Electron-ion dynamics and fast instabilities in the LHC

L. Mether (EPFL)
K. Poland, G. Iadarola, G. Rumolo (CERN)

Swiss Physical Society Annual meeting
EPF Lausanne
28 – 31 August, 2018
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
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
  - 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
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
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
  - 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
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
  - 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
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
  - 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=c0rK2bLT ImQ
Sequence of events in 16L2

NB! Schematic, not to scale
Sequence of events in 16L2

A macro-particle of frozen air (N\textsubscript{2}, O\textsubscript{2}) is detached, possibly triggered by e-cloud.
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 macro-particle enters the beam halo
2. The particle becomes ionized by the beam protons
3. The positively charged macro-particle 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
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.
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.

NB! Schematic, not to scale.
A macro-particle of frozen air (N₂, O₂) 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/m³.

NB! Schematic, not to scale.
Sequence of events in 16L2

A macro-particle of frozen air (N₂, O₂) 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 10¹⁹ – 10²² atoms/m³.

The beam ionizes some of the gas in its path.

NB! Schematic, not to scale.
Sequence of events in 16L2

A macro-particle of frozen air (N₂, O₂) 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 10¹⁹ – 10²² atoms/m³.

The beam ionizes some of the gas in its path.
Sequence of events in 16L2

A macro-particle of frozen air (N₂, O₂) 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 10¹⁹ – 10²² atoms/m³.

The beam ionizes some of the gas in its path. Its interaction with the generated electrons/ions causes the fast instabilities.
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 \(10^{19} – 10^{22} \text{ atoms/m}^3\).

The beam ionizes some of the gas in its path. Its interaction with the generated electrons/ions causes the fast instabilities.
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$^3$.

The beam ionizes some of the gas in its path. Its interaction with the generated electrons/ions causes the fast instabilities.
Sequence of events in 16L2

A macro-particle of frozen air (N₂, O₂) 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/m³.

The beam ionizes some of the gas in its path. Its interaction with the generated electrons/ions causes the fast instabilities.
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$^3$.

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

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

NB! Schematic, not to scale
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
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

![Graph showing Single species and Multi-species comparison](image)
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 $\sigma_{\text{ion}}$ of nitrogen recommended by Itikawa [16], measured by Rapp and Englander-Golden [17], and determined using the BEB model [18].

BUG et al., Phys. Rev E.88
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, $10^{21} \text{ m}^{-3}$

**Electrons**

$N_2$ gas, $10^{21} \text{ m}^{-3}$