Synchrotron frequency shift as a probe of the CERN SPS reactive impedance

HB2014 – 11/13/14

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Outline

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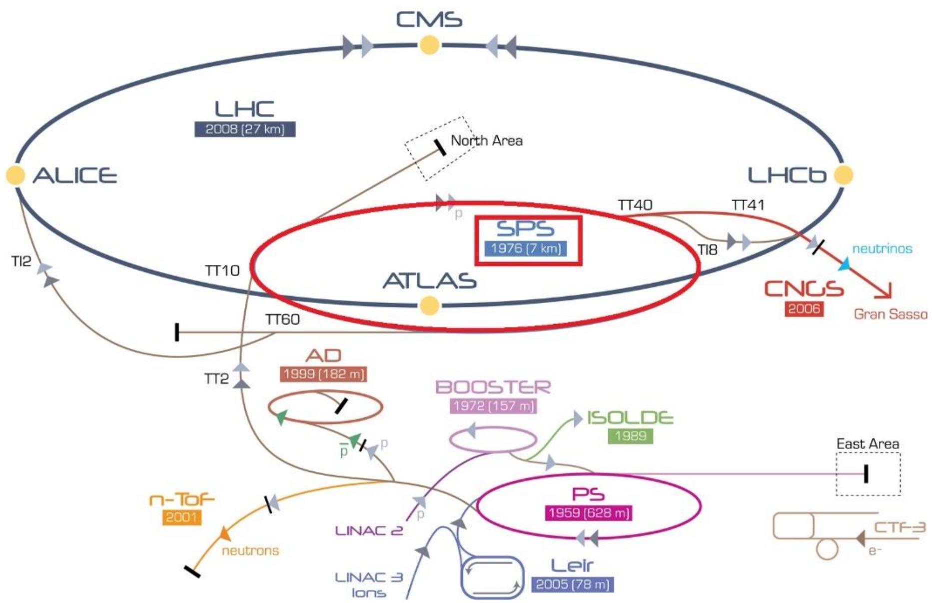
- **Measurements**
- **Simulations**
- **Analytical results**
- **Conclusions**

Introduction and motivations



- ❑ The **HL-LHC project** at CERN requires an **increase of intensity**, but **intensity requirements cannot be fulfilled** for the moment in the **SPS**, one of the reason being **longitudinal instabilities**.

- ❑ A **detailed impedance model** is under development in order to simulate intensity effects and **identify the source of the instabilities**.

- ❑ This **model was tested** against sets of measurements **to proof its accuracy.**

Quadrupole frequency shift

- **Bunch length oscillations** (quadrupolar $m = 2$) at injection in the SPS (26 GeV/c, **above transition**) are measured and analyzed in order to measure the **synchrotron frequency shift as a function of intensity**.

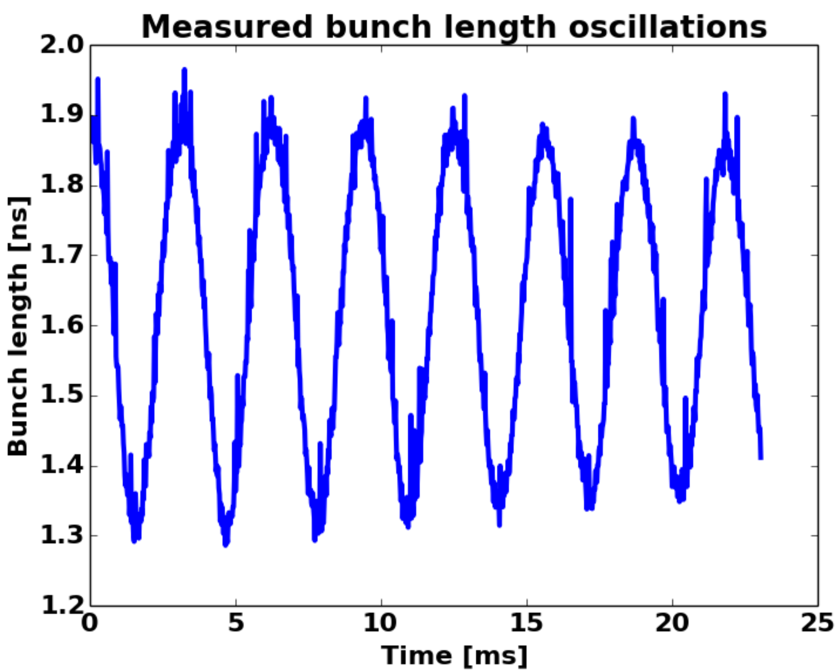
- This shift is due to the convolution of the **reactive part of the impedance** and the bunch spectrum, and is divided in two contributions : the **incoherent frequency shift** (from the stationary bunch distribution) and the **coherent frequency shift** (from the perturbation) [1]

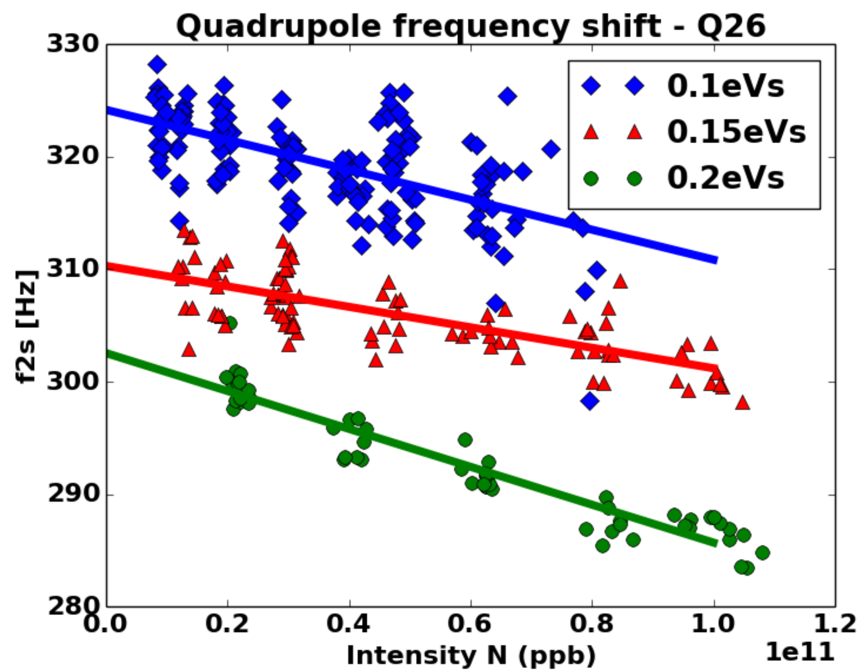
$$f_{s,m}(N_b) \approx m\, f_s^{(0)} + m\, \Delta f_{inc}(N_b) + \Delta f_{coh}(m, N_b)$$

- Measurements and simulations were compared in order to test the current SPS impedance model, and a **dependence on emittance (~ bunch length) and distribution type** was observed and analyzed.

Measurement method

- A mismatch bunch is injected in the SPS and its quadrupole oscillations are measured and analyzed

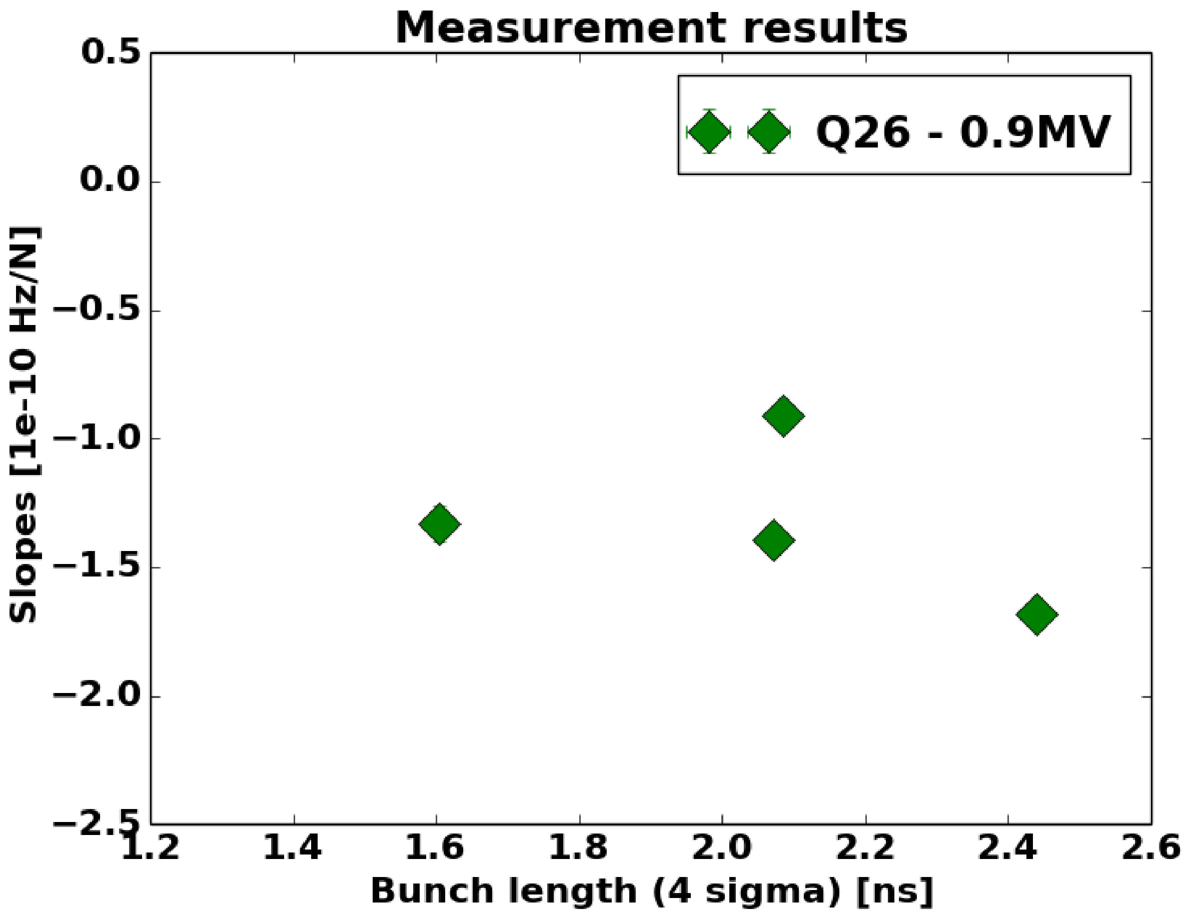




- Bunch length is defined as $\tau = 4\sigma_{RMS}$

- Scanning intensities ($1 \cdot 10^{10}$ to $8 \cdot 10^{10}$) and emittances (0.1eVs to 0.2 eVs)

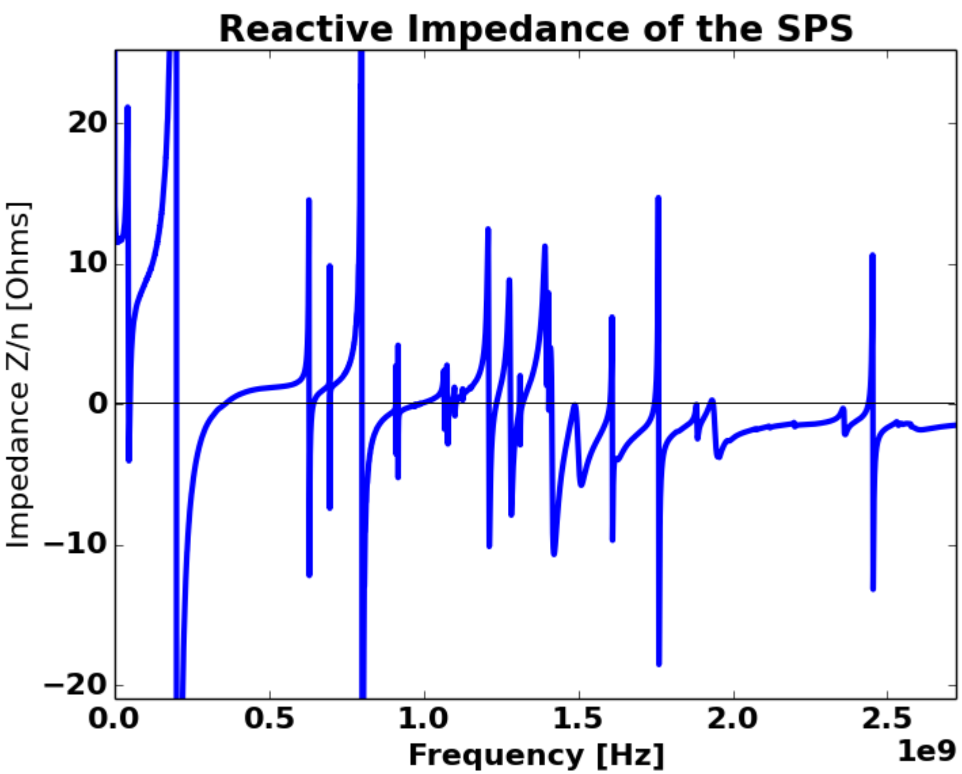
Measurement results – Q26



- **Each point** in simulations corresponds to the **slope** of the quadrupole frequency shift as a function of intensity, for bunches of the **same bunch length**.

Impedance model

❑ Actual SPS impedance model [2]

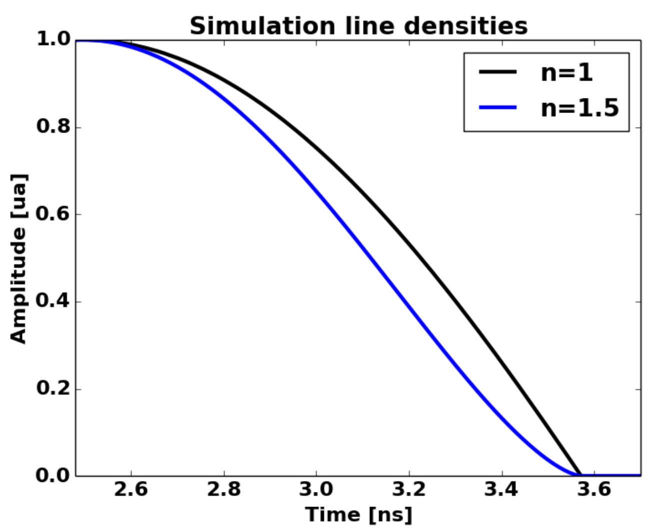


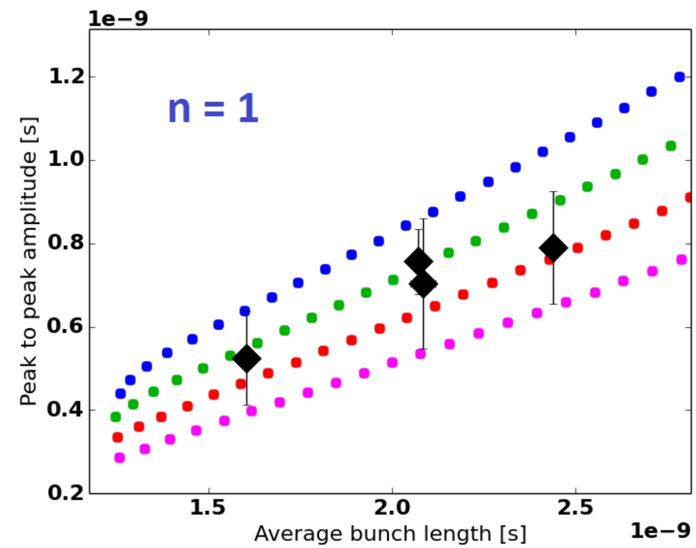
Main reactive impedance ($\Im[Z/(f/f_0)]$):

- ❑ Kickers (inductive, 5.5Ω)
- ❑ Vacuum flanges (inductive, 0.5Ω)
- ❑ RF systems (capacitive)
- ❑ Space charge (capacitive, -1.0Ω) [3]

Simulation method

- Using **BLonD simulation code** [4]



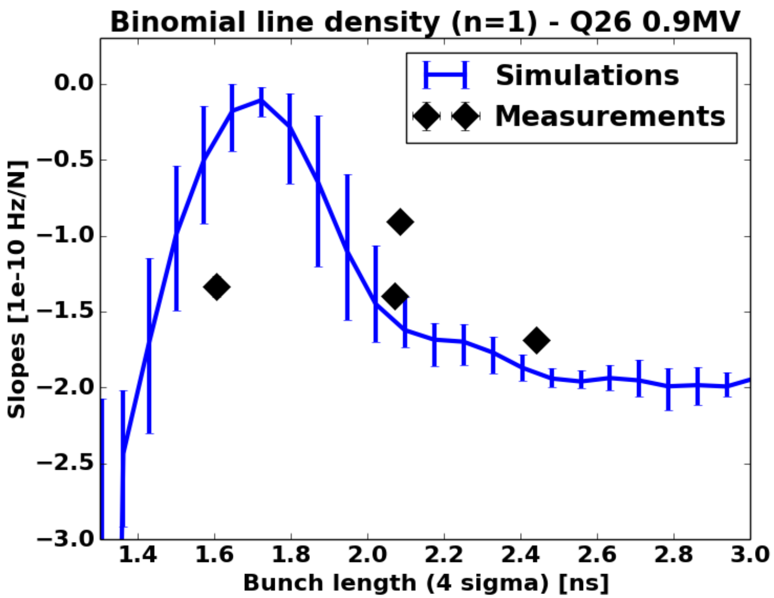


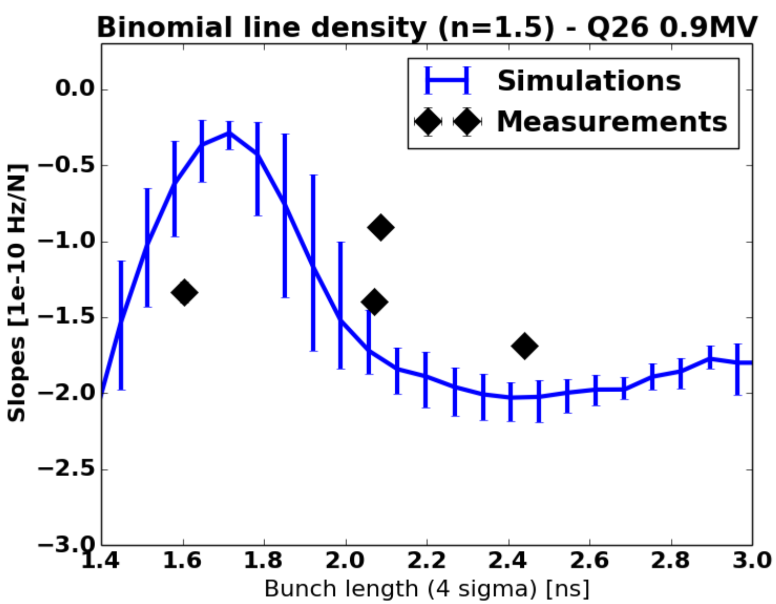
- Binomial profile at injection

$$\lambda(t) = \lambda_0 \left[1 - \left(\frac{t}{\tau}\right)^2\right]^n \; ; \; n = 1\text{: } \textit{Parabolic line density}$$

- The **bunch length τ, the intensity and the momentum spread are scanned**, in order to cover the full panel including measurements

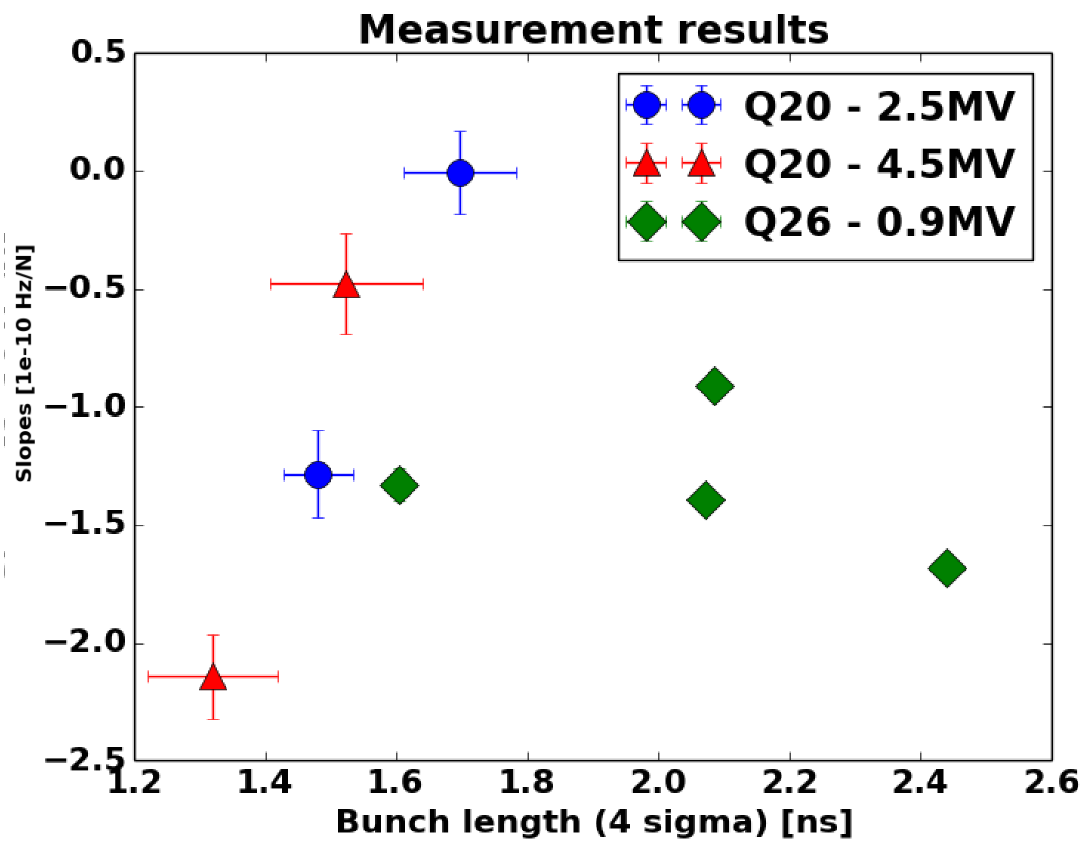
Simulation results – Q26





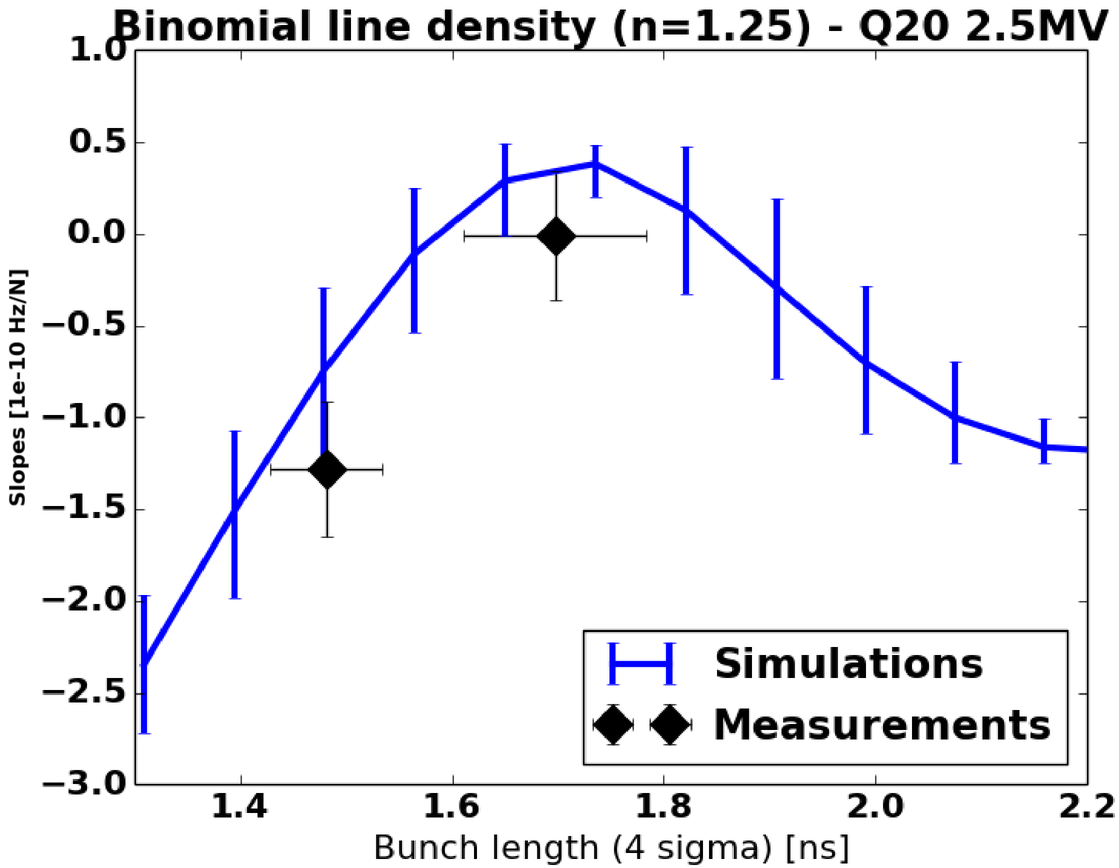
- A **non monotonous dependence** of the slope as a function of bunch length is observed in simulations
- The **error bars** in simulations corresponds to the range due to the different **momentum spreads**
- The **maximum is reduced** by **increasing n** in the binomial distribution.
- The simulations give a **good agreement** with measurements.

Measurement results – Extended



- Two different optics: Q26 and Q20 (slopes were **scaled to Q26 – 0.9MV** in order to be compared on the same plot).
- **The Q20 measurements reveals the maximum around $\tau = 1.7$ns.**

Simulation results – Q20



- The **same properties** were seen with simulations and measurements with the **Q20 optics**.

Incoherent frequency shift

- Numerical computation of the **incoherent frequency shift** [5]

- This shift is due to the **stationary spectrum** of the bunch

$$f_s(N) \approx f_s^{(0)} \left(1 + \frac{\alpha N Z_1}{2}\right)$$

$$Z_1 = \int_{-\infty}^{+\infty} \frac{df}{f_0}\, \sigma_0(f)\, \Im\big(Z(f)\big)\, \frac{J_1(f\hat{\tau})}{f_0\,\hat{\tau}/2}$$

$f_s^{(0)}$: synchrotron frequency

Z_1 : effective impedance

σ_0 : stationary bunch spectrum

$\hat{\tau}$: single particle oscillations amplitude

- Above transition, $\boldsymbol{\alpha < 0}$, so **inductive impedance give** $\boldsymbol{Z_1 > 0}$ so the **slope is steeper** (vice-versa for capacitive impedance)

Coherent frequency shift

- **Coherent frequency shift** was estimated for the quadrupolar case and has a **non negligible effect** on the slope [6].

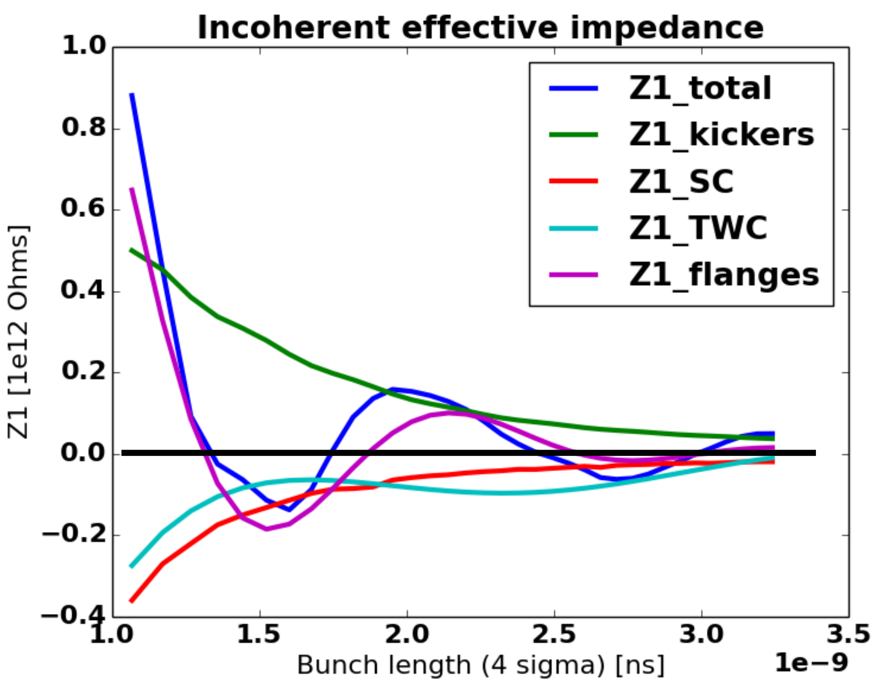
$$f_{2s} \approx 2f_s + \beta\, N\, Z_2$$

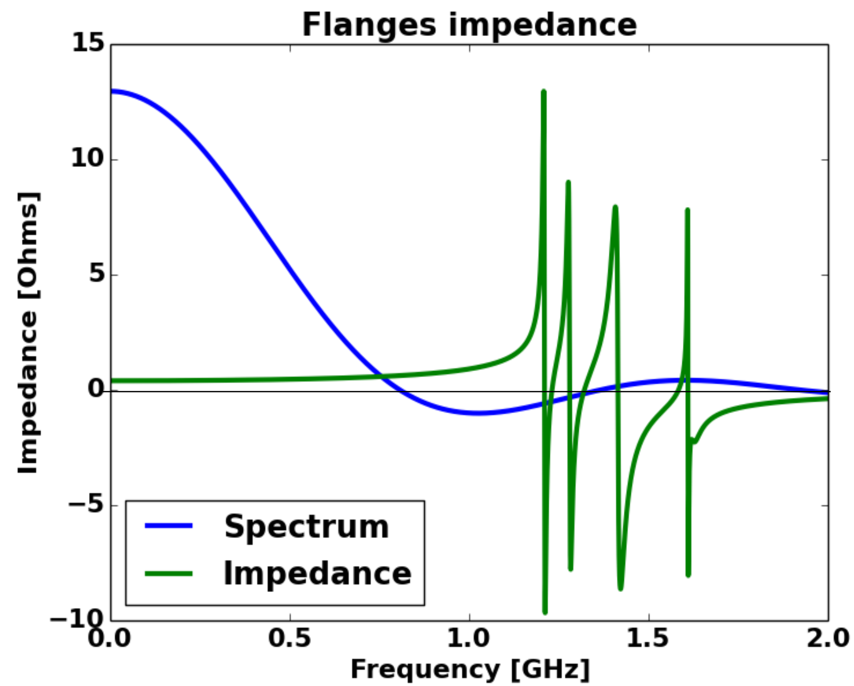
$$Z_2 = \frac{\sum_{p=-\infty}^{p=+\infty} h_2 \frac{Z}{p}}{\sum_{p=-\infty}^{p=+\infty} h_2} \;;\; p = \frac{f}{f_0} \;;\; h_2 = \frac{J_{5/2}(p\omega_0\tau)^2}{p\omega_0\tau}$$

- The **coherent shift goes in the opposite direction than the incoherent shift** (capacitive impedance leads to a steeper slope and vice-versa), and is **due to the perturbation** on the bunch distribution with respect to the stationary bunch distribution.

- Note that analytical formulas are valid for small perturbations from stationary case, but **large deviations exist in measurements**.

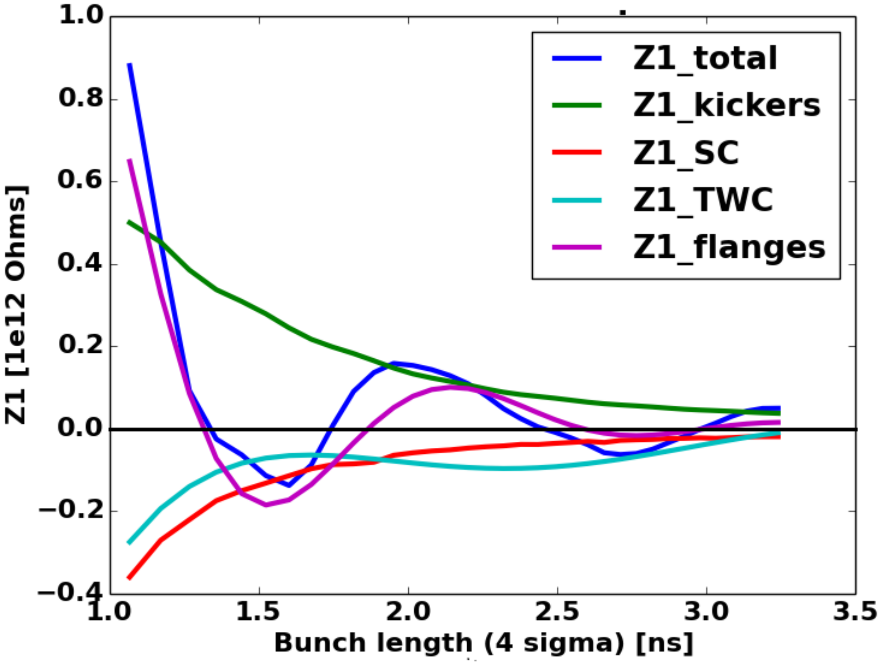
Parabolic spectrum

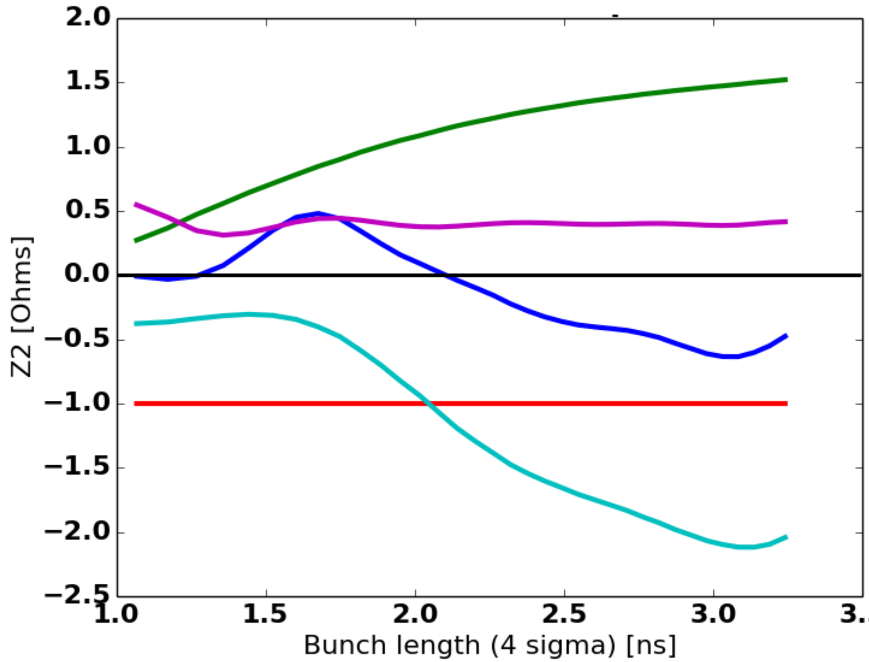




- **The impedance type (inductive vs. capactive) changes as a function of bunch length for the flanges due to the negative lobe of the parabolic spectrum, turning inductive impedance into effective capacitive impedance.**

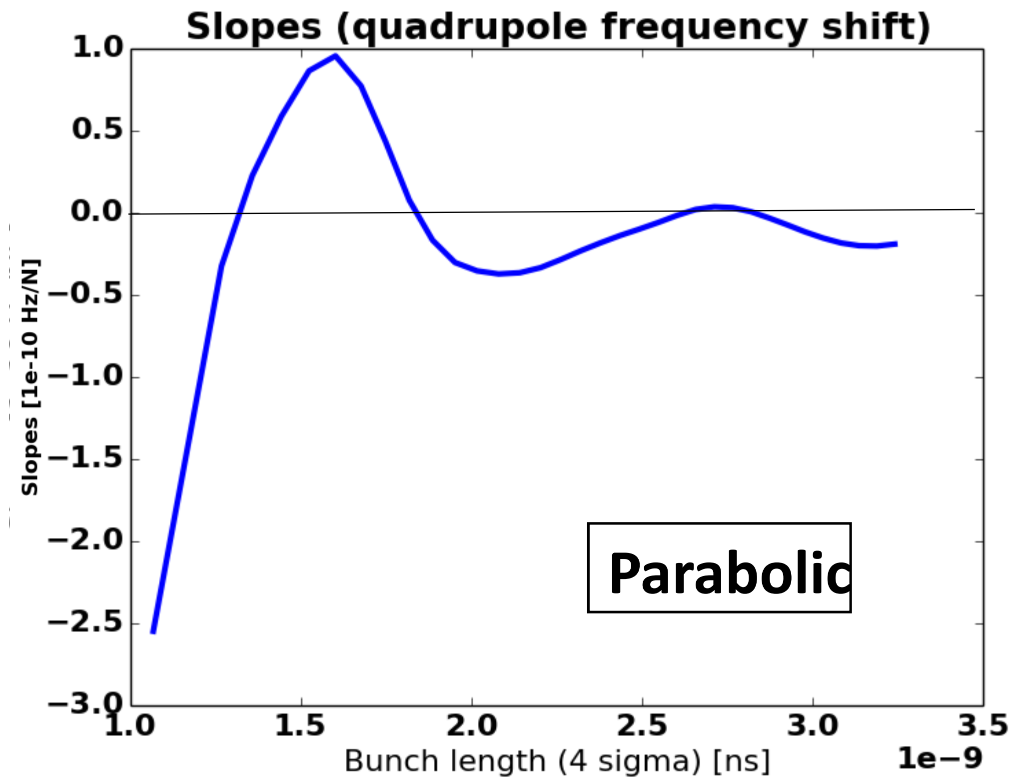
Effective impedance





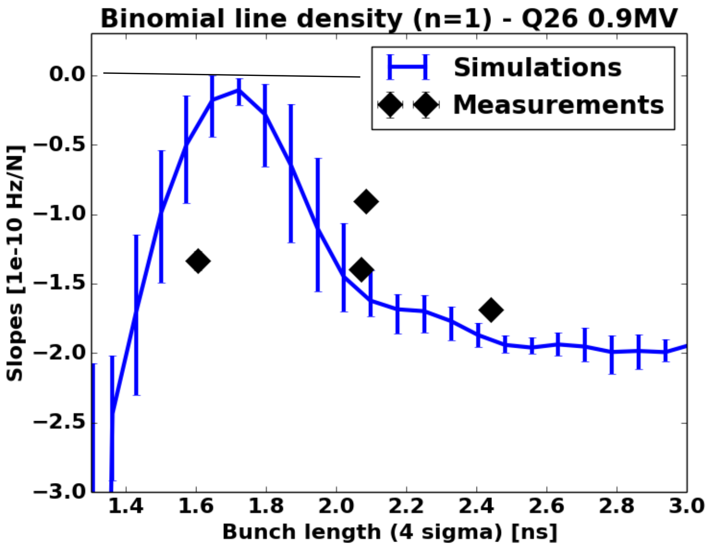
- The effective impedances have a **dependence on bunch length**, due to the **flanges for Z_1 (incoherent),** and due to the **RF systems and the kickers for Z_2 (coherent)**

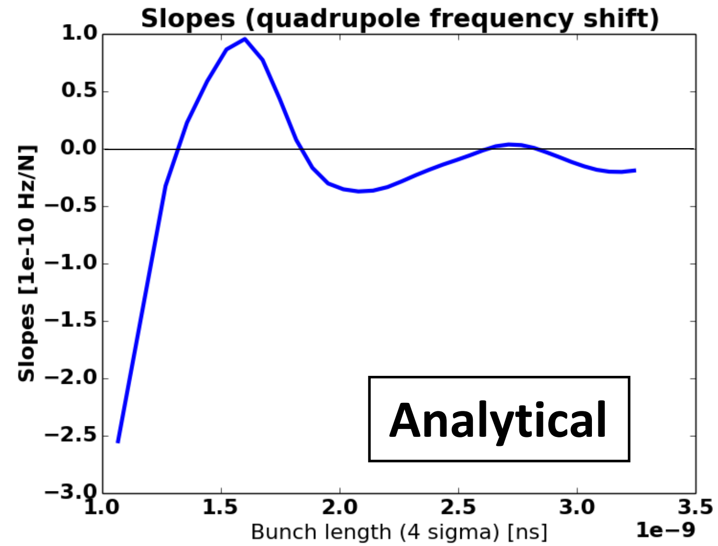
Analytical results – Slope



- The slope is computed with incoherent and coherent shift.
- The **parabolic** distribution is sampling **inductive or capacitive depending on the bunch length**

Conclusions





- **The incoherent quadrupole frequency shift has a dependence on bunch length due to the coupling with high frequency impedances (flanges), while the coherent shift dependence is due to the RF systems and the kickers.**
- More measurements are foreseen by **generating a small mismatch by increasing the RF voltage** in the SPS, in order to have **smaller perturbations**.
- Measurements at **higher energies** are planed in order to **eliminate the space charge** impedance.
- Information on the synchrotron frequency shift are needed in order to apply **emittance blow-up with RF noise**. The dependency with bunch length is to be known in order to apply correctly the RF noise.

References

[1] J. L. Laclare, “Bunched Beam Coherent Instabilities”, CERN 87-03, p.264, CAS Proceedings, (1987).

[2] J. Varela Campelo, C. Zannini, B. Salvant, «SPS Impedance Model Update», Meetings of the LIU-SPS Beam Dynamics Working Group, CERN, Geneva, Switzerland (2014), http://paf-spsu.web.cern.ch/paf-spsu/meetings/2008.htm

[3] L. Wang, «The geometry effect of the space charge impedance LSC code», ICFA mini-Workshop on “Electromagnetic wake fields and impedances in particle accelerators" , Erice, Italy, 2013

[4] BLonD code: https://github.com/dquartul/BLonD/

[5] K. Y. Ng, «Physics of Intensity Dependent Beam Instabilities», Ed. World Scientific Publishing, 2006

[6] A. Chao, «Physics of Collective Beam Instabilities in High Energy Accelerators», Ed. John Wiley & Sons, 1993