~ 21*	*kbytes*	*/ sample*
@ 25 Hz	*~ 4.2 Mbit/s + protocol overhead*		

- *Achievable peak rates (bursts): 100Mbit/s resp. 1Gbit/s (depending on Ethernet interface)*



Feedback delays

- The total delay determines actual bandwidth and performance.
- Delays are inevitable and part of digital control systems. Some sub-systems that contribute to the loop delay:
  - Beam Position Monitor System :

acquisition (255 turns@f_{rev}~11kHz)	~	*10 ms*
processing and sending	~	*5 ms*
technical network	<	*1 ms*

  - Feedback Control :

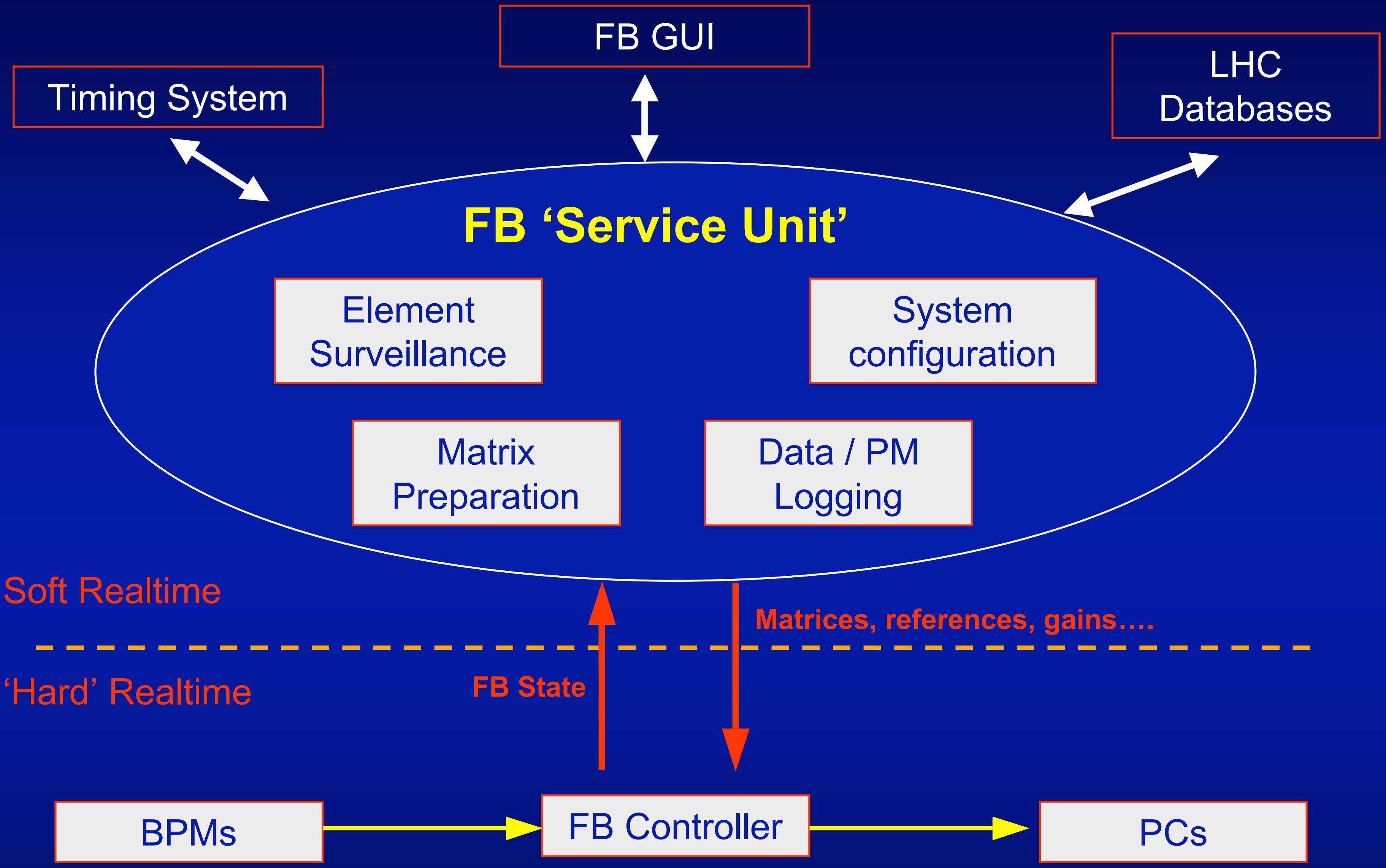
network inbound (100 MBit/s)	~	*3 ms*
data processing (essentially matrix multiplication)	~	*15 ms*
network outbound	~	*3 ms*
technical network	<	*1 ms*

  - PC System :

network inbound	~	*3 ms*
WorldFIP (50 Hz) clock	~	*20-40 ms*

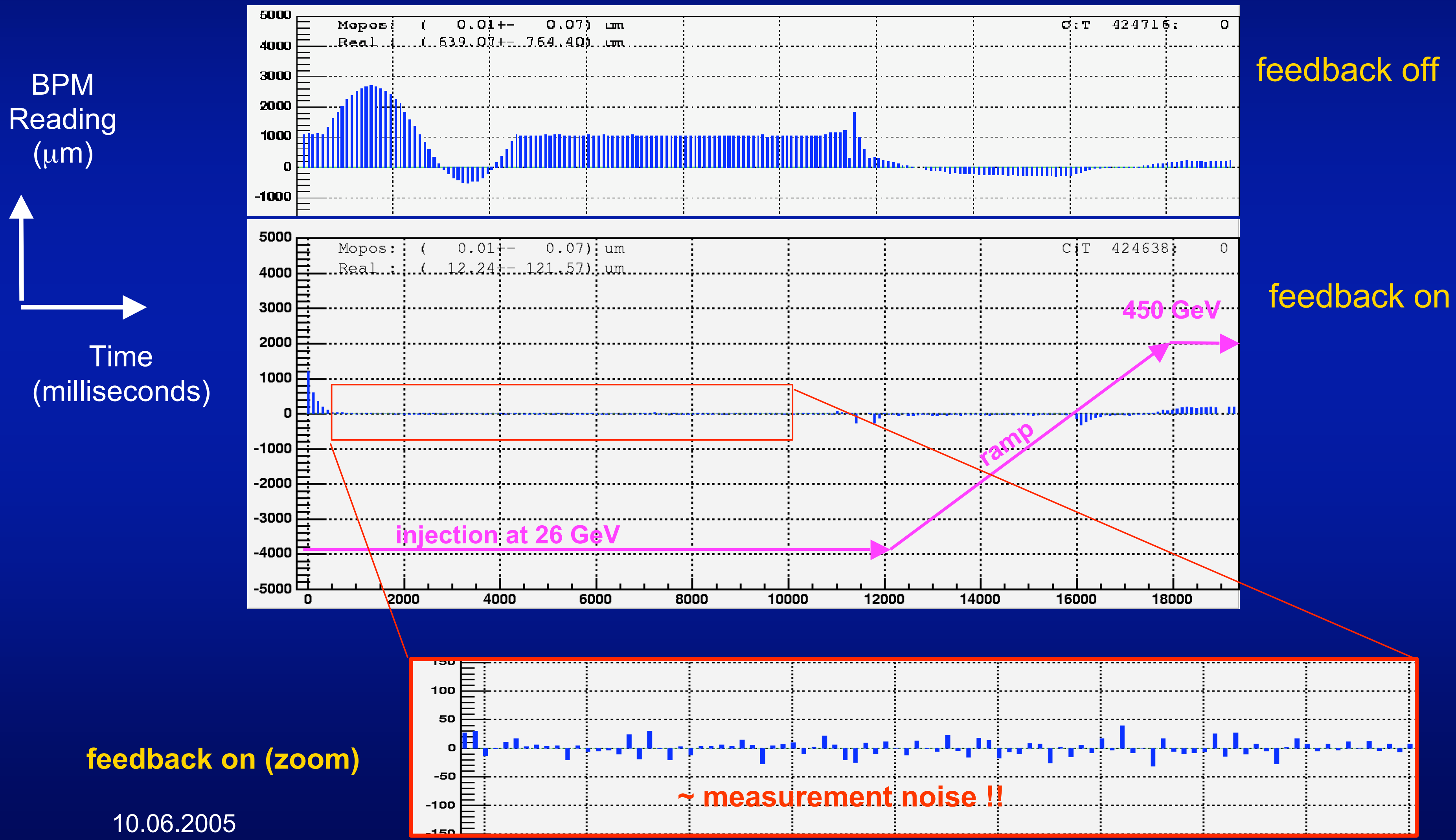
~ 30 ms

Total ~ 60-80 ms


FB GUI
Timing System
LHC Databases
FB 'Service Unit'
Element Surveillance
System configuration
Matrix Preparation
Data / PM Logging
Soft Realtime
Matrices, references, gains….
'Hard' Realtime
FB State
BPMs
FB Controller
PCs

FB proto-type at the SPS

Steering example with external noise over one SPS cycle, pulsed mode, FB running at 100 Hz.



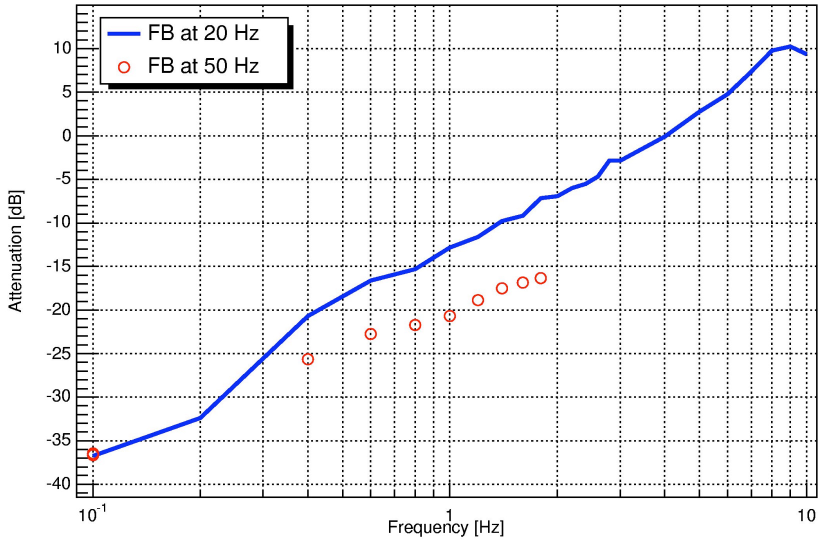
10.06.2005

Prototype results / 2003

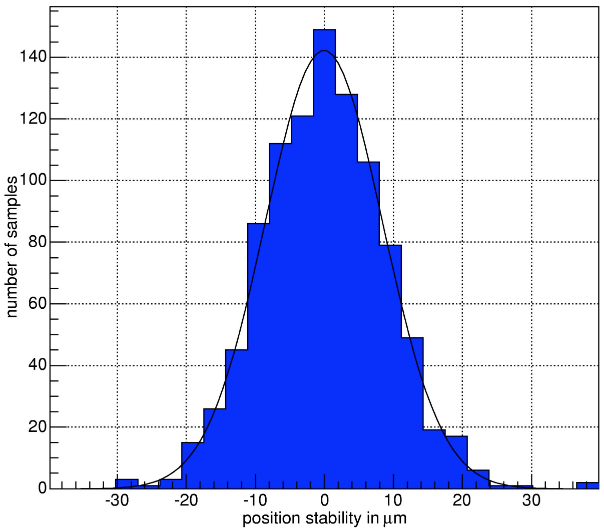
Feedback tests demonstrated good performance

- Stabilised the beam at 4 BPMs.
- Max. feedback sampling frequency 100 Hz.
- Position stabilization to 8.5 μm.

Feedback attenuation (gain)



Position residual @ 100 Hz
σ = 8.5 μm



The orbit FB 'Test-bed'

The test-bed is a complement to the Orbit Feedback Controller :

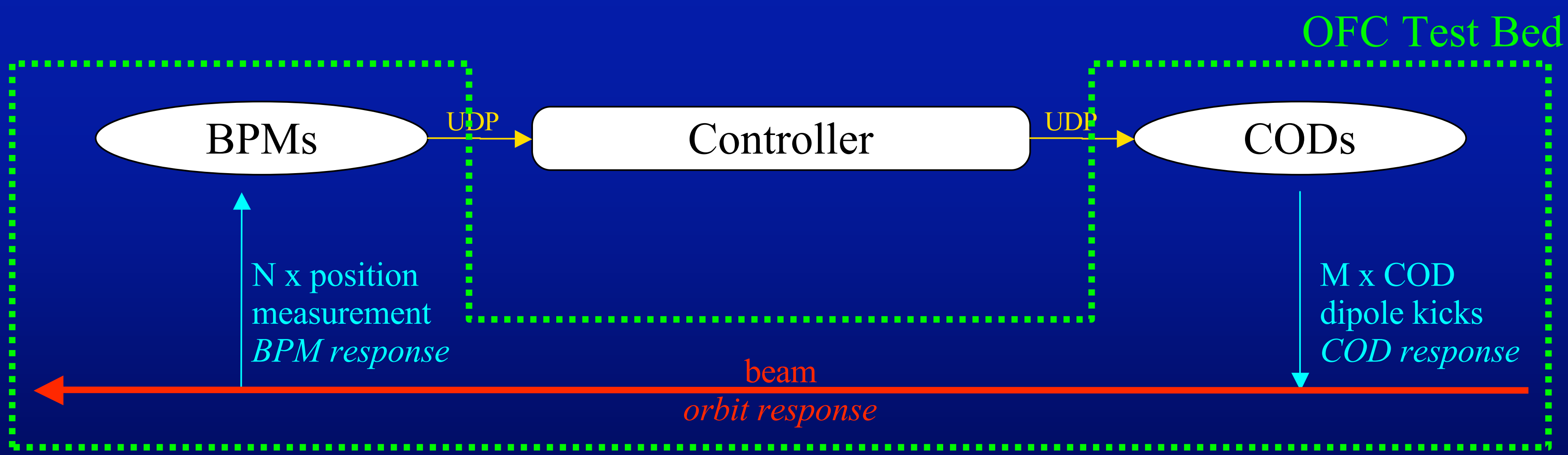
- Simulates the orbit response of COD →BEAM →BPM

  Includes the correct dynamic behaviour of the PC + magnet circuit.

- Same data delivery mechanism & encoding as in the real front-end

  Transparent for the FB system → simple "offline" debugging.

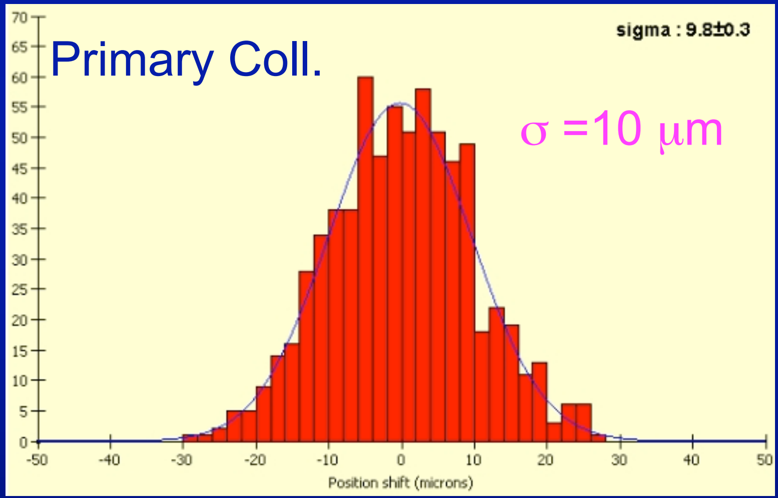
- Feedback performance can be tested and validated under various scenarios with the test-bed.

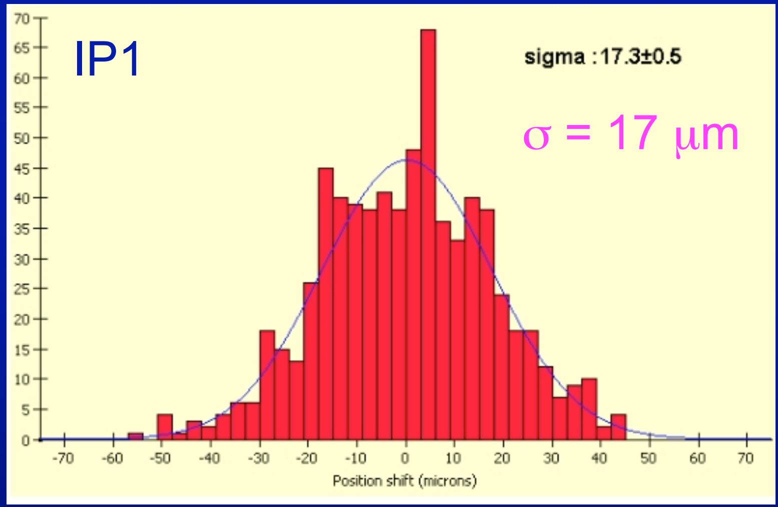


Ground motion correction in collision

- “Reasonably conservative” global correction strategy.
  ~ rather insensitive to isolated faulty BPMs.
- Decouple rings (i.e. common beam pipe elements not used).

Residual orbit shifts after ~ few hours of coast / 1 beam

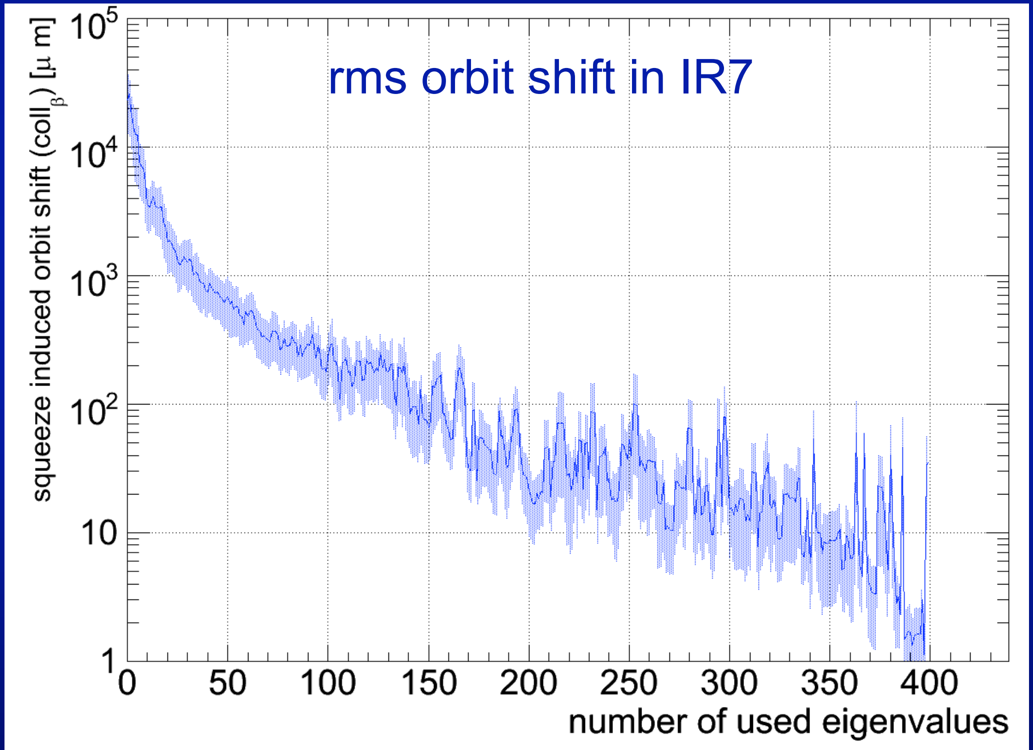




Note the large residual drift @ IP1 despite a 100 x smaller β
$\leftrightarrow$ correction strategy !

Simulation of squeeze

- Achievable residual orbit shift due to the squeeze using <u>ONLY</u> a global correction.
- A local correction can provide a 'perfect' correction because the perturbation in IR7 is basically a free betatron oscillation propagating into the collimation IR.



More eigenvalues for Singular Value Decomposition
↔ more aggressive correction

<u>Conditions :</u>

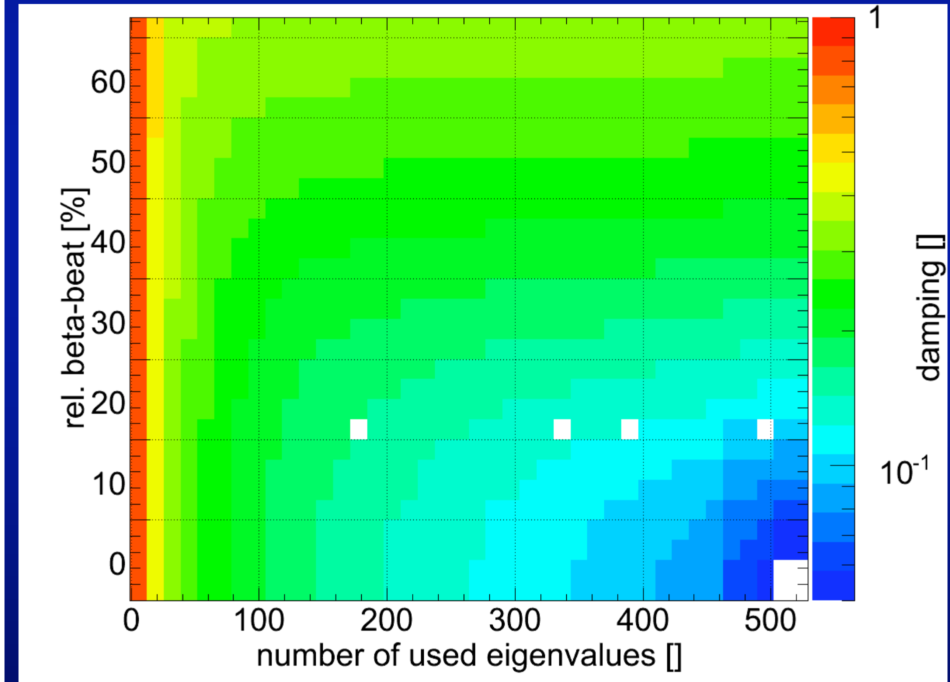
- **Initial orbit rms 1 mm.**
  (before squeeze)
- **Misalignment rms 0.5 mm.**

Influence of β-beating on correction

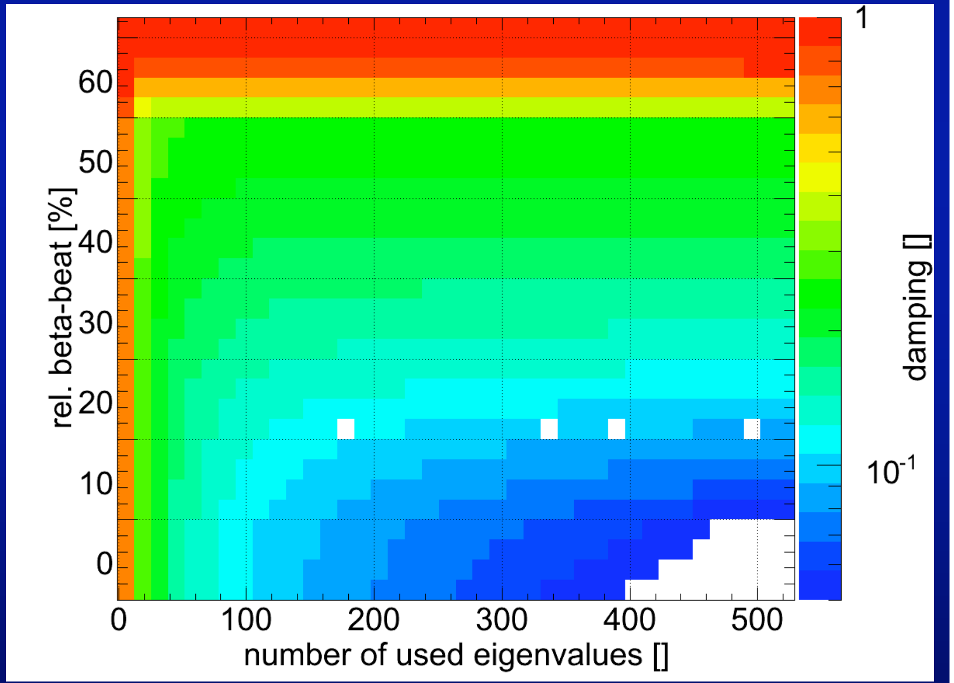
Orbit rms reduction (rms after / rms before) as a function of the β-beat (plots indicate ~ 2 x rms beating ~ peak β-beat) for a correction based on the NOMINAL optics.

→ convergence is maintained up to peak β-beat of ~ 50%

Injection optics



Collision optics (0.5 m)



increasing number of eigenvalues (SVD correction) → more aggressive (and risky) correction