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16L2 modelling: status and plans

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Sequence of events in 16L2

The problems in 16L2 are thought to have been caused by air that was left in the vacuum system after the EYETS and frozen inside the beam chamber:

Macroparticles or "flakes" of the frozen gases (mainly nitrogen or oxygen) could be detached, possibly triggered by e-cloud, and enter the beam

→

The energy deposited by the beam in the macro-particle could be sufficient to induce a phase transition to a gas, leading to a local pressure bump of high density

→

The beam would ionize some of the gas in its path, and the fast instabilities could be due to its interaction with the generated electrons and/or ions

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Our aim is to try to validate the last part of the sequence of events by modelling.

Starting from the assumption that there is a high (uniform) gas density in the beam chamber, can we reproduce the observations in a consistent manner?

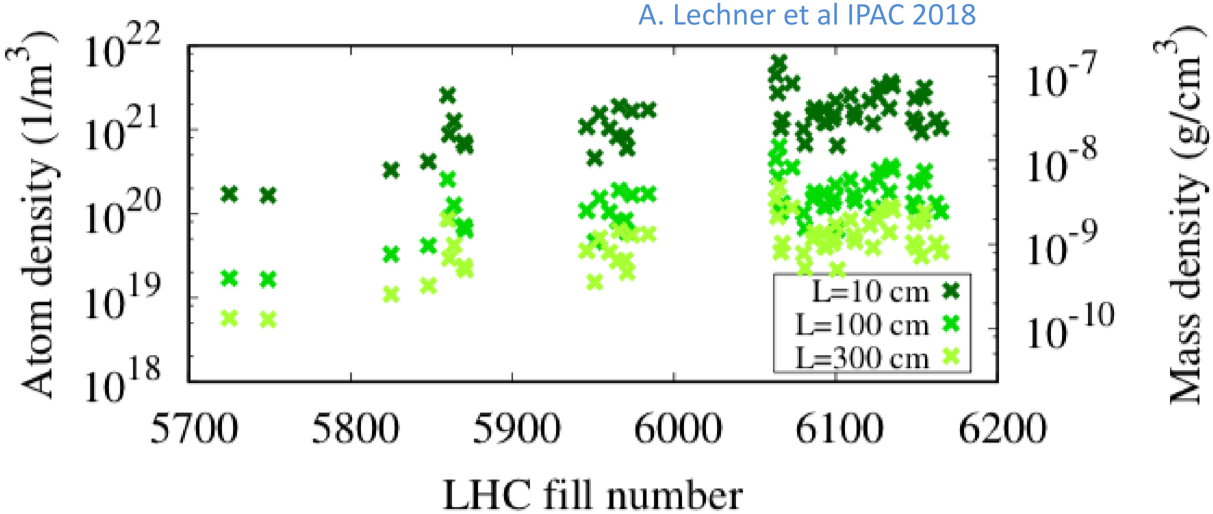
Constraints from loss observations

The source of the losses is most likely in (at least partly) in a drift space

Atomic densities in 16L2 were estimated based on the measured loss rates

- The location of the losses could be identified to within around 1 m
- Assuming N_2 gas and a pressure bump extending transversally over the full beam cross section and over the length L → density range ~ $10^{19} – 10^{21}\ L^{-1}m^{-2}$
- Events were observed for all densities in the range

A. Lechner et al IPAC 2018



Instability observations

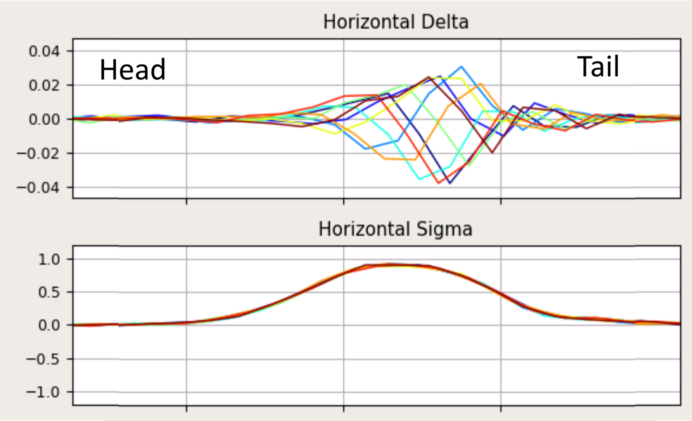
Very fast instabilities, with rise times typically between 1 – 100 turns

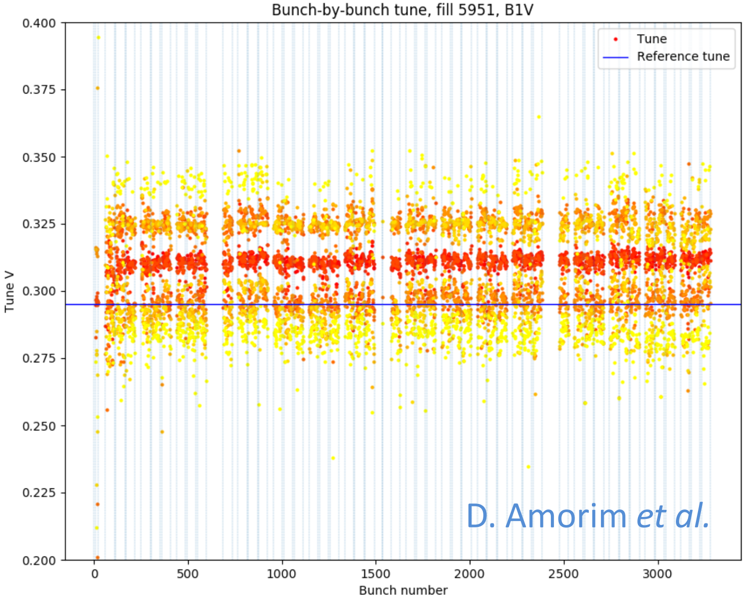
- Varyingly single-bunch and coupled-bunch motion

Several characteristics pointed specifically to the involvement of electrons:

- Intra-bunch motion at the tail of bunches
- Positive tune shifts (up to 10^{-2})
- Several considerations implied that electron densities of 10^{16} L^{-1}m^{-2} over a length L could induce such effects

B. Salvant, T. Levens





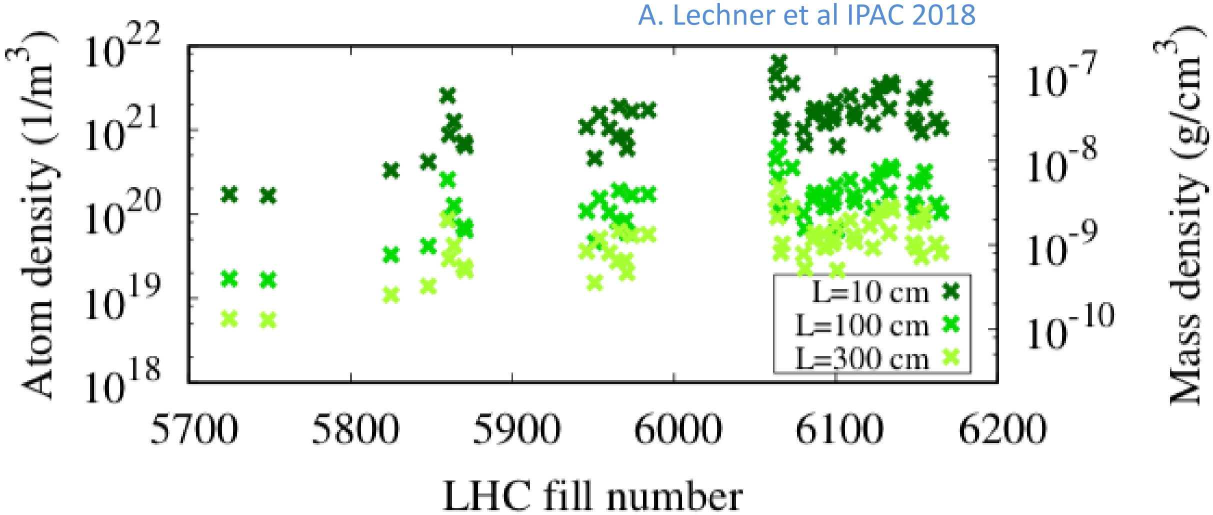
D. Amorim *et al.*

Simulating the 16L2 pressure bump

Gas ionization and electron/ion impact model:

- Ions and electrons are generated based on an input atomic density according to the cross-section for beam-induced ionization
  A. Mathewson, S.Zhang, LHC-VAC/AGM, 1996
- Ions reaching the chamber walls are absorbed without any further effect
- Electrons can produce secondary electrons when hitting the wall according to the usual SEY models
- The atomic density range $10^{18} - 10^{23}\ m^{-3}$ essentially covers the predicted range, including the uncertainty in length

A. Lechner et al IPAC 2018



Stability studies with single species

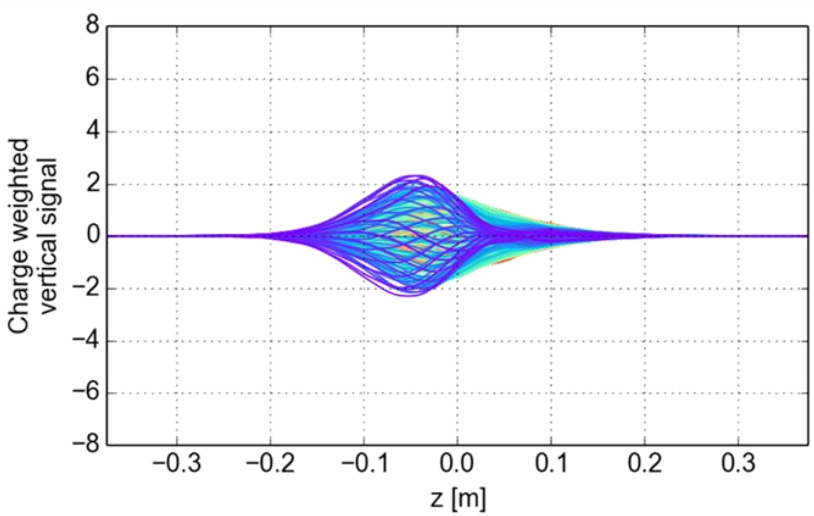
Initial stability studies (with cloud space charge turned off) showed that electron densities of $10^{16}\ L^{-1}\mathrm{m}^{-2}$ over the length L = 10 cm could indeed induce the observed effects

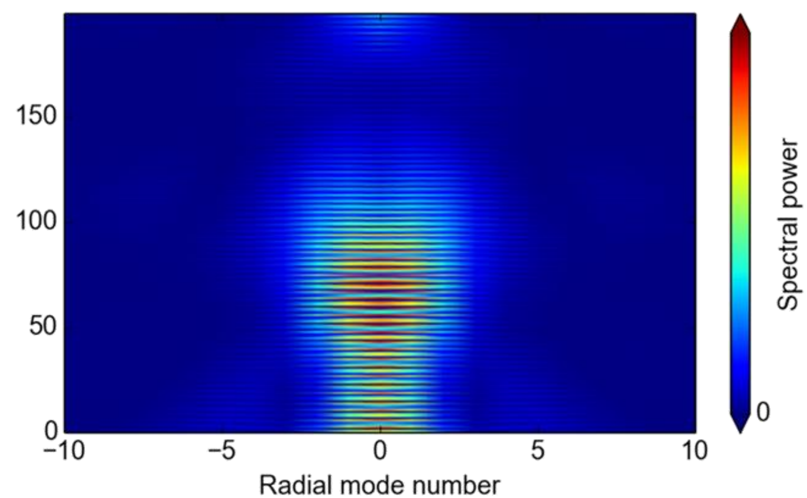
- Fast rise times, tune shifts up 10^{-2} and intra-bunch motion (although not exact match)

However, stability studies with electrons generated through beam ionization suggested that gas densities around $10^{26}\ \mathrm{m}^{-3}$ would be required to induce such effects

- That is several orders of magnitude higher than expected from losses

In addition, equivalent ion simulations showed that ions would induce strong instabilities already for gas densities of $10^{24}\ \mathrm{m}^{-3}$



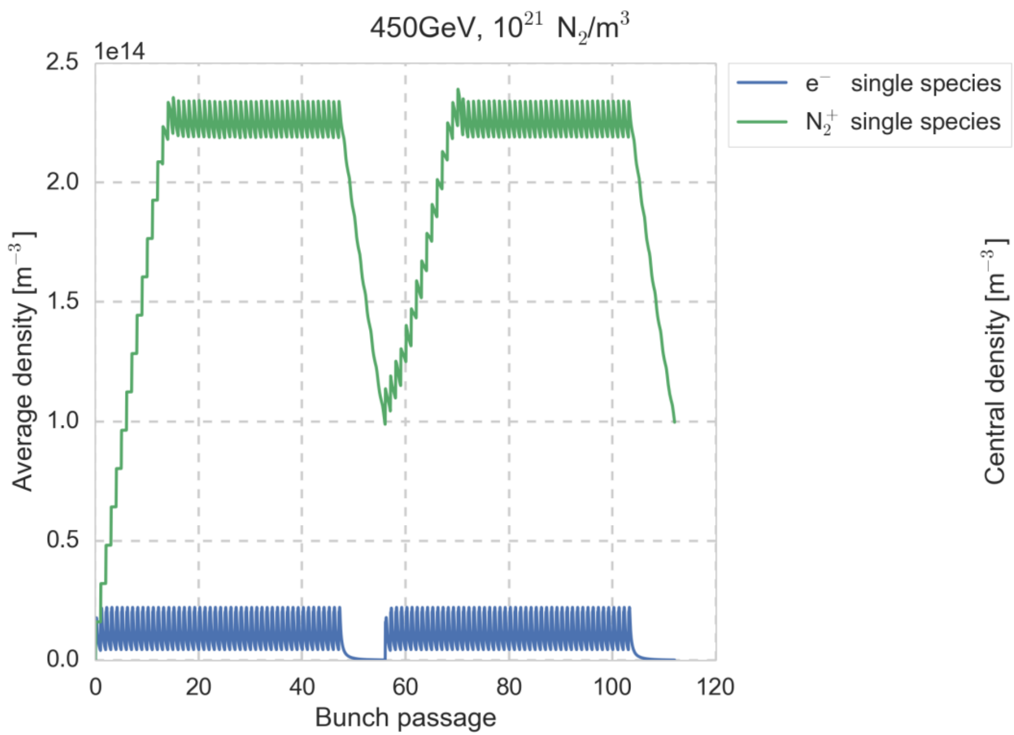


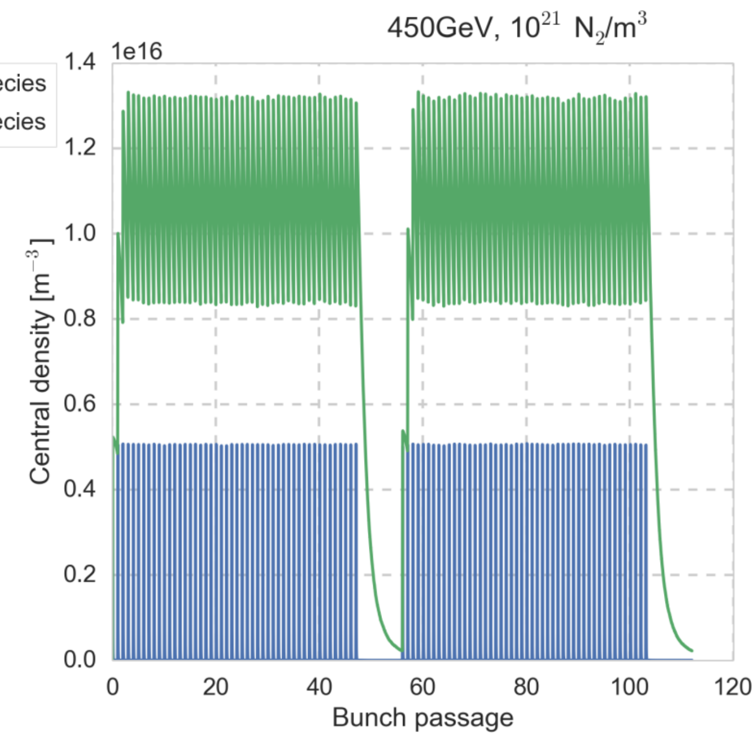
Build-up with single species

Build-up studies with single species show no build-up of electrons along bunch trains

On the contrary, a build-up of the average ion density by around a factor 10 is seen

- However, since the ions move away from the beam location as soon as they are produced, the build-up is not expected to significantly modify the stability along the bunch train





Studies with single species

The combined single species stability and build-up studies suggest that it is not possible to generate high enough electron densities to induce the observed effects

- Ions and electrons are produced in equal amounts by beam ionization, and ions would drive the beam unstable at lower gas densities

In addition, both for ions and electrons, the gas densities required in the simulations to produce instabilities within the observed number of turns are inconsistent with loss observations

However, it is not surprising that these studies are inconsistent with observations

- By simulating the two species separately, we are making the assumptions that they don't influence each other in any way
- At lower densities this may be a good assumption, but certainly not at the high (charge) densities involved in this special case

To study the problem and try to reproduce the observations we set out to extend the simulation tools to be able to simulate both species together

Multiple species in PyECLOUD

To enable multiple species in PyECLOUD, the concept of *clouds* was introduced:

- Each cloud has its own macro-particle system, dynamics, impact and generation processes (secondary emission, photoemission, generation through gas ionization)

Clouds interact with each other only through their space charge, for now

- May be extended with cross-species interactions, e.g. electron-induced ionization

Main elements in the build-up simulation:

```
beam and timing
space charge
secondary beams flag
secondary beams list
+
multiple clouds flag
cloud list
```

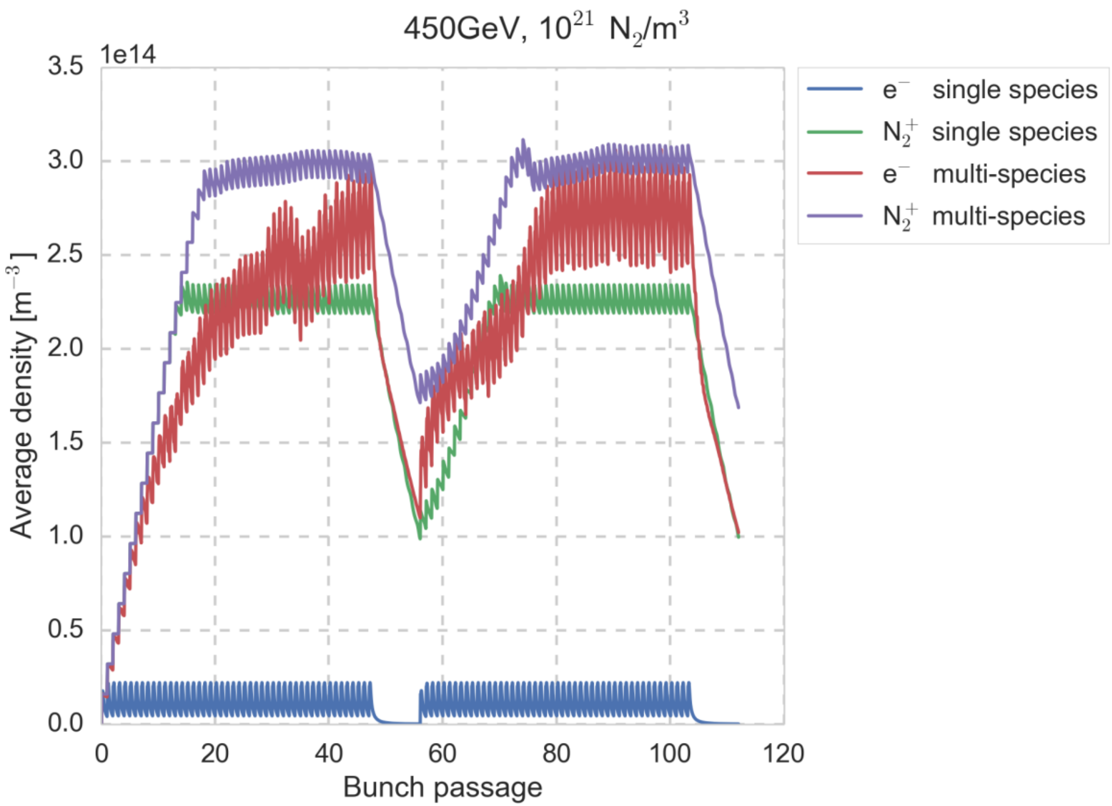
cloud:

```
cloud.MP system
cloud.dynamics
cloud.impact management
cloud.pyecloud saver
cloud.gas ionization flag
cloud.gas ionization
cloud.photoemission flag
cloud.photoemission
cloud.rho copied from sc
```

Build-up with multi-species

The multi-species build-up studies confirm that the electrons and ions do significantly influence each other

- The average density of both species builds up over several bunch passages
- Electron densities are enhanced by roughly an order of magnitude, ions less (the effect depends also on the beam energy, gas density and SEY)



Build-up with multi-species

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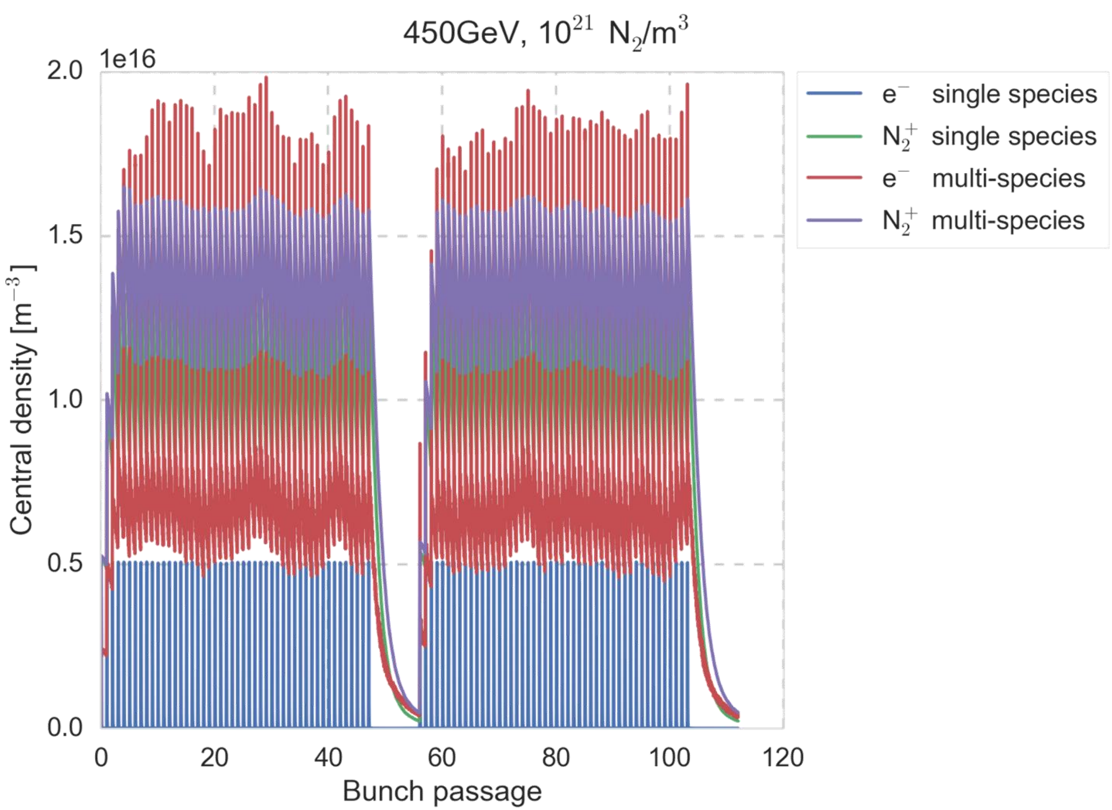
- The average density of both species builds up over several bunch passages
- However, the densities in the centre of the chamber during the bunch passage seem to stay roughly constant after the first few bunch passages

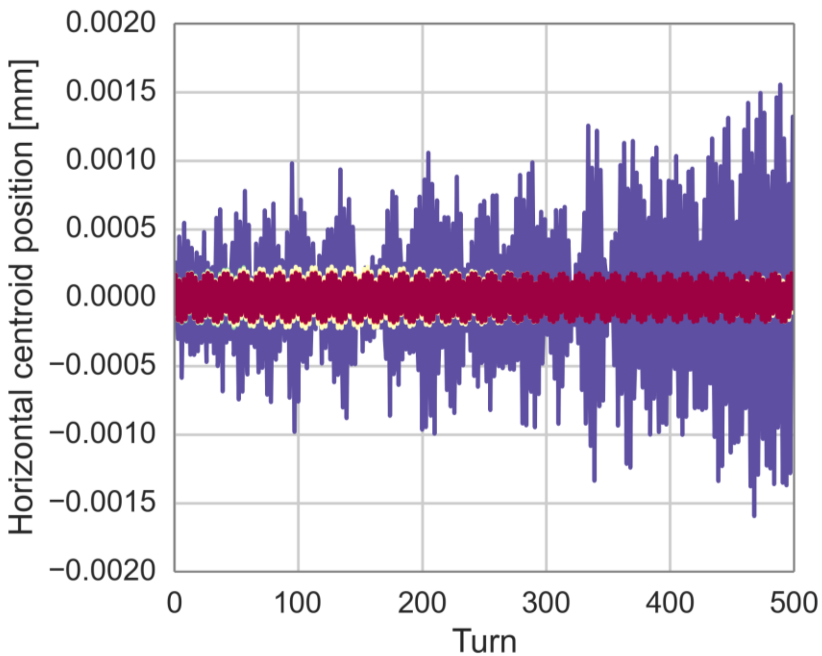


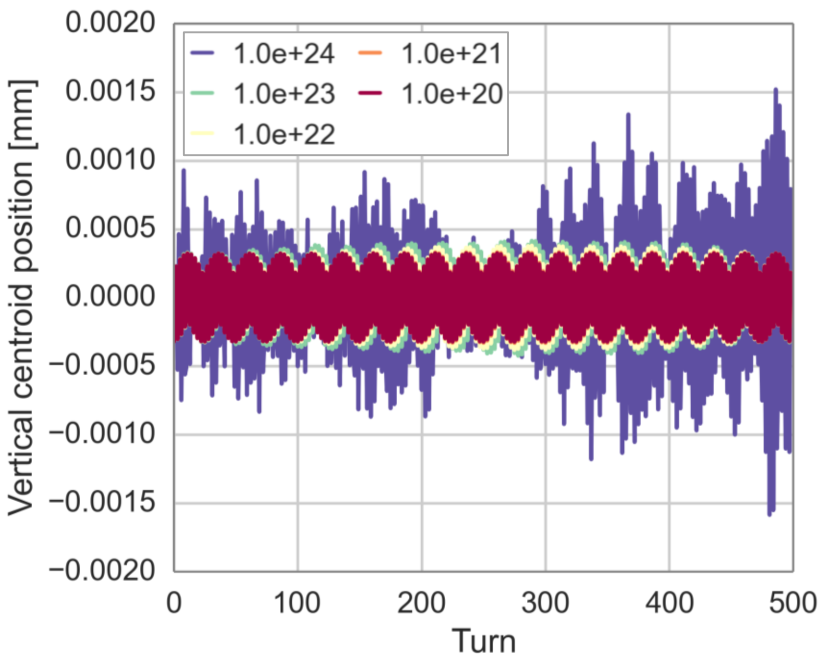
Stability studies with multi-species

The first multi-species stability studies show the onset of instability at a density of 10^{24} m^{-3} for the first bunch in the train

- This is still a higher density than predicted from the losses
- The characteristics of the instability are similar to the single-species ion instabilities

However, the dynamics could be different towards the end of the train, where the ion-to-electron ratio in the centre of the chamber during the pinch is different

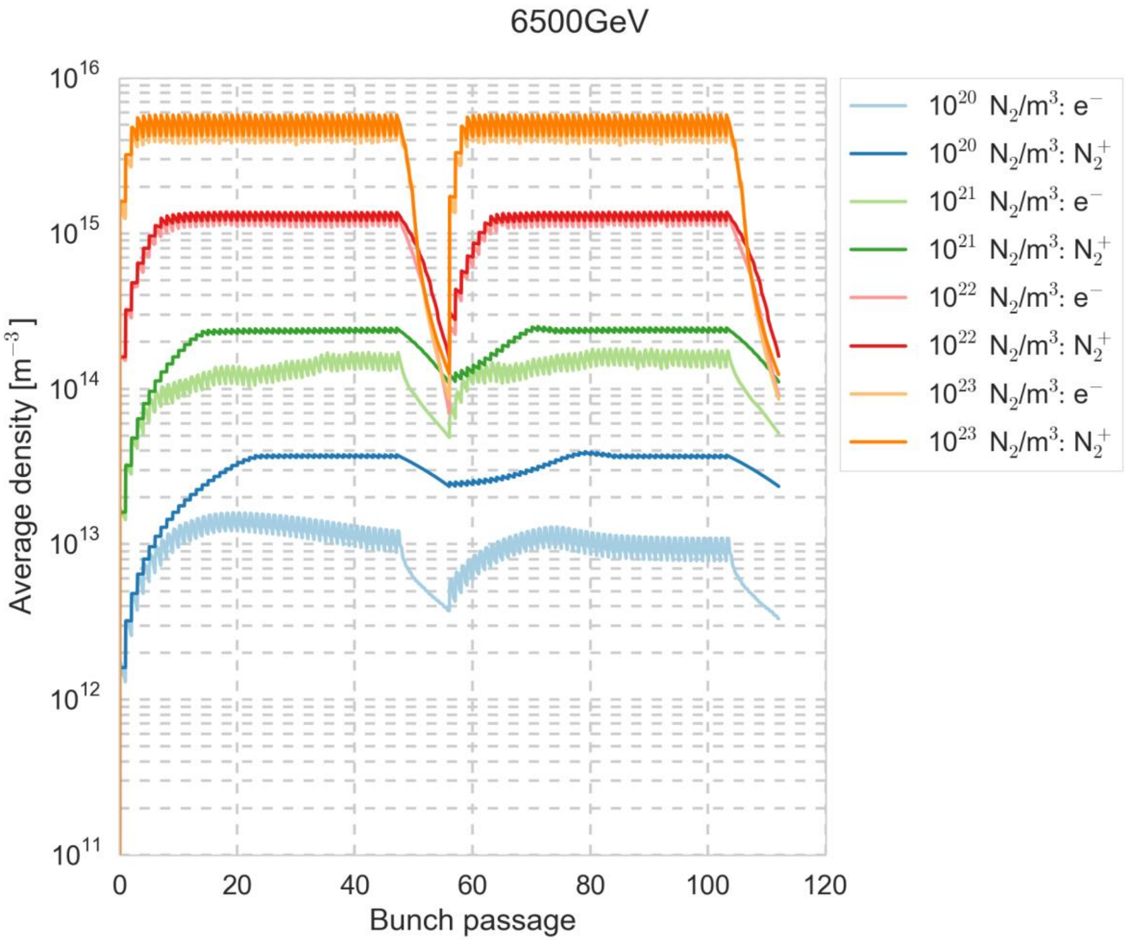




Build-up with different parameters

Before setting up instability studies with saved electron and ion distributions, we wanted to study how these depend on various parameters

- The average electron and ion densities after saturation seem to depend roughly linearly on the gas density



Build-up with different parameters

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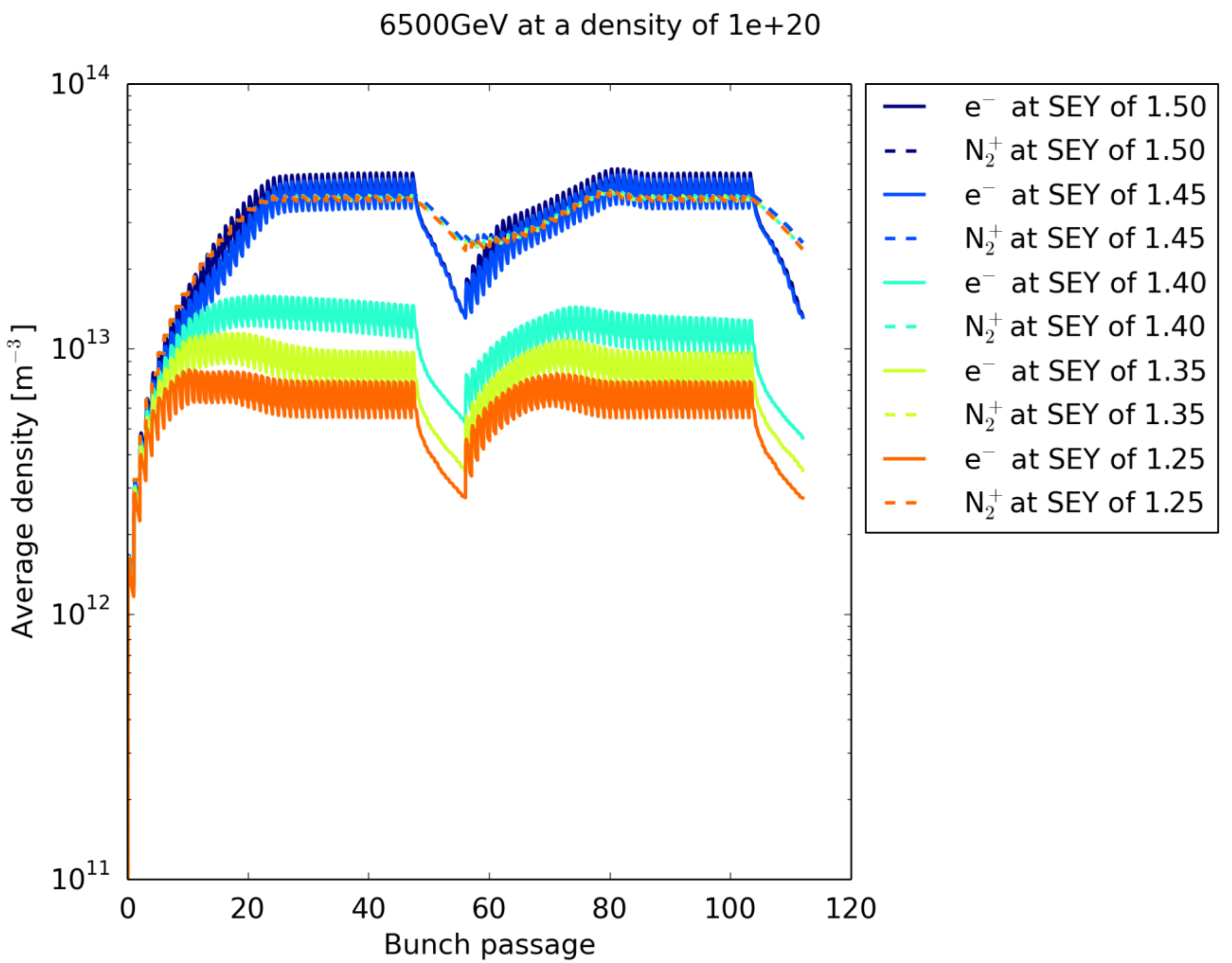
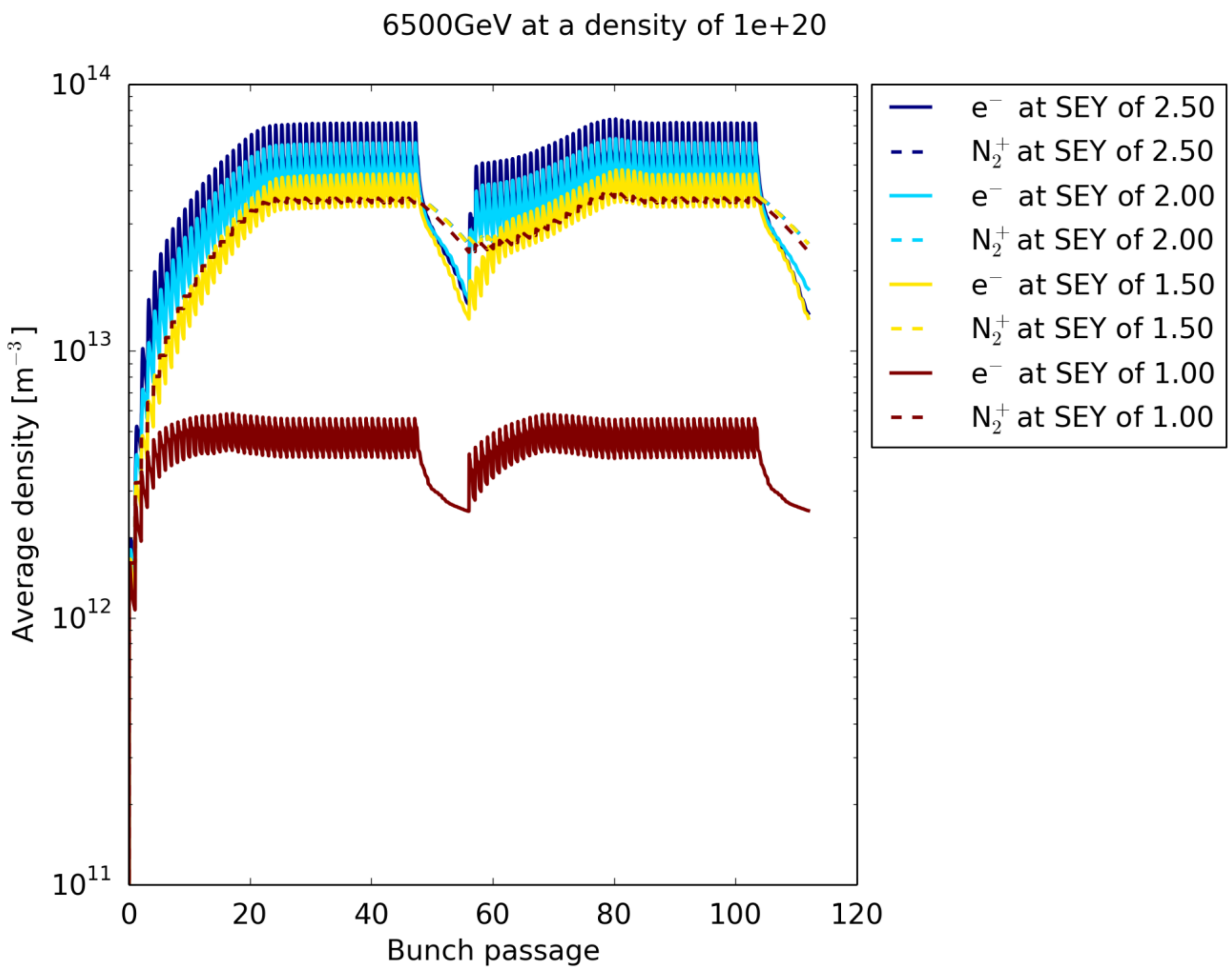
- At lower gas densities, the electron density at saturation depends on the SEY (threshold at 1.4-1.45)



Build-up with different parameters

Before setting up instability studies with saved electron and ion distributions, we wanted to study how these depend on various parameters

- Above threshold the electron density doesn't depend very strongly on the SEY



Studies with multi-species

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The multi-species build-up studies confirm that we did not capture the full dynamics with single species – a build-up of ion and electron densities occur over the bunch trains

- The electron and ion densities depend roughly linearly on the gas density
- There is an order of magnitude difference in electron density below and above the multipacting threshold, only small variation above threshold
- For the stability studies, we can pick an SEY above 1.5 and scan only the gas densities

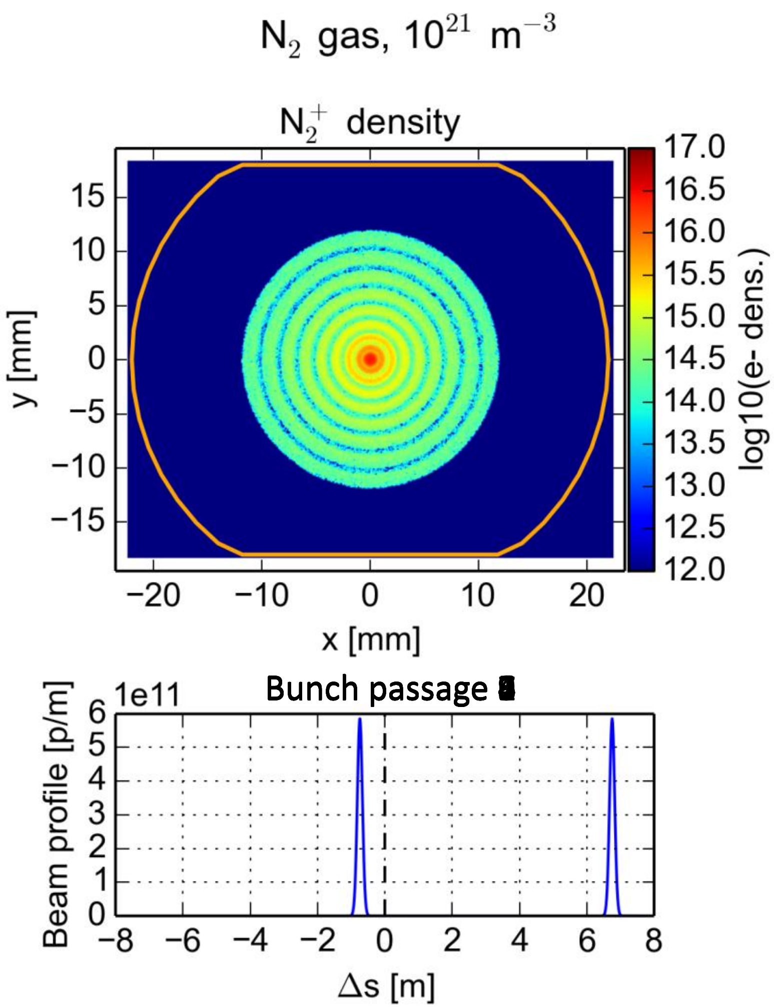
The first multi-species stability simulation (at the beginning of the bunch train) shows instabilities from densities of 10^{24} m^{-3}

- From the build-up studies we see that there is an enhancement of electron densities of around 1 order of magnitude
- Extrapolating from the stability study (assuming that the dynamics don't change much), this means that instabilities could set for gas densities around 10^{23} m^{-3} – still not consistent with the prediction from losses
- To be confirmed with further stability simulations

Ion and electron motion

Looking at the movement of the two species during the build-up (bunch passage 1-10)

- Ions gradually move from the centre towards the walls



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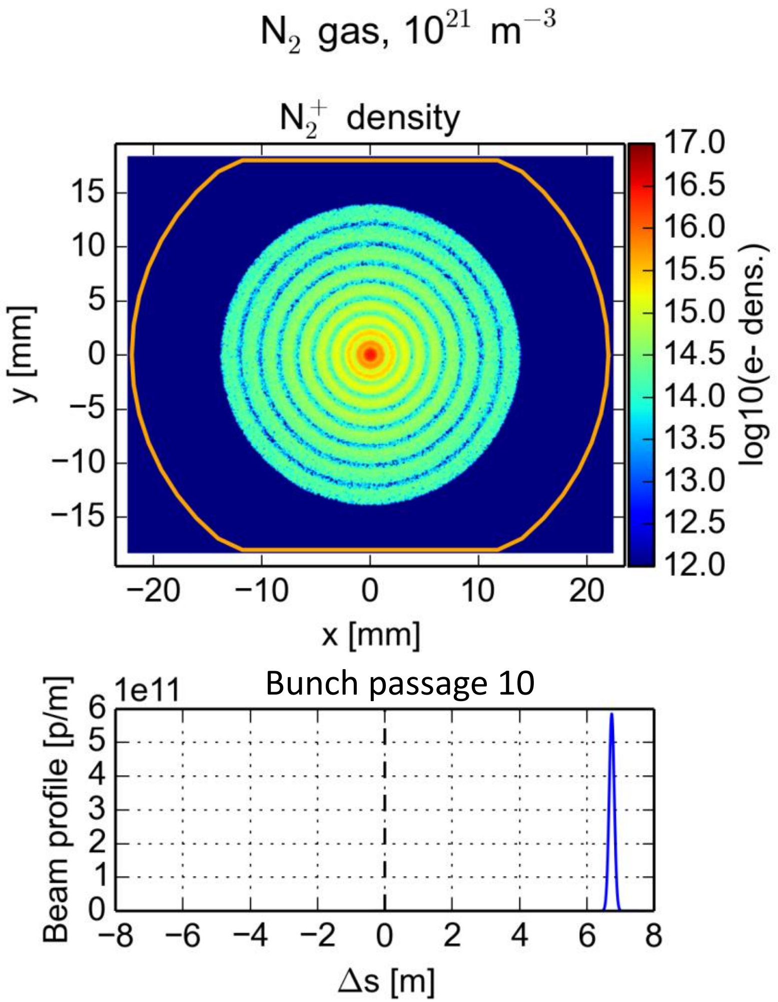
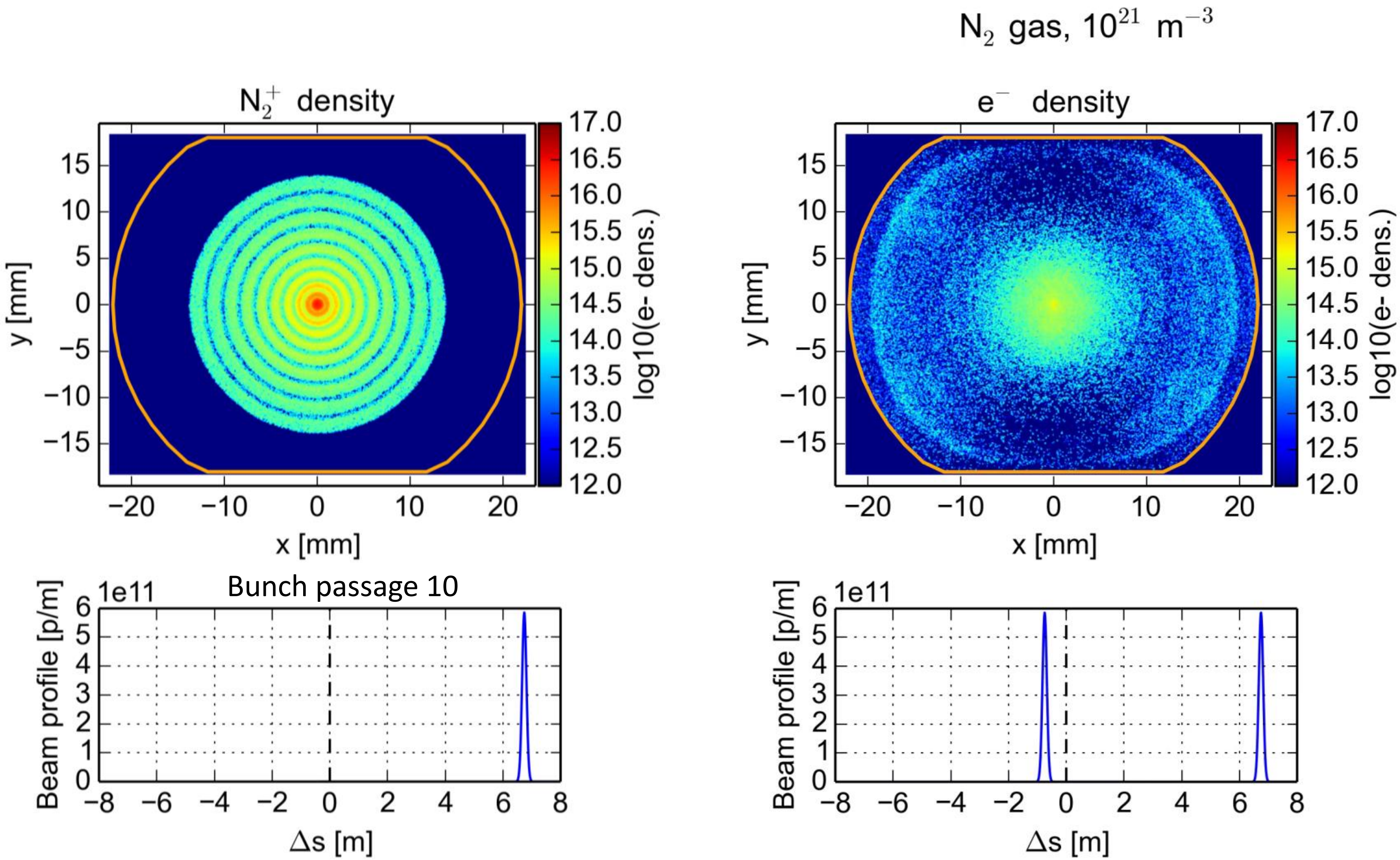


Ion and electron motion

Looking at the movement of the two species during the build-up (bunch passage 1-10)

- Ions gradually move from the centre towards the walls
- The electrons follow a more complex motion



Electron-induced ionization

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

During a typical e-cloud build-up process, where the electrons cross the chamber once per bunch passage, this effect is estimated to at most roughly double the electron population (assuming a cm-size chamber)

In the case of the pressure bump, electrons move across the chamber several times between two bunch passages

- Could they significantly increase the ionization fraction?
- Electron energies are being evaluated to address the question

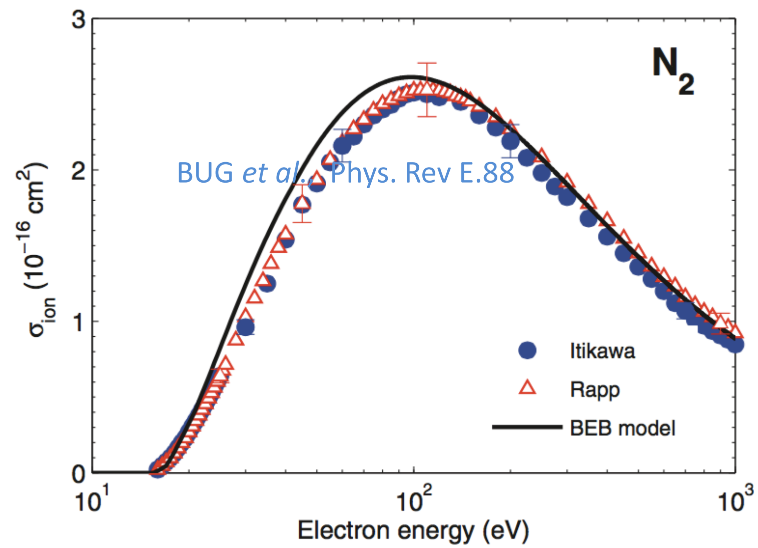
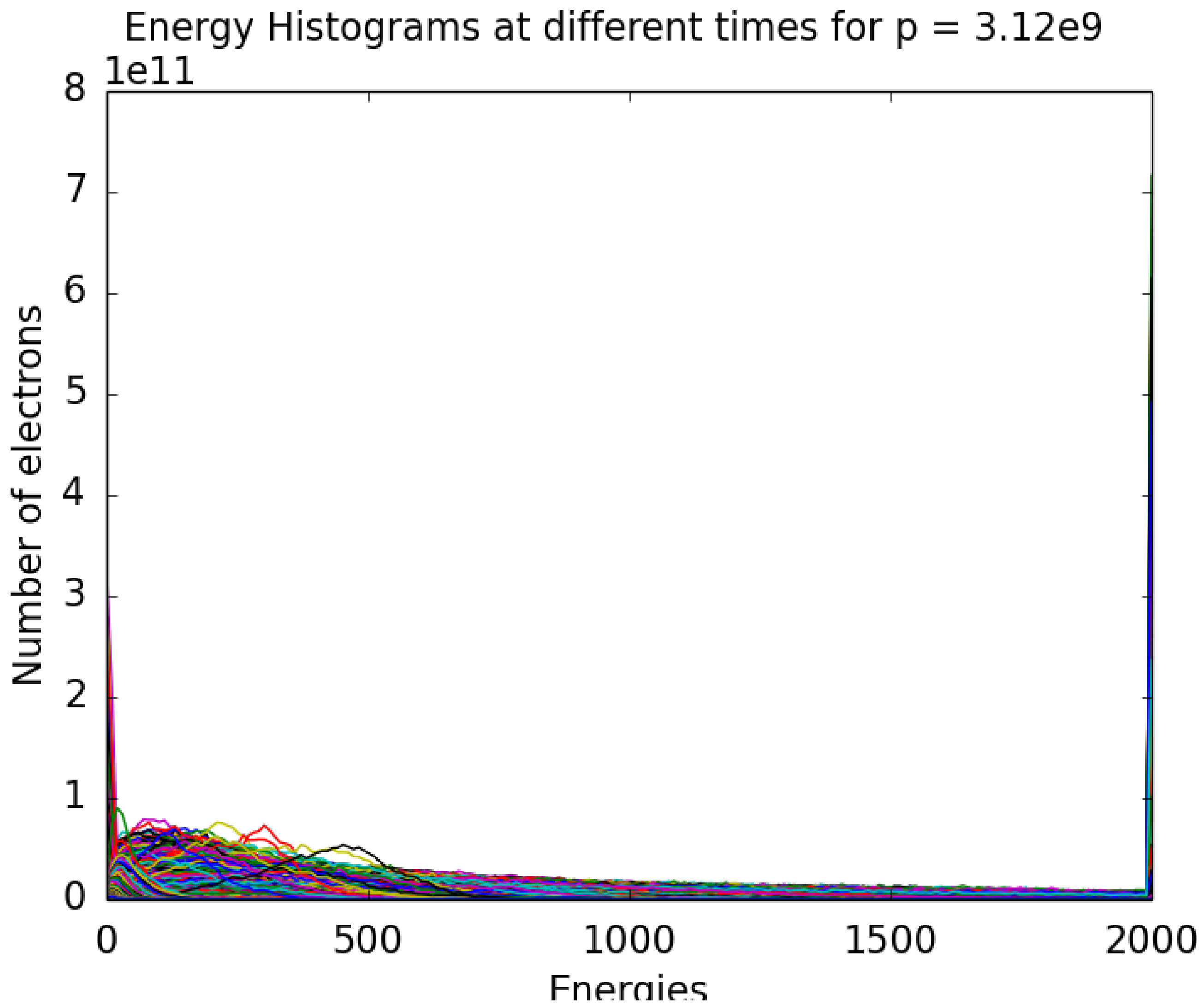


FIG. 1. (Color online) Electron-impact-ionization cross sections σ_{ion} of nitrogen recommended by Itikawa [16], measured by Rapp and Englander-Golden [17], and determined using the BEB model [18].

Electron energies

Electron energy spectrum during multi-cloud build-up



Electron energies

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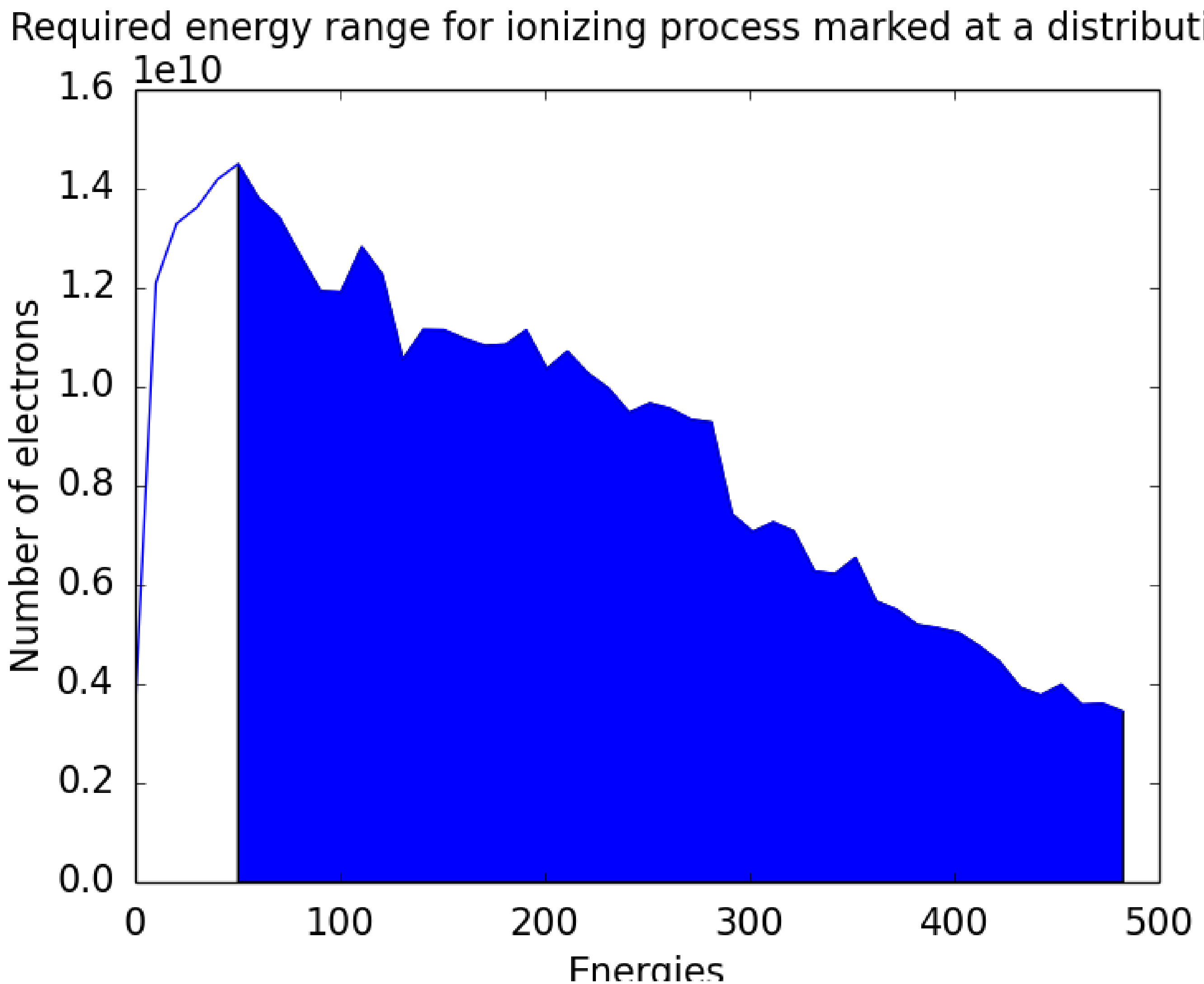

Electron energies

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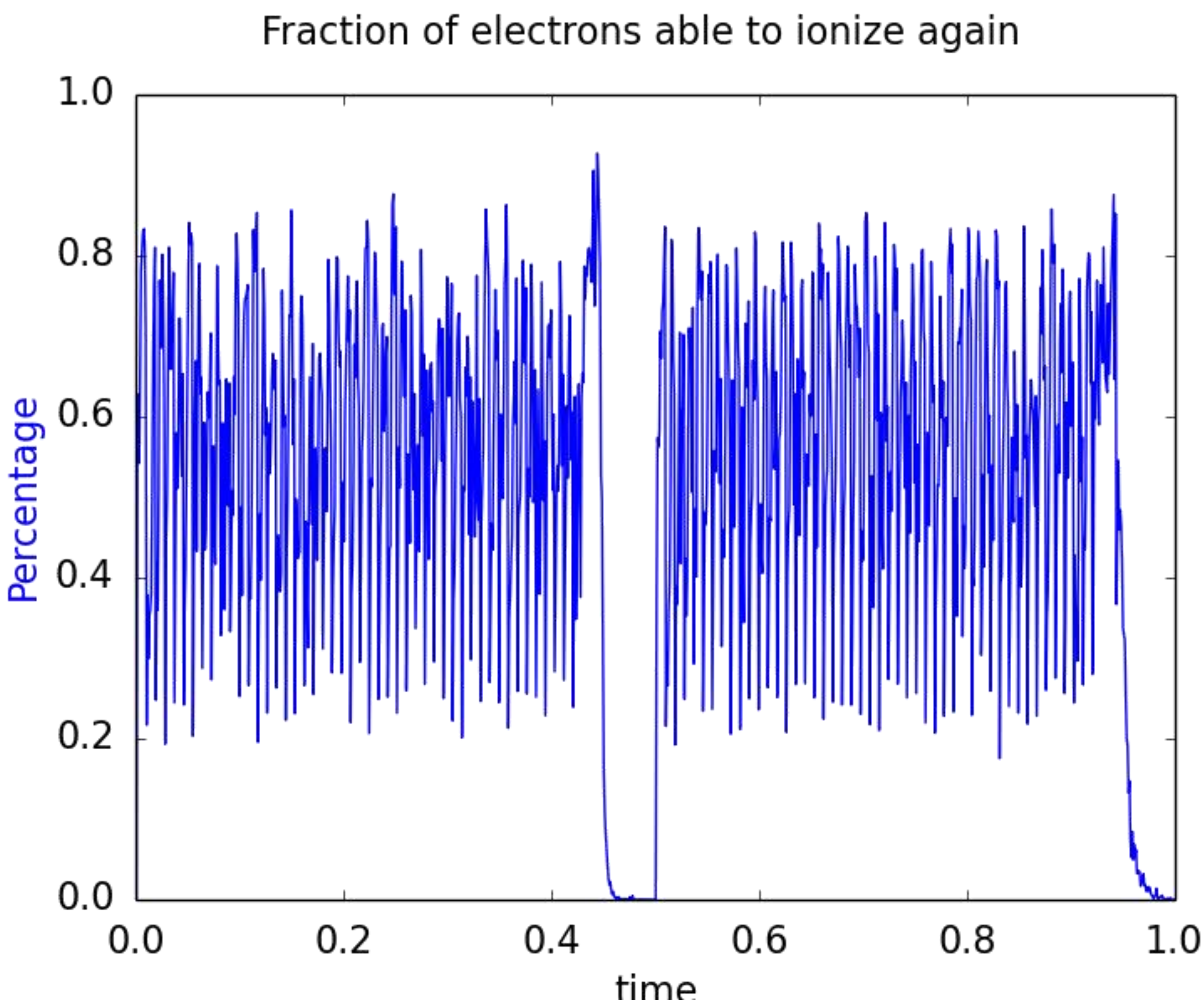
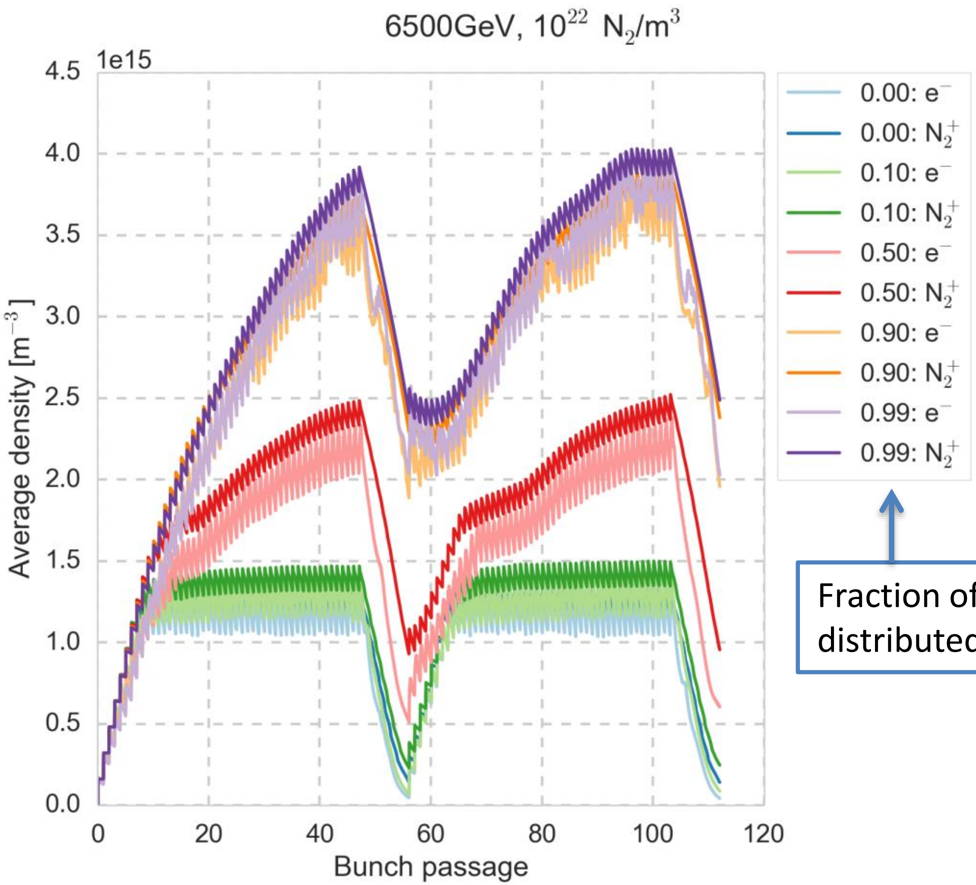


Distributed ionization

Electron-induced ionization would not only increase the electron and ion fractions for a given density, but also affect where electrons and ions are generated – does this matter?

- To probe the effect, simulations were done with a fixed ionization rate, but a varying fraction of the ions and electrons generated uniformly across the chamber, instead of in the beam



Fraction of uniformly distributed ionization

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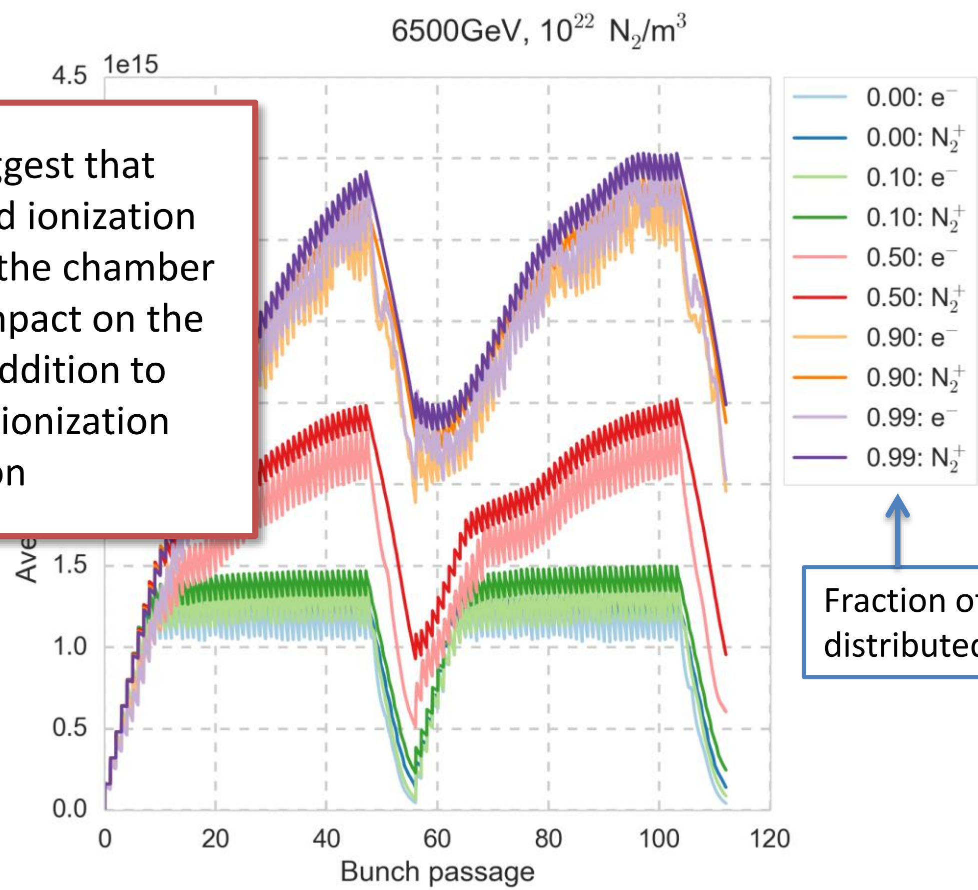

The results suggest that electron-induced ionization occurring across the chamber could have an impact on the dynamics, in addition to increasing the ionization fraction

Fraction of uniformly distributed ionization

Conclusions

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We have tried to reproduce the instability observations for densities predicted by losses

- To be confirmed with the instability simulations along the train, but based on simple extrapolation it seems that we are not quite matching the observations yet
- Electron-induced ionization could significantly affect the electron and ion densities that are produced with a given gas density, which may get our model closer to the observations
  - I think we need to explore this option further

Another consistency check that could be done is to estimate the heat load from the electrons and ions in this model

- It should not be visible on the cell heat load, since no change was observed there

Other effects that could be important

- It has been suggested by the vacuum team that the pressure is dynamically changing (due to outgassing from electron and ion impacts) which should be taken into account
  - can this effect be relevant on the time scale of a few bunch trains?
  - How would an evolving pressure affect the gas density estimates from the losses?
- Are collisions (with neutrals) negligible as we are assuming in the model?

Outlook

Further possible studies that could be done include

- The effect of the solenoid, 8b4e
- The effect of different ion species
  - I think that these studies are more relevant only once we have a model that roughly agrees with the basic observations

Other applications of the tools:

- To study the role and effect of ions during a standard e-cloud build-up process
  - Heat load from ions, effect on electron dynamics
  - Systematic scans for different magnetic fields, SEY and vacuum pressure
- We have been asked to study the effect on stability of a PBC-FT experiment, where they want to inject gas up to 10^{18} m^{-3}

In addition the new code capabilities can be useful also for other purposes

- Dividing electrons into several clouds could help to overcome the re-occurring problem of poor macro-particle resolution outside of the main multipacting regions
- Fast beam-ion instability studies with realistic vacuum compositions