Pushing the LHC peak luminosity in 2011: Beam instabilities

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in the Mini-Chamonix Workshop

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With the invaluable contributions of: W. Höfle, K. Li, E. Métral, N. Mounet, F. Roncarolo, B. Salvant, E. Shaposhnikova, M. Taborelli, C. Yin-Vallgren

BE-ABP-ICE

Goal & outline

- Based on observations, theory and simulations, review possible instability mechanisms and extrapolate stability criteria for
  - 50ns beams with N_b up to 1.7e11 ppb and $\varepsilon_{x,y}$<2μm
  - Nominal 25ns

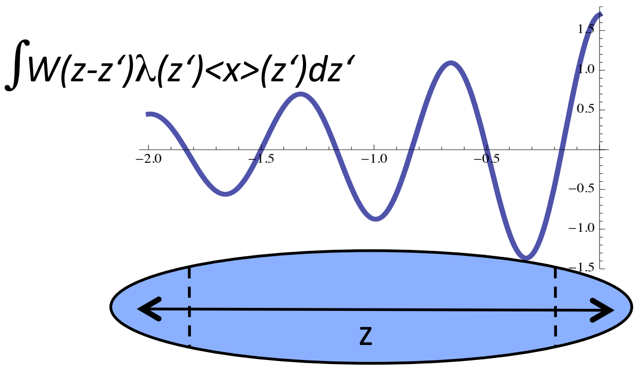
⇒ Instabilities driven by the machine impedance:
  - Single bunch: Head-tail instabilities and TMCI
  - Excitation of coupled bunch modes

⇒ Electron cloud effects on the beam
  - Build up conditions
  - Coherent instabilities & tune footprint
    - → Thresholds
    - → Parameter dependence

⇒ Longitudinal instabilities

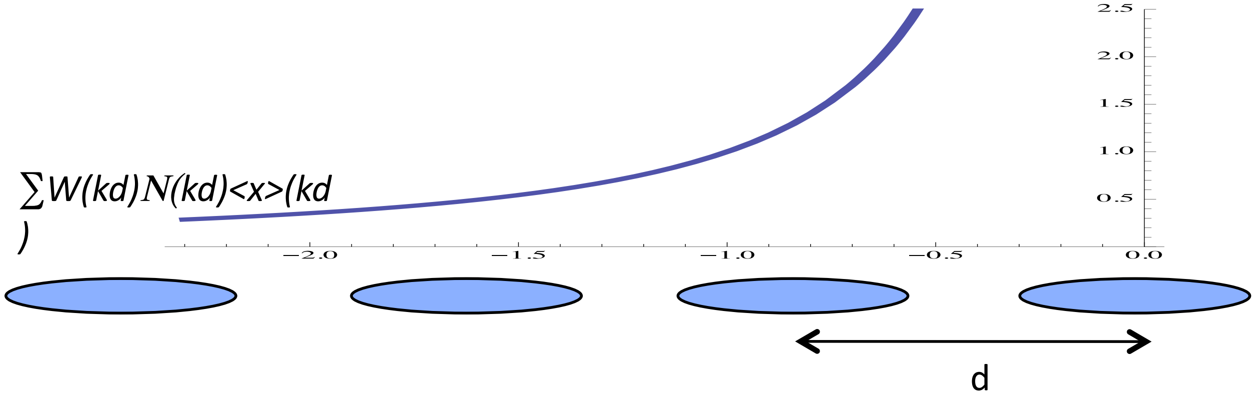
Impedance driven instabilities: possible effects

- **Single bunch instabilities**
  - Headtail modes
    - ⇒ Modes $|m| \geq 1$ unstable when $Q' > 0$
    - ⇒ At all intensities, however with growth rate proportional to bunch intensity
    - ⇒ Can be damped with tune spread with amplitude (octupoles)
  - Transverse Mode Coupling Instability
    - ⇒ Only above an intensity threshold ($N_b > N_{th}$)
    - ⇒ The threshold is usually increased by positive chromaticity and octupoles
    - ⇒ Possibly cured by a high bandwidth feedback system



Impedance driven instabilities: possible effects

- Single bunch instabilities
  - Headtail modes
  - Transverse Mode Coupling Instability (TMCI)
- **Coupled bunch instabilities**
  - Rigid bunch oscillations
    - ⇒ At all intensities, however with growth rate proportional to bunch intensity
    - ⇒ Can be damped with transverse feedback
  - Higher order modes
    - ⇒ Are characterized by both intra-bunch and bunch-to-bunch oscillation
    - ⇒ Can be Landau damped with octupoles



Overview on possible instabilities (transverse plane)

Protons per bunch, N_b

- Single bunch instabilities
  - Headtail modes
  - Transverse Mode Coupling Instability (TMCI)
- Coupled bunch instabilities
  - Rigid bunch oscillations
  - Higher order modes
- **Electron cloud effect**
  - In general, multi-bunch effect, because bunch trains are needed to build up an electron cloud
  - Can be source of Electron Cloud Instability (ECI)
    - By coupling the motion of subsequent bunches through a bunch-to-bunch wake (rigid or headtail modes). E.g. horizontal coupled bunch ECI is observed in the SPS and suppressed with the damper
    - By coupling the motion of head and tail of the same bunch and exciting a headtail mode. E.g. vertical single bunch ECI is observed in the SPS and suppressed with high chromaticity

Bunch spacing, number of bunches, number of batches

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Transverse emittances, $\varepsilon_{x,y}$

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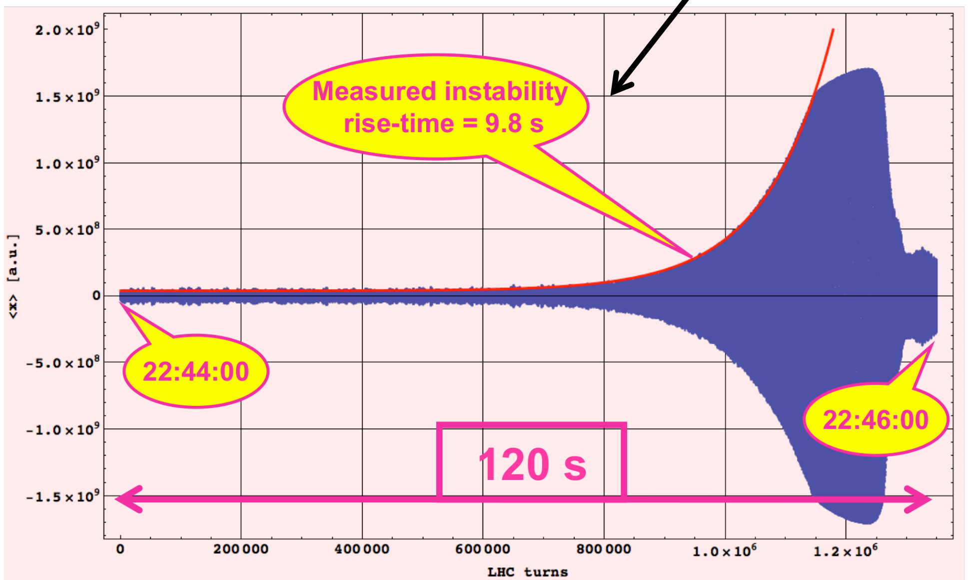
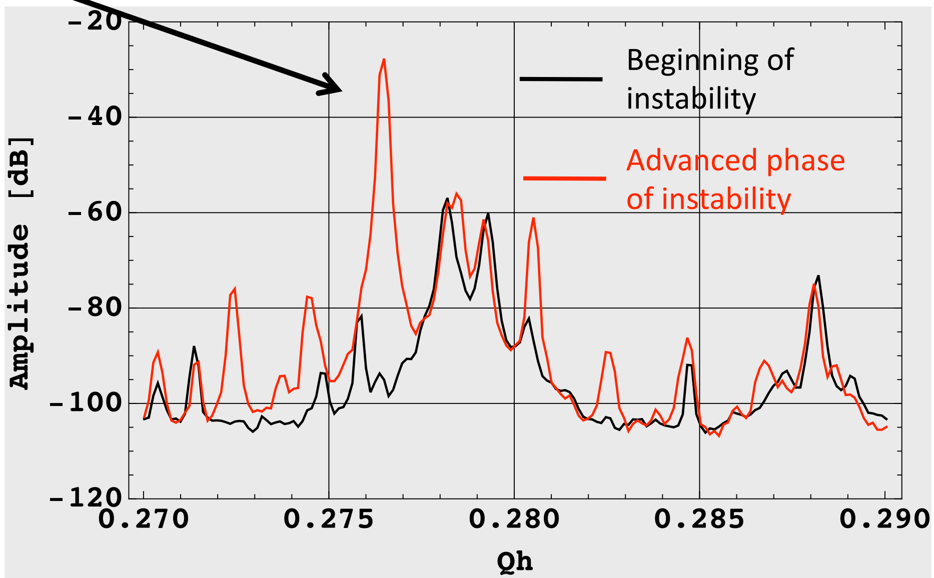
Single bunch instabilities
Headtail modes

- First observed in the LHC on acceleration of the nominal bunch
  - Excited on the ramp (around 2 TeV) with ~6 Q' units
  - Measured rise time of ~10s
  - Clearly a mode m=-1, as seen from the spectrum
  - Suppressed with Landau damping through octupoles



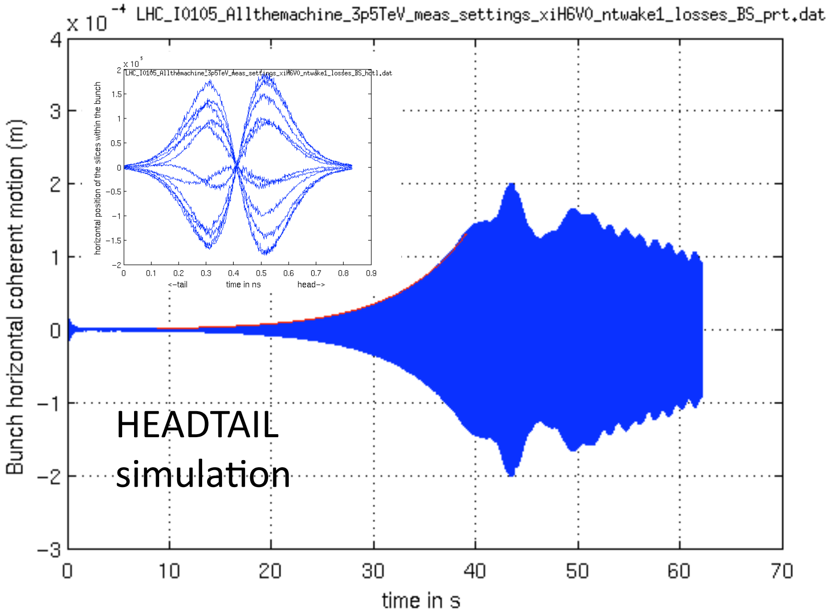


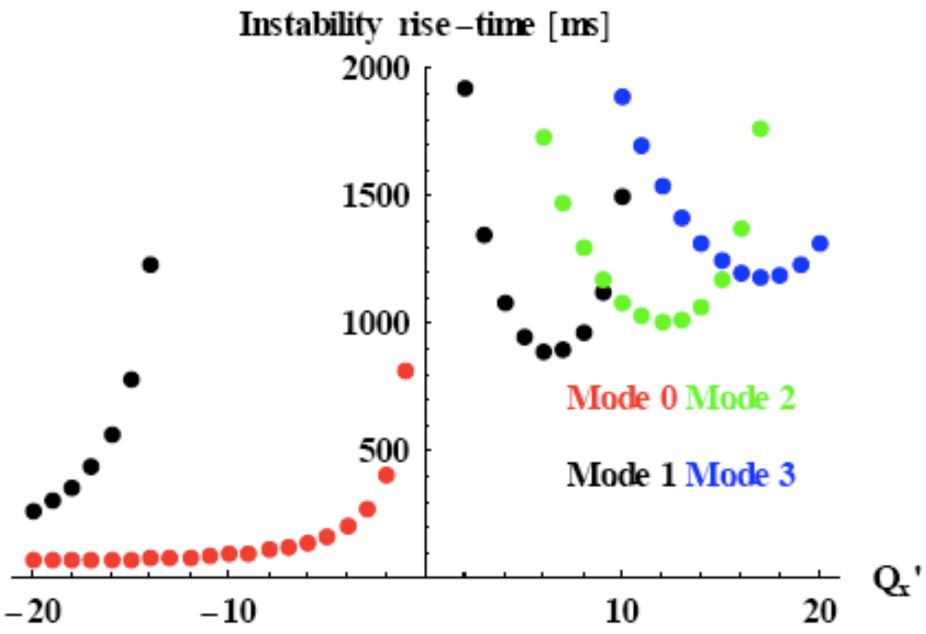
Courtesy E. Métral

Single bunch instabilities
Headtail modes

- Explained and reproduced with simulations and theory (nominal intensity)
  - Growth rate proportional to bunch intensity
  - Efficiency of octupole stabilization depends on transverse emittance

⇒ Depending on chromaticity control or requirements, larger bunch intensity and smaller transverse emittances might take stronger octupole currents for the suppression of this instability





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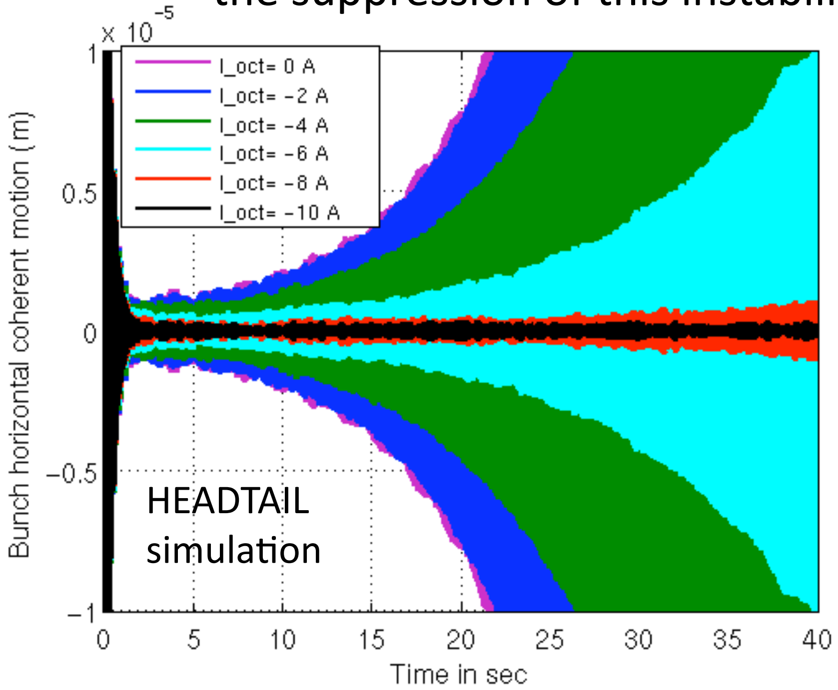
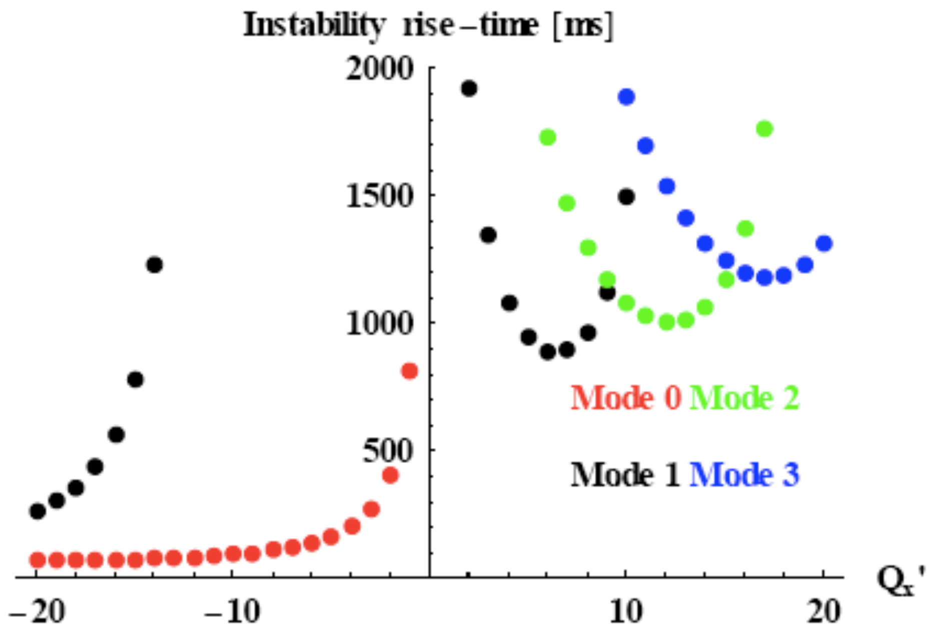
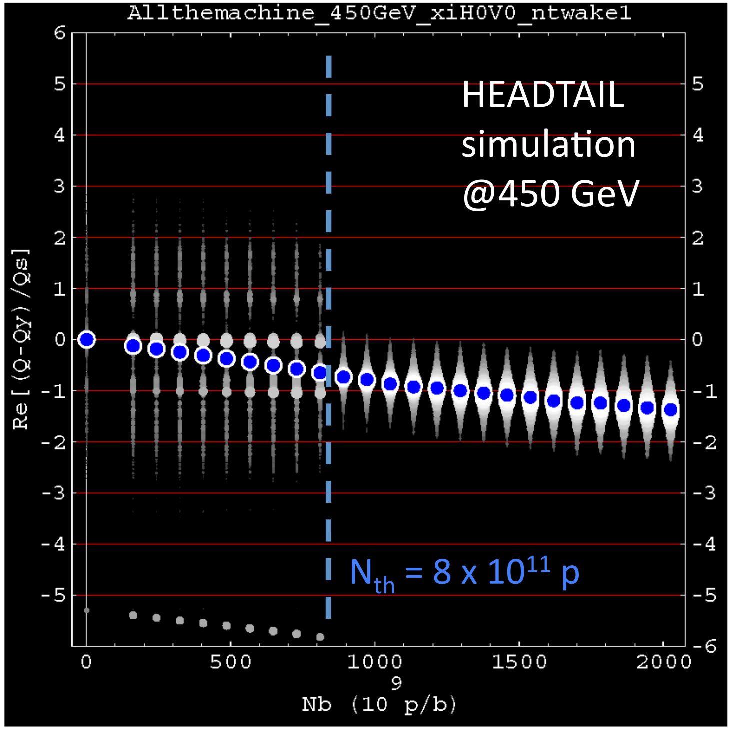


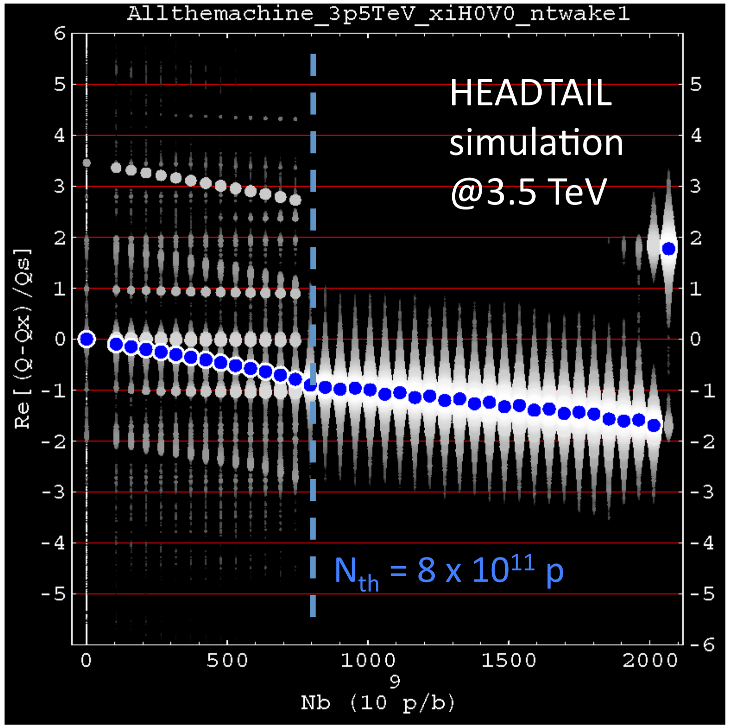


Courtesy E. Métral, B. Salvant

Single bunch instabilities
TMCI

- Not observed experimentally with intensities presently injected into the LHC
  - Up to 2.8 x 10^{11} p at 450 GeV
  - Up to 1.7 x 10^{11} p at 3.5 TeV
- Indeed simulated thresholds with our impedance model are higher with the nominal collimator settings at both injection and top energy



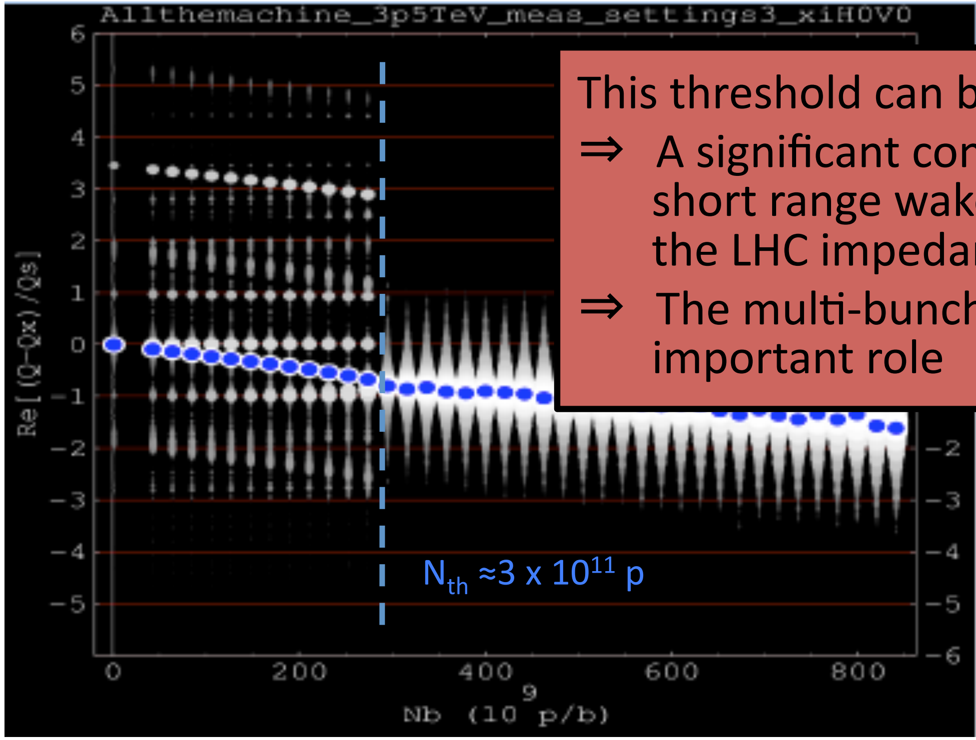


Courtesy B. Salvant

Single bunch instabilities
TMCI

- However, tight collimator settings (presently considered , at least at flat top) lower the TMCI threshold by more than a factor 2

⇒ Even with these settings, single bunch intensities up to 3 x 10^{11} should not suffer from TMCI



This threshold can be actually lower if:

⇒ A significant contribution to the global short range wake is still missing from the LHC impedance database

⇒ The multi-bunch effect plays an important role

Courtesy N. Mounet

Overview on possible instabilities (transverse plane)

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  - Headtail modes
  - Transverse Mode Coupling Instability (TMCI)
- **Coupled bunch instabilities**
  - **Rigid bunch oscillations**
  - **Higher order modes**
- Electron cloud effect
  - In general, multi-bunch effect, because bunch trains are needed to build up an electron cloud
  - Can be source of Electron Cloud Instability (ECI)
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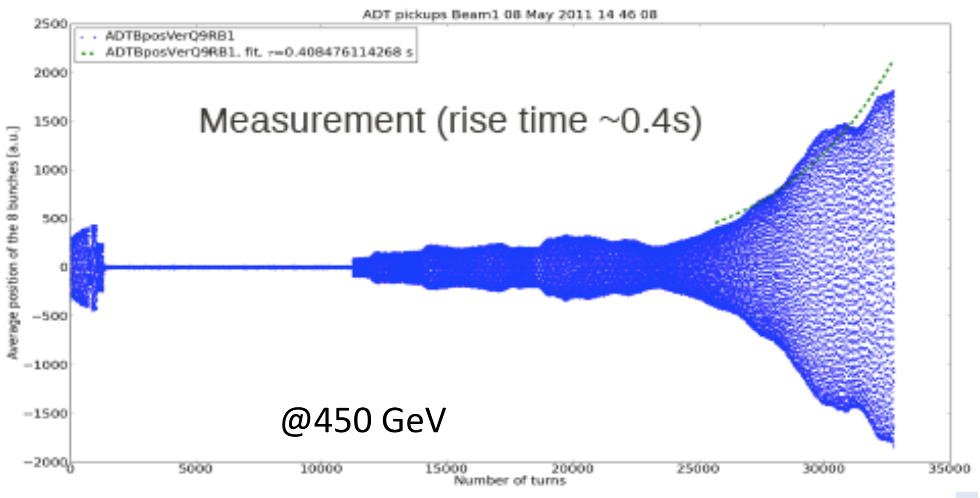
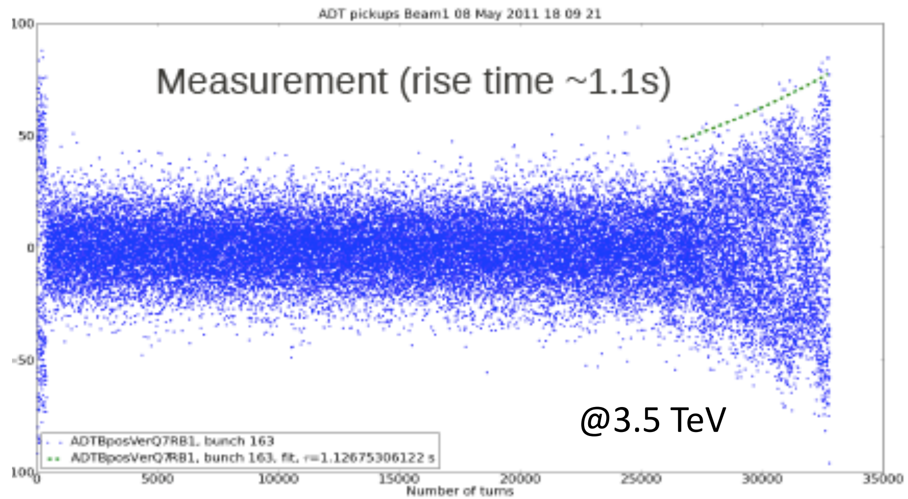
Coupled bunch instabilities
Rigid bunch mode (m=0)

- Damped by the transverse feedback system in routinely operation
- LHC MD 8th May 2011
  - Inject two batches of 12 and 36 bunches (50ns spacing)
  - Switch off the feedback system with ~0 chromaticity (it was tried both at injection and top energy)
  - Coupled bunch instability (mode 0) excited



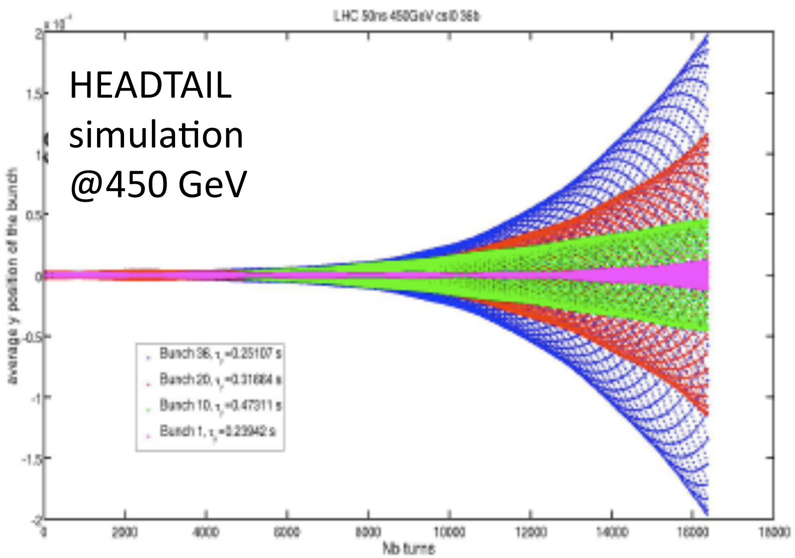


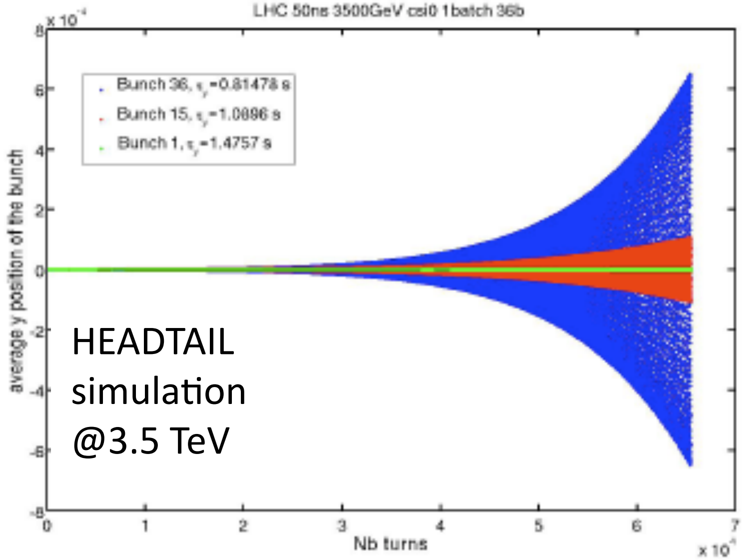
Courtesy N. Mounet

Coupled bunch instabilities
Rigid bunch mode (m=0)

- HEADTAIL simulations (multi-bunch mode) could reproduce the measured rise times within a factor 1.4 at injection and 2 at top energy

⇒ Higher charge per bunch, higher number of bunches, closer spacing (25ns), tighter collimator settings could all contribute to decrease the rise times measured during the MD, but should be still in a range in which the damper can suppress this unstable mode. Simulations could be used to check this

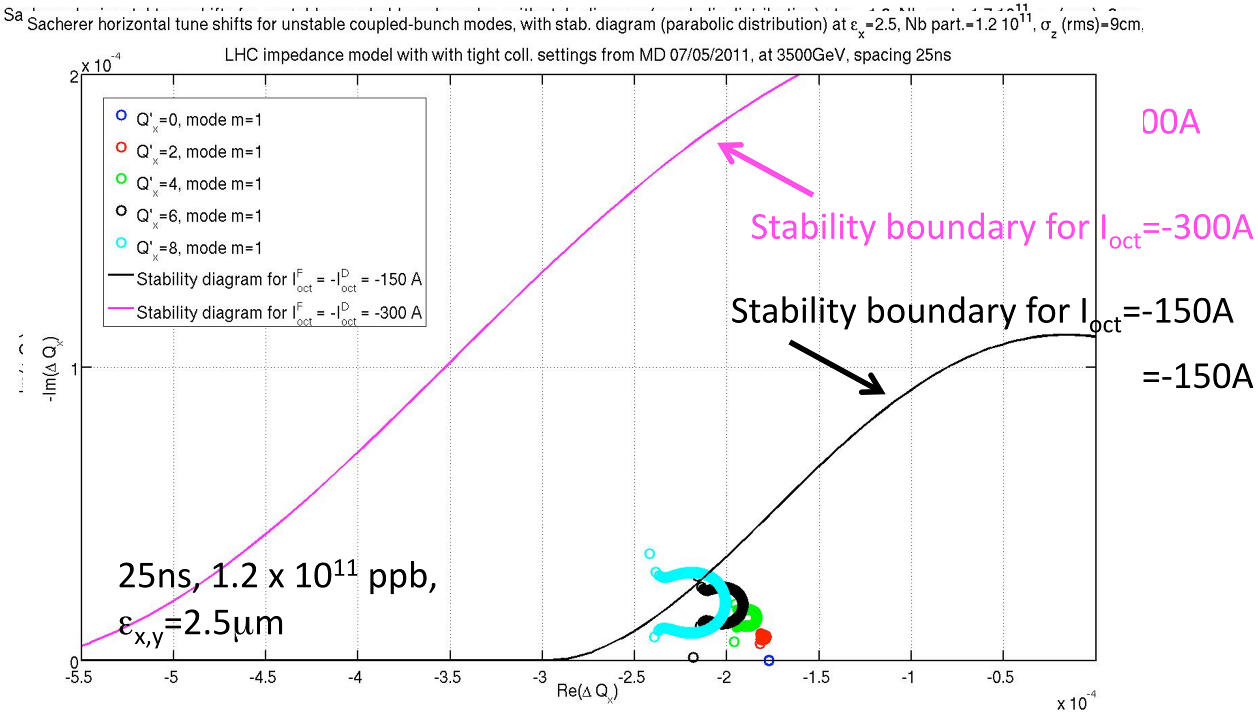




Courtesy N. Mounet

Coupled bunch instabilities
Headtail modes (m≥1)

- The growth rates of the coupled bunch headtail modes m=1 are evaluated analytically with Sacherer's formula
- Worst case considered → tight collimator setting at 3.5 TeV
- Two cases have been checked
  - 25ns with 1.2 x 10^{11} ppb and 2.5μm transverse emittance, Q' from 0 to 8 units
  - .



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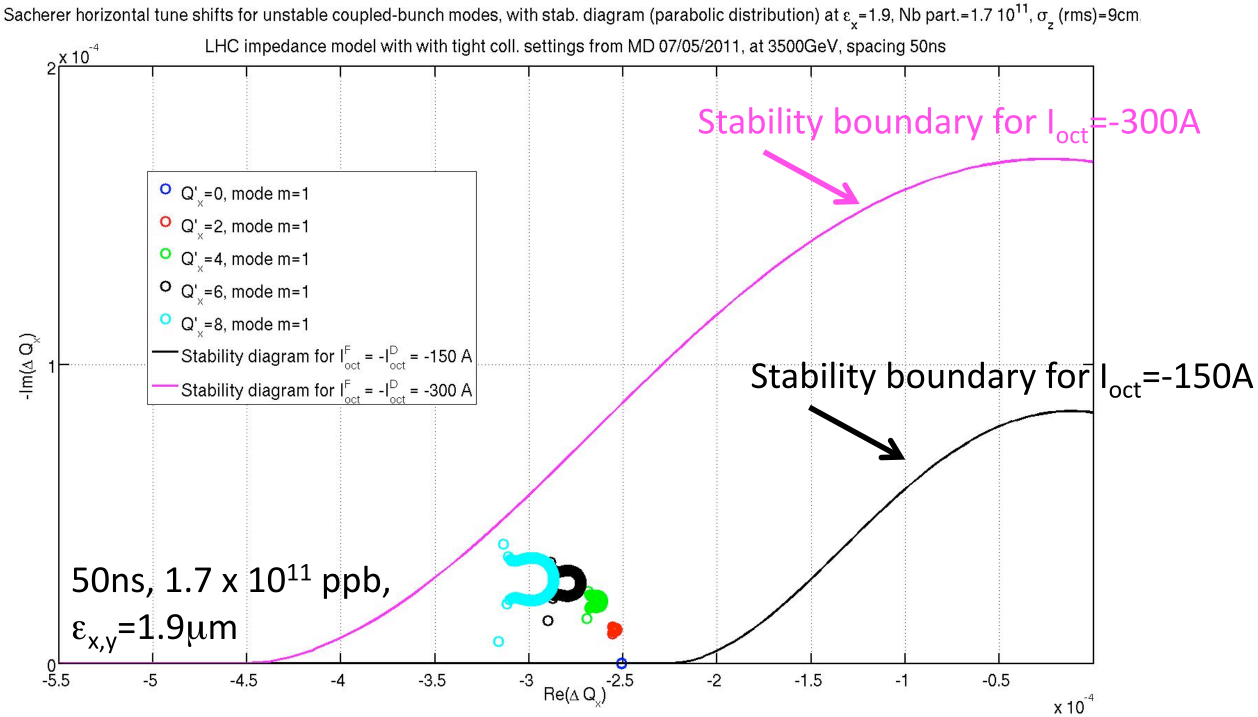
  - 25ns with 1.2 x 10^{11} ppb and 2.5μm transverse emittance, Q' from 0 to 8 units
  - 50ns with 1.7 x 10^{11} ppb and 1.9μm transverse emittance, Q' from 0 to 8 units



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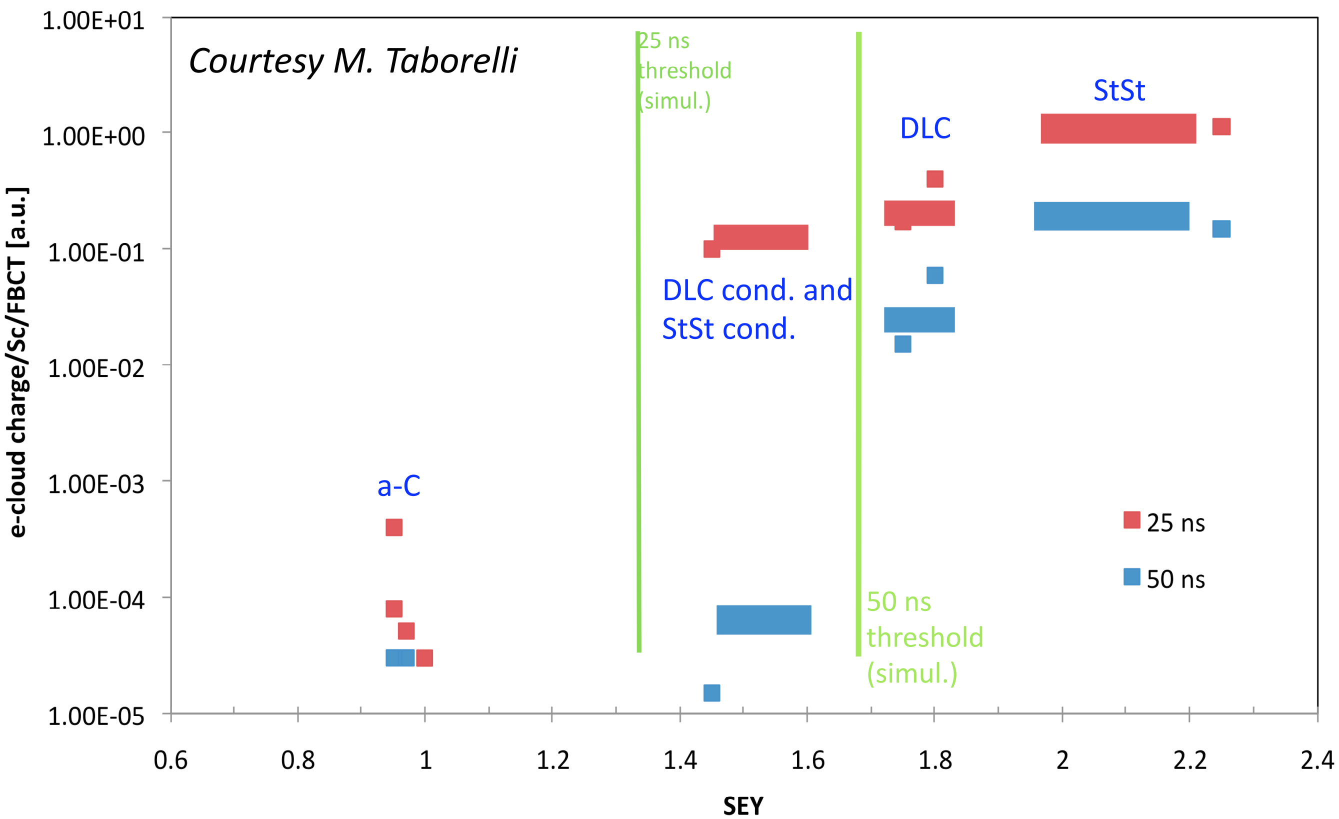
Electron cloud effects
Considerations on the build up

- Build up is stronger with closer bunch spacing (in the LHC range)
  - SPS experience
    - Threshold SEY_{max} is about 1.7 with 50ns beams and 1.3 with 25ns beams (nominal intensity)
    - Surface scrubbing leads to SEY_{max}=1.5-1.6 on StSt (measured) and saturates at this value



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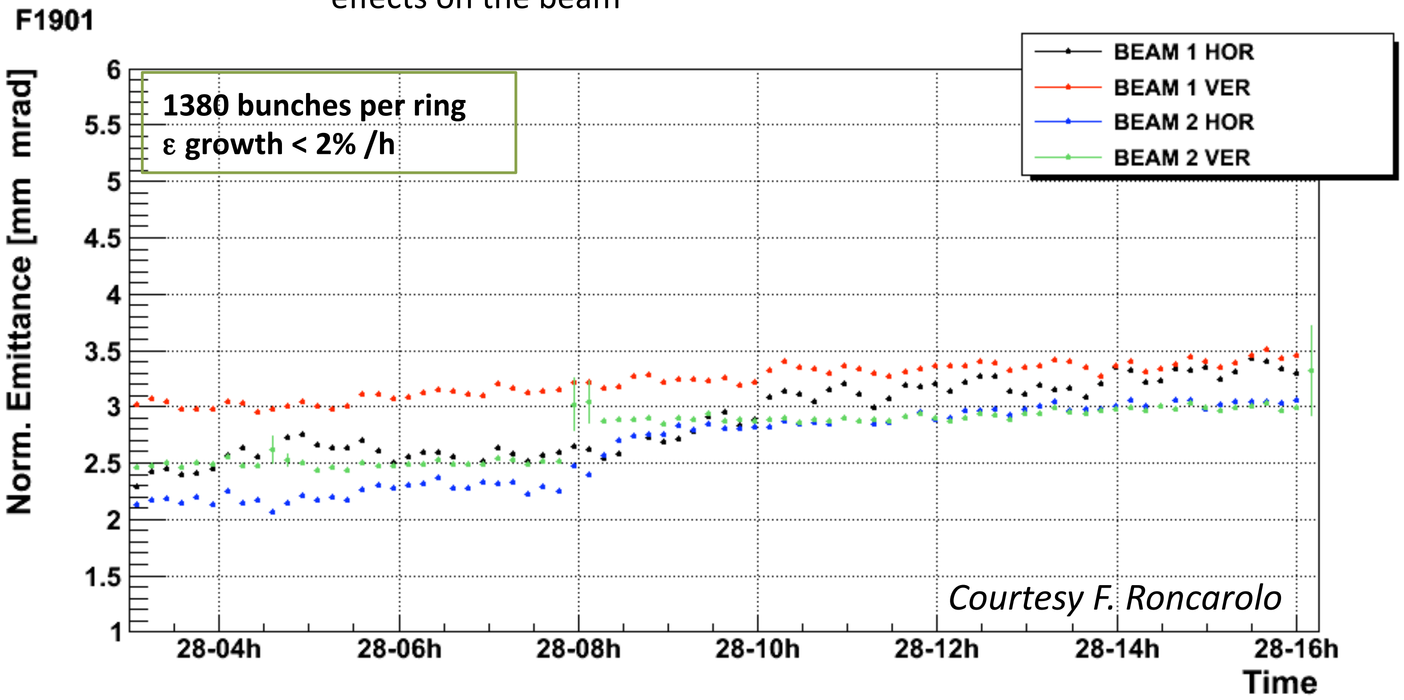
  - LHC
    - Presently, nominal 50ns beams do not suffer from obvious electron cloud limitations (after 10 days dedicated scrubbing + few months of "free scrubbing" with physics) → $SEY_{max} \leq 1.7$
    - First injections of 25ns beams in batches of 24 bunches → difficult to conclude on electron cloud effects on the beam



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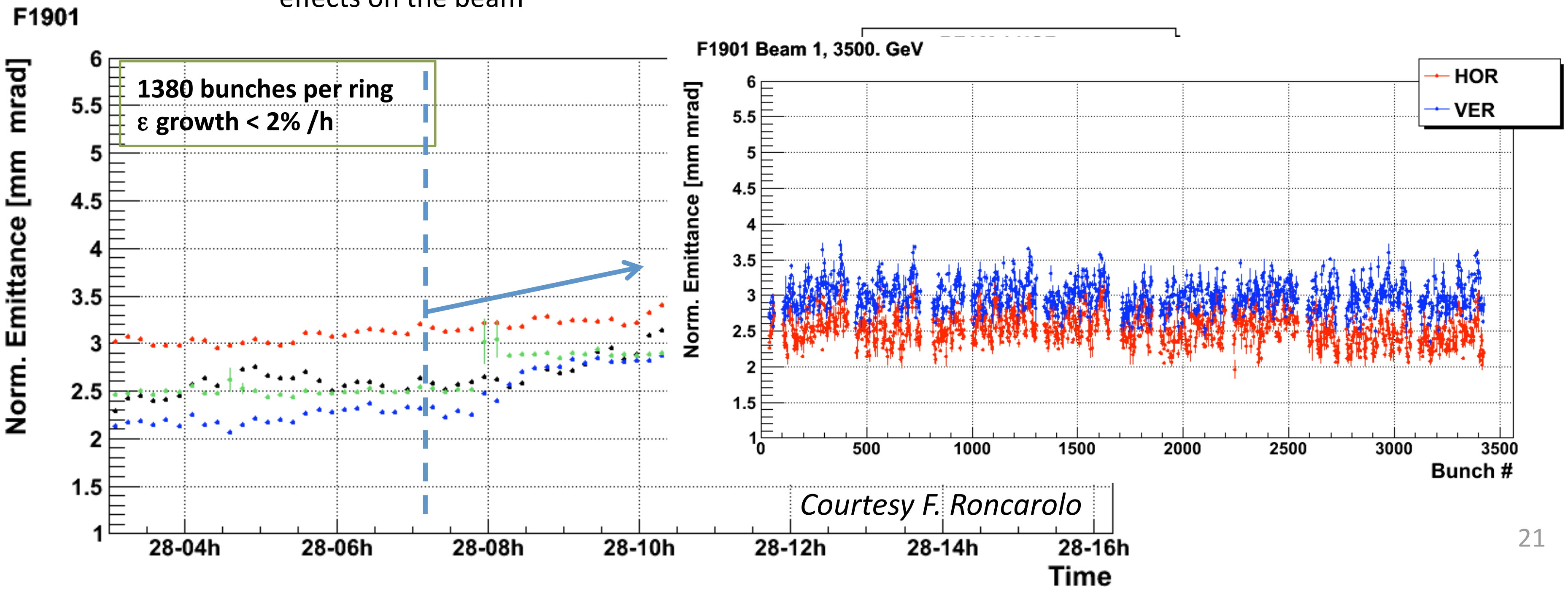

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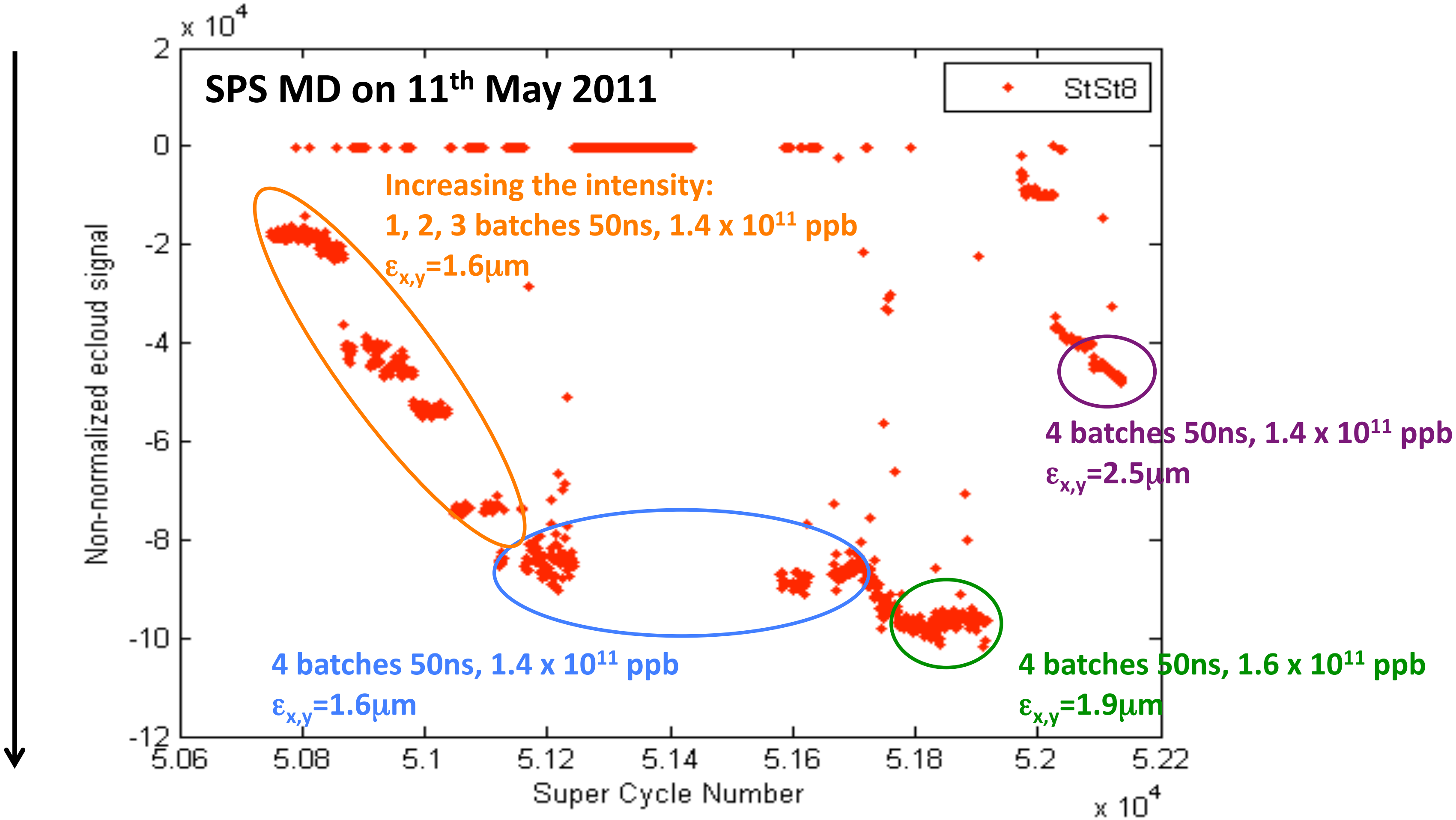
    - First injections of 25ns beams in batches of 24 bunches → difficult to conclude on electron cloud effects on the beam
- Effect of bunch intensity
  - Simulations suggest a decrease of the electron cloud activity when increasing the intensity per bunch of 50ns beams to values higher than nominal
  - Lack of clear experimental verification in the SPS
- Effect of transverse emittances
  - Little influence expected when the SEY is far above the threshold value for build up
  - Smaller emittances can significantly enhance the electron cloud when SEY is close to the threshold value for build up

Electron cloud effects
Considerations on the build up

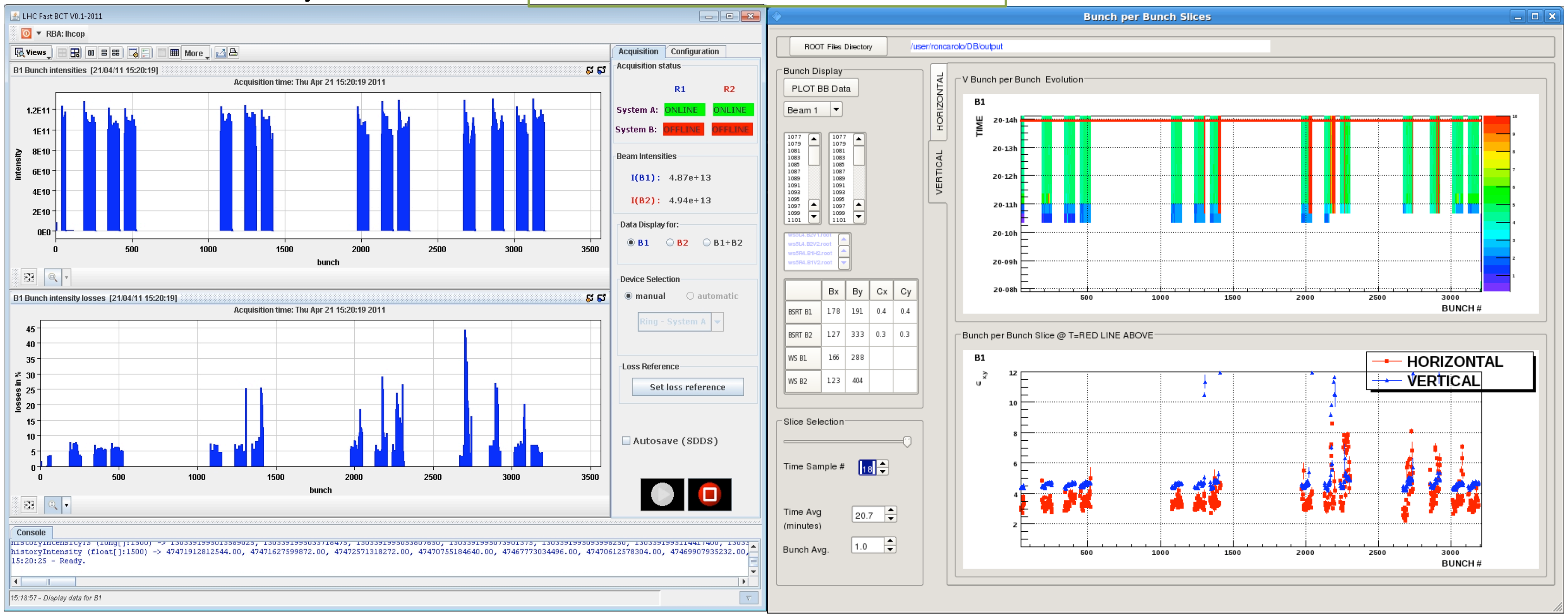


Courtesy C. Yin Vallgren

Electron cloud effects
Single bunch ECI

- During the scrubbing run and first physics runs, some bunches at the tails of batches were observed to suffer from emittance growth (BSRT) and larger losses (FBCT), probably a signature of coherent instability

Beam 1 (flat top screen shots), Fill 1728



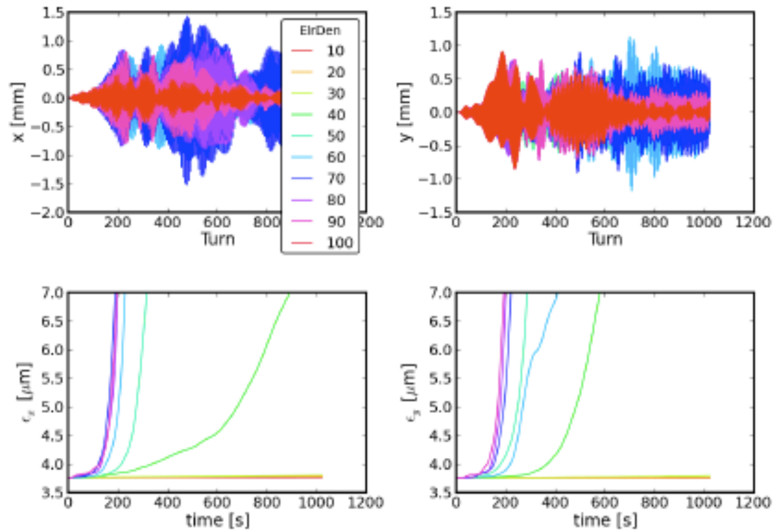
Electron cloud effects
Single bunch ECI

- During the scrubbing run and first physics runs, some bunches at the tails of batches were observed to suffer from emittance growth (BSRT) and larger losses (FBCT), probably a signature of coherent instability
- ECI can be enhanced by:
  - More electron cloud
    - 50ns with higher charge per bunch (?) and smaller transverse emittances
    - 25ns (at least one order of magnitude more)
  - Smaller transverse emittances
    - Due to stronger pinching effect
    - Experimental verification at the SPS in 2008

Electron cloud effects
Single bunch ECI

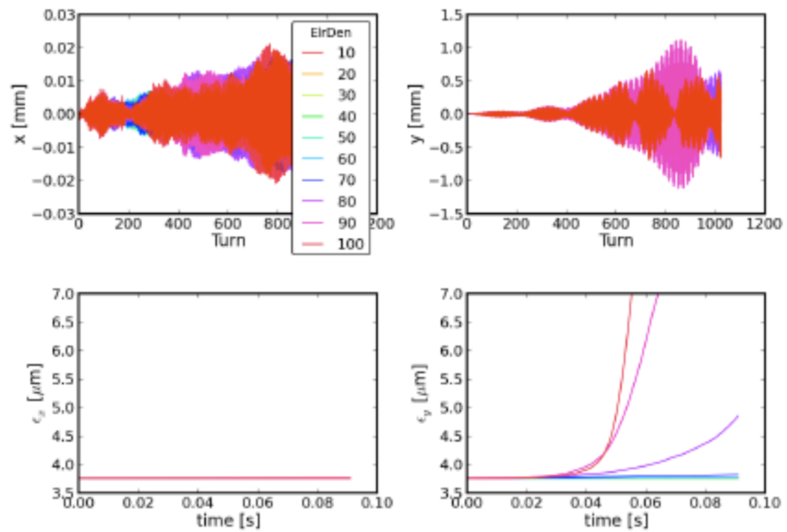
- HEADTAIL simulations of ECI @ 450 GeV and $\varepsilon_{x,y}$=1.5 to 3.5μm , electron cloud density threshold value for the onset of the ECI
  - Field-free region (total length ~30% of the ring) → 1 – 1.4 x 10^{12} m^{-3}
  - Arc dipoles (total length ~60% of the ring) → 0.85 – 1.1 x 10^{12} m^{-3}
- Threshold values are probably about a factor 2 lower if the electron cloud is present both in the dipoles and in field-free regions. These densities are compatible with central densities from 25ns beams

Field free



Dipole

Courtesy K. Li



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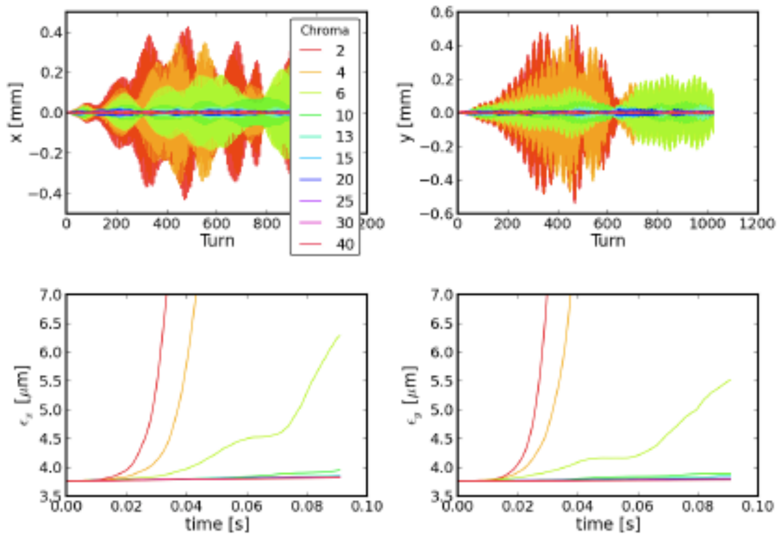
- Q'=15 is sufficient to recover stability

Field free



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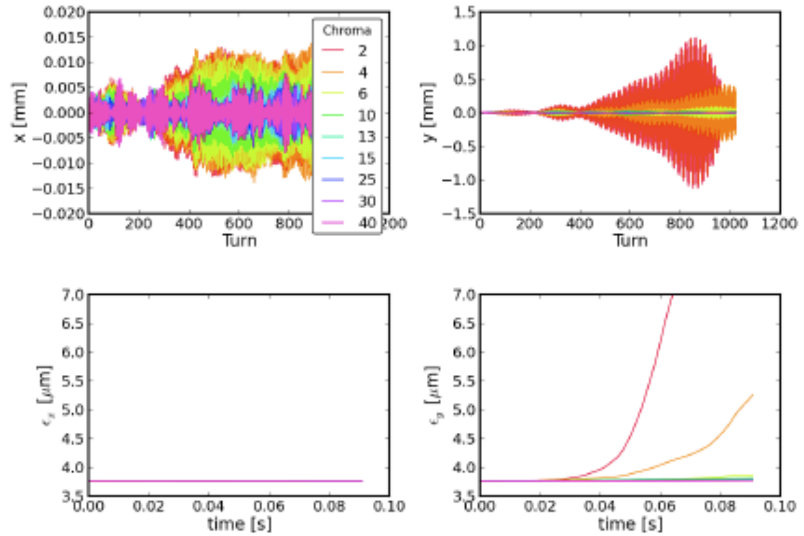
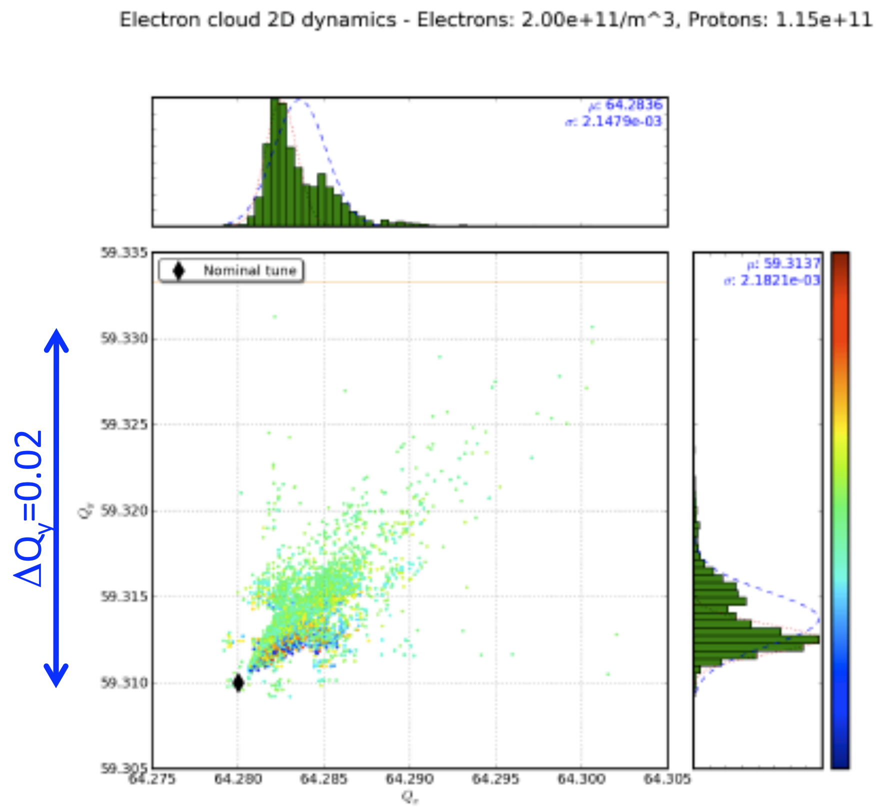


Electron cloud effects
Tune footprint

- HEADTAIL simulations @ 450 GeV with electron cloud density values below threshold for the onset of the ECI are used to quantify possible tune spreads from electron cloud

Field free



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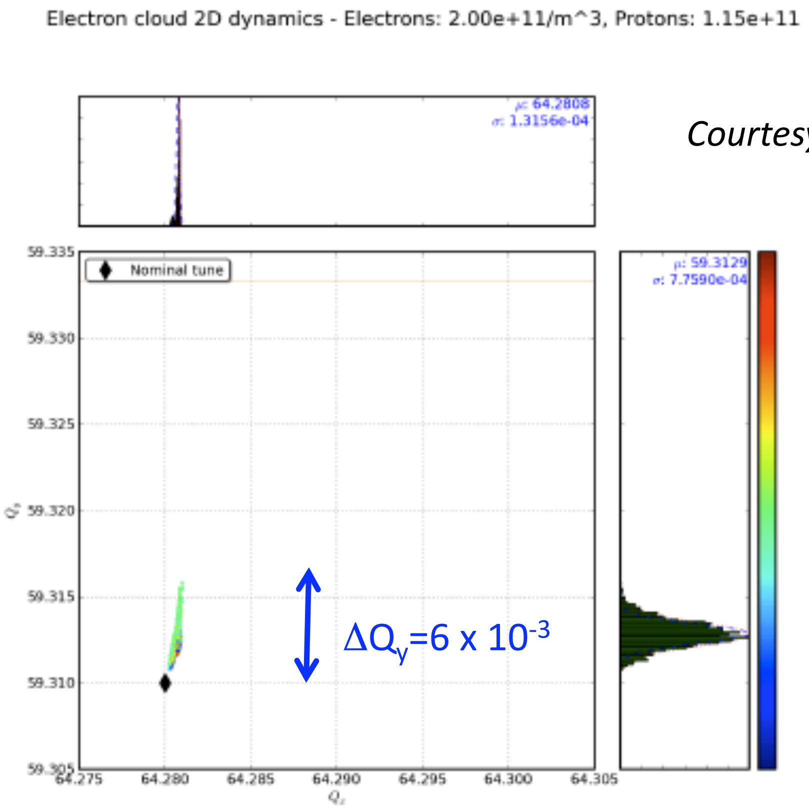
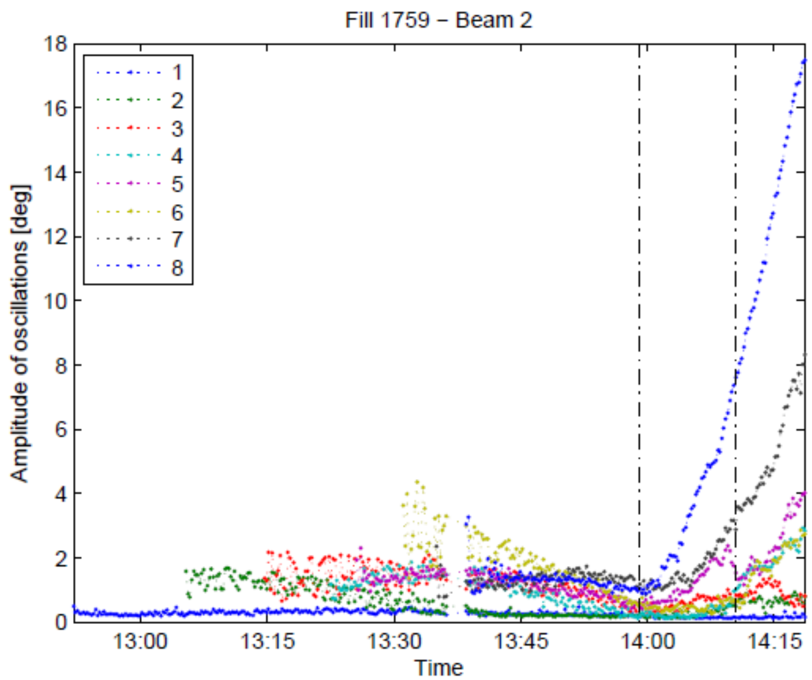


Courtesy K. Li

Longitudinal plane
Dipole and quadrupole instabilities

- Loss of Landau damping is observed at injection in the LHC
  - For intensities above 1.5 x 10^{11} ppb and longitudinal emittances below 0.75 eVs without phase loop
  - The phase loop works well for single bunch injection but is less efficient for multi-bunch injections
  - Oscillation growth is very slow and stops when the longitudinal emittance has grown above the threshold value
- Dipole oscillations can also become unstable along the ramp for intense bunches



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- Quadrupole oscillations are excited at flat top for small longitudinal emittances

Both can be stabilized by longitudinal emittance blow up along the ramp

Courtesy E. Shaposhnikova

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- Dipole oscillations can also become unstable along the ramp for intense bunches
- Quadrupole oscillations are excited at flat top for small longitudinal emittances
- There is no observation of longitudinal coupled bunch instabilities

Courtesy E. Shaposhnikova

Summary

	50ns with higher N_b and lower $\varepsilon_{x,y}$	25ns nominal
Single bunch headtail instabilities	More Landau damping required	Present Landau damping settings sufficient
TMCI	Both safely below threshold, multi-bunch effect?	
Coupled bunch instabilities (m=0)	Transverse feedback	
Coupled bunch instabilities (headtail modes)	More Landau damping required	Present Landau damping settings marginally sufficient
Electron cloud build up	Larger than now, maybe more scrubbing needed	Significantly larger than now, efficiency of scrubbing?
Single bunch ECI	Higher chromaticity setting to suppress it during scrubbing	Higher chromaticity setting to suppress it, if e-cloud level tolerable