Dust and beam instabilities: The "16L2" events at LHC - what we know, what we do not know

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Based on work by many colleagues from:
BE-ABP, BE-OP, SY-BI, SY-RF, SY-STI, TE-CRG, TE-MPE, TE-VSC

Workshop on Dust Charging and Beam-Dust Interaction in Particle Accelerators
CERN
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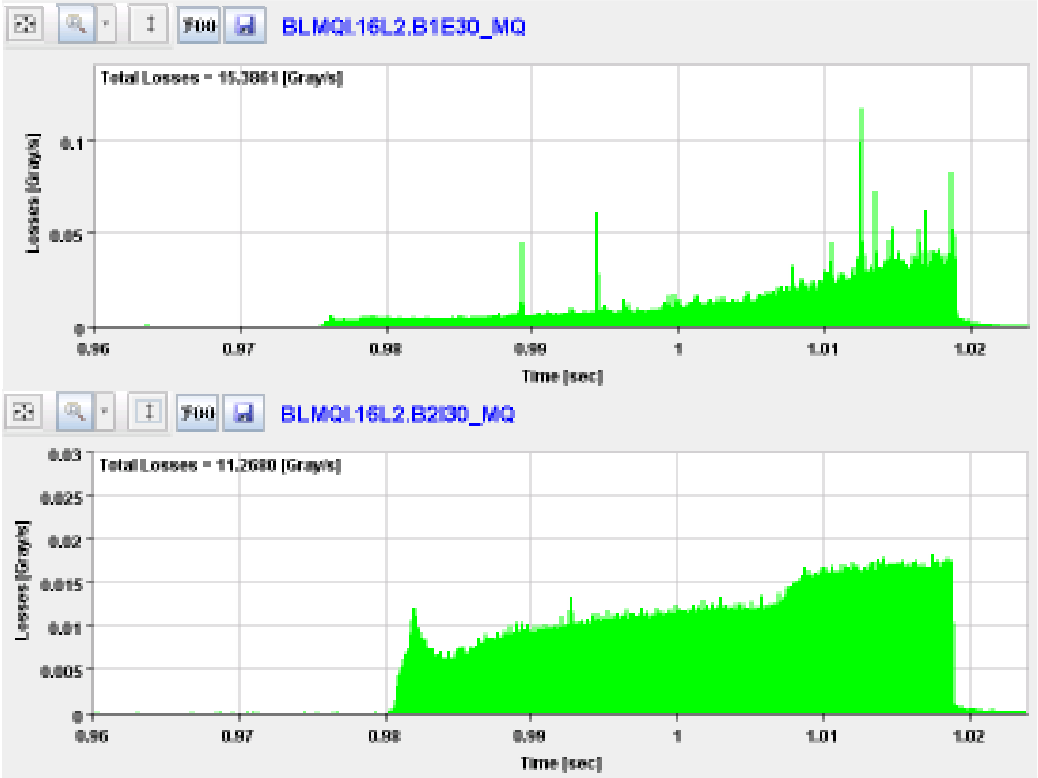
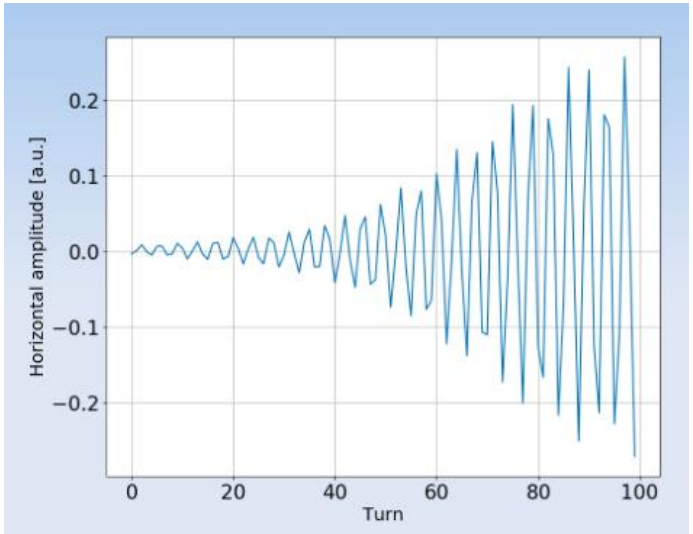
Introduction

- The so-called “16L2” events occurred repeatedly during LHC operation in 2017:
  - Sudden, high beam losses in half-cell 16L2 with characteristic time profile
  - Coherent beam motion with very fast rise times

→ Systematically lead to beam dumps due to high losses in 16L2 or collimation region



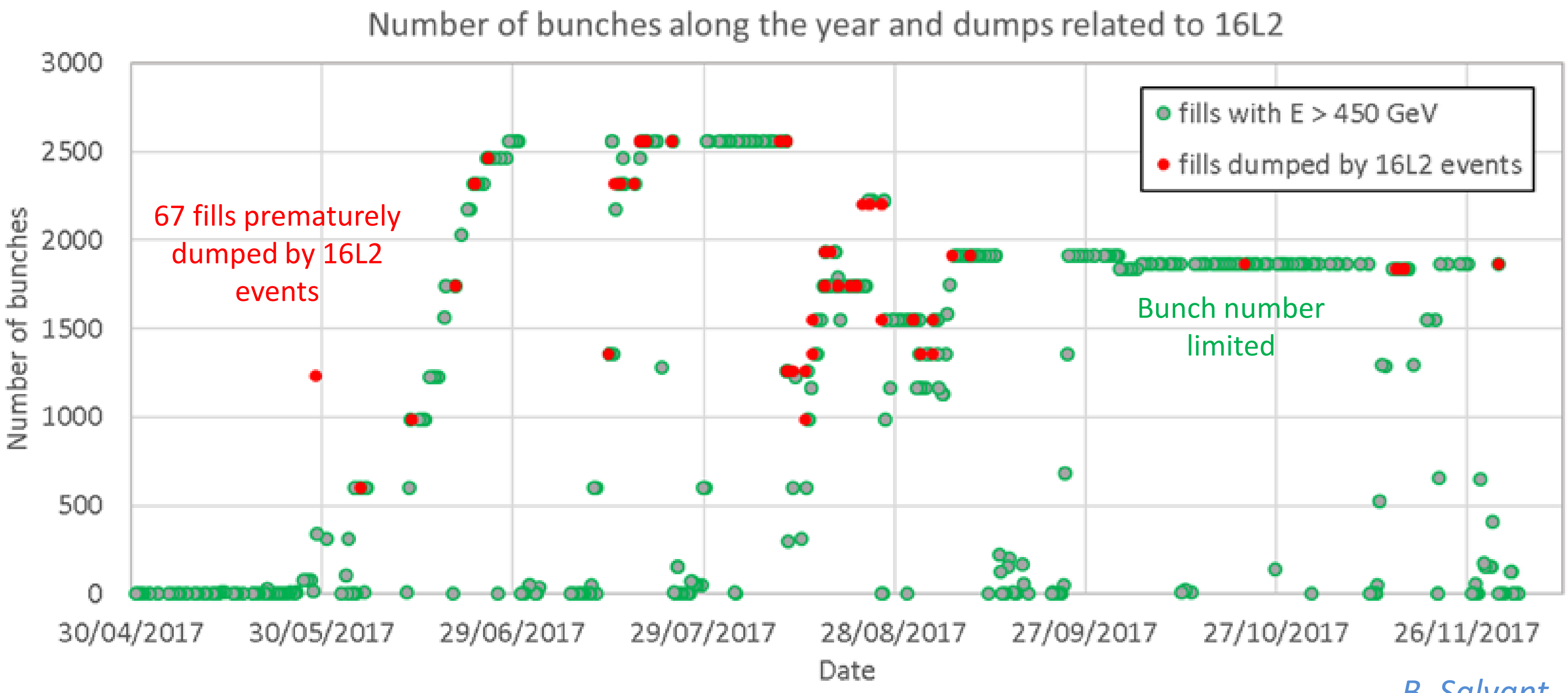
D. Mirarchi



X. Buffat

Introduction

- During 2017, in total 67 fills were prematurely dumped by 16L2 events
  - Significant impact on luminosity production until mitigation measures were identified
- The bunch number had to be limited to avoid events for most of the year
  - Could be partly compensated by increasing bunch intensity
- The LHC nevertheless reached its target integrated luminosity for the year



B. Salvant

Outline

- Introduction

- Losses
  - Loss localization
  - Source of losses
  - Loss characteristics and interpretation

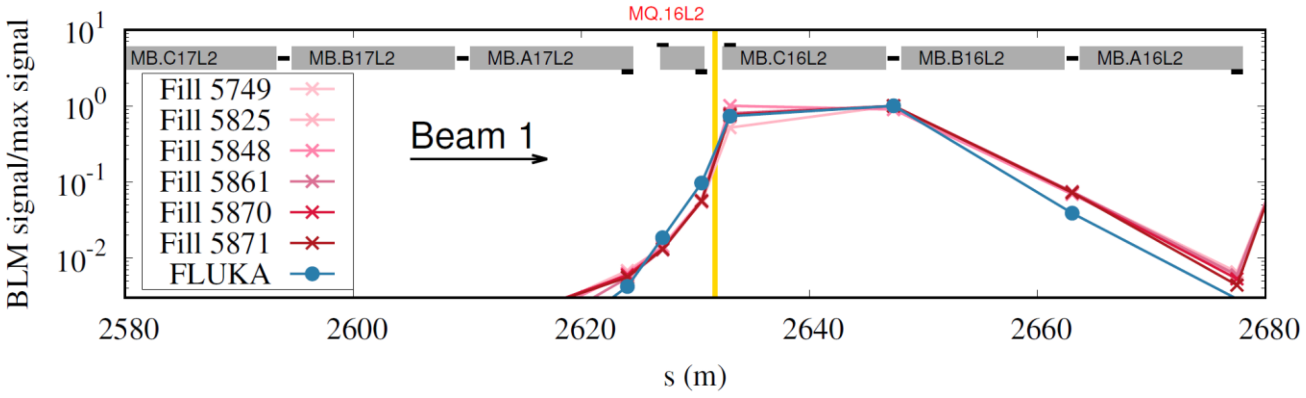
- Instabilities
  - Instability characteristics and observations
  - Simulation model

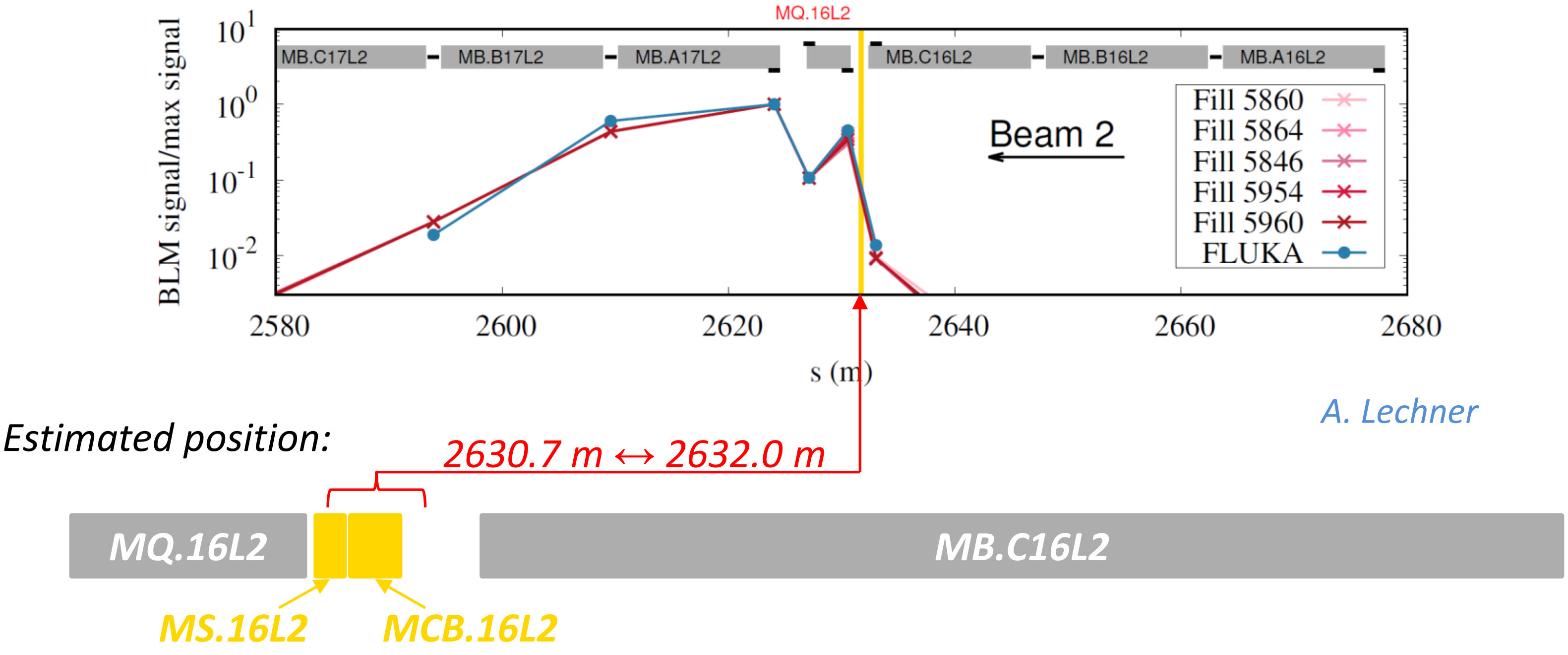
- Release mechanism and mitigation

- Conclusion

Loss localisation

- Energy deposition simulations (FLUKA) determined location of loss source to within ~1.3 m





A. Lechner

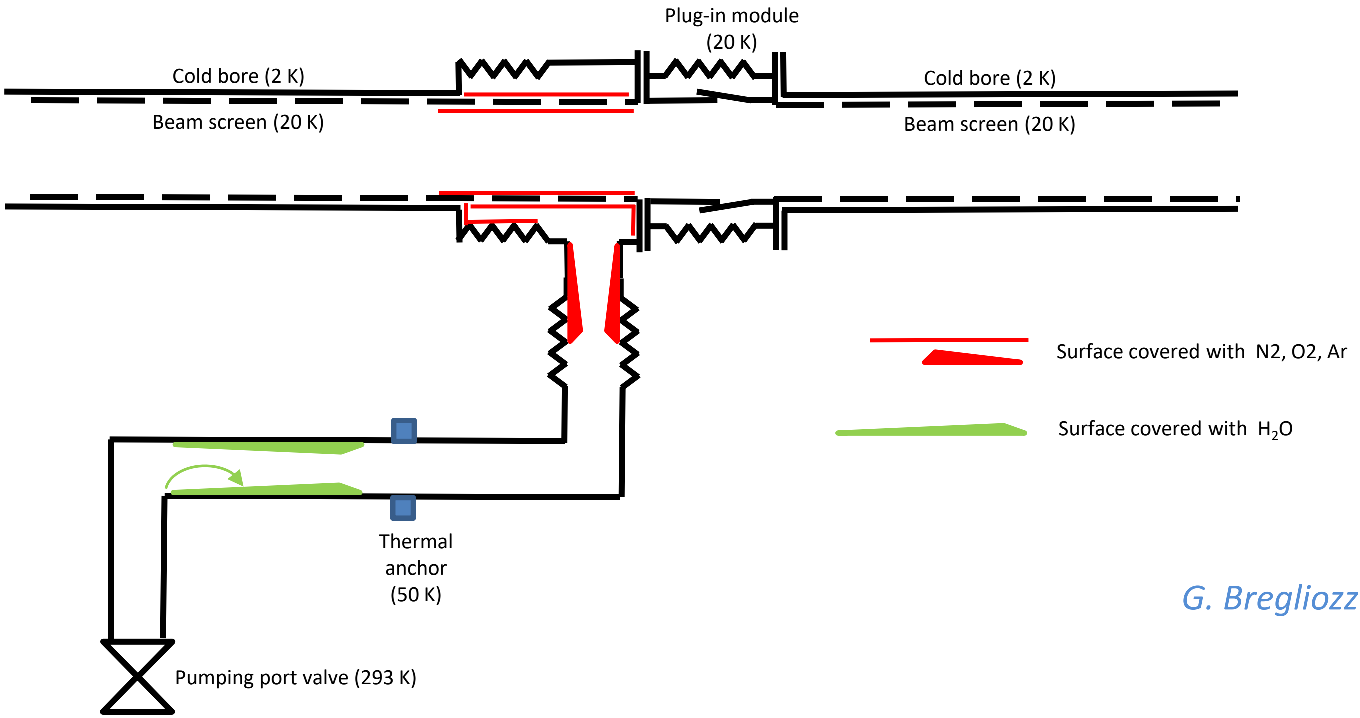
Estimated position:

2630.7 m ↔ 2632.0 m

Source of losses

- Before the start of the 2017 LHC run, the sector where 16L2 is located was warmed up to room temperature for the exchange of a magnet
  - The precise location of the losses corresponds to where a pumping port was connected to both beam apertures for the venting of the sector

- Most likely source of events: an accidental air inlet after pump-down with the beam screens at 20 K, leading to formation of “frost” of air (N_2 and O_2) on the beam screens



G. Bregliozzi

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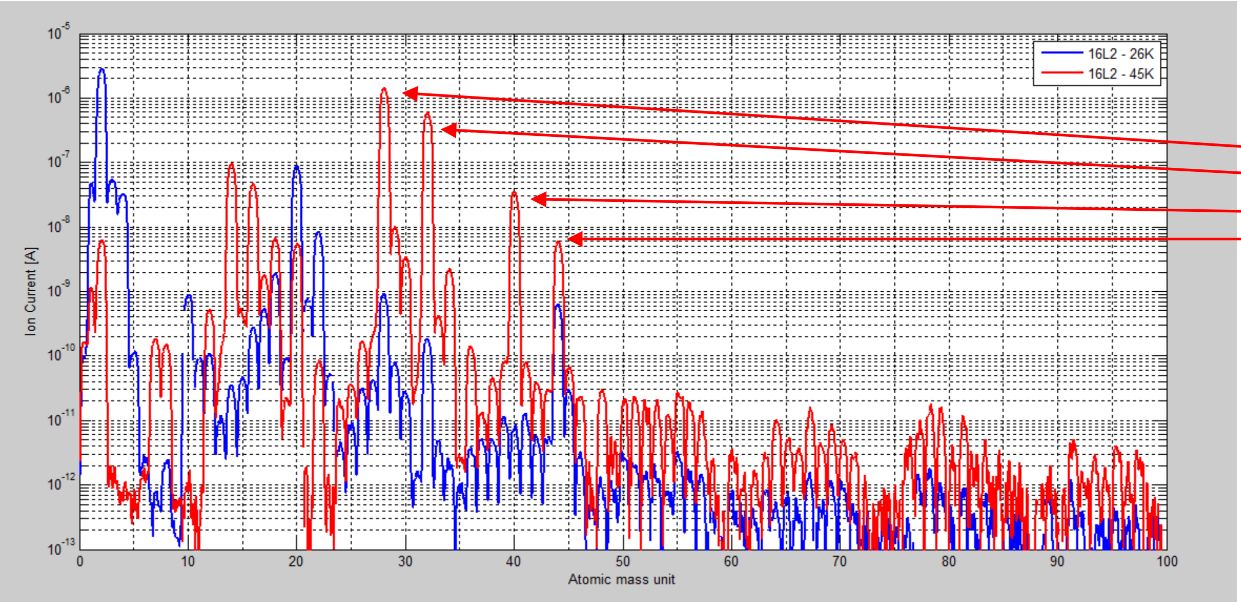
  - Contamination by atmospheric air confirmed during warm-up at the end of 2017



Composition of Atmospheric Air

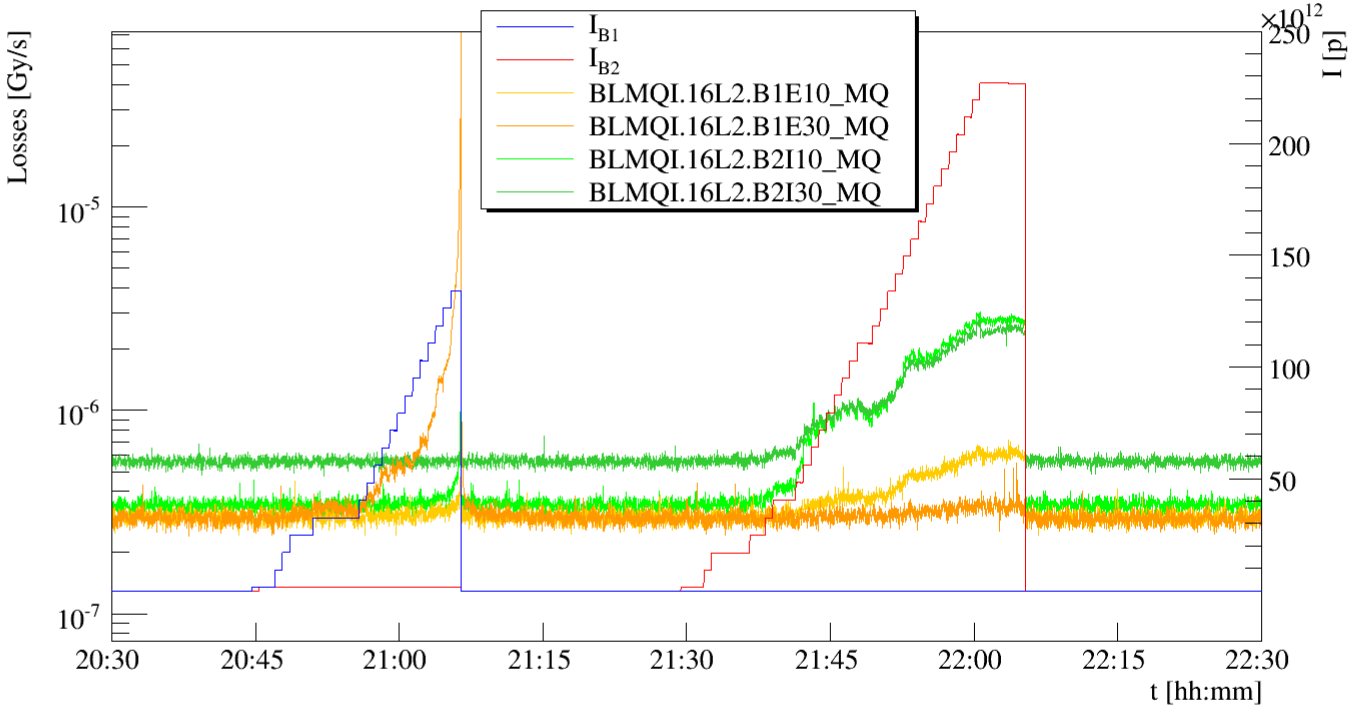
Gas	*Volume %*	*Partial Pressure (torr)*
N_2	78.08	5.94×10^{2}
O_2	20.95	1.59×10^{2}
Ar	0.93	7
CO_2	0.033	2.5×10^{-1}
Ne	1.8×10^{-3}	1.4×10^{-2}
He	5.24×10^{-4}	4.0×10^{-3}
CH_4	2.10^{-4}	1.5×10^{-3}
Kr	1.1×10^{-4}	8.4×10^{-4}
H_2	5.0×10^{-5}	3.8×10^{-4}
N_20	5.0×10^{-5}	3.8×10^{-4}
Xe	8.7×10^{-6}	6.6×10^{-5}
O3	7×10^{-6}	5.3×10^{-5}
H_20*	1.57	1.19×10^{1}

**50% relative humidity at 23°C*

G. Bregliozzi

Observed losses

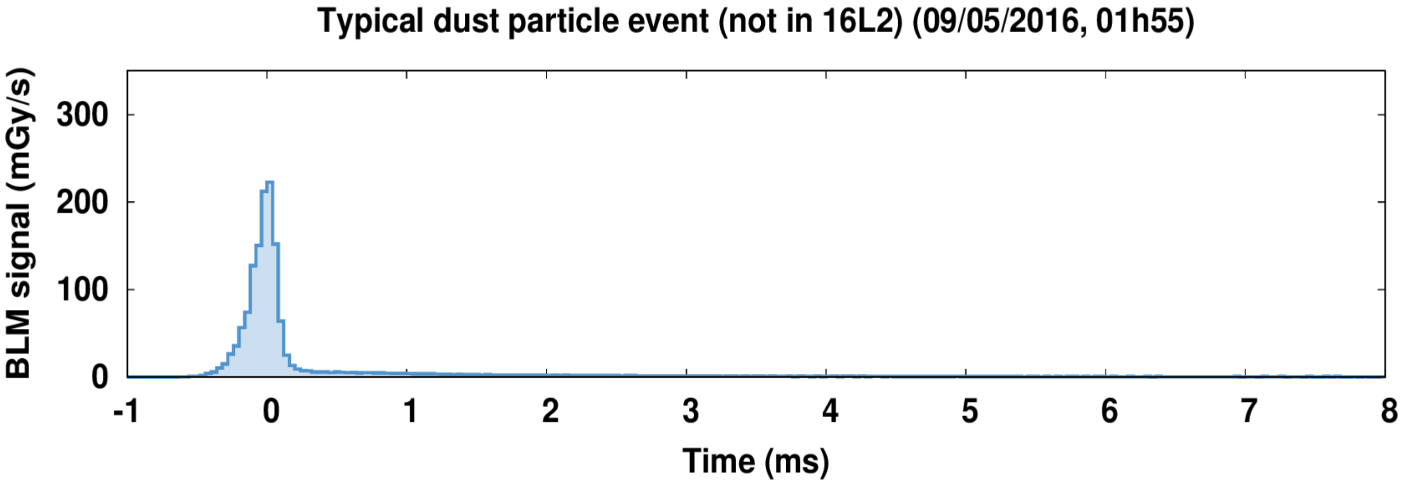
	Steady state losses
Typical duration	Entire fill
Typical loss rate	~1 μGy/s
Beam instability	No
Beam dump	No



D. Mirarchi

Observed losses

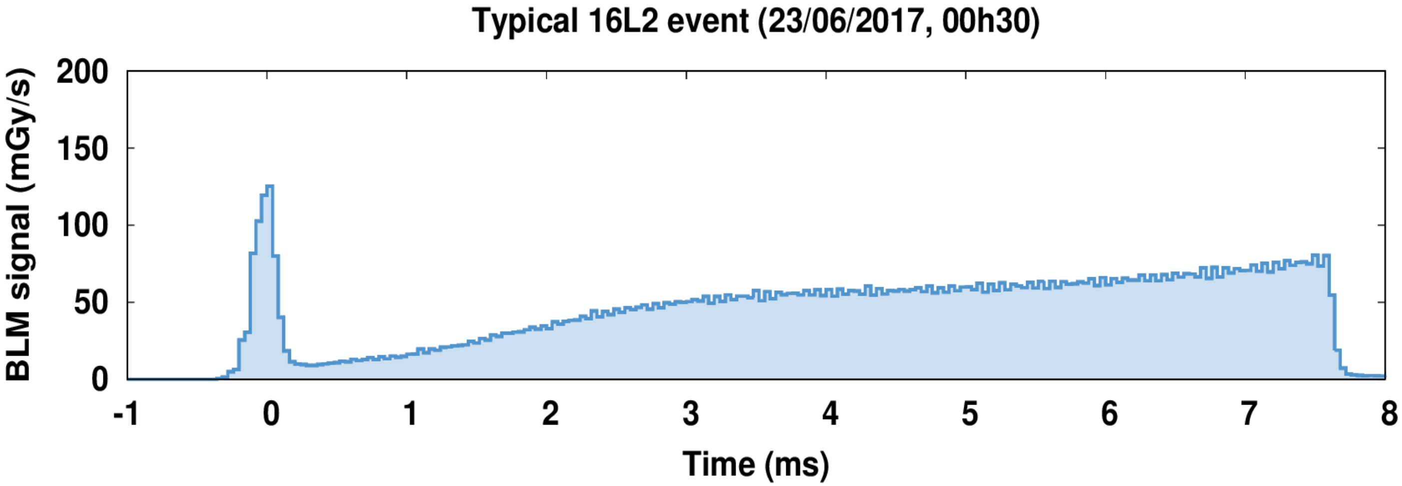
	Steady state losses	UFO-like spikes
Typical duration	Entire fill	~1 ms
Typical loss rate	~1 µGy/s	1-100 mGy/s
Beam instability	No	No
Beam dump	No	Typically not



A. Lechner

Observed losses

	Steady state losses	UFO-like spikes	Loss plateau
Typical duration	Entire fill	~1 ms	~10 ms
Typical loss rate	~1 µGy/s	1-100 mGy/s	10-100 mGy/s
Beam instability	No	No	Yes
Beam dump	No	Typically not	Yes



A. Lechner

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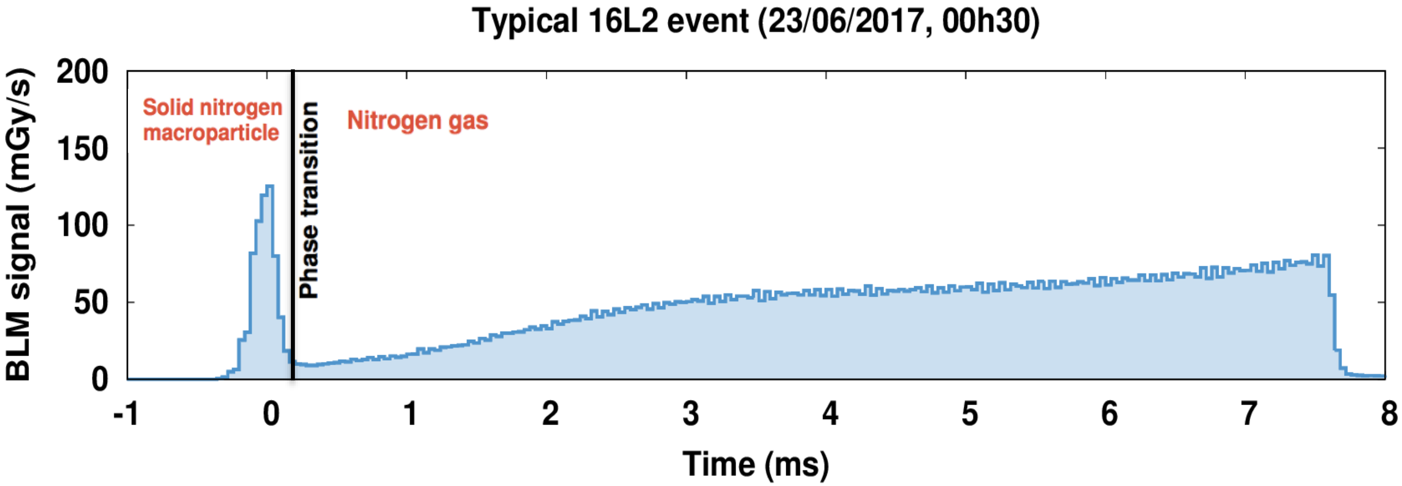
Beam dump	No	Typically not	Yes
Possible explanation	Beam-gas scattering due to N_2 outgassing	N_2 particle enters the beam, is positively charged and heated up by Coulomb interactions and is repelled by the beam	N_2 particle enters the beam, is positively charged, but heated up sufficiently to undergo a phase transition to gas



A. Lechner

Possibility of macro-particle phase transition

- Beam interaction with macro-particle:
  - Coulomb interactions → ionize and deposit energy in macro-particle
  - Inelastic nuclear interactions → particle showers, detected by beam loss monitors (BLMs)

A. Lechner

While the inelastic scattering events don’t contribute to energy deposition, they allow to estimate the path length of protons within the macro-particle, and therefore the deposited energy

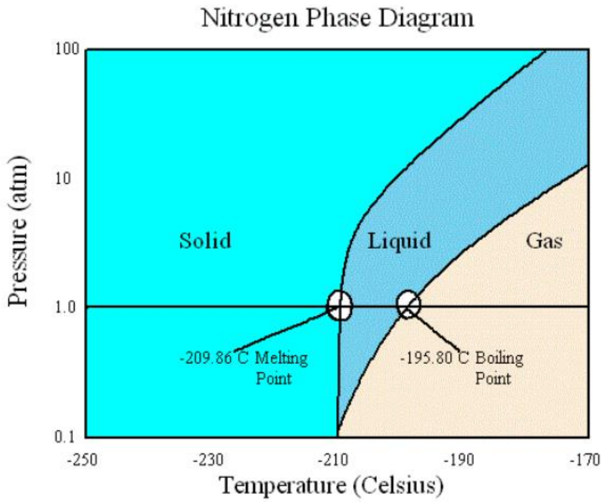
Stopping power and scattering length determined by FLUKA simulations

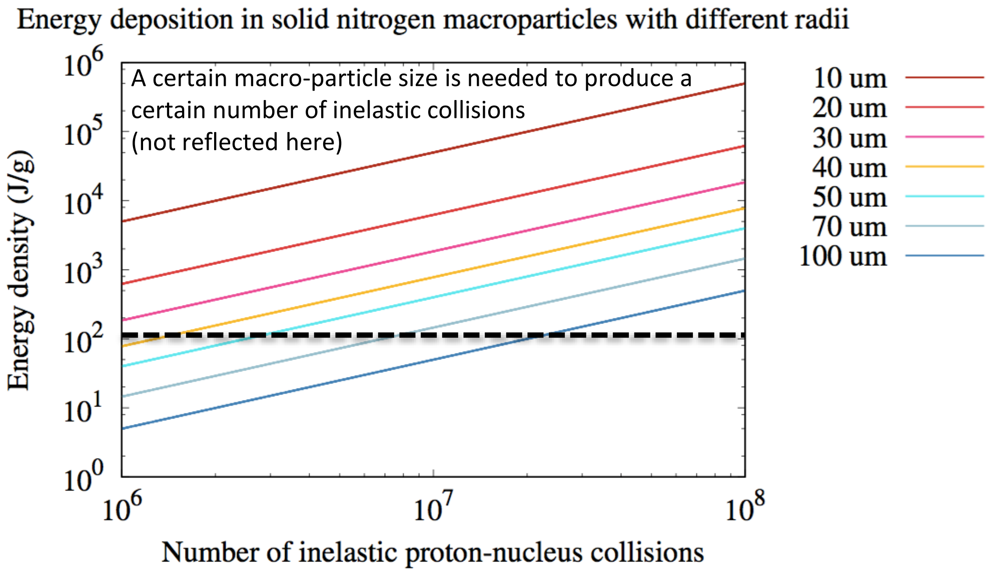
$$\epsilon_d(N_i, r) = \left.\frac{dE}{dx}\right|_r N_i \lambda \frac{3}{4\pi r^3} \qquad [MeV/cm^3]$$

Number of inelastic collisions estimated from BLM signals

Assuming spherical shape

Minimum required energy density estimated from nitrogen phase diagram and specific heat





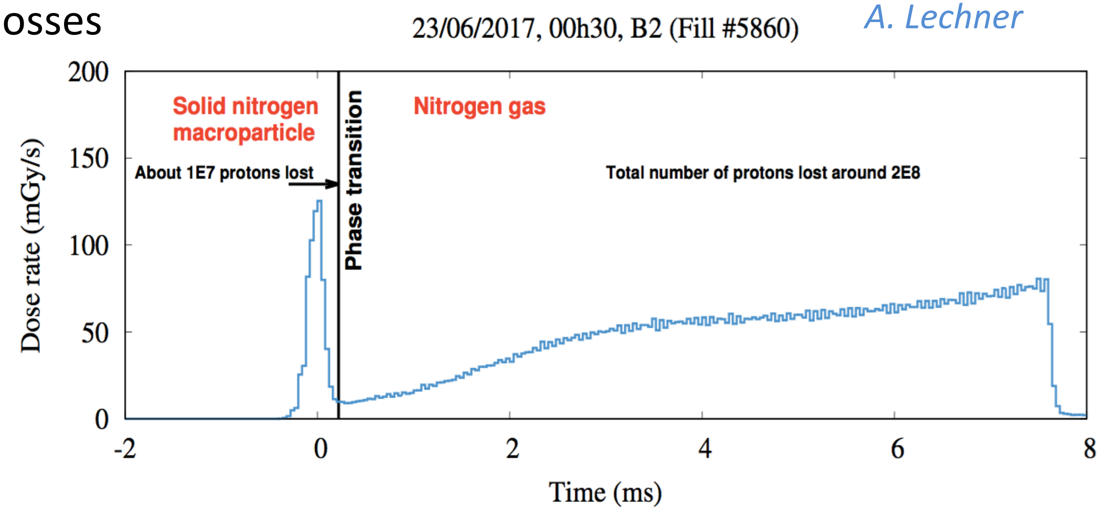
A certain macro-particle size is needed to produce a certain number of inelastic collisions (not reflected here)

Possibility of macroparticle phase transition

- For a typical case of 10^7 inelastic losses

For a macro-particle with a radius smaller than a few tens of μm, the energy density could become high enough (>**110 J/g**) to induce a phase transition to gas

A. Lechner

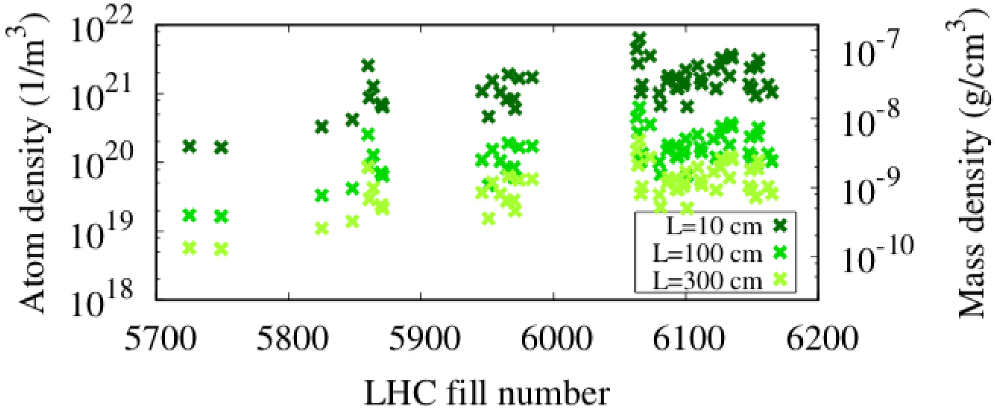


  - » The presence of gas could explain the observed loss duration of tens of milliseconds, which is not possible for solid macroparticles, since they are repelled by the beam

- The atomic gas density can be estimated based on the measured loss rates

Assuming that
- only nitrogen gas is present
- the gas extends over the entire beam cross section

Atomic density: $10^{19} – 10^{21}\,L^{-1}\mathrm{m}^{-2}$



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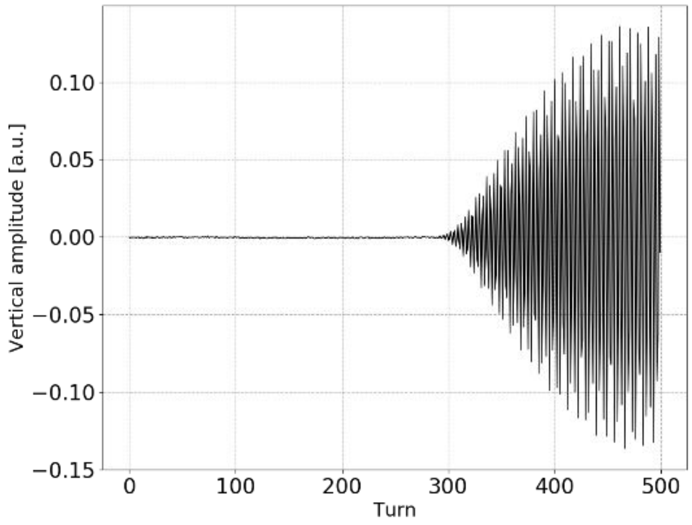
Instability characteristics

- The 16L2 beam instabilities were very fast, with rise times of 10-100 turns
  - Impossible to damp with any available means
  - Such fast instabilities usually not observed after the beam commissioning phase

Example of 16L2 instability



X. Buffat

Instability characteristics

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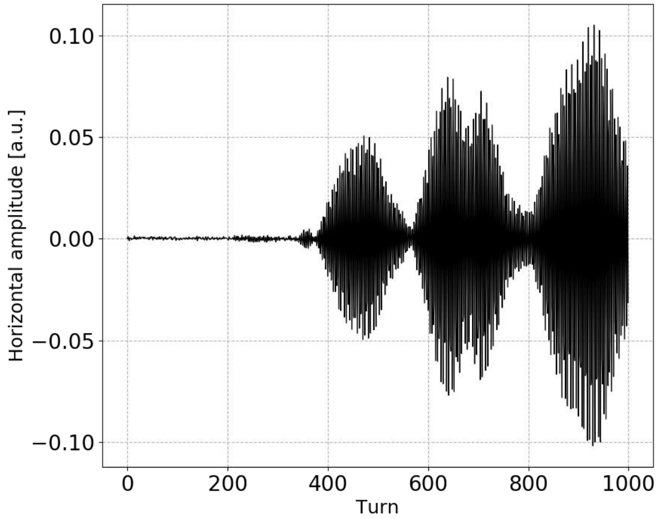
  - Impossible to damp with any available means
  - Such fast instabilities usually not observed after the beam commissioning phase

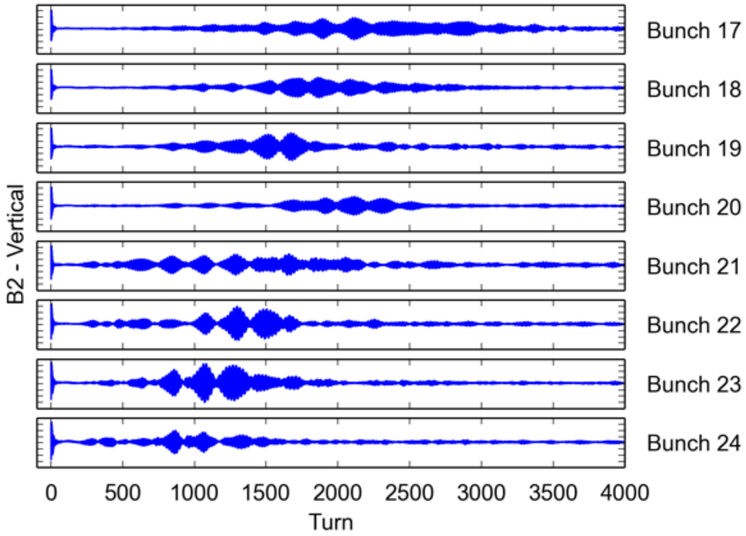
- Similarly fast instabilities can be caused by electron cloud at the very beginning of operation after air exposure, before the beam screens are conditioned
  - However, the effect is then accumulated over most of the machine as opposed to over only a few meters in this case → very strong interaction with beam in 16L2

Example of long 16L2 instability



X. Buffat

Instability during beam commissioning



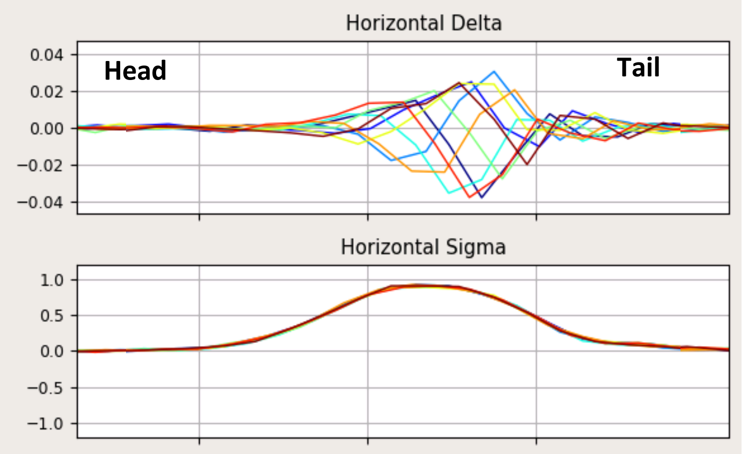
G. Iadarola

Additional observations

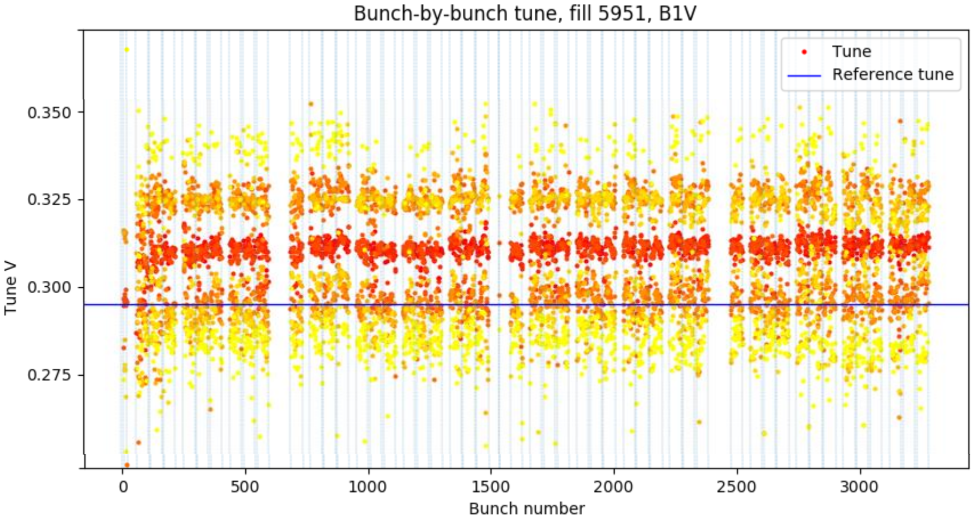
- Additional observations from a few events suggest that large electron densities could have been present

- Intra-bunch motion at the tail of bunches
  - Electrons are sufficiently light to be able to move significantly over the length of a bunch

- Large positive tune shifts (up to 2×10^{-2})
  - Positive tune shift, i.e., additional focusing, can be caused by negative charges in the beam



B. Salvant, T. Levens

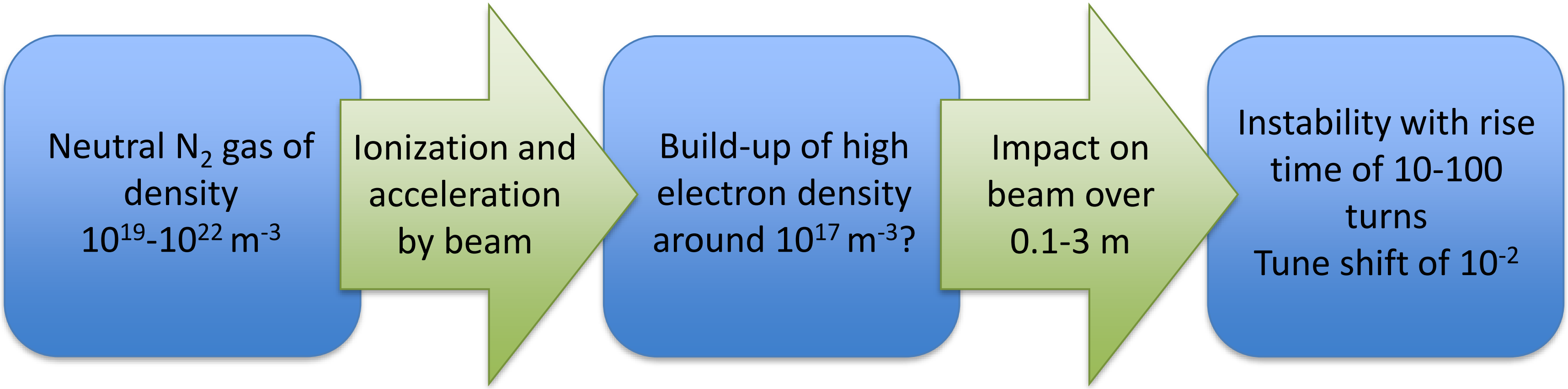


D. Amorim

Instability modelling

- Analytical estimations and first simulations indicated that an electron density of around 10^{17} m^{-3} over 10 cm could give rise to the observed effects

- To gain more confidence in our understanding of the assumed sequence of events, aimed to consistently model in simulations the evolution from gas to beam instability



Neutral N_2 gas of density 10^{19}-10^{22} m^{-3}

Ionization and acceleration by beam

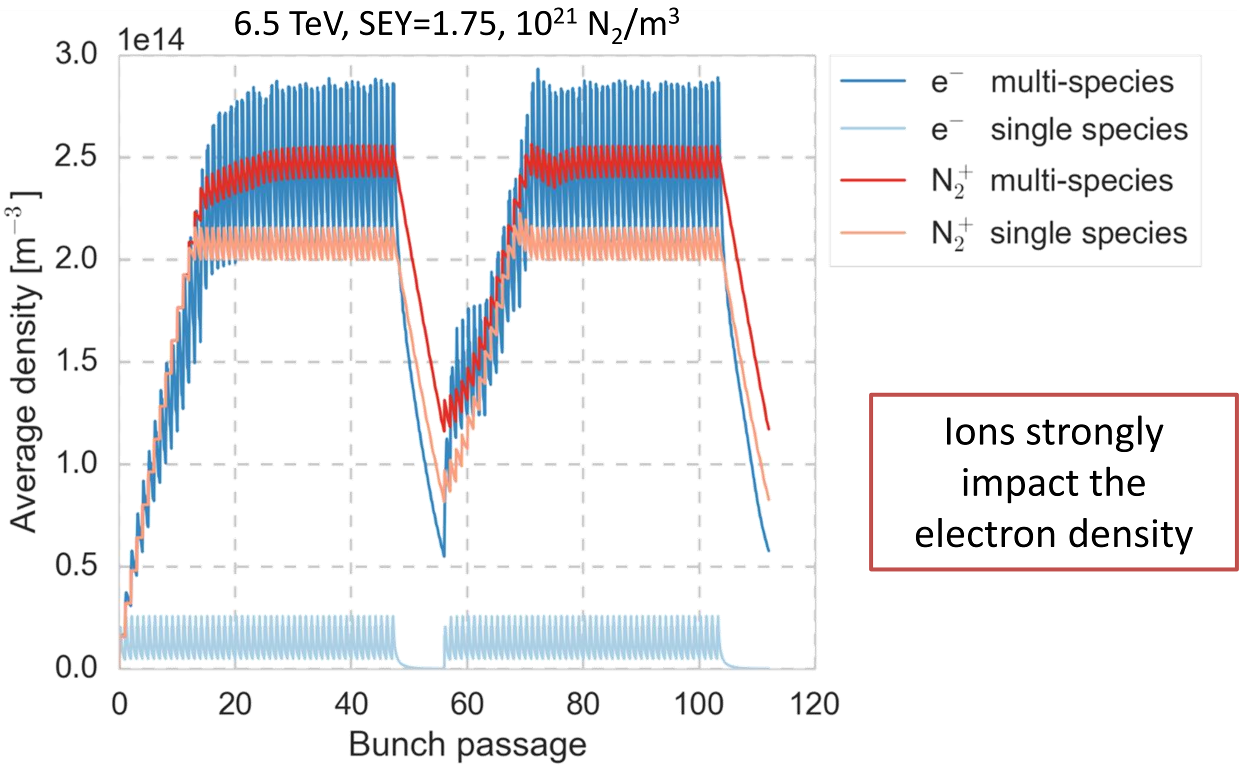
Build-up of high electron density around 10^{17} m^{-3}?

Impact on beam over 0.1-3 m

Instability with rise time of 10-100 turns
Tune shift of 10^{-2}

Simulation model

- To reach a consistent picture, several ingredients which have a negligible effect under usual conditions in the machine had to be added to the simulation models
  - Presence of both **positively and negatively charged ionization products**



6.5 TeV, SEY=1.75, 10^{21} N_2/m^3

Ions strongly impact the electron density

Simulation model

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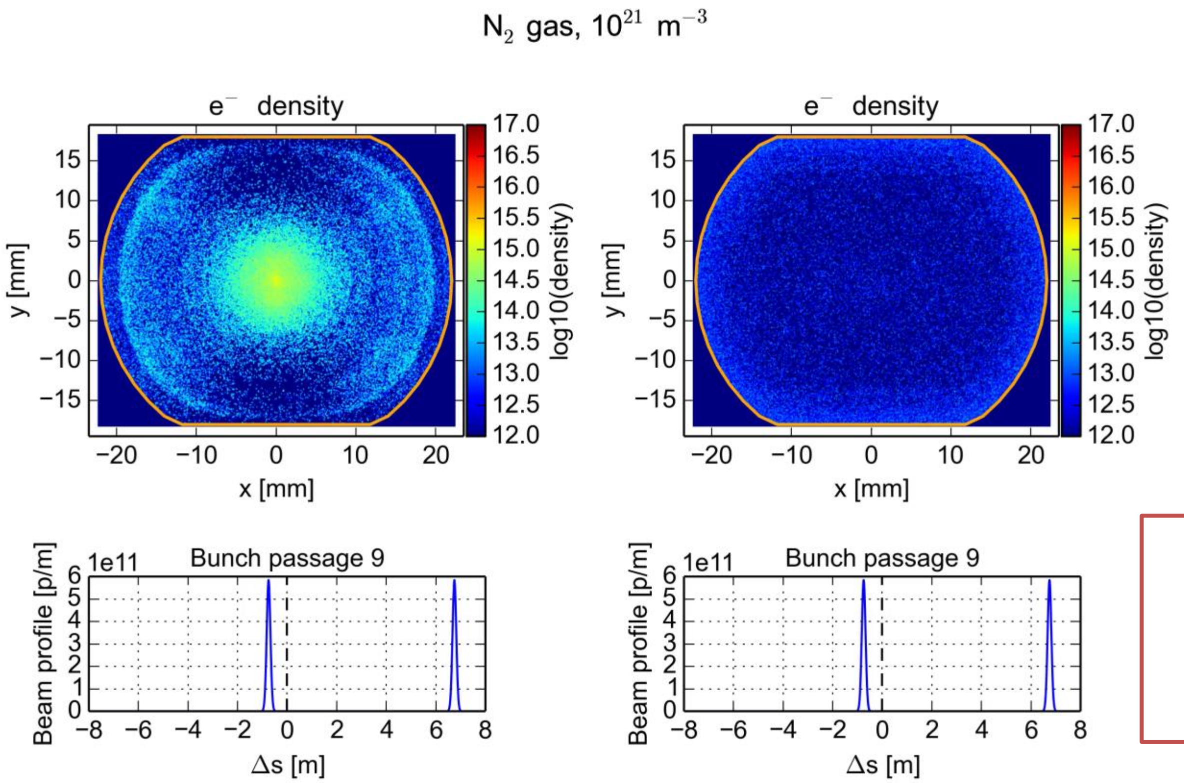
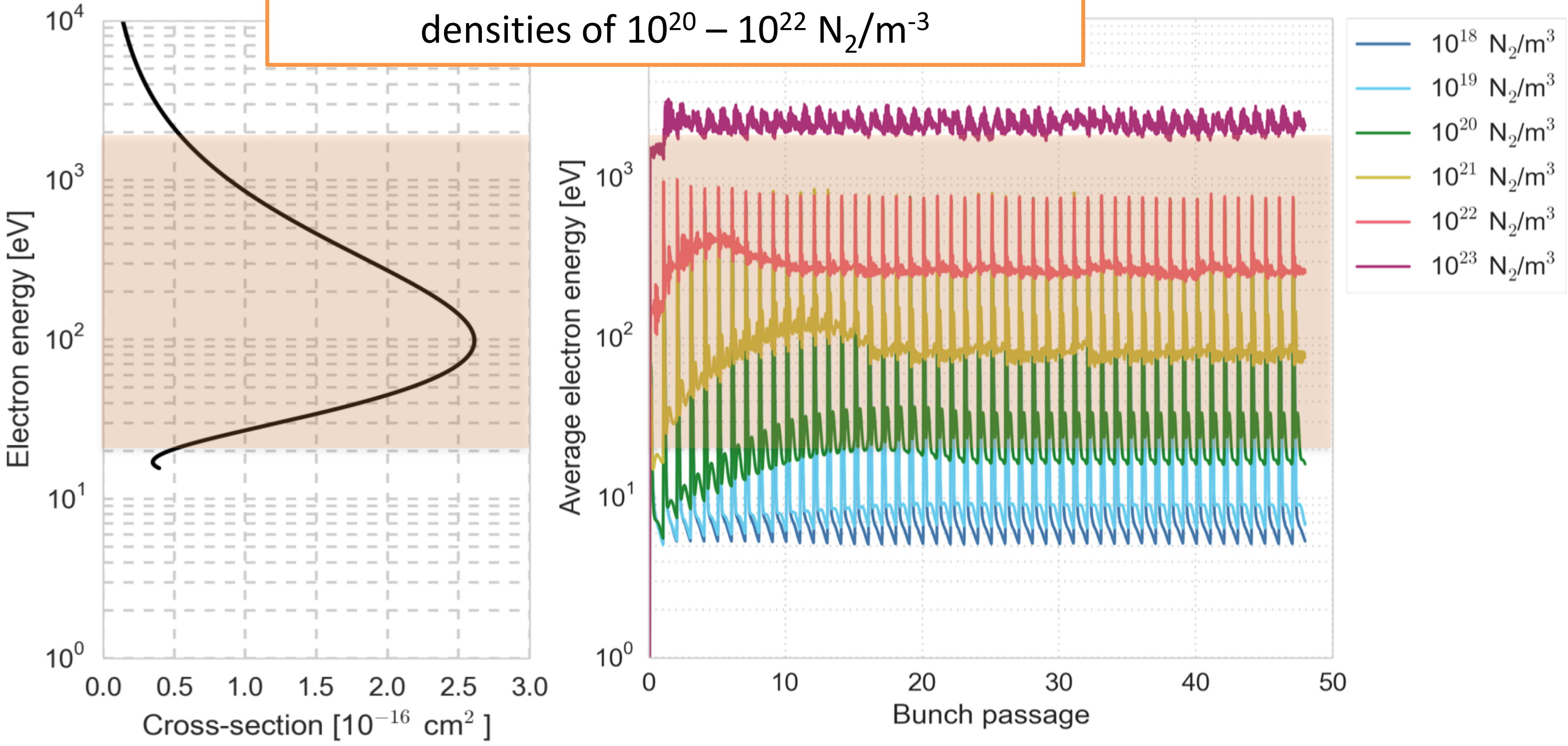


Ions strongly impact the electron density and dynamics

Simulation model

- To reach a consistent picture, several ingredients which have a negligible effect under usual conditions in the machine had to be added to the simulation models
  - Presence of both positively and negatively charged ionization products
  - **Electron impact-ionization**

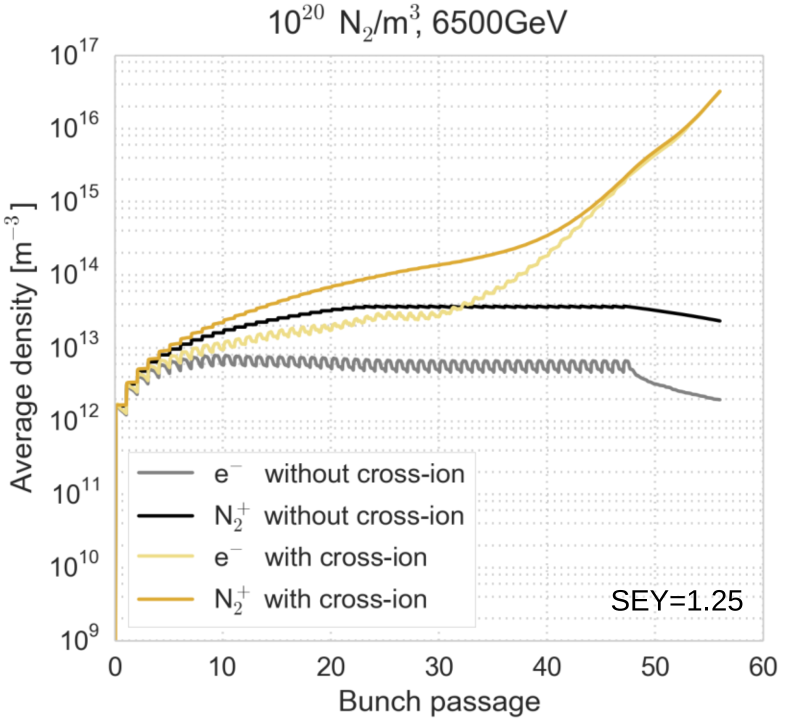


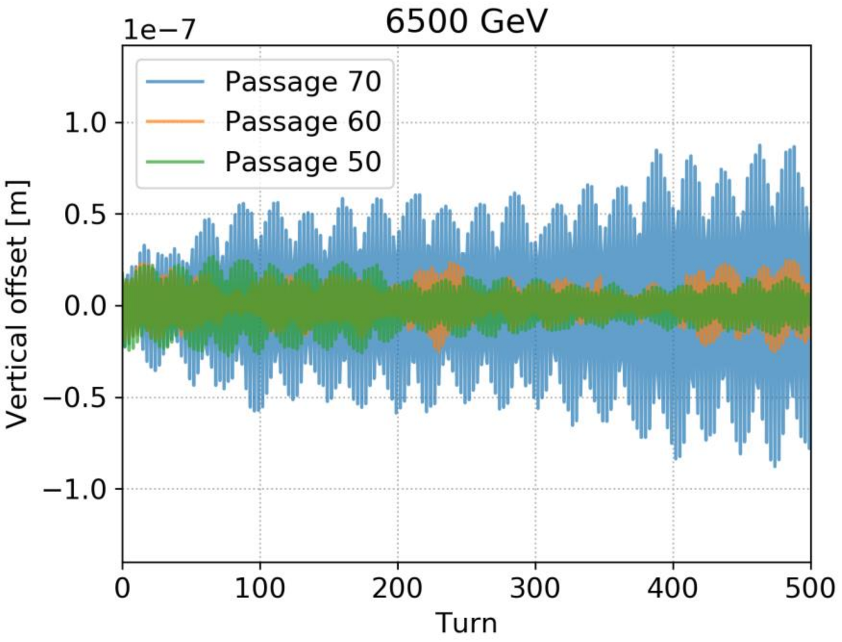
Electron energies are favourable for electron impact-ionization in particular for neutral gas densities of 10^{20} – 10^{22} N_2/m^{-3}

Simulation model

- ○ To reach a consistent picture, several ingredients which have a negligible effect under usual conditions in the machine had to be added to the simulation models
  - » Presence of both positively and negatively charged ionization products
  - » Electron impact-ionization

- ○ With these ingredients, we can reproduce the events to the order of magnitude level





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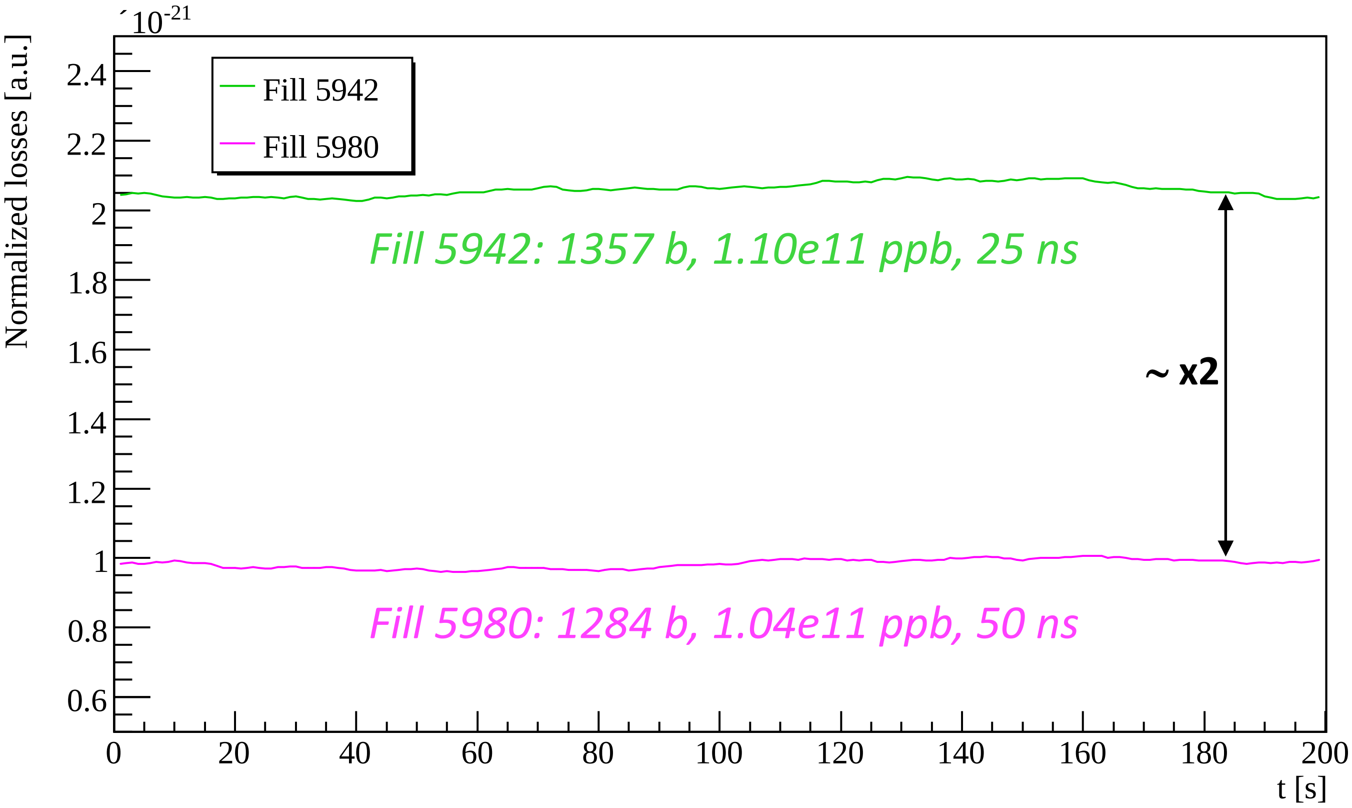
Electron cloud as trigger

- There is strong evidence that electron clouds, in addition to causing the instability, played an important role in triggering the events

- Steady state losses significantly reduced during single test with e-cloud free bunch pattern (25 ns → 50 ns bunch spacing), but strongly limits number of bunches



Fill 5942: 1357 b, 1.10e11 ppb, 25 ns

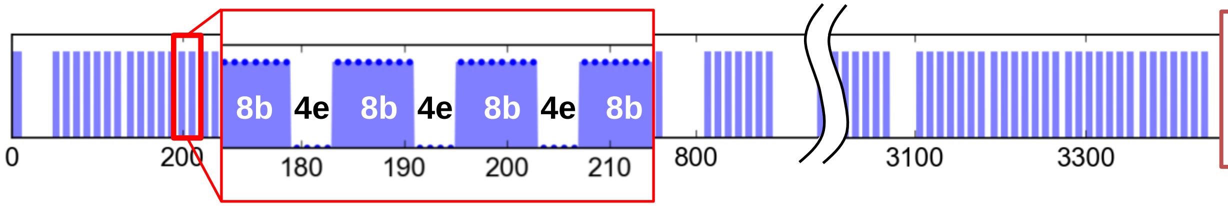
Fill 5980: 1284 b, 1.04e11 ppb, 50 ns

D. Mirarchi

Mitigation from 8b+4e scheme

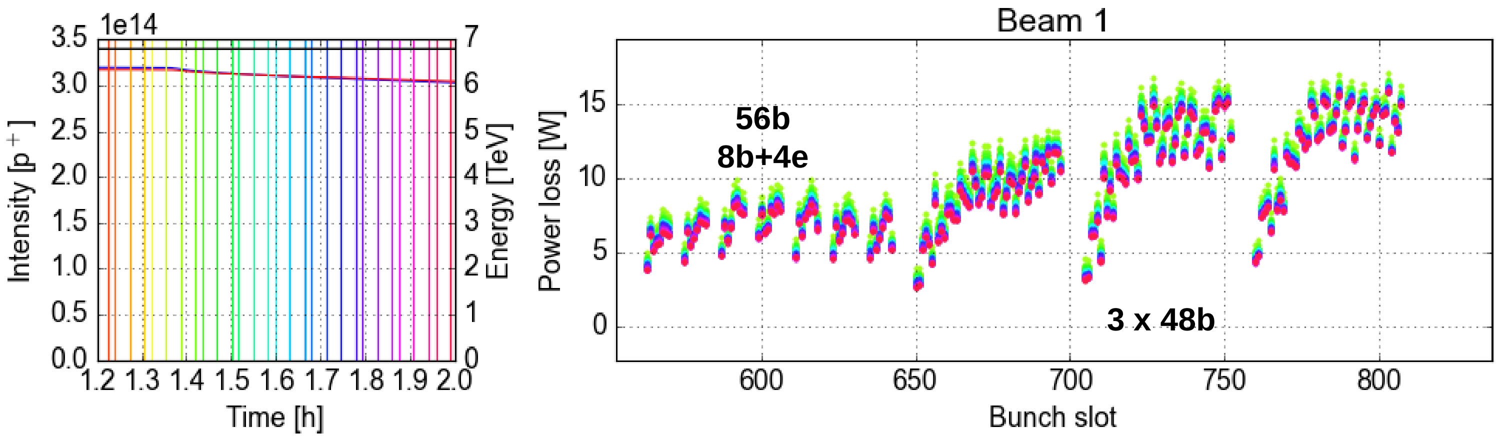
- Operating with e-cloud reducing “8b+4e” bunch pattern lead to a strong reduction of spikes (UFO-like events) and dump events

8b+4e filling scheme



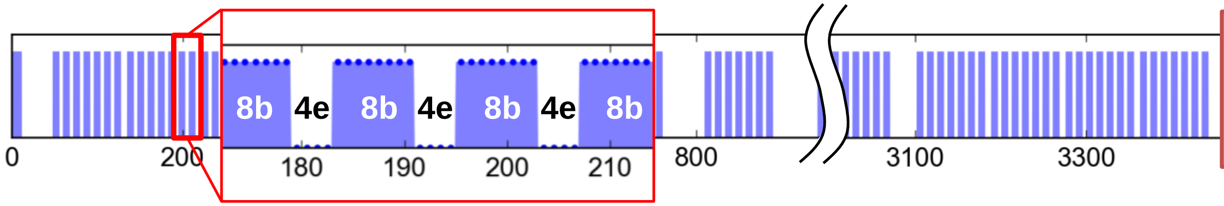
Number of bunches per beam limited to ~2000

RF stable phase measurement

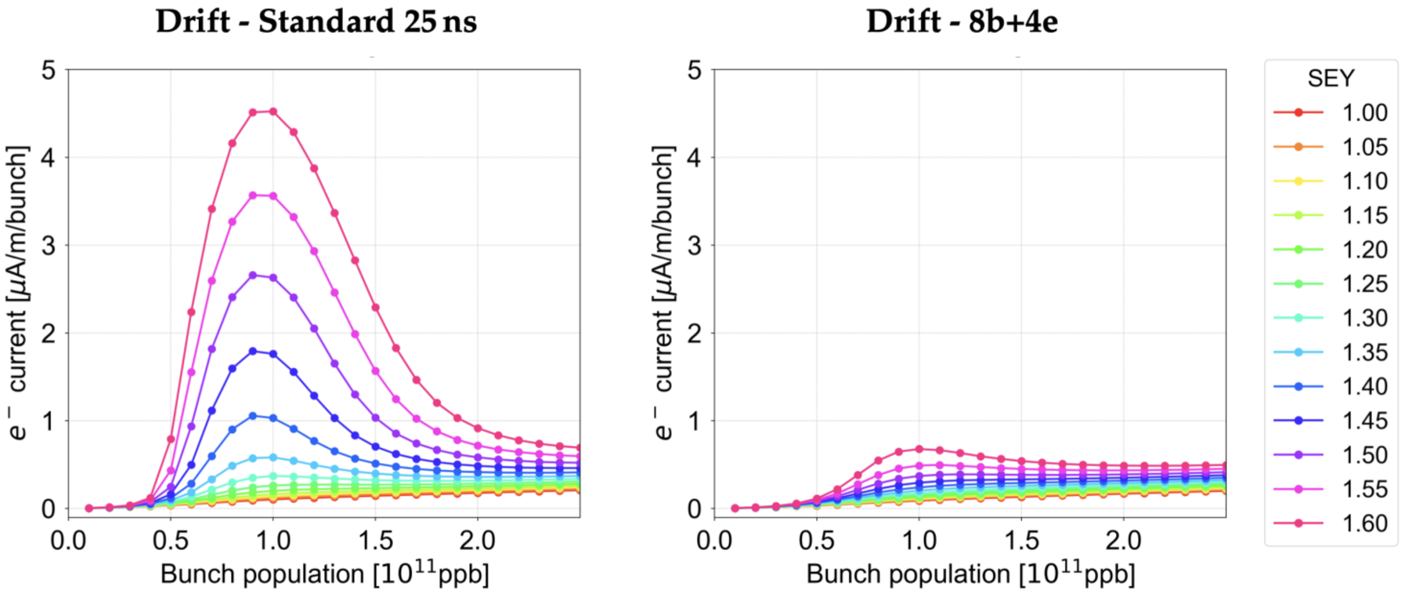


Mitigation from 8b+4e scheme

- Operating with e-cloud reducing “8b+4e” bunch pattern lead to a strong reduction of spikes (UFO-like events) and dump events
  - Enabled stable operation with 1900 bunches and bunch intensity up to 1.15×10^{11} p^{+}


8b+4e filling scheme

Number of bunches per beam limited to ~2000


Drift - Standard 25 ns

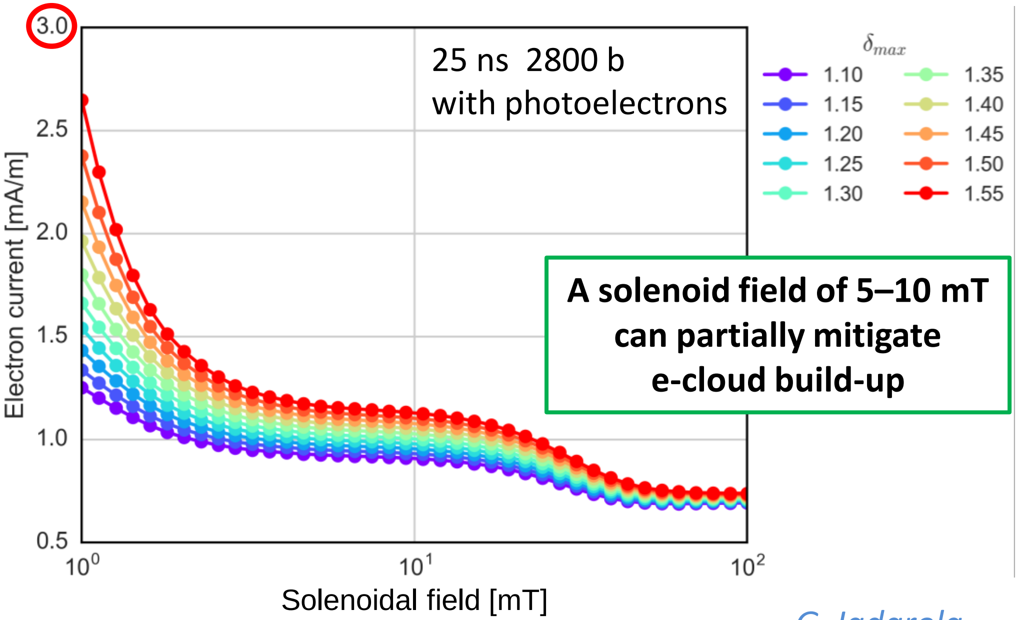
Drift - 8b+4e

G. Skripka

Mitigation from solenoid

- Installation of a solenoid in the field free region of 16L2 further improved the situation
  - The solenoid mitigates e-cloud build-up by confining the electrons along field lines
- Allowed another increase in bunch intensity to 1.25 × 10^{11} p^+

A. Milanese



A solenoid field of 5–10 mT can partially mitigate e-cloud build-up

G. Iadarola

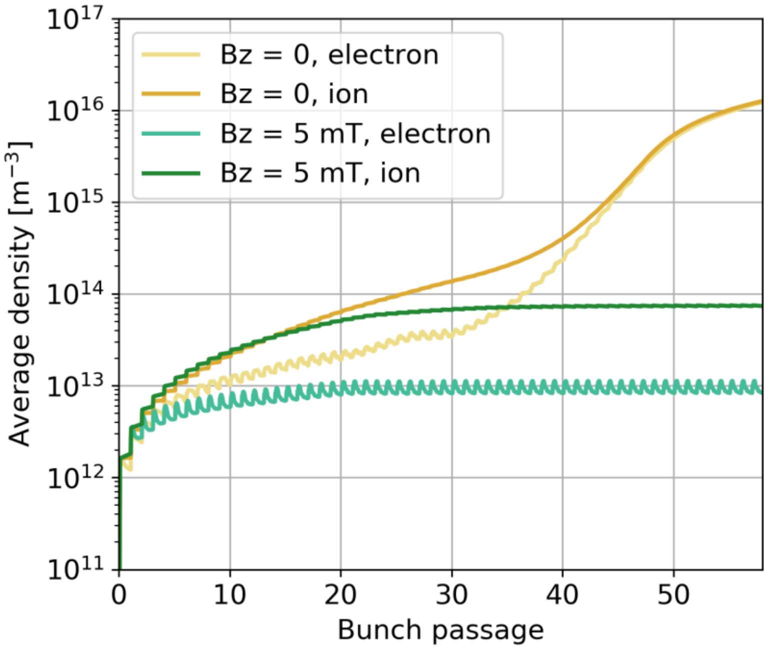
Mitigation from solenoid

- Installation of a solenoid in the field free region of 16L2 further improved the situation

- Simulations show that the solenoid field also has a mitigating effect on the build-up of electron density from a neutral gas density

  → Could prevent instability and beam dump even after gas formation has occurred

6.5 TeV, 10^{20} N_2/m^3, 5 mT



Conclusion

- The 16L2 events were caused by macro-particles released from a source of frozen air (N_2 and O_2) due to an accidental air inlet with beam screens at cold (20 K)
  - Presence of air molecules confirmed by measurements during subsequent warm-up

- Clear experimental evidence that electron cloud was involved in/responsible for the release process of the macro-particles
  - Due to charging of the particle?

- Very strong indications that the beam could deposit sufficient energy in a particle to cause a phase transition to gas → the defining feature of the 16L2 events
  - Crucial for explaining both the loss profile and the strong beam instabilities

- Strong indications that high electron densities were responsible for the associated beam instabilities
  - Qualitatively reproduced in simulation models, but only after including effect of generated ions and electron-induced ionization

Pressure $\approx$ *1 mbar at room temperature (300K)*

Volume $\approx 4\ m^3$

Mol of Air ≈ 0.3

$M_{N2} \approx 8.5\ g$

Density of solid $N_2 \approx 0.8\ g/cm^3$

Condensed Air $V_C \approx 10.5\ cm^3$ *per beam line*

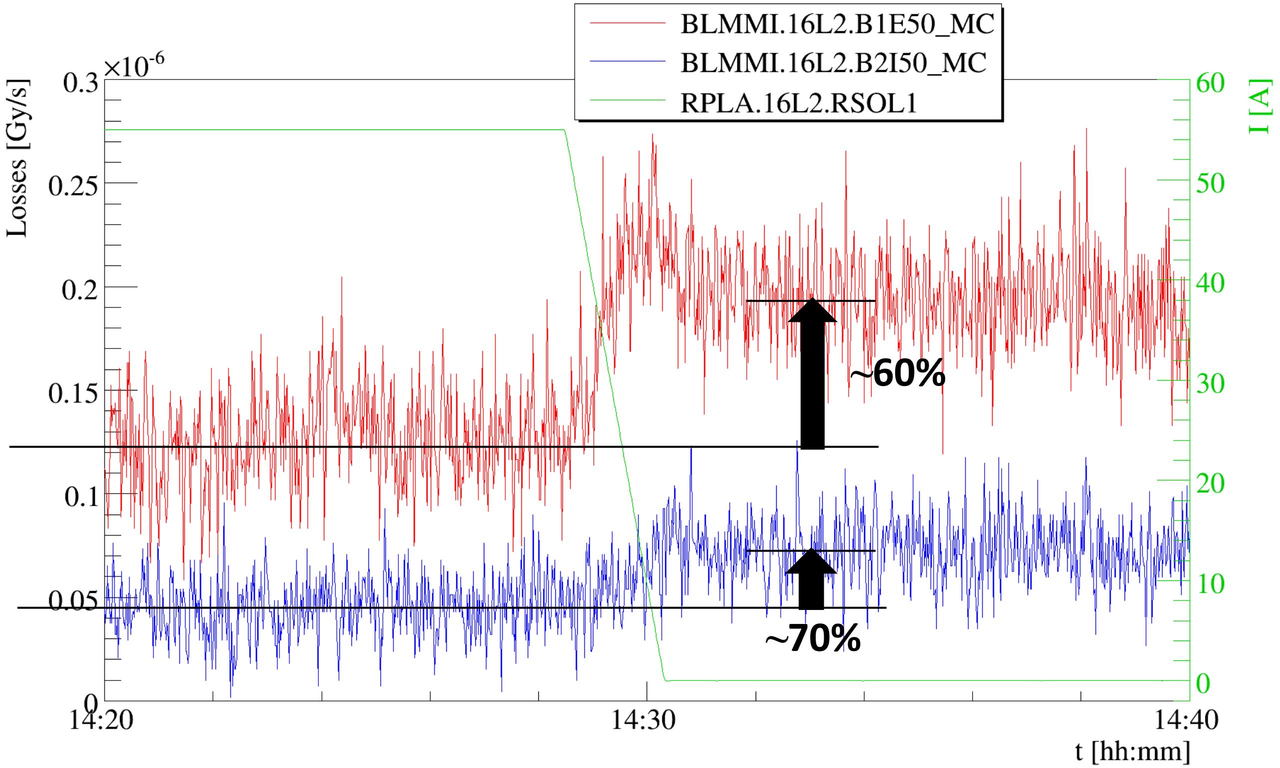
$V_{STP} \approx 7\ l$ *per beam line*

Estimated quantity of water vapor

$M_{H2O} \approx 0.1\ g$ *per beam pipe*

Mitigation from solenoid

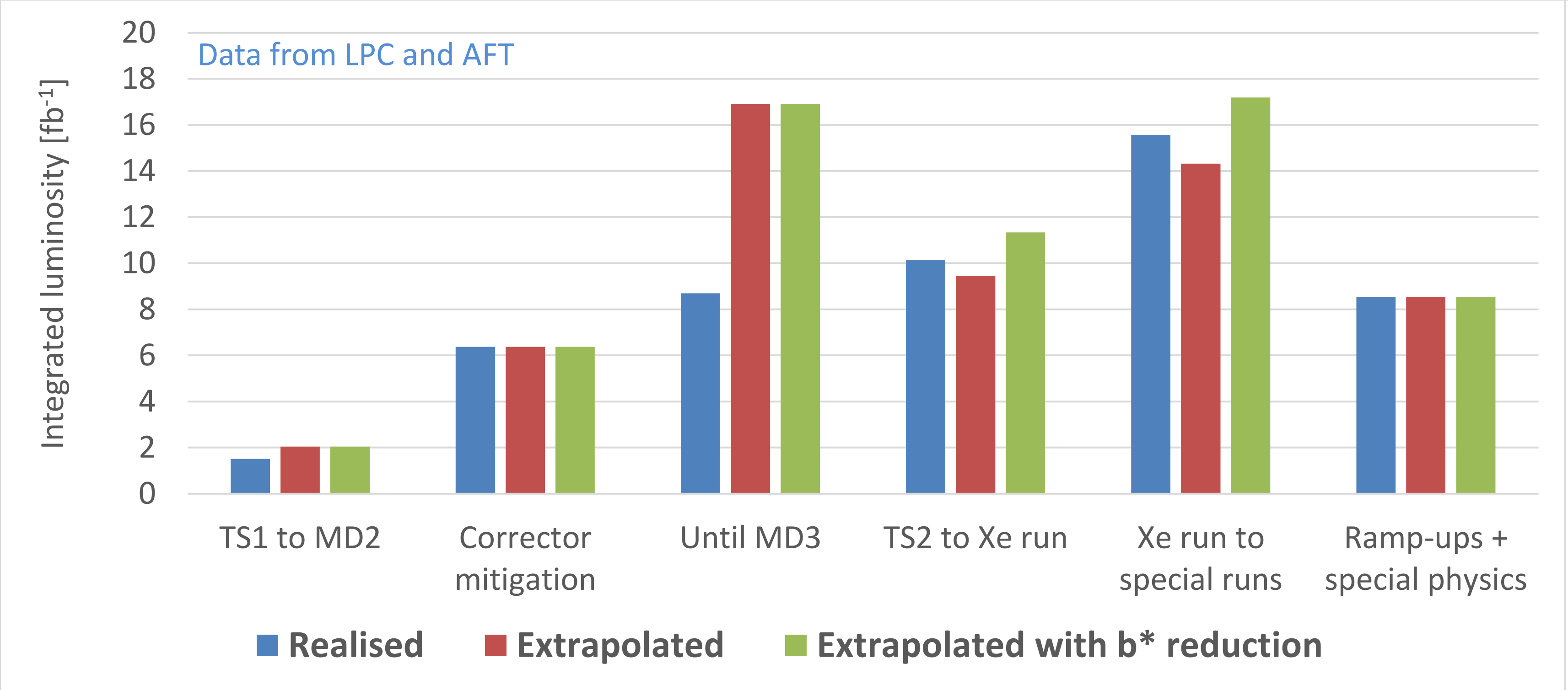
- Installation of a solenoid in the field free region of 16L2 further improved the situation
  - Decreased steady state losses by 60 – 70 %



D. Mirarchi

Impact on performance

- LHC performance in 2017 – what could it have looked like without the 16L2 issue?
  - The corrector current mitigation allowed to run with 2556 bunches for 12 days
  - Assume the same luminosity production per available day for all physics periods
    - Remove fault-time explicitly due to 16L2 (beam loss root cause, beam screen flushing…)
    - Ramp-ups, special physics periods, MDs etc. not included
  - Luminosity gain going to 30 cm β* and 1.22 × 10^{11} ppb estimated to 20% (after TS2)



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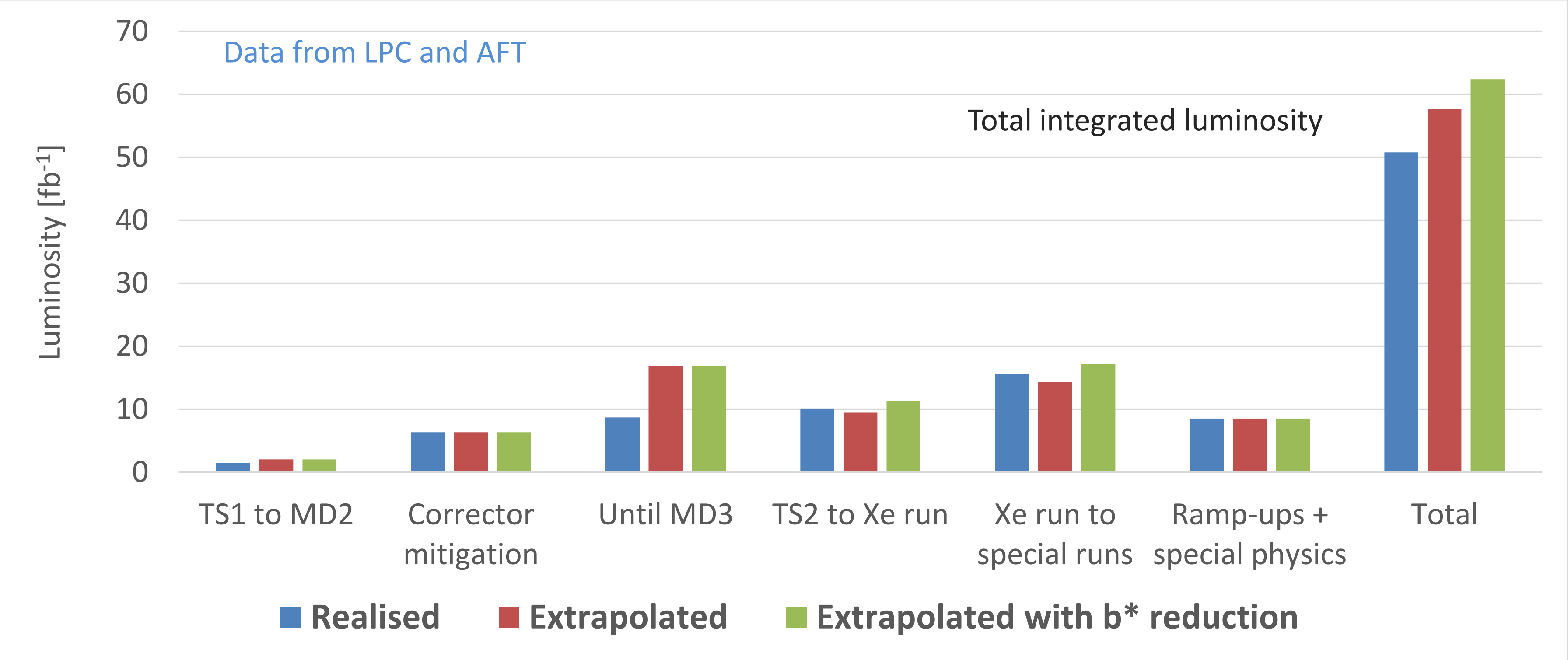


Instability modelling

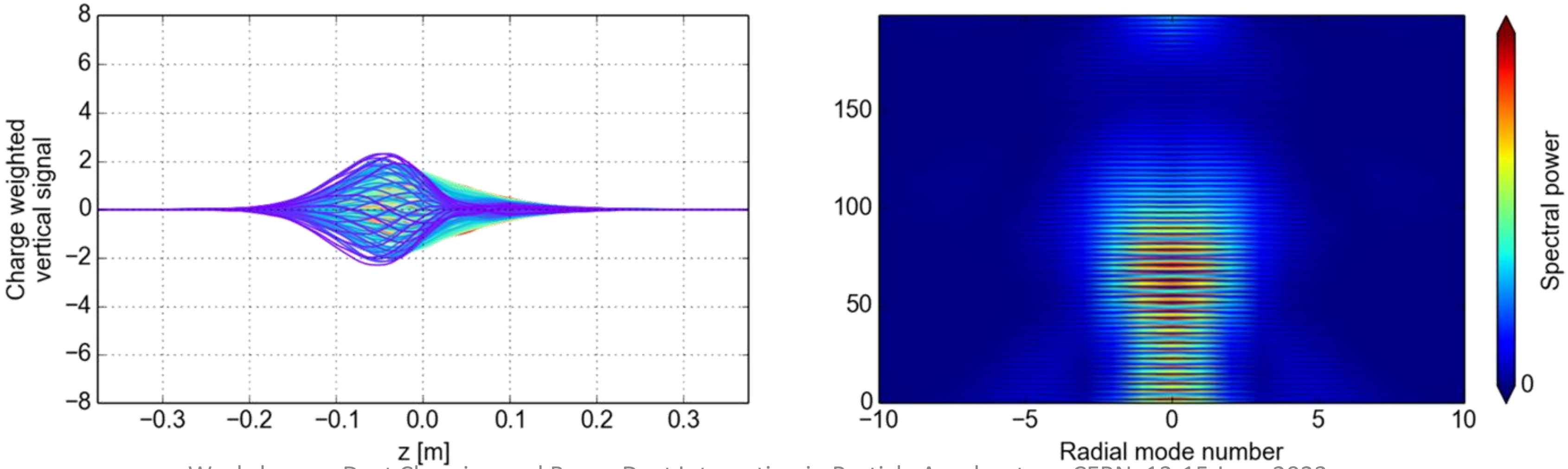
- For a tune shift of 10^{-2}, the required electron density is ~5e17 m^{-3} over 10 cm
  - Estimated based on formula for ion trapping in electron machines

X. Buffat

- An equivalent broad-band resonator impedance model for an e-cloud
  - Based on F. Zimmermann et al
  - Shunt impedance R_s = 150 – 500 MΩ/m at frequency f_r = 2.6 GHz
  - Could reproduce observed rise time and intra-bunch motion

N. Biancacci *et.al*

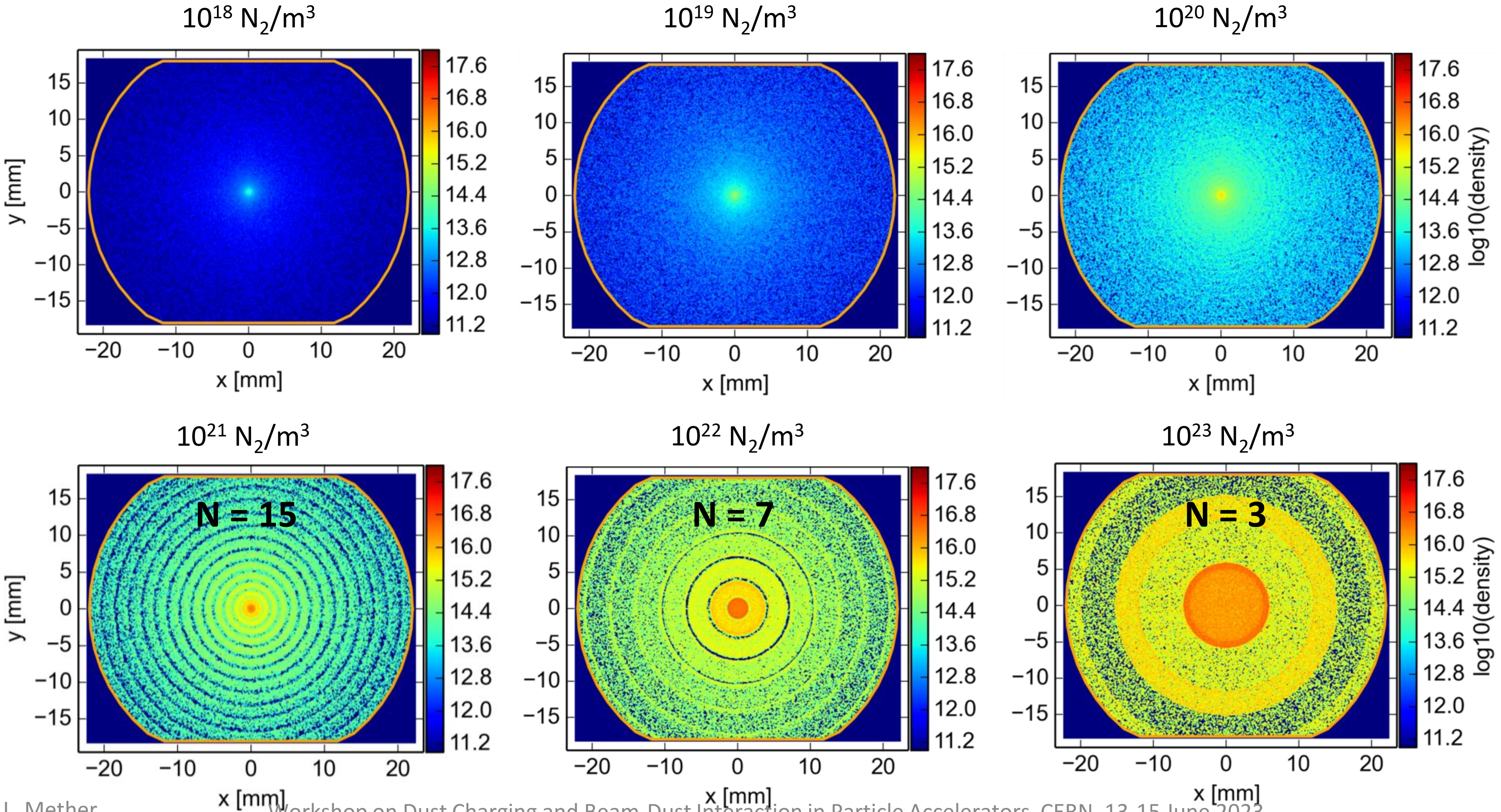
- Electron cloud simulations confirm that a density of 10^{17} m^{-3} over 10 cm may lead to
  - A positive tune shift of 10^{-2}, instability rise times below 100 turns, and intra-bunch motion at the tail of the bunch



Ion distribution

"Rings" in the ion distribution consist of ions generated at different bunch passages

- The number of rings corresponds to the time it takes for the ions to reach the chamber wall and is determined by the ion e-field

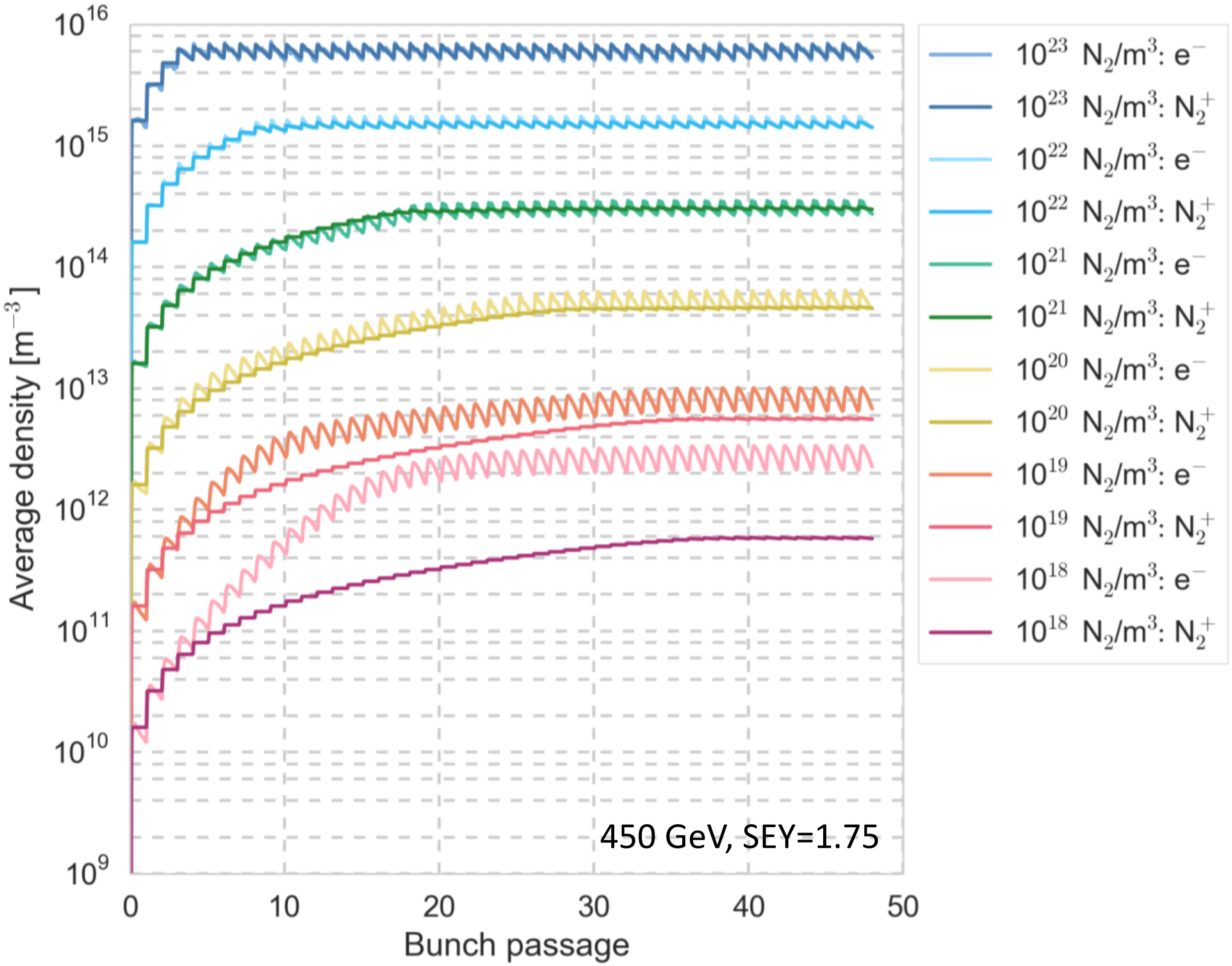


10^{18} N_2/m^3 10^{19} N_2/m^3 10^{20} N_2/m^3

10^{21} N_2/m^3 10^{22} N_2/m^3 10^{23} N_2/m^3

Multi-species build-up

Multi-species simulations show that electron multipacting becomes less important than beam-induced ionization from gas densities around 10^{20} N_2/m^3 and the dynamics are qualitatively and quantitatively different compared to single-species simulations



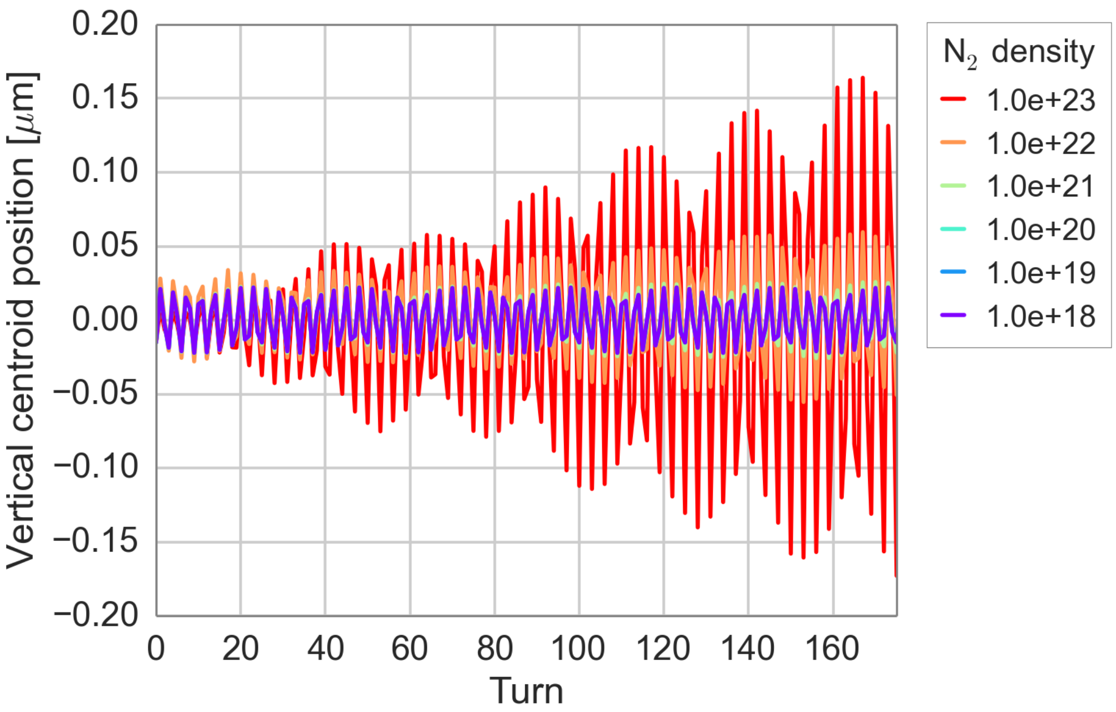
450 GeV, SEY=1.75

Stability studies

The first multi-species beam dynamics simulations show instabilities from gas densities of 10^{22} N_2/m^3 over the length $L = 10$ cm, corresponding to $10^{21}\,L^{-1}m^{-2}$

- This covers only the upper range of the observed instabilities in the machine ($10^{19} – 10^{21}\,L^{-1}m^{-2}$)

- Electron-induced ionization may help to increase the electron and ion densities for a given gas density



Electron-induced ionization

- The beam-gas ionization cross-section at injection and top energy is estimated to be around 2 Mb = 2 × 10^{-18} cm^2
- 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 during the simulations

BUG *et al.*, Phys. Rev E.88

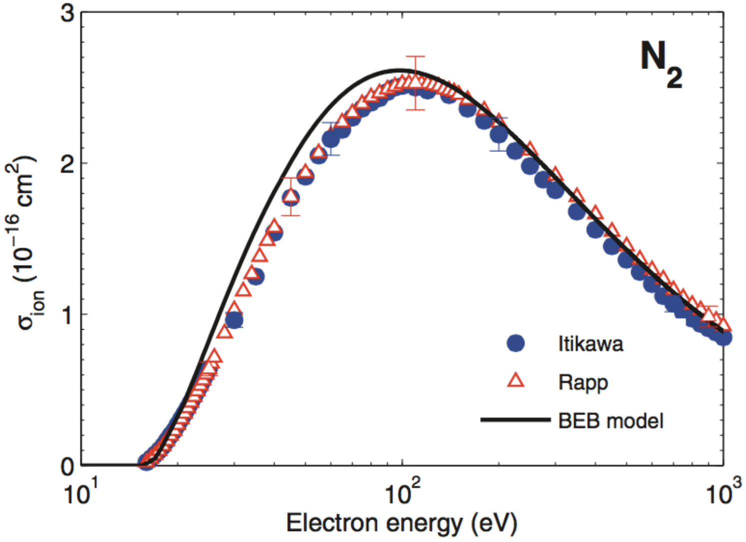


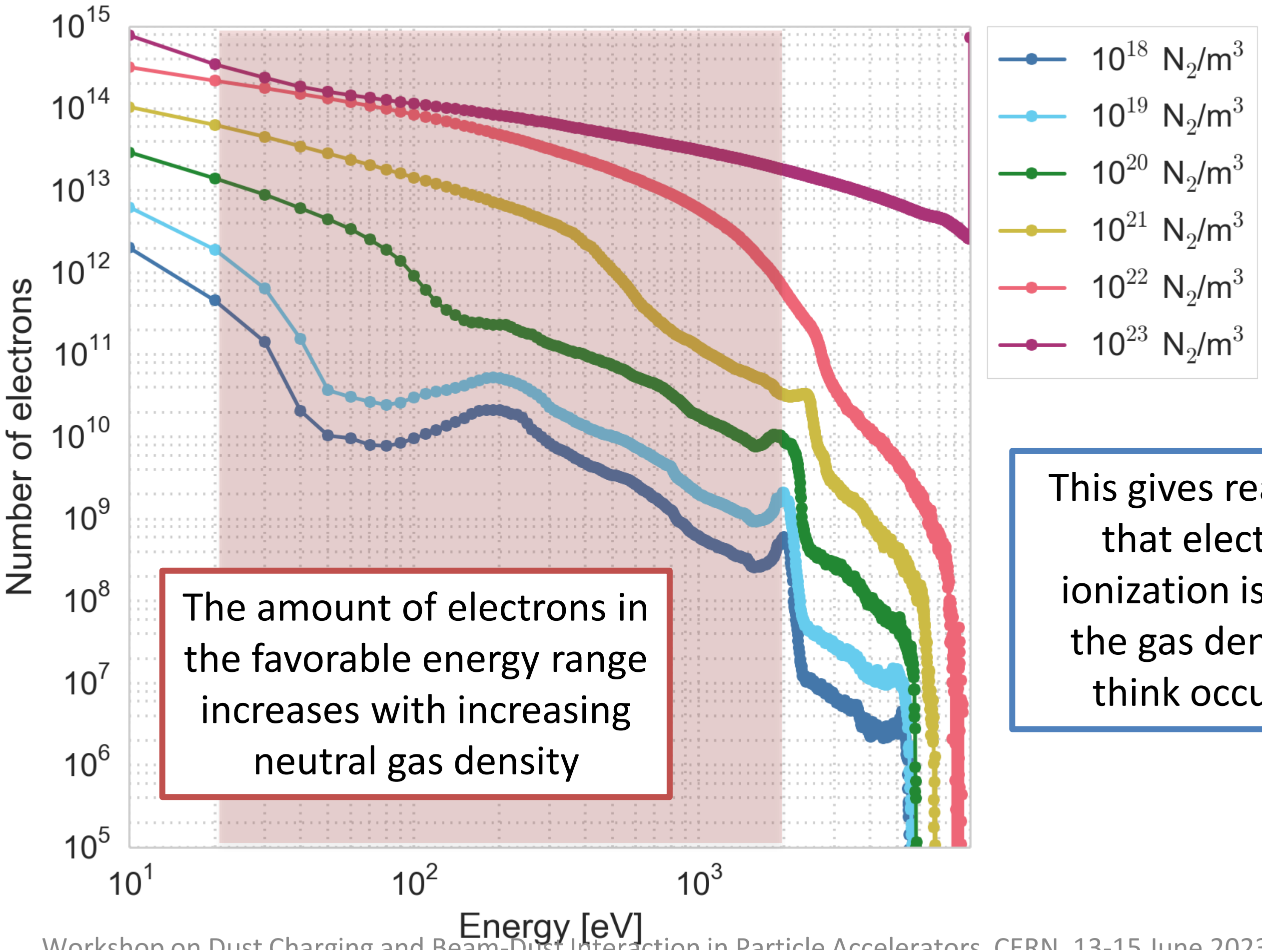
FIG. 1. (Color online) Electron-impact-ionization cross sections σ_{ion} of nitrogen recommended by Itikawa [16], measured by Rapp and Englander-Golden [17], and determined using the BEB model [18].

Electron energy spectrum

Electron energies during the multi-species build-up were previously analysed

- See e-cloud meeting #67

Energies are favourable for electron impact-ionization in particular for neutral gas densities of $10^{20} – 10^{22}$ N_2/m^{-3}



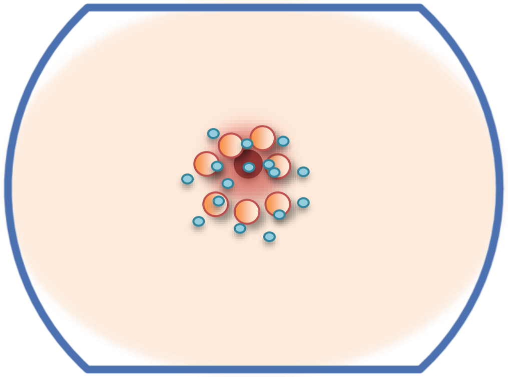
The amount of electrons in the favorable energy range increases with increasing neutral gas density

This gives reason to believe that electron impact-ionization is important for the gas densities that we think occurred in 16L2

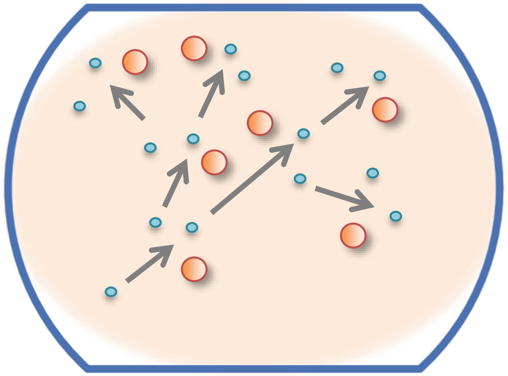
Recent studies and development (2019)

- Implementation of cross-species ionization
  - For the implementation of the cross-species ionization, we keep the same simplifying assumptions as are made for the beam-induced ionization
  - Assume a uniform gas density in the chamber
    (no neutral macro-particles, no collisions → not full-scale plasma simulations)
  - Single ionization only

Beam-induced ionization



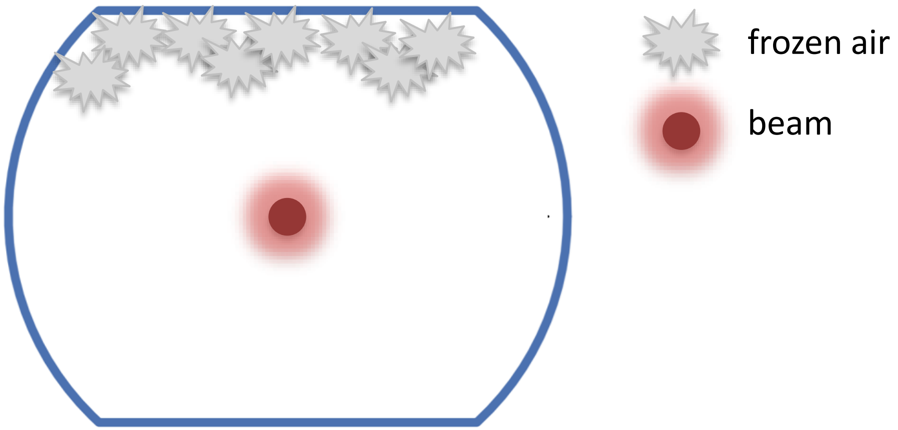
Electron-induced ionization



- See e-cloud meeting #69

Sequence of events in 16L2

The problems in 16L2 were caused by air frozen inside the beam chamber, through the following sequence of events:



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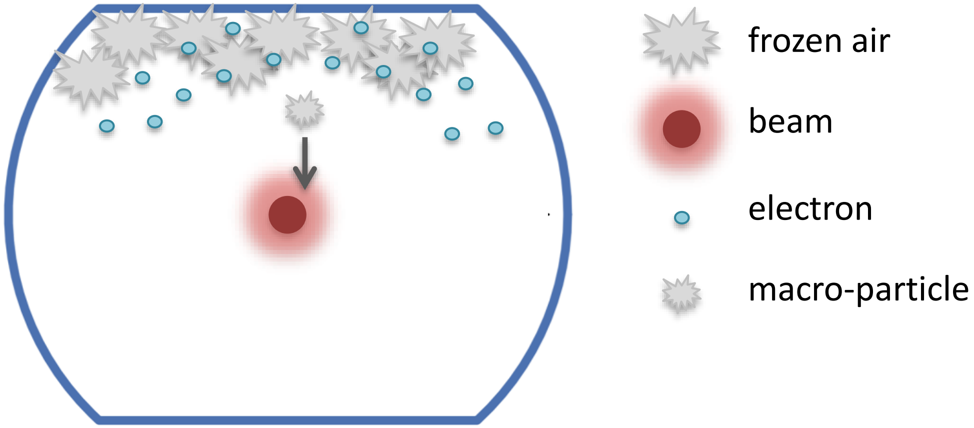
triggered by e-cloud?



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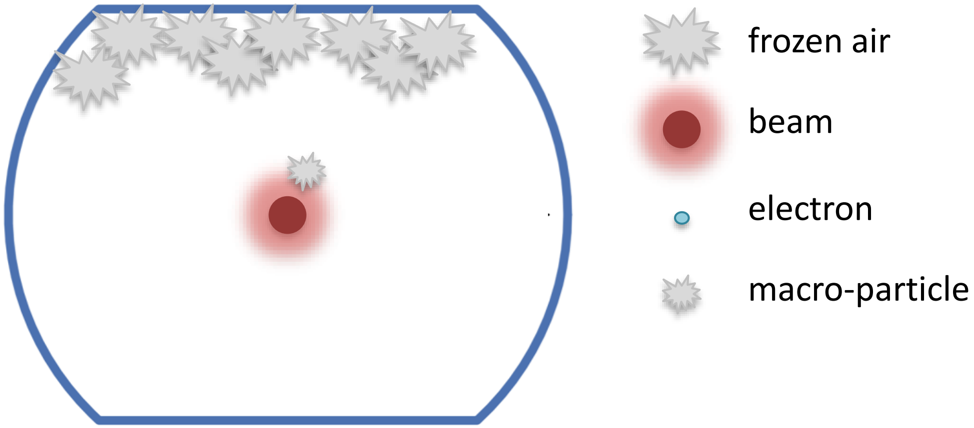
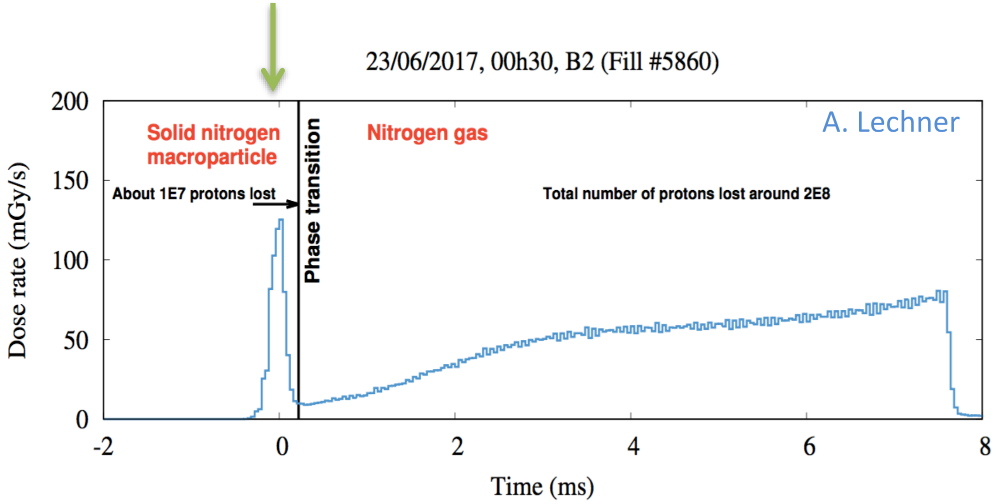
and enters the beam





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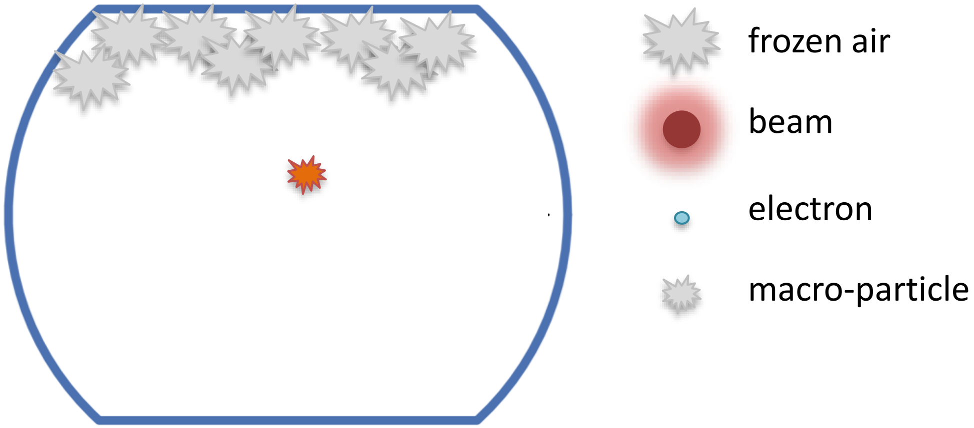
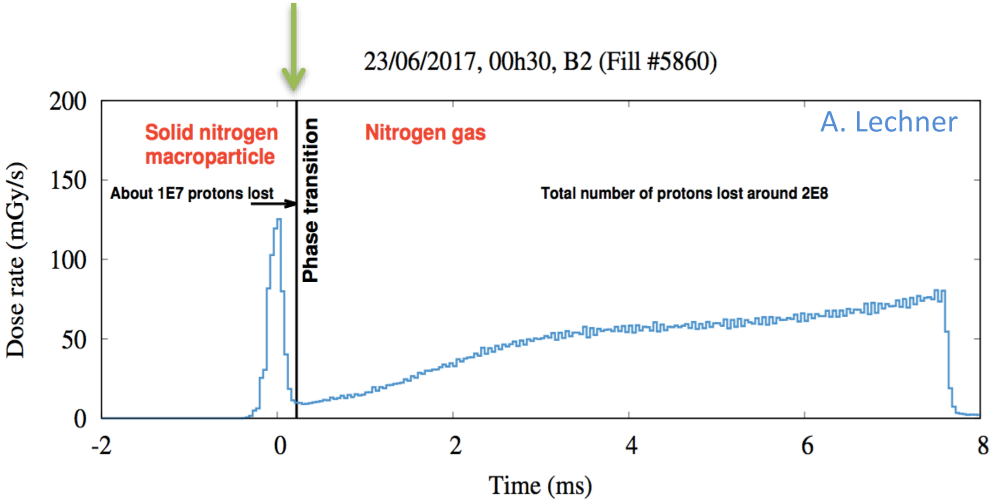
The macro-particle undergoes a phase transition to a gas





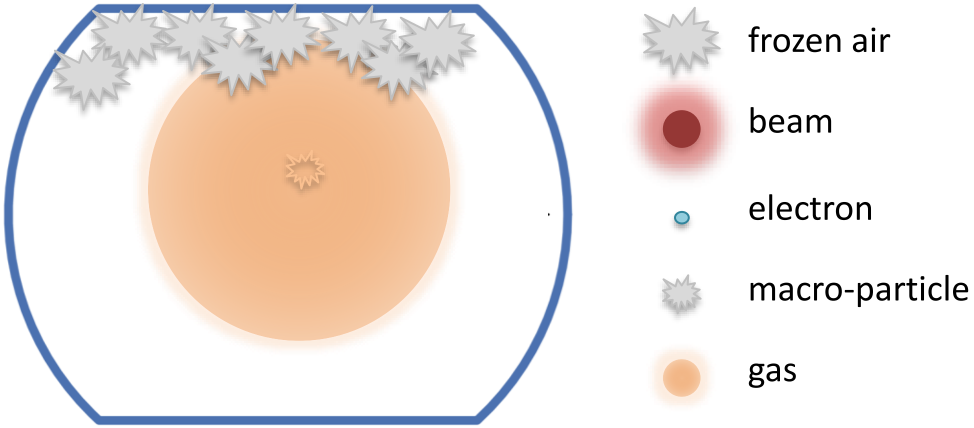
Sequence of events in 16L2

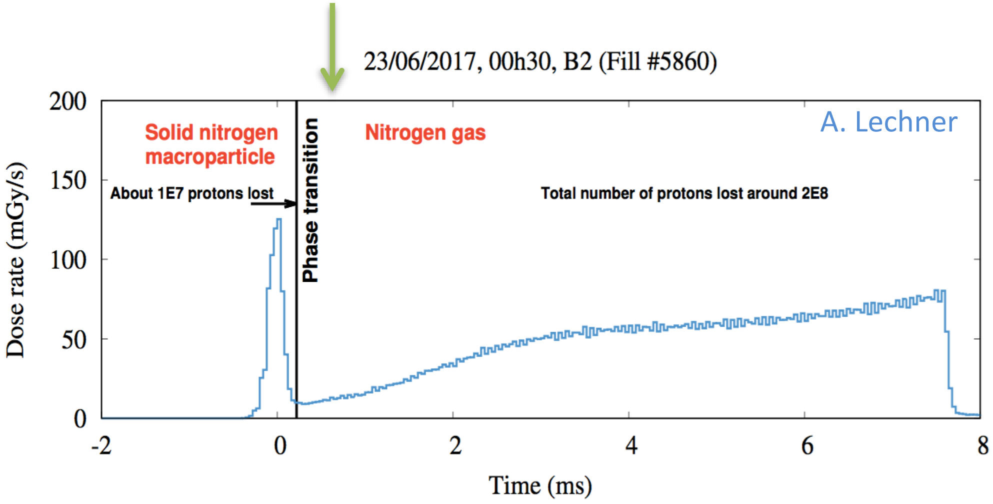
The problems in 16L2 were caused by air frozen inside the beam chamber, through the following sequence of events:

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

↓

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





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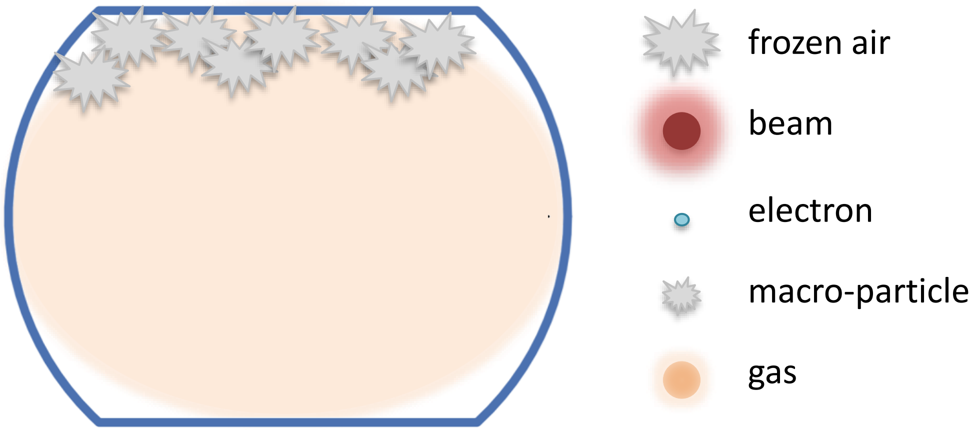

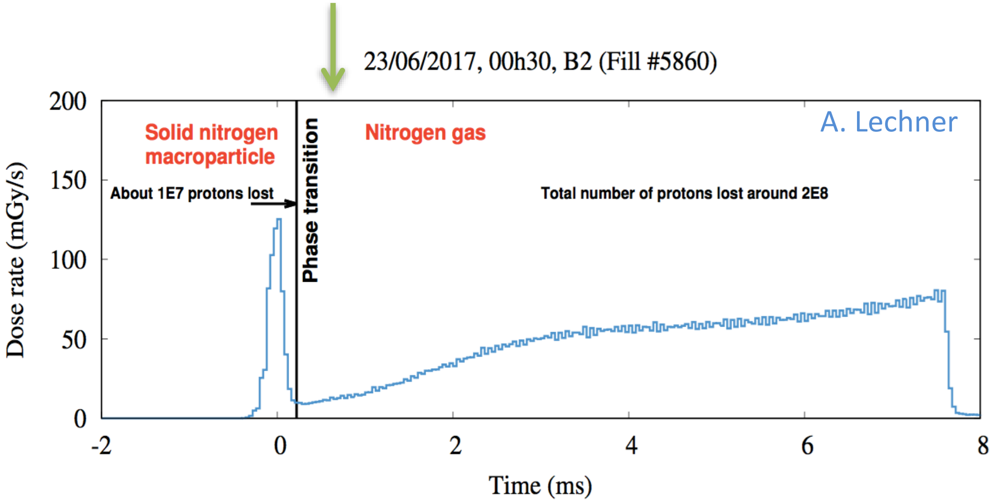
23/06/2017, 00h30, B2 (Fill #5860)

A. Lechner

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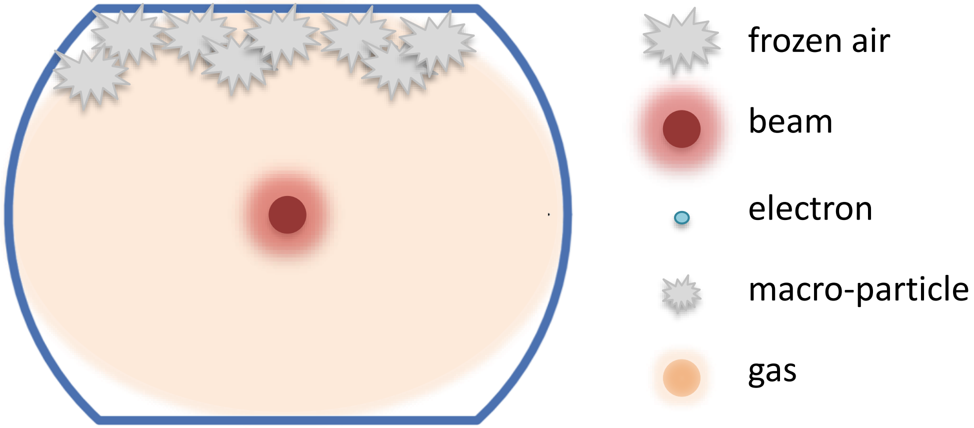
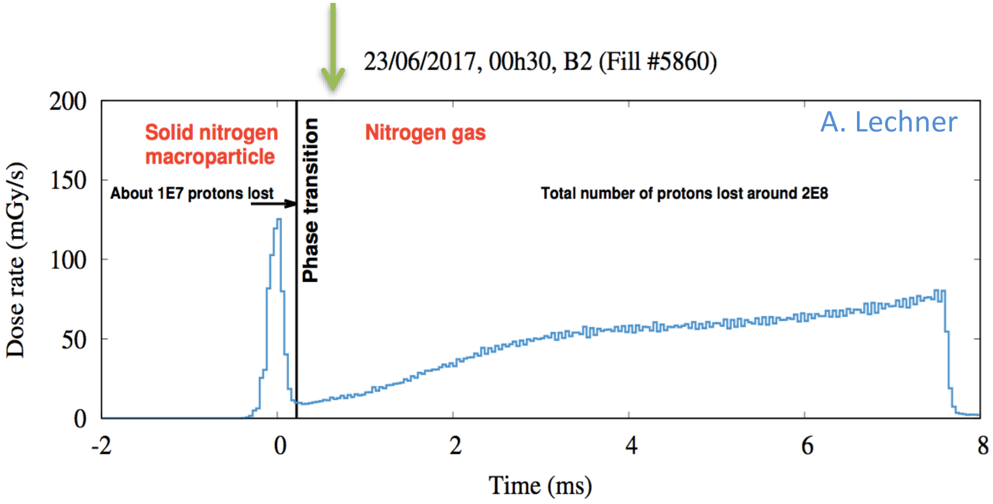
The macro-particle undergoes a phase transition to a gas, leading to a a high local gas density

The beam ionizes some of the gas in its path

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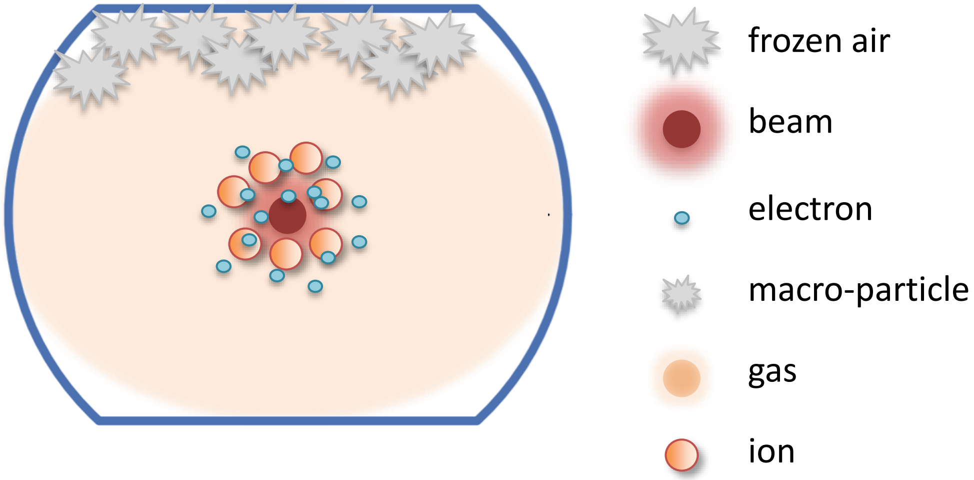

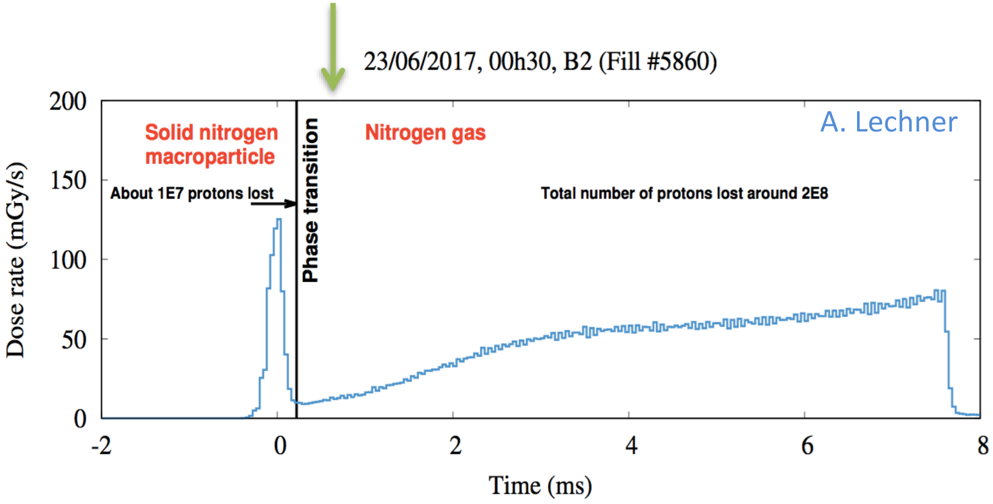

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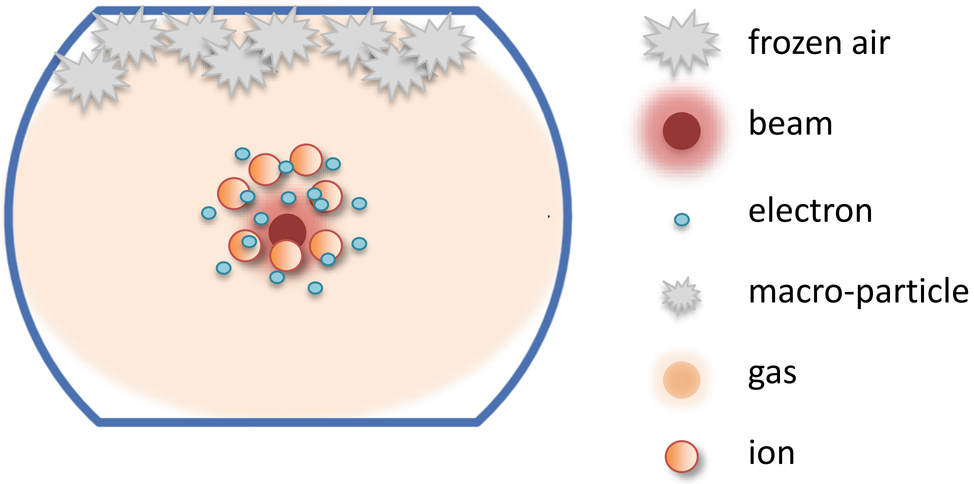
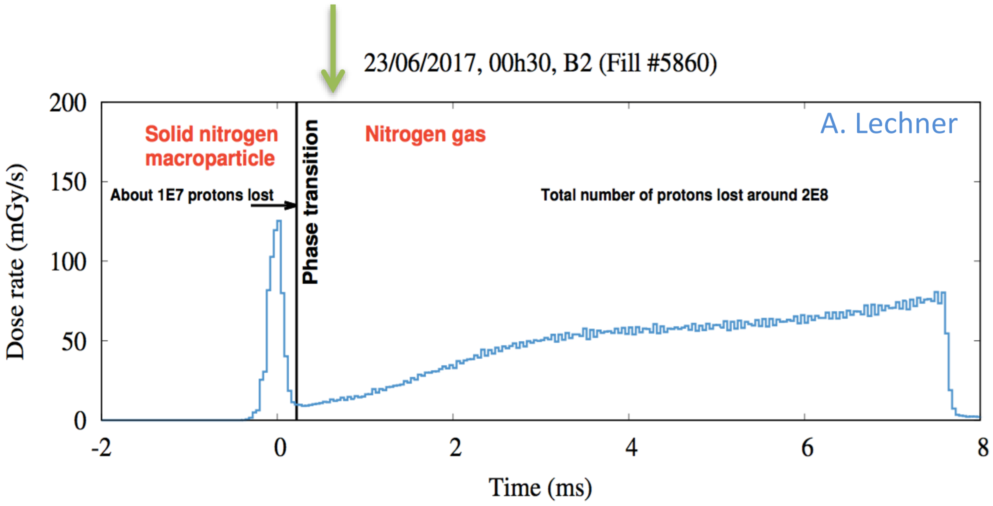
The beam ionizes some of the gas in its path. Its interaction with the generated electrons/ions causes the fast instabilities





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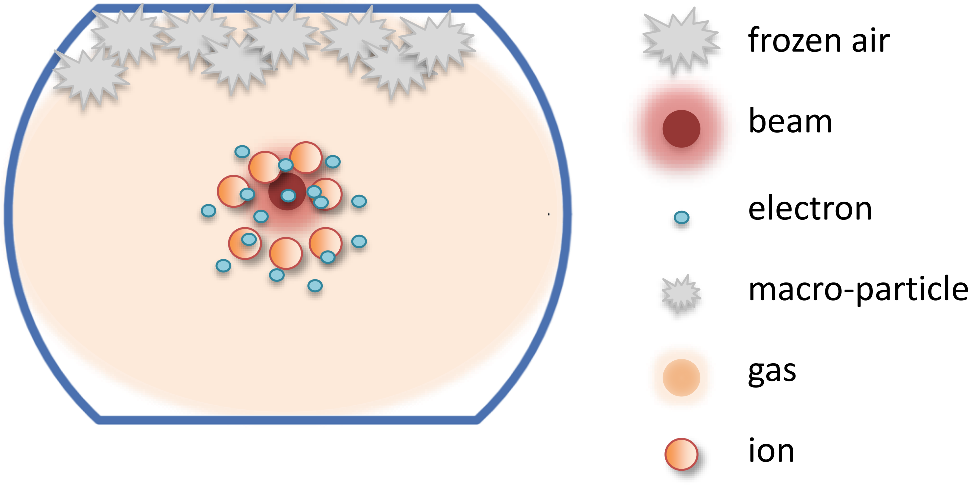

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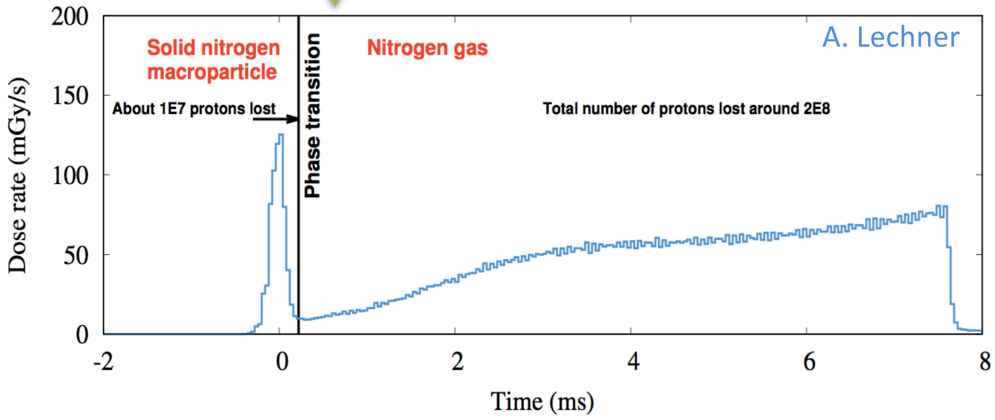

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