Continuous LHC Beta-Beat Measurements - Prototyping at the CERN-SPS

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Motivation

- Motivation: System dependence on known/constant beta-function:
  - Machine Protection and Collimation, Physics, Squeeze Diagnostics
  - Classic methods: 'kick'-type excitation & BPMs, K-modulation & Q-PLL, Closed-orbit-response (LOCO)
    → cannot achieve the required precision/time-scales under nominal conditions!
- β-Phase Advance Method - Turn-by-Turn
  - BBQ based Test-Setup in SPS LSS5
  - Systematic and statistical noise contribution
  - Exploitation Examples: SPS lattice drifts & off-momentum beta-beat
- β-Phase Advance Method - Orbit
- Next Steps & Control of Betatron-Function

Feedback Overview Worldwide

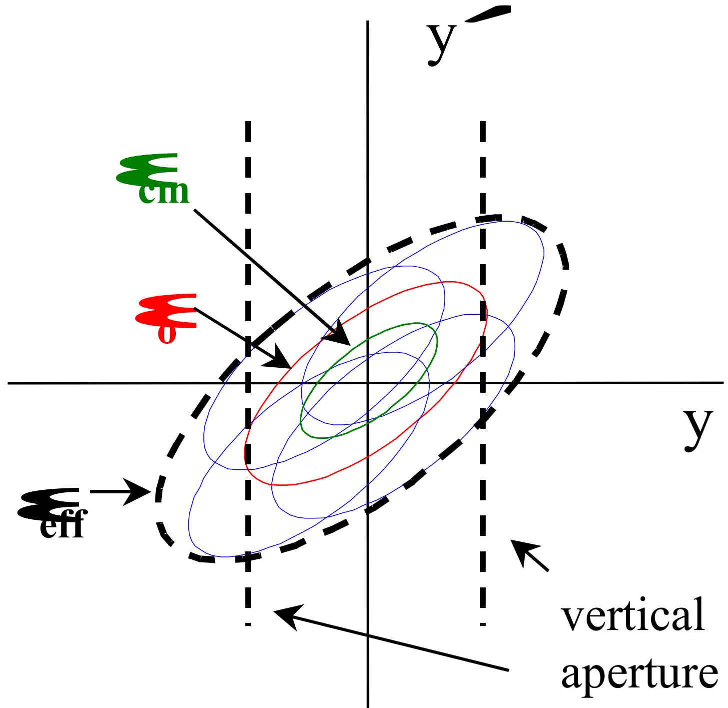
- Accelerators can be grouped into three groups
  - Light Sources: (list not exhaustive[1-3])
    ALBA, ANKA, ALS, APS, BSRF, BESSY, CLS, DELTA, ELETTRA, ESRF, INDUS2, LNSLS, SLS, DIAMOND, SOLEIL, SPEAR3, Spring-8, Super-ACO...
    - mostly orbit and energy feedback (radial steering) only
  - Lepton Collider: LEP[4], PEP-II[5], KEK-B
    - orbit and tune feedback (mostly during ramp)
  - Hadron Collider: Hera, LHC, RHIC, Tevatron
    - mostly slow orbit feedback, except:
      - Hera: Orbit, Tune
      - RHIC: Tune[6]/Coupling, Chromaticity[7]
      - LHC: Orbit/Energy, Tune/Coupling, Chromaticity, … optic!?!

Beam Parameter Stability in Lepton Machines (e^+e^- Collider, Light Sources, ...)

- Main requirements for orbit stability[8]:
  - Effective emittance preservation
    (τ_d sampling/integration time, τ_f fluctuation time)

$$\tau_d \gg \tau_f: \quad \epsilon_{eff} = \epsilon_0 + \epsilon_{cm}$$

$$\tau_d \ll \tau_f: \quad \epsilon_{eff} \approx \epsilon_0 + 2\sqrt{\epsilon_0 \epsilon_{cm}} + \epsilon_{cm}$$



L.Farvacque, ESRF

  - Minimisation of coupling
    (vertical orbit in sextupoles)
  - Minimisation of spurious dispersion
    (vertical orbit in quadrupoles)
  - Collider Luminosity and collision point stability (in case of two separated rings)

$$L = L_0 \cdot \exp\left\{\frac{(\Delta x)^2}{2\sigma_x^2} + \frac{(\Delta y)^2}{2\sigma_y^2}\right\} \cdot 1/\sqrt{1+\left(\frac{\theta_c \sigma_z}{2\sigma_{x/y}}\right)^2} \cdot \quad \ldots$$

Δx/Δy [σ]	0	0.5	1	2	3	4
L/L_0 [%]	100	≈ 94	≈ 79	≈ 37	≈ 11	≈ 2

- Traditional requirements on beam stability...

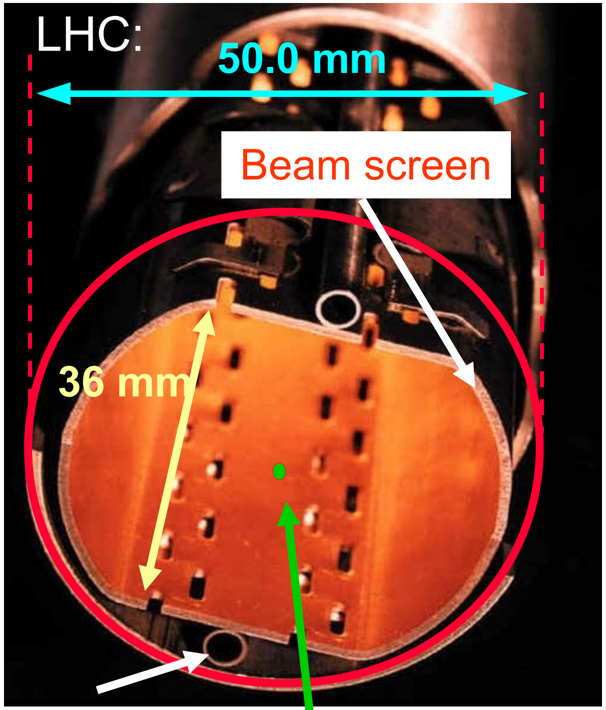
  ... to keep the beam in the pipe!

- Increased stored intensity and energy:

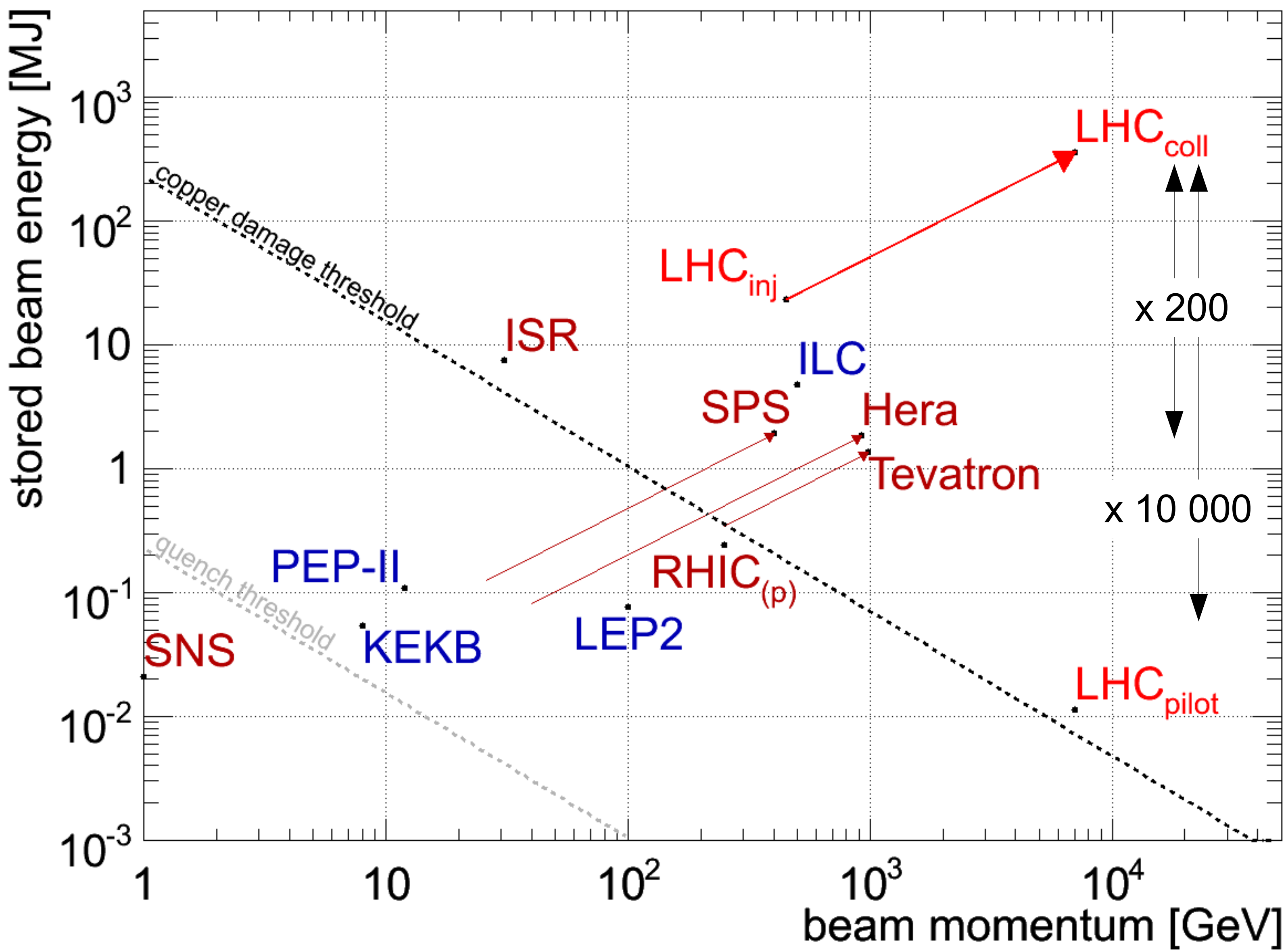
  → sufficient to quenches all magnets and/or to cause serious damage[9]

- Requirements depend on:

  1. Capability to control particle losses in the machine
     - Machine protection & Collimation
     - Quench prevention
  2. Commissioning and operational efficiency



IWBS'04: "LHC is a pretty dangerous machine" Livingston Style plot



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

Maximum LHC Energy of 7 TeV

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

E_{MQE} < 30 mJ/cm^{-3} vs. E_{stored} = 350 MJ/beam (nominal LHC)

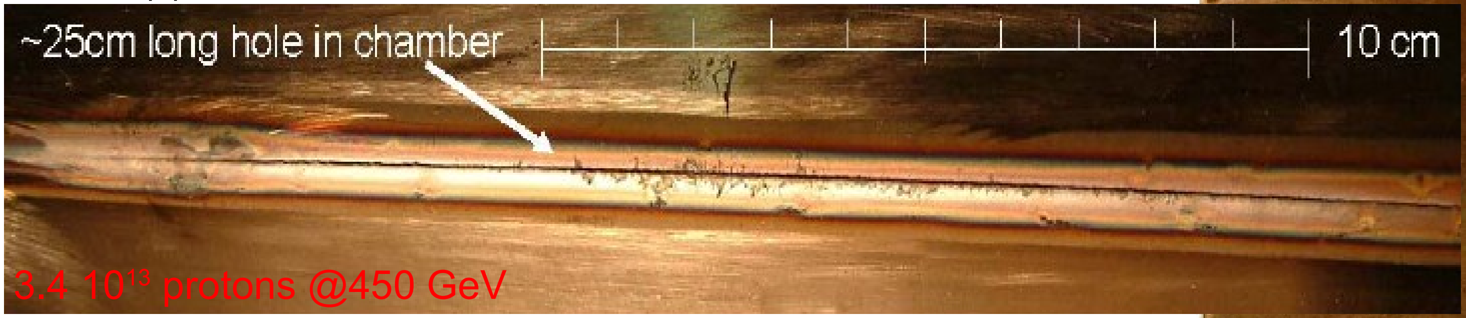
(or: N_{loss} < 10^8 protons/m vs. N_{total} ~ 3 10^{14} protons)

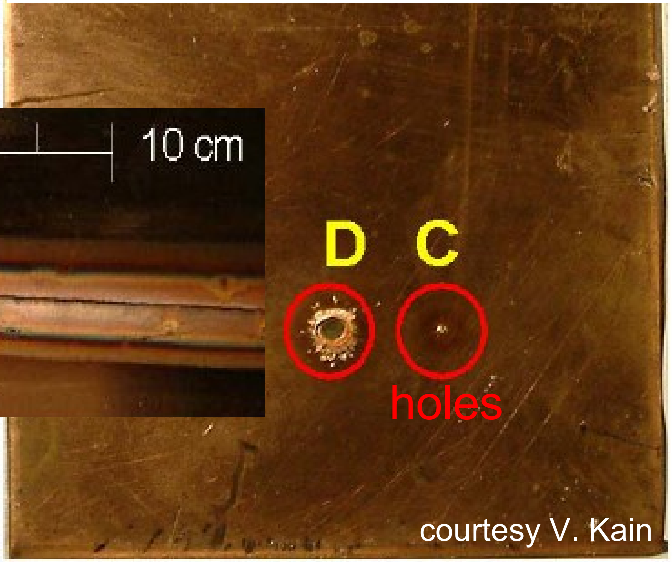
→ sufficient to quench all magnets and/or may cause serious damage

  - 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

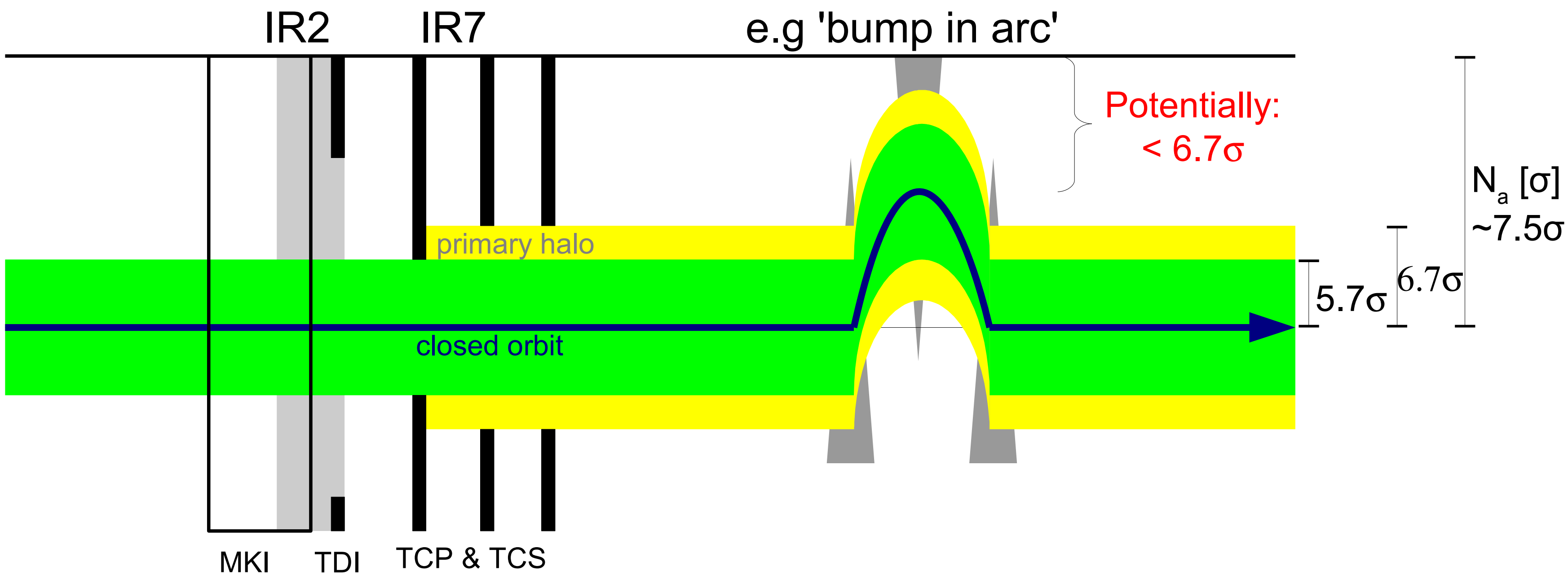




for details see: Chamonix XIV:
“Damage levels - Comparison of Experiment and simulation” and PAC'05

Compromised Machine Protection via Orbit Bumps

- Combined failure: Local orbit bump and collimation efficiency (/kicker failure):

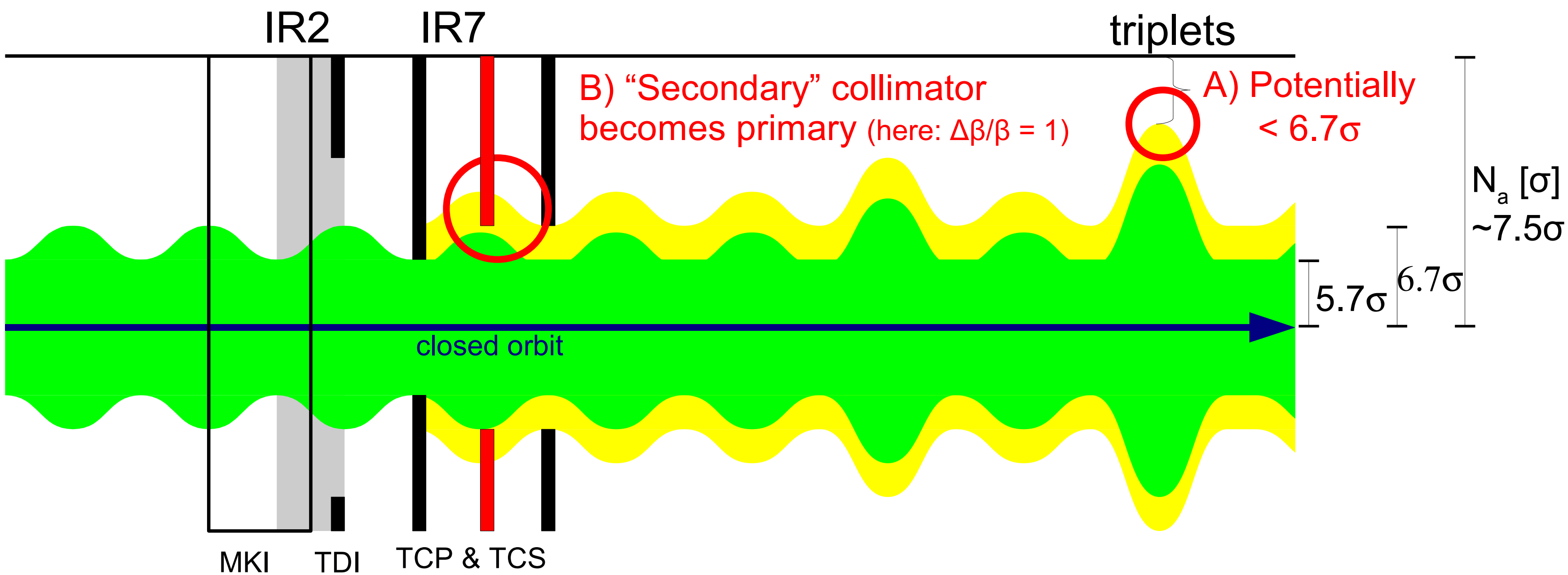


- Primary collimator (TCP) limits $|x_\beta(s)|_{max}$ locally to <5.7σ, secondary collimator (TCS) at~ 6.7σ
- To guarantee two stage cleaning efficiency/machine protection:
  - Local: TCP must be >0.7σ closer than TCS w.r.t. the beam → Orbit FB
  - Global: no other object (except TCP) closer to beam than TCS

→ Orbit bumps may compromise function of machine protection/collimation

→ tackled by LHC Orbit Feedback → present R&D efforts on new BPM electronic

- Combined failure: beta-beat and collimation efficiency



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

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

A) β-Beat reduces required protection: Δβ/β ≈ 20 % → 20% tighter collimator settings

B) β-Beat reduces cleaning performance

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

Performance Limitations & Constraints on β*

If retraction is adjusted such to allow some maximum transient beta beat and orbit error, then **constraint of β^*:**

N.B. $C = \beta_{trip} \cdot \beta^*$

$$\beta^* \geq \frac{C^2}{a^2_{triplet} \cdot \beta_{coll}} \cdot \left(n_{prim} + \Delta A_{max} + 1.7 \cdot \left[n_{prim} \cdot \sqrt{\frac{\Delta\beta_{max}}{\beta_0}} + \frac{\Delta x^{max}_{orbit}}{\sigma_x} \right] \right)^2$$

Increase triplet aperture

IR Upgrade

Increase beta at collimators

Small primary gap

Sufficient number of secondaries at specific phases

Minimize any transient beta beat → **β-beat meas. + RT-Feedback?**

Minimize transient orbit changes → **LHC Orbit Feedback**

Larger β^* - A way to relax operational collimator tolerances!

(However, loose passive protection)

- Maximum allowed safe beam intensity[1,2]:

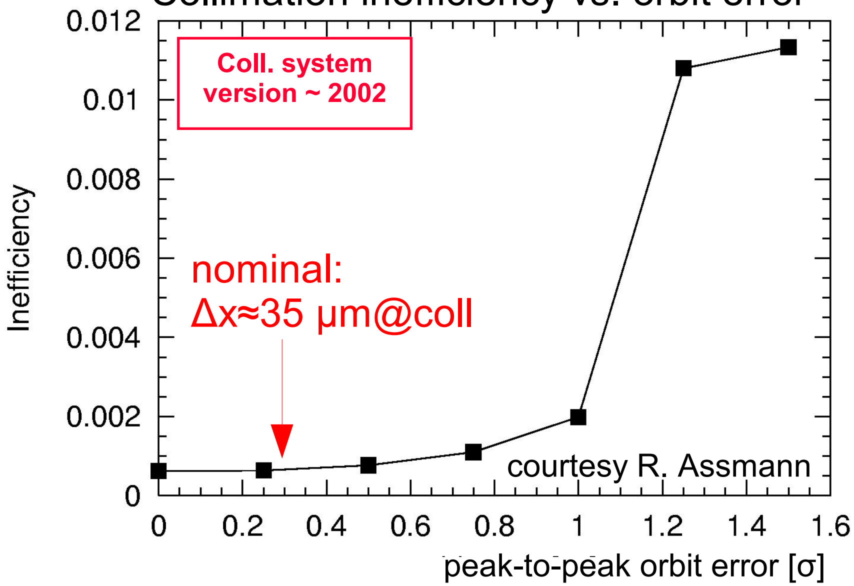
$$N_{max} \leqslant \frac{\tau_{min} \cdot R_q \cdot L_{dil.}}{\eta}$$

  – Min. accept. lifetime: $T_{min} \approx 10$ min.
  – Dilution length: $L_{dil} \approx 50$ m
  – Quench level (@7 TeV) R_q: $R_q \approx 7.6 \cdot 10^6$ prot./m/s
  – Collimation inefficiency: η

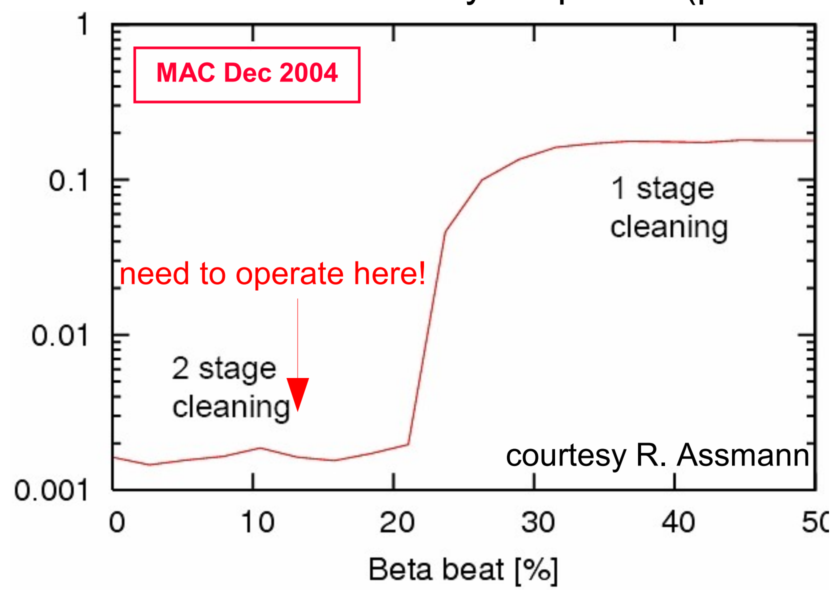
Peak-Luminosity:

$$L_{max} \approx \frac{1}{4\pi} \cdot \frac{N_{max} \cdot n_b f_{rev}}{\beta^* \epsilon}$$

Collimation inefficiency vs. orbit error



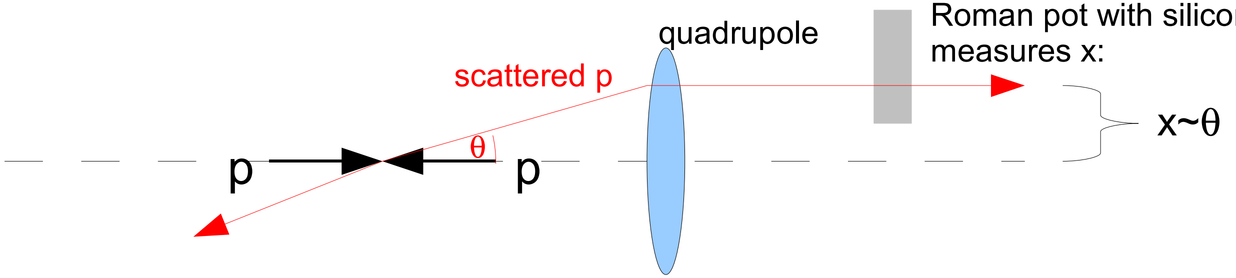
Collimation inefficiency vs. β-beat (β*=0.55 m)



[1] R. Assmann, "Collimation and Cleaning: Could this limit the LHC Performance?", Chamonix XII, 2003
[2] S. Redaelli, "LHC aperture and commissioning of the Collimation System", Chamonix XIV, 2005
[3] R. Steinhagen, "Closed Orbit and Protection", MPWG #53, 2005-12-16

Constraint II: Diffractive Physics
p-p Luminosity using Optical Theorem

- Special parallel to point focusing machine optic ($\beta_0 \approx 1600$ m)



– Roman Pots move close to the beam halo, measure dN/dt down to:

$$t_{min} = (p\,\theta_{min})^2 \sim \frac{p^2}{\beta_0 \beta_d} \cdot x_{min}^2$$

– Observables: abs. Luminosity, total p-p cross-section, diffractive physics

  - Requires good knowledge on
    – Beta-functions β_0 at IP and β_d at detector
    – Beam momentum p
    – minimum distance of roman pot x_{min} w.r.t. beam centre

– Desired: $\Delta L/L \approx 1\% \rightarrow \Delta t/t \approx 1\% \rightarrow 0.5 \cdot \Delta\theta/\theta \approx \Delta x/x \approx 5 \cdot 10^{-3}$

→ absolute beam position stability at roman pot (x_{min}~ 1mm) < 5 µm!!

→ value of betatron function at IP and RP: → $\Delta\beta/\beta \approx 1\%$!!

Limitations on Squeeze Diagnostic

- Squeeze involves > 45 individual magnetic strength settings (Optics), so far: no continuous check on effective optics during/at the end of individual steps

- "Classic" methods may not reach/be compatible with nominal requirements
  - K-modulation induced Q-Changes: $$\Delta Q \approx \frac{1}{4\pi} \cdot \beta(s) \cdot \Delta k(s)$$
    - Limit: knowledge on quadrupole transfer function (hysteresis, D&S, $\beta|^{max} \approx 4.2$km & $\Delta Q^{max} < 10^{-3} \rightarrow \Delta k/k_{nom} < 5 \cdot 10^{-5}$)

  - Kick + turn-by-turn analysis of BPM (phase and/or amplitude), limits:
    - Potential particle loss (beta-functions at triplet) & emittance blow-up
    - Systematic phase errors, amplitude detuning/Landau damping
      - large kicks may probe phase advances (dynamic aperture) which may not be relevant for nominal beam operation/parameters
      - beam will be collimated at 6 sigma (kick amplitudes < 1.2 mm @7TeV)!
    - … not ideal for continuous monitoring/regular operation.

  - Closed orbit response analysis (LOCO):
    - resolution/performance compatible with nominal operation
    - Limit: scan requires several minutes per IP (full scan: ~2 OP-shifts)

Betatron Function via Phase-Advance Measurement

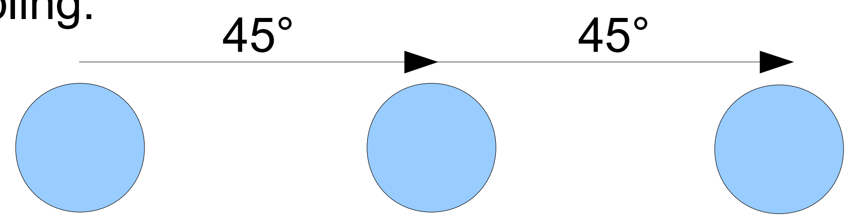
- Long history at CERN. Original idea dates back to SL-BI report (doctoral thesis)
  P.Castro, *Luminosity and Betatron Function Measurement at [..] LEP*, CERN SL/96-70 (BI)

- … beating in amplitude related to beating in phase:

$$\frac{\Delta\beta}{\beta}(s) = \frac{1}{2\sin(2\pi Q)} \oint \beta_k \cos(2\cdot|\mu(s)-\mu(a)|-2\pi Q)\,\Delta k(a)\,da$$

$$\mu(s) := \int_0^s \frac{1}{\beta(a)}\,da \quad \longrightarrow \quad \frac{\Delta\mu}{\mu}(s) \sim -\frac{\Delta\beta}{\beta}(s)$$

- Phase sampling:



Case I: $\Delta\varphi$ →   0   ← $-\Delta\varphi$ $\Delta\mu_{12}$ =45° - $\Delta\varphi$, $\Delta\mu_{13}$ =90° - 2 $\Delta\varphi$

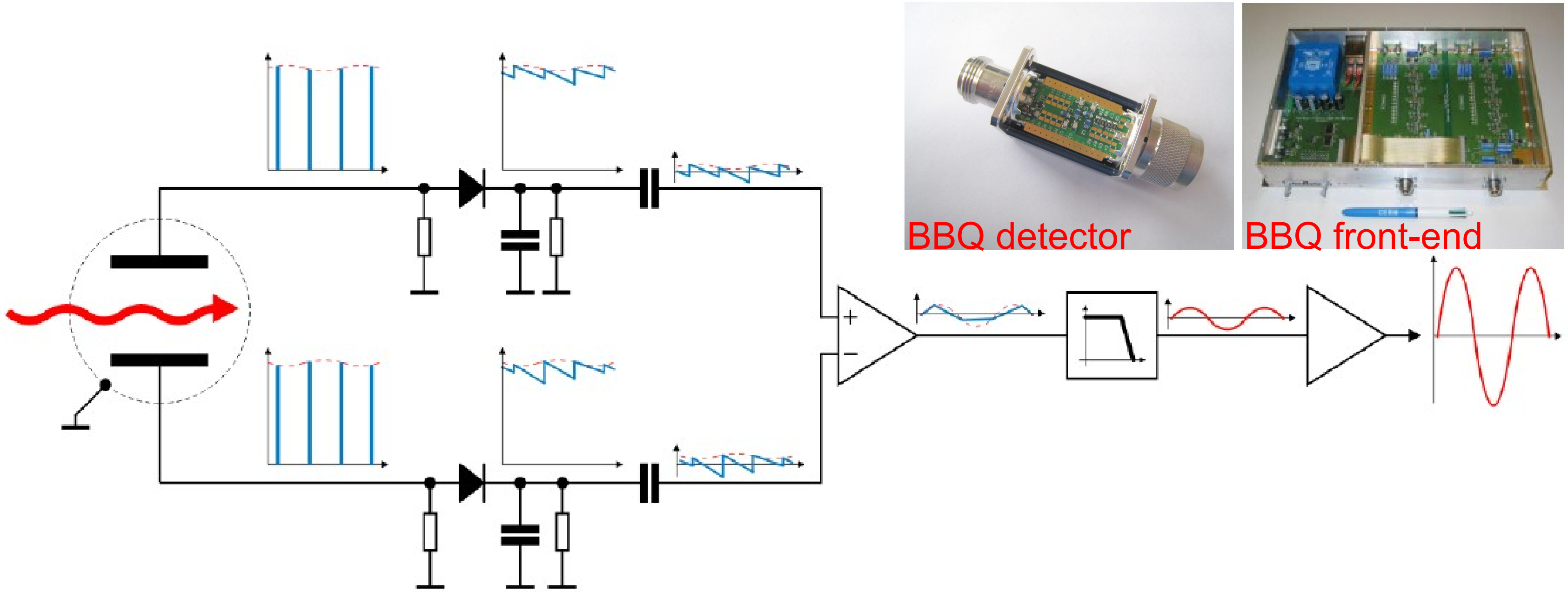
Case II: 0 $\Delta\varphi$ →   0 $\Delta\mu_{12}$ =45° + $\Delta\varphi$, $\Delta\mu_{13}$ =90°

- Beta-Beat reconstruction (FB/Control would work with phases):

$$\frac{\Delta\beta_1}{\beta_1} = \frac{\cot(\Delta\mu_{12}^{meas.}) - \cot(\Delta\mu_{13}^{meas.})}{\cot(\Delta\mu_{12}^{theo.}) - \cot(\Delta\mu_{13}^{theo.})} \qquad \frac{\Delta\beta_2}{\beta_2} = \frac{\cot(\Delta\mu_{12}^{meas.}) - \cot(\Delta\mu_{23}^{meas.})}{\cot(\Delta\mu_{12}^{theo.}) - \cot(\Delta\mu_{23}^{theo.})} \qquad \frac{\Delta\beta_3}{\beta_3} = \frac{\cot(\Delta\mu_{23}^{meas.}) - \cot(\Delta\mu_{13}^{meas.})}{\cot(\Delta\mu_{23}^{theo.}) - \cot(\Delta\mu_{13}^{theo.})}$$

N.B. Phase-Beating usually used for correction!

Base-Band-Q Principle on a Slide

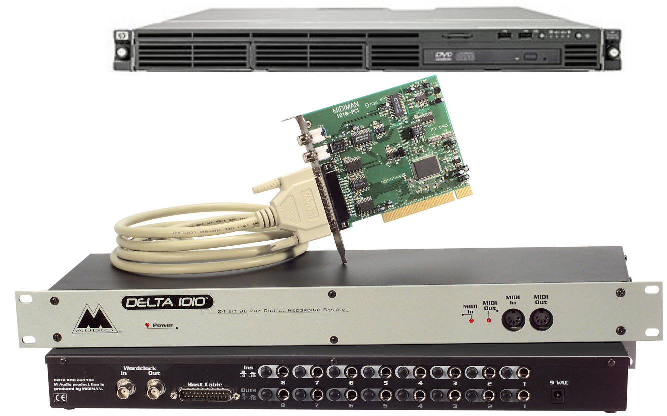


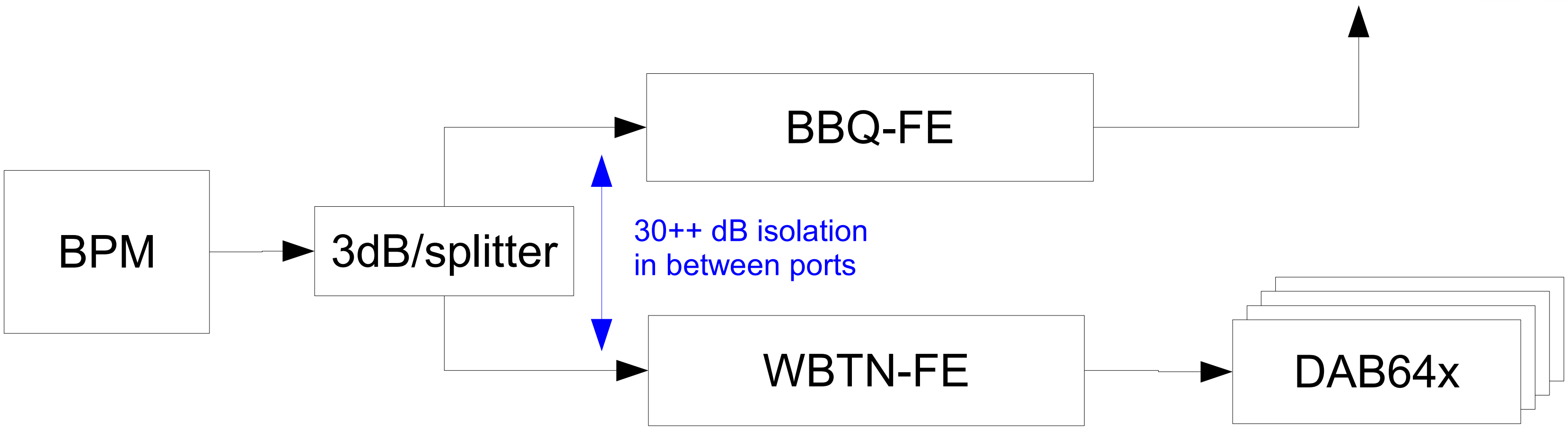
- Basic principle: AC-coupled peak detector
  - no saturation, self-triggered, no gain changes between pilot and nominal
  - intrinsically down samples spectra: ... 6 GHz → 1kHz ... f_{rev}
    - Base-band operation: very high sensitivity/resolution ADC available
    - Measured resolution estimate: < 10 nm → ε blow-up is a non-issue
- One of the few turn-key systems in the LHC
  - easy/very fast commissioning – done in parallel with RF capture

Beta-Beat/LHC BPM Prototype System in the SPS-LSS5 Test Setup

- Yet another exploitation of the BBQ Principle

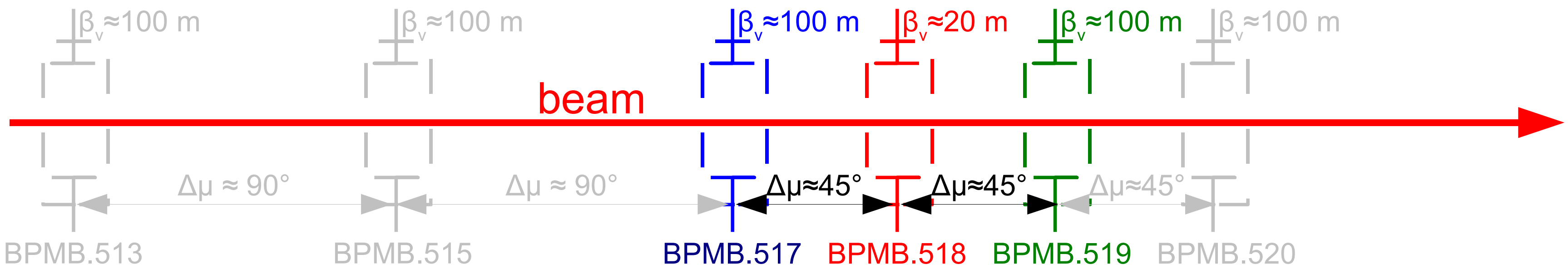
- Digital acquisition: HP Proliant 16”, 1U + M-AUDIO Delta 1010
  - 8 analogue inputs/outputs, 16”, 1U
  - frequency response: 20Hz-22kHz, +/-0.3dB
  - >100 dB dynamic range/S/N ratio
  - THD: 0.00072% (A/D), 0.00200% (D/A)



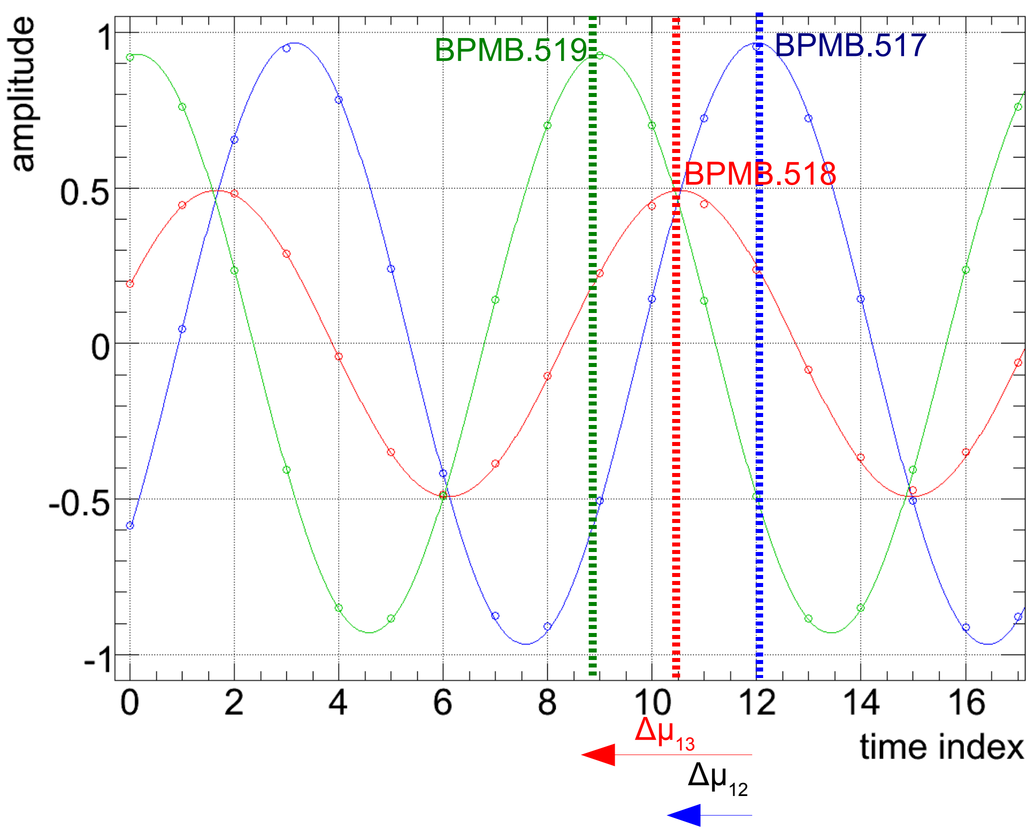


- First iteration: KISS – keep it simple and safe

- With all it pro's and con's: splitting of signals allowed effective cross-calibration and performance comparisons...



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



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

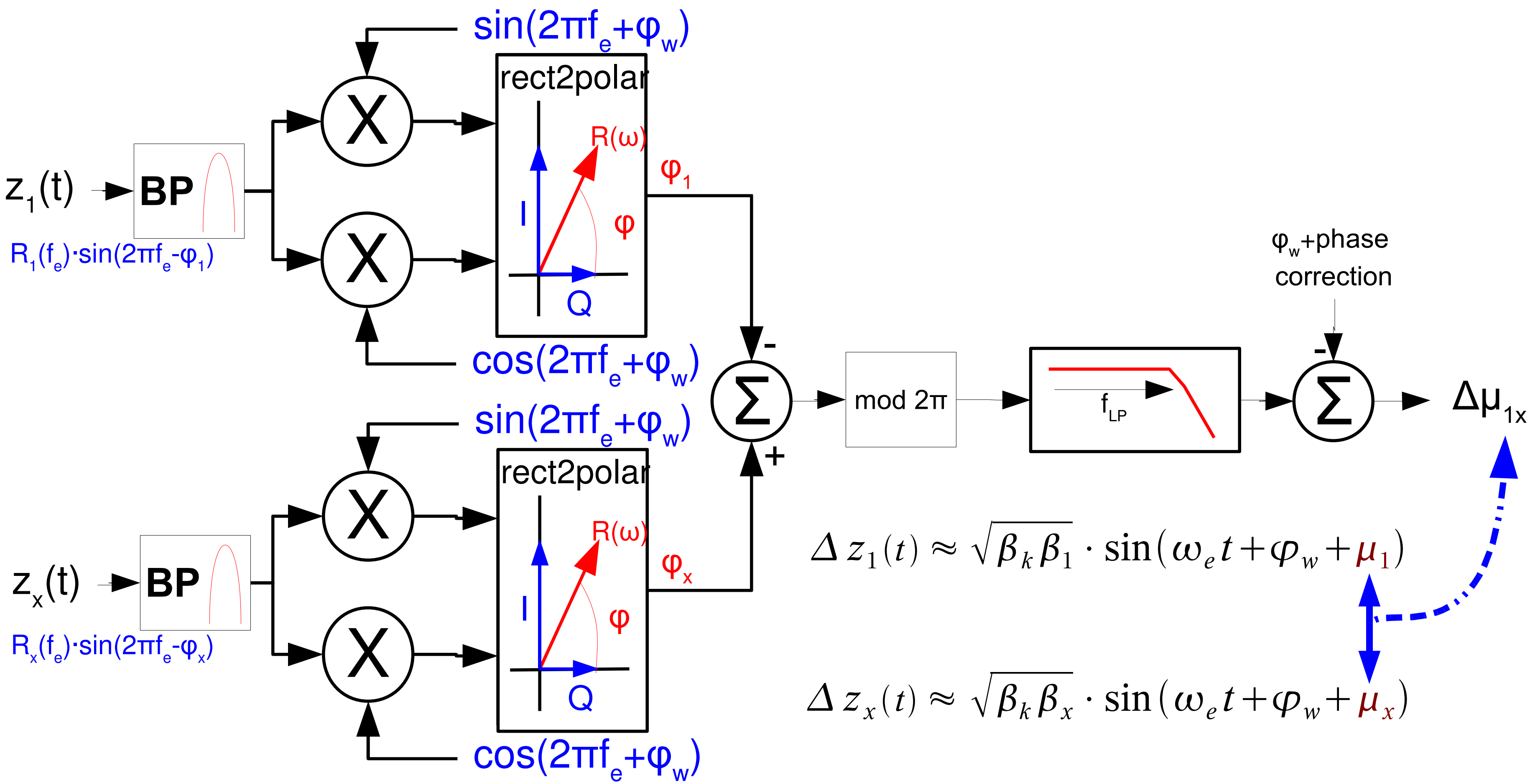
$$\frac{\Delta\beta_2}{\beta_2} = \frac{\cot(\Delta\mu_{12}^{meas.}) - \cot(\Delta\mu_{23}^{meas.})}{\cot(\Delta\mu_{12}^{theo.}) - \cot(\Delta\mu_{23}^{theo.})}$$

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

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

Sample-by-Sample Phase Demodulation Scheme

- Modified mixing scheme:

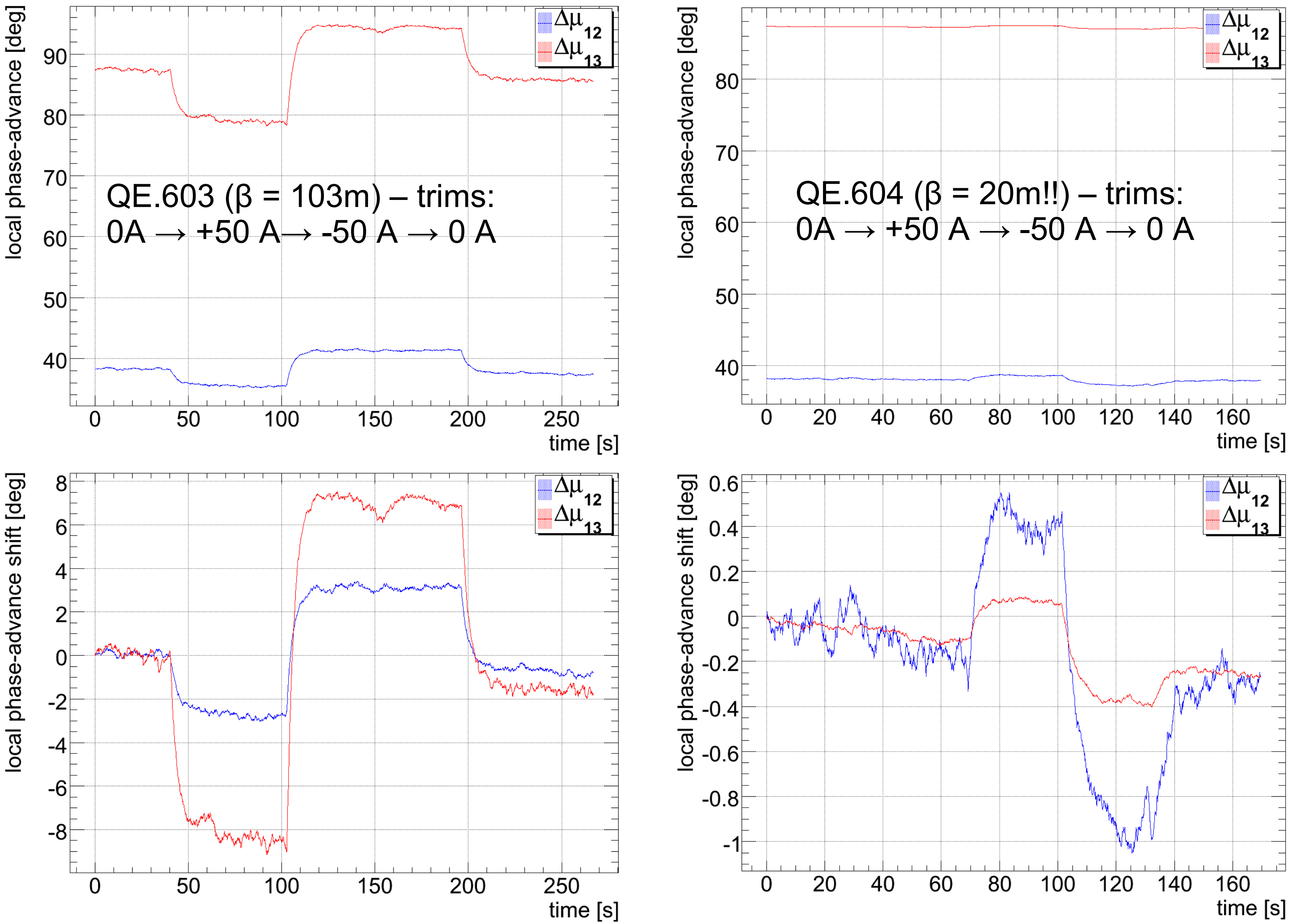


$$\Delta z_1(t) \approx \sqrt{\beta_k \beta_1} \cdot \sin(\omega_e t + \varphi_w + \mu_1)$$

$$\Delta z_x(t) \approx \sqrt{\beta_k \beta_x} \cdot \sin(\omega_e t + \varphi_w + \mu_x)$$

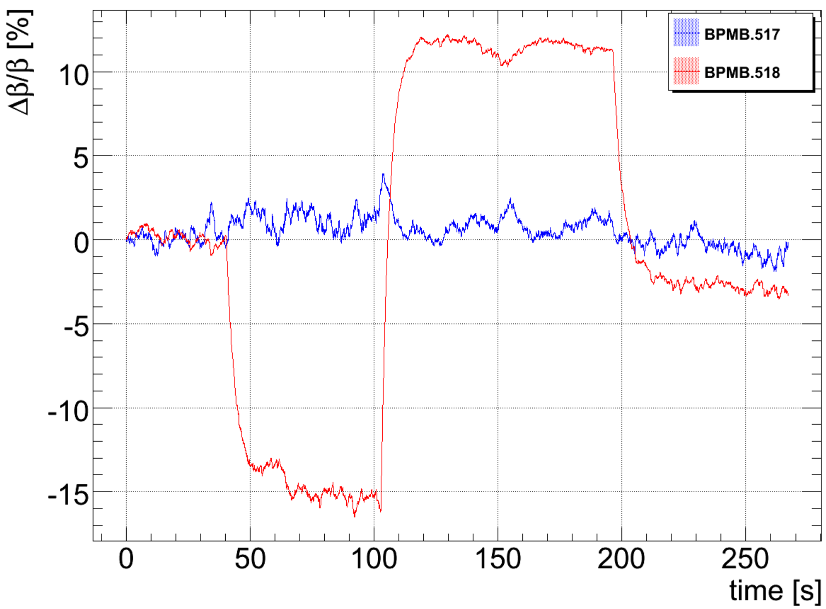
- Alternative to mixing method: Wavelet Transform, IIR Hilbert transformer
  - trade-off: higher bandwidth ↔ lower phase precision

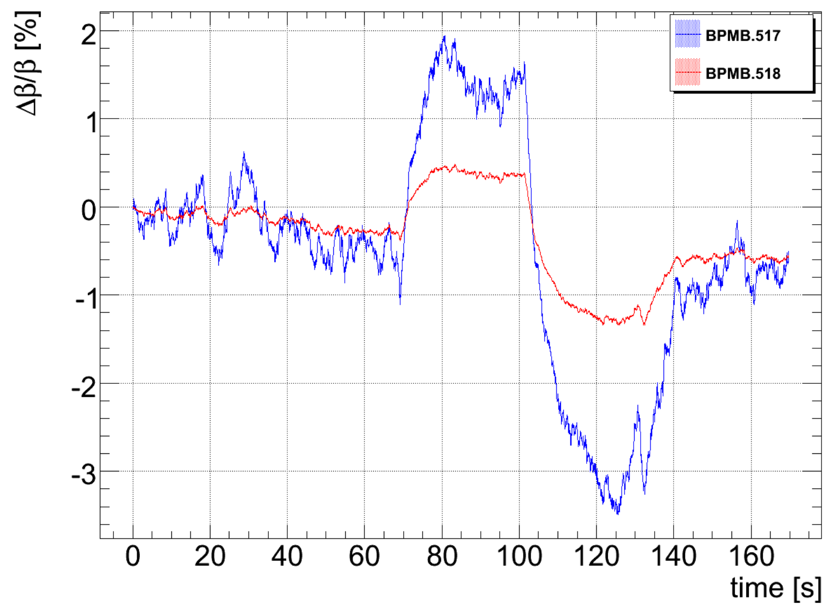
QE.603/QE.604 induced β-Phase-Advance Beating



QE.603/QE.604 induced β-Beating

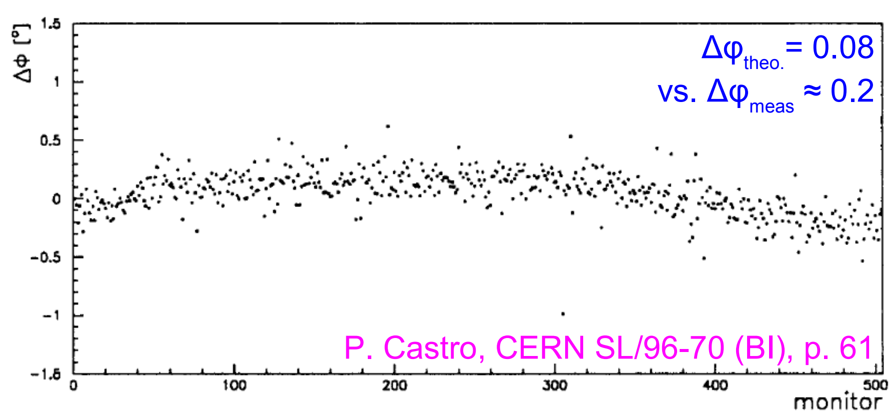
- Corresponding beta-beat: $$\frac{\Delta\beta_1}{\beta_1} = \frac{\cot(\Delta\mu_{12}^{meas.}) - \cot(\Delta\mu_{13}^{meas.})}{\cot(\Delta\mu_{12}^{theo.}) - \cot(\Delta\mu_{13}^{theo.})}$$





- 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!



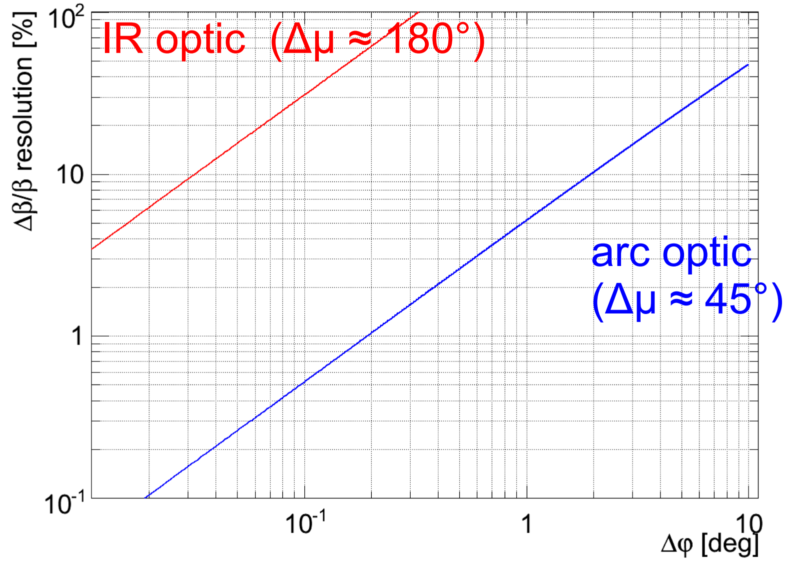
- Residual resolution/systematic error

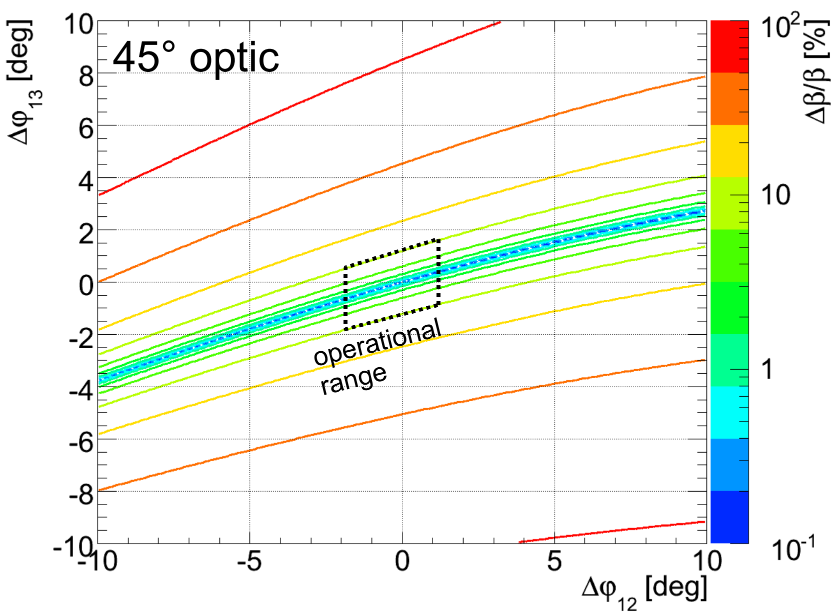
$$\frac{\Delta\beta_1}{\beta_1} = \frac{\cot(\Delta\mu_{12}^{meas.}) - \cot(\Delta\mu_{13}^{meas.})}{\cot(\Delta\mu_{12}^{theo.}) - \cot(\Delta\mu_{13}^{theo.})}$$

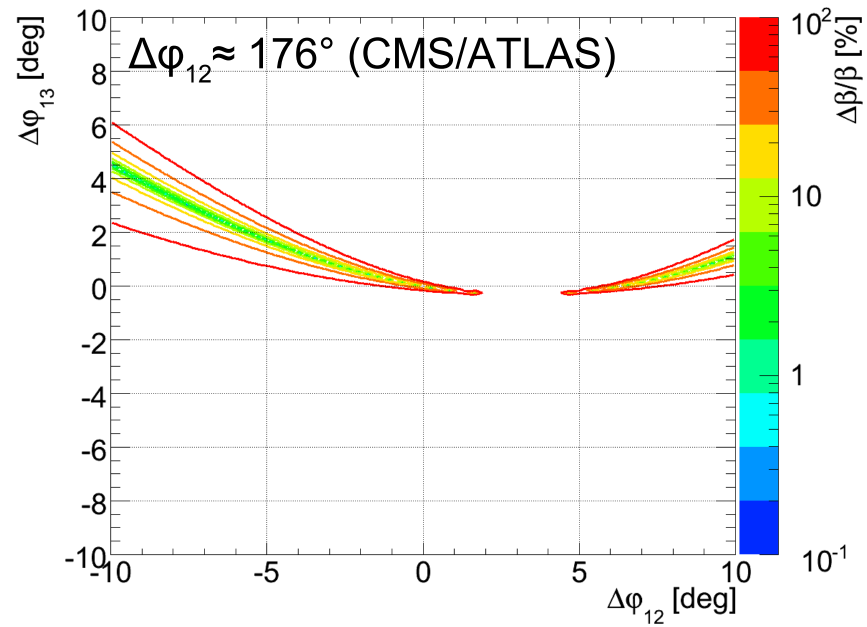
$$\Delta\mu_{1i}^{meas.} := \Delta\mu_{1i}^{theo.} + \Delta\varphi_{1i}$$

  – ARC optics: requires error below ~1°
  – IP optics: requires error below ~0.02°

N.B. Plots have logarithmic z-scale!



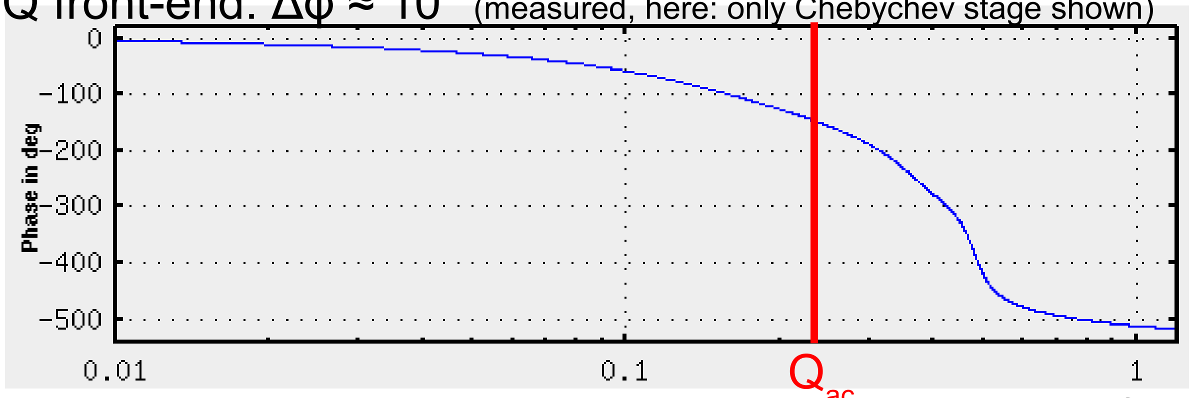




Beta-Beat Measurement Error Sources I/II
Systematic Phase Errors

- Sources – usually depend on observation/excitation frequency
  - Systematic delays: $\Delta\varphi = 2\pi \cdot \Delta\tau f$
    - Pick-up to acquisition system cable length (e.g. 100 m@ Q_{AC}=0.25 f_{rev})
      - SPS: $\Delta\varphi \approx 2°$ LHC $\Delta\varphi \approx 0.5°$: $\Delta\beta/\beta_{sys.} \approx$ 3-10% (45° lattice)

        → cable delay compensation mandatory for direct β^*-Measurements
  - Low-frequency pre-processing and analogue front-end asymmetry (mostly filters, N.B. Current has been not optimised for those issues)
    - Delta 1010 – analogue pre-filter: $\Delta\varphi \approx 7°$ (measured)
    - ADC clock synchronisation (especially across stations)
    - BBQ front-end: $\Delta\varphi \approx 10°$ (measured, here: only Chebychev stage shown)



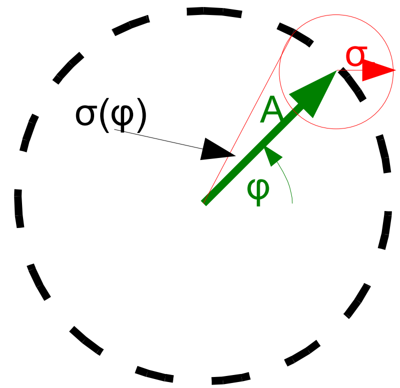
    - Systematic drift: < 0.1° → will be further reduced

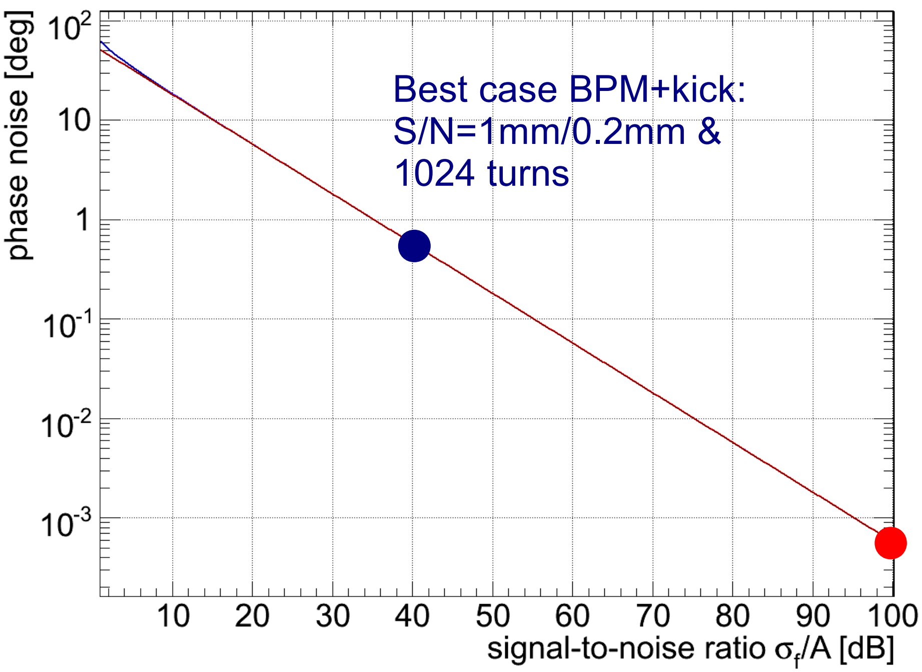
Beta-Beat Measurement Error Sources II/II
Statistical Phase Noise

- Statistical noise adds vectorial to the carrier signal:
  - excitation amplitude (carrier signal): A
  - noise in time (frequency) domain: σ_t (σ_f)
  - Equivalent number of turns: N

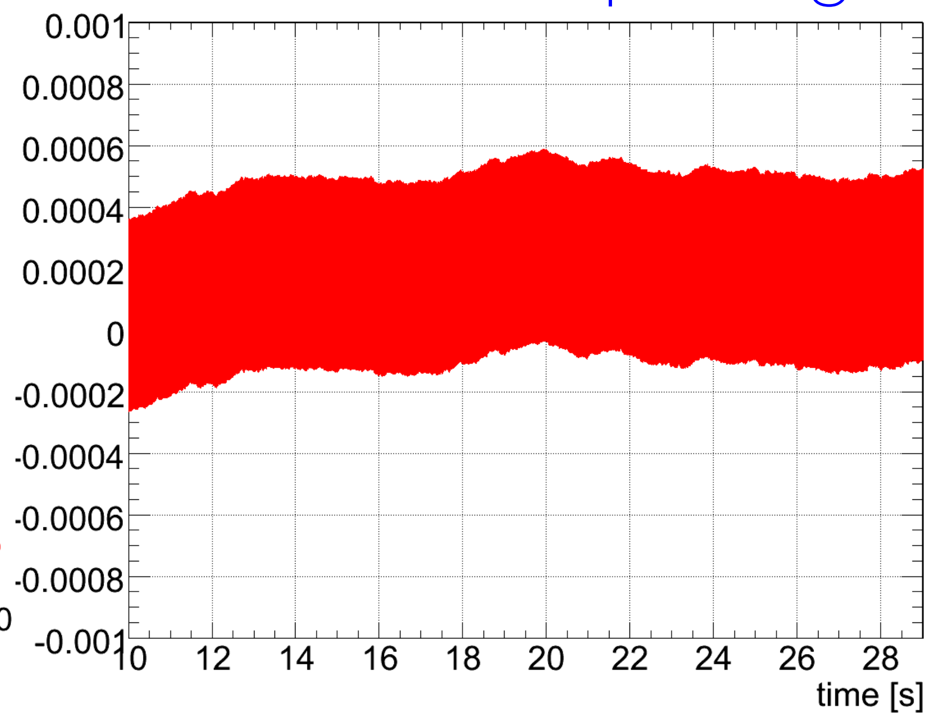
$$\sigma(\varphi) = \arcsin\left(\frac{\sigma_f}{A}\right) = \arcsin\left(\sqrt{\frac{2}{N}}\frac{\sigma_t}{A}\right)$$

for small noise to signal ratios $\approx \sqrt{\frac{2}{N}}\frac{\sigma_t}{A}$



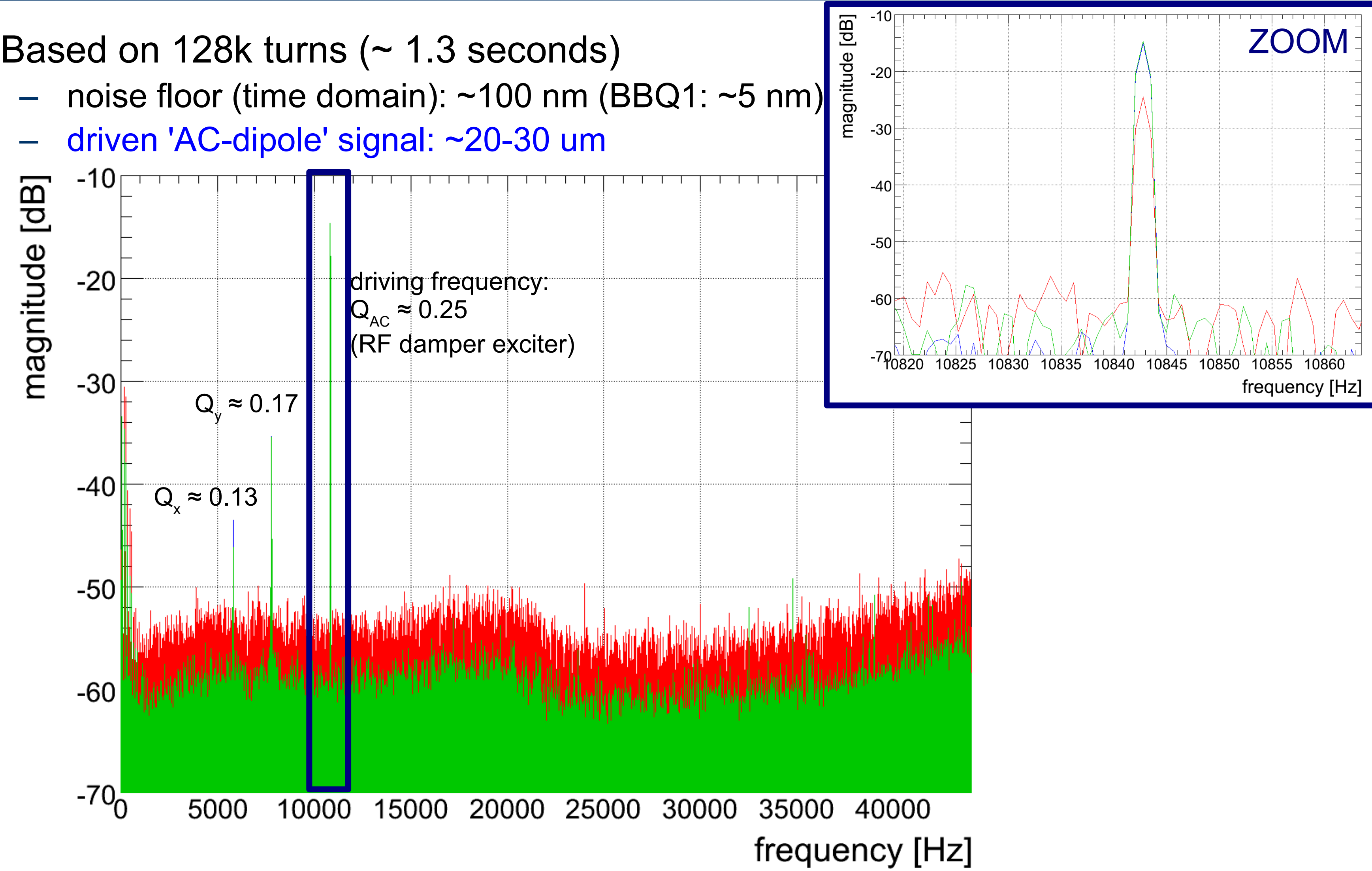


Delta 1010 intrinsic phase noise@1Hz



Typical SPS Beam Spectrum
single bunch, ~ 7 ·10^10 protons@270GeV (coasting)

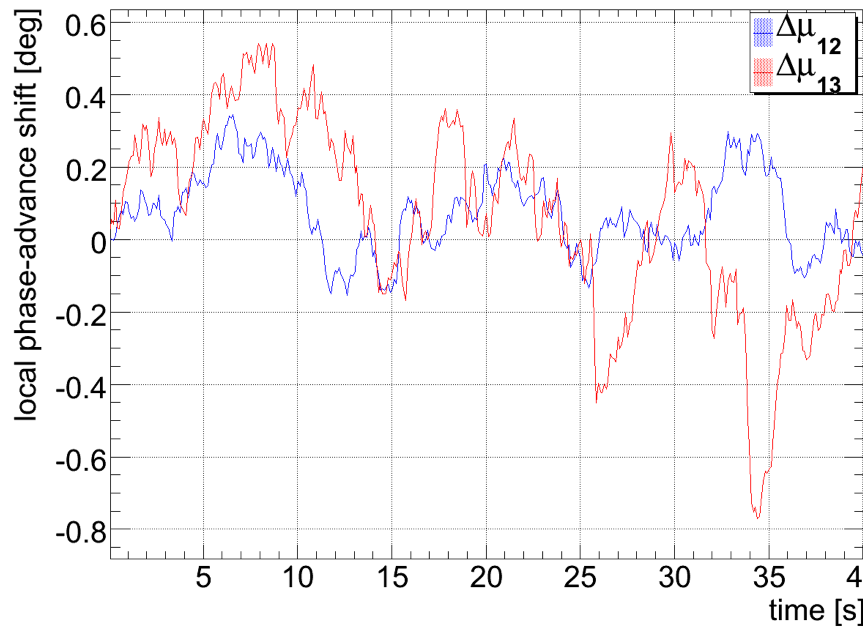
- Based on 128k turns (~ 1.3 seconds)
  - noise floor (time domain): ~100 nm (BBQ1: ~5 nm)
  - driven 'AC-dipole' signal: ~20-30 um

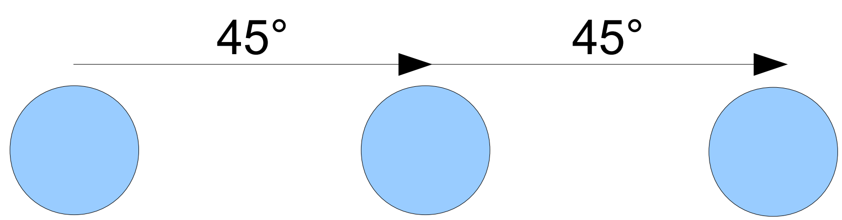


  - LHC BPMs give ~30 dB less signal than BBQ1 installation (buttons vs. 30 cm strip-line)
  - Residual tune signals ~ 0.5/2 um (calibrated w.r.t. Signal seen on SPS BPMs)
  - off-resonance excitation → no emittance blow-up

Residual Beta-Beat Drifts - Revisited

- Residual phase motion (blue: BPM1->2, red: 0.5*BPM1->3)
  - Acquisition/electronic induced noise would be “equal”/randomly distributed over all channels
  - GM induced sextupole shifts
    - $\Delta x \approx 100$ um r.m.s. $\rightarrow \Delta\beta/\beta \approx 0.1\text{-}0.2\%$
    - bit too large to be the only perturbation source...

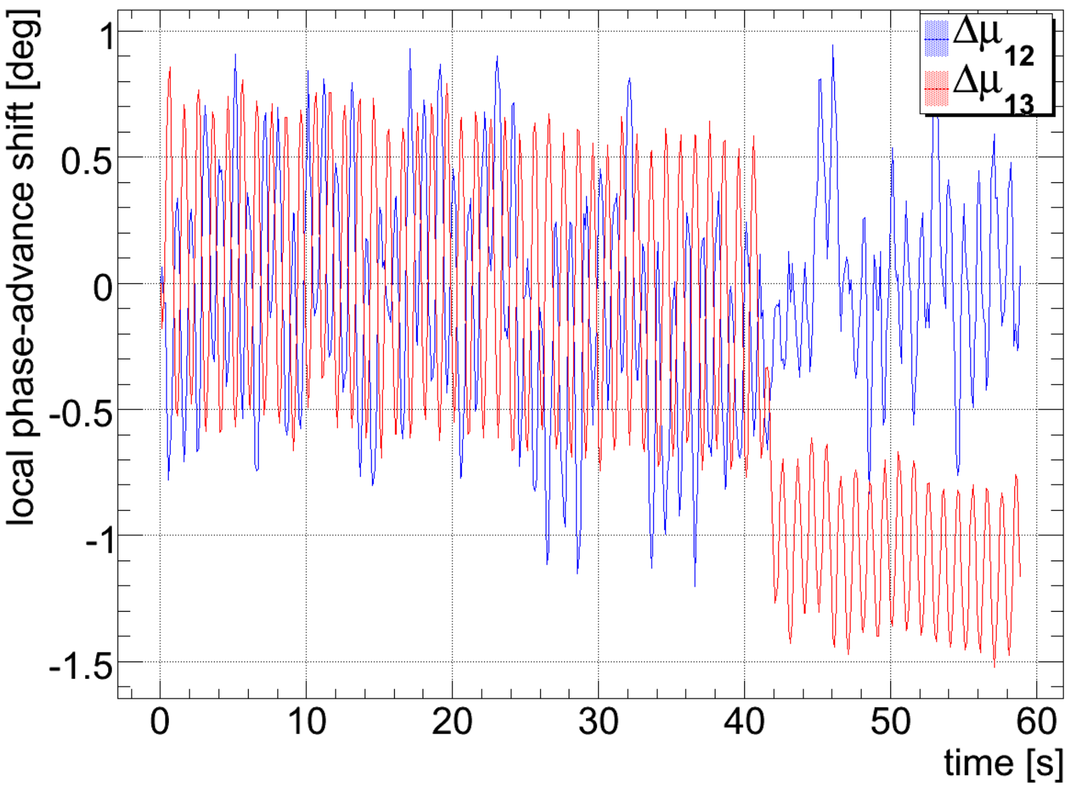




Case I: $\Delta\varphi$ → 0 ← $-\Delta\varphi$ $\Delta\mu_{12}$ =45° - $\Delta\varphi$, $\Delta\mu_{12}$ =90° - 2 $\Delta\varphi$

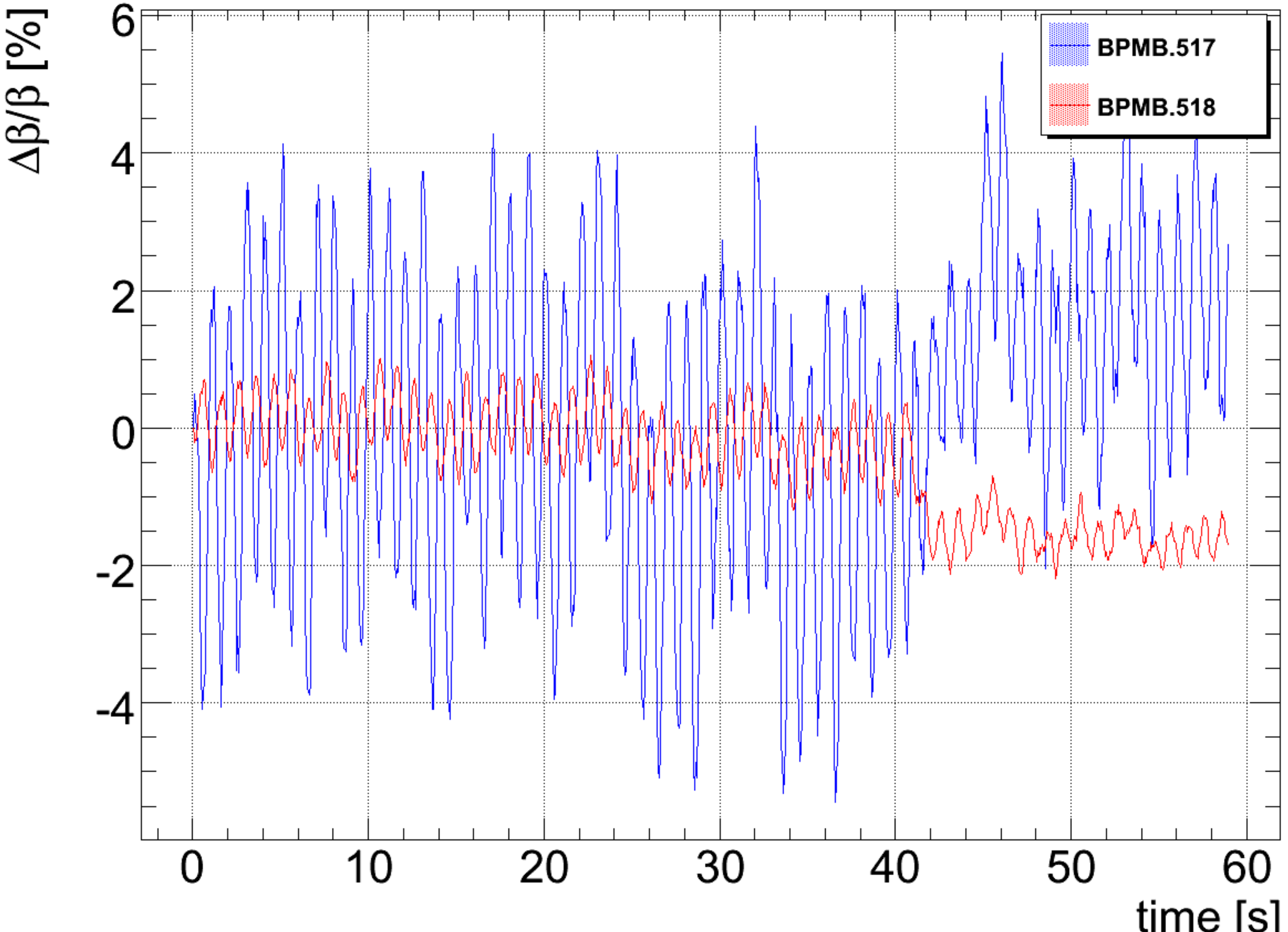
Case II: 0 $\Delta\varphi$ → 0 $\Delta\mu_{12}$ =45° + $\Delta\varphi$, $\Delta\mu_{12}$ =90°

- System can be further exploited for fast and transparent measurements of physics affecting $\Delta\beta/\beta$ that earlier required significant amount of beam time
- Example: vertical off-momentum β-Beat:
  - Continuous radial modulation: $\Delta p/p \approx 1\cdot10^{-3}$ @ 1 Hz
  - One full measurement data set every second!
  - (N.B. Step in phase → off-centre horizontal orbit in lattice sextupoles)



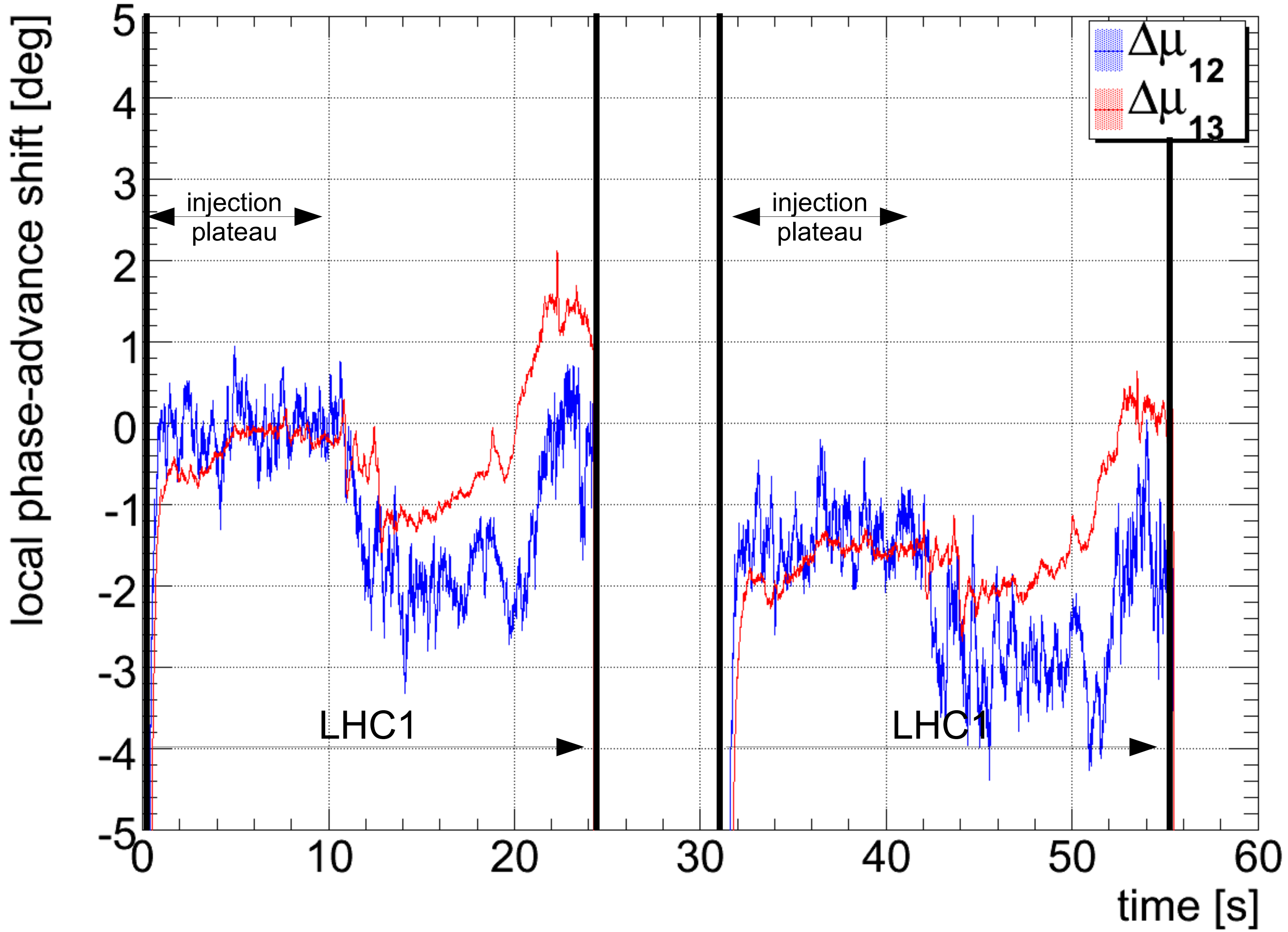
Chromatic Beta-Beating II/II

- RF modulation: $\Delta p/p \approx 1\cdot10^{-3}$ @ 1 Hz



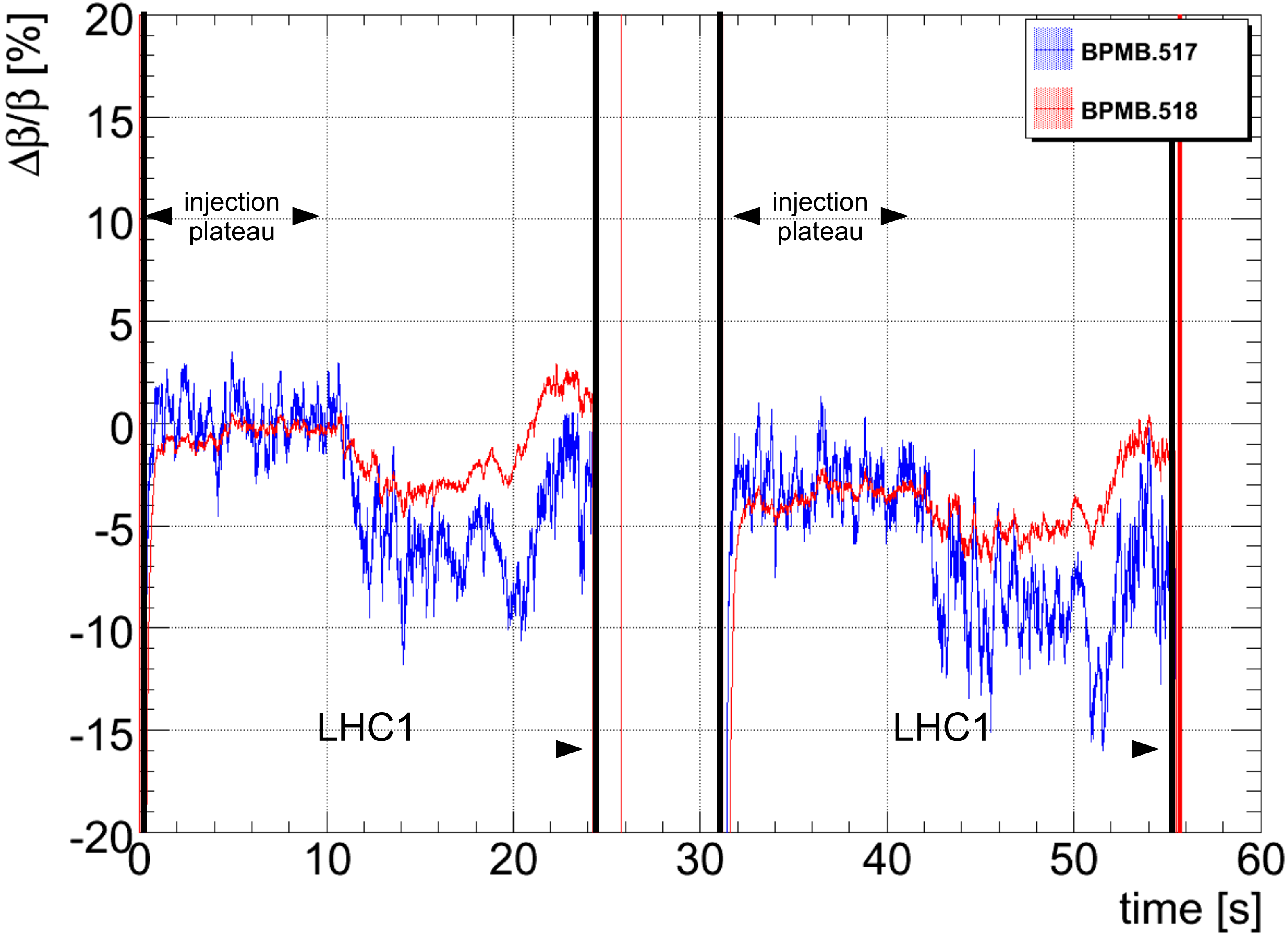
Example: SPS LHC1 Cycle-to-Cycle Stability II/II
Phase-Beating

- In between two coasts...



Example: SPS LHC1 Cycle-to-Cycle Stability II/II - Beta-Beat

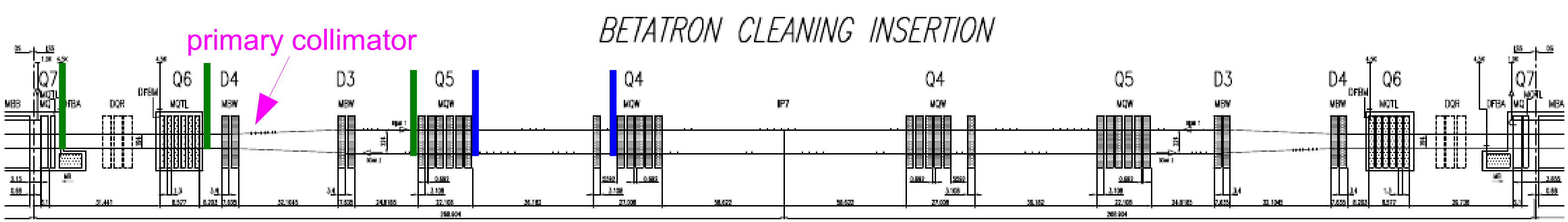
- In between two coasts...



Next Steps I/II:
Improvement to LHC Test Installations:

- Beside the intrinsic loss of signal due to the 3dB-signal splitter, initial tests show that sharing and cross-talk effects in been the regular WBTN and Beta-Beat system appears to be minimal.
  - Affects mainly performance with ultra-low intensity bunches ($<2\cdot10^9$ p/bunch)

- Further Setup Improvement:
  - systematic drifts of analogue front-end stages 0.1°/0.5 hour (β* meas)
  - Scalability and possible system integration (in view of LHC application)
  - Install 3 (+2) β-beat acquisition chains, both planes, either B1 or B2, in parallel to the regular BPM system, e.g. in LHC beta-cleaning insertion:



(c) Schematic layout IR7

→ 2009: evaluate dynamic LHC beta-beat → re-evaluate

→ larger scale/full implementation (2010+)

Next Steps II/II: Beta-beat Control

The LHC Prototype system's usefulness is two-fold:

- Provided β does not change: study real beta-beat as a function of time and use measured values to possibly relax collimation requirements
- Diagnostic and control of experimental insertion optics changes!
- Provided β does change: same as above but – in addition – use real beta-beat values as an input to a real-time feedback loop (e.g. primary/secondary collimators, IPs)
  - Correction scheme similar to LHC Orbit FB system using the dispersion suppressor's and other individually powered quadrupoles (N.B. we are not as "free" in correcting μ as for correcting the orbit)

$$\frac{\vec{\Delta}\mu}{\mu} = \underline{R}_{\mu} \cdot \vec{\delta}_{DS} \quad \overset{SVD}{\longrightarrow} \quad \vec{\delta}_{DS} = \underline{\tilde{R}}_{\mu}^{-1} \cdot \frac{\vec{\Delta}\mu}{\mu}$$

  - Additional regions of interest: experimental insertions, Inj./Extr. , ...
- The possible merit...
  → remove/reduce protection/cleaning limitations on β* & stored intensity

"Isn't this worth being further investigated?" → confirmed by APC, LCC

Conclusions

- A real-time β-beat measurement system has been successfully tested at the SPS based on the continuous measurement of the cell-to-cell phase advance.
  - Achieved resolution: $\Delta\beta/\beta < 1\%$ @ 1 Hz measurement bandwidth
  - Required S/N ratio: ~ 20 µm/100 nm → ε blow-up is a non-issue
    - compatible with nominal LHC operation
  - Shared pick-up scheme compatible with regular WBTN function

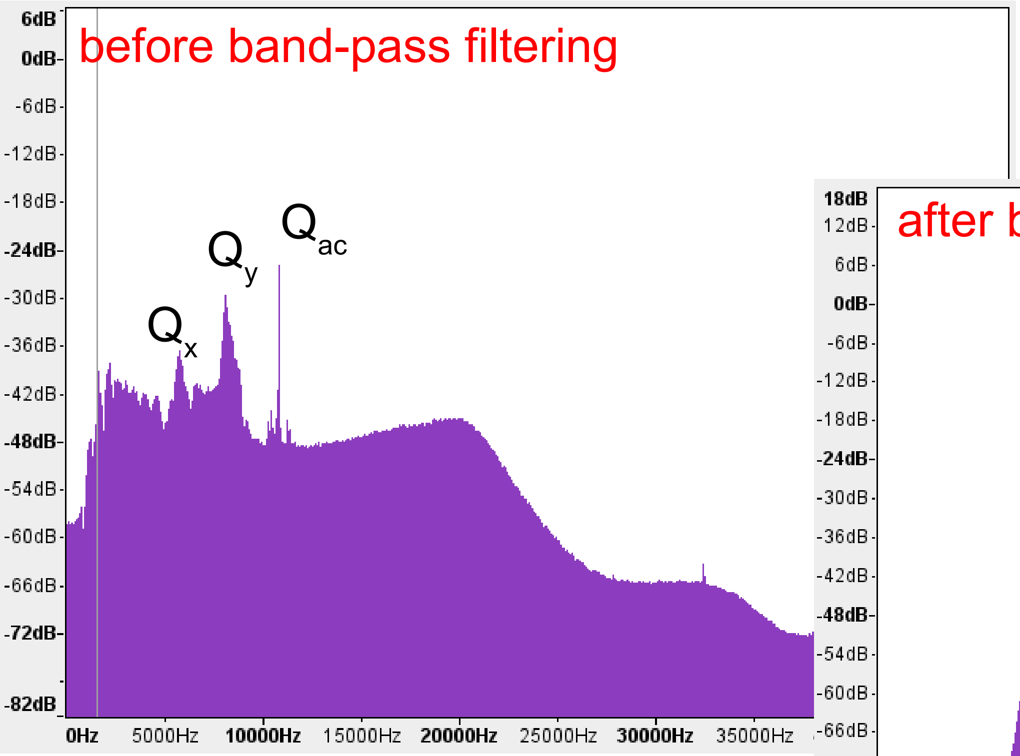
- Measured residual 1% drift of SPS lattice and off-momentum beta-beat
  - Diagnostic of higher-order fields (chromatic β-Beat, single-turn Q, ...)

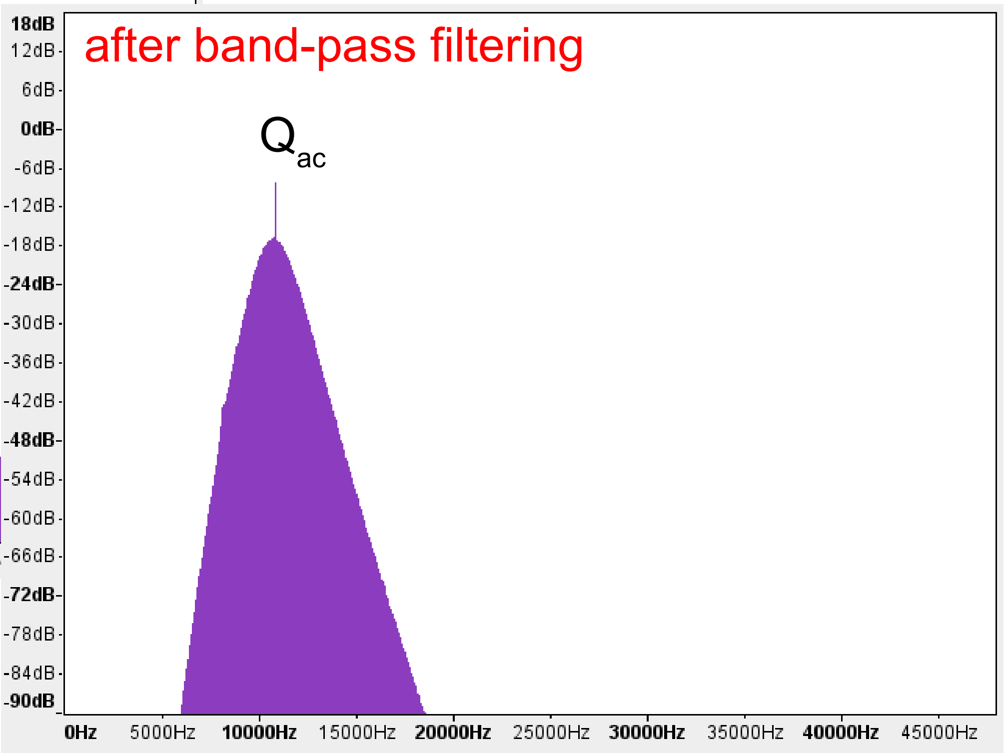
- Present limitations of the system:
  - 45° optics (LHC arcs): < 0.01° ↔ $\Delta\beta/\beta \ll 1\%$ @ 1Hz bandwidth
    - residual beta-function stability and S/N ratio
  - Exp. Insertion optics: ~ 0.1° ↔ $\Delta\beta/\beta \approx 30\%$ ($\Delta\mu_{12} \approx 178°$)
    - systematic phase and drifts, can be improved, target: $\Delta\beta/\beta_{IP} \approx 3\%$
  - Systematic phase (drifts): ADC clock across stations that are km apart
  - Controls & integration: radiation hardness, pulling of cables, …

additional supporting slides

Example: SPS LHC1 cycle-to-cycle stability necessary correction

- Fourier Spectrum before and after band-pass filter (carrier at 10.8 kHz)





Impact of Sharing the same Button Pick-up – Disclaimer I/II

- Tests with beam in the SPS indicate that there is no obvious cross-talk in between the regular LHC WBTN (orbit) and the tested diode-based acquisition electronic used for the continuous beta-beat measurement.

- However: sharing intrinsically halves signals seen by the acquisition chain
  - Reduced minimum intensity detectable by button-type BPM ($2 \rightarrow 4 \cdot 10^9$)
    - Only relevant for IR7, may be less of an issue:
      - redundancies in IR7: multiple BPMs per cell & collimator
      - only affected for below pilot intensities ($< 2.6 \cdot 10^9$ p/bunch)
    - N.B. Not an issue for strip-line pickups and/or nominal beam:
      - signals are attenuated simplify intensity gain-switching

- If this proves to be really an issue, installation of additional pick-ups in the region of interest may be required.

Impact of Sharing the same Button Pick-up – Disclaimer II/II

- 3 dB splitter transfer function (variation in between splitter → ~ 50-100 um)

- Effects on orbit, Energy, Tune, Q' and C⁻ can essentially cast into matrices:

$$\Delta\vec{x}(t) = \underline{R}\cdot\vec{\delta}(t) \quad with \quad R_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2\sin(\pi Q)}\cdot\cos(\Delta\mu_{ij} - \pi Q) + \frac{D_i D_j}{C(\alpha_c - 1/\gamma^2)}$$

matrix multiplication

  – LHC matrices' dimensions:

$$\underline{R}_{orbit} \in \mathbb{R}^{1070\times 530} \qquad \underline{R}_{Q} \in \mathbb{R}^{2\times 16} \qquad \underline{R}_{Q'} \in \mathbb{R}^{2\times 32} \qquad \underline{R}_{C^-} \in \mathbb{R}^{2\times 10/12}$$

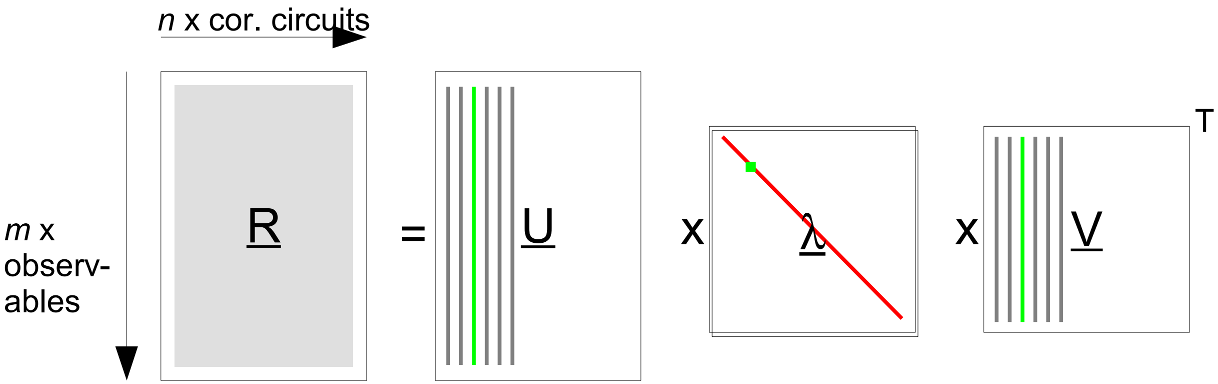
  – control consists essentially in inverting these matrices:

$$\left\|\vec{x}_{ref} - \vec{x}_{actual}\right\|_2 = \left\|\underline{R}\cdot\vec{\delta}_{ss}\right\|_2 < \epsilon \;\rightarrow\; \vec{\delta}_{ss} = \tilde{R}^{-1}\Delta\vec{x}$$

- Some potential complications:
  – Singularities = over/under-constraint matrices, noise, element failures, spurious BPM offsets, calibrations, ...
  – Time dependence of total control loop → "The world goes SVD...."

Space-Domain: Singular Value Decomposition (SVD) on a slide

Linear algebra theorem*:



eigen-vector relation:

$$\lambda_i \vec{u}_i = \underline{R}\cdot\vec{v}_i$$

$$\lambda_i \vec{v}_i = \underline{R}^T\cdot\vec{u}_i$$

- though decomposition is numerically more complex final correction is a simple vector-matrix multiplication:

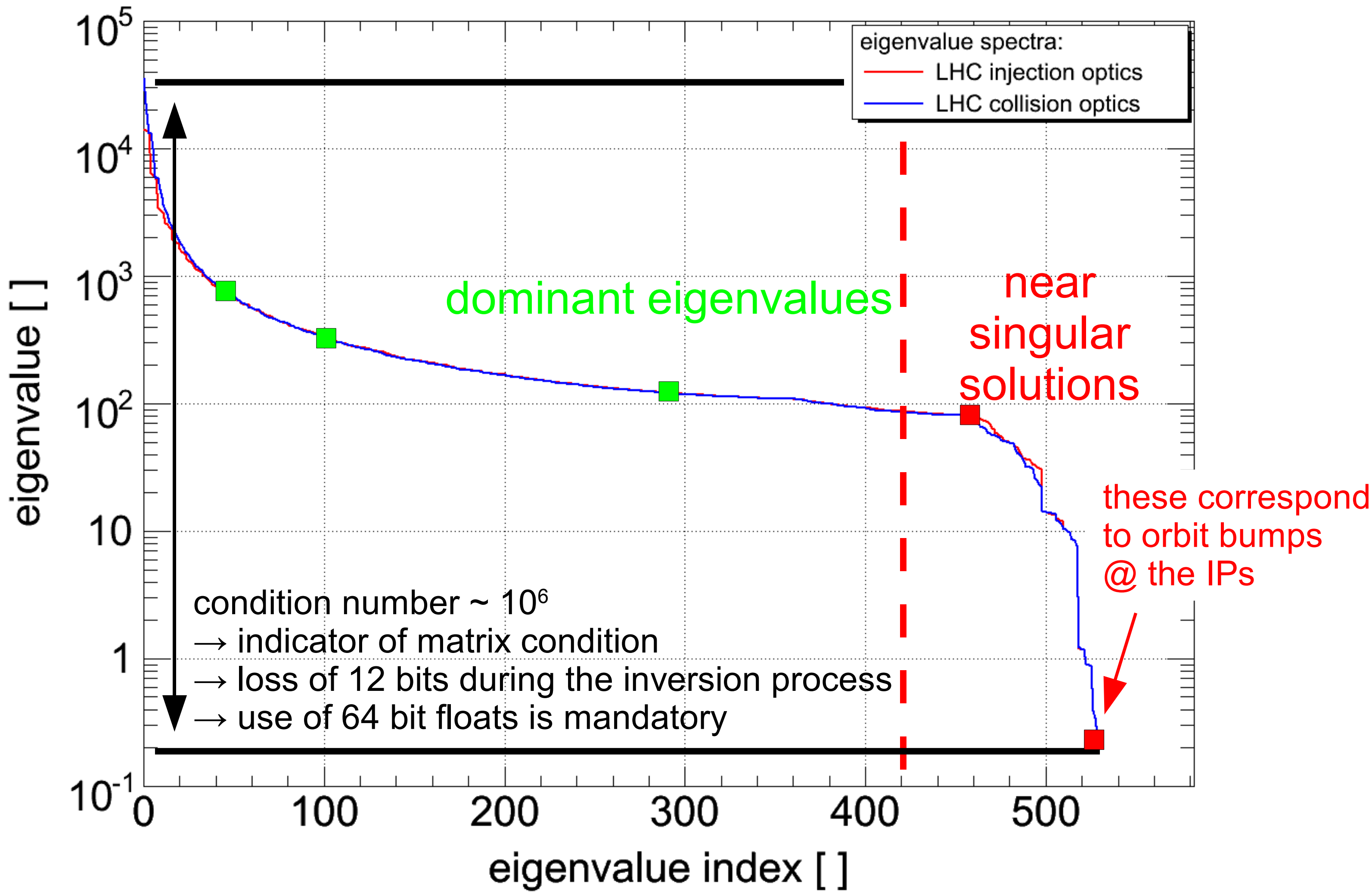
$$\vec{\delta}_{ss} = \tilde{R}^{-1}\cdot\Delta\vec{x} \quad with \quad \tilde{R}^{-1} = \underline{V}\cdot\underline{\lambda}^{-1}\cdot\underline{U}^T \quad \Leftrightarrow \quad \vec{\delta}_{ss} = \sum_{i=0}^{n}\frac{a_i}{\lambda_i}\vec{v}_i \quad with \quad a_i = \vec{u}_i^T\Delta\vec{x}$$

- numerical robust, minimises parameter deviations Δx <u>and</u> circuit strengths δ
- Easy removal of singularities, (nearly) singular eigen-solutions have λ_i~0
  - to remove those solution: if $\lambda_i \approx 0 \rightarrow$ '$1/\lambda_i$:= 0'
  - discarded eigenvalues corresponds to solution pattern unaffected by the FB

*G. Golub and C. Reinsch, "*Handbook for automatic computation II, Linear Algebra*", Springer, NY, 1971

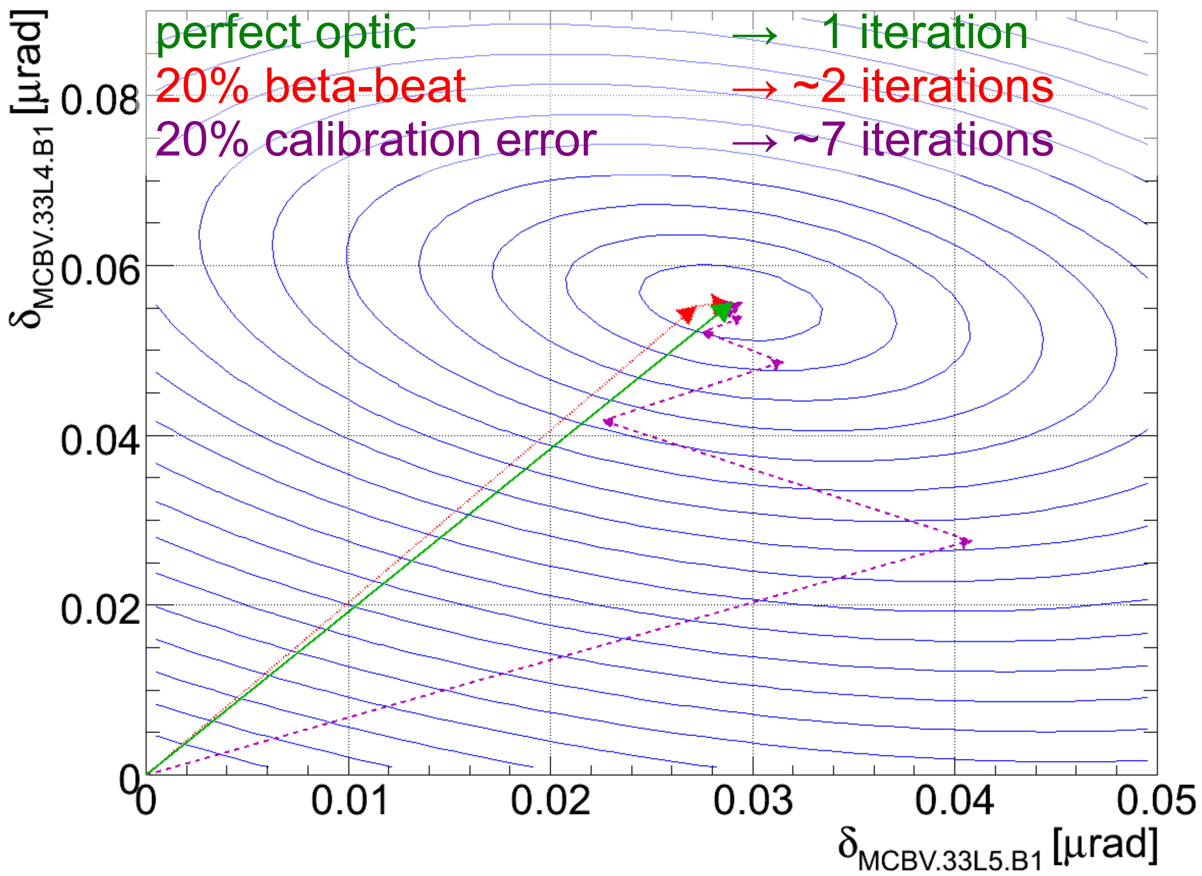
SVD example: LHC eigenvalue spectrum

Eigenvalue spectra for vertical LHC response matrix using all BPMs and CODs:

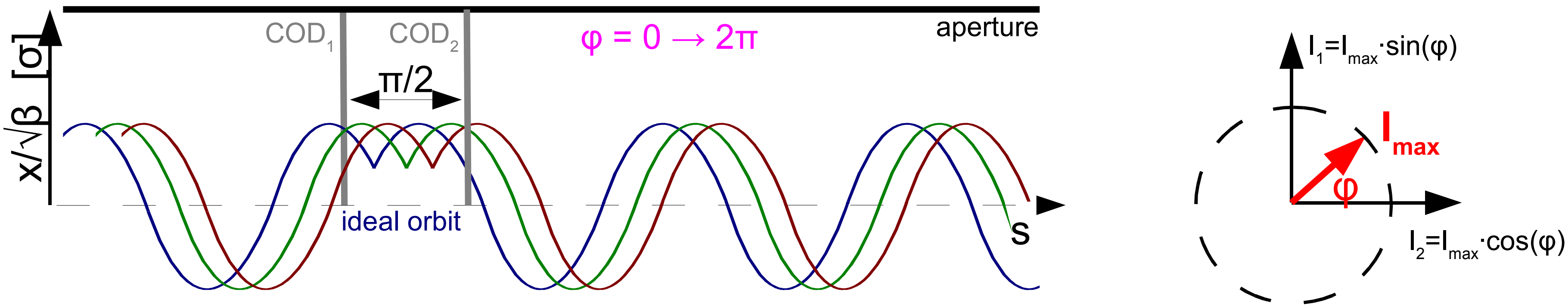


Optics and Calibration Uncertainties
Gradient Based Search Features

- Optics imperfections may deteriorate the convergence speed but do not affect absolute convergence (response functions are 'monotonic'):
- Example: 2-dim orbit error surface projection



- Scan using two COD magnets (currents: I_1 & I_2) with π/2 phase advance:

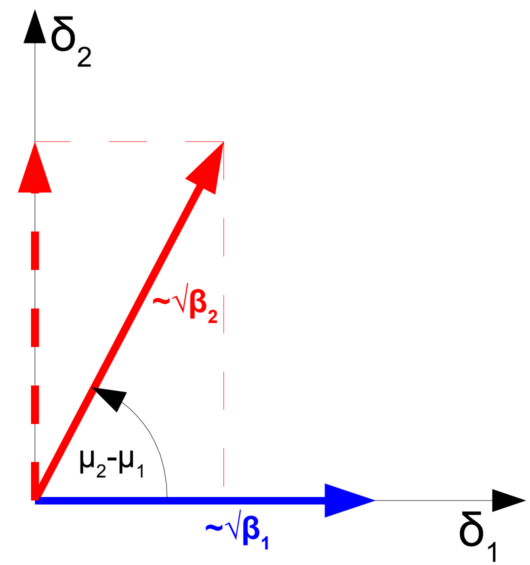


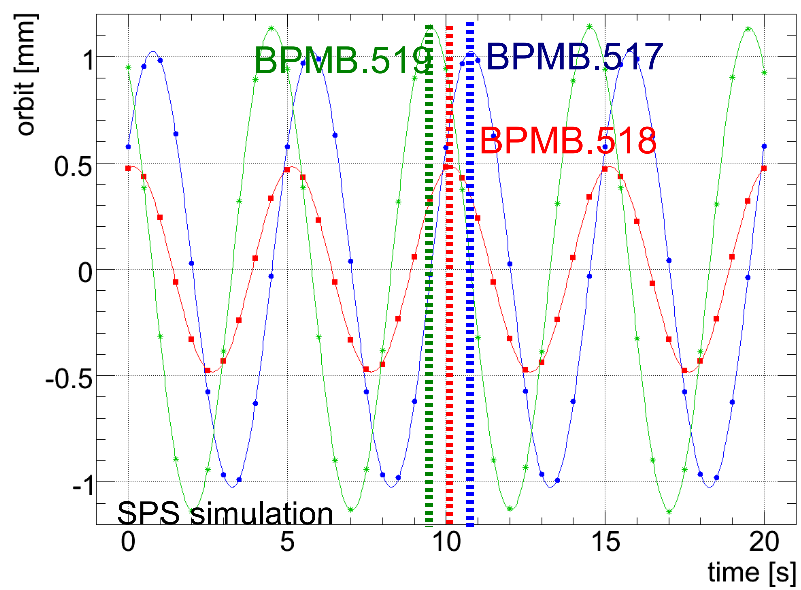
  - Scan φ = 0→n·2π, requires ~10-20 seconds/plane/beam (1 mm @ 450 GeV)
    - also required for fill-to-fill aperture and BPM calibration/sanity checks
  - Measurement idea: convert amplitude-phase to pure phase modulation
    - construct/calibrate orthonormal set of CODs
    - Rotate 2D-COD vector while monitoring real-time orbit (LHC Orbit FB)

$$\Delta x(s) \approx \underbrace{\frac{C_{BPM}(s)\sqrt{\beta(s)}}{2\sin(\pi Q)}}_{const.\ for\ s=const.} \cdot \underbrace{\begin{Bmatrix} +\sqrt{\beta_1}\cdot\cos(|\mu(s)-\mu_1|-\pi Q)\cdot\delta_1(t) \\ +\sqrt{\beta_2}\cdot\cos(|\mu(s)-\mu_2|-\pi Q)\cdot\delta_2(t) \end{Bmatrix}}_{A\cdot\sin(|\mu(s)-2\pi f\cdot t|-\pi Q+\varphi_e)}$$

→ similar treatment as turn-by-turn BPM-to-BPM phase-advance measurement

- .. a-priori insensitive to BPM/COD calibration
  (phase measurement)
- However, requires orthonormal pair of CODs, either by lattice design or via calibration:
  1. COD $\sqrt{\beta_1}/\sqrt{\beta_2}$ ratio - calibration: $\sqrt{\beta_1}\cdot\delta_1 \stackrel{!}{=} \sqrt{\beta_2}\cdot\delta_2$
     - average orbit excursion in arc, rem. systematic error is very small: ~ error on β_{avg} (N.B. Q=const!)
  2. COD1→2 phase-advance difference from 90°
     - Average k1/k2 phase using all arc BPMs (systematic: un-even BPM spacing)
- Same principle can be applied one-to-one on transfer lines





- Main idea – convert amplitude into phase modulation using trigonometric identity:

$$\cos(\alpha)\cdot\cos(\omega t)-\sin(\alpha)\cdot\sin(\omega t) = \cos(\alpha+\omega t)$$

$$a\sin(x)+b\sin(x+\alpha) = \sqrt{a^2+b^2+2\mathrm{ab}\sin(\alpha)}\cdot\sin(x+\varphi), \quad with$$

$$\varphi = arctan2(b\sin(\alpha), a+b\cos(\alpha))$$

$$\sqrt{\beta_1}\cdot\delta_1 \stackrel{!}{=} \sqrt{\beta_2}\cdot\delta_2$$

Phase-Advance Beating
Diode- & Orbit- based sampling

- True real-time (continuous) measurements
- Harmonic driven oscillation (no windowing, damping effects)
- Fast measurements: 1Hz, 10 - 20 s vs. 4-8 h/beam (LOCO)
- Operate well off-tune resonance → emittance blow-up free

Particular for diode-based method:

- Superb resolution: $\Delta\mu \approx 0.1° \leftrightarrow \Delta\beta/\beta_{res} < 1\%$
  - Diode-scheme resolution: 10-100 nm
    → required amplitude < 30 μm
- Bandwidth: ~0.1 – 10 Hz
- Compatible with nominal LHC operation
- by-product: PLL-type tune measurements
- For the time being: only local measurements
- (Sharing of pick-ups)

Particular for orbit-based method:

- Measurement resolution:
  2μm@1Hz vs. 200 μm (turn-by-turn)
- part of injection MP and BPM quality checks
- Bandwidth: ~ 0.05 – 0.1 Hz
- available at all LHC locations (BPMs)
- Very slow process (easy monitoring/less critical for machine protection)
- Ortho-normalisation of COD exciter pair
- incompatible with orbit/energy-feedback or lumi-operation (beam separation at IP)
- amplitudes still needs to be ~ tens micrometer (limit: orbit/BPM short-term stability, 5-10 μm)
- May not be compatible with nominal LHC collimation (limit: 35 μm)
- COD-to-COD phase-advance calibration