LHC Injectors Upgrade

Indirect space charge induced injection oscillations in the PS

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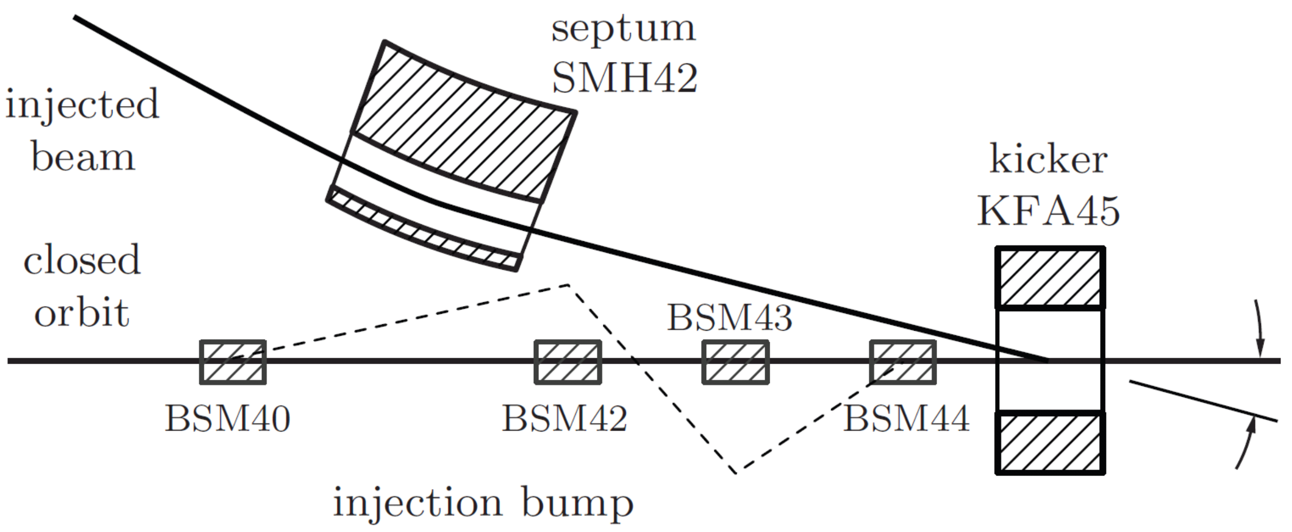
Overview

- Motivation
- Measurements at injection and data analysis
- HEADTAIL simulations
- Conclusions
- Outlook

Motivation

- slow **losses** observed for a few 100 μs after injection
- losses in the injection region constitute one of the **limitations for high intensity beams** → access very difficult in case of septum breakdown

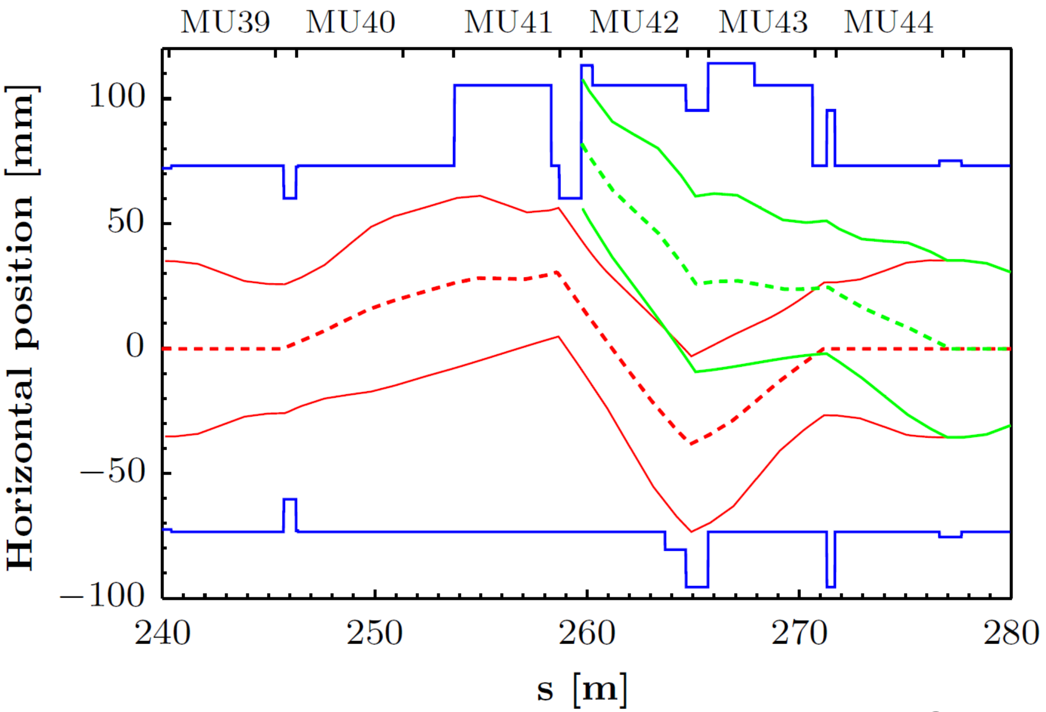
single-turn injection process

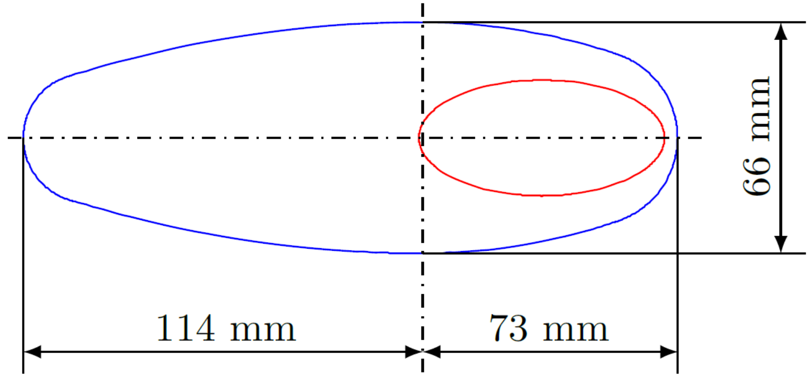


Motivation

- slow **losses** observed for a few 100 μs after injection
- losses in the injection region constitute one of the **limitations for high intensity beams →** access very difficult in case of septum breakdown

aperture and beam envelope in the injection region





Motivation

- **transverse oscillations** observed at injection contribute to these losses → emphasis on vertical oscillations.

- oscillations currently cured with the transverse damper

- however: underlying **mechanism**?

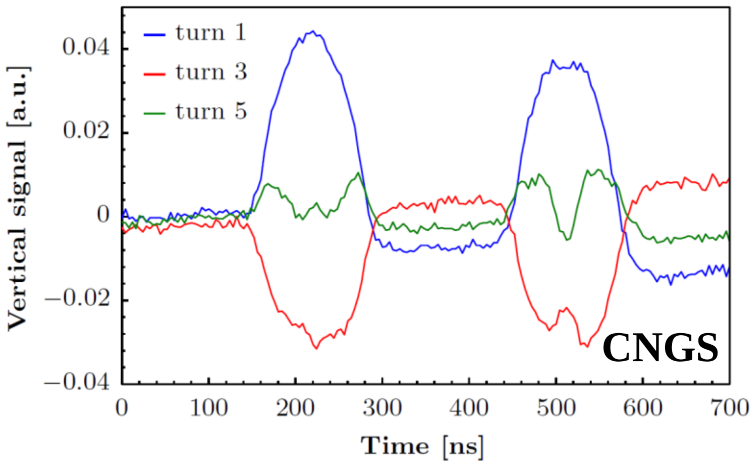
  effect on **future** high intensity beams?

  effect on **future** beams for the HL-LHC?

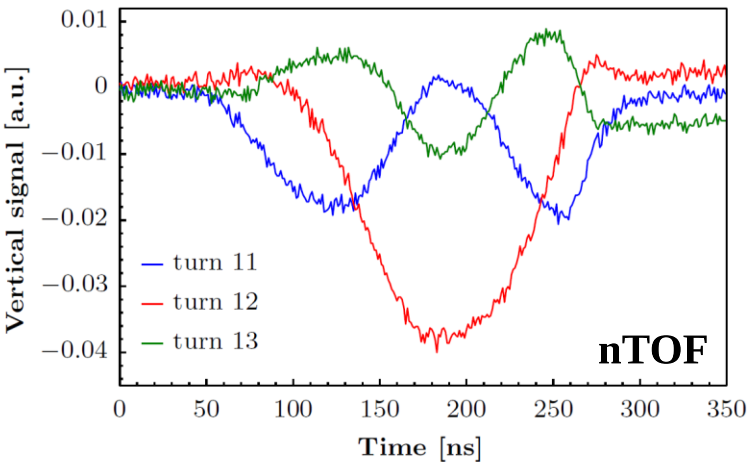
Measurements at injection

- measurements done with the operational settings
- wide-band PU in SS94 used to observe transverse and longitudinal signals
- fast build up of **intra-bunch oscillations** (few turns after injection)
- oscillations primarily observed in the vertical plane
- visible on different types of beams and each time the beam is injected → more pronounced for high-intensity users

$I_p = 375 \cdot 10^{10}$ ppb

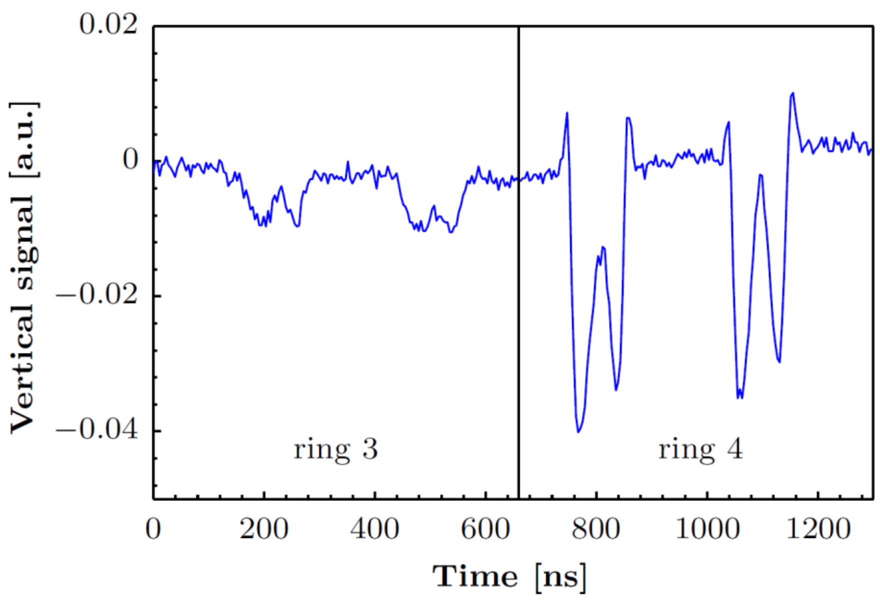


$I_p = 700 \cdot 10^{10}$ ppb



Measurements at injection

- different behavior of the oscillations depending on the PSB ring
- *example*: CNGS, $I_p = 750 \cdot 10^{10}$ per PSB ring, 2 rings injected

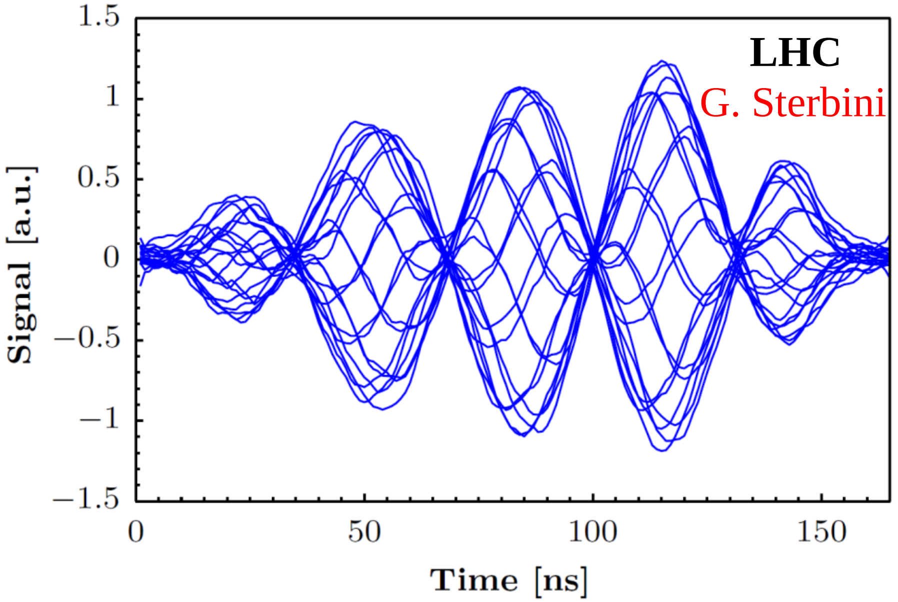


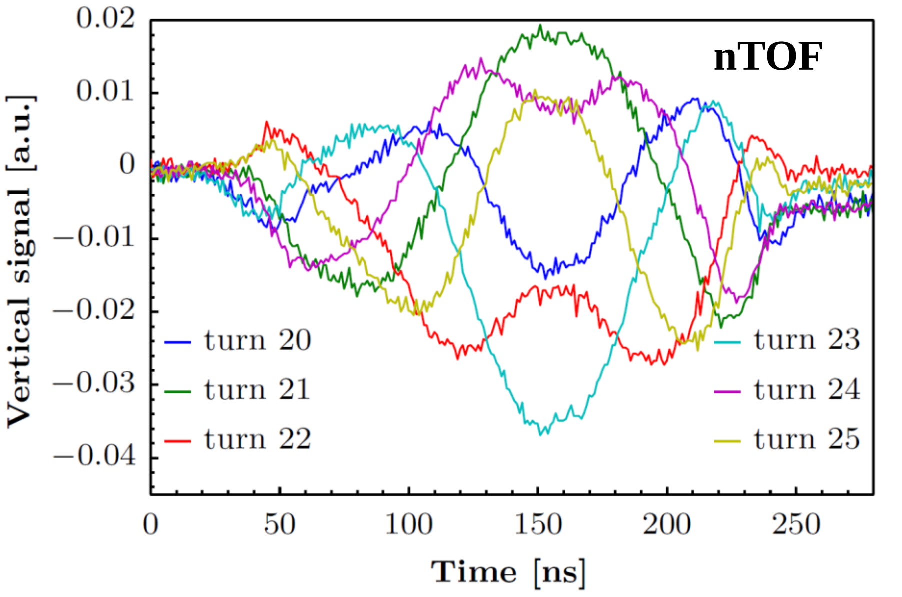
→ **optimized steering** in the BTP-line reduces these oscillations

Data analysis

<u>First assumption: observations correspond to head-tail instability</u>

usually observed in the horizontal plane on LHC-type beams (in the absence of stabilizing mechanisms)



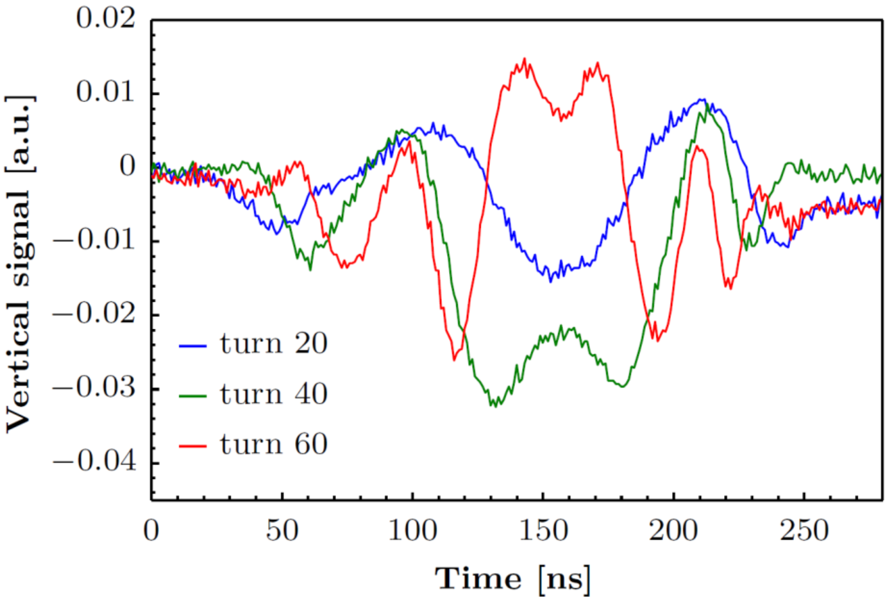


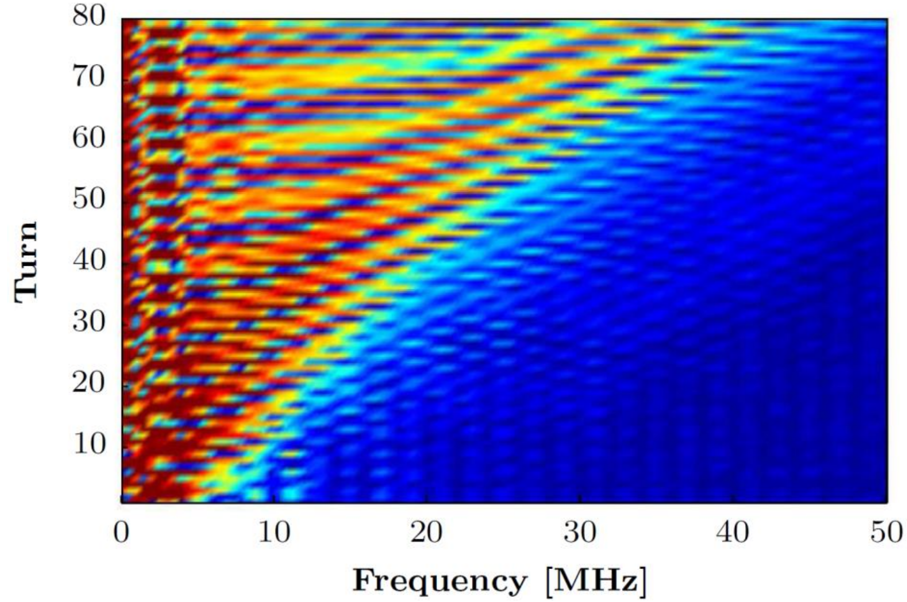
<u>however</u>:

- time scale very short compared to one synchrotron period (~ 400 turns)
- no mode structure appearing

Data analysis

<u>Increasing intra-bunch oscillation frequency (in the vertical plane)</u>

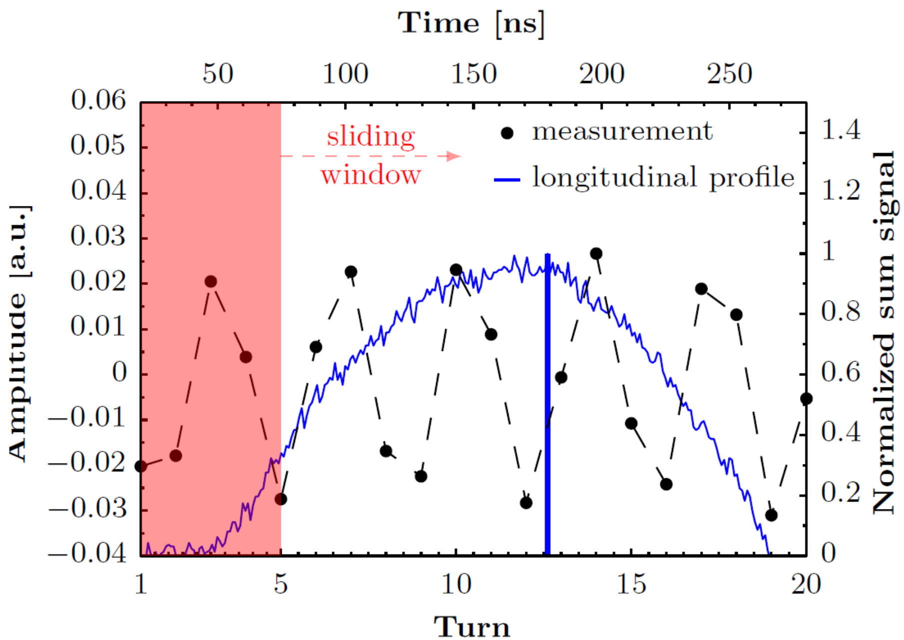


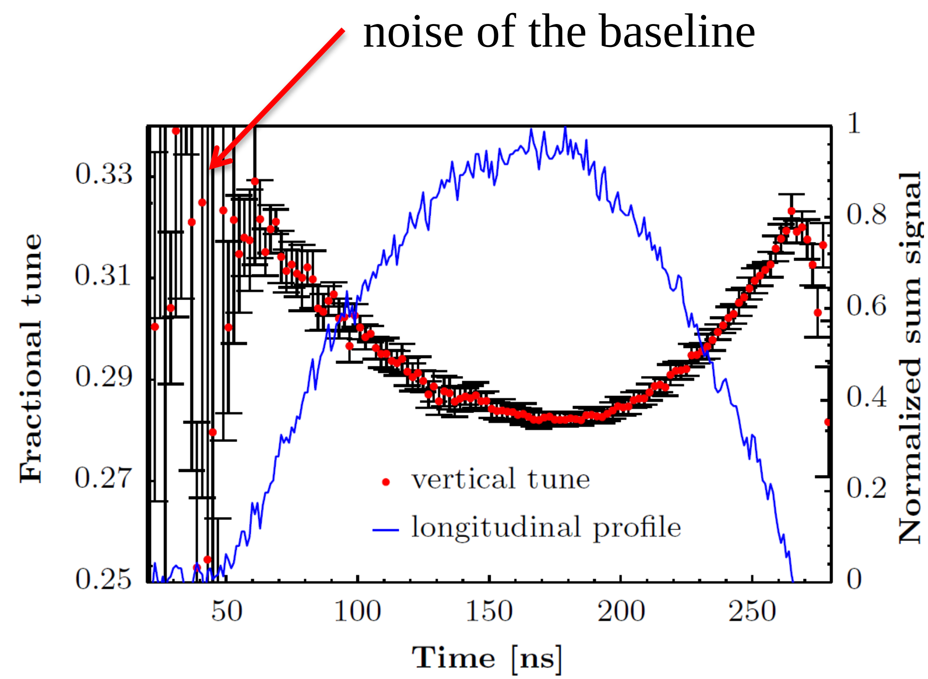


frequency spectrum based on a turn-by-turn FFT → limited resolution due to small number of data points

Data analysis

Detuning along the bunch





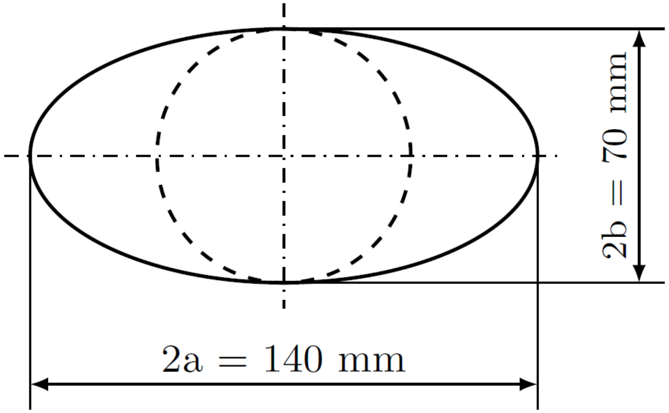
- sinusoidal fit computed over a window of 5 turns for each bin
- repeated for the first 20 turns → average value
- assumption: linear machine, longitudinal motion negligible
- programmed: Q_v=6.33
- **parabolic detuning** observed (proportional to the line density)

HEADTAIL simulations

- HEADTAIL: simulation code for collective effects
  bunches are longitudinally sliced
  macro particles within each slice receive a kick based on a certain wake field

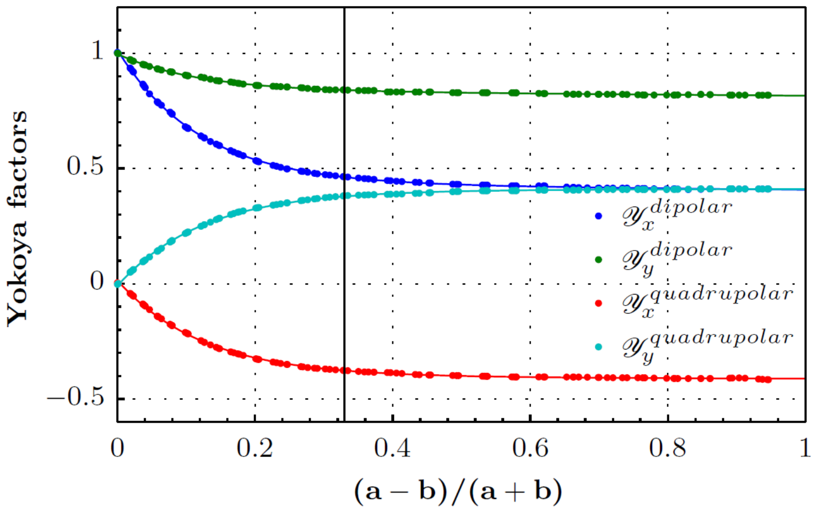
- **ImpedanceWake2D** is used to obtain wall impedance and wake functions for a circular chamber

- for the case of the PS the wake computations are based on a **continuous stainless steel chamber** with the shown dimensions (about 70% of the PS is equipped with this type)



Wake functions

- wake functions for an elliptic geometry obtained from the circular one using the appropriate **Yokoya** factors



$$W_{x,\,elliptic}^{dipolar} = \mathscr{Y}_x^{dipolar} \cdot W_{x,\,cylindric}^{dipolar},$$

$$W_{y,\,elliptic}^{dipolar} = \mathscr{Y}_y^{dipolar} \cdot W_{y,\,cylindric}^{dipolar},$$

$$W_{x,\,elliptic}^{quadrupolar} = \mathscr{Y}_x^{quadrupolar} \cdot W_{x,\,cylindric}^{dipolar},$$

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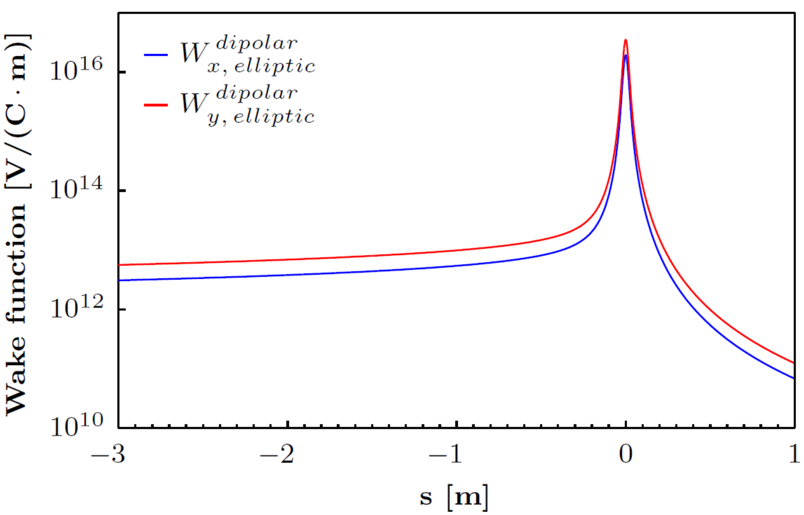
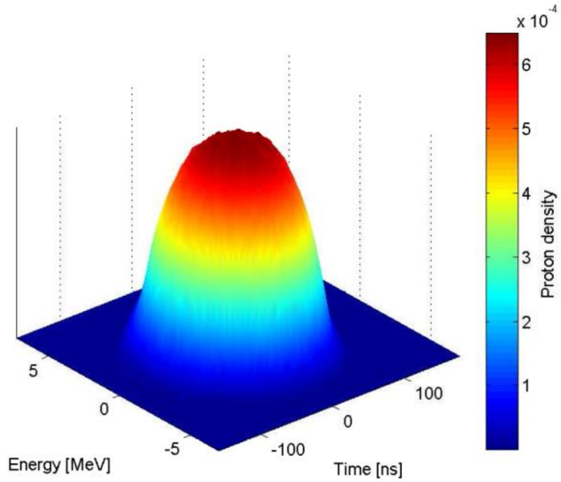
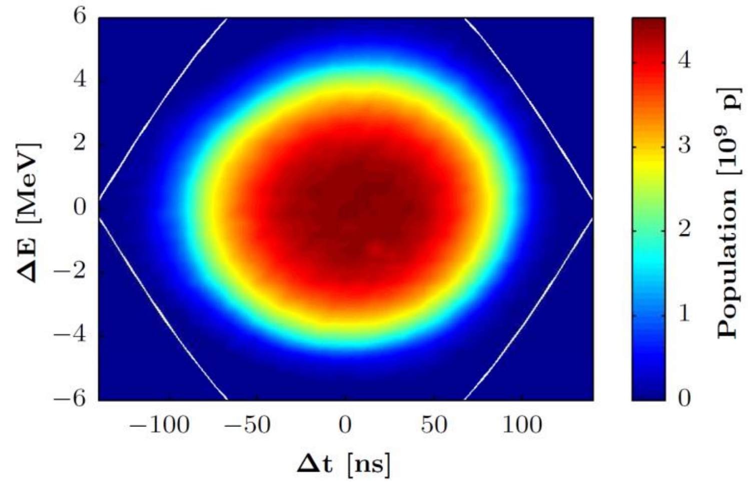


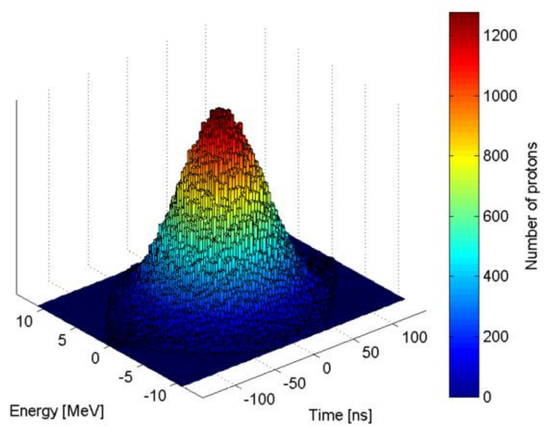
Longitudinal distribution

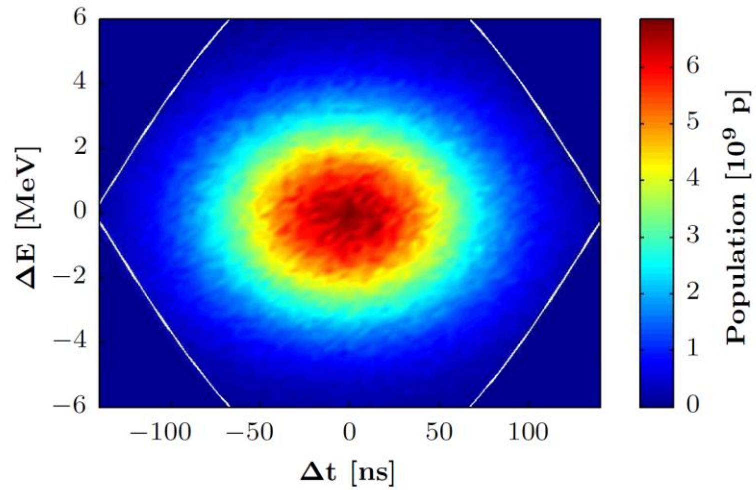
measurement at PSB extraction





distribution created by HEADTAIL





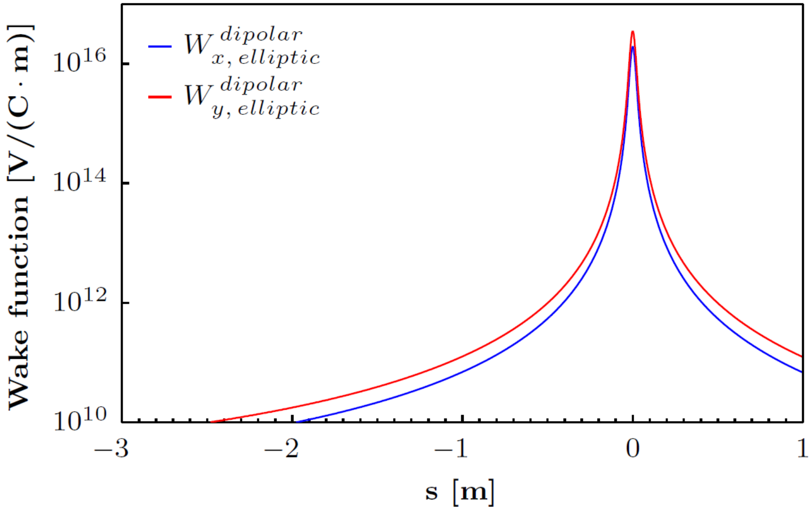
Discrimination between resistive and indirect space charge impedance

Slicing of the bunch

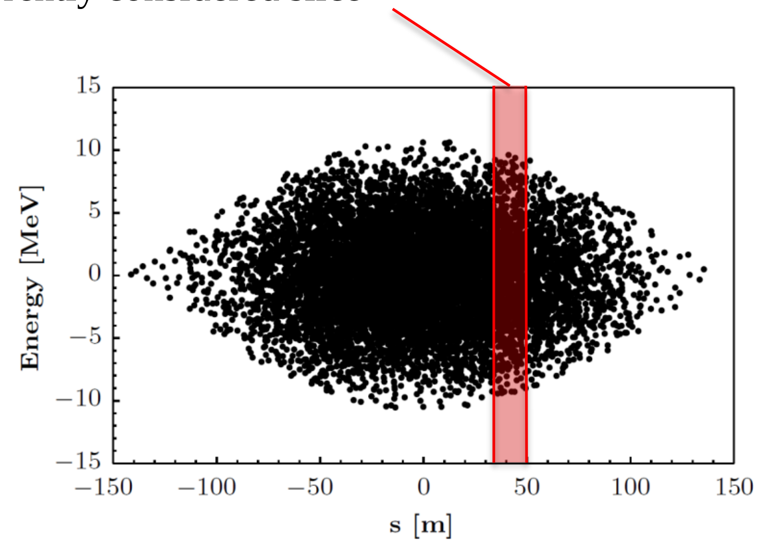
- $\pm 3\sigma_z$ considered as total bunch length
- bunch divided into **1700** equally thick slices

Indirect space charge impedance

decrease of the resistivity of the beam pipe allows determination of indirect space charge impedance only ($10^{-7} \rightarrow 10^{-14}$ in this case)



currently considered slice

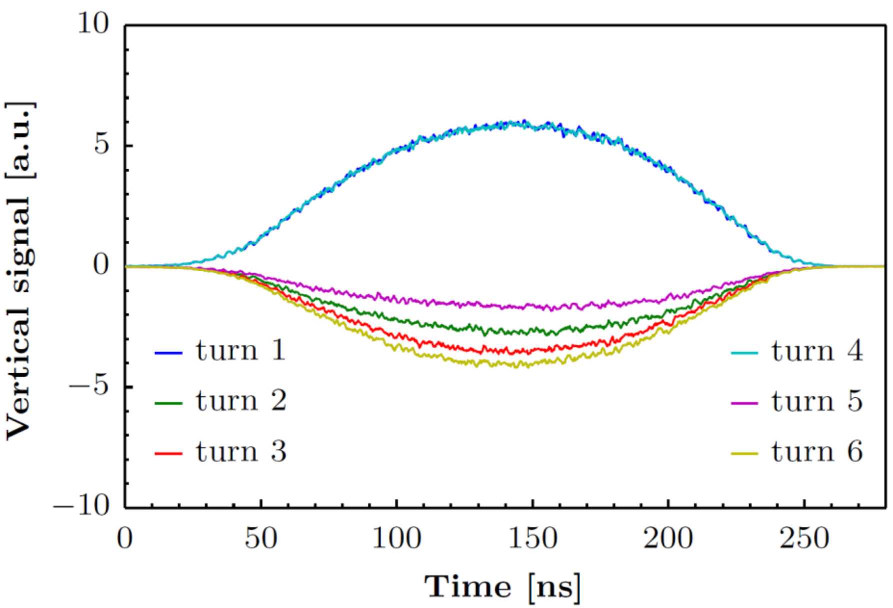


effect of these slices on the current one accounts for **resistive wall impedance only**

indirect space charge impedance is taken into account by using the SC wake function on the left and considering all slices

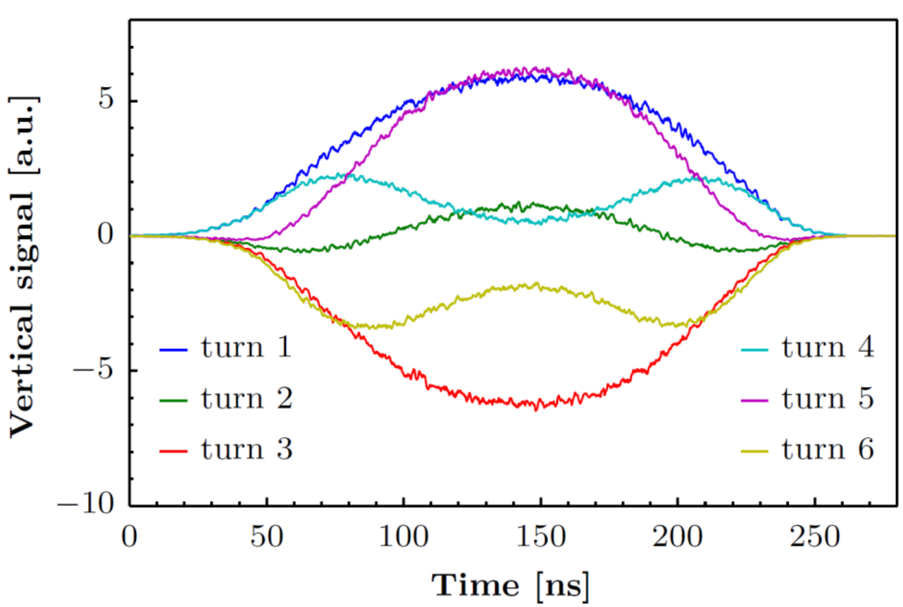
Discrimination between resistive and indirect space charge impedance

<u>resistive wall impedance only</u>



decoherence due to chromaticity

<u>indirect space charge impedance only</u>

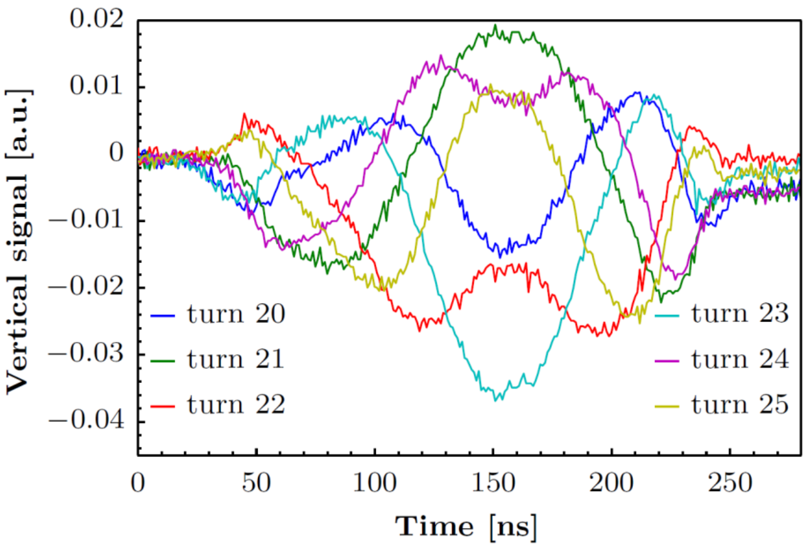


very similar results as observed in the machine

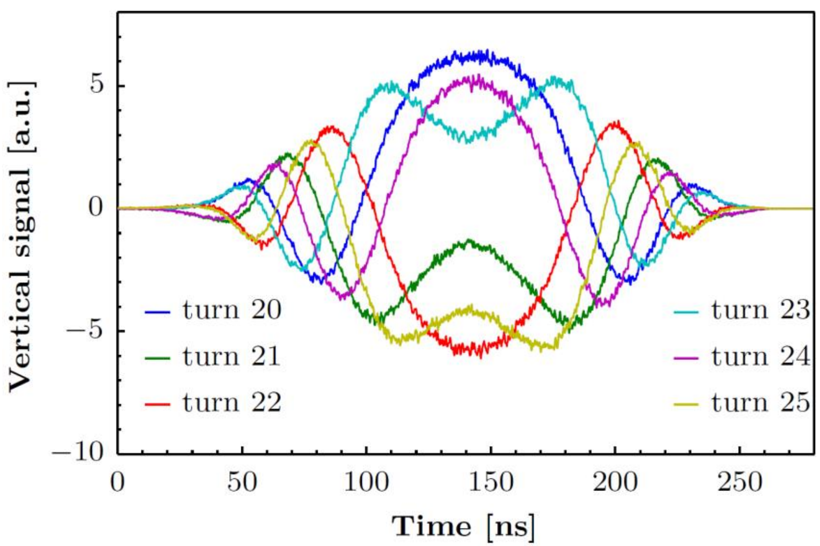
Indirect space charge effects are driving the observed phenomenon

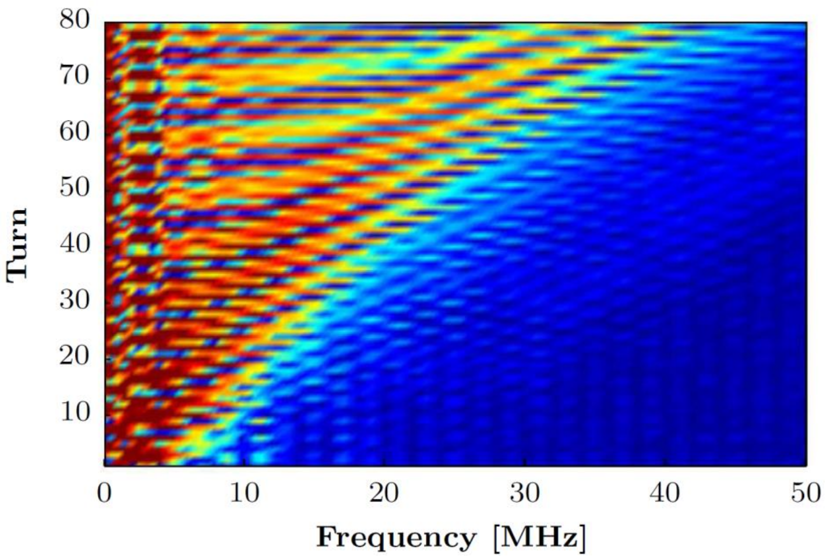
Simulation results

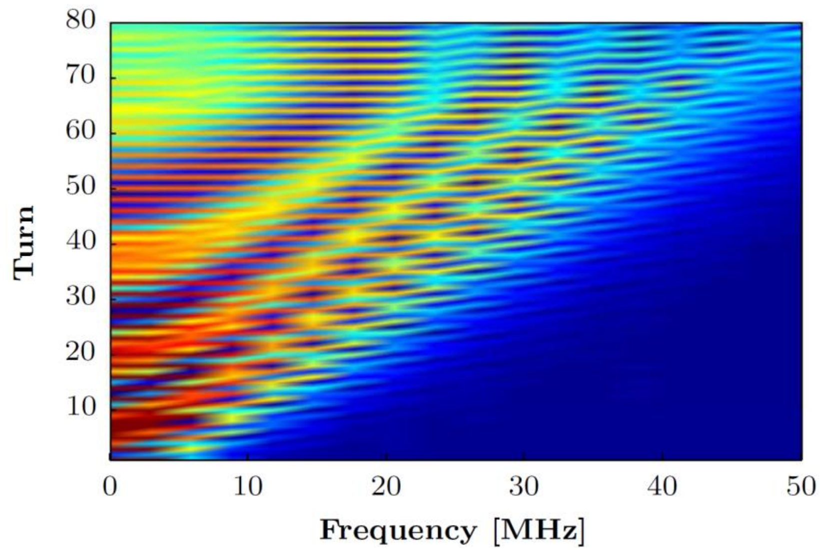
measurement



simulation

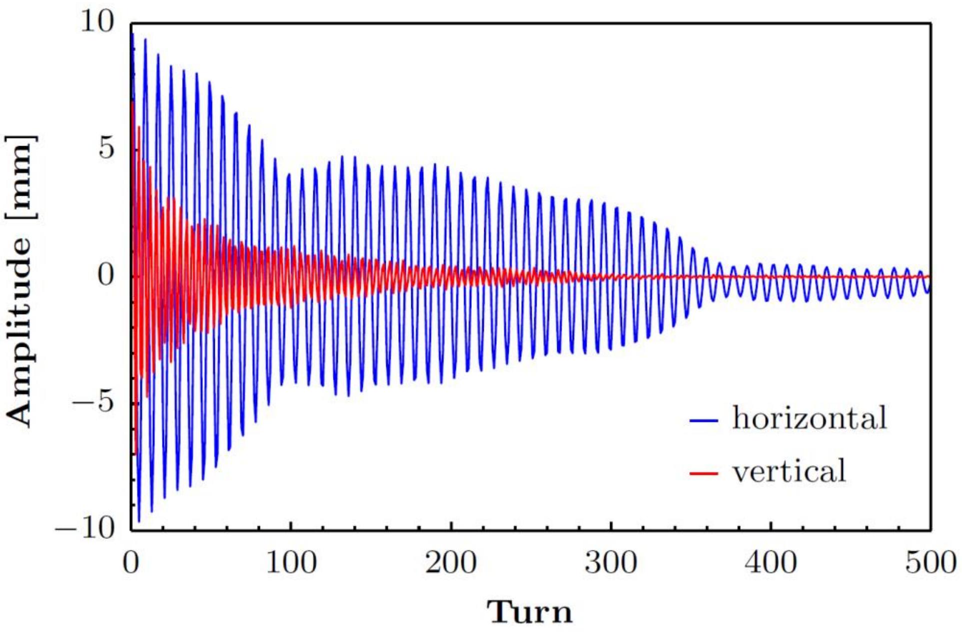






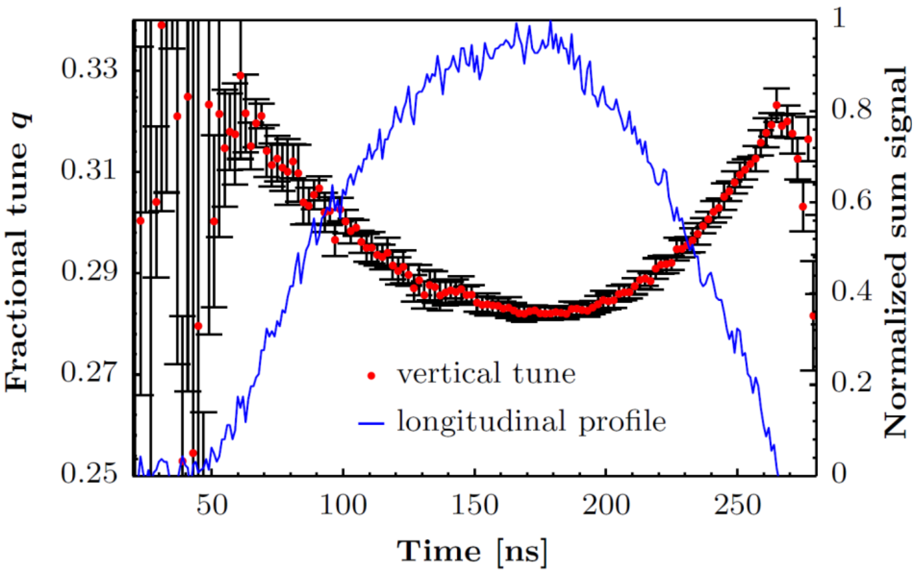
Simulation results

- indirect space charge impedance causes a **real tune shift**
- **no unstable behavior** of the beam observed
- centroid motion decays because of natural chromaticity

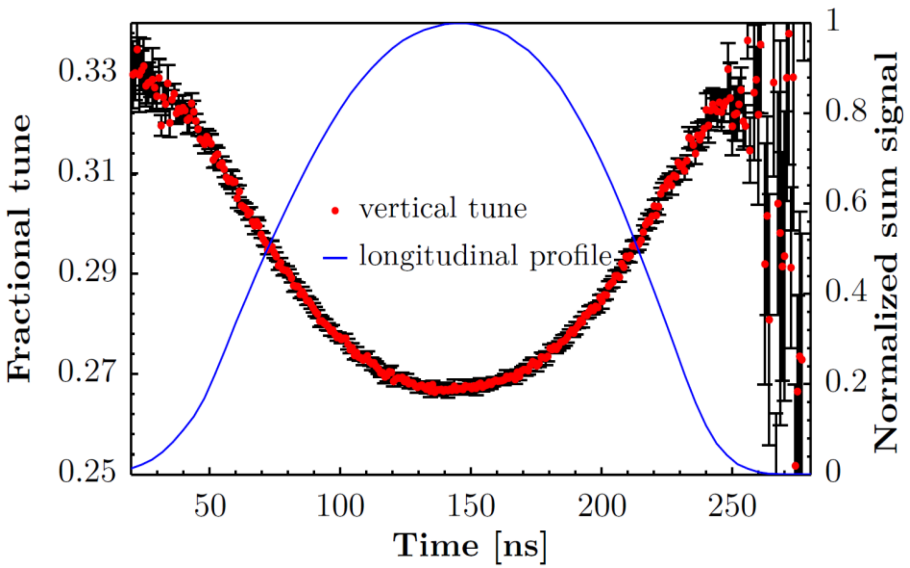


Simulation results

measurement



simulation



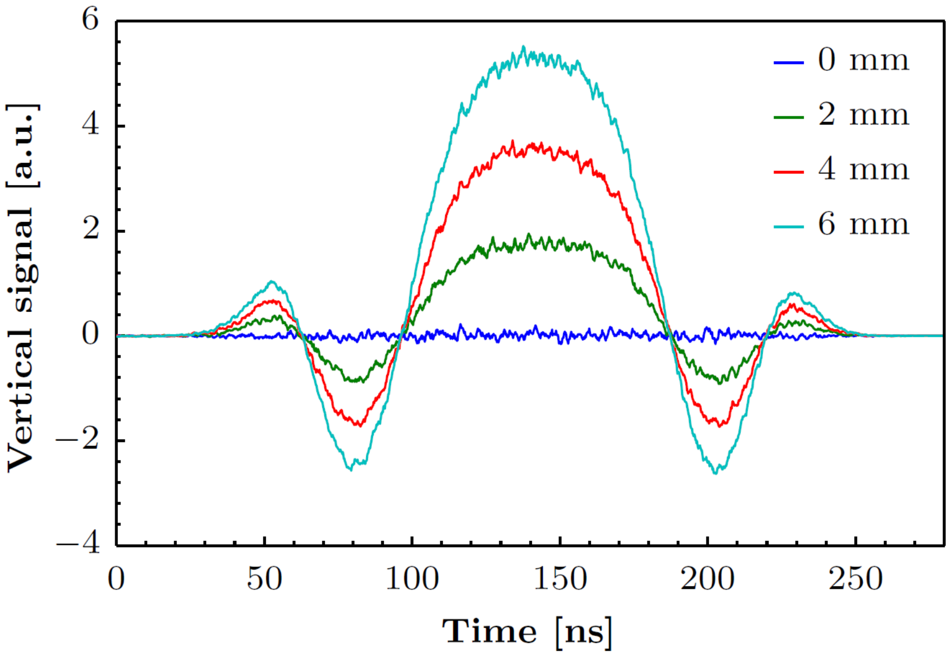
max. tune shift in this simulation is approx. 0.01 larger than in the measurement

→ effect very sensitive to the longitudinal distribution

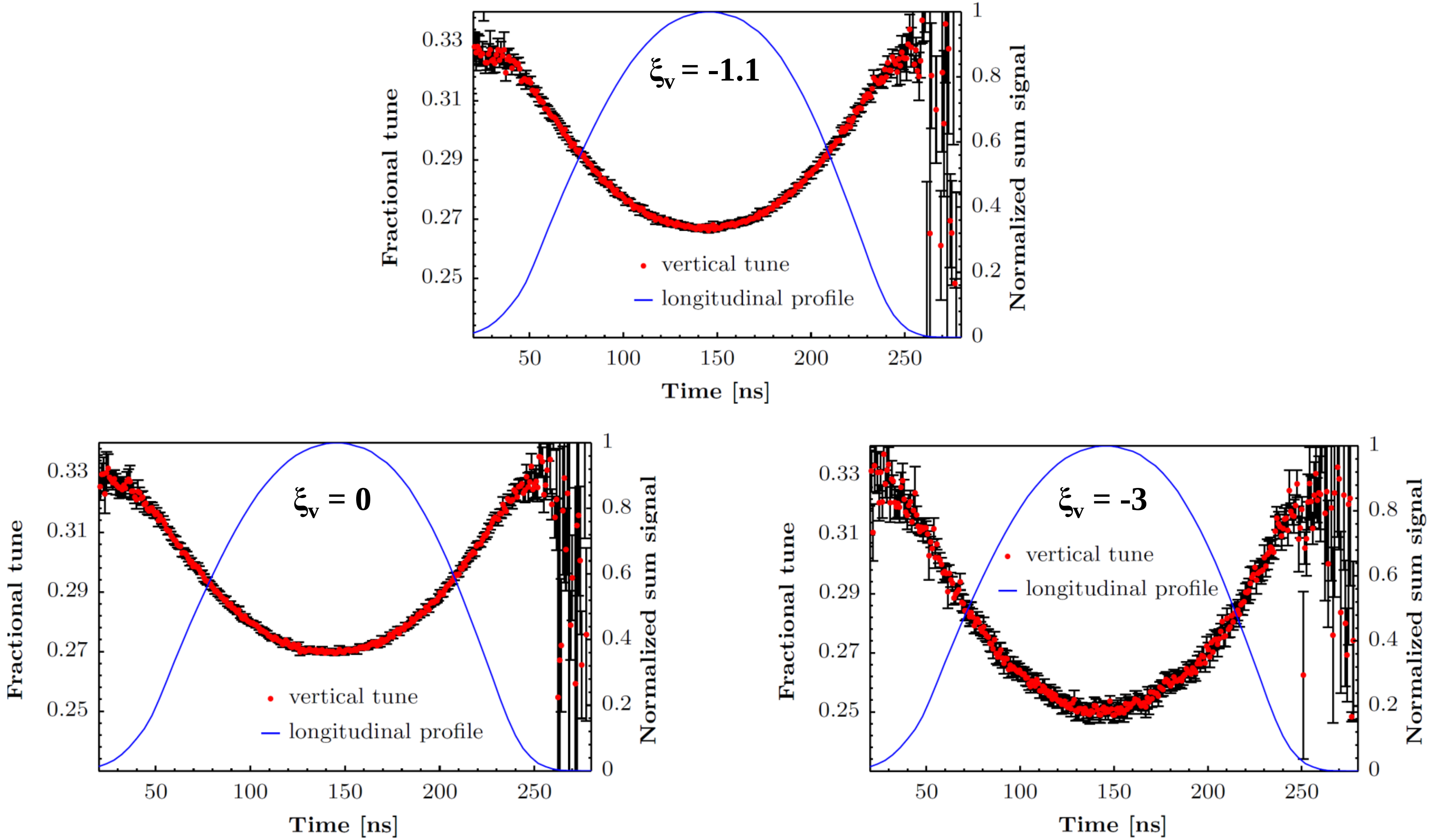
→ modelling of the machine vacuum chambers

Different injection errors

- without injection error no oscillations are observed
- **amplitude** of the oscillation **changes** depending on the error
- **frequency remains** the same

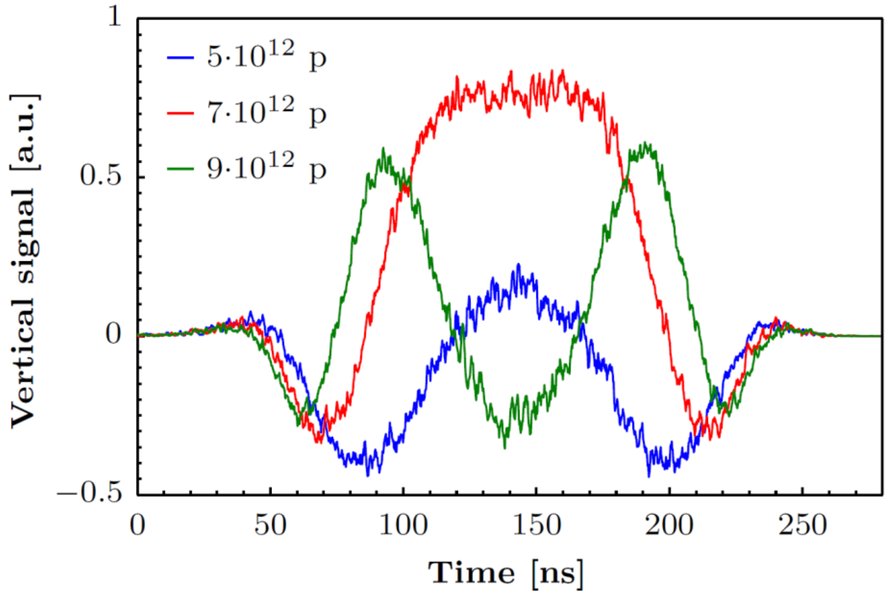


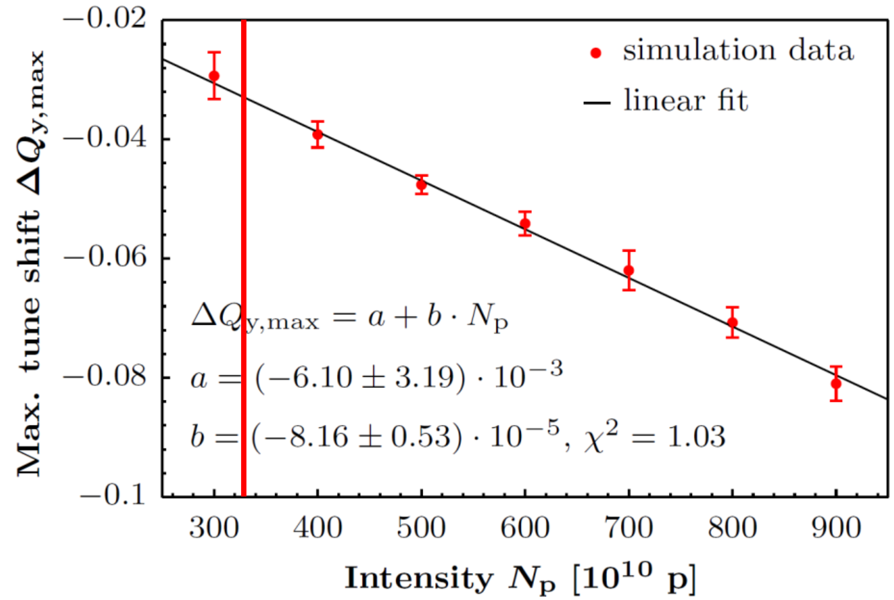
Effect of chromaticity



Intensity scan

- intra-bunch oscillation frequency depends on intensity
- simulations show a linear relationship between intensity and tune shift

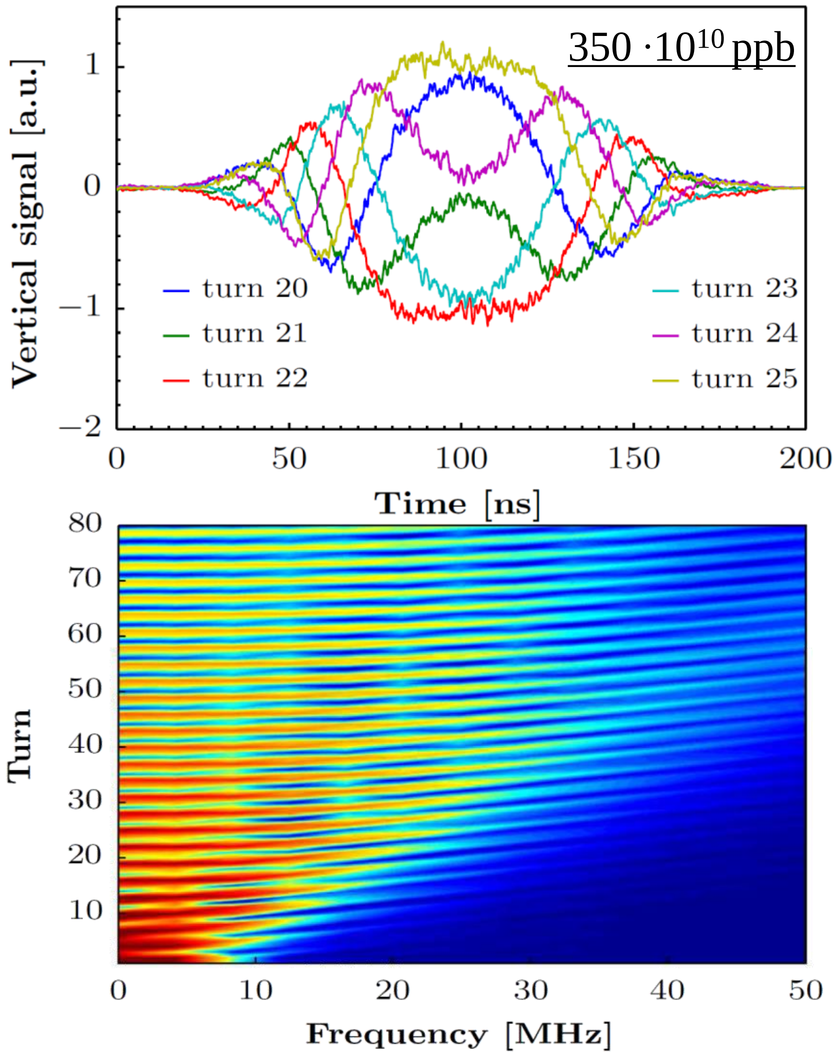




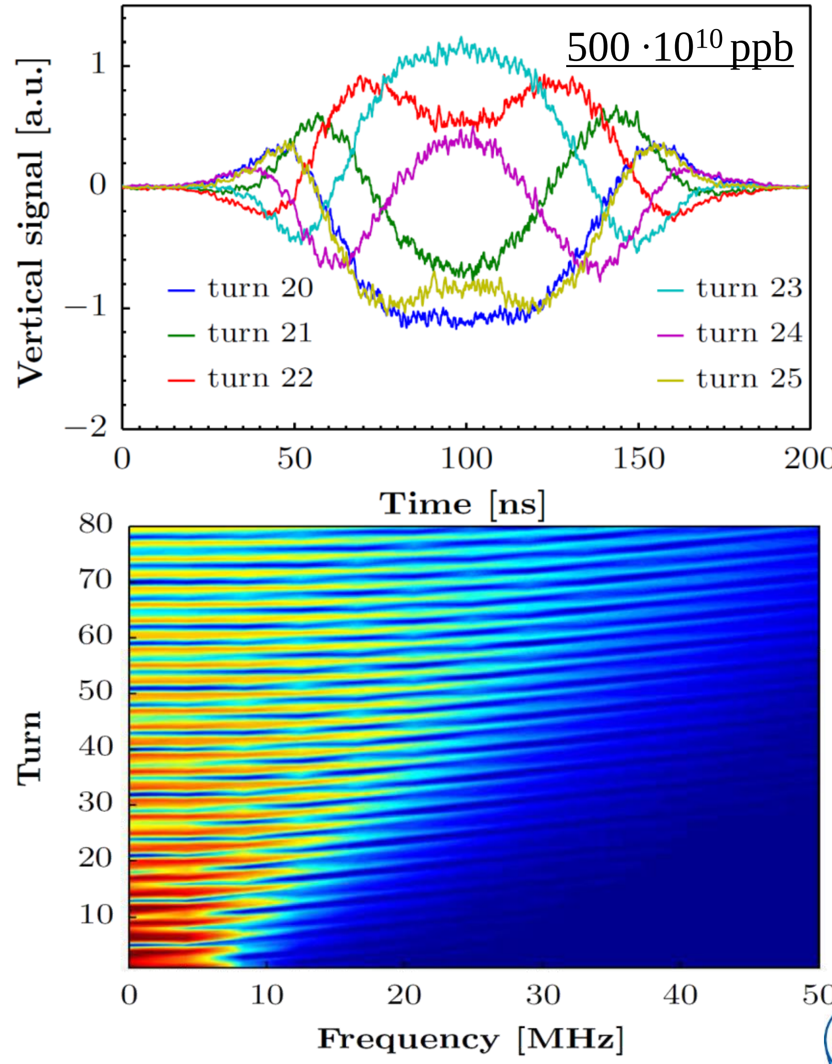
- recent simulations show that these oscillations will also be present on beams for the HL-LHC → effect on brightness remains to be studied

Influence on future beams

CNGS at 1.4 GeV

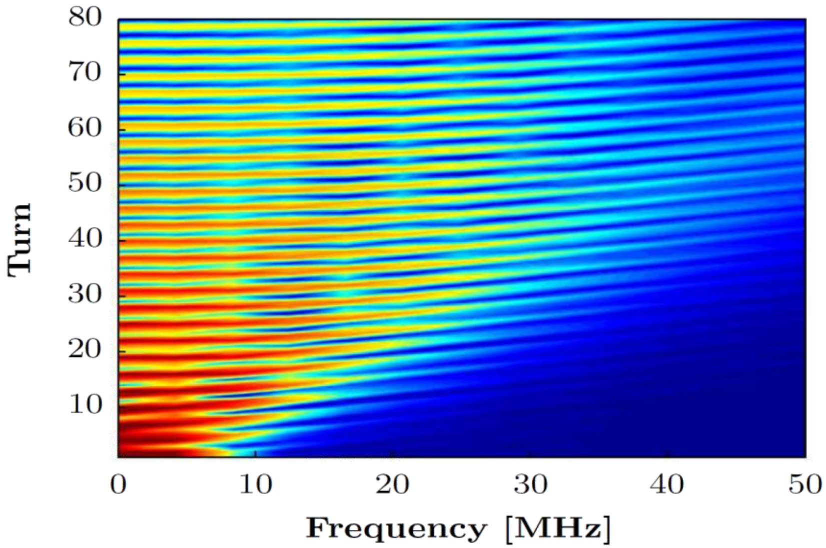


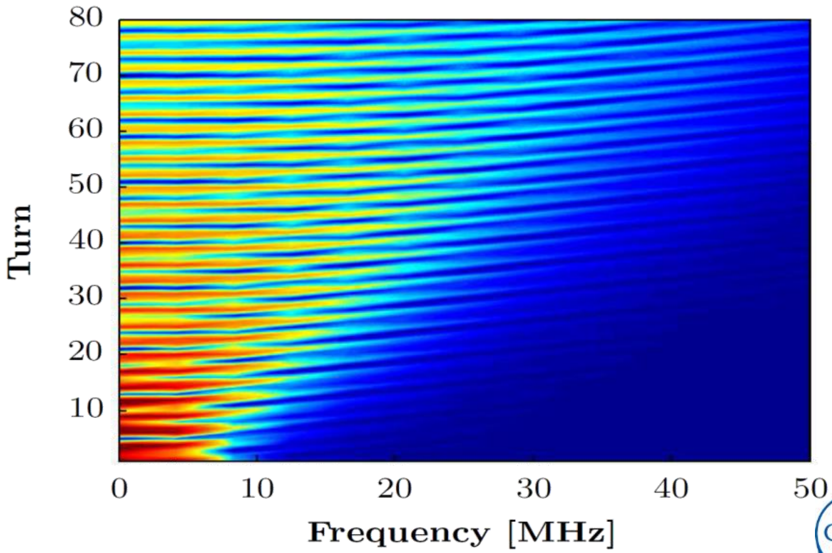
Future beam for ν-production at 2 GeV



Influence on future beams

- increase of injection energy more important than increase of intensity
- transverse damper able to reduce injection oscillations on today's CNGS beams
- future beams even less demanding for the transverse damper





Conclusion

- The observed injection oscillations on high-intensity beams can be explained by the effect of the **indirect space charge impedance** on a beam injected **off-center**.
- No exponential growth of the centroid motion is observed – the purely imaginary impedance does not cause an instability.
- The impedance of a **simple elliptic geometry** is sufficient to reproduce the measurements.
- The oscillation frequency depends crucially on the **longitudinal distribution**.
- The amplitude of the injection error only influences the amplitude of the oscillation and not its frequency.
- Publication to PRST-AB submitted in April

Outlook

- Additional means to reduce these oscillations: flat bunches?
- After LS1: additional measurements on CNGS required to compare with simulations
- Further investigation of the different injection errors for bunches arriving from different rings and their effect on the observed oscillations
- Additional measurements at different energies.

LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

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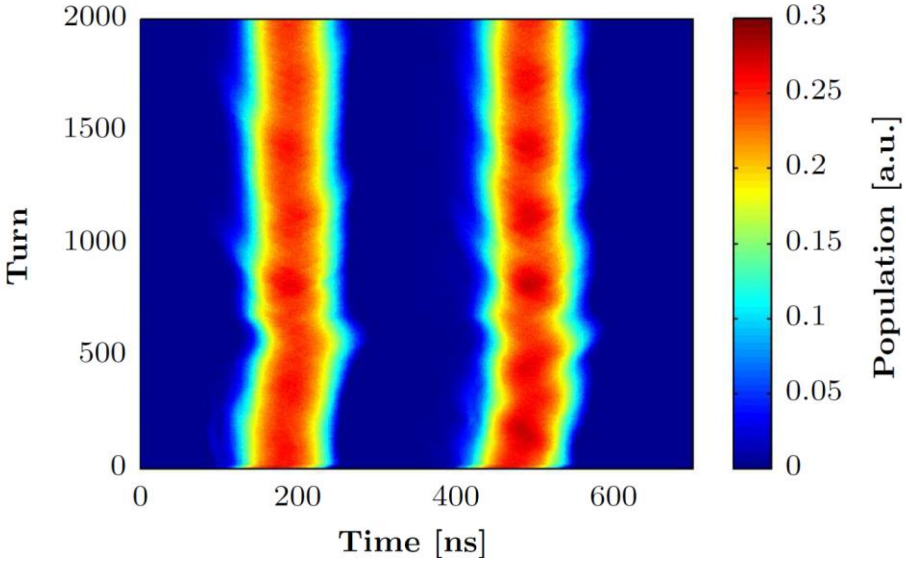
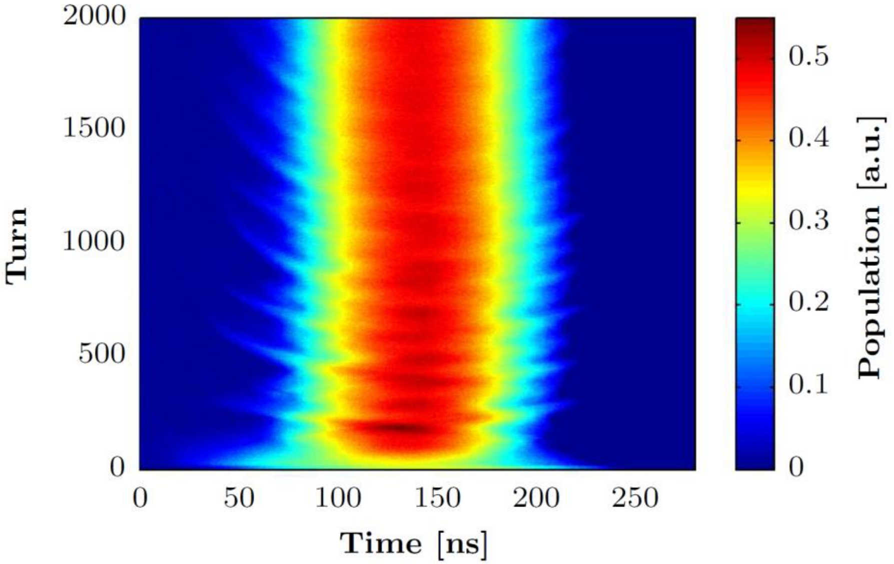
Longitudinal distributions

CNGS

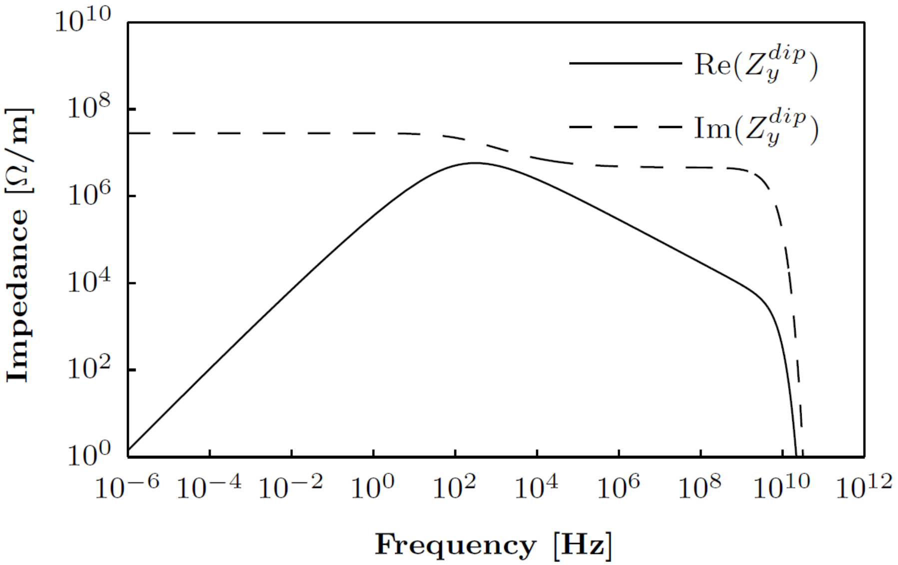


TOF



Vertical dipolar impedance

<u>wall impedance</u>



<u>indirect space charge impedance “only”</u>