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Electron-ion dynamics and fast instabilities in the LHC

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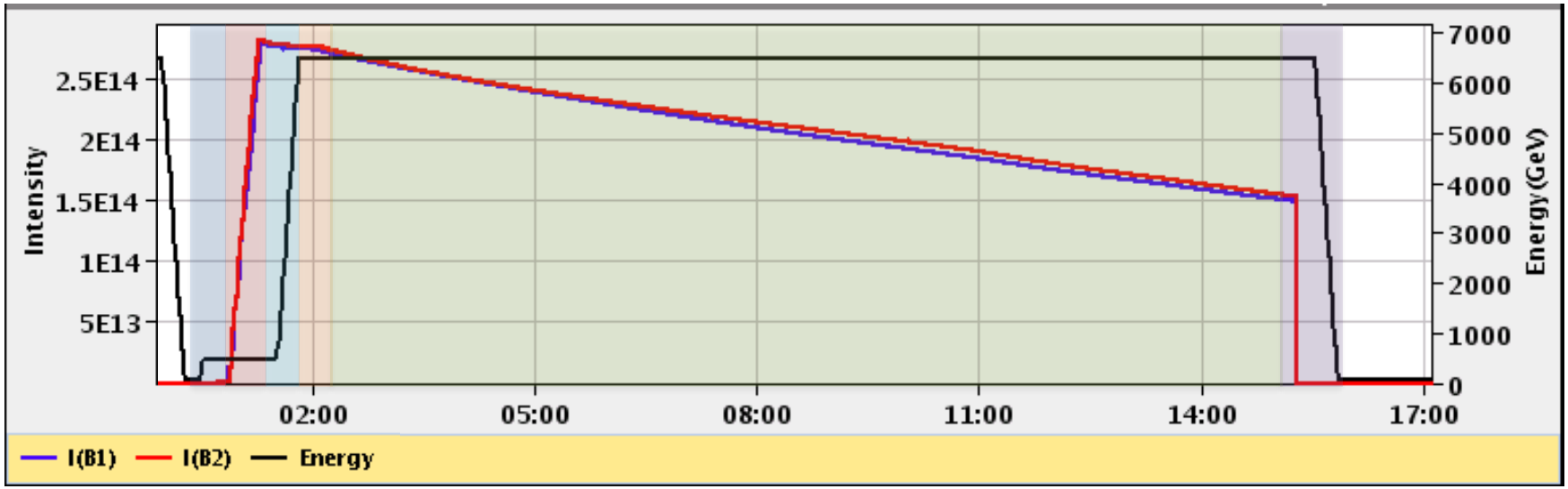
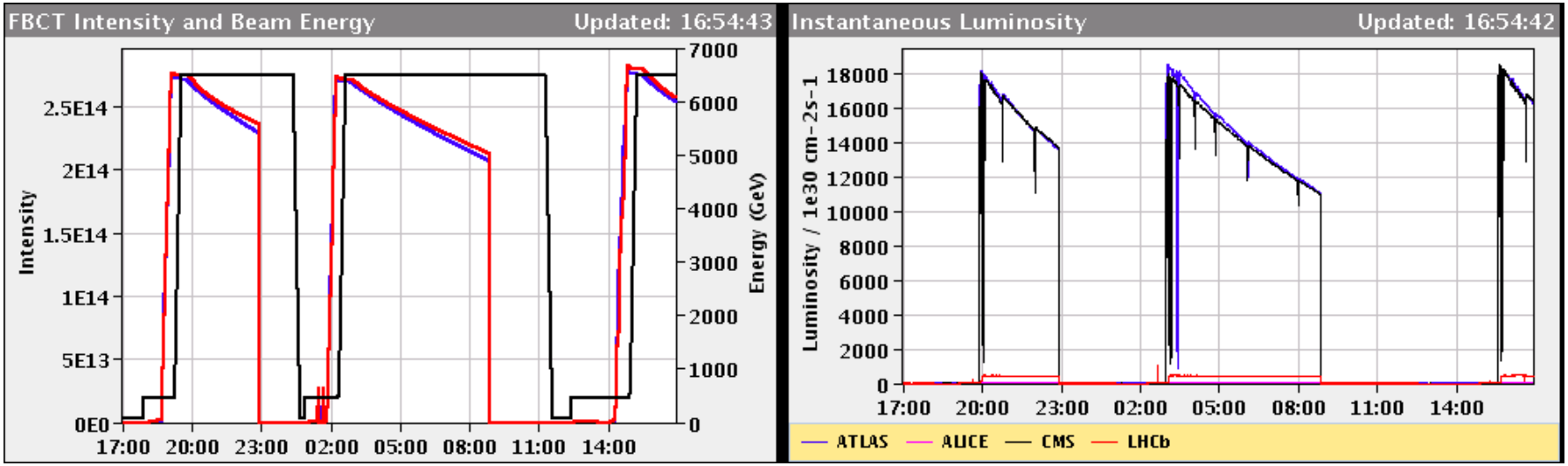
The LHC fill cycle

- The machine is prepared for injection
- The two rings are filled with around 2600 bunches
- The magnets are ramped and the beams are accelerated to the collision energy
- The beams are focused and their separation is decreased until the beams are brought into collision
- For optimal luminosity production, the beams stay in collision for around 12-14 hours
- The beams are dumped, the magnets are ramped down and the cycle starts over
- **Ideally, it takes 2-3 hours after a beam dump until collisions can start again**



Beam dumps

- Sometimes the beams have to be dumped prematurely to protect the machine
  - » Potentially resulting in several hours of overhead without luminosity production before the beams can be brought into collision again



Beam dumps

- Sometimes the beams have to be dumped prematurely to protect the machine
  - » In case of a problem with a crucial hardware or software

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Comments (29-Aug-2018 18:16:47)
        Dumped by an electrical perturbation.
        At least 5 hours before restart.
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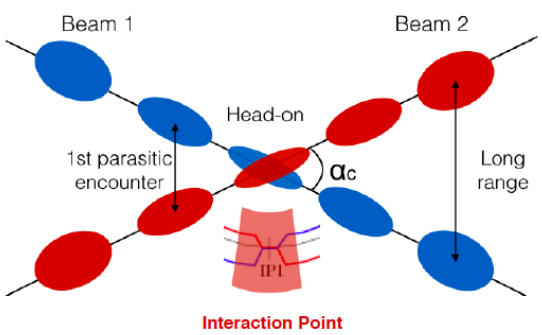
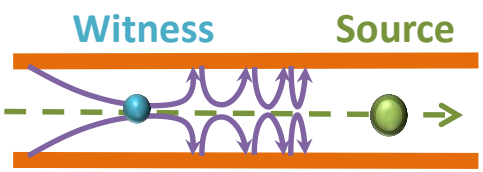
  - » In case of beam instabilities: the beam oscillating with growing amplitude
    - Can be (partially) mitigated with chromaticity, Landau damping from octupole magnets and a feedback system

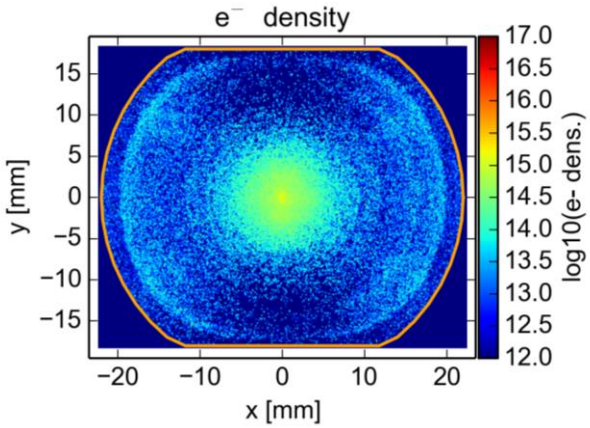
Beam-beam



Wake fields & impedance

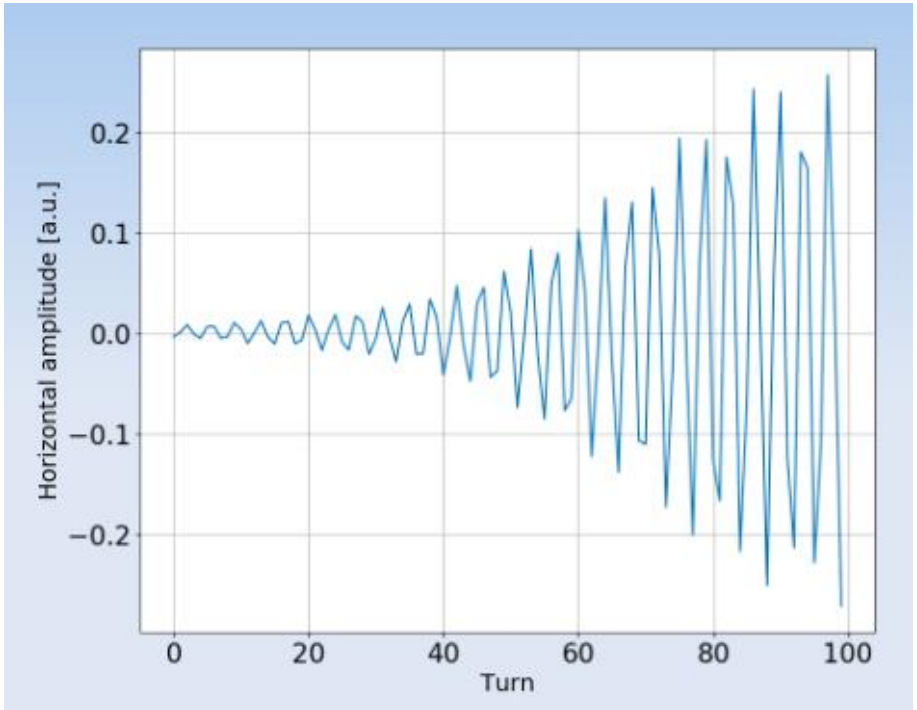


Electron cloud



Fast instabilities

- In 2017 a new type of instabilities were observed in the LHC
  - » The instabilities are very fast and violent, usually leading to beam dumps in less than 100 turns after their onset
  - » It is not possible to prevent the instabilities with any usual mitigation strategies, such as octupole magnets or transverse feedback



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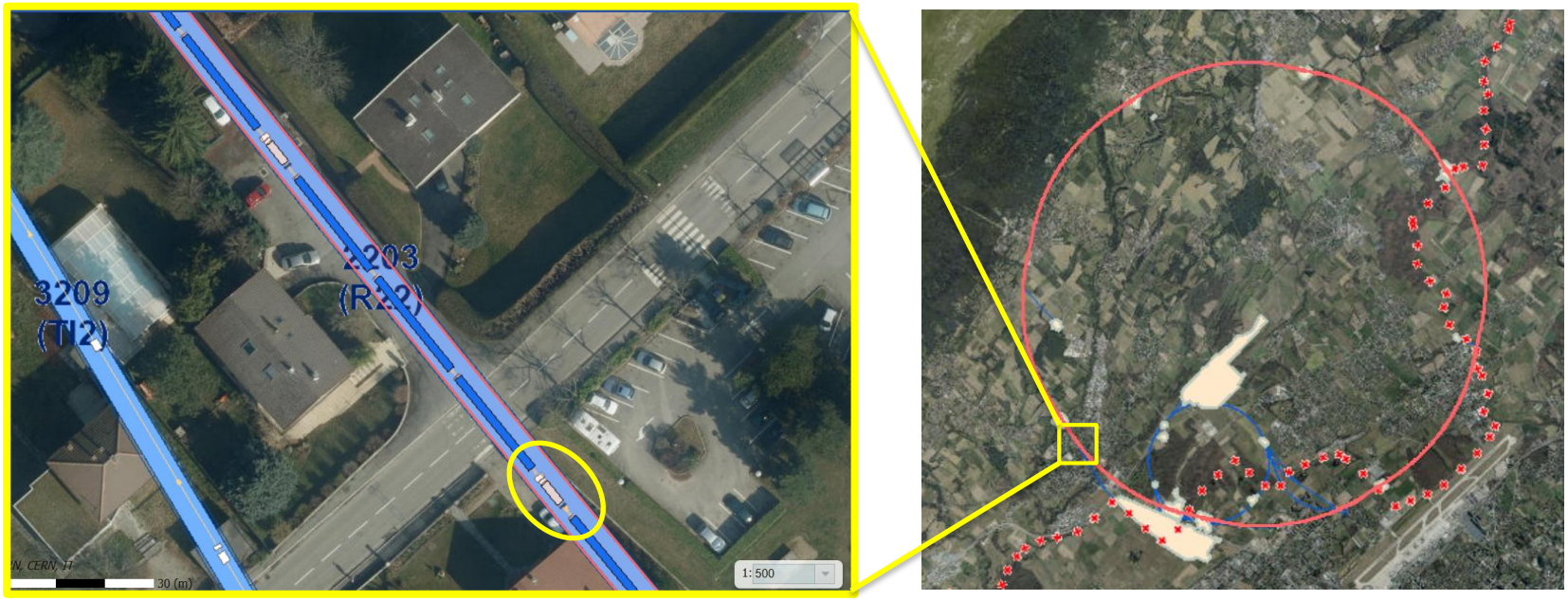
  - » The instabilities are associated with an unusual pattern of beam losses observed in the beam loss monitors in a specific location of the LHC: 16L2



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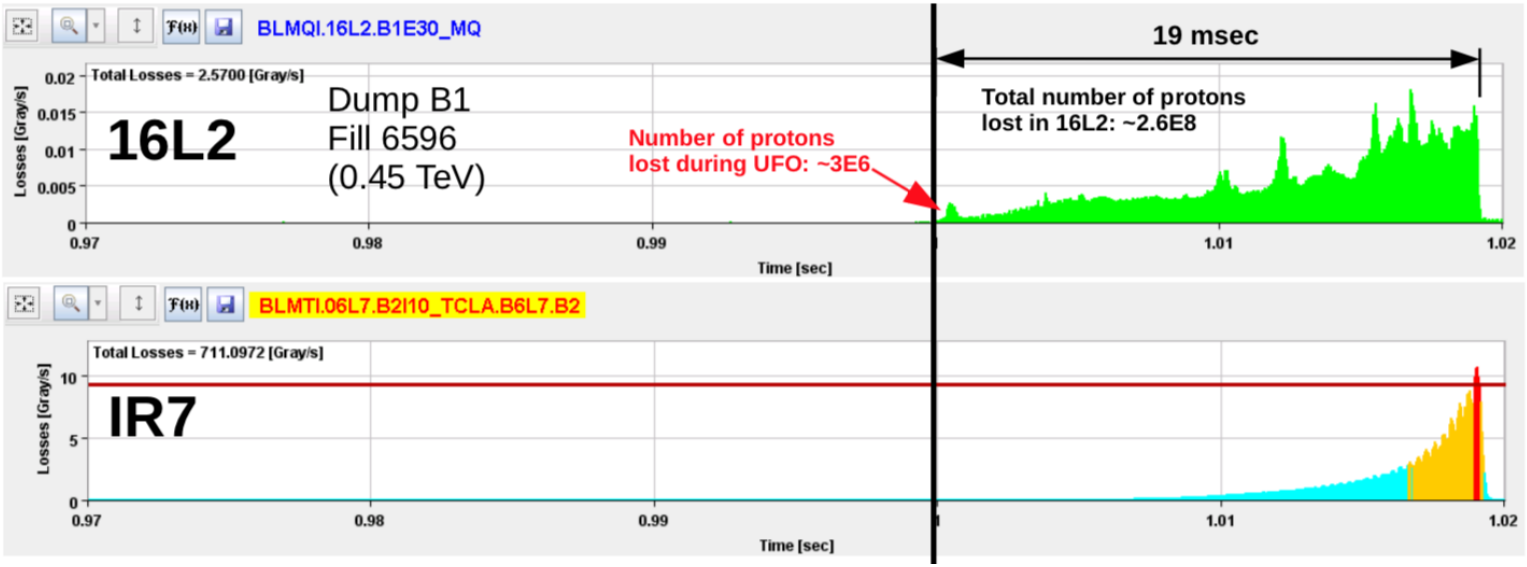

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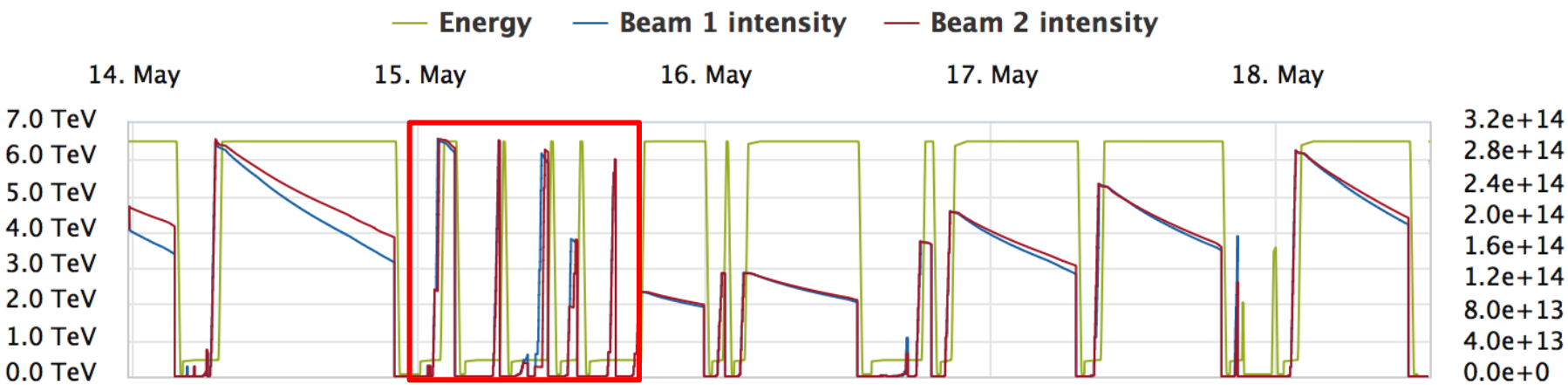
  - » The instabilities are associated with an unusual pattern of beam losses observed in the beam loss monitors in a specific location of the LHC: 16L2
  - » In 2017, they often occurred before collisions had been started and in several consecutive fills, with a significant impact on luminosity production



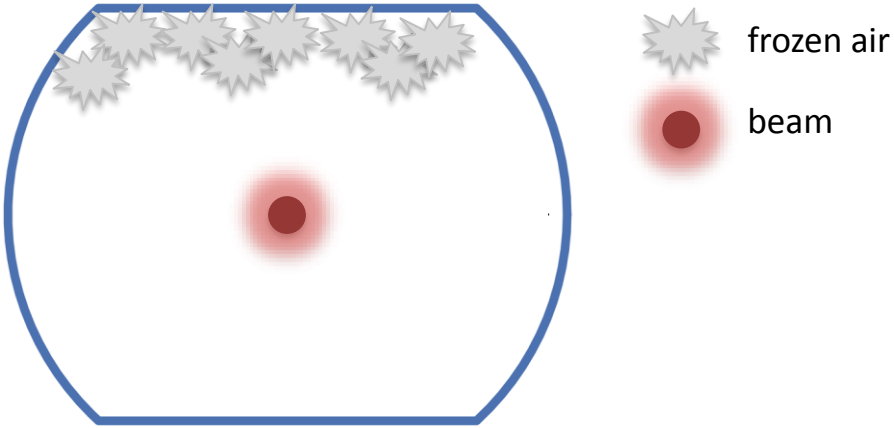
Identifying the cause

- Several considerations pointed to the events being related to a vacuum issue
  - » e.g. the beam losses imply that the beam is interacting with something, however no aperture restriction could be observed in the location
    → interaction with a gas?

- It was understood that some air entered the beam vacuum pipe during the preceding cool-down of the machine
  - » However, in the beam chamber where the temperature is 5 – 20 K, the gas is frozen onto the chamber walls
  - » The frozen gas is thought to give rise to the fast instabilities through a complex sequence of events…

https://www.youtube.com/watch?v=c0rK2bLTimQ

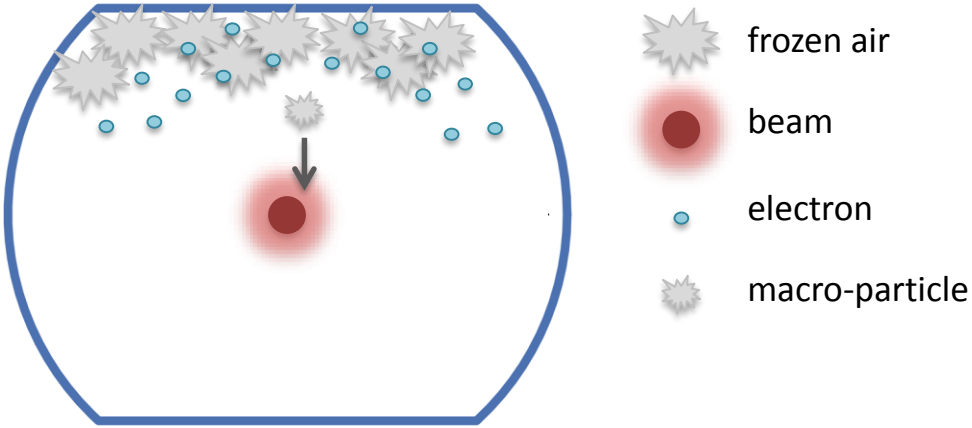
Sequence of events in 16L2



NB! Schematic, not to scale

Sequence of events in 16L2

A macro-particle of frozen air (N_2, O_2) is detached, possibly triggered by e-cloud



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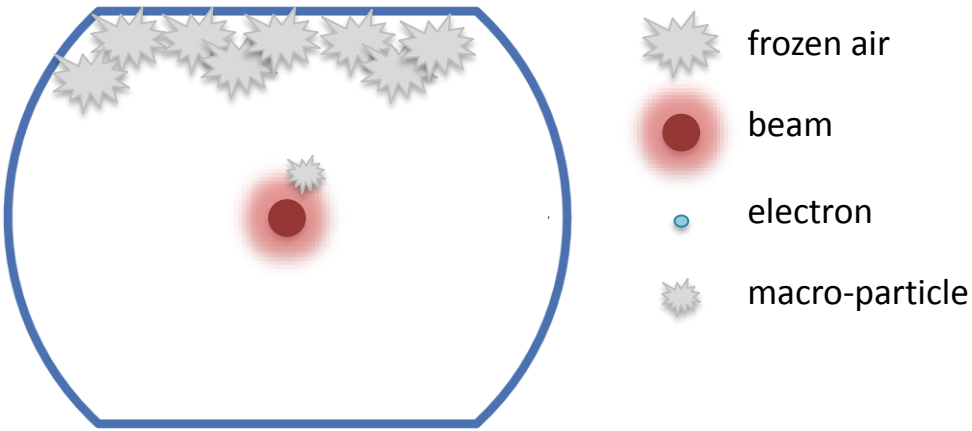
Sequence of events in 16L2

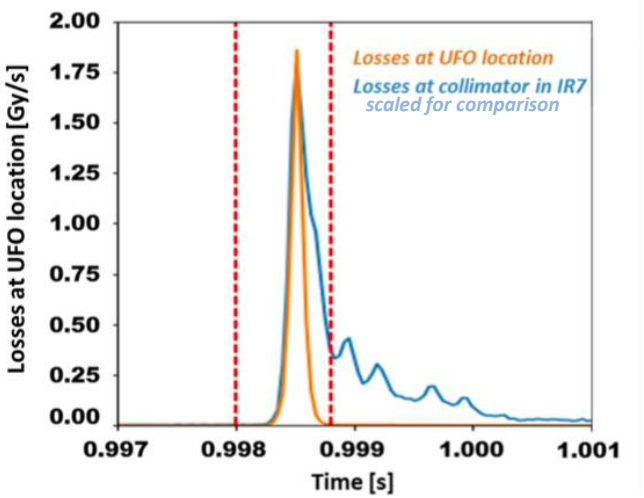
A macro-particle of frozen air (N_2, O_2) is detached, possibly triggered by e-cloud, and enters the beam



Such "UFO" events occur regularly in the LHC:

1. A macroparticle enters the beam halo
2. The particle becomes ionized by the beam protons
3. The positively charged macroparticle is repelled by the beam

- The events show a characteristic beam loss pattern
- Can lead to beam dumps or magnet quenches
- Do not cause coherent motion



L. Grob et al IPAC 2018

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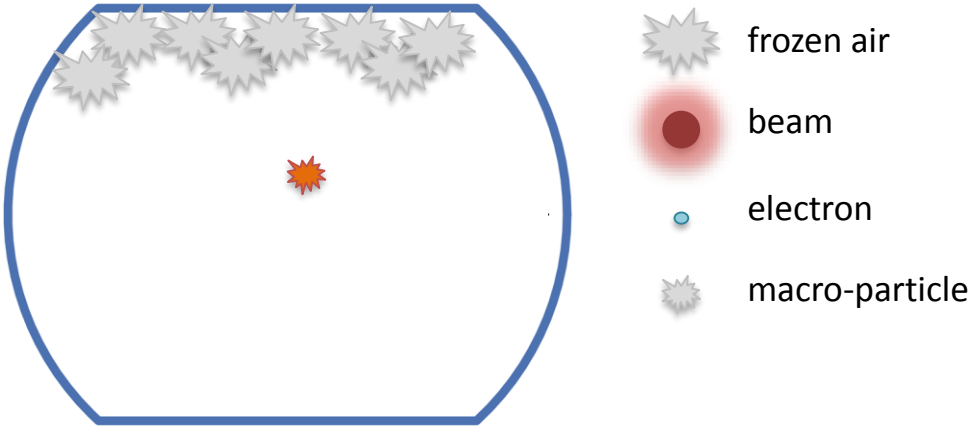
The macro-particle undergoes a phase transition to a gas



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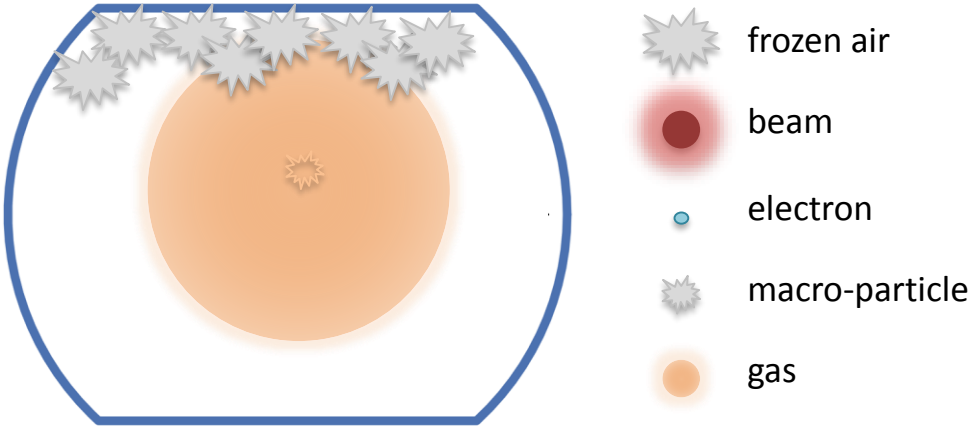
Sequence of events in 16L2

A macro-particle of frozen air (N_2, O_2) is detached, possibly triggered by e-cloud, and enters the beam

The macro-particle undergoes a phase transition to a gas, leading to a high local gas density



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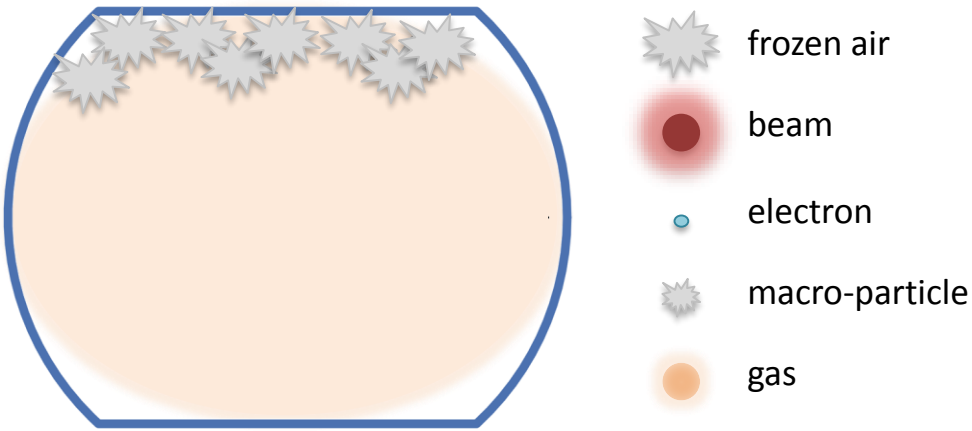
Sequence of events in 16L2

A macro-particle of frozen air (N_2, O_2) is detached, possibly triggered by e-cloud, and enters the beam

↓

The macro-particle undergoes a phase transition to a gas, leading to a high local gas density of 10^{19} – 10^{22} atoms/m^3



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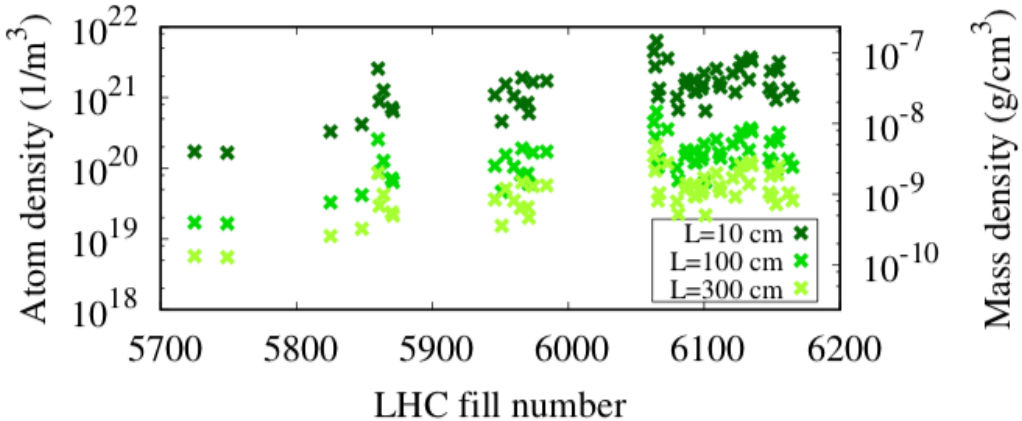

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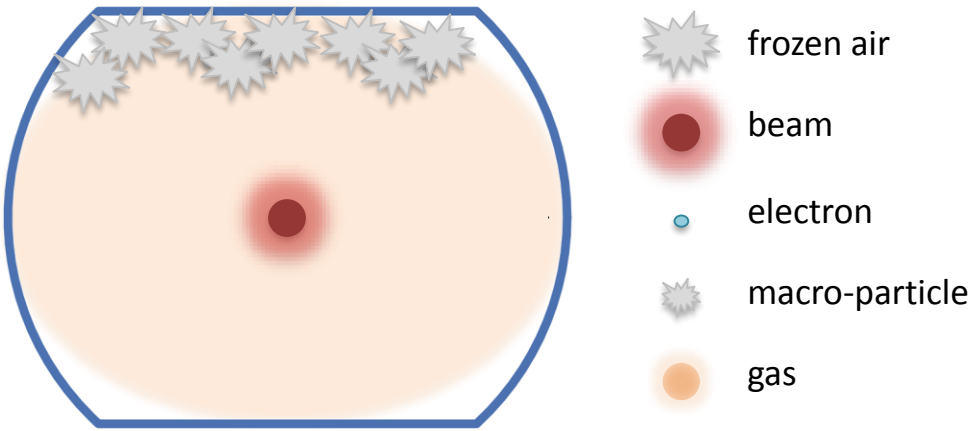
The beam ionizes some of the gas in its path



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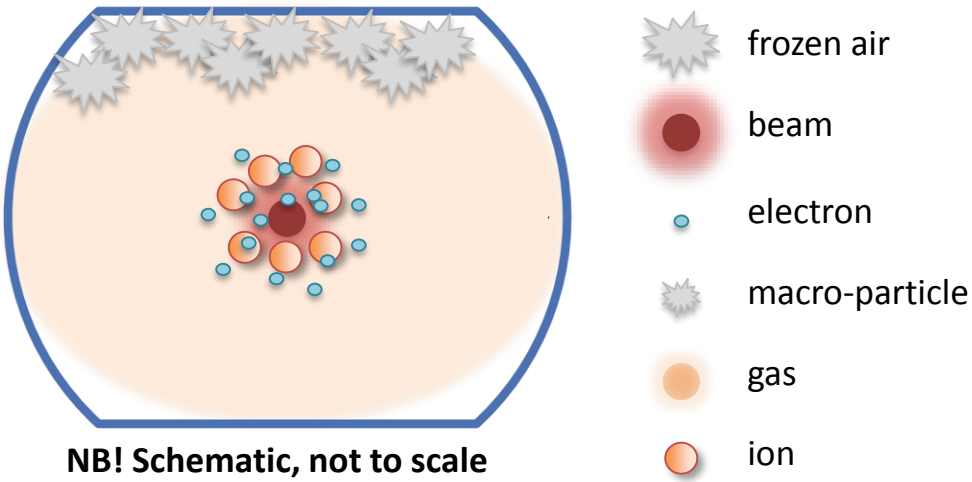

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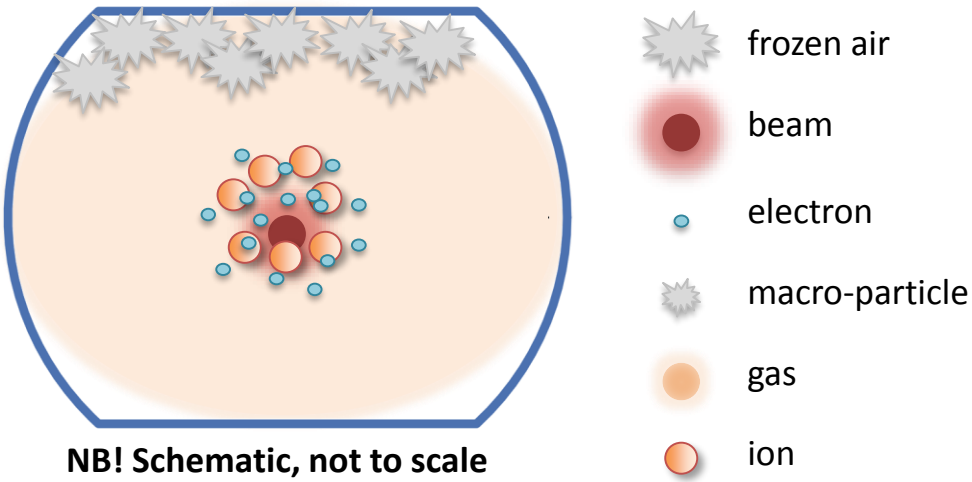
The beam ionizes some of the gas in its path. Its interaction with the generated electrons/ions causes the fast instabilities



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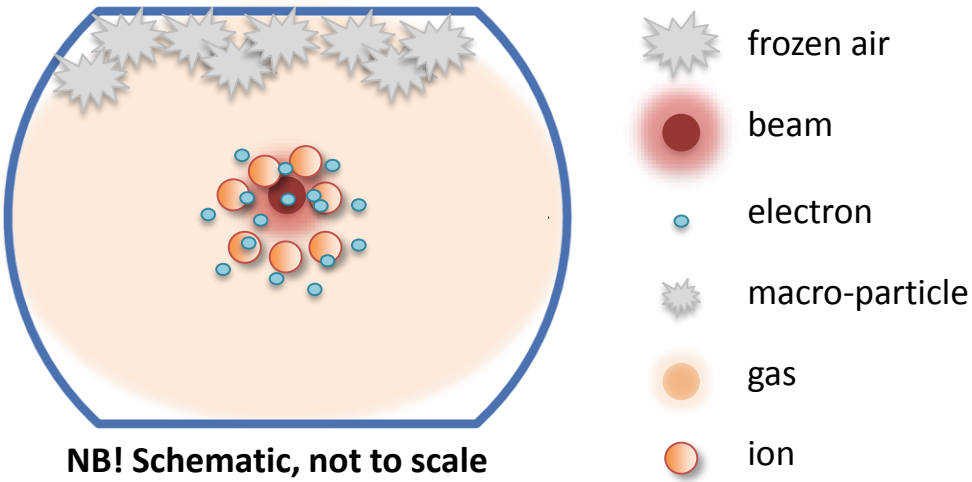

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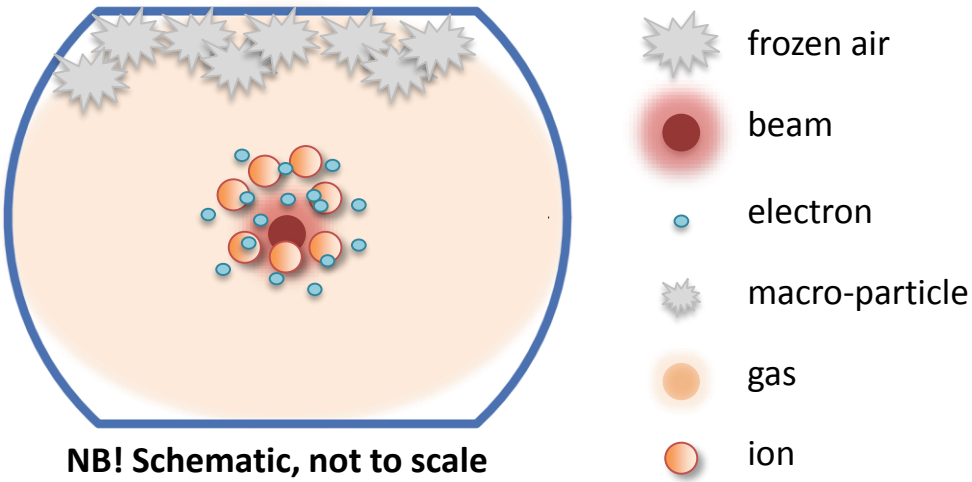

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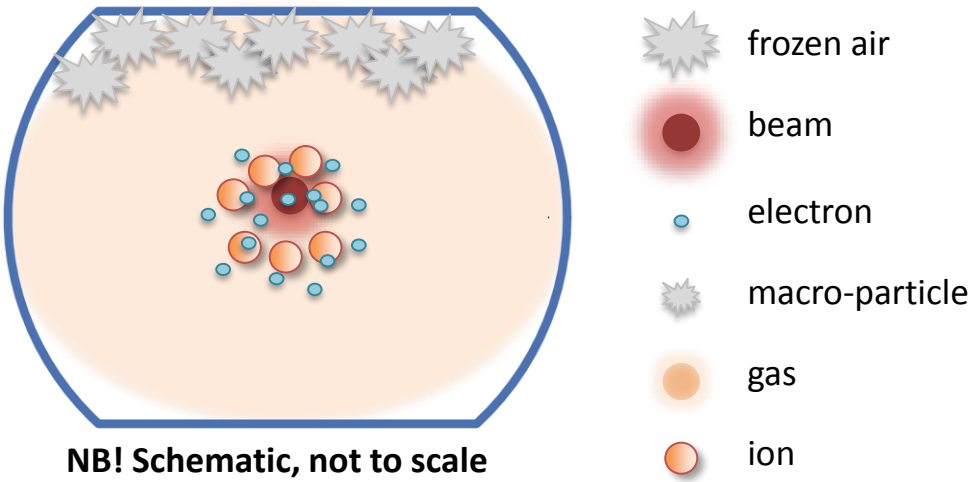

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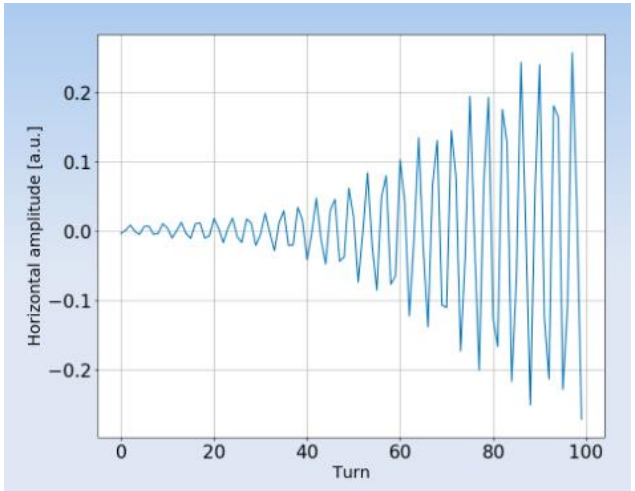

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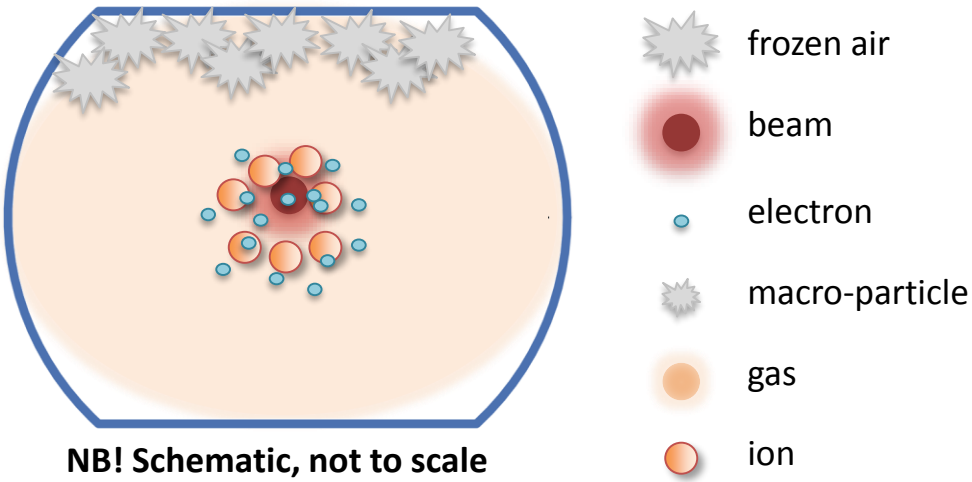


NB! Schematic, not to scale

To be sure that we have understood the problem and to study it further, we use simulation models

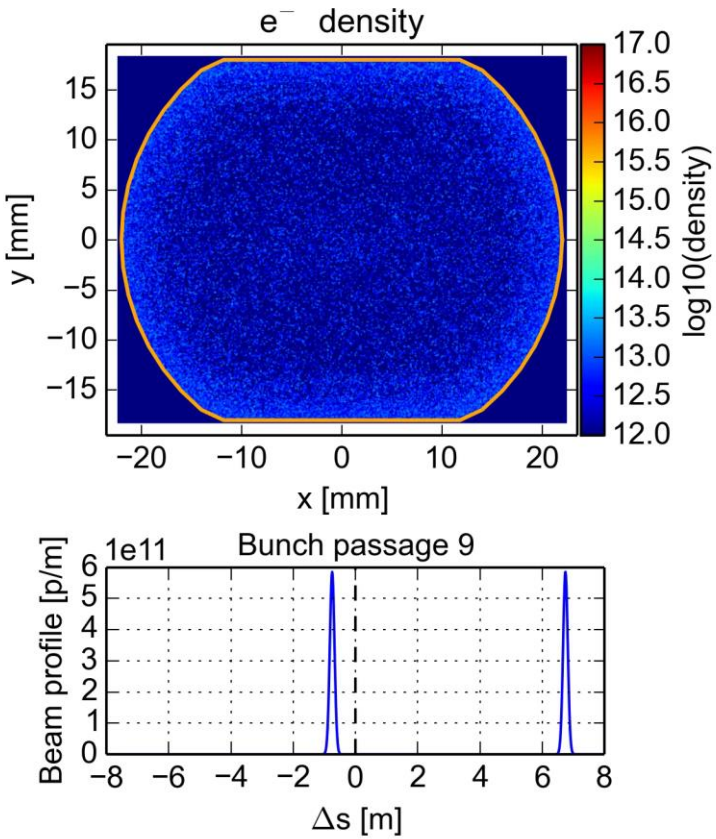
→ A new tool developed for simulating the system:

- Generation of electrons and ions through beam-induced ionization
- The evolution of the beam-electron-ion system

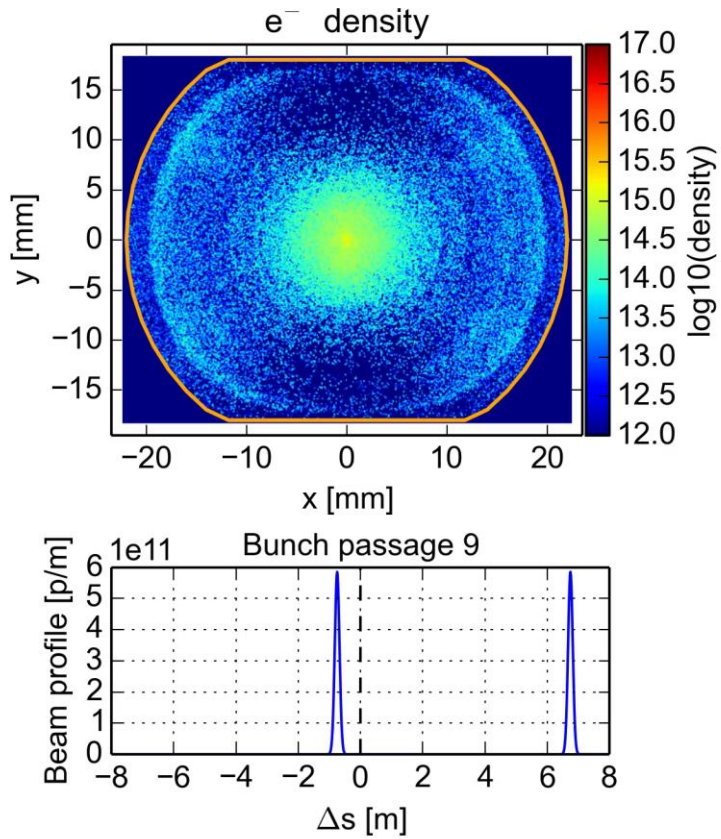
Simulation studies

- The electron motion is significantly altered when the effect of ions is taken into account
  - » The simulations suggest that the fast instabilities are caused by the high gas density through electron accumulation enhanced by the presence of ions
  - » Work in progress with further effects being included, e.g. electron-induced ionization

Electrons with no ions



Electrons with ions in chamber



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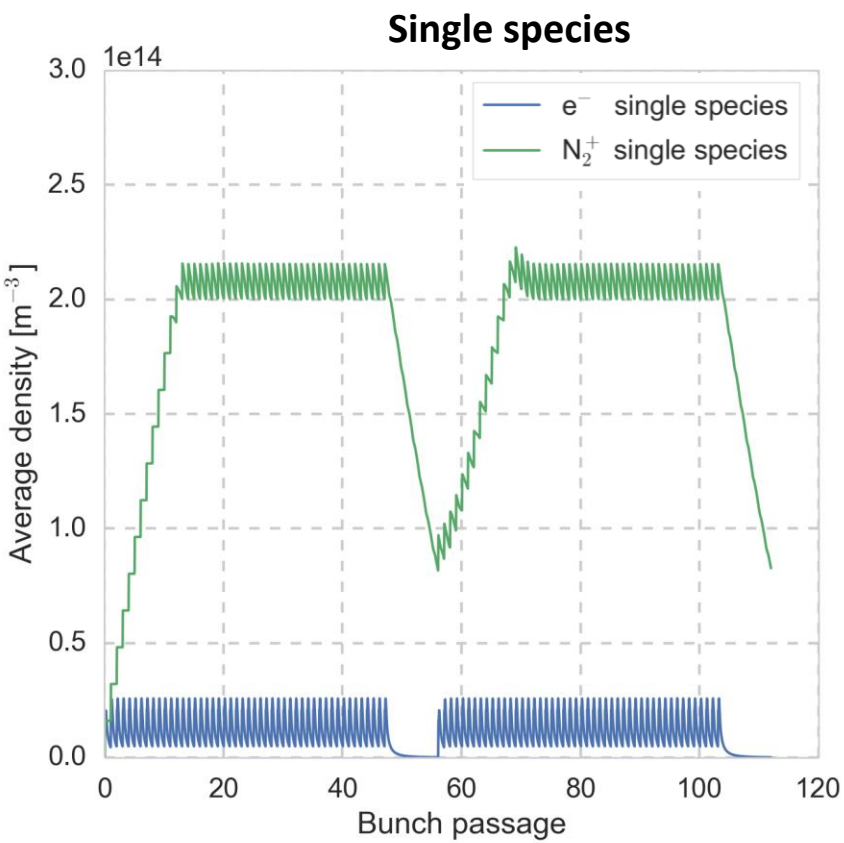
FÉDÉRALE DE LAUSANNE

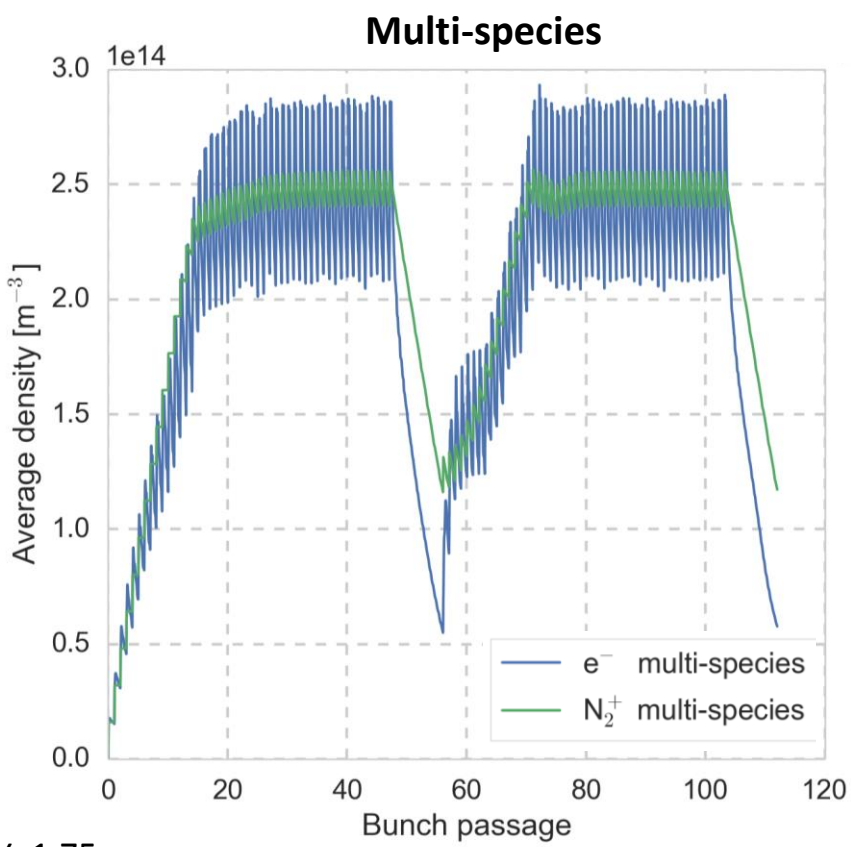
Thank you!

Multi-species build-up

Both electrons and ions are affected by the opposite species!

- The presence of ions significantly enhances the electron build-up!!
  - » Electron densities increase by roughly an order of magnitude





6.5 TeV, SEY=1.75

Electron-induced ionization

Additional electrons and ions may be produced by the interaction of the gas with the e-cloud itself

- Electrons in the energy range of 50 – 500 eV have a 50 – 100 times larger ionization cross section than the beam particles

- The amount of ionization depends on the electron energy distribution

Electron energies are being evaluated to estimate their potential for ionization

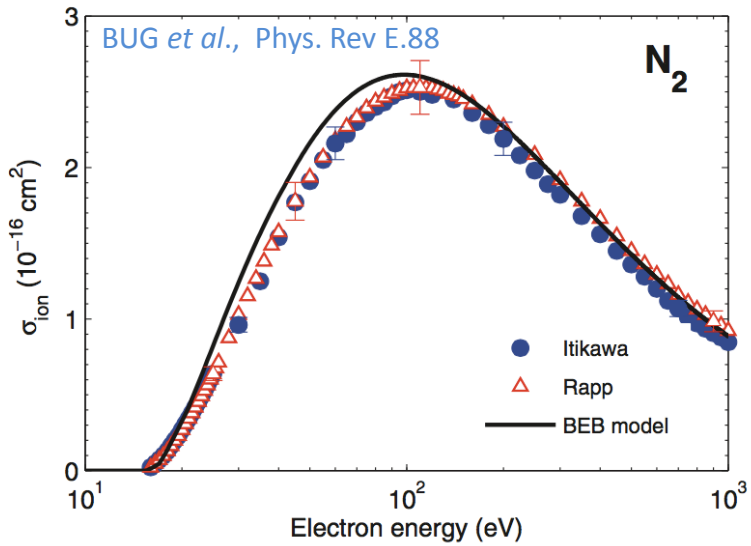


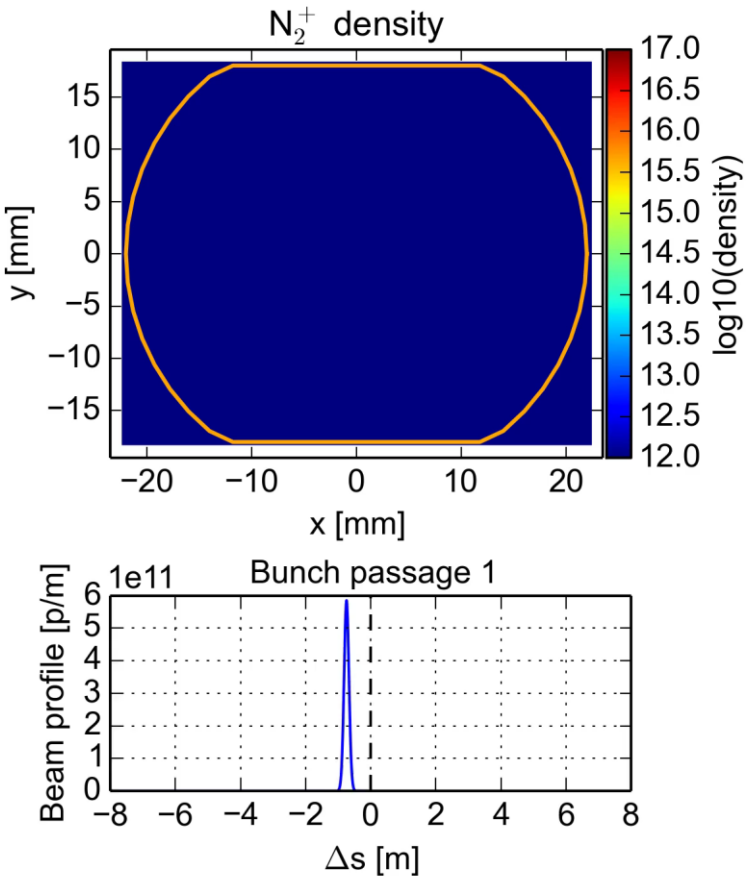
FIG. 1. (Color online) Electron-impact-ionization cross sections σ_{ion} of nitrogen recommended by Itikawa [16], measured by Rapp and Englander-Golden [17], and determined using the BEB model [18].

Ion motion

- Ions gradually move from the centre towards the beam screen
  - » The electron motion is caused by the attractive force of the ion density in the centre

Ions

N_2 gas, 10^{21} m^{-3}



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