# LHC Orbit Stabilisation Tests at the SPS

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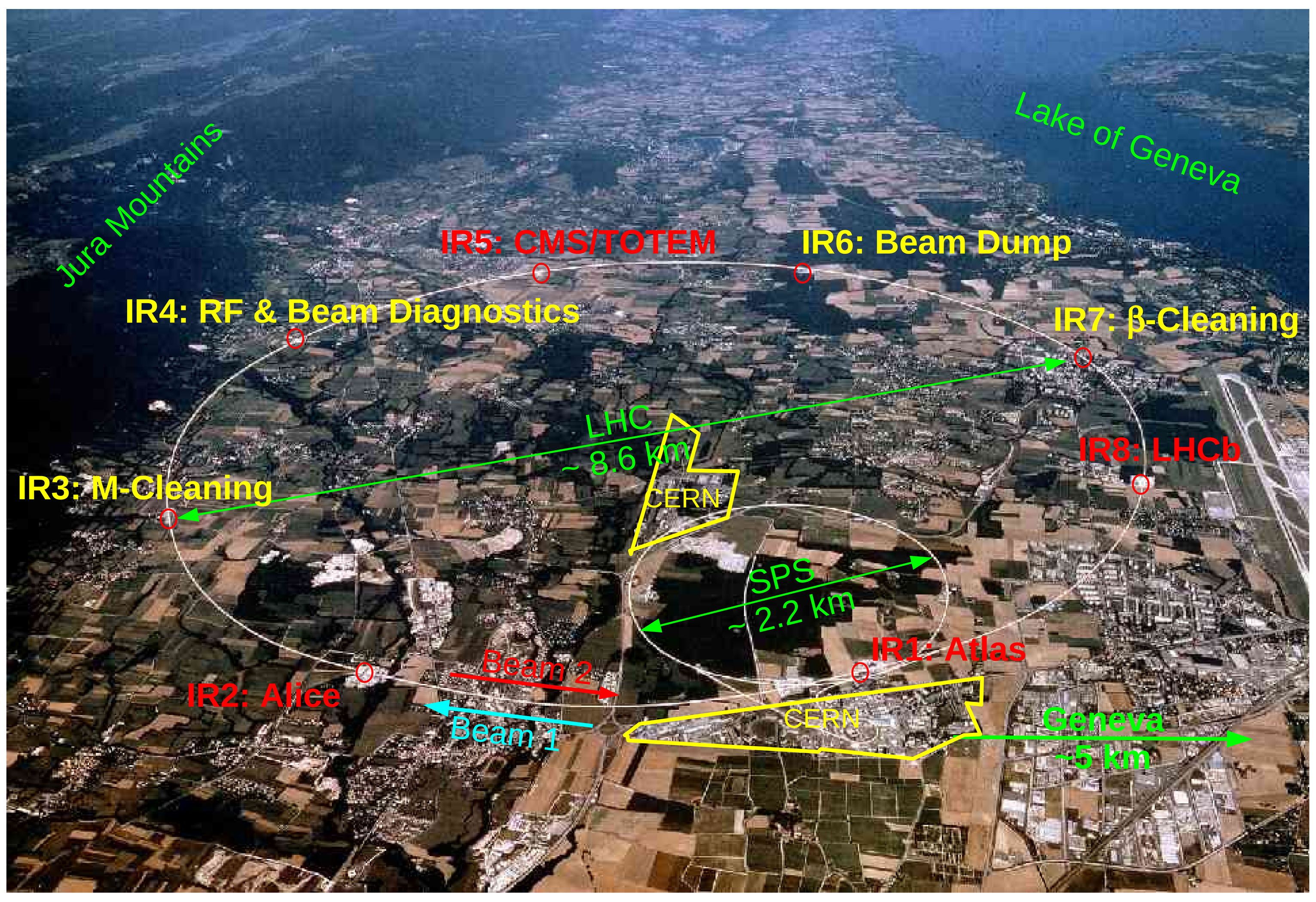
### Large Hadron Collider Schematics:




The LHC, presently being built at CERN, is a superconducting hadron collider in the vicinity of Geneva, Switzerland, with a circumference of 27 km and an average depth of 100 m. It will store, accelerate and collide two proton beams from an initial momentum of 0.45 TeV to a maximum particle momentum of 7 TeV at a nominal luminosity of $10^{34}$ $cm^{-2}s^{-1}$. Except of the four interaction regions, the beams are mostly stored in two beam pipes. The eight insertions are used for HEP detectors, the RF, beam instrumentation, cleaning- and beam dump system.

### Orbit Perturbations:

Three classes of orbit perturbations, which are important for the orbit feedback control, are expected:

Machine-inherent:
- Decay and snapback of magnet's multipole momenta
  (main dipole moment is dominant)
- Optics changes: e.g. squeeze of beam in insertions
- Eddy currents in the vacuum chamber wall
- Dynamic effects: ramp, beam-beam

-> Largest contribution, perturbations up to ~ 30 mm/(x min.)
(depending on the pre-alignment and β-beat; 'x' is scalable within limits)

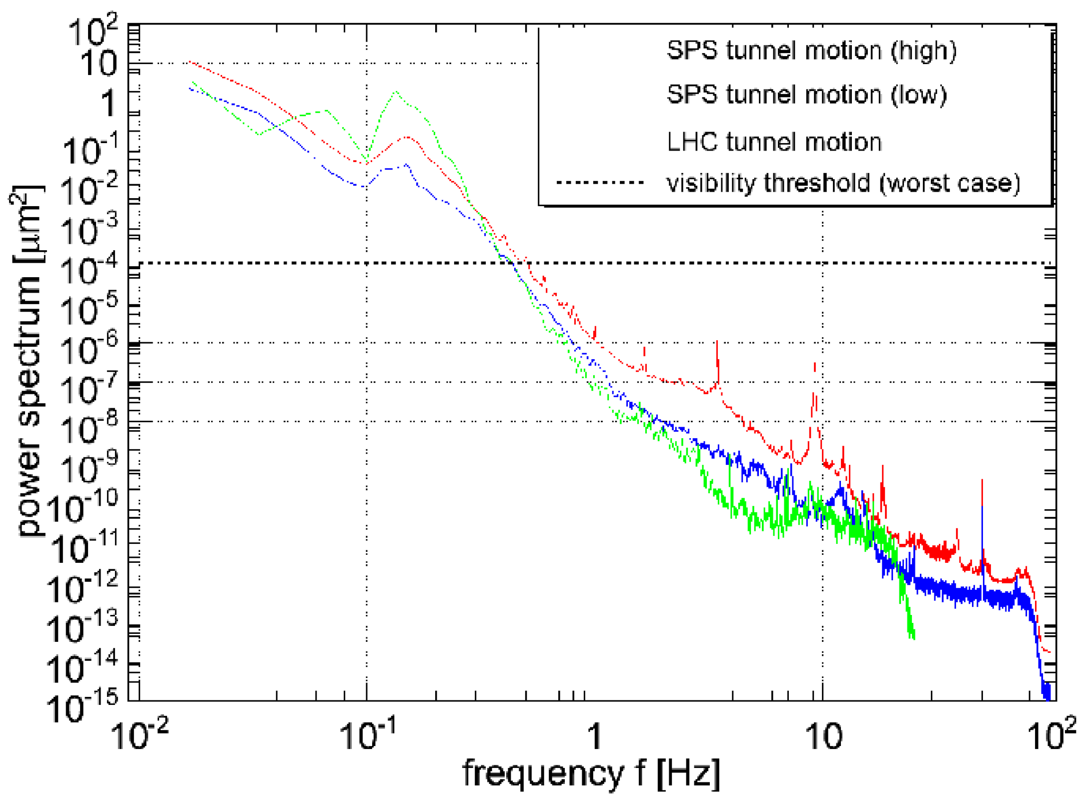
Machine element failures:
- Closed orbit dipole magnets

-> Expected maximum drifts < 85 μm/s
(feed-forward compensation after PC warning)

Environmental sources (through moving quadrupoles):
- Ground motion
- Expanding and contracting magnet girders due to changes of:
- tTmperature
  - Air pressure
- Other effects....

-> Expected drift velocities smaller than « 10 μm/s

### LHC/SPS Ground Motion Spectra:




The `high' SPS spectrum was recorded during ongoing installation work. The $1/f^2$ dependence that is typical for Brownian motion and drifts, and the hum around 0.1 Hz due to ocean swelling are visible. The detection threshold corresponds to the ground-motion level having a 1 μm effect on the beam, assuming κ=100. Both tunnels are extremely quiet and are barely influenced by cultural noise. The power spectra are essentially the same. Hence, it is possible to predict orbit drifts at the LHC from SPS results.

### Optics Amplification:

The resulting orbit r.m.s. movement $\Delta x_{beam}$ can be described by an amplification κ(f) of the quadrupoles' r.m.s. movement $\Delta x_{quad}$:

$$\Delta x_{beam} = \kappa(f)\cdot\Delta x_{quad}$$

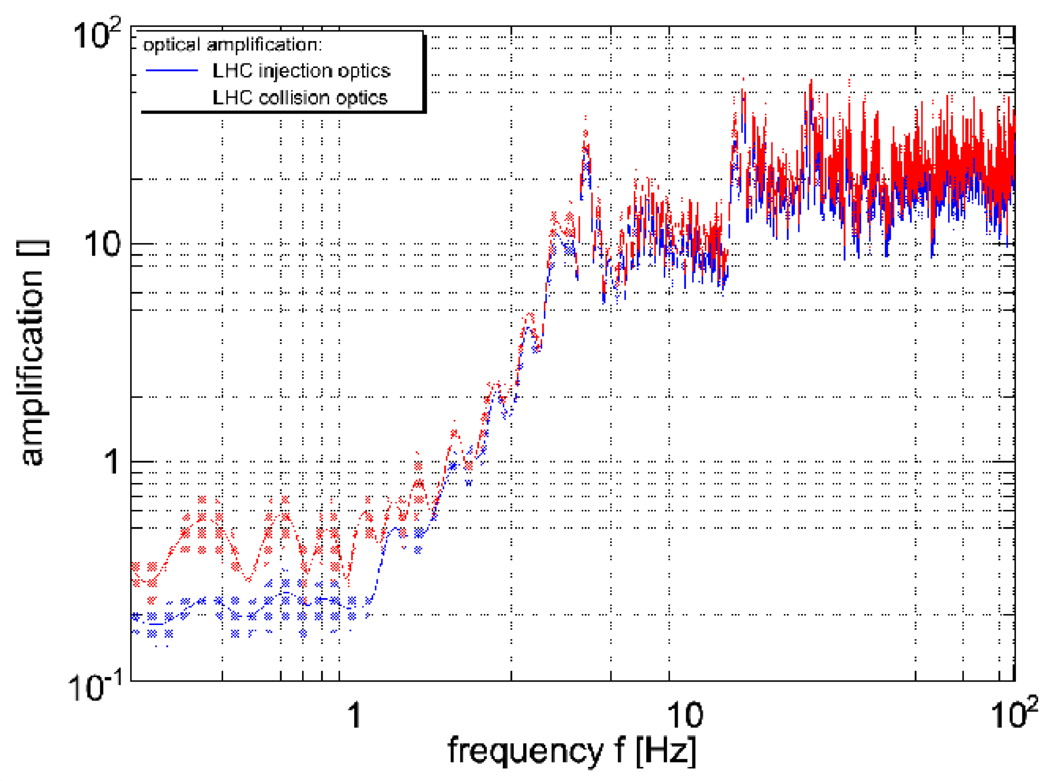
### Uncorrelated Ground Motion Amplification:

For Brownian (random) motion: κ(f)=*const*

| | |
|---|---|
| SPS: | κ(f) ~ 28 |
| LHC: injection optics: | κ(f) ~ 20 |
| collision optics: | κ(f) ~ 40 |

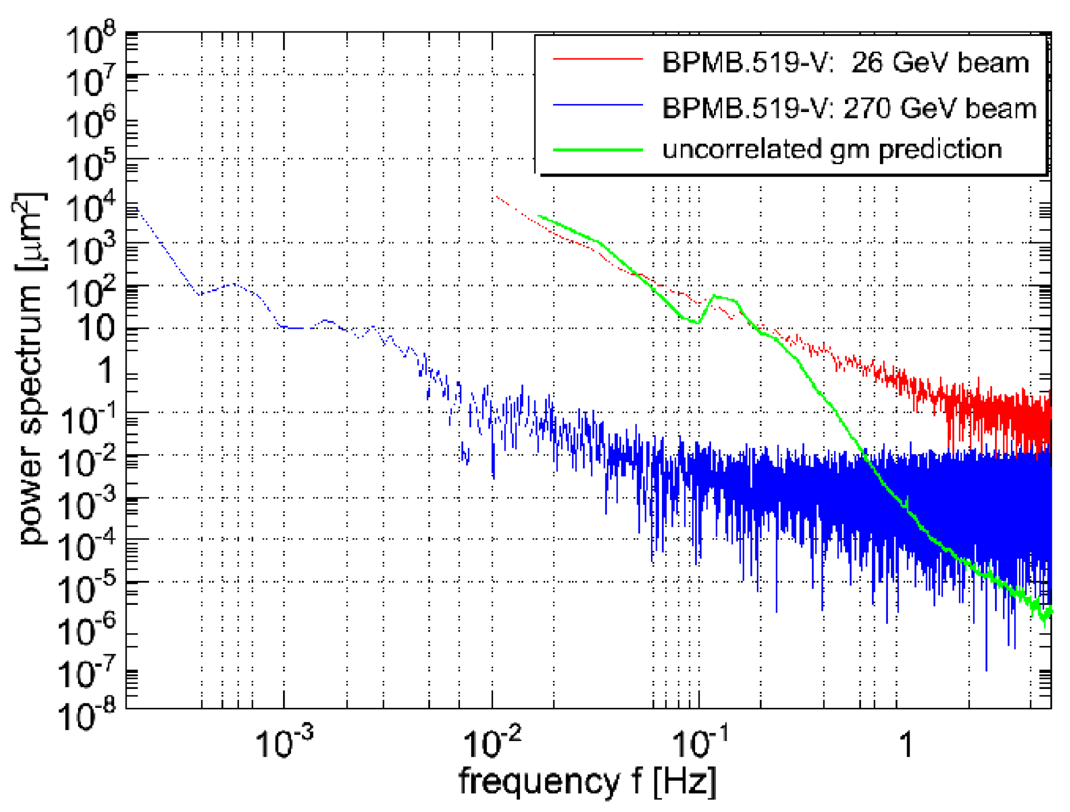
For the LHC, uncorrelated ground motion dominates over correlated ground motion. Though the latter may have a stronger amplification for frequencies above 3 Hz, they contribute less because the power spectra decreases rapidly above this frequency.

### Correlated Motion Amplification:




Vertical optics amplification factor as a function of ground motion frequency. The calculations, based on the LHC injection and collision optics, assume a constant wave propagation speed in clay surrounding the tunnel of c ≈ 2000 m/s. For very low frequencies (e.g. tides) κ(f) vanishes. The resonance is visible once the frequency approaches the first betatron resonance around 5 Hz.

### SPS Beam Power Spectra:




Power spectra of the SPS and LHC tunnel motion. The white-noise floor of the BPM for high frequencies is visible. The 26 GeV coast is rather dominated by slow drifts, for instance, of the magnetic fields, than by ground motion. The predicted power spectrum for a worst-case (κ=28) propagation of the tunnel motion on the beam is shown.
In comparison with the actual 270 GeV coasting beam, it is evident that the peak due to the ocean hum is, to a large extent, correlated. From the SPS diameter, one can estimate the coherence length of this type of ground movement to be at least 2.2 km.

### Orbit Stability Requirements:

Traditional orbit requirements in hadron machines:

.... to keep the beam in the pipe!

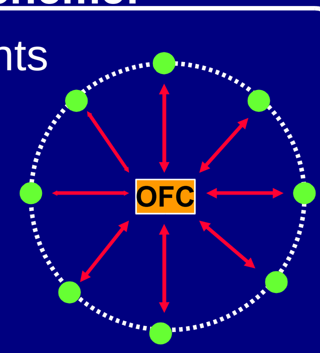
The LHC requires a continuous orbit control for safe and reliable machine operation during all phases (injection, acceleration, final focus, coast for physics) in order to improve operation and to avoid quenches. Constraints on the orbit:

Global (r.m.s)
- Physical machine aperture and operation ~500 μm
- ...
- Minimisation of electron cloud ~200 μm
  (Preserving the 'scrubbing efficiency')

Local (absolute):
- Protection devices (in 6 of 8 LSS) < 100-400 μm
- Centring the beam at the dampers < ~200 μm
  (preserving dynamic range of its ADC)
- Pre-alignment for the luminosity fb < ~200 μm
- ...
- Collimation System (IR 3 & 7) < 70 μm
  (= σ/3 @ 7 TeV, with σ = r.m.s. beam size)
- TOTEM experiment (tough!) < 10 μm
  (improvement of physics analysis)

### Centralised Global Orbit Feedback Scheme:

The local extent, number of requirements and coupling of the two beams in the insertions make a global feedback system necessary. Its prototype was developed and successfully tested at the SPS using the same infrastructure as foreseen for the LHC.

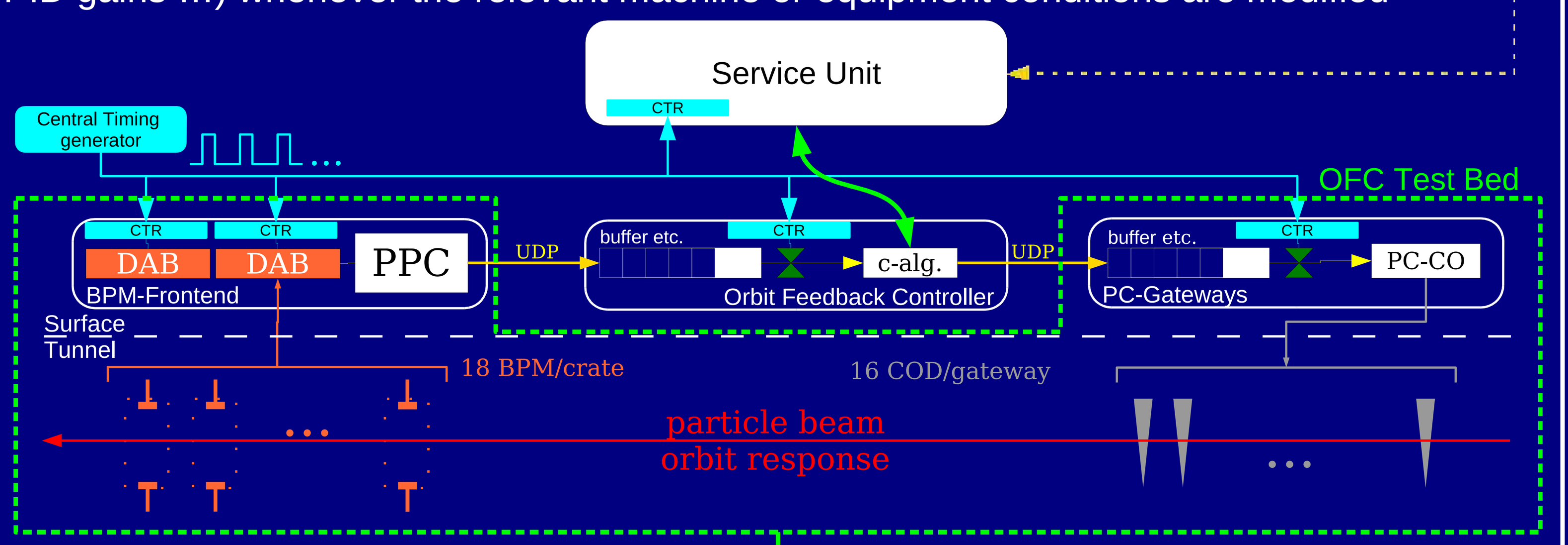



LHC Layout:
- Two rings, $\Delta\mu_{FODO}\approx 90°$, average $\beta_{max}/\beta_{min}\approx 6$
- 4 crossing insertions (coupling!)

- 1056 beam position monitors
  - BPM spacing: $\Delta\mu_{BPM}\approx 45°$
  - Measurement precision (nominal beam): 1 mm
  - Measure in both planes: > 2112 readings!
- 530 correction dipole magnets/plane
  - Natural time constant: t ≈100 s
  - Bandwidth (for small signals): $f_{bw}\approx$ 1-2 Hz
- Central Orbit Feedback Controller (OFC)
  - Space domain:
    - SVD scheme with pseudo inverse matrix:
      $\Delta\delta_{kick} = M^{-1}\Delta x_{BPM}$
  - Time domain:
    - One PID controller per COD and Smith-Predictor to compensate for constant delays
      (keeps the PID gains clean and independent from constant propagation delay and fb sampling frequency)

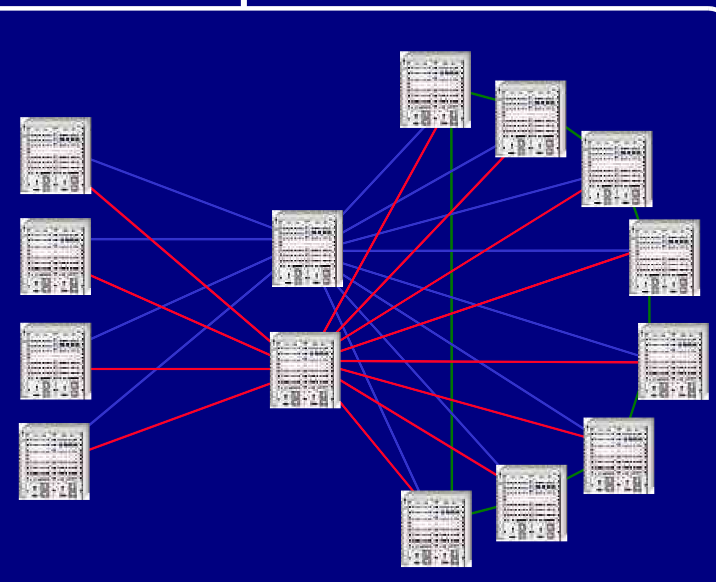
## Feedback Architecture:

- Orbit Feedback Controller (OFC) - performs the actual fb:
  - I. Reception of all BPM front-end data through the Ethernet (UDP)
  - II. Comparison with a reference and sanity checks (filter erroneous data)
  - III. Correction in space (SVD) and time (PID, Smith-Predictor)
  - IV. (Feed-forward algorithm to backup failing COD magnets)
  - V. Send the new settings to PC gateways
- Service Unit (SU) to the feedback controller:
  - Monitoring of machine states (energy, optics, mode [injection, ramp, squeeze,..)
  - Interface to LHC controls, machine operation and experts
  - Data monitoring (logging)
  - Sanity checks (BPM and COD faults)
  - Update of the orbit response matrices and quantities derived from it (SVD decomposition, PID gains …) whenever the relevant machine or equipment conditions are modified



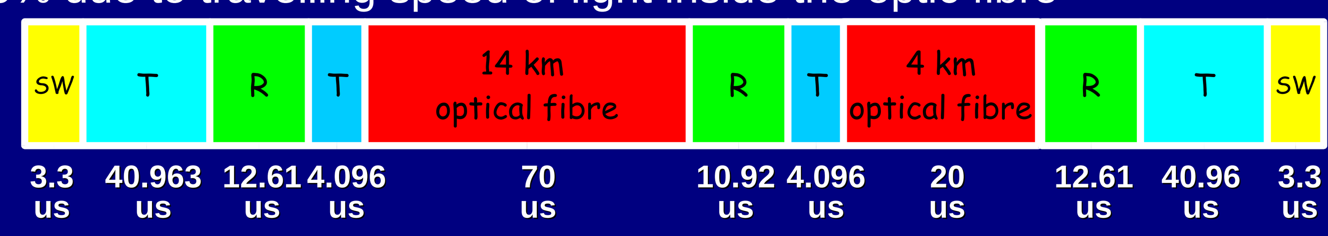

## Gigabit Ethernet Communication between Front-end Computers:

All orbit feedback data communication will go through CERN's 'Technical Network':



- Switched network
- Core: Enterasys X-Pedition 8600 Routers
  - 32 Gbits/s non-blocking
  - $3\cdot10^7$ packets/s troughput
  - No data collisions
  - No data loss
  - Double (triple) redundancy
  - Covers the 27 km circumference
  - Layout corresponds to geographic layout
- Quality of Service (QoS): packets are served based on their priority
  - ne queue dedicated to orbit feedback ≈private network for the orbit feedback
  - "Nearly" deterministic response (possible jitter has a hard upper limit)
  - Worst case transmission delay: < 320 µs << target fb sampling delay (40 ms)

    (Measurement: 512 bytes, IP5 -> Control room ~18 km, courtesy of M. Zuin, CERN)
    - 20% due to infrastructure (router/switches)
    - 80% due to travelling speed of light inside the optic fibre

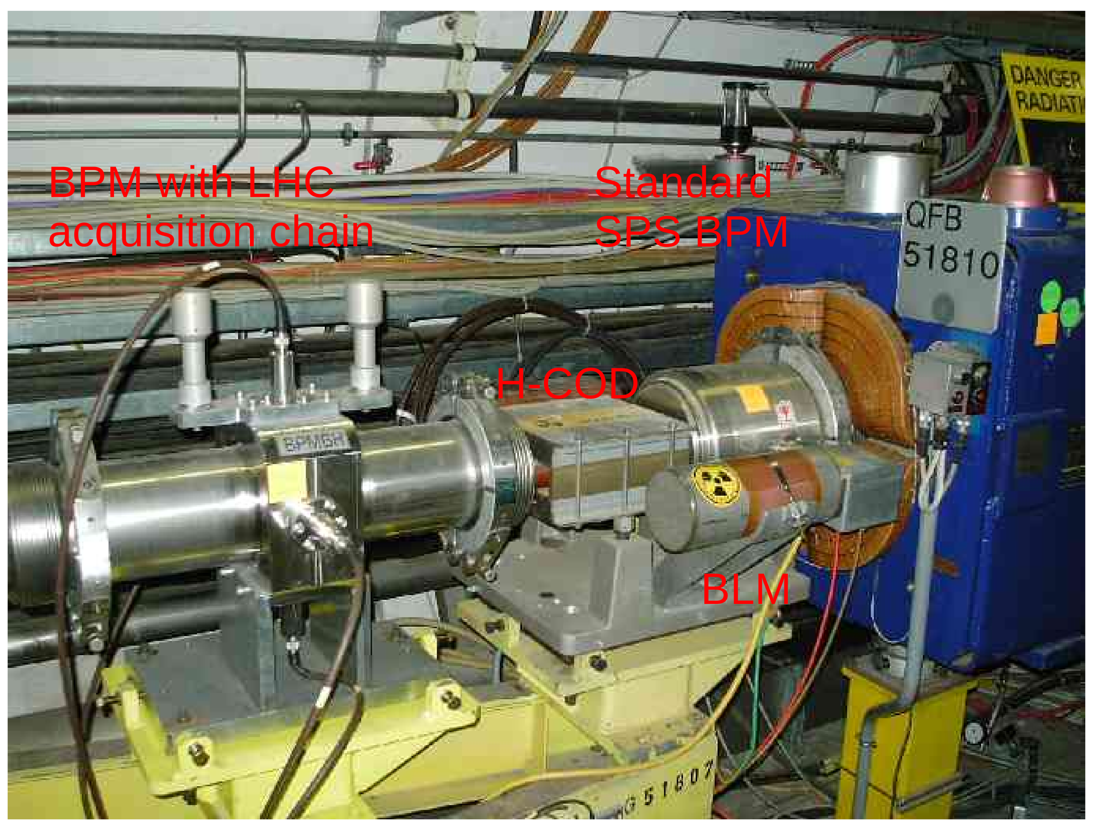



R: Router, SW: Switch, T: delay due to bandwidth (dep. on whether 100/1000 MBit/s)

Network delays are negligible for the orbit feedback

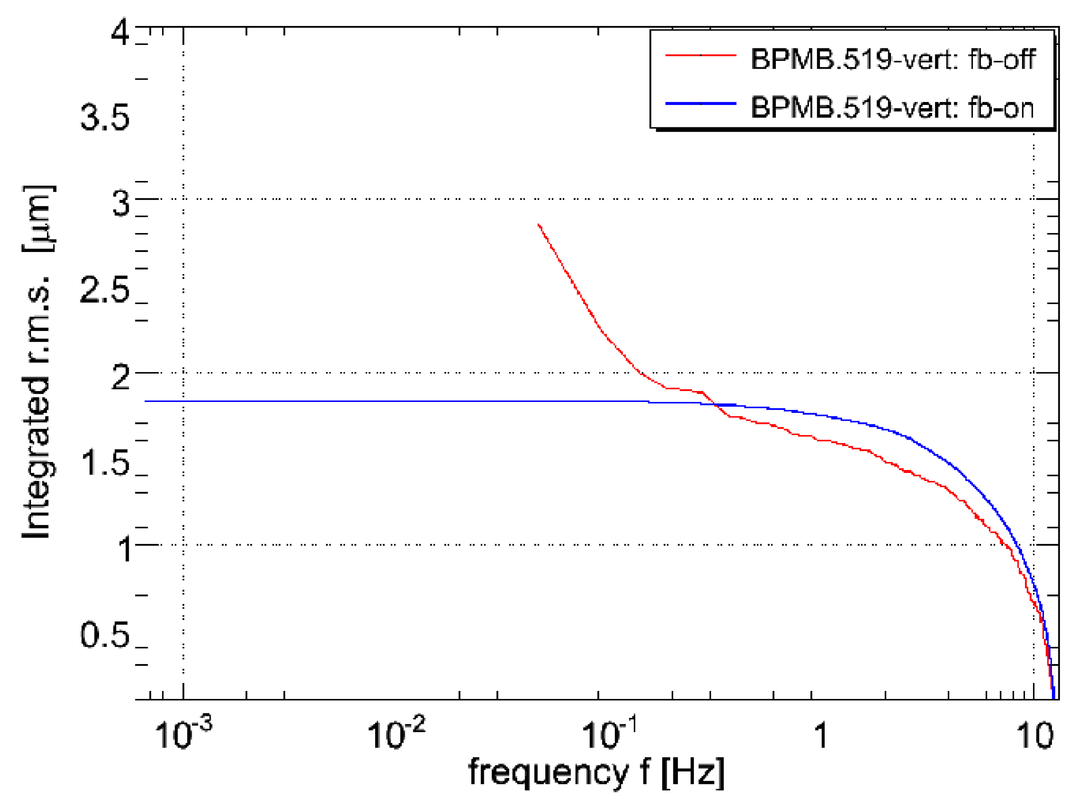
The delays created in front-end computers are an order of magnitude larger and more critical for the reliability of the total system.

## SPS Test Setup:




For the feedback tests, six BPMs with full LHC BPM acquisition system but ~ 40% larger (SPS) aperture were available.
The standard corrector dipole magnets were enabled to receive current changes in real-time and the network was upgraded to the same hardware that is foreseen for the LHC.

## Feedback Results:




Integrated r.m.s. orbit stability with feedback 'on' and 'off' for a 270 GeV beam in the SPS.
The achieved 1.8 µm stability (corresponding to 2‰ σ, σ: r.m.s. beam size) over one fill is comparable to those of modern light sources. The excitation of the orbit to the BPM noise level for frequencies above the effective orbit feedback bandwidth of 0.3 Hz is visible.

## OFC Test Bed:

- Test bed complementary to the Orbit Feedback Controller (OFC):
  - Simulates the open loop and orbit response of COD->BEAM->BPM
  - Real-time: simulates eight times faster than OFC
  - Same data delivery mechanism and timing as in the real front-end
    - Transparent for the OFC
    - Same code for real and simulated machine:
      - possible and meaningful "off-line" debugging for the OFC
  - OFC strategies can be tested without beam:
    - Decay/snapback, squeeze
    - Ground motion simulations
    - Other environmental influences
  - Tests of controller implementations (scheduling of CPU, network, timing....)

## BPM Precision and Long-term Stability:

The present system is essentially limited by the residual noise of the BPM system, visible in the beam motion spectra, which relies on a wide band normaliser bunch-by-bunch measurement. Closed orbit measurement at one BPM ($x_i(j)$: position of bunch i at turn j):

$$x_{co} = \sum_{j}^{255\,turns} \sum_{i}^{n_{bunch}} x_i(j)$$

- reduce BPM noise: 255 turns -> 20 ms (LHC)
- BPM design: 1% linearity w.r.t. half-aperture
- feedback stability: $\Delta x_{co} \approx 1.8$ µm

  -> bunch-by-bunch precision:
  - SPS: $\Delta x_{bunch} <$ 115 µm (measurement)
  - LHC: $\Delta x_{bunch} <$ 85 µm (prediction)

-> conforms with design and orbit stability requirement

Open issues:
- Exp. results: systematic due error bunch length and intensity variation of up to ~135 µm (within design!)
- Compensation of remaining systematics might be required at the collimator locations for long-term stability.

## Long-term Stability of the Feedback Loop:

Since delays and their determinism in the data processing of the front-ends affect feedback stability and performance, the numerical implementation of algorithms becomes important:

OFC must handle large matrices (~30 MB)
- Core of orbit correction:
  - Multiplication of inverse orbit response matrix with input position vector (~4•106 double multiplications per sample @50Hz): ~ 400 MFLOPS
  - 1.5 GByte/s local memory data transfer
  - Several ms processing on a high-end SMP system (presently ~15 ms)
  - Similar requirements as for Web, file or database servers:
    - High performance and high reliability (->feasible),
    - But: hard real-time constraints: total execution time has to be deterministic and less than 20/40 ms to fit the 25/50 Hz feedback frequency requirement
  - Real-time: BPM and COD control data
    - Avg. bandwidth: ~13 Mbit/s
    - Short bursts: full I/O load within 1-2 ms (100 MBit/s resp. 1GBit/s, burst duration desired to be short in order to minimise the total loop delay)

## Conclusions:

Major challenges for long-term orbit stability:

- BPM systematics
- Deterministic delays:
  - Feedback loop
  - Front-end computers

Results:
- Tests confirm to BPM and feedback systems design
- Network delays have not been observed
- Orbit drifts: Ground motion drifts less critical compared to machine-inherent sources
- Present LHC orbit feedback prototype can steer on the micrometre level and can maintain an absolute orbit within the collimation requirements over one run, provided the systematic effects of bunch lengths and intensity on the BPM readings are within limits

Outlook:
- The remaining BPM systematics and their possible compensation will be further investigated

J.R. Steinhagen, 2005