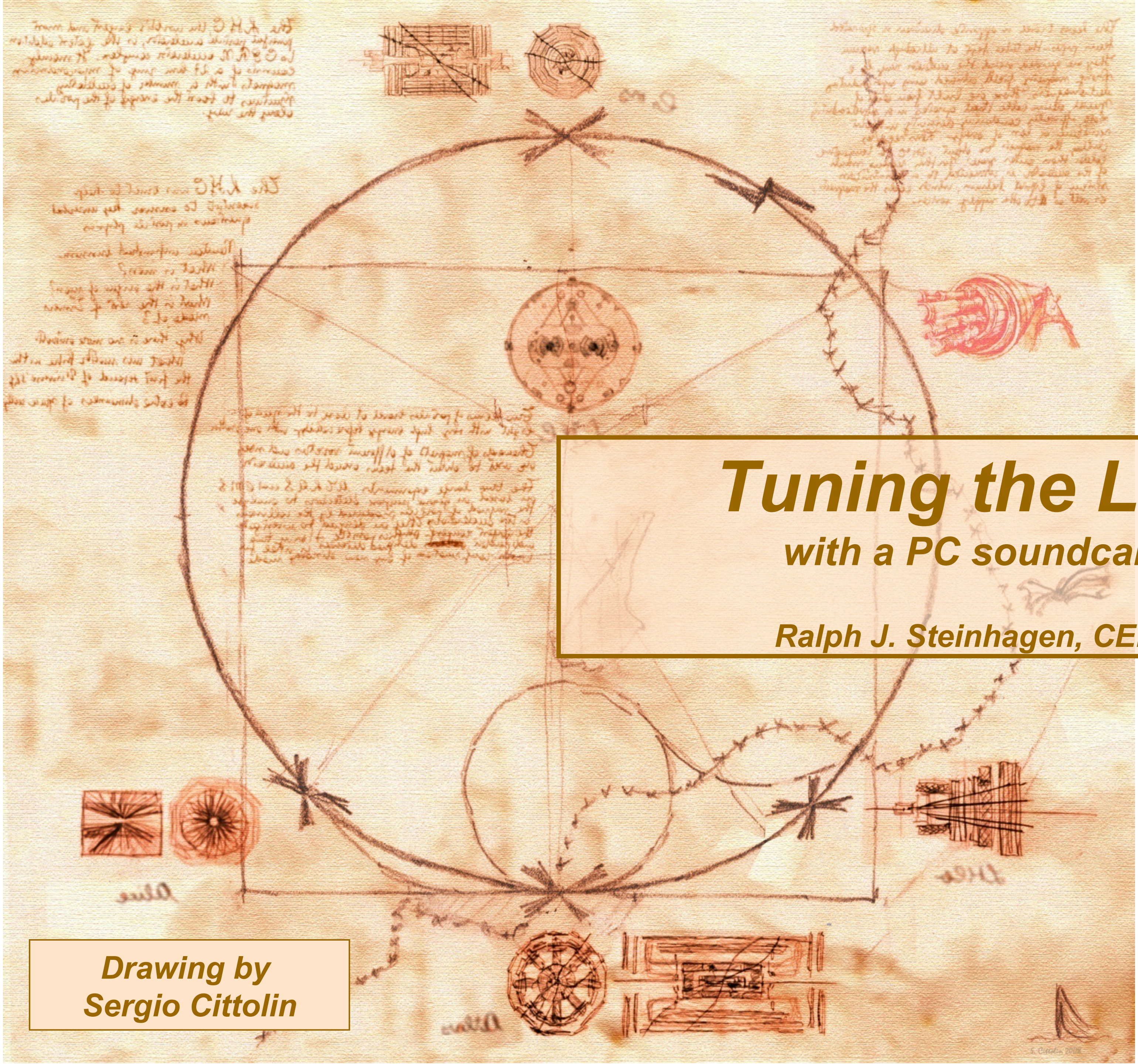


Tuning the LHC

with a PC soundcard

Ralph J. Steinhagen, CERN

Drawing by Sergio Cittolin

Outline

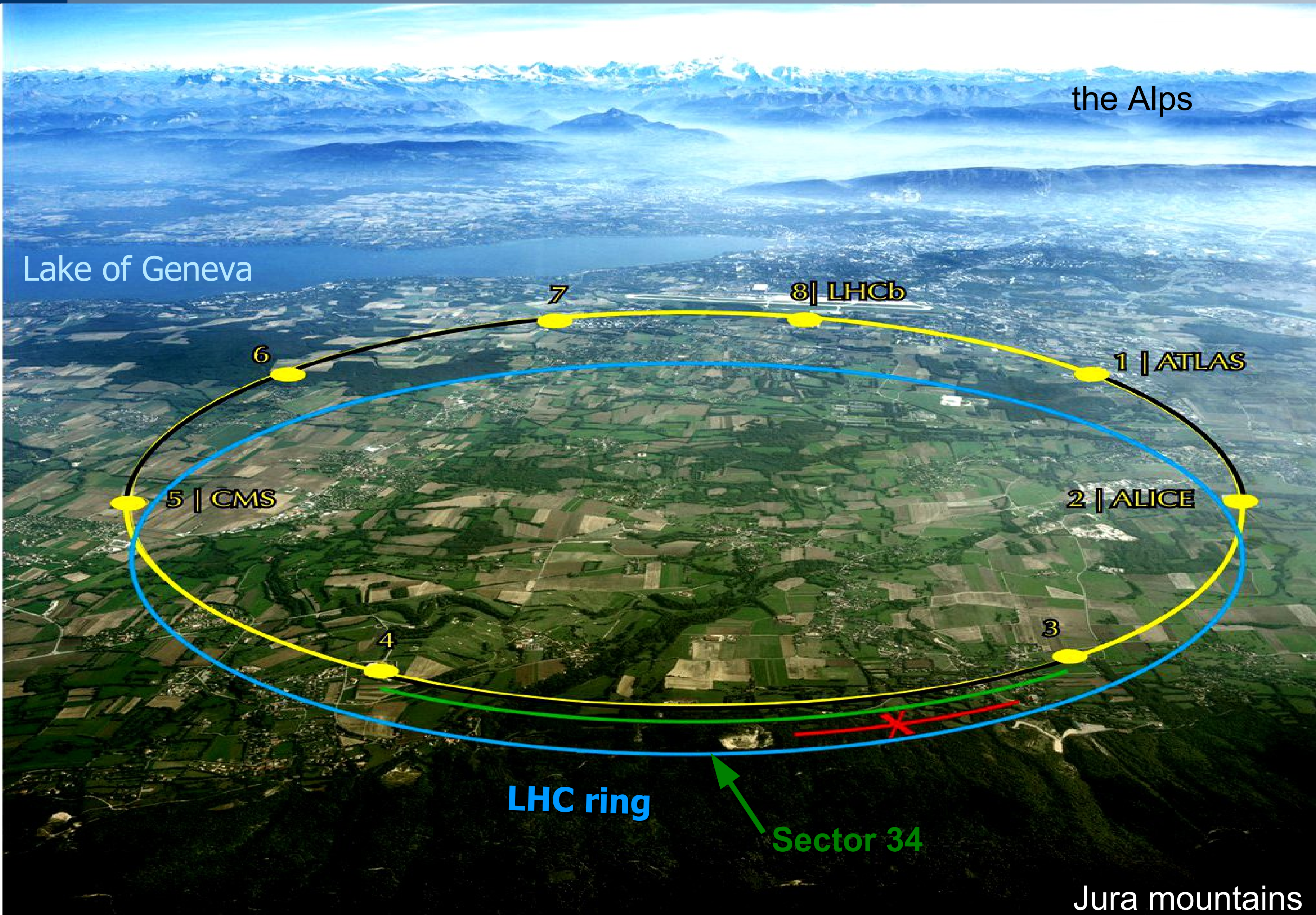
- Introduction to LHC
  - Parameter Motivation – Intensity, Energy & Machine Protection
- Beam Related Risks
  - Machine Protection and Collimation
  - Why to 'tune' a particle accelerator
    - Base-Band-Tune (BBQ) Meter
  - Some results and impression
- Later on Friday: a bit more on LHC commissioning

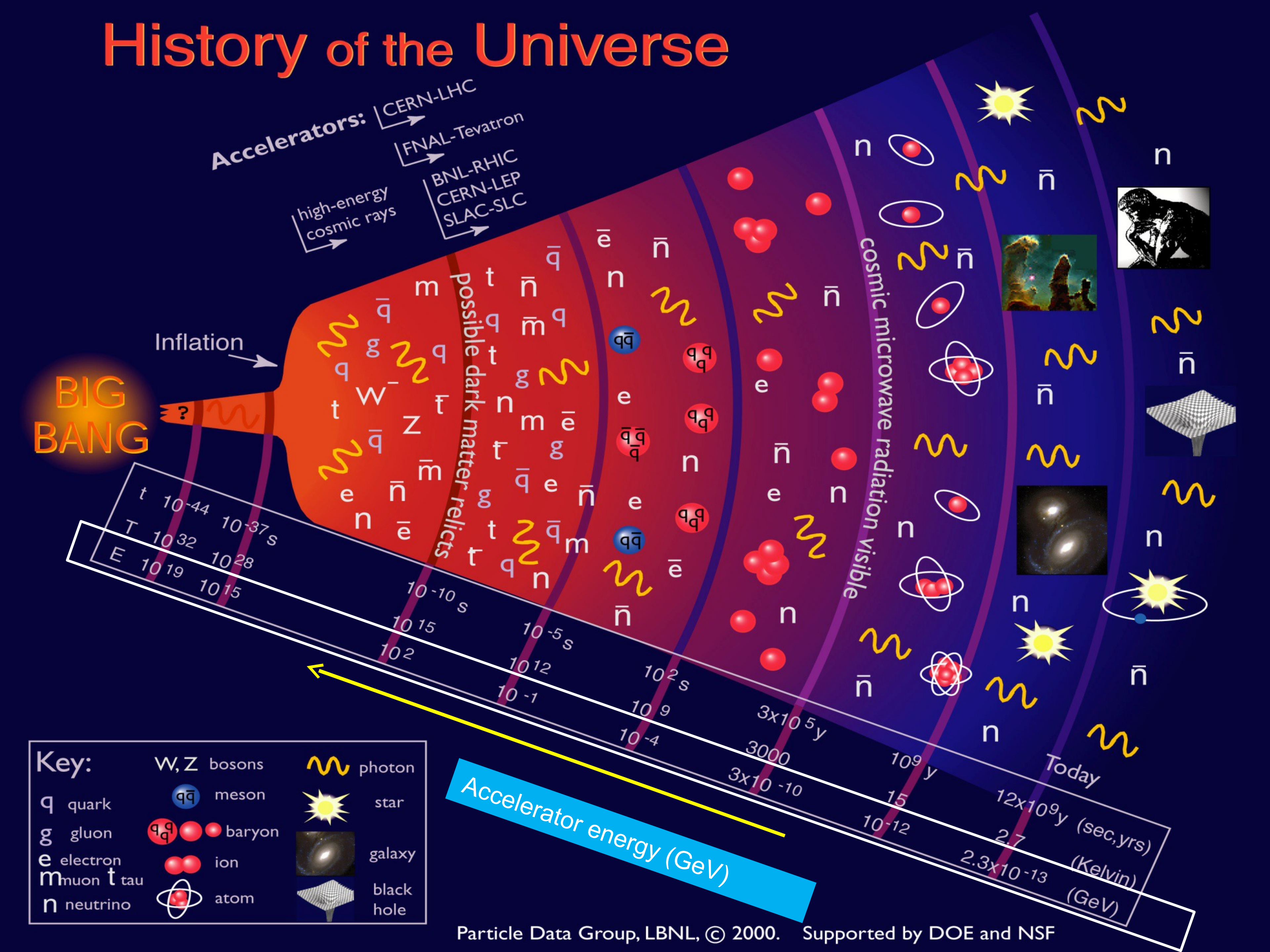
To put things into perspective

- CERN – "Down-Under"

…operating the biggest accelerator in one of the smallest countries in the World

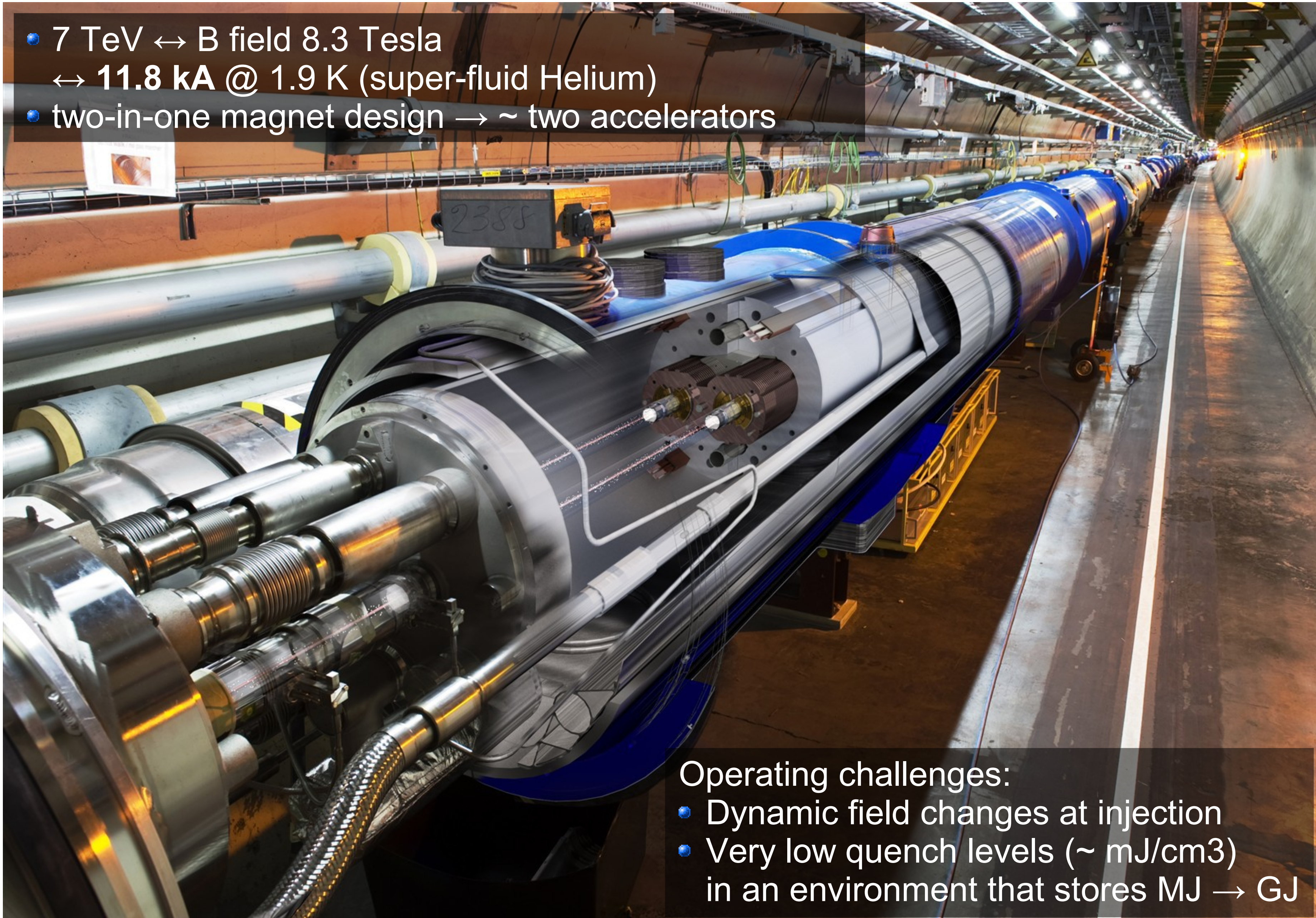
The Large Hadron Collider LHC
Installed in the LEP tunnel, 27 km, Depth of 70-140 m




History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Accelerator energy (GeV)
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

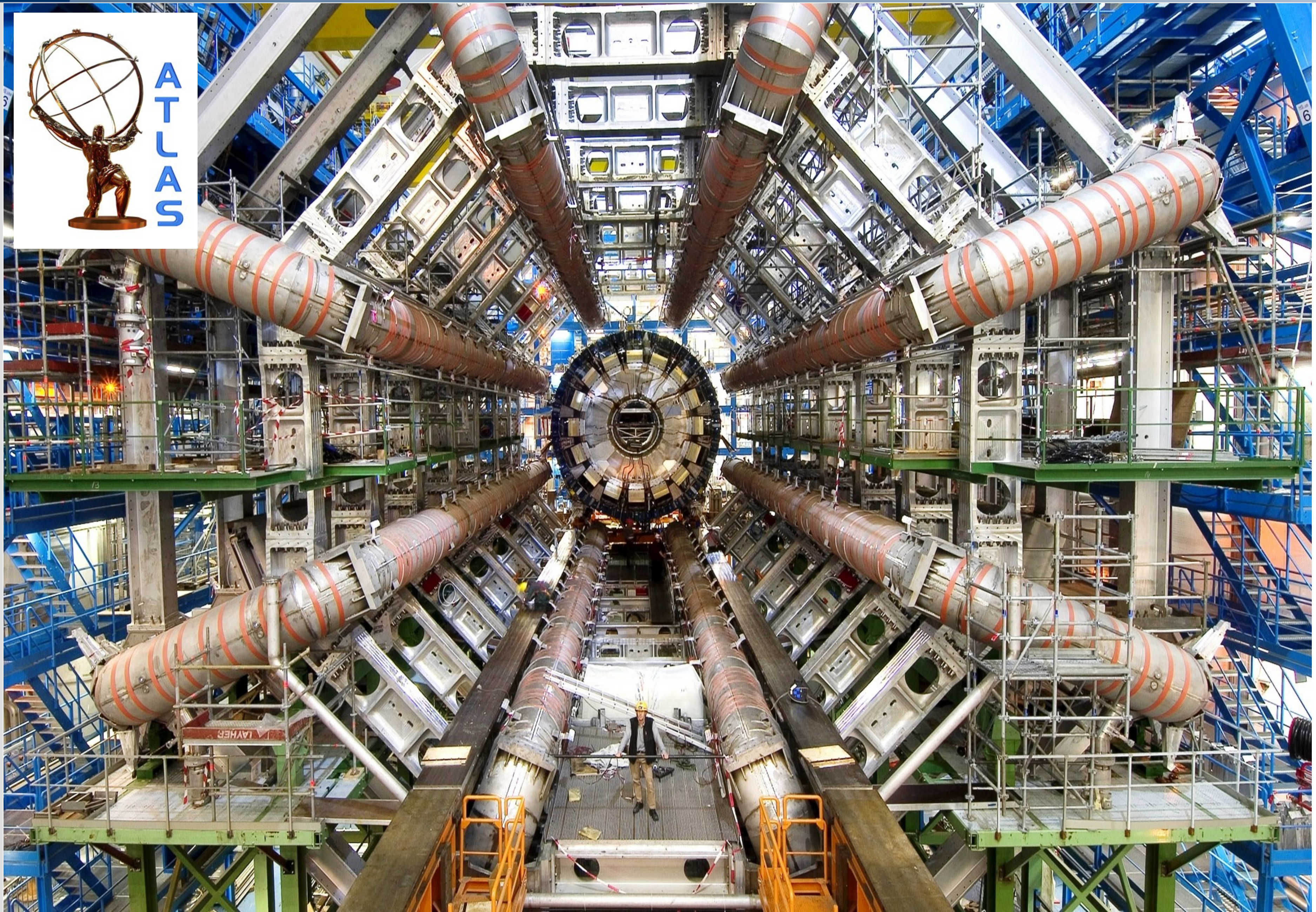
27 km Circumference – 1232 LHC dipole magnets

- 7 TeV ↔ B field 8.3 Tesla
  ↔ **11.8 kA** @ 1.9 K (super-fluid Helium)
- two-in-one magnet design → ~ two accelerators

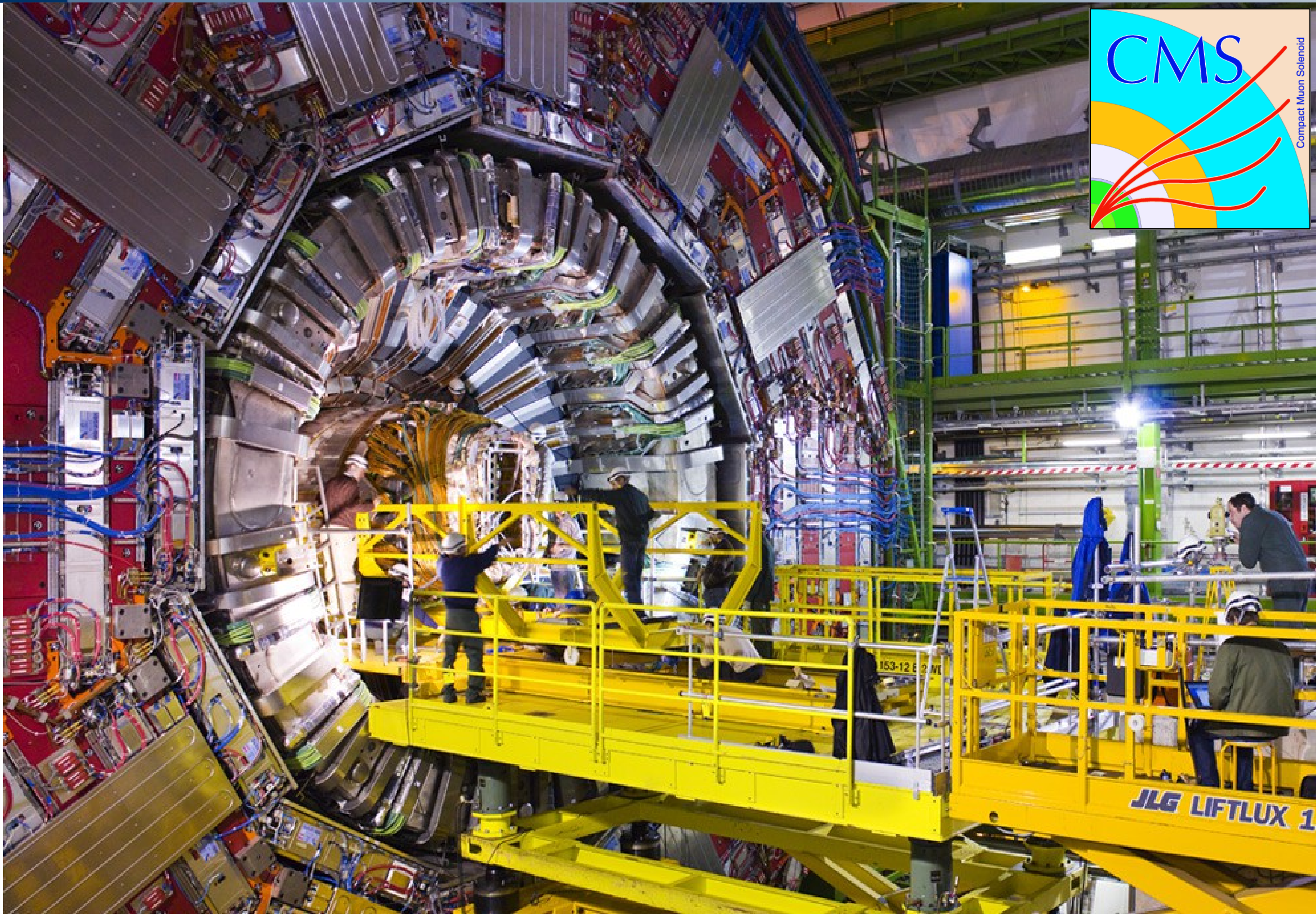


Operating challenges:
- Dynamic field changes at injection
- Very low quench levels (~ mJ/cm3)
  in an environment that stores MJ → GJ

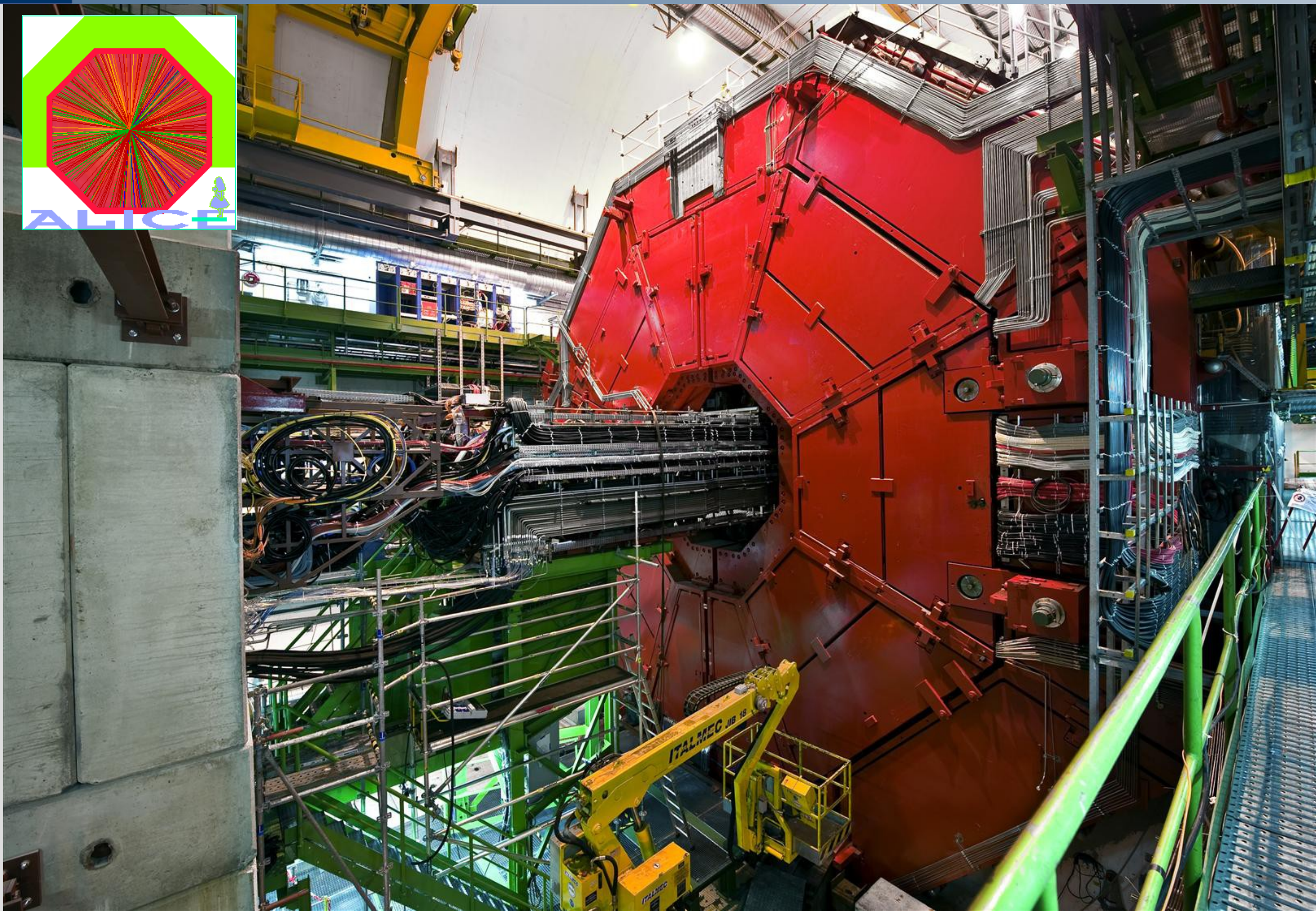
ATLAS



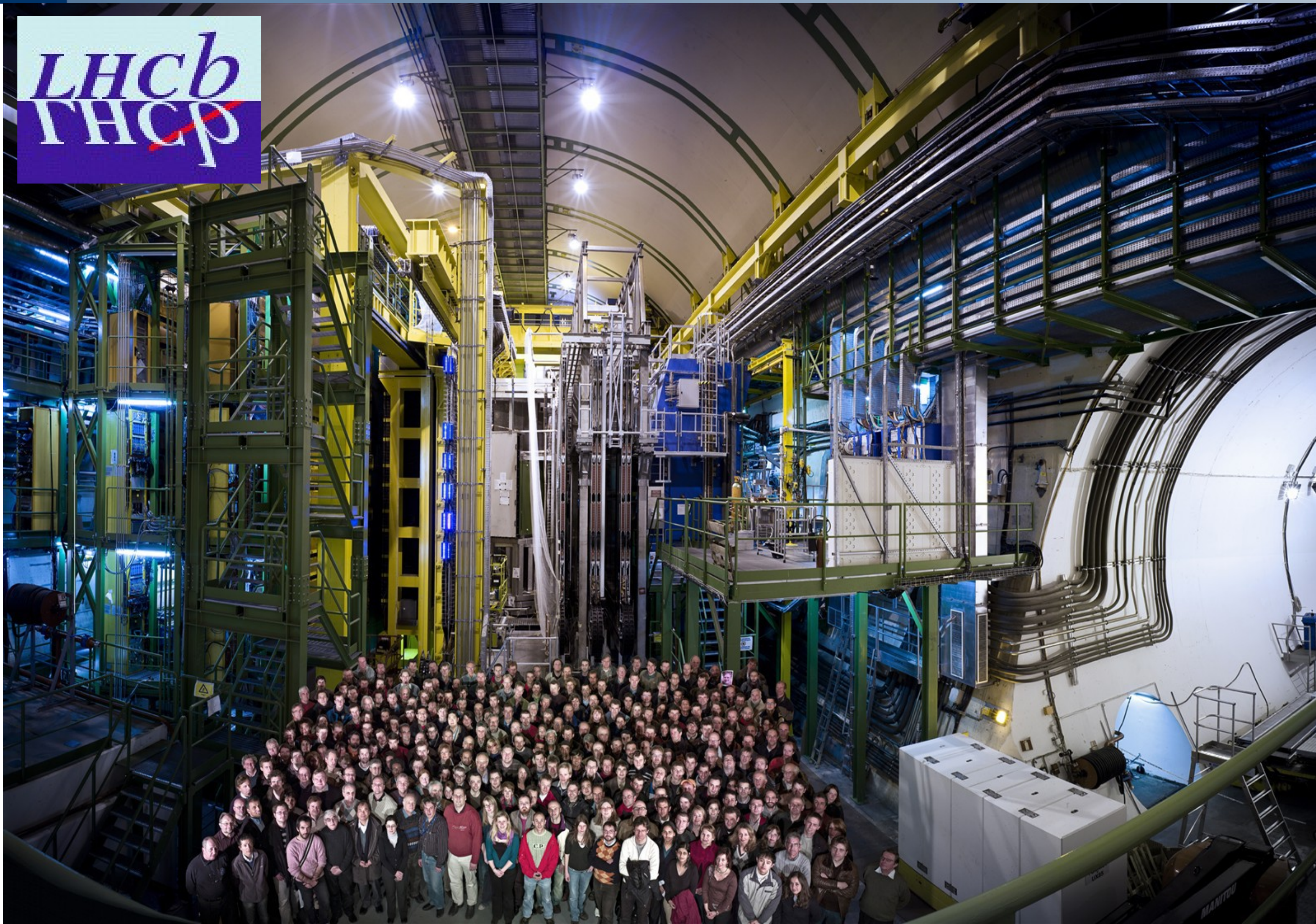
CMS



ALICE



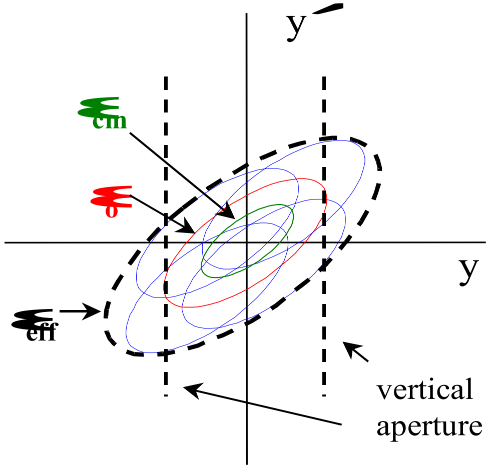
LHCb



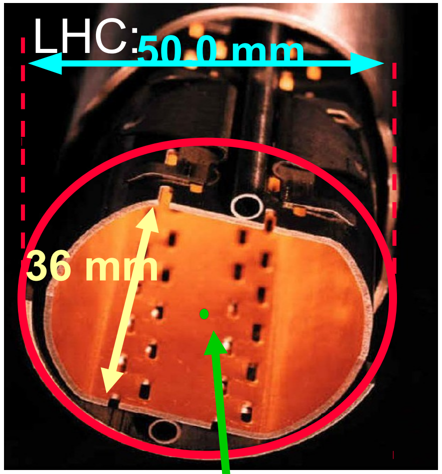
Beam Parameter Stability

- Lepton accelerators:
  - Effective emittance preservation
  - Minimisation of coupling (orbit in sextupoles)
  - Minimisation of spurious dispersion (orbit in quadrupoles)
  - Collider Luminosity and collision point stability

→ Nearly all 3rd generation light-sources deploy at least orbit/energy feedbacks

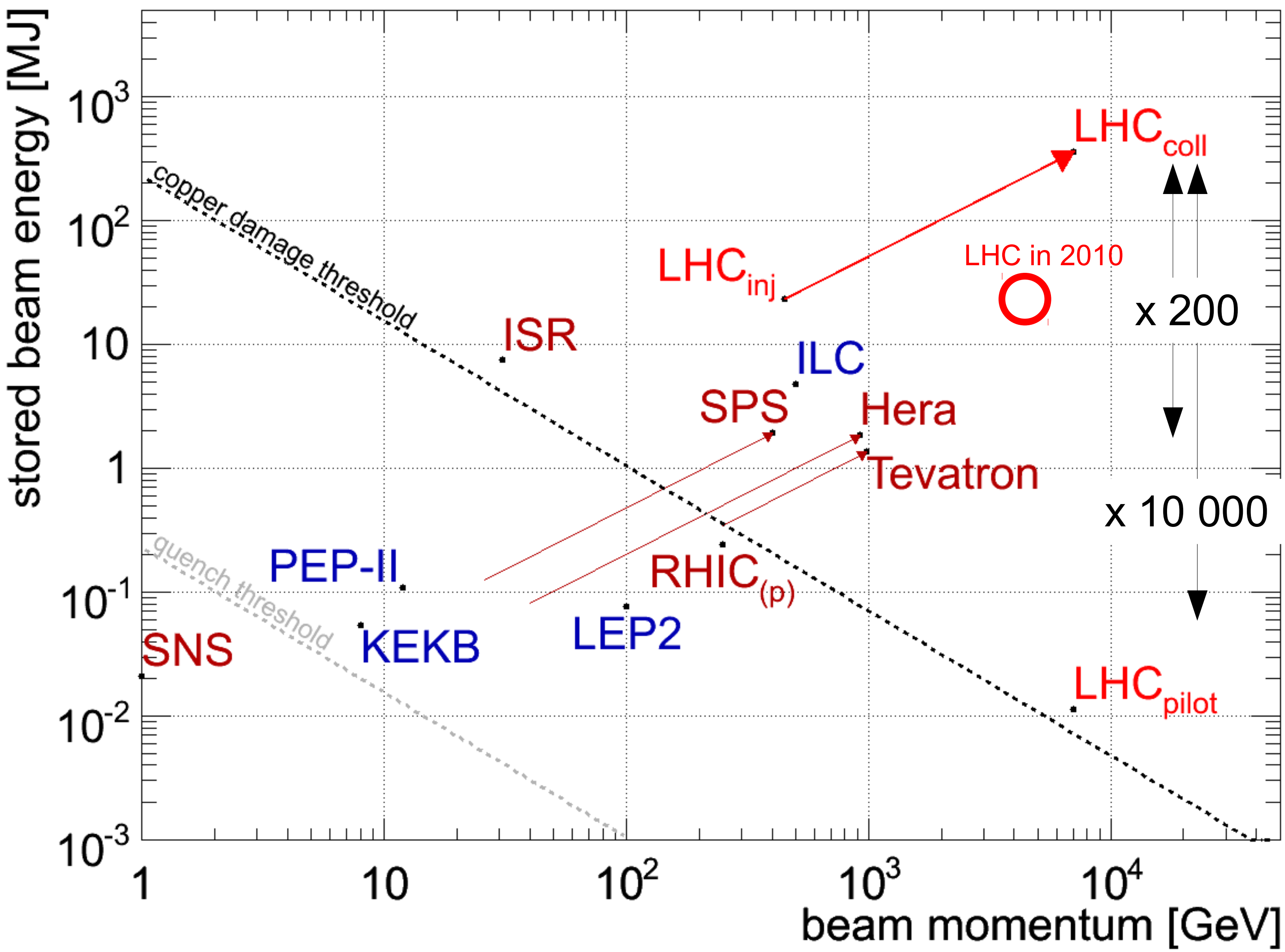


- Hadron Colliders and LHC in particular:
  - Traditionally: ... keep the beam in the pipe!
  - Present: sig. increased stored intensity and energy → quenches and/or serious damage
    1. Capability to control particle losses in the machine
    2. Commissioning and operational efficiency



Beam 3 σ envel.
~ 1.8 mm @ 7 TeV

Risks with Beam:
Total Stored Beam Energy



- LHC requires respect and vigilant treatment ...not much margin to err

see Chamonix XIV: “Damage levels - Comparison of Experiment and simulation” and PAC'05 for details

What you can do with a Fraction of the stored Beam Energy

- LHC superconducting dipoles may loose superconducting state ("quench")
  - minimum quench energy E_{MQE} @7 TeV for t~10 – 20 ms

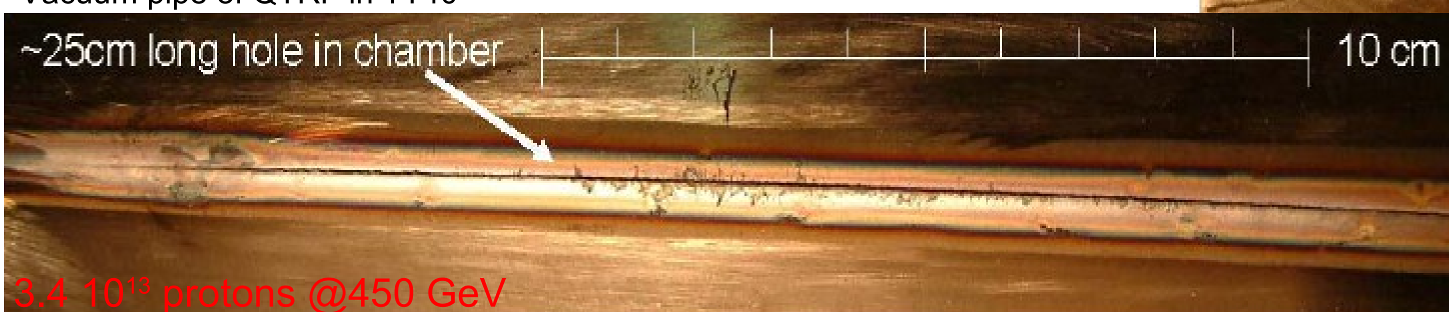
$$E_{MQE} < 10\ \text{mJ/cm}^{-3} \ \text{vs.}\ E_{stored} = 350\ \text{MJ/beam}$$

→ sufficient to quench all magnets and/or may cause serious damage

  - requires excellent control of particle losses
- Example: un-controlled vs. controlled energy release

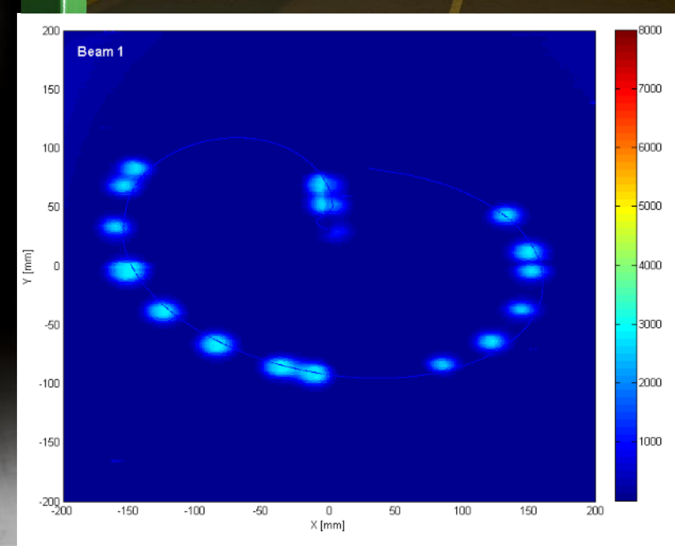
C = 5.4 10^{12} protons @ 450 GeV
D = 7.9 10^{12} protons @ 450 GeV

Vacuum pipe of QTRF in TT40

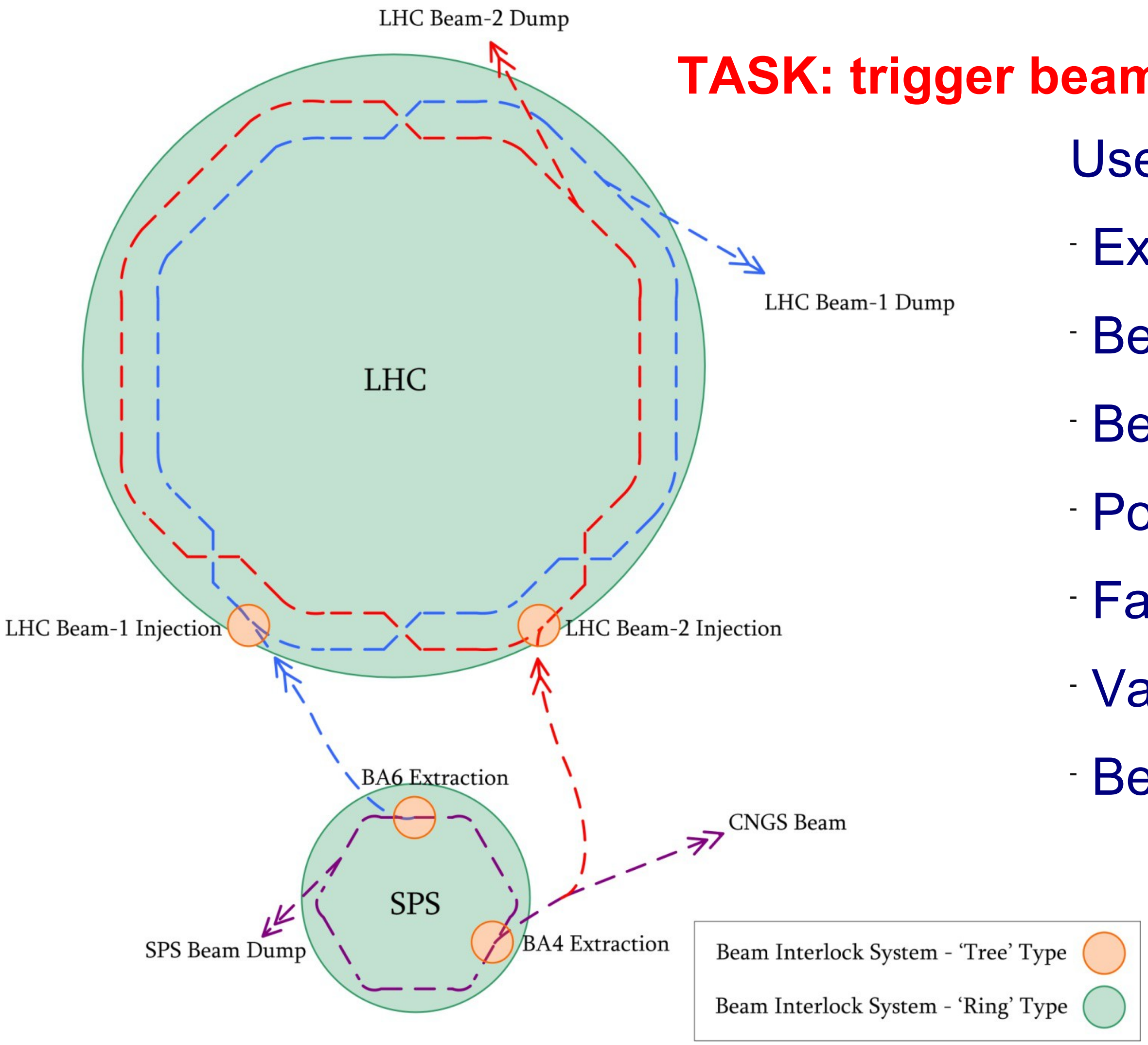


for details see: Chamonix XIV:
"Damage levels - Comparison of Experiment and simulation" and PAC'05

The only device withstanding an impact of a nominal LHC Beam:
… in a deep, quiet and dark corner... the LHC Beam Dumps



Core- Machine Protection System I/II
Beam Interlock System



TASK: trigger beam dump within 3 turns

User inputs include:

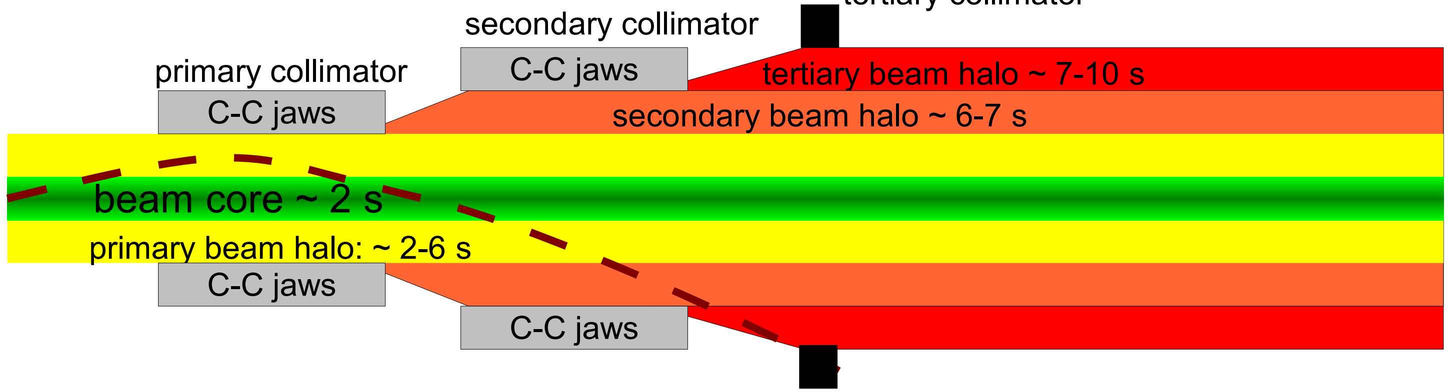
- Experiments
- Beam Loss Monitors
- Beam Position Monitors
- Powering, QPS
- Fast magnets
- Vacuum
- Beam dump

MTBF Design, over-all system: >10k years, beam dump: > 1 million years!

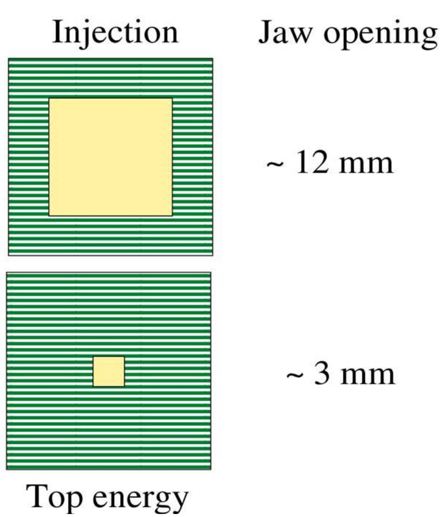
OK in 2010 → 999 999 more years to go

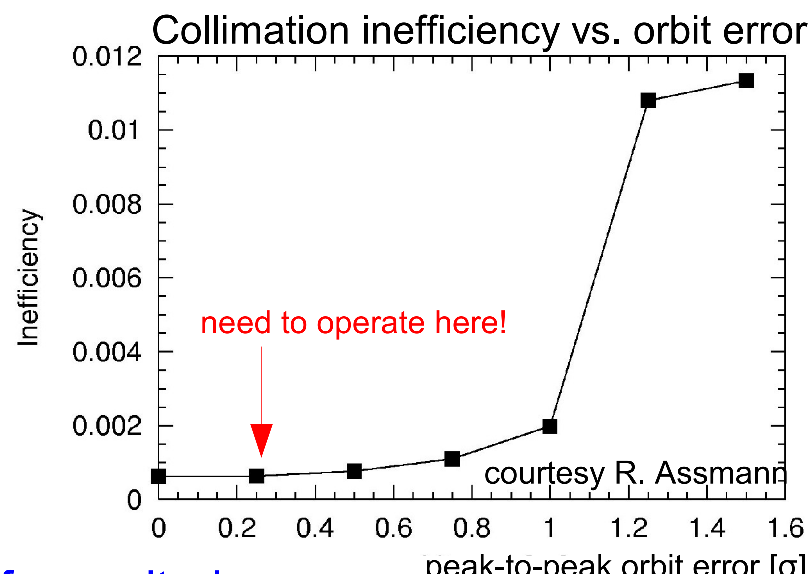
Core- Machine Protection System II/II
Collimation and Beam Cleaning System

- Two- (three-) stage cleaning system:



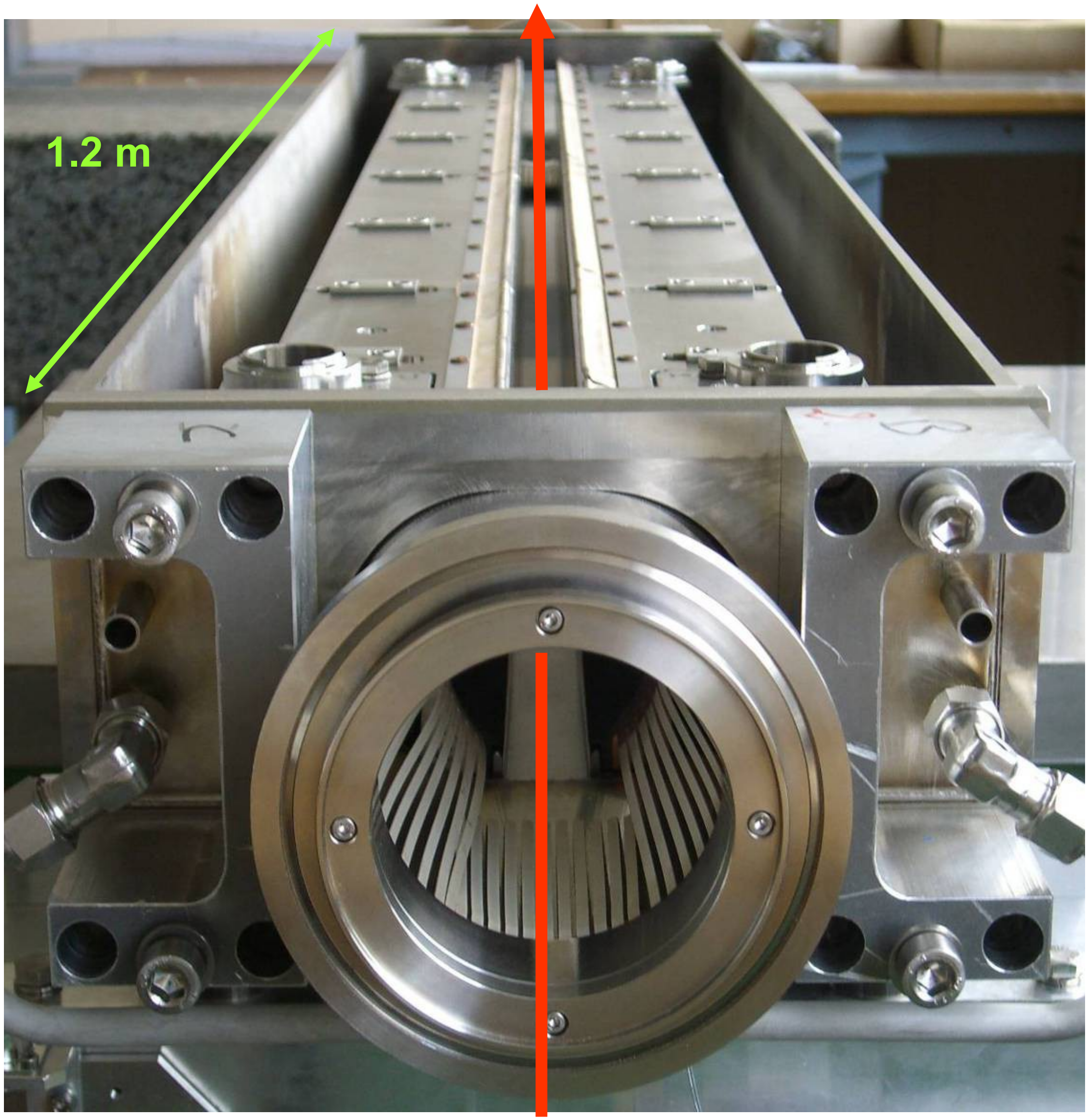
  – requires tight orbit stability requirement:
    ~ 25 µm at coll. jaws → less than the thickness of a human hair



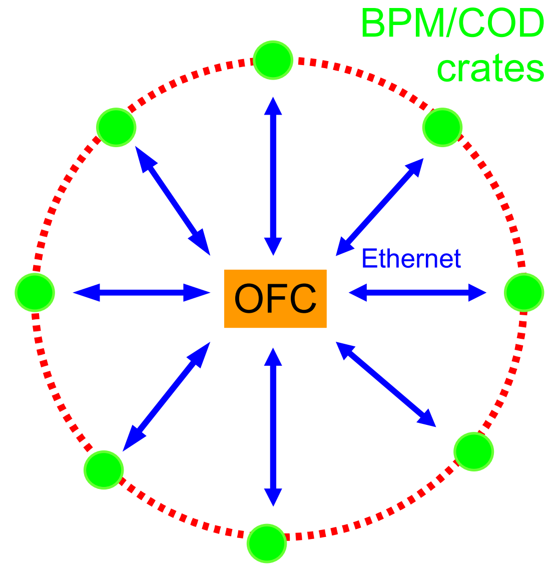


- Natural stability insufficient by orders of magnitude...
  "...firing two needles across the Atlantic and getting them to collide"

Primary Collimator



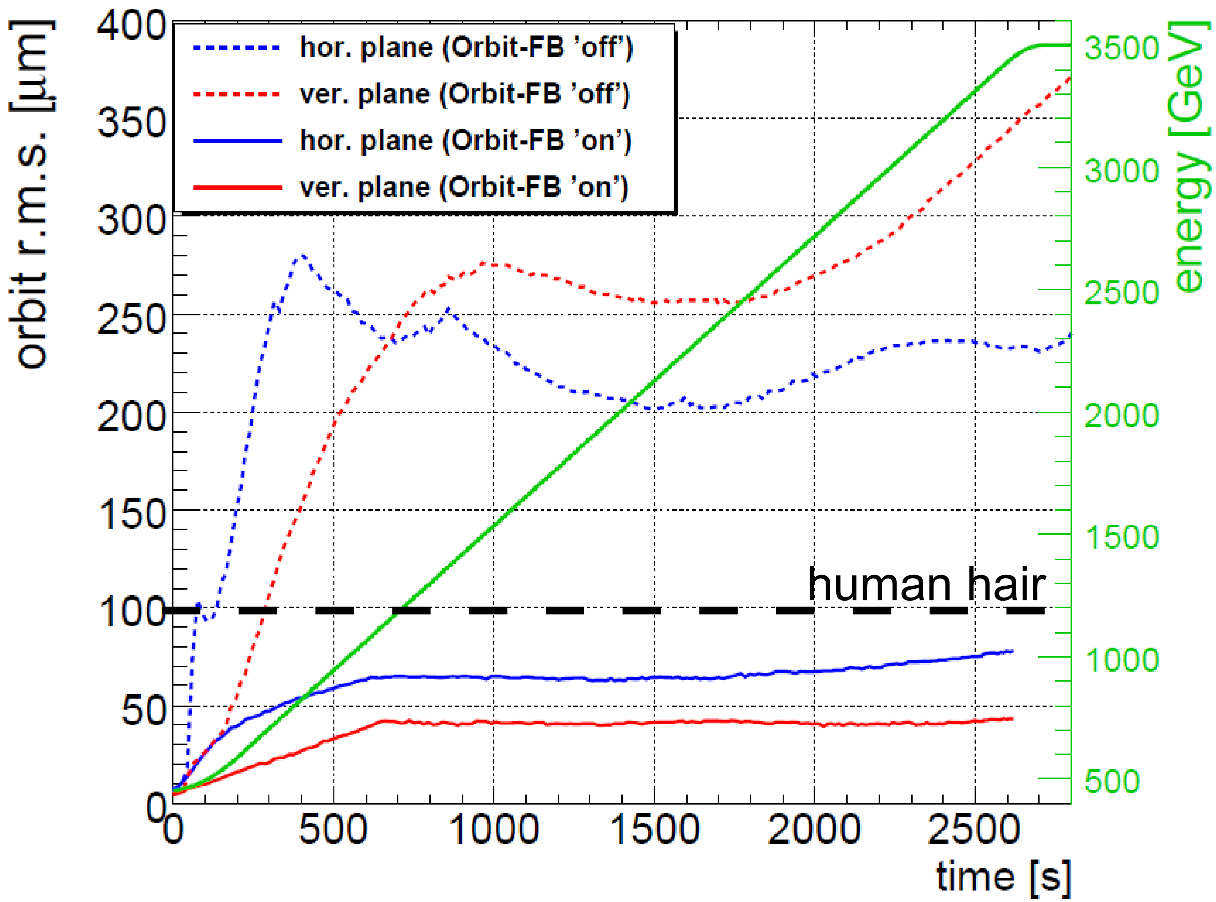
beam



- Requirements distributed over 27 km opted for central global feedback system handing Orbit, Tune, Chromaticity, Coupling and Energy.
- E.g Orbit-Feedback, with more than 3100 involved devices the largest and most complex LHC feedback:
  - 1070 beam position monitors
    - BPM spacing: $\Delta\mu_{BPM} \approx 45°$
    - Measure in both planes: > 2140 readings!
  - One Central Orbit Feedback Controller (OFC)
    - Gathers all required beam measurements, computes and sends currents via Ethernet to the power converter, stabilising beam around its reference:
      - high numerical and network load on controller front-end computer
      - most flexible (especially when correction scheme has to be changed quickly)
      - only way to handle cross-talk and coupling between the various feedbacks
  - 530 correction dipole magnets/plane (some are shared between B1&B2)
- Total >3500 devices involved ↔ more than half the LHC is controlled by FBs!

Orbit Feedback Performance

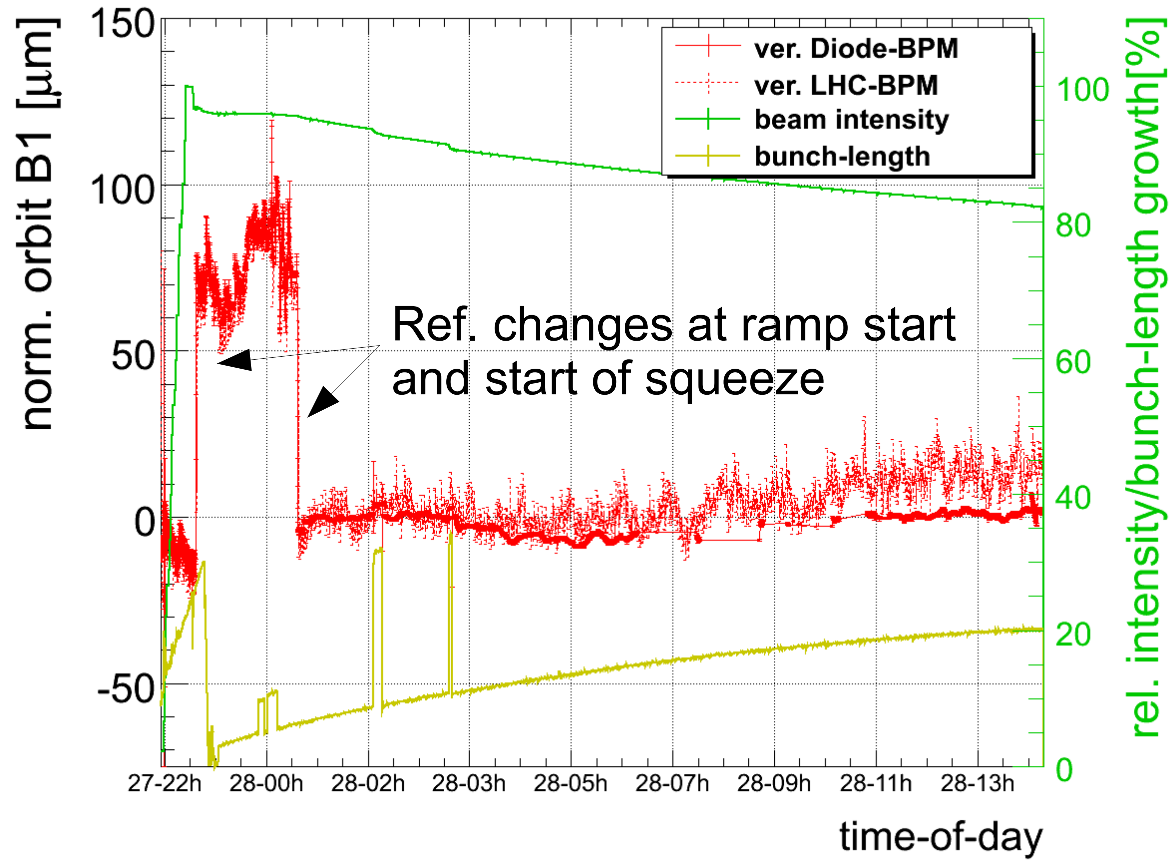
- Orbit feedback used routinely and mandatory for nominal beam
  - Stability in the ramp: ≤ 80 μm rms (over 27 km!)



  - For comparison: beam size: σ ≈ 1 mm → 0.2 mm

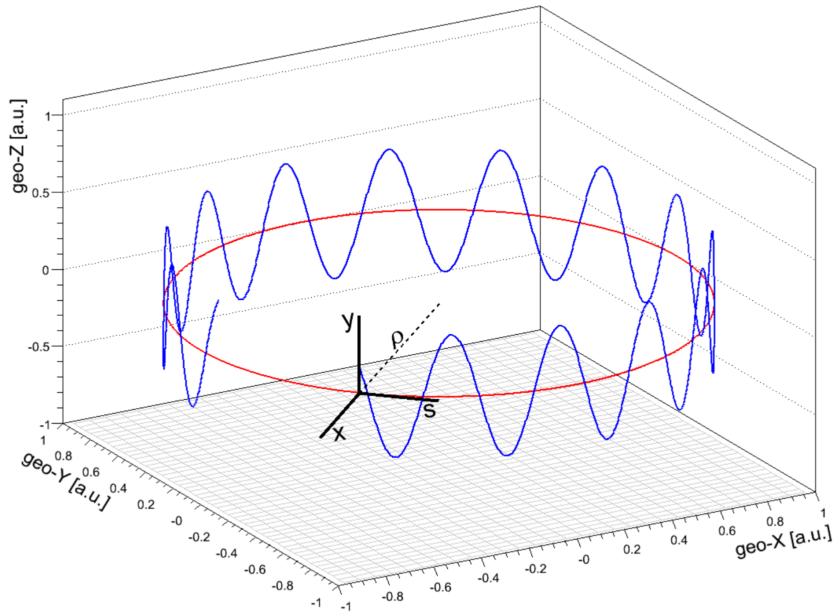
Orbit Stability during one LHC Fill

- Injection probe-beam, injection physics beam, ramp, squeeze, stable physics
  - Stability at one reference pick-up in LSS4



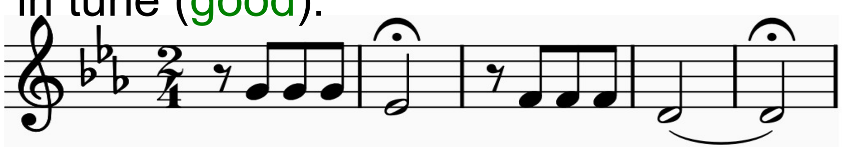
- Orbit stability during physics < 5 µm over 15 hours
- New high-accuracy diode-based beam position monitor system: Δx_{res} < 0.5 µm (limited by orbit stability)

Tuning the LHC – a Diagnostics

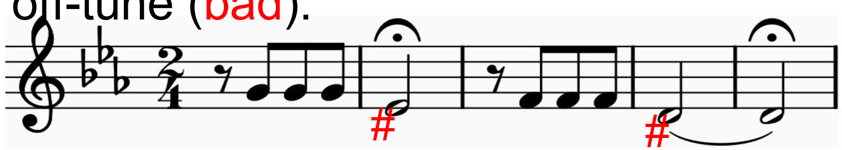


- Laymen/Musician's view (Beethoven's 5th):

in tune (good):



off-tune (bad):



- Audience will leave the concert

↔ Beam will leave the vacuum pipe

- Importance of tune:
  - defines beam life-time
  - strong impact on beam physics experiments:

"I don't think we've quite repeated the experiment - last time we did it, the glass gave out a middle 'c'."

World famous Example of structural Resonances
Tacoma Narrows Bridge Collapse

- http://en.wikipedia.org/wiki/Tacoma_Narrows_Bridge_(1940)

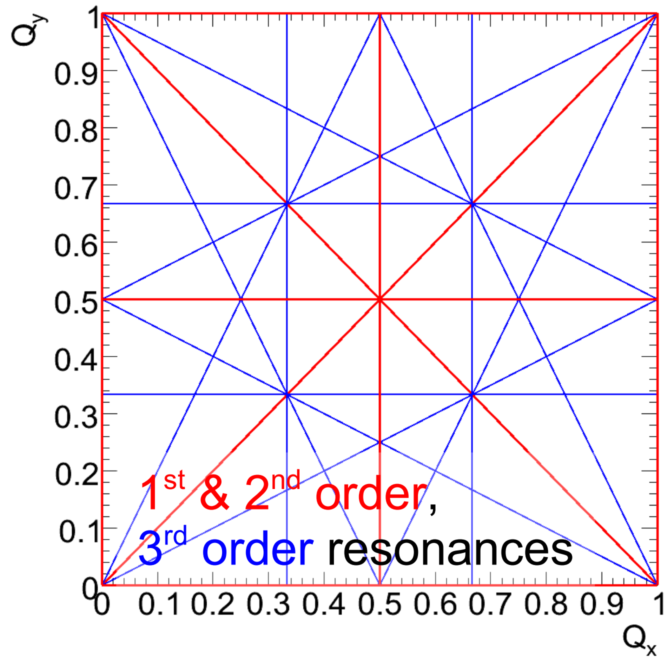
- Video: http://upload.wikimedia.org/wikipedia/commons/1/19/Tacoma_Narrows_Bridge_destruction.ogg

Tune Stability Requirements & Constraints II/III

- Unstable particle motion for resonance condition:

$$p = m \cdot Q_x + n \cdot Q_y \quad \wedge \quad m, n, p \in \mathbb{Z}$$

  – resonance order: $O = |m| + |n|$

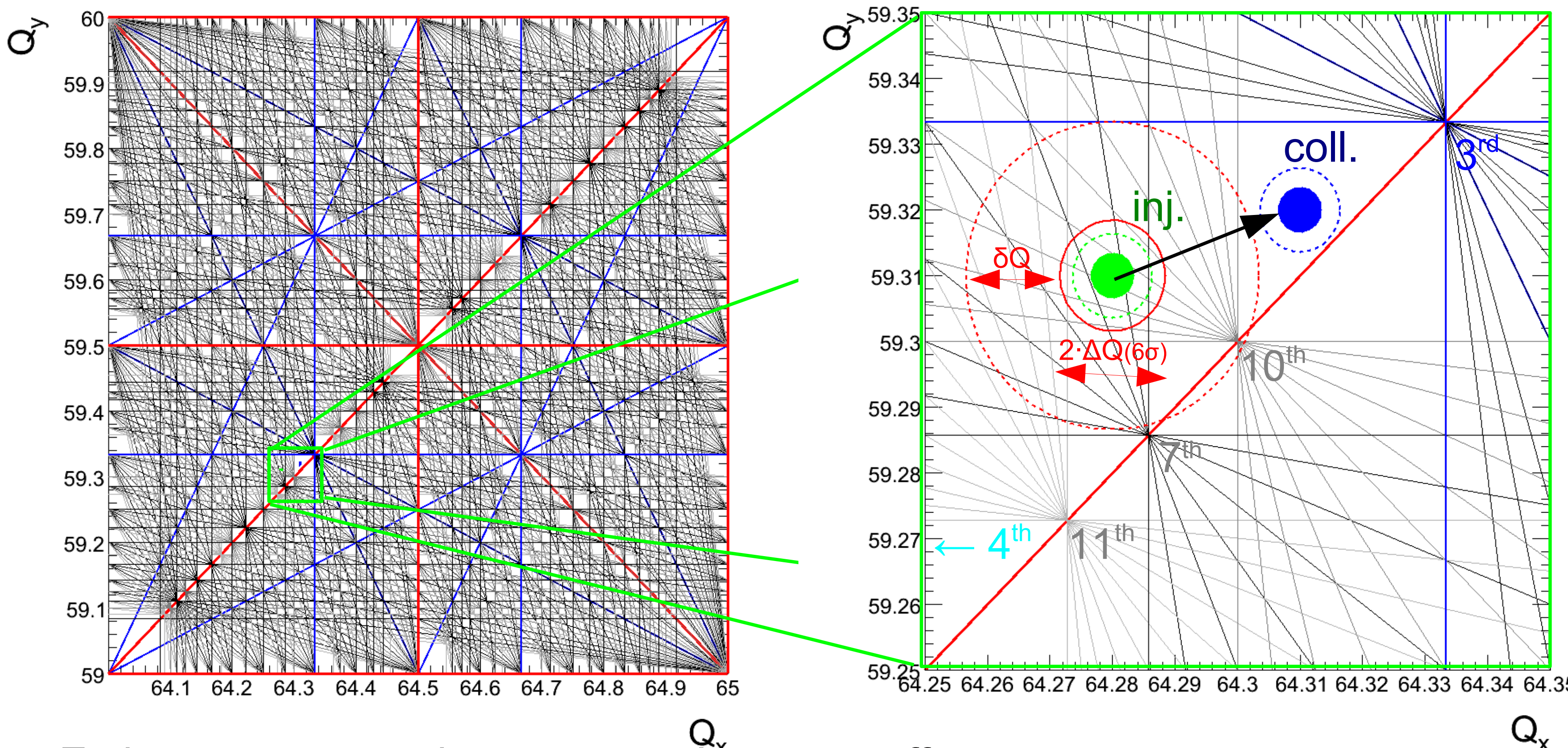


- Lepton accelerator: typ. avoid up to ~ 3rd order
- Large Hadron Collider:
  – negligible synchrotron radiation damping
  – need to avoid up to the 12th order to mitigate irreversible beam size growth

"Hadron beams are like elephants –

treat them bad and they'll never forgive you!"

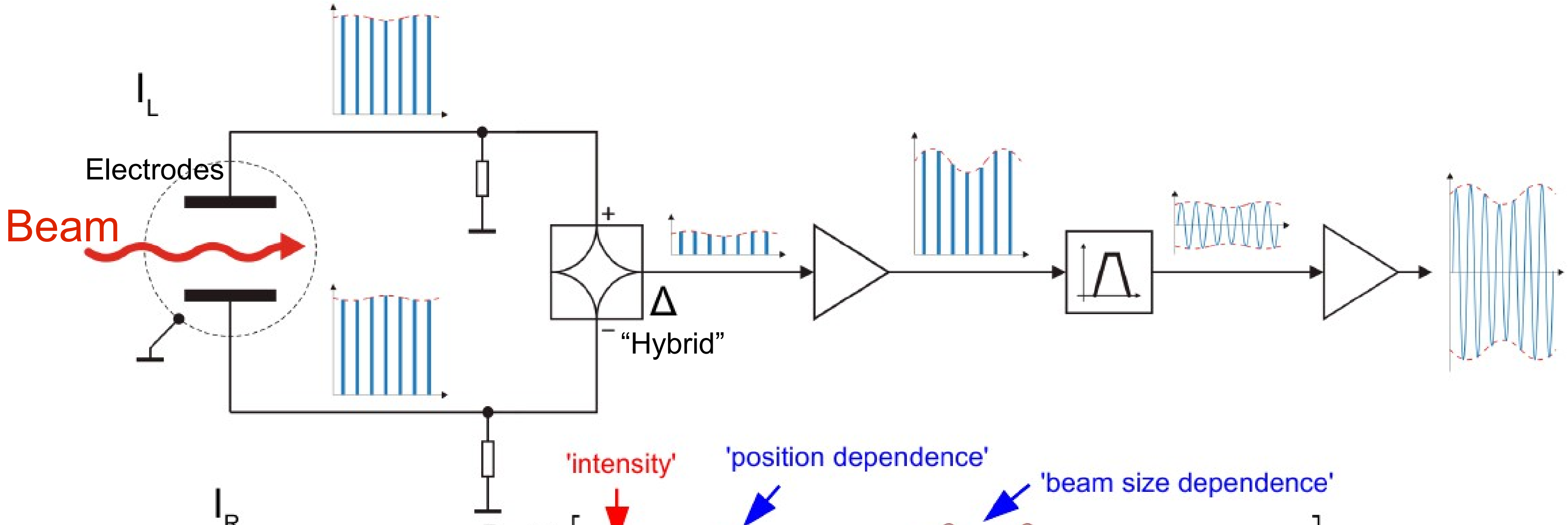
- Example LHC: Tune stability requirement: ΔQ ≈ 0.001 vs. exp. drifts ~ 0.06



- Emittance preservation or protons' memory effect
  - Limit excitation to necessary minimum: δa << 10 μm = ~1/20 beam size !!
    → favours passive/sensitive systems

… was a long-time issue for most hadron colliders: many complex, expensive systems with limited robustness to be used as an input for an automated FB...

Tune Diagnostics Instrumentation
Classic Detection Scheme

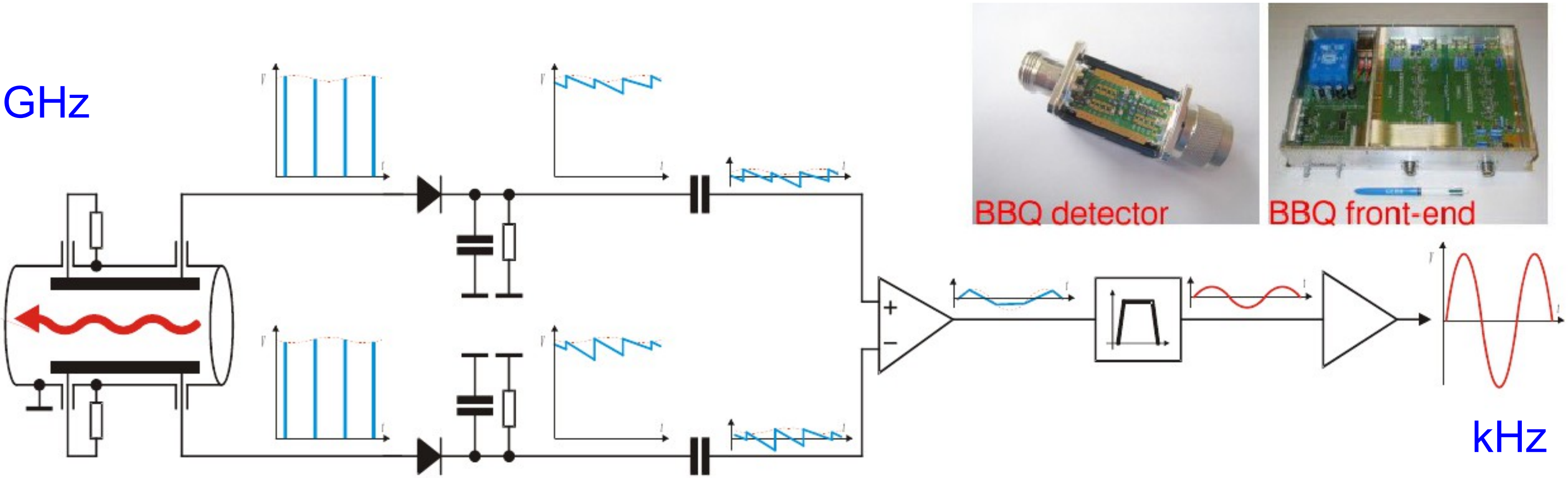


$$I_{L/R}(t) = \frac{I_\omega(t)}{2\pi}\left[2\psi \mp 2\frac{x}{R}\sin(\psi) + \frac{x^2-y^2}{R^2}\sin(2\psi) + h.o.\right]$$

Real-world challenges:

- Intensity signal is by far the largest contribution, e.g. LHC → 200-300 V
- 'position dependence' is often dominated by static orbit
  - typically 1-2% of intensity signal
  - nm size betatron oscillations (use-full for tune) → few µV
- Usually very short bunch signal: ns (hadron beams) → ps (electrons)
  - Issue with direct sampling: ns signals → 8 bit ADC resolution

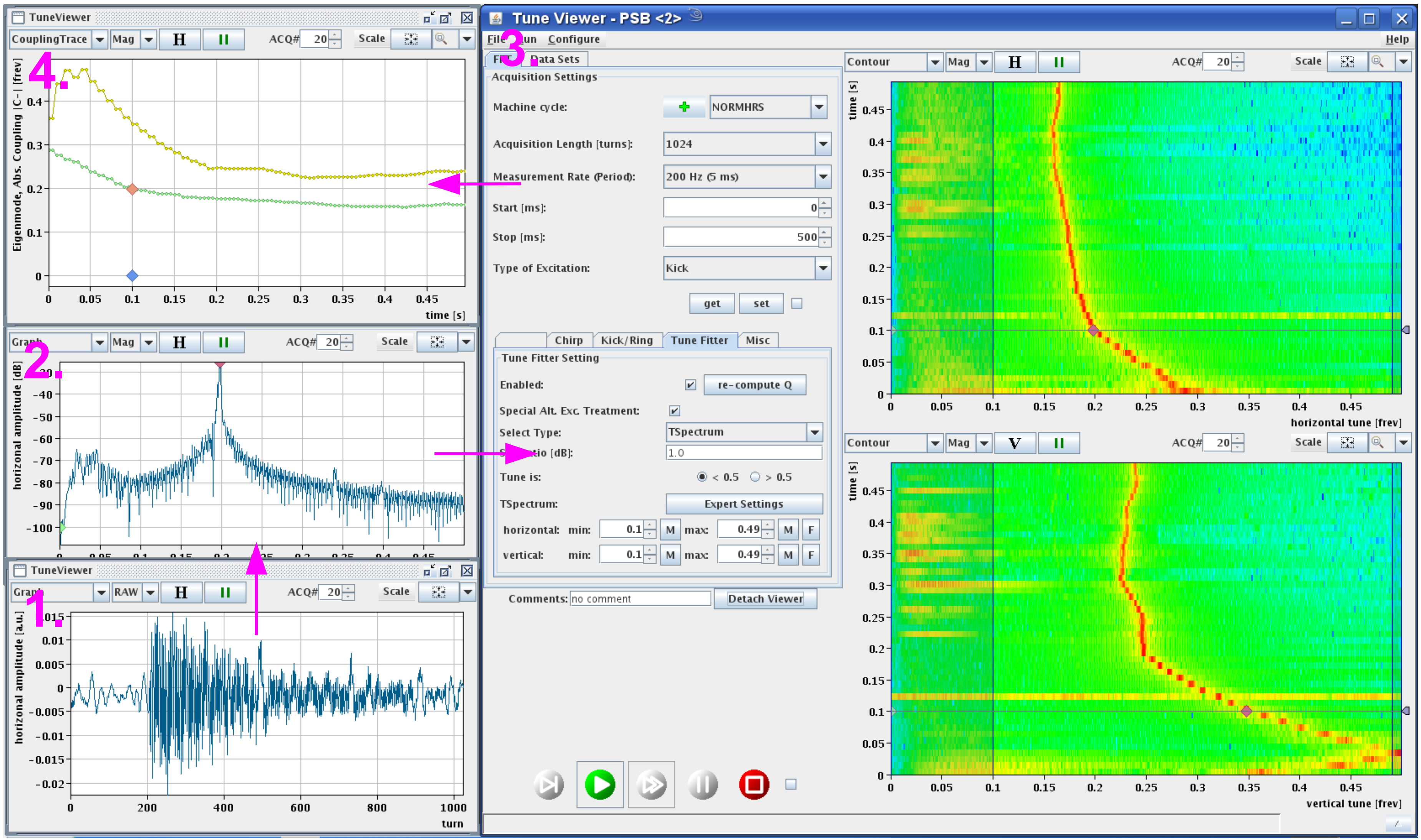
LHC Tune Diagnostics Instrumentation – Direct-Diode-Detection



- Basic principle: AC-coupled peak detector[1] *… or classical audio-AM radio*
  - intrinsically down samples beam spectra: GHz → kHz
    - thus 'Base-Band-Tune Meter' (aka. BBQ)
    - Base-band operation: very high sensitivity/resolution ADC available
      - Initially and still acquired using a PC sound-card/consumer grade-ADC
    - Measured resolution: < 10 nm/turn → ε blow-up is a non-issue
  - AC-coupling removes common-mode → only relative changes play a role
    - capacitance keeps the "memory" of the to be rejected signal
  - robust: no saturation, self-triggered, no gain changes to accommodate single vs. multiple bunches or low vs. high intensity beam

[1]M. Gasior, *"The principle and first results of betatron tune measurement by direct diode detection"*, CERN-LHC-Project-Report-853, 2005

BBQ Example Spectra
CERN-PSB, $f_{rev} \approx 2$ MHz

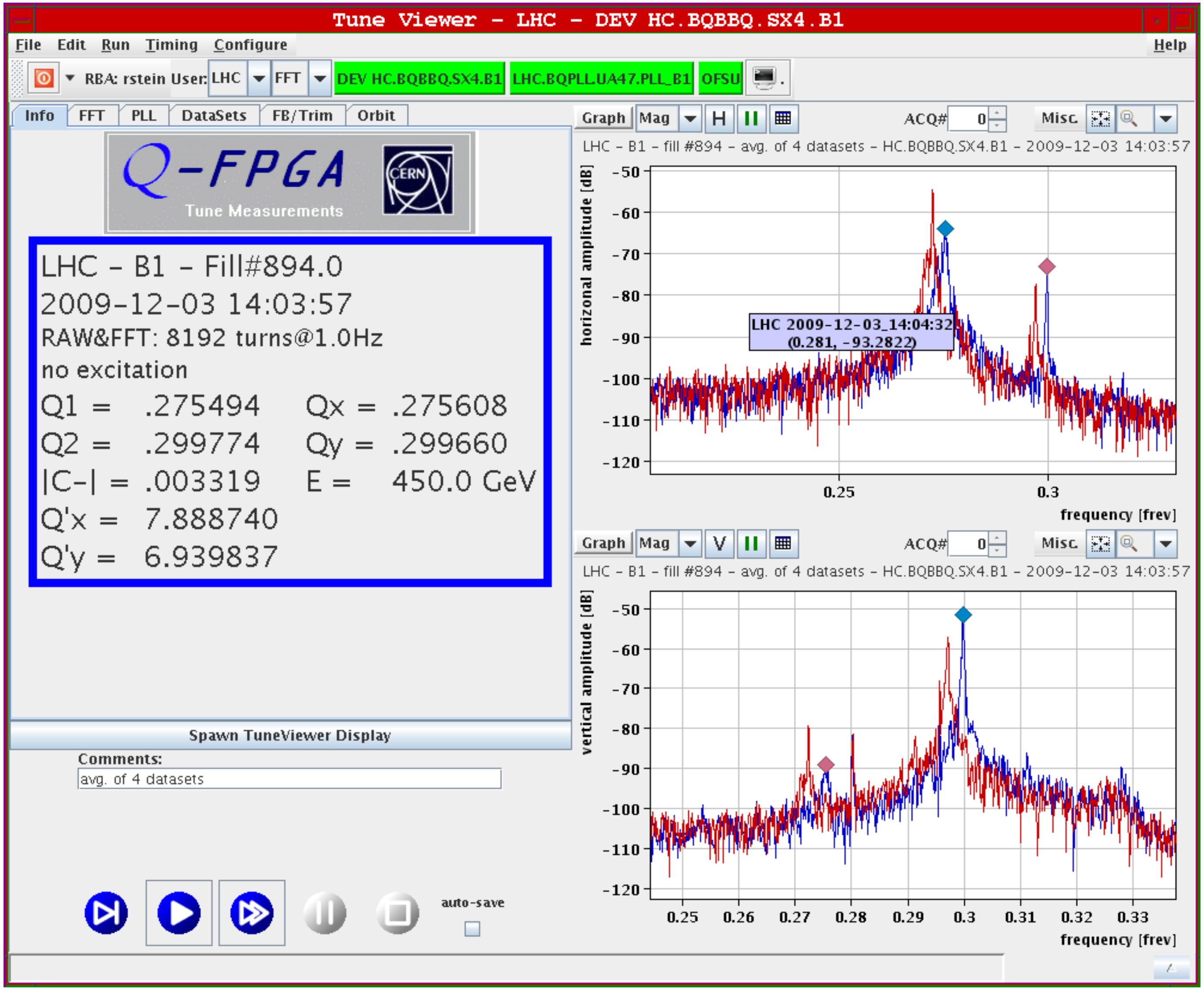


- BBQ +fast ADC +FPGA-based digital signal processing chain, FFTs @ 500 – 1 kHz!
  - provides real-time Q diagnostics for operation

- Initial design assumption: no residual tune signatures on the beam (0 dB S/N)
  - Anticipated constant driving of the beam and – to limit the required excitation levels – the highly-sensitive BBQ system was developed
    - further exploited by a FFT and PLL system
  - Hypothesis: BBQ nm-level sensitivity would be sufficient to operate below the “radar” of excitation impacting operation/protection (less than 1 µm)
    - seemed to be confirmed by tests at the SPS, RHIC, Tevatron, …

- After the start-up we were blessed (and/or cursed):
  1. BBQ proved to provide a turn-by-turn resolution of better than 30 nm
     - 30+dB more sensitivity than other LHC systems (ADT: 1µm, BPM: 50 µm)
  2. Ever-present residual Q oscillations on the few 100 nm to few µm level

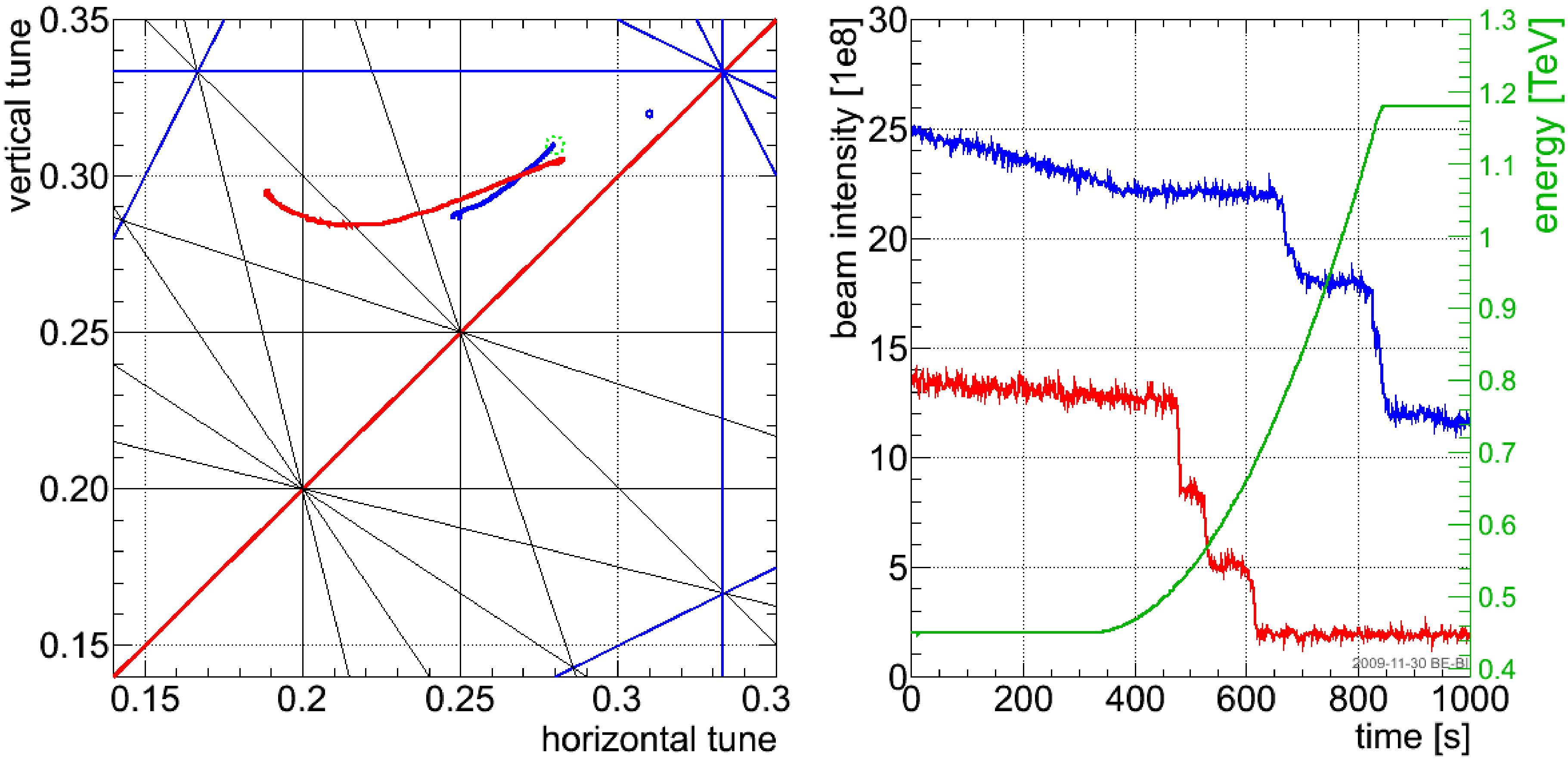
Recap: LHC Q/Q' Diagnostics and Residual Noise on the Beam II/II



- Luxurious 30-40 dB signal-to-noise ratios enabled the passive monitoring, tracking and feedbacks without any additional excitation

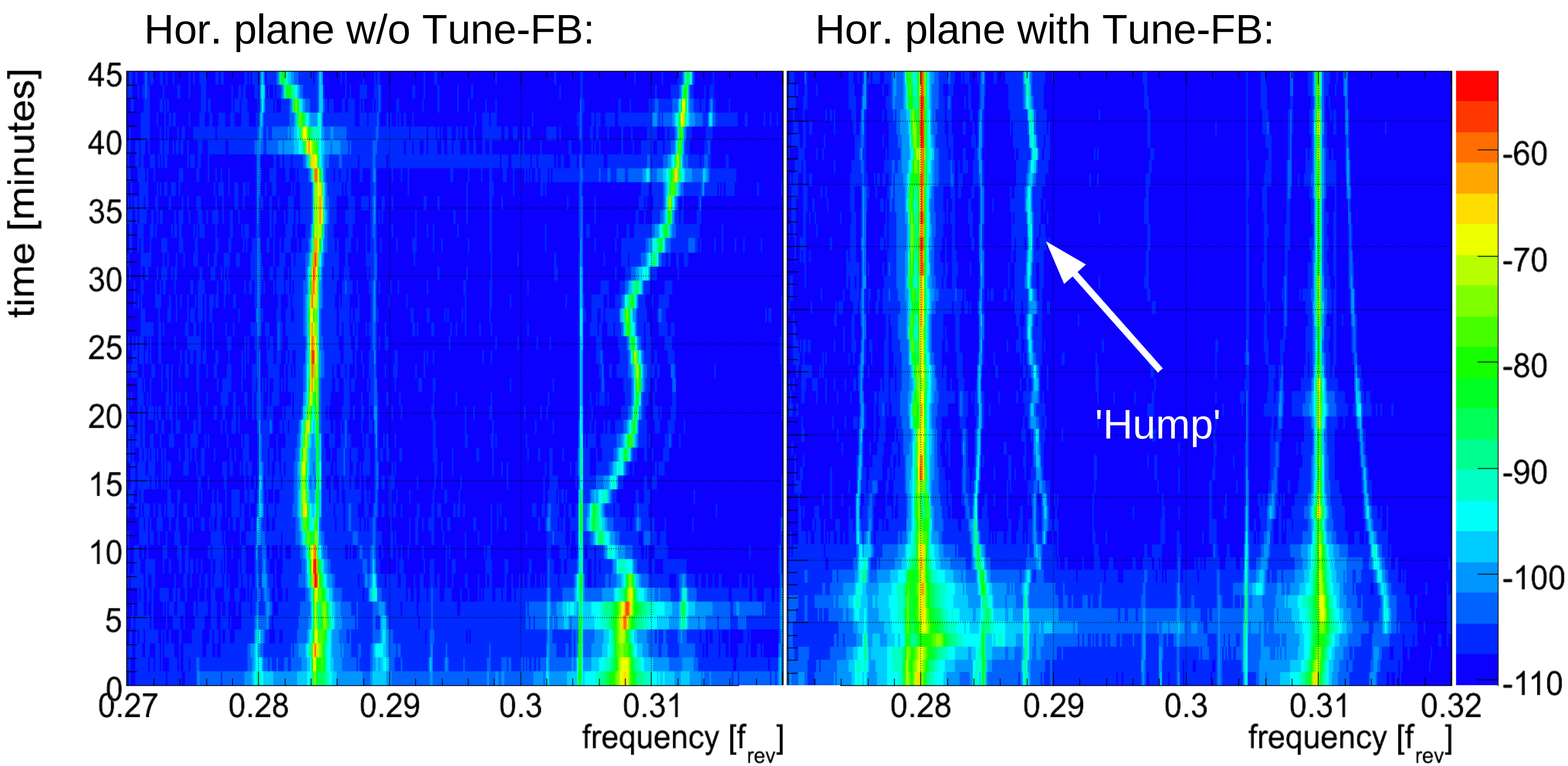
Base-Band-Tune (BBQ) System Performance
Example: 2009-11-24 @00:15 – First LHC Ramp

- The Base-Band-Tune (BBQ) system was work horse from LHC Day-I



  – typical tune measurements resolution in the range of 10^{-4} … 10^{-5}

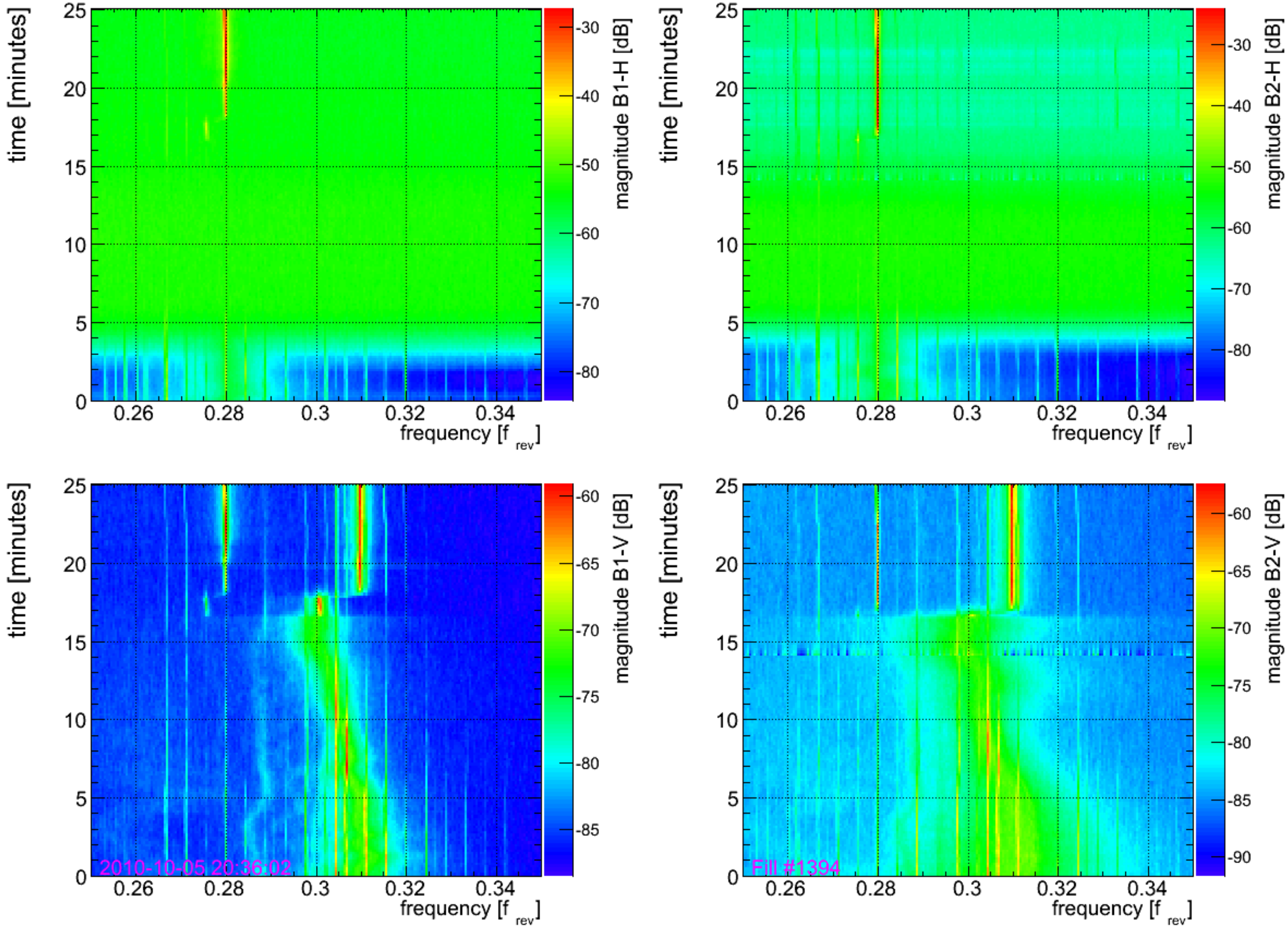
Base-Band-Tune (BBQ) Spectra during the Ramp



- Sensitivity allows to see non-tune oscillations on the beam, e.g.:
  - mains harmonics, interference line from UPS equipment, the 'Hump'
  - Valuable diagnostics to improve individual equipment and machine as a whole
    - Example: transverse FB induced tune shift ↔ pick-up to kicker phase advance

BBQ Example: Mains Harmonics

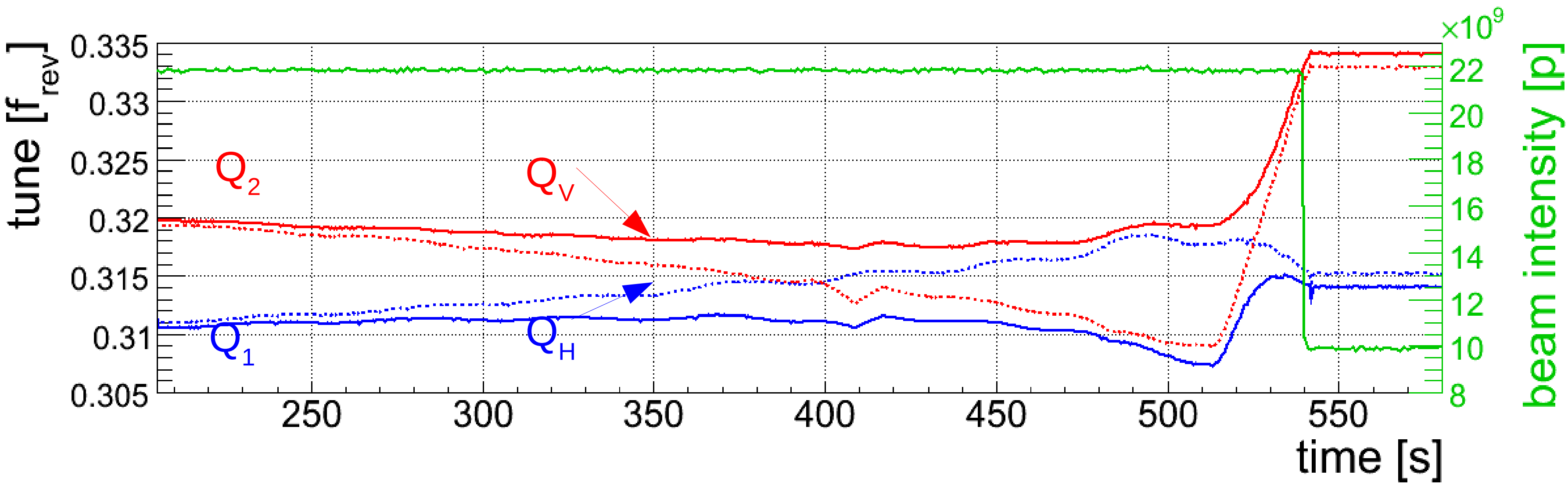
- Besides Q'(t), MB mains harmonics can be a source of beam size growth



- No a big problem but nominal working points were exactly on one of them

BBQ Example during β*-Squeeze

- First β* Squeeze iteration without Tune-FB
  - complex change of machine optics to reduce the beam size in the experimental interaction regions

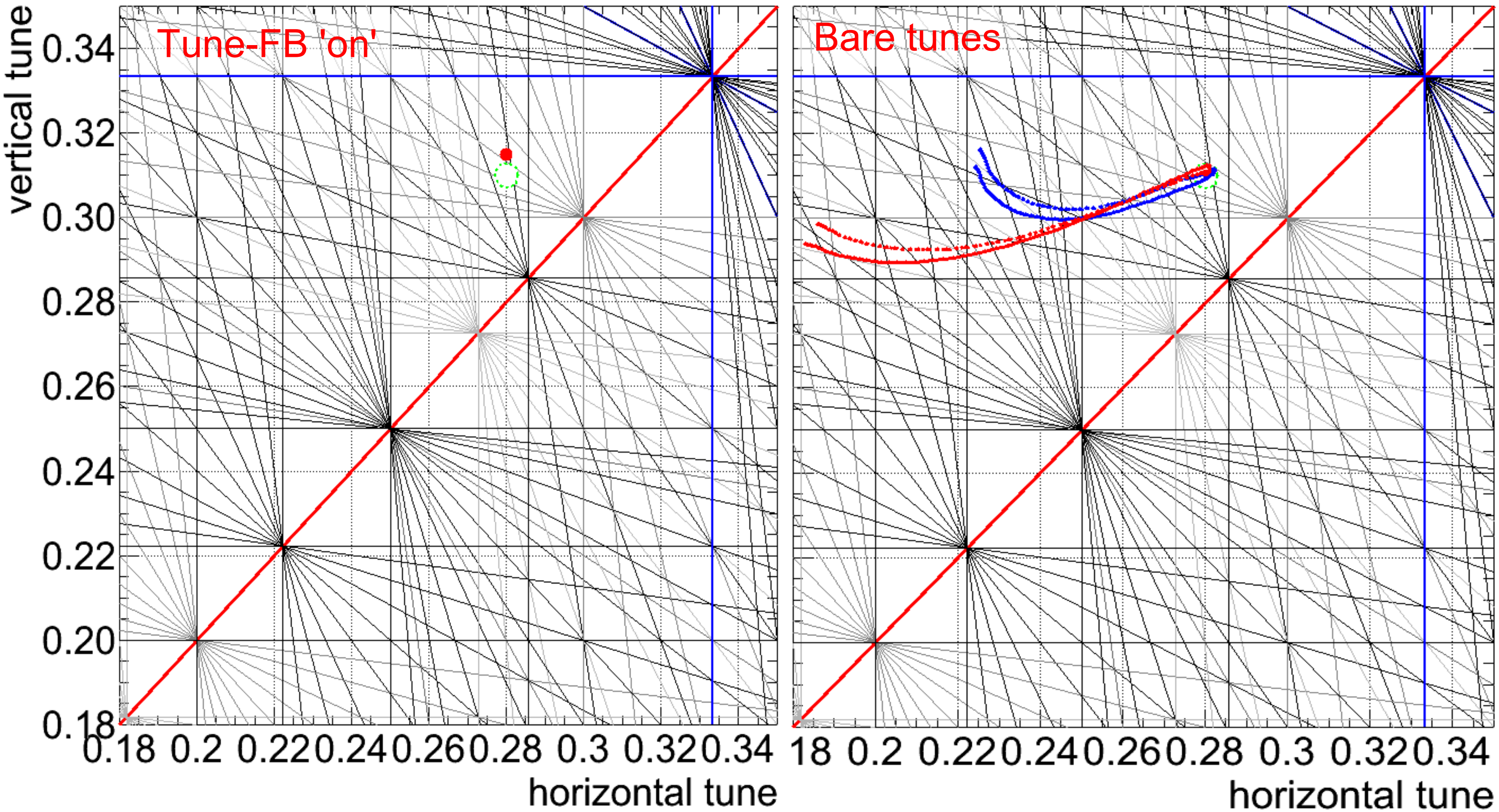


- Coupling induced crossing of unperturbed tunes (dashed line) and eventually third-order resonance crossing of the vertical eigen-mode (solid line) leading to particle loss

"this is the stuff you are looking for when preparing for accelerator schools."

Tune-Feedback in Action

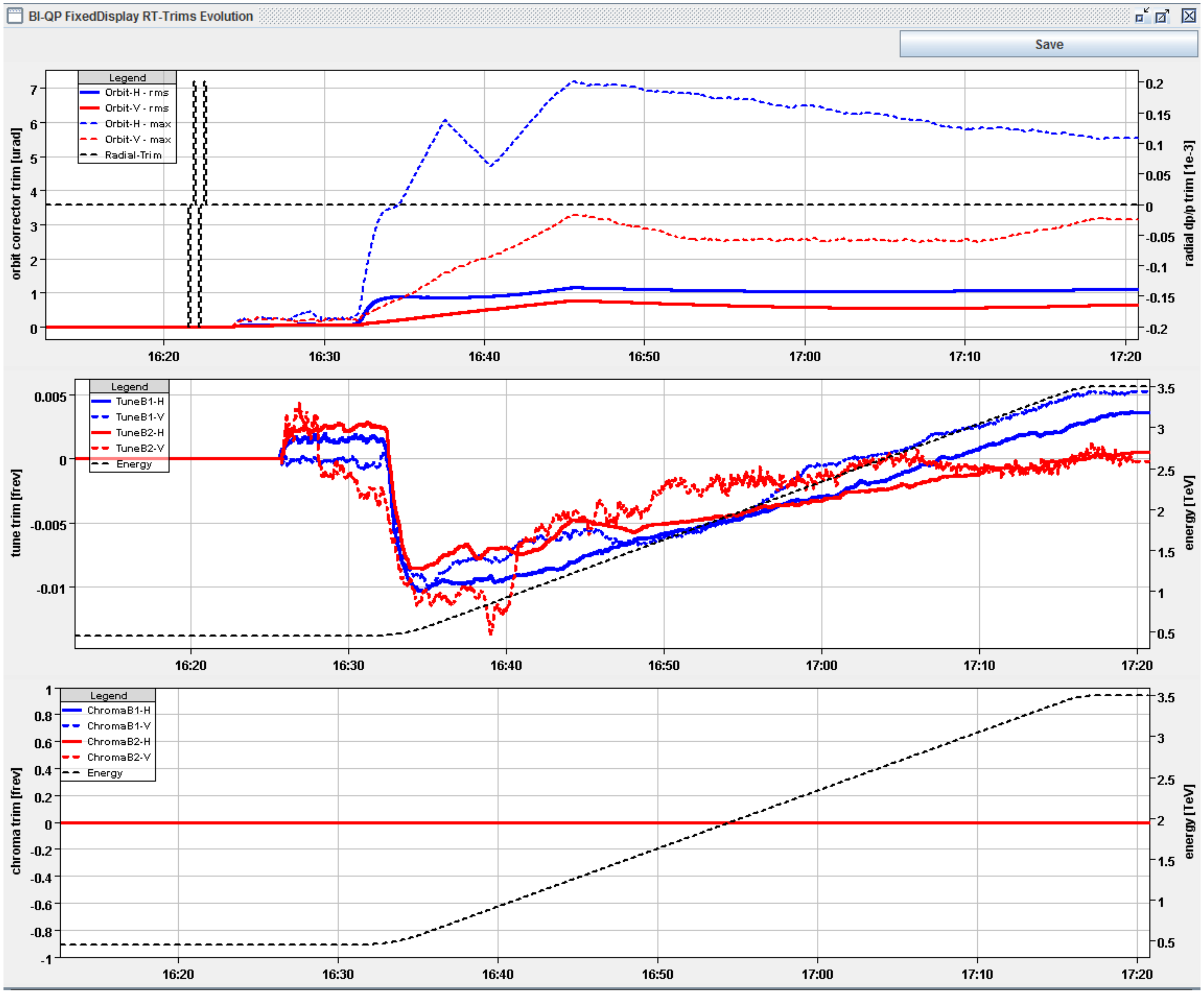
- BBQ signal was used early-on as input to the Tune- and Chromaticity-FB



- More than half of 270++ LHC ramps would have been lost without Tune-FB

Feedbacks in Action : Ramp

- Trims became de-facto standard to assess the FB and machine performance



Fill 1309

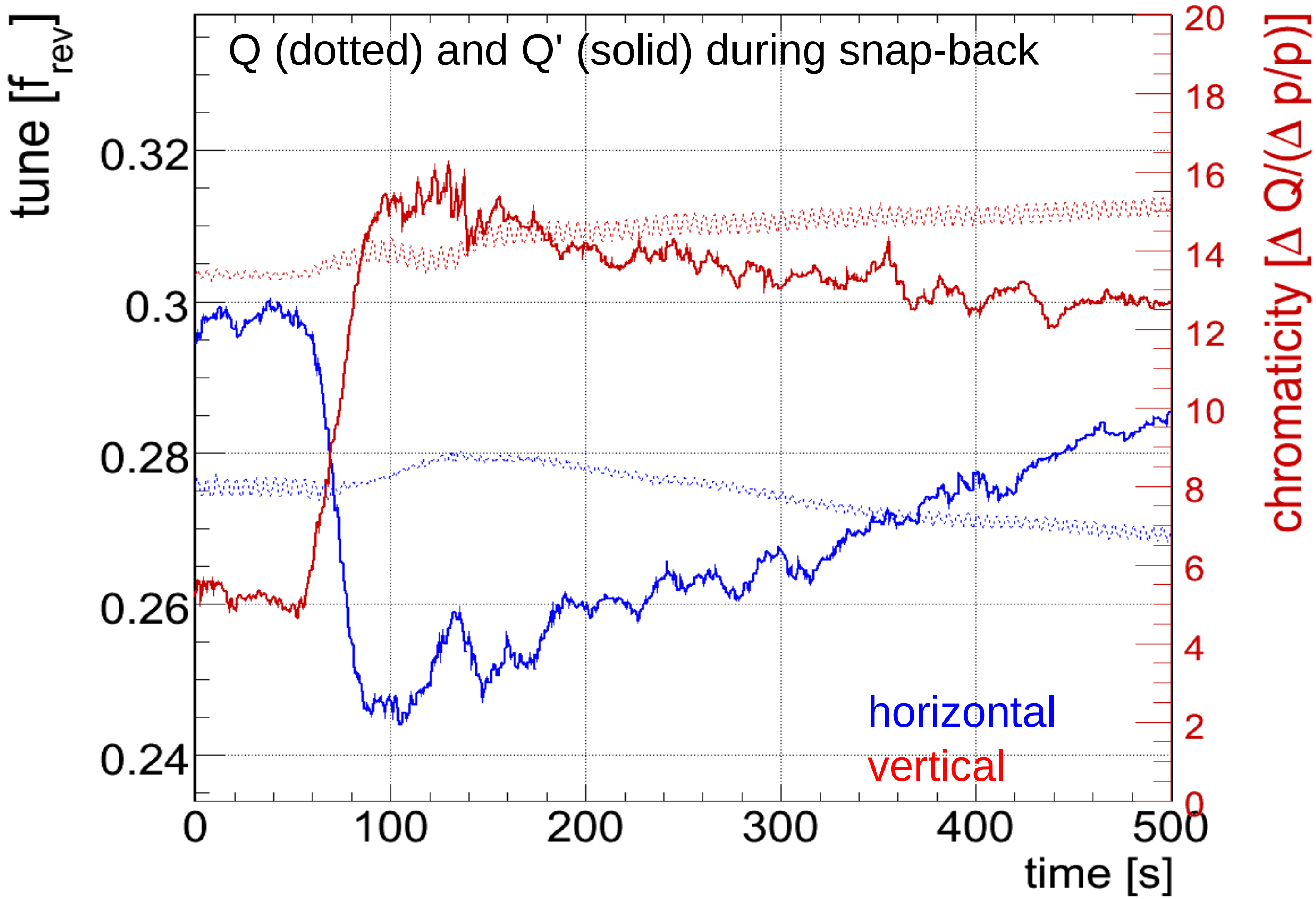
29.08.2010

OFB trims (μrad)

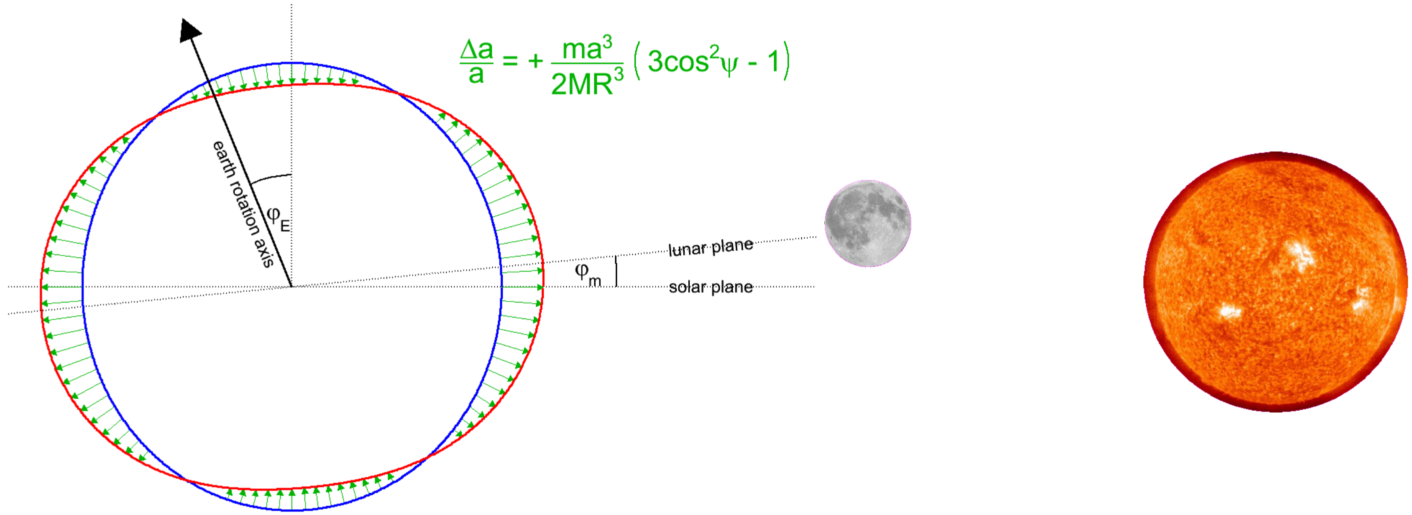
QFB trims

Energy (TeV)

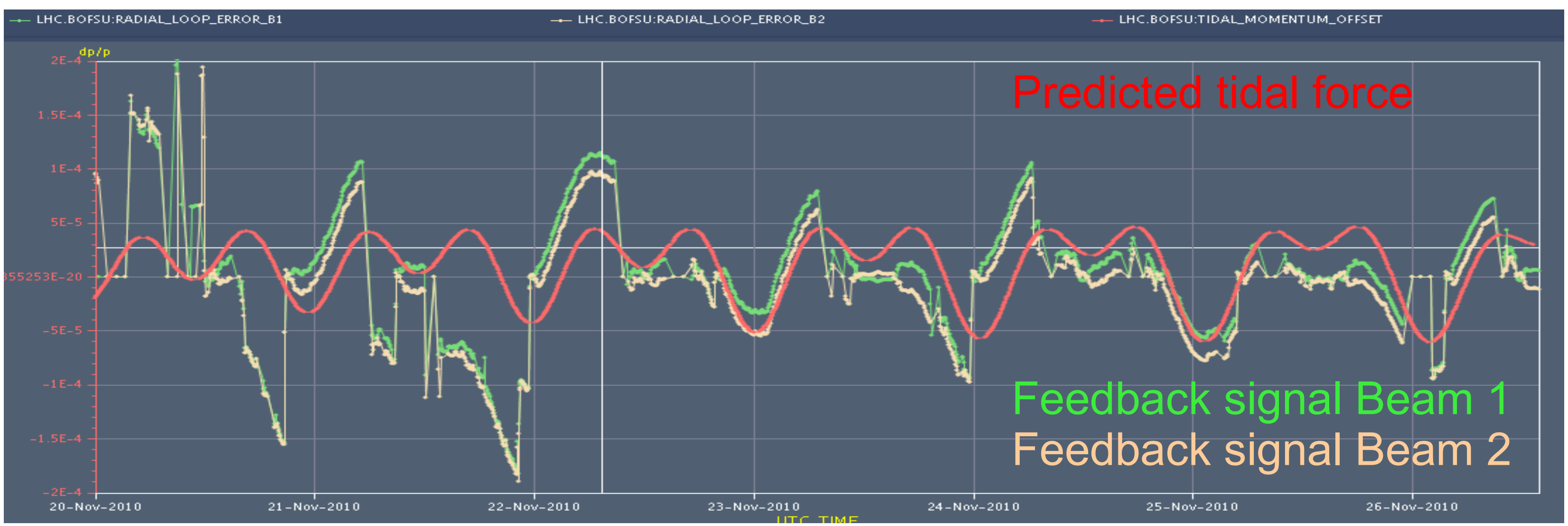
- Further exploitation: measure tune dependence on energy ↔ chromaticity



Solar and Lunar Forces Squishing and Squashing the LHC

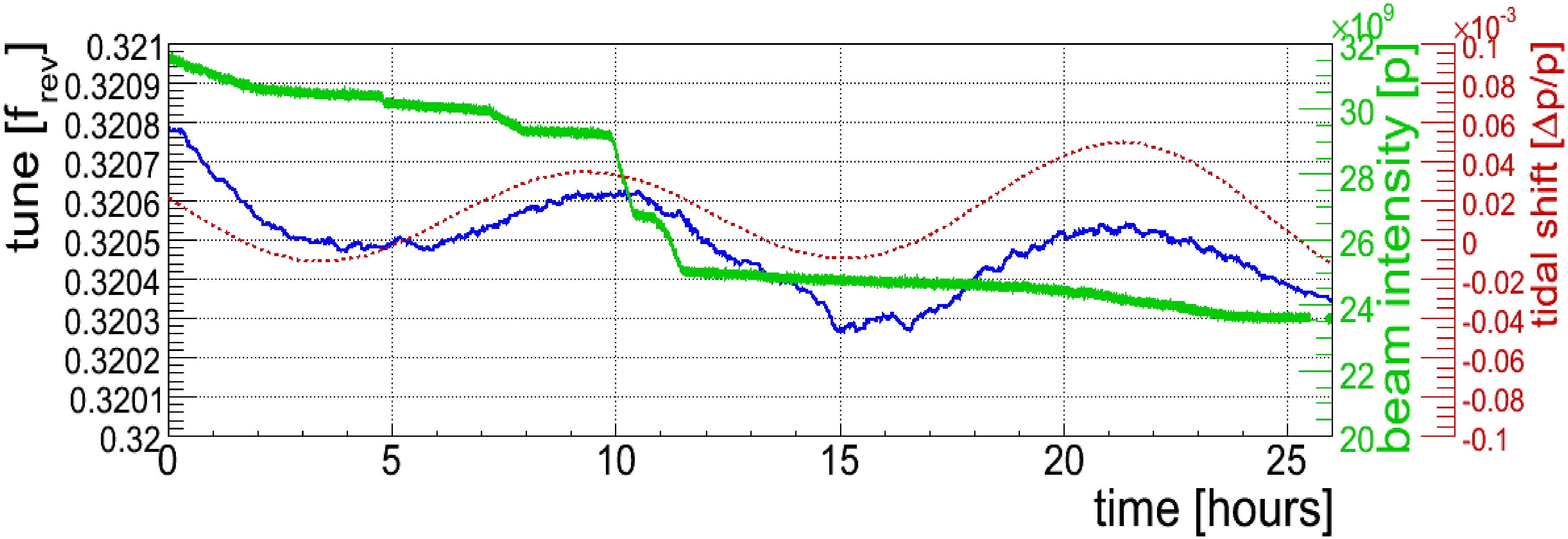


– Known effect from LEP → changes the machine circumference/energy



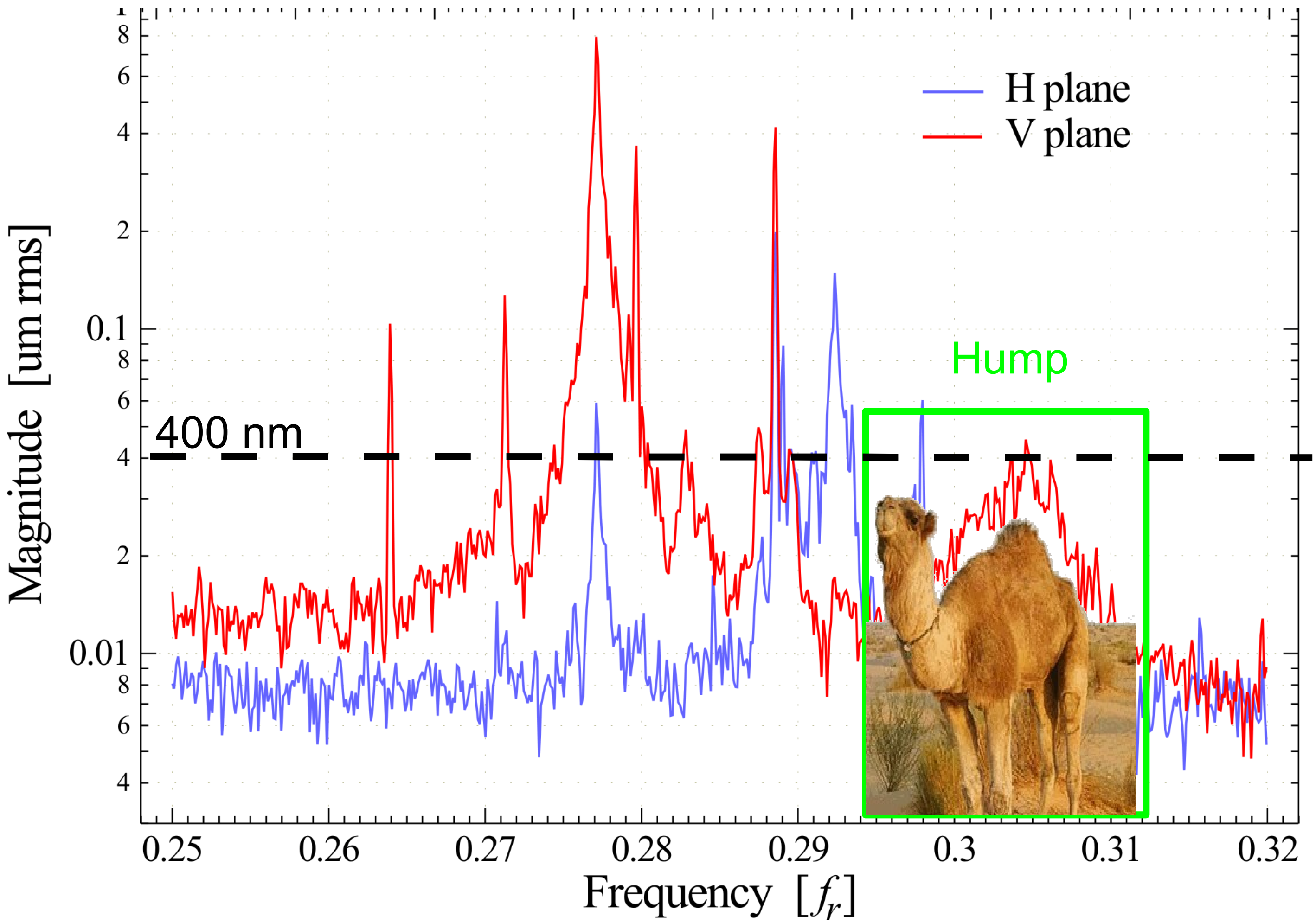
Tune Evolution during Physics

- Machine circumference/energy changes are propagated via Q' to the tune



- Probably the slowest high-precision Q' measurement in the World
  - Short-Term Tune-Stability of ~10^{-6}!

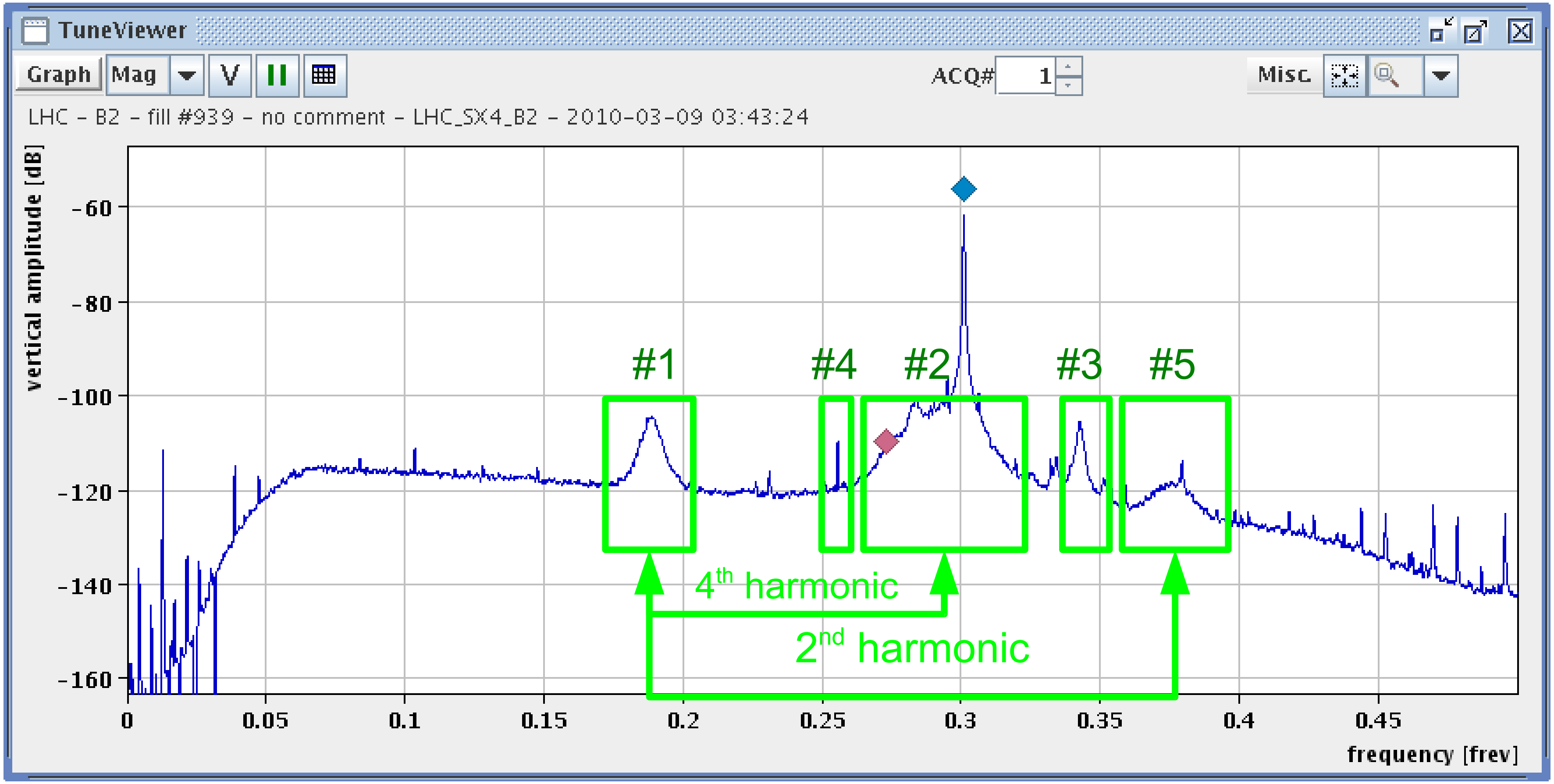
The Mystery of the Year: the 'Hump'



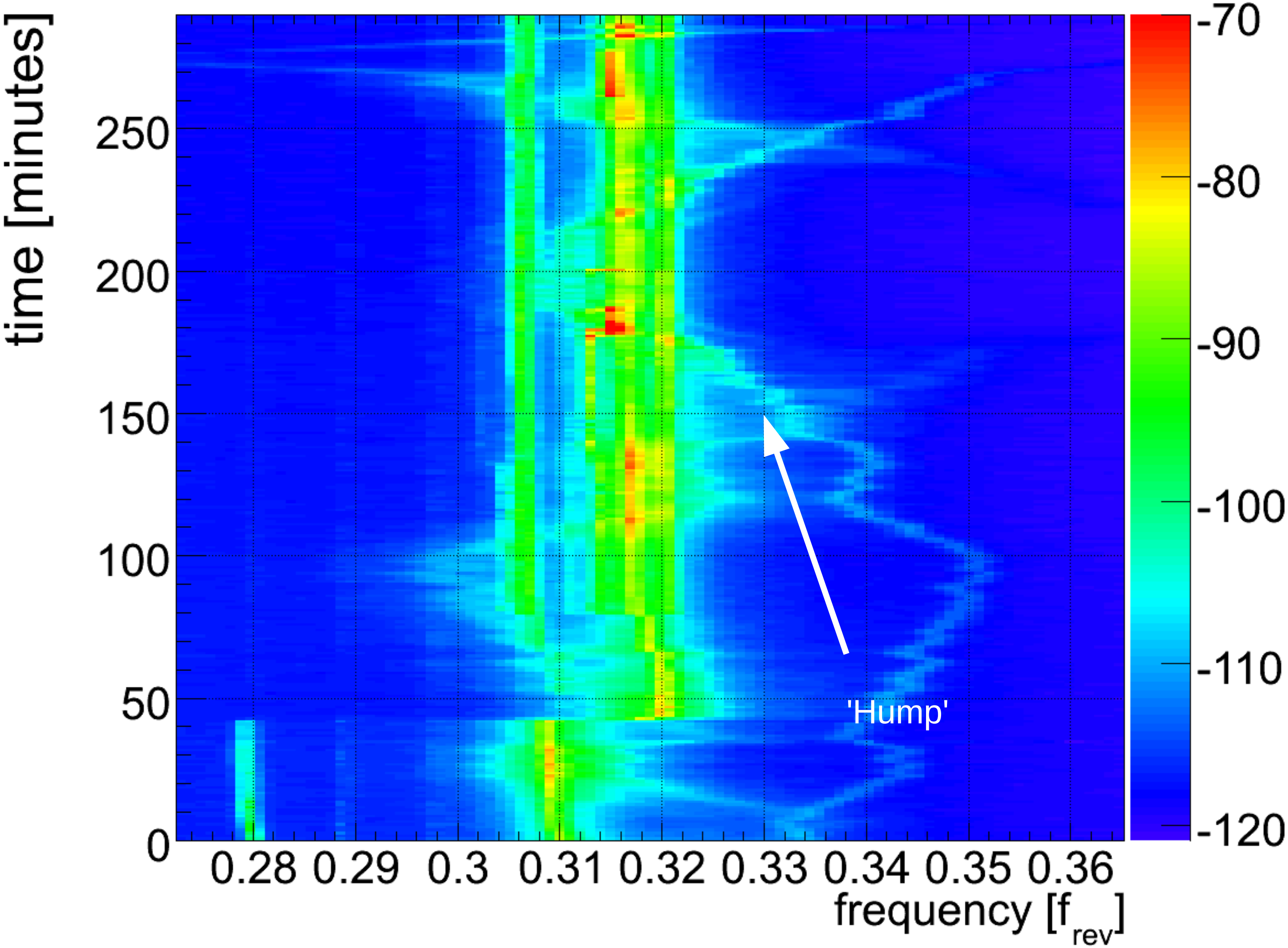
- Structure of the perturbation depends on the observation time-scale, e.g.
  - 0.1 Hz b→ broad 'hump', or
  - 10 Hz acquisition BW → narrow-bw line with shifting mean frequency

'Hump' comes in families... harmonics

- A non-issue if the tune working point wouldn't be exactly on one of them

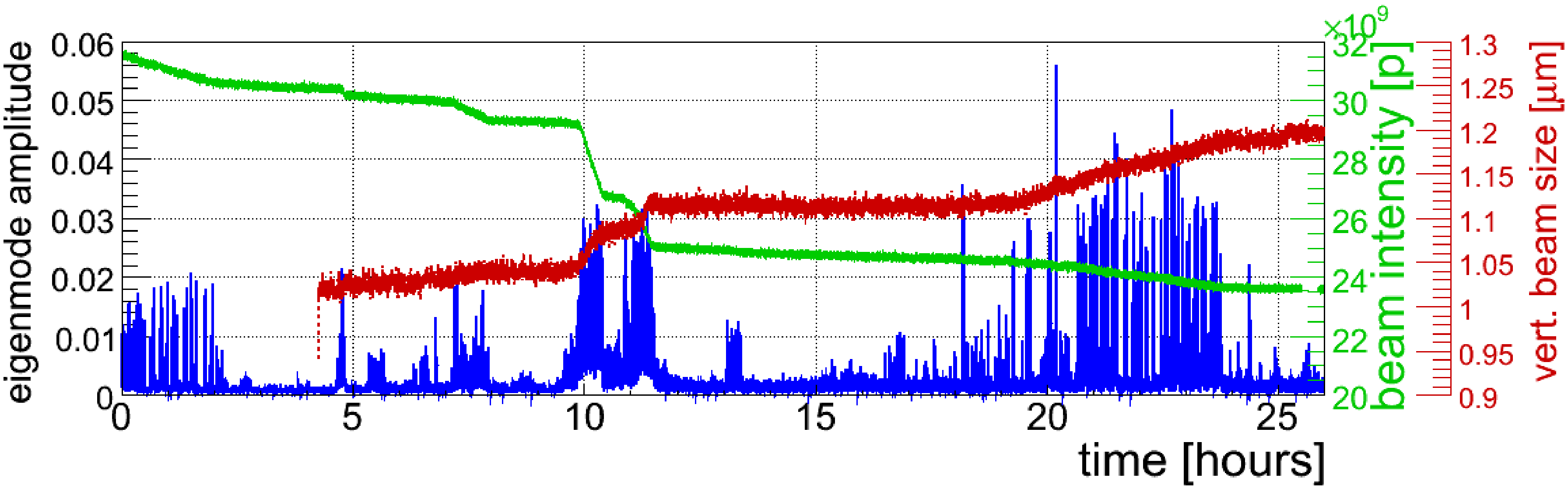


- Accepted Control-Room Jargon: being “humped”



Hump Structure on longer Time-Scales

- Can cause significant intensity/luminosity loss during physics:



- Origin of this perturbation still a LHC mystery...
  – Partially mitigated by transverse feedback

- “Who you gonna call?” → 'Humpbusters': a legion of never-tired and never-ceasing experts with the aim of hunting down this phenomena, if not …
  – “run away from the hump” == shift the tune whenever it's in the vicinity.

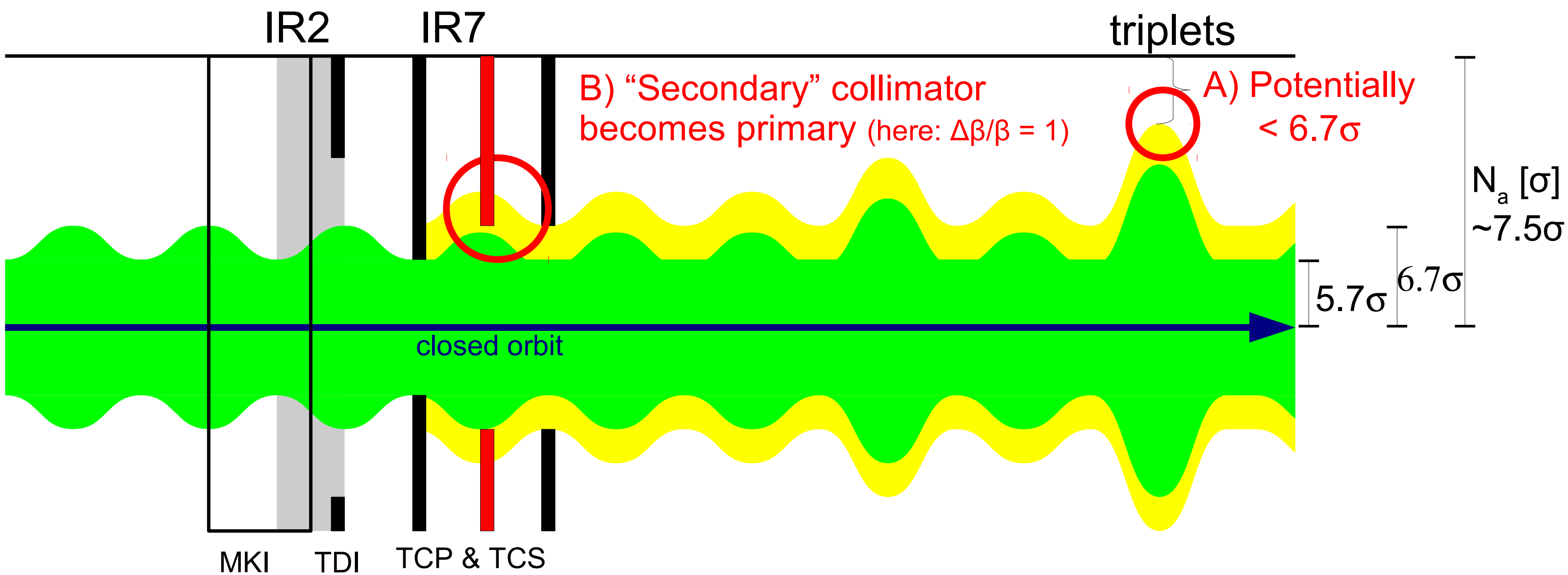
Summary

- The LHC requires an excellent control of particle loss in a superconducting environment that stores MJ → GJ energies
  - provided by the LHC Machine Protection and Cleaning Systems
- Beam-based feedback systems are mandatory for nominal beam operation and increase LHC's reliability and availability for physics
  - 'Orbit' and 'Tune'-FB are used and operate reliably early-on (firsts ramps)
- Absence of synchrotron radiation and thus natural damping make the control of particle loss and control of emittance blow-up more challenging
  - Tune beam diagnostics – typically requiring small excitation – has to work in the LHC in non-intrusively → origin & development of the BBQ
- The BBQ's nm-scale oscillation and it's exploitation by a FFT and PLL based system allowed power-full tune, chromaticity and coupling diagnostics that facilitated a fast and reliable LHC commissioning with beam
  - Provided additional diagnostics of beam interference which allowed to investigate effects like the 'hump' early on.

Thank you for your Attention

Continuous Beta-Beat Measurements I/III

- Combined failure: beta-beat and collimation efficiency

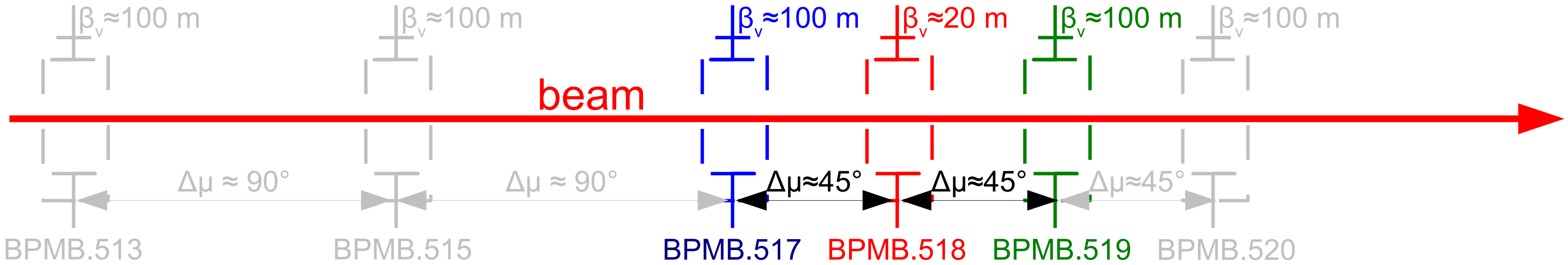


- "Collimator gap must be 10 times smaller than available triplet aperture!"[1]

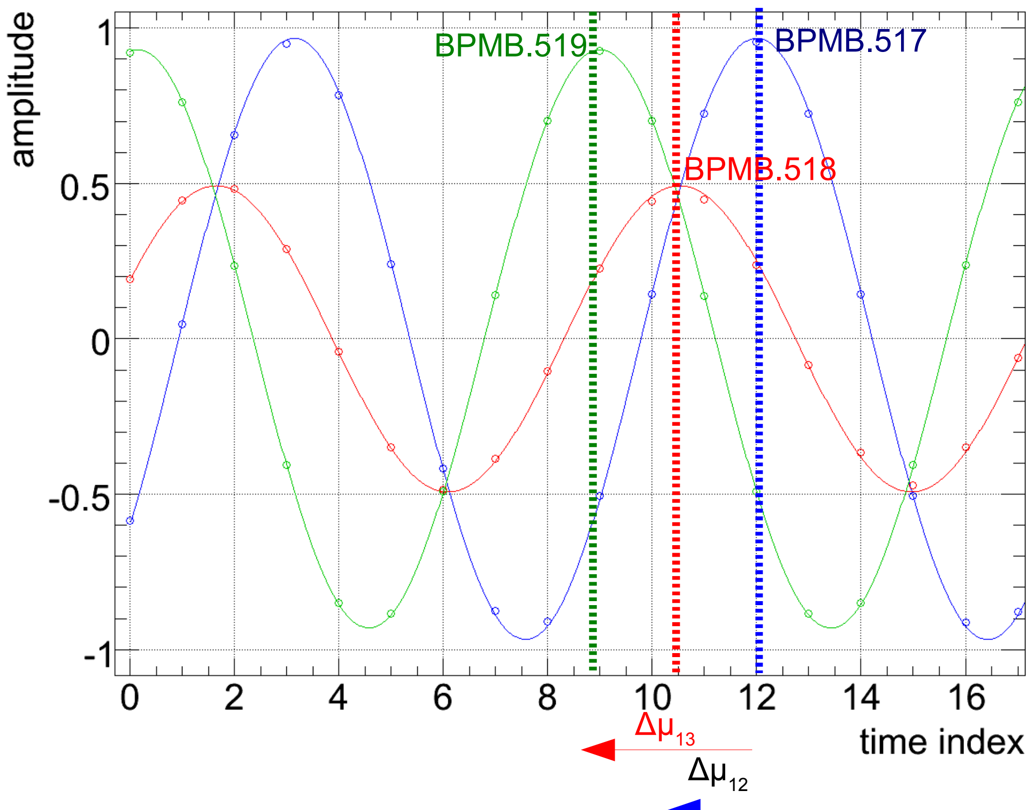
$$a_{coll} \leqslant a_{triplet} \cdot \overbrace{\sqrt{\frac{\beta_{coll}}{\beta_{triplet}}}}^{\sim 0.15} \cdot \overbrace{\left(\frac{A^{max}_{primary}}{A^{max}_{secondary}}\right)}^{\sim 0.6}$$

[1] R. Assmann, "Collimation and Cleaning: Could this limit the LHC Performance?", Chamonix XII, 2003

Continuous Beta-Beat Measurements II/III



- Measurement (markers), sinusoidal fit (solid line):



$$\frac{\Delta\beta_1}{\beta_1} = \frac{\cot(\Delta\mu_{12}^{meas.}) - \cot(\Delta\mu_{13}^{meas.})}{\cot(\Delta\mu_{12}^{theo.}) - \cot(\Delta\mu_{13}^{theo.})}$$

$$\frac{\Delta\beta_2}{\beta_2} = \frac{\cot(\Delta\mu_{12}^{meas.}) - \cot(\Delta\mu_{23}^{meas.})}{\cot(\Delta\mu_{12}^{theo.}) - \cot(\Delta\mu_{23}^{theo.})}$$

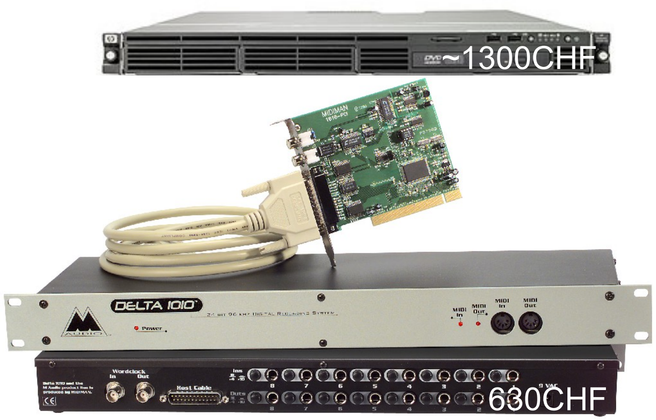
$$\frac{\Delta\beta_3}{\beta_3} = \frac{\cot(\Delta\mu_{23}^{meas.}) - \cot(\Delta\mu_{13}^{meas.})}{\cot(\Delta\mu_{23}^{theo.}) - \cot(\Delta\mu_{13}^{theo.})}$$

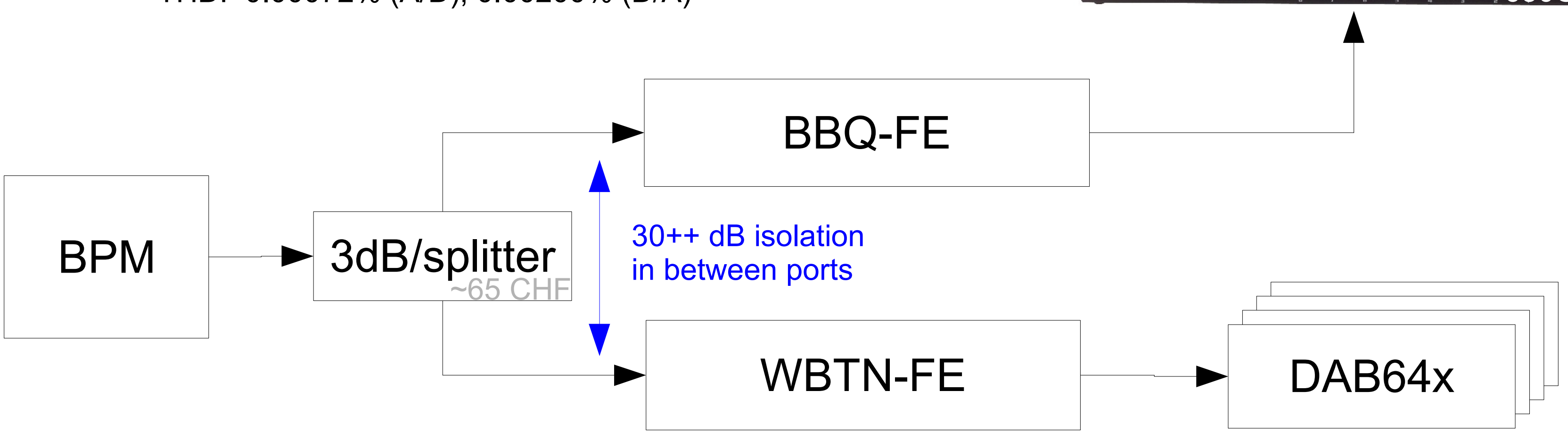
[1]P.Castro, *Luminosity and Betatron Function Measurement at [..] LEP*, CERN SL/96-70 (BI)

Continuous Beta-Beat Measurements III/III

- Yet another exploitation of the BBQ Principle:
  - AC-coupled peak detector:
    - no saturation, self-triggered, no gain changes between pilot and nominal
    - intrinsically down samples spectra: ... 6 GHz → 1kHz ... f_{rev}
    - Base-band operation: very high sensitivity/resolution ADC available
    - Measured resolution estimate: < 10 nm
      → ε blow-up is a non-issue

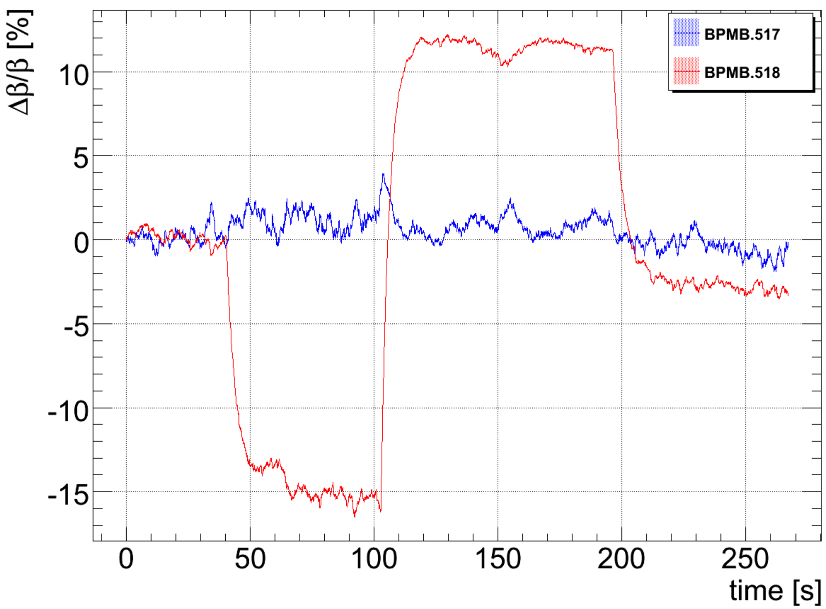
- Digital acquisition: HP Proliant 16”, 1U + M-AUDIO Delta 1010
  - 8 analogue inputs/outputs, 16”, 1U
  - frequency response: 20Hz-22kHz, +/-0.3dB
  - >130 dB dynamic range/S/N ratio
  - THD: 0.00072% (A/D), 0.00200% (D/A)

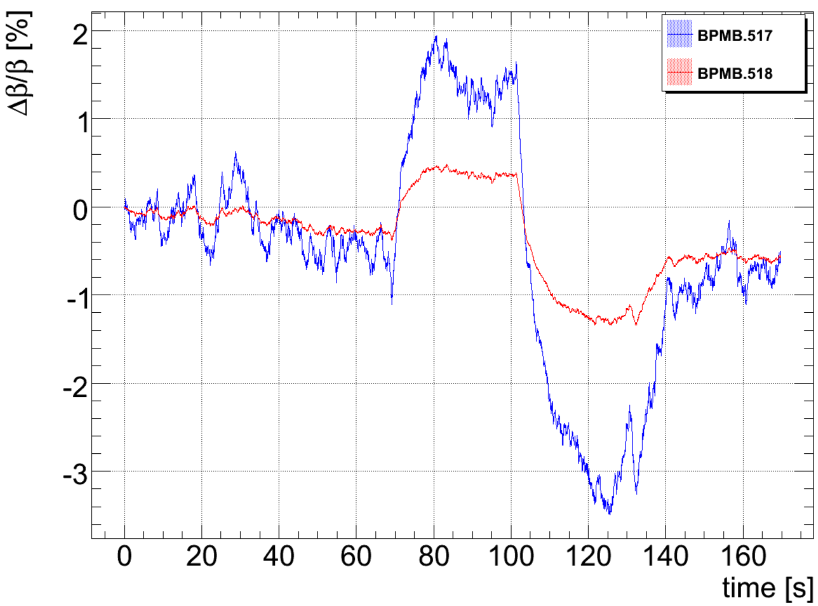




QE.603/QE.604 induced β-Beating

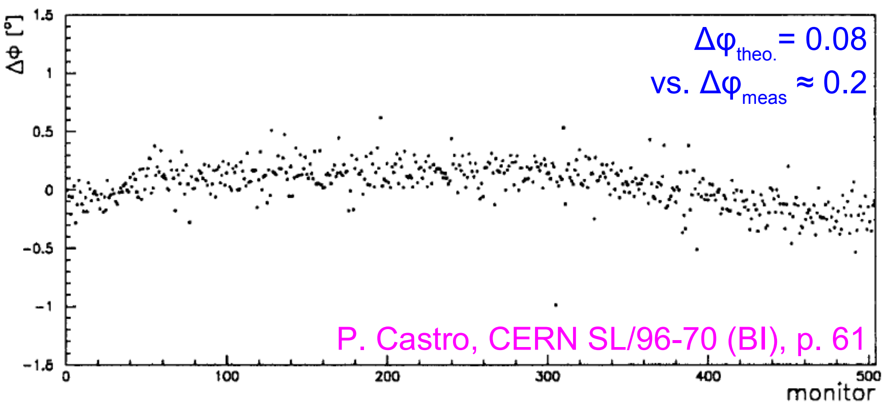
- Corresponding beta-beat: $$\frac{\Delta\beta_1}{\beta_1} = \frac{\cot(\Delta\mu_{12}^{meas.}) - \cot(\Delta\mu_{13}^{meas.})}{\cot(\Delta\mu_{12}^{theo.}) - \cot(\Delta\mu_{13}^{theo.})}$$

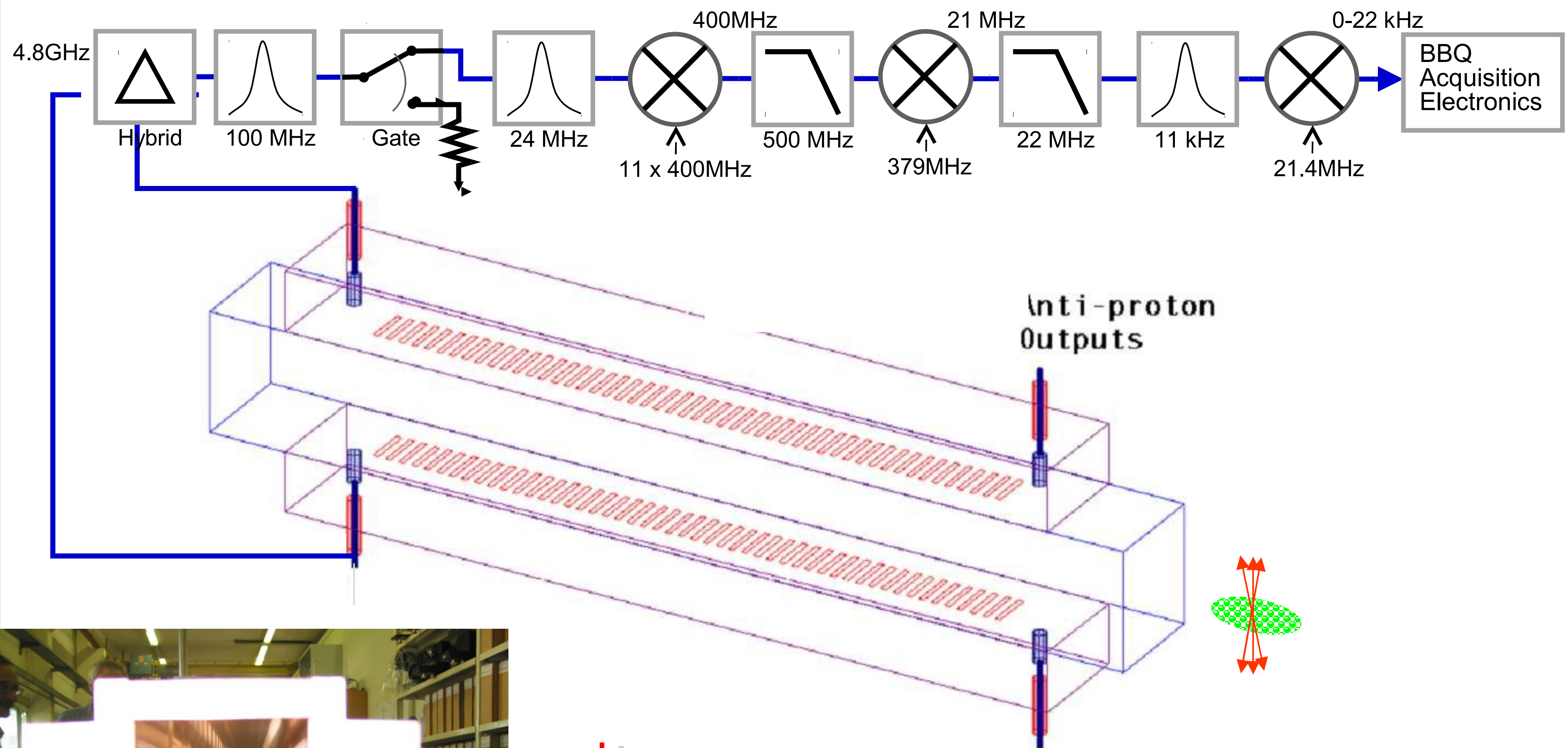


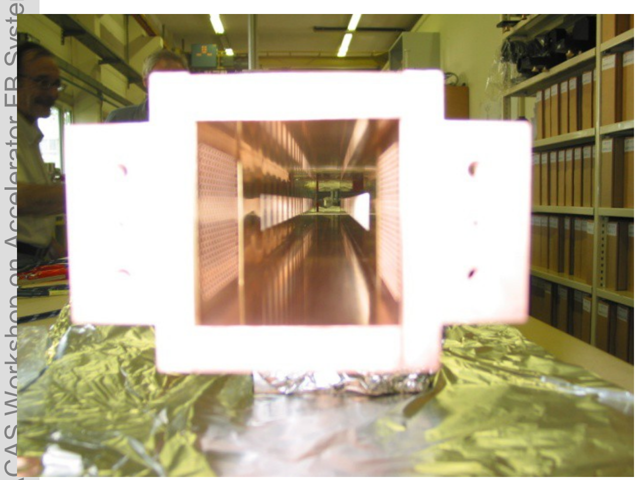


- Measured beta-beat is compatible with magnet calibration curves.
- Peak-to-peak β-beat "noise": ~ 0.5 %
  - unlikely due to diagnostic
  - seen already at LEP:
    (though not time resolved)

  → real drift of the optics!



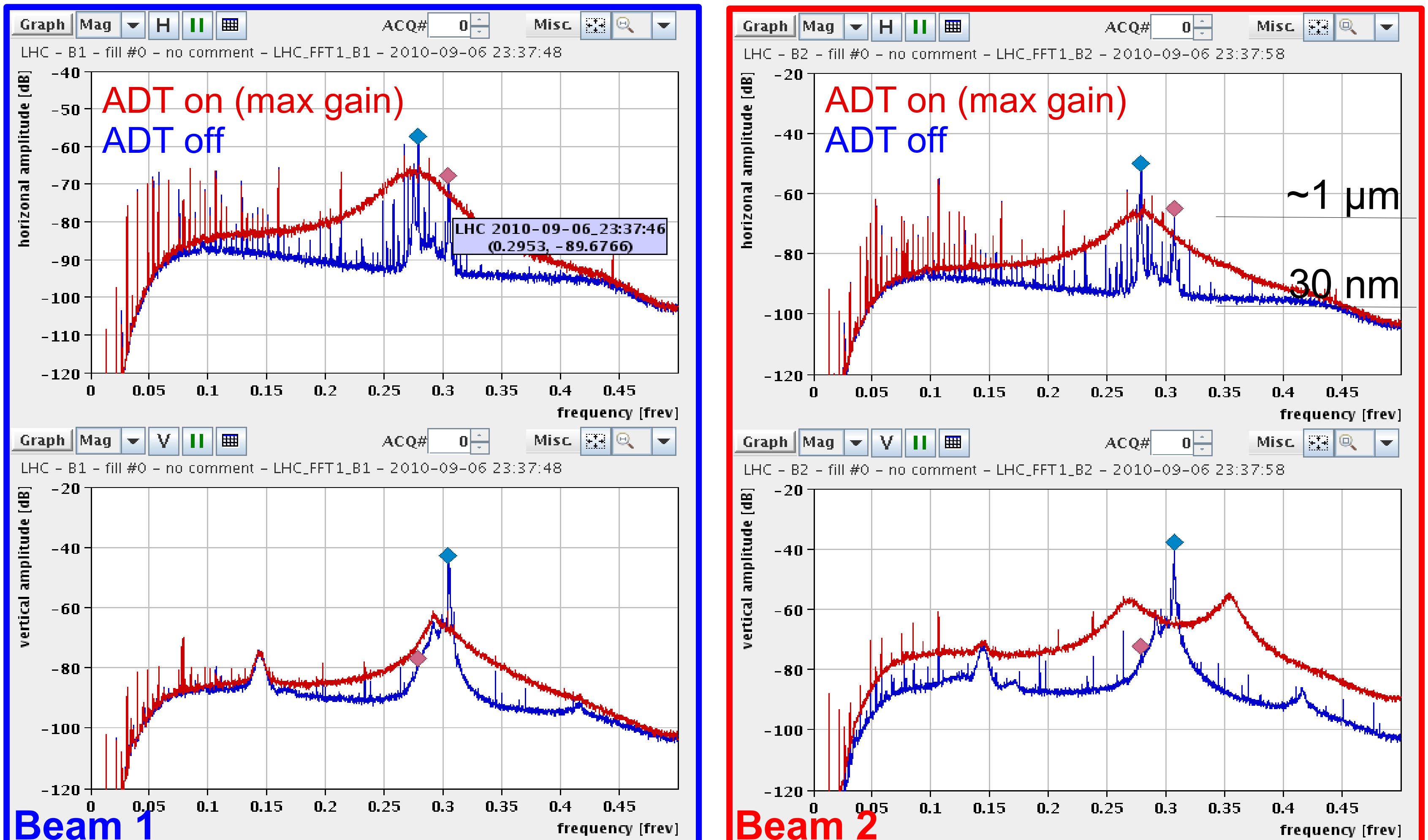




4.8 GHz Slotted Waveguide Structure
60 x 60 mm aperture x 1.5 meters long
Gated, triple down-mixing scheme to baseband
Successive filtering from bandwidth of 100MHz to 11kHz
Capable of Bunch by Bunch Measurement

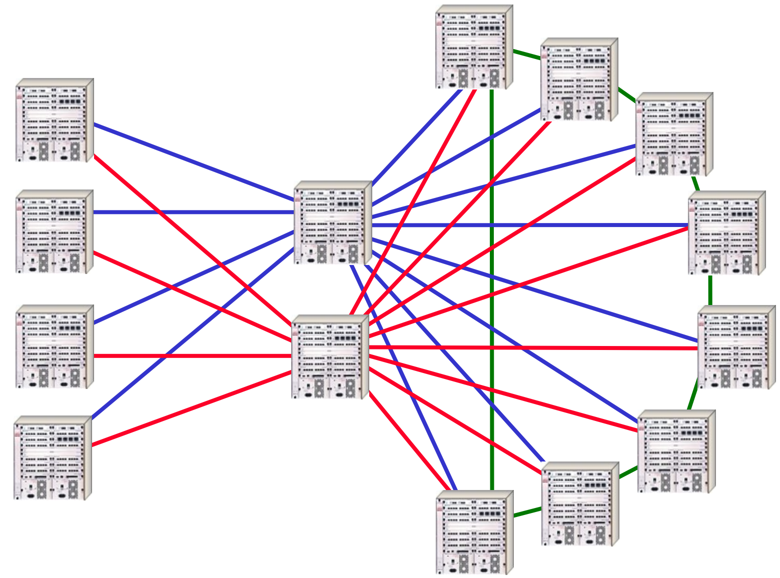
Features: ADT Interference on Tune Diagnostic

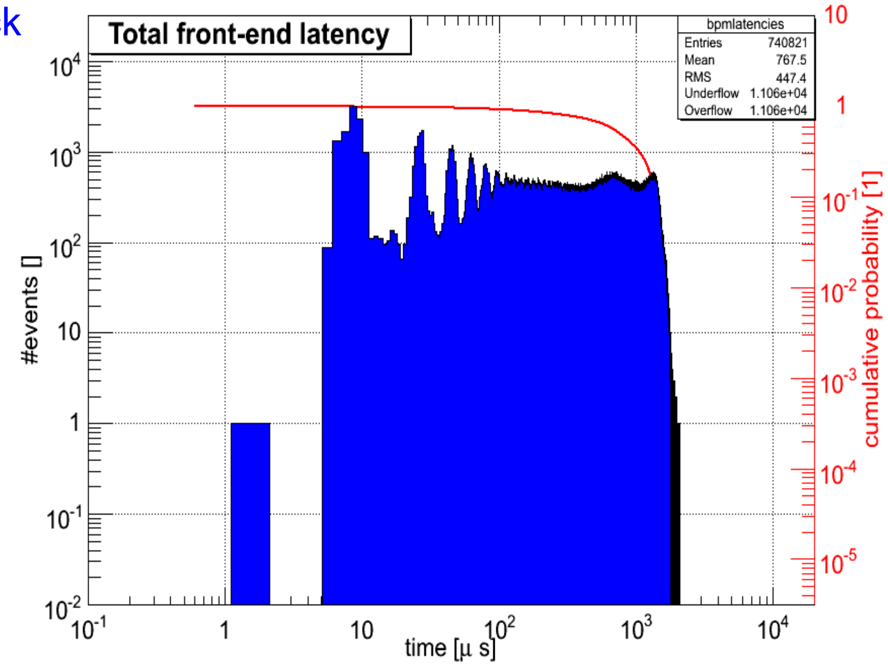
- BBQ noise-floor raised by 30 dB, wide Q-peak → reduces ΔQ_{res}~10^{-4} → ~10^{-2}
  - Used to diagnose/optimise transverse damper (fast bunch-by-bunch feedback)
    - induced tune-shift ↔ phase advance between pick-up and exciter



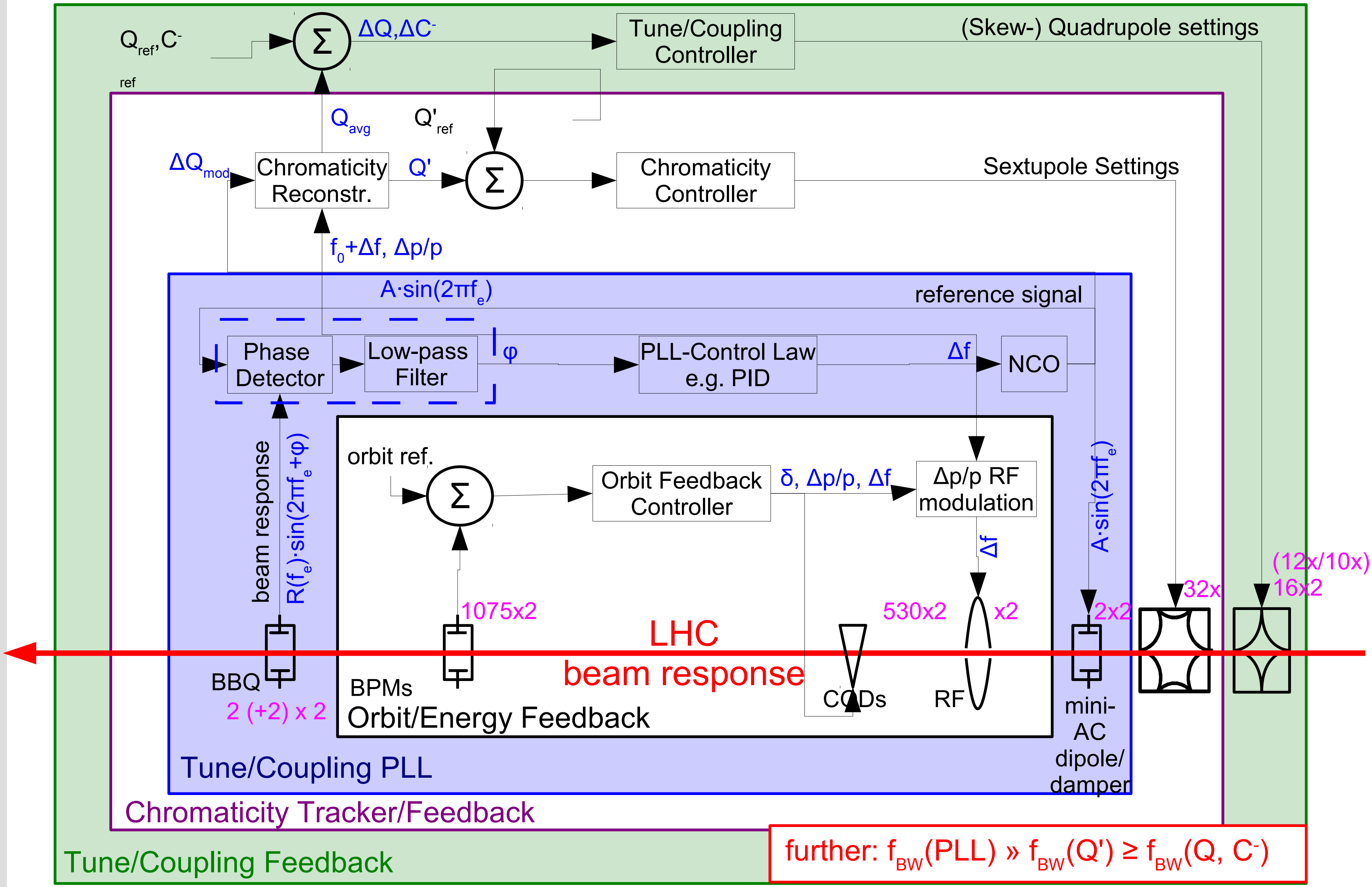
Technical Network and Data Communication

- CERN's Technical Network as backbone
  - Store & Forward switched network
    - no data collisions/data loss
  - double (triple) redundancy
- Core: “Enterasys X-Pedition 8600 Routers”
  - 32 Gbits/s non-blocking, $3 \cdot 10^7$ packets/s
  - 400 000 h MTBF
  - hardware QoS
    - One queue dedicated to real-time feedback
    - ~ private network for the orbit feedback
- Routing delay ~ 13 µs
- longest transmission delay ~ 320 µs
  - 80% due to travelling speed of light
- worst case max network jitter « targeted feedback sampling (25 Hz)!





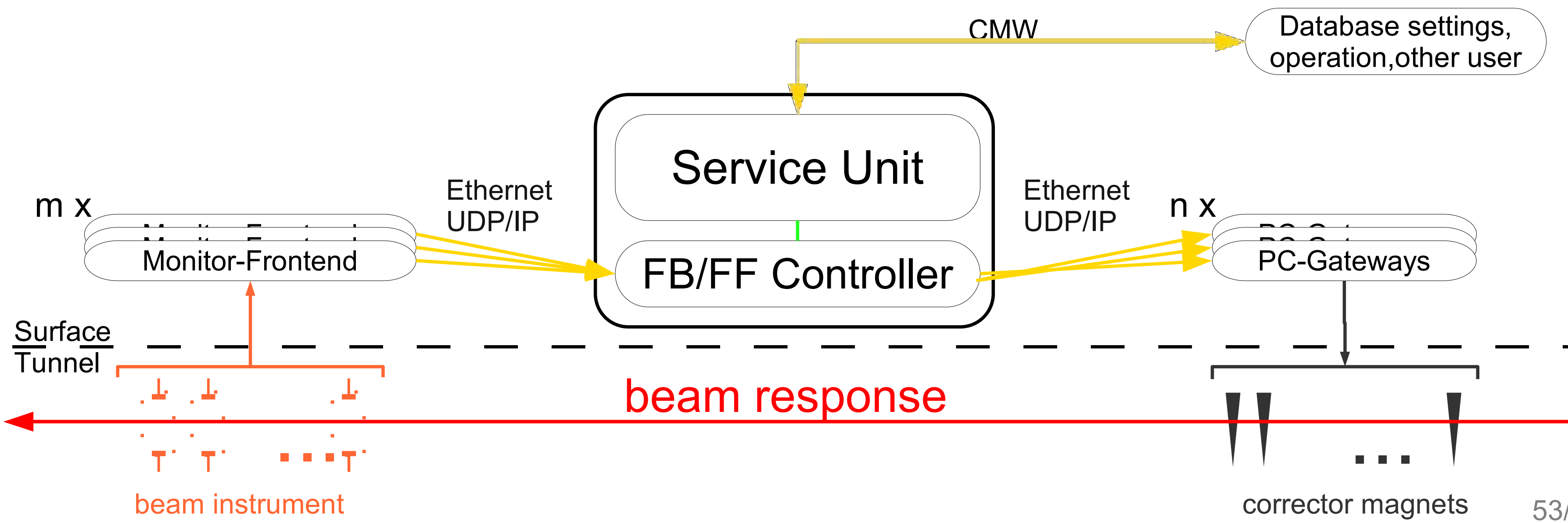
To avoid Coupling and Cross-Talk between FBs...
… Cascading between individual Feedbacks



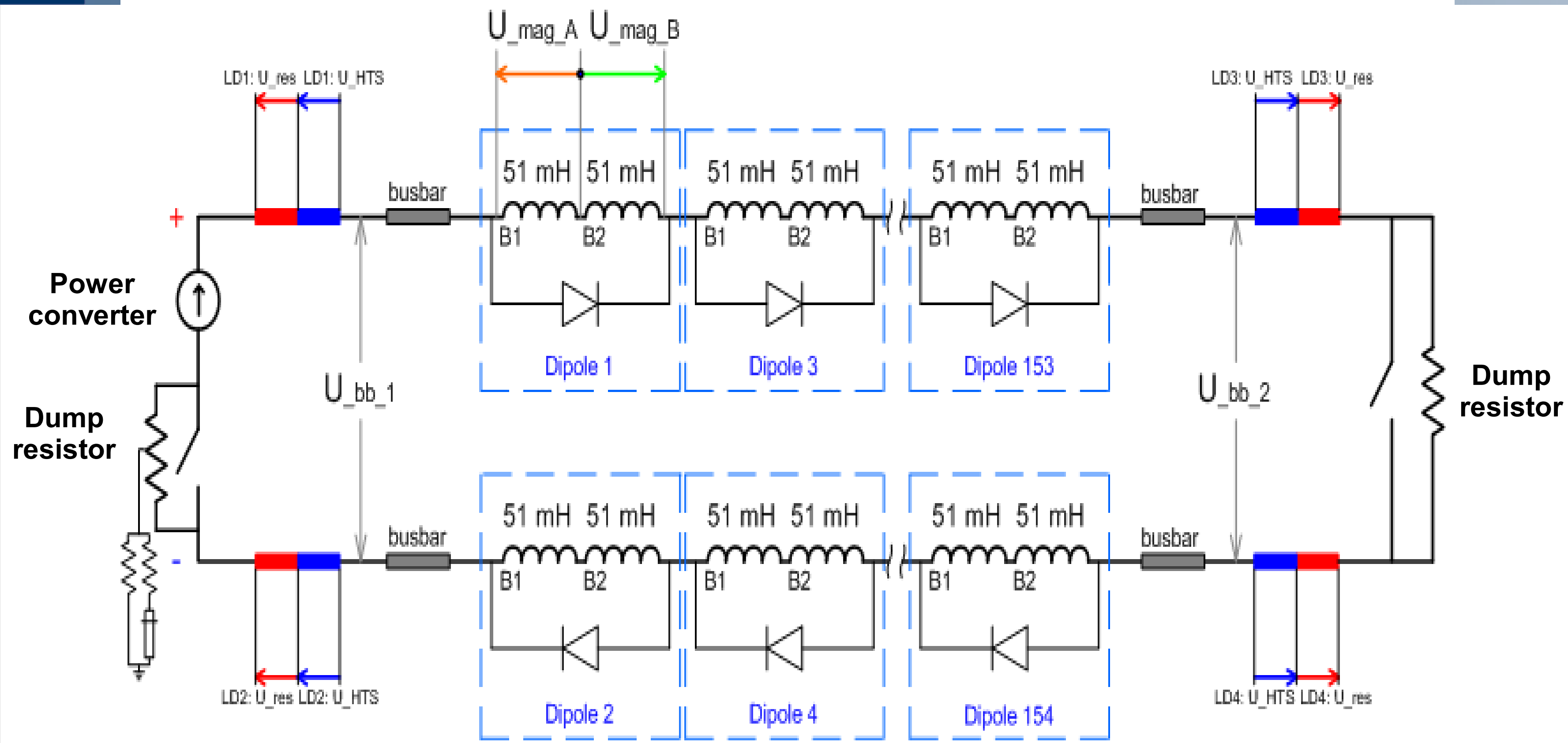
Common Feedback/Feed-forward Control Layout

LHC feedback control scheme implementation split into two sub-systems:

- Feedback Controller: actual parameter/feedback controller logic
  - Simple streaming task for all feed-forwards/feedbacks:
    (Monitor → Network $)_{FB}$→ Data-processing → Network → PC-Gateways
  - Runs real-time operating system
  - Average load:
  - Can run auto-triggered
- Service Unit: Interface to users/software control system



Quench Detection and Energy Discharge



1. The quench is detected based on voltage measurements over the coils (U_mag_A, U_mag_B).
2. The energy is distributed over the entire magnet by force-quenching with quench heaters.
3. The power converter is switched off.
4. The current within the quenched magnet decays in < 200 ms, circuit current now flows through the ‚bypass‘ diode that can stand the current for 100-200 s.
5. The circuit current/energy is discharged into the dump resistors.

Accelerator Collider Optimisation Considerations

- All high-energy-physics (HEP) particle quests starts at:

Event Rate → the frequency a given particle is created per second
Physics detectors

cross-section → probability that a given particle is created
Mother Nature defines that for us and typically depends on energy

$$\dot{N}_{event} = L \cdot \sigma_{physics}$$

Luminosity → the frequency of how often the particles are brought in to collisions
Accelerator design and operation

- Push maximum peak luminosity
  - essentially: increase number of particles inside the machine and squeeze them to a confined space to increase the probability of a collision
- Push achievable energy E:
  - Minimise synchrotron radiation losses:
    - e^+e^- → hadrons collider ($p^+p^\pm$, ...)
    - Choice: linear vs. circular
      - Optimise RF cavities + normal conducting magnets (CLIC,ILC)
      - Standard RF cavities + superconducting magnets (Tev,RHIC,LHC)

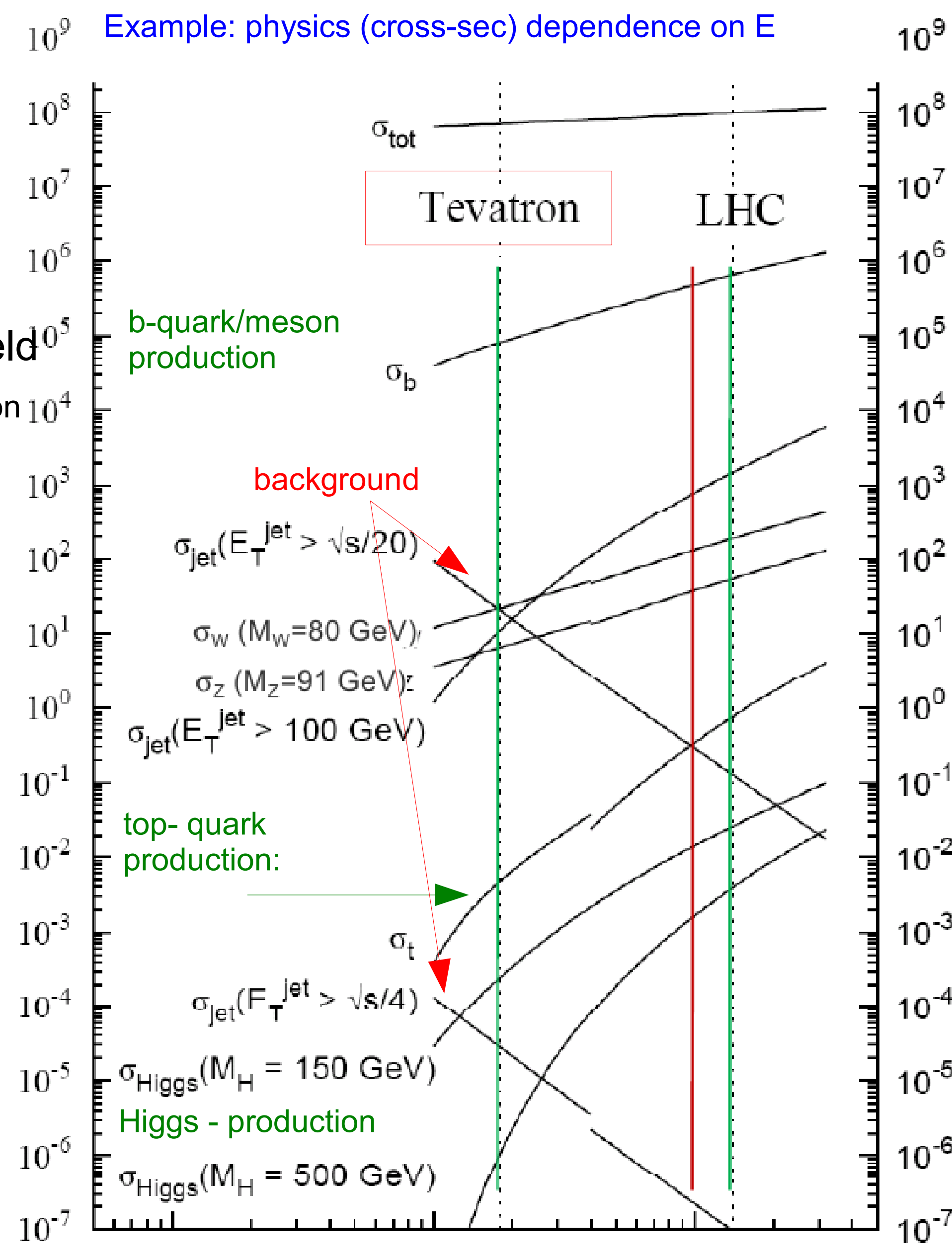
Why maximum Multi-TeV Collision Energies?

- Physicists want as high as possible
  - useful (competitive) HEP

Need to find a balance between:

- Dipole field which can be reached
- Risks associated with operating at that field
  - splices stability, thermal runaway, splice detection
- Operational efficiency of other systems
  - e.g. cryo recovery time:
    ~ 3h @ 5TeV vs. >6h @ 7TeV)

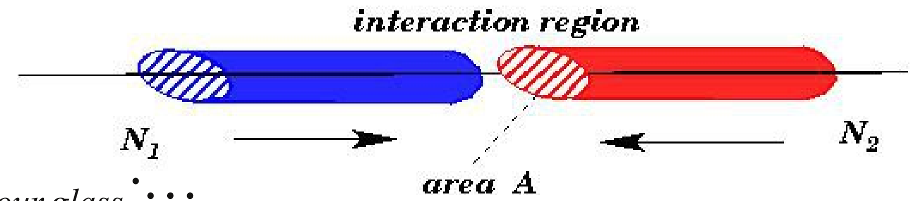
- Decided this year to run at reduced 3.5 TeV instead of 7 TeV (design)



Luminosity: $dN_{event}/dt = L\, s_{process}$

- Collider design:

$$L = \frac{N^2 k f_{rev}}{4\pi\sigma_x\sigma_y} \cdot F_{crossing} \cdot F_{hour\,glass} \cdot \ldots$$



	LHC	Tevatron
– N: number of particles per bunch,	N_p= 12 10^{10}	N_p=30 10^{10}
– k: total number of bunches,	k = 1 ... 2808	k = 36
– σ_x, σ_y: hor./vert. r.m.s. beam size in IR	$\sigma_x=\sigma_y$ ~ 17 µm	$s_x=s_y$~30 µm
– f_{rev}: revolution frequency,	f_{rev}= 11.2 kHz (fixed)	f_{rev}= 47.7 kHz
– $F_{crossing}$, $F_{hourglass}$: numerical form factors,	$F_{cross.}$(285 mrad)~0.8	$F_{cross.}$(0)=1
	1- $F_{hourgl.}$~ 0.4%	1- $F_{hourgl.}$~ 38%

- Most parameters are defined by the accelerator geometry and lattice
- The "most effective" parameter: total stored intensity

$$I_{stored} = Nk$$

LHC: $I_{stored} \approx 3.2\,10^{14}\ protons \quad \Rightarrow \quad E_{stored} \approx 350\ MJ\ @\ 7\mathrm{TeV}$