Real-time orbit control @ the LHC

Summary of the mini-workshop held Oct 6th 2003

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With emphasis on control aspects

Details of all presentations are available on :

http://proj-lhcfeedback.web.cern.ch/proj-lhcfeedback/workshop/workshop.htm

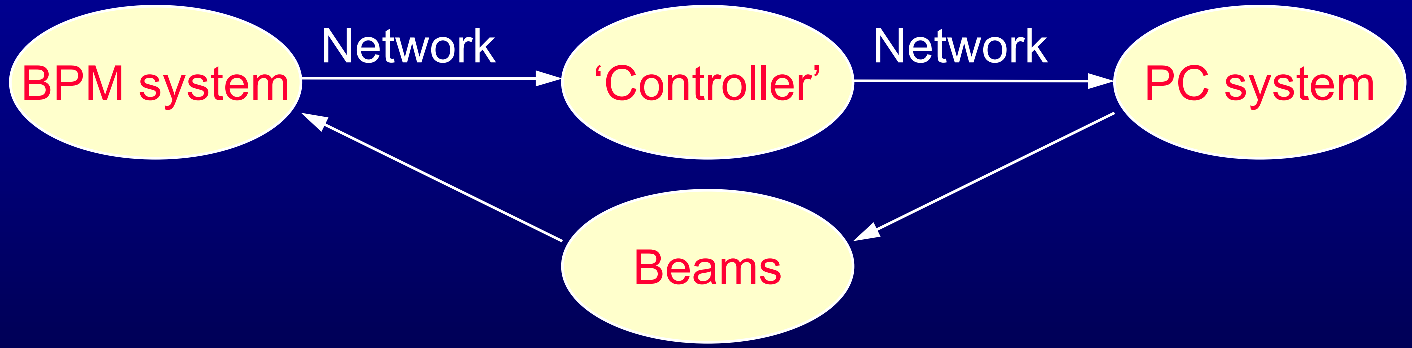
Real-time orbit control : what's that ?

The aim of real-time orbit control system is to stabilize the orbit of the LHC beams during ALL operational phases within the required tolerances.

It is a real-time system in the sense that the system must be deterministic – this very important during critical phases.

The LHC system is 'unique' because it is distributed over a large geographical area and because of the large number of components.

Very very schematically - we have 5 players :



People

The partys that are inlvolved :

- BDI : beam position system
- PC : orbit corrector control
- CO : communication, servers, ‘controls infrastructure’
- OP : main ‘user’

Core-team for prototyping work at SPS

- BDI : L. Jensen, R. Jones — BPM HW & Readout
- CO : J. Andersson, M. Jonker — Server, PC control
- OP : R. Steinhagen, J. Wenninger — Algorithms, FB loop, measurements

But also : M. Lamont, Q. King, T. Wijnands, K. Kostro and others

Orbit control @ the LHC

Requirements :

- Excellent overall control over the orbit during all OP phases.
  - RMS change < 0.5 mm – for potential perturbations of up to 20 mm.
- Tight constraints around collimators (IR3 & 7), absorbers … :
  - RMS change < ~50-70 μm for nominal performance.

- 'New' and very demanding requirement from the TOTEM exp. :
  - Stability of ~ 5 μm over 12 hours around IR5. Main problem : not sure the BPMs are that stable in the first place.

EXPECTED sources of orbit perturbations :

- Ground motion, dynamic effects (injection & ramp), squeeze.
- Mostly 'drift- or ramp-like' effects.

→ frequency spectrum is < 0.1 Hz

Limitations from power converters & magnets

There are 250-300 orbit corrector magnets per ring and per plane (mostly cold).

SC orbit correctors :

- Circuit time constants : $\tau \cong$ 10 to 200 s (arc correctors ~ 200 s).
  For comparison, in the SPS : $\tau \cong$ 0.5 s
- EVEN for SMALL signals, the PCs are limited to frequencies ≤ 1 Hz.
  At 7 TeV small means really small : ~ 20 μm oscillation / corrector @ 1 Hz.

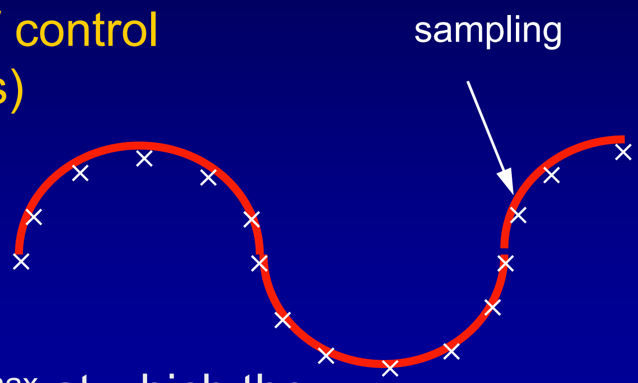
Warm orbit correctors : only a few / ring

- Circuit time constants τ ~ 1 s → PC can run them > 10 Hz.
- But there are too few of them to make anything useful with them !

→PCs will limit correction by the FB
to frequencies ≤ 1 Hz !

Real-time…

Real-time control implies deterministic correction / control
→ stable delays (at least within some tolerances)



Digital loop performance depends on :

- Sampling frequency **f_s**
- Delay

As a rule of thumb, given the highest frequency f_p^{max} at which the FB should perform well,

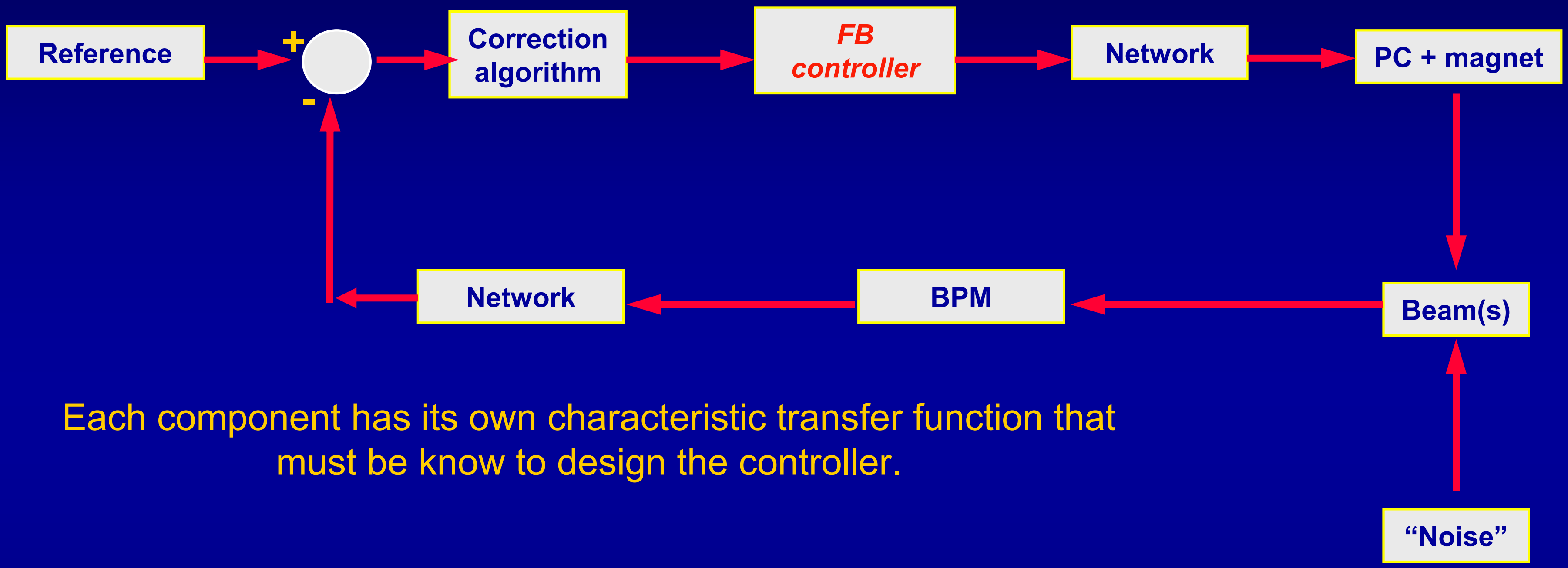
$$f_s > 20\text{-}30 \times f_p^{max}$$

i.e. f_p^{max} = 0.1 Hz → f_s ~ 3 Hz expected 'noise'
= 1 Hz → f_s ~ 30 Hz to reach the PC limit

Delay < $(1/ f_p^{max}) \times 0.05$ ~ 50-500 ms

I recommend to use the PC limit of 1 Hz as design target and not the expected noise : gives margin + best use of HW !

RT feedback building blocks



Each component has its own characteristic transfer function that must be know to design the controller.

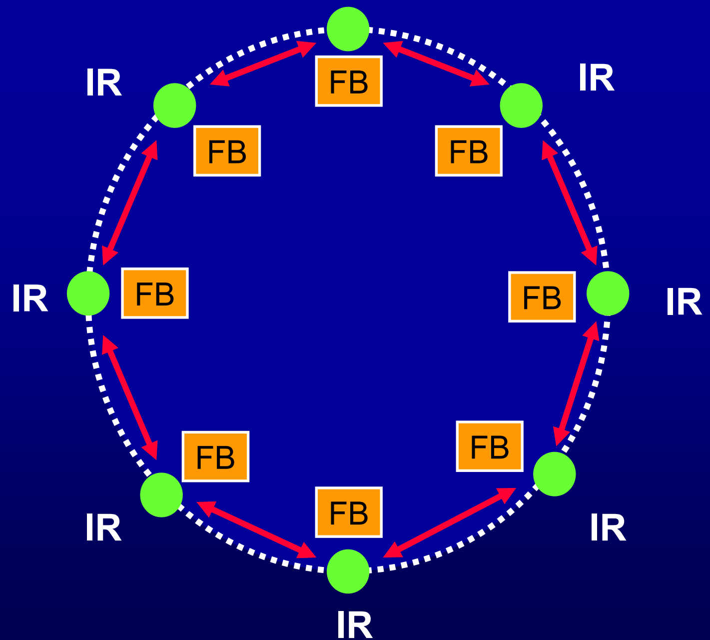
This RT loop spans the entire LHC machine.
For good performance :

- the reliability of each component must be adequate.
- the delays must be 'short' ~ O(100 ms) and stable.

Global architecture

Local / IR

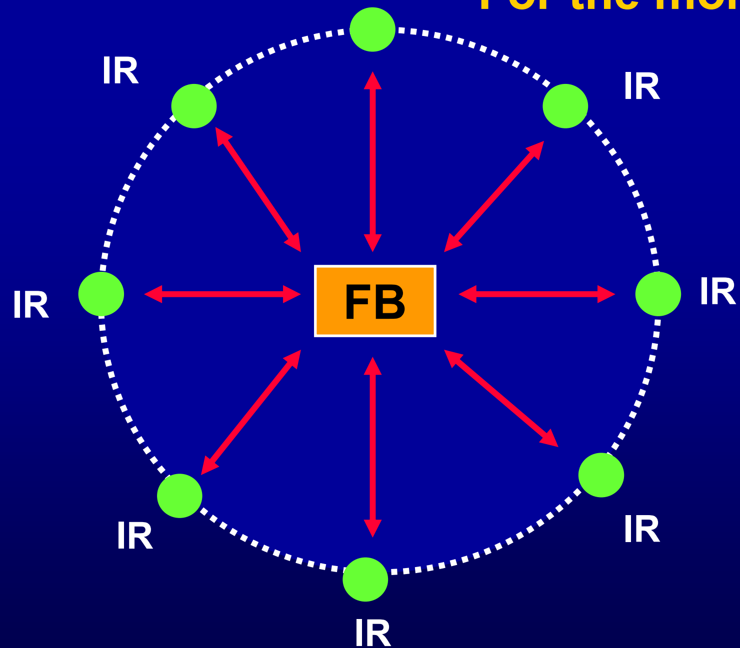
- ✓ reduced # of network connections.
- ✓ less sensitive to network.
- ✓ numerical processing faster.
- ✓ …
- × less flexibility.
- × not ideal for global corrections.
- × coupling between loops is an issue.
- × problems at boundaries.
- × ..



Central

- ✓ entire information available.
- ✓ all options possible.
- ✓ can be easily configured and adapted.
- ✓ …
- × network more critical : delays and large number of connections.
- × …

Preferred !!
For the moment…



Beam Position Monitors

Hardware :

- 500 position readings / ring / plane ~ 1000 BPMs for the 2 rings
- Front-end crates (standard AB-CO VME) are installed in SR buildings
  - 18 BPMs (hor + ver) ⇔ 36 positions / VME crate
  - 68 crates in total → 8-10 crates / IR

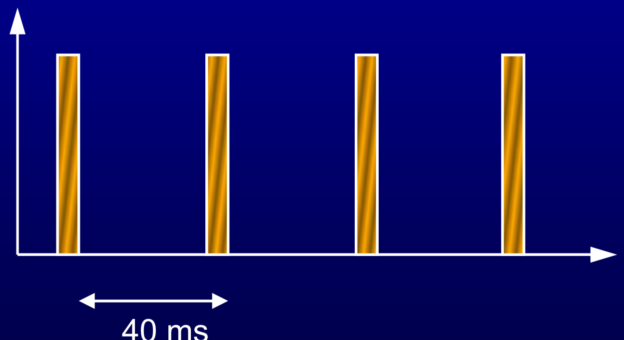
Data streams :

- Nominal sampling frequency is 10 Hz – but I hope to run at 25 Hz…
  > 100 times larger than the frequency of fastest ***EXPECTED*** CO perturbation.
- **Average** data rates per IR :
  - 18 BPMs x 20 bytes ~ 400 bytes / sample / crate
  - 140 BPMs x 20 bytes ~ 3 kbytes / sample / IR

@ 25 Hz – from each IR :

Average rate ~ 0.6 Mbit/s

Instantaneous rate ~ 25 Mbit/s (1 msec burst)



More on BPMs

An alternative acquisition mode is the multi-turn mode :

- For each BPM one can acquire up to 100’000 turns of data / plane.
- The acquisition itself does not interfere with RT close orbit,
  but readout + sending to the user does !!

Data volumes :

- 100’000 x 2 (planes) x 18 (BPMs) x 4 bytes ~ 16 Mbytes / crate
- This data must be extracted without interfering with RT closed orbit.
- There are even proposals to ‘feedback’ at 1 Hz on machine coupling… with such data (only 1000 turns !) :
  - Per IR : 10 x 8 x 16/100 Mbit/s ~ 10 Mbit/s

We must carefully design the readout to prevent
‘destructive’ interference of other ‘BPM services’ with RT closed orbit !

LHC Network

What I retained from a (post-WS) discussion with J.M. Jouanigot

- It has lot's of capacity > 1 Gbit/s for each IR.
- It has very nice & very fast switches (μs switching time).
- It has redundancy in the connections IR-CR.
- Is it deterministic ?
  - **It is not** - but delays should be small (< 1 ms), and stable if the traffic is not too high.
  - All users are equal – but 2 network profiles are available in case of problems.

- With the SPS network renovation, we will be able to test a network that looks much more lHC-like in 2004.
- I suspect that as long as we do not know details on data rates, it is difficult to make precise predictions for the LHC.

'Controller'

Main task of the controller / central server(s) :

- Swallow the incoming packets (~ 70 / sampling interval).
- Reconstruct the orbit & compare to reference orbit.
- Calculate (matrix multiplication … or more) new deflections.
- Apply control algorithm to new and past deflections.
- Verify current & voltage limits on PCs.
- Send corrections out…

Other tasks :

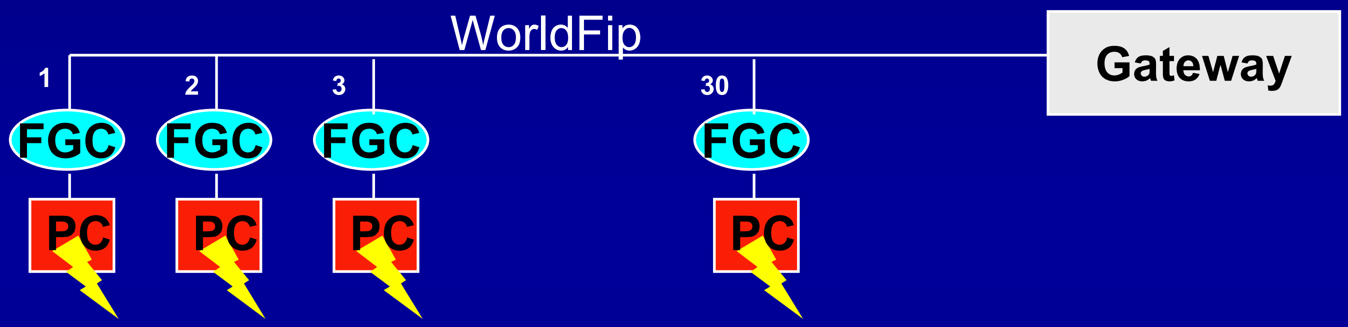
- Monitor HW status (BPMs & correctors), feed back on response matrices.
- Get beam energy & machine state info (⇔ algorithm, optics, reference orbit…).
- Logging & post-mortem.
- Interaction with operation crews (ON, OFF, parameters…).

→ The controller will (most likely) consist of a number of threads that will be running on a dedicated 'machine' and that need some form of RT sheduling and synchronization !

PC control

Architecture :

- Each PC is controlled by one Function Generator Controller (FGC).
- Up to 30 FGCs (PCs) per Worlfip bus segment.
- 1 gateway controls a given Worldfip segment.
- Orbit correctors are accessed over ~ 40 gateways.



Timing & access :

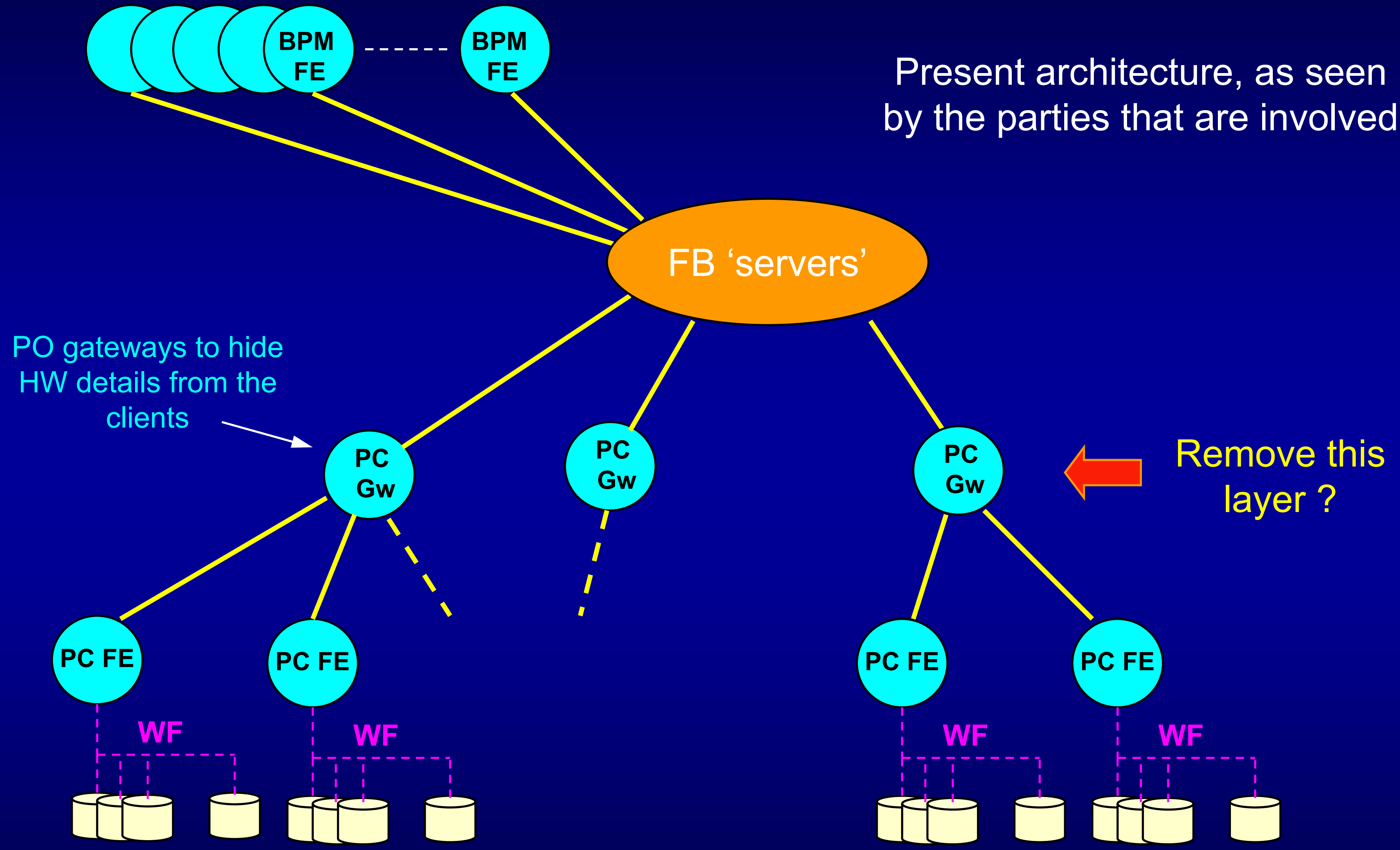
- **The WorldFip bus is expected to run @ 50 Hz – 20 ms cycle.**

  → the FB sampling frequency must be **f^s = 50 Hz / n   n=1,2,3….**

- The delay (WorldFip + PC set) is ~ 30-40 ms.
- Present idea is to send all settings to some 'central' PO gateways that will dispatch the data to the lower level gateways & Worldfip.

Schematically…

Present architecture, as seen by the parties that are involved



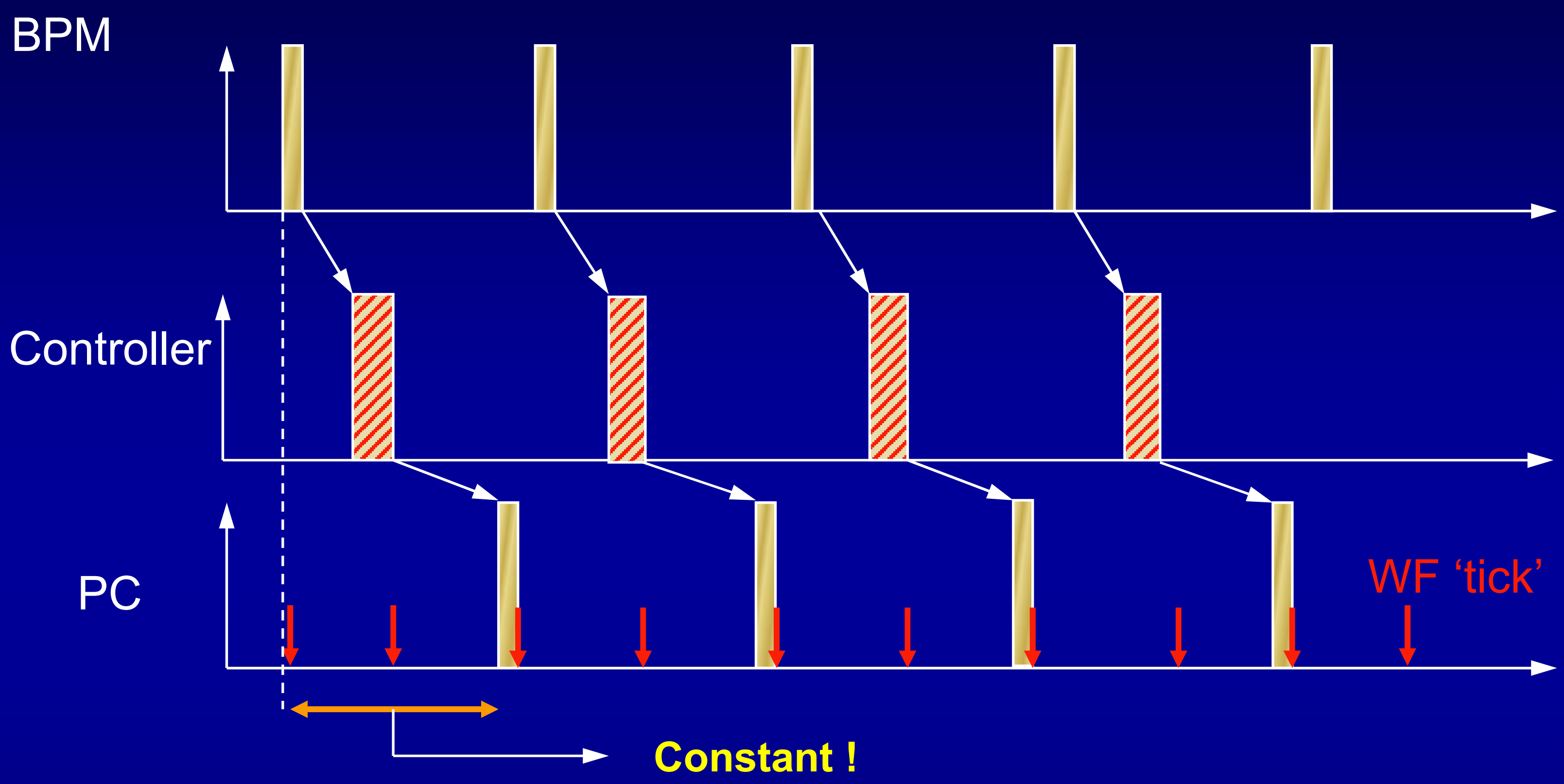
Delays

Estimated delays – in ms :

BPMs	5-10
Network / inbound	1
Packet reception	30
Correction	10-40
Packets out	10
Network / outbound	1
PC control	30-40
Total	80-120 ms

- Just acceptable if you consider the PC limits of 1 Hz.
- For a 25 Hz sampling rate, this is already > 1 period !

Synchronization



- All BPM crates are synchronized via BST to 1 turn.
- All PC WF segments are synchronized (GPS).

→ Synchronize RT acquisition and WF segments to maintain stable delays.

Orbit drifts in the "FB perspective"

Consider :

- FB sampling rate : 10 Hz
- BPM resolution : 5 µm (~ nominal LHC filling)
- Tolerance : 200 µm (injection/ramp), 70 µm (squeezed, physics)

Compare orbit drift rates in some 'typical' and most critical situations..

Phase	Total drift/ total duration	drift/ FB interval	No. samples to reach tolerance
Start ramp ('snapback')	**2 mm / 20 s**	**10 µm**	20
Squeeze	**20 mm / 200 s**	**10 µm**	**7**
Physics (LEP, pessimistic)	**4 mm / hour**	**1 µm**	**70***

Note : those are approximate numbers, but they give an idea of the 'criticality' of the communications.
(*) : not for TOTEM…

What happens if we lose a sample ?

- During the ramp and squeeze phases :
  - Not nice, but not yet death – we have a small 'margin'.
- In collisions (not for TOTEM !!) , during injection :
  - Most likely nobody will notice (except the FB itself),
    provided we hold the latest settings.
  - If conditions are similar to LEP, we can afford to loose a few samples at 7 TeV.

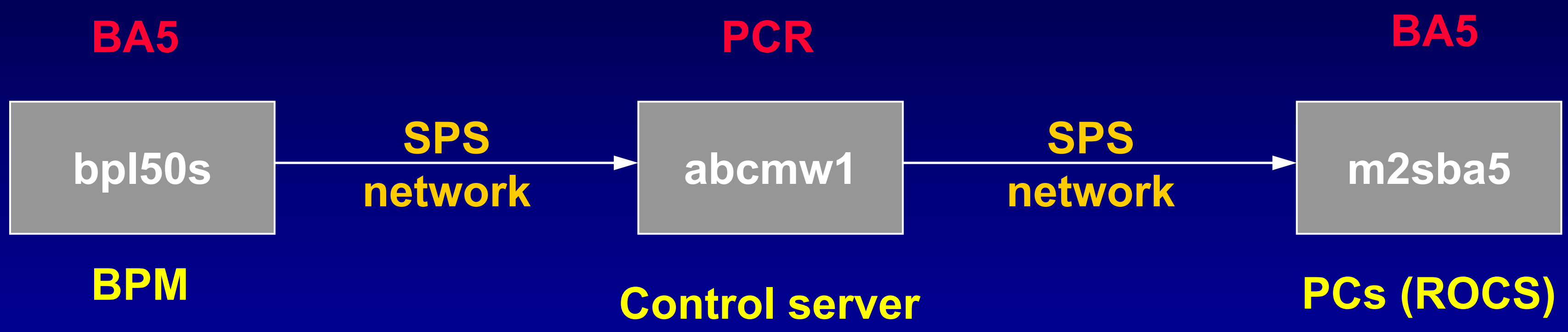
- We can also rely on reproducibility to feed-forward average corrections from one fill to the next (only ramp & squeeze)

  → may reduce the workload on the FB by ~ 80% - but not guaranteed !

  → we become less sensitive to packet losses !

- We must keep in mind that :
  - Packet losses remain a hassle and require more conservative gain settings !
  - We cannot tolerate to have long drop-outs (> 500 ms) in critical phases.
  - **Loosing a front-end is also an issue - it is more complex to handle than a lost packet !**

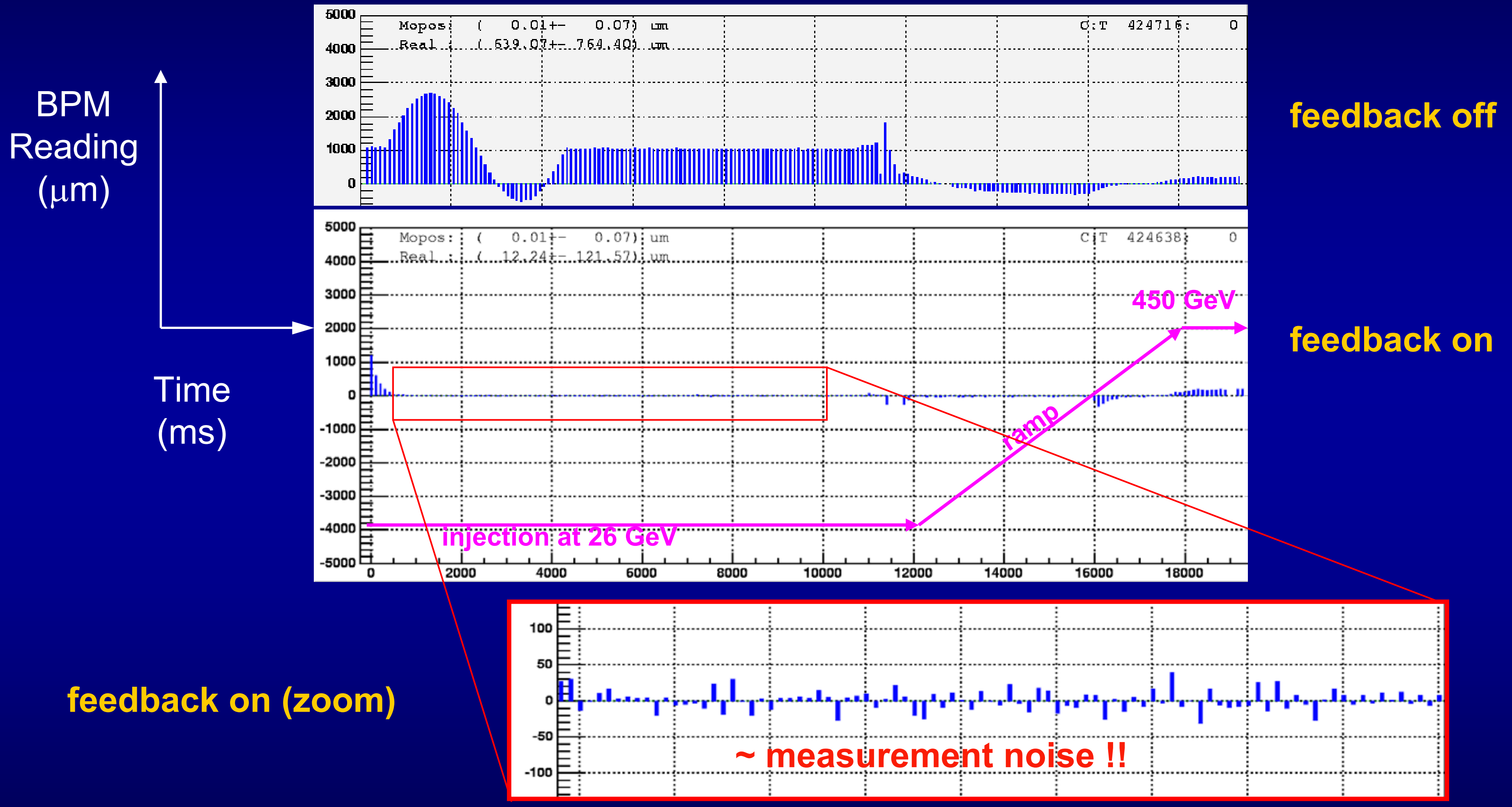
SPS prototyping in 2003



- BPMs : VME crate with LHC ACQ cards ~ identical to LHC, but only 4 BPMs (6 in 2004).
- Communication:
  - BPMs → Server : **UDP (and later CMW / TCP)**
  - Server → PCs : **UDP**
- Central control server for correction, gain control, data logging…
- Maximum sampling rate pushed to 100 Hz !
- Present ('old') SPS network was a problem –
  - 'frequent' packet losses.
  - sometimes important delays (>500 msec).

An extremely valuable exercise – a lot of time was spend testing the system on the LHC beams.

And it worked …very well !



Looking back @ LEP / I

Although the issues at LEP & LHC are of a different *nature*, one can learn from LEP :

- No real-time orbit acquisition at LEP.
- Very strict orbit control required to achieve best luminosity.
- Orbit drifts were due to slow ground motion & low-beta quad movements.
- During 'physics' (i.e. *stable* collisions) the orbit was stabilized by a feedback.
- FB parameters :
  - Sampling period ~ 15 and 120 seconds.
  - Non-deterministic, variable delay > 5 seconds.
  - Corrections were triggered above a threshold : ~ 50 to 200 μm rms.
- FB performance :
  - **It had no problem to stabilize the orbit to < 100 μm (if desired !).**
  - **We regularly operated with 1 to 3 missing BPM FEs (power supplies…)**
    → no incidence on performance – thank you GLOBAL FB !

Since the same tunnel will host the LHC, there is a fair chance
that the LHC beams will exhibit similar drifts in physics.
But you are never 100% sure & and LEP was not critical for beam loss !

Looking back @ LEP / II

The ramp & squeeze were the actual *machine efficiency killers* :

- A large fraction of beams that went into the ramp never made it into physics.
- The culprits :
  - Tune control → corrected from 1997 onwards by a real-time tune FB.
  - Orbit control : **remained a problem until the last day !**
- The problem :
  - Orbit changes in R & S were large (many mm rms).
  - The orbit changes were not sufficiently reproducible (long access…).
    → Feed-forward of corrections was not sufficiently predictable.
  - Ramp commissioning and cleaning was very difficult.

A 1-2 Hz orbit FB would have cured all our R & S problems !
I think that it is in the ramp and squeeze phases that the orbit FB will be most useful and critical for the LHC !
Again, LEP survived because beam loss was no isssue !

For the LHC we have a chance to anticipate !

Conclusions

- The importance of an orbit FB for the LHC was recognised at an early stage of the LHC design.
- As a consequence both BPM and PC systems were designed with RT capabilities.
- The RT orbit system must be commissioned at an early stage of the machine startup in 2007 – possibly before we first ramp the beams.
- With the SPS we have a valuable (although limited) test ground for ideas and implementations – in particular for controls issues.
- We still have some time, but there are number of items to be tackled and some design choice to be made.

Hist list of issues

… as I see / feel them at the moment

1 - Data collection from many clients ***(*)
Delays, reliability….

2 - Network AND front-end availability ***
Packet loss rate, delays…

3 - RT operating systems & sheduling **
The SPS tests were based on fast response, not determinism !

Future efforts

Operating system & process sheduling :

- Interference RT tasks & heavy data transfer in BPM Front-ends.
  - Tests possible with SPS setup – **2004**.
- RT scheduling on orbit server(s) side.
  - Re-design the SPS prototype with LHC oriented & re-usable architecture – **2004.**

Network / data collection :

- Check out the new IT network in the SPS in **2004**.
- Tests in the IT lab / SM18 (traffic generators…).
- Question : **do we need a dedicated network ?**
  - The need is not 100% obvious to me, but if we get, we take it !
  - Must span ~ all the LHC !
- Data collection tests.
  - We must ‘convince’ ourselves that a central server can swallow 70 packets @ 25 Hz over > 24 hours without crashing & with adequate response time.

Future efforts / open questions II

Architecture and overall optimization :

- Optimization of BPM layout in FEs, number of correctors…
  → may reduce the number of clients by 20 or so.
- Accelerator simulations of faults… **2004-2005…**

Synchronization :

- Synchronization scheme for BPMs, FB server & PCs.

SPS tests : 2004

- Continue studies in the SPS (Network, loop, BPM Front-end…).
- ‘Interaction’ FB & proto-type collimators in LSS5.

It's not all orbit…

Eventually we also have to deal with :

- Q (Tune) feedback.
- Chromaticity feedback ?
- Feed-forward of multipoles from SM18 reference magnet.

Those systems are simpler because :

- 1 'client' that generates data & much smaller number of PCs.

…and more delicate because :

- Measurement rates depend on beam conditions (Q, Q').
- Measurement number / fill may be limited – emittance preservation.
- Feed-forward is intrinsically more tricky.

So far little controls activity…

Next event : workshop on reference magnets / feed-forward in March 2004 by L. Buttora, J. Wenninger et al. – to be confirmed.