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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Simulations of electron-ion effects and relevance to LHC experience in 2017

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

61st ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams
Daejeon, Korea
18 - 22 June, 2018

Motivation

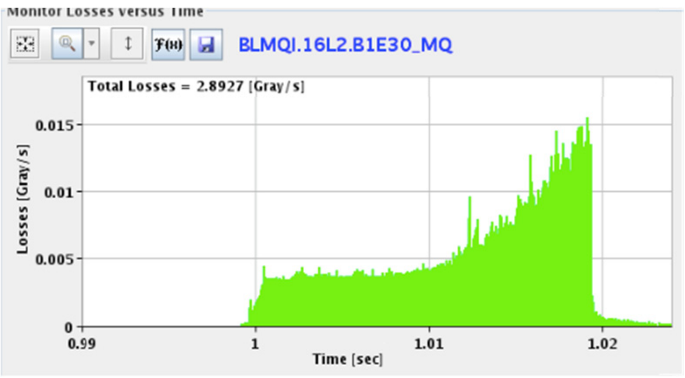
Throughout 2017 operation, abnormal losses were observed in the LHC

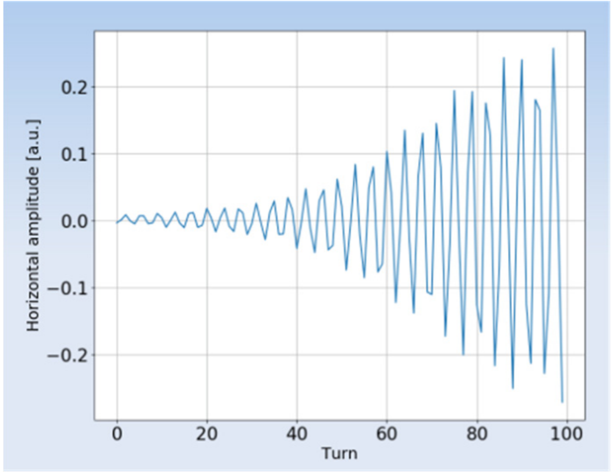
- Located in the half-cell ‘16’ Left of Point 2 (16L2)

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





X. Buffat

L. Ponce *et al.*

Sequence of events in 16L2

The problem is thought to have been caused by air that was left in the vacuum system after a magnet exchange, 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

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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

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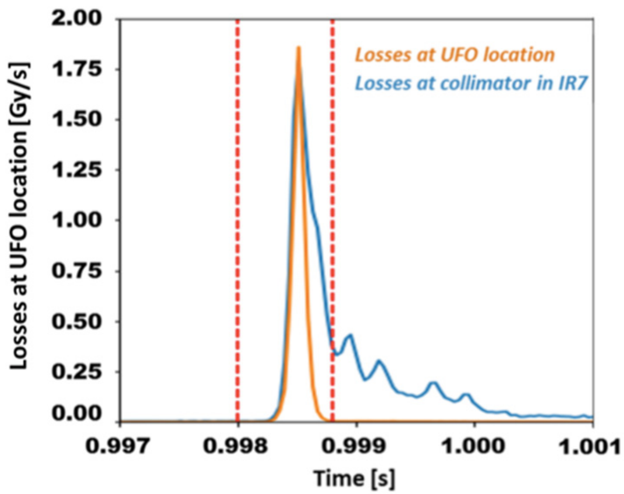

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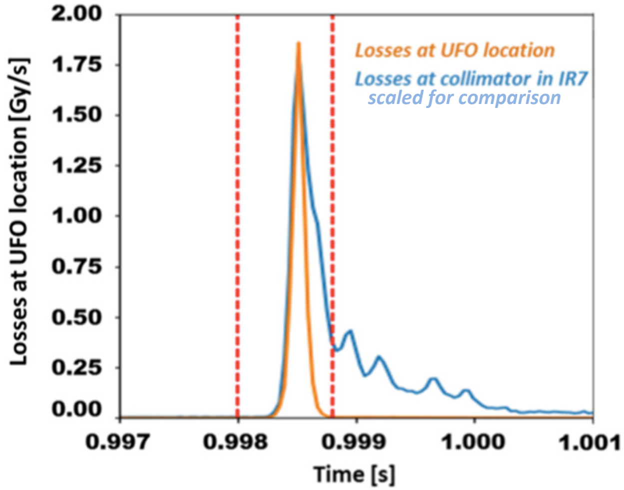

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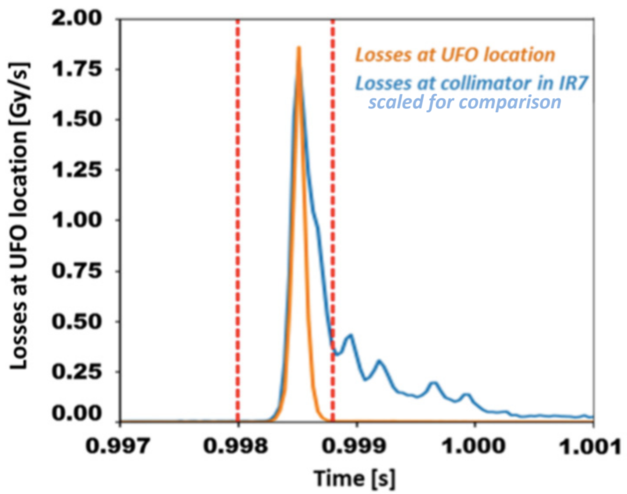

L. Grob et al IPAC 2018

Sequence of events in 16L2

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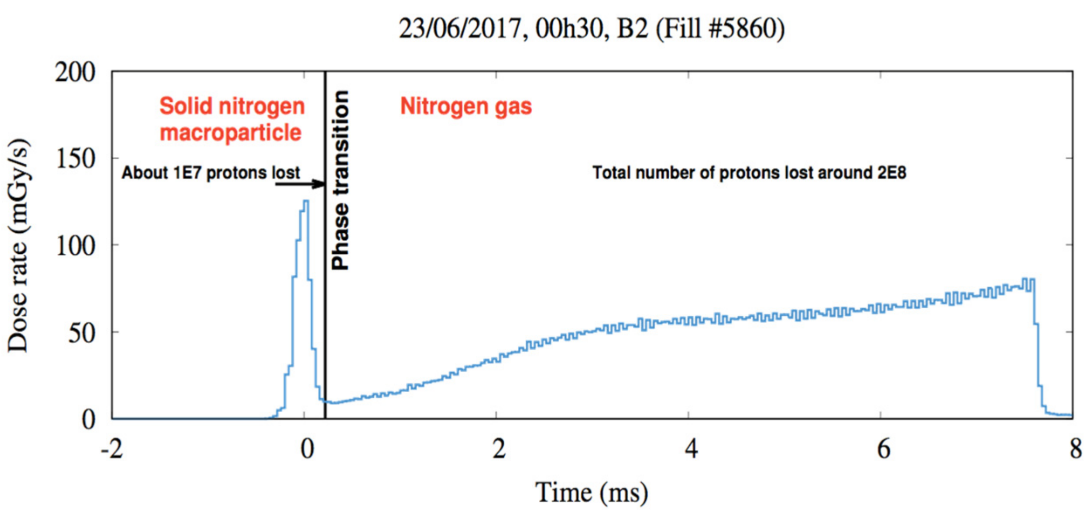
The energy deposited by the beam in the macro-particle could be sufficient to induce a phase transition to a gas, leading to a local pressure bump of high density



A. Lechner et al IPAC 2018

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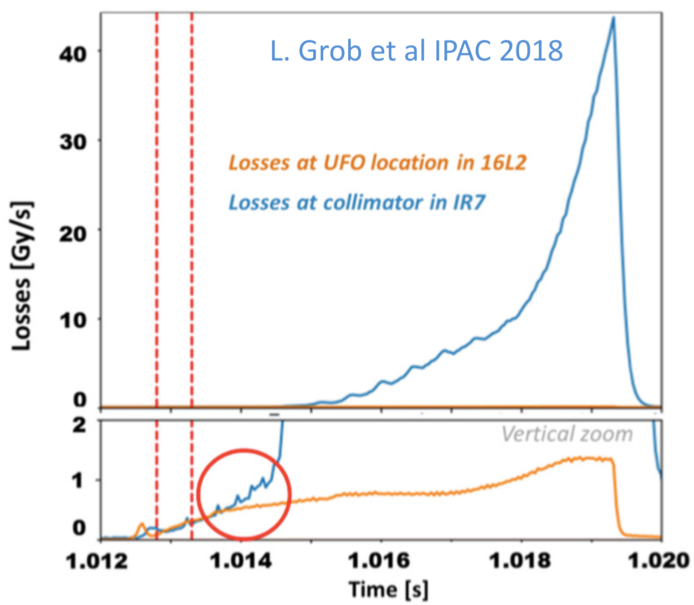
→ The energy deposited by the beam in the macro-particle could be sufficient to induce a phase transition to a gas, leading to a local pressure bump of high density

→ 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



The fastest instability rise times ever observed in the LHC

No help from damper, chromaticity or octupoles

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L. Grob et al, IPAC 2018
B. Lindström et al, IPAC 2018

A. Lechner et al, IPAC 2018

Can we model these events and reproduce the observed coherent effects?

Simulation tools

Simulation tools for studying electron cloud build-up and its effect on beam dynamics

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Simulation tools

Simulation tools for studying electron cloud build-up and its effect on beam dynamics

For each time step

v

Simulation tools

Simulation tools for studying electron cloud build-up and its effect on beam dynamics

PyECLOUD
(for e-cloud build up)

For each time step

v

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For each time step

Generate **seed e⁻**

v

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(for e-cloud build up)

For each time step

Generate **seed e$^-$**

Evaluate **rigid beam field** at e$^-$ locations

v

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Compute e$^-$ motion (t->t+Δt)
(possibly with substeps)

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Detect **impacts** and generate **secondary electrons**

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For each time step

Generate **seed e^-**

Evaluate **rigid beam field** at e^- locations

Evaluate the **e^- electric field** (Particle in Cell)

Compute e^- motion ($t \rightarrow t+\Delta t$) (possibly with substeps)

Detect **impacts** and generate **secondary electrons**

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PyHEADTAIL bunch

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Simulation tools

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Simulation tools for studying electron cloud build-up and its effect on beam dynamics

PyHEADTAIL

PyHEADTAIL bunch

- Transverse tracking with Q', octupoles etc.
- Longitudinal tracking
- Transverse feedback
- Impedances
- Space charge
- …

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PyHEADTAIL bunch → PyHEADTAIL slicer →

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PyECLOUD
(PyEC4PyHT object)

For each slice

Generate **seed e^-**

Evaluate **beam slice electric field** (Particle in Cell)

Evaluate the **e^- electric field** (Particle in Cell)

Apply **kick on the beam particles**

Compute e^- motion (t->t+Δt) (possibly with substeps)

Detect **impacts** and generate **secondary electrons**

Legend: **From PyHEADTAIL** **From PyECLOUD** **Developed ad hoc**

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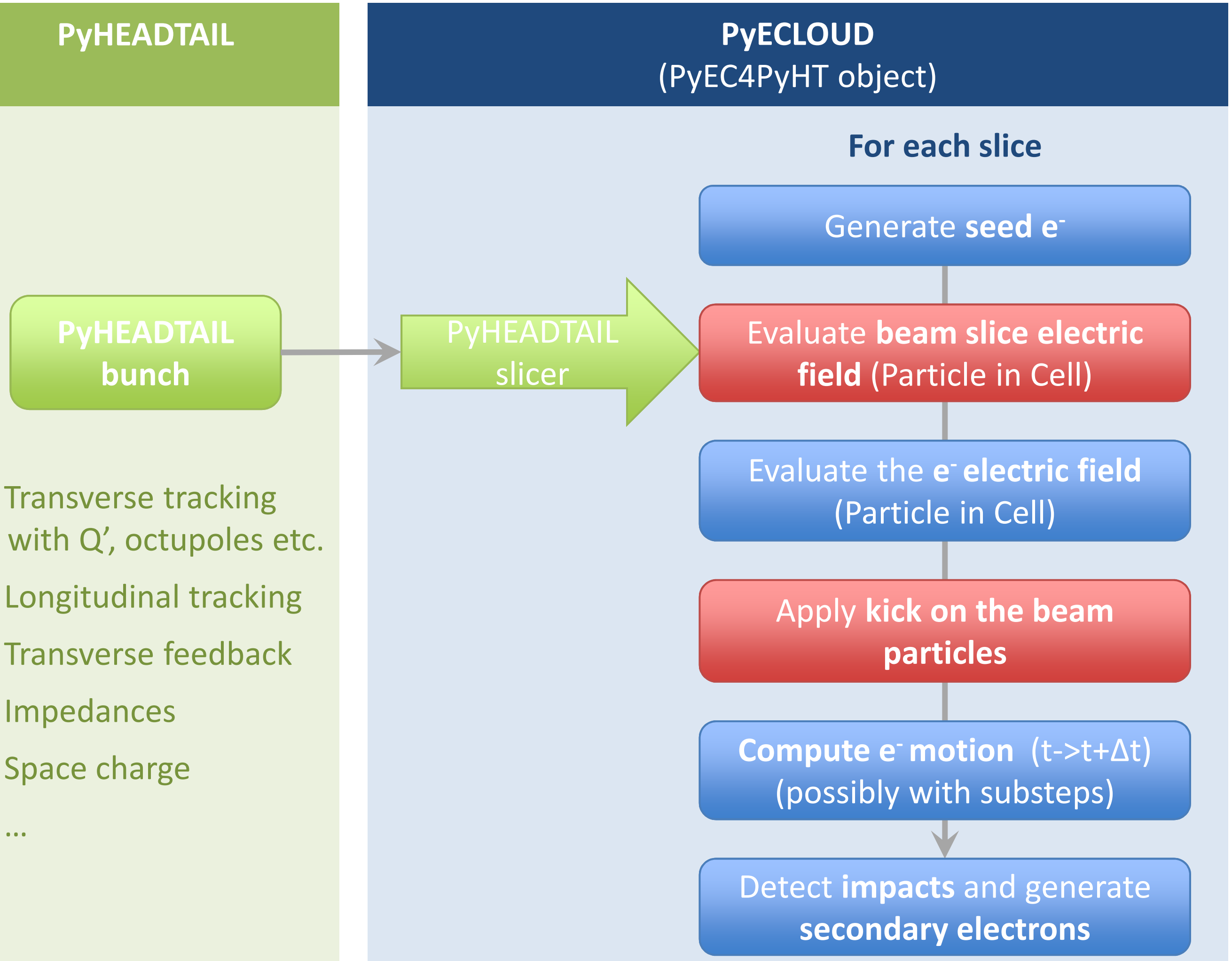

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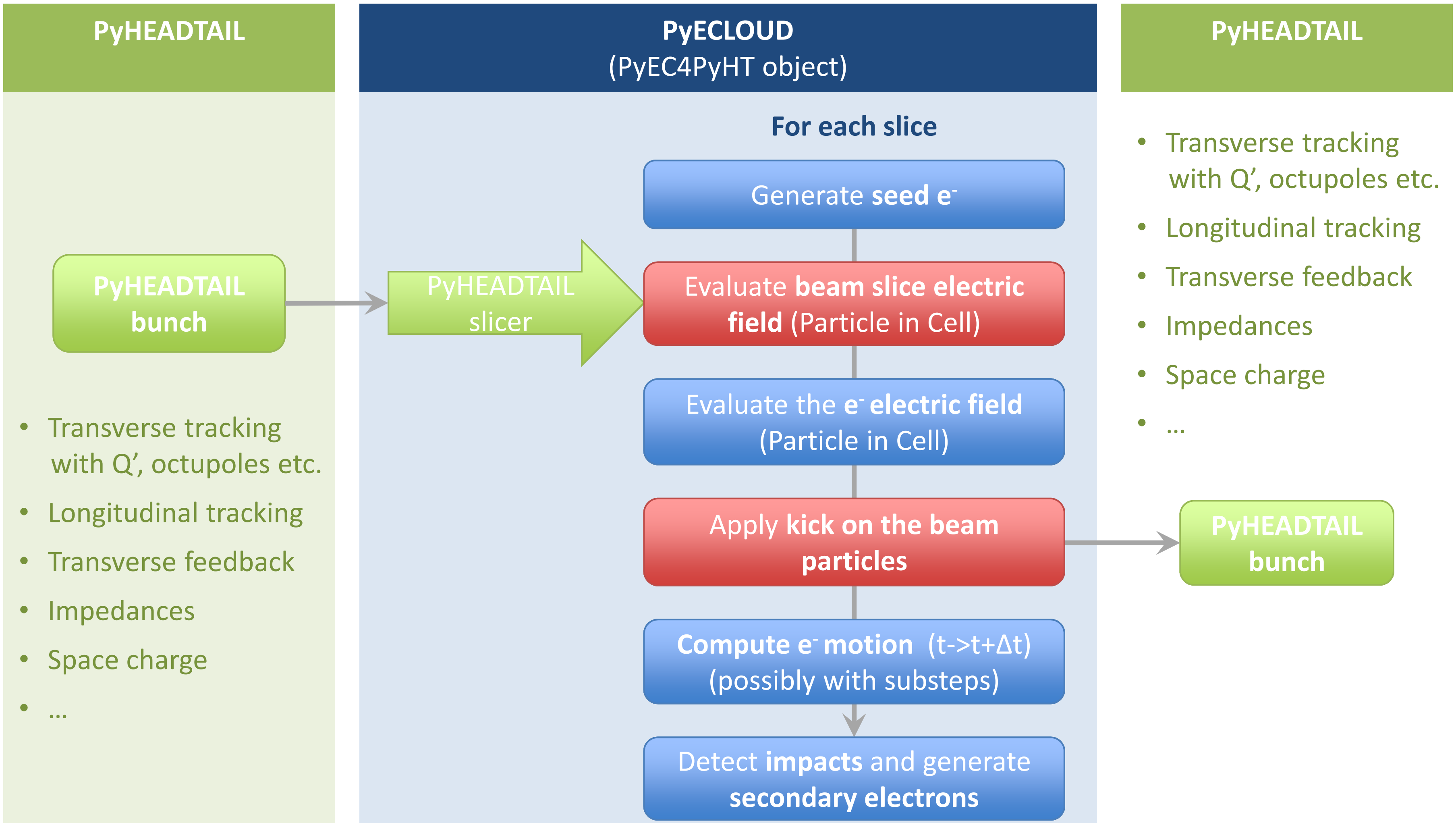

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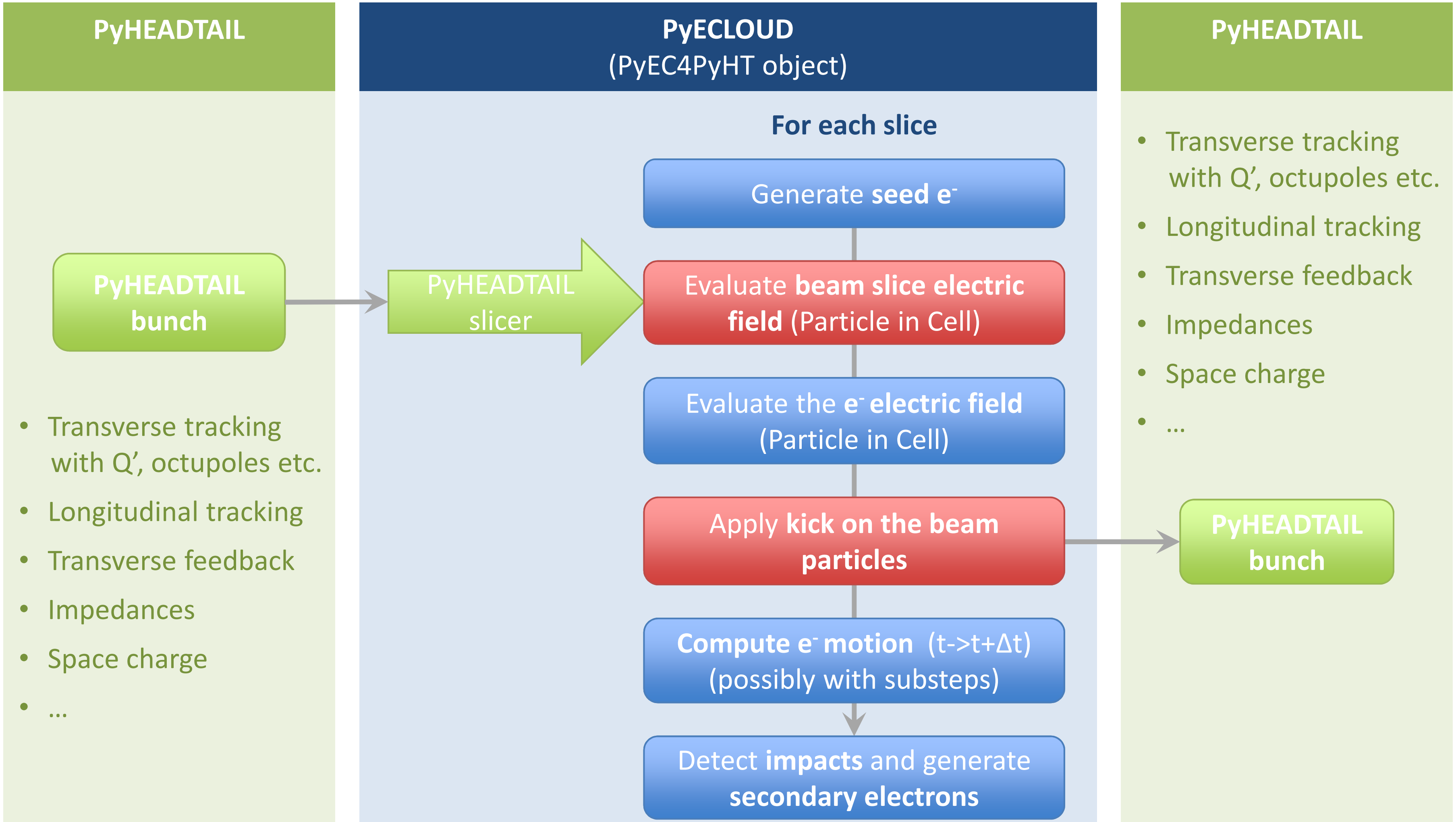

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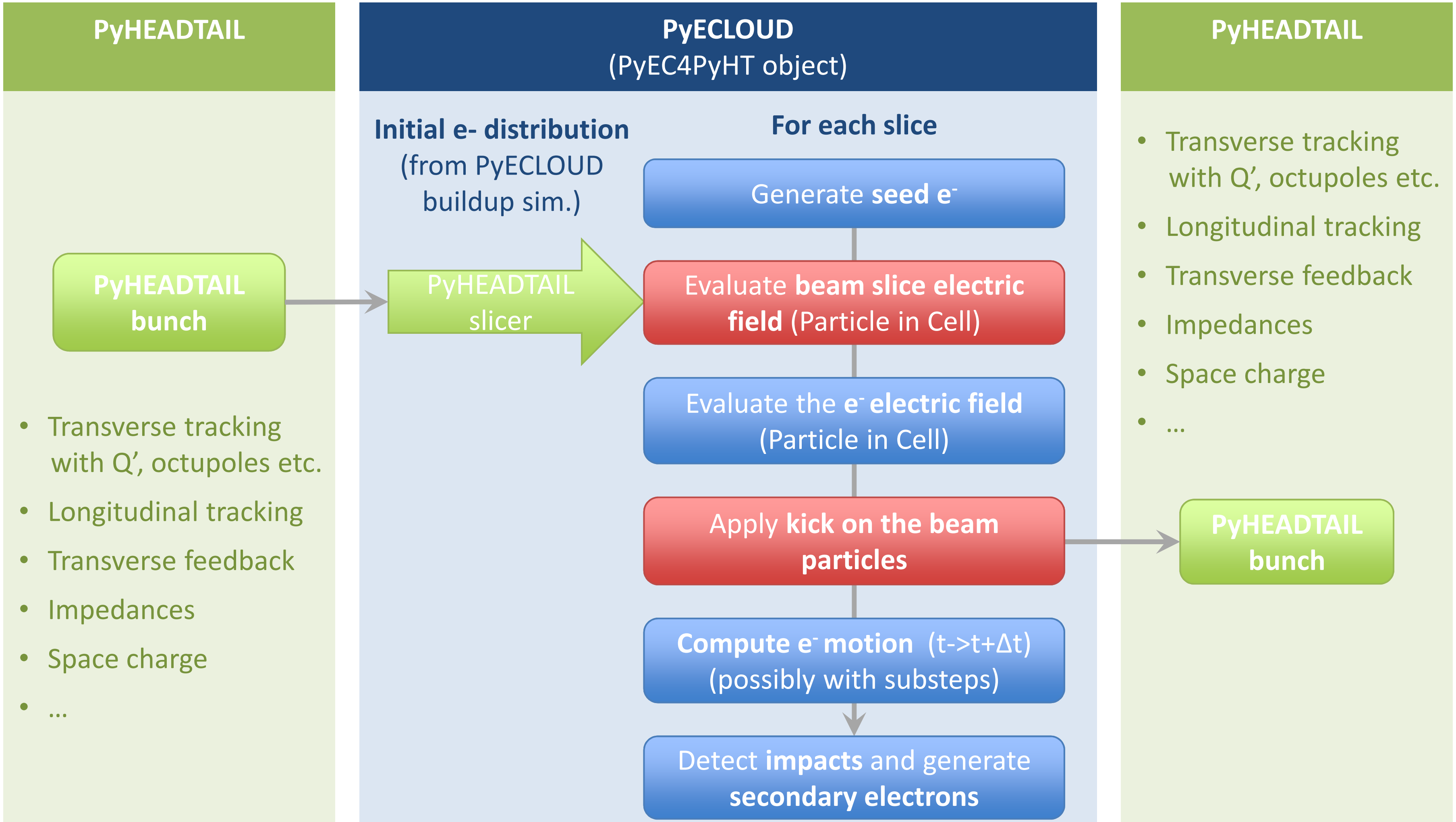

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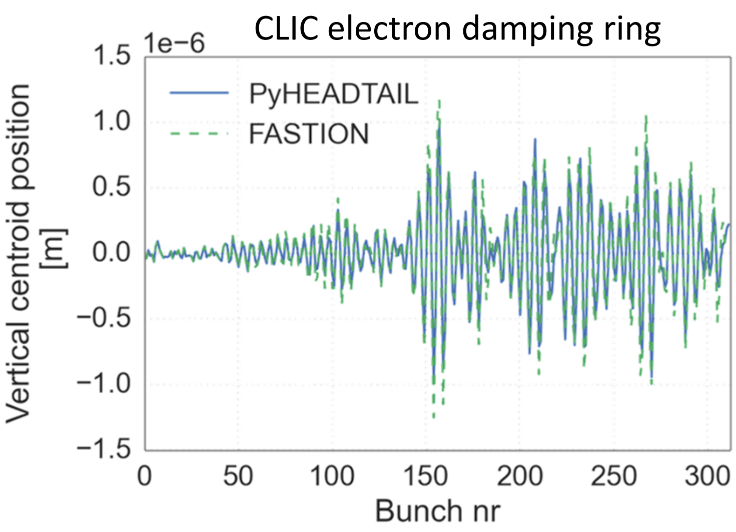
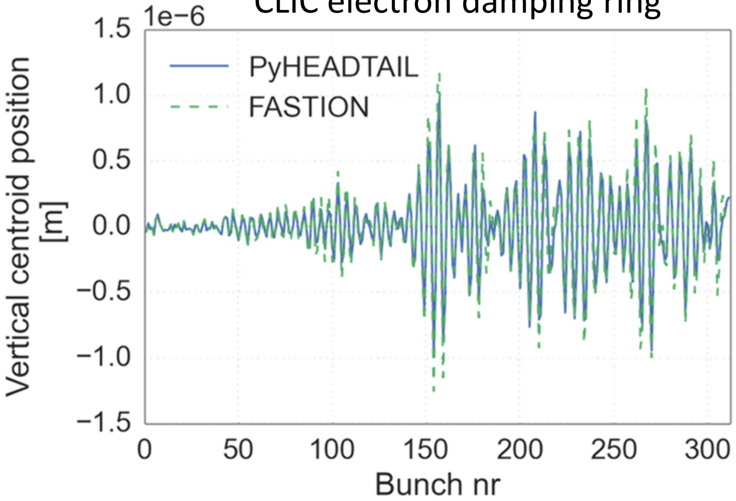
Generalization to different species



Generalization to different species

The PyECLOUD + PyHEADTAIL simulation setup was previously generalized to simulating multi-bunch ion accumulation in electron machines to study the fast beam-ion instability (HB2016)

CLIC electron damping ring



The PyECLOUD build-up simulations could quickly be extended to clouds and beams of any charge and mass

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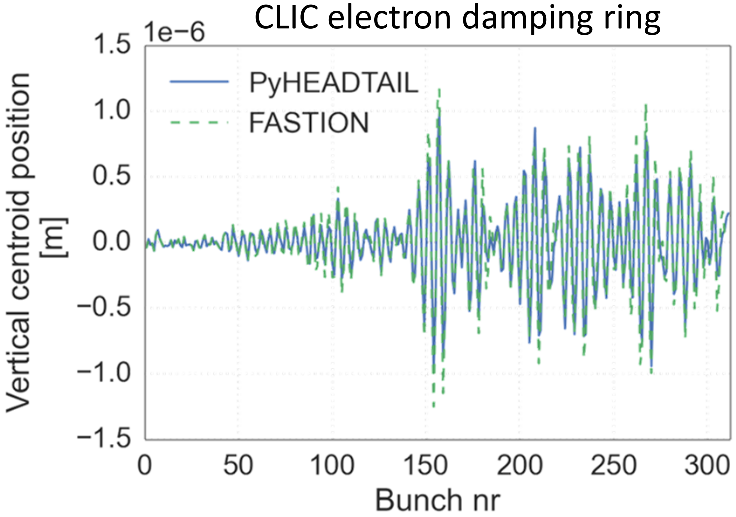

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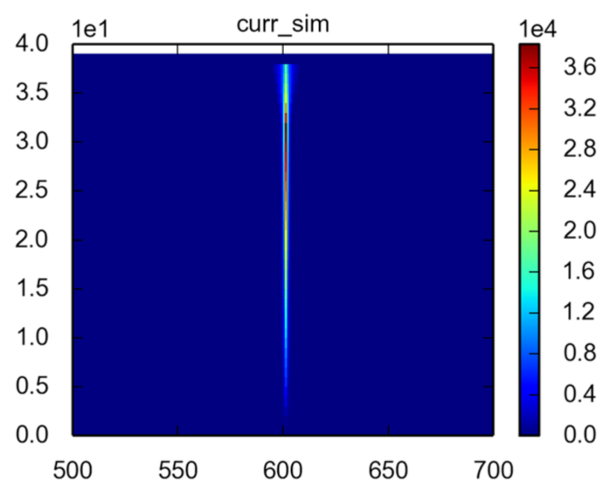

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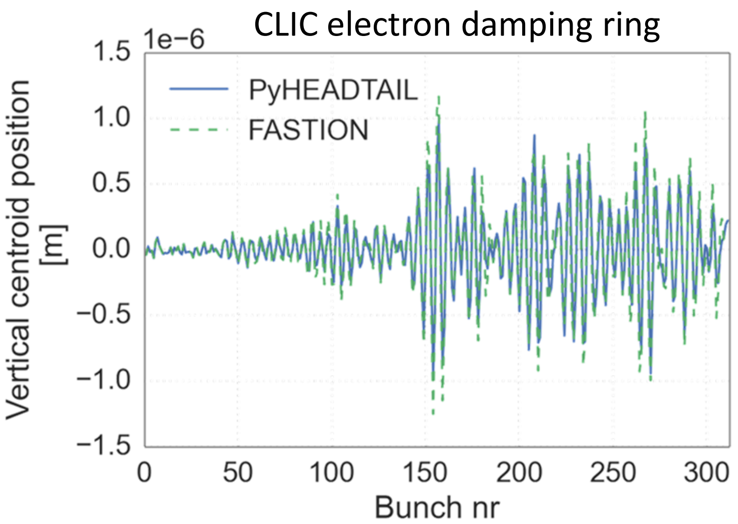

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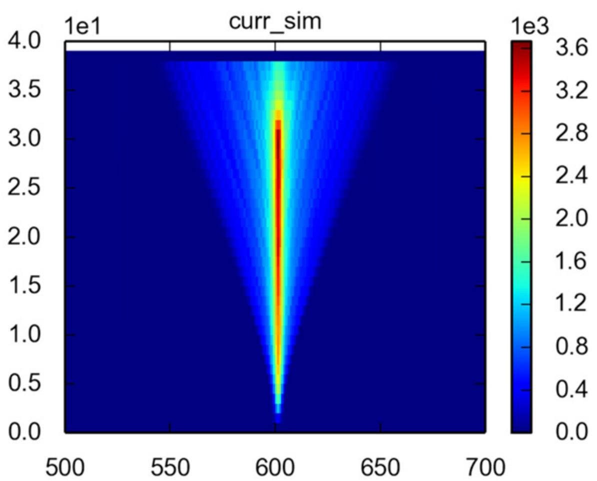

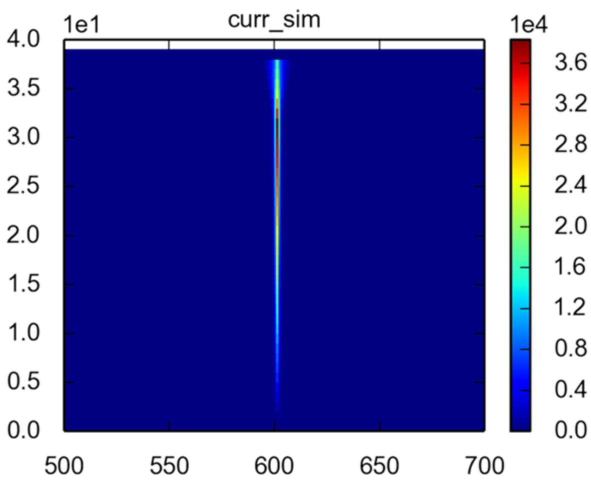

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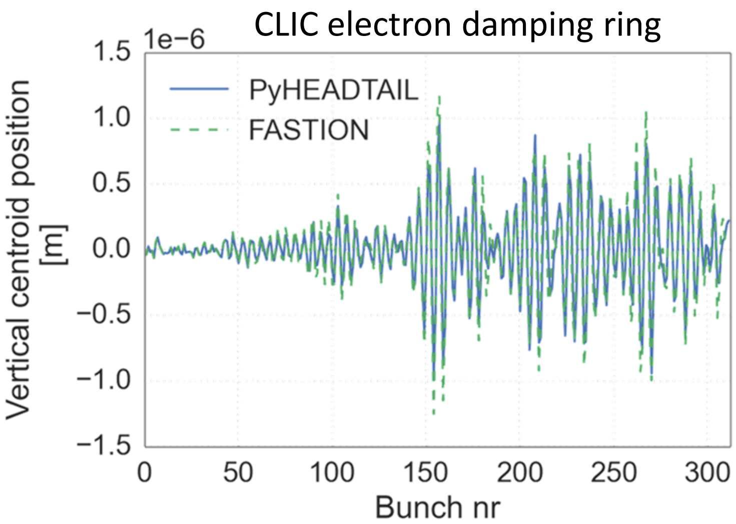

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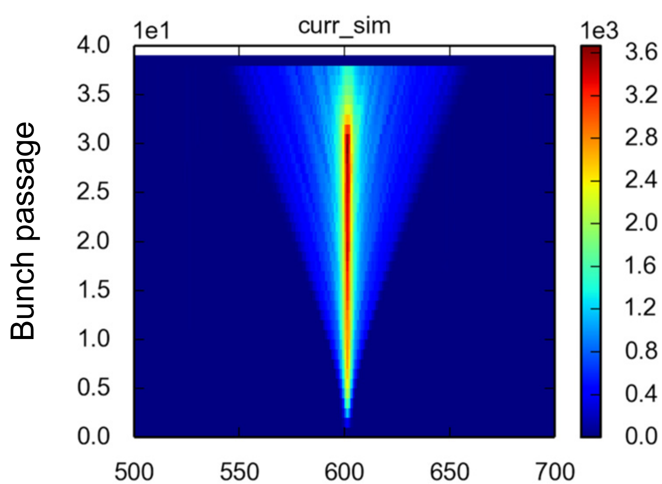

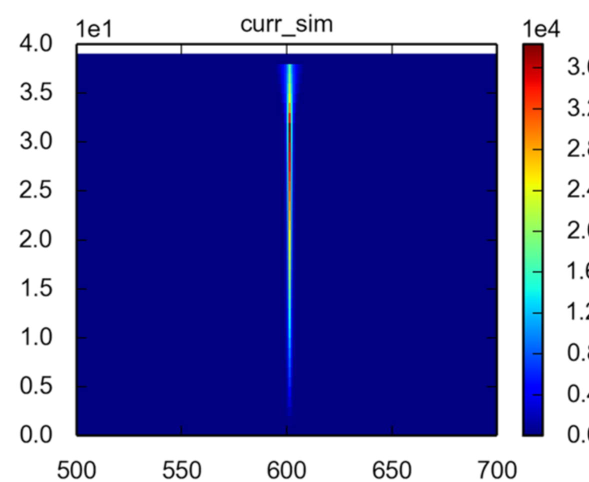

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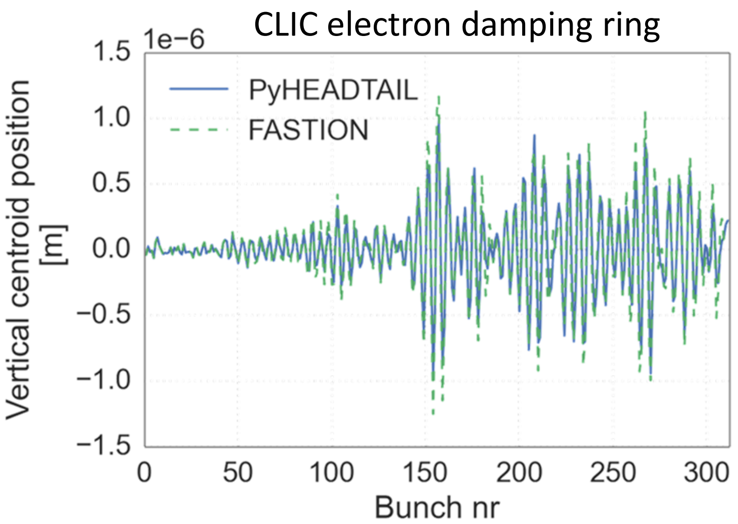

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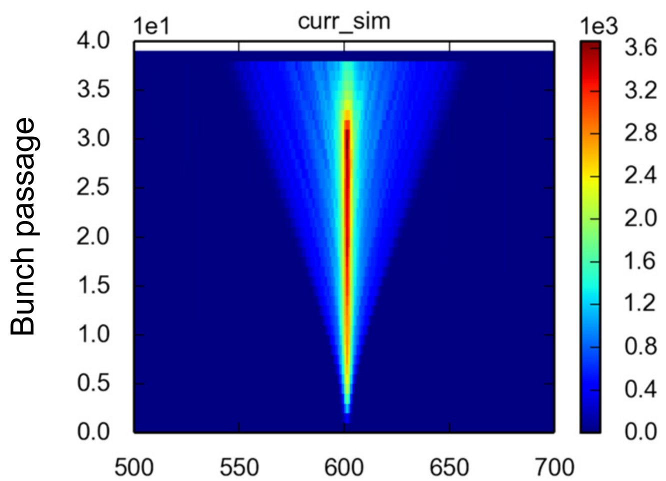

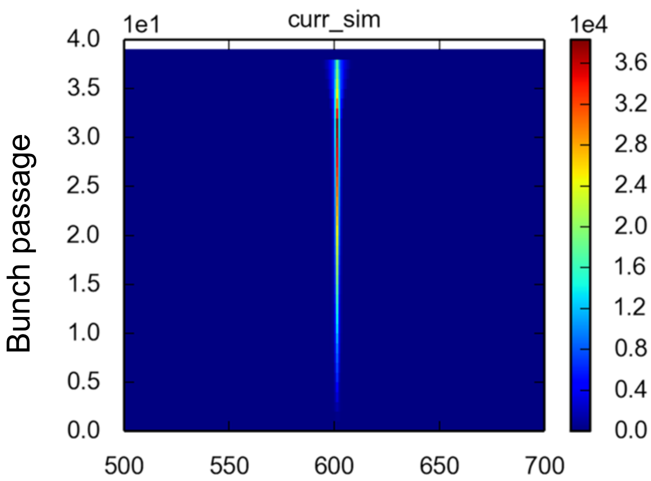

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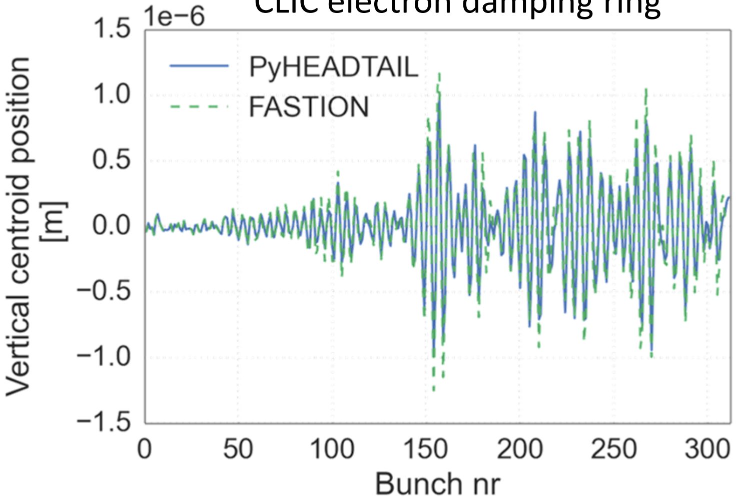

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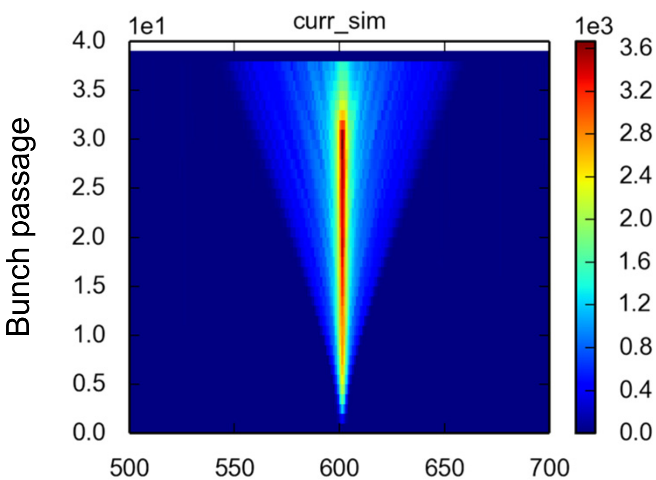

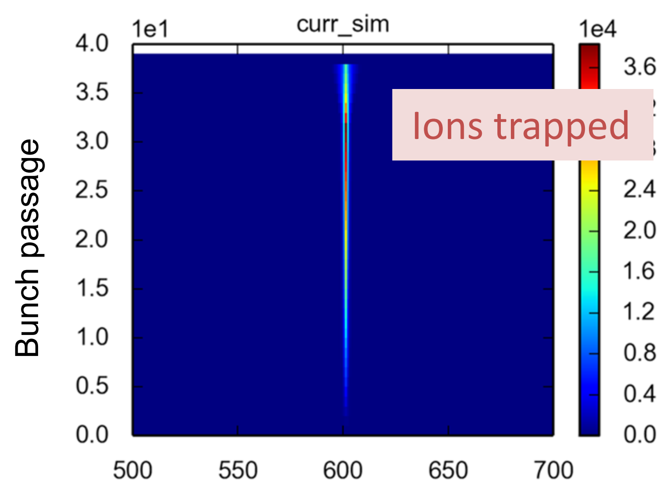

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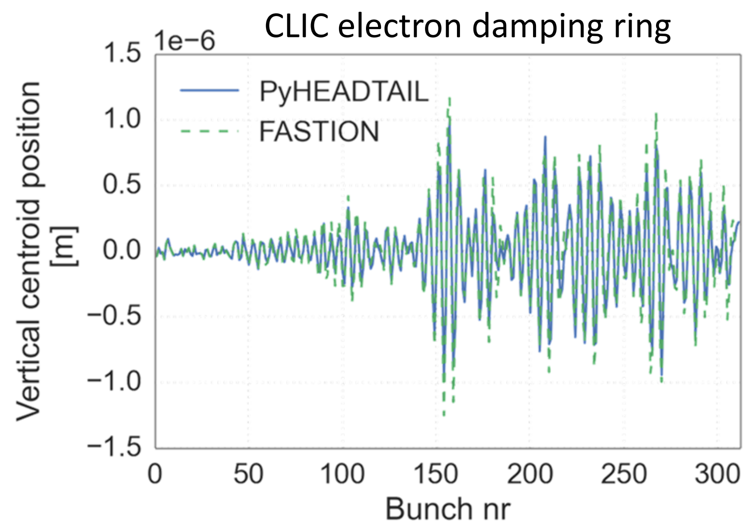

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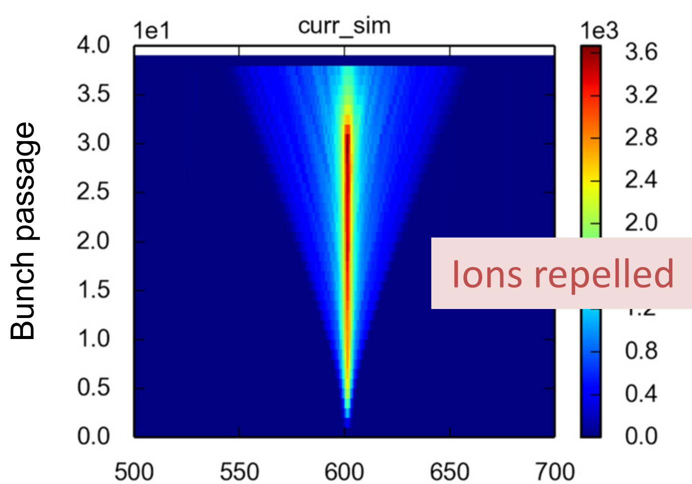

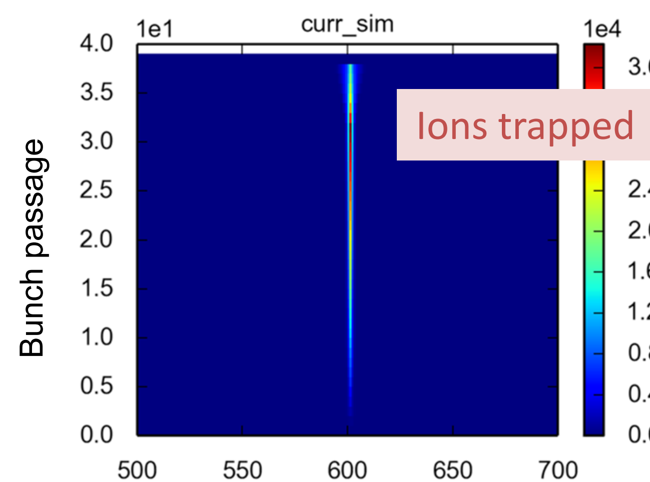

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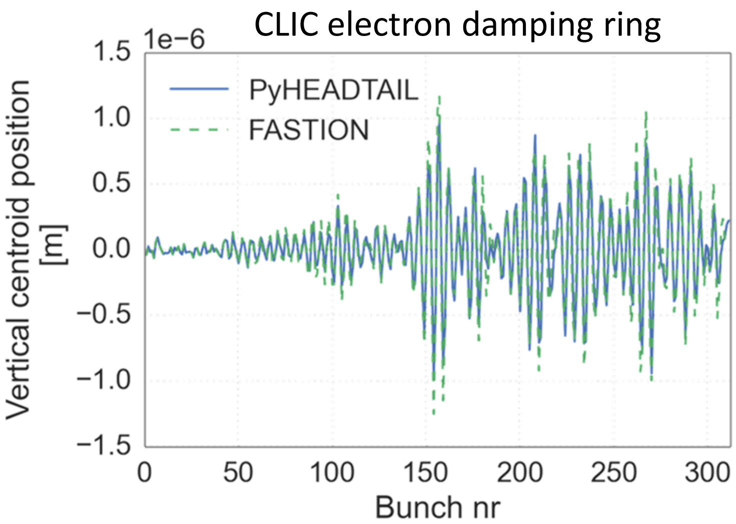

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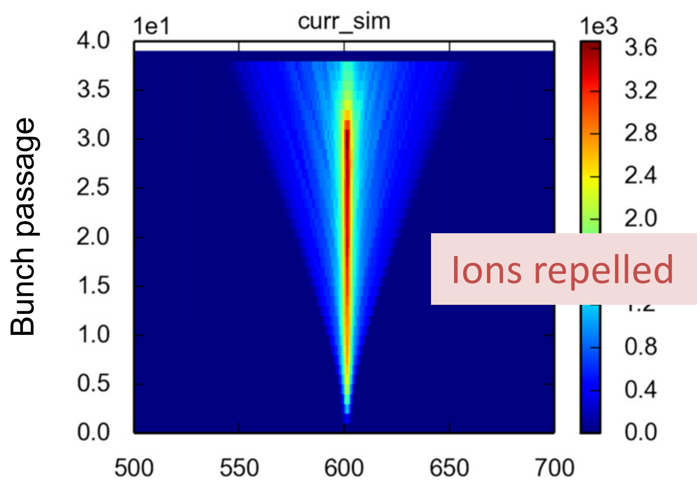

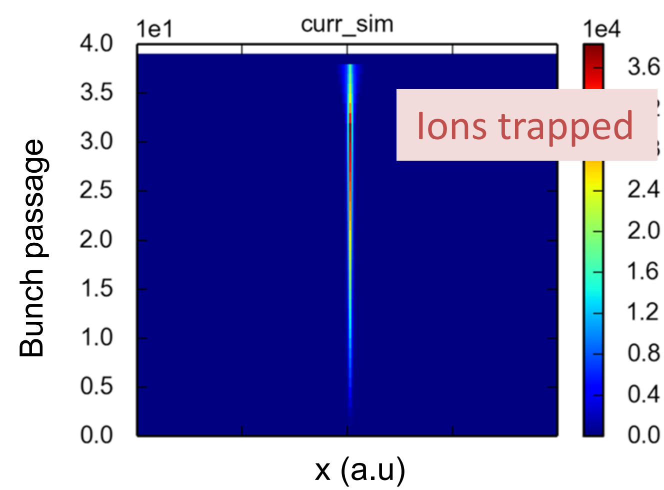

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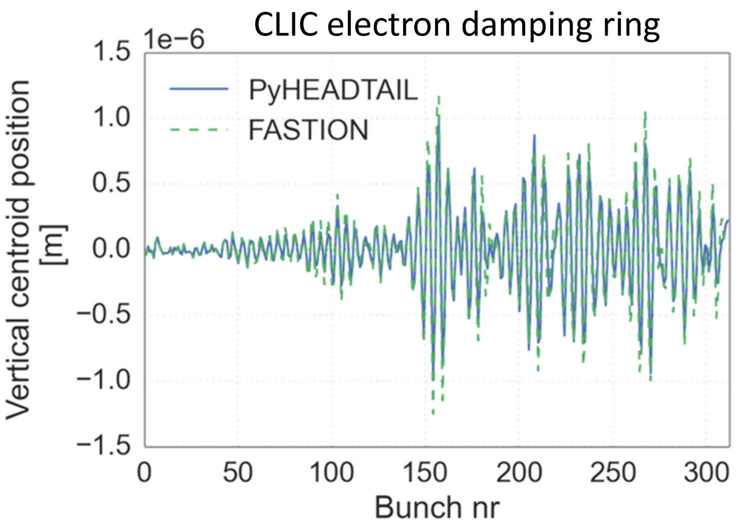

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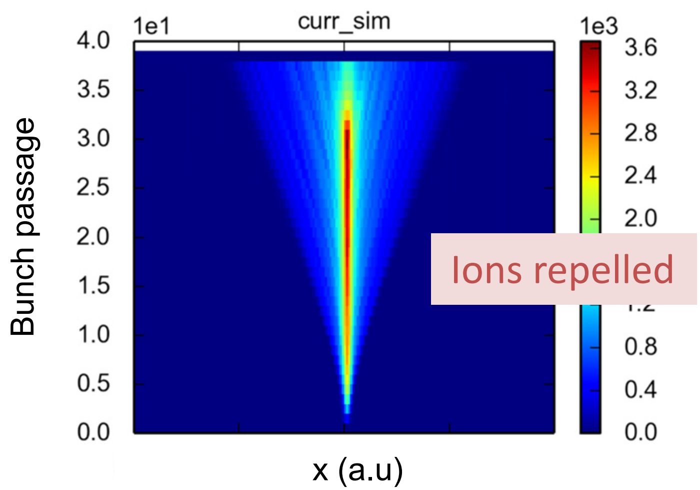
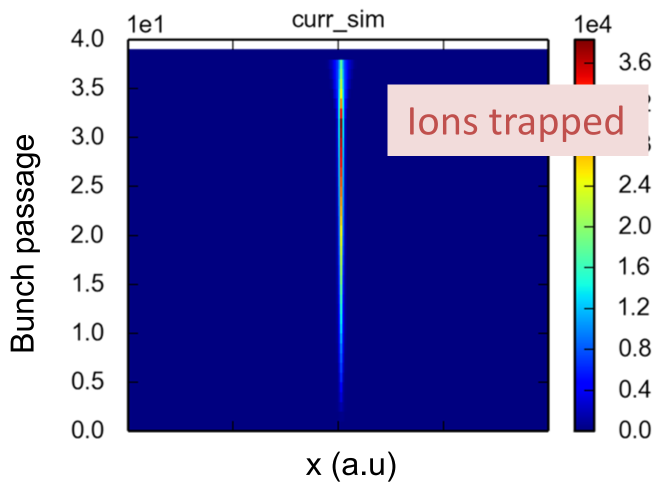
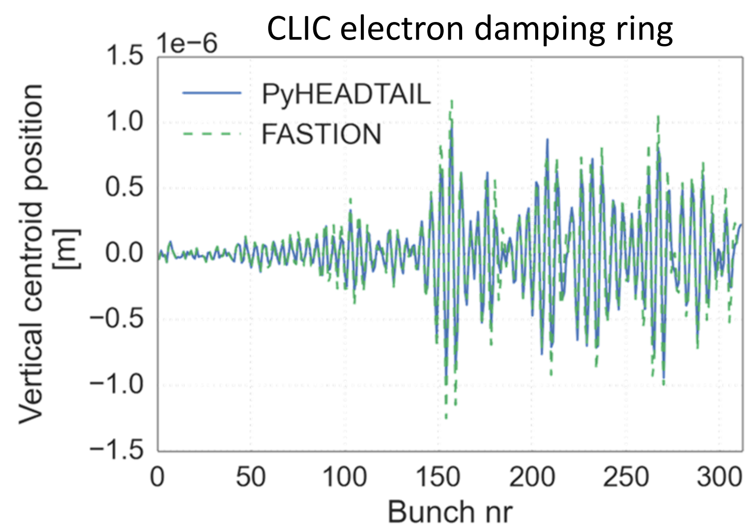




Generalization to different species

The PyECLOUD + PyHEADTAIL simulation setup was previously generalized to simulating multi-bunch ion accumulation in electron machines to study the fast beam-ion instability

(HB2016)



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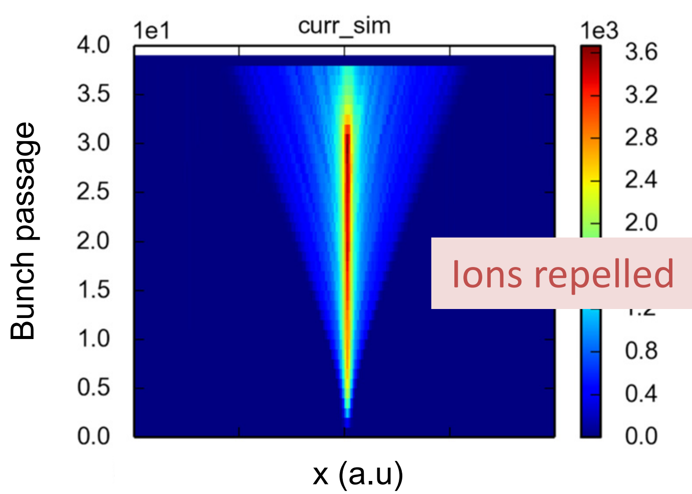

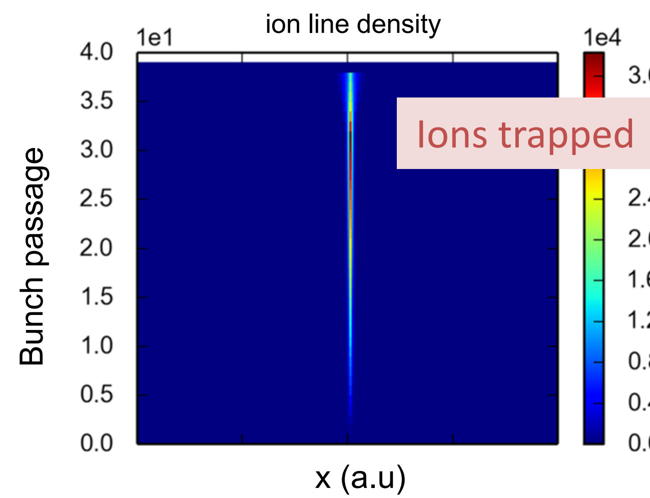

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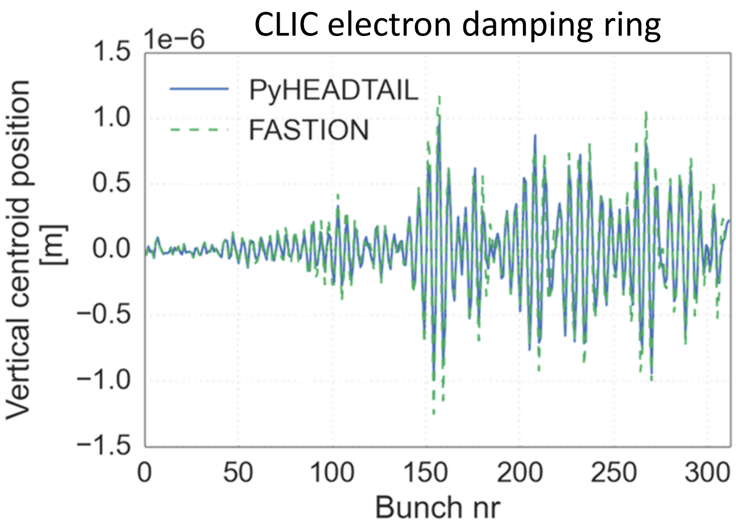

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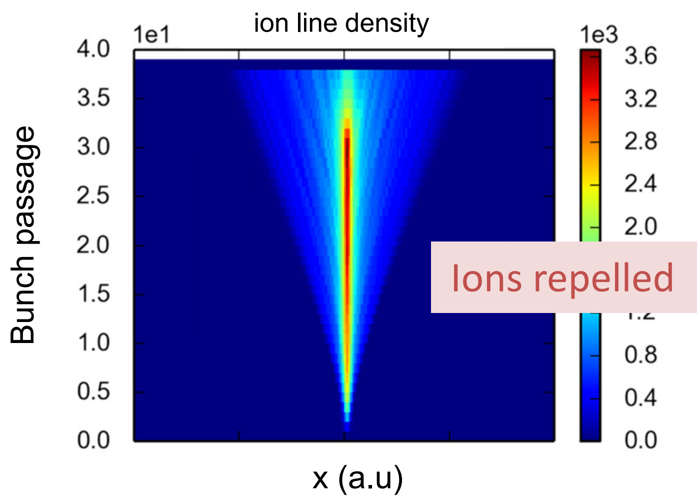

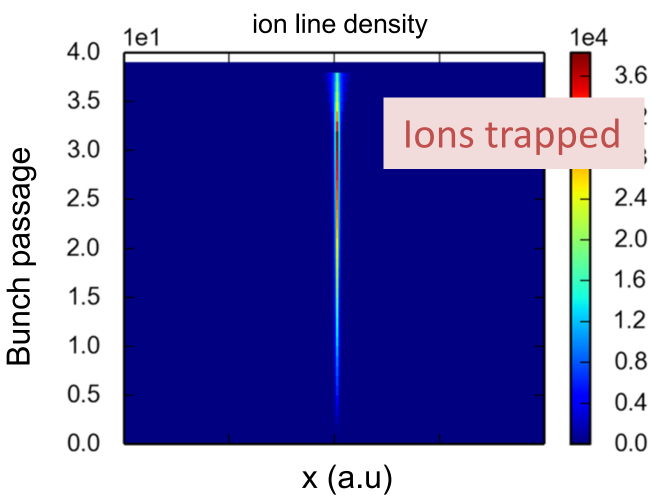

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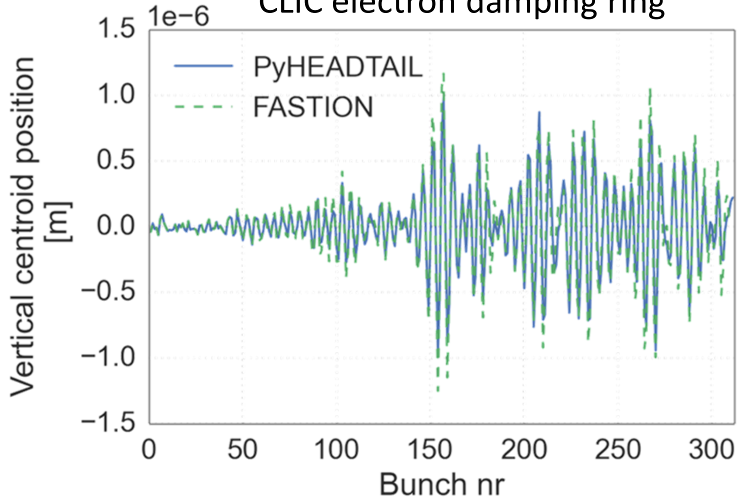
CLIC electron damping ring



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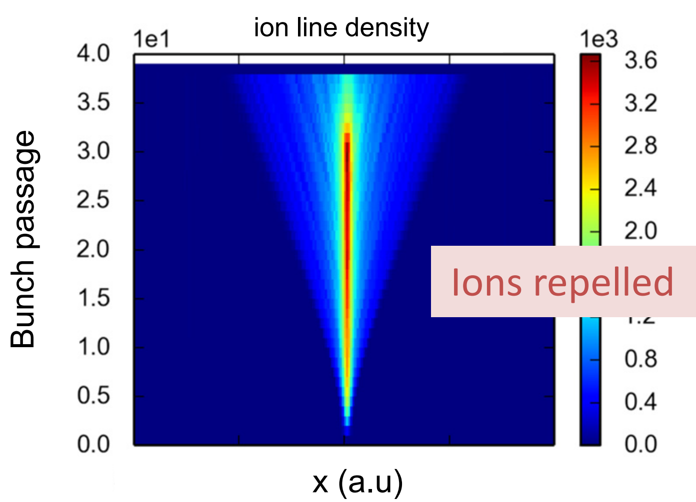

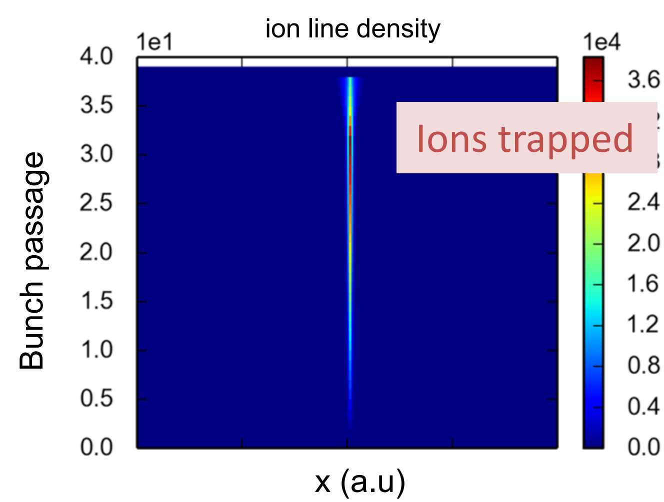

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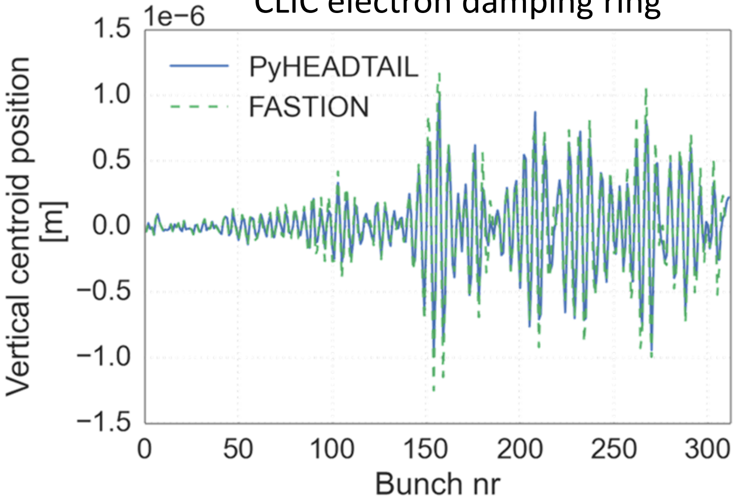

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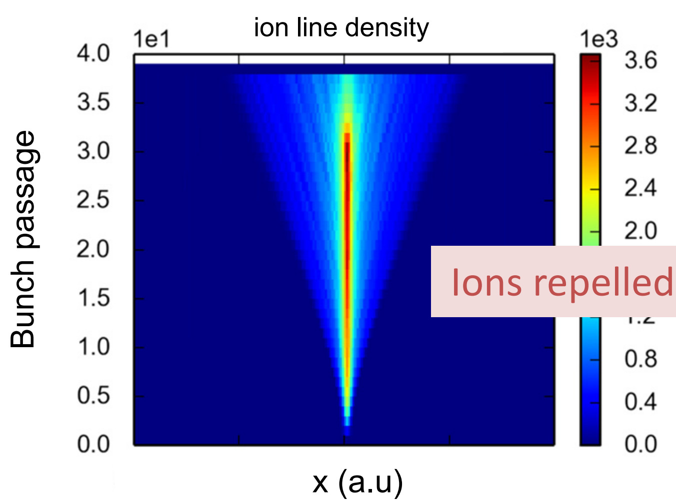

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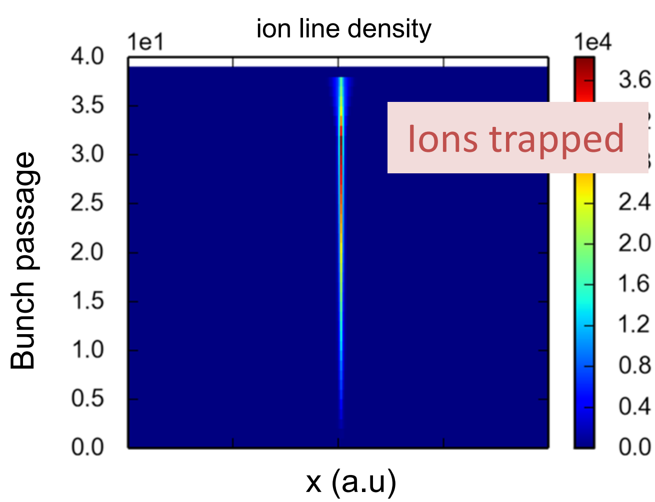

Generalization to different species

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In all cases only one species can be simulated, implicitly assuming that all others can be ignored

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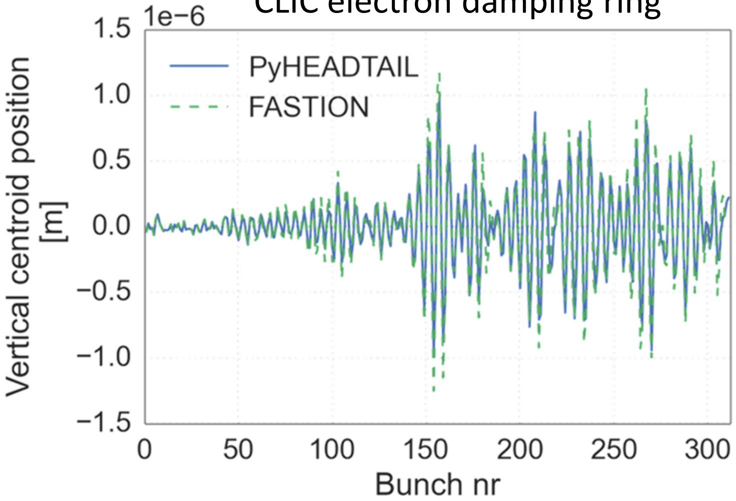

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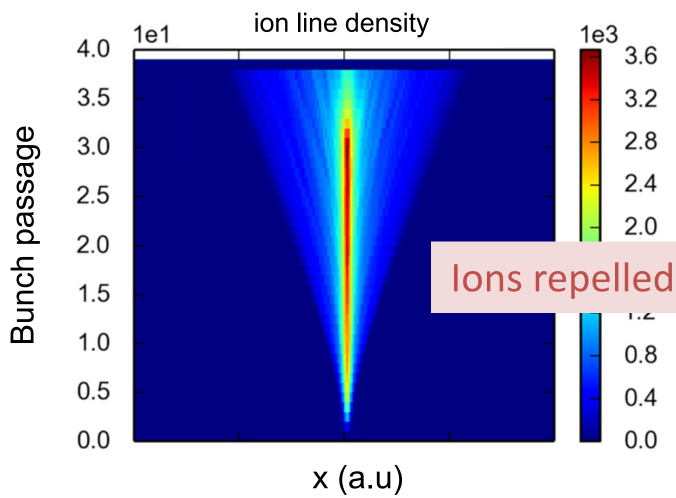

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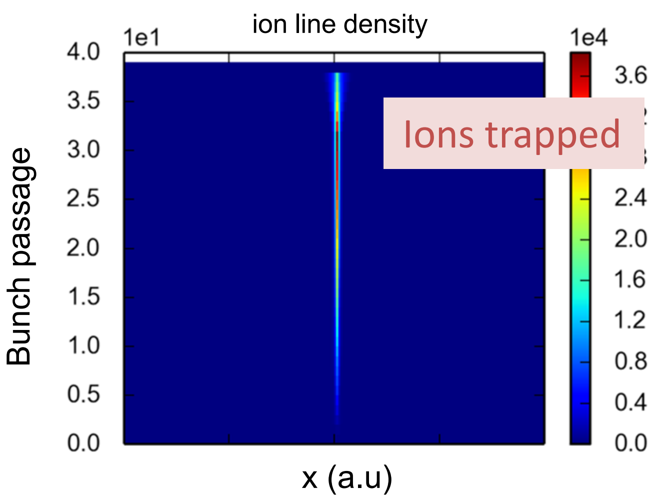
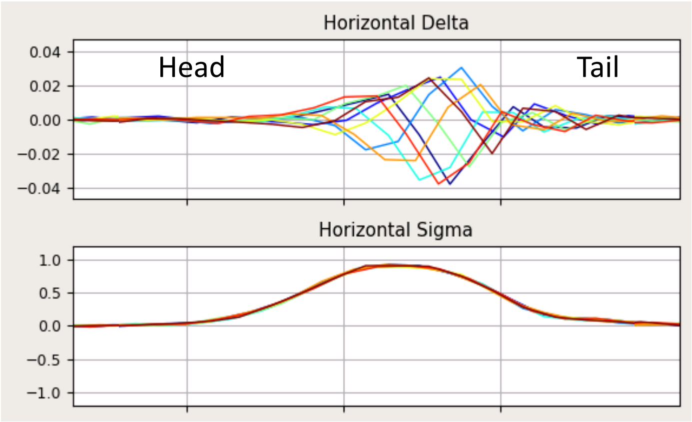
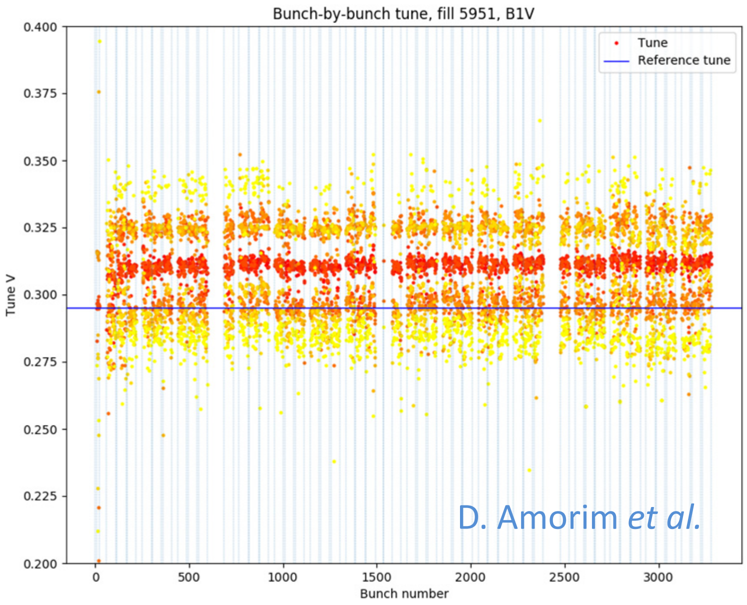


Instability observations

B. Salvant, T. Levens





Instability observations

In several cases the characteristics of the instability pointed specifically to the involvement of electrons:

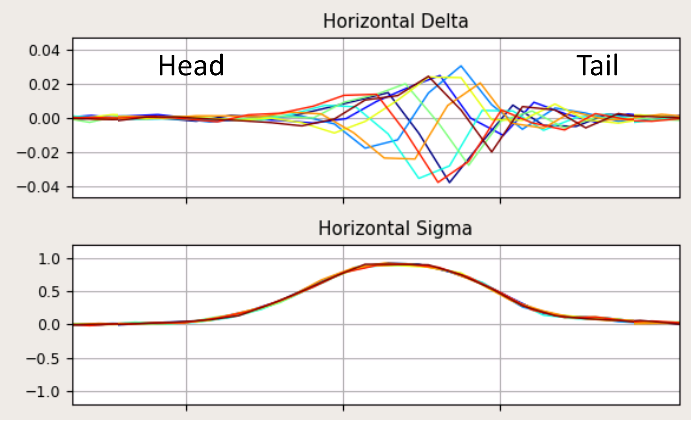
- Intra-bunch motion at tail of bunches
- Positive tune shifts (up to 10^{-2})

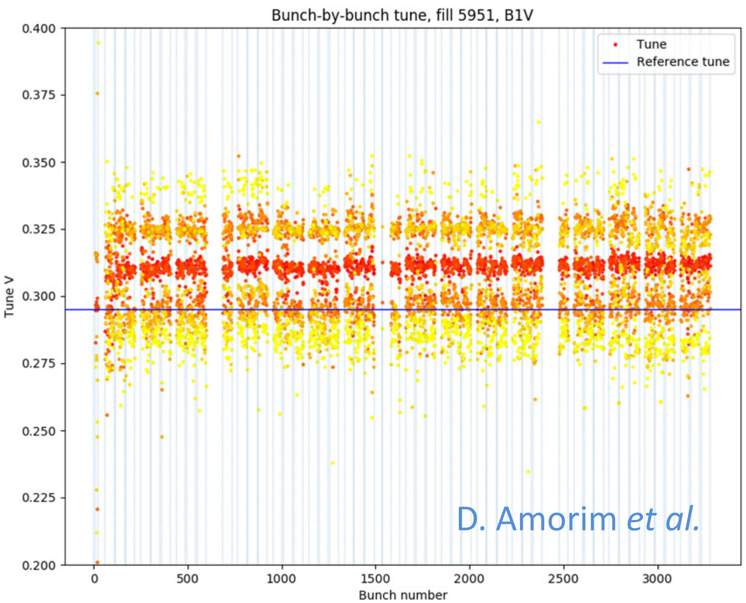
Several considerations, including beam dynamics simulations with electrons, suggest that electron densities of 10^{16} L^{-1}m^{-2} over a length L could induce such effects

Electrons and ions are of course produced in equal amounts and, at such high densities, can be expected to influence each other strongly

- 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

B. Salvant, T. Levens





D. Amorim *et al.*

Multiple species in PyECLOUD

```
cloud:
```

```
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cloud.pyecloud saver
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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

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space charge
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secondary beams list
+
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Multi-species test

Multi-species test

The multi-species implementation has been verified against a standard e-cloud build-up simulation for the LHC, starting from a uniform initial electron distribution

The electrons were divided into three clouds:

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Cloud 2 and 3: a quarter of ref density

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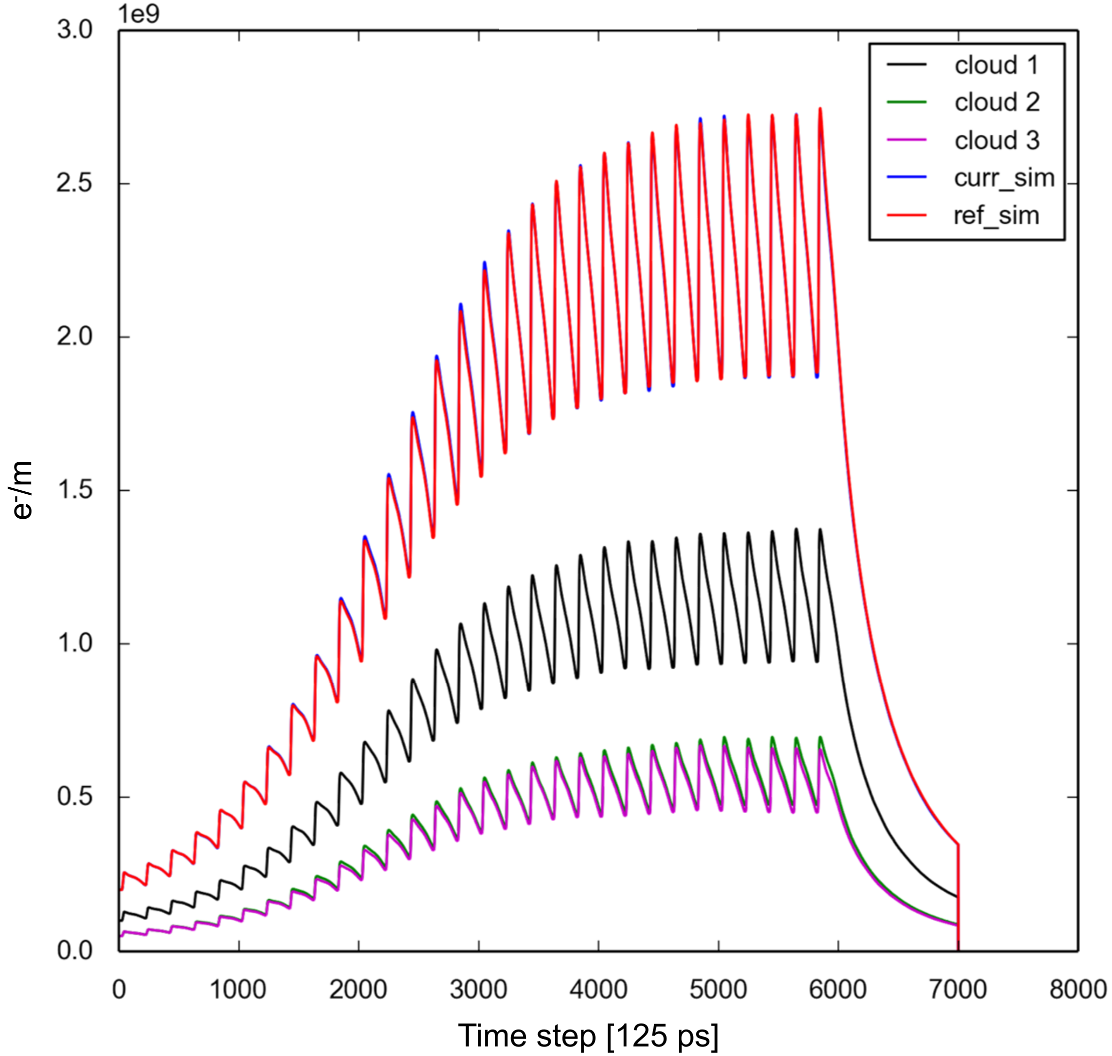
Multi-species test

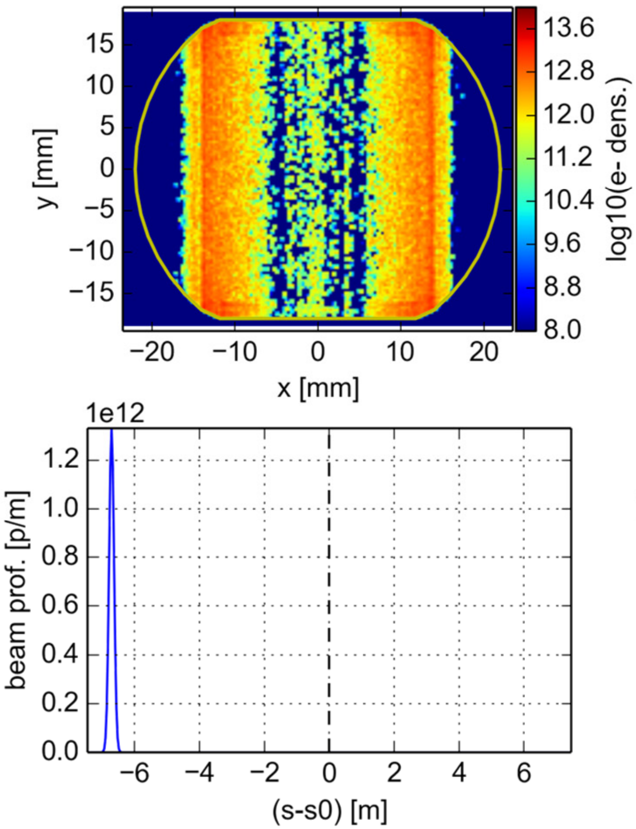
The electron line densities of the three clouds add up (in blue) to the line density of the reference simulation



Multi-species test

Total electron density and densities of individual clouds after 30 bunch passages:

Total density
including all clouds



Cloud 1:
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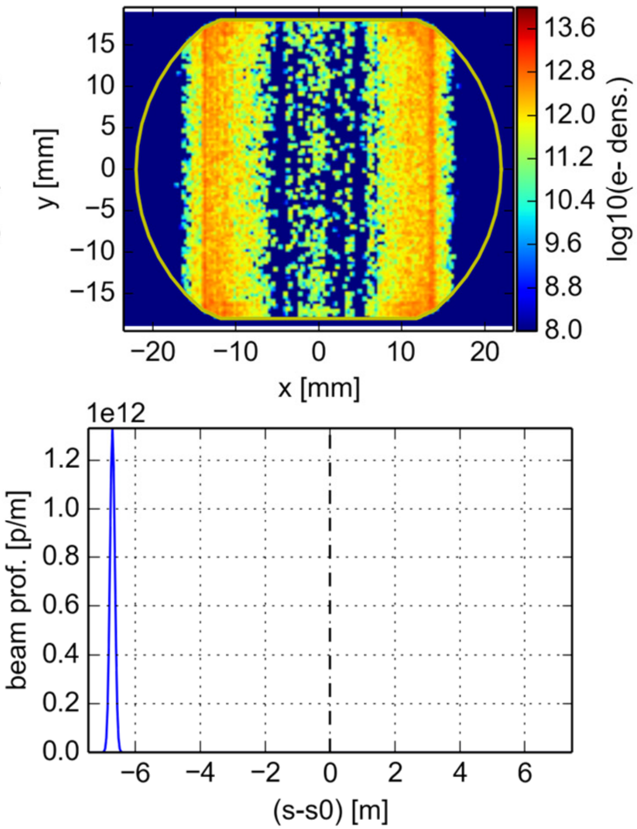
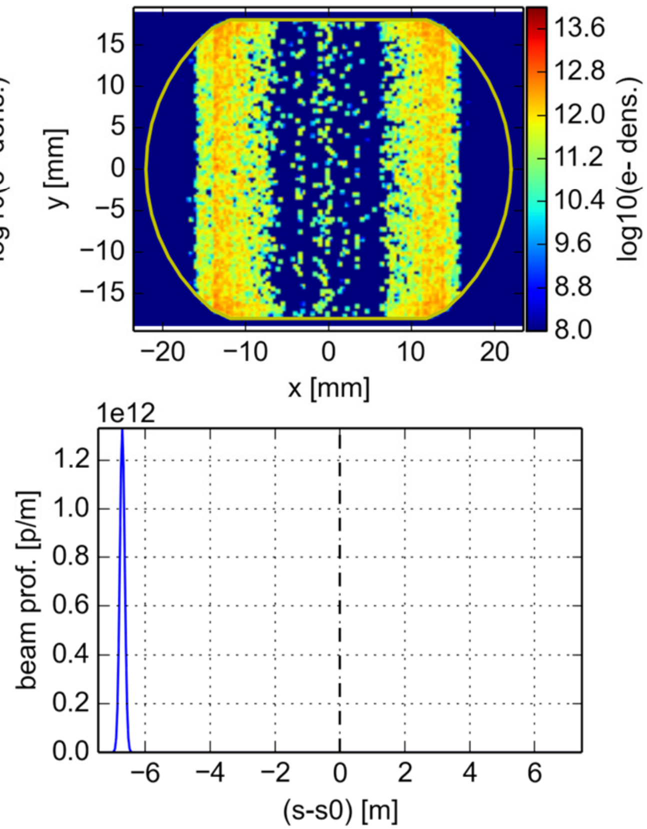


Cloud 2:
a quarter of total density



Application to LHC pressure bump

In simulations, ions and electrons are generated from 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 may produce secondary electrons when hitting the wall

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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 over the full beam cross section and over the length L → density range ~ $10^{19} – 10^{21}\, L^{-1}\mathrm{m}^{-2}$

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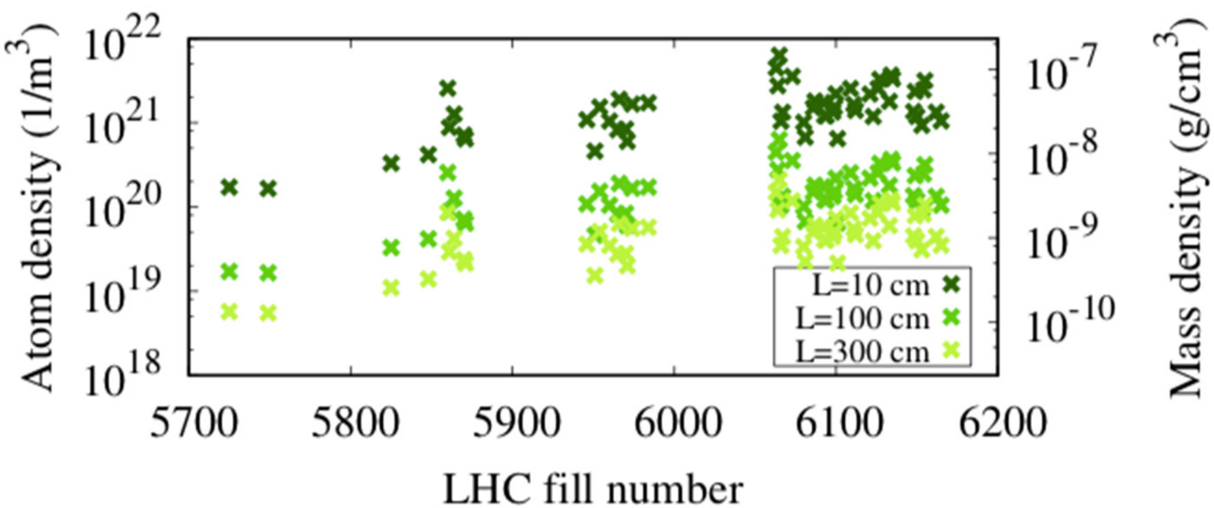

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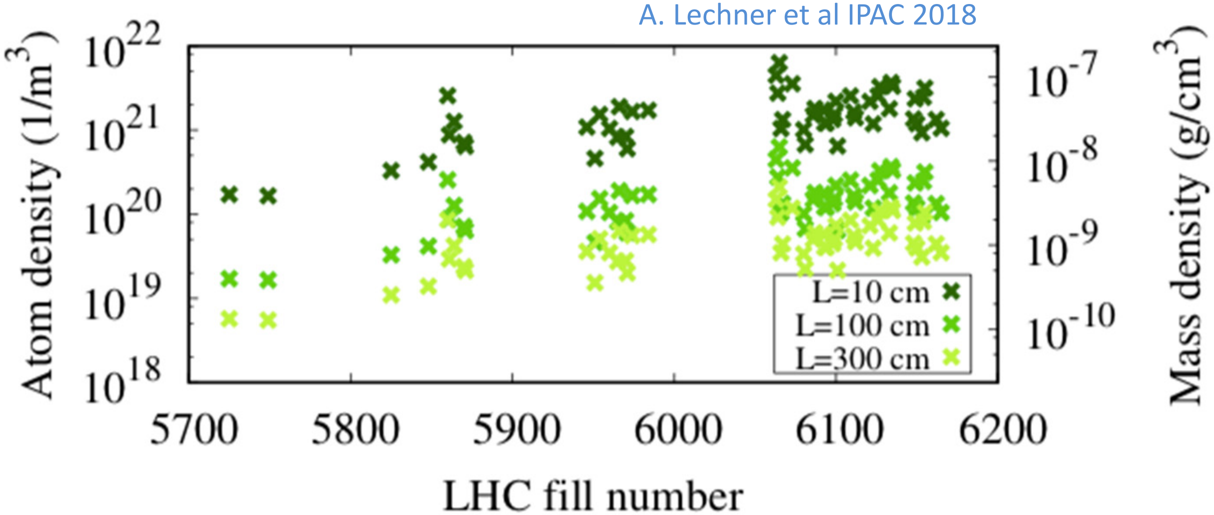
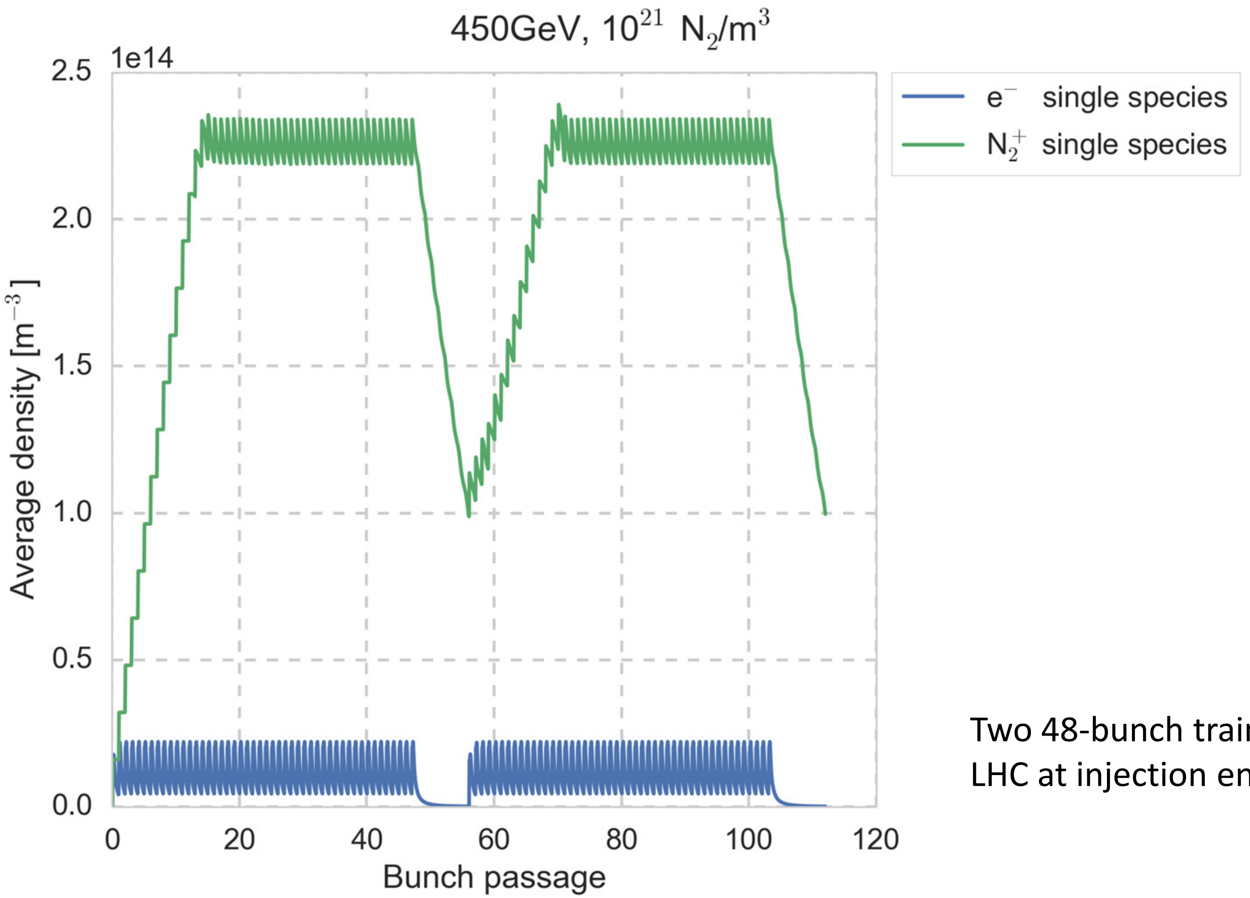
A. Lechner et al IPAC 2018



Build-up with single species

When electrons are simulated without ions, no accumulation along the train occurs



Two 48-bunch trains in the LHC at injection energy

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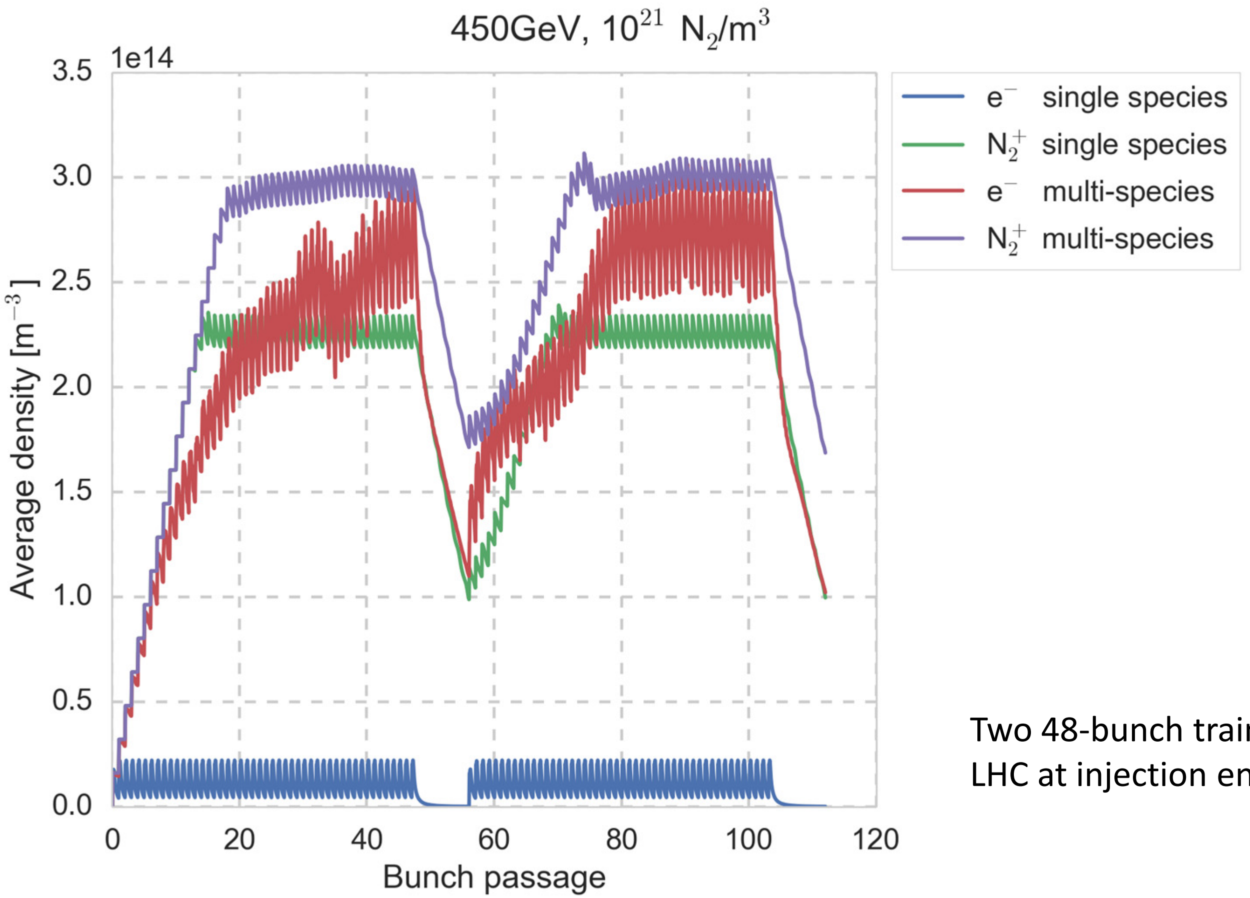
When electrons and ions are simulated together in otherwise identical conditions, the density of both species build-up over several bunch passages



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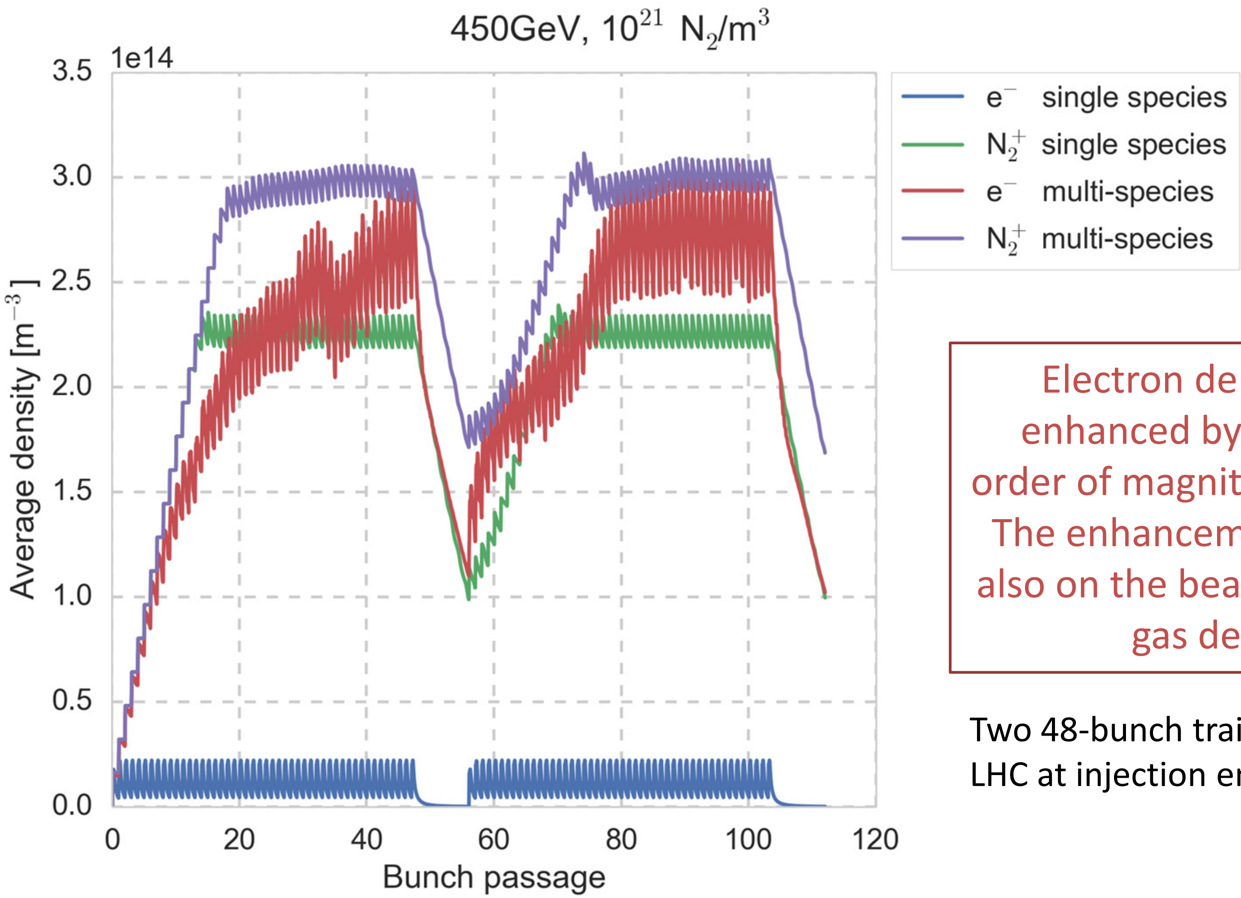


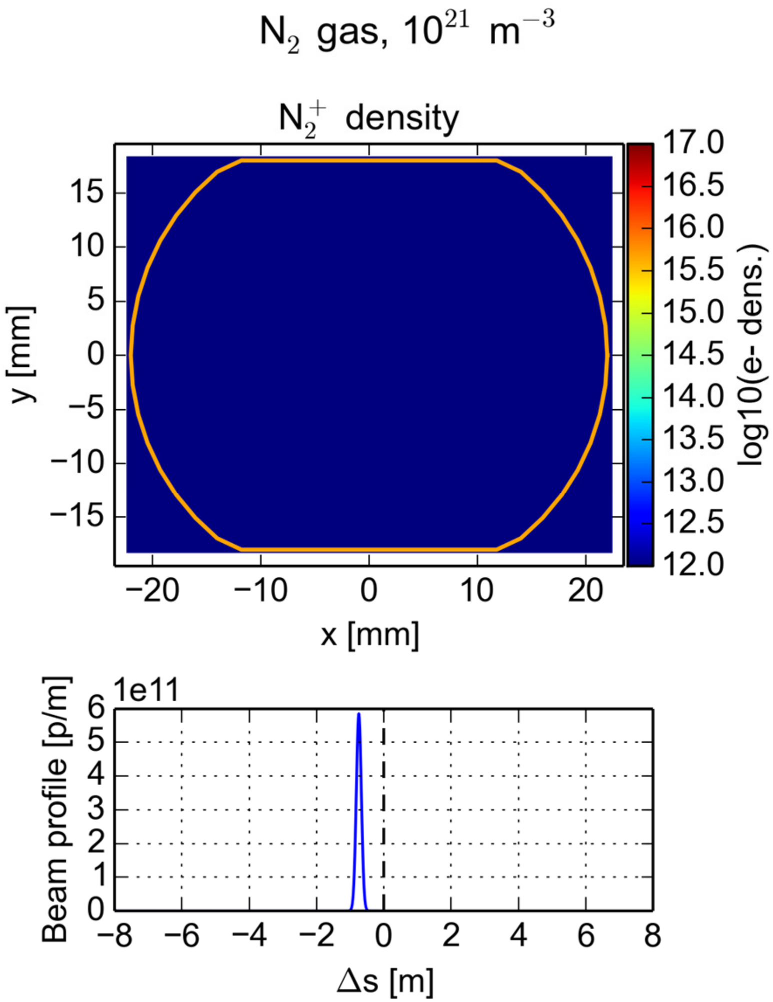
Electron densities are enhanced by roughly an order of magnitude, ions less. The enhancement depends also on the beam energy and gas density

Two 48-bunch trains in the LHC at injection energy

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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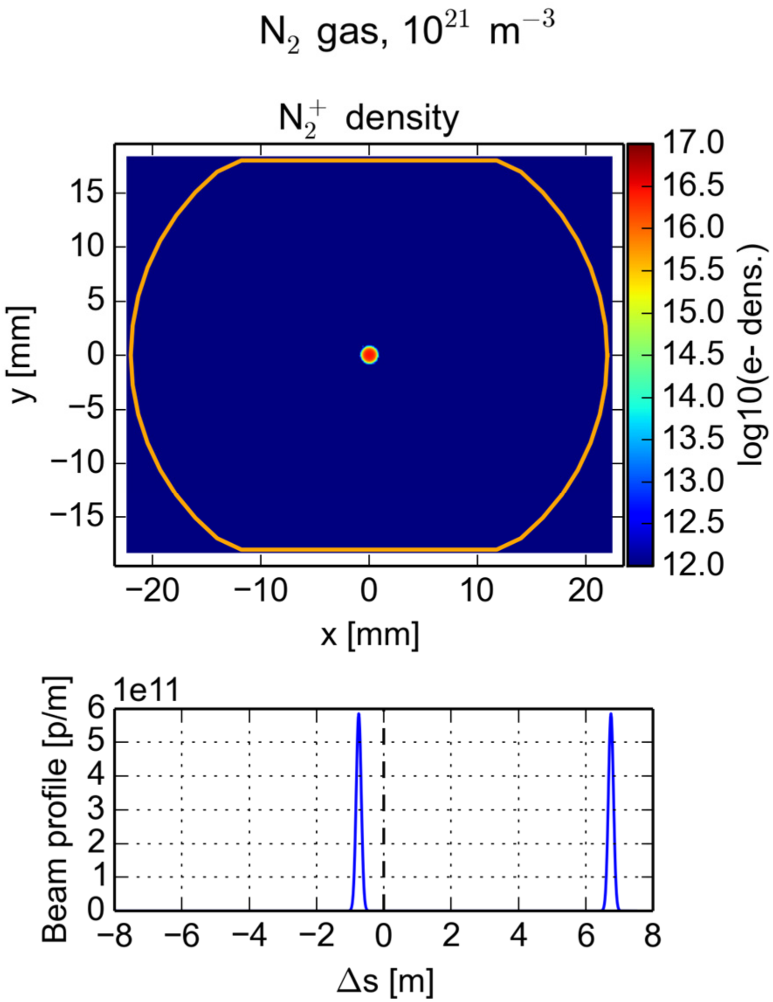

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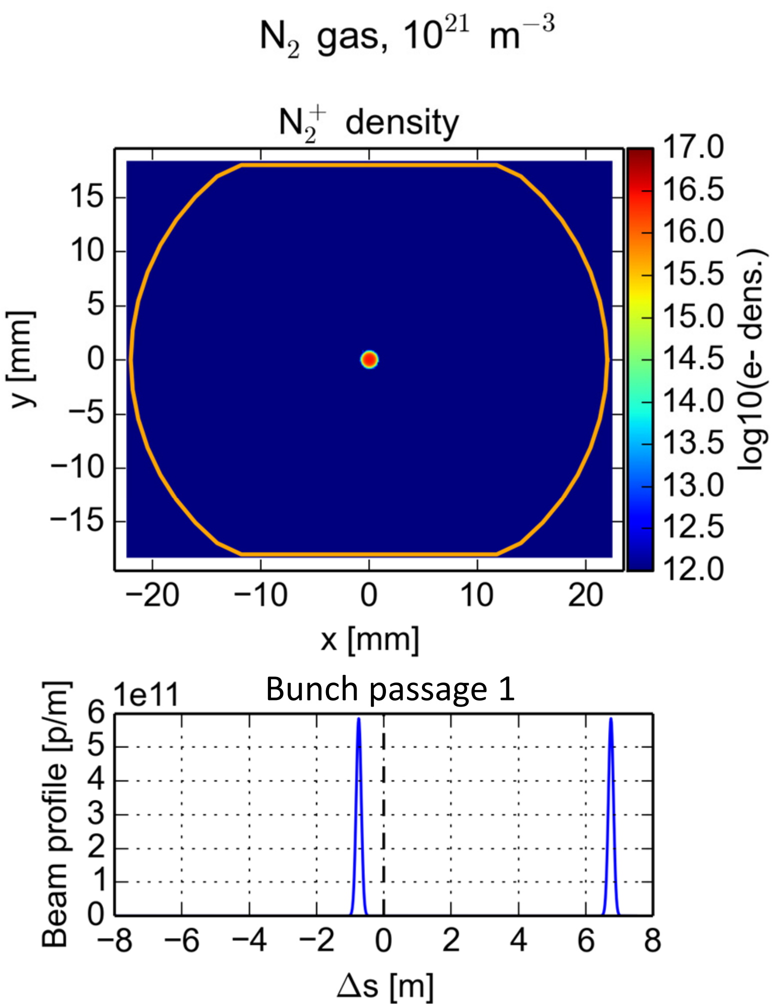

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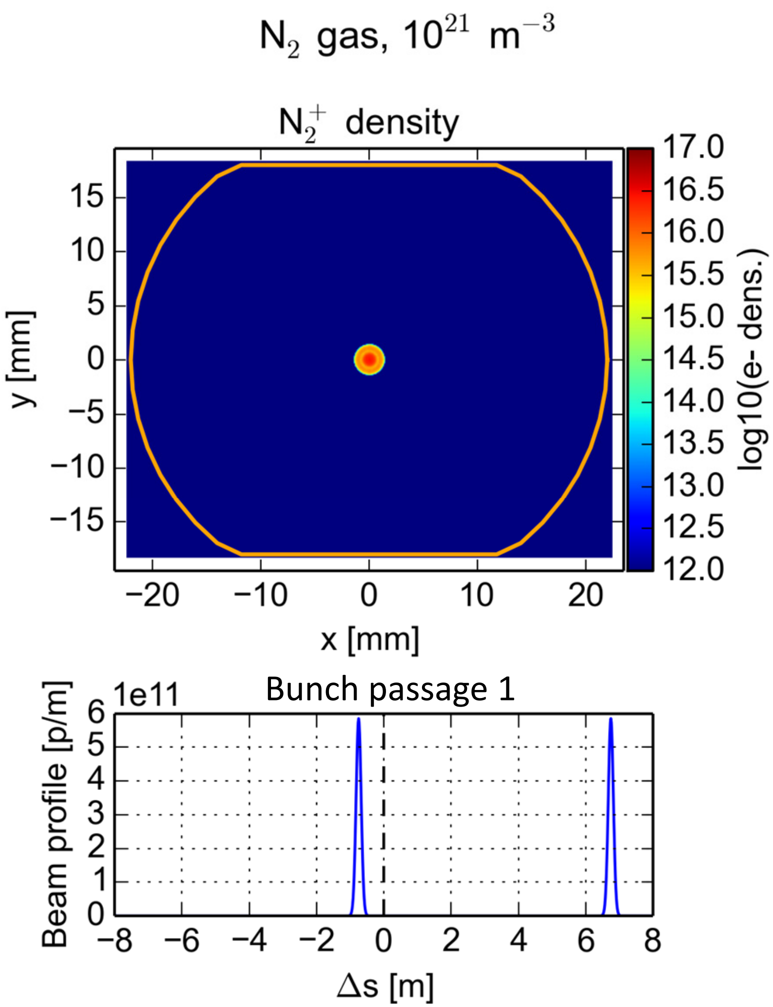

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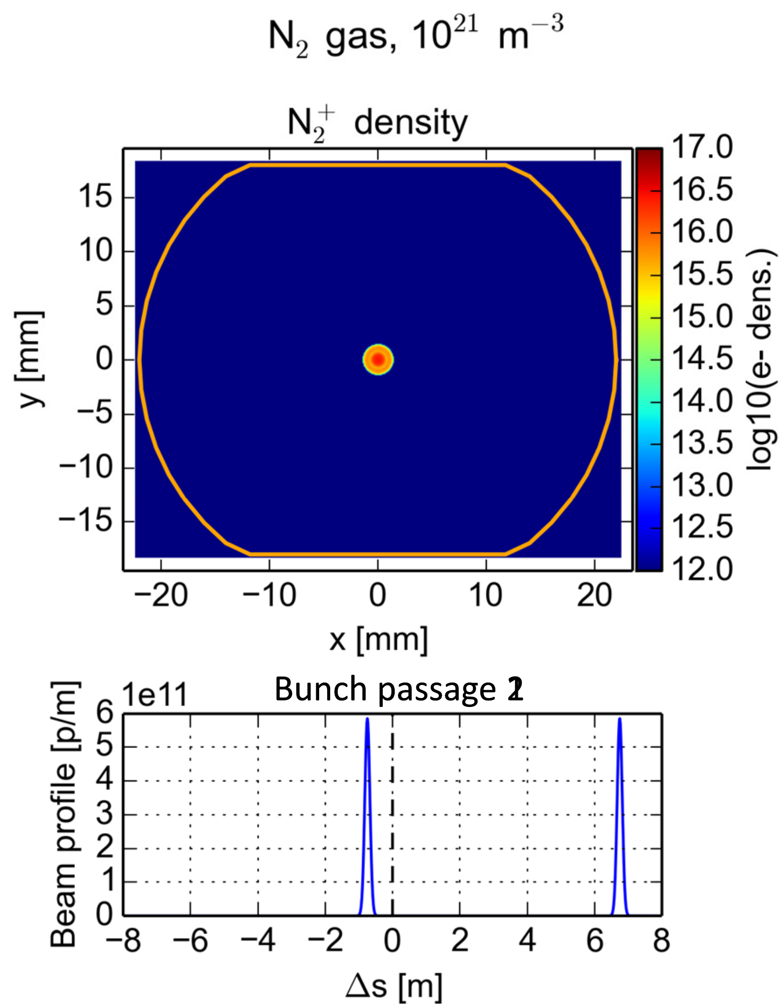

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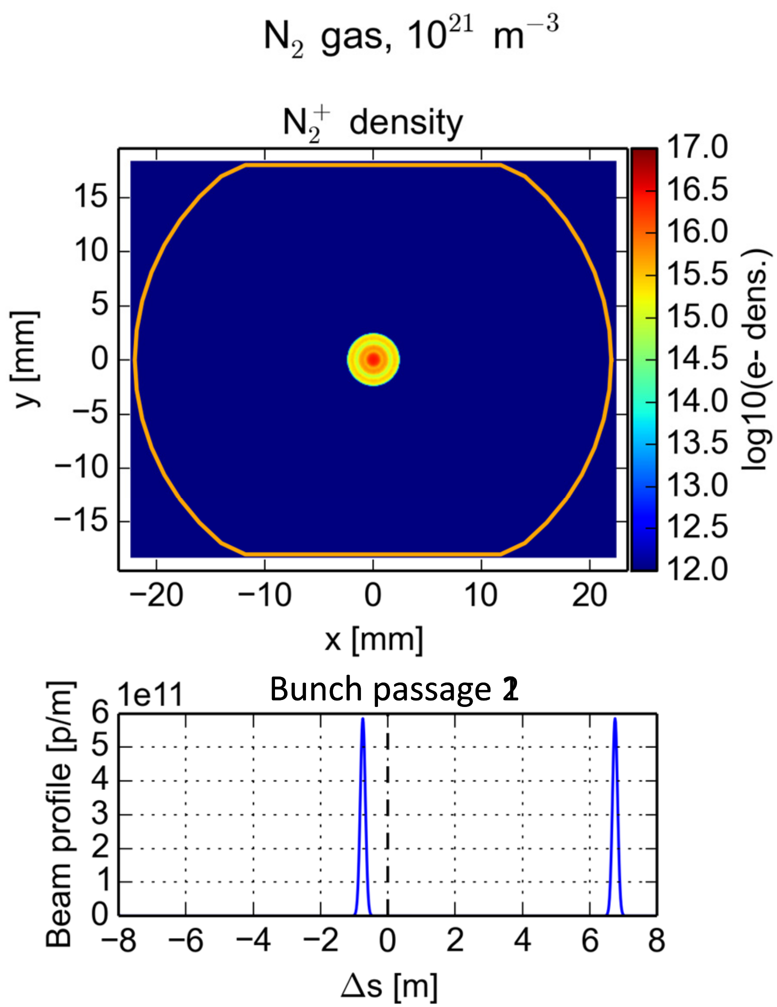

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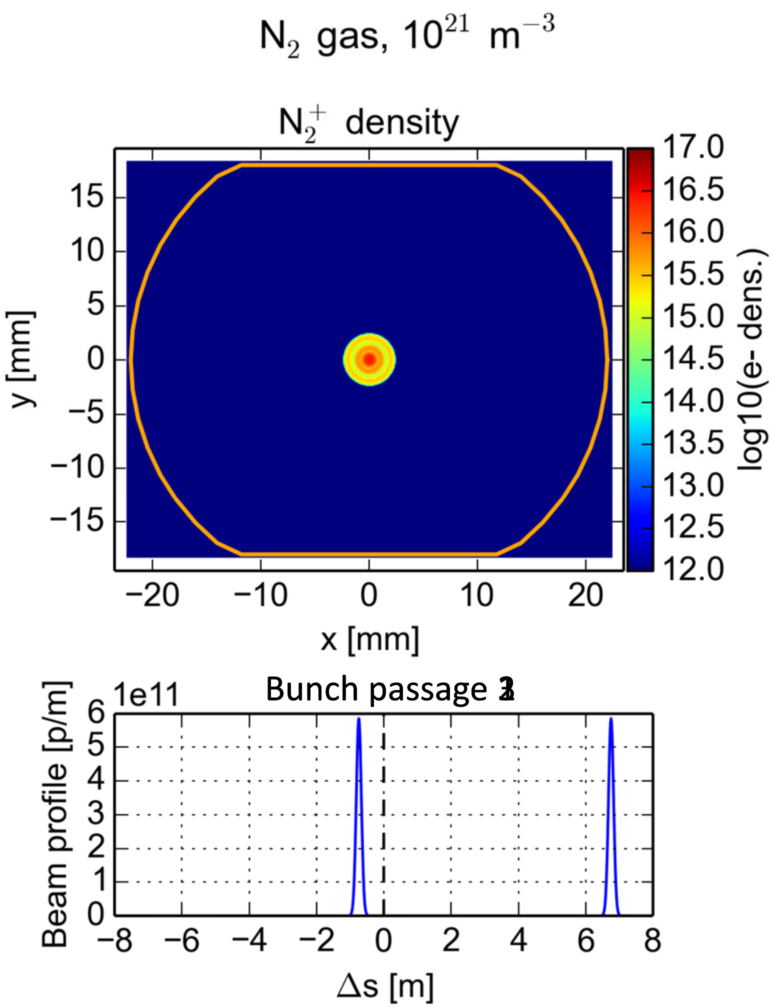

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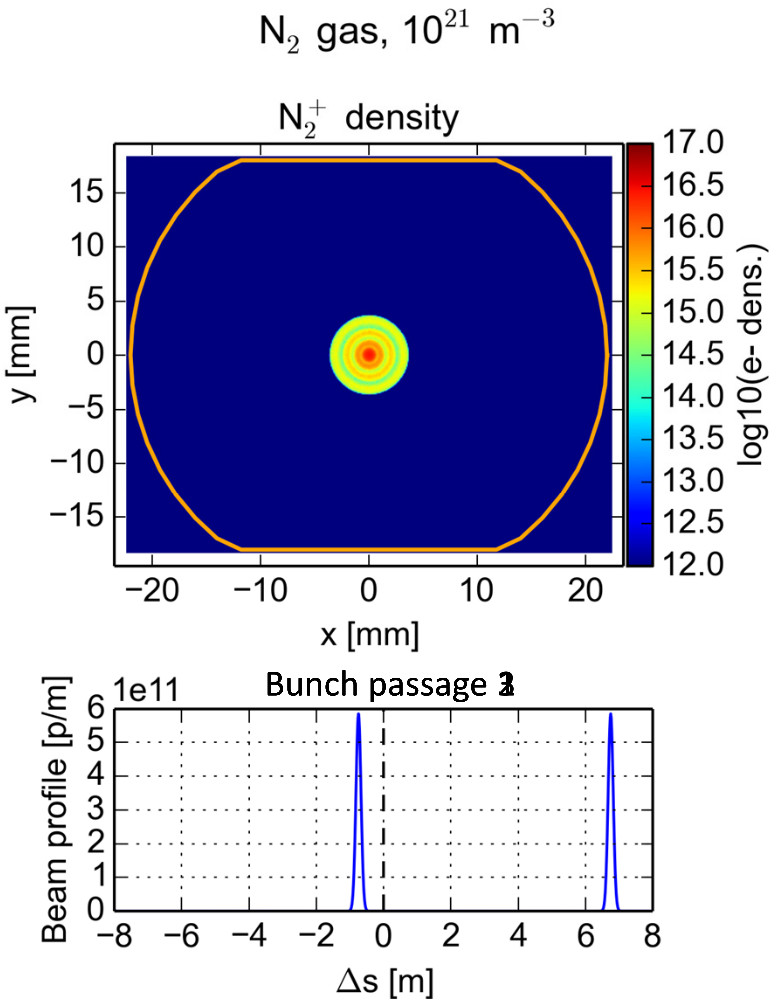

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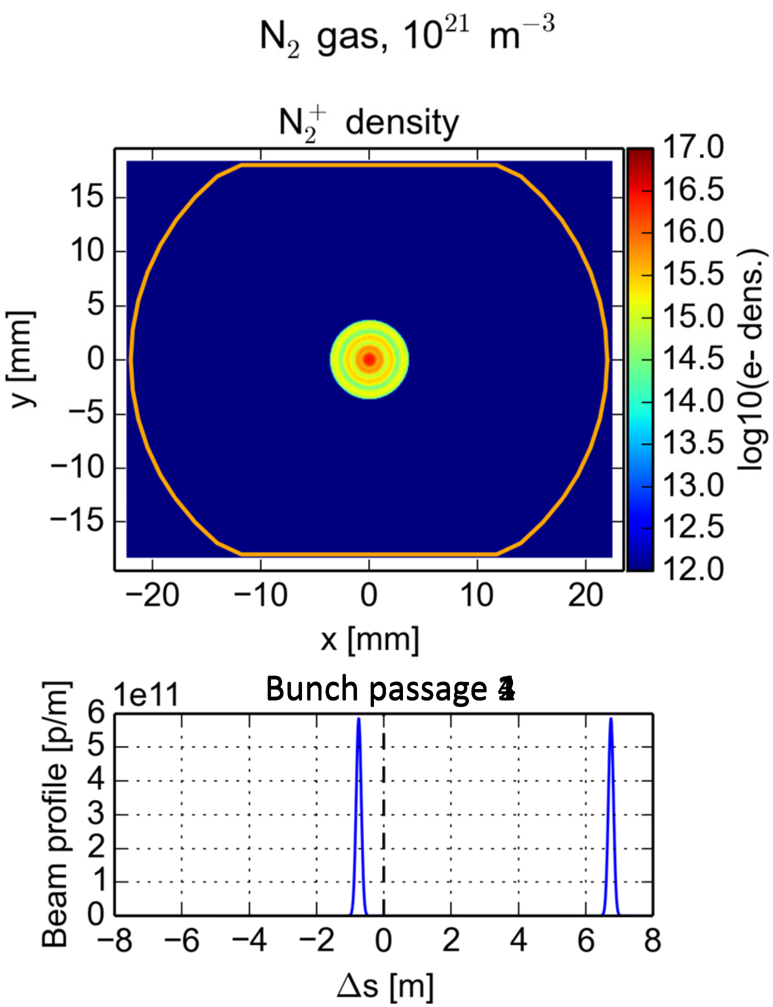

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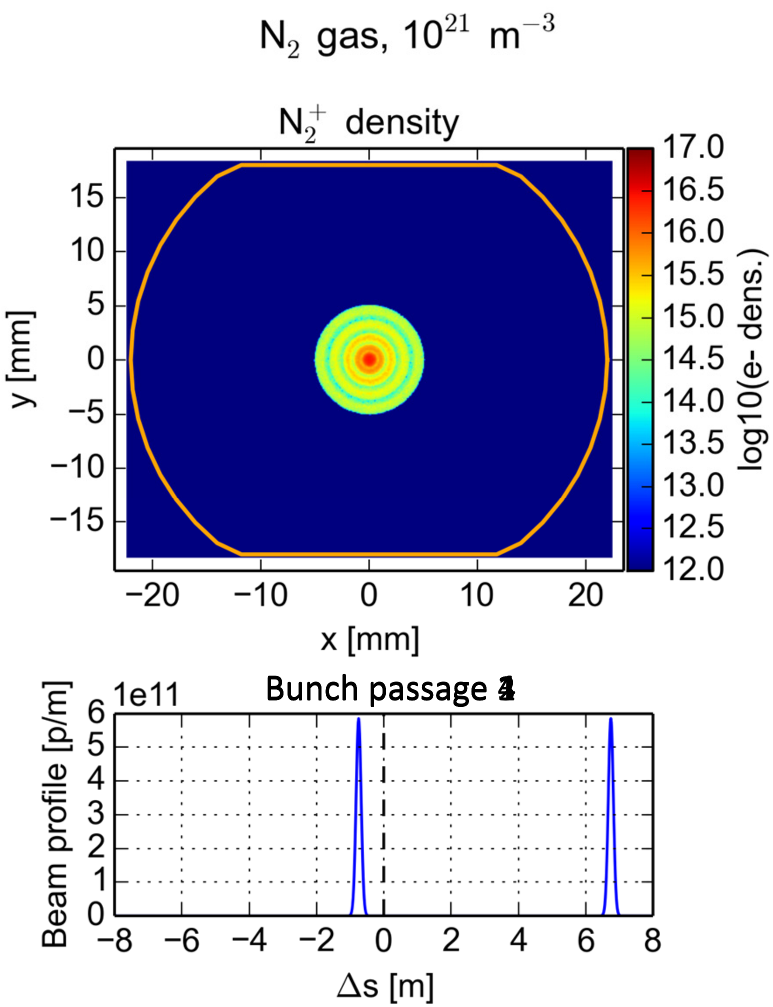

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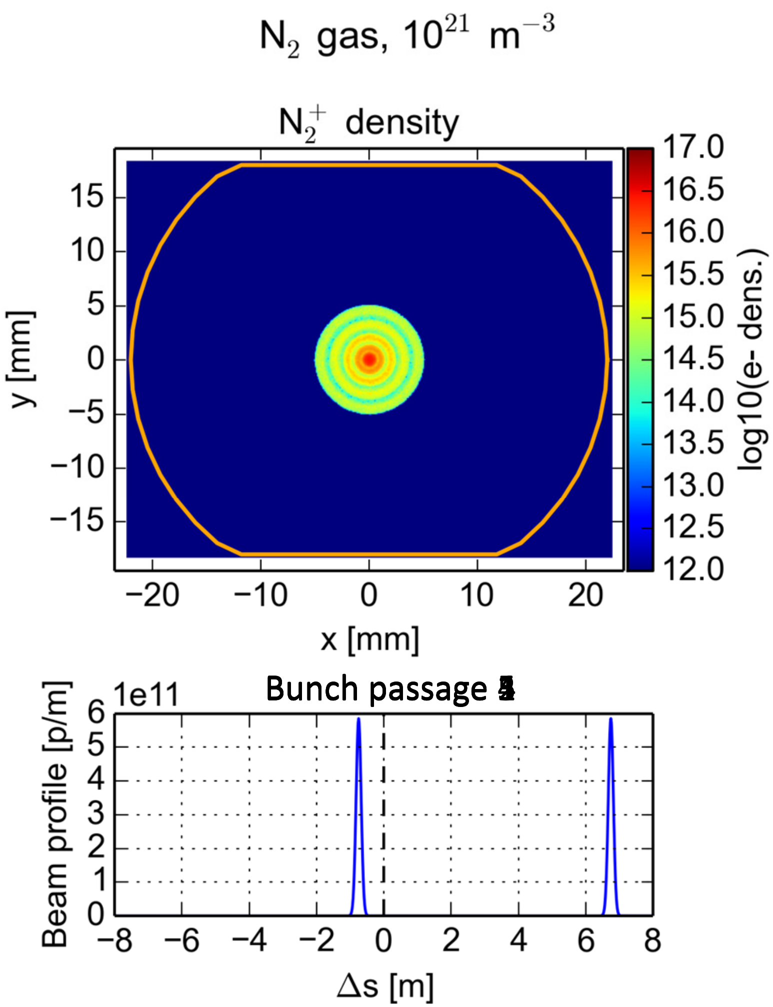

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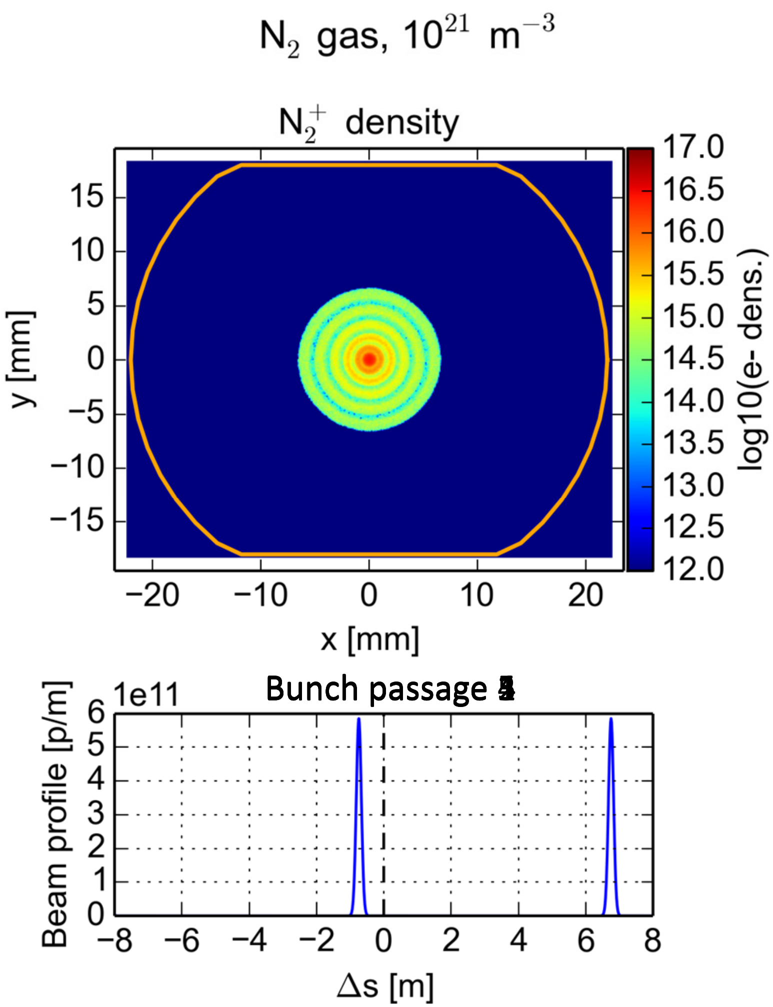

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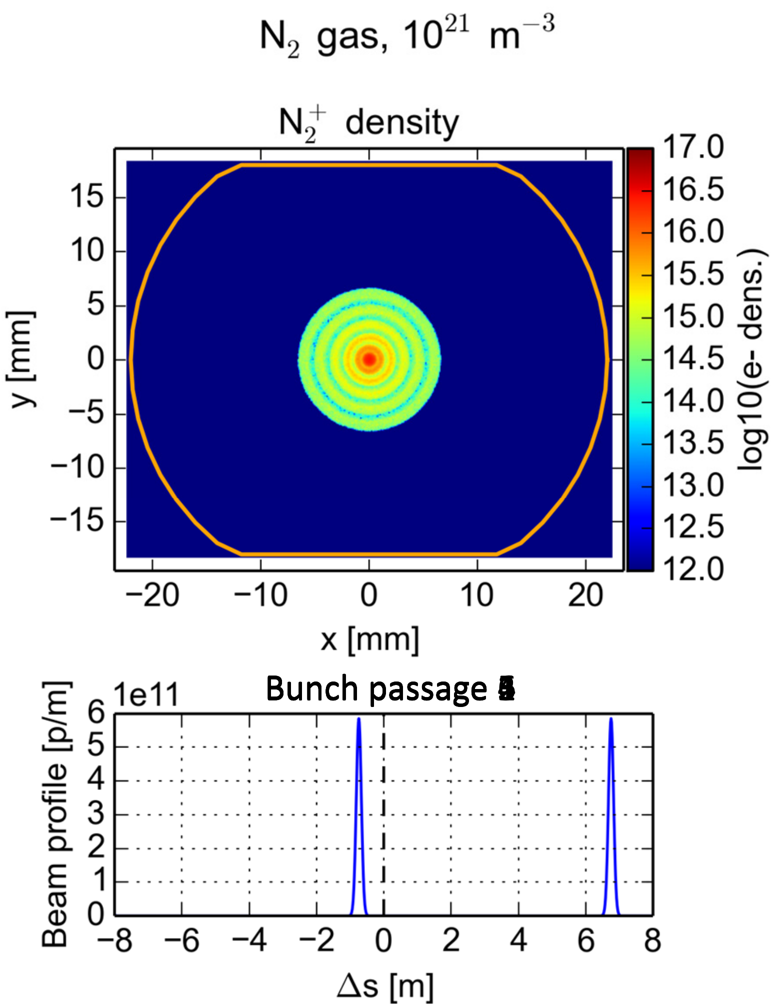

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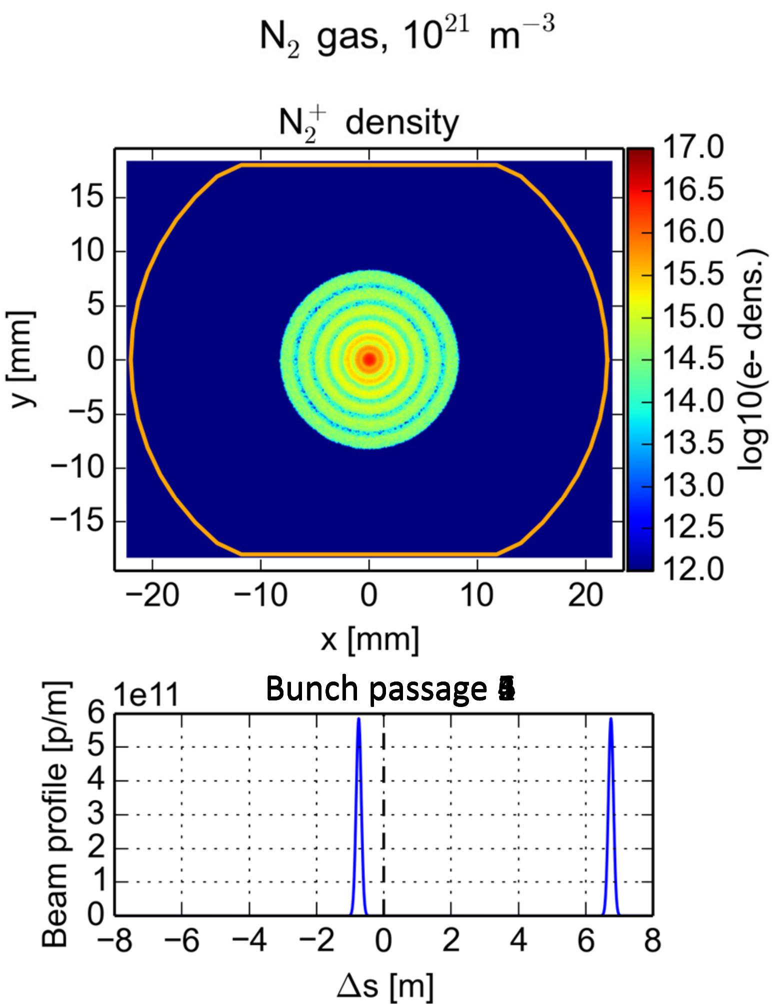

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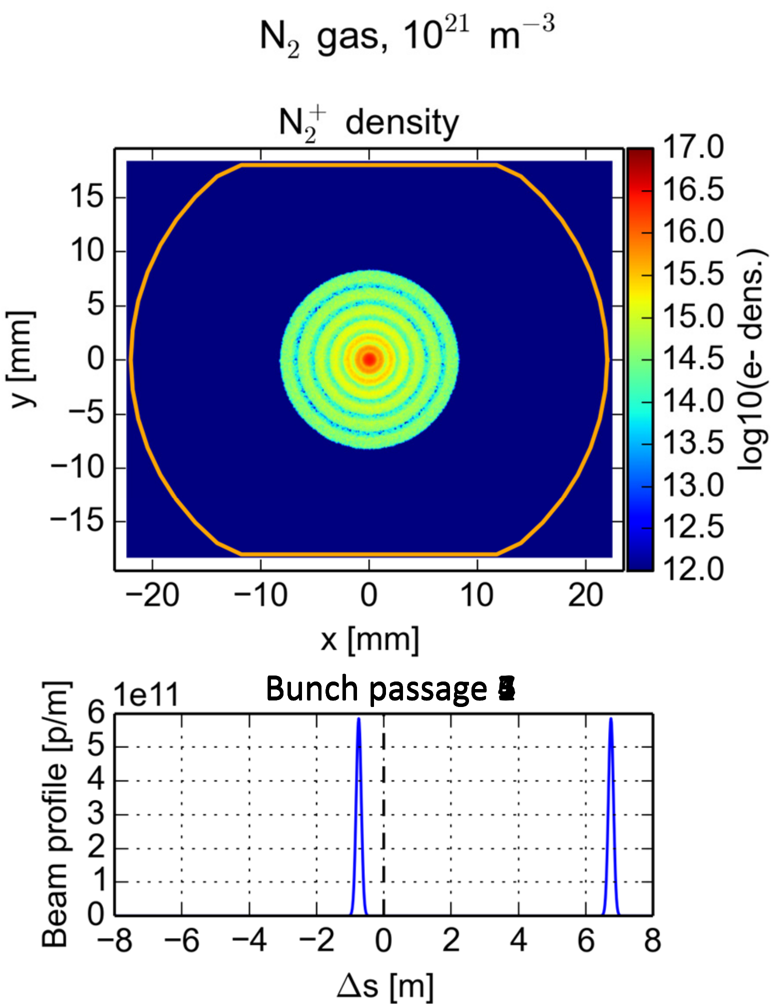

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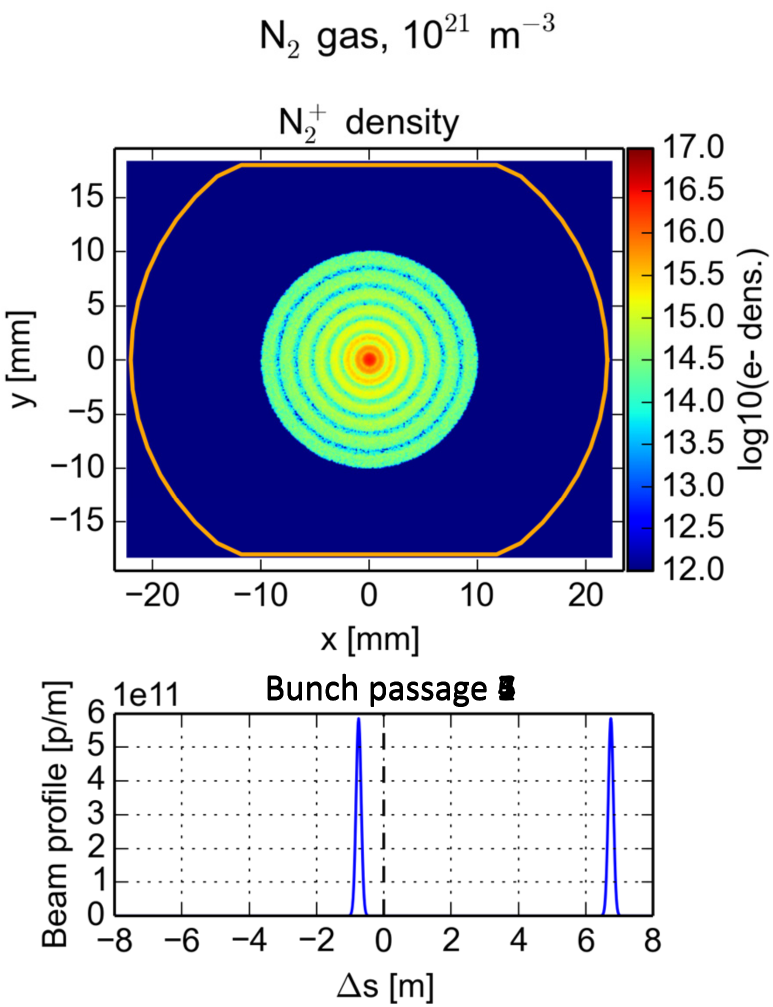

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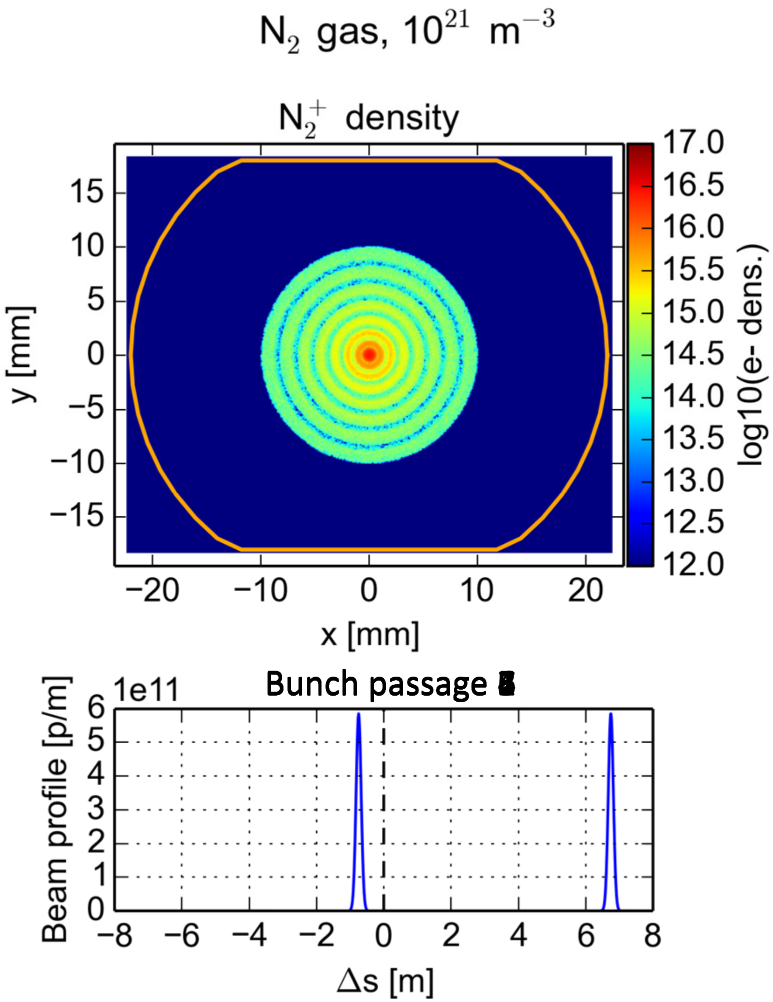

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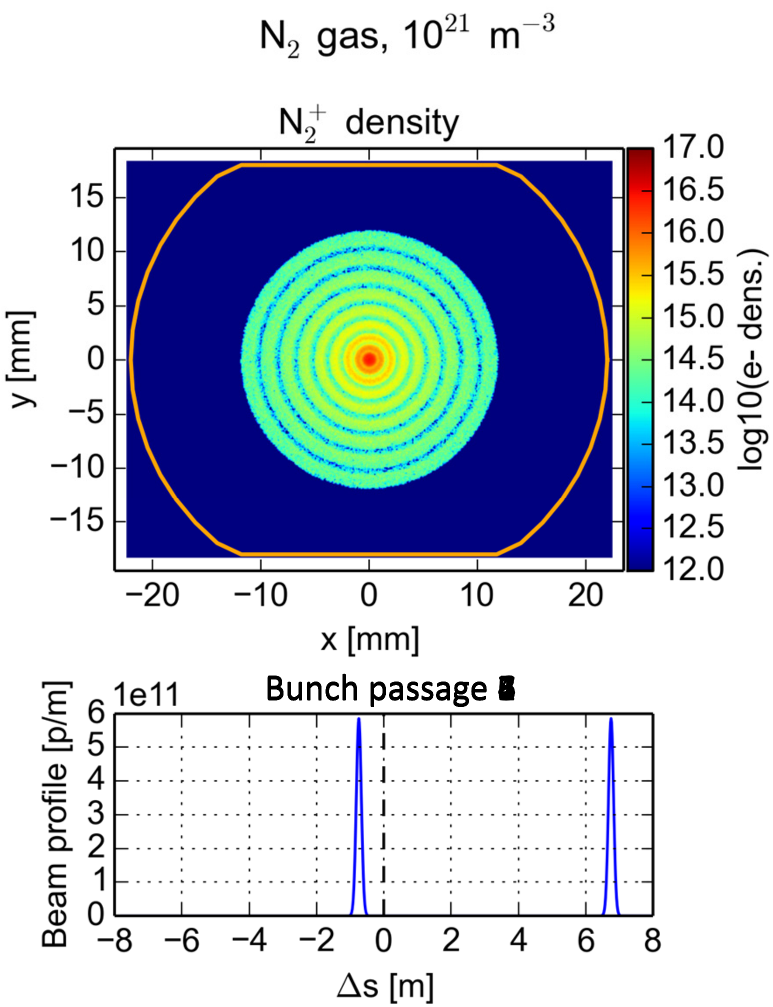

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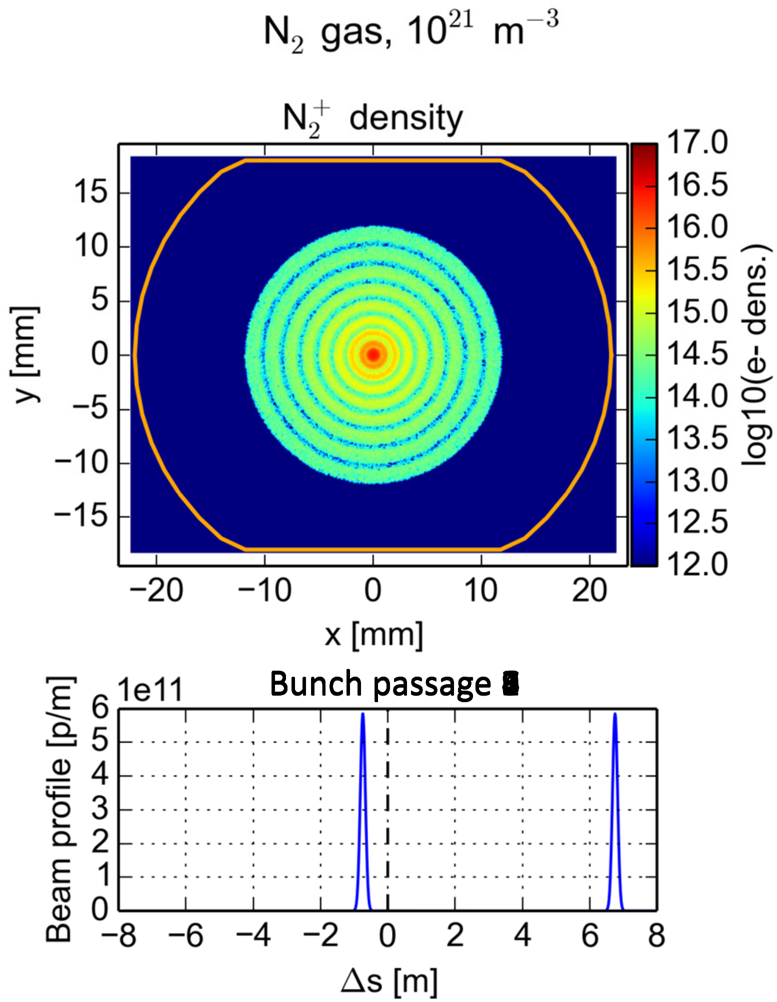

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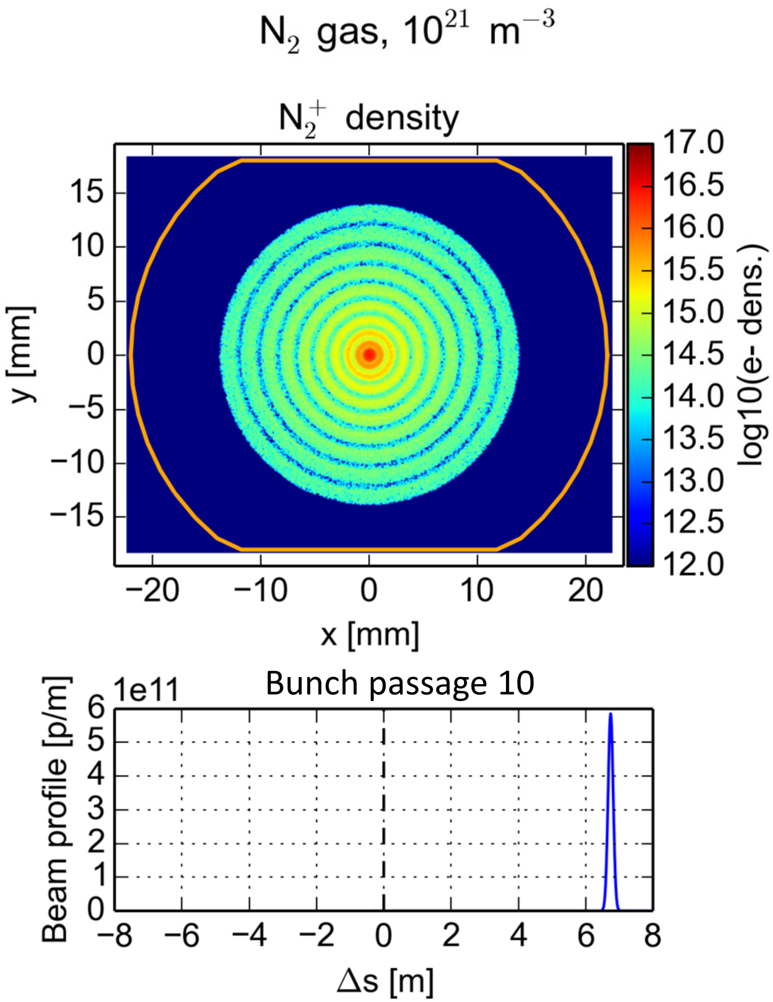
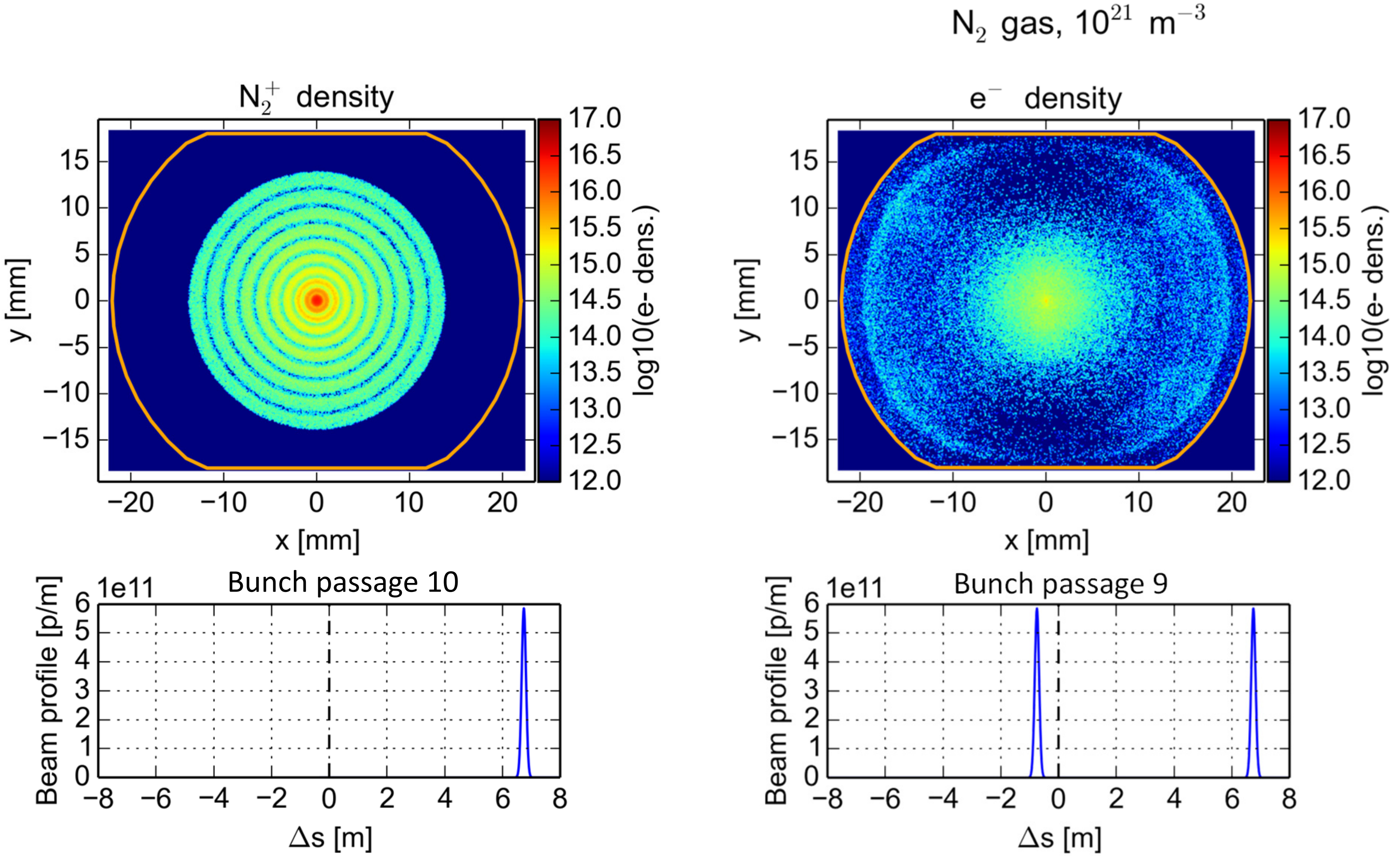


Ion and electron motion

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

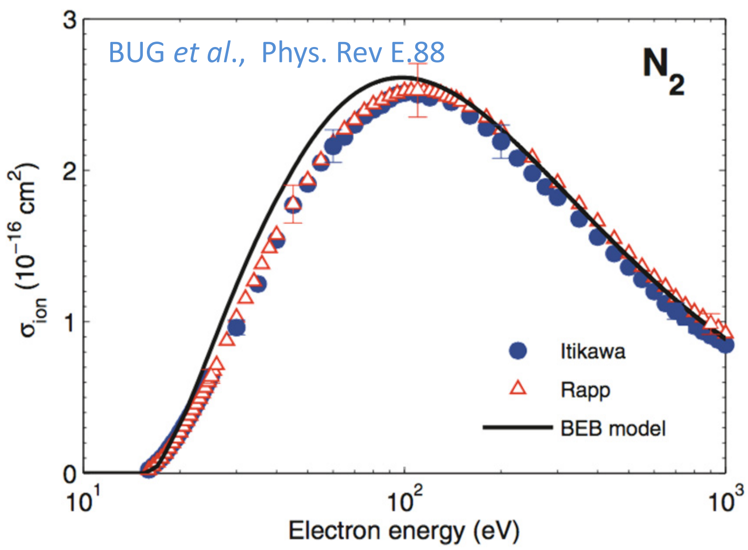


FIG. 1. (Color online) Electron-impact-ionization cross sections σ_{ion} of nitrogen recommended by Itikawa [16], measured by Rapp and Englander-Golden [17], and determined using the BEB model [18].

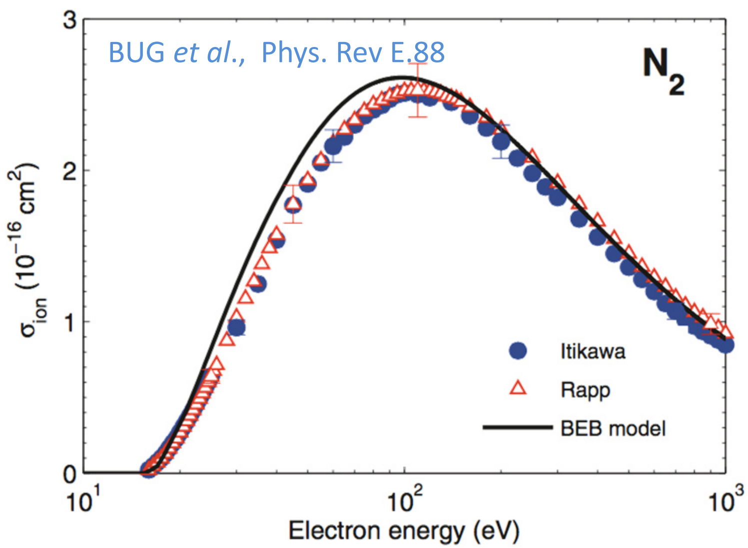
Electron-induced ionization

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



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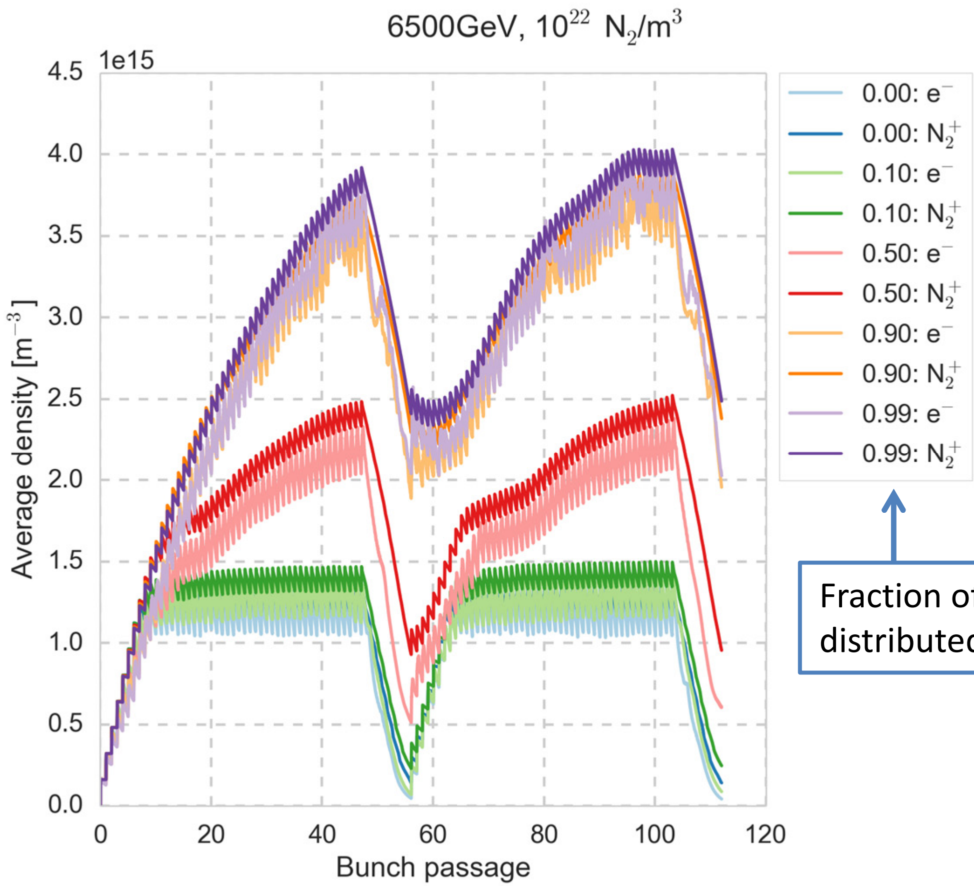
Distributed ionization

The dynamics of the build-up seem to be somewhat sensitive to whether ionization occurs only in the beam or distributed around the chamber

- 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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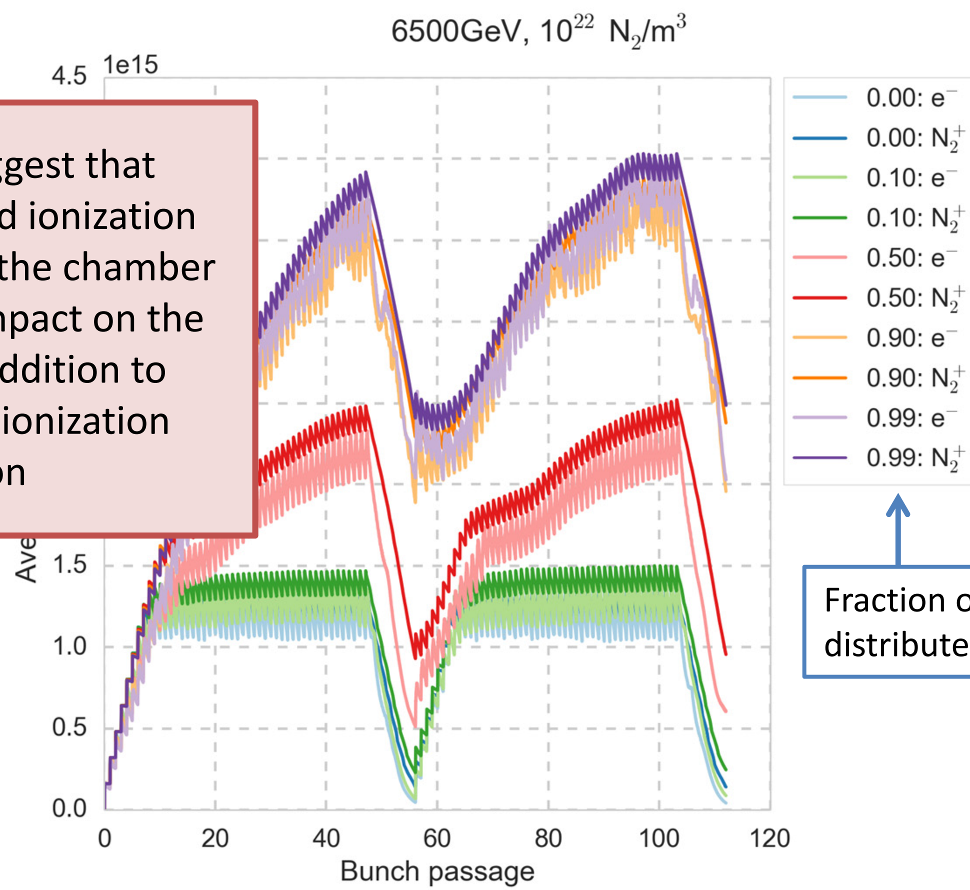

The results suggest that electron-induced ionization occurring across the chamber could have an impact on the dynamics, in addition to increasing the ionization fraction

Fraction of uniformly distributed ionization

Summary & Outlook

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FÉDÉRALE DE LAUSANNE

The multi-species development work was motivated by recent events in the LHC, with a suspected localized transient pressure bump of very high density

- First simulation studies show a significant effect on the dynamics of the build-up when ions and electrons are considered together
- The effect of the two species on beam stability is under study

The needs to expand the tool with additional processes are under consideration

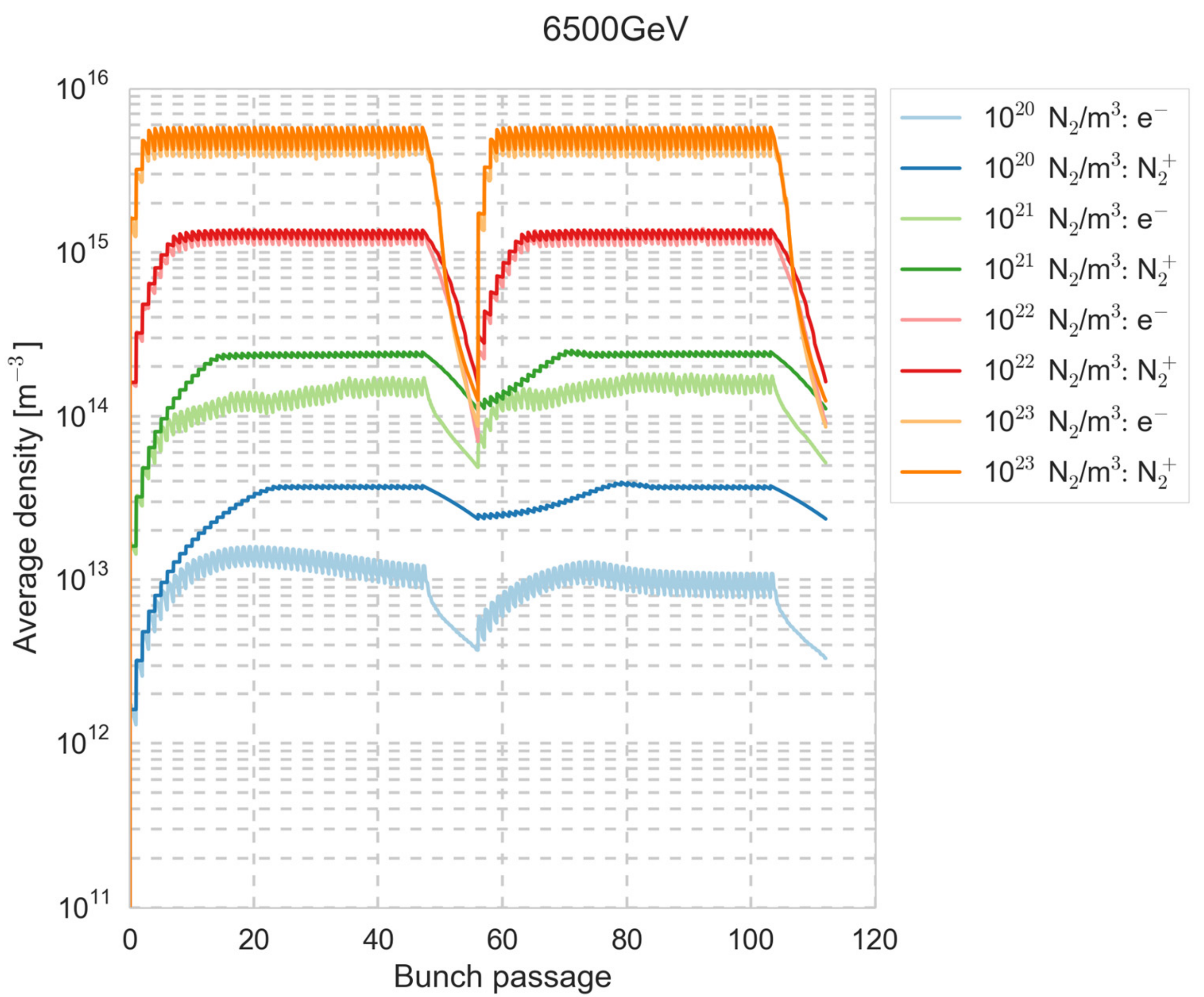
- Impact ionization? Electron velocities are being evaluated to give an answer
- Anything else?

In addition to this very specific use case, the new code capabilities can be useful also for other purposes, e.g.

- To study the role and effect of ions during a standard e-cloud build-up process
- Dividing electrons into several clouds can in some cases help to overcome a re-occurring problem of poor macro-particle resolution outside of the main multipacting regions
- Fast beam-ion instability studies with realistic vacuum compositions

Pressure bump with multi-species

Multi-species build-up for different gas densities

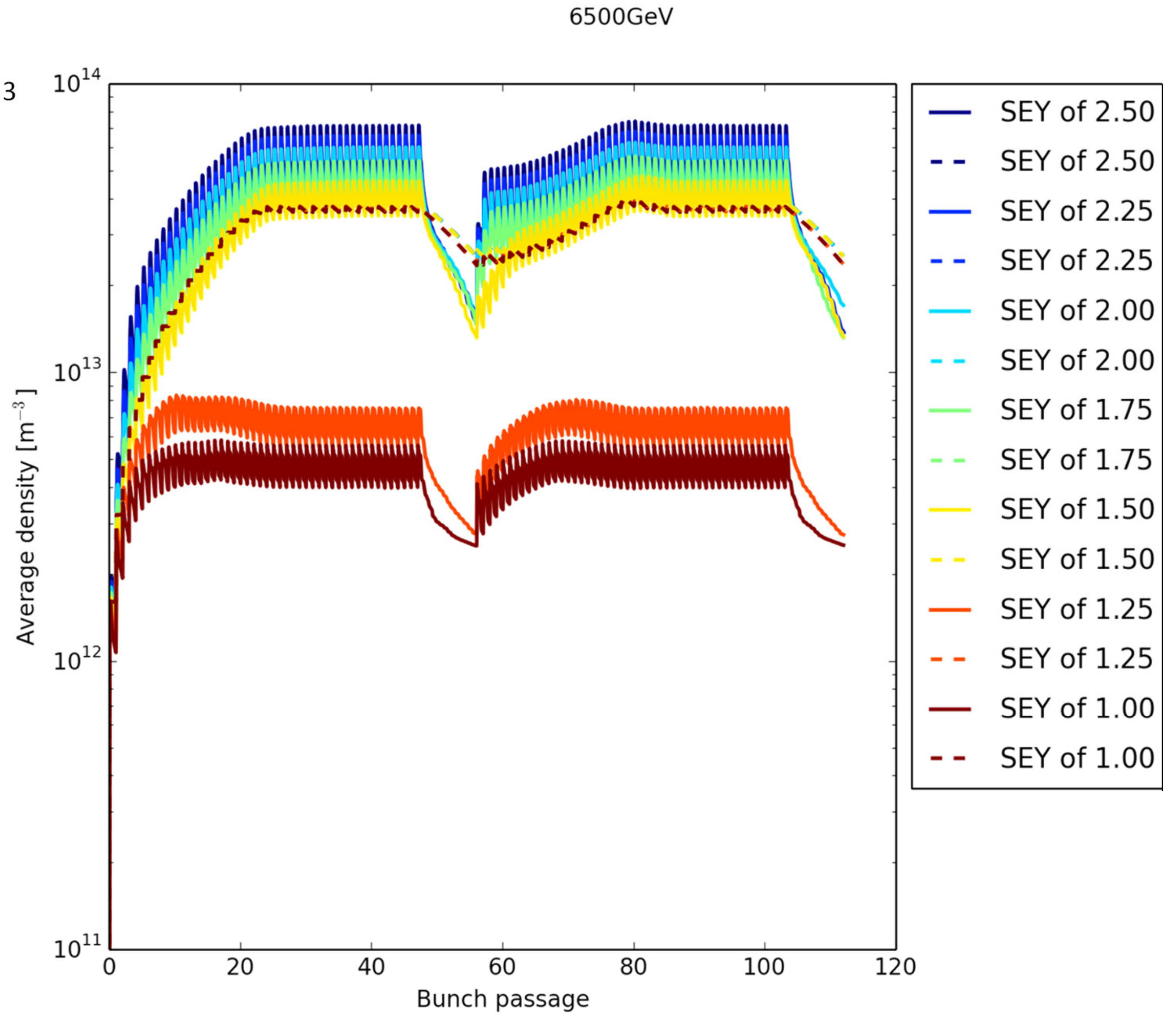


Pressure bump with different SEY

N_2 gas density: 10^{19} /m^3

Dashed lines: ions

Solid lines: e$^-$



Multispecies example

Electron line density / bin in horizontal coordinate