Some Notes on:

Continuous LHC Beta-Beat Measurements – Status and Prospects for 2011 –

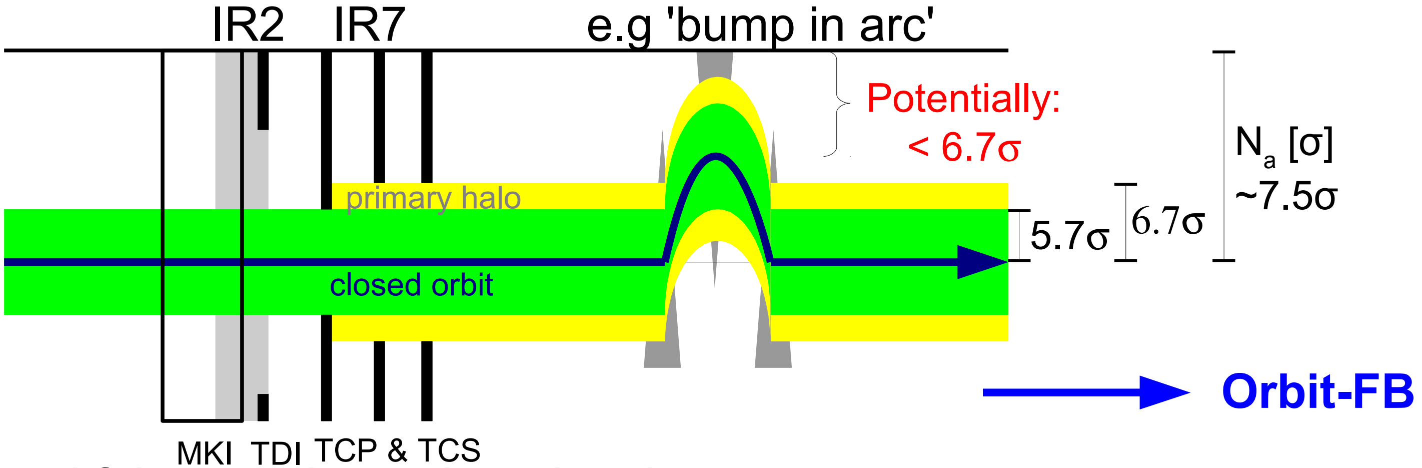
R. J. Steinhagen, A. Boccardi, E. Calvo Giraldo,
M. Gasior, J. L. Gonzalez, O. R. Jones, BE-BI

Outline

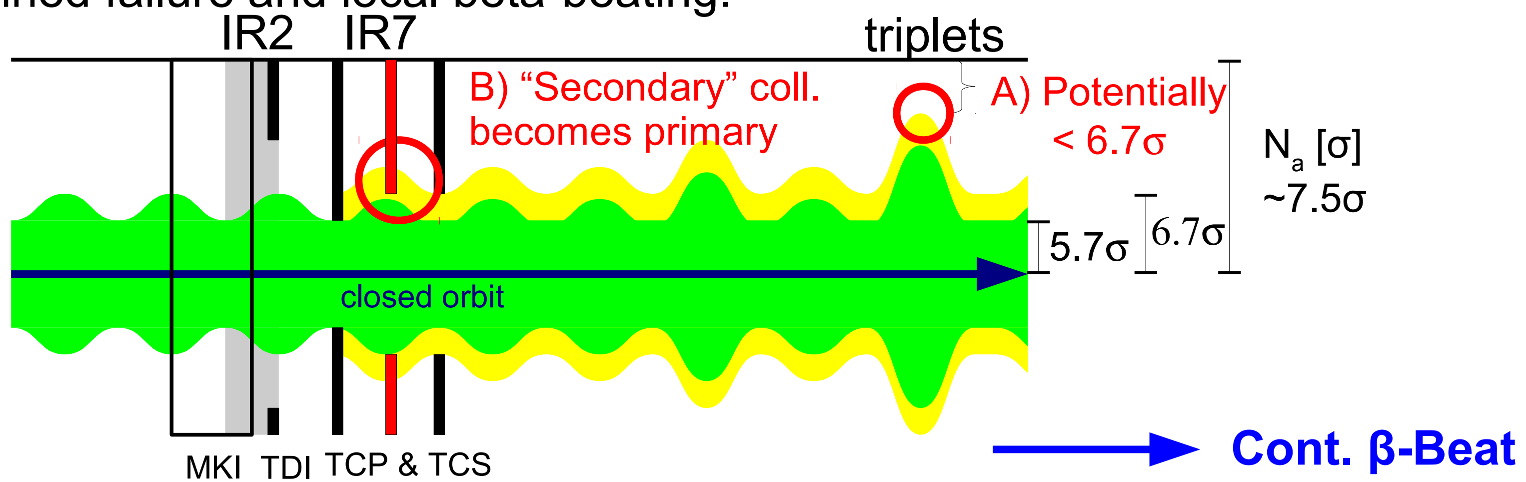
- Motivation – LHC dependence on known & constant beta-function
  - Machine Protection and Collimation, Physics, Squeeze Diagnostics
  - various existing techniques: 'kick'-type excitation & BPMs, K-modulation & Q-PLL, Closed-orbit-response (LOCO)
    - do not achieve required resolution, and/or
    - not compatible with nominal LHC operation (ex. levels/beam intensities)
- The aim of the continuous beta-beat measurement studies at the LHC was to
  - provide a proof-of-feasibility for the measurement technique, and
  - to assess magnitude and time-scale of the LHC lattice changes.
- Continuous Beta-Beat system working principle
  - difference to BPM-based acquisition
  - Fundamental constraints and limits
  - LHC installation
- Some examples taken at the SPS and LHC

Compromised Machine Protection
Local Orbit Bumps & Beta-Beating

- Combined failure and local orbit bumps:



- Combined failure and local beta-beating:

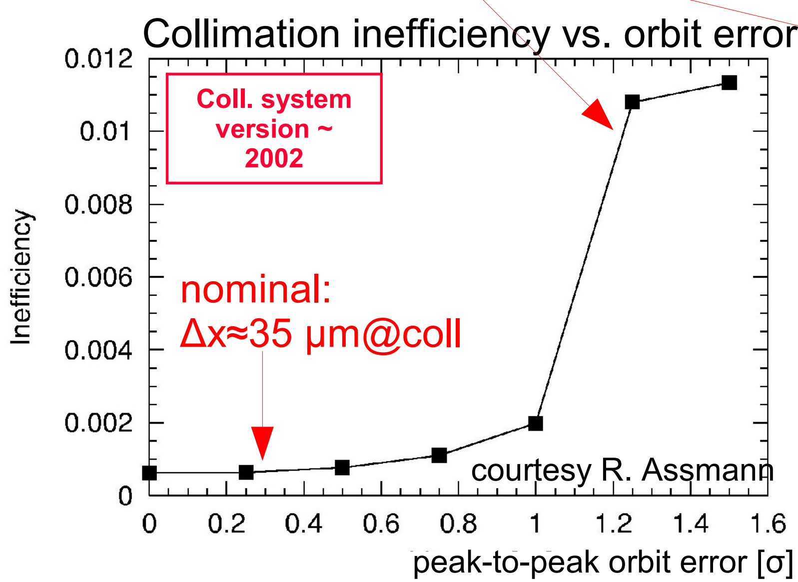


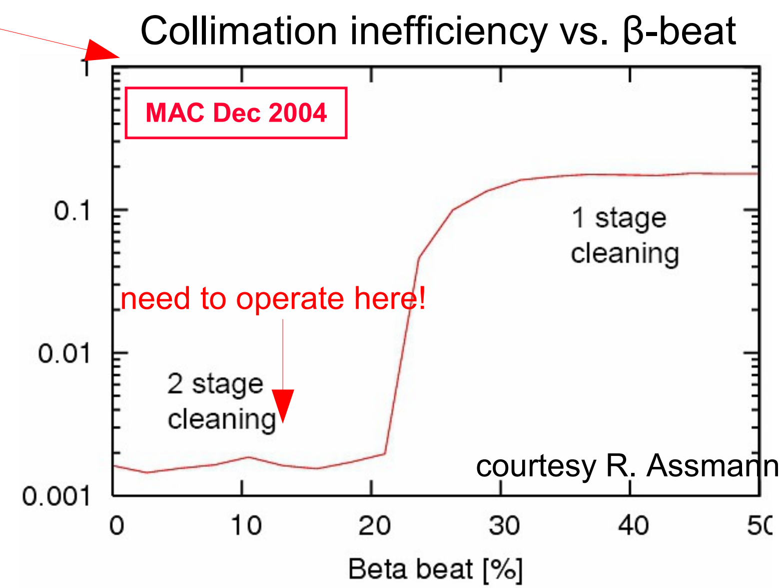
- Limits maximum safe intensity and minimum β* in the LHC
  - Mitigation: tighter collimator settings (but implies less aperture → poorer life-time)

Collimation Performance Limitations & Constraints on β*

- Two beta-beat components:
  - Static-global → AC-dipole driven + BPMs (R. Tomas et al.)
    - absorbed by the beam-based collimator alignment procedure
  - Dynamic-local → continuous beta-beat system (BI, IPAC'10)
    - check whether these requirements are kept in a fully dynamic case
      → initial installation around the primary collimators in IR7

$$N_{max} \leqslant \frac{\tau_{min} \cdot R_q \cdot L_{dil.}}{\eta} \longrightarrow L_{max} \approx \frac{1}{4\pi} \cdot \frac{N_{max} \cdot n_b f_{rev}}{\beta^* \epsilon}$$





- Nominal collimator settings also imply maximum um-level beam excursions before scraping the beam

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 & $\Delta Q^{max} < 10^{-3} \rightarrow \Delta k/k_{nom} < 5 \cdot 10^{-5}$)
    - Betatron-coupling, ...
    - Only local (& slow) measurement
  - 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 representative for nominal beam operation
      - beam will be collimated at 6 sigma (kick amplitudes < 1.2 mm @7TeV)!
    - … not ideal for continuous monitoring/regular operation (ε blow-up).
  - 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

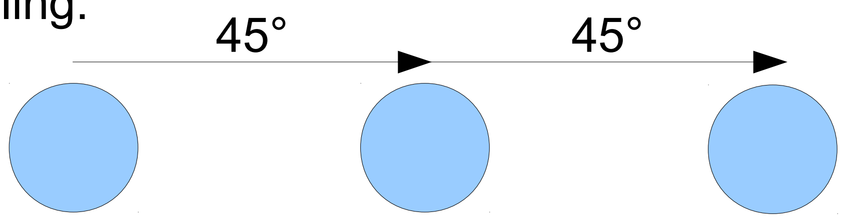
- Long history at CERN. Original idea dates back to AB-BI report (doctoral thesis)
  P.Castro, *Luminosity and Betatron Function Measurement at [..] LEP*, CERN SL/96-70 (BI)

- … beating in amplitude related to beating in phase:

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

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

- 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):

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

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

Beta-Beat Sensitivity and Error Estimates

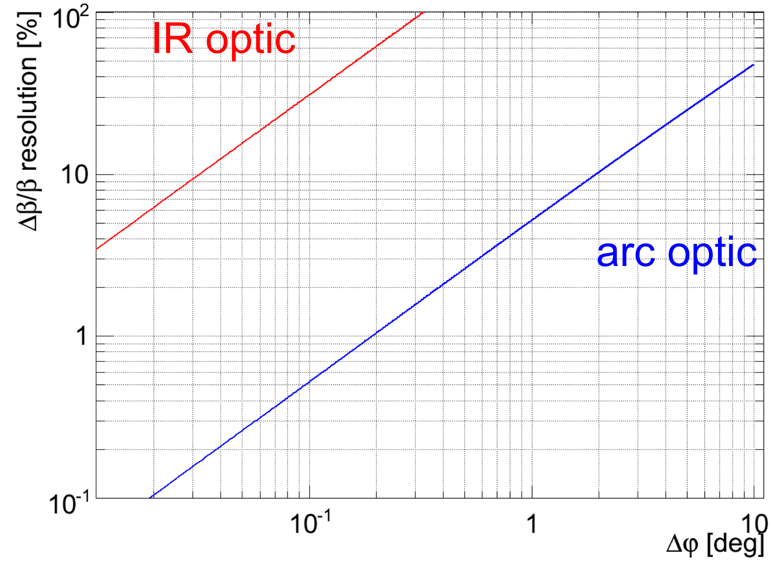
- Residual resolution/systematic error

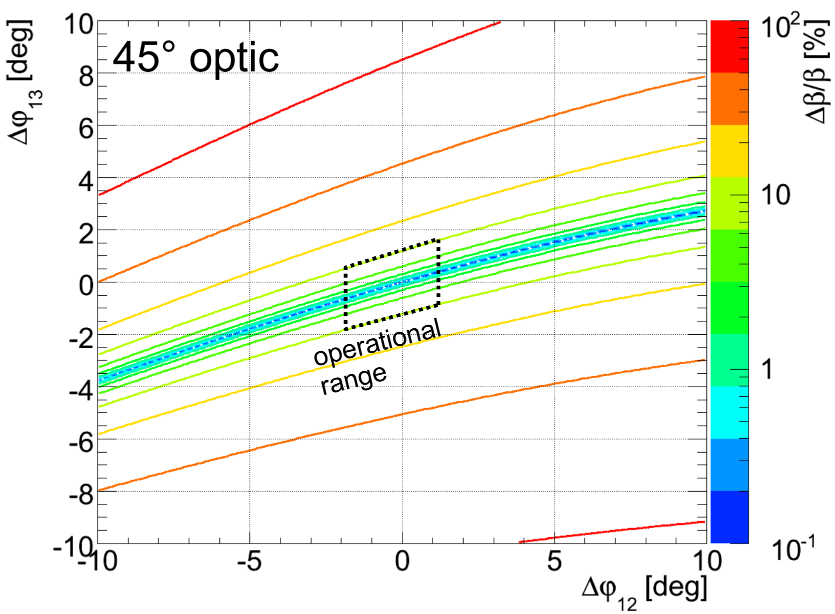
$$\frac{\Delta\beta_1}{\beta_1} = \frac{\cot(\Delta\mu_{12}^{meas.}) - \cot(\Delta\mu_{13}^{meas.})}{\cot(\Delta\mu_{12}^{theo.}) - \cot(\Delta\mu_{13}^{theo.})}$$

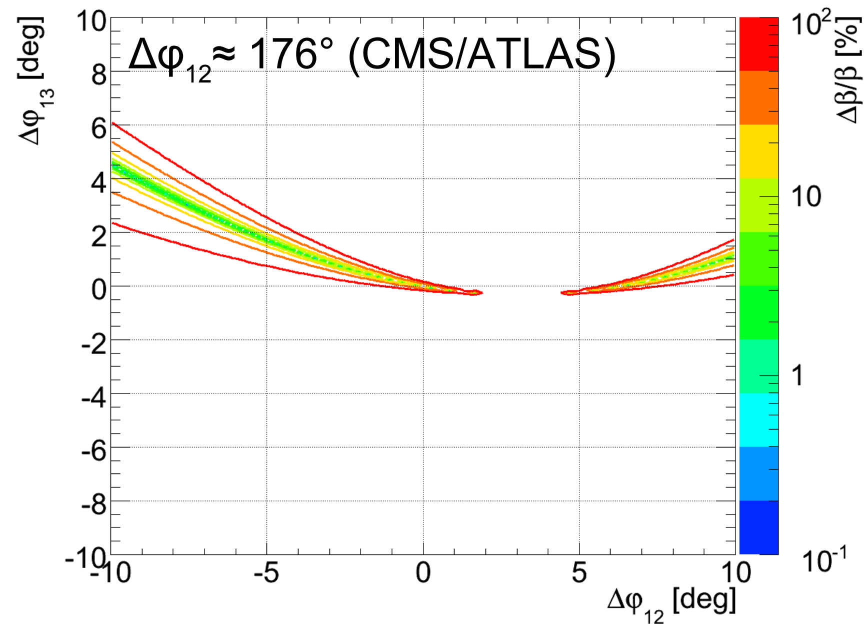
$$\Delta\mu_{1i}^{meas.} := \Delta\mu_{1i}^{theo.} + \Delta\varphi_{1i}$$

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

N.B. Plots have logarithmic z-scale!





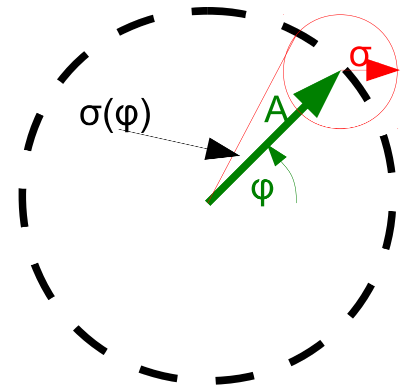


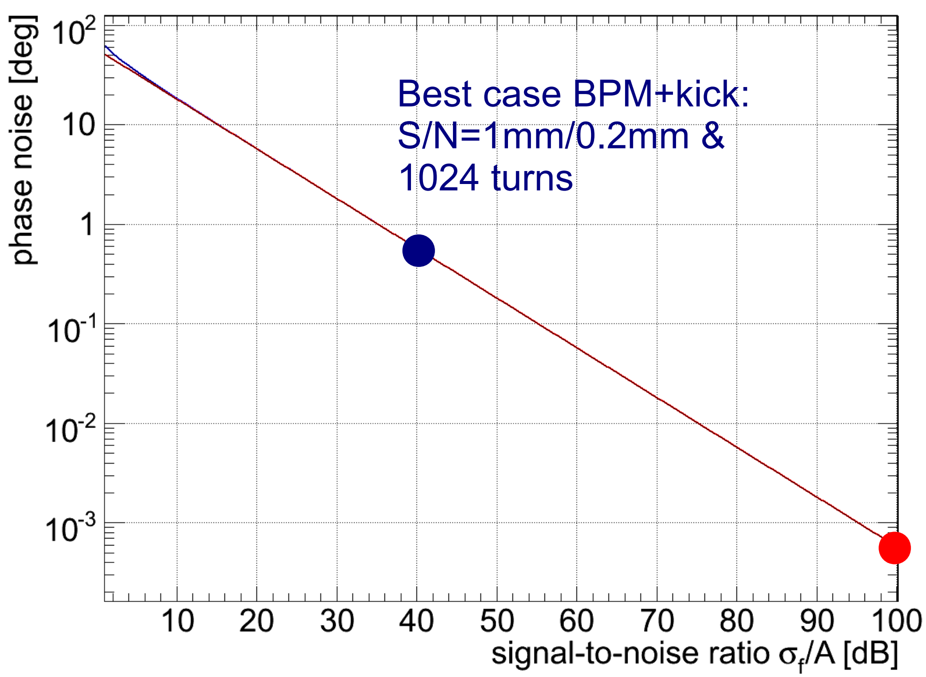
Beta-Beat Measurement Error Sources I/II
Statistical Phase Noise

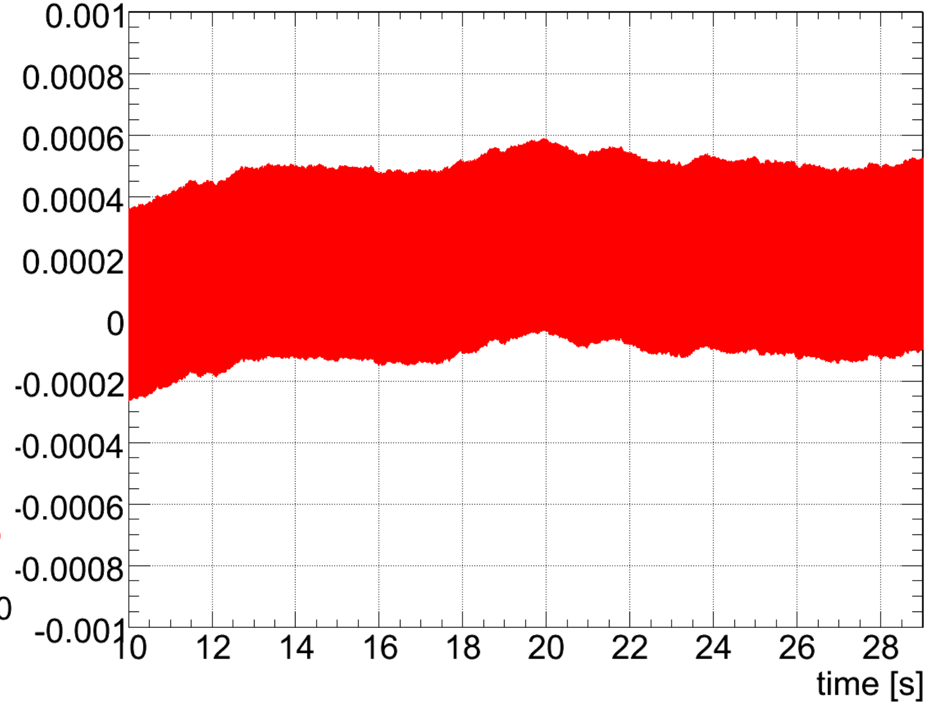
- Statistical noise adds vectorial to the carrier signal:
  - excitation amplitude (carrier signal): A
  - noise in time (frequency) domain: σ_t (σ_f)
  - Equivalent number of turns: N

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

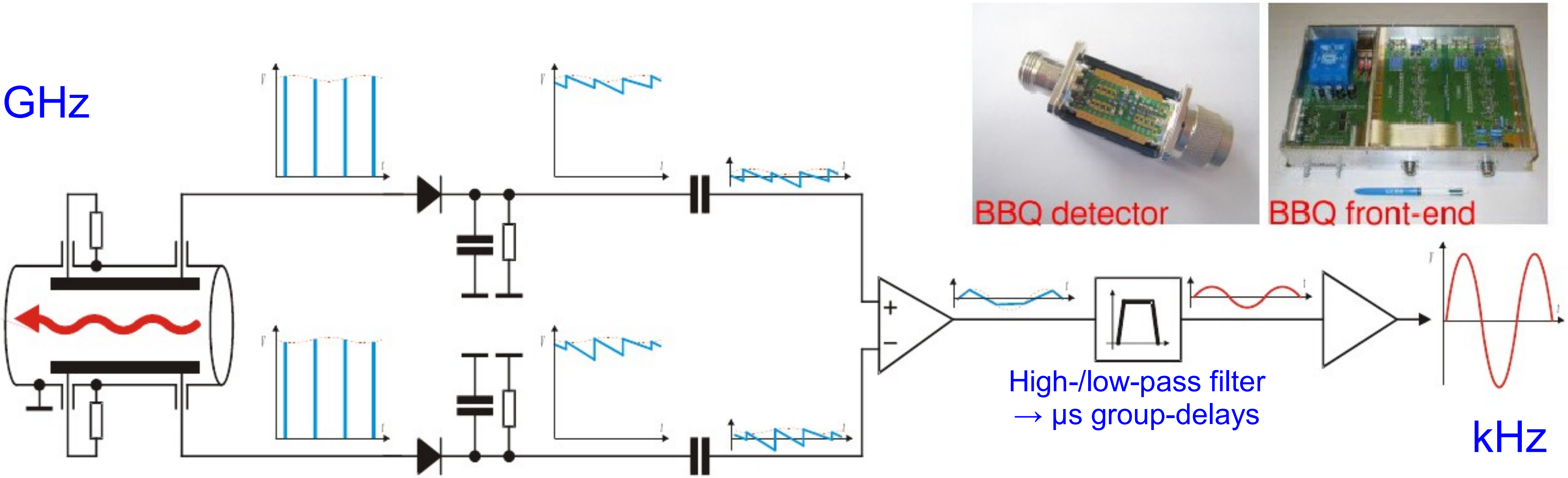
for small noise to signal ratios $\approx \sqrt{\frac{2}{N}}\frac{\sigma_t}{A}$







LHC Tune Diagnostics Instrumentation – Direct-Diode-Detection



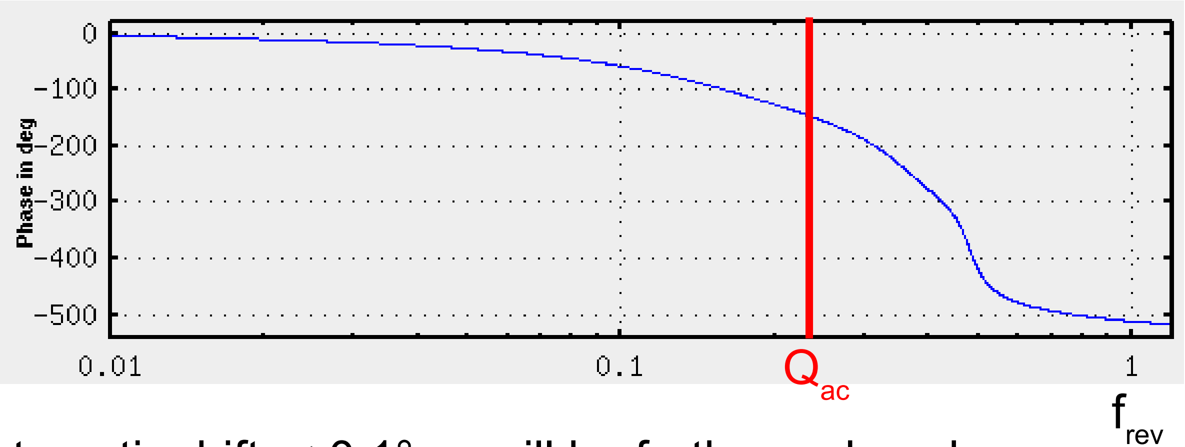
- Basic principle: AC-coupled peak detector[1]
  - intrinsically down samples beam spectra: GHz → kHz ('Base-Band-Tune Meter')
    - Base-band operation: very high sensitivity < 10 nm/turn → ε blow-up is a non-issue
  - AC-coupling removes common-mode → only relative changes play a role
    - capacitance 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

- However: BBQ ≠ Beam Position Monitor
  - Fundamentally different acq. techniques but yielding same 'phase-advance information)
  - (Analogue: TF measurement using step generator and scope vs. network analyser)

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

Beta-Beat Measurement Error Sources II/II
Base-Band Operation and Systematic Phase Errors

- Sources – usually depend on observation/excitation frequency
  - Systematic delays: $\Delta\varphi[deg] = 360° \cdot \Delta\tau f$
    - Pick-up to acquisition system cable length (e.g. 100 m@ Q_{AC}=0.25 f_{rev})
      - SPS: Δφ ≈ 2° LHC Δφ ≈ 0.5°: $\Delta\beta/\beta_{sys.}$ ≈ 3-10% (45° lattice)
    - However, is suppressed for relative beta-beat measurements
  - Low-frequency pre-processing and analogue front-end asymmetry (mostly HP/LP-filters → μs-level group delays)
    - Delta 1010 – analogue pre-filter: Δφ ≈ 7° (measured)
    - BBQ front-end: Δφ ≈ 10° (measured, here: only Chebychev stage shown)

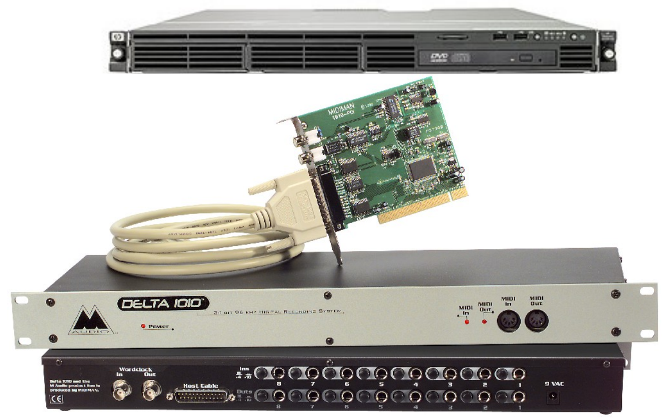


    - Systematic drift: < 0.1° → will be further reduced

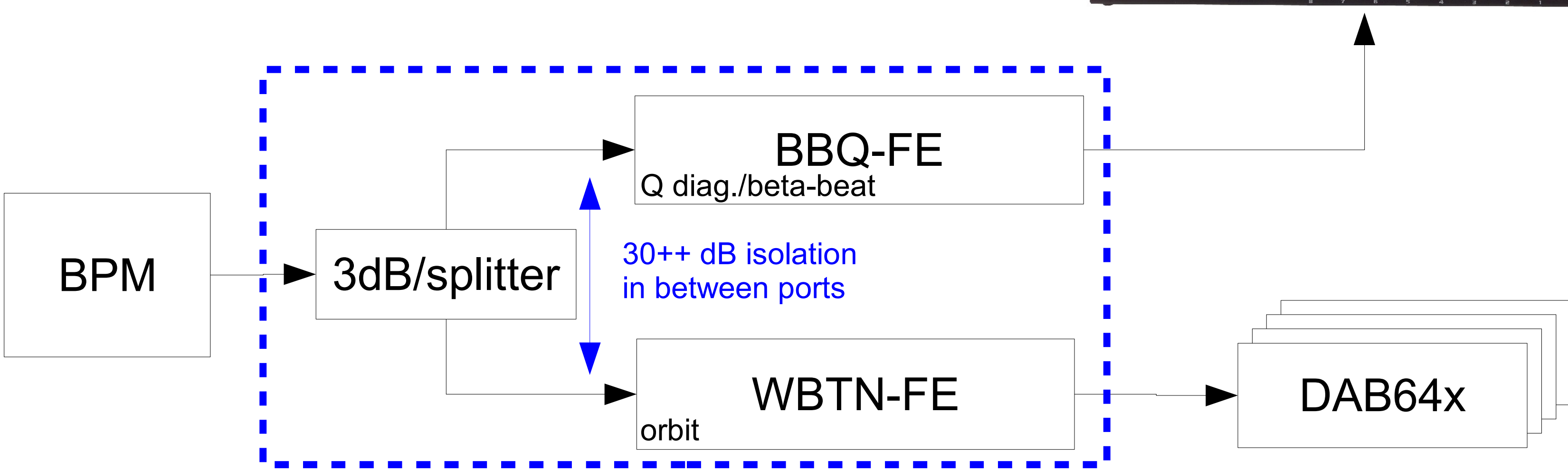
2010/11 Test Setup in the SPS and LHC

- KISS 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)
  - N.B. til-date: no single-event upsets despite being next to the primary B1 collimators

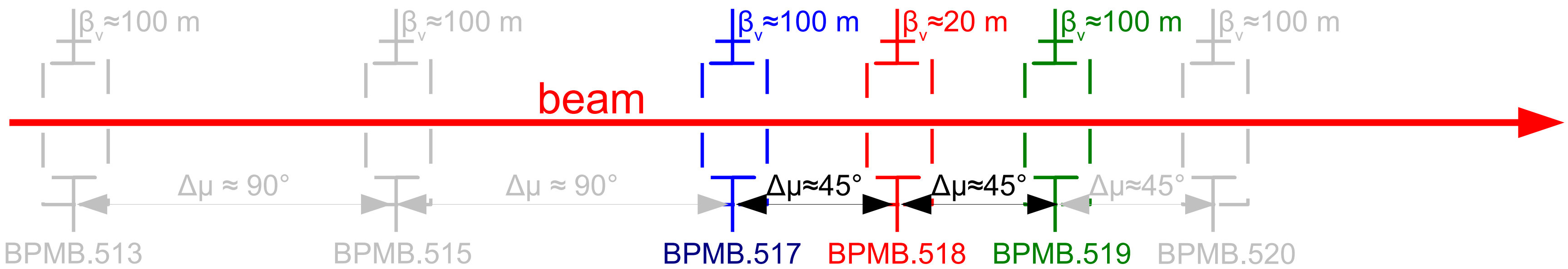
allows simple filtering and post-processing in audio domain



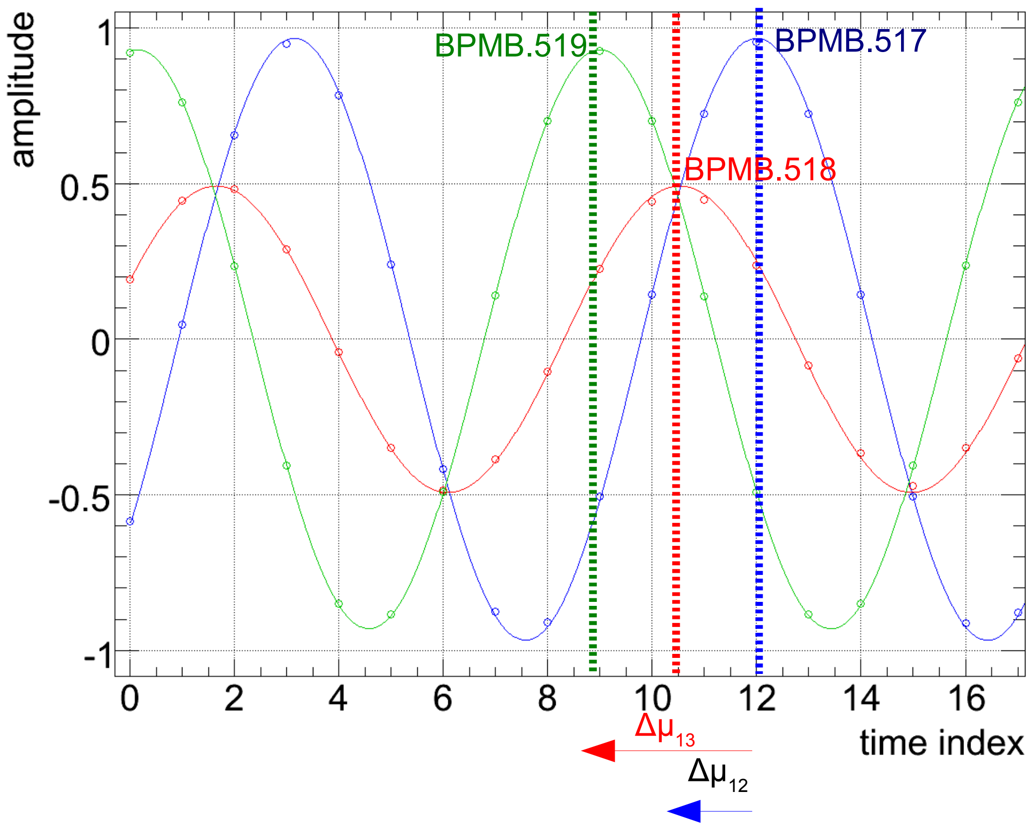
- Tests with beam in the SPS & LHC confirm that there is no obvious cross-talk in between the regular LHC WBTN (orbit) and the diode-based continuous beta-beat acquisition electronics.



Example: Beta-Beat/LHC BPM Prototype System in the SPS-LSS5



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



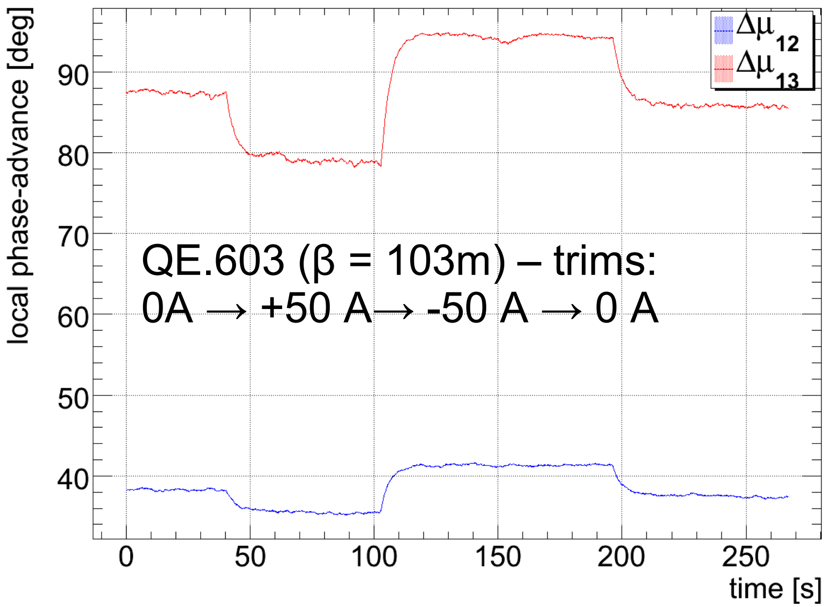
$$\frac{\Delta\beta_1}{\beta_1} = \frac{\cot(\Delta\mu_{12}^{meas.}) - \cot(\Delta\mu_{13}^{meas.})}{\cot(\Delta\mu_{12}^{theo.}) - \cot(\Delta\mu_{13}^{theo.})}$$

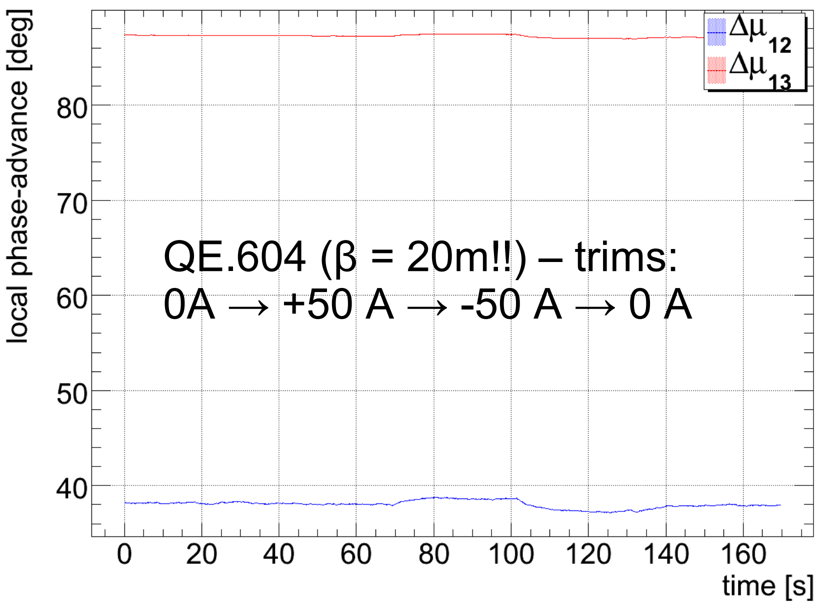
$$\frac{\Delta\beta_2}{\beta_2} = \frac{\cot(\Delta\mu_{12}^{meas.}) - \cot(\Delta\mu_{23}^{meas.})}{\cot(\Delta\mu_{12}^{theo.}) - \cot(\Delta\mu_{23}^{theo.})}$$

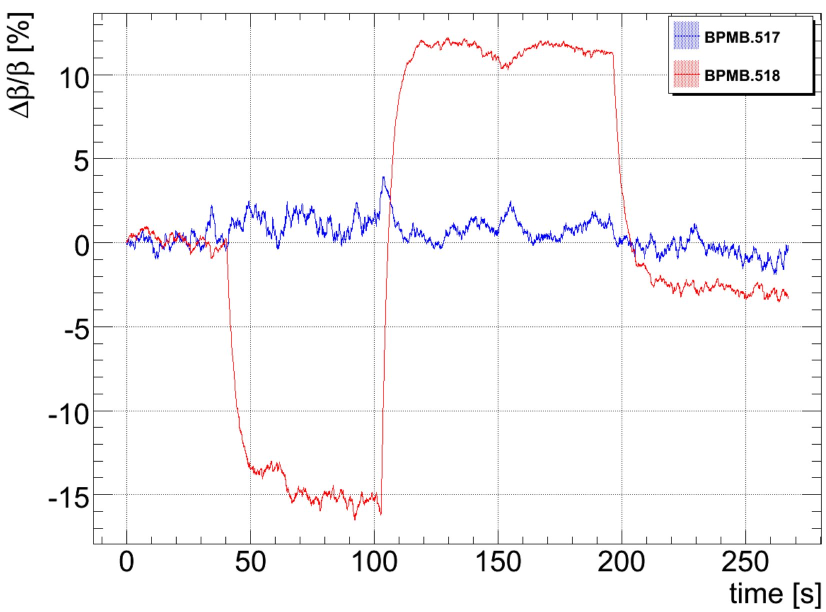
$$\frac{\Delta\beta_3}{\beta_3} = \frac{\cot(\Delta\mu_{23}^{meas.}) - \cot(\Delta\mu_{13}^{meas.})}{\cot(\Delta\mu_{23}^{theo.}) - \cot(\Delta\mu_{13}^{theo.})}$$

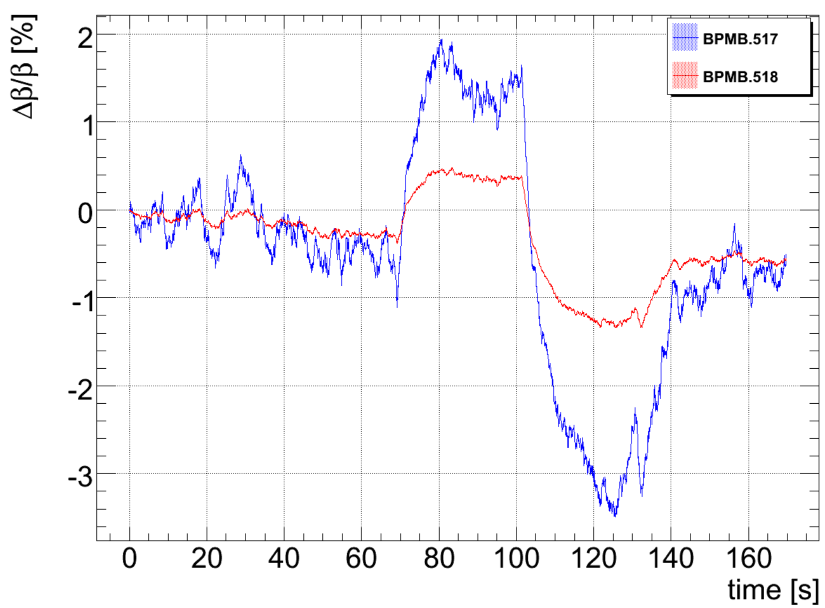
[1]P.Castro, *Luminosity and Betatron Function Measurement at [..] LEP*, CERN SL/96-70 (BI)

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

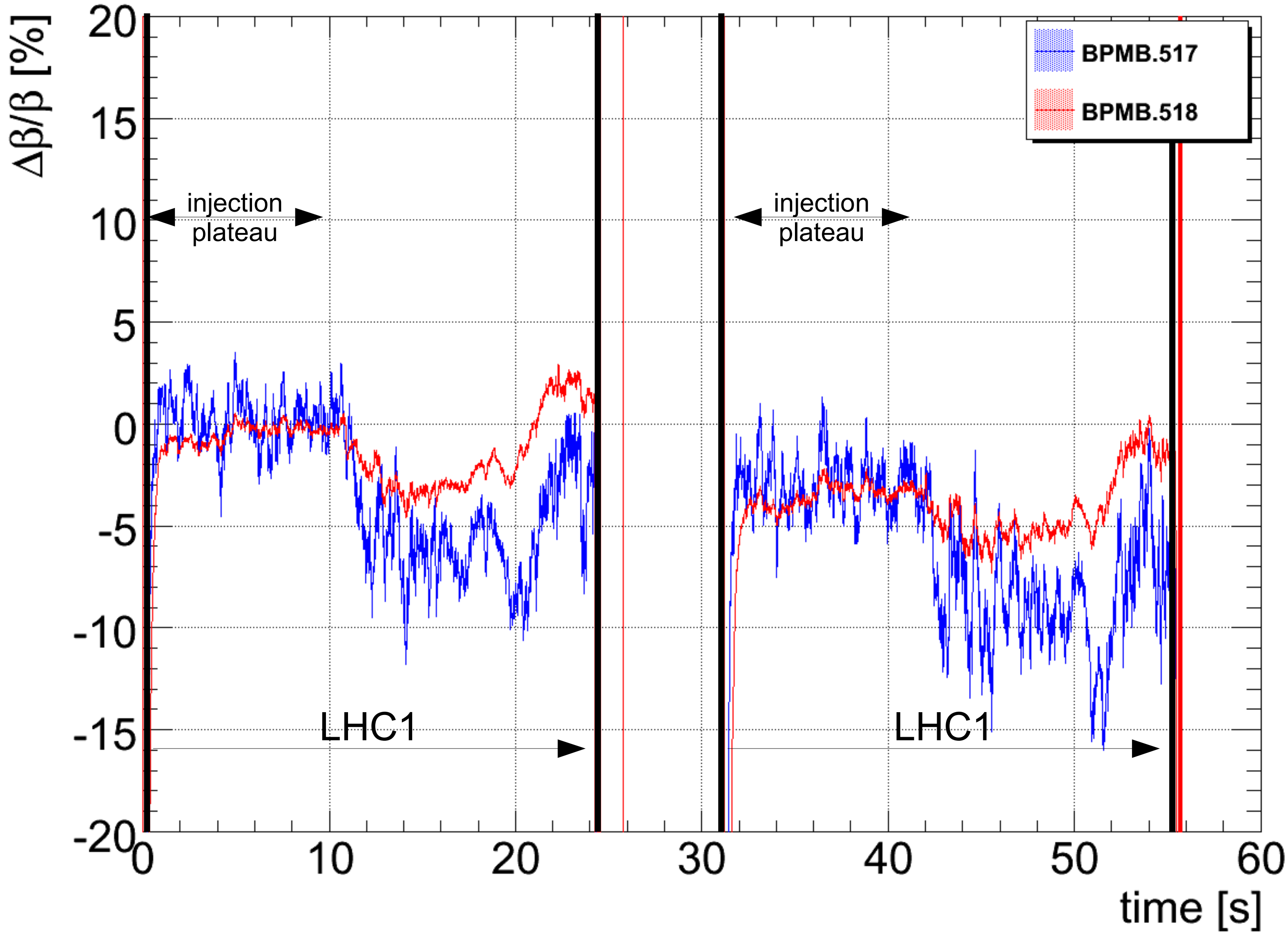






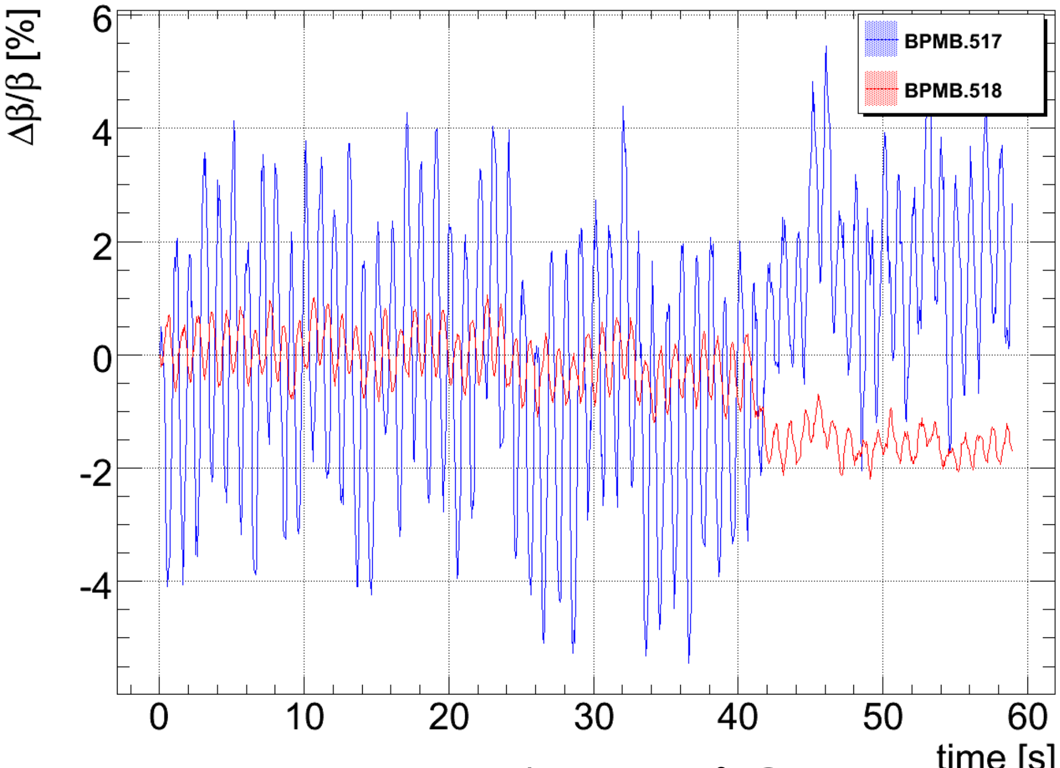


- In between two coasts...



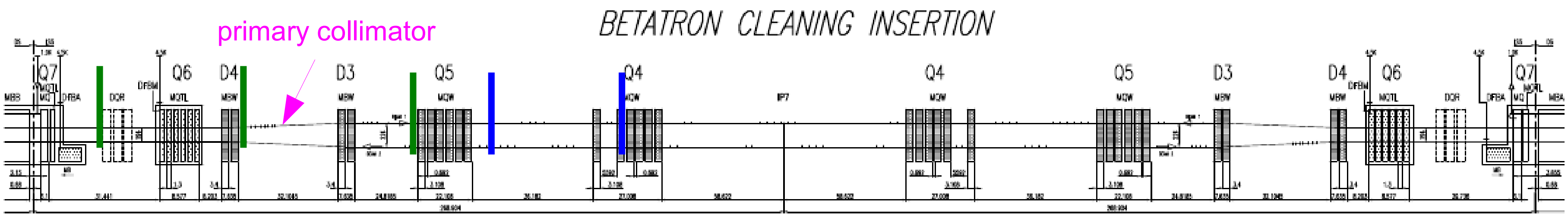
Further Exploitation Possibilities

- System can be further exploited for fast and transparent measurements of physics affecting Δβ/β that earlier required significant amount of beam time
- Example: vertical off-momentum β-Beat:



  - Continuous radial modulation: $\Delta p/p \approx 1\cdot 10^{-3}$ @ 1 Hz
  - One full measurement data set every second!
  - N.B. Step in phase → off-centre horizontal orbit in lattice sextupoles

LHC Continuous Beta-Beat Measurements Setup

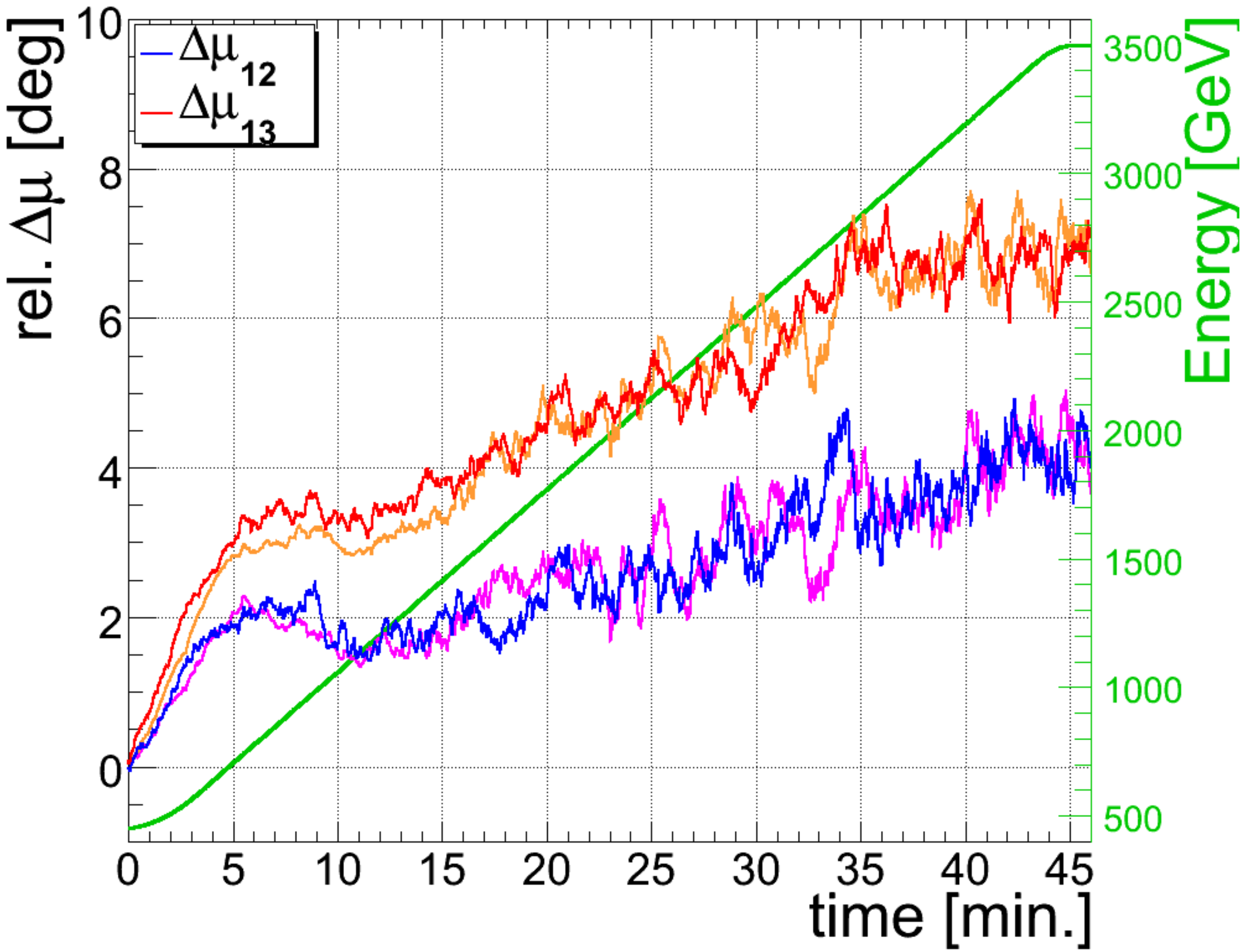


(c) Schematic layout IR7

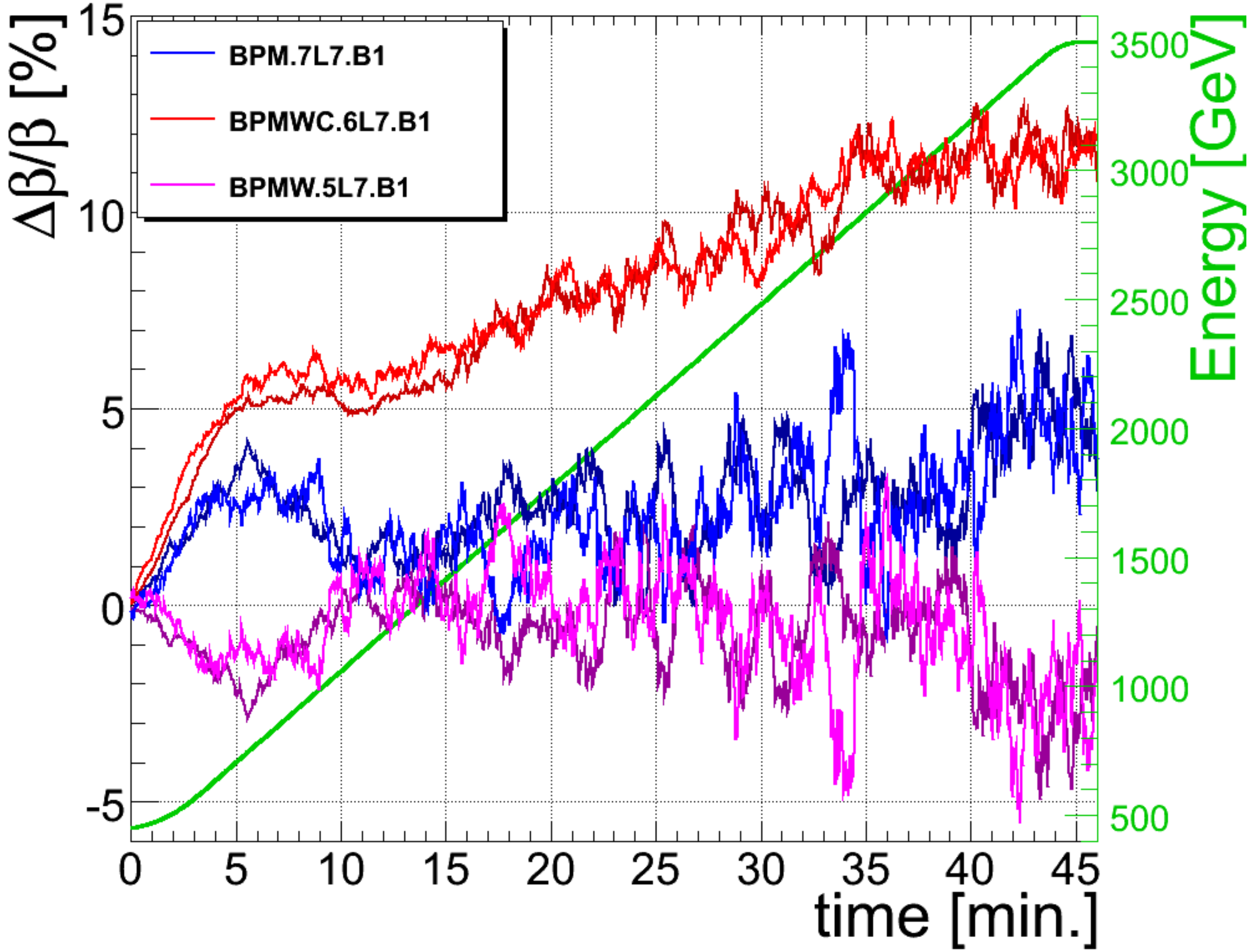
- Located in RR73, the minimum installation without pulling additional cables
- Pick-ups: BPM.7L7.B1 → BPMWC.6L7.B1 → BPMW.5L7.B1
  - phase-advance in between of Δμ≈ 45°
  - dual-plane → 6 channels
- Present installation using 3dB-Splitters works fine for a few (<6-8) pick-up locations but does not scale well (costs) for massive deployment
  (dominated by HF cabling, connector, mechanics, etc...)
  - Re-used default BBQ front-ends (not optimised for phase stability)
    - Non-issue for relative beta-beat change measurements
    - Was/can be cross-calibrated (once) against standard BPMs

LHC Beta-Beat during the Energy Ramp I/III – Raw BPM-to-BPM phase-advance measurement

- Perfectly pre-cycled machine, off-resonance excitation, < μm excitation level
  - excellent phase resolution, reduces with energy (N.B. const. kick strength)



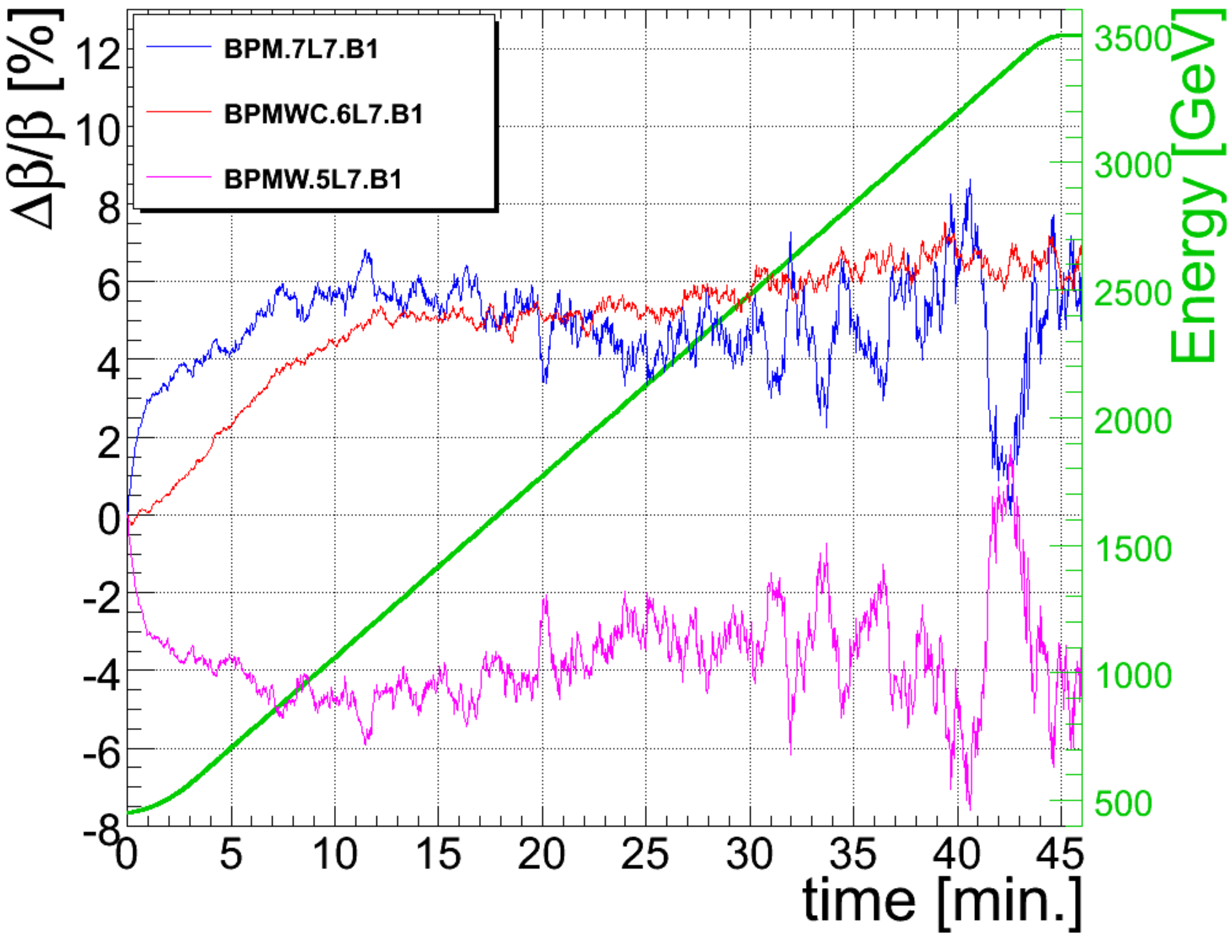
LHC Beta-Beat during the Energy Ramp II/III – Reconstructed Local Beta-Beat



- Excellent fill-to-fill reproducibility of about 1% – provided machine underwent a standard magnetic pre-cycle and no quenches have occurred.
- Complemented also by Rogelio's reproducibility assessment

LHC Beta-Beat during the Energy Ramp III/III – Evolution during a "less-perfect" Ramp

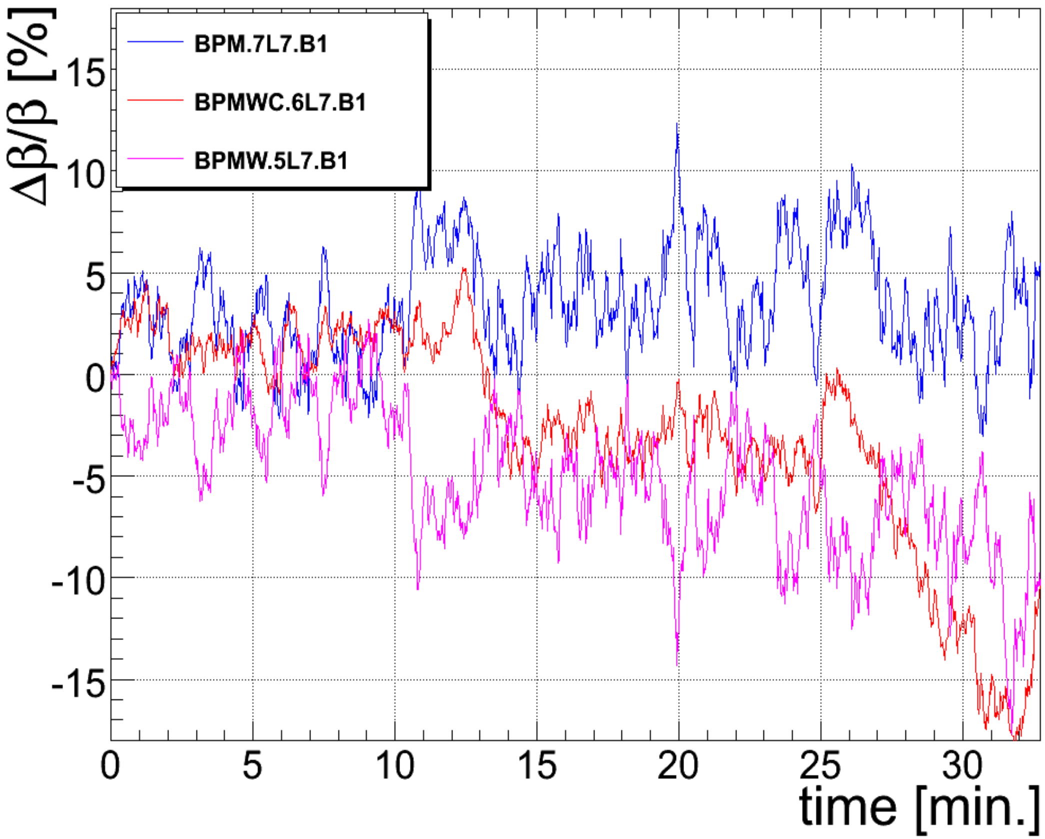
- 3/8 main dipole circuits being pre-cycled to 2 kA instead of the default 6 kA.
- Percent-level correction of the transfer function of one of the warm quadrupole magnet in the vicinity of the test setup



- Still, small compared to required dynamic beta-beat of $\Delta\beta/\beta|_{max} < 20\%$

LHC Beta-Beat during Squeeze

- Squeezing from β* = 10 m → β* = 2 m in all four IPs



- Nodes at optics matching points & leakage of squeeze of about 5% in IR7
- For the time being considered as small and compatible with present collimation requirements for low-intensity beams in the LHC.
- N.B. Meas. much noisier due the reduced signal-to-noise ratio during the β*-squeeze of only 16 dB (reduced excitation strength at top energy + small bunch intensity)

Conclusions

- The aim of the continuous beta-beat measurement studies at the LHC was to
  - provide a proof-of-feasibility for the measurement technique, and
  - to assess magnitude and time-scale of the LHC lattice changes.

- Continuous beta-beat measurement system could achieve a 1% resolution
  - only limited by the maximum off-resonance excitation power, and
  - for excitations being kept below a micro-meter
    → transparent for nominal LHC operation.

- 2010 measurements seem to confirm that fill-to-fill beta-beating is reproducible within 1% – provided machine underwent a nominal pre-cycle

- Present SPS/LHC installation using 3dB-Splitters works fine for a few pick-up locations but does not scale well (costs) for massive deployment (dominated by HF cabling, connector, mechanics, etc...)

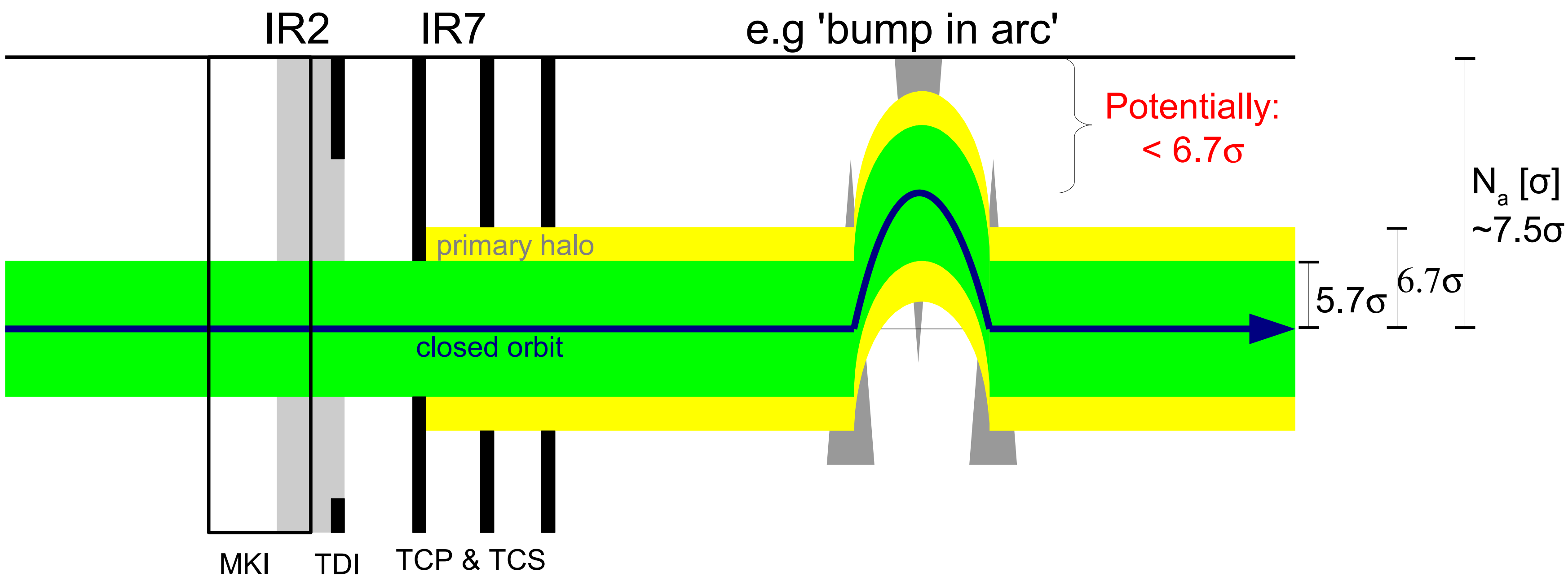
- If there is some interest/requirement: should and needs be specified as part of a future BPM system at an early stage, e.g. SPS MOPOS renovation & future LHC BPM upgrade additional supporting slides

Beta-Beat Sources

- Beta-Beat Sources
  - Quadrupole gradient and Momentum errors
  - Feed-down due to off-centre horizontal orbit in lattice sextupoles
  -
- Requirements: Brüning, Fartoukh, *LHC Project Report 501*

Peak hor. β-beating [%]	Mechanical aperture	14 / 15 (inj. / col.)
Peak vert. β-beating [%]	Mechanical aperture	16 / 19 (inj. / col.)
R.M.S. hor. β-beating [%]	Mechanical aperture	4.8 / 5.2 (inj. / col.)
R.M.S. vert.. β-beating [%]	Mechanical aperture	5.5 / 6.6 (inj. / col.)

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



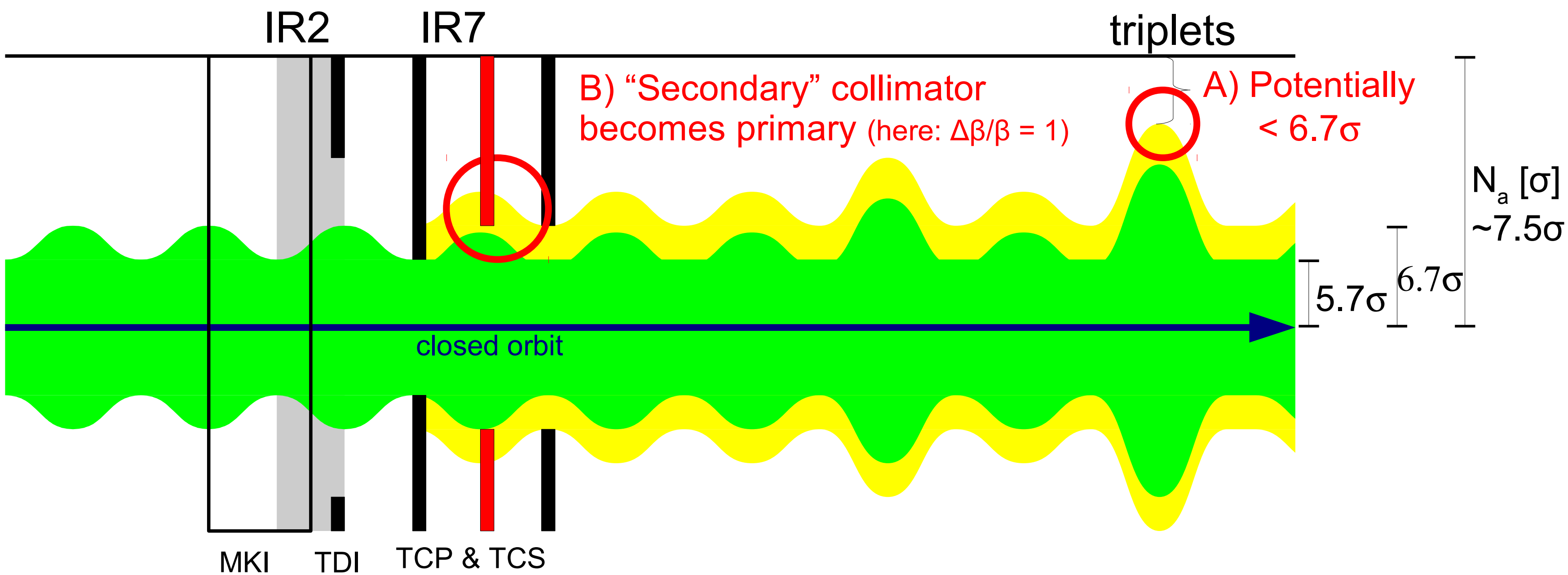
- To guarantee two stage cleaning efficiency/machine protection:
  - Local: TCP must be >0.7σ closer than TCS w.r.t. the beam → Orbit FB
  - Global: no other object (except TCP) closer to beam than TCS

→ Orbit bumps may compromise function of machine protection/collimation

→ tackled by LHC Orbit Feedback

Compromised Machine Protection through Beta-Beat

- 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)