On the Continuous Measurement of the LHC Beta-Function
- Prototype Studies at the CERN-SPS

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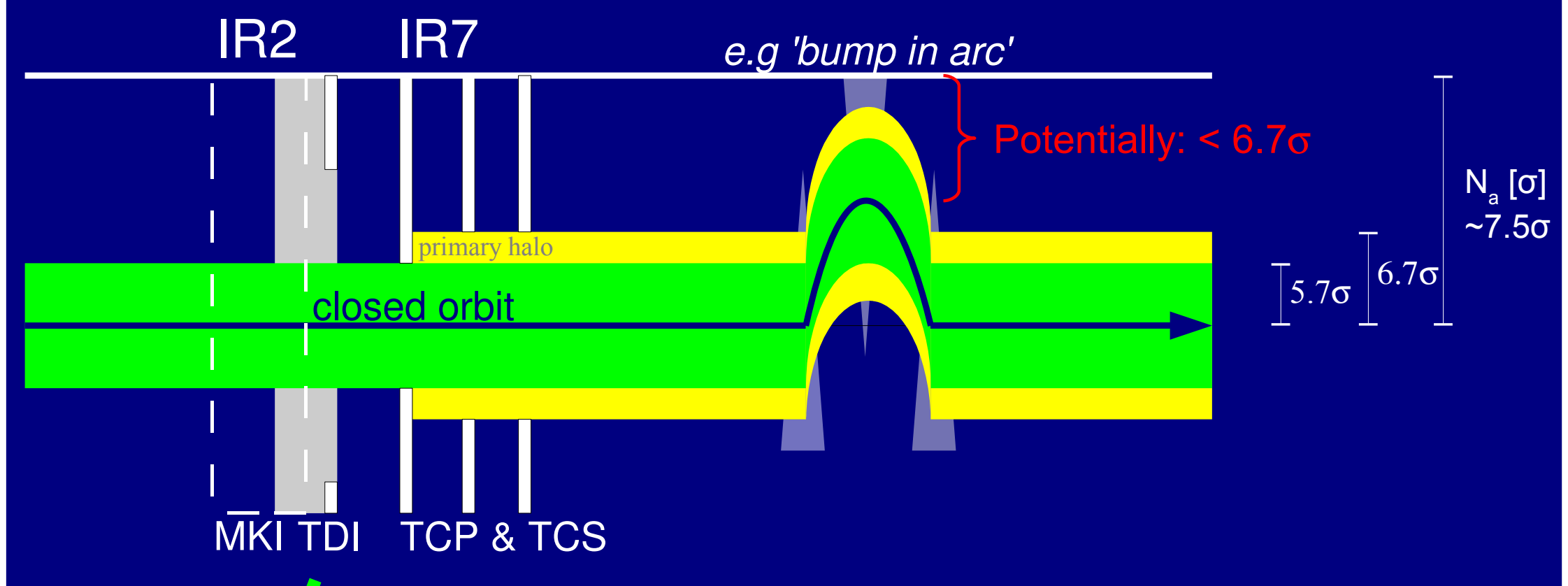
Abstract

Until now, the continuous monitoring of the LHC lattice has been considered impractical due to tight constraints on the maximum allowed beam excitations and acquisition time usually required for betatron function measurements.
As a further exploitation of the Base-Band-Tune (BBQ) detection principle, already widely used for tune diagnostics, a real-time beta-beat measurement prototype has been successfully tested at the CERN SPS and is based on the continuous measurement of the cell-to-cell betatron phase advance. Tests show that the phase resolution is better than a degree corresponding to a peak-to-peak beta-beat resolution of better than a percent. Due to the system's high sensitivity, it required only micrometre-range excitation, making it compatible with nominal LHC operation. This contribution discusses results, measurement systematics and exploitation possibilities that may be used to improve the nominal LHC performance.
The aim of the continuous beta-beat measurement system is to provide the means to assess magnitude and time-scale of LHC lattice perturbations, to use the obtained information to improve the protection and other accelerator systems and -- if necessary -- to locally stabilise the betatron function within a beam-based feedback system.

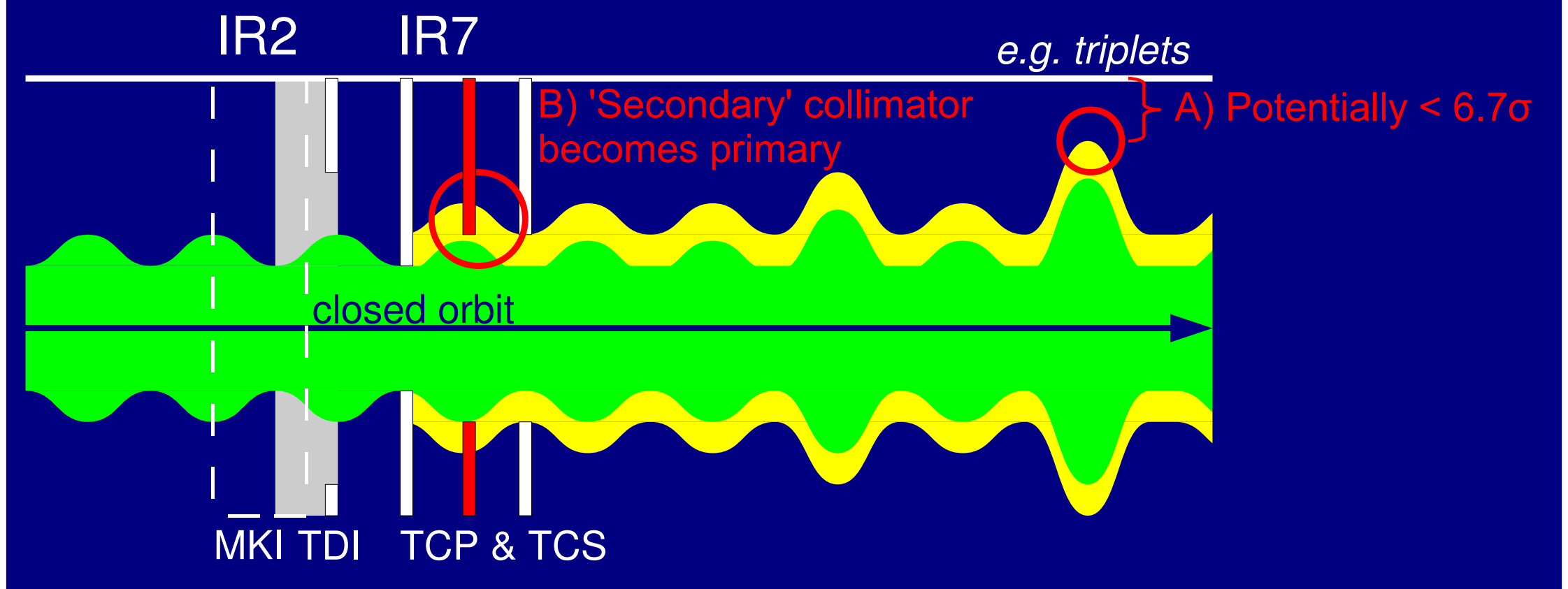
① Rationale – Machine Protection

Failure Case 1 – Closed Orbit Perturbations:



✓ → **LHC Orbit & Energy Feedback**

Failure Case – Static/Dynamic Beta-Beat:



→ **Real-time Δβ/β meas. (this study)**

② Rationale – Luminosity Performance

Achievable luminosity is ultimately limited by the ability to control particle loss inside the machine:

$$L_{max} = \frac{1}{4\pi}\cdot\frac{\overbrace{\boxed{N_{max}\cdot n_b^2}}^{\text{max. safe beam intensity}} f_{rev}}{\underbrace{\boxed{\beta^*}}_{\text{min. safe final-focus squeeze factor}}\epsilon}$$

- Collimation imposes a limit on minimum safe β*
  → direct impact on L_{max}, reduction of constraints allows:
  - Smaller safe β* → more luminosity
  - More safe beam intensity → more luminosity
- The β*-squeeze relies on the reproducibility from one setup-fill to the next physics-fill
  - Expected to be one of the most critical operation
  - Large dynamic optics change causing significant feed-down effects perturbing the orbit, tune, chromaticity, loss of aperture, … → prime candidate for beam loss
  - Monitoring is not possible by classic methods:
    - *K-modulation:* uncertainties on triplet trims, time-scale, scalability w.r.t. multiple quadrupole magnets
    - BPM-based: limited triplet aperture, emittance budget

③ Beta-Beat Measurement Principle:

Interdependence between betatron function and betatron phase advance:

$$\Delta\mu_{i,j} := \int_{s_i}^{s_j} \frac{1}{\beta(s)}\, ds \qquad (1)$$

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

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

Three redundant meas.
→ can be used to identify:
a) instrumentation errors,
b) strong local gradient errors

$\Delta\mu_{ij}^{meas.}, \Delta\mu_{ij}^{nom.}$: *measured vs. nominal phase advance* ; $i, j = 1,2,3$: *BPM index*

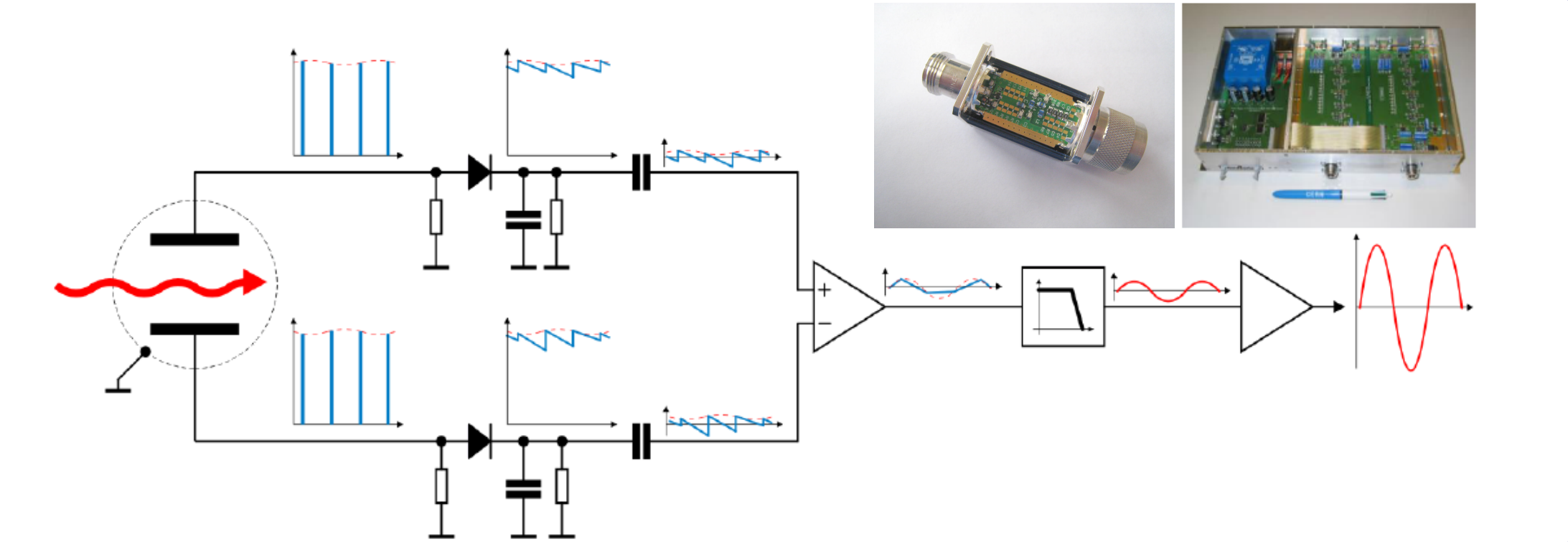
Using Eq. (1) with e.g. a symmetric final-focus insertion (waist β*):

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

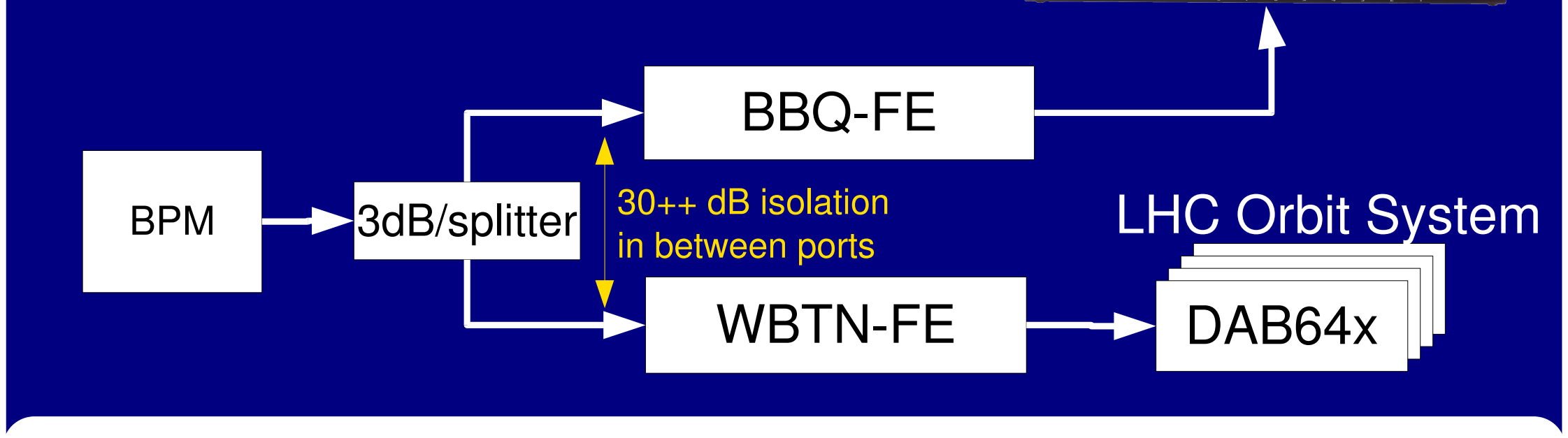
$$\rightarrow \quad \Delta\mu(s) = \int_{s_1}^{s_2} \frac{1/\beta^*}{1+(s/\beta^*)^2}\, ds = \boxed{\left[\arctan\left(\frac{s}{\beta^*}\right)\right]_{s_1}^{s_2}}$$

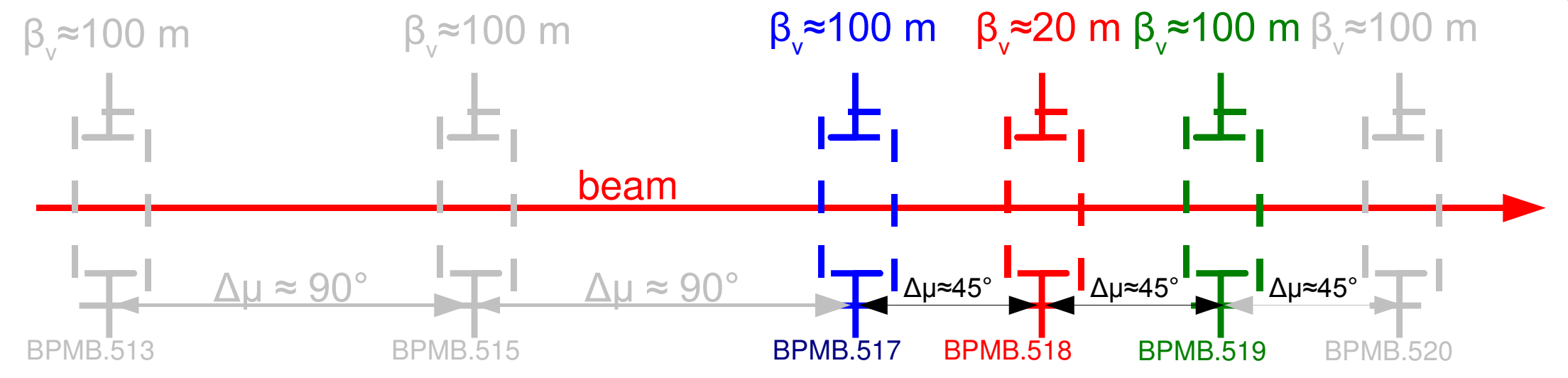
→ any phase-based optic recon. has intrinsic singularities every π!

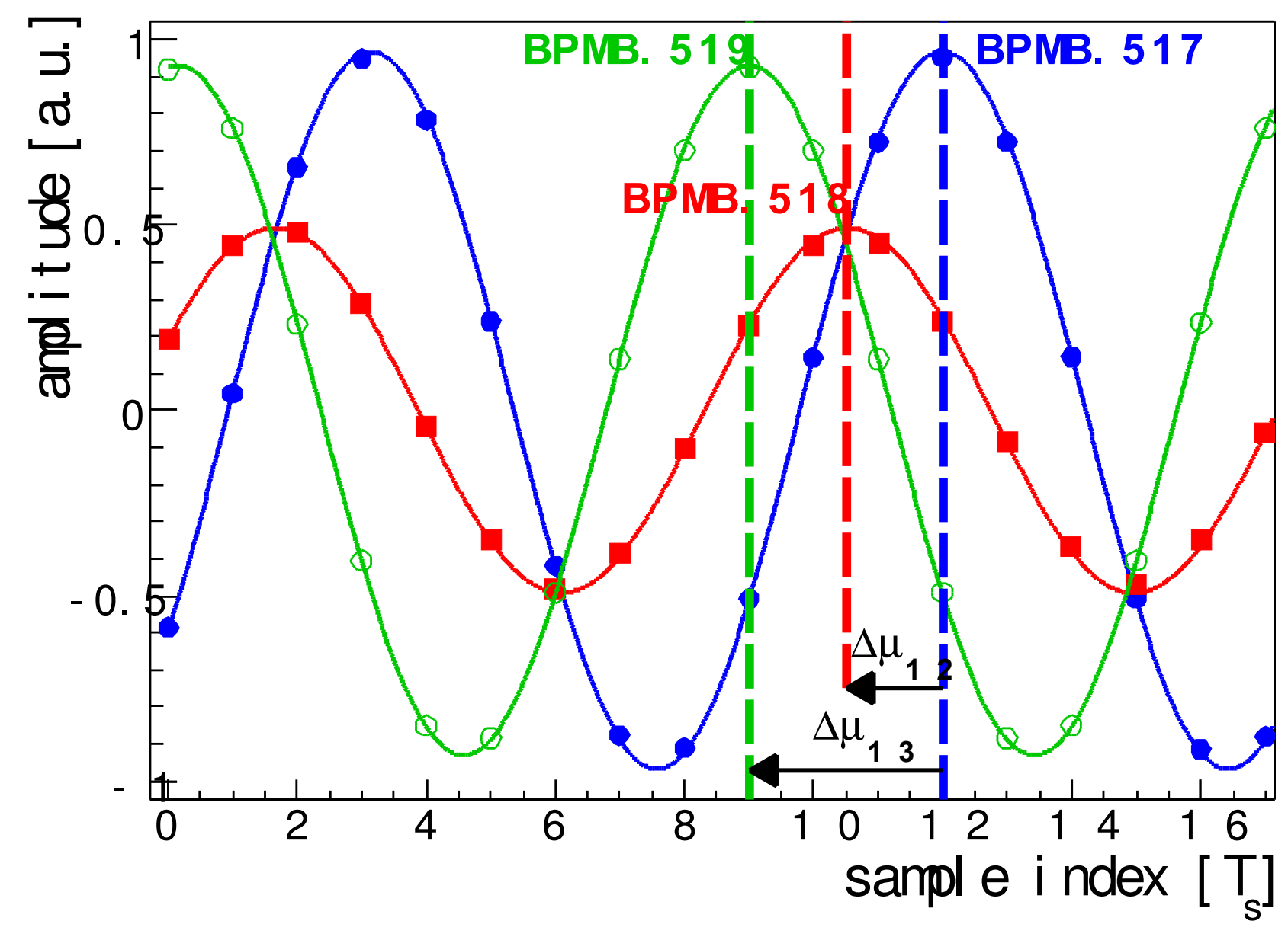
④ SPS-LSS5 Beta-Beat Measurement Setup
- Yet Another Base-Band-Q Exploitation:



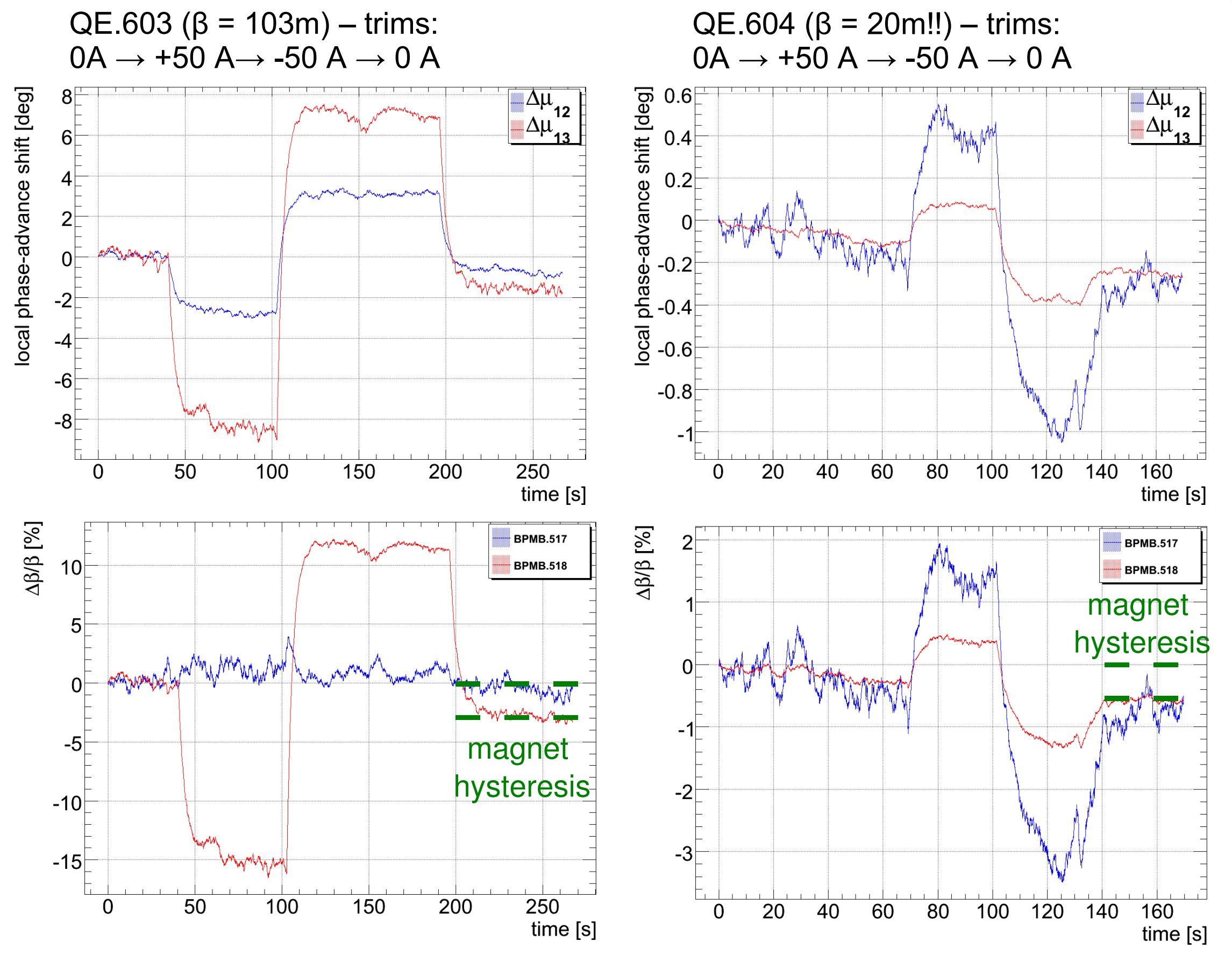
- Basic principle: AC-coupled peak detector
  - no saturation, self-triggered, no gain changes
  - intrinsically down samples spectra:
    ...a few GHz → 1kHz ... f_{rev}
    - Base-band operation: very high sensitivity/resolution ADC available
    - Measured resolution estimate:
      < 10 nm → ε blow-up is a non-issue







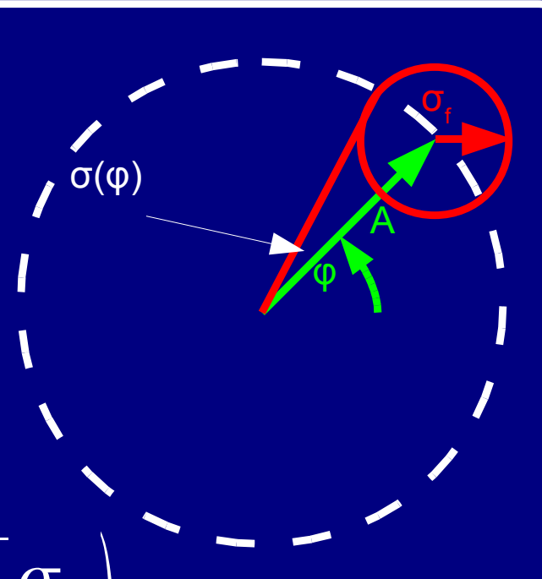
⑤ Test with 270 GeV Coasting Beam in the SPS



- Δβ/β amplitude agrees with BPM-based estimate
- Resolution $\Delta\beta/\beta_{res.}$ < 0.1% @ f_{bw}≈1Hz (N.B. $\Delta\beta/\beta_{res.}\cdot f_{bw}$ = const.)
- Magnet hysteresis visible
- Small-amplitude variations on short time-scales visible
  - True optics changes – effect already seen at LEP (though not being time resolved)

⑥ Measurement Accuracy & Limitations

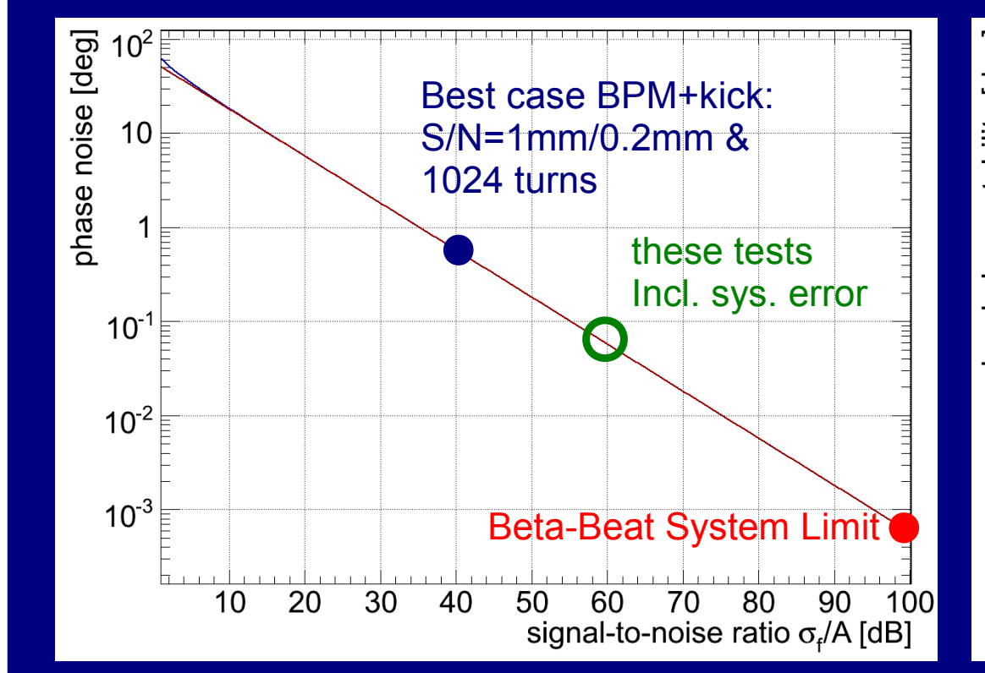
Statistical noise:



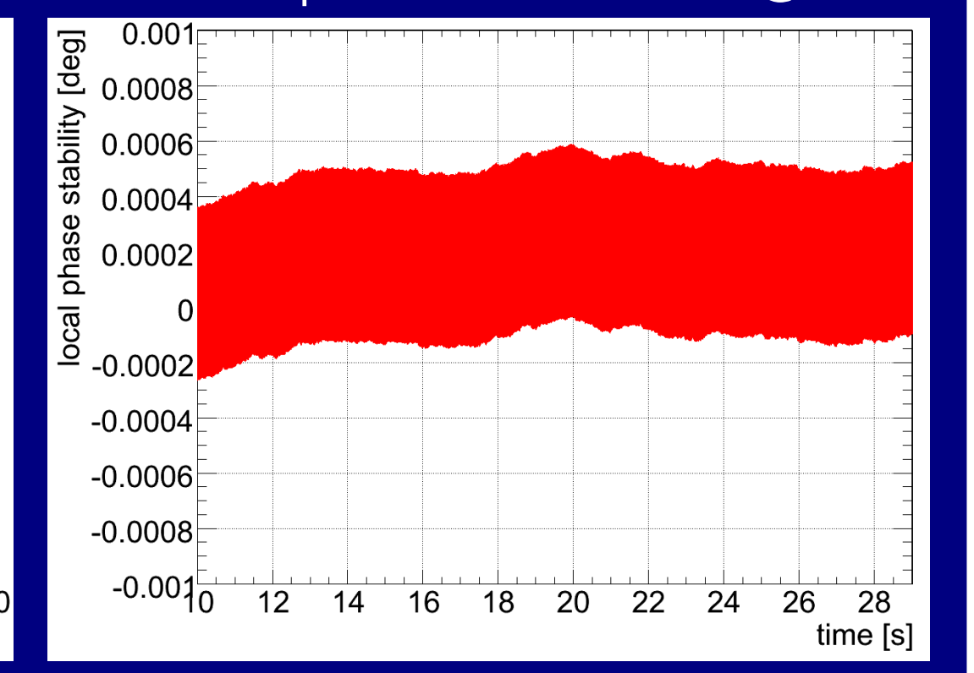
- Excitation amplitude (carrier signal): A
- Noise in time (frequency) domain: σ_t (σ_f)
- Equivalent number of turns: N

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

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



Intrinsic Acquisition Phase Noise @1Hz



Systematic Errors

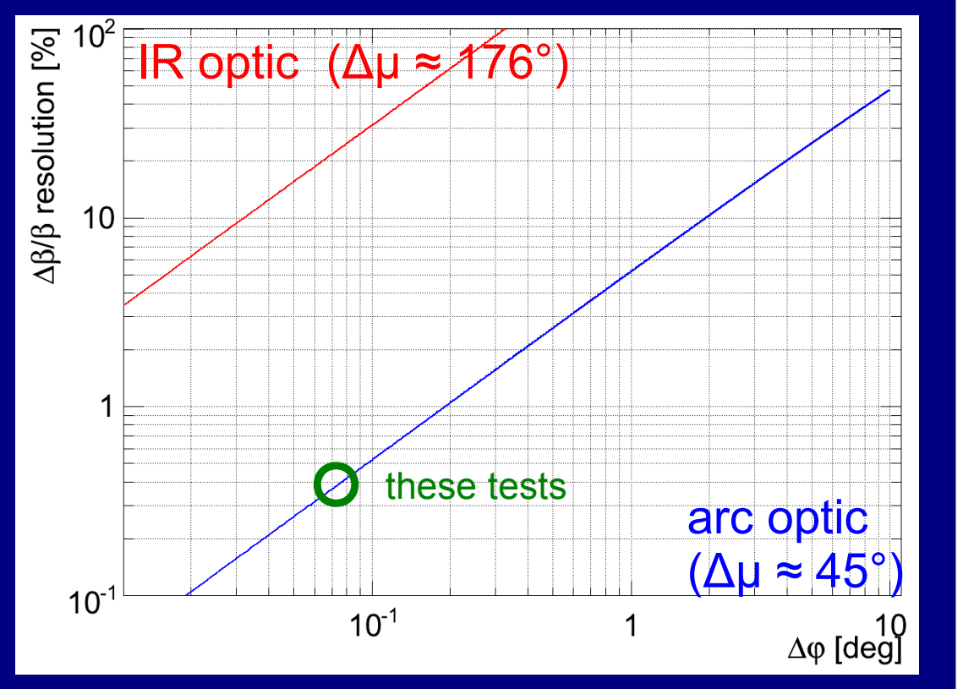
(cable length, time of flight, low-frequency pre-processing, analogue front-end, etc.)

ARC optics:

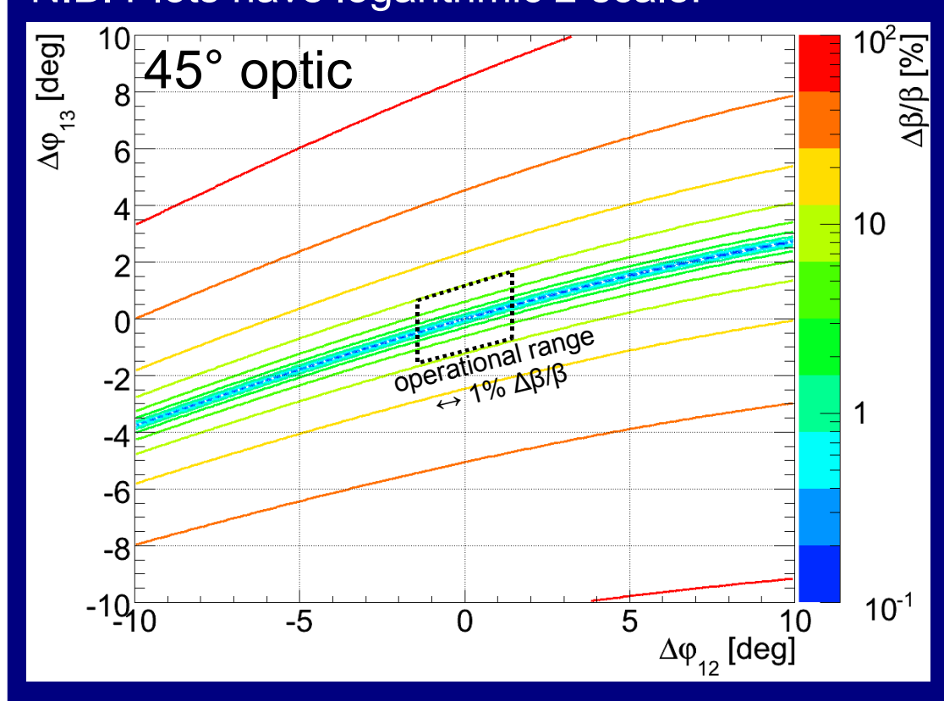
- requires error below ~1°

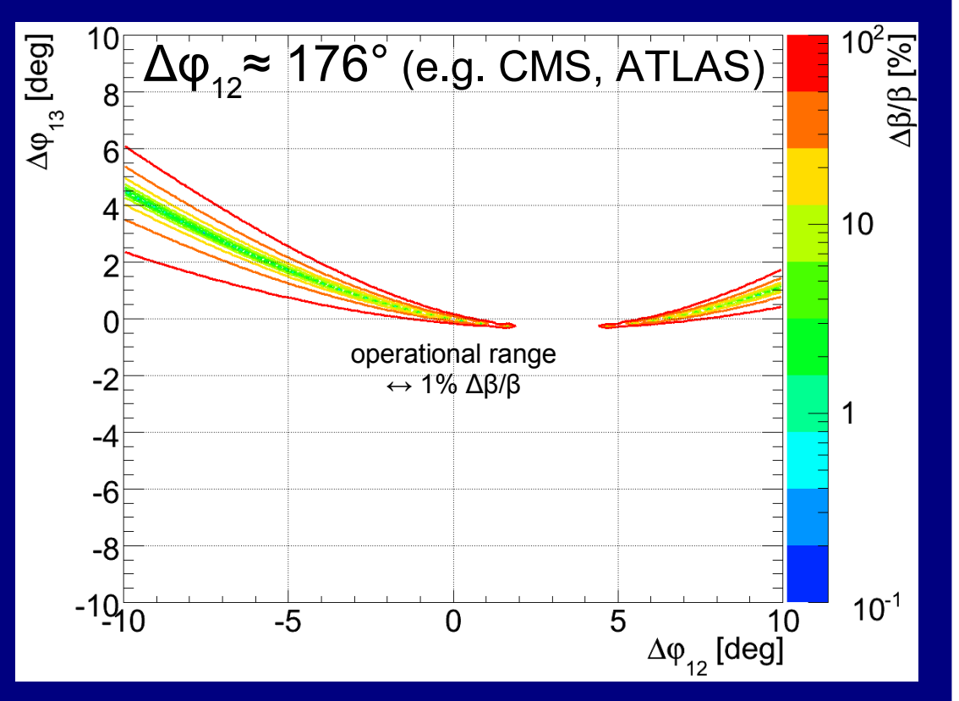
IP optics:

- requires error below ~0.02°



N.B. Plots have logarithmic z-scale!



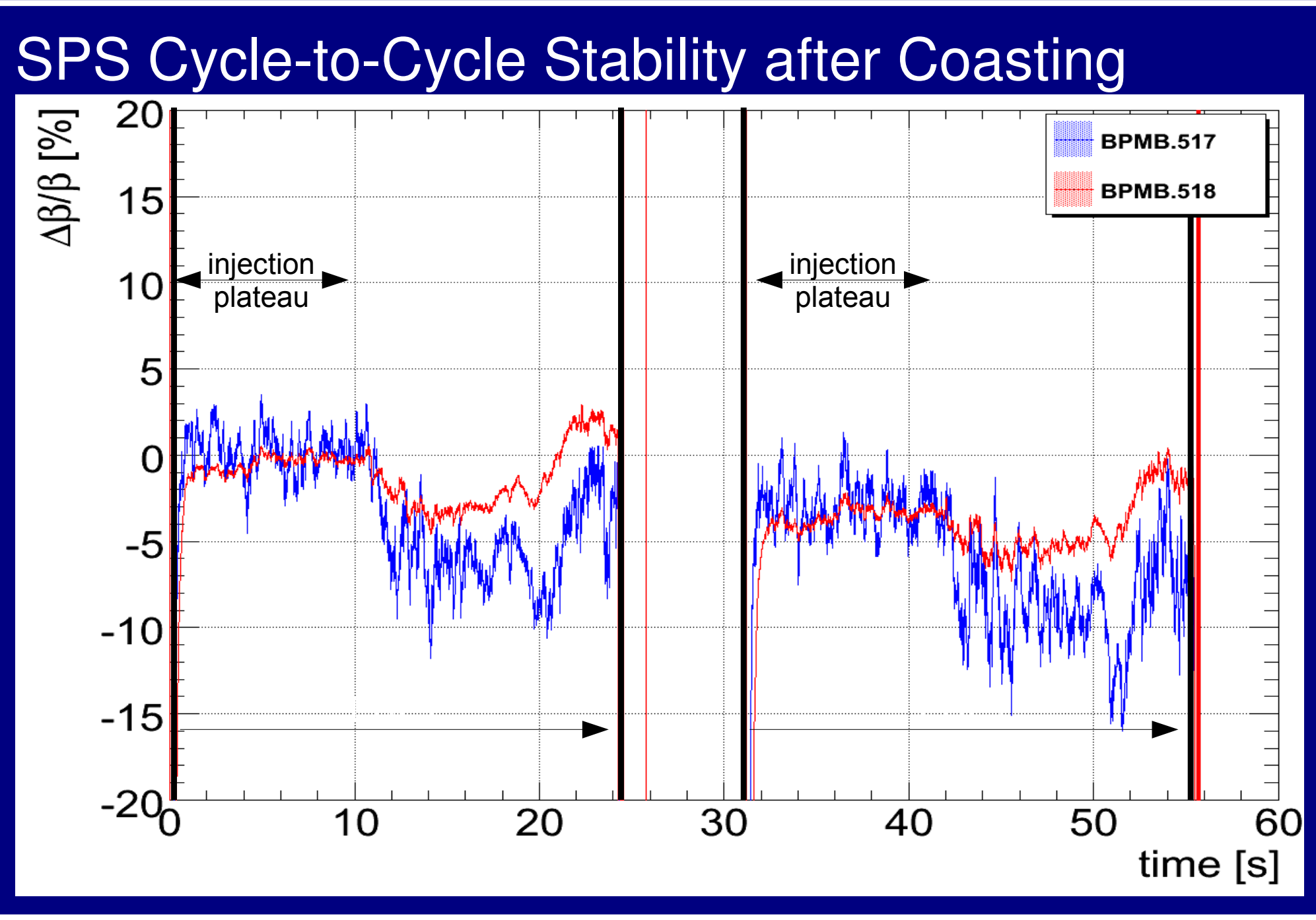


Achieved in the SPS: σ(φ) < 0.1°

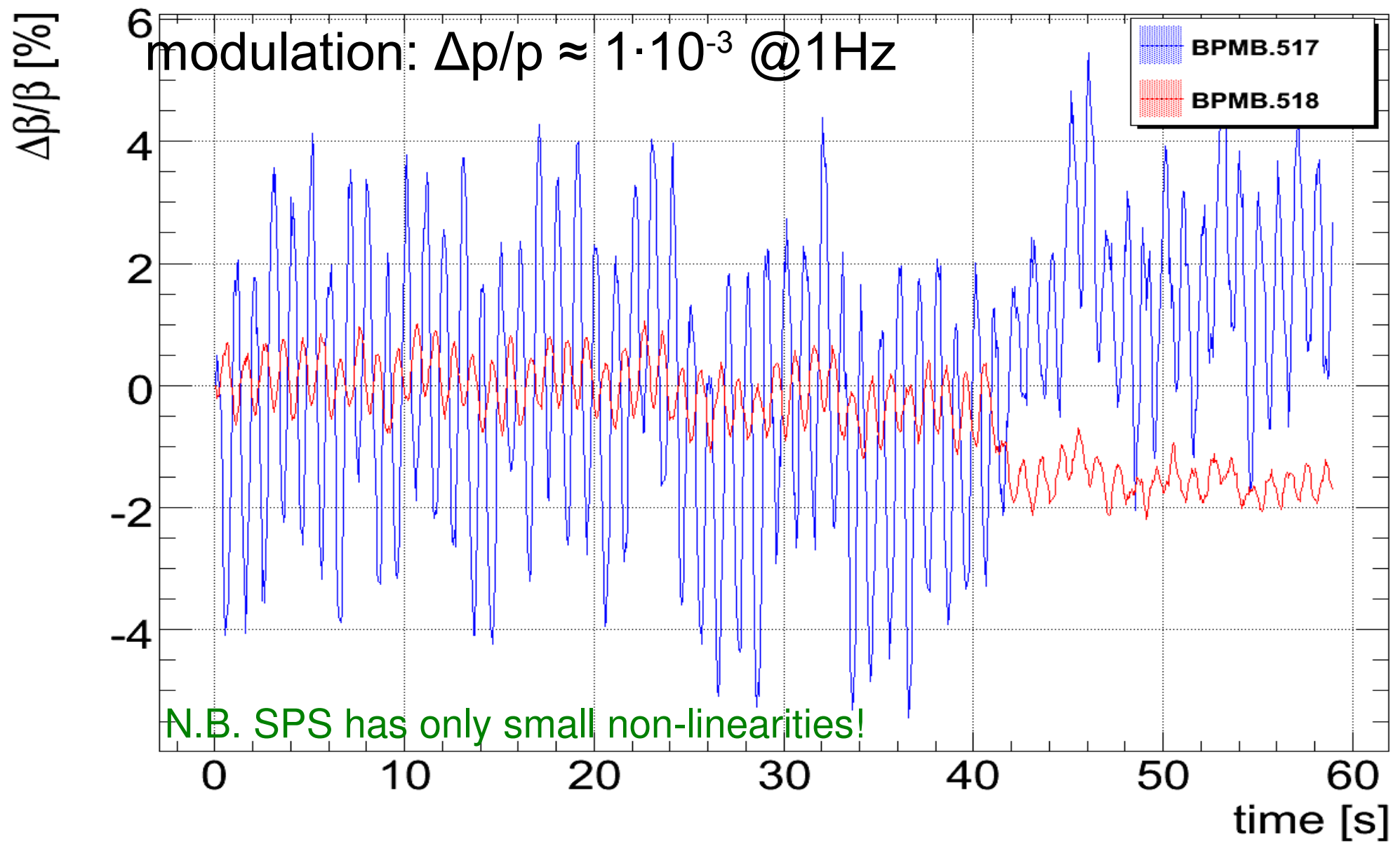
→ LHC: σ(φ) < 0.01°
→ allows final-focus monitoring during nominal LHC operation

⑦ Additional Exploitation Possibilities: Beta-Beat as Indicator of Higher-Order Beam Processes

SPS Cycle-to-Cycle Stability after Coasting



Off-Momentum (Chromatic) Beta-Beat



Conclusion

The SPS tests have shown that the proposed system can achieve 0.1% resolution at a 1Hz rate, with excitations kept below 30 µm, thus making this type of measurement transparent for nominal LHC operation. Based on these tests, the prototype is being optimised to support non-perturbative final-focus monitoring on the percent level. Such beam diagnostics of higher-order effects have been in-accessible previously, and should facilitate LHC to reach its design performance.

J.R. Steinhagen, 2009