Investigation of e^-/ion dynamics for very high gas densities (16L2 regime)

L. Mether
G. Iadarola, K. Poland, G. Rumolo

e-cloud meeting
10 May, 2019

Outline

- Introduction
  - 16L2 sequence of events
  - Recap of past studies
- Further investigation of build-up
  - Electron energy spectrum
  - Electric fields

Motivation

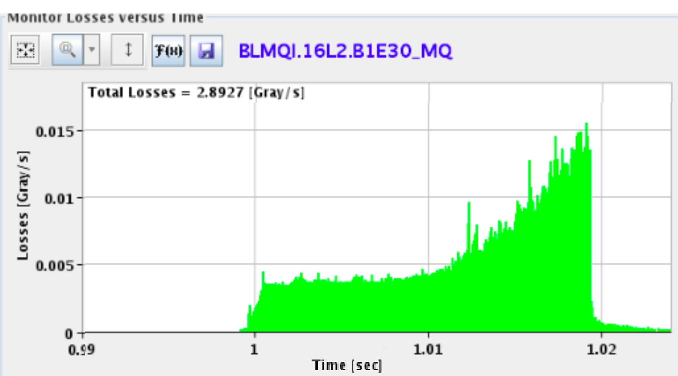
Throughout 2017 operation, abnormal losses were observed in the LHC

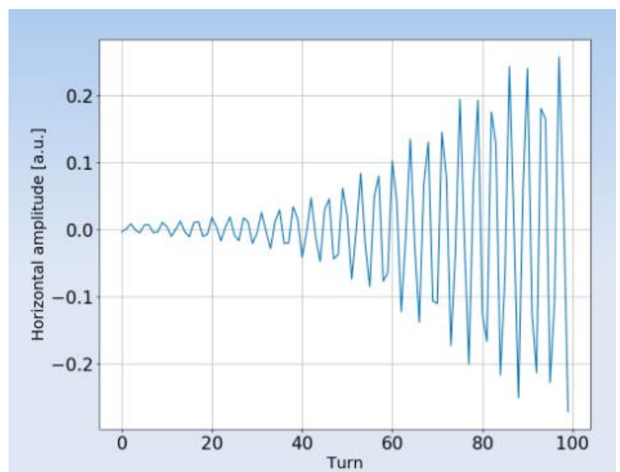
- Located in the half-cell '16' Left of Point 2 (16L2)

68 premature dumps with the following signature occurred during 2017:

- Sudden onset of high beam losses in 16L2
- Coherent beam motion with extremely fast rise times (~1–100 turns)
- Beam dump either due to losses on the collimation system or directly in 16L2

To stay operational, the LHC was limited to fewer than the nominal number of bunches for most of the 2017 run. Several 16L2 events occurred also in 2018.





X. Buffat

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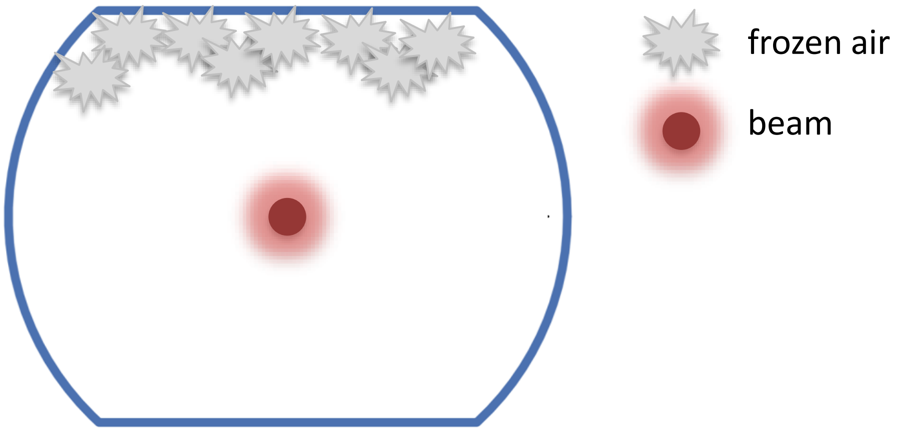

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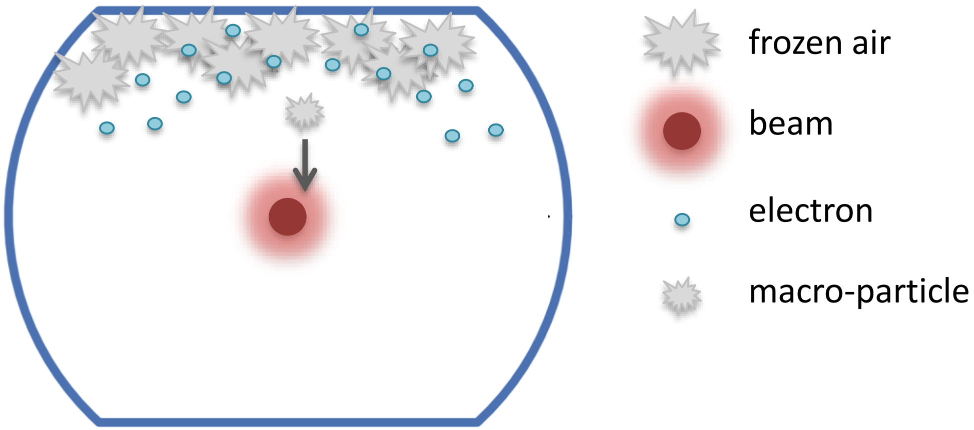

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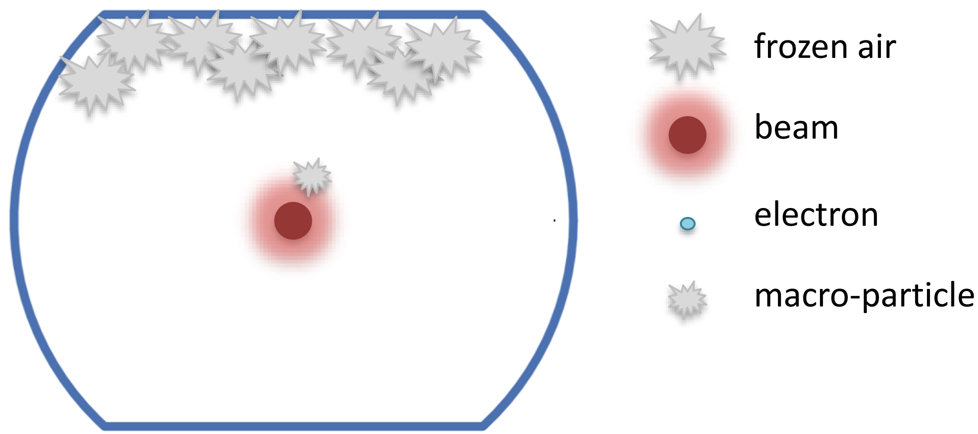

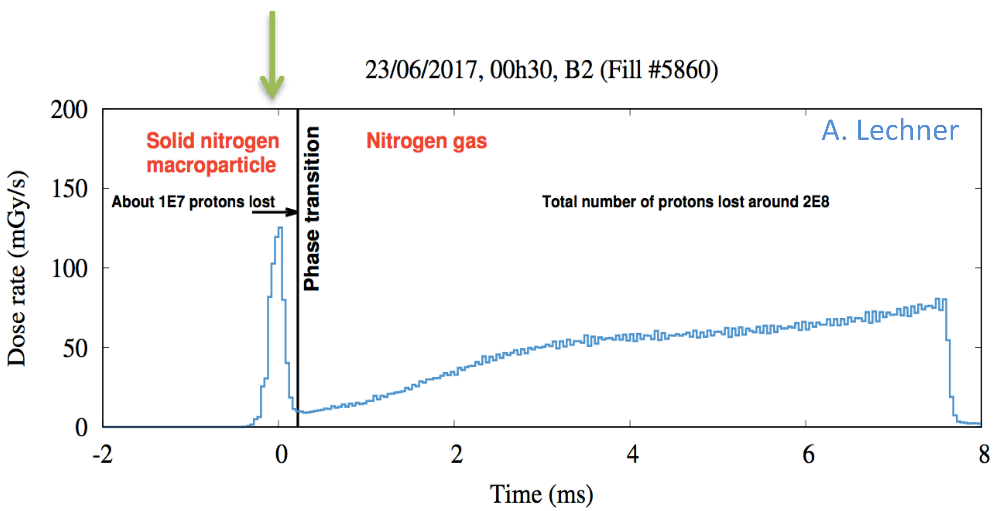

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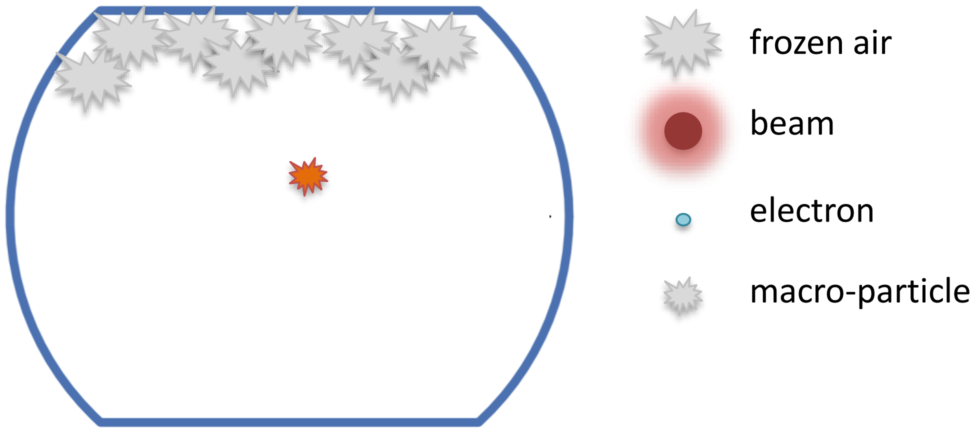

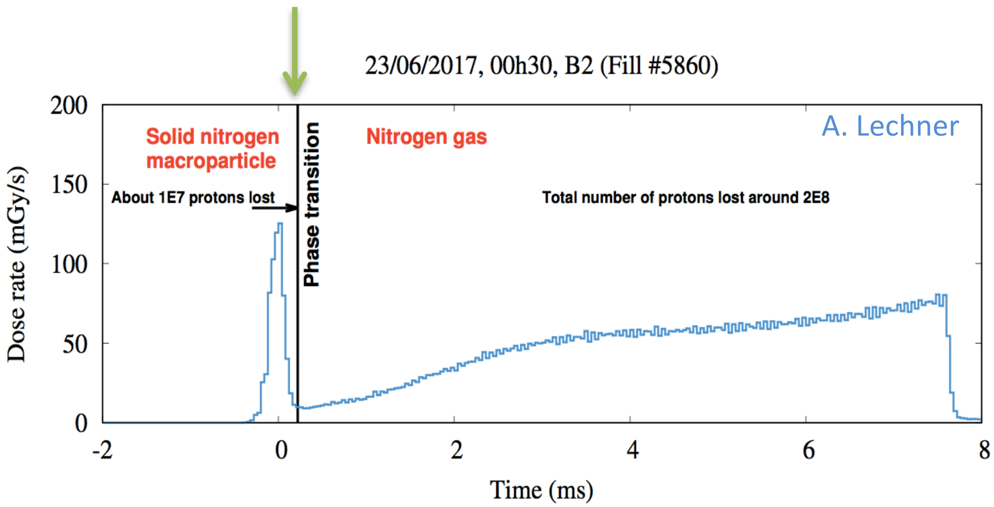

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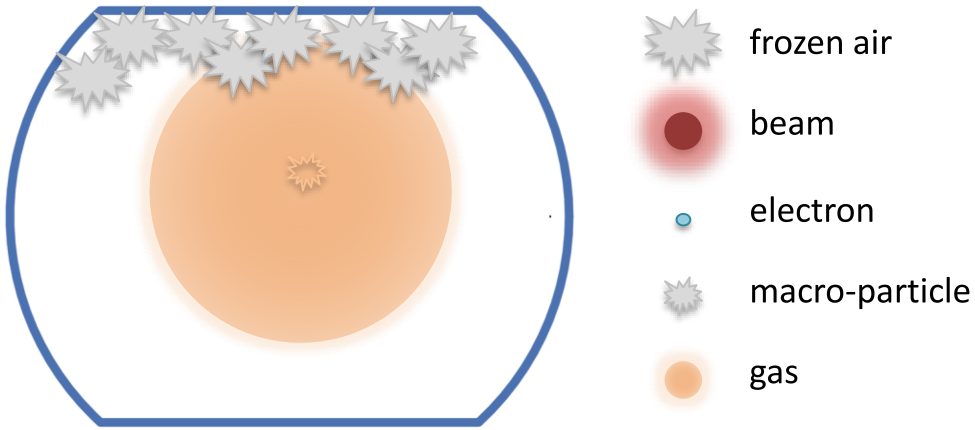

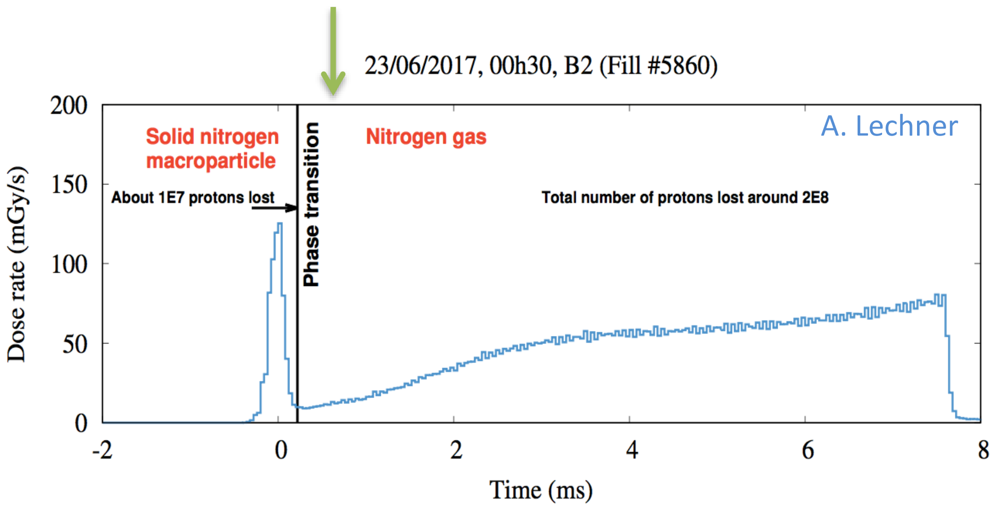

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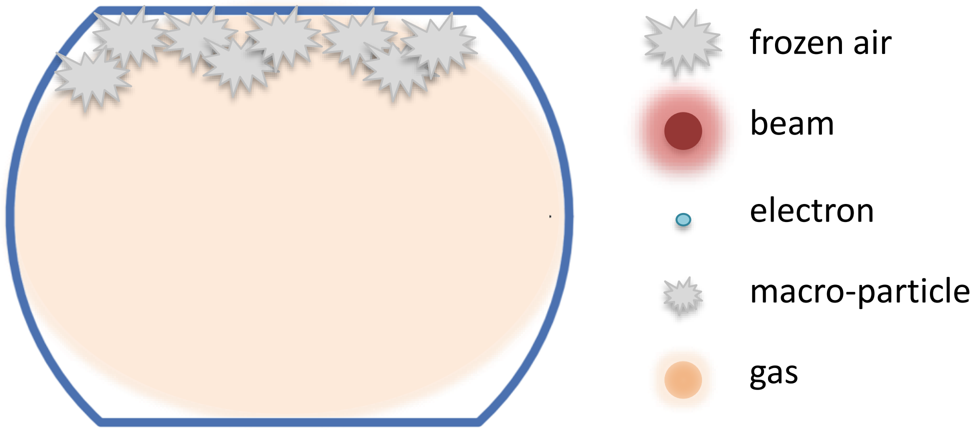

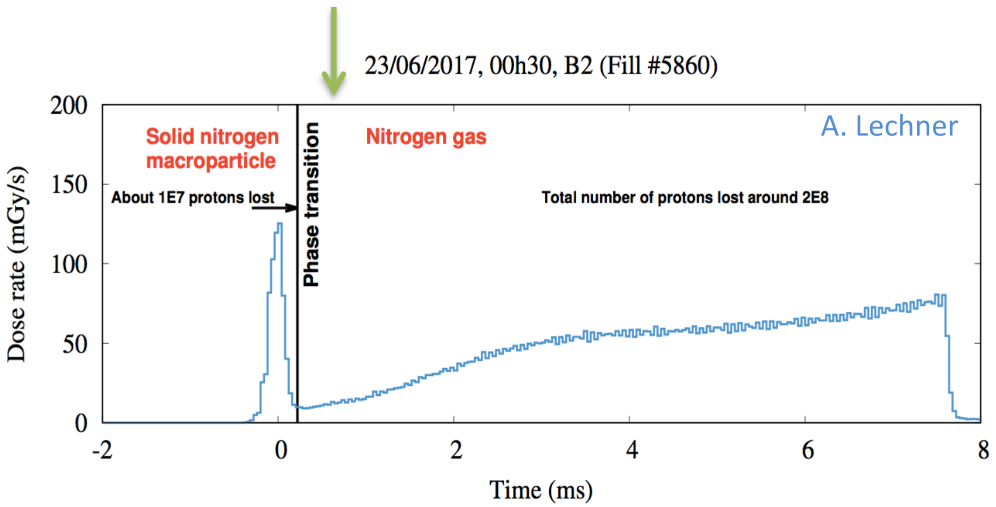

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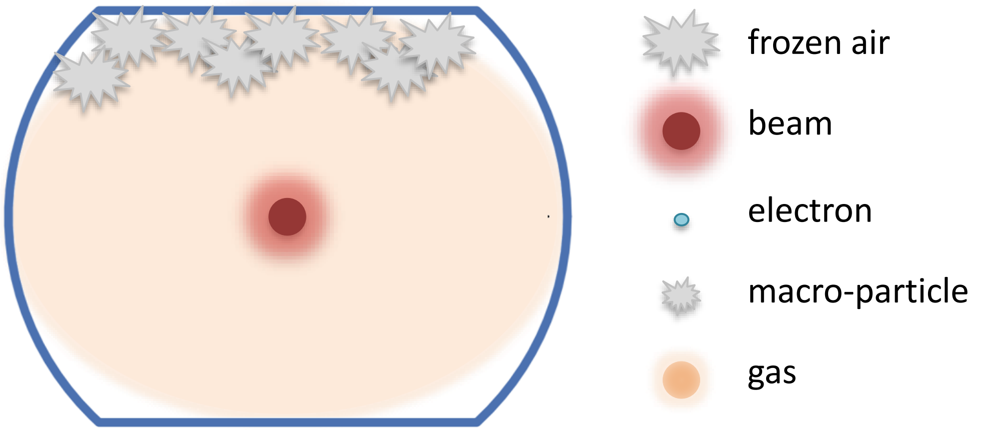

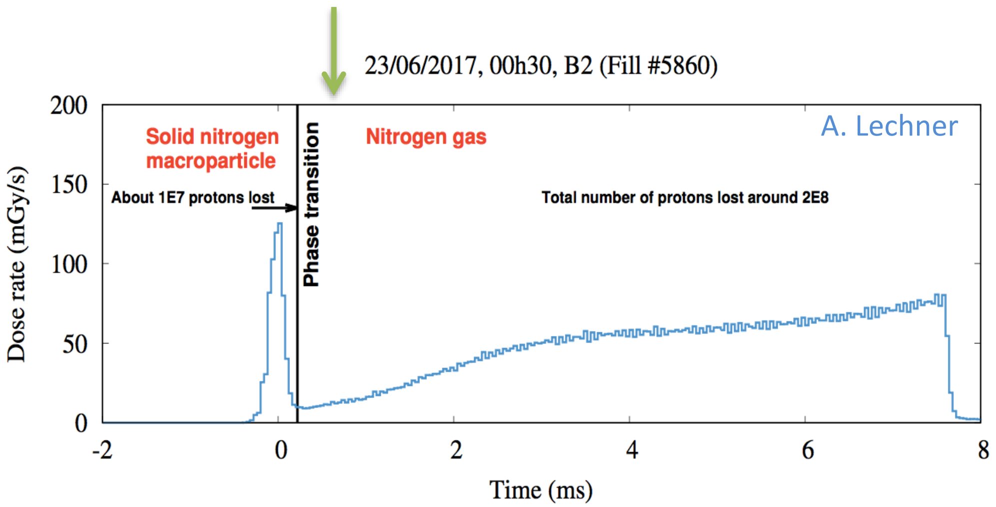

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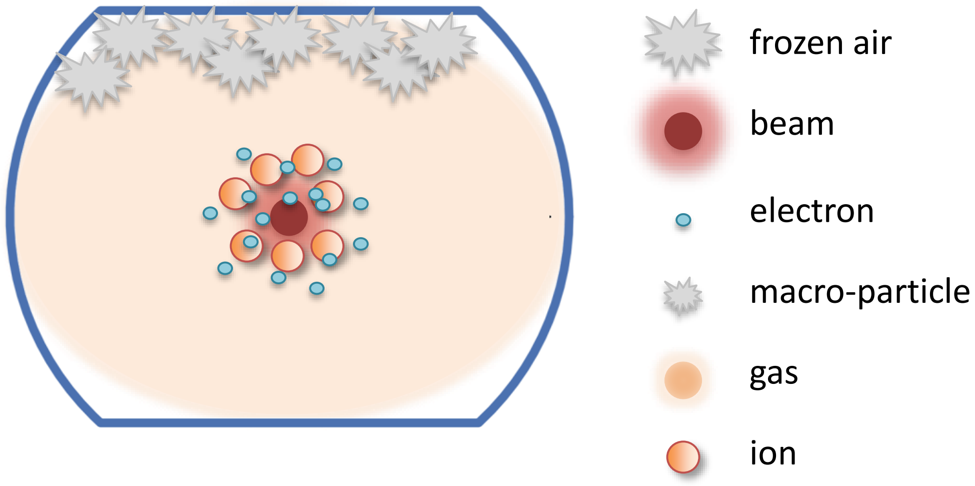

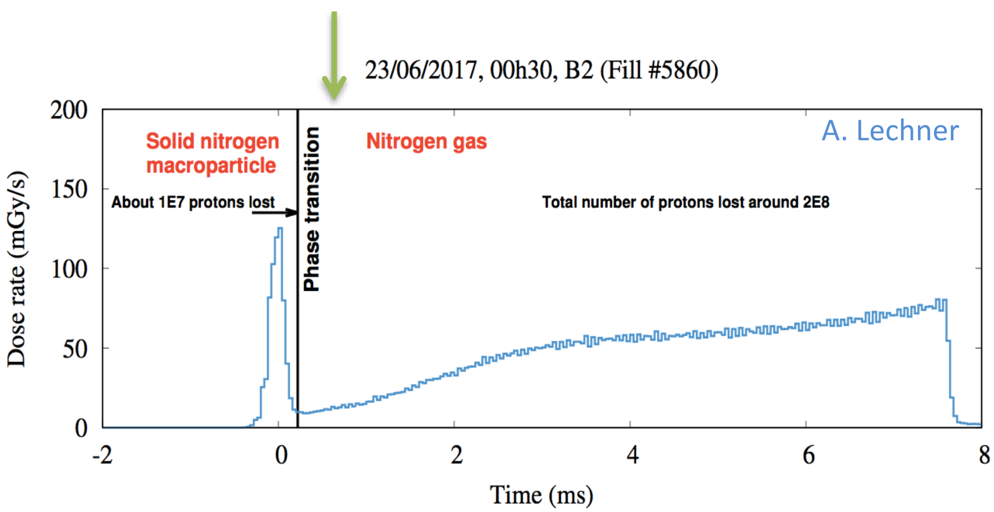

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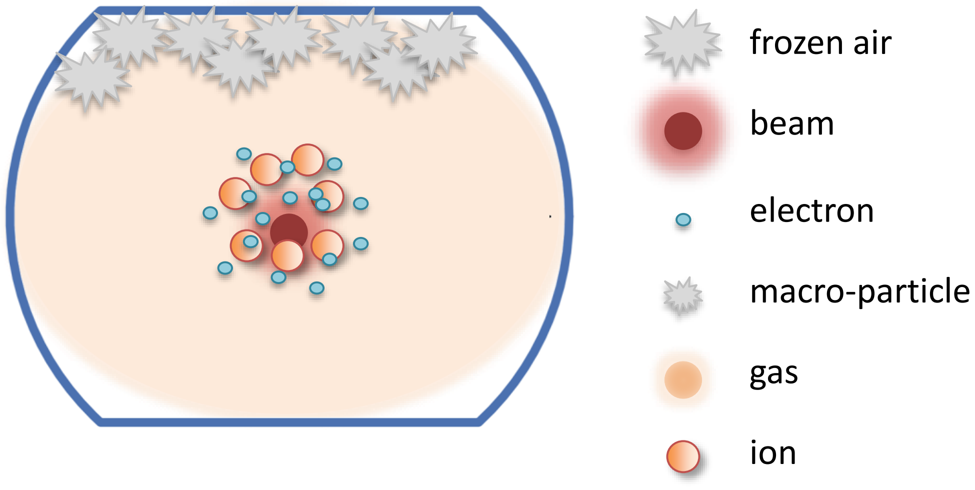

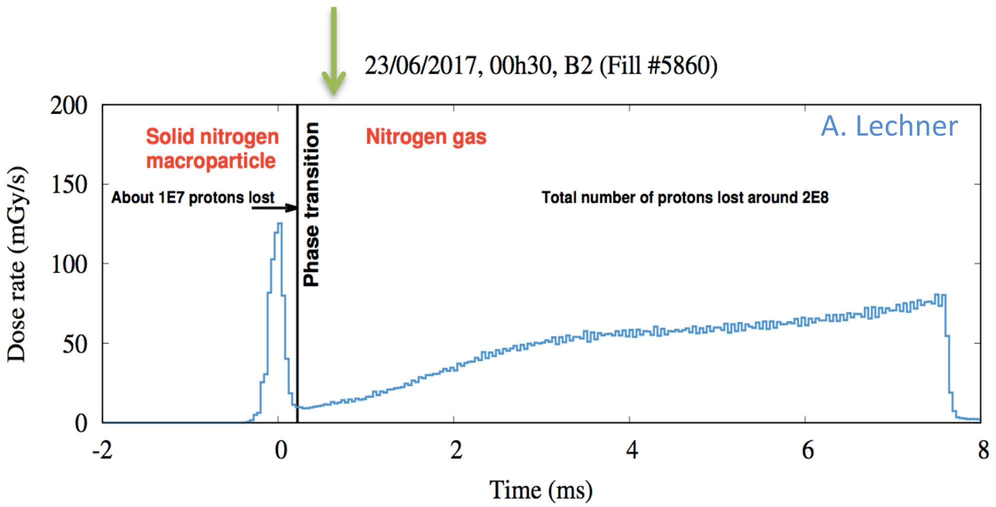

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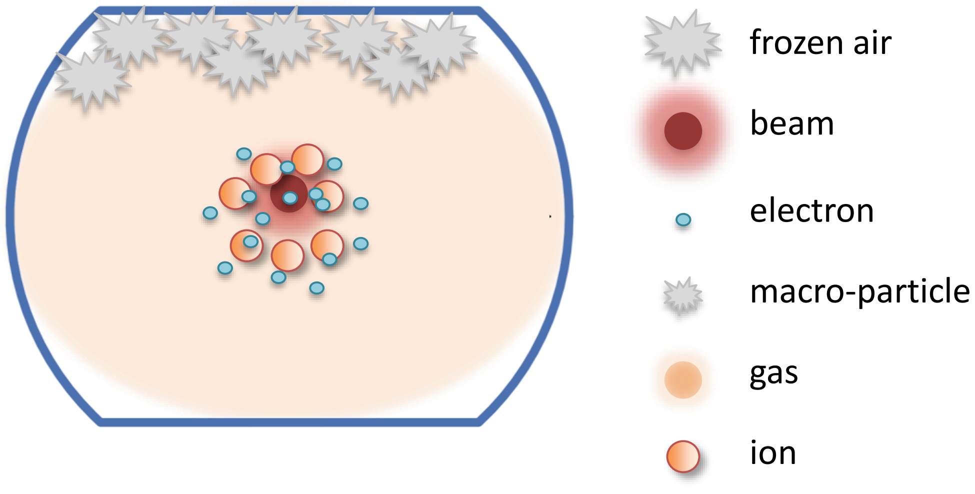

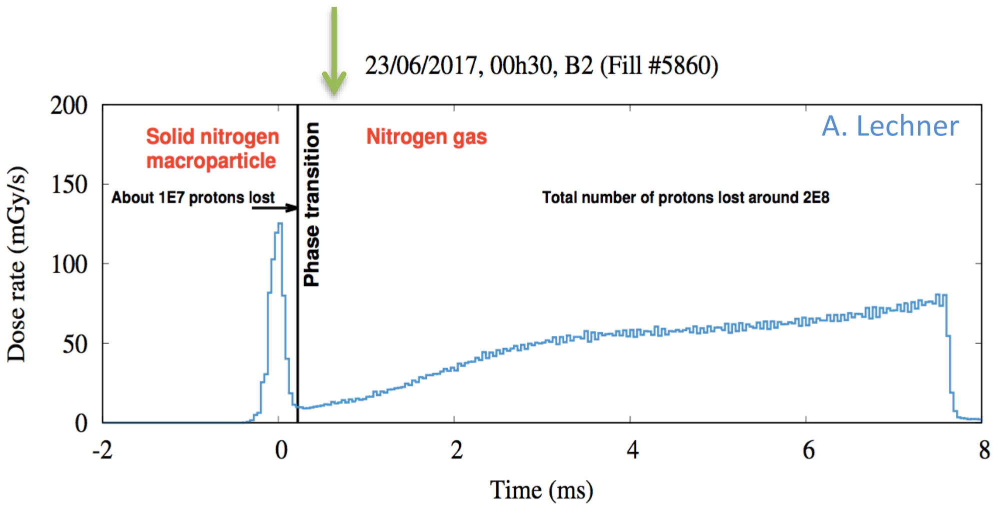

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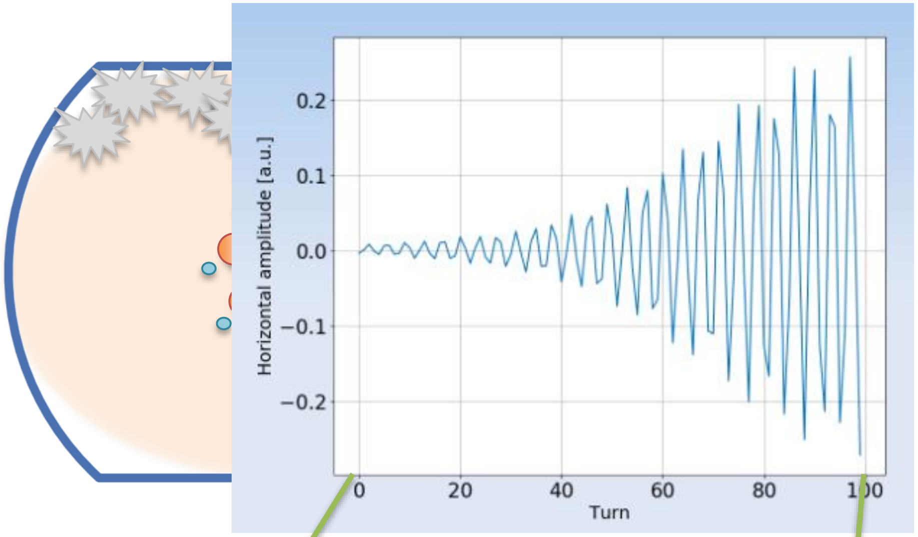

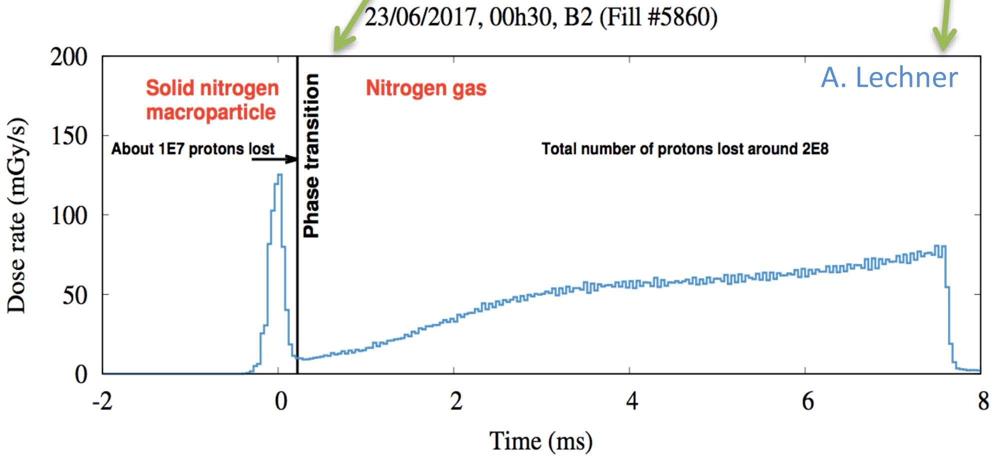

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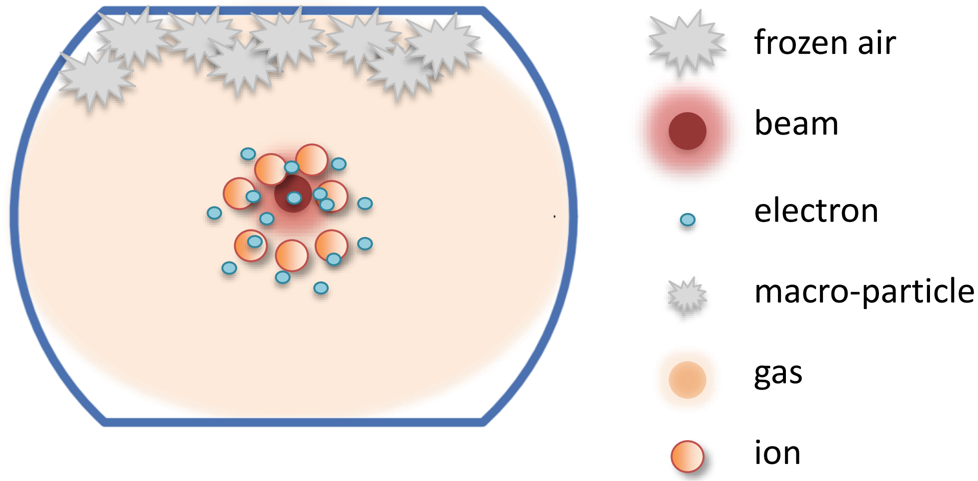


Our aim is to model the last part of this sequence of events:

- If we assume a high gas density in the beam chamber, can we reproduce the observations in a consistent manner?

Information from loss observations

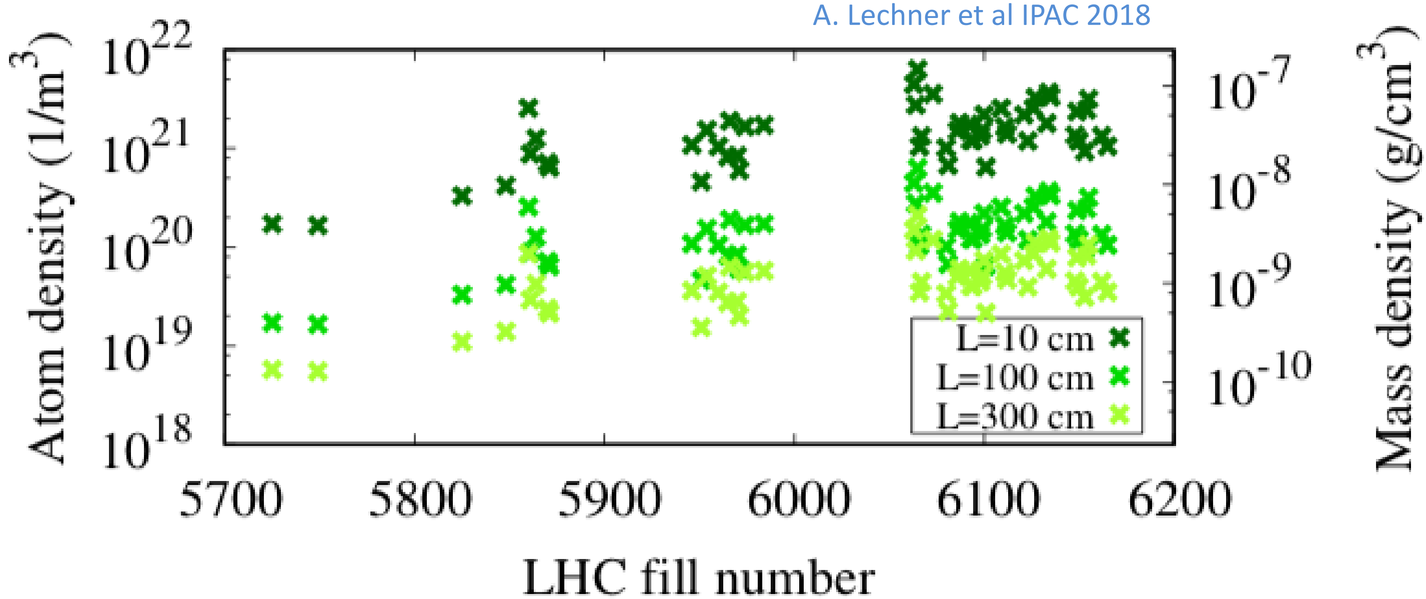
The events take place around the interconnect → mostly a field free region

- The source of the losses can be at most a few (~3) meters long

The gas density could be estimated based on the loss rates:

- In 2017 events, the density range was $10^{19} – 10^{21}$ L^{-1}m^{-2}, for gas covering the length L
- This is assuming N_2 gas that extends over the full transverse beam cross section

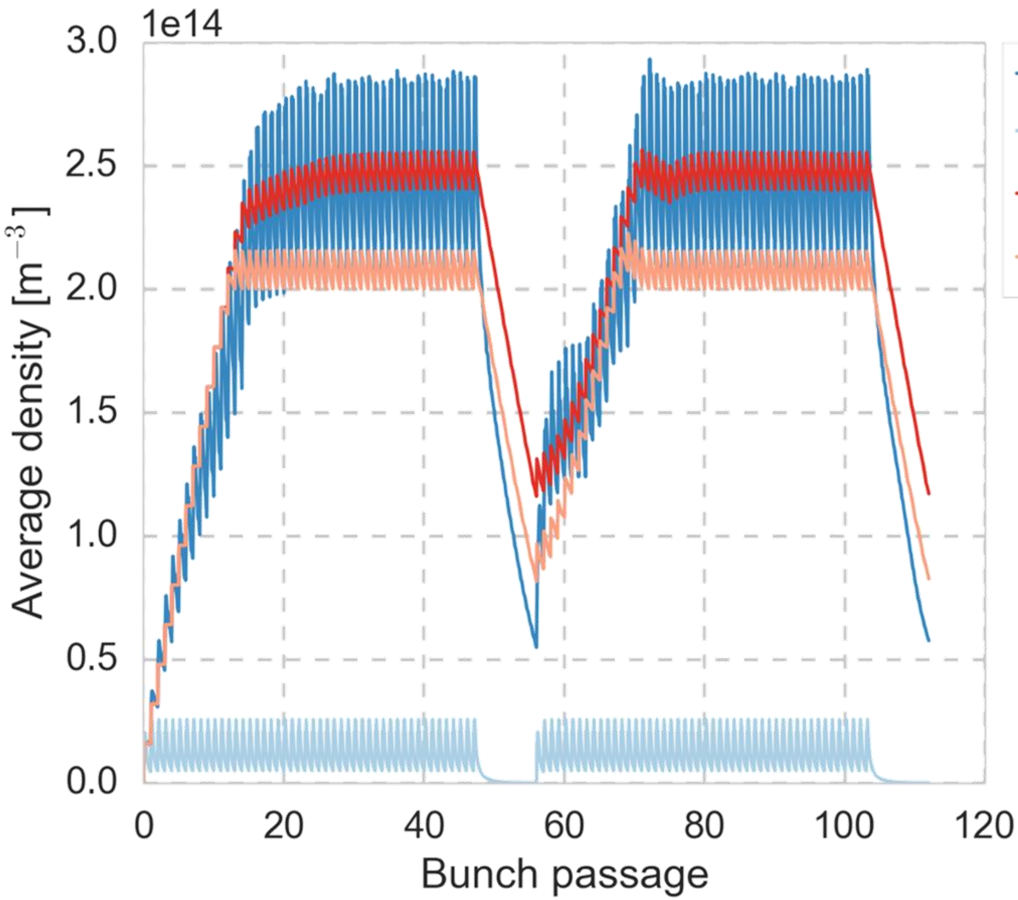
A. Lechner et al IPAC 2018



Multi-species PyECLOUD

Multiple clouds were enabled in PyECLOUD to model the 16L2 events

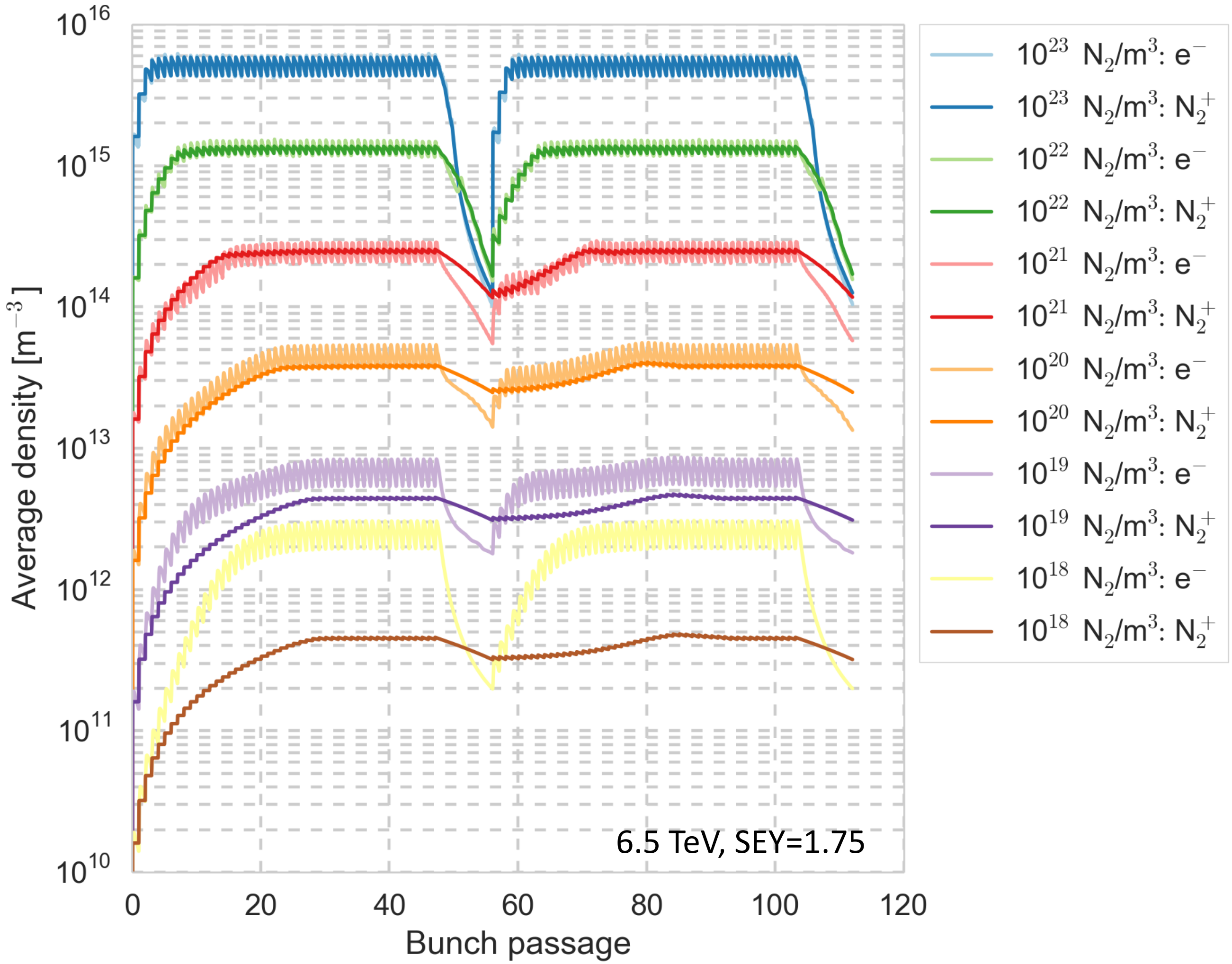
- Simulations show significantly different dynamics from a gas density of around 10^{20} N_2/m^3 when ions and electrons are simulated together
- In particular the electrons behave very differently in the presence of ions



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

Multi-species build-up

- For high gas densities the electron and ion densities saturate at the same values
  - The densities at saturation depend roughly linearly on the gas density

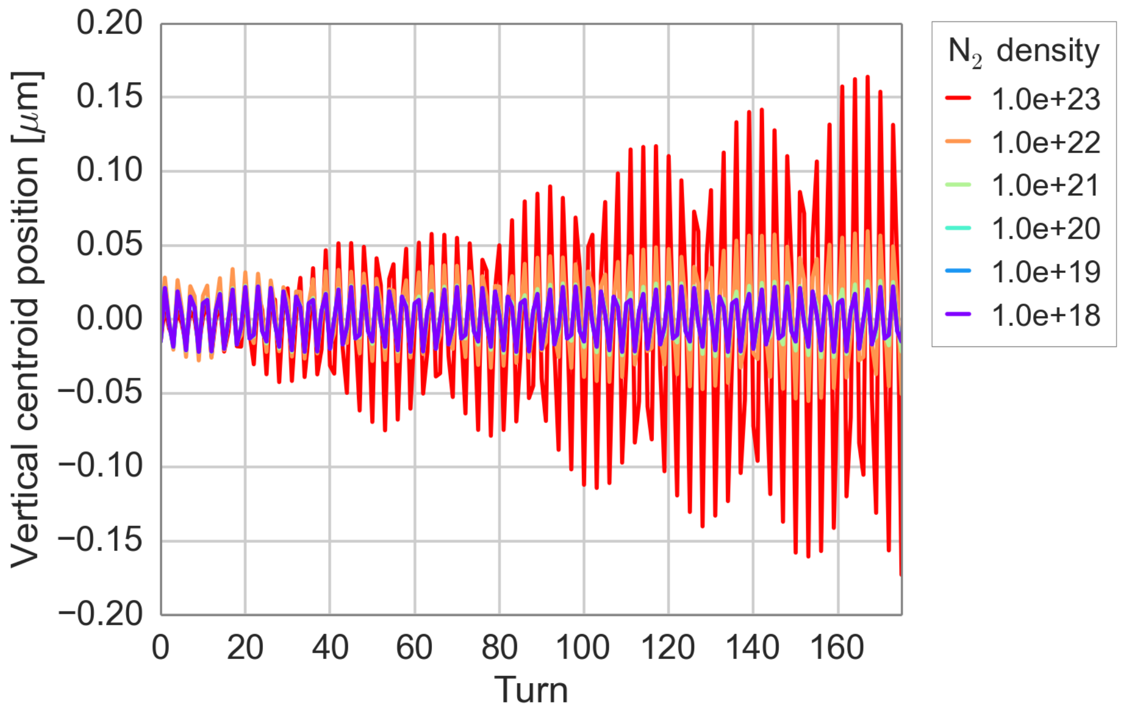


Stability studies

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 simulation model considers only beam-induced ionization, but 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

Saving of energy histograms in PyECLOUD

- Previously only impacting particle energies were stored during the simulations

- The option to record energy histograms of all particles was implemented (L. Giacomel)

Cross-ionization module under implementation

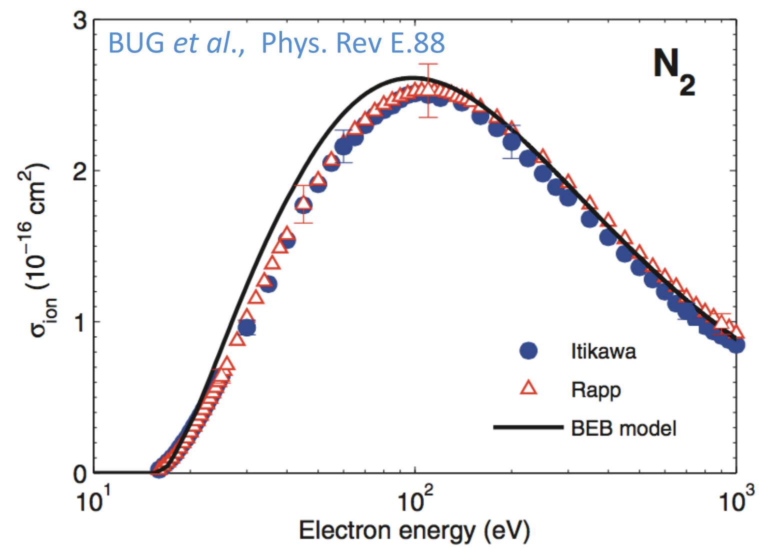


FIG. 1. (Color online) Electron-impact-ionization cross sections σ_{ion} of nitrogen recommended by Itikawa [16], measured by Rapp and Englander-Golden [17], and determined using the BEB model [18].

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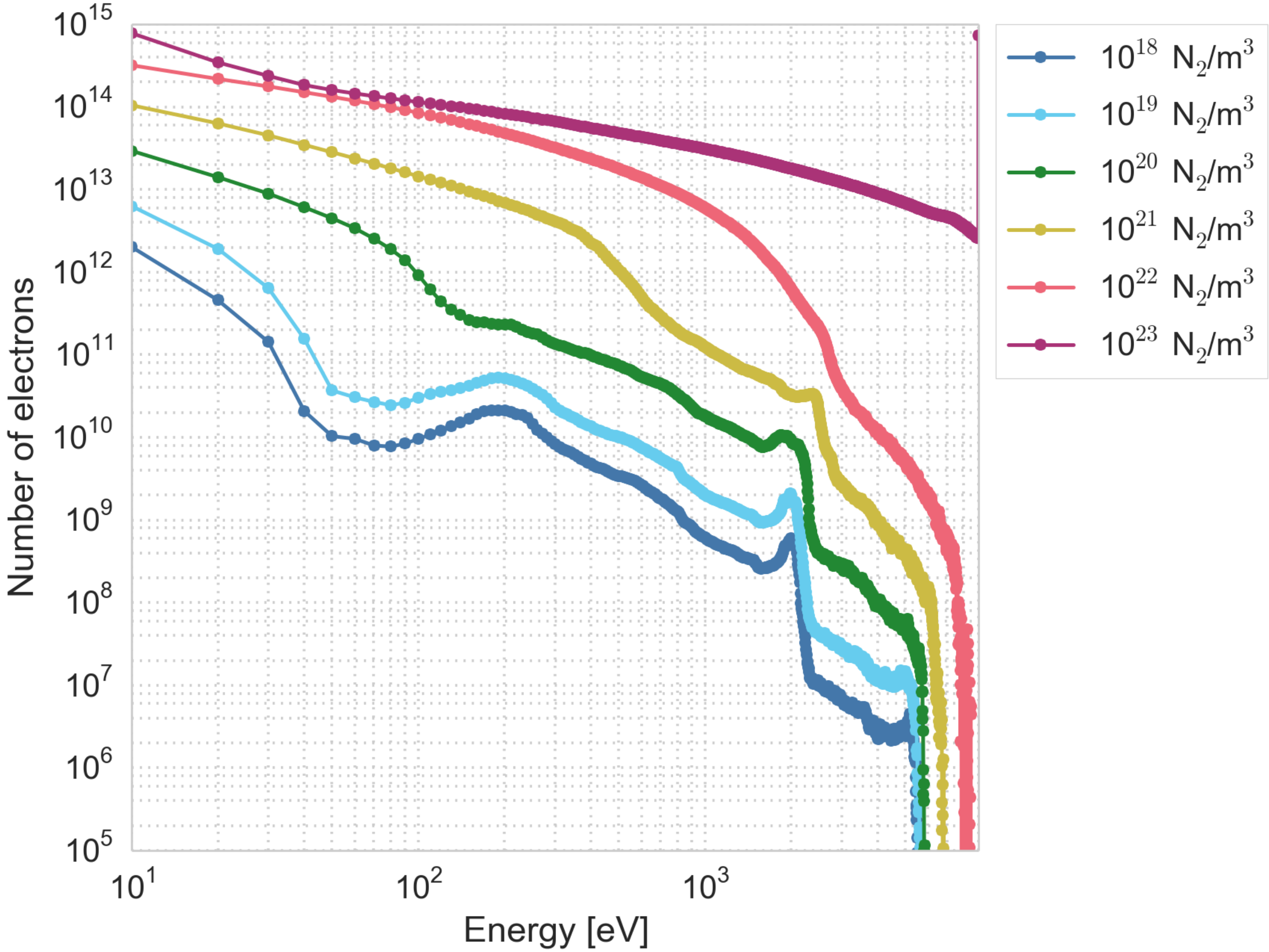
Electron energy spectrum

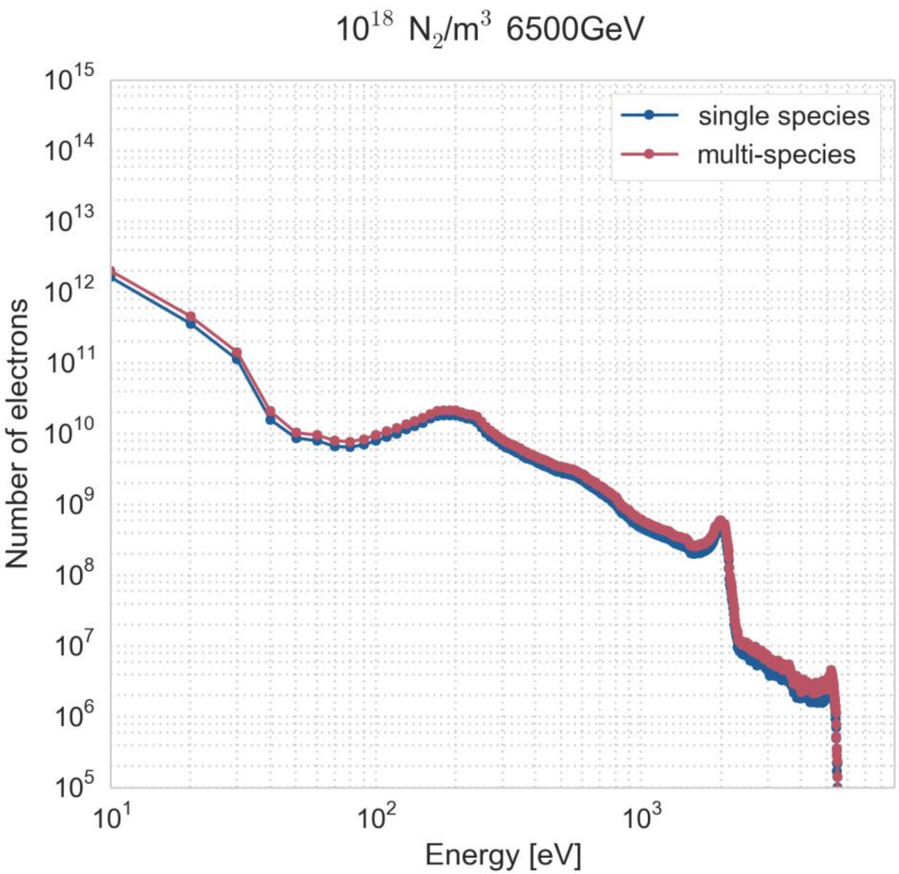
Electron energy spectra averaged over the passage of a BCMS bunch train (48 b) at 6.5 TeV for different gas densities

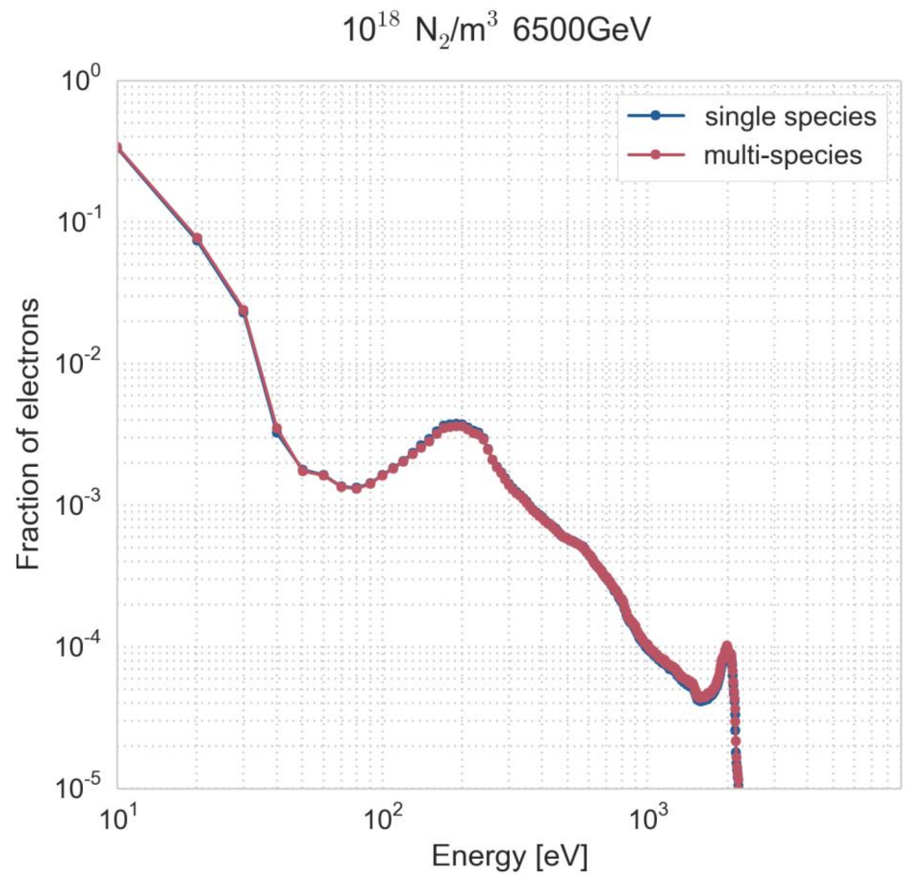


Electron energy spectrum

Comparing the energy spectrum against single-species electron simulations

- With 10^{18} N_2/m^3, the ions barely impact the energy spectrum

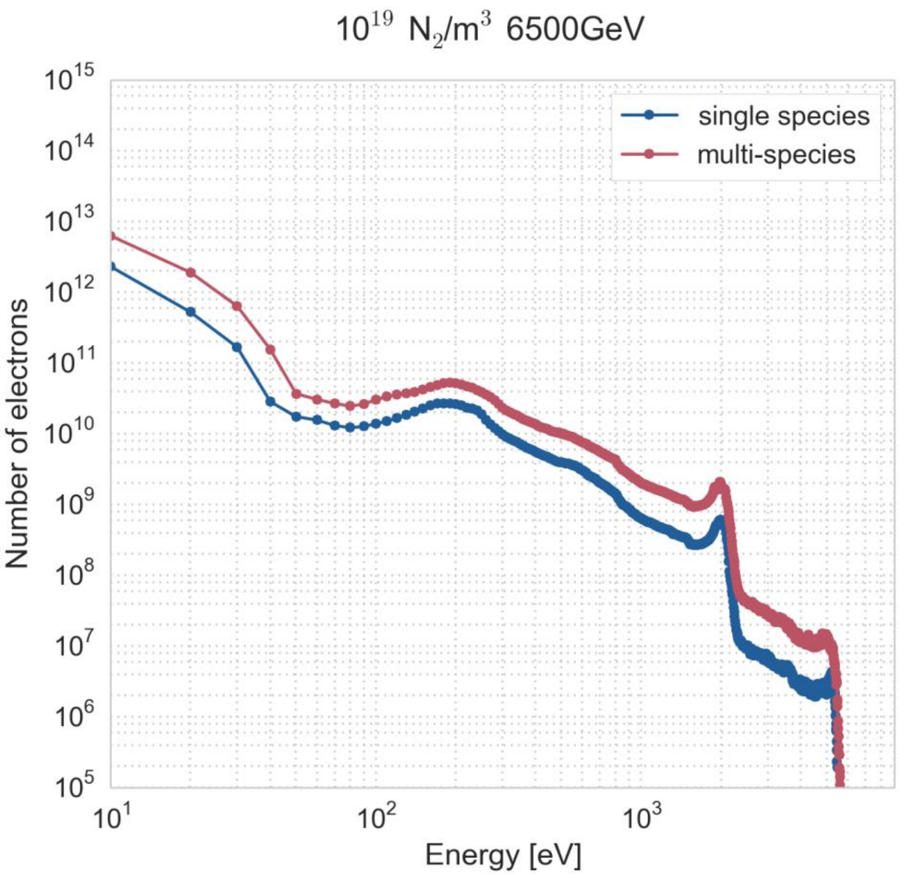


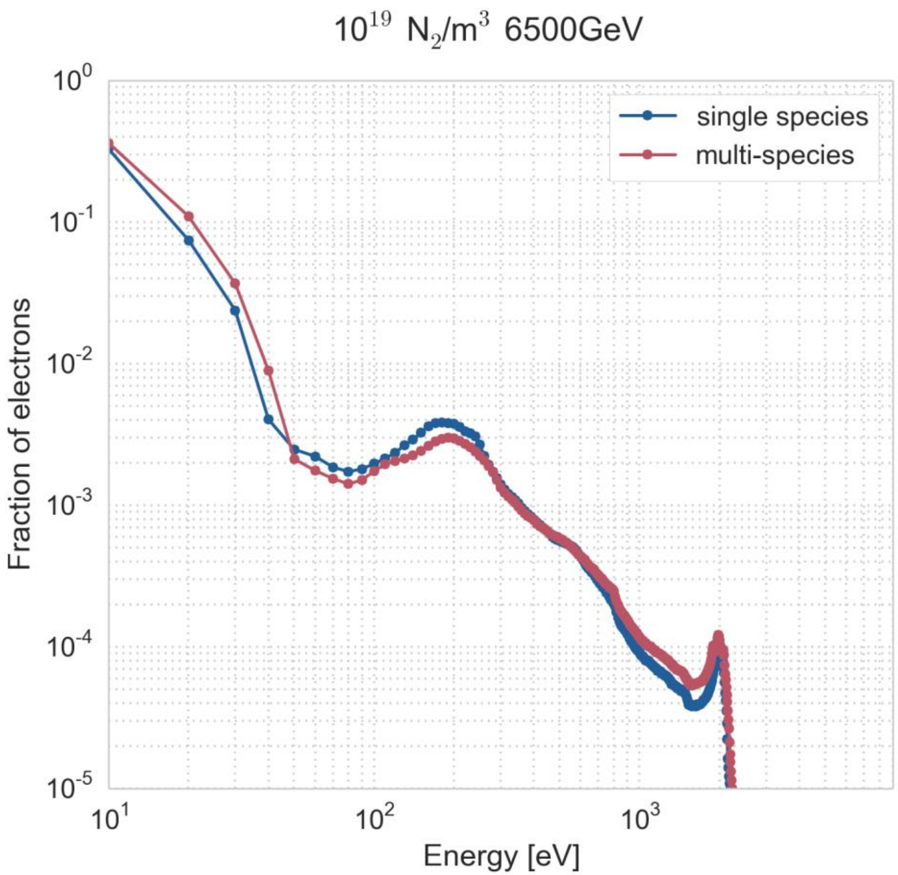


Electron energy spectrum

Comparing the energy spectrum against single-species electron simulations

- With 10^{19} N_2/m^3, the number of electrons is increased, but the energy spectrum is not affected much

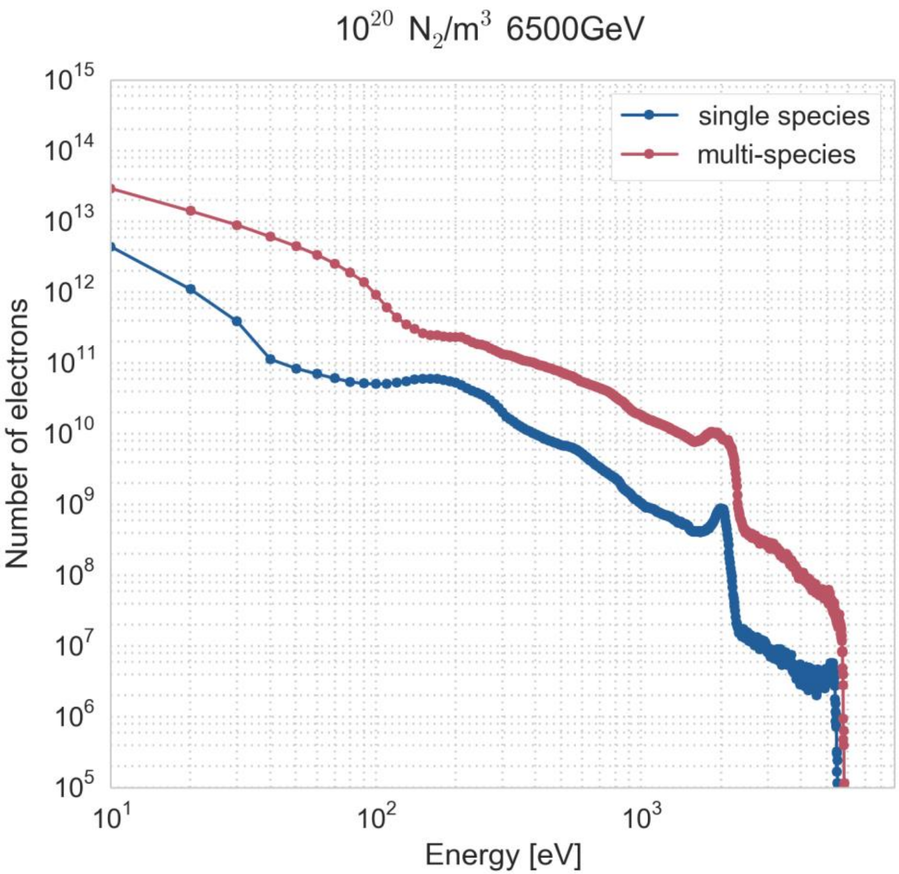


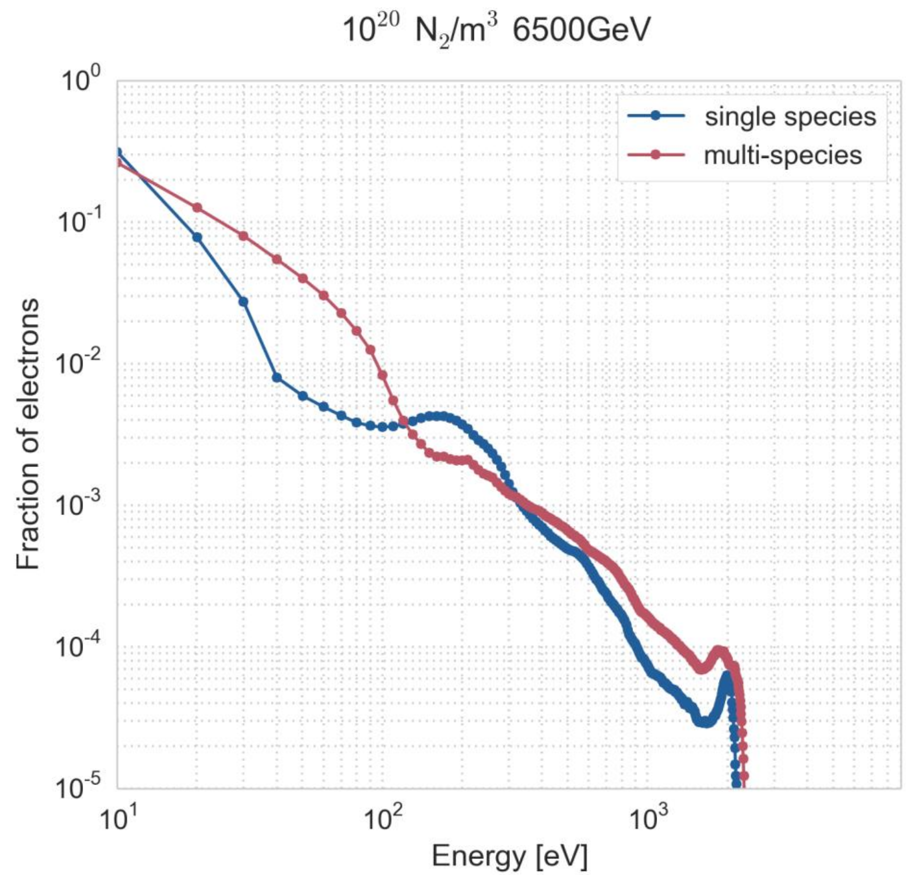


Electron energy spectrum

Comparing the energy spectrum against single-species electron simulations

- With 10^{20} N_2/m^3, the shape of the energy spectrum is significantly changed
- Also the single-species spectrum is slightly modified compared to lower densities

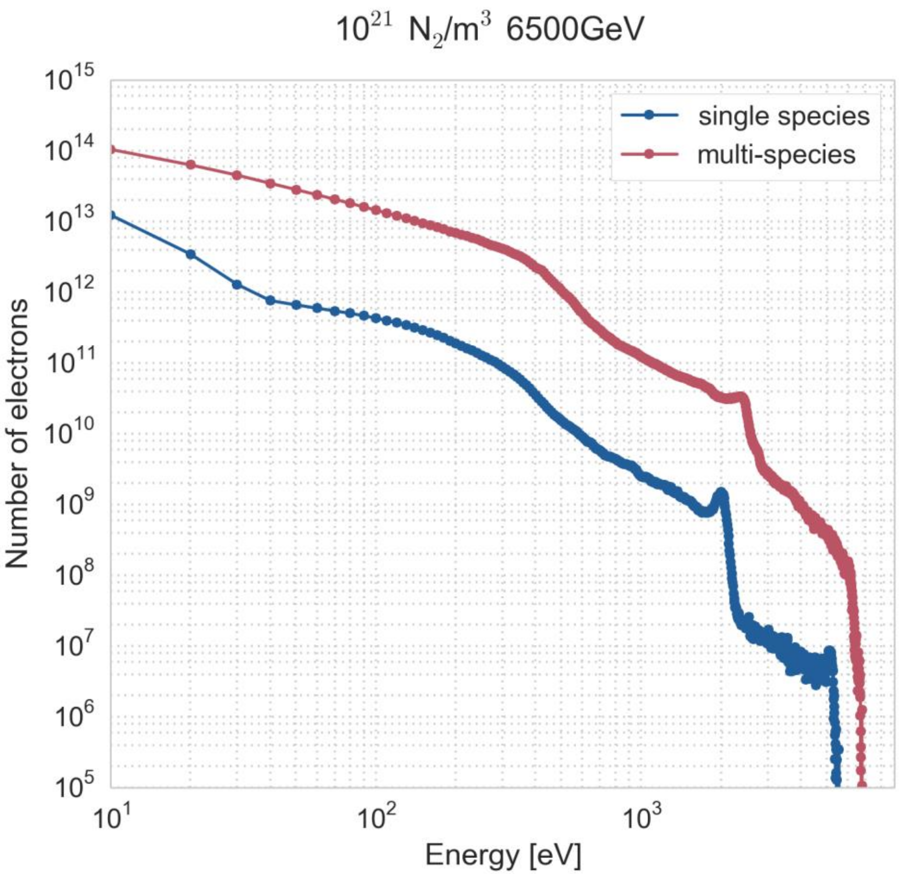


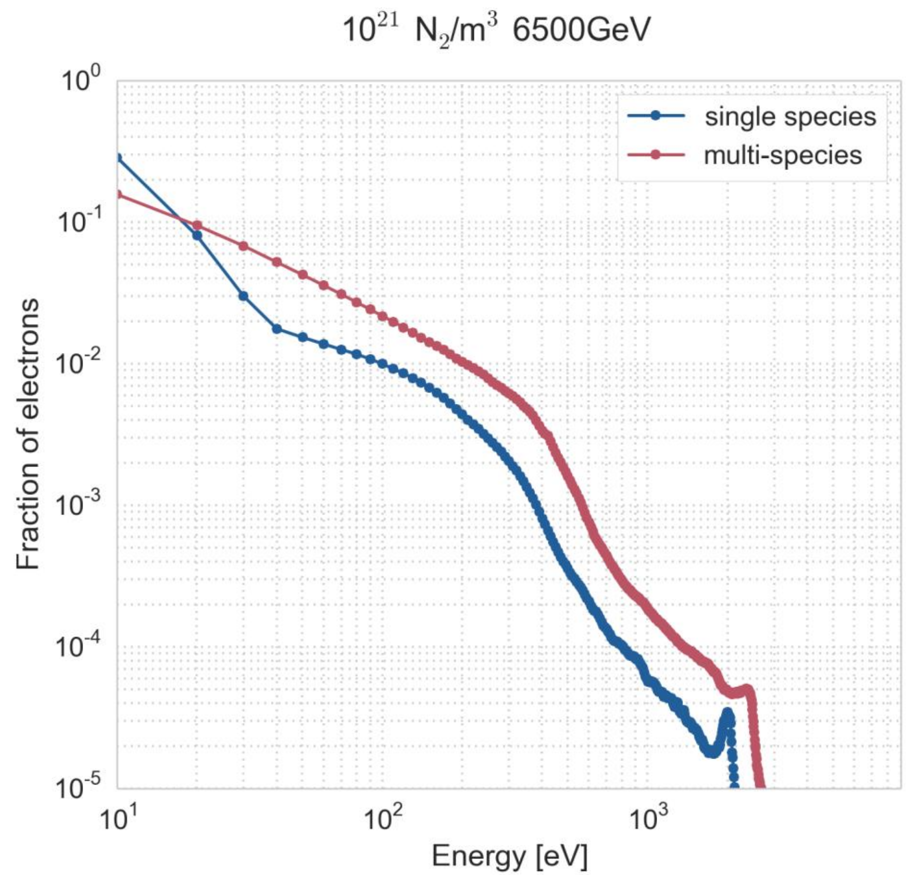


Electron energy spectrum

Comparing the energy spectrum against single-species electron simulations

- Above 10^{20} N_2/m^3, the shape of the energy spectrum is significantly changed





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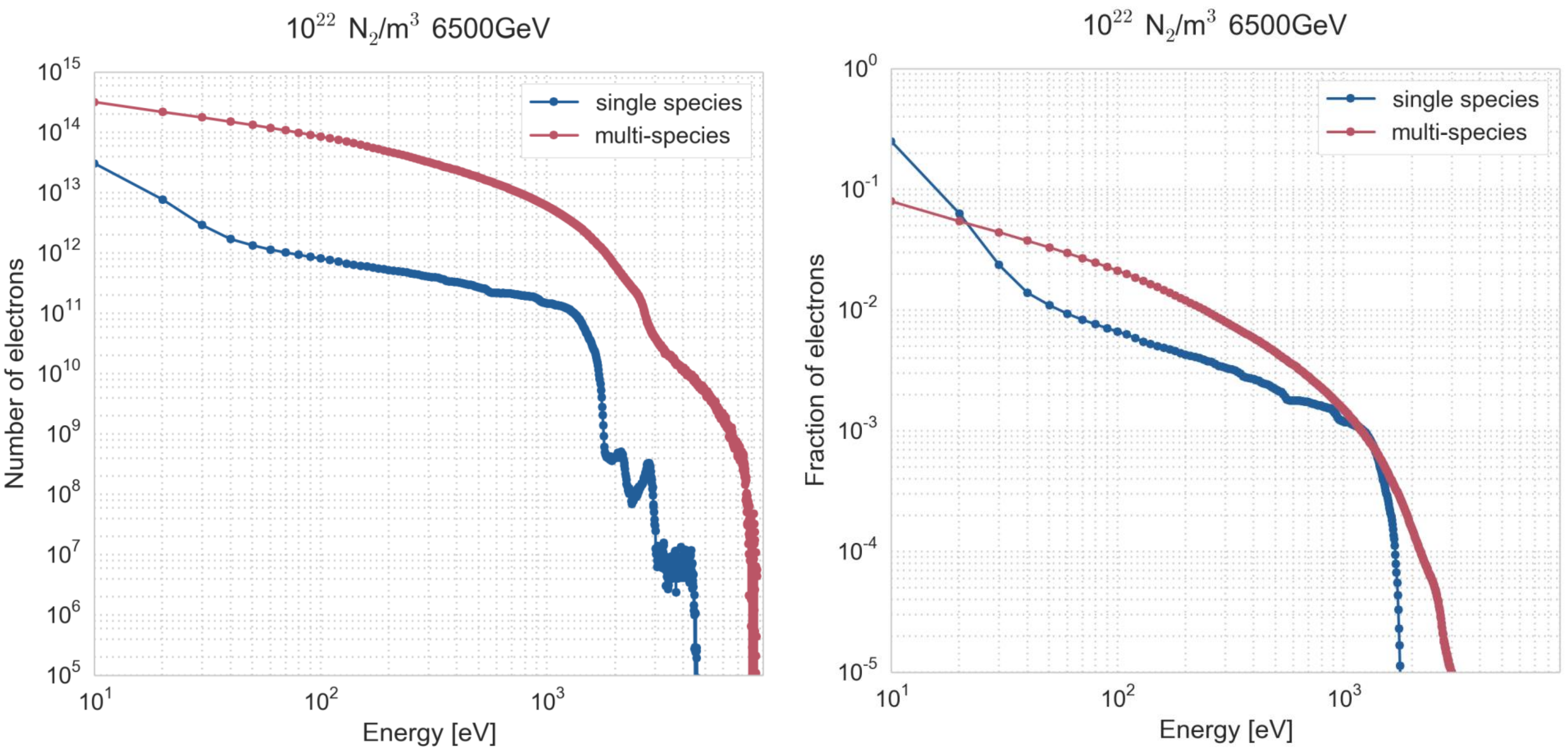

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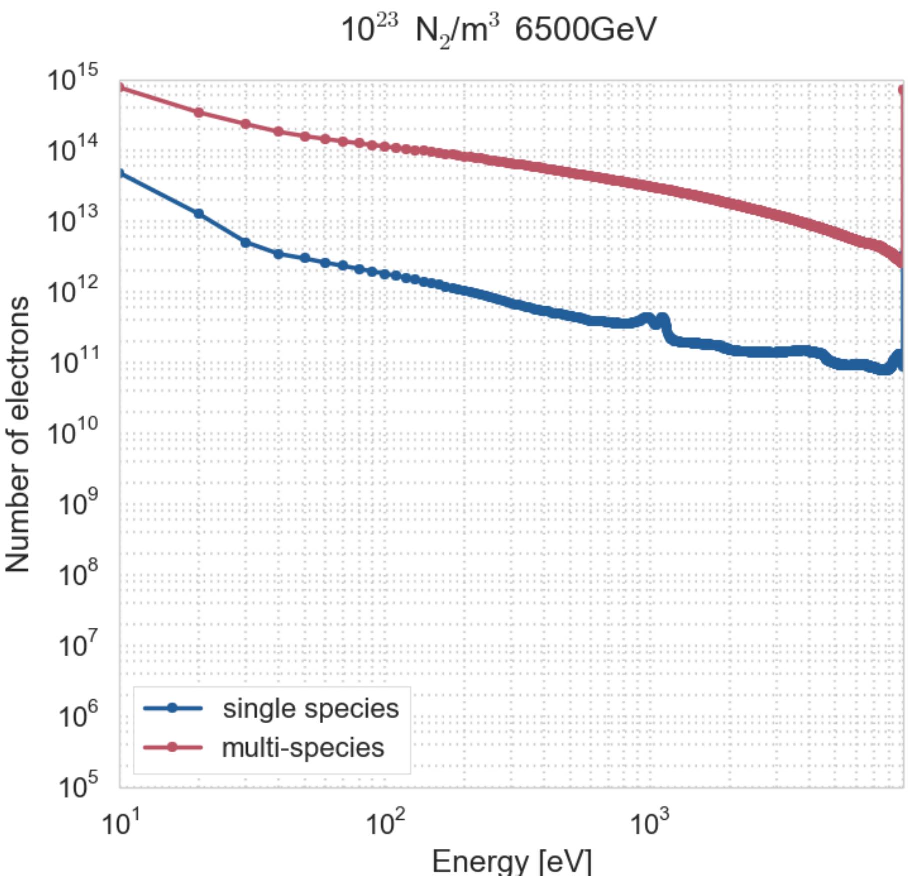
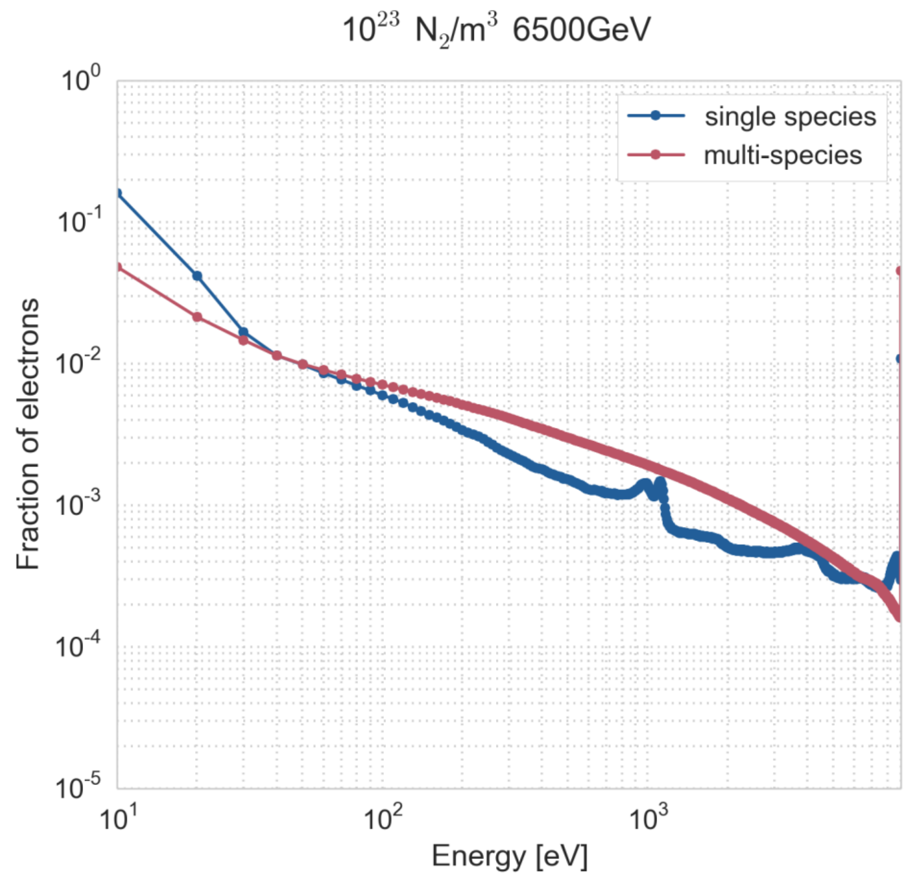
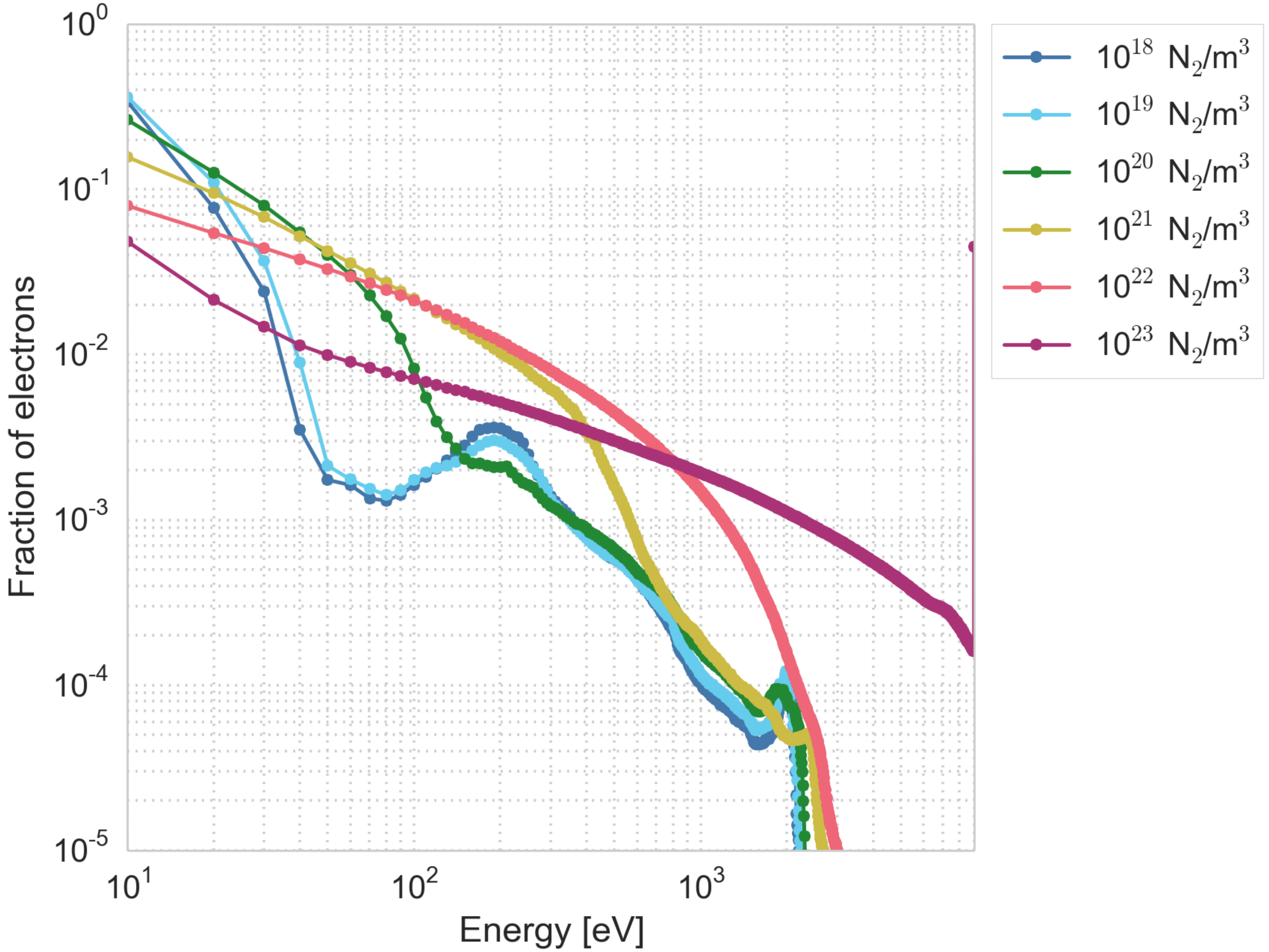




Electron energy spectrum

The electron energy distribution changes significantly when the gas density increases

- The distribution shifts towards higher energies for higher gas densities



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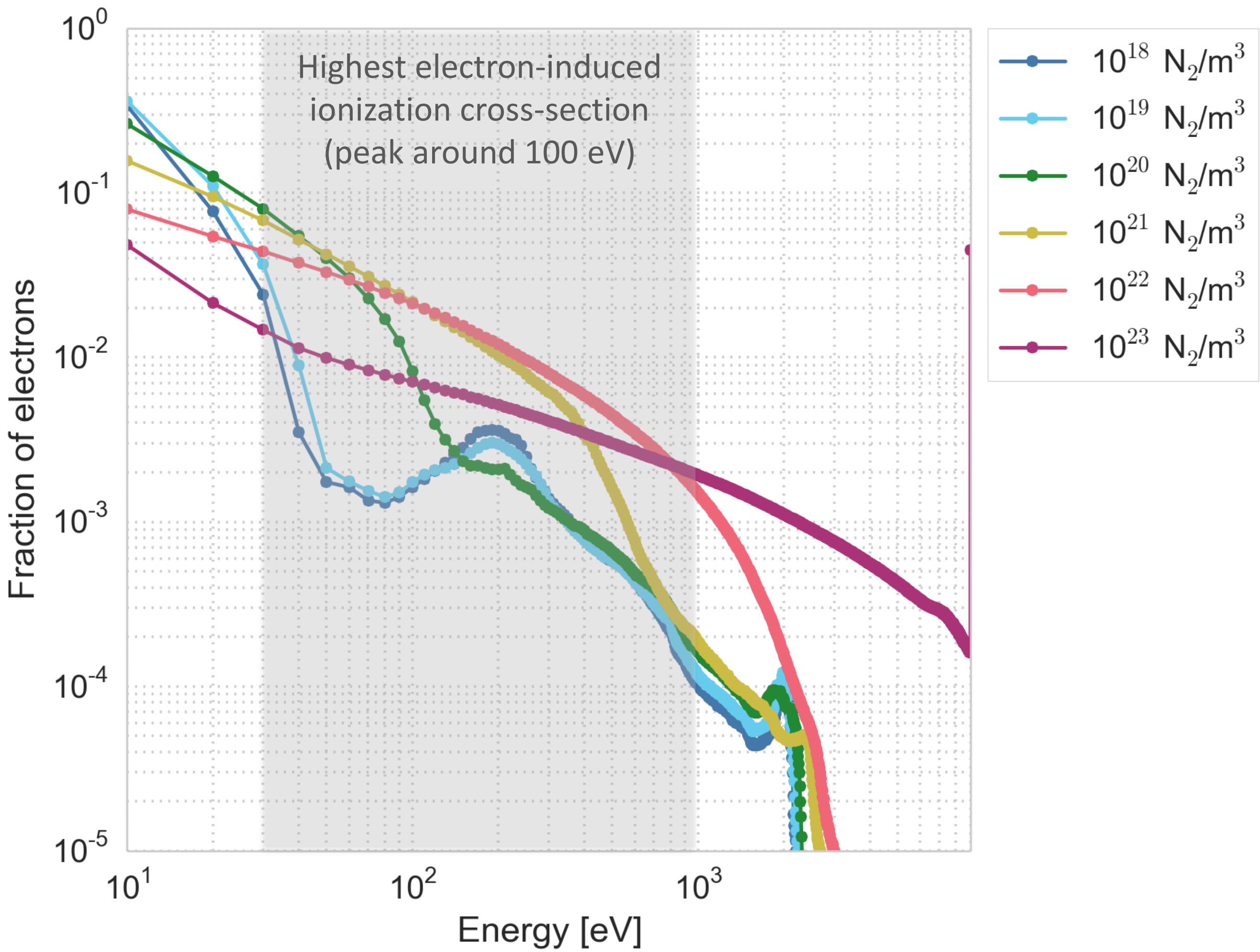

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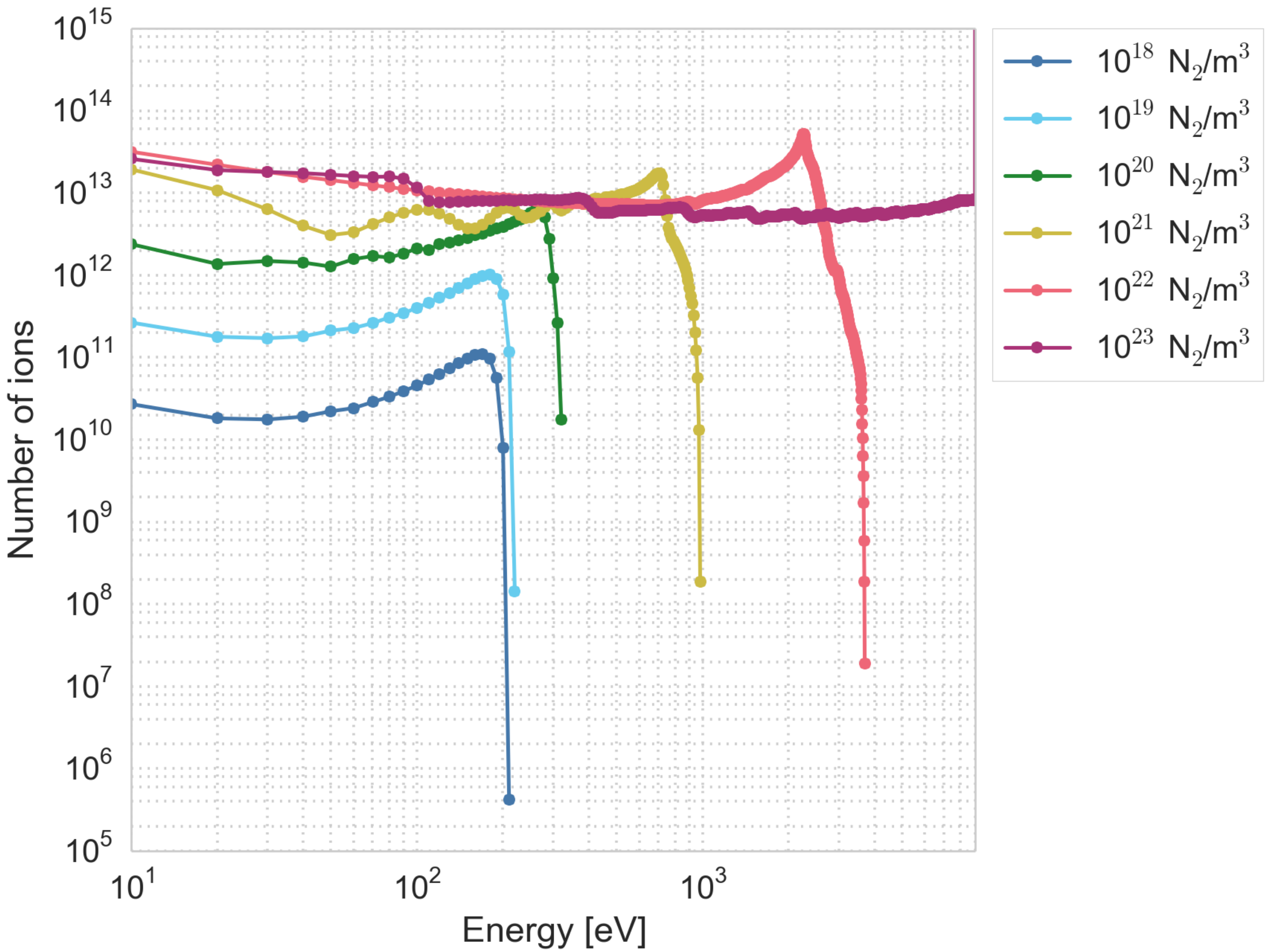
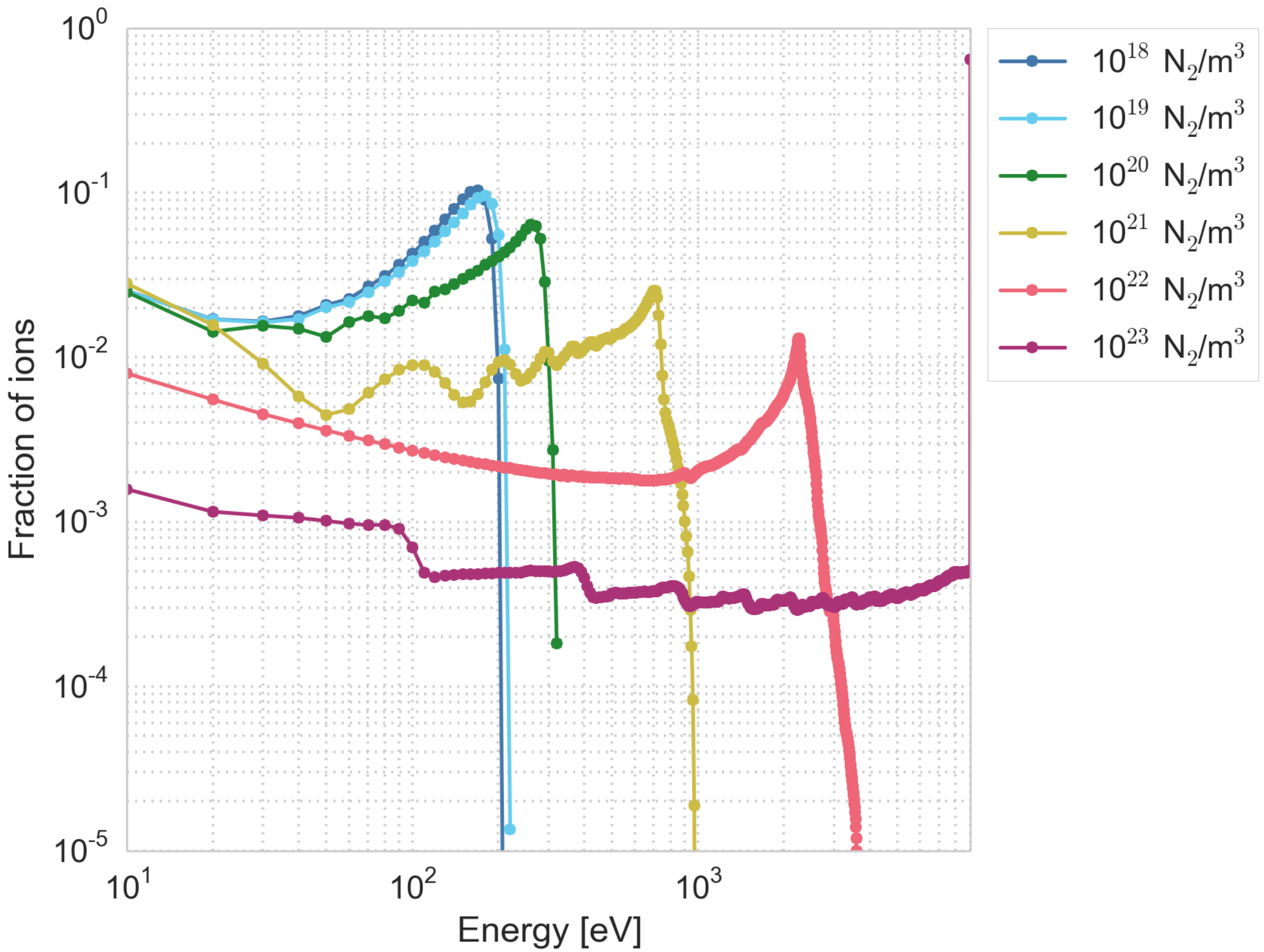


Ion energy spectrum

Also the ion energy distribution changes significantly when the gas density increases

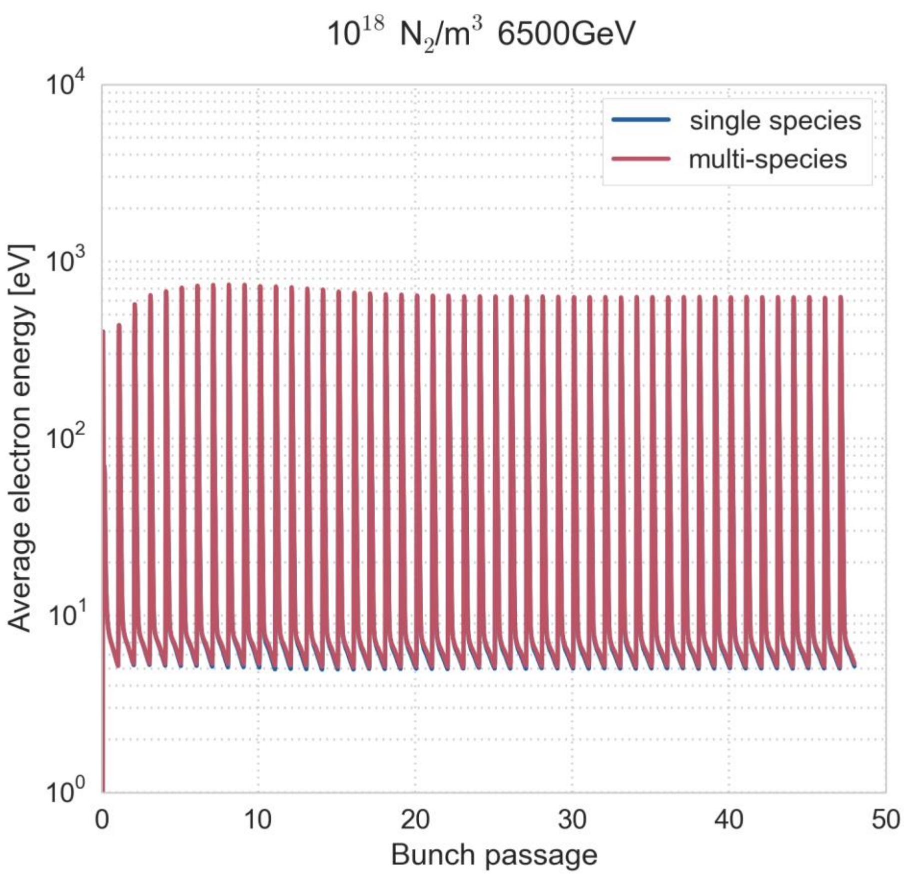
- As for the electrons, a significant effect on the spectrum is seen as of 10^{20} N_2/m^3

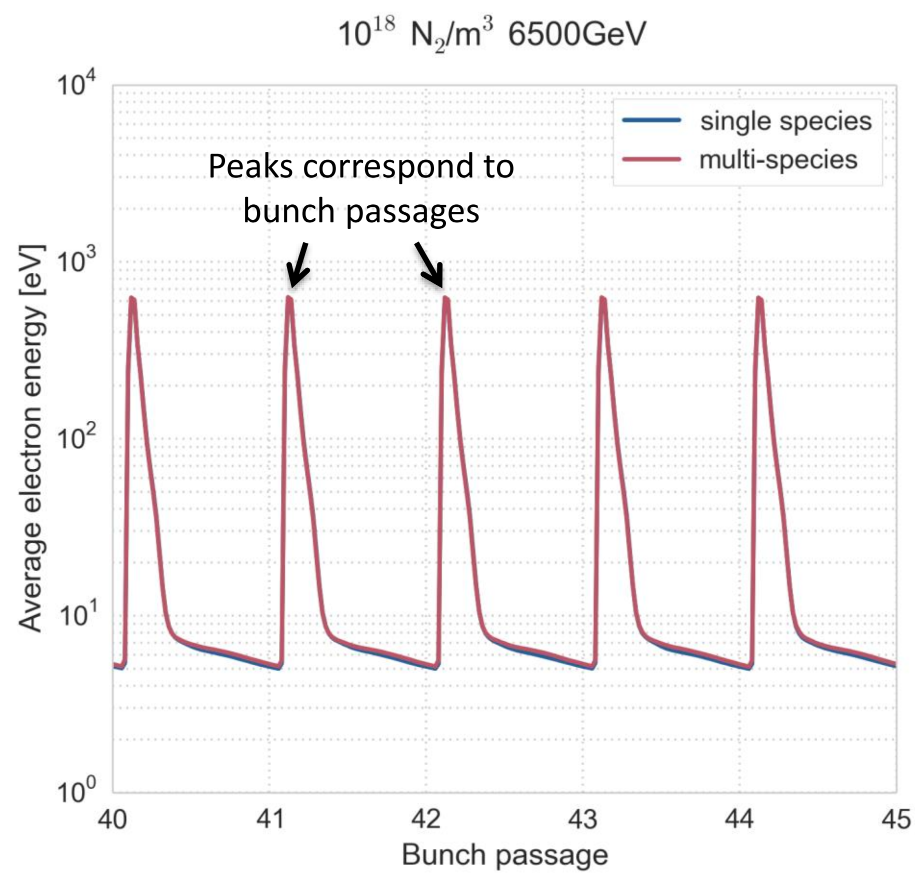


Average electron energy

Comparing the average electron energies at every time step during a BCMS bunch train passage against single-species electron simulations

- With 10^{18} N_2/m^3, the impact of the ions is negligible





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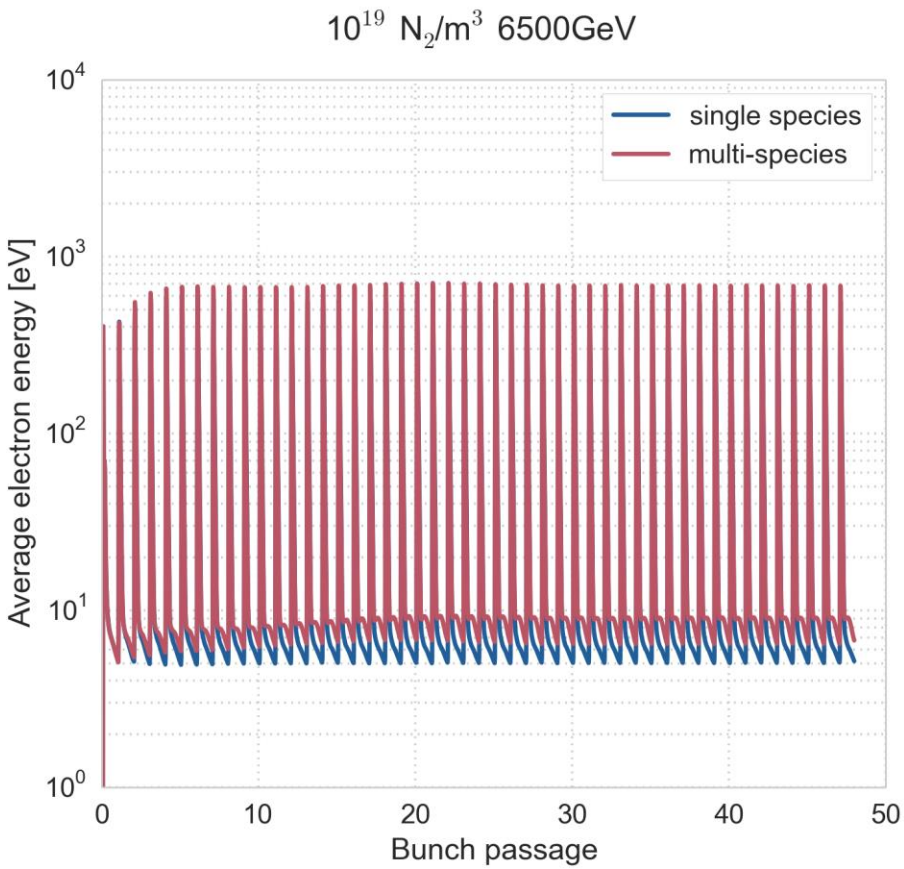
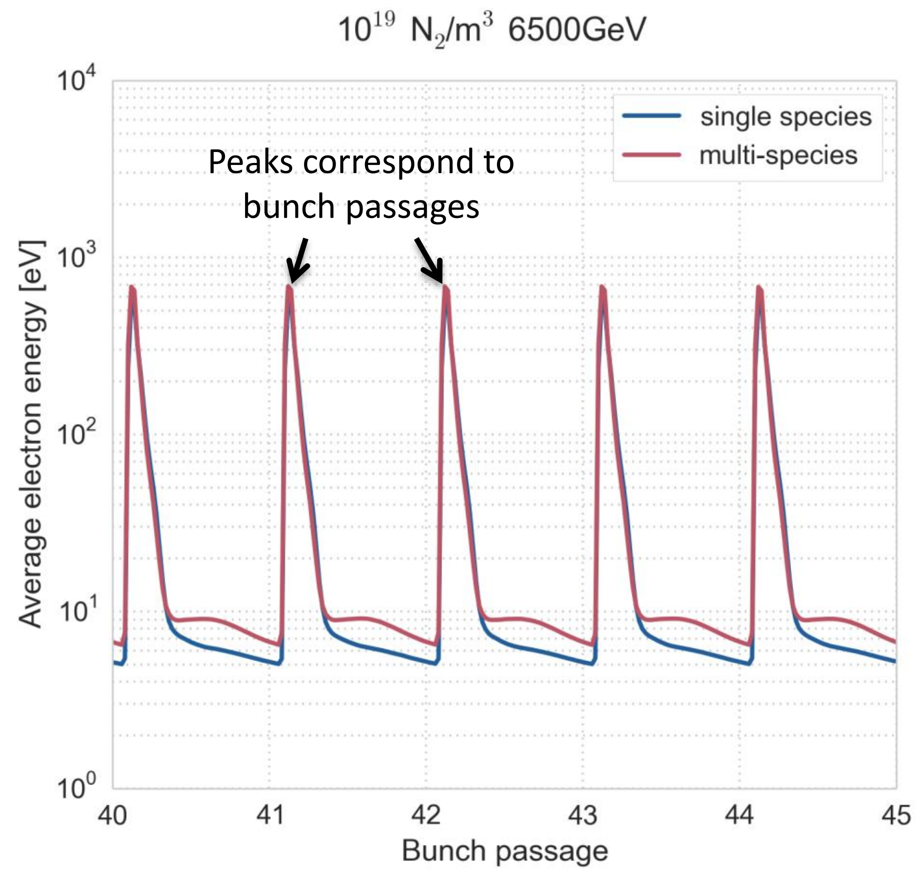
- With 10^{19} N_2/m^3, the energy between bunch passages is slightly higher





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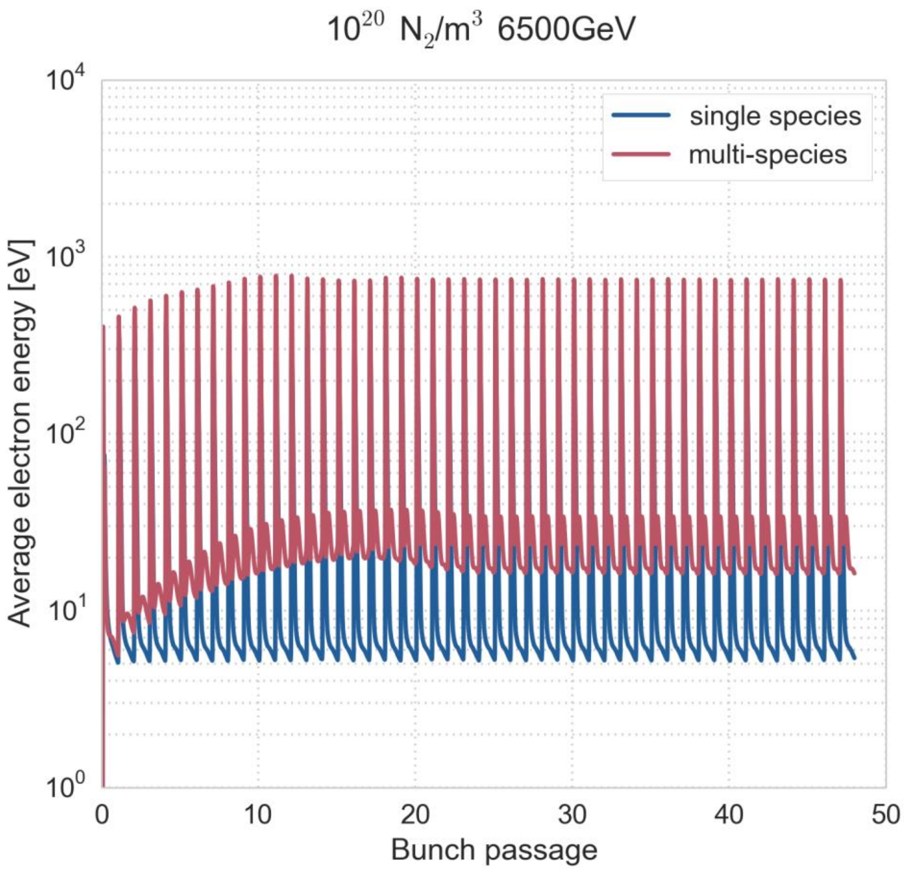
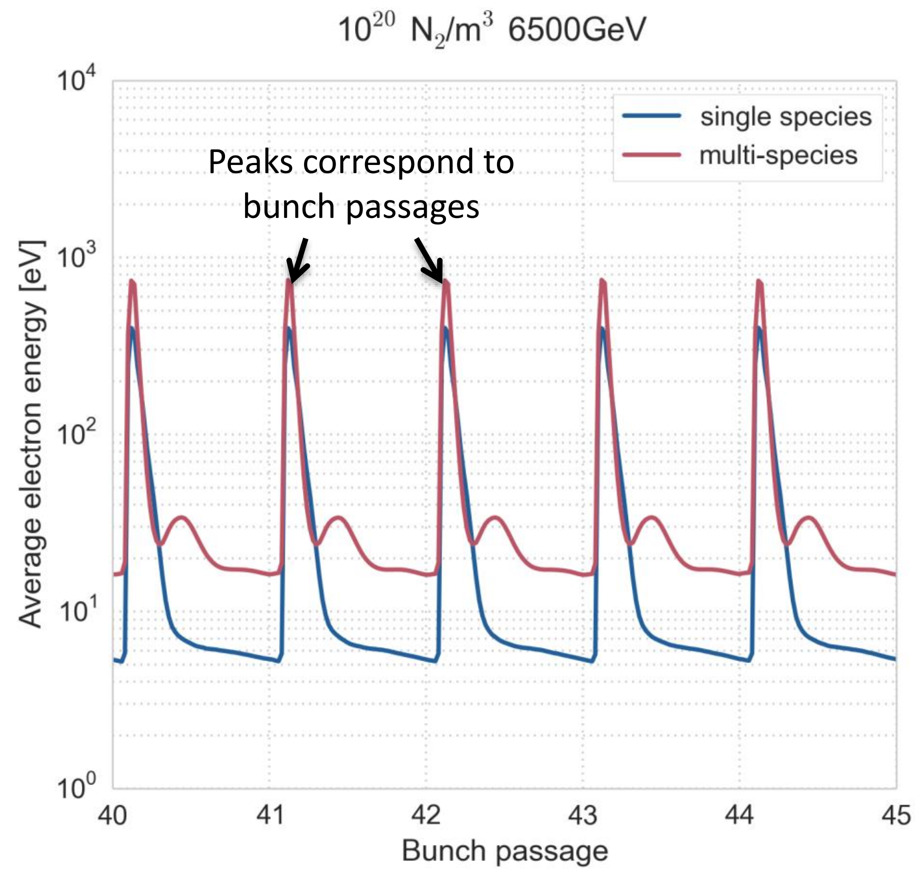
- For higher densities, the energy between bunch passages is significantly higher





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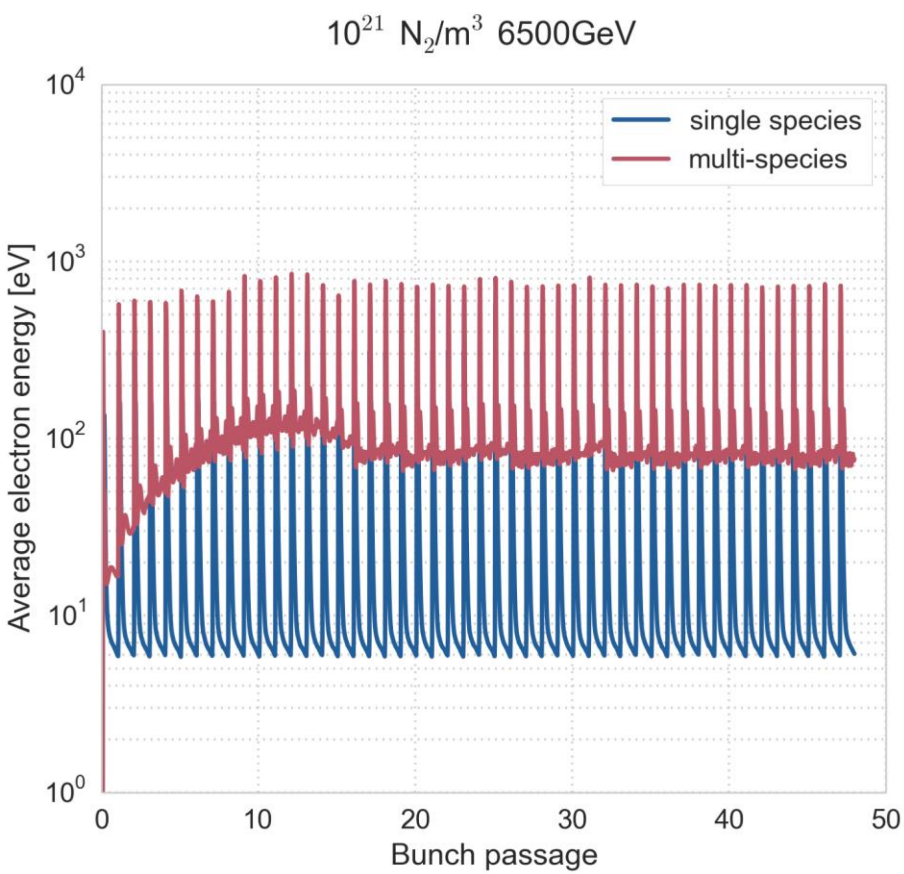

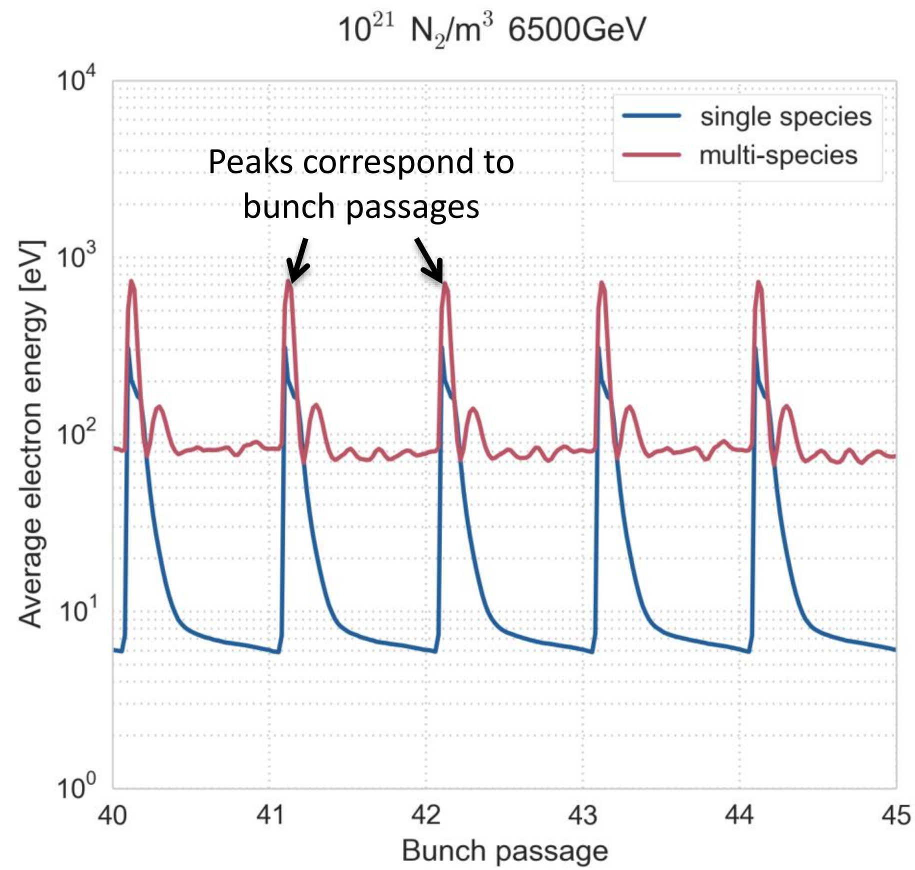

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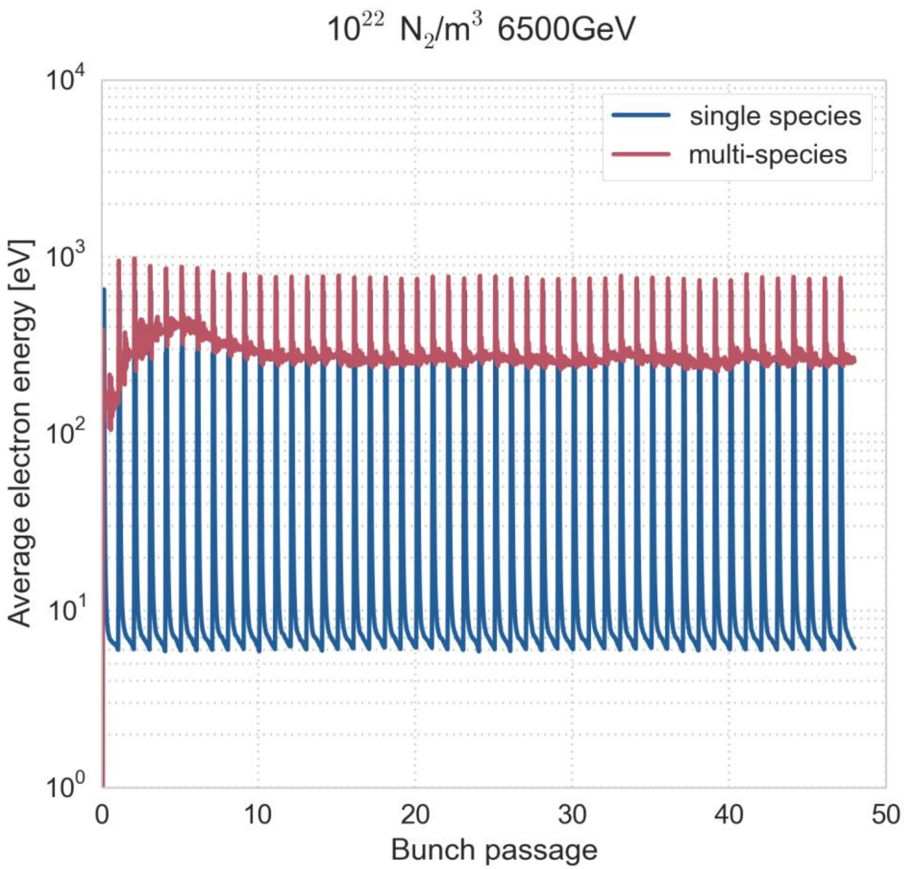
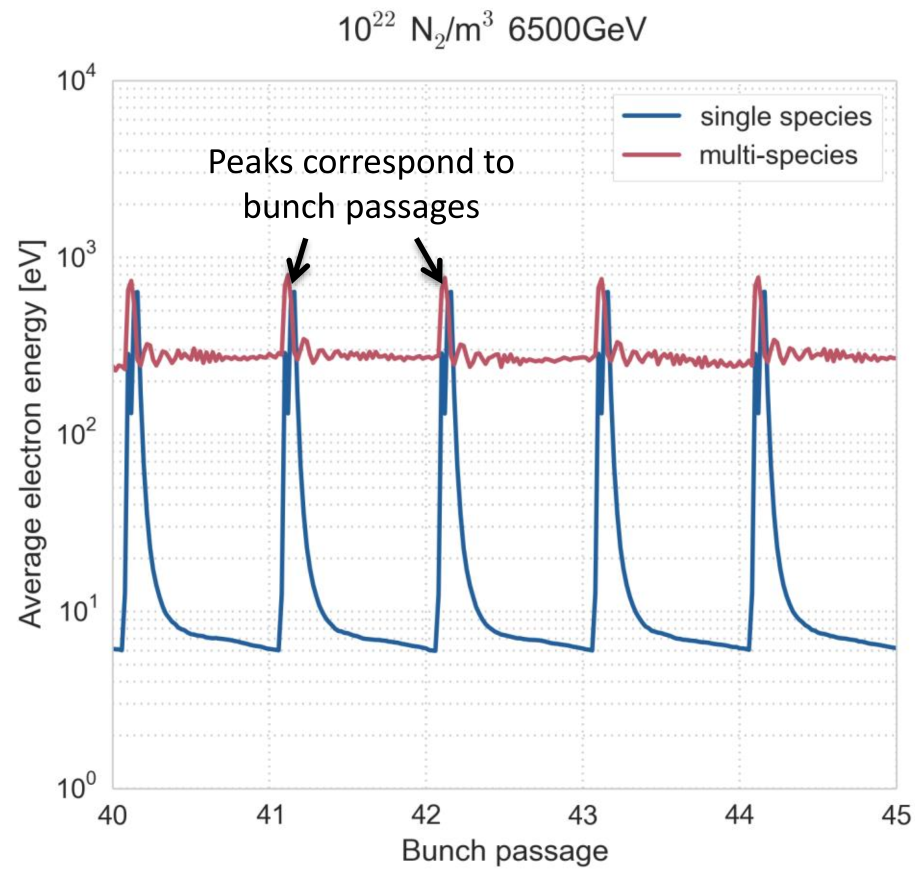
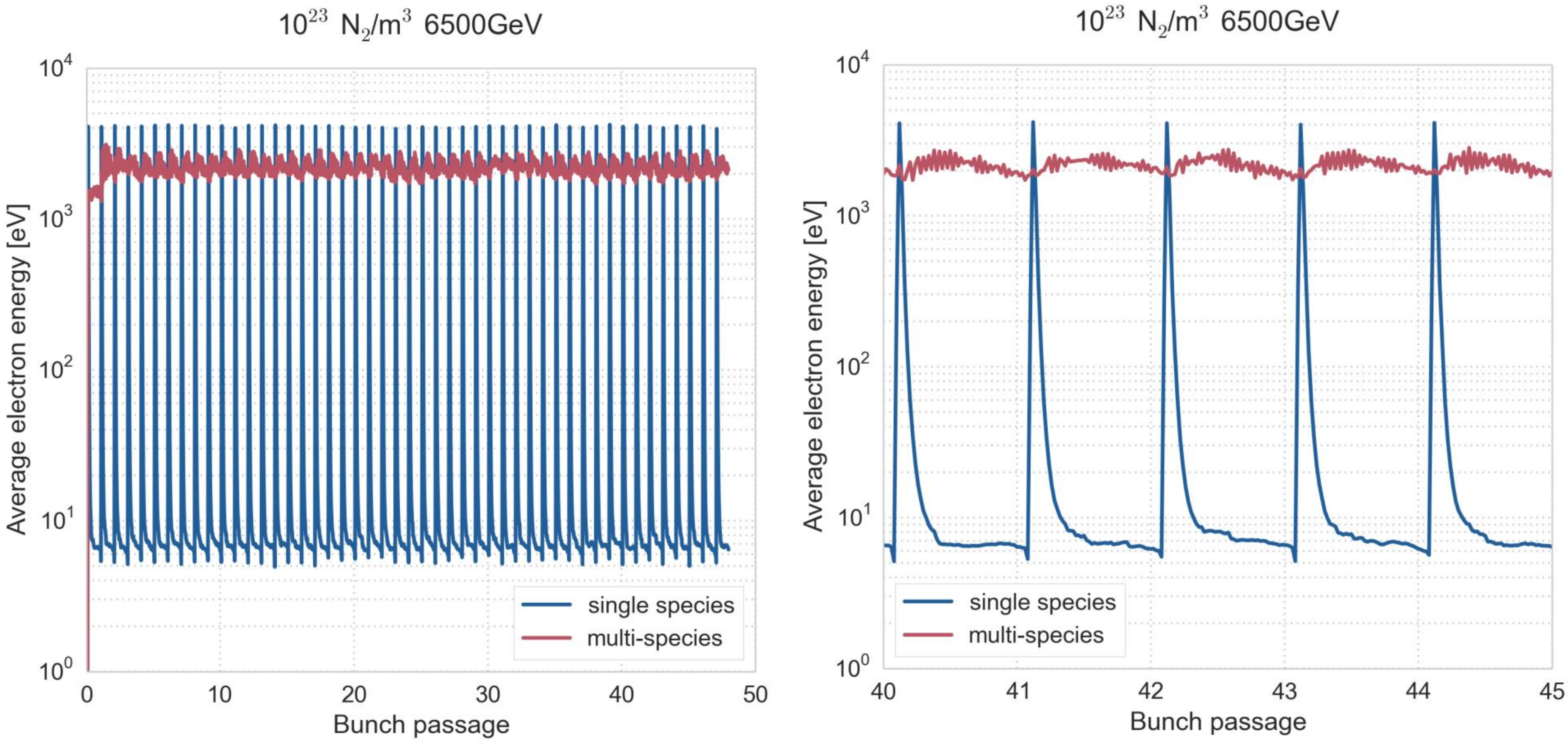




Average electron energy

Comparing the average electron energies at every time step during a BCMS bunch train passage against single-species electron simulations

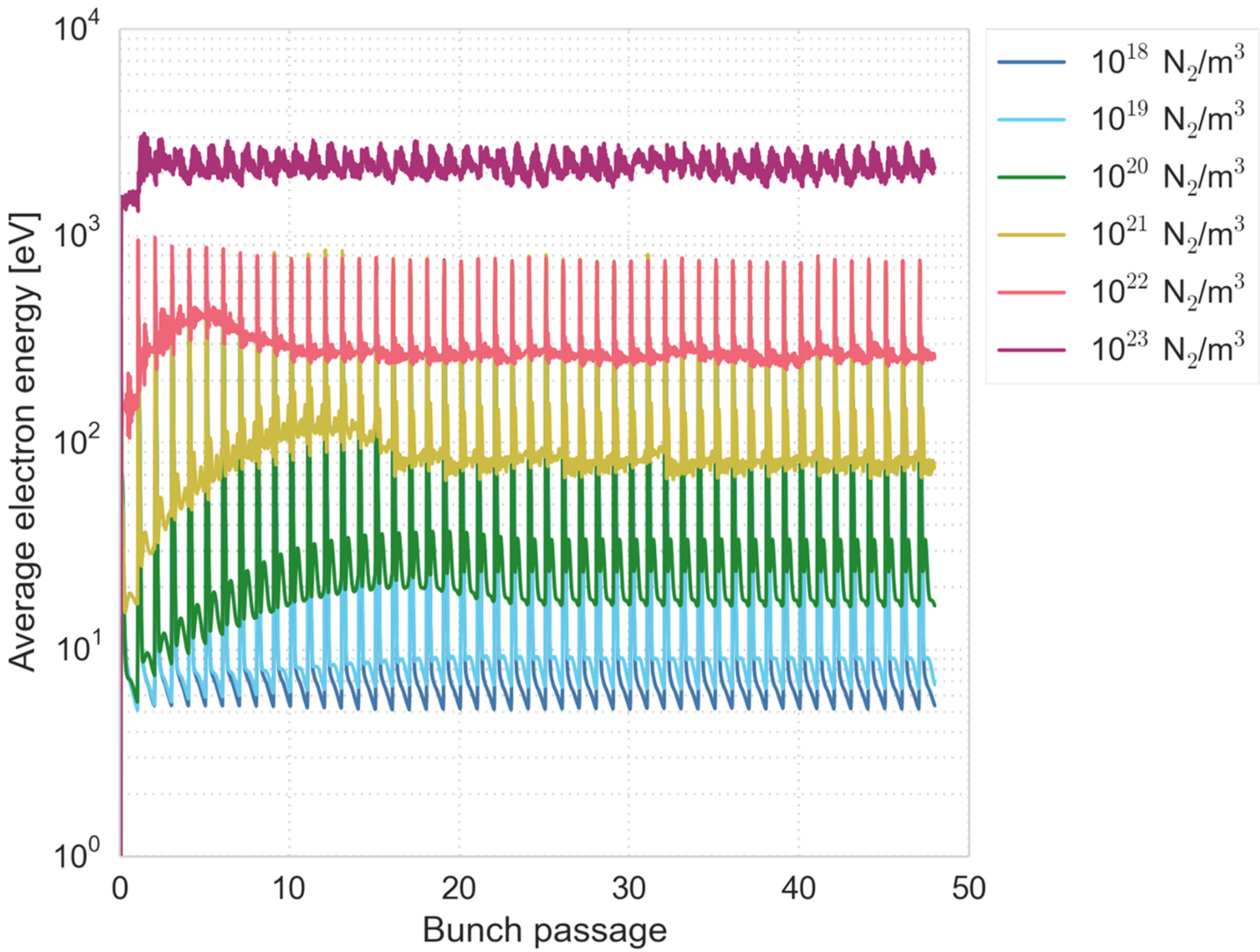
- With 10^{23} N_2/m^3, the bunch passage is barely seen on the electron energies



Average electron energy

The energy during bunch passages is independent of the gas density (below 10^{23} m^{-3})

- The energy between bunch passages increases for higher gas densities



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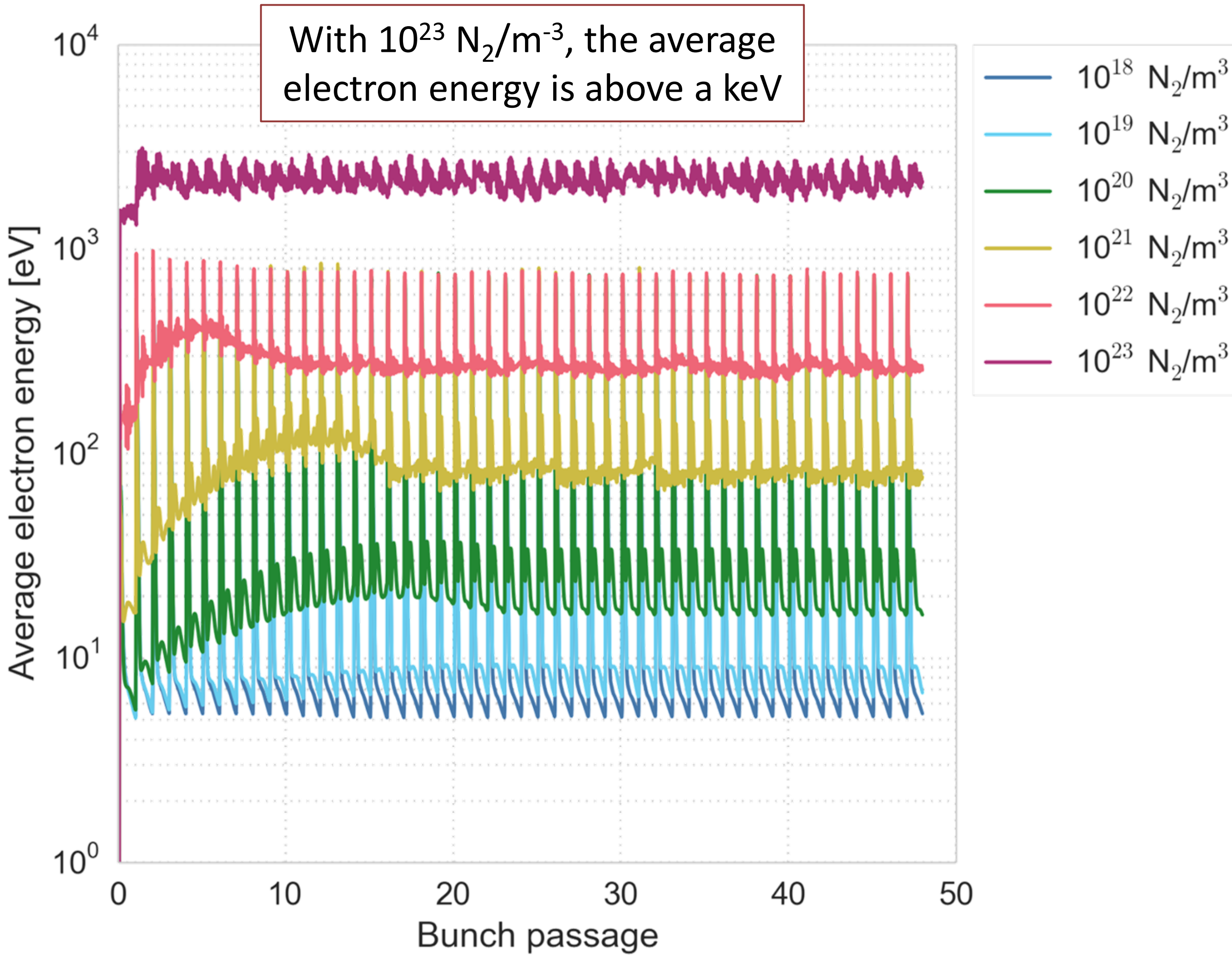
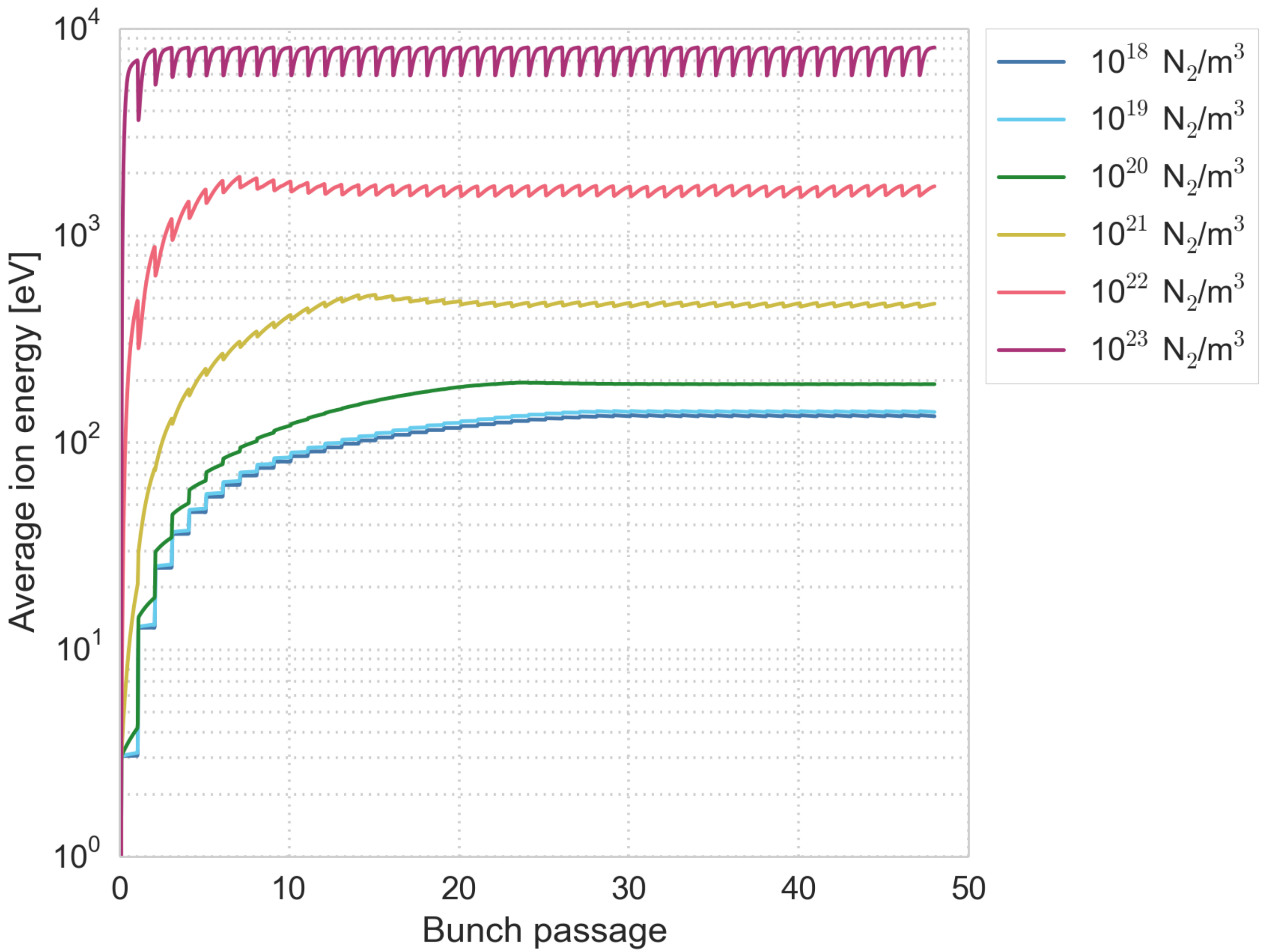


Average ion energy

The ion energies are barely affected by the bunch passages

- For any given gas density the ion energies are higher than the electron energies



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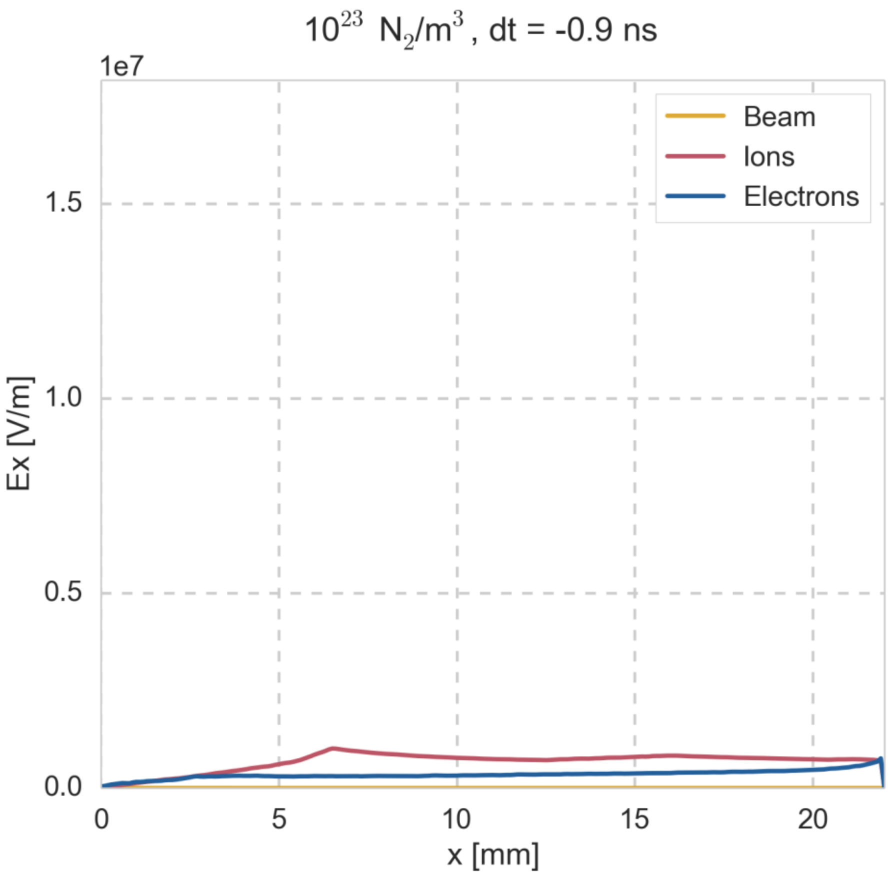

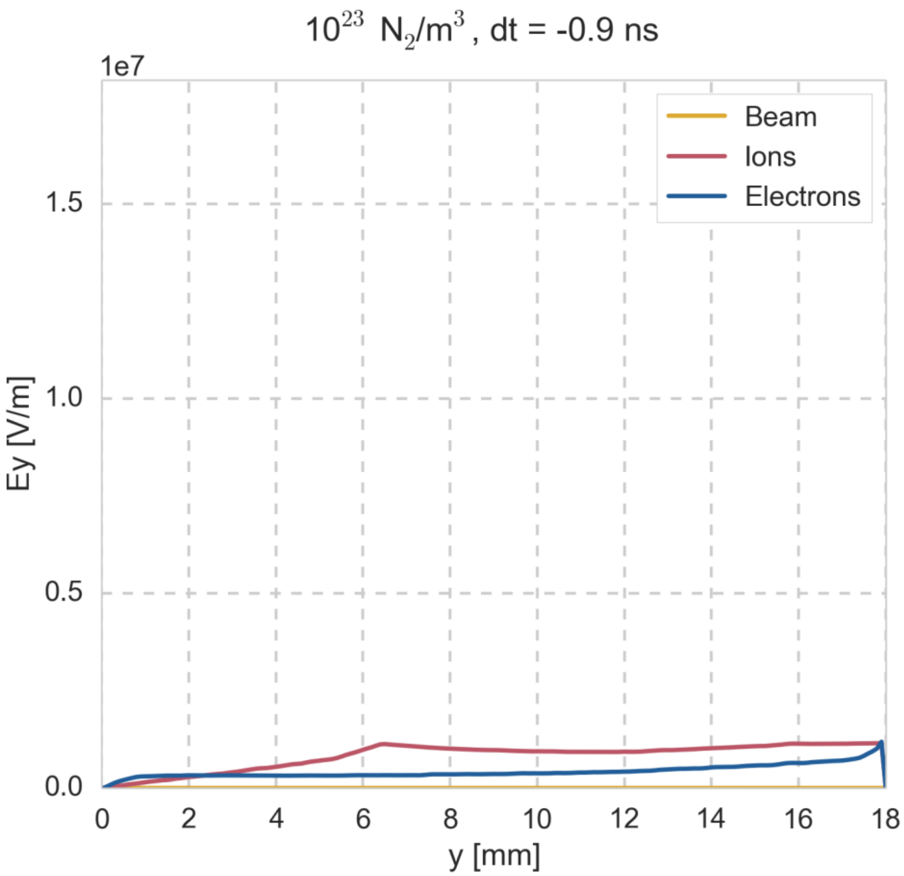

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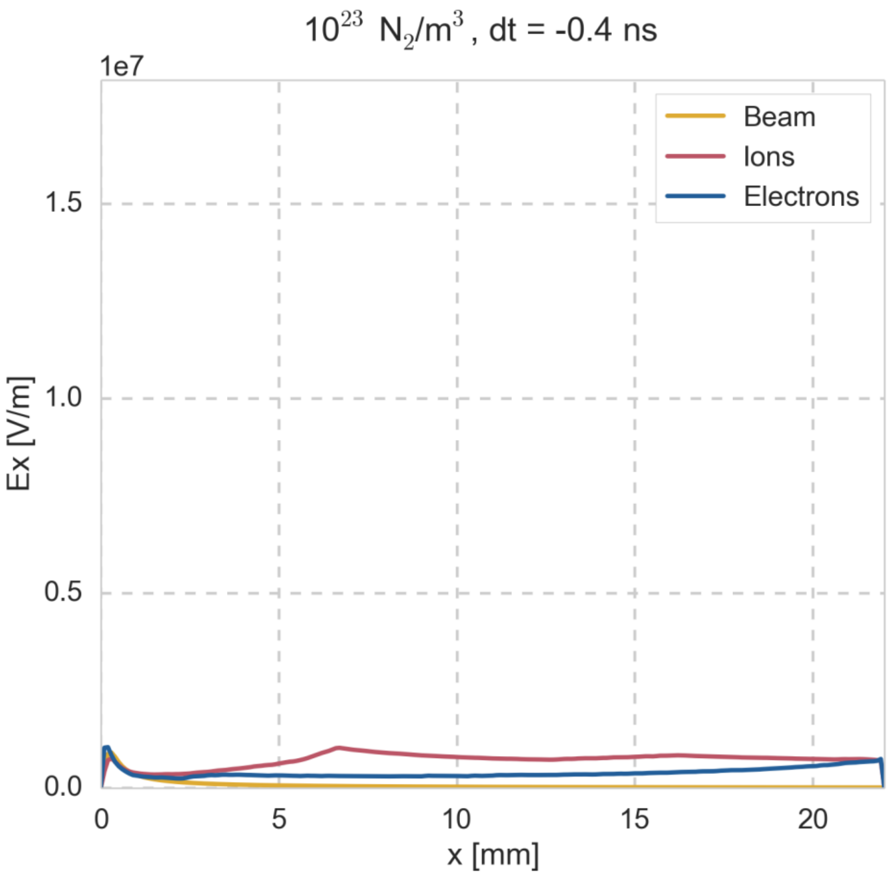

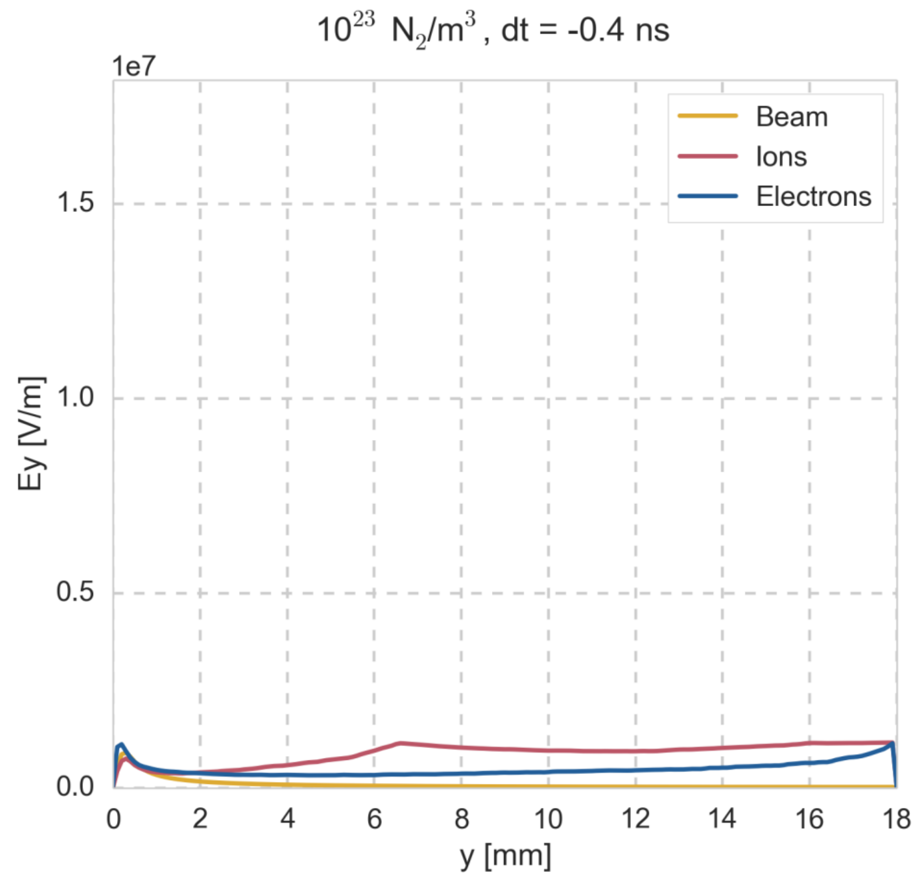

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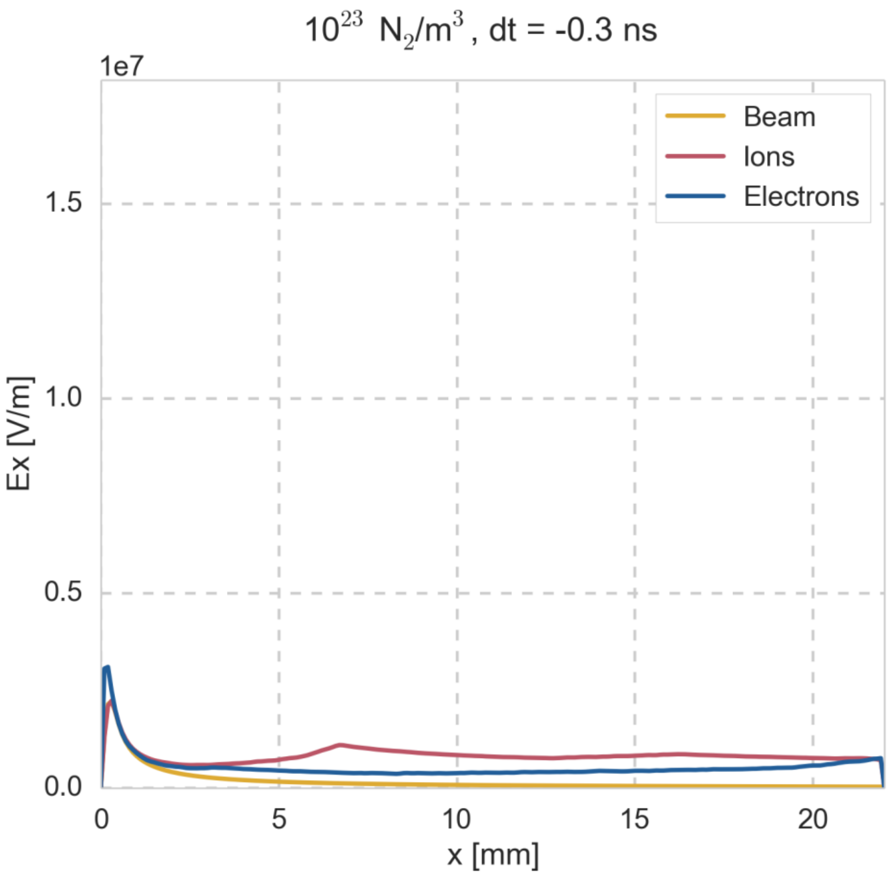
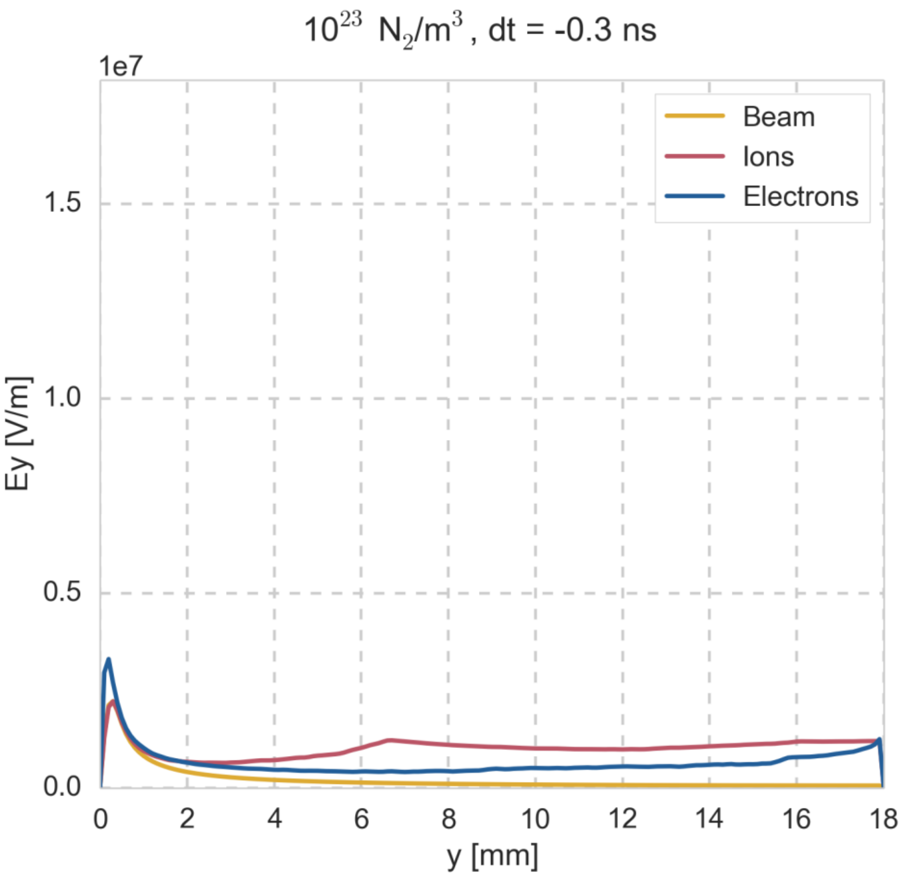
- When the head of the bunch is passing, the electron field is the strongest





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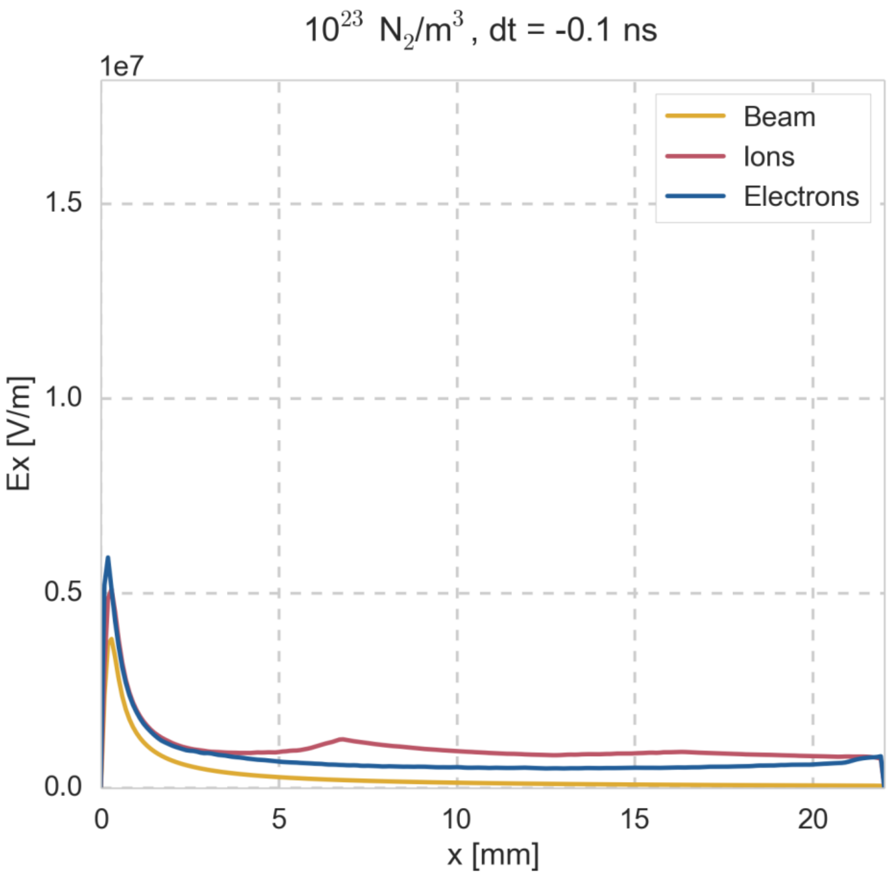

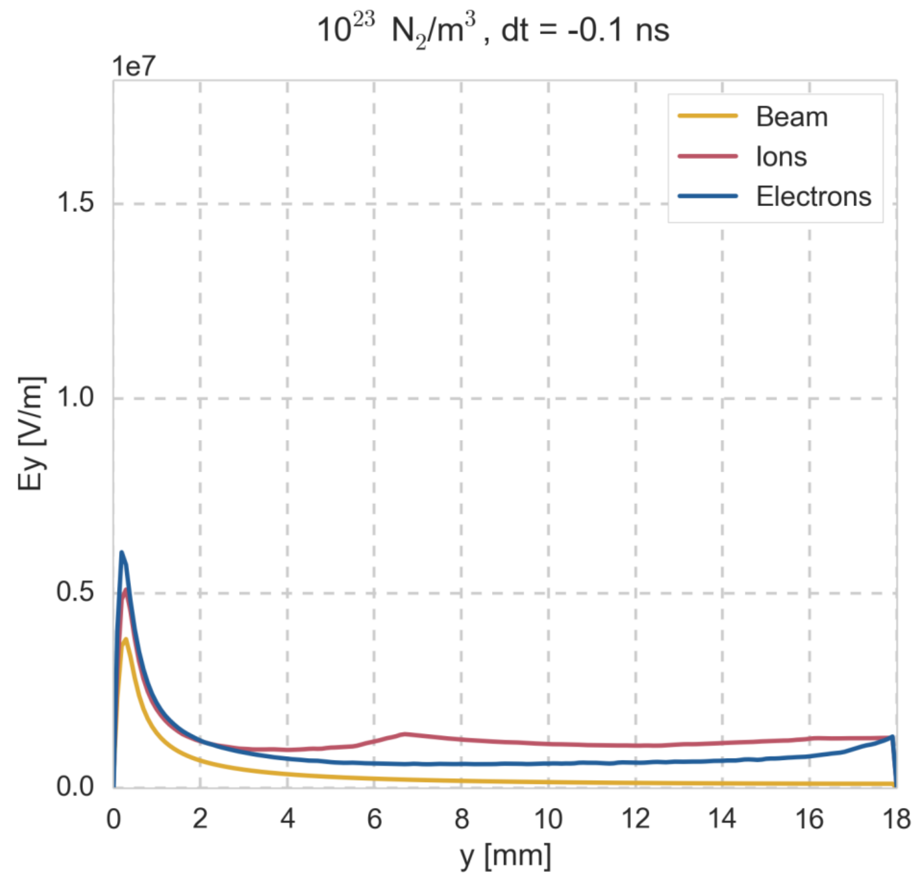

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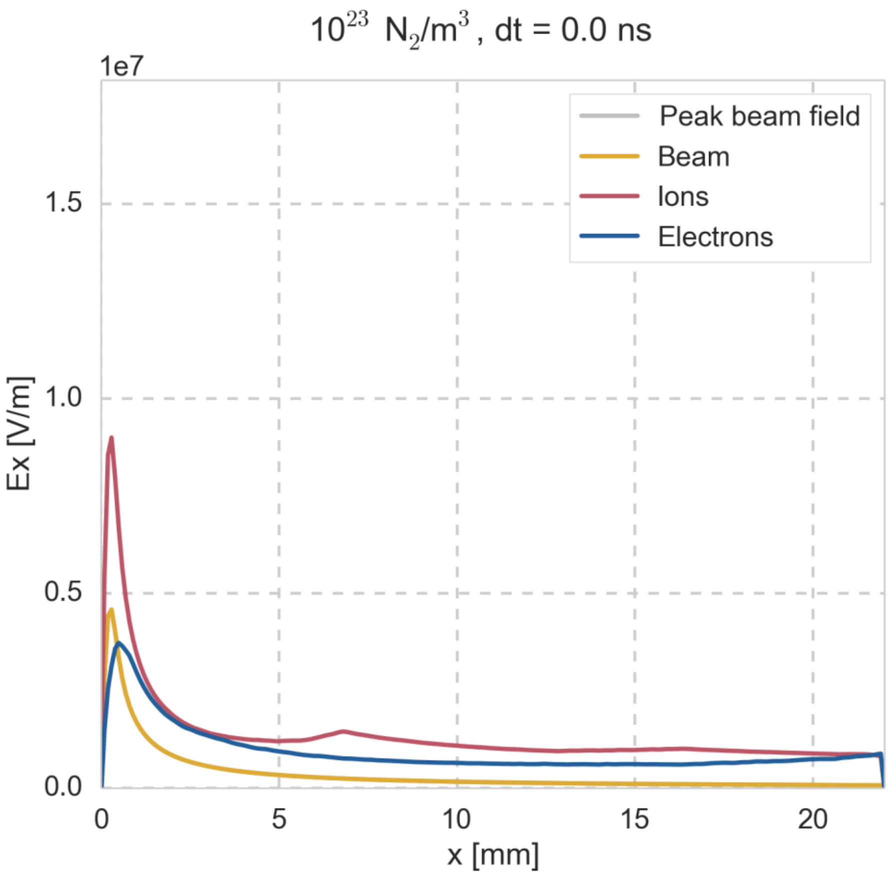
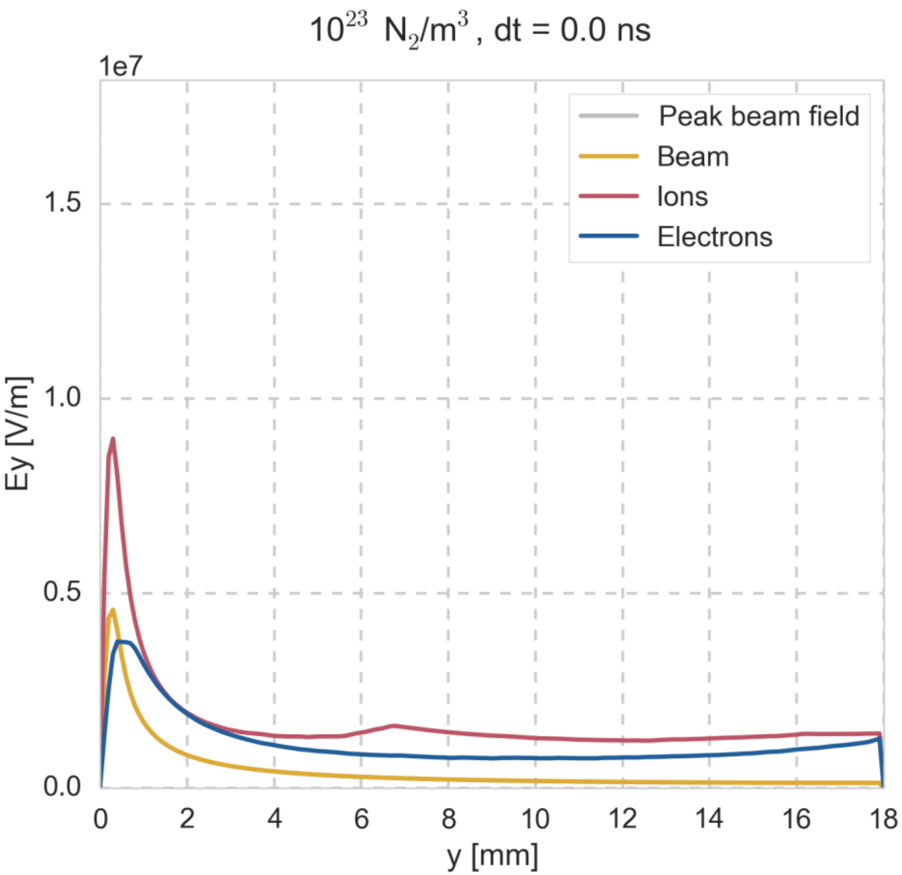
- When the bunch centroid passes, the ion field is the strongest





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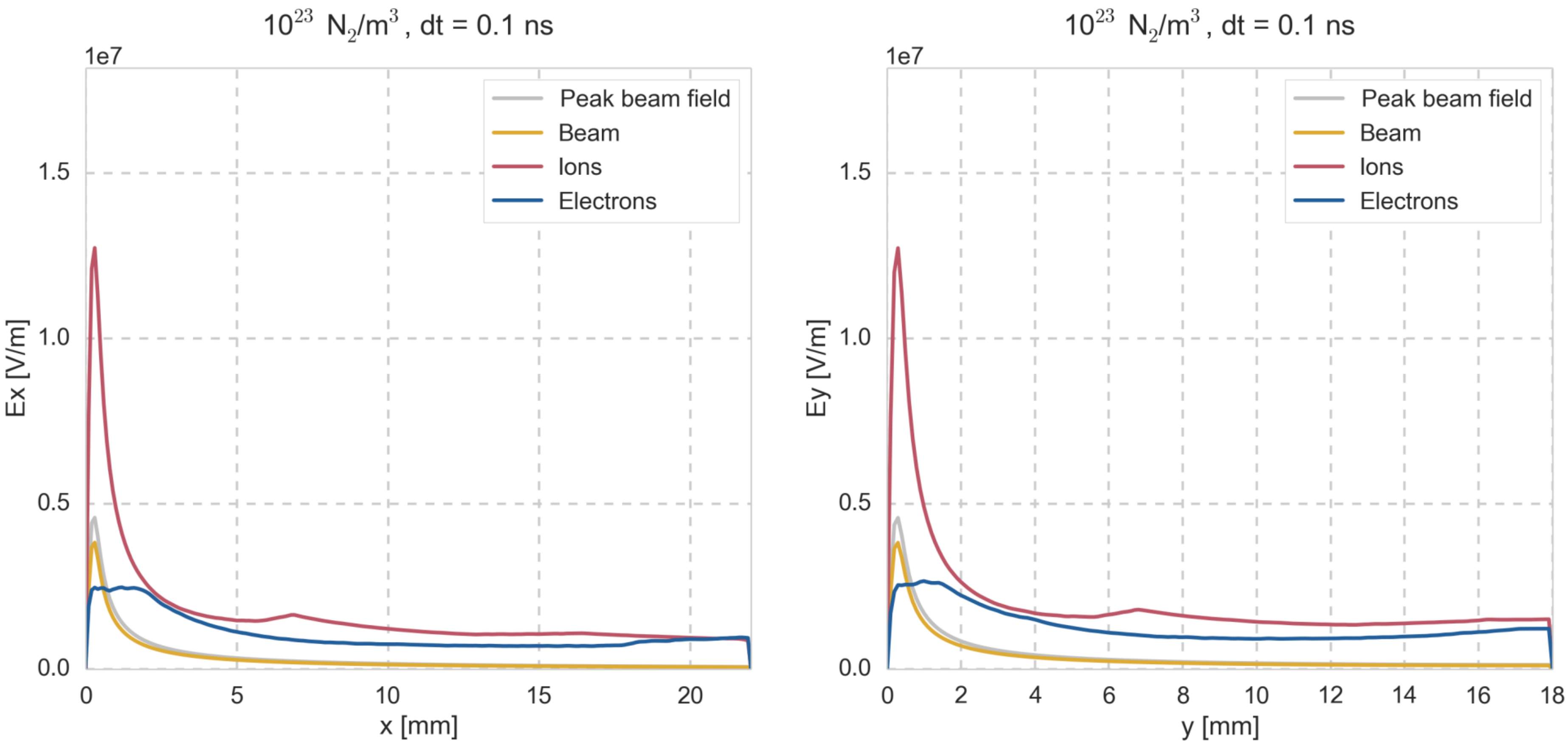
- The ion field grows until the tail of the bunch has passed



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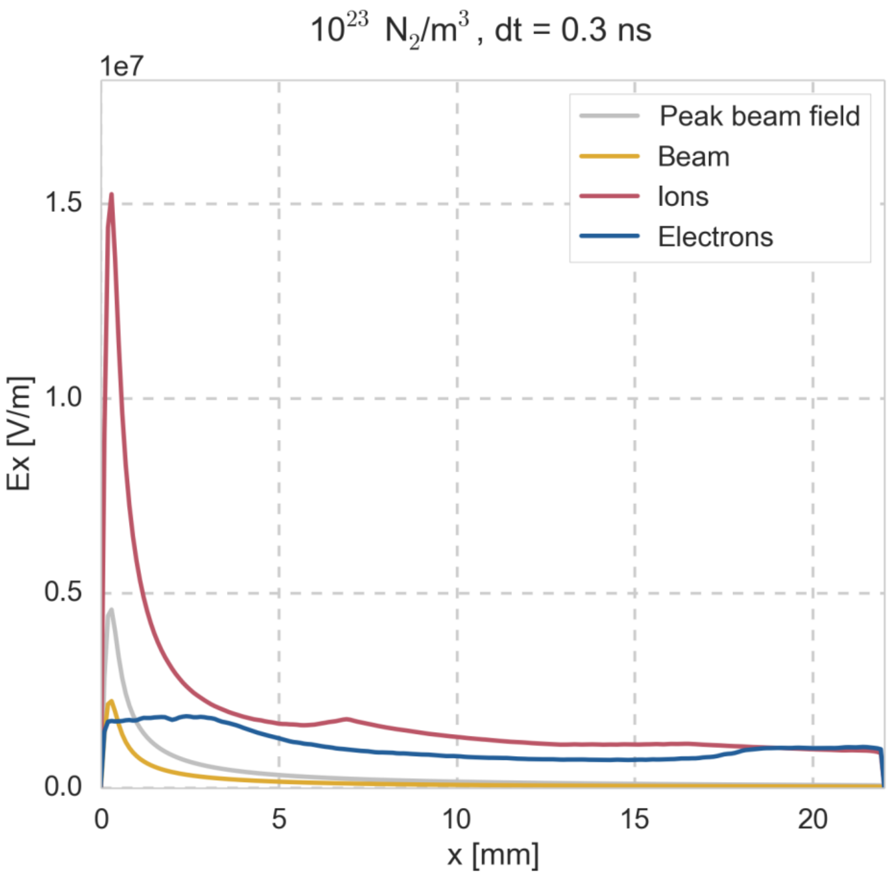

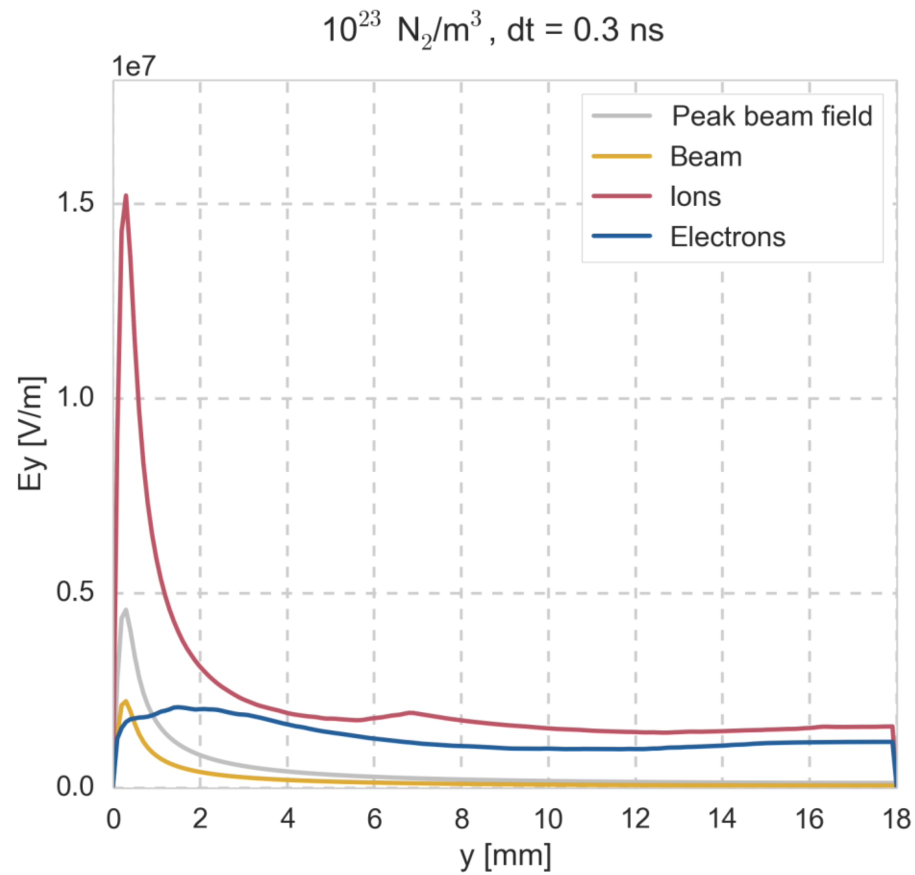

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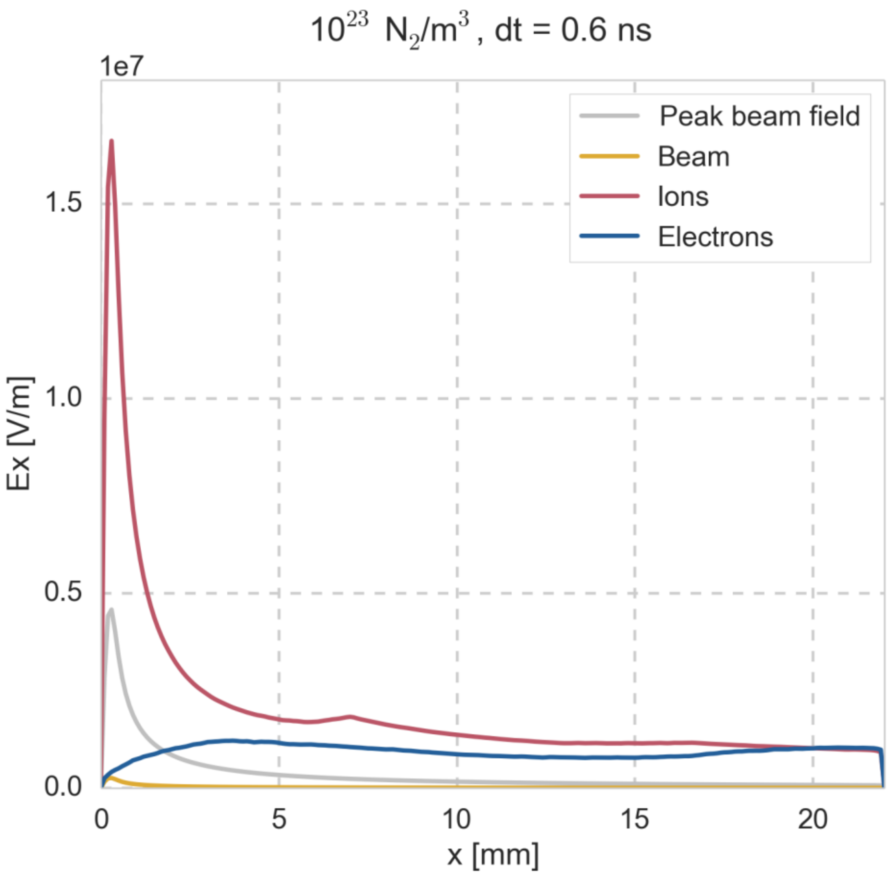

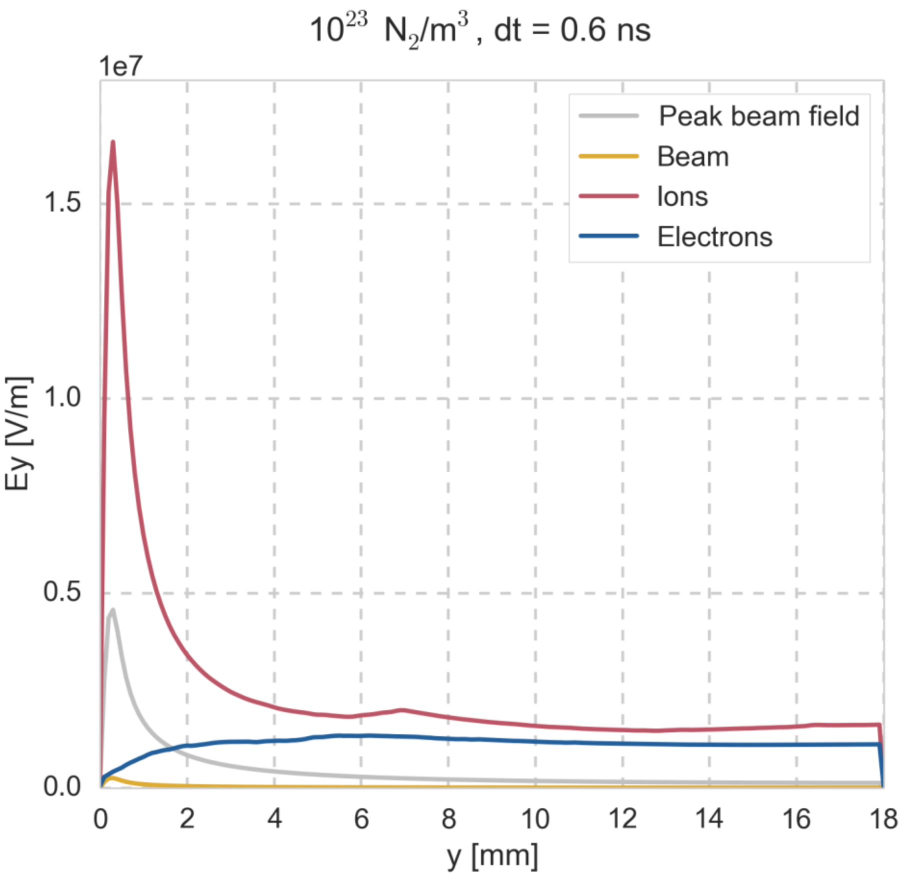

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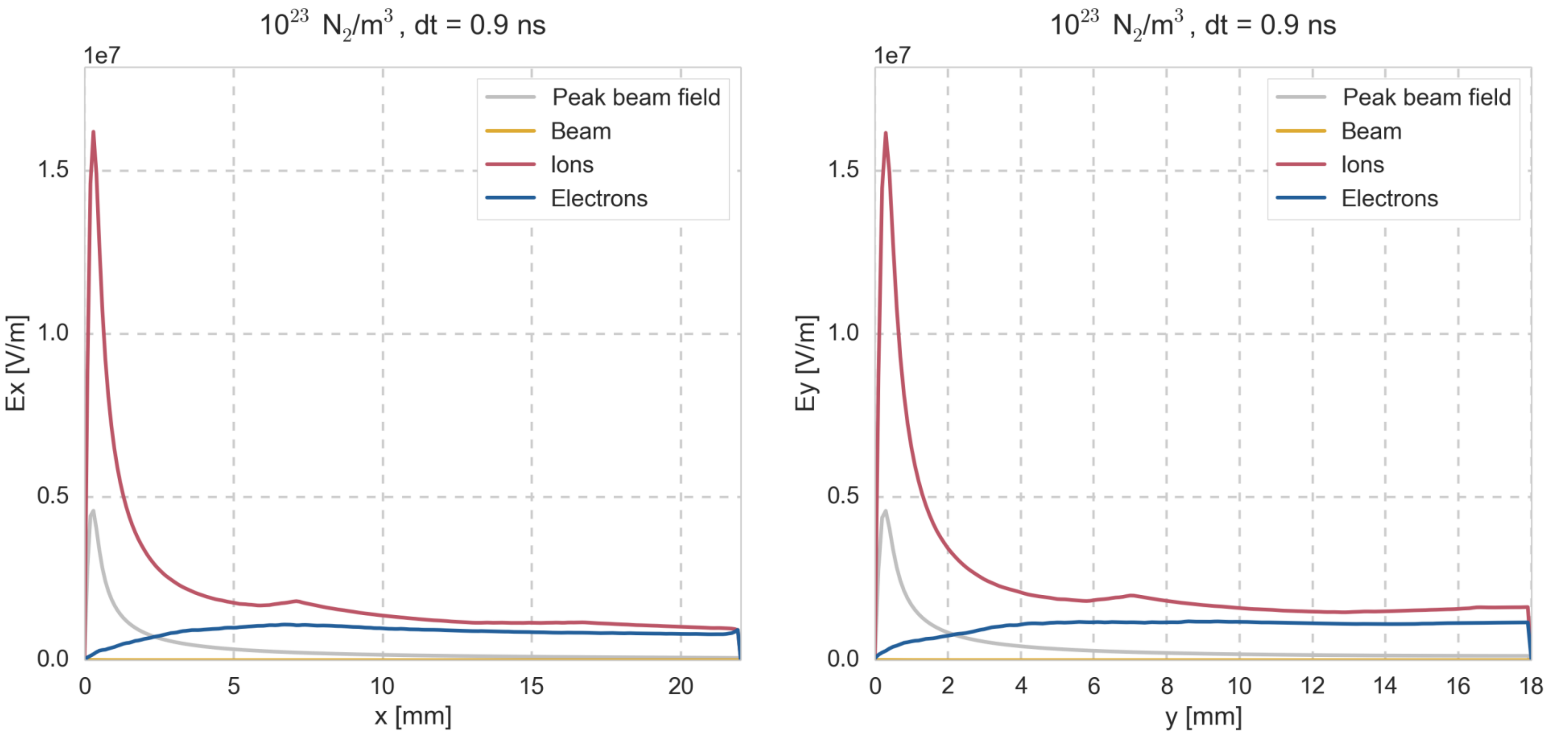

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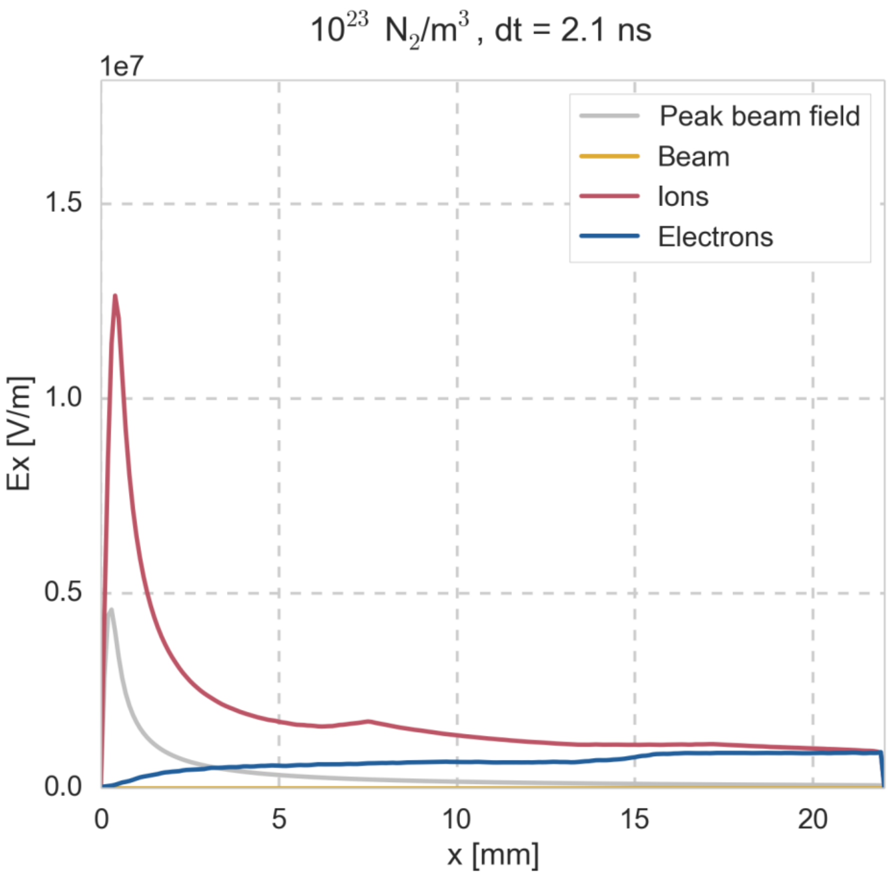
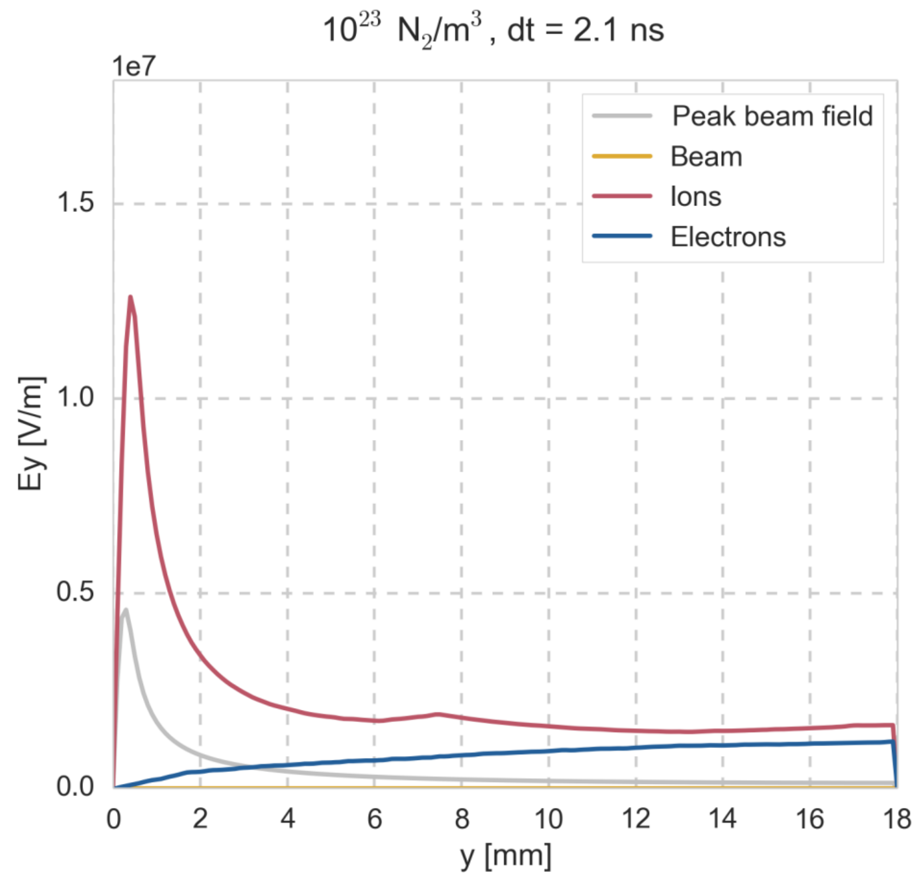
The observations with 10^{23} N_2/m^3, can be understood by comparing the electric fields of the beam, electron and ion charge distributions during a 25 ns bunch passage

- As the ions are relatively slow, the field strength decreases slowly over several ns





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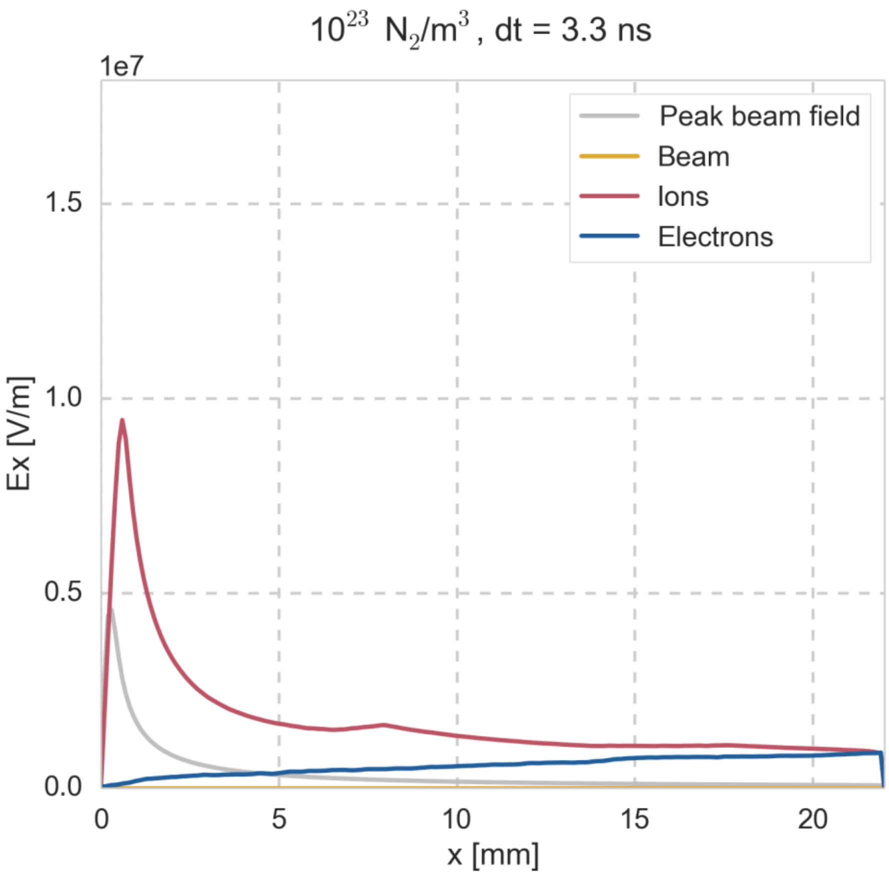

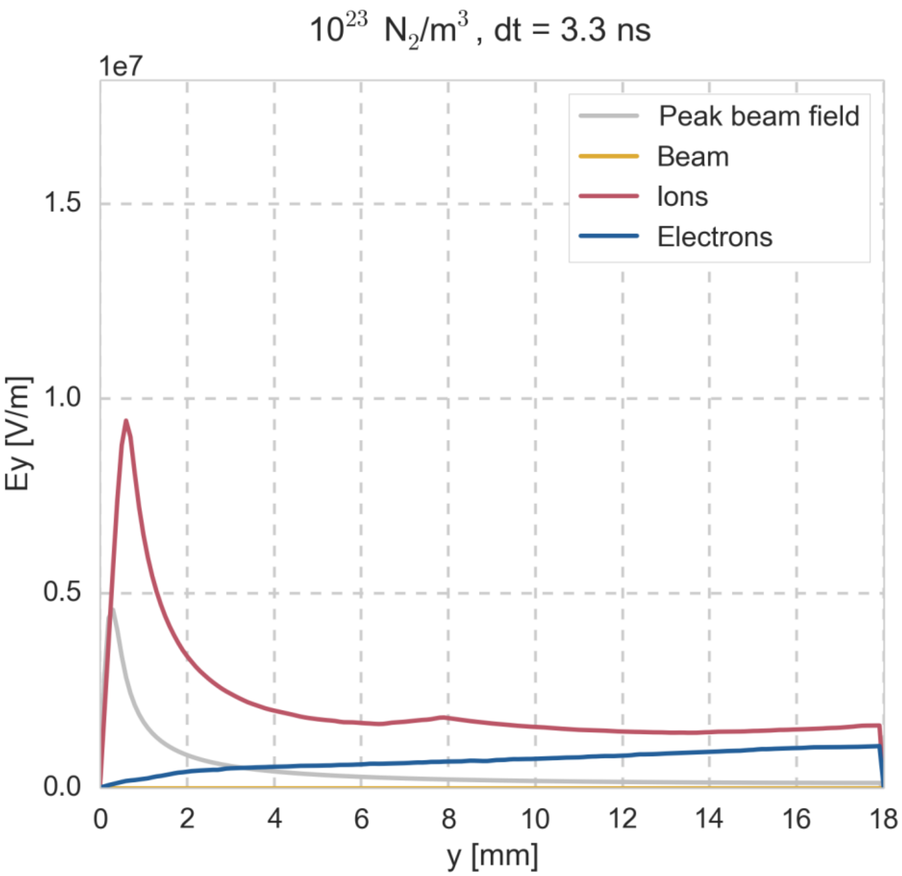

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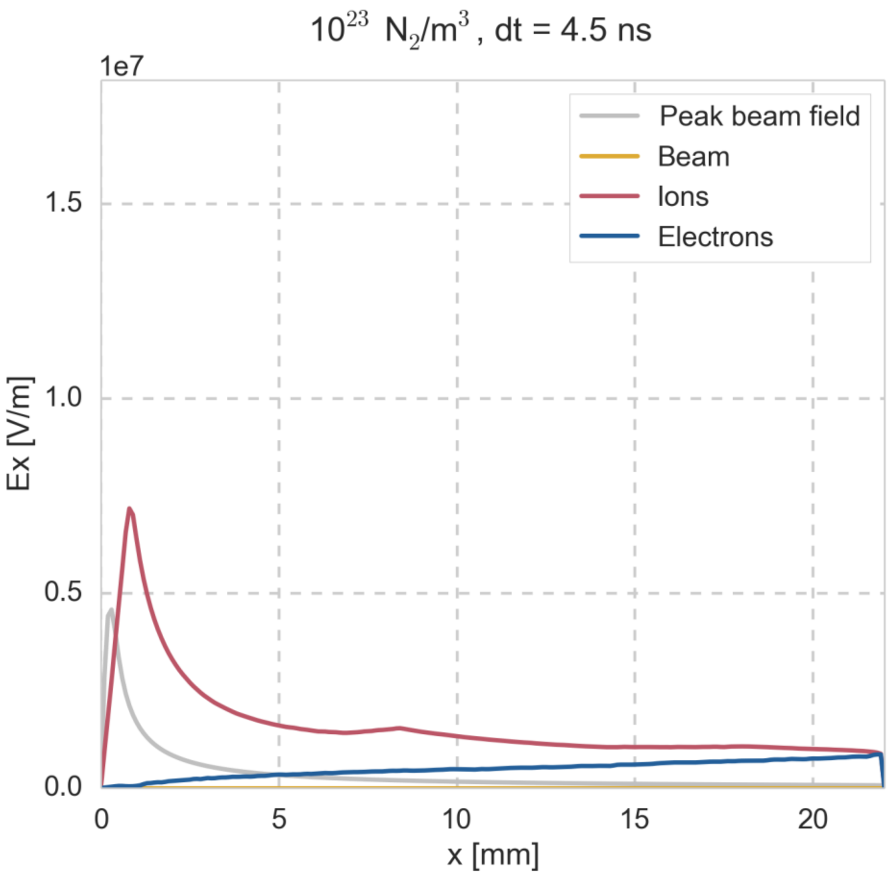

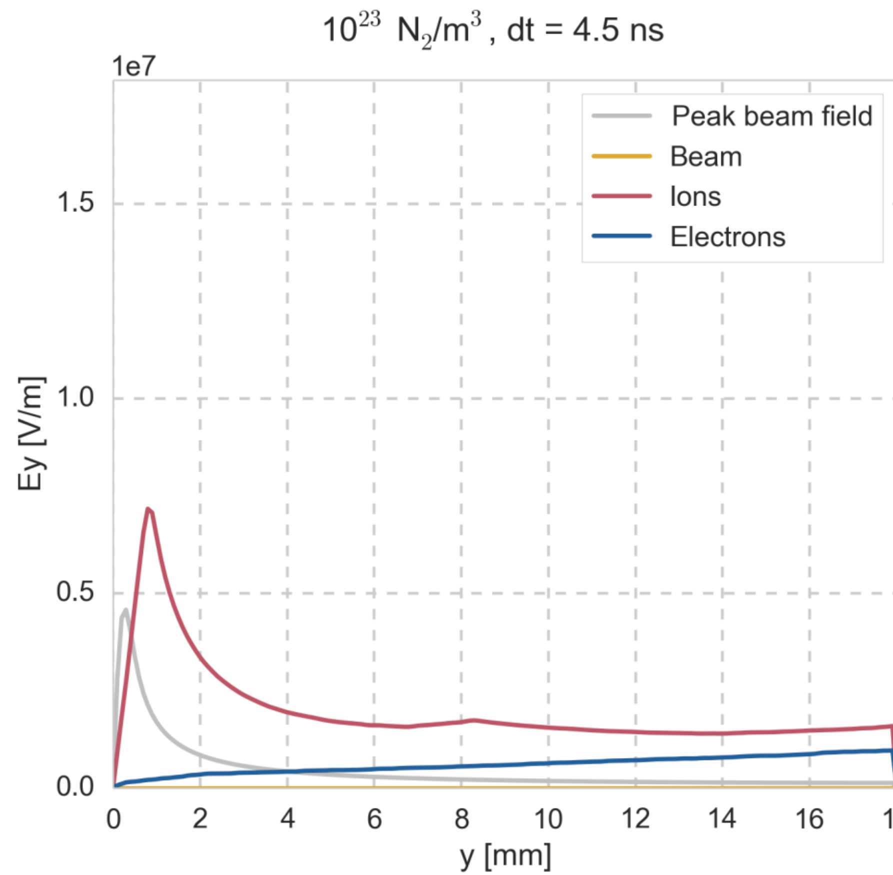

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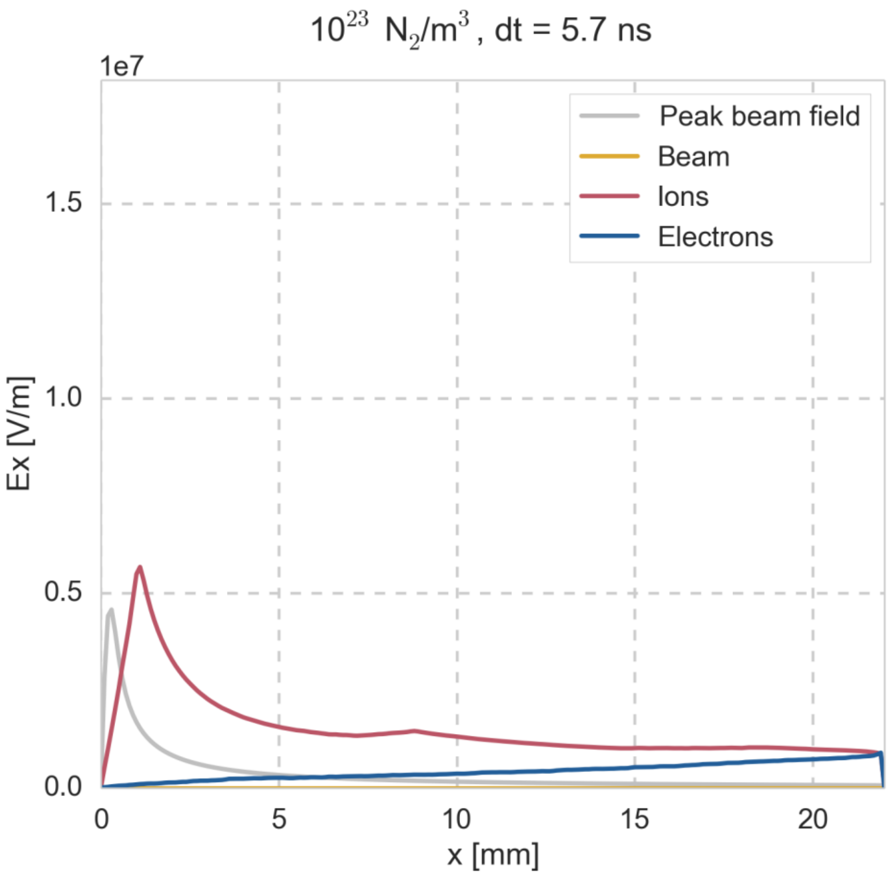

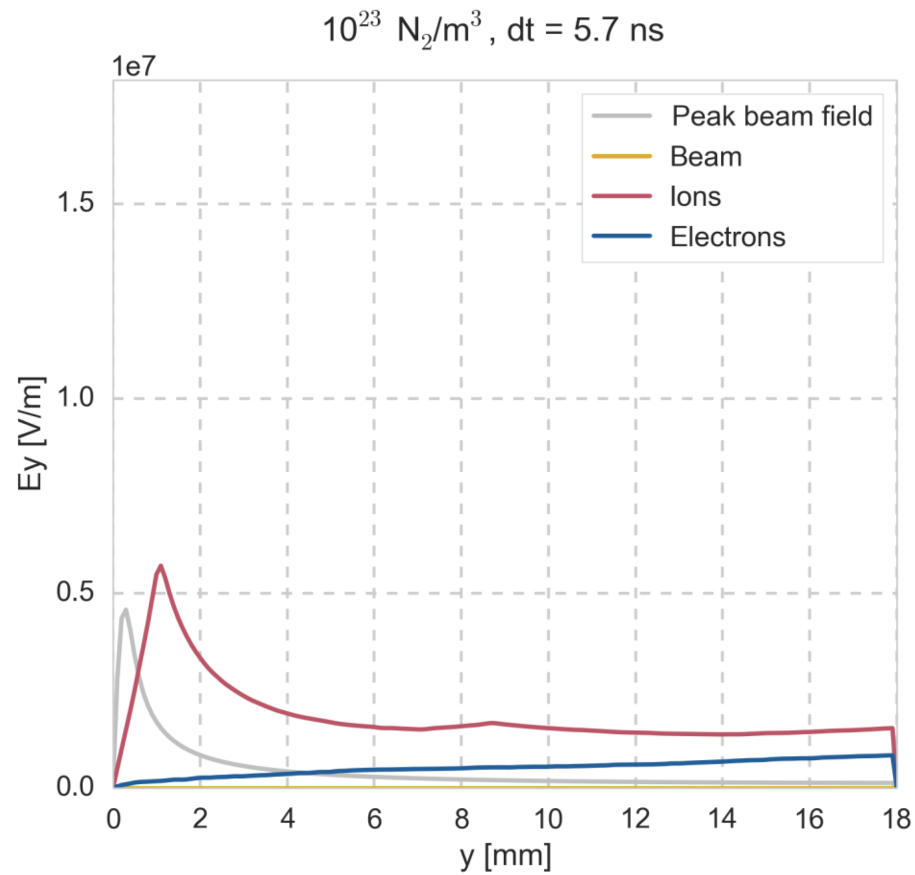

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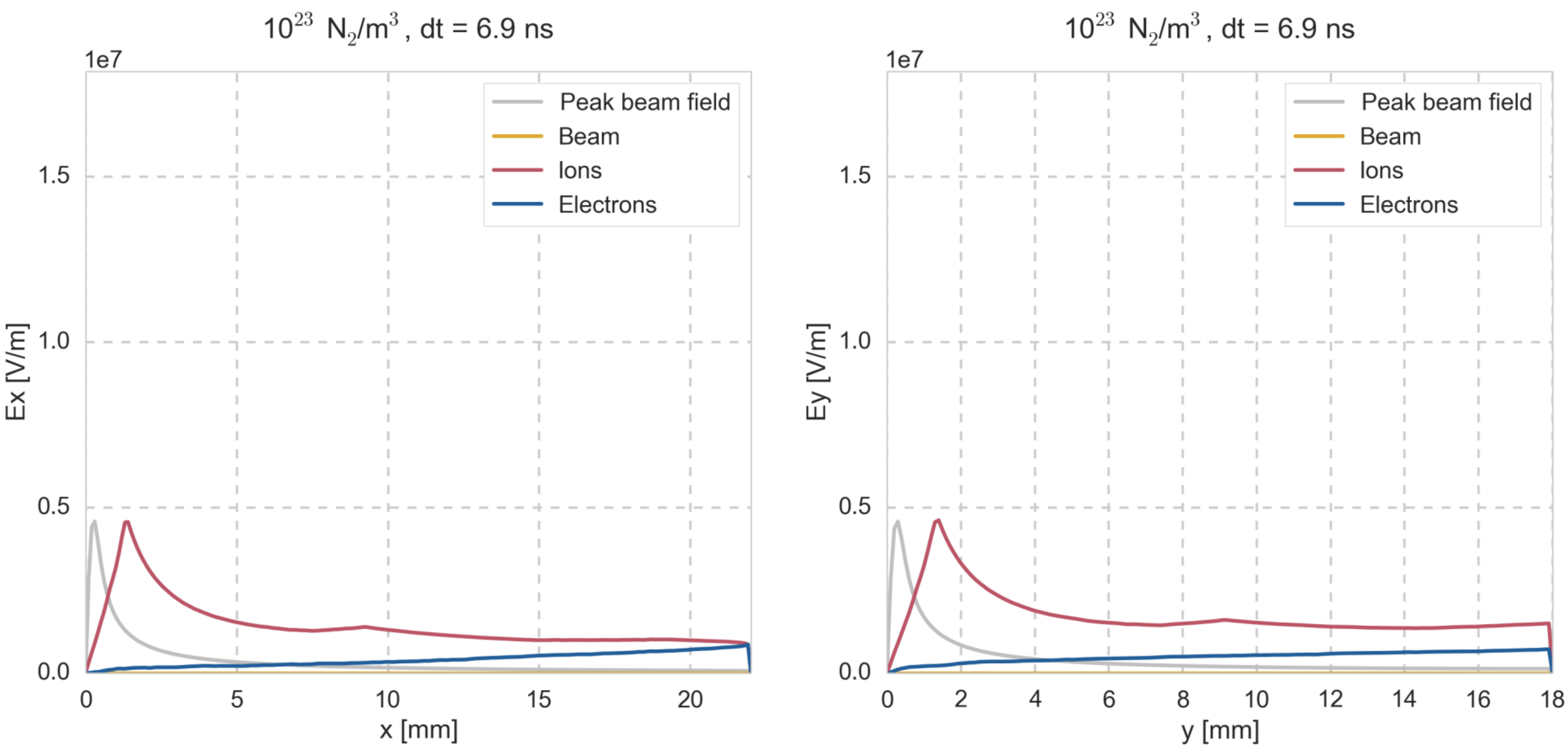
- About 6 ns after the bunch passage, the ion field peak equals the peak beam field



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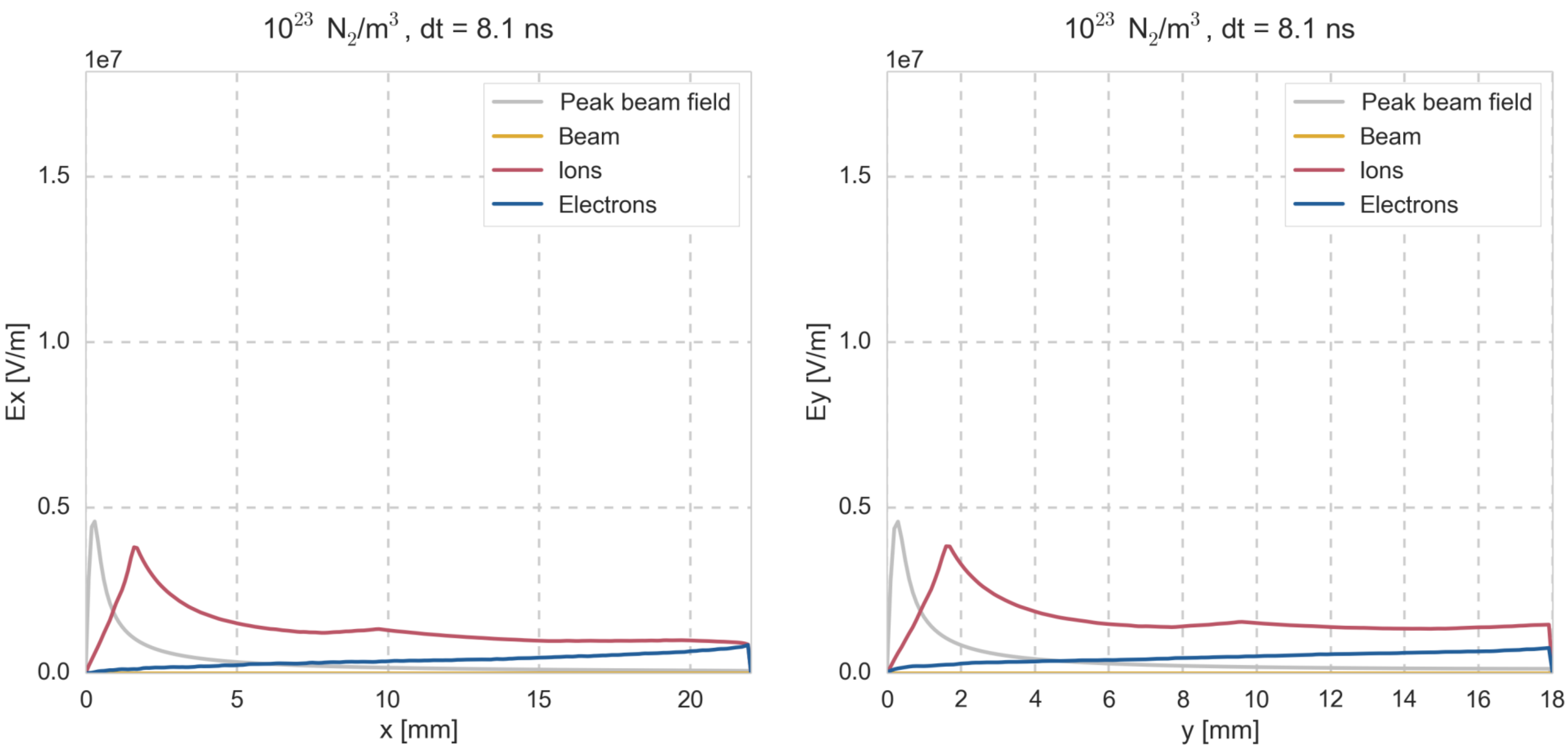

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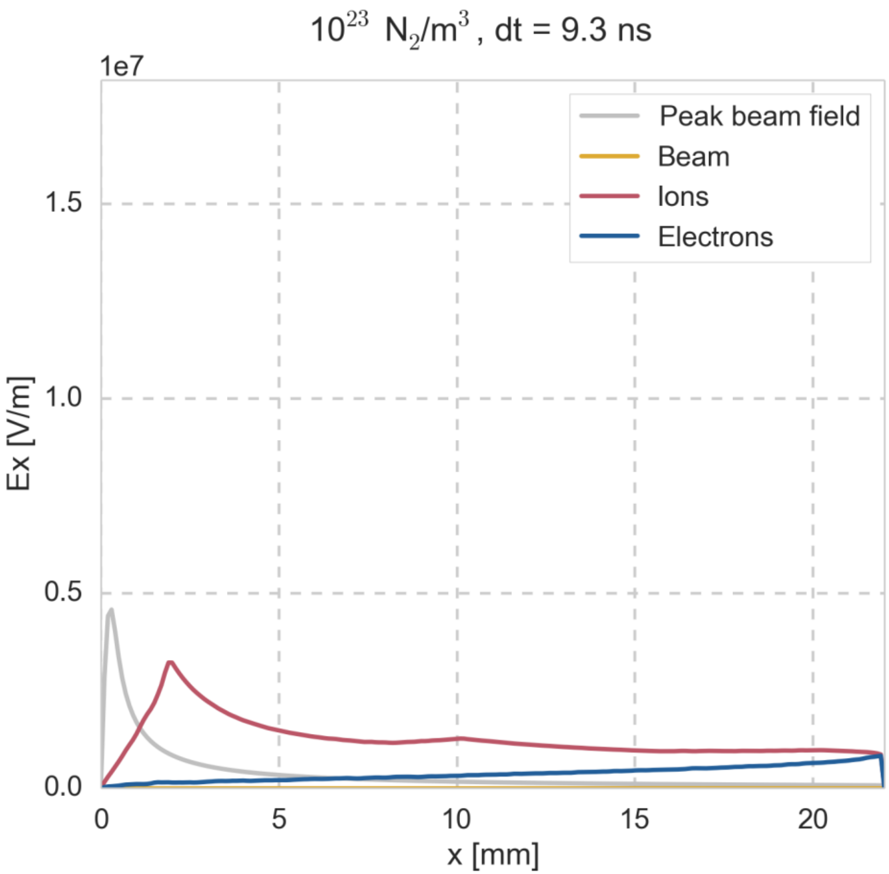

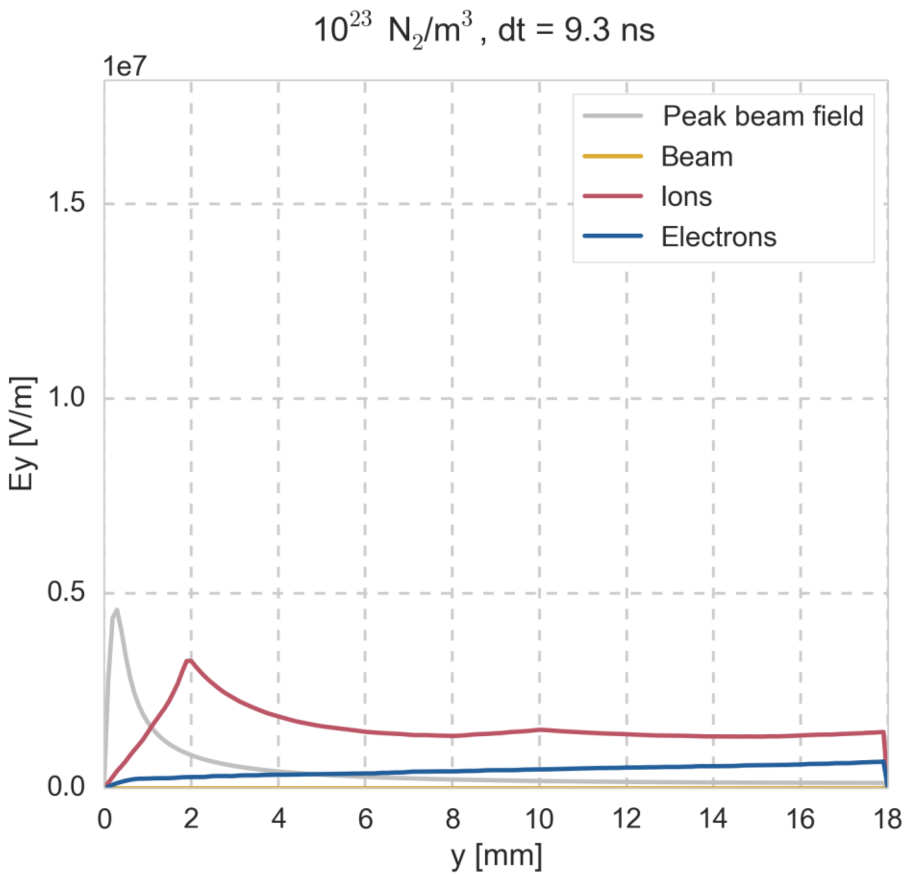

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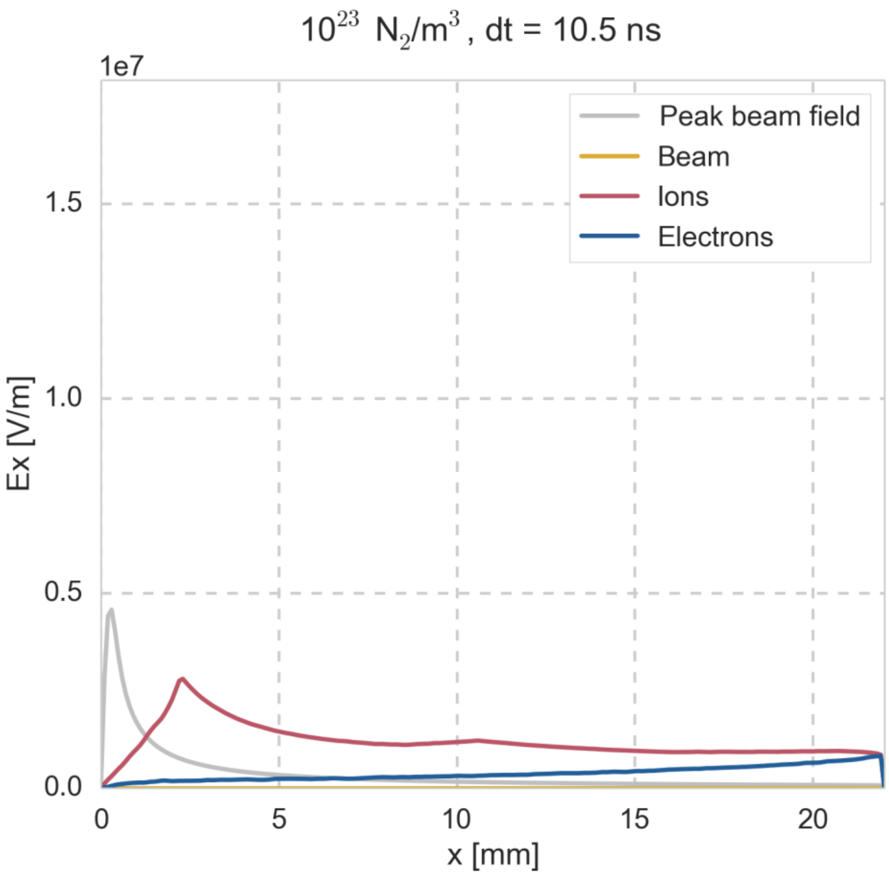

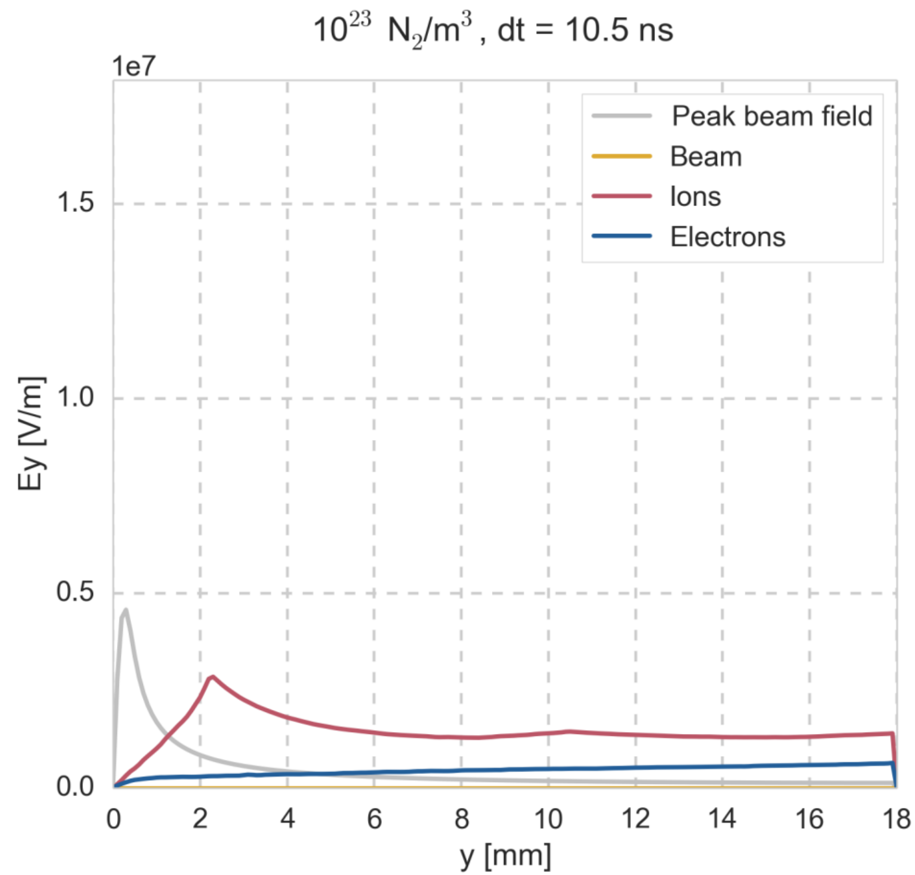

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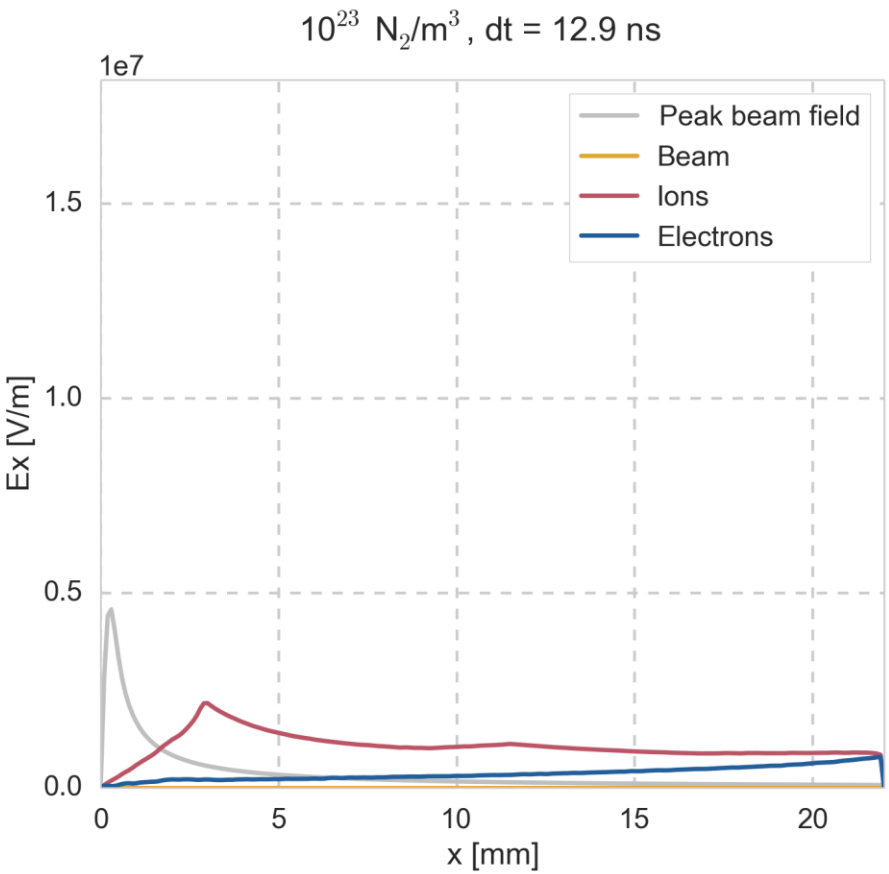

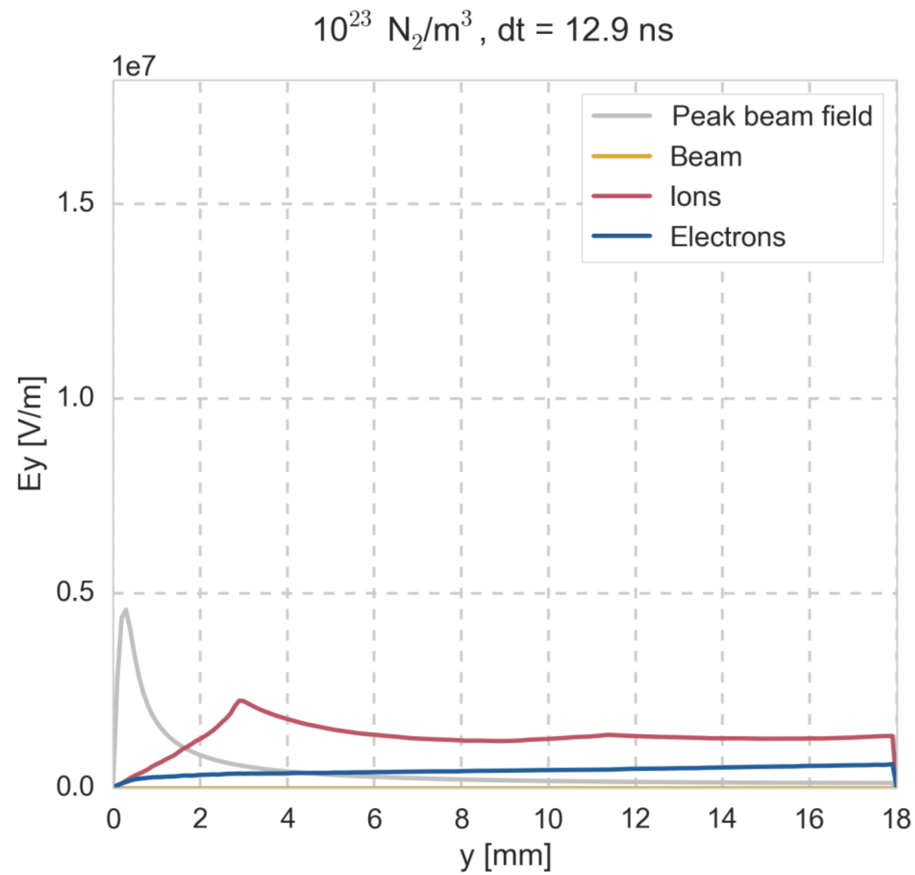

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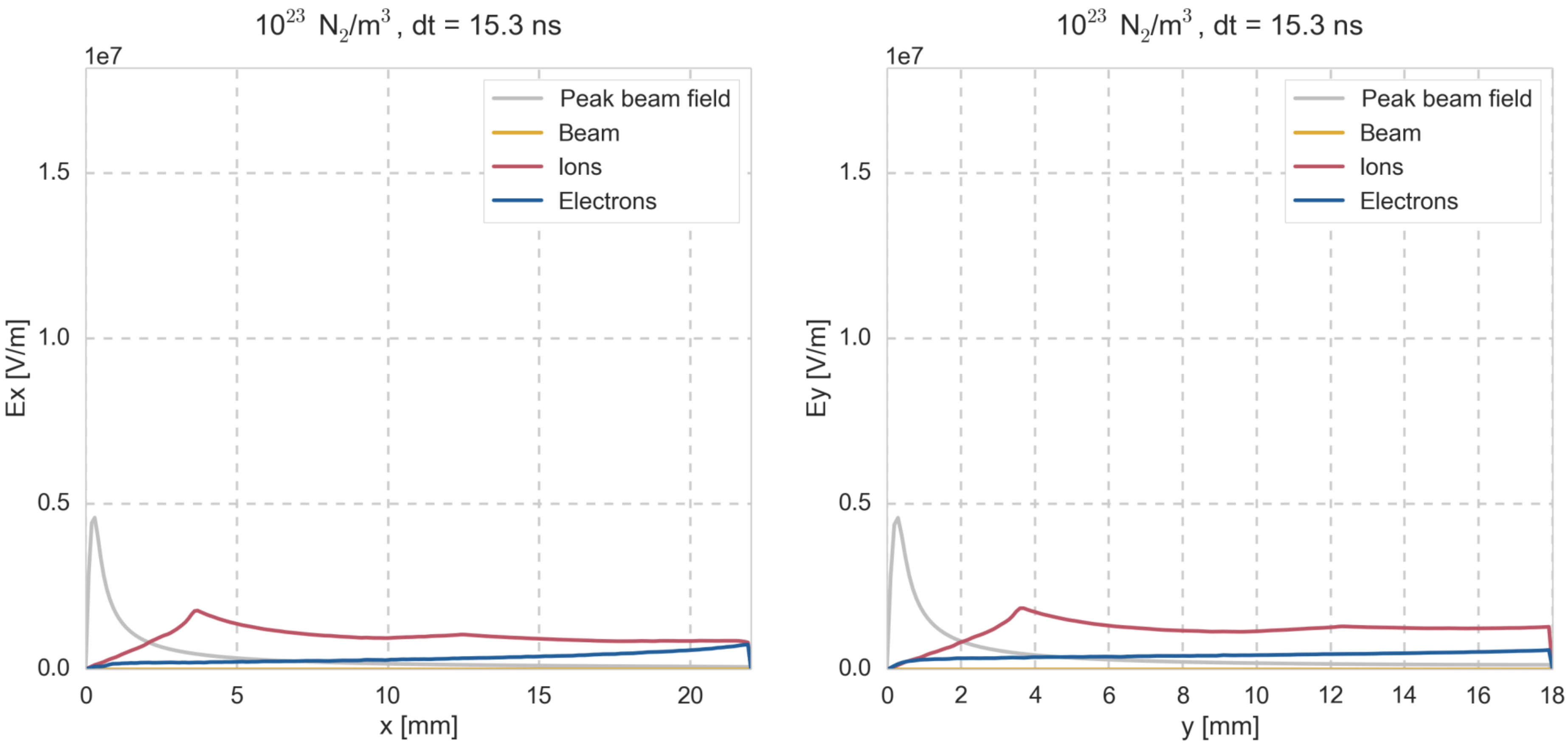

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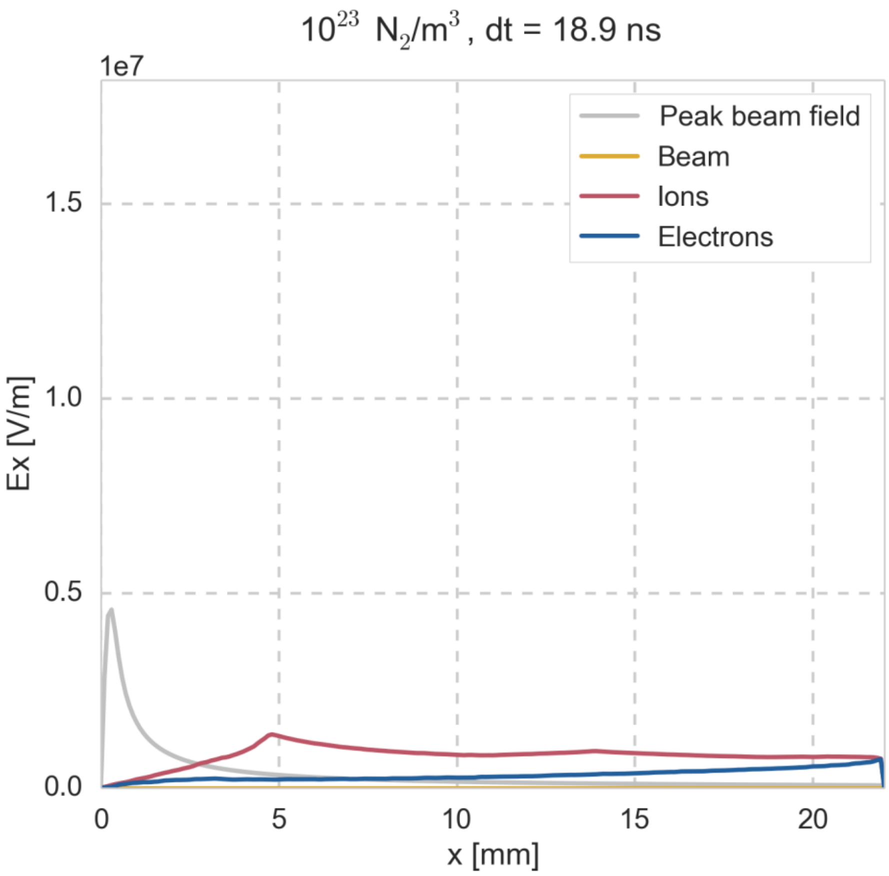
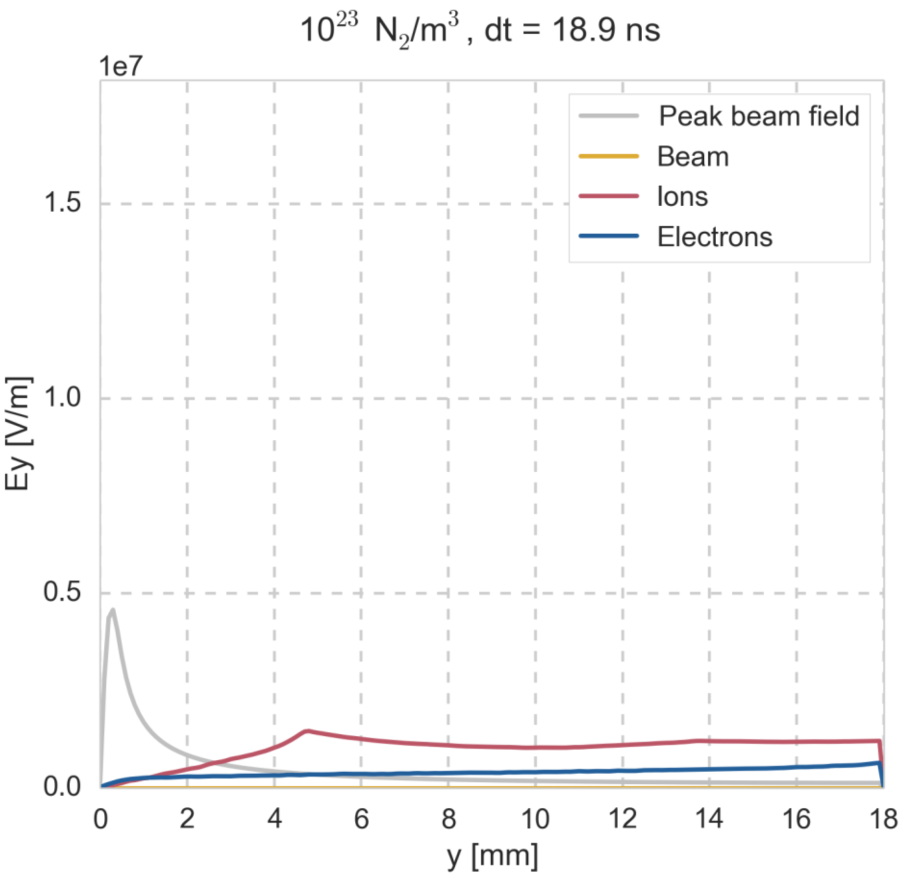
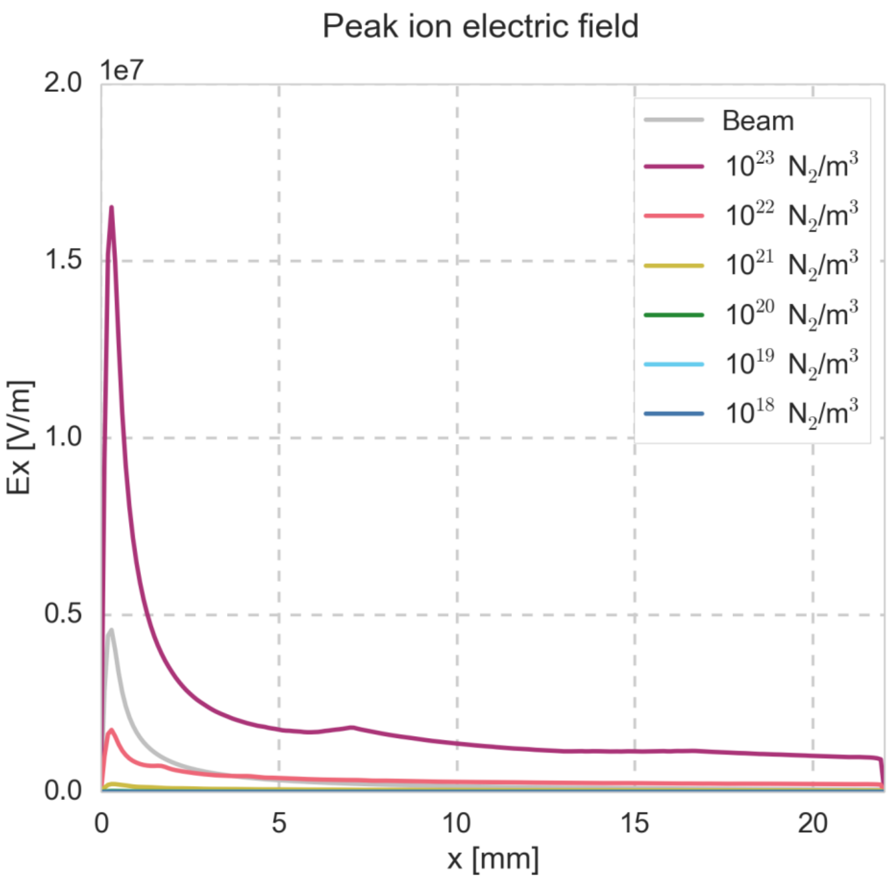


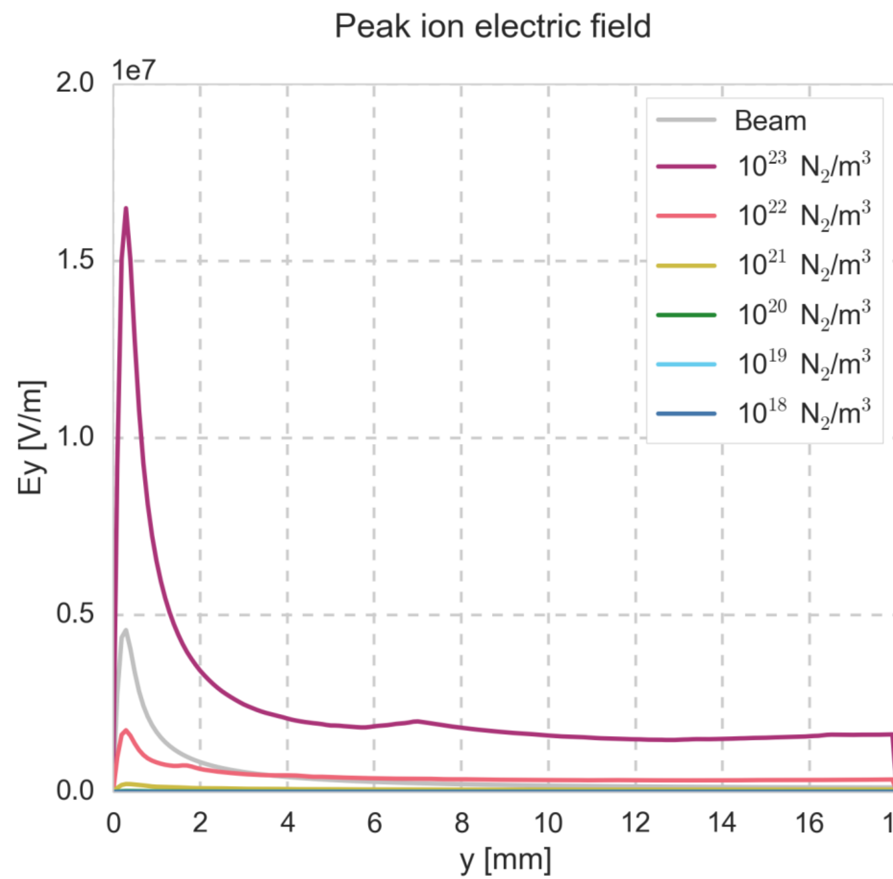


Ion electric fields

With gas densities of 10^{22} N_2/m^3 and below, the beam field during the centroid passage is stronger than the peak ion field

- However, the ion field is present also between bunch passages





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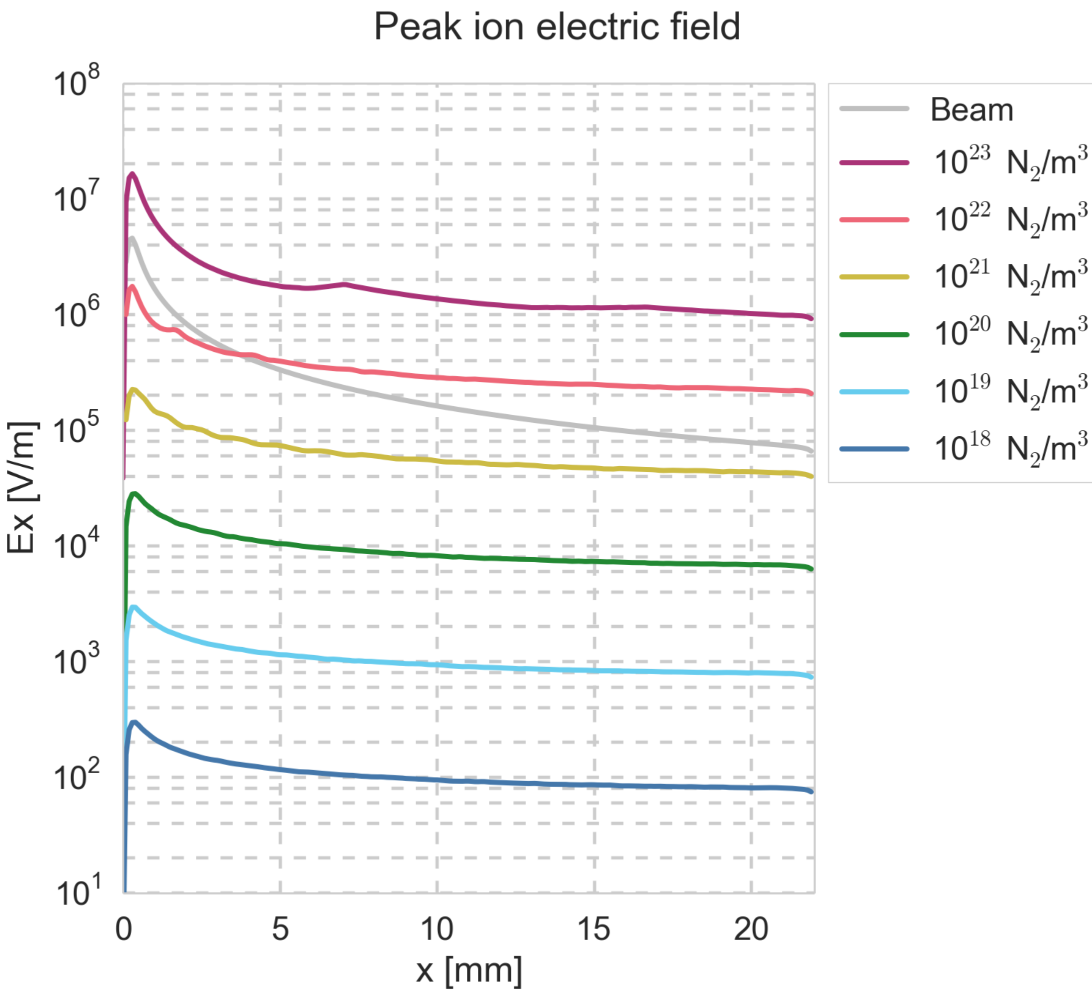
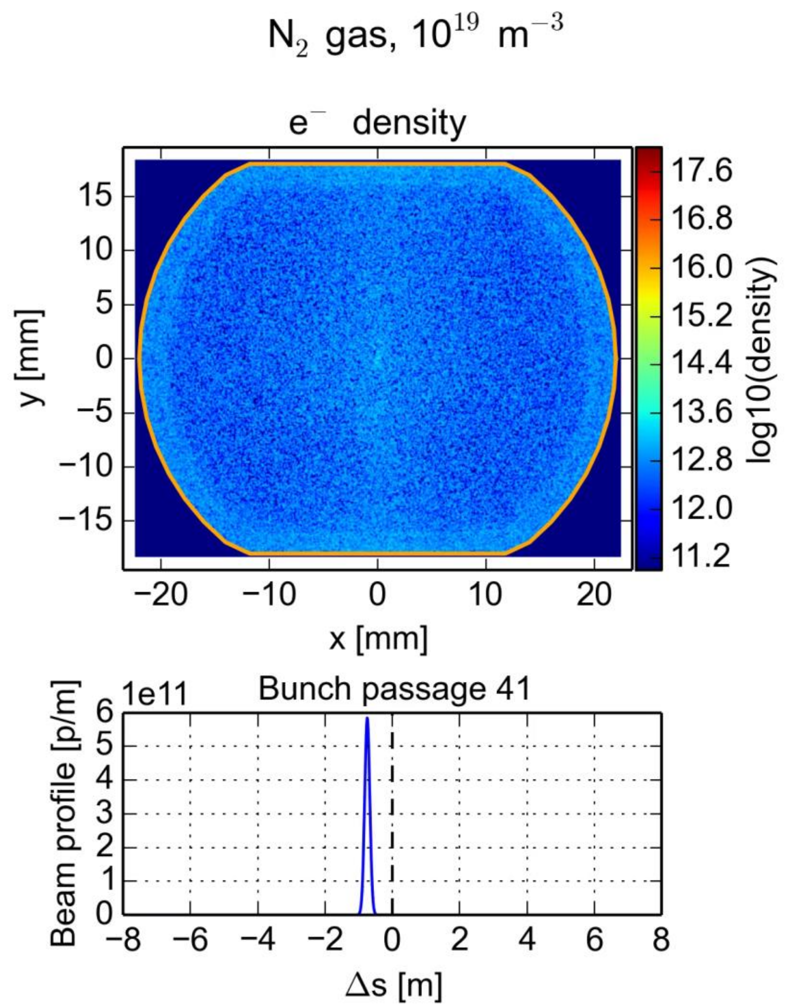


Electron motion



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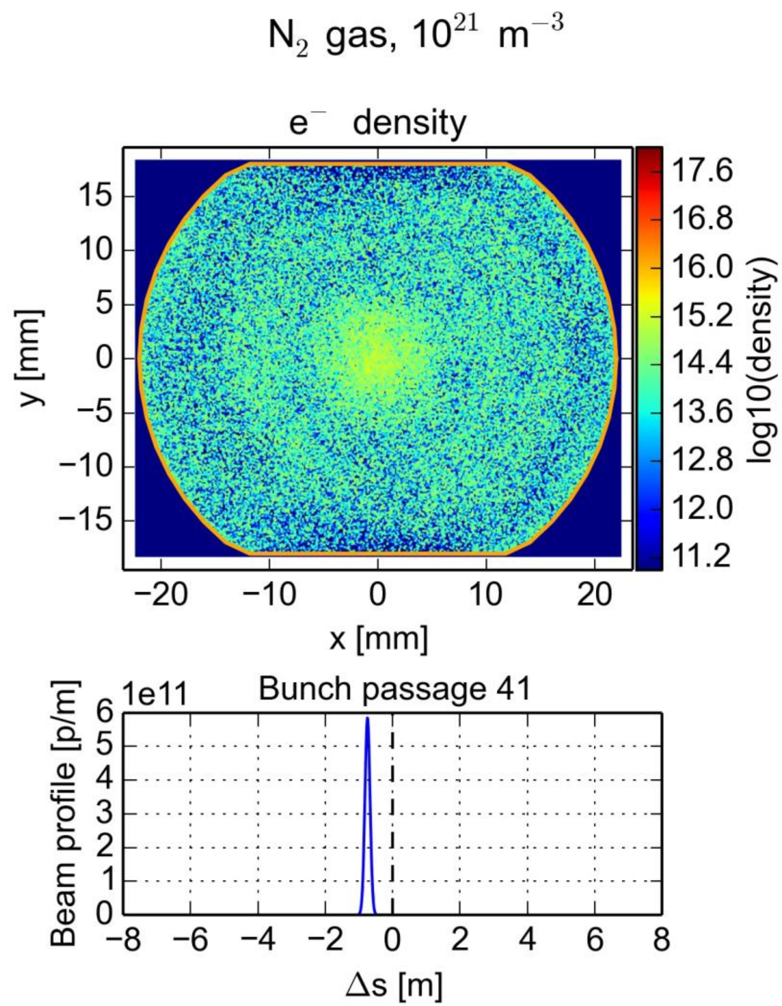

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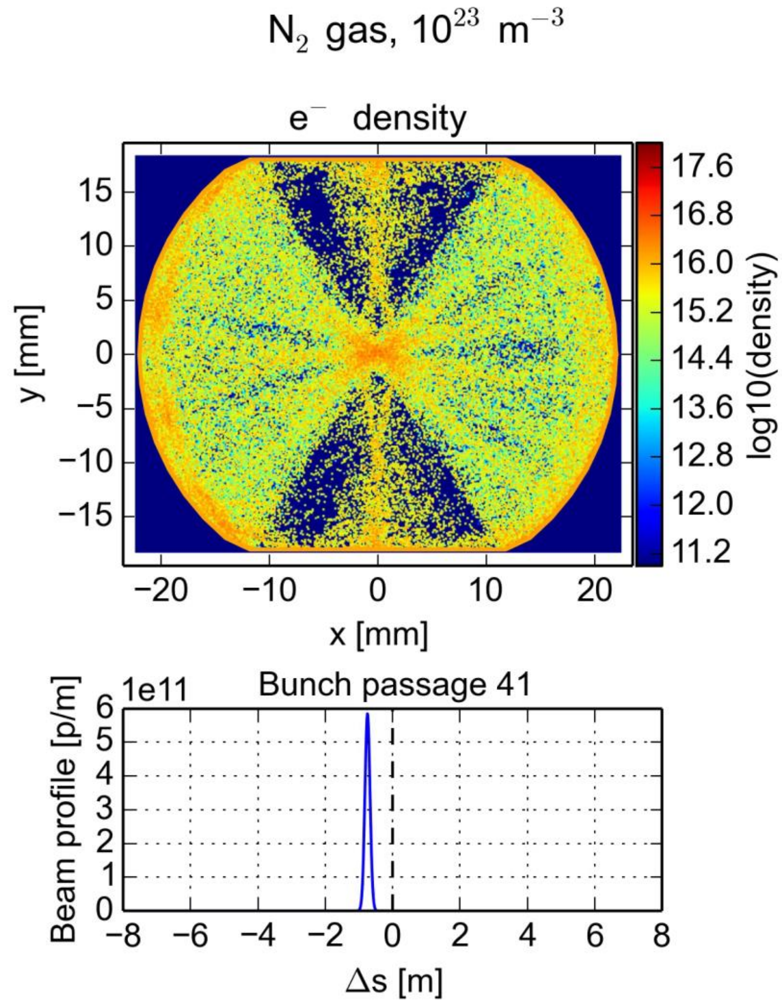

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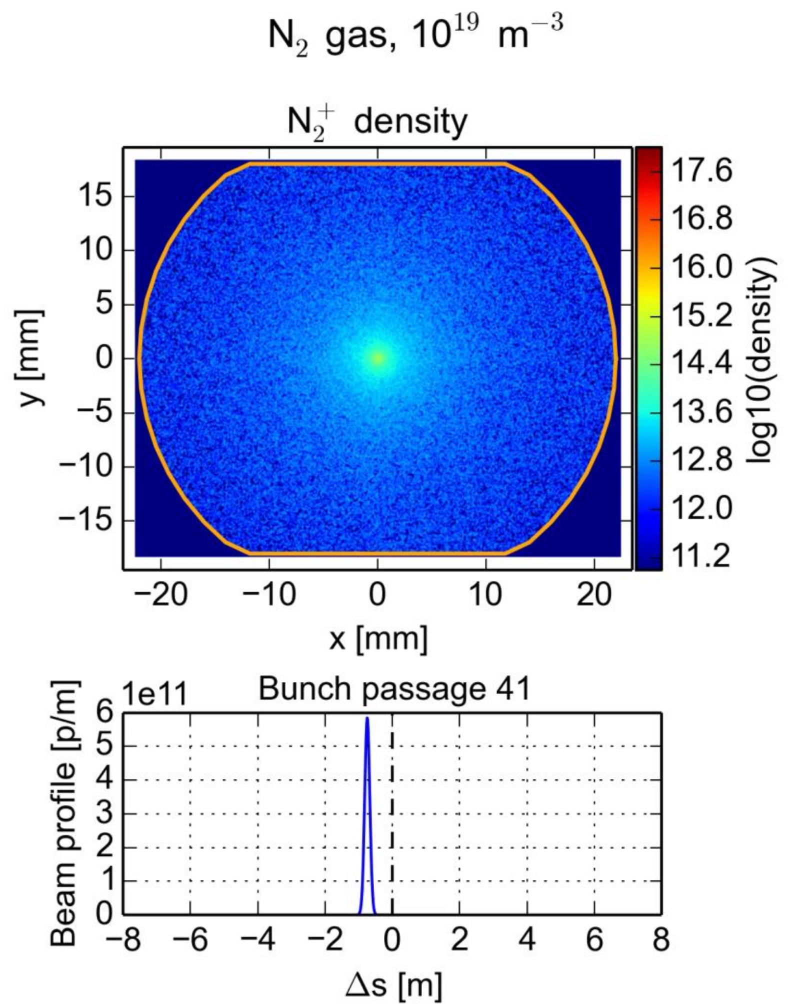
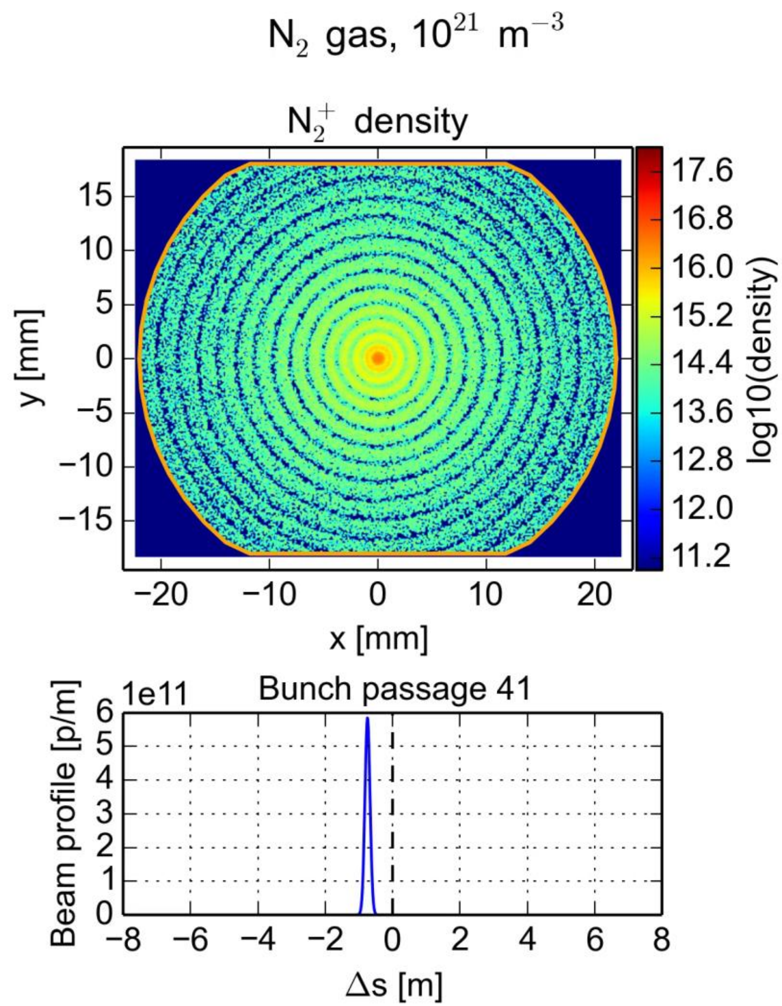


N_2 gas, 10^{19} m^{-3}
N_2^+ density
y [mm]
x [mm]
log10(density)
17.6
16.8
16.0
15.2
14.4
13.6
12.8
12.0
11.2
15
10
5
0
−5
−10
−15
−20
−10
0
10
20
1e11
Bunch passage 41
Beam profile [p/m]
Δs [m]
6
5
4
3
2
1
0
−8
−6
−4
−2
0
2
4
6
8

Ion motion



N2 gas, 10^21 m^-3
N2+ density
y [mm]
x [mm]
log10(density)
17.6
16.8
16.0
15.2
14.4
13.6
12.8
12.0
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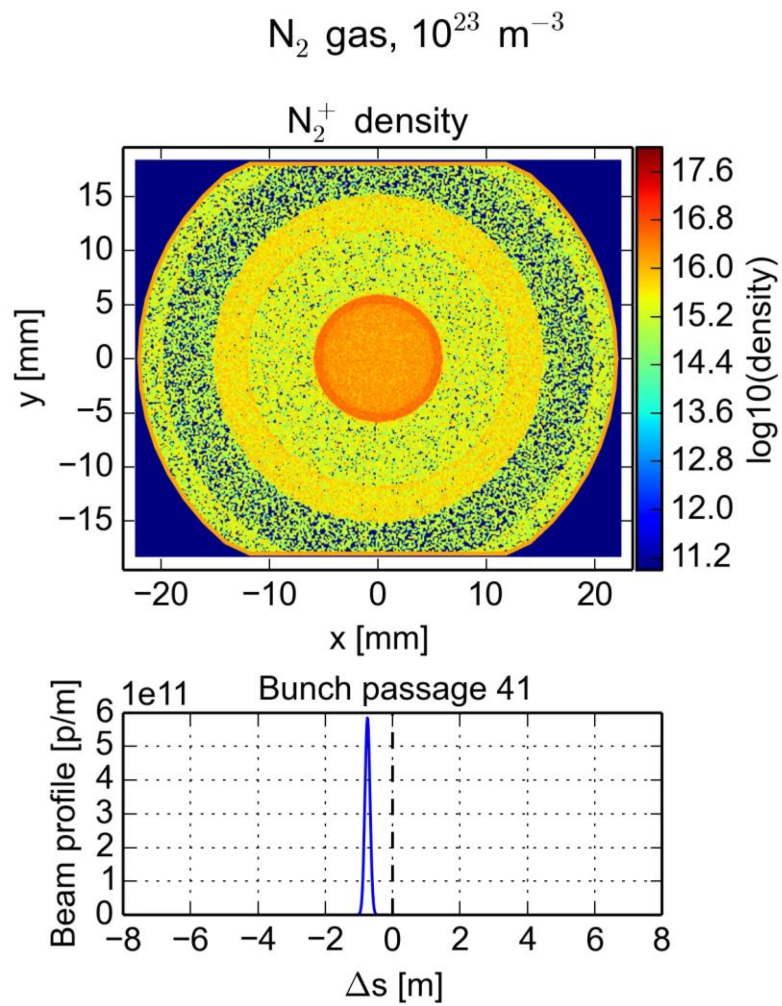
Bunch passage 41
1e11
Beam profile [p/m]
Δs [m]

Ion motion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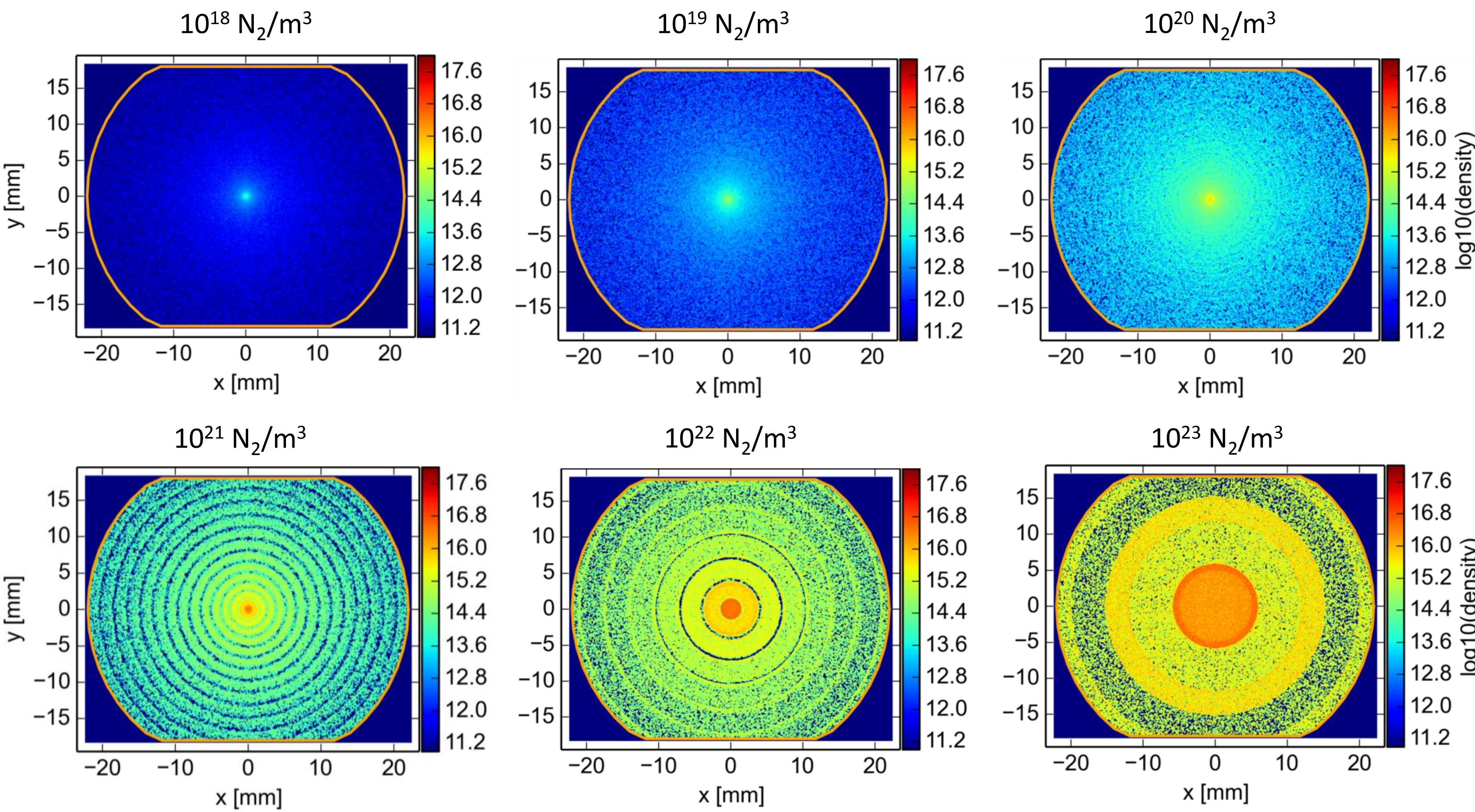
8

Ion distribution

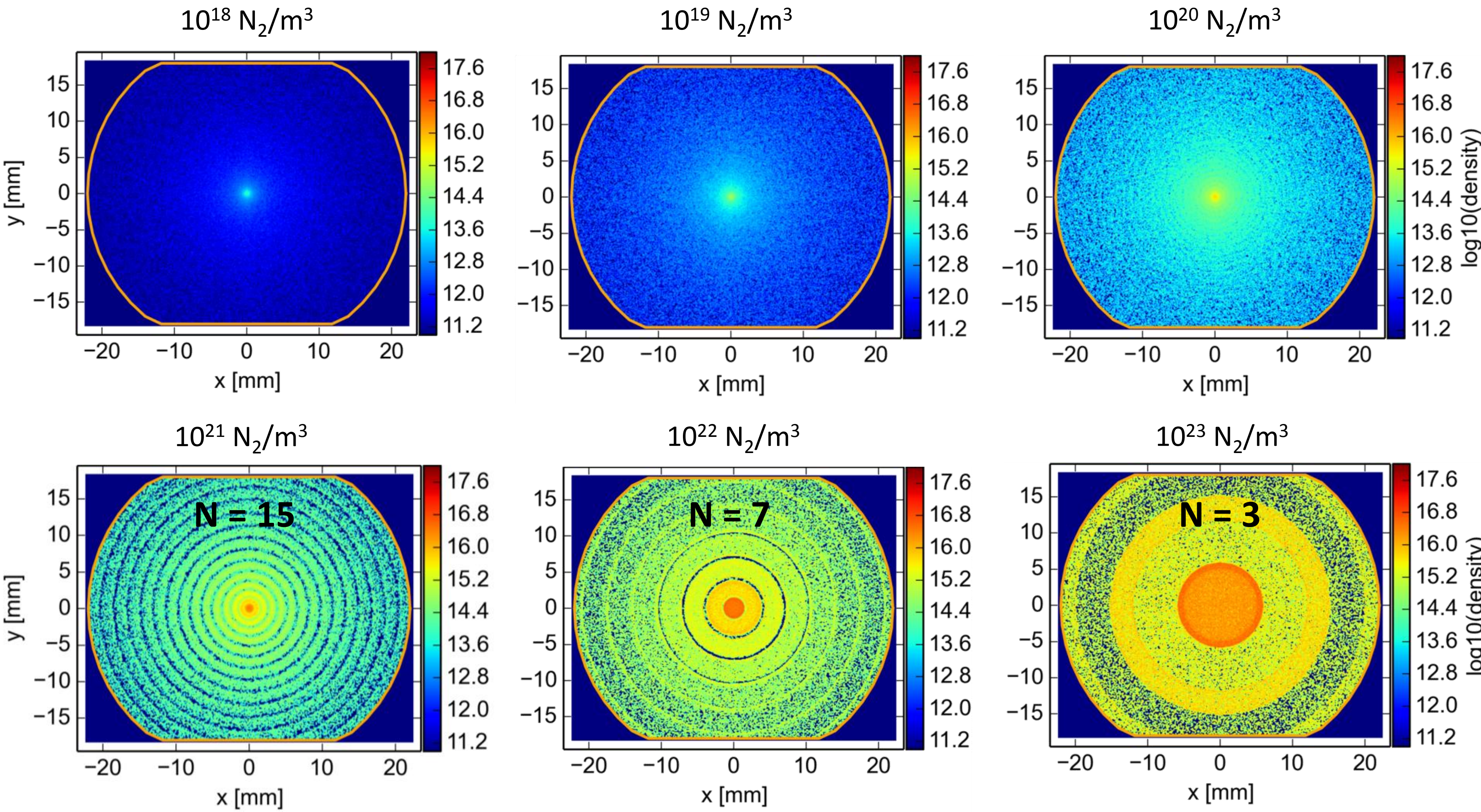
"Rings" in the ion distribution consist of ions generated at different bunch passages



Ion distribution

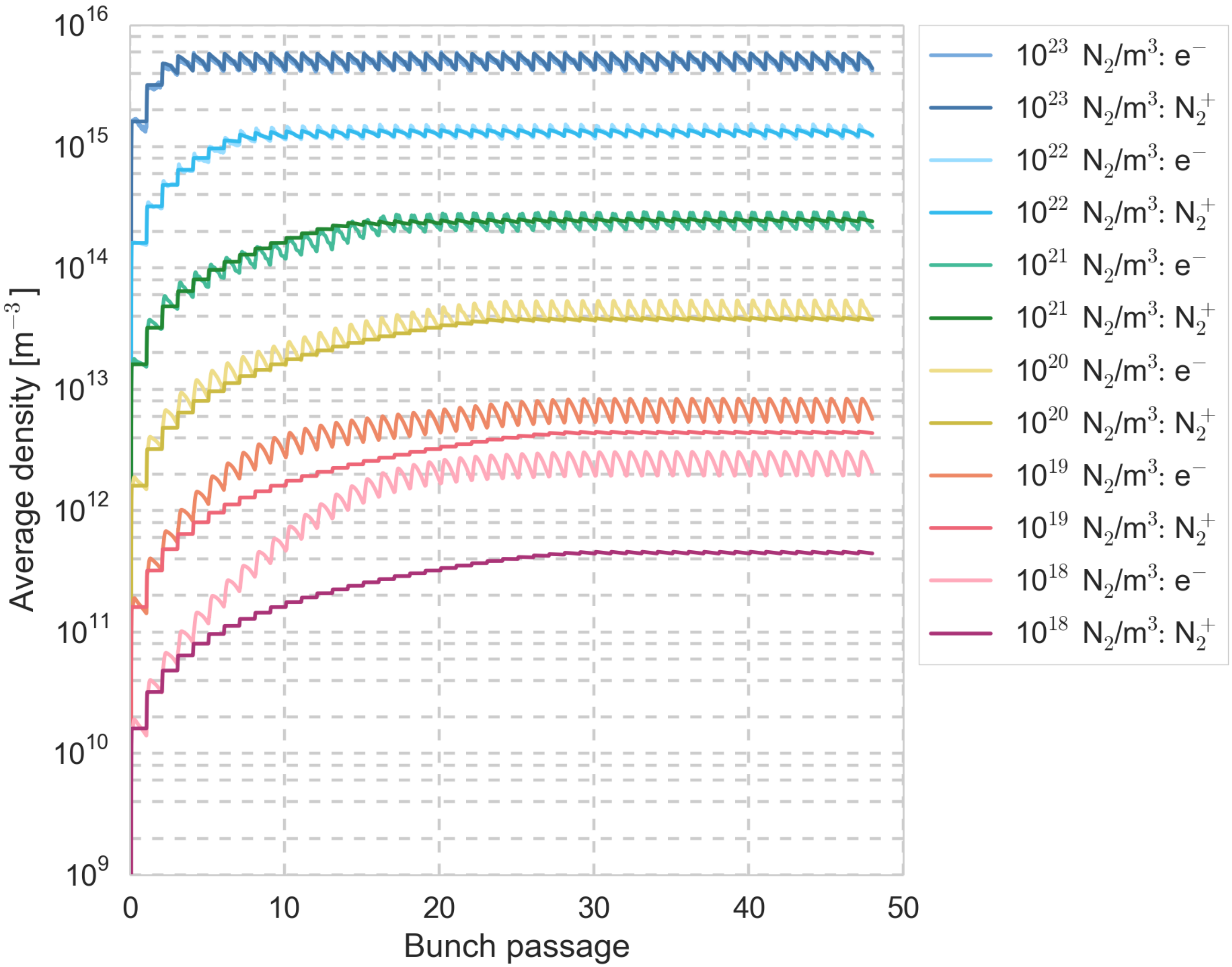
"Rings" in the ion distribution consist of ions generated at different bunch passages

- 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



Ion distribution

The number of “ion rings” corresponds to the rise time of the average densities



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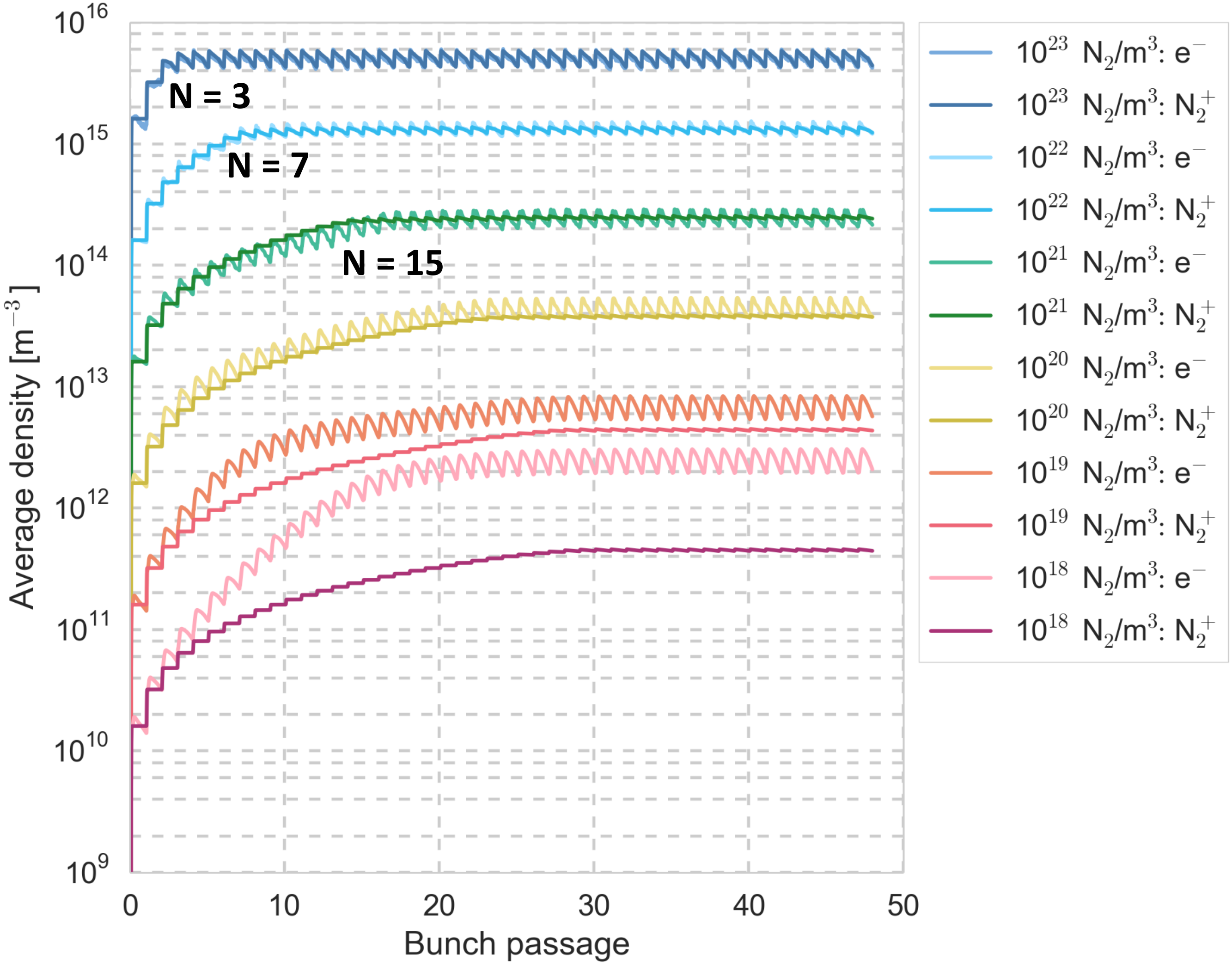


Conclusions

The dynamics of the electron-ion system are largely determined by the electric field of the ion distribution

- Non-trivial dynamics occur for gas densities of 10^{20} N_2/m^{-3} and above

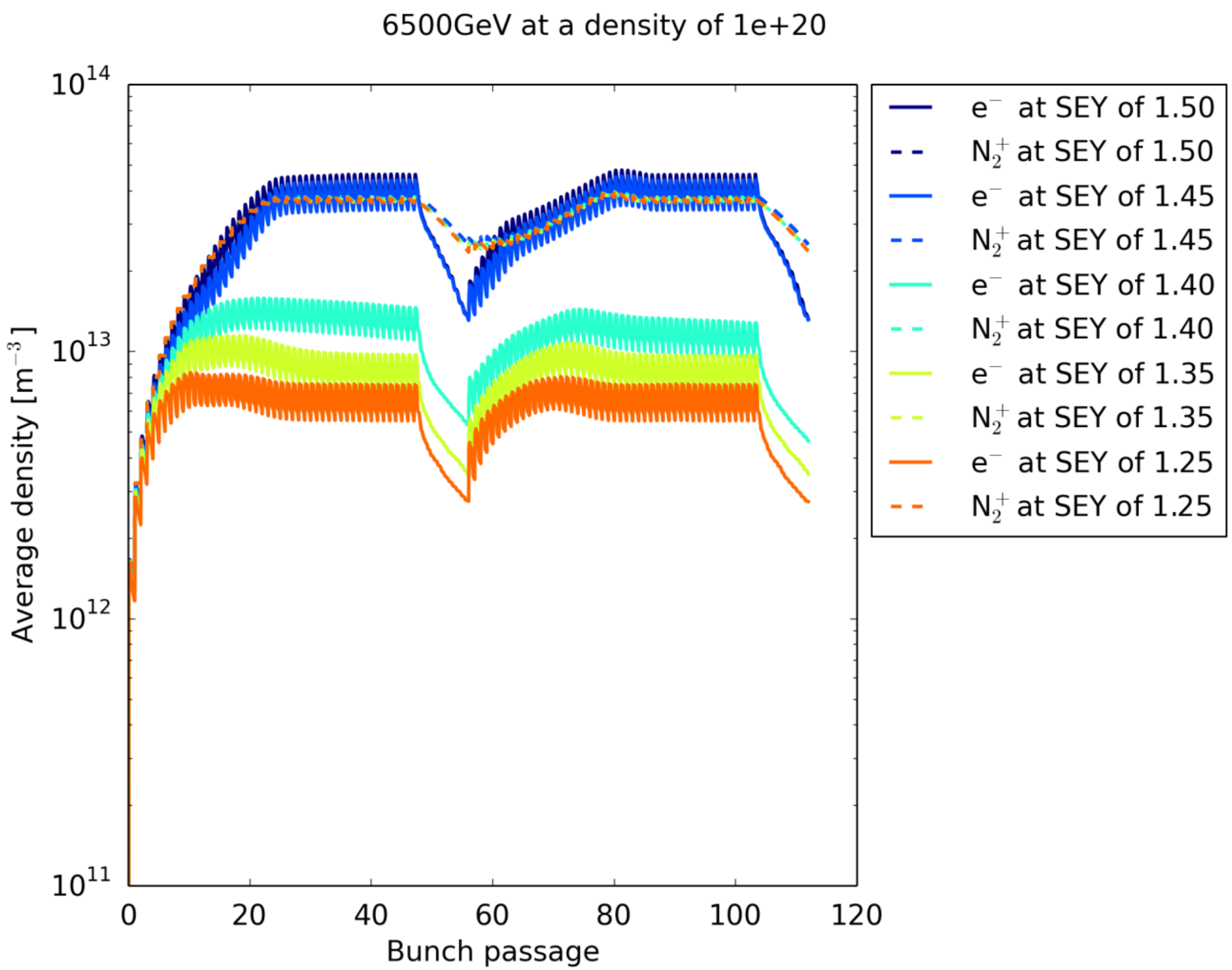
- For gas densities of 10^{23} N_2/m^{-3}, the ion electric field is stronger than the beam field → energies in the keV range

In particular for gas densities in the range $10^{20} - 10^{22}$ N_2/m^{-3}, electron energies are favourable for electron impact-ionization

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

- 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