Synchronous Phase Shift at LHC

Simulations and Diagnostics I

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Outline

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Introduction

- Particle energy loss compensated by the RF:

$$\sin\phi_s = \frac{W}{eV} \quad \Rightarrow \quad \langle W \rangle = \frac{e\,V}{N_{Tot}} \sum_{k=1}^{K} N_k \,\sin\phi_{sk}\,,$$

- Main beam energy loss mechanisms:
    - Synchrotron Radiation
    - Resistive Impedance
    - Interaction between the beam and the e-cloud

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    - Depends on bunch intensity and length
  - Interaction between the beam and the e-cloud
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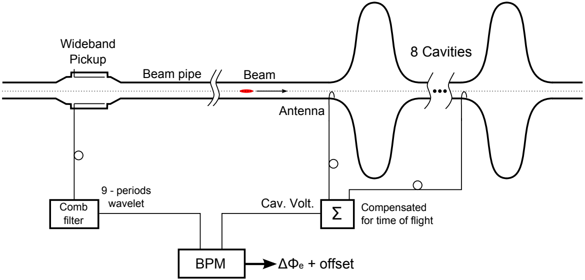
- For beams with small spread in bunch intensities and lengths ⇒ It is possible to measure the energy loss due to e-cloud

Outline

Mesurement method

- Beam Phase Module (BPM):
  - measures phase error as the difference between:
    - bunch phase from a 3 GHz bandwidth pickup
    - phase of the vector sum of voltage from 8 cavities
  - eliminates the beam loading effect
  - provides individual bunch phase error measurements



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Average phase error measurements

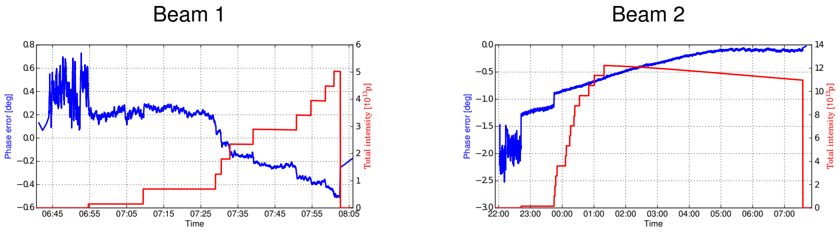
- Average phase error of all the bunches in the ring

$$\langle \phi_s \rangle = \frac{1}{K} \sum_{k=1}^{K} \phi_{sk}$$

- All measurements were done at the LHC flat bottom (450 GeV)
- Phase error is measured with respect to the total intensity
- The module precision is of about 0.1 degrees:
  - Average over 40 measurements (25 s) after injections
- Voltage program was changed from 3.5 MV in 2010 to 6 MV in 2011 and 2012 (Flat Bottom)
- Bunch lengths and filling pattern have influence on the e-cloud:
  - The phase error is proportional to the heat load only for uniform bunches (intensity and length)

Average phase error measurements

- Examples:



- Beam 1: Phase error shifts at each batch injection
- Beam 2: Phase error drifts probably due to thermal effects

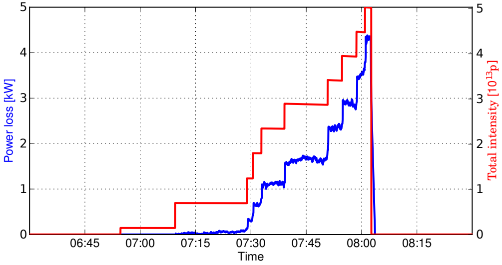
Power loss estimation

50 ns bunch spacing beam

- The total beam power loss can be approximated by:

$$P_L \approx N_{Tot}\, e\, V\, f_{rev}\, \langle \phi_s \rangle$$

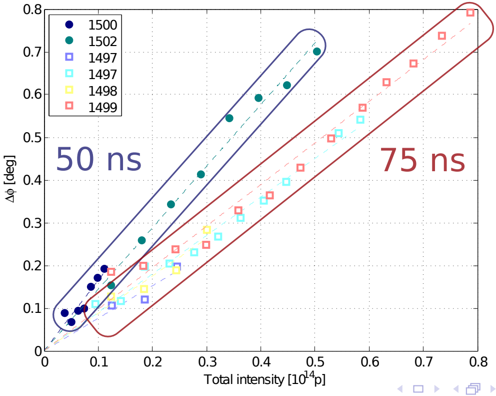
If bunch intensities are similar and phase error shift is small



Phase error shift wrt. total intensity

Observations from 2010. 75 ns and 50 ns bunch spacing beams

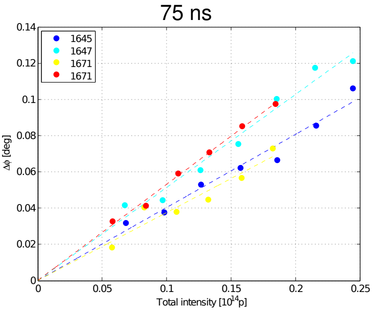
- Phase error shift increases with total intensity in the ring
- Phase error shift is larger for the 50 ns than for the 75 ns beam

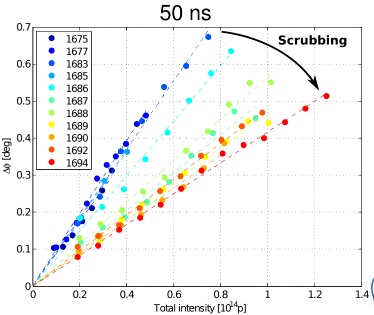


Phase error shift wrt. total intensity

Observations from 2011. 75 ns and 50 ns bunch spacing beam.

- 75 ns: Phase error shift is small and similar for different fills
- 50 ns: Phase error shift decreases from fill to fill ⇒ scrubbing

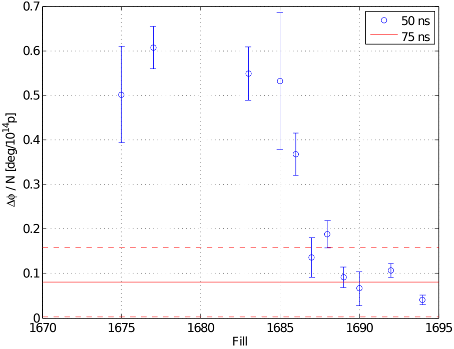




Phase error shift wrt. total intensity

Scrubbing run (April, 2011). 50 ns bunch spacing beam

- Phase error shift per particle decreased during the scrubbing run
- After the scrubbing run the phase error shift is similar for the 75 ns and the 50 ns beams

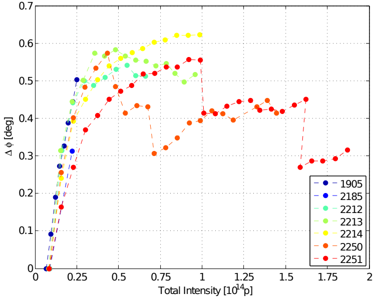


Phase error shift wrt. total intensity

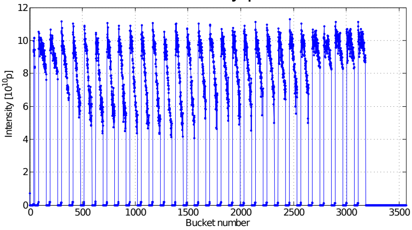
Observations from 2011. 25 ns bunch spacing beam

- Electron cloud reaches saturation after a few batch injections
- Instabilities and transverse emittance growth ⇒ Particle losses ⇒ Reduced electron cloud density

Average phase error wrt. intensity



Bunch intensity pattern



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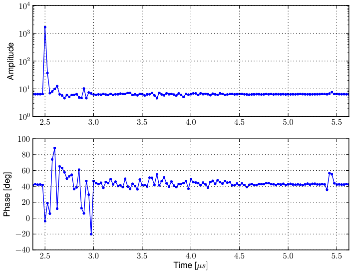
Measurements correction

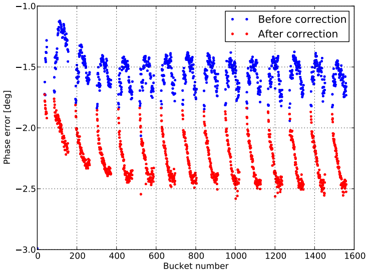
- Single bunch phase error measurements are distorted by:
  - non ideal Beam Phase Module response
  - reflections in the connectors
  - localized mismatches in the cables (400 m long)
- Assuming linearity of the system response:
  - It is possible to extract the impulse response
  - Data are deconvolved with the impulse response
- Impulse response was measured with a single bunch

Measurements correction

Impulse response

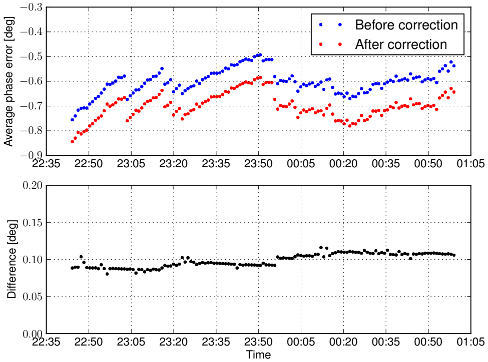


Results of correction



Measurements correction

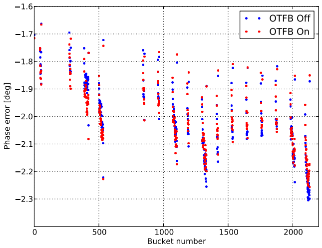
- This distortion does not have a significant effect on the average phase error measurements (0.1 deg offset)



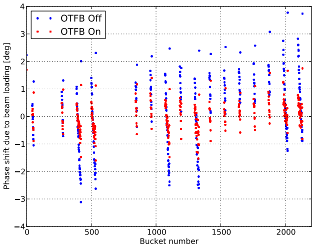
Beam loading effect

- The effect of the beam loading was checked:
  - Phase error measured with the One Turn Feedback ON and OFF (it reduces beam loading)
  - Comparison with the bunch positions from the Beam Quality Monitor (BQM)

Phase error



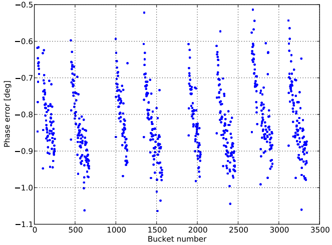
Phase error shift due to beam loading



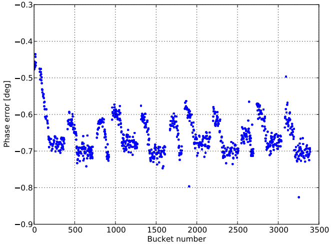
Observations with 50 ns bunch spacing beam

- Measurements started after the scrubbing run
  - Electron cloud is very small for the 50 ns beam, but visible
- Scrubbing effect during 2011 from physics fills

Fill 1798. 21-05-2011



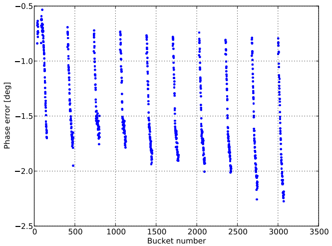
Fill 2267. 30-10-2011



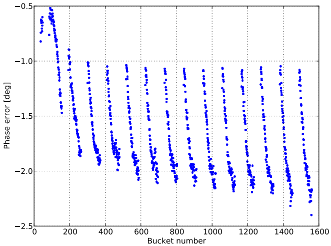
Observations with 25 ns bunch spacing beam

- Electron cloud density is higher than for the 50 ns beam
- Effect of the batch spacing:
  - Electron cloud is reduced for large batch spacing

Fill 2212. 14-10-2011
6.325 μs spacing



Fill 2214. 14-10-2011
925 ns spacing

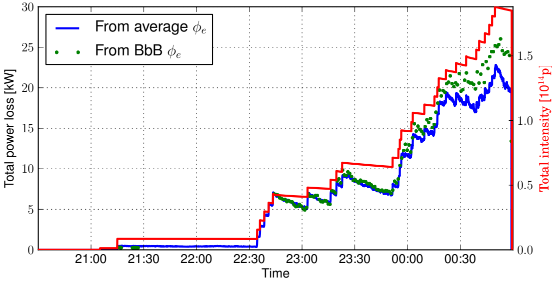


Power loss estimation

- Total beam power loss:

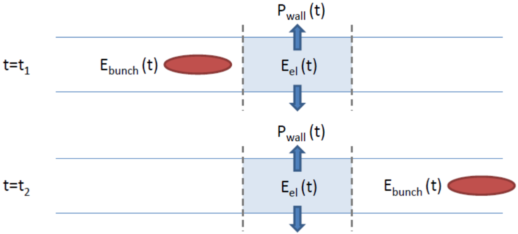
$$P_L = \sum_k N_k \, e \, V \, f_{rev} \, \phi_{sk}$$

- Power loss from bunch by bunch phase error is more accurate than using the average phase error



Comparison with simulations (G. Iadarola and G. Rumolo)

- Energy loss calculated from energy balance:

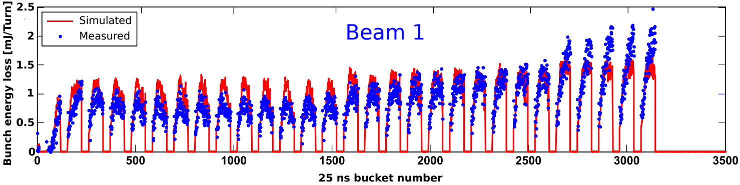


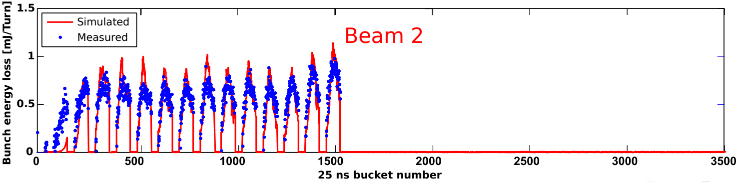
$$[E_{bun}(t_2) + E_{el}(t_2)] - [E_{bun}(t_1) + E_{el}(t_1)] = \int_{t_1}^{t_2} P_{wall}(t)\mathrm{d}t$$

$$[E_{bun}(t_2) - E_{bun}(t_1)] = [E_{el}(t_2) - E_{el}(t_1)] + \int_{t_1}^{t_2} P_{wall}(t)\mathrm{d}t$$

Comparison with simulations (G. Iadarola and G. Rumolo)

- Bunch lengths and intensities are measured and taken into account in the simulations for both the build-up and energy loss
- $\delta_{max} = 1.5$, R = 0.7 and some uncaptured beam





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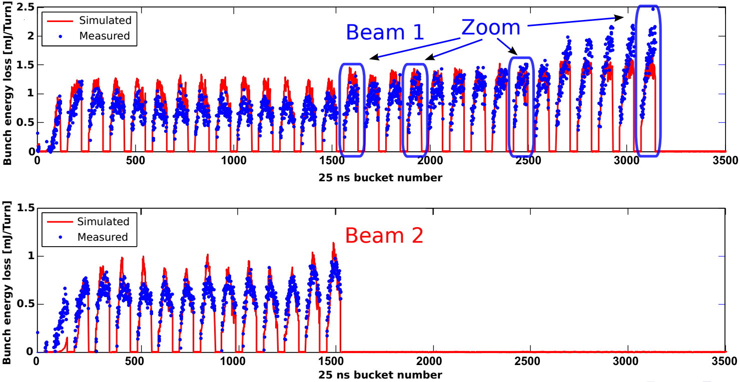

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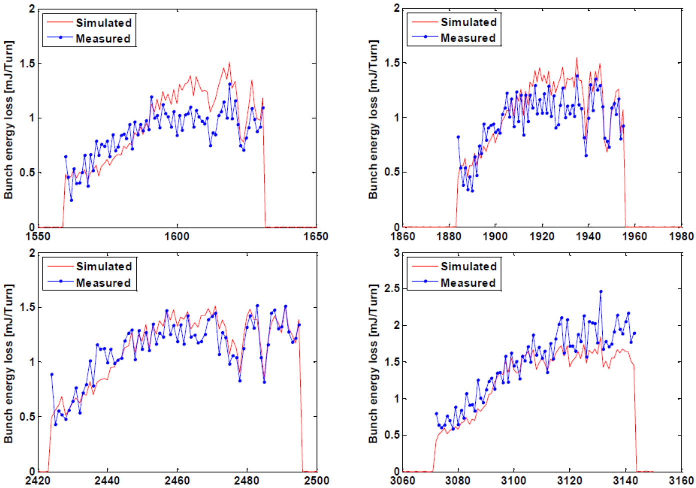

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Conclusions

- Accurate phase error measurements are possible in the LHC thanks to the Beam Phase Module high resolution
- Phase error shift measurements could be used as a novel electron cloud diagnostics
- Average phase error shift is useful to see the total energy loss due to the electron cloud
- Bunch by bunch phase error provides information about the electron cloud build up
  - Benchmark allows to define parameters (δ_{max} and R) for simulations
- Next steps:
  - Take into account the effect of the resistive impedance
  - Calibrate with the new Beam phase module installed in the cavern (UX45)

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