Review of instabilities with ions or/and electrons and possible mitigations

L. Mether

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ICFA mini-Workshop on Mitigation of Coherent Beam Instabilities in particle accelerators
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Introduction

Additional electromagnetic fields in the beam environment, apart from externally applied RF and magnetic fields, perturb the motion of the beam particles and may give rise to instabilities

- Whereas impedance and space charge are caused by the electromagnetic fields induced by the beam itself, electron and ion instabilities are two-stream instabilities that are caused by the presence of another set of charged particles, which affects the beam through its electromagnetic field
- Typically, this other set of particles is generated by the beam itself directly or indirectly
- Electrons and ions are produced e.g. by ionization of residual gas in the beam chamber, photoemission, outgassing
  - The equally charged species is repelled by the beam and eventually reaches the chamber walls
  - The oppositely charged species is attracted by the beam field and may accumulate

→ Ion accumulation in electron machines

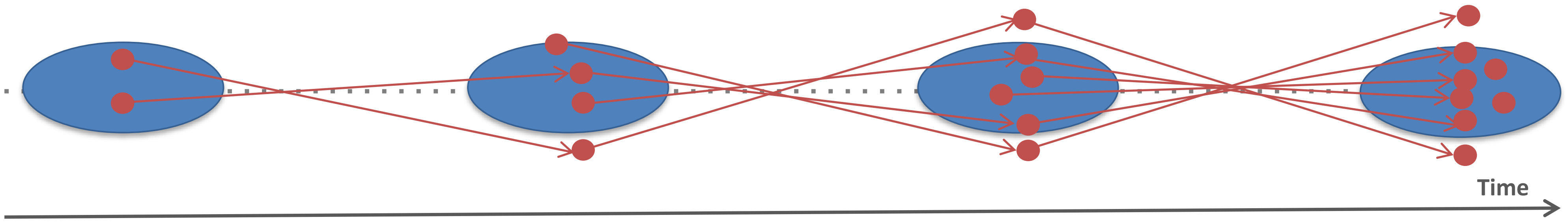
→ Electron cloud build-up in positron, proton or ion machines

Outline

Ion accumulation in electron machines

Beam-induced gas ionization gives rise to electrons and ions along the beam path

- Positive ions are attracted by the negative beam field and may oscillate around the bunch train
- Electrons are repelled by the beam towards the walls and eventually absorbed

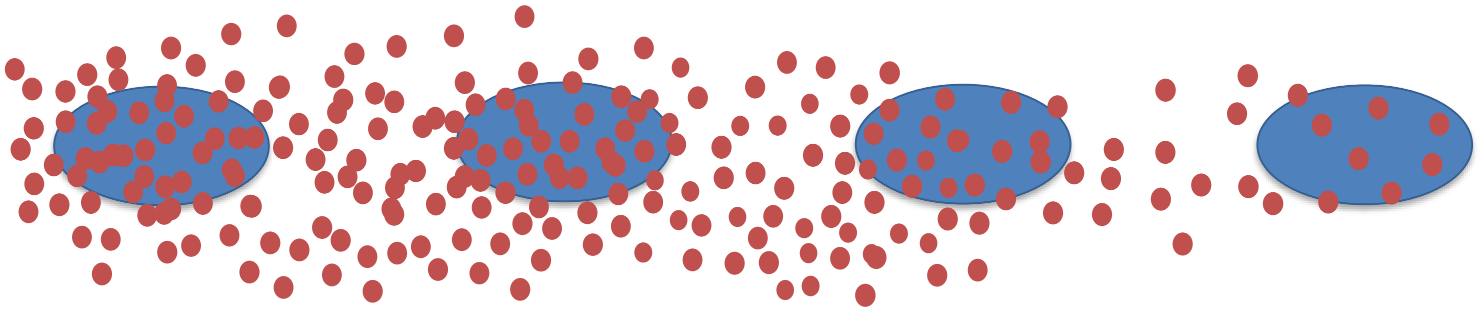


- In synchrotrons without clearing gap, the ion density builds up over several turns
  → Conventional ion instability (can usually be avoided with a clearing gap)

- In linacs or synchrotrons with a clearing gap, ions build up only during one train passage
  → Fast beam-ion instability

Fast beam-ion instability

The ions transfer information on the offset of their generating bunch to the following bunches and thus may lead to coupled-bunch instabilities due to transverse offsets between bunches



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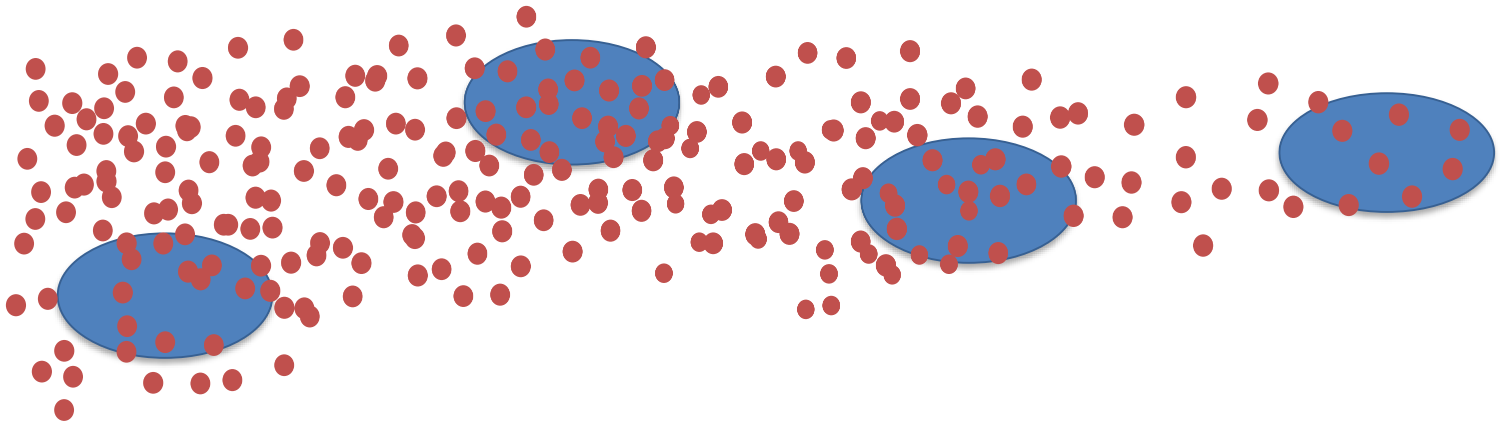


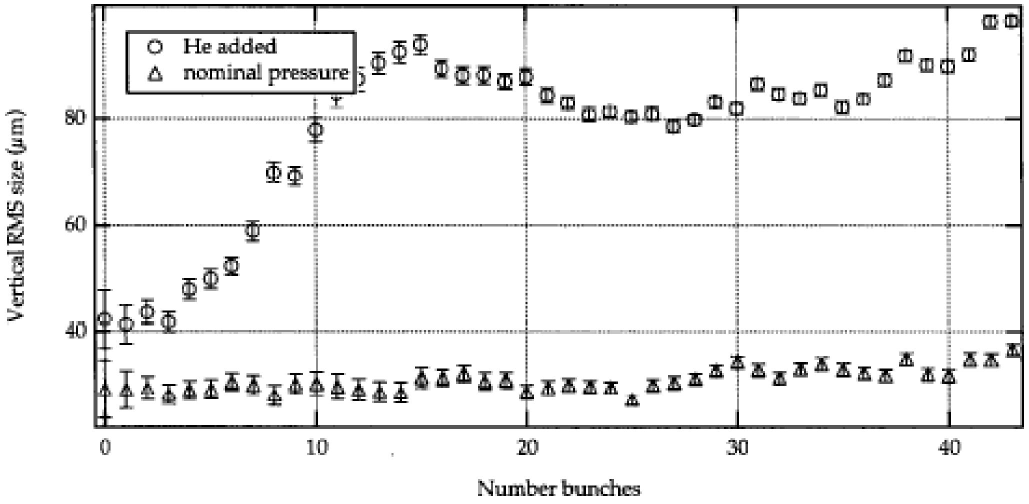
- The instabilities are typically accompanied by emittance growth
- The ions also introduce a tune shift along the bunch train
- Since the ion density increases along the bunch train, the effects are stronger at the tail of trains

Machine observations

- Conventional ion instabilities have been observed in several machine since several decades

- Fast beam-ion instabilities have been observed since the 90's, soon after their theory was developed, in several machines
  - » ALS
  - » PLS
  - » BESSY II
  - » ELETTRA
  - » ALBA
  - » SOLEIL
  - » Cesr-TA

Measurement at ALS



J. Byrd, A. Chao, S. Heifets, et al. Phys. Rev. Lett. 79 (1997), 79-82

- In most cases the instability has been observed only in the presence of vacuum degradation (or feedback issues)
  - » During commissioning
  - » Due to a local pressure rise, e.g. due to impedance-induced heating
  - » During experiments with additional injected gas

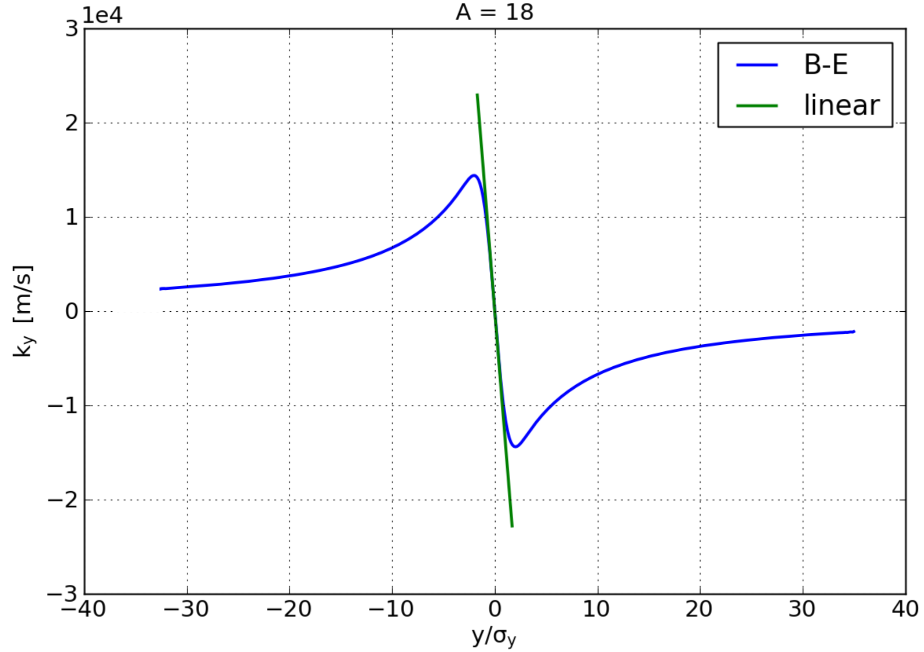
Analytical model: Ion trapping

The instability can be modelled using the linear approximation of the Bassetti-Erskine formula for a Gaussian beam field

- An ion with mass number *A*, receives a velocity kick by the beam

$$\frac{2N_b r_p c}{A}\frac{x,y}{(\sigma_x+\sigma_y)\sigma_{x,y}} = k_{x,y} * x, y$$

N_b = bunch intensity,
r_p = classical proton radius,
$\sigma_{x,y}$ = transverse beam size



Raubenheimer et al., Phys. Rev. E 52, 5, 5487,
Stupakov et al., Phys. Rev. E 52, 5, 5499

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- During the bunch spacing T_b the ions drift
  By analogy with the stability condition of a linear beam trajectory, $|\mathrm{Tr}(M)| < 2$, the motion is stable if $\boldsymbol{k_{x,y}T_b < 4}$

→ Trapping condition for ion mass number: $A > A_{\mathrm{trap}} = \frac{N_b r_p T_b c}{2\left(\sigma_x + \sigma_y\right)\sigma_{x,y}}$

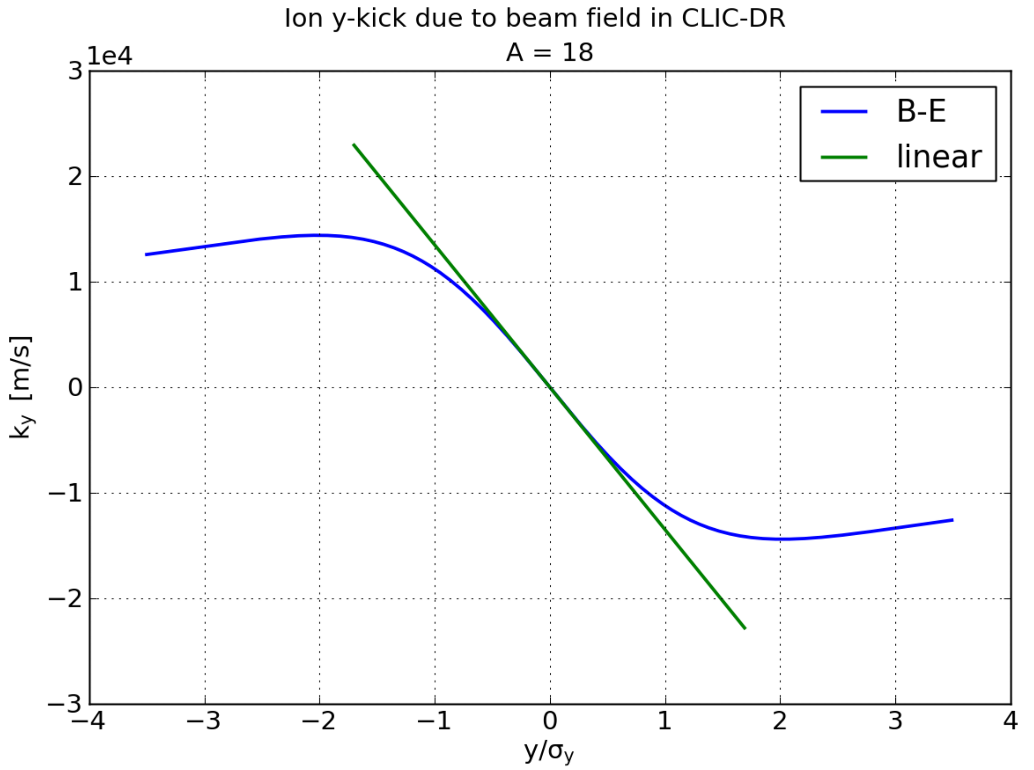
- Estimated instability rise time: $\tau_{\mathrm{inst}}^2 \propto \frac{\gamma^2 A \omega_\beta}{n_b^4 N_b^3 P^2 T_b c}\left(\sigma_x + \sigma_y\right)^3 \sigma_{x,y}^3$

n_b = nr of bunches,
P = pressure,
ω_β = betatron frequency

Raubenheimer et al., Phys. Rev. E 52, 5, 5487,
Stupakov et al., Phys. Rev. E 52, 5, 5499

Analytical model: Beyond linear approximation

The linear approximation is good only in a small region around the centre of the beam: $x,y \leq 0.5\ \sigma_{x,y}$



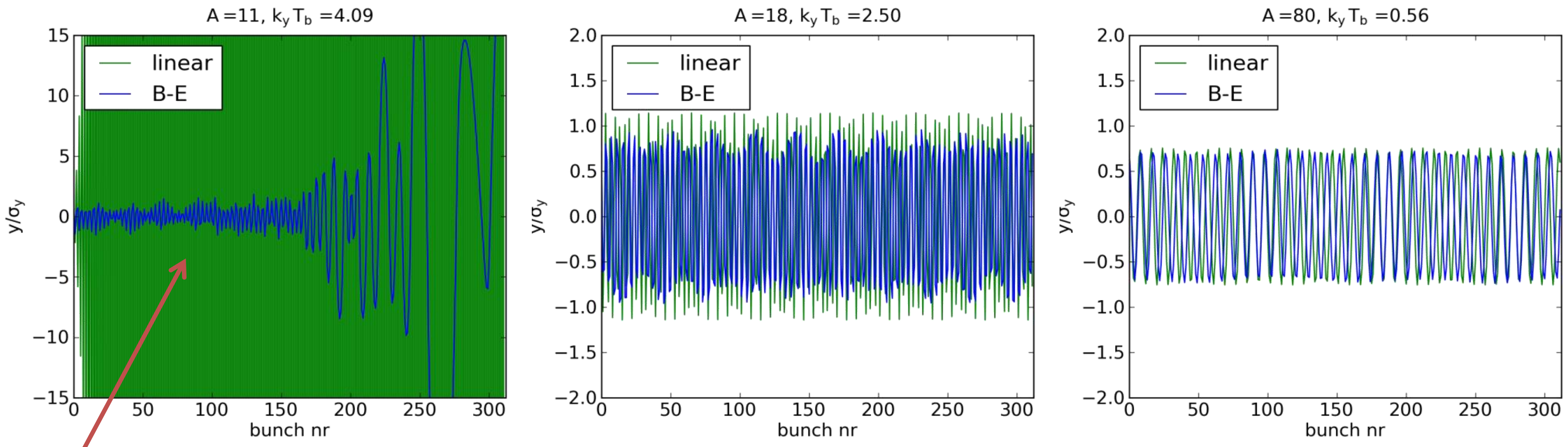
Analytical model: Beyond linear approximation

The linear approximation is good only in a small region around the centre of the beam: $x,y \leq 0.5\ \sigma_{x,y}$

- In the non-linear regime, ion trajectories are altered

Trajectories for ion of mass A during the passage of a CLIC bunch train

$x_0 = 0.7\ \sigma_x$, $y_0 = 0.7\ \sigma_y$



Ion is trapped for several bunch passages

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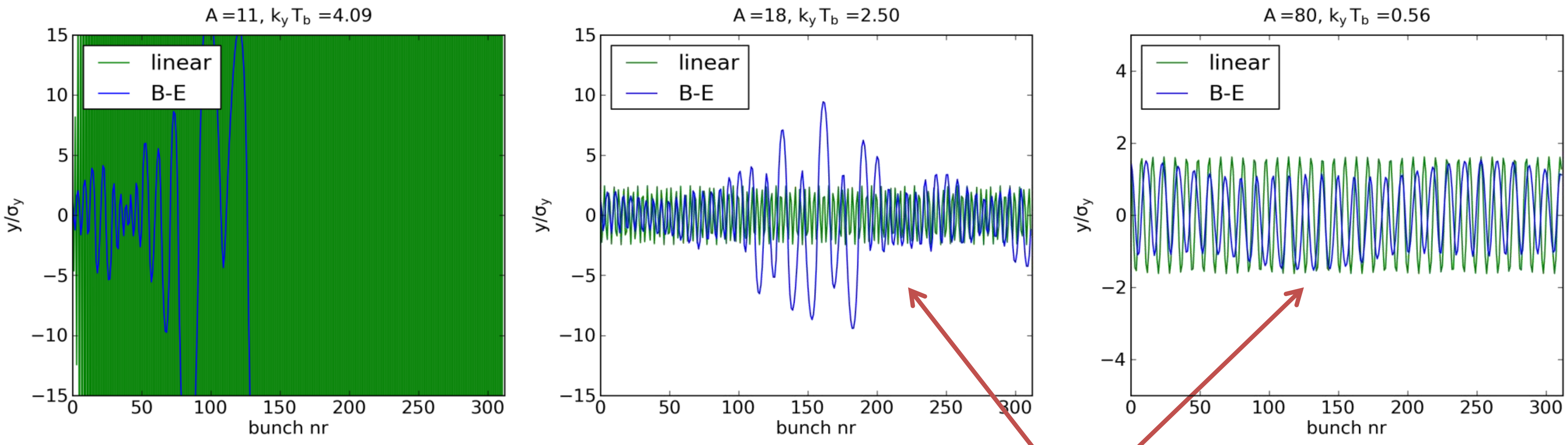


Ion trajectories are less uniform

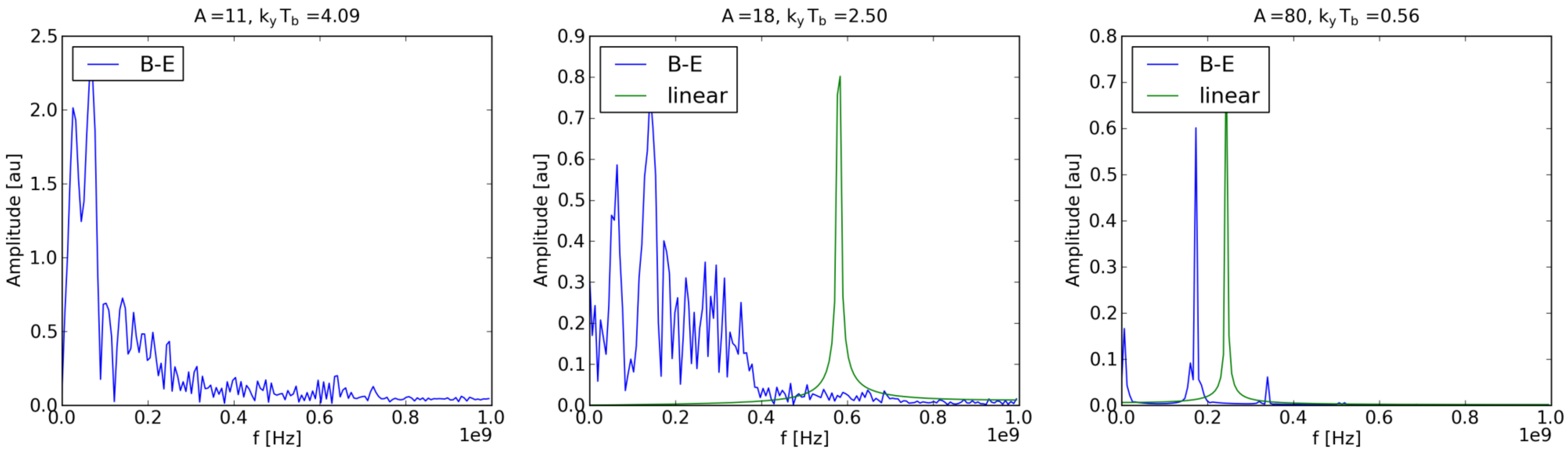
Analytical model: Beyond linear approximation

The linear approximation is good only in a small region around the centre of the beam: $x,y \leq 0.5\ \sigma_{x,y}$

- In the non-linear regime, ion trajectories are altered and ion frequencies receive a spread

Oscillation frequencies for ion of mass A during the passage of a CLIC bunch train

$\mathbf{x_0 = 1.5\ \sigma_x,\ y_0 = 1.5\ \sigma_y}$



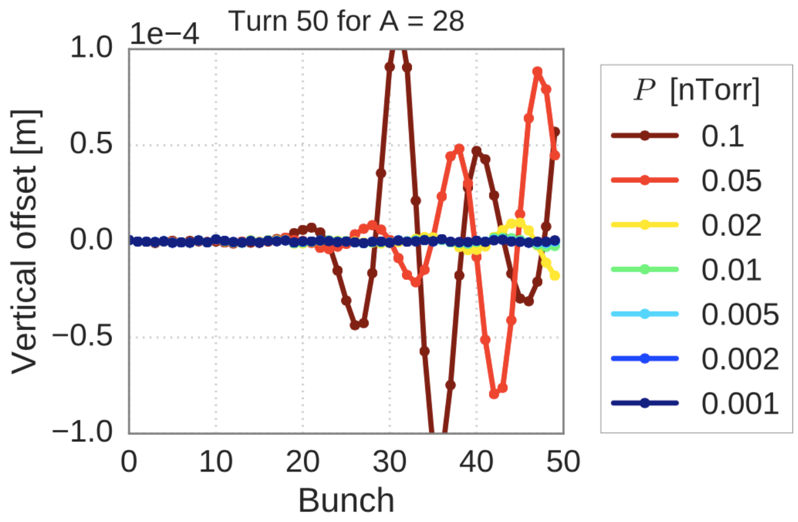
The non-linear beam field introduces a spread in the ion oscillation frequency

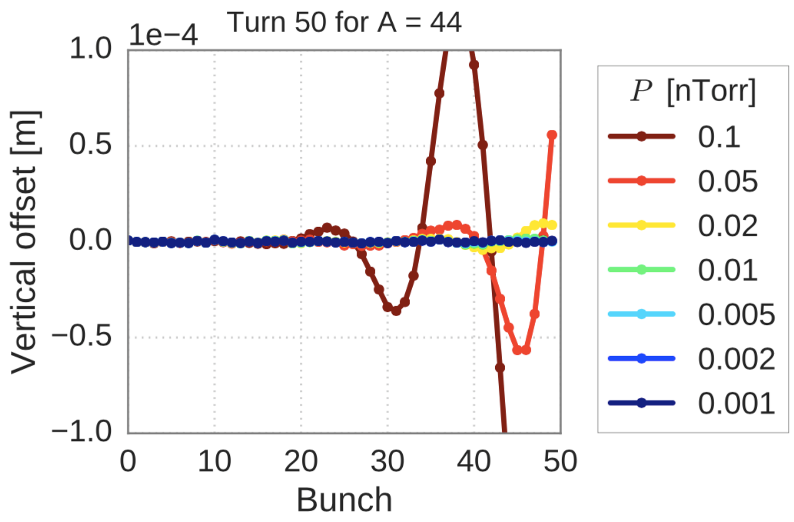
Simulation studies

Unexpected trapping was observed in a recent simulation study of the fast beam-ion instability in the FCC-ee, with CO (A=28) and CO_2 (A=44)

- ○ Two β functions considered ("arcs", "straight sections") → different trapping conditions A_{trap} ≈ 10 and A_{trap} ≈ 80

- ○ In the straight sections (A_{trap} ≈ 10) typical results were obtained
  - » The instability sets in at the end of trains, moving towards the front of the train
  - » The instability is **stronger for lower A**





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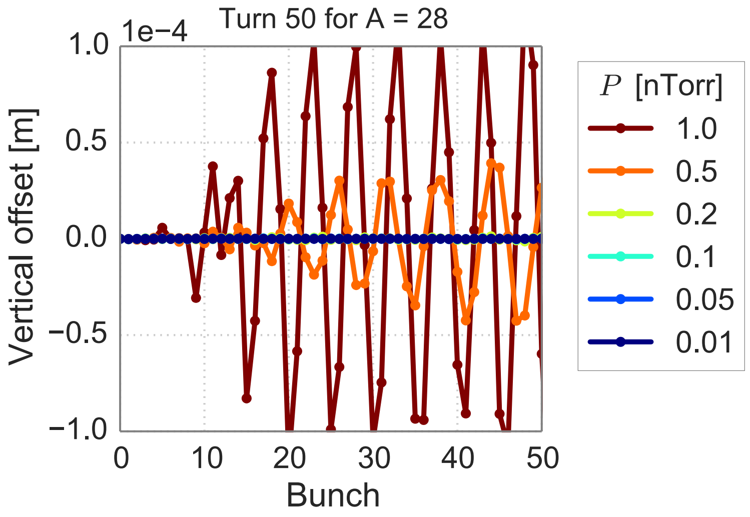
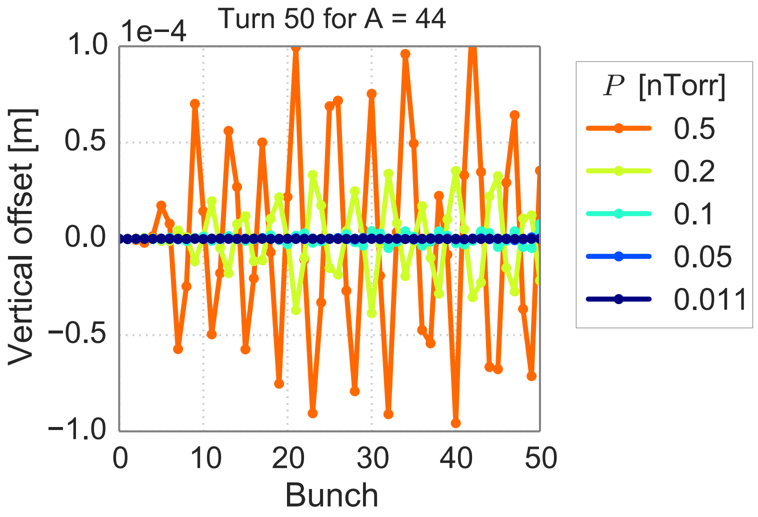
- In the arcs (A_{trap} ≈ 80) instabilities were unexpectedly observed, but with atypical characteristics
  - The instability develops simultaneously over most of the train
  - The instability is **stronger for higher A**





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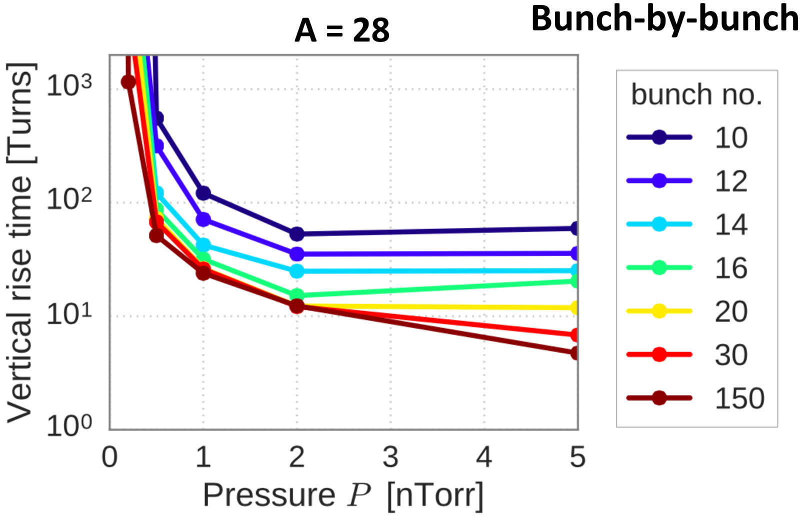
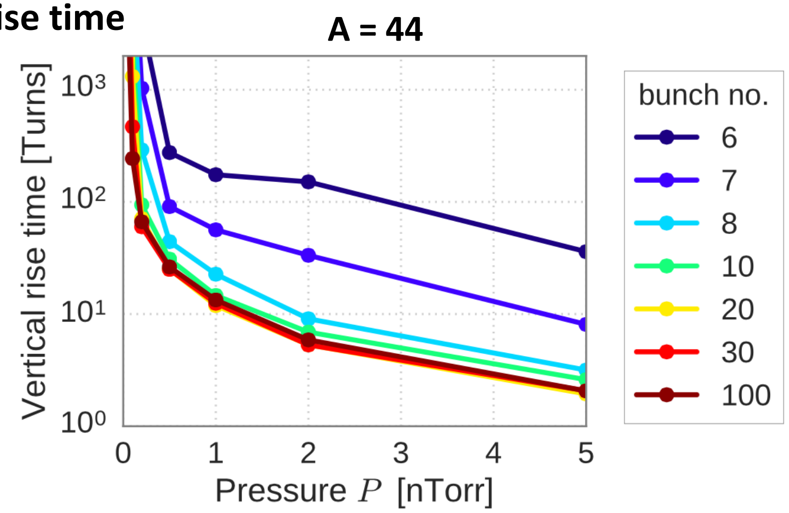
- In the arcs (A_{trap} ≈ 80) instabilities were unexpectedly observed, but with atypical characteristics
  - The instability develops simultaneously over most of the train
  - The instability is **stronger for higher A**
  - Bunch-by-bunch rise times (based on emittance) saturate after the first few bunches

Bunch-by-bunch rise time

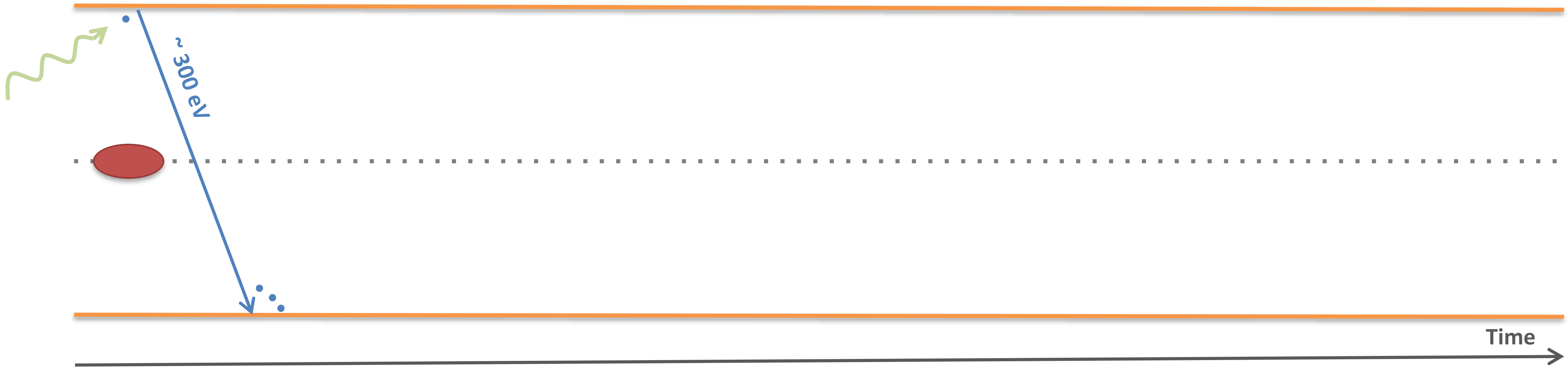




Electron cloud build-up

Seed electrons from e.g. gas ionization or photoemission are accelerated by the beam field

- When the accelerated electrons hit the wall, secondary electron emission can occur



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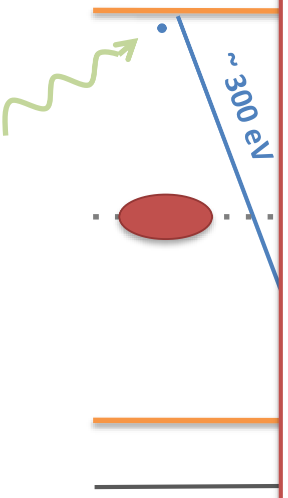
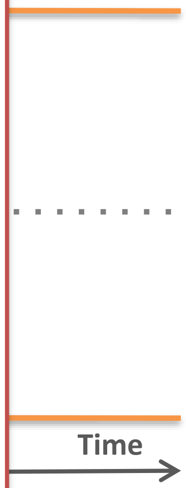
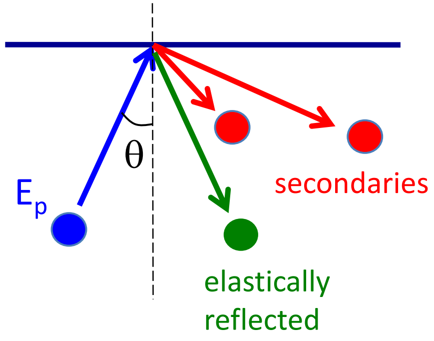




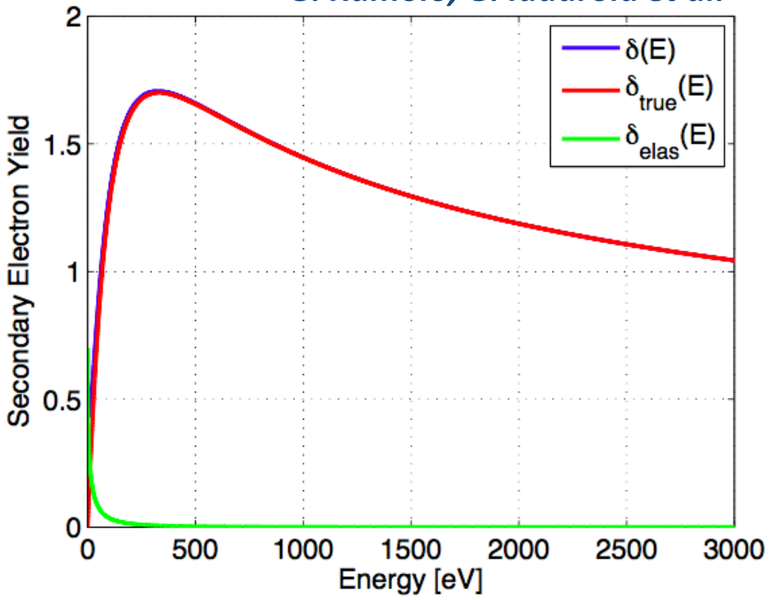
Secondary electron emission

The secondary electron yield (SEY) is a function of the energy and angle of incidence of the impacting electrons



In general, the SEY of a surface depends on the surfaces chemical and physical properties

G. Rumolo, G. Iadarola et al.



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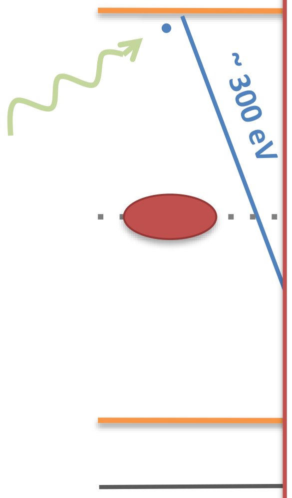

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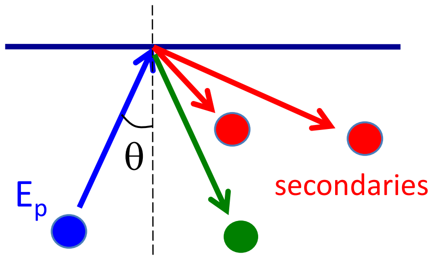

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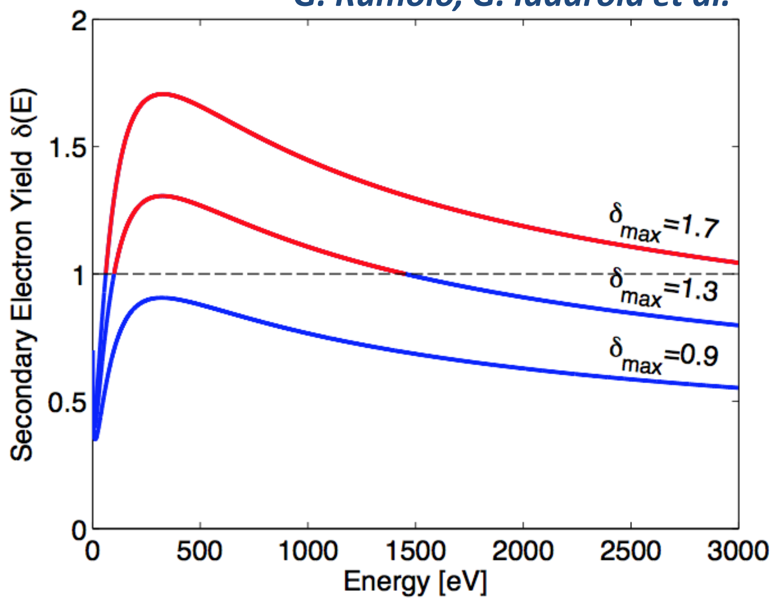

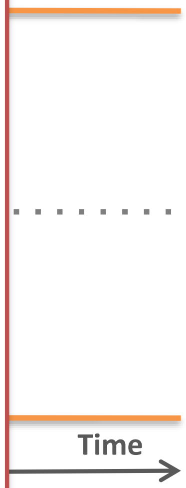

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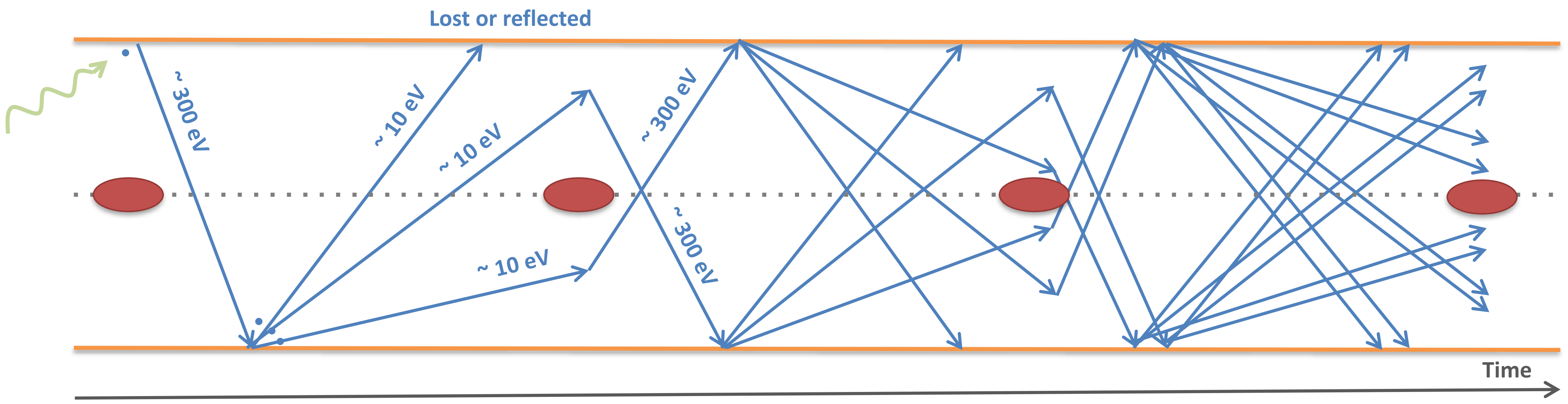


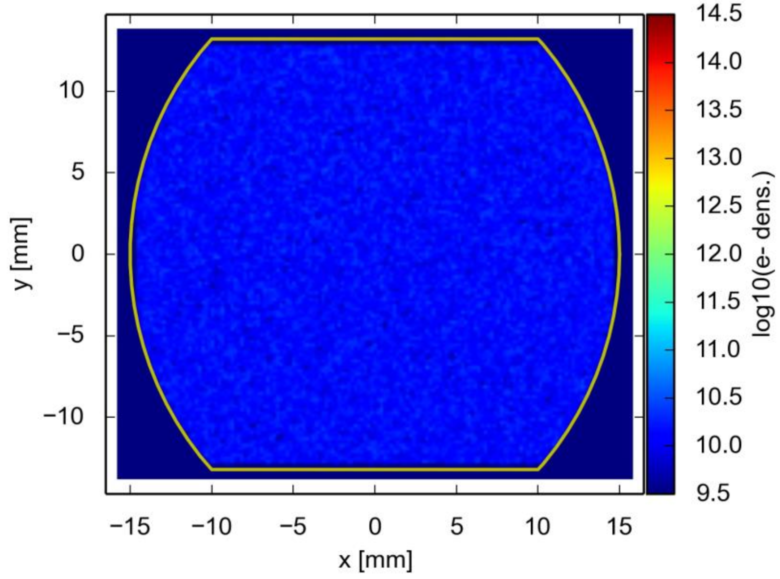
- Secondary electron emission can lead to avalanche electron multiplication
  - » Conditions depend on the bunch spacing, chamber geometry, magnetic fields, and bunch charge and length as well as the secondary emission yield
  - » After the passage of several bunches, the electron distribution inside the chamber reaches a stationary state – the electron cloud

Single-bunch electron cloud instability

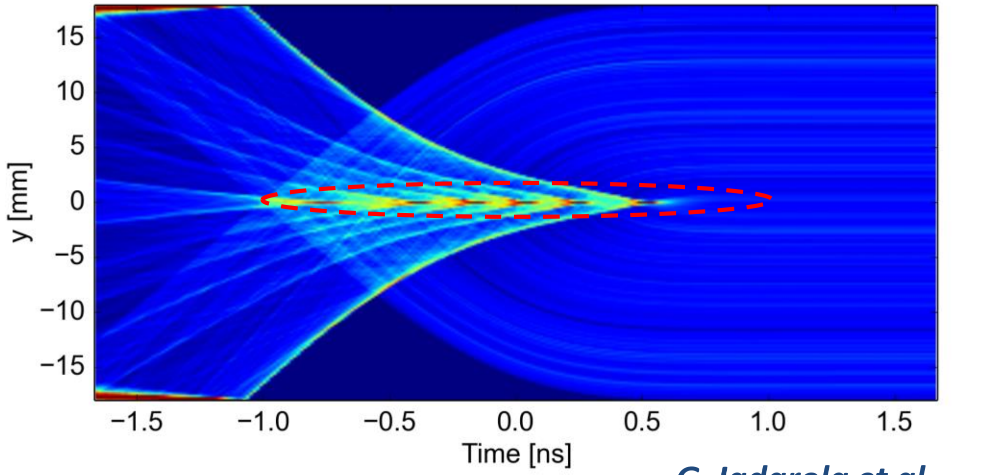
Whereas ions barely move during the passage of individual bunches, electrons move significantly during the passage of a single bunch

- Electrons attracted by the beam field are pulled into the bunch (*pinch*) where they oscillate in the beam field during the bunch passage
- This gives rise to a z-dependent (increasing) electron density along the bunch, which can give rise to head-tail coupling and eventually drive the bunch unstable

Electron density during 4 bunch passages in an FCC-hh drift space



Electron density during the passage of an LHC-like bunch



G. Iadarola et al.

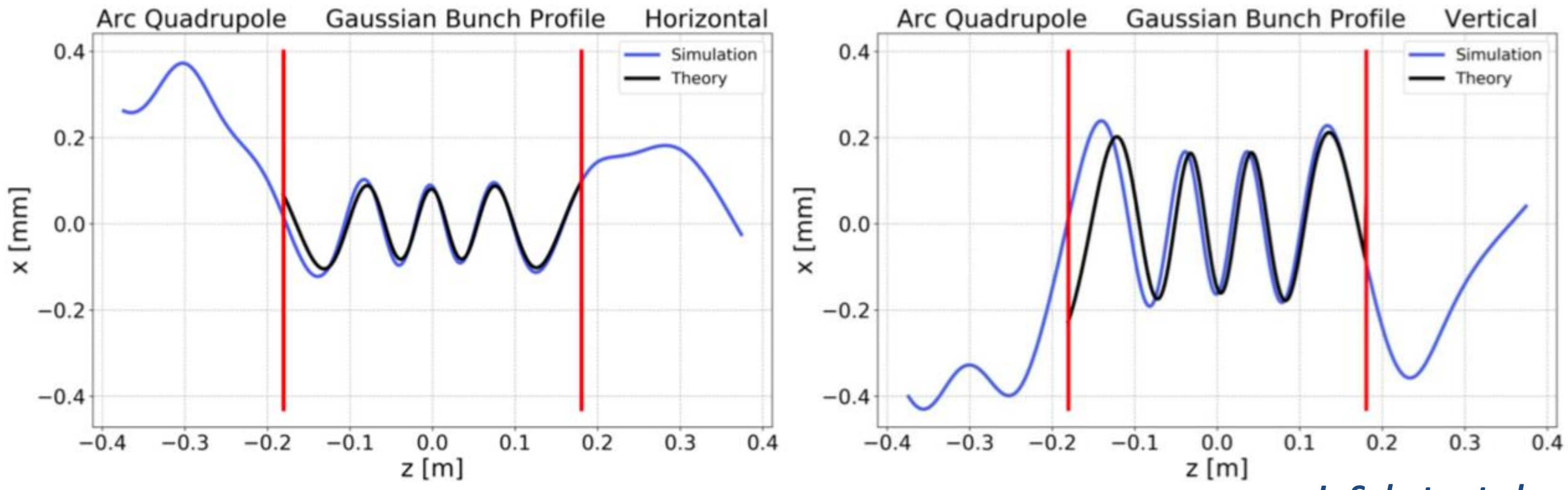
Single-bunch electron cloud instability

The electron oscillations in the beam field can be modelled similarly to the ion motion in the electron beam

- In the linear regime, i.e. for an electron with an oscillation amplitude that is smaller than the rms beam size, there is good agreement between the linear analytical theory and simulations

$$\frac{d^2x}{dt^2}+\frac{q_e}{m_e}\frac{\lambda_z}{2\pi\varepsilon_0\sigma_x(\sigma_x+\sigma_y)}x=0 \qquad \lambda_z(z)=\frac{q_eN_b}{\sqrt{2\pi}\sigma_z}e^{-\frac{z^2}{2\sigma_z{}^2}}$$

Electron motion through an LHC-like bunch



L. Sabato et al.

Single-bunch electron cloud instability

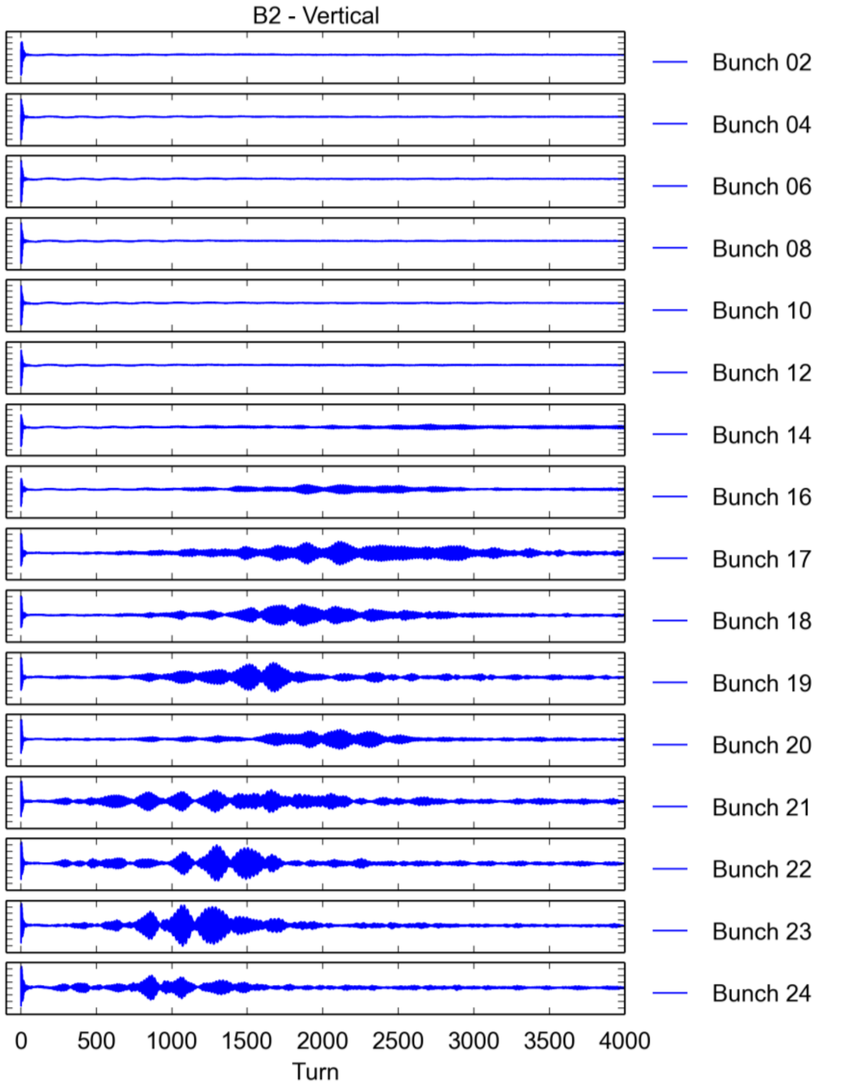
As a consequence of the electron motion, fast intra-bunch motion is characteristic for single bunch electron cloud instabilities

- The instabilities often result in strong transverse emittance growth

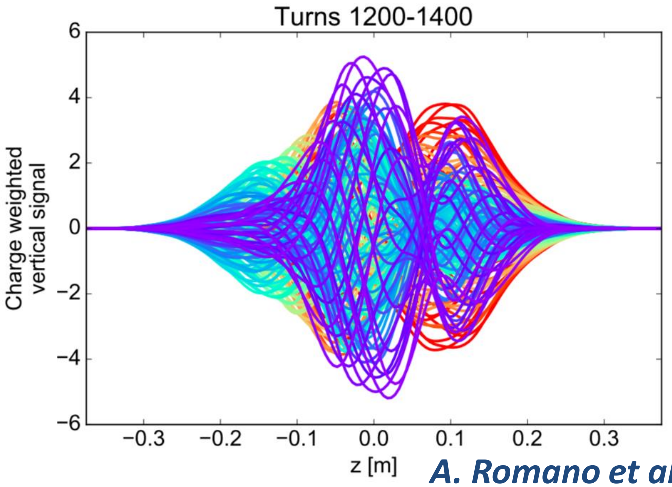
Since the electron cloud builds up along the bunch train, bunches at the tail of trains see a larger electron density and are typically more affected

- The instability rise times can be rather short 100s – 1000s of turns

Measurement at LHC



Simulation of LHC quadrupole



A. Romano et al.

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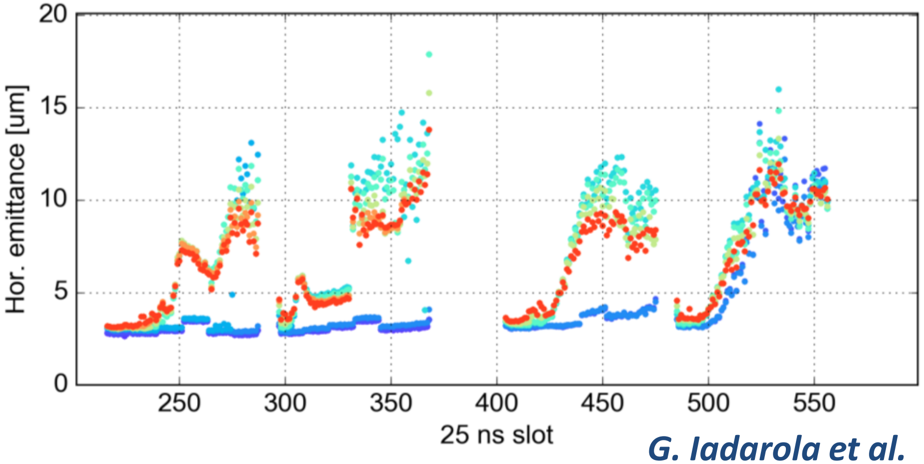
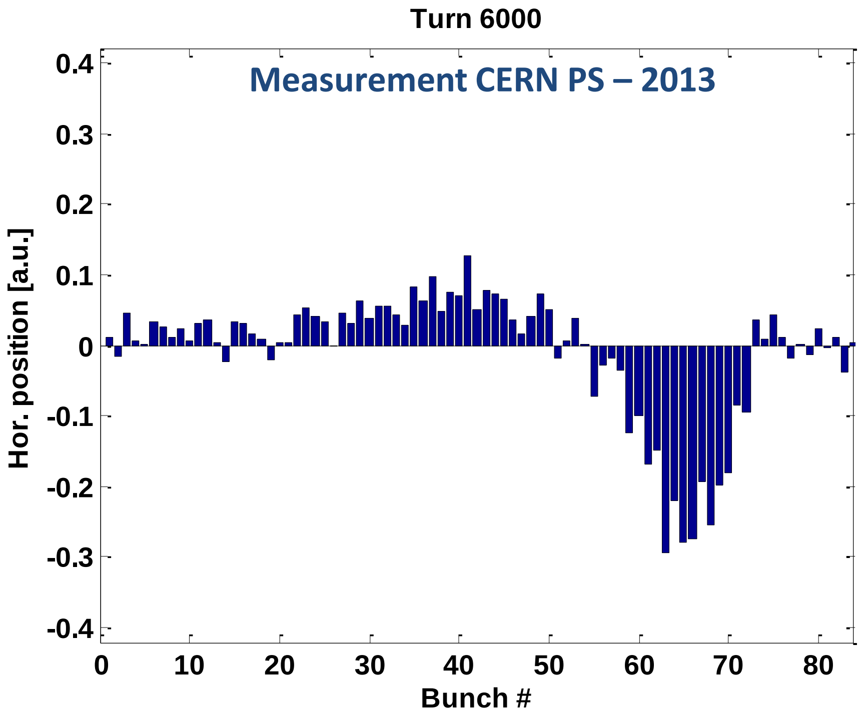


G. Iadarola et al.

Coupled-bunch electron cloud instability

- Since the electron cloud builds up over the several bunch passage, it can also be responsible for bunch-to-bunch coupling and coupled-bunch instabilities due to transverse offsets between bunches



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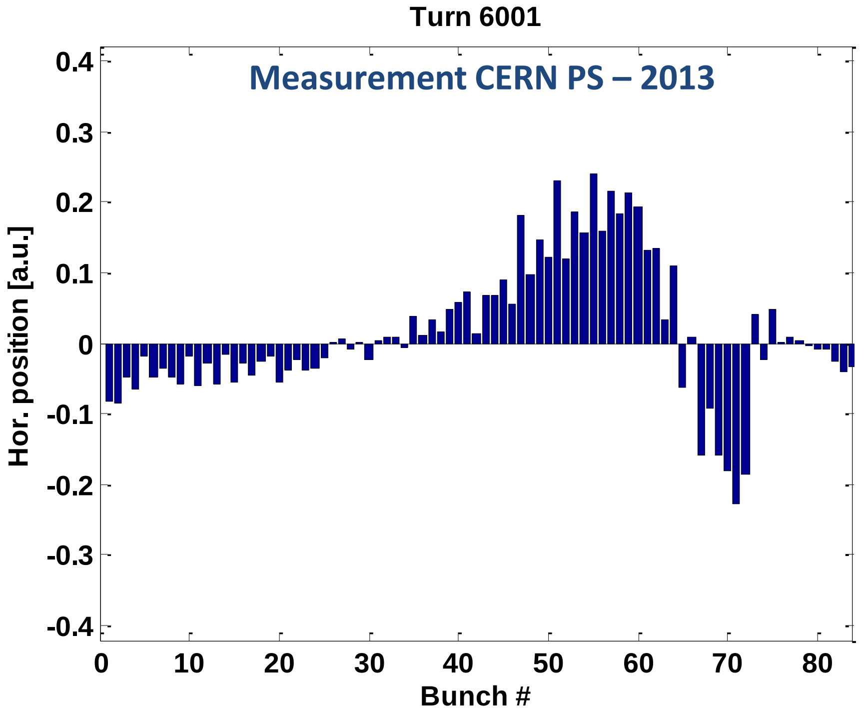

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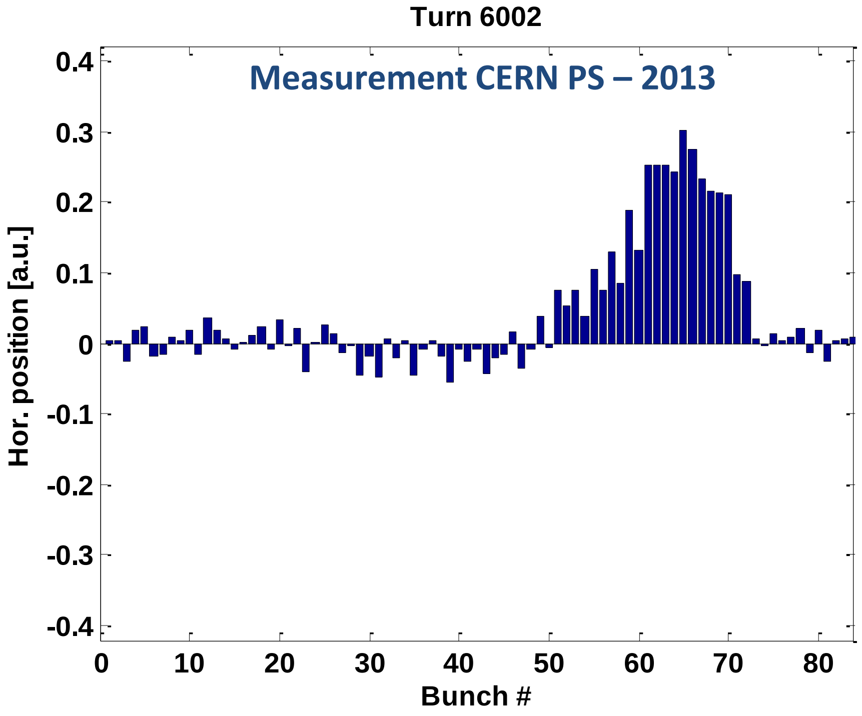

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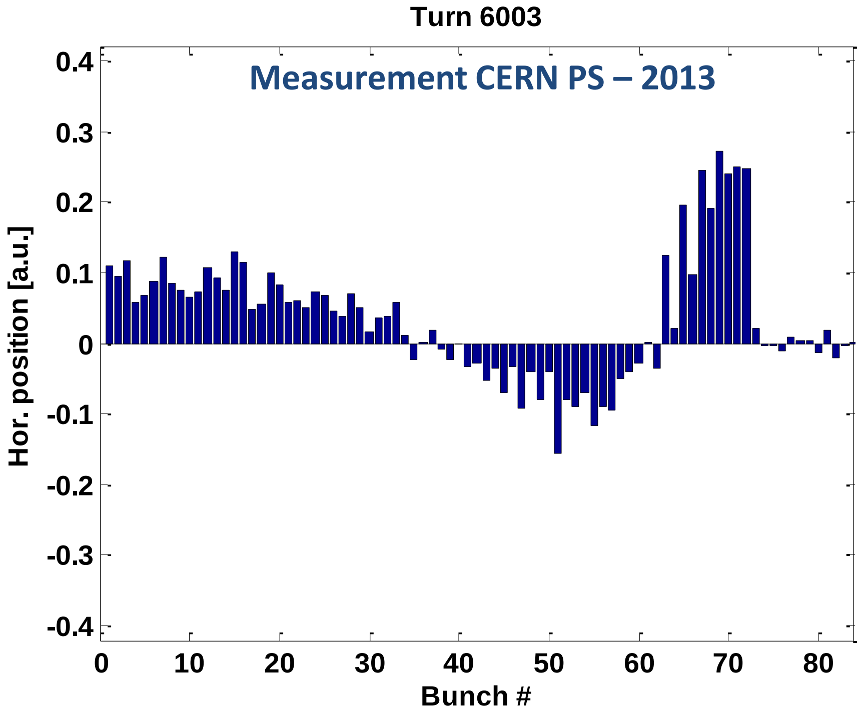

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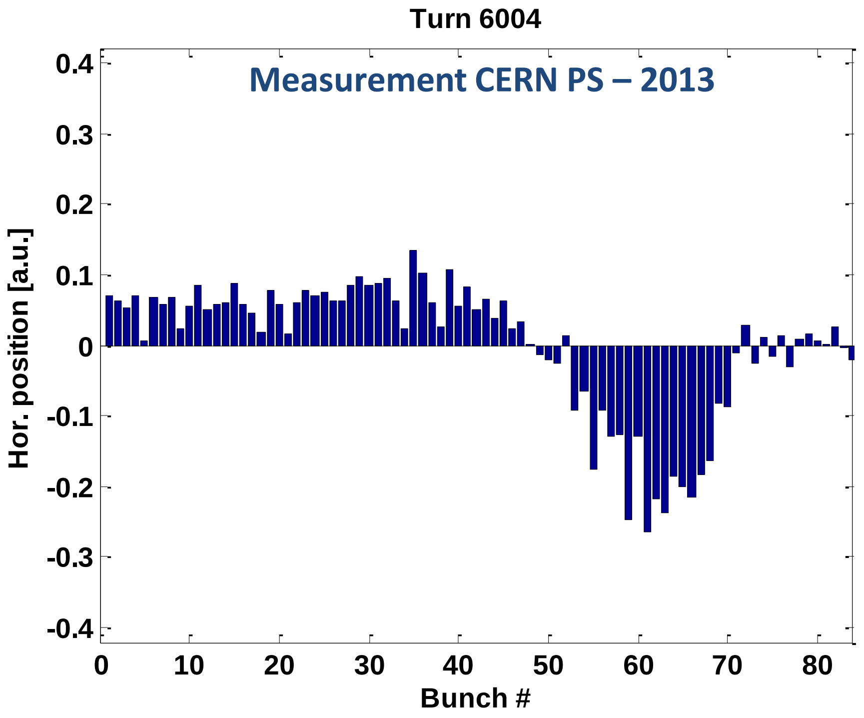

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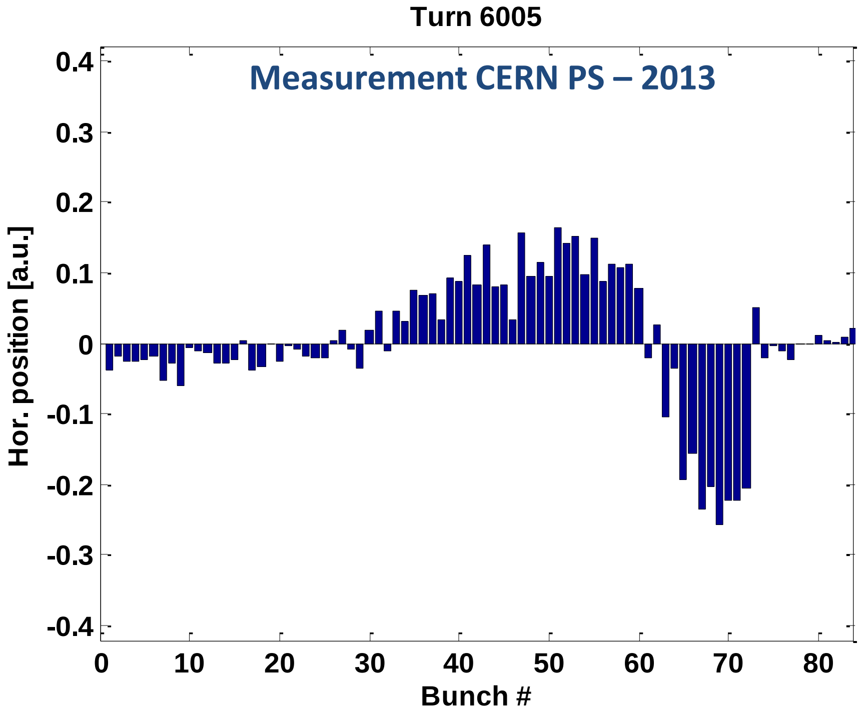

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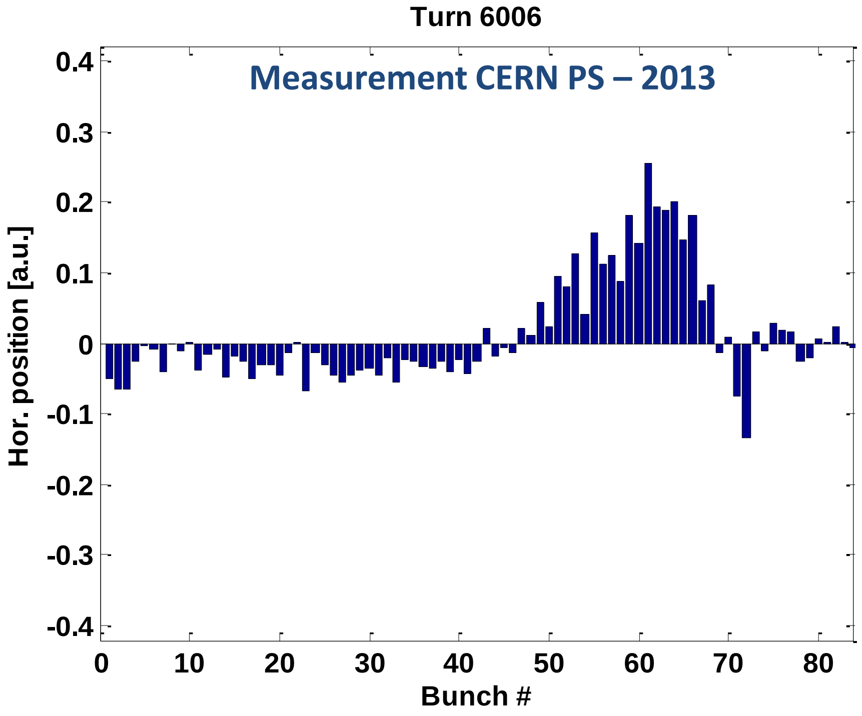

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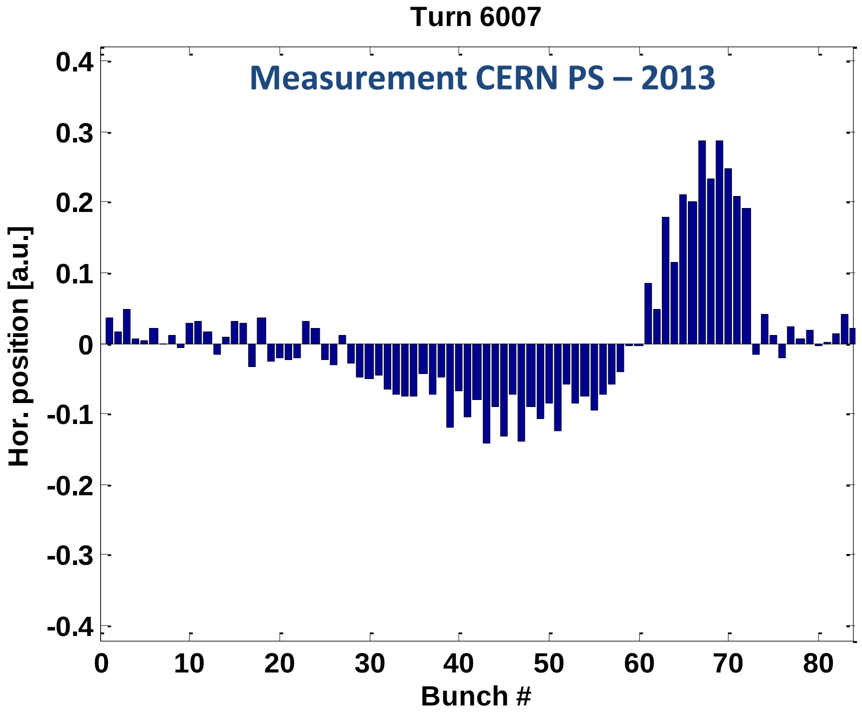

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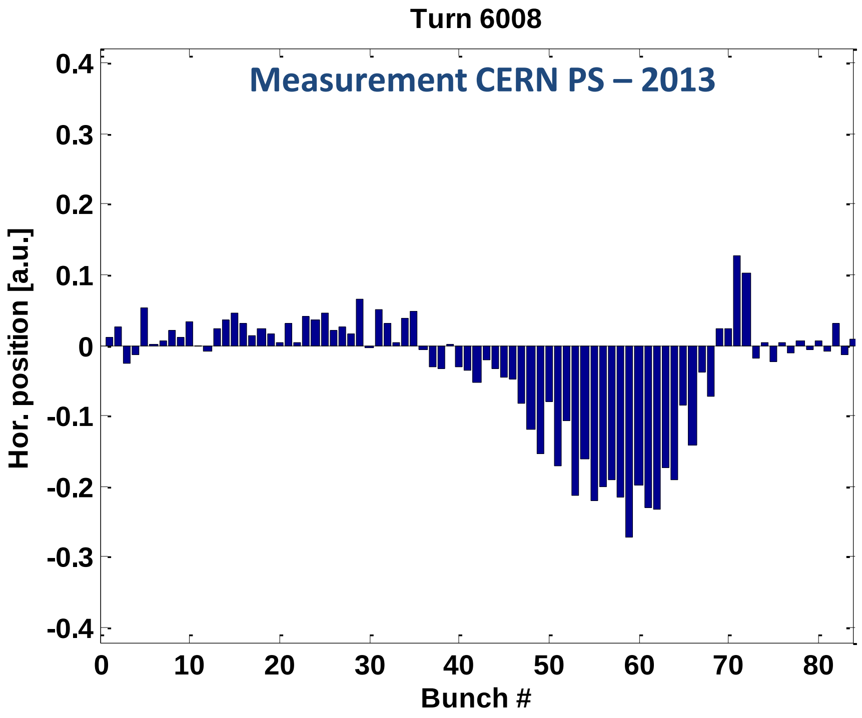
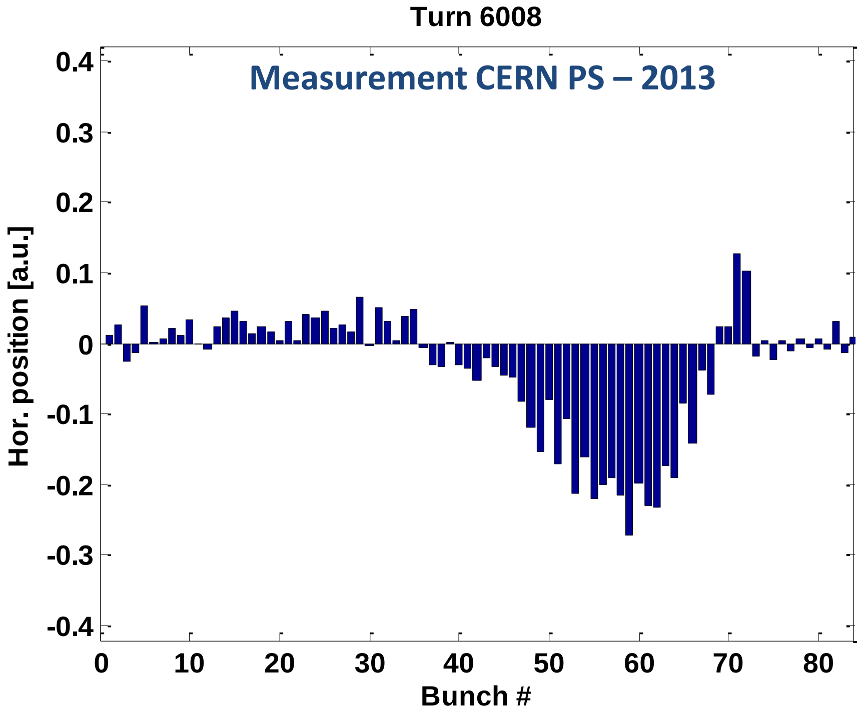


Coupled-bunch electron cloud instability

- Since the electron cloud builds up over the several bunch passage, it can also be responsible for bunch-to-bunch coupling and coupled-bunch instabilities due to transverse offsets between bunches
- Similarly to the fast beam ion instability, the coupled-bunch electron cloud instabilities can be modelled analytically with a (wake field like) cloud-beam coupling model

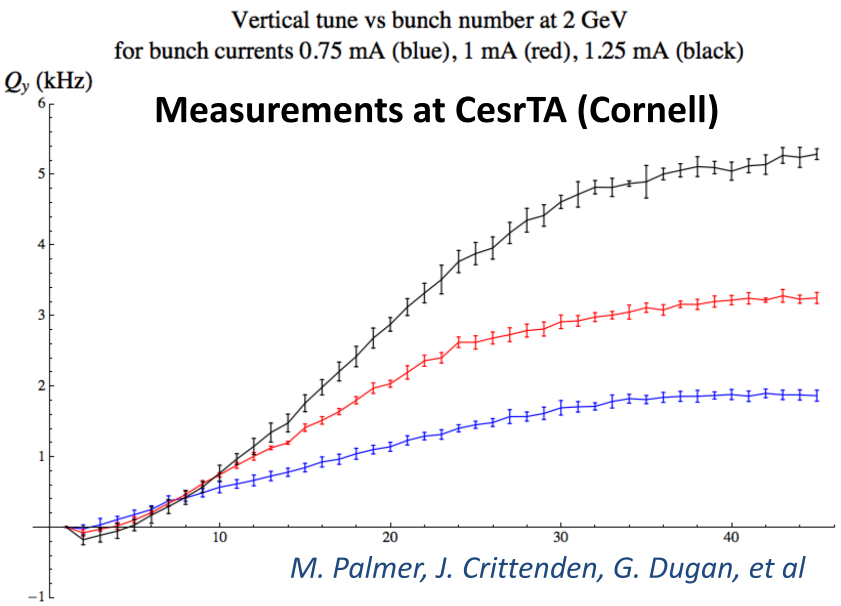


G. Arduini et al., [31st Advanced ICFA Beam Dynamics Workshop on Electron-Cloud Effects], Napa, CA, USA, 2004
S. Antipov, [Fast Transverse Beam Instability Caused by Electron Cloud Trapped in Combined Function Magnets], 2017

Additional electron cloud effects

In addition to instabilities, electron clouds can cause several other unwanted effects

- ○ Positive tune shift along the bunch train, due to defocusing by the electrons
- ○ Incoherent effects: tune spread, emittance growth, slow losses
- ○ RF stable phase shift to compensate for beam energy lost to electrons
- ○ Outgassing, pressure rise
- ○ Heat load on the chamber walls, due to the power deposited by impinging electrons
  - » Potentially problematic in superconducting machines



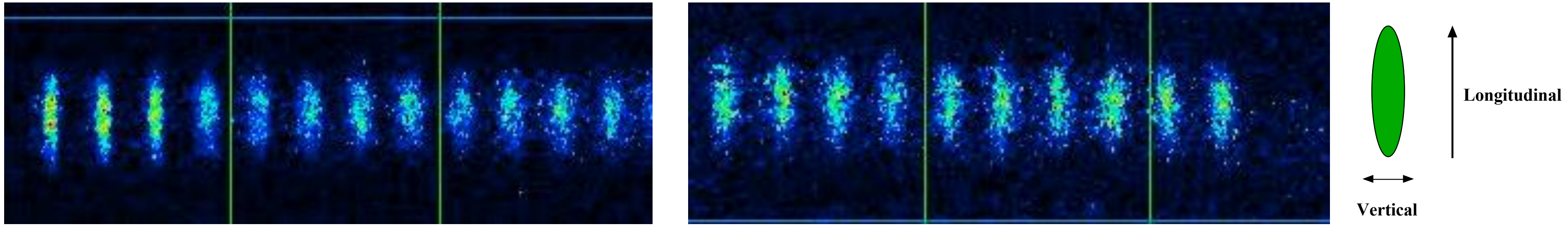
see talks by K. Ohmi, K. Paraschou, Thu afternoon for more details on coherent and incoherent effects

Electron cloud machine observations

- Electron cloud instabilities were first observed in the 60’s in Novosibirsk INP, Argonne ZGS, BNL AGS

- Since then electron cloud effects have been observed in many machines
  - CERN ISR, Bevatron,
  - Los Alamos PSR
  - CERN SPS and PS
  - KEKB, PEP-II
  - RHIC, Tevatron,
  - SNS, DaΦne,
  - ANKA, PETRA III,
  - J-PARC, Cesr-TA
  - FERMILAB recycler

Vertical emittance blow up at KEK-LER



K. Ohmi, K. Oide, F. Zimmermann, et al

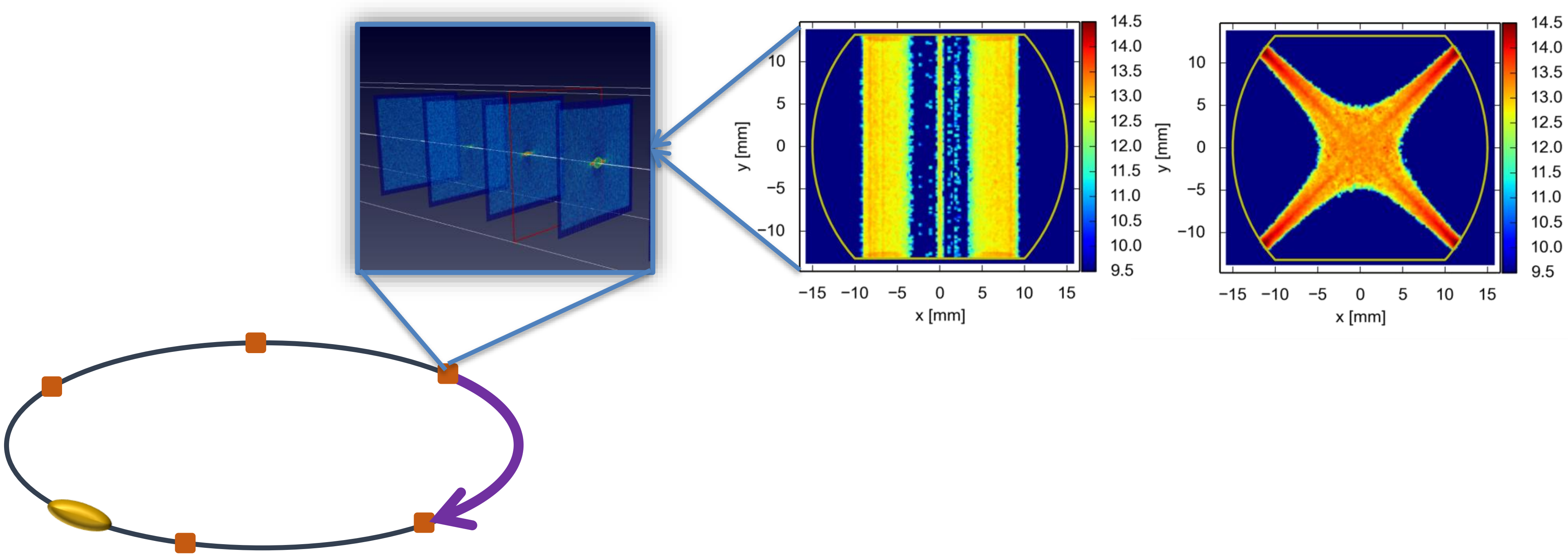
- Currently electron cloud effects are present e.g. in the LHC and at SuperKEKB

- Observations include instabilities, tune shifts along bunch train, emittance degradation, pressure rise, effects on instrumentation, heat load on cryogenic devices

Simulating e-cloud effects

Although some analytical models exist, a comprehensive understanding of electron cloud effects relies on macro-particle simulations

- For single-bunch electron cloud instabilities the problem can be divided into two parts
  - Electron cloud build-up simulations with a rigid beam
  - Single-bunch stability simulations with initial electron distribution saved from build-up simulation



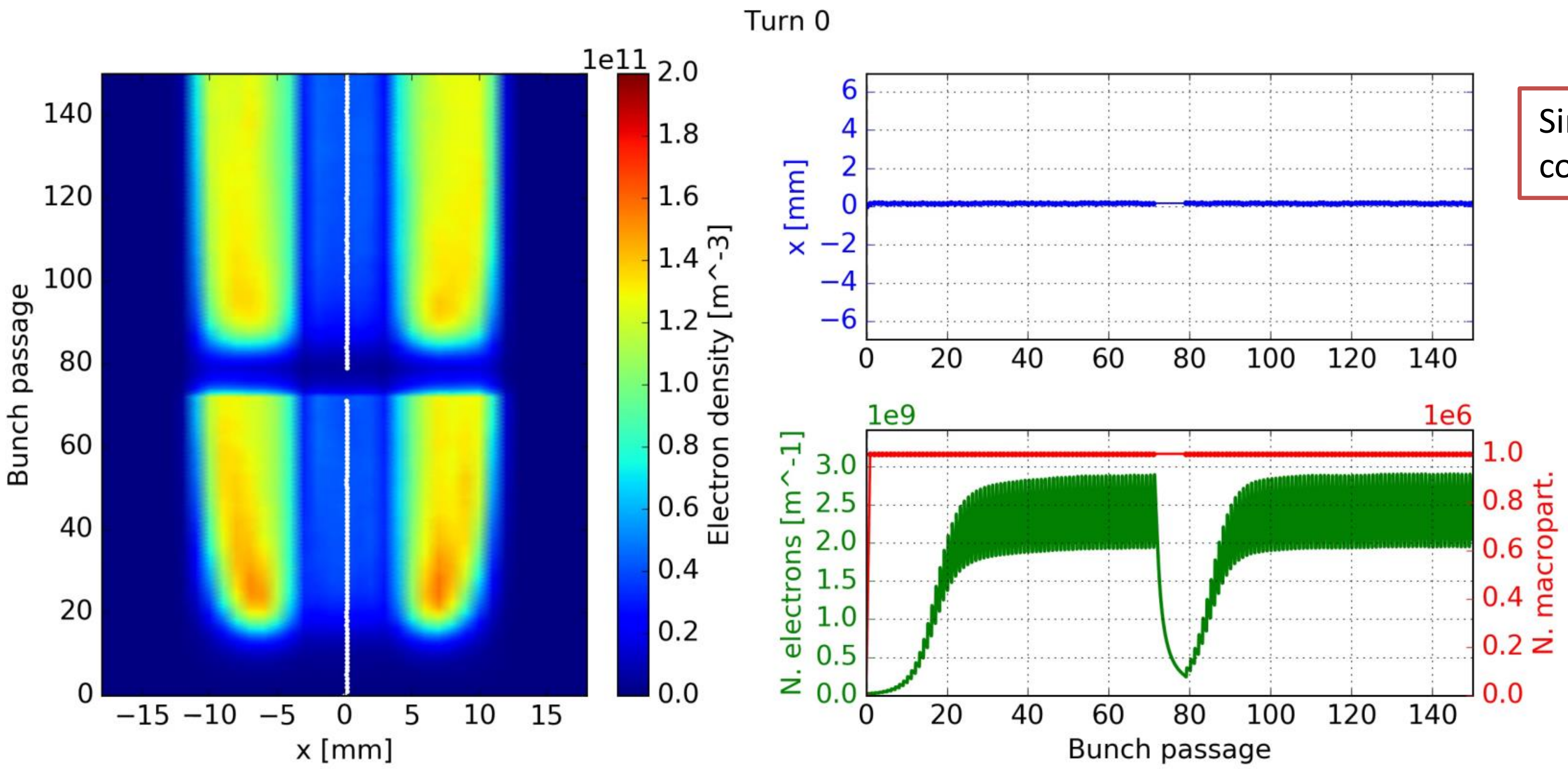
Simulating e-cloud effects

Although some analytical models exist, a comprehensive understanding of electron cloud effects relies on macro-particle simulations

- For coupled-bunch instabilities the build-up must be performed dynamically for the full bunch train to capture the instability

Simulated couple-bunch instability in LHC dipole

The same tools can be used also for studying fast beam-ion instabilities



Simulated on ~800 CPU cores over ~7 days

Simulating e-cloud effects

Full scale electron cloud simulations are computationally very heavy (and time-consuming)

- » The entire chamber must be simulated, and at the same time the small beam be resolved very well
- » The fast electron motion requires small time steps (~10^{-11} s), but the instability evolution can take several seconds

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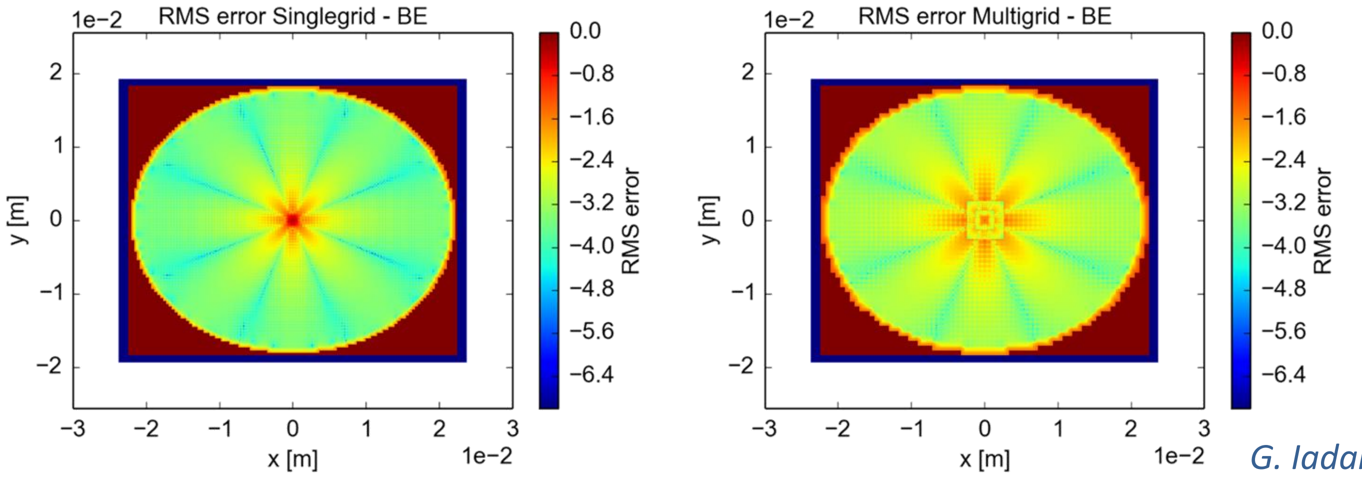
○ Benefit from advanced computational methods such as multi-grid Poisson solvers and parallel computing



G. Iadarola et al

Simulating e-cloud effects

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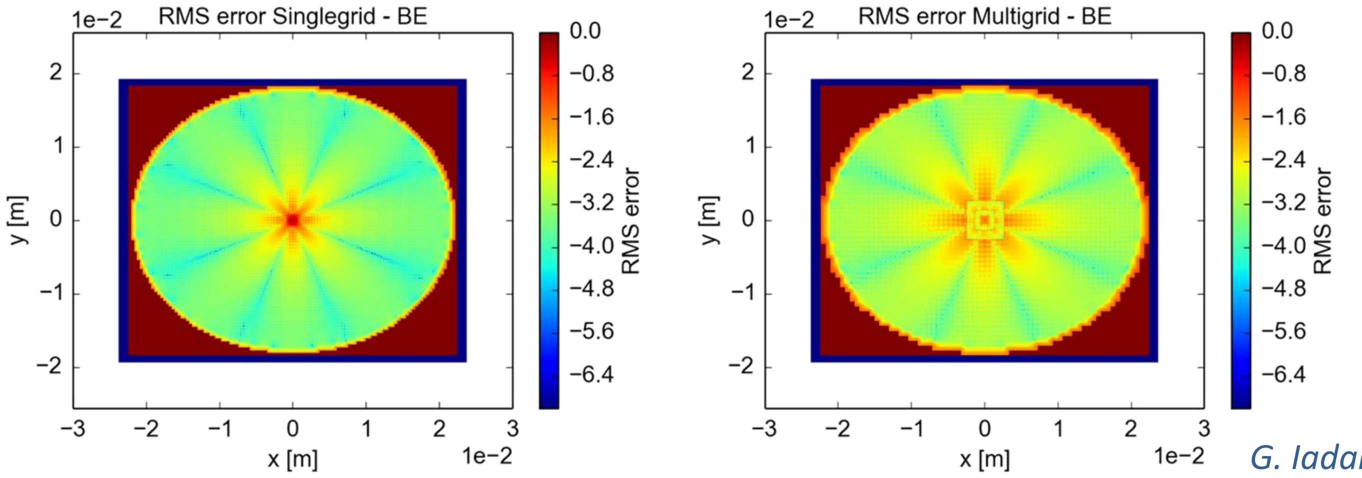


G. Iadarola et al

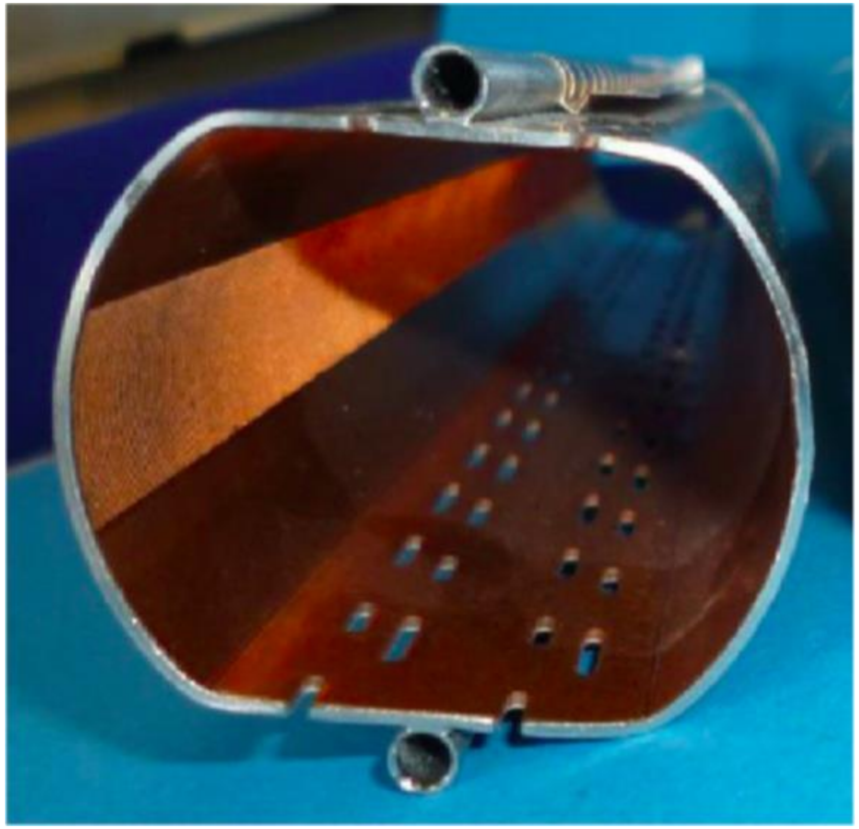
- » Due to the sequential nature of the electron cloud build-up, parallelization strategies are more limited than e.g. for simulations with impedance
- » Even with such techniques, a single simulation can require several weeks of computing time on multiple CPU cores

Mitigation strategies

Electron and ion instabilities can be mitigated by preventing the accumulation of electrons/ions

- Suppression of primary electron/ion production
  - Good vacuum – especially important for ion instabilities
  - Surfaces with low outgassing
  - Suppression of photoemission, e.g. with saw-tooth surfaces

LHC beam screen



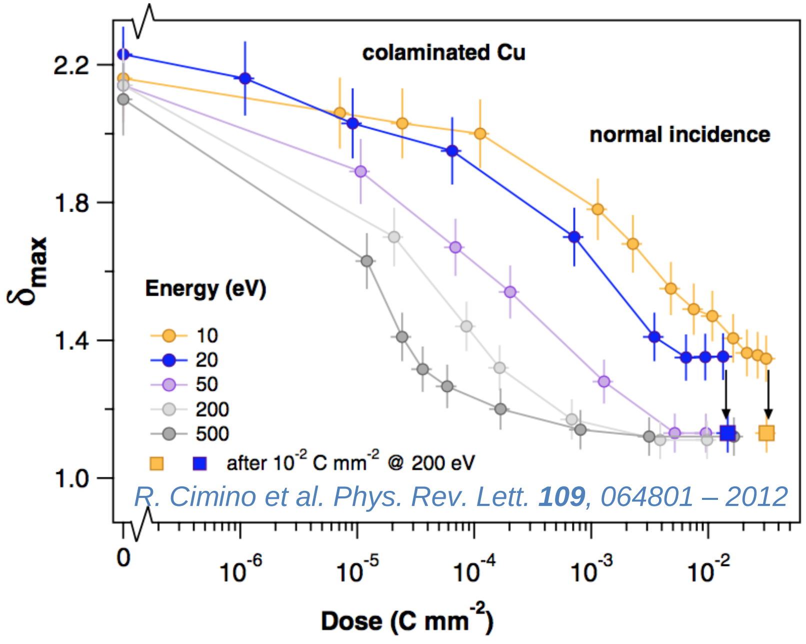
Mitigation strategies

Electron and ion instabilities can be mitigated by preventing the accumulation of electrons/ions

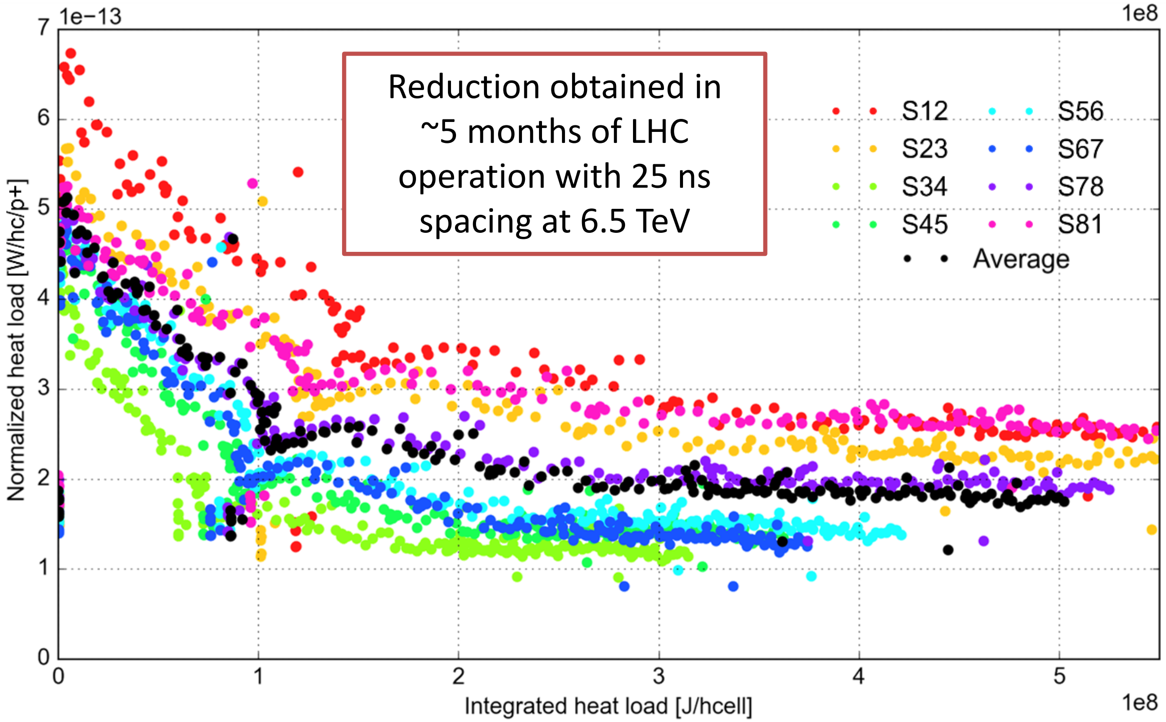
- Suppression of secondary electron emission – for electron instabilities
  - Surface conditioning with electrons (*scrubbing*) to lower SEY (reachable SEY limited)
  - Surface coating with intrinsically low SEY (price, effect on impedance)
  - Changed surface morphology: roughness, laser ablation (price, effect on impedance)

see talks by R. Cimino and O. Malyshev, Wed afternoon

Scrubbing curve



R. Cimino et al. Phys. Rev. Lett. ***109****, 064801 – 2012*

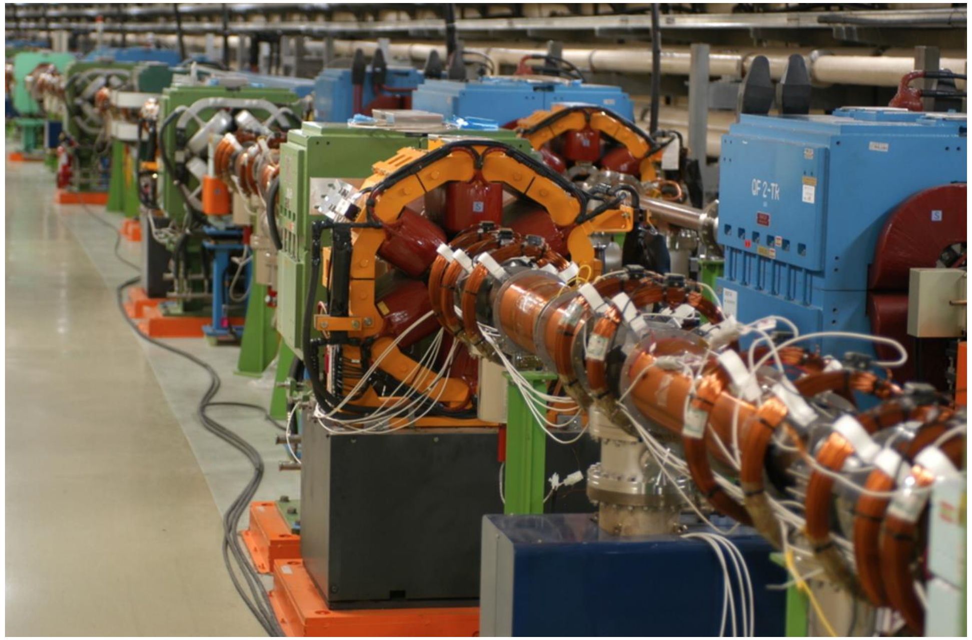


Mitigation strategies

Electron and ion instabilities can be mitigated by preventing the accumulation of electrons/ions

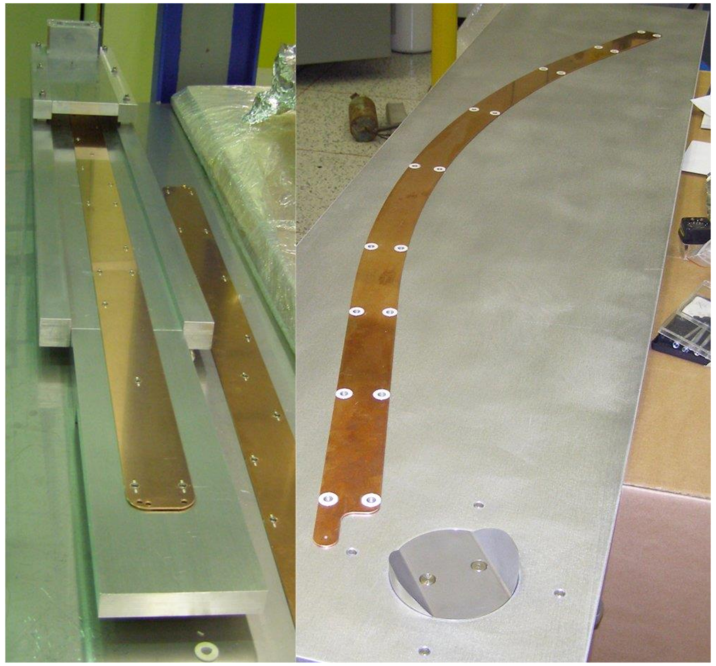
- Actively perturb electron motion:
  - Clearing electrodes (only local, effect on impedance)
  - Solenoid fields (only applicable in field-free regions)
  - Permanent magnets

Anti e-cloud solenoids at SuperKEKB



H. Koiso, Commissioning Status of High Luminosity Collider Rings for SuperKEKB, IPAC17

Cleaning electrode in the DAΦNE bending magnets



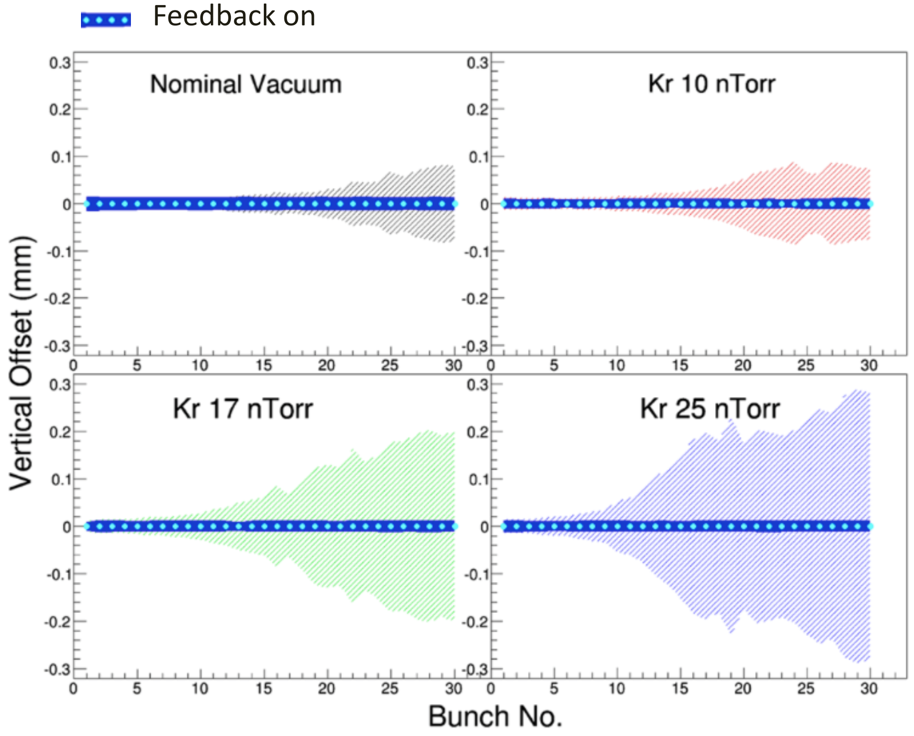
M. Zobov, "Operating Experience with Electron Cloud Clearing Electrodes at DAFNE", ECLOUD12

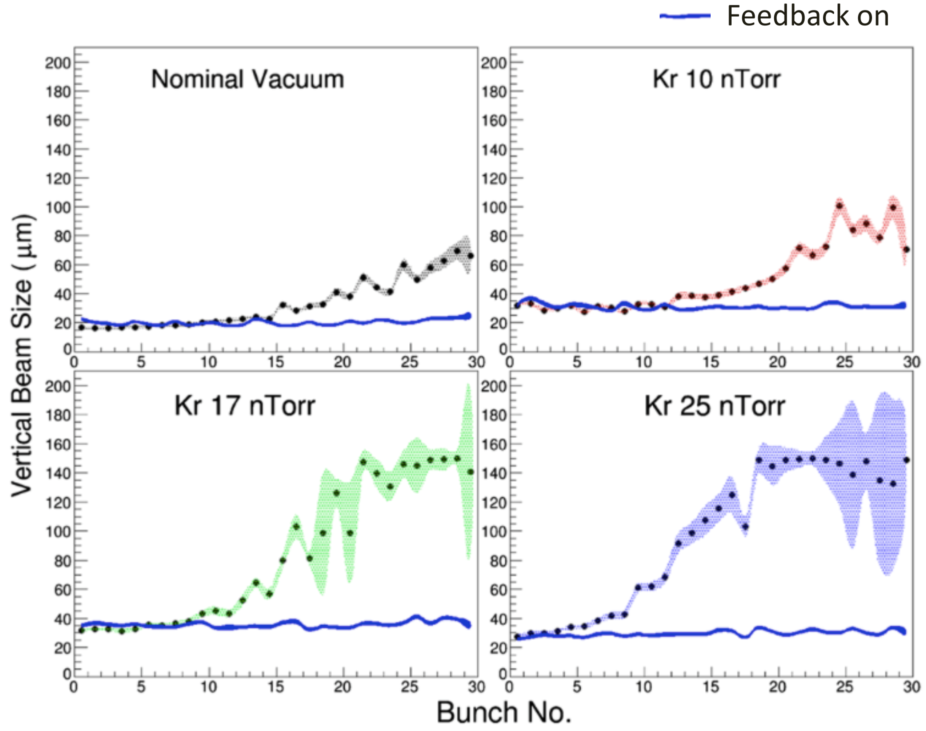
Mitigation strategies

If accumulation cannot be prevented, there are some means of addressing the resulting instabilities

- Coupled-bunch instabilities
  - A transverse feedback typically efficiently suppresses both electron and ion coupled-bunch instabilities

Measurements at Cesr-TA with injected Kr gas (Apr 2014)



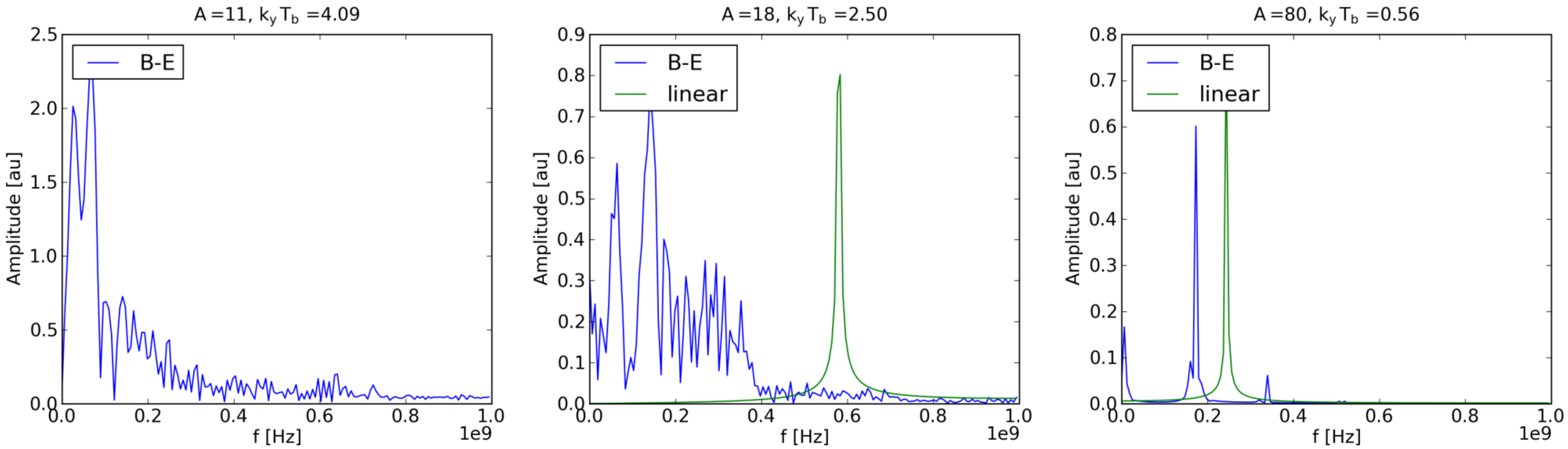


A. Chatterjee et al., Phys. Rev. ST Accel. Beams 18 (2015) 6, 064402

Mitigation strategies

If accumulation cannot be prevented, there are some means of addressing the resulting instabilities

- Coupled-bunch instabilities
  - A transverse feedback typically efficiently suppresses both electron and ion coupled-bunch instabilities
  - Landau damping can also to some extent mitigate coupled-bunch instabilities
    - For ion instabilities, a spread in the ion oscillation frequencies e.g. due to the non-linearity of the beam field and the presence of different ion species can give rise to Landau damping
      see talk by G. Stupakov, Tue afternoon

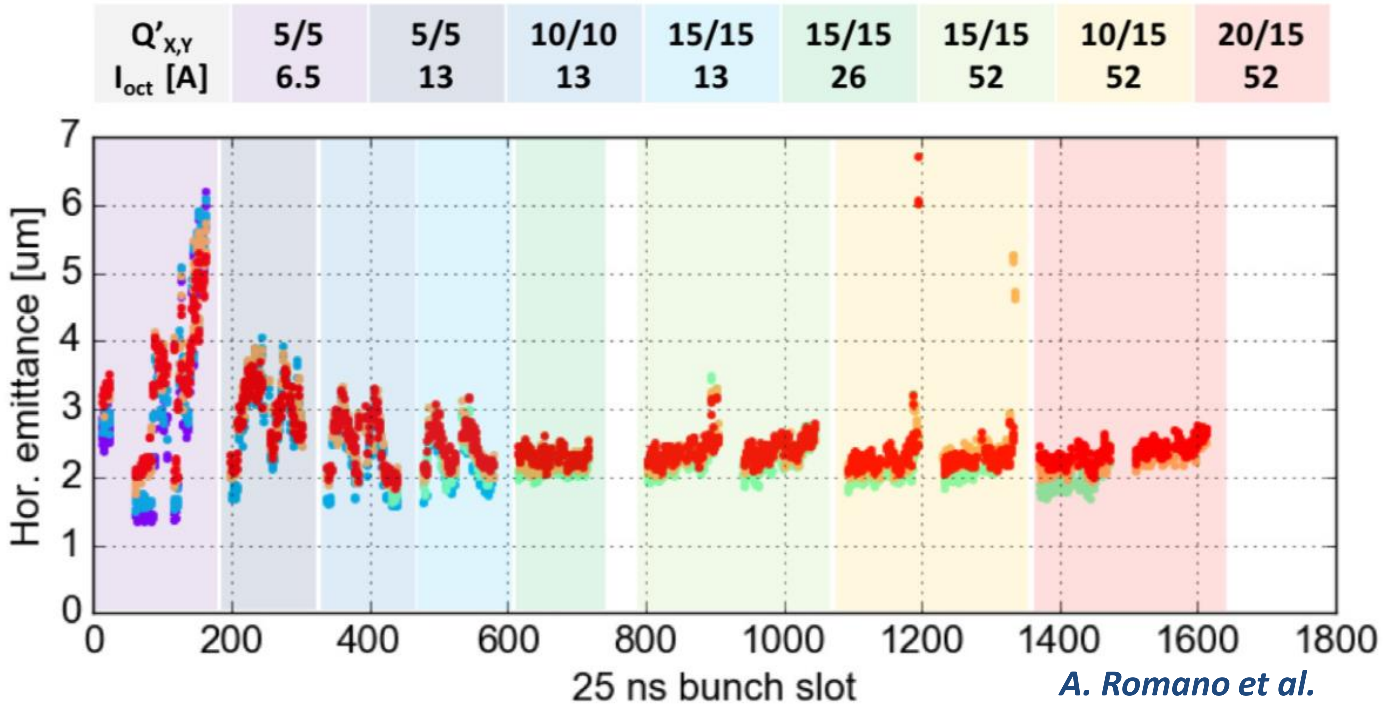


Mitigation strategies

If accumulation cannot be prevented, there are some means of addressing the resulting instabilities

- Single-bunch electron instabilities
  - Chromaticity and/or octupoles can suppress the instabilities to some extent (lifetime and emittance degradation)
  - Transverse feedbacks are typically not able to suppress these instabilities
    - A future high-bandwidth feedback could supress also the fast intra-bunch motion

Measurement at LHC

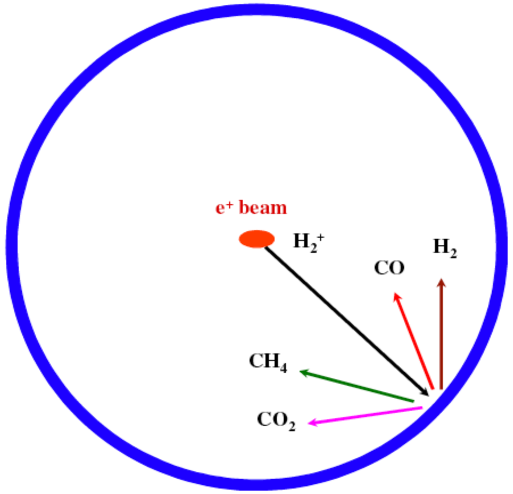


A. Romano et al.

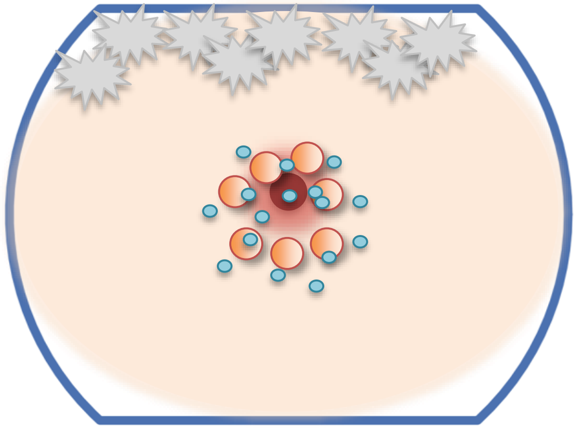
The other species

We have assumed that any seed particles charged with the same sign as the beam can be ignored, since they are repelled by the beam and and eventually reach the chamber walls – is this reasonable?

- Effects on the wall can occur
  - » Outgassing due to ions in positron/proton machines and electrons in electron machines
  - » Secondary electron emission in electron machines
- It is reasonable to ignore the second species when the amount of seeds produced by each bunch is small compared to the accumulated charge in the electron or ion cloud
  - » If this is not the case, e.g. in the case of very high gas pressures in the beam pipe, the two particle species may significantly impact each others dynamics and the beam → three-stream instability?
  - » Such a situation is thought to have occurred in the LHC during the last two years of the previous run (2017-2018)



Schematic of LHC events

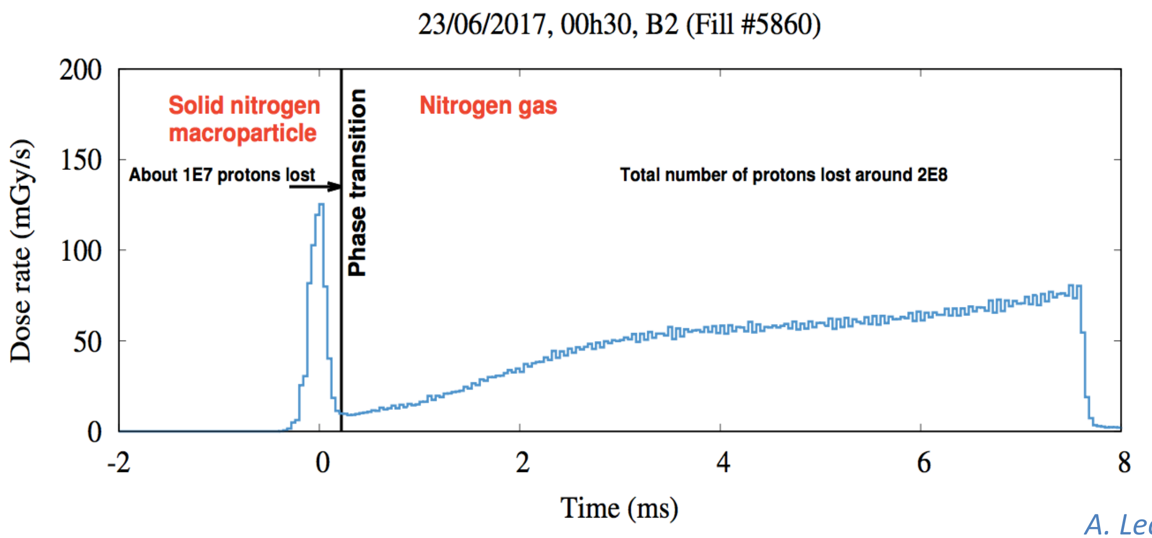


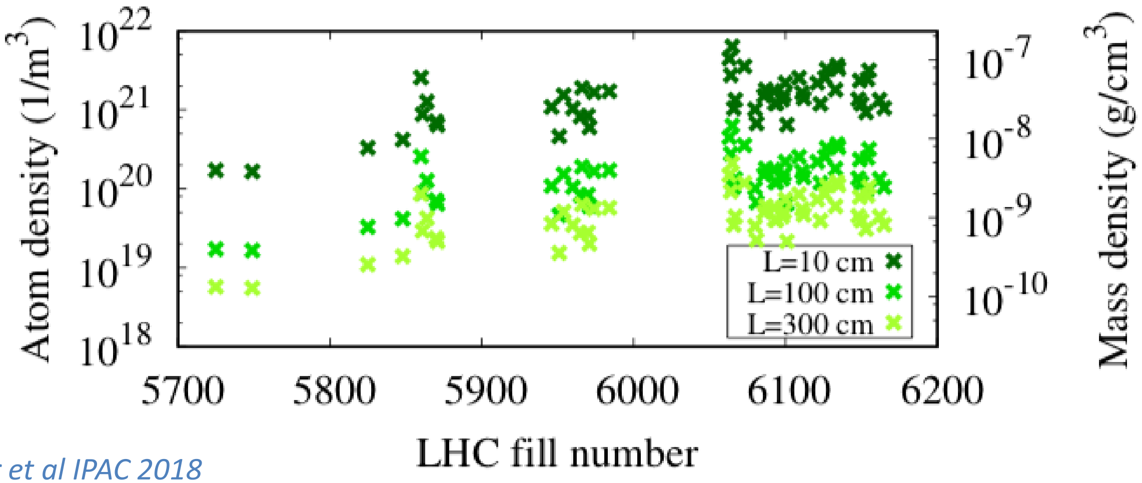
Electron-ion instability events in the LHC

The LHC events were characterized by very fast beam instabilities inevitably leading to beam dumps, which were accompanied by unusual beam losses in a certain location (16L2) of the machine

- The instabilities are thought to have been caused by a very high local gas density
  - Beam loss rates predict gas densities in the range $10^{19} – 10^{22}$ m^{-3}, depending on the longitudinal extent of the gas
  - Based on the beam loss pattern, the local pressure bump is believed to have occurred from the beam-induced phase transition of macroparticles of frozen air, present due to an air-inlet during the preceding machine cool-down

Beam losses during an LHC 16L2 event and the gas density deduced from events all in 2017





A. Lechner et al IPAC 2018

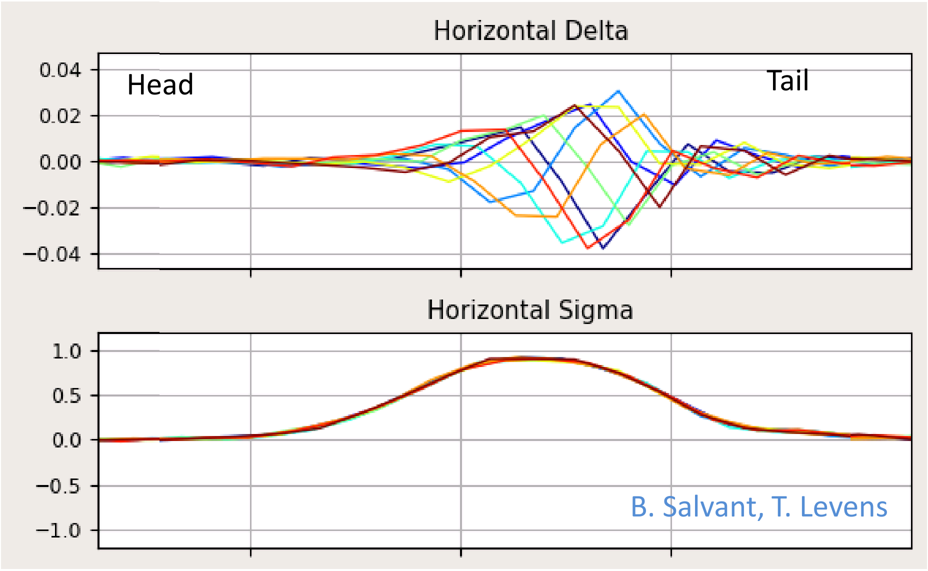
Modelling the LHC 16L2 instability events

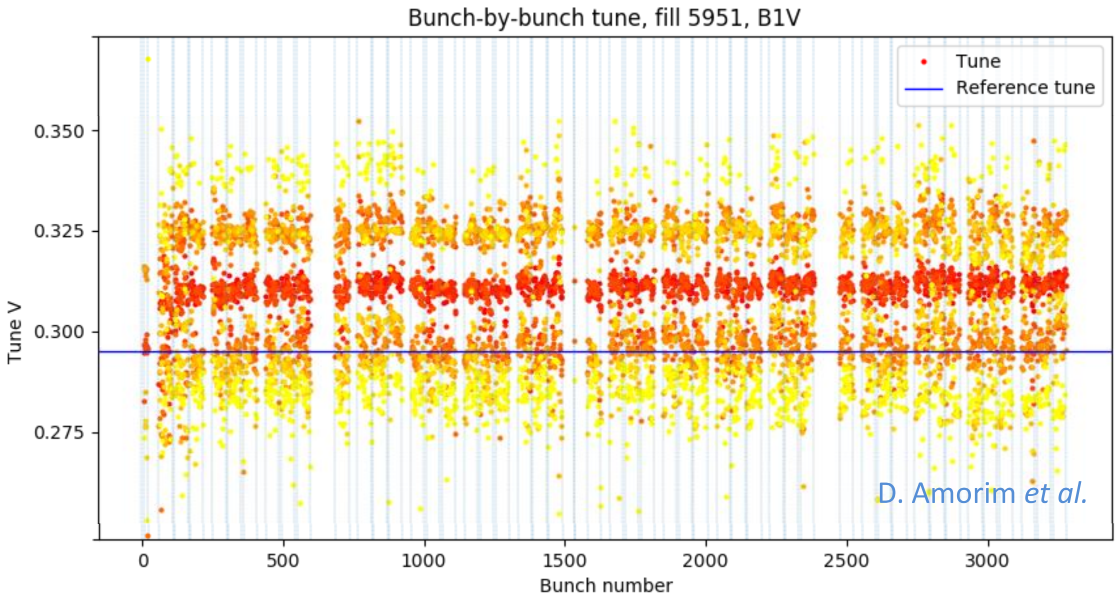
Observations of large positive tune shifts and intra-bunch motion suggest that large electron densities were present during the events

- Electron cloud simulations with high gas densities could not reproduce the observations

- To attempt to model the instability, electron cloud simulation tools were extended with multi-cloud tools to model both the build-up and beam stability with electrons and ions simultaneously

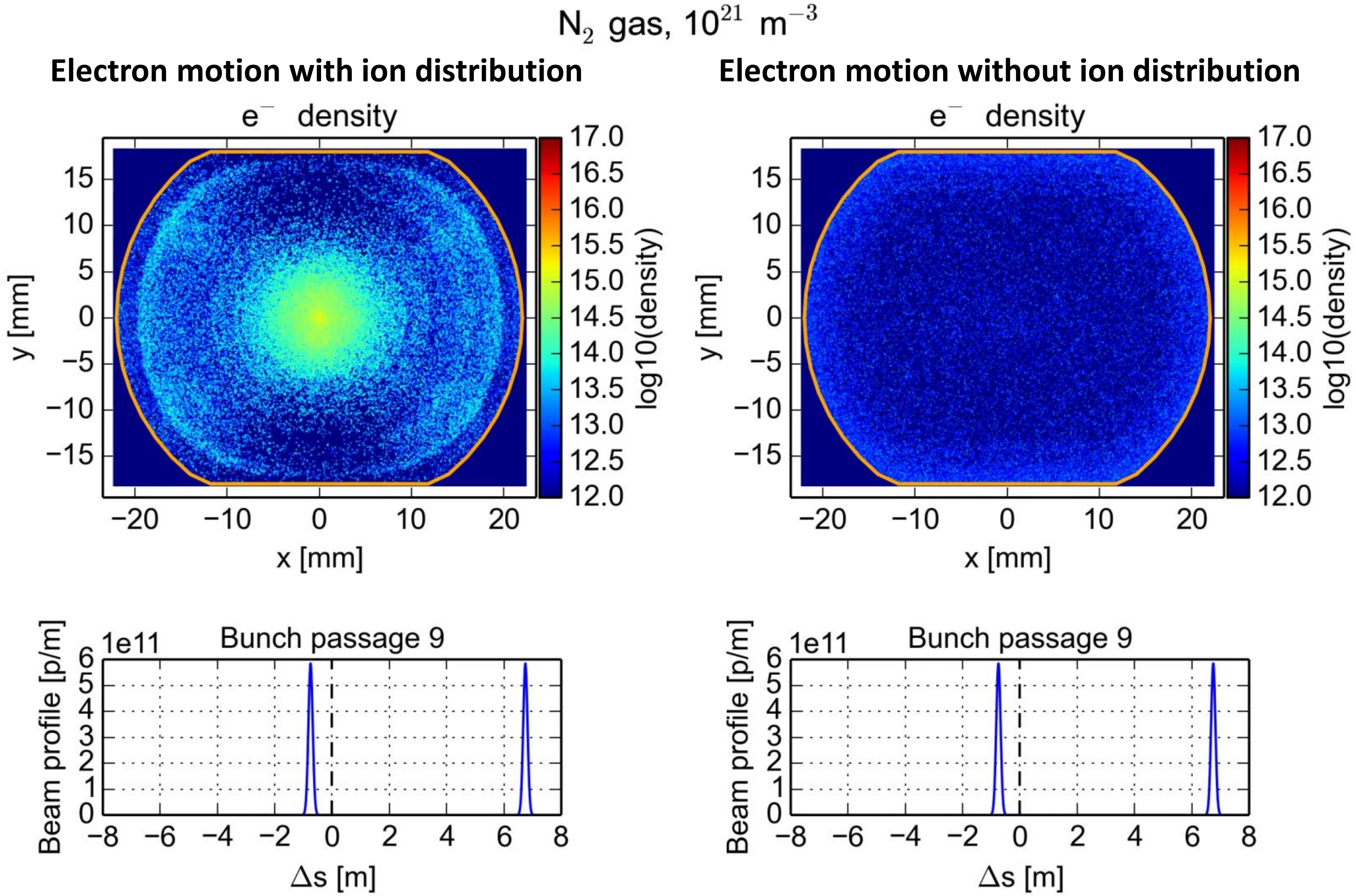
Intra-bunch motion and bunch-by-bunch tune shifts measured during LHC 16L2 events in 2017





Impact of ions on electron dynamics

Simulations with high gas densities show a significant impact on the electron dynamics, when the field of the ion population in the beam chamber is taken into account → in this particular case the ions in the chamber cannot be ignored!



Summary

- Electron and ion instabilities have been observed in both running and past machines
  - Electron cloud is commonly present in several operating machines
  - Ion instabilities are observed mainly under vacuum degradation, but may become more prevalent in future machines with higher brightness

- Detailed modelling tools are readily available
  - Several analytical models have been developed, in particular for coupled-bunch instabilities
  - Macro-particle simulations can model the phenomena comprehensively using modern computational tools, but large amounts of computing time and resources are still needed for realistic simulations

- Predictions and development of mitigation strategies are important
  - For electron cloud, the development and implementation of mitigation strategies are needed for several on-going as well as future projects
  - For ion instabilities accurate studies are needed to assess their impact in future machines

- An instability mechanism relying on the interplay between electron and ions is possible under certain conditions and has (most likely) been observed in the LHC