Continuous Measurement and Control Beta-Beating in the LHC

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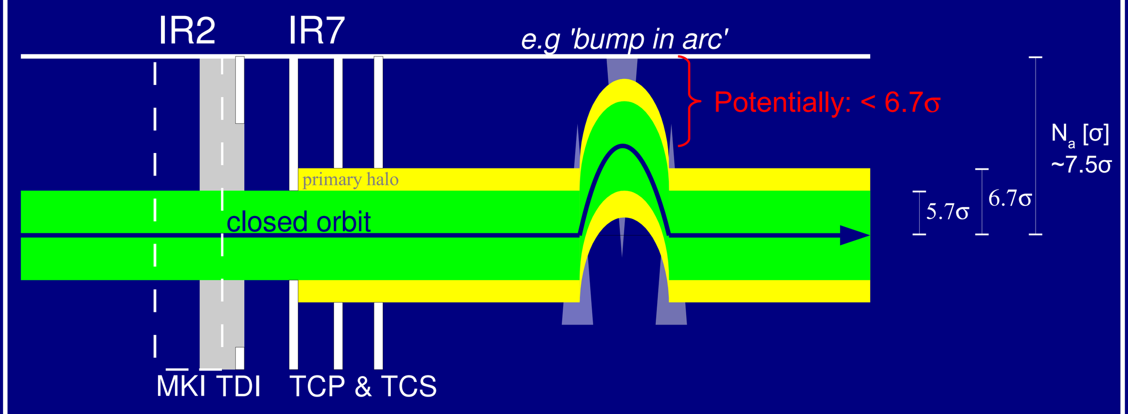
Abstract

The beta function has a fundamental impact on the LHC performance and on the functioning of its machine protection and collimation systems. A new beta-beat diagnostic system, prototyped at the SPS, has been used to verify the time-dependent variations of the LHC lattice with unprecedented 1\% beta-beta resolution and at a measurement bandwidth of about 1 Hz.

This contribution discusses the first results of local continuous beta-function measurements in the LHC collimation region, the systematic measurement errors and their compensation. The impact on nominal LHC operation and the potential to provide an input for an automated local feedback control of the beta-function are presented.

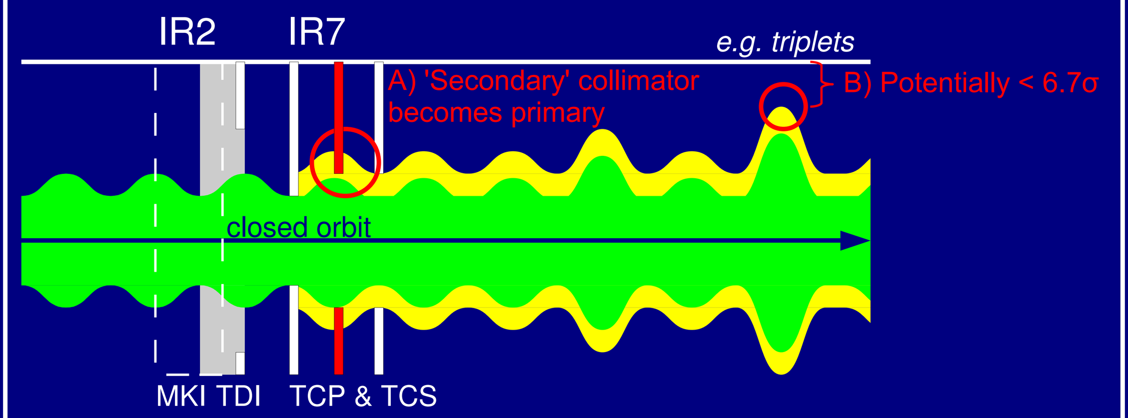
1 Rationale – Machine Protection

Failure Case 1 – Closed Orbit Perturbations:



✓ ➜ **LHC Orbit & Energy Feedback, WEPEB041**

Failure Case – Static/Dynamic Beta-Beat:



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

Installed test system in the vicinity of the primary and secondary collimators (TCP & TCS) to assess the typical dynamic variations while ramping and squeezing.

2 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)

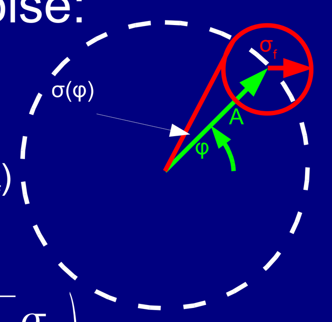
$$\frac{\Delta\beta_1}{\beta_1} = \frac{\cot(\Delta\mu_{12}^{meas.}) - \cot(\Delta\mu_{13}^{meas.})}{\cot(\Delta\mu_{12}^{nom.}) - \cot(\Delta\mu_{13}^{nom.})}$$

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

Impact and limit of statistical noise:

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

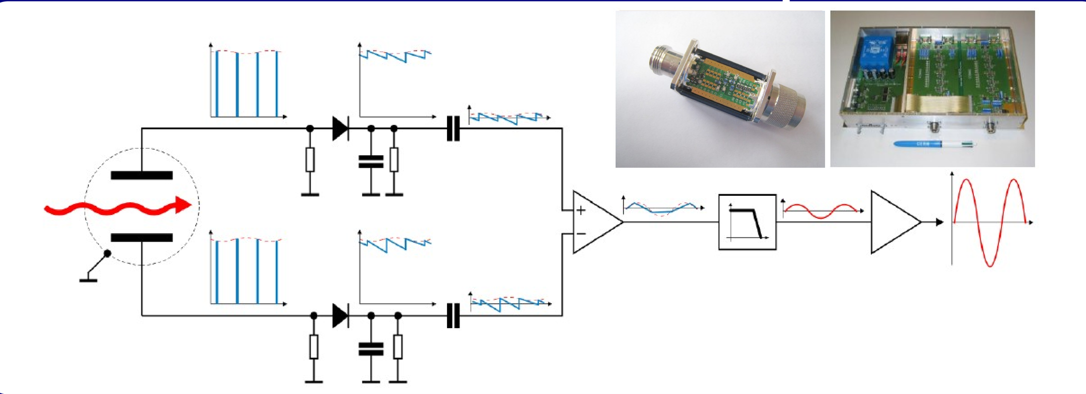


$$\sigma(\varphi) = \arcsin\left(\frac{\sigma_f}{A}\right) = \arcsin\left(\sqrt{\frac{2}{N}}\frac{\sigma_t}{A}\right)$$

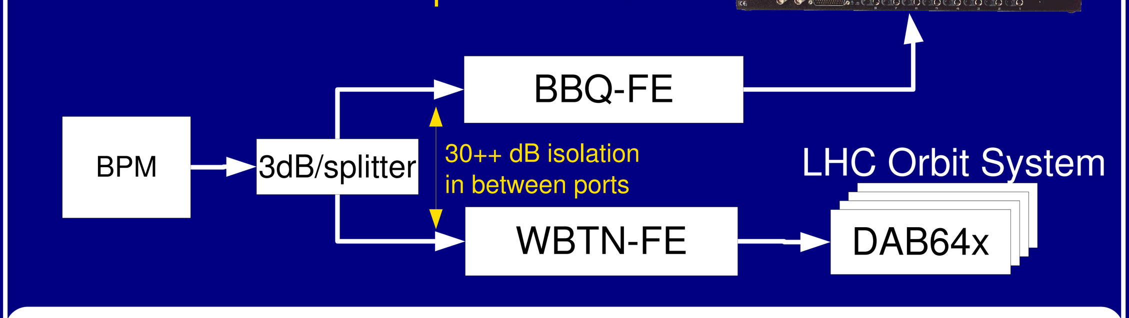
for small noise to signal ratios $\approx \sqrt{\frac{2}{N}}\frac{\sigma_t}{A}$ — Intrinsic Acquisition Phase Noise @1Hz

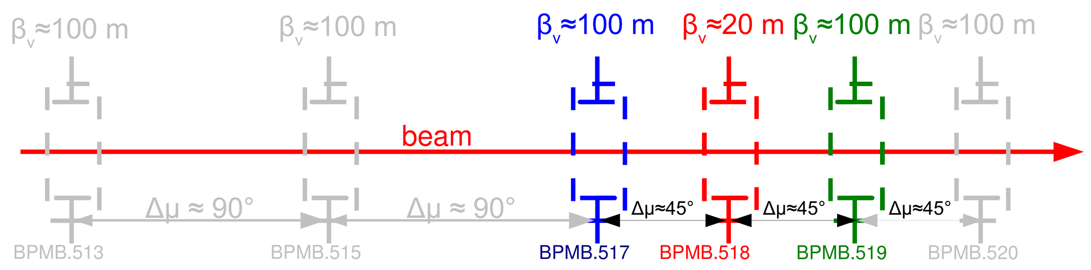
Achieved in the LHC: $\sigma(\varphi) < 1°$ ↔ $(\Delta\beta/\beta)_{res} \approx 1\%$

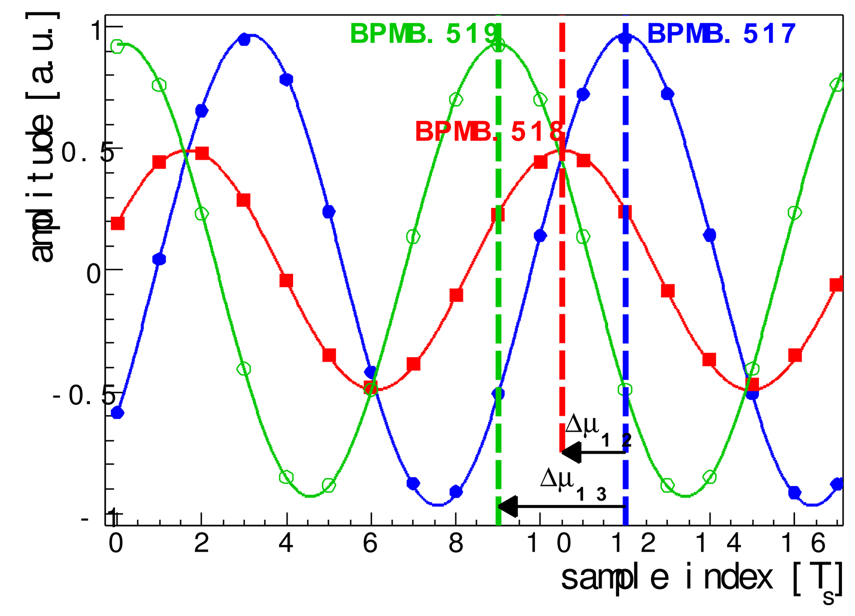
3 SPS-LSS5 Beta-Beat Measurement Setup - Yet Another Base-Band-Q Exploitation:



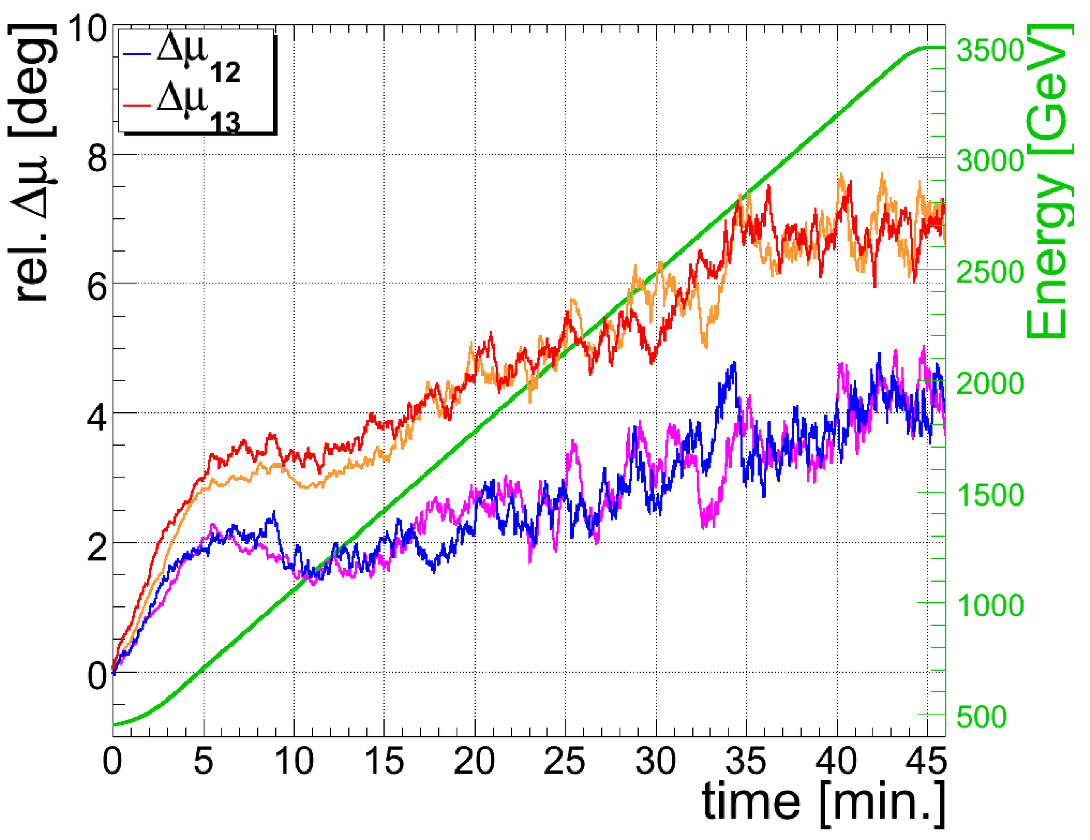
Basic principle: AC-coupled peak detector
- no saturation, self-triggered, no gain changes
- intrinsically down samples spectra: ...a few GHz → 1kHz ... f_{rev}
- Base-band operation: very high sensitivity/resolution ADC available
- Measured resolution estimate: < 10 nm → ε blow-up is a non-issue

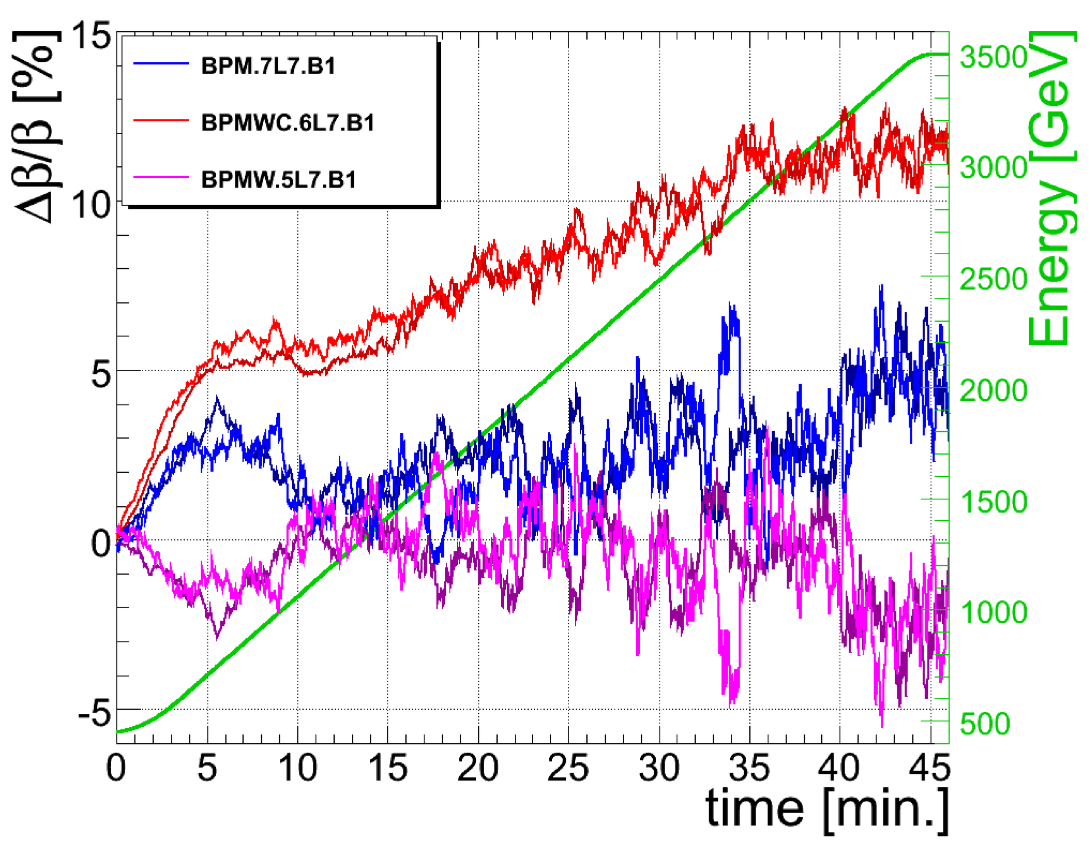






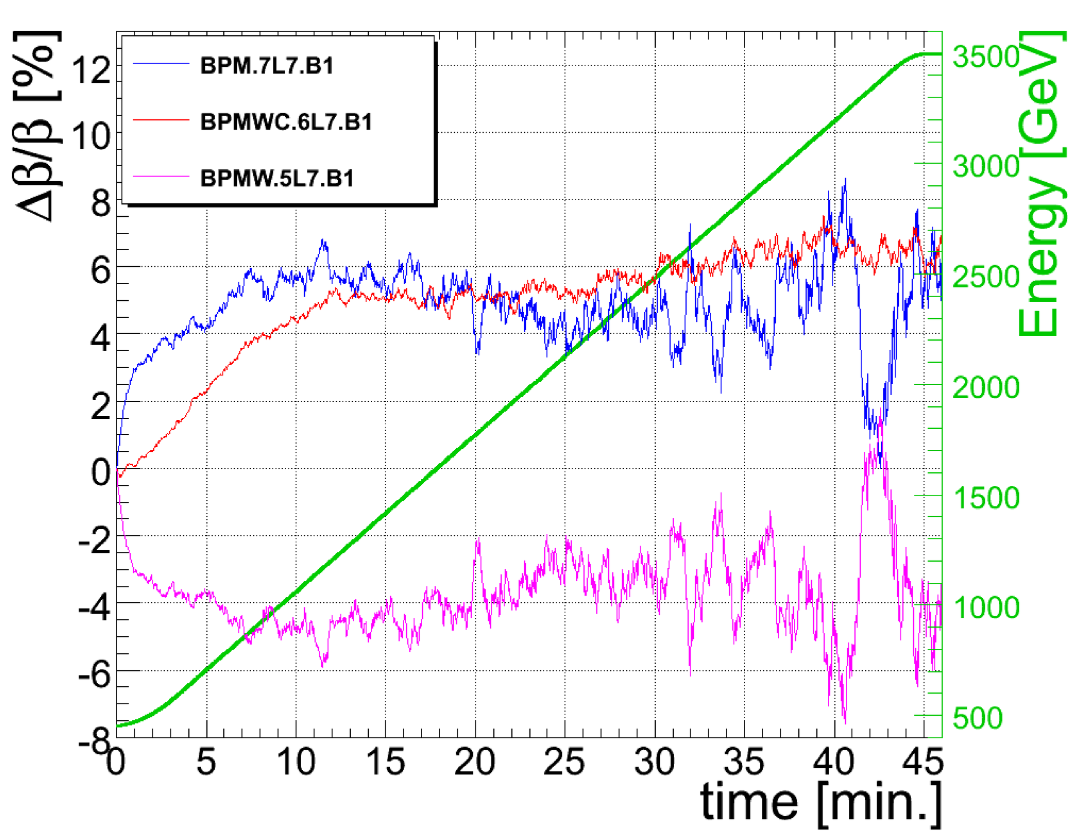
4 Beta-Beating during Two Energy Ramps





Excellent fill-to-fill reproducibility of about 1 % – provided machine underwent a standard magnetic pre-cycle and no quenches have occurred.

5 Beta-Beating after Non-Standard Pre-Cycle



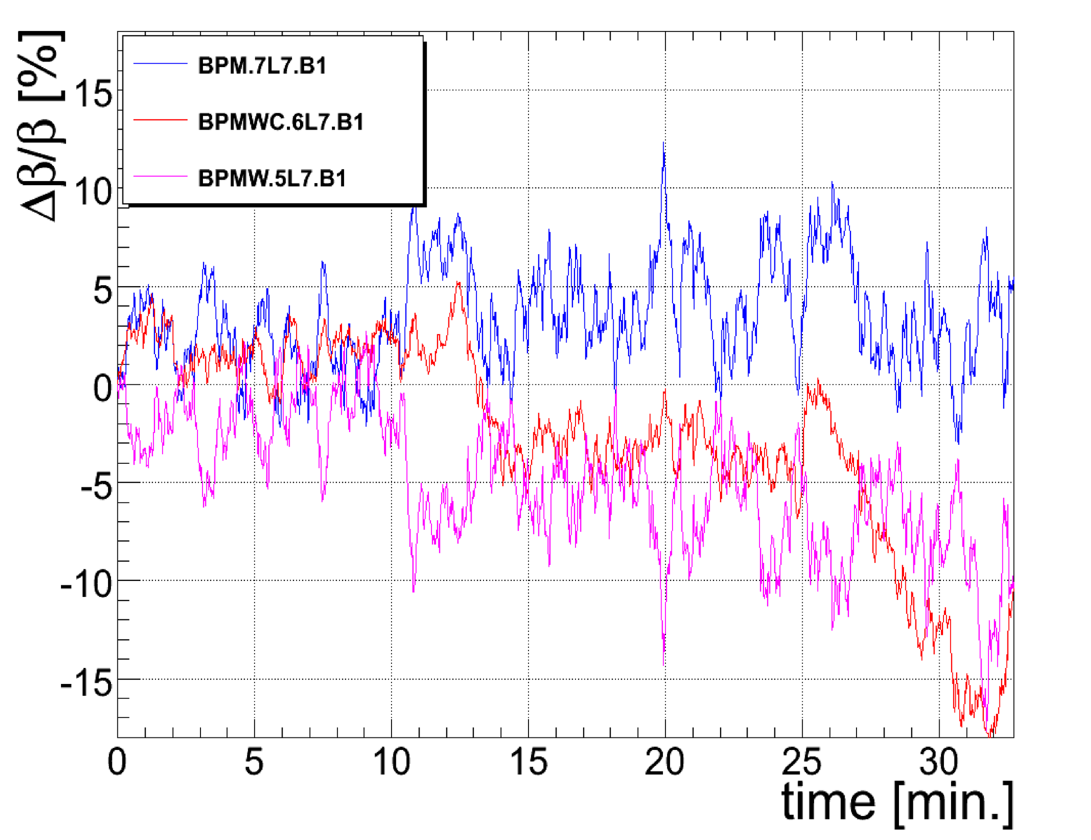
Beta-beat evolution during a successive ramp:
- three out of the eight main dipole circuits being pre-cycled to 2 kA instead of the default 6 kA.
- percent-level correction of the transfer function of one of the warm quadrupole magnet in the vicinity of the test setup

➜ **~4% difference compared to standard ramp**

- Demonstration of dynamic beta-beat changes in a superconducting accelerators
- Small compared to collimator requirements on dynamic beta-beat of $\Delta\beta/\beta|_{max} < 20\%$

However, this being only a local measurement of one given failure scenarios → more measurements are required and ongoing regular monitoring...

6 Beta-Beating During β*-Squeeze



Squeezing from β* = 10 m → β* = 2 m in all four IPs: ATLAS (IR1), ALICE (IR2), CMS (IR5) and LHCb (IR8)

- Nodes in beta-beat evolution correspond to given optics matching points
- Leakage/non-closure of squeeze of about 5% in LHC beta-cleaning insertion (IR7)
- For the time being considered as small and compatible with present collimation requirements for low-intensity beams in the LHC.

- Measurement 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

→ Further measurements with possibly larger excitations are required to asses this effect more precisely.

Conclusion

The aim of the presented studies was to provide a proof-of-feasibility and to assess magnitude and time-scale of the LHC lattice changes during the energy ramp for a selected location in the ring. Limited by the maximum power of the chosen exciter, the continuous beta-beat measurement system could achieve a 1% resolution, with excitations kept below a micro-meter, thus making this type of measurement transparent for nominal LHC operation. These preliminary measurements seem to confirm that beta-beating evolution is reproducible within 1% for the measured LHC ramps which is a tribute to the magnetic field stability of the LHC -- provided the machine underwent a nominal pre-cycle.