LHC Orbit Feedback Control

Ralph J. Steinhagen,

Accelerators & Beams Department, CERN and

3rd Inst. of Physics, RWTH Aachen,

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Outline

- Introduction
- The Large Hadron Collider
  - Superconducting main dipole magnets
  - LHC Cleaning System
- LHC Orbit Feedback System
  - Feedback design
    - Space
    - Time
  - Results from SPS prototype studies
- Conclusions

The Large Hadron Collider

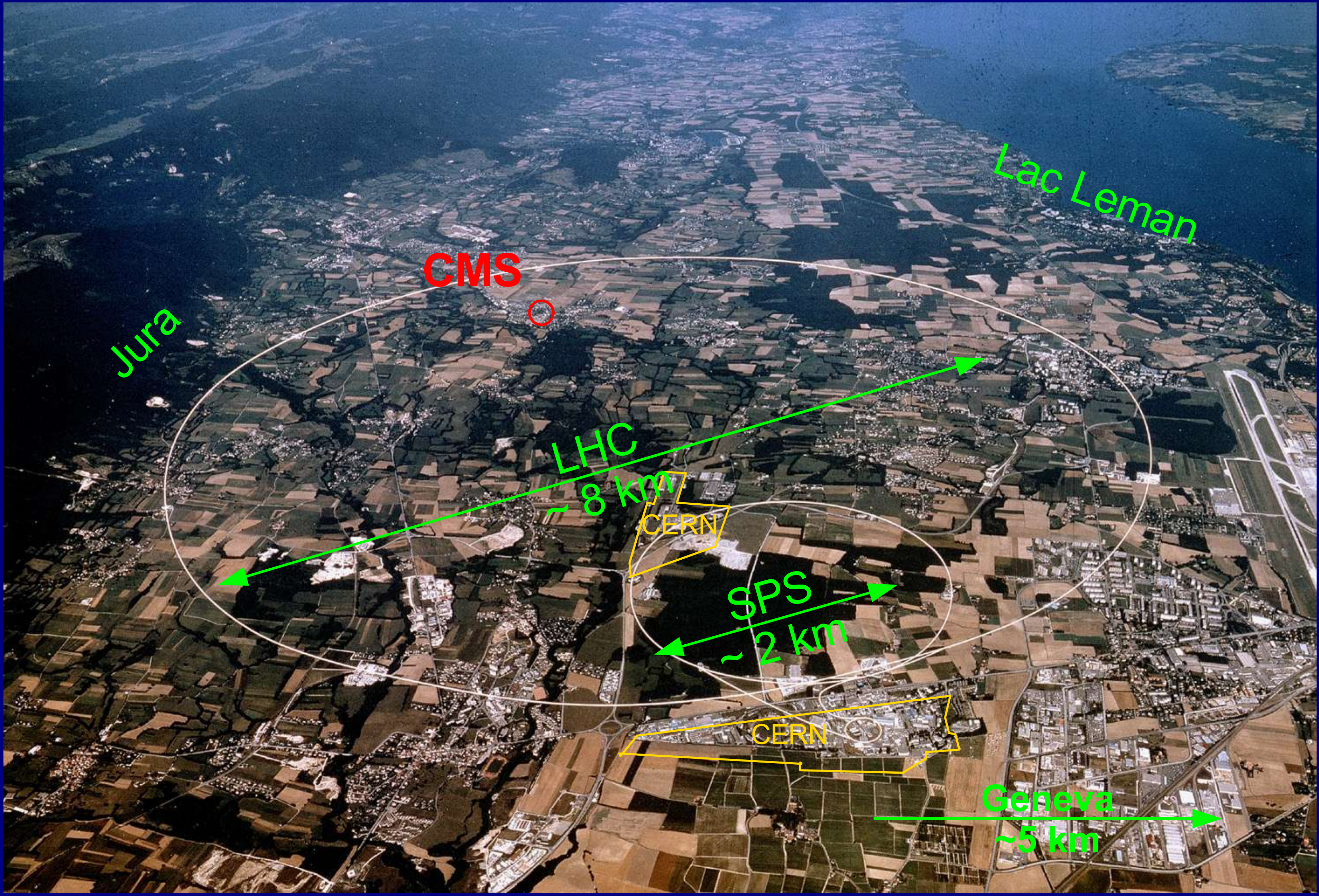
- The Large Hadron Collider (LHC) is CERN's next generation of proton-proton collider that will be installed in the former LEP tunnel, which has an average depth of 100 m and a circumference of 27 km.
- In order to verify and explore new aspects of the standard model and other theories, the LHC will store, accelerate and collide two proton beams:
  - max (inj.) energy p.p.: E = 7 (0.45) TeV
  - nominal luminosity: L = $\sim 10^{34}$ $cm^{-2} s^{-1}$
- Choice for protons is a consequence of strong dependence of the synchrotron radiation losses on the mass of the particle and available RF voltage (< 100 MV):

$$\Delta E_{s-rad.} = \frac{q^2}{3\epsilon_0} \cdot \frac{1}{\left(m_0 c^2\right)^4} \cdot \frac{E^4}{\rho} \quad \rightarrow \quad \frac{\Delta E_{proton}}{\Delta E_{electron}} = \left(\frac{m_e c^2}{m_p c^2}\right)^4 \approx 10^{-15}$$

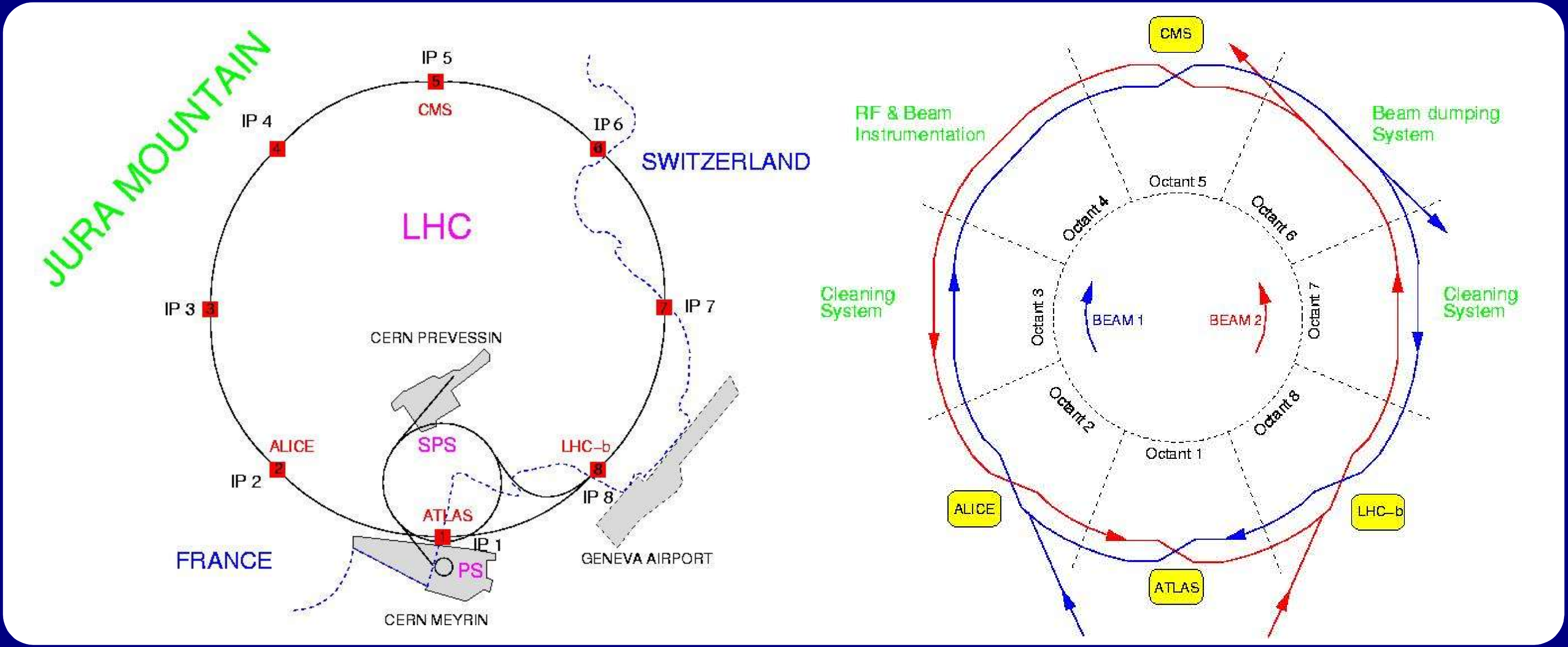
(ΔE: *energy loss per turn; q*: charge; m_0:mass of particle*;* ρ: bending radius; *E*: initial energy of the particle)

- Synchroton losses per turn @ 7 TeV: 7 keV (proton) vs. 700 PeV (leptons)

The Large Hadron Collider
Aerial view



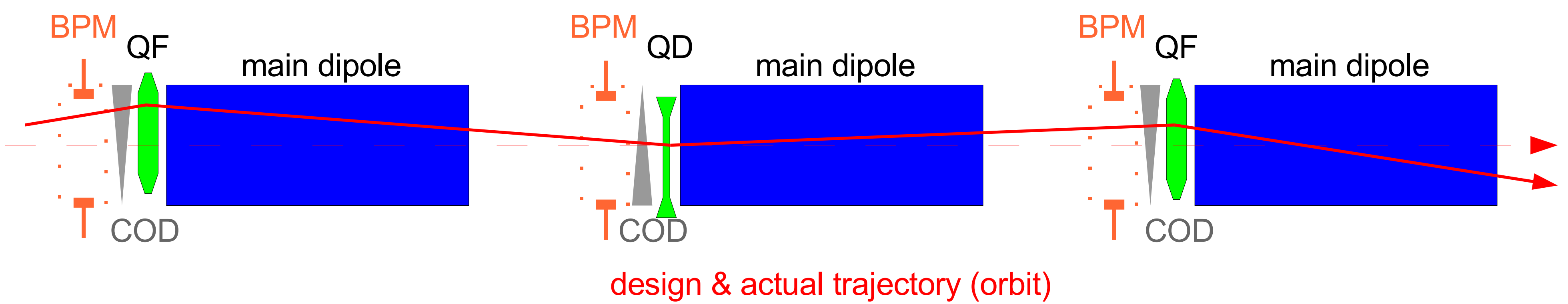
The Large Hadron Collider
general layout



- eight-fold symmetry:
  - eight arcs interleaved with straight sections for:
    - Machine elements (RF, BI, Cleaning System, Beam dump...)
    - Detectors in the crossing sections (CMS, ATLAS, Alice and LHC-b)
- two beams:
  - separate vacuum pipes for most parts of the machine
  - advantage of being widely independent and individually tuneable

The Large Hadron Collider
general FODO arc layout

- 1278 main dipole magnets cover the ~27 km circumference
  -> keep the beams on their circular design trajectory
- Interleaved with:
  - Focusing (QF) and defocusing (QD) quadrupoles
    -> create betatron oscilations
  - Orbit correction Dipoles (CODs)
    -> compensate quadrupole offsets and other misaligments
  - Sextupole, Octupole, ..., Dodecapole
    -> control of chromaticity and higher order non-linearities
  - [..]
  - Beam instrumentation: position (BPM), beam loss , emittance monitors,...



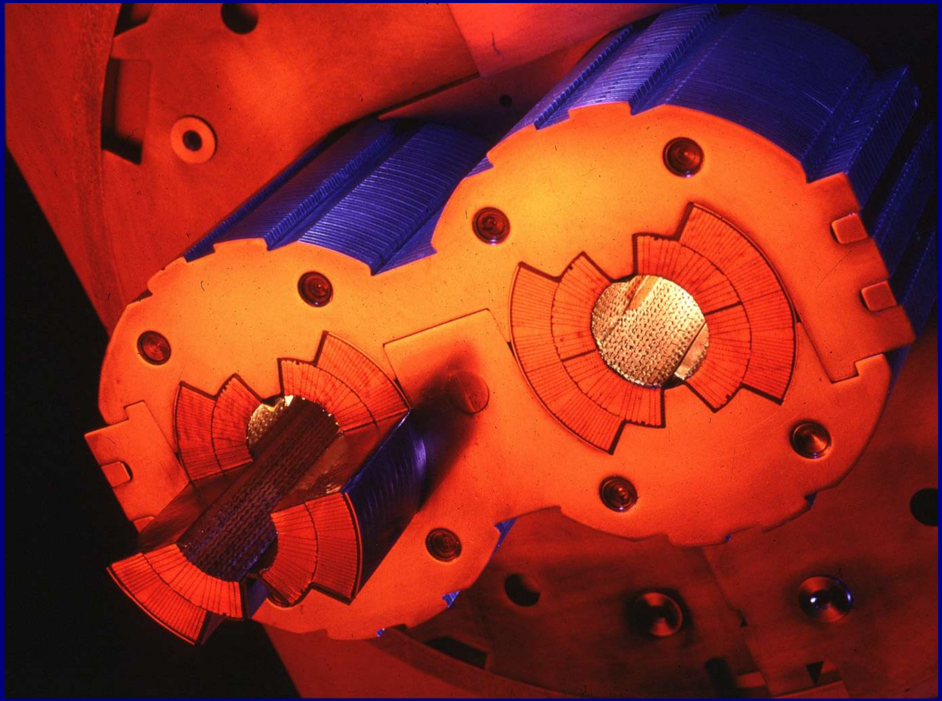
The Large Hadron Collider main dipole magnets

- The required magnetic field in order to keep counter rotating charged particles on a circular trajectory:

$$B = \frac{1}{q} \cdot \frac{p}{\rho}$$

  - momentum p = 7 *TeV/c*
  - radius $\rho = \rho_{LEP} \approx 3$ km
  - charge q

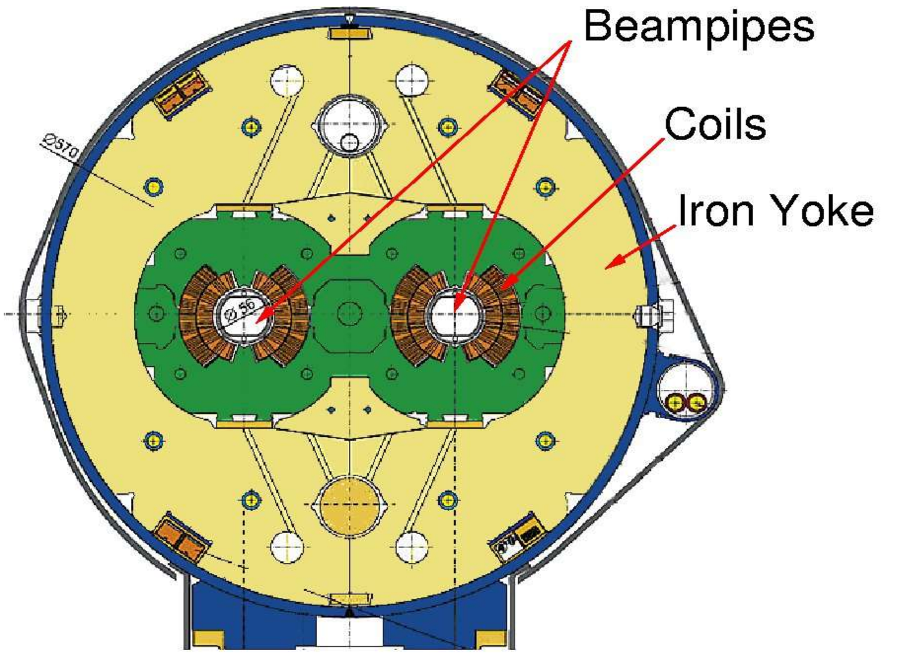
-> B = 8.33 Tesla

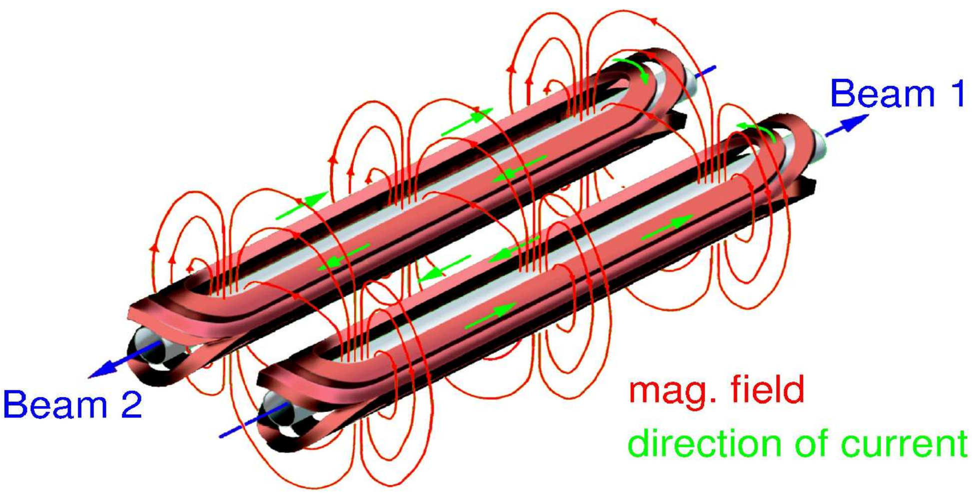


- Present normal conducting magnets only up to ~ 2 T

-> LHC main dipole (& most other) magnets are superconducting

The Large Hadron Collider
instancing: main dipole magnets



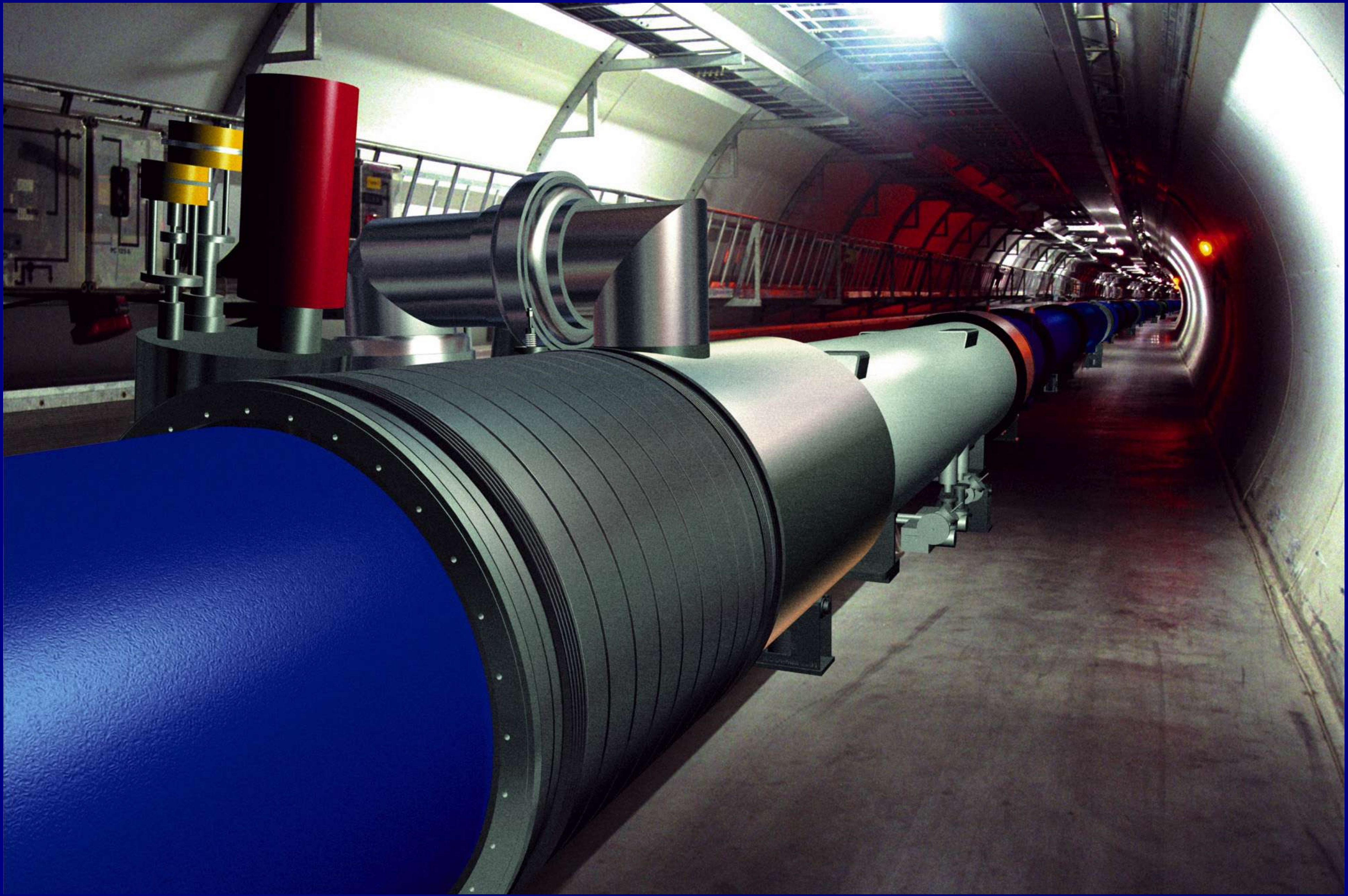


- '2-in-1' design:
  - One magnet with two opposite fields for the two circulating beams
  - most equipment kept in the same cryostat

Parameters		
Operating Temperature	1.9	K
Magnetic Length	14.3	M
Inductance	0.11	H
Nom Field at 7 TeV	8.33	T
Nom. Current	11850	A
Bending Radius ρ	2804	M
Bending Angle	5.1	Millirad
Stored Energy	7.5	MJ
Quench Limit* at 7 TeV	30	mJ/cm^3

*For fast losses on the ms scale

The Large Hadron Collider
main dipoles in tunnel



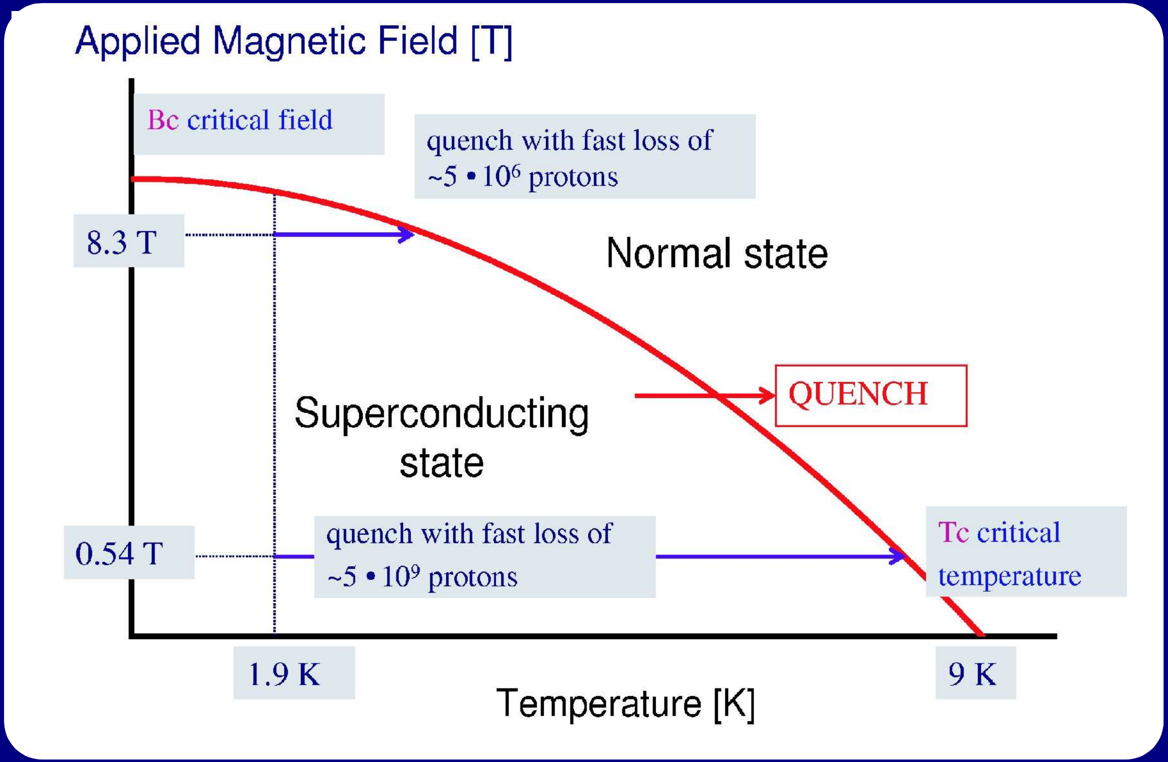
The Large Hadron Collider
main dipoles in tunnel

The Large Hadron Collider main dipole: *quench*

- Superconductivity is lost if:
  - magnetic field
  - current density
  - or temperature

  exceed their critical parameter

  -> quench



- dominant cause for quenches:
  - temperature increase due to particle absorption

- for main dipole magnets, energy deposition within 10-20 ms must not exceed:

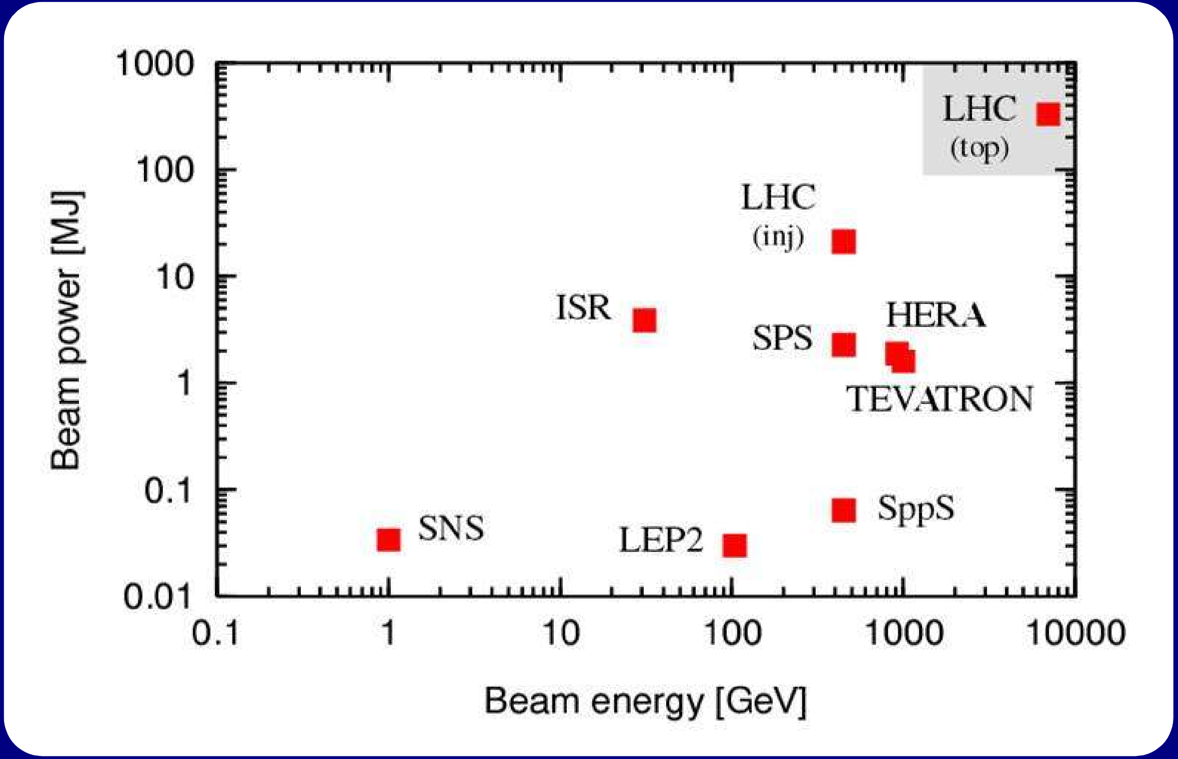
$$\approx 30 \frac{mJ}{cm^3}$$

The Large Hadron Collider
Beam Energy

- each of the LHC beams:
  - 2808 bunches x 1.1 * 10^{11} protons per bunch x 7 TeV per proton
  - beam sizes 0.4 - 1.0 mm (in the arcs)

-> total beam energy ~ 350 MJ

-> beam energy density ~ 5.6 GJ/mm^2



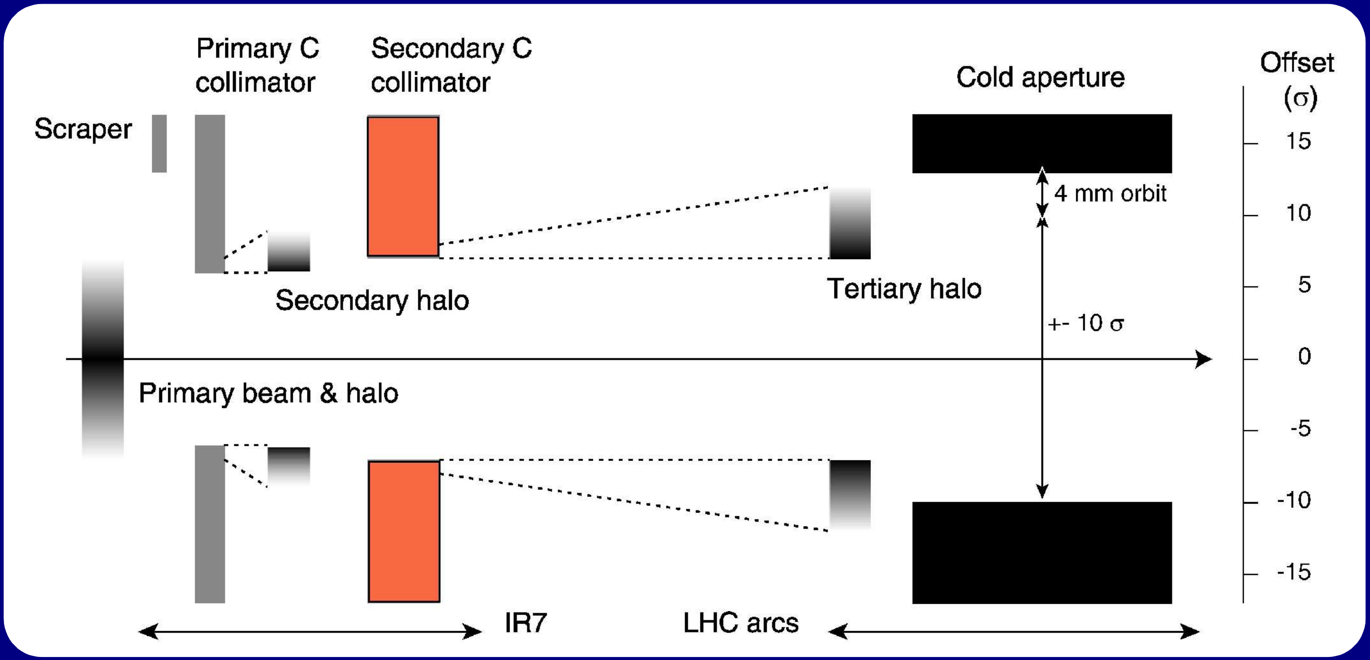
- sufficient to quench all LHC magnets at once if evenly distributed
- disassemble magnets and other equipment
- The beam dumps are the only elements surviving a full beam impact

- The 350 MJ can be released within:
  - milli to micro second (1 – 20 turns !!!)
    - Equipment malfunction etc.
    - in the vacuum chamber
      - Residual beam gas
      - Electron cloud effects
      - ...
    - Long range beam-beam
    - Non-linearities of accelerator optics
  - few hours
    - Interactions at the collision points inside the detectors
    - normal diffusion processes

-> Accelerator has to be screened from those losses!

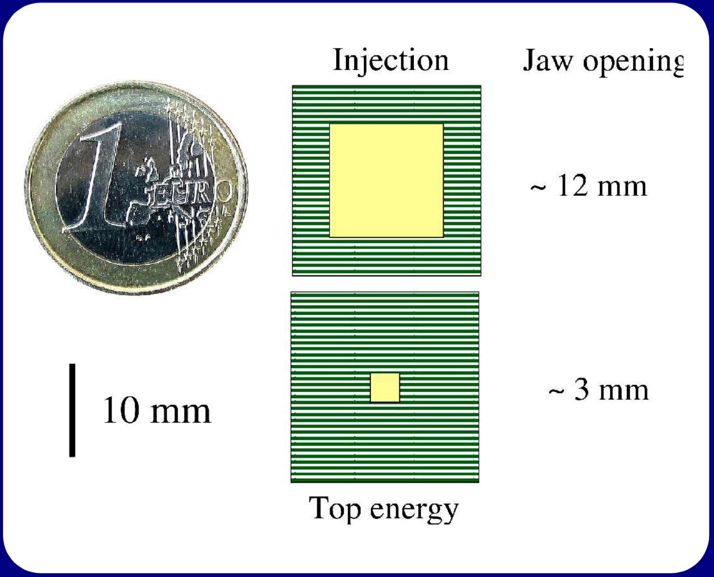
machine protection working group: lhc-mpwg.web.cern.ch
collimation working group: lhc-collimation.web.cern.ch

The Large Hadron Collider
Collimation – first line of protection

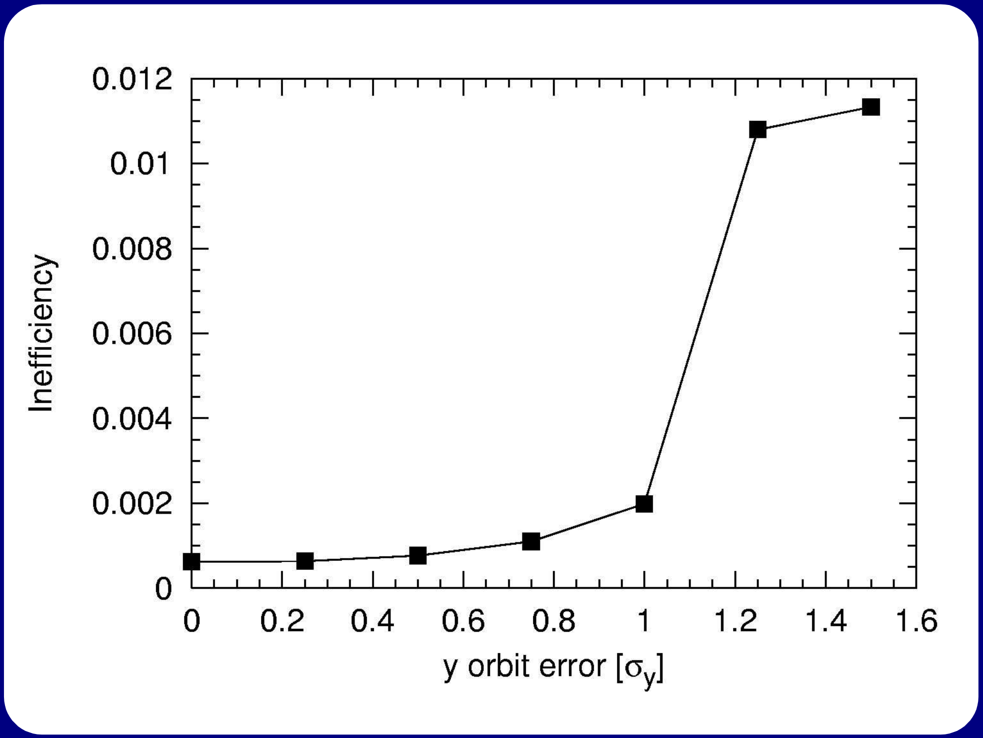


- removes the high amplitude particles before they may be lost in the cryogenic aperture
- Consists of two stages

- Primary collimator:
  - light material (low Z) in order to survive primary beam impact
  - scatters the particle into primary beam halo
- Secondary collimator:
  - Intercepts (absorbs) the scattered particles of the primary beam halo
- (Tertiary collimator, absorber near experiments for protection)



- Cleaning inefficiency depends critically on the beam position error in the collimator section:



- Cleaning inefficiency = number of escaping protons / number of impacting protons

- Max. allowed cleaning inefficiency [%]: ~ 10^{-3}

-> beam position (closed orbit) stabilised within ~ 0.4 σ

@ 7 TeV (β = 30/180 m) ~ 44 - 120 μm

LHC Orbit Feedback Control
beam movement?

- two classes of orbit movement:
  - Environmental (through moving quadrupoles):
    - ground motion
    - expanding and contracting magnet girders due to changes of
      - temperature
      - air pressure
    - other effects....

  -> expected drift velocities smaller than < 10 μm/s

  - machine inherent:
    - decay & snapback of magnet's multipole momenta (main dipole moment is dominant)
    - optics changes: e.g. squeeze of beam in insertions
    - persistent currents in the vacuum chamber wall
    - dynamic effects: ramp, beam-beam
    - machine element failures (power converter and magnet dropouts)

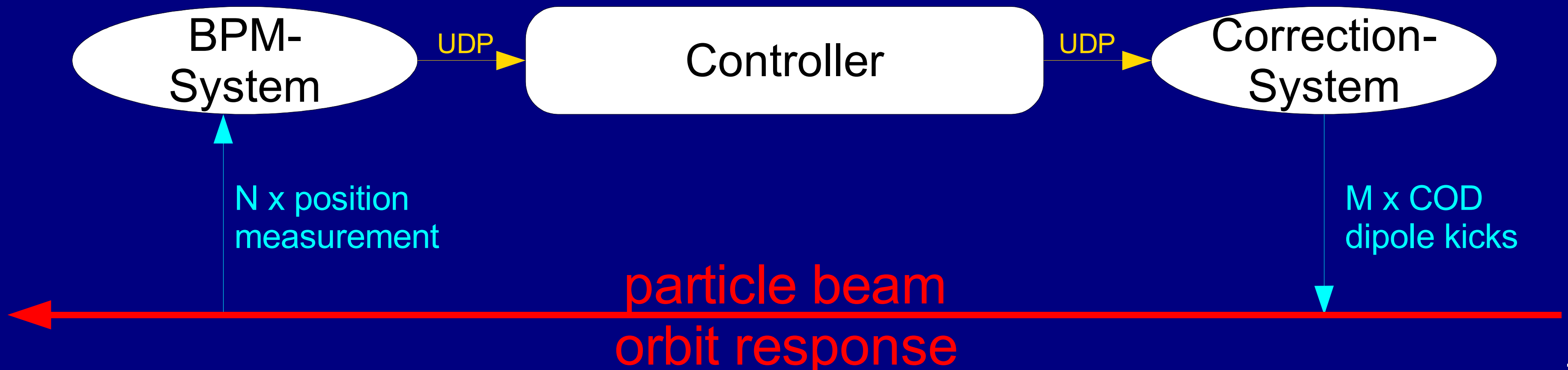
  -> largest contribution, perturbations up to 20 mm/(x minutes)
  ('x' is scalable within limits)

LHC Orbit Feedback Control
Layout

- role of the future LHC Orbit Feedback System:
  minimisation of closed orbit perturbations

$$x_i(t)=x_{reference\_i}= const$$

- LHC: first proton collider where a continuous control of the beam position is required during all operational phases
- In each plane, the beam position of the two LHC rings is sampled by ≈ 1100 beam position monitors (BPMs) and is controlled by ≈ 600 correction dipole magnets (CODs) that are individually powered
- Since all equipment is distributed over the 26.7 km circumference, data exchange between a central feedback controller and the BPMs and CODs is an important issue.



- The control of the orbit $\Delta x_i(t)$ with CODs is described by the beam response matrix R_{ij} to dipole kicks δ_j and by the dynamics of the electrical circuit and power converter of the CODs $\delta_j=\delta_j(t)$.
- To simplify the problem the coupled differential equation system are separated into space and time domain and solved independently using techniques from control theory and linear algebra:
  - beam position at the i[th] monitor due to a dipole kick d of the j[th] COD

$$\Delta x_i(t) = \sum^{n} R_{ij} \cdot \delta_j(t)$$

  - Simplified COD response ('O(1)') due to an external excitation $E_j(t)$:

$$\ddot{\delta}_j(t) + 2\zeta_j \omega_{0j} \dot{\delta}_j(t) + \omega_{0j}^2 \delta_j = E_j(t)$$

(R_{ij}:orbit response matrix, ζ: damping, $\omega_{0:}$ eigen-frequency)

- find pseudo-inverse orbit response matrix $\underline{R}^{-1}$ of $\underline{R}= (R_{ij})$, while keeping feasibility constraints (saturation and rate limit of COD power converter etc.)

  - Stopped Gauss' (*MICADO*):
    - starting with most dominant pivot element and stop once defined convergence limit is reached.

  - Singular Value Decomposition (SVD):
    - decomposition of $\underline{R}$ into eigen states $\underline{V}$, corresponding eigen value matrix $\underline{S} = \text{diag}(\lambda_1,...,\lambda_n)$ and unitary matrix $\underline{U}$
      - $\underline{R} = U\ S\ V^T$ -> $\underline{R}^{-1} = \underline{U}^T \text{diag}(1/\lambda_1, 1/\lambda_2,...)\ \underline{V}$
    - easy elimination of near singular solutions (if $(\lambda_\iota \sim 0)$ '$1/\lambda_i$'=0)
    - Solution yield steady state deflections: $\delta= (\delta_0, \delta_1, .. ,\delta_m)$

- Design of a controller that sends excitation signals (reference currents) $E_j(t)$ to the power converter that optimise the rise time
- Laplace transformation to COD response equation yields

$$G(s)=\frac{\omega_0^2}{s^2+2\zeta\omega_0 s+\omega_0^2}$$

- We chose *zero-pole matching* of the dominant plant poles: Compensation using zeros of a PID controller (gains K_p, K_i and K_d) :

$$D(s)=K\left(K_p\cdot 1+\frac{K_i}{T_i s}+K_d\cdot T_d s\right)$$

- Resulting K_p and K_d with K_i *as free parameter:*

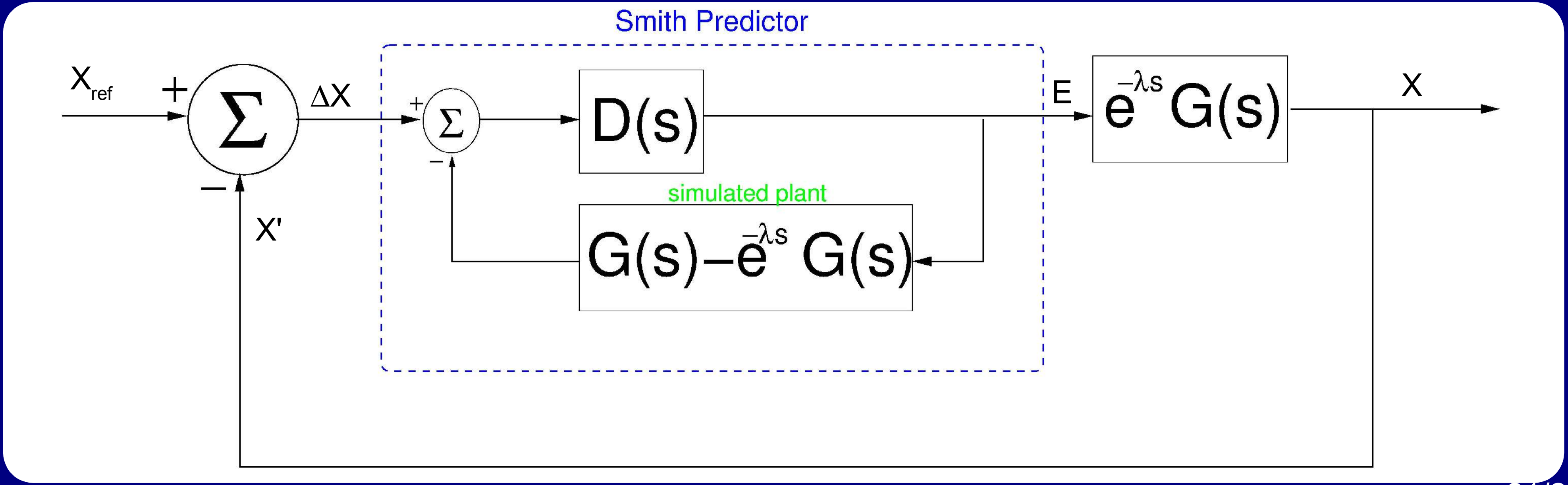
$$K_p=\frac{2\zeta}{\omega_0 T_s}K_i \quad \wedge \quad K_d=\frac{1}{\omega_0^2 T_s^2}K_i$$

LHC Orbit Feedback Control
Controller Design

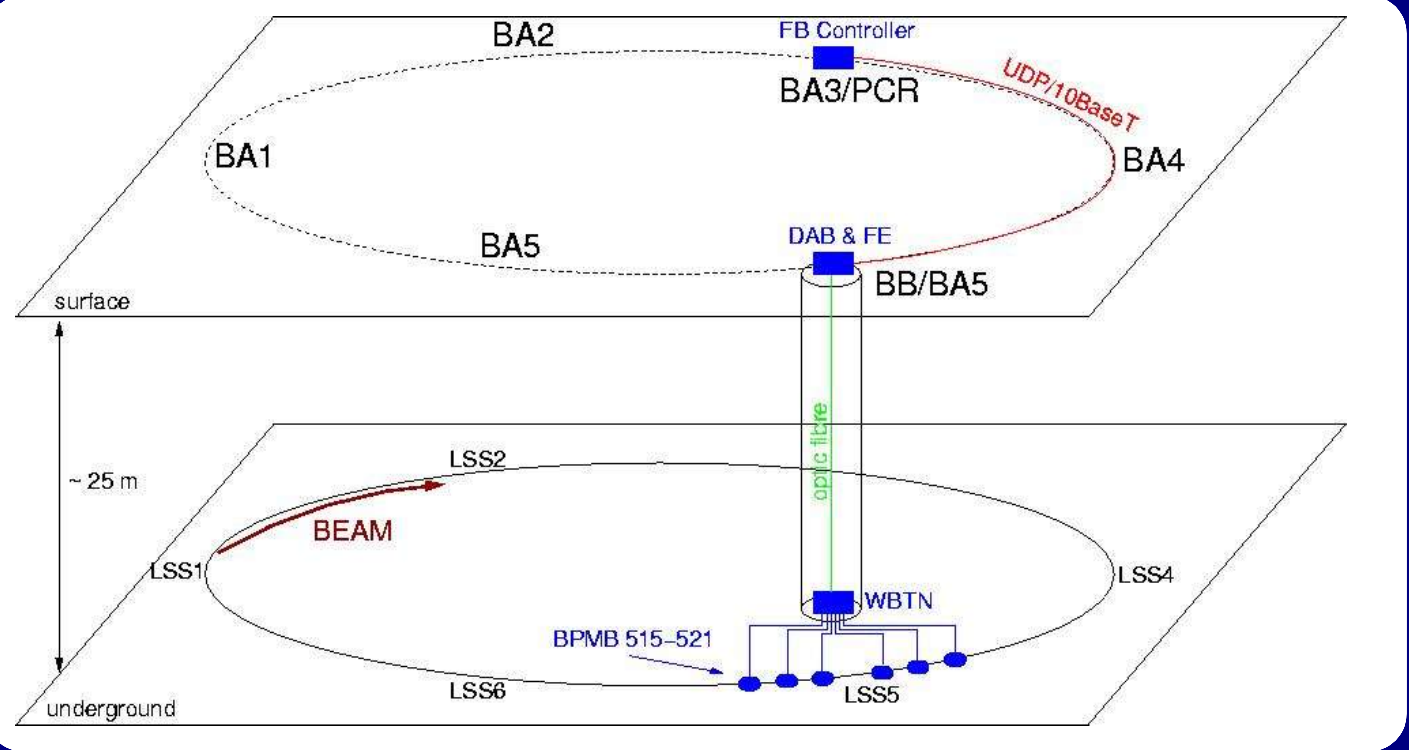
- Real implementation: addition pole due to sampling T_s transport lag T_c, network T_{net} and front-end OS T_{misc} delay:

$$G_{delay}(s)=\frac{1}{\lambda\cdot S+1} \wedge \lambda=T_s/2+T_c+T_{net}+T_{misc}$$

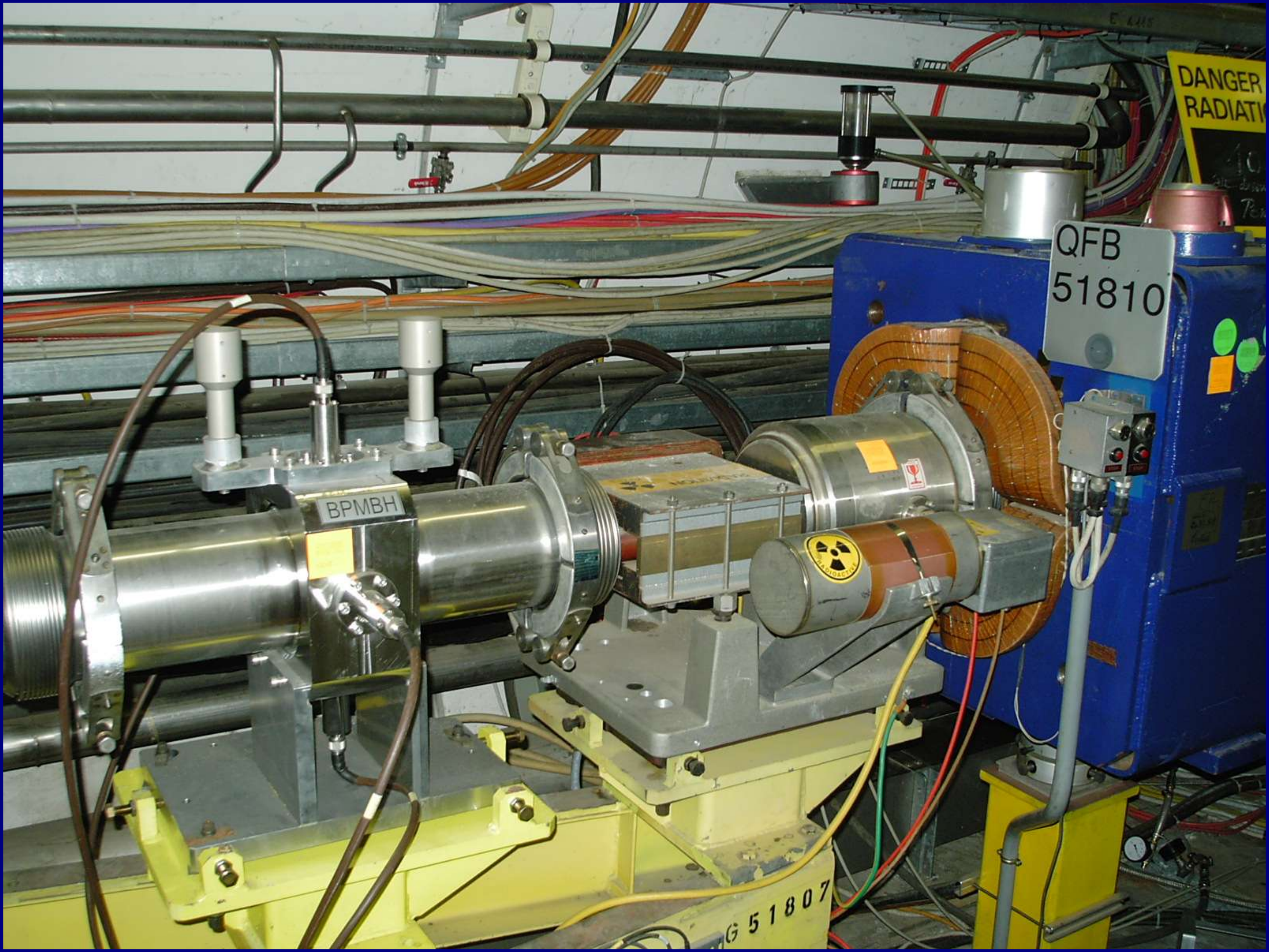
- Foreseen:
  - 'Smith-Predictor' extension of the PID to compensate the delay pole
  - Subtract simulated difference of plant with and without delay from Δx
  - G(s) and λ have to precisely known and constant
    - 'real-time' constraints



- For the SPS prototype studies:
  - 6 dedicated position monitors (*BPMBs*) with full LHC acquisitionin LSS5
  - Power converters of CODs have been enabled to receive real-time reference current changes.
  - The pre-processed BPMB data is sent from the surface building BA5 over Ethernet connection to the Prevessin Control Room (PCR) to a PC that houses the controller performing the correction and sends the steering data back to the COD power converter controller.

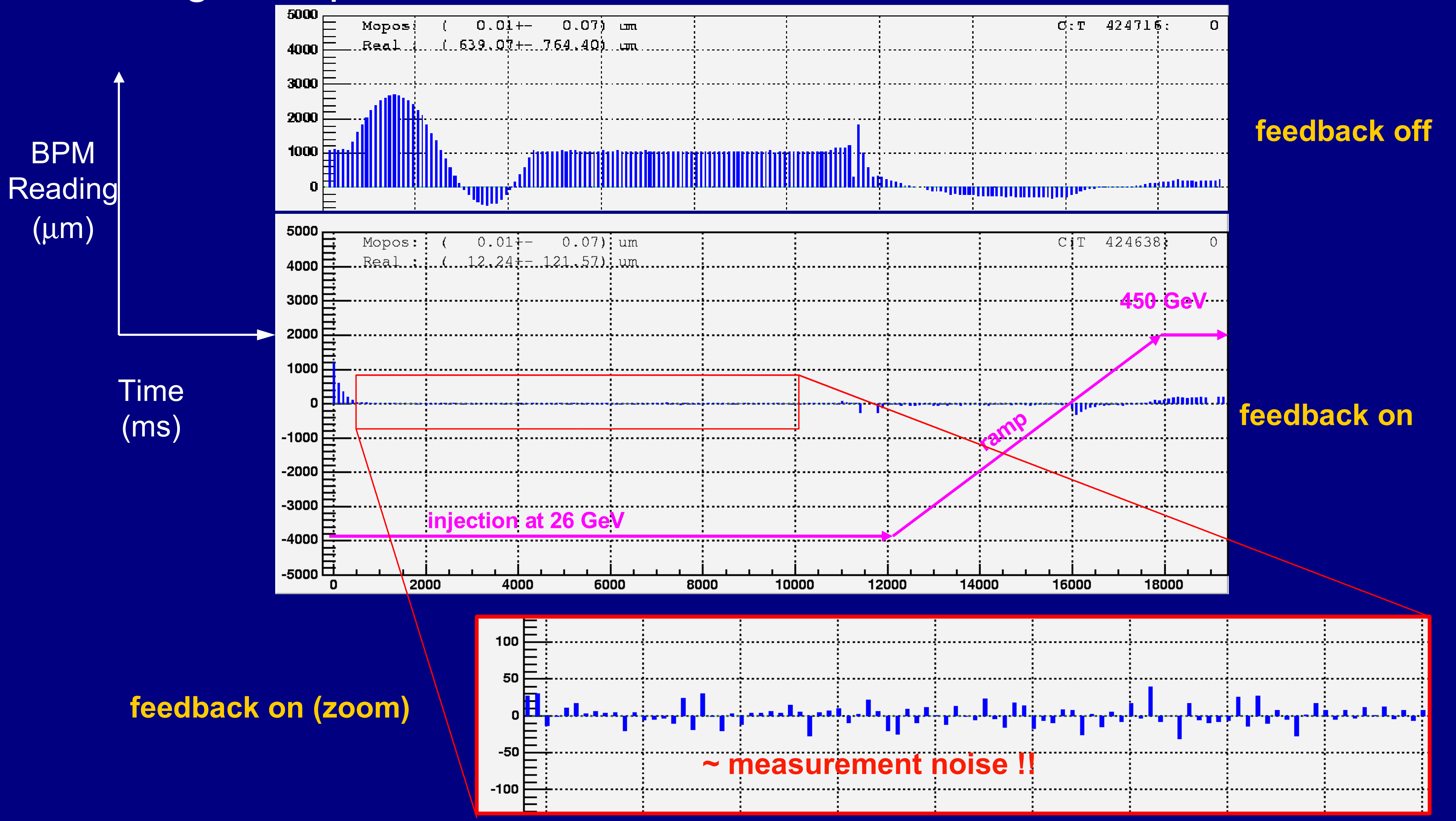


LHC Orbit Feedback Control
SPS *Test Setup*



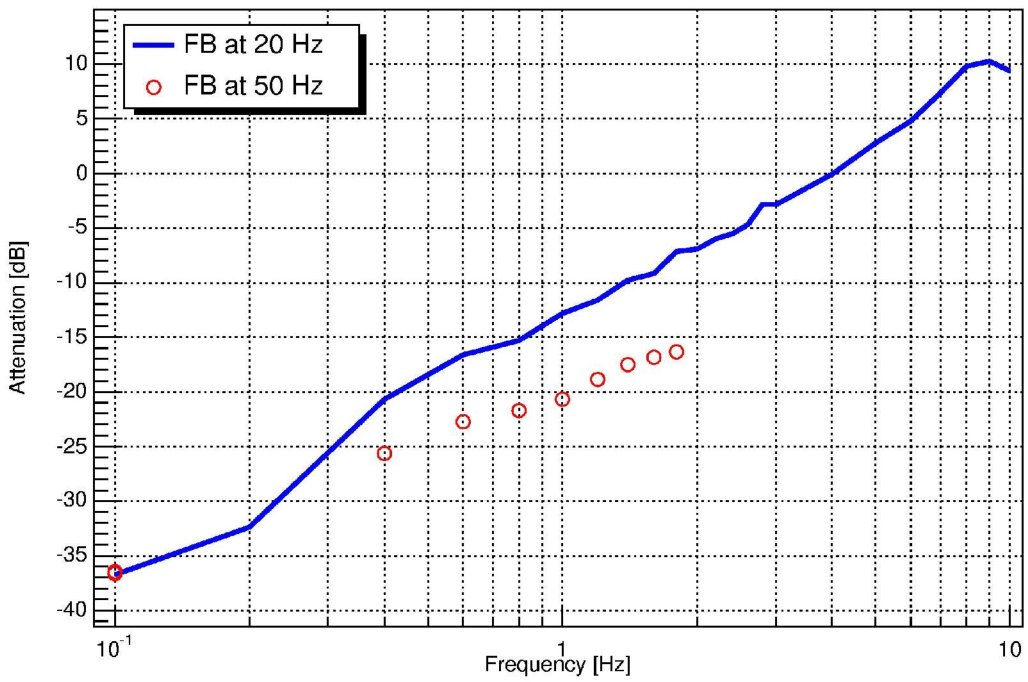
Results I/II

Steering example with additional external noise:

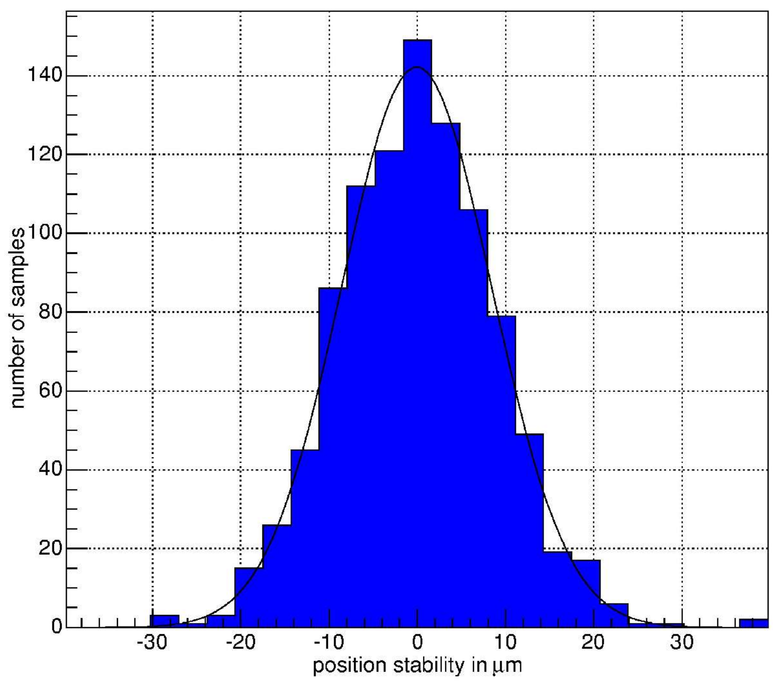


- Feedback loop showed an average good performance
  - SPS system:
    - Stabilised the beam at 4 BPMB
    - Max. feedback sampling frequency 100 Hz
    - position within 8.5 μm

Feedback attenuation



Position distribution @ 100 Hz
σ = 8.5 μm



Conclusions

- The LHC requires excellent control of particle losses in order to protect the cryogenic magnets in the presence of a high intensity beam.
- Performance of LHC Cleaning System depends critically on the beam position stability that has to be stabilised by the real-time Orbit Feedback System.
- First order controller model and design established
- Tests of the LHC BPM acquisition system and development of the SPS orbit feedback prototype:
  - max. feedback frequency 100 Hz (enough for targeted 25 Hz)
  - beam within 8.5 µm locally stabilised in the SPS

Outlook

- more work/studies on:
  - beam movement sources
    - Ground motion
    - Magnetic misalignments (Decay & Snapback)
  - BPM systematics and possible compensations
    - Intensity
    - bunch length
    - injection pattern
  - machine failure modes and retaliatory actions of the feedback

  - Further *'test bed'* (accelerator simulation) development and matching with real machine measurements
  - Improvement of feedback loop and its test (in the test bed environment)

  - a lot more to do till machine startup in 2007....

Acknowledgement

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Dr. J. Wenninger for his support and supervision

The many colleagues in AB-OP, AB-BDI, AB-PO, AB-CO, AB-RF, IT and AT for their fruitful discussions, helps, hints and contributions

you for your attendance and attention!

Accelerator MINI-HOWTO

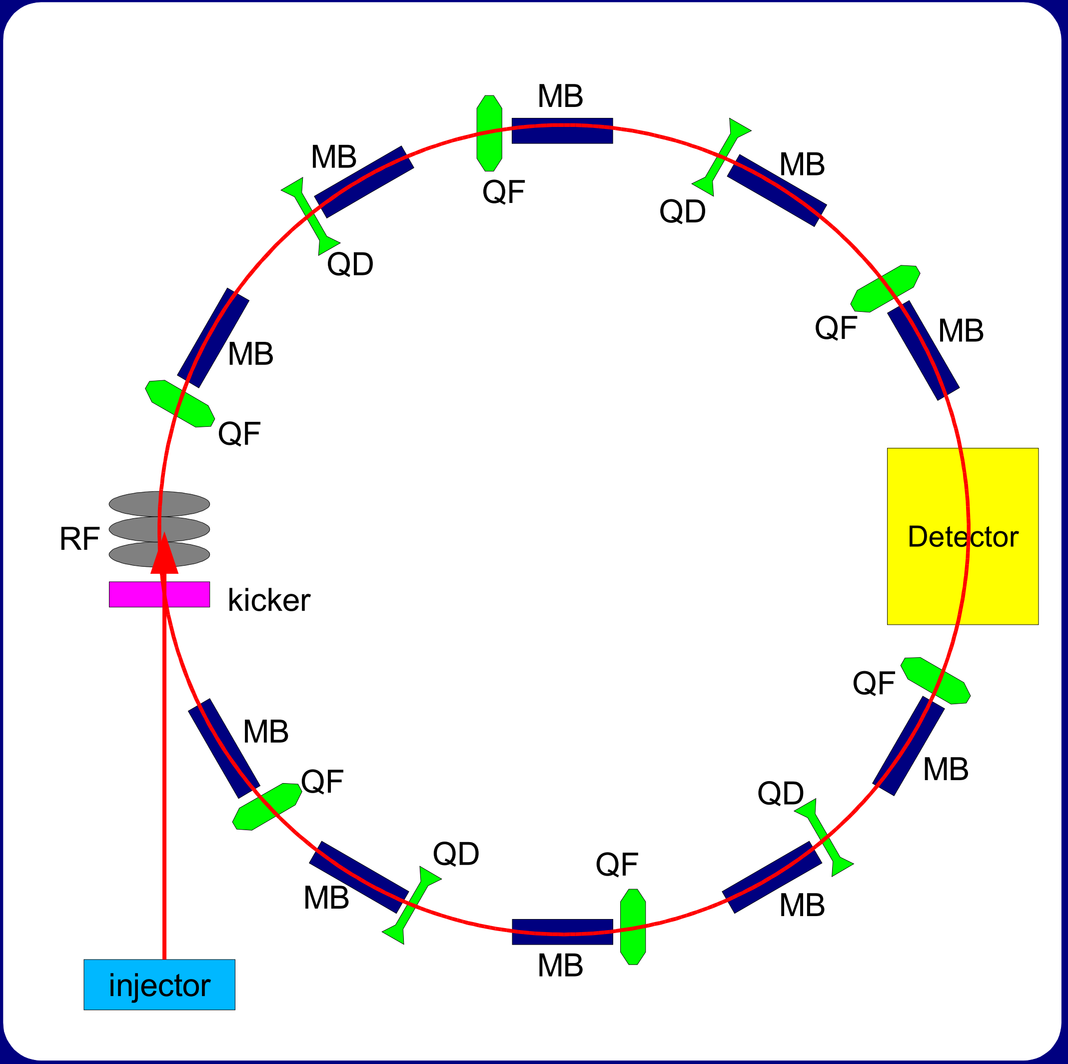
"For an accelerator, one needs..." :

- particle source (injector)
- Radio-frequency (RF) cavities
- Main dipole magnets (MB)
- Fast pulsed kicker magnet
- Quadrupole magnets (QD & QF)
- [..]
- Dodecapole magnets
- Instrumentation: beam position, loss, intensity, longitudinal and transverse profile, phase relations, luminosity ...
- the particle detectors

- Control strategy

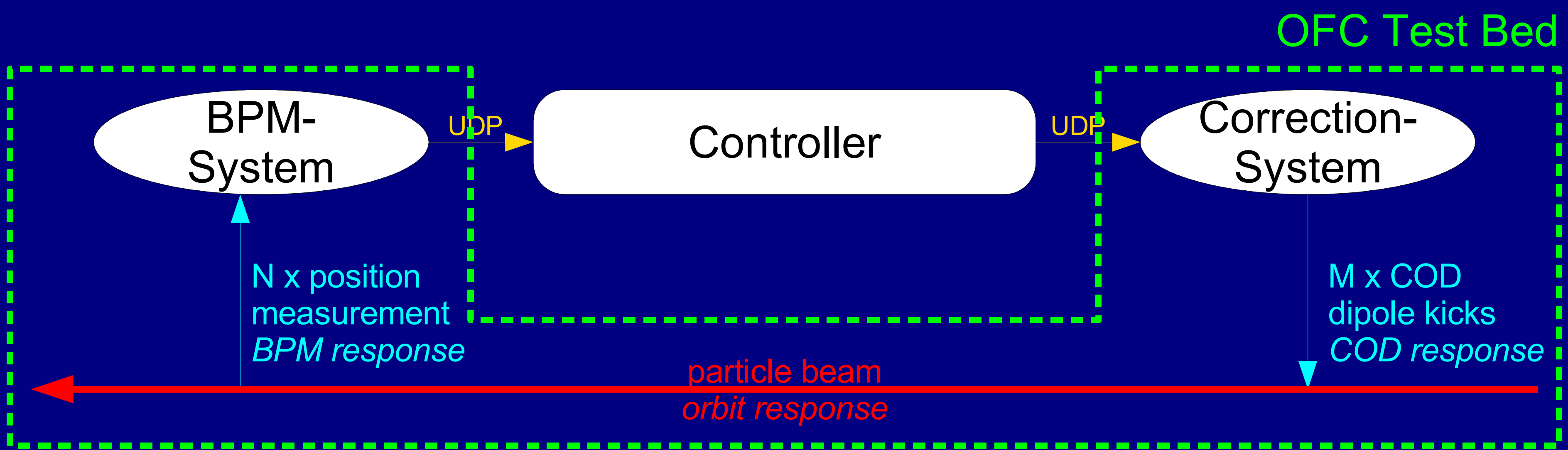
and much more....

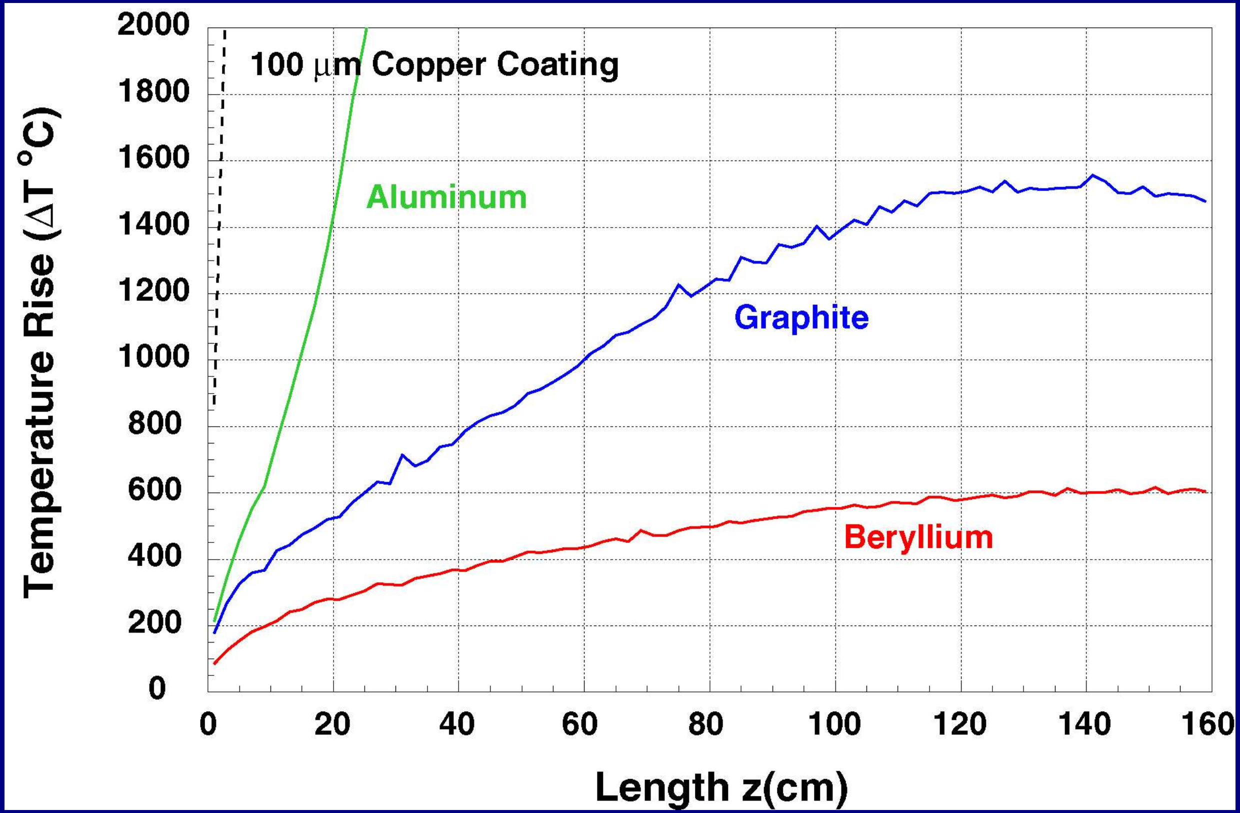
x2 for p-p collisions



OFC Test Bed

- Test bed: complement to the Orbit Feedback Controller (OFC)
  - Accelerator analogue to the Monte Carlo simulation of the detectors
  - Simulates the open loop and orbit response of COD->BEAM->BPM
    - BPM systematics (non-linearities, noise, calibration...)
    - correct dynamic behaviour of the PC + magnet circuit
    - Other higher order effects
  - Same data delivery mechanism and encoding as in the real front-end
    - transparent for the OFC
    - simple "offline" debugging for OFC
  - Real-time and SMP: runs at up to 128 Hz (1 kHz) for a full LHC (SPS) orbit simulation
  - OFC implementations can be tested and validated under various scenarios




100 μm Copper Coating
Aluminum
Graphite
Beryllium
Temperature Rise (ΔT °C)
Length z(cm)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
160

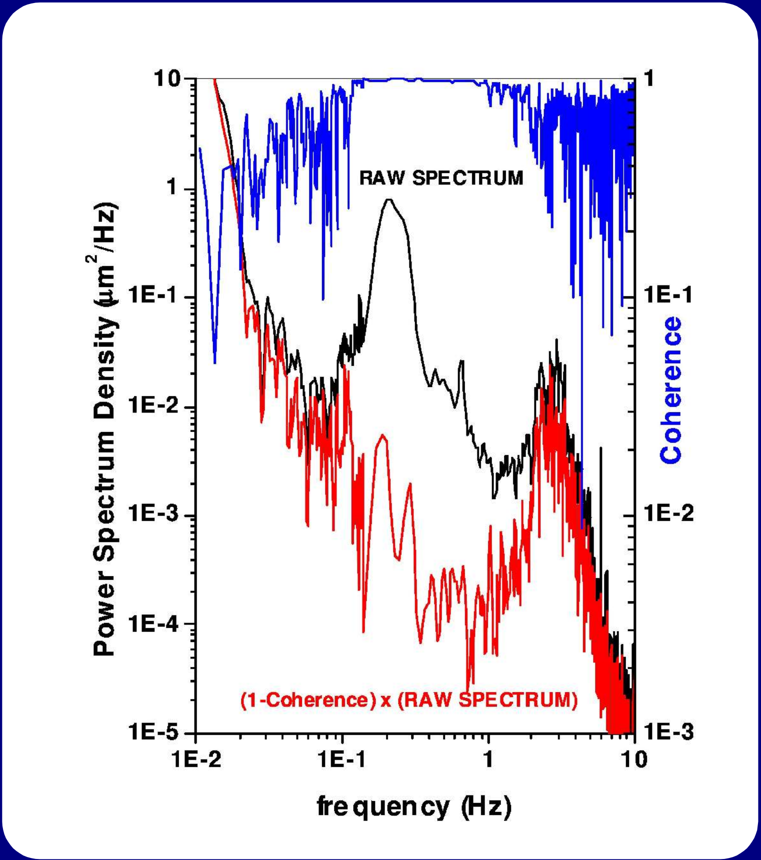
Groundmotion

- During collision ground motion will contribute most to closed orbit movements.
- Each off-centred quadrupole introduce a dipole kick $\delta_j(t)$ and moves the beam:

$$\Delta x_i = R_{ij} \delta_j(t)$$

- R_{ij}: orbit response matrix, describes the relation of the dipole kicks of the j-th magnet on the beam position measured at the i-th monitor
- random ground motion is enhanced by the accelerator:
  - SPS: $S_{orbit} \sim 28 S_{gm}$
  - LHC: $S_{orbit} \sim 35 S_{gm}$

(S_{orbit}, S_{gm}: power spectrum of the orbit / ground motion)



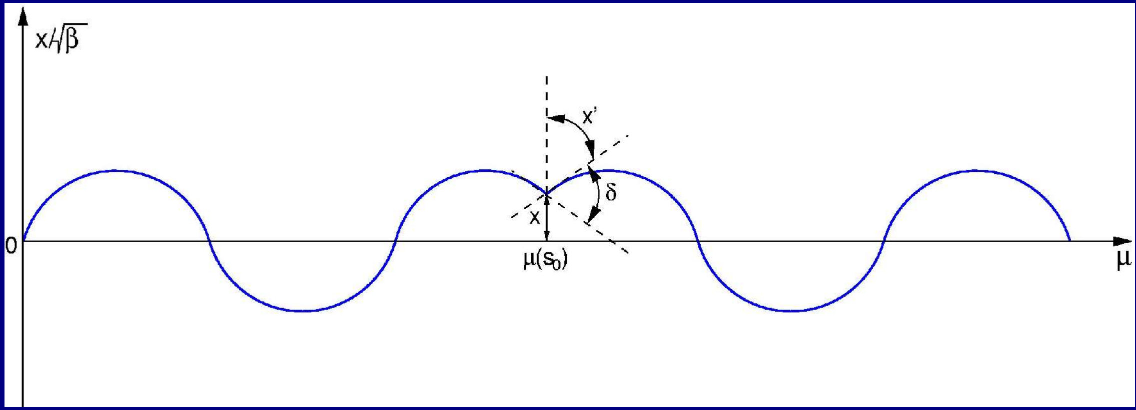
- requirements on the orbit position:
  - Global (r.m.s)
    - physical machine aperture and operation — 500 µm
    - minimisation of electron cloud/ — 200 µm
      (Preserving the 'scrubbing efficiency')
    -
  - Local (absolute):
    - centering the beam at the dampers — < 200 µm
    - collimation section (IR 3 & 7) — < 70 µm
      (cleaning efficiency is depends on the beam position)
    - pre-alignment for the luminosity feedback — < 70 µm
      (preserving dynamic range of its ADC)
    - TOTEM experiment — < 10 µm
      (tough!)

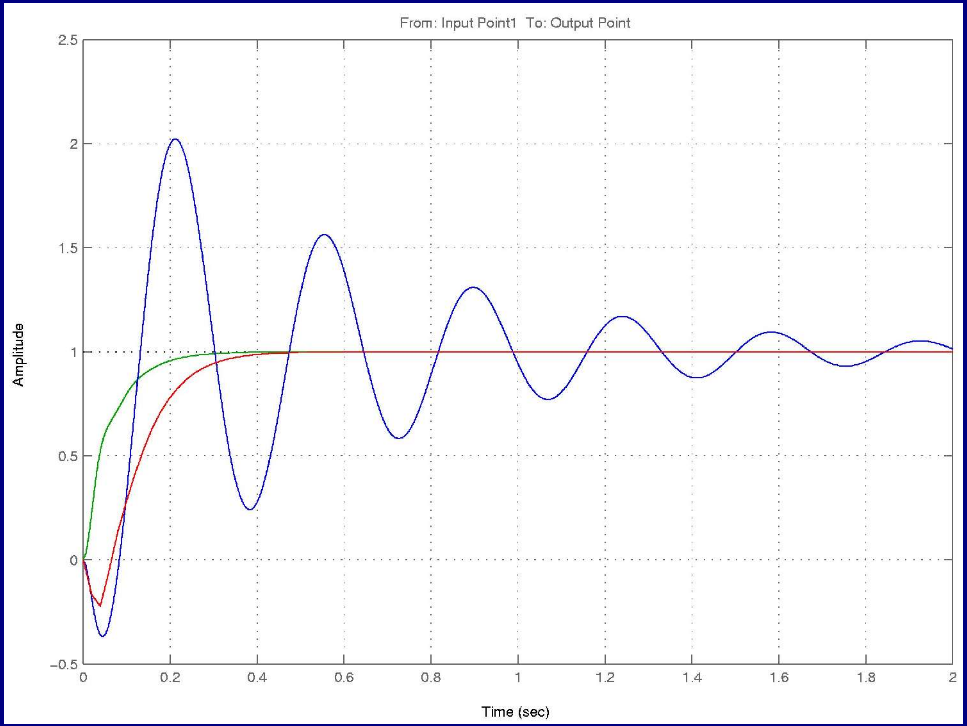
LHC Orbit Feedback Control
BPM & Correction system

- BPMs: ~1100, over the two rings distributed
(controlled by approximately 80 front-end crates)
  - Each measure horizontal and vertical position
    - Redundancy (to a certain extend), sampling at high and low β
    - Measurement precision: 200 μm/shot
      -> closed orbit (255 turns) ~5 μm
    - possible (tested) sampling rates up to 100 Hz

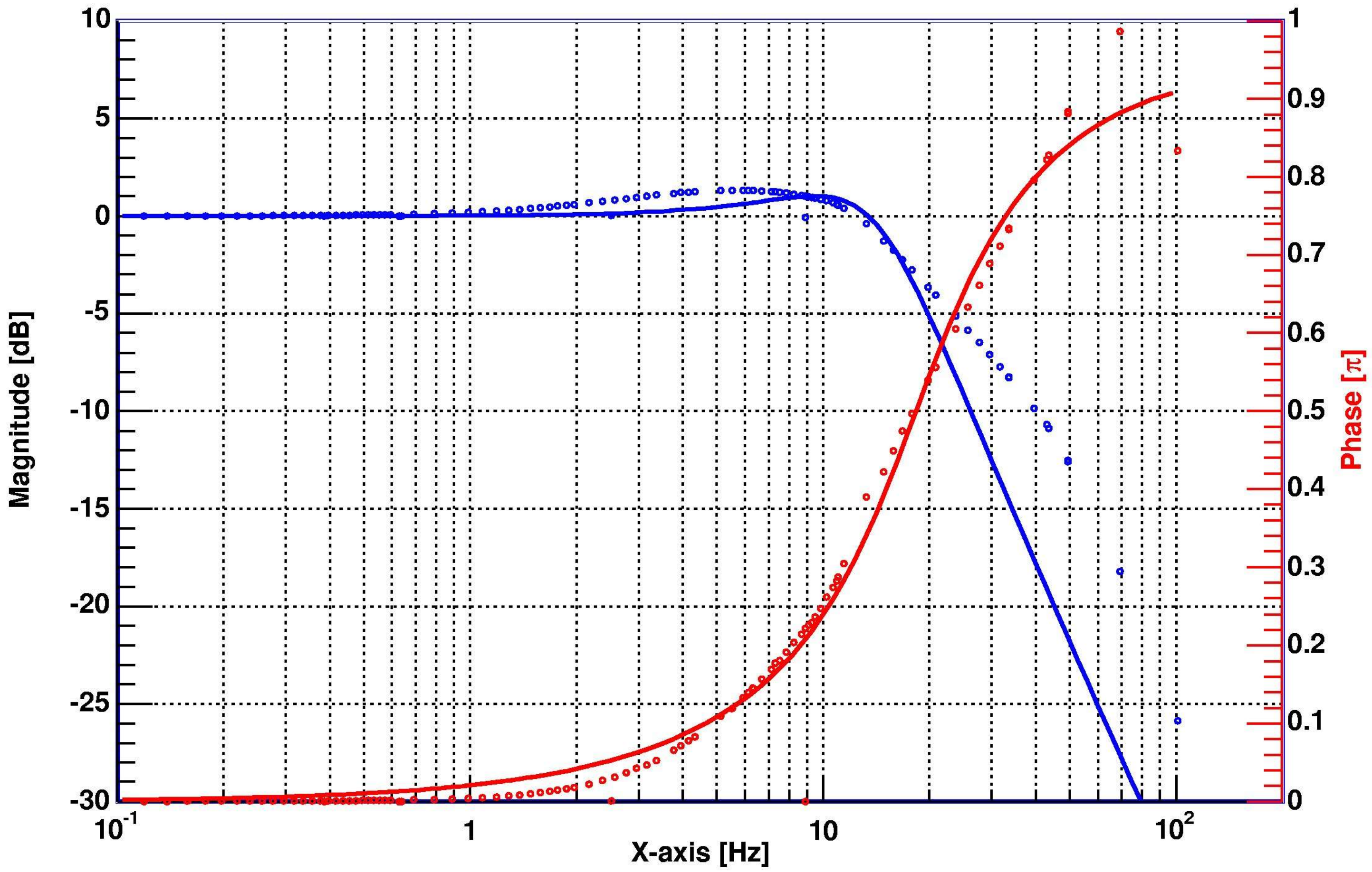
- CODs: Both rings (H&V) are equipped with about ~600 individually powered correction dipole magnets (controlled by approximately 40 front-end crates)
  - Maximum kick strength ($\delta_{max}p$): *570 μrad TeV/c*
  - natural time constants of magnets:
    - cold magnets (most) 200 s
    - warm magnets (only a few) 10 s
  - Power converter steers with effective bandwidth f_b of ~ 1 Hz

  -> the PC can generate (compensate) orbit oscillations (at high β)
  ~13 μm @ 1 Hz
  - access rate is limited to f_s=50 Hz, determines max. feedback frequency!


x/√β
x'
δ
x
0
μ(s0)
μ


From: Input Point1 To: Output Point
Amplitude
Time (sec)
2.5
2
1.5
1
0.5
0
−0.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

LHC Orbit Feedback Control
COD response – Bode Plot



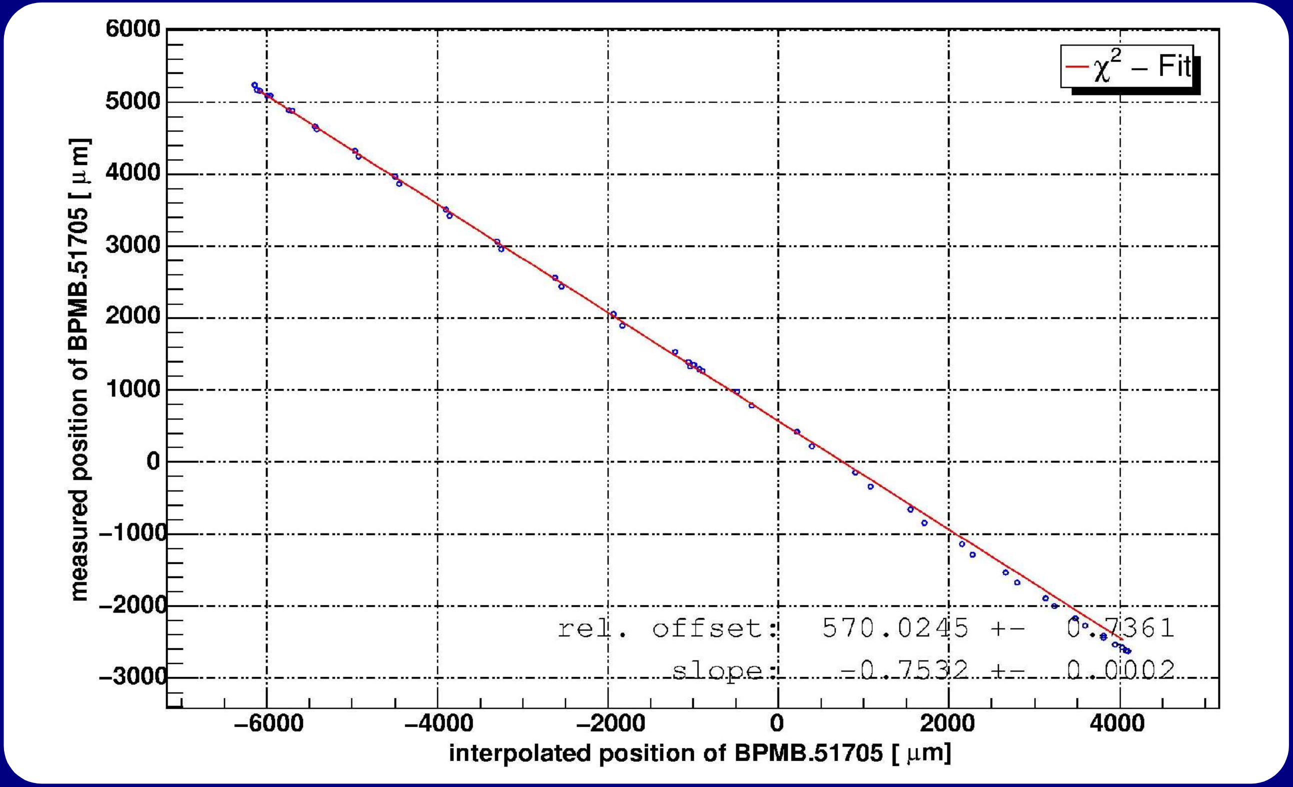
- Measurement (dashed) and fit ω_0 = 14 Hz and ζ = 0.52 (solid lines)

- luminosity depends on the position of both beams in the IR:

$$L = \frac{N_1 N_2 f_{rev} k_{bunch}}{2\pi\sqrt{(\sigma_{x_1}^2+\sigma_{x_2}^2)(\sigma_{x_1}^2+\sigma_{x_2}^2)}} \cdot e^{-\left[\frac{(\bar{x}_1-\bar{x}_2)^2}{2(\sigma_{x_1}^2+\sigma_{x_2}^2)}+\frac{(\bar{y}_1-\bar{y}_2)^2}{2(\sigma_{y_1}^2+\sigma_{y_2}^2)}\right]}$$

LHC Orbit Feedback Control

BPMB response - Calibration



- BPMB calibration using the neighbouring SPS monitors in order to match

$$X'(s)=X(s) \Leftrightarrow M(s):=1$$

- In this particular case, the magnitude of the slope and its sign shows that this BPMB has a sign error that has to be taken into account.
- The BPM further introduces a sampling delay
- Successful tested for sampling rates up to 100 Hz.

The Large Hadron Collider
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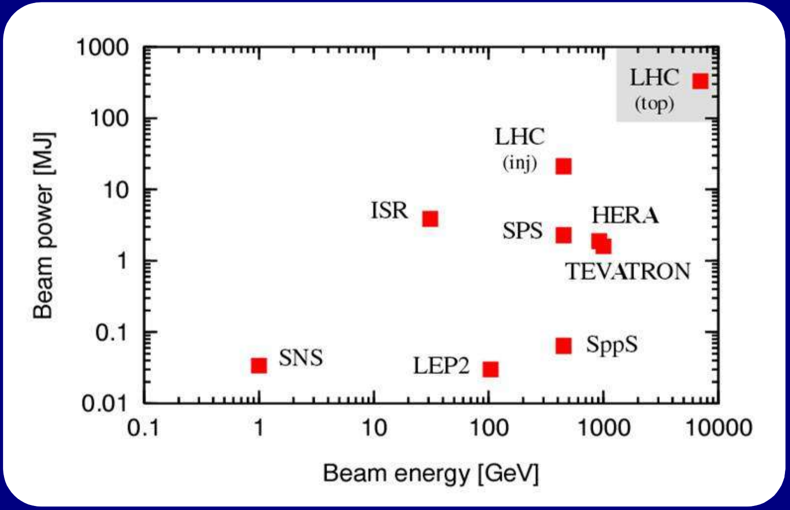

- Beam Energy is equivalent to:
  - heat from cryogenic temperature and melt of 500 kg Cupper
  - chemical energy of
    - 24 kg sugar
    - 8 l of gasoline
    - 95 kg TNT
  - sufficient to quench all LHC magnets at once if evenly distributed
  - disassemble magnets and other equipment