LHC Injectors Upgrade

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Transverse beam dynamics issues in the PS

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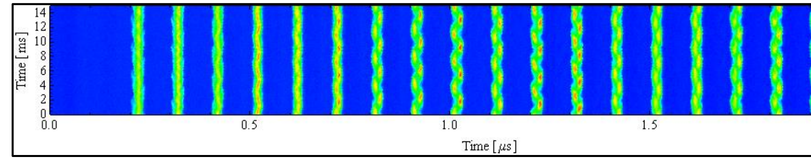
on behalf of PS-LIU team

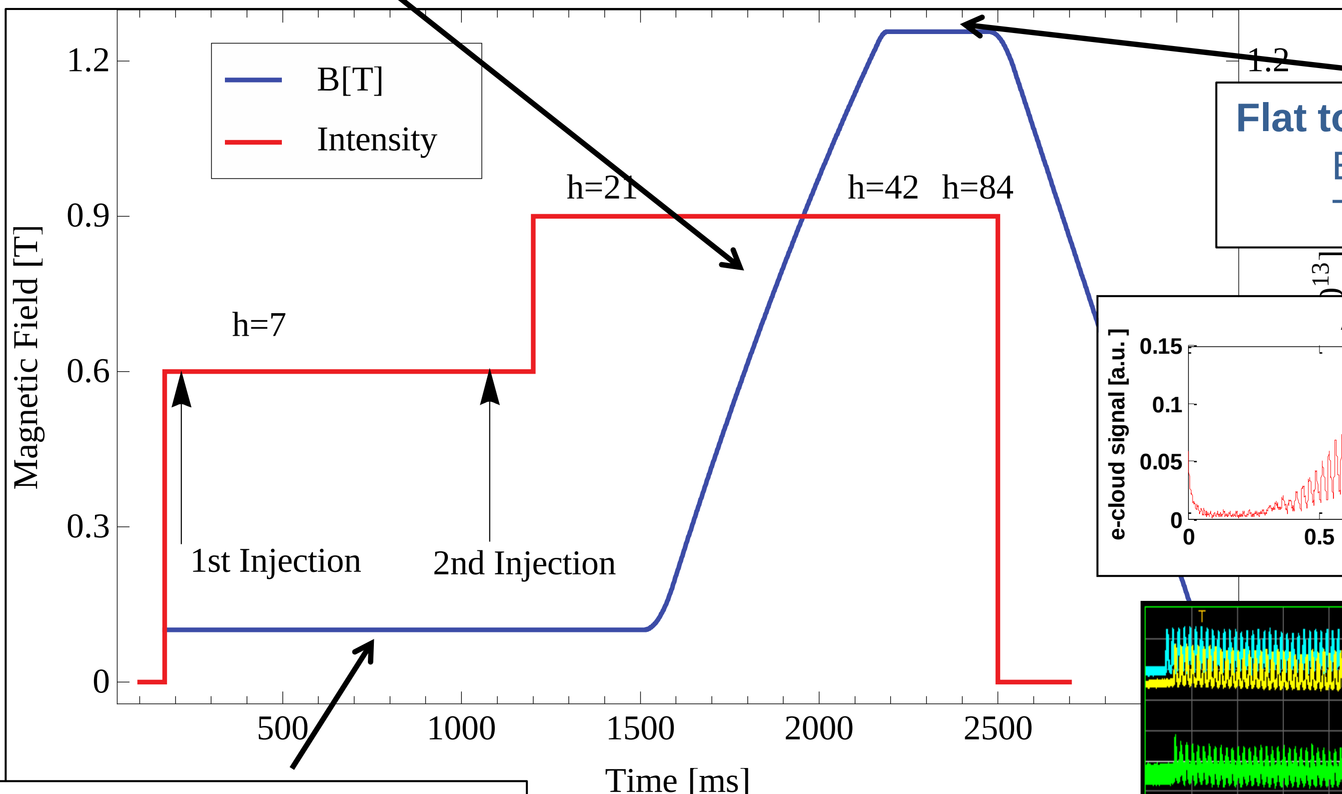
Outline

I. Transverse challenges
II. Space Charge at injection
III. Injection oscillations
IV. Transverse damper and feedback
V. Flat-top challenges
VI. Transition instabilities
VII. Summary and Conclusions

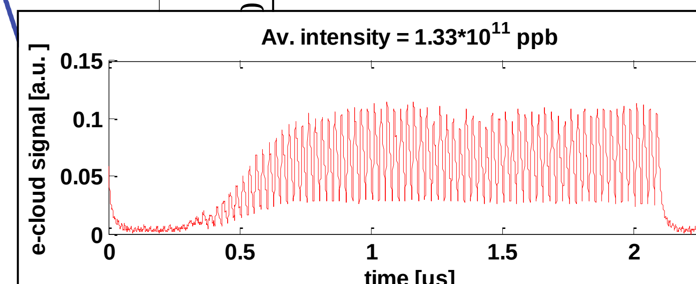
Transverse Challenges in the PS

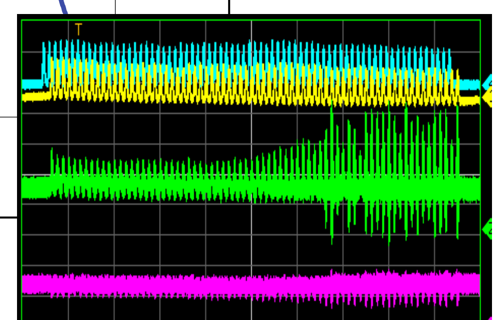
Acceleration:
Transition crossing



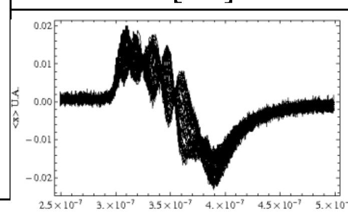


Flat top:
Electron cloud
Transverse instabilities

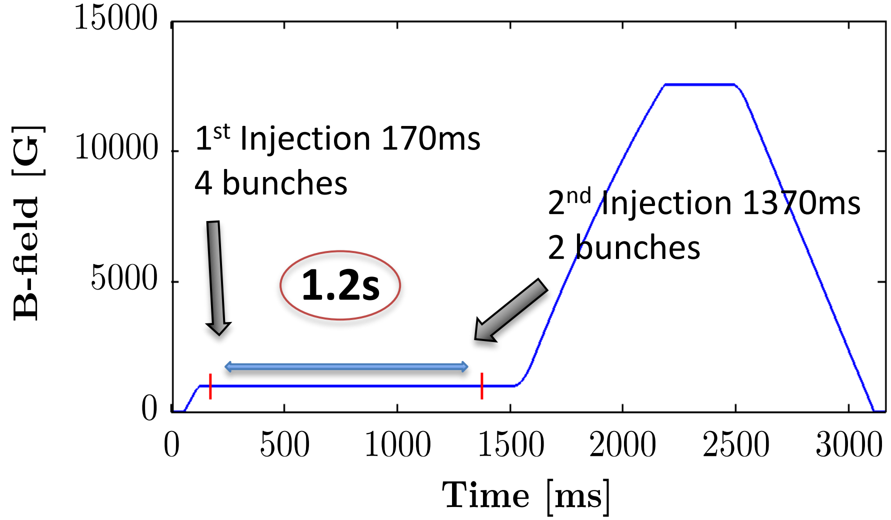




Injection flat bottom:
Injection oscillations
Space charge
Headtail instability



Space Charge at injection



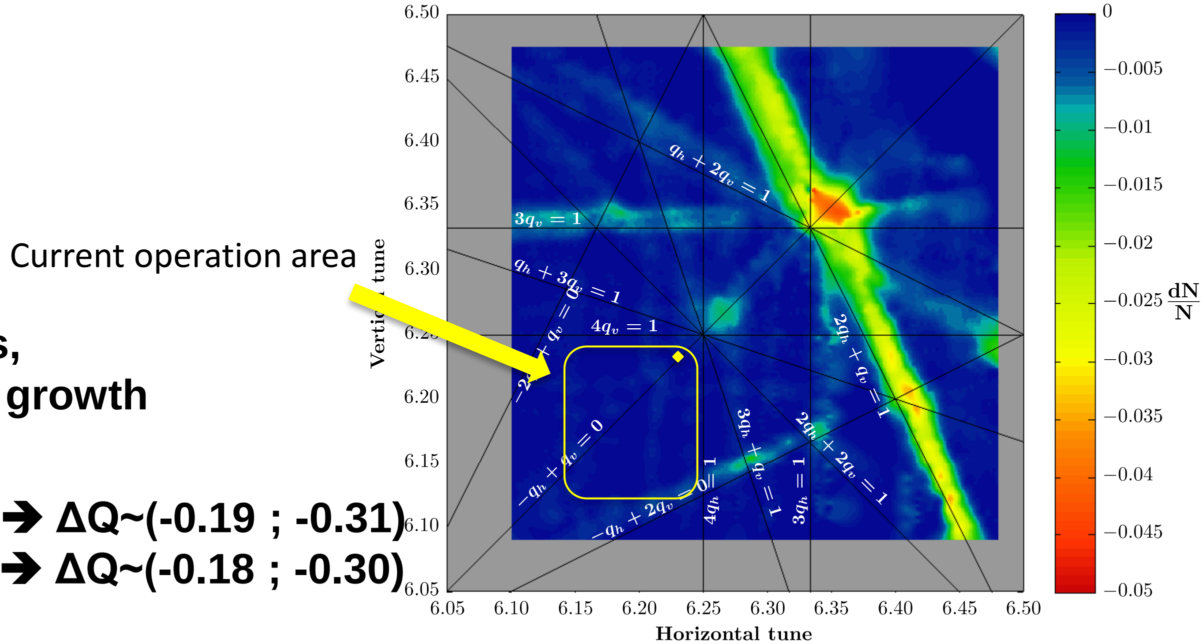
- Current injection **energy**: **1.4 GeV**

- **Typical tune-spread** of current operational beam~**(-0.2 ; -0.28)**

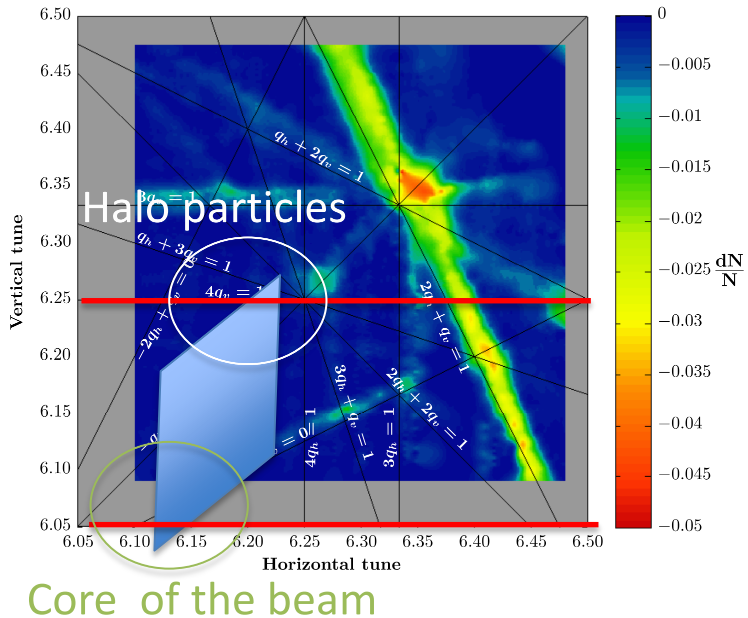
- LHC double batch injection: Long **flat bottom: 1.2s**

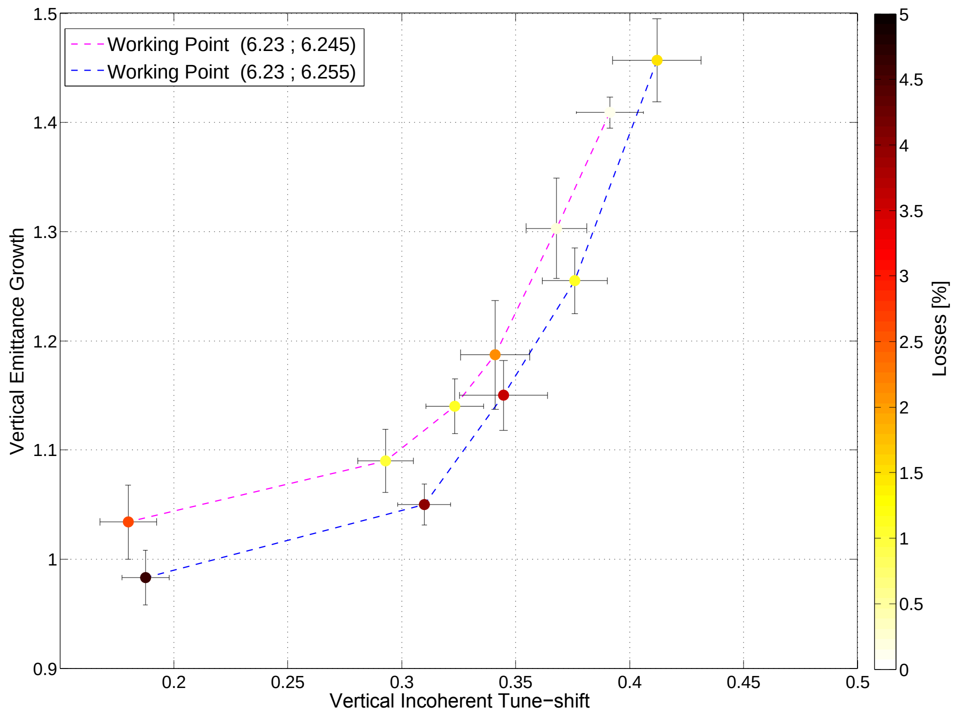
- LIU Budgets: **5% beam loss,** **5% emittance growth**

- Requests @2GeV: **LIU ➔ ΔQ~(-0.19 ; -0.31)**
  HL-LHC ➔ ΔQ~(-0.18 ; -0.30)



Space Charge at injection



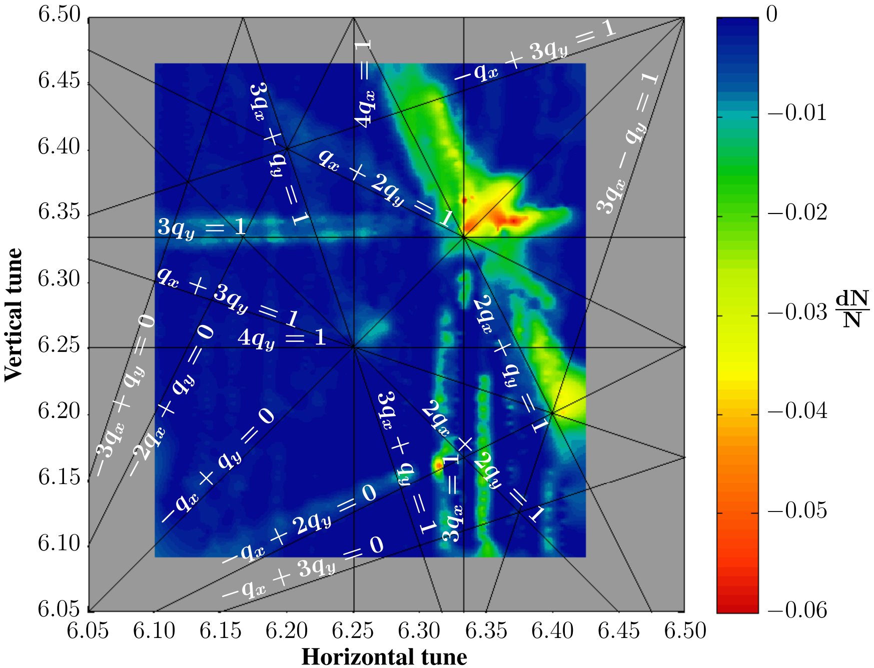


- The beam tune-spread is trapped between the 4qy=1 and the integer resonances.
  - ➔ The choice of the working point is a compromise between losses and emittance blow-up

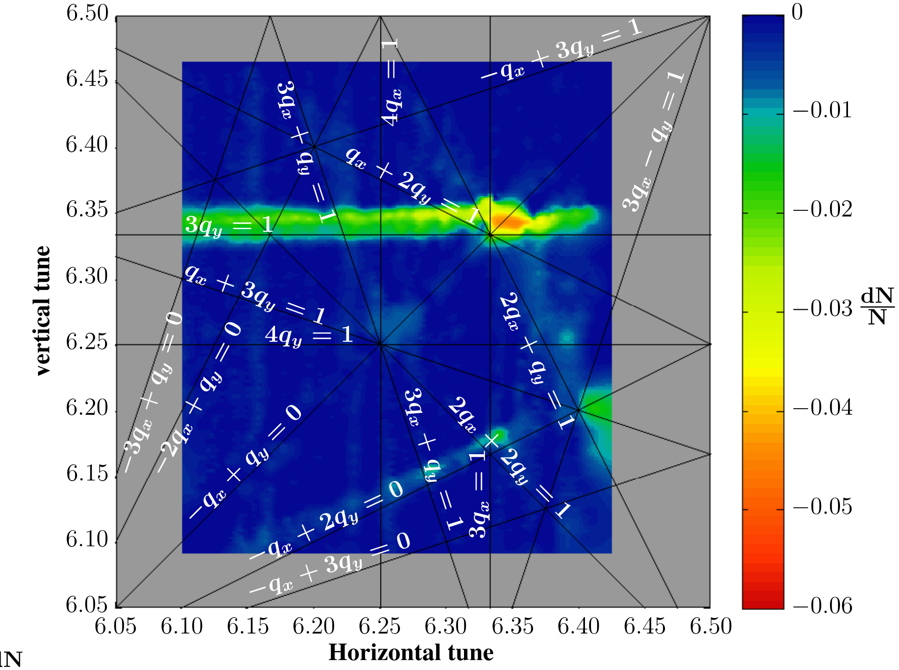
- To respect the LIU budgets of beam loss and emittance growth, $\Delta Q_{max} \approx -0.31$

Space Charge at injection

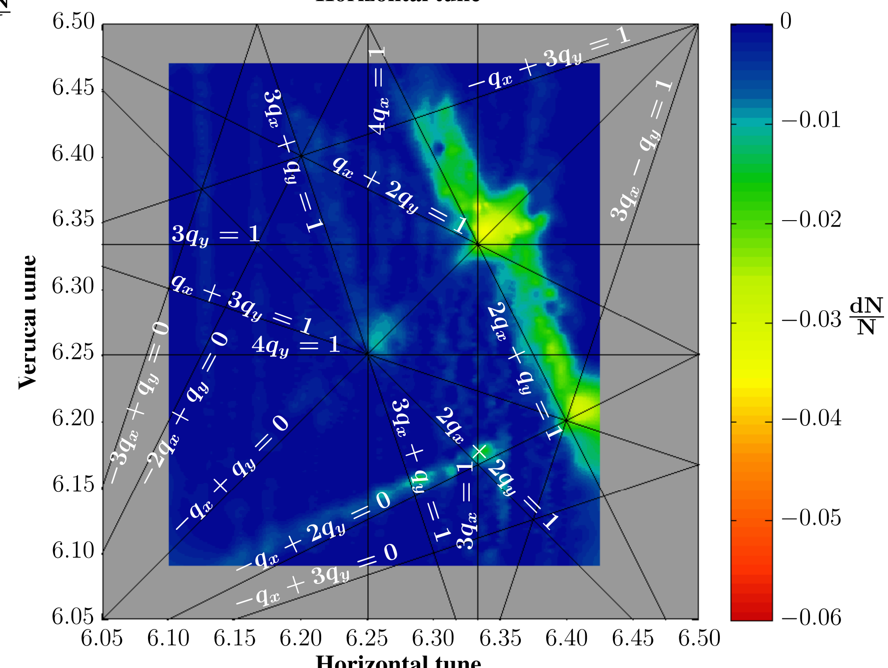
Vertical tune scan



2Qx+Qy compensation



3Qy compensation

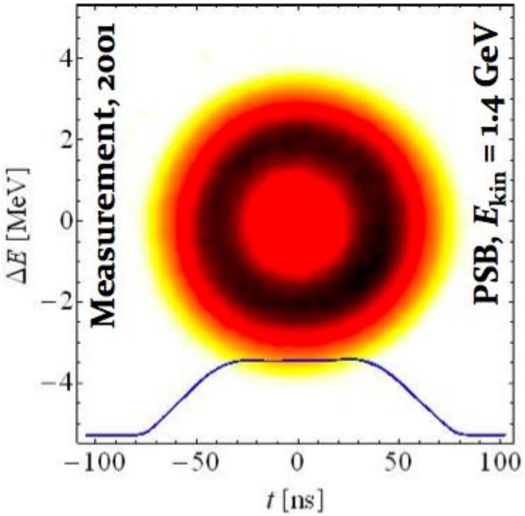


➔ Successful implementation of a resonance compensation scheme

Space Charge at injection

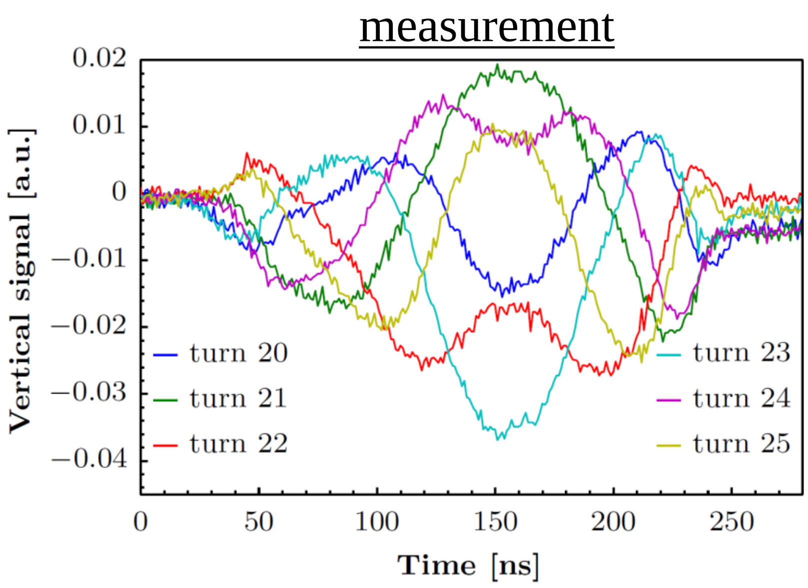
➔ The resonance compensation would empty larger area for the working are, but the **$4Q_y$=25 resonance is still limiting this area**.

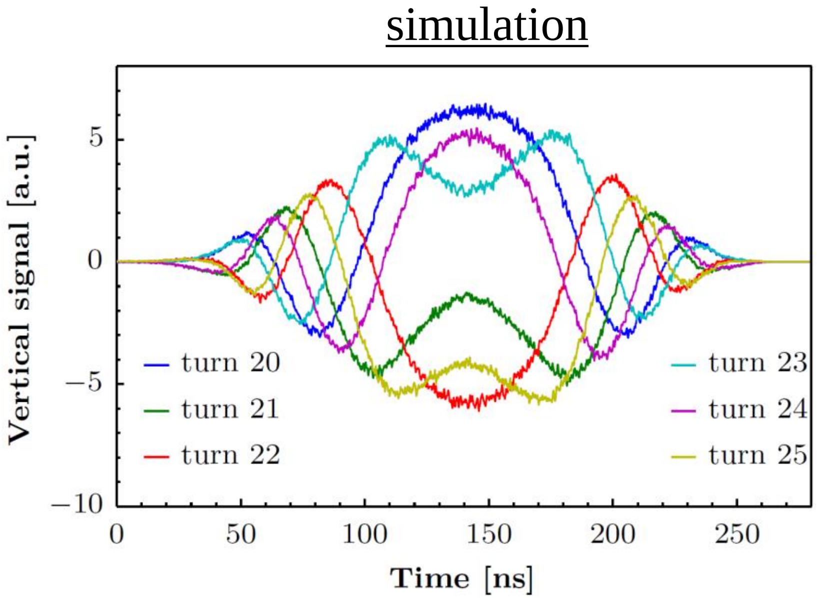
- Solutions under investigation for 4Qy resonance (to be studied in 2014) :
  - Simulation study with the change of the integer for the vertical tune shows promising results to avoid the 4Qy resonance
  - Changing the optics: larger horizontal dispersion & larger vertical dispersion
  - Longitudinally hollow bunches



Injection Oscillations

- At **injection of high intensity beams**, intra-bunch oscillations were observed.
- **No unstable behavior** observed associated to losses.
- A study revealed that the cause of these oscillations is **indirect space charge**.
- Problem first observed in 1998. Explained in 2013
- The **effect of these oscillations on the emittance of future beams** (HL-LHC: 32.5 10^{11} ppb, LIU :28 10^{11} ppb) has to be studied.
- **TFB damp it effectively**. Effect on the emittance to be studied



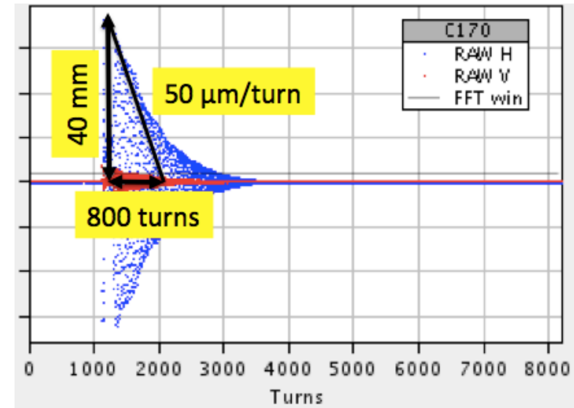


Transverse Damper and Feedback

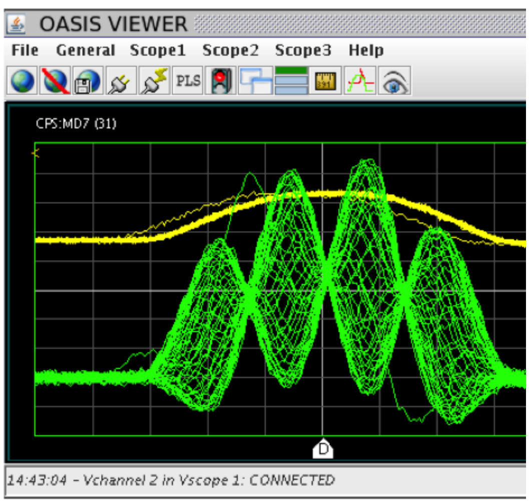
- The TFB was designed to damp injection orbit errors of 3mm (peak to peak) within 50 µs, to limit the caused emittance growth:

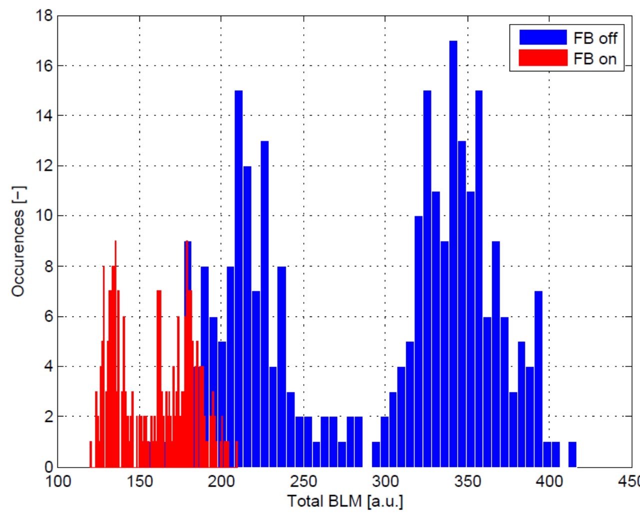
$$\frac{\Delta\epsilon_n}{\epsilon_n} = \frac{\beta_r\gamma_r}{\epsilon_n}\,\frac{\Delta x^2 + (\beta_{H,V}\Delta x' + \alpha_{H,V}\Delta x)^2}{2\beta_{H,V}}$$

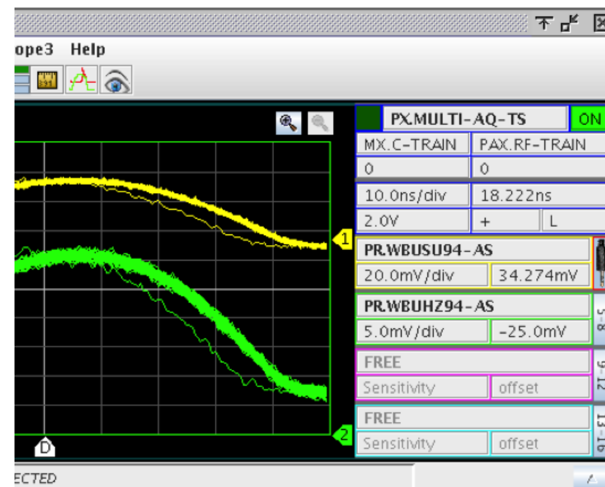
Injection oscillation`



- It also has been used as feedback to dump Headtail instabilities at injection. (Chromaticity should be controlled at 2GeV)





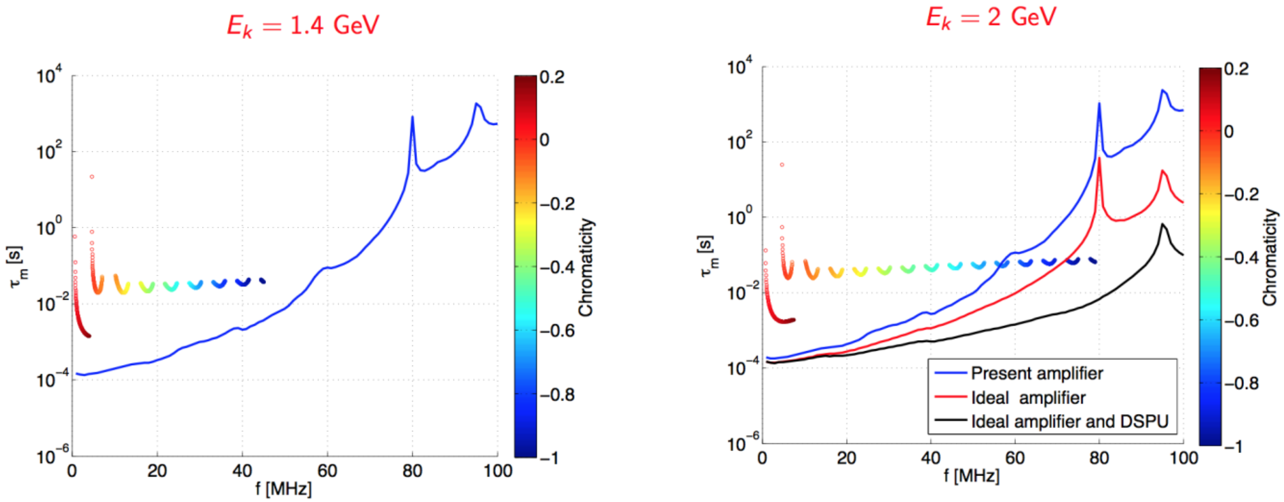


Transverse Damper and Feedback

- Upgrade of the TFB (2015): new amplifiers to dump injection oscillations at 2GeV

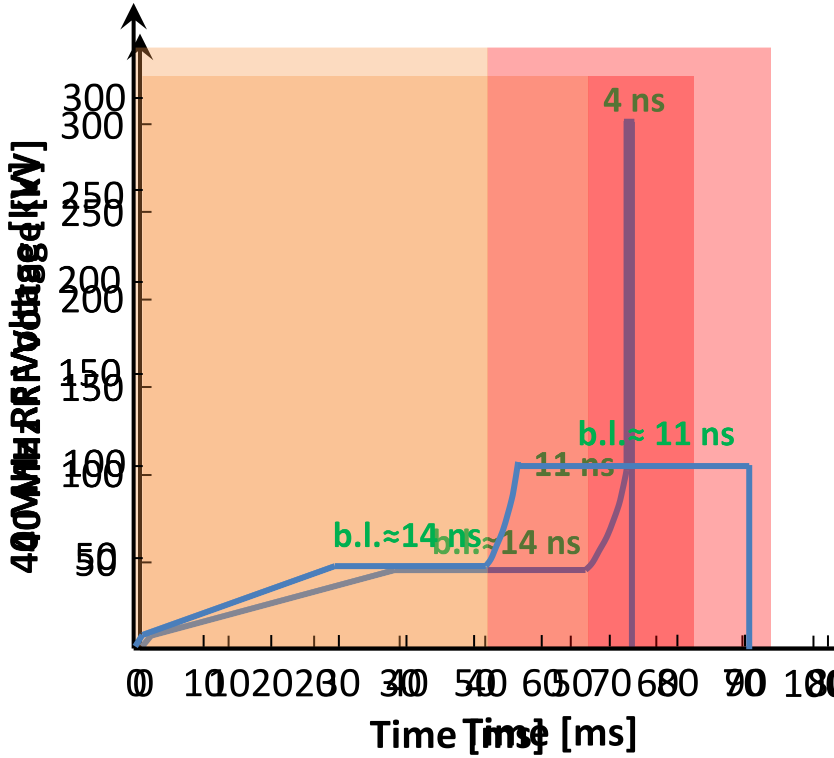
	Current Amplifier	New Amplifier
Peak Power [kW]	3	5
CW Power [kW]	0.8	5
-3dB Bandwidth [MHz]	23	100

- We will probably need to control the chromaticity at 2 GeV to avoid high order headtail mode not accessible by the damper depending if no linear coupling will be used.

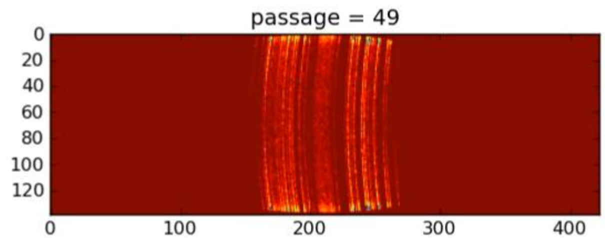


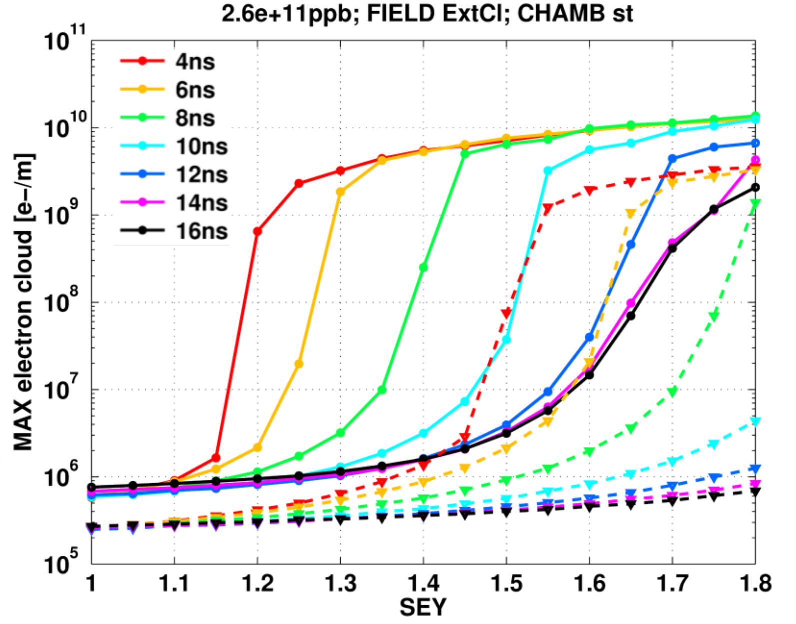
Flat-top challenges

- **Up to now e-cloud in the PS has never been a limitation** for the production of the 25 ns LHC type beams but **transverse instabilities** are observed when “storing” 25 ns beams at 26 GeV (new transverse feedback proved to help)
- **40 MHz RF Voltage program** can be tailored to mitigate e-cloud effects without affecting beam quality at extraction (tested in MD)
- To predict the e-cloud behavior at higher intensities **PyECLOUD modules** have been developed for the simulation of combined function magnets
- Extensive **simulation studies have been performed** for the main chamber profiles installed in the main magnets and in the straight sections



Pycloud simulations for combined function magnets established to predict future operation



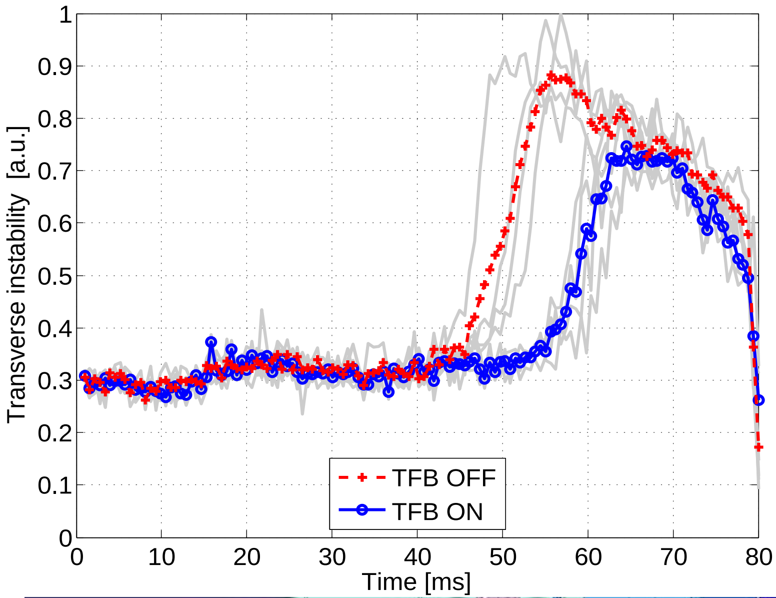


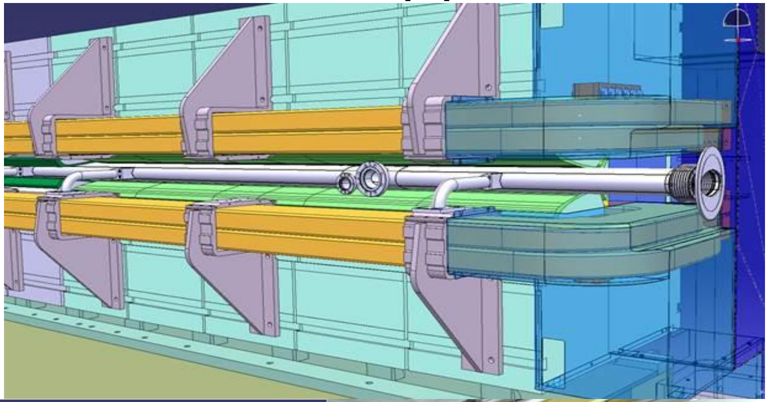
Flat-top challenges

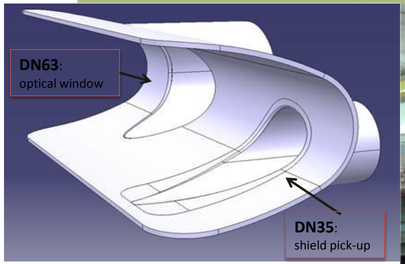
- **TFB** able to delay the observed instability by ~10ms

- **A main magnet has been equipped for e-cloud detection** during LS1 (shielded pickup and optical window)

- Measurement campaign planned after LS1 to characterize the e-cloud formation in the PS main magnets (for different beam conditions, possibly up to LIU bunch intensity)

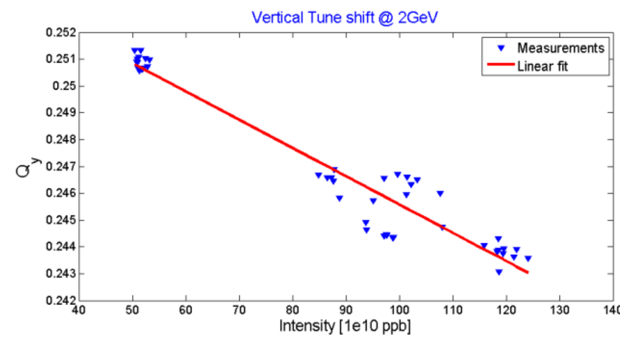






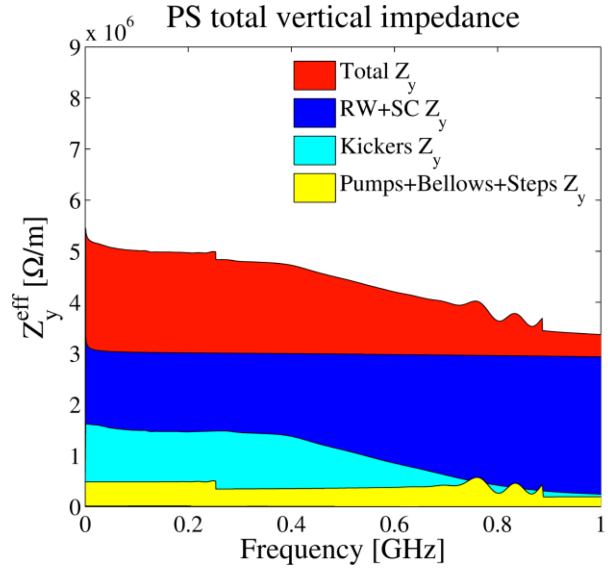
Instabilities at Transition

- **Instabilities at transition are not a limitation for the LHC beams** and they are not expected to be for future beams. Study ongoing to confirm this assumption based on non-LHC high-intensity beams studies.



- **The PS impedance model is being improved** to have a better understanding of the source of these instabilities.

- **About 70%** of the measured impedance has been **explained**.



- A measurement campaign is planned at the restart of the machine

Summary and conclusions

- Injection flat-bottom:
  1. Injection oscillations: → TFB, effect on the emittance?
  2. Space charge: → 2GeV injection upgrade, Resonance compensation, studies on going (change of vertical integer, new optics, hollow bunches…etc)
  3. Headtail instability: → TFB

- Transition instabilities: No limitation expected

- Flat-top:
  1. Electron Cloud / Transverse instabilities: → TFB

LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

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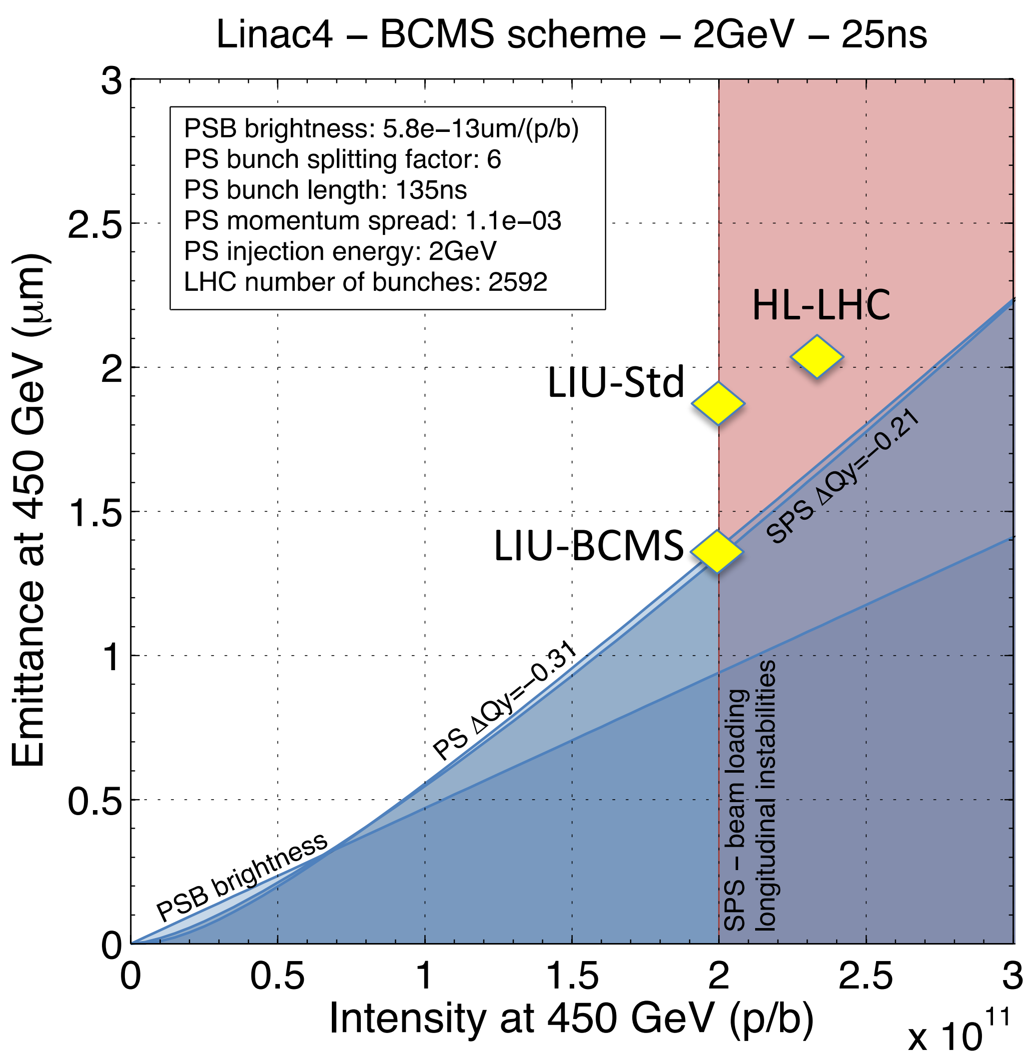
Backup slides

BCMS scheme (48 bunches / PS batch)



LIU upgrades

- SPS 200 MHz upgrade
- SPS e-cloud mitigation
- PSB-PS transfer at 2 GeV

Limitations BCMS scheme

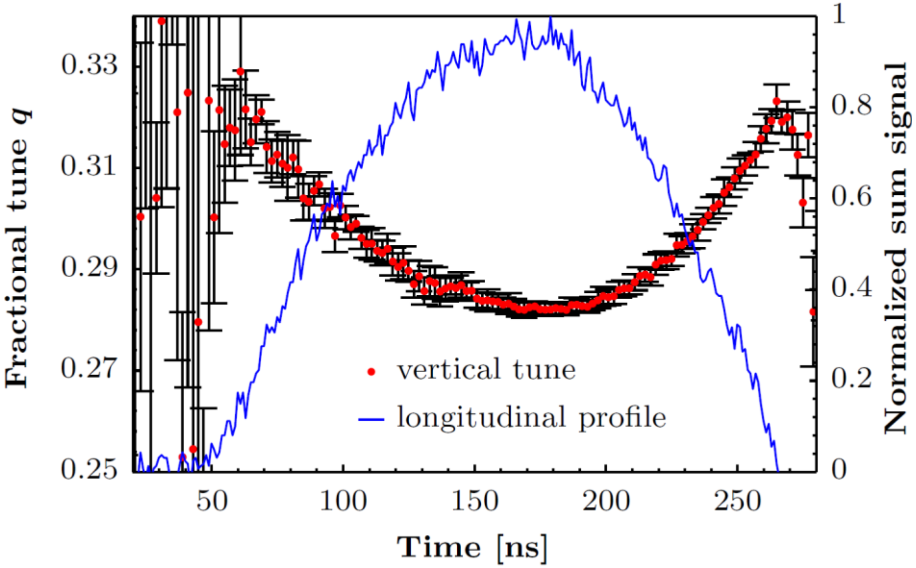
- SPS: longitudinal instabilities + beam loading
- PS: space charge
- SPS: space charge

Performance reach

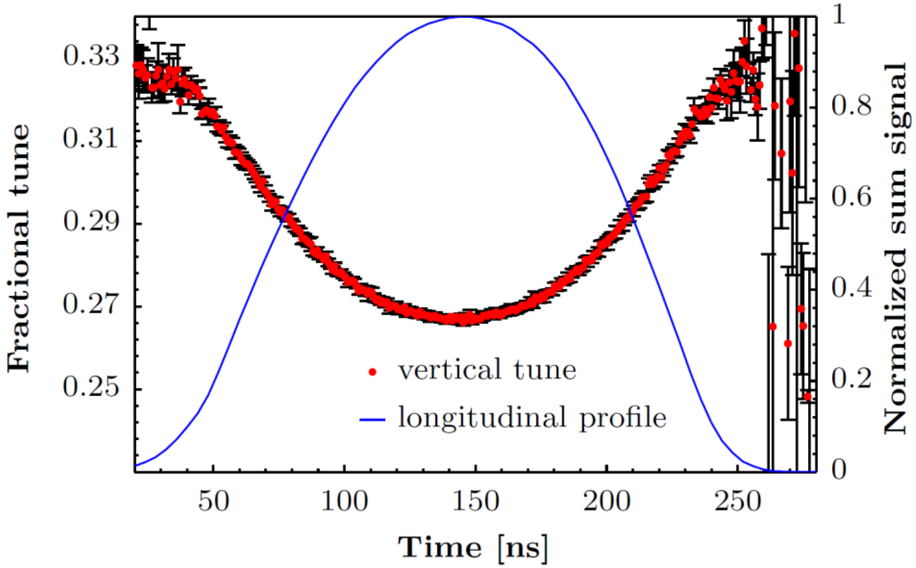
- 2.0×10^{11}p/b in 1.37μm (@ 450GeV)
- 1.9×10^{11}p/b in 1.65μm (in collision)

Injection oscillations

measurement

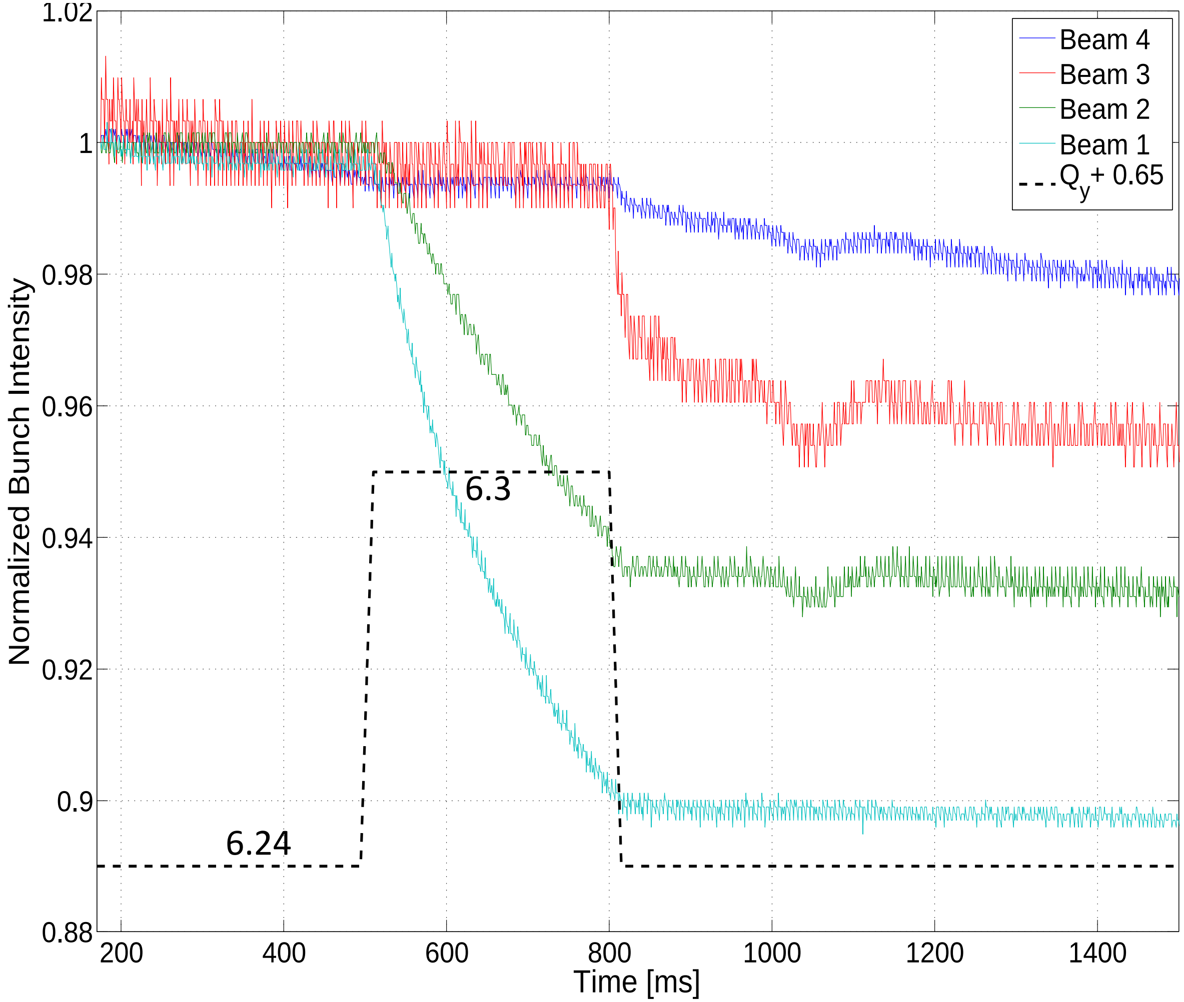


simulation



max. tune shift in this simulation is approx. 0.01 larger than in the measurement
→ effect very sensitive to the longitudinal distribution

4^{th} order Resonance



Horizontal tune fixed at 6.23

Vertical tune: 6.24->6.3->6.24

Maximum detuning due to space charge:

Beam 1 : (-.22 ; -.4)

Beam 2 : (-.18 ; -.37)

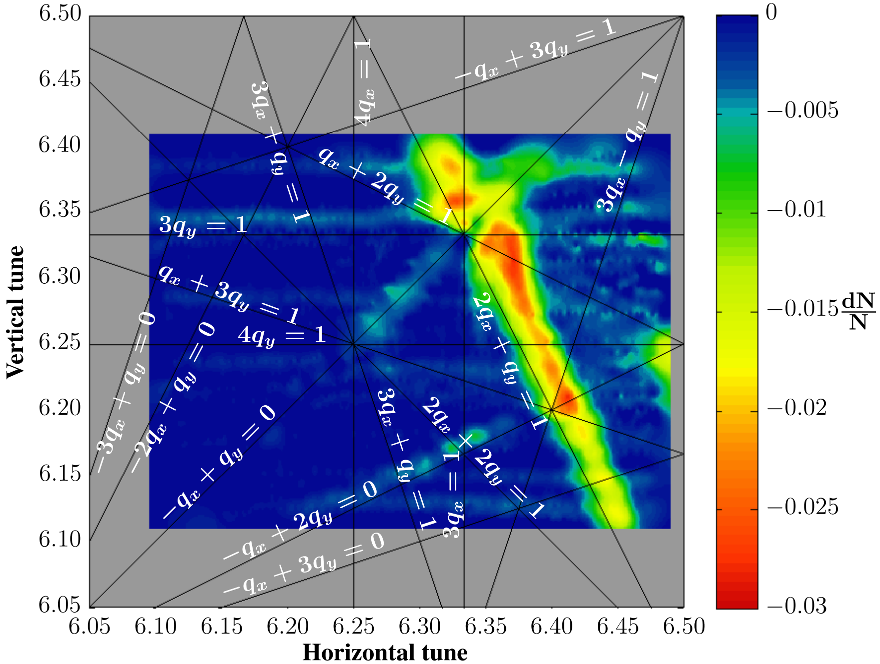
Beam 3 : (-.08 ; -.07)

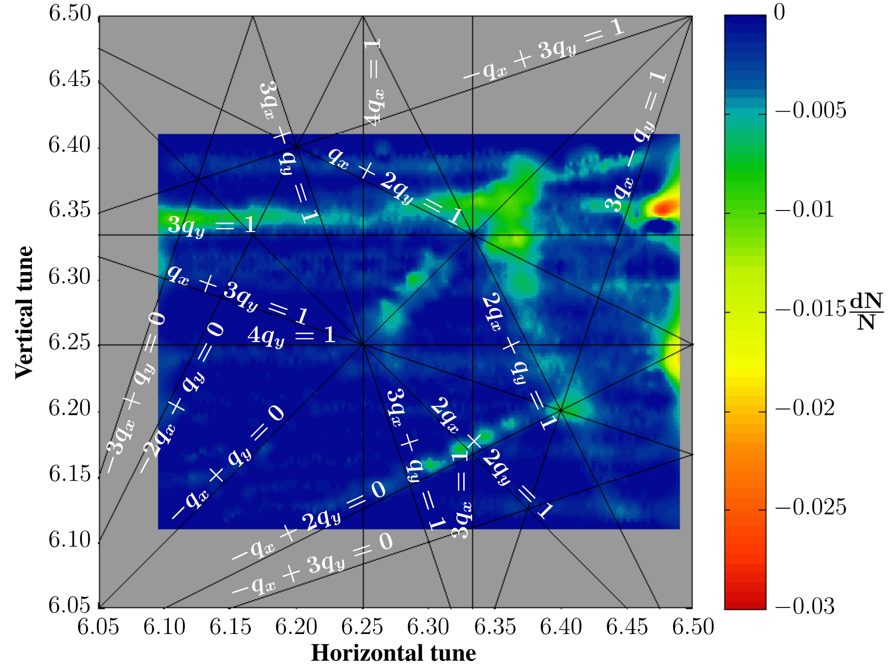
Beam 4 : (-.01 ; -.01)

➔ The 4^{th} order resonance seems to be excited by space charge

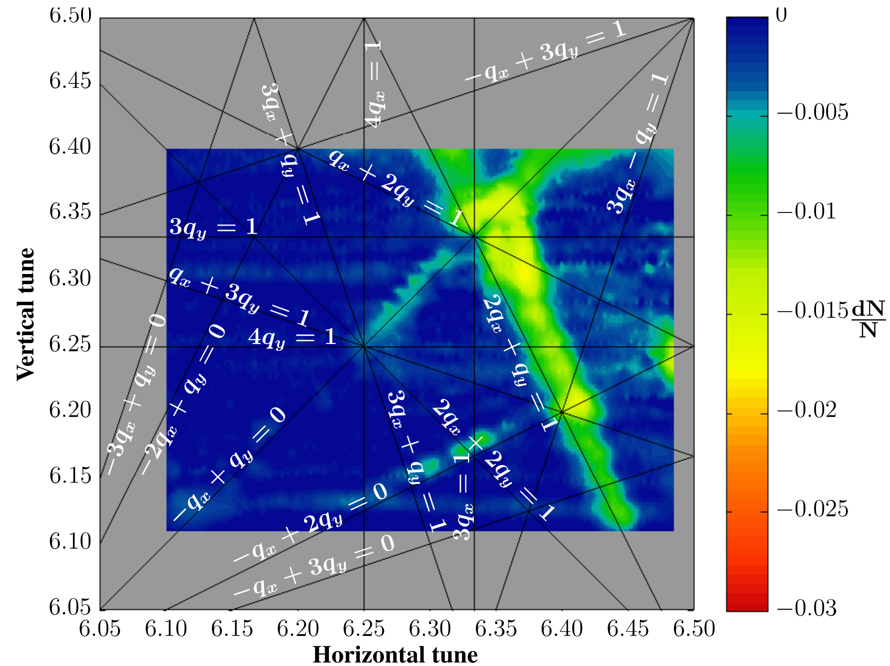
Resonance compensation

Horizontal tune scan





2Qx+Qy compensation



3Qy compensation