



Science and
Technology
Facilities Council



NIBS'26

The Dense Core of Compensating Hminus Beams

22nd September 2026

Dan Faircloth¹

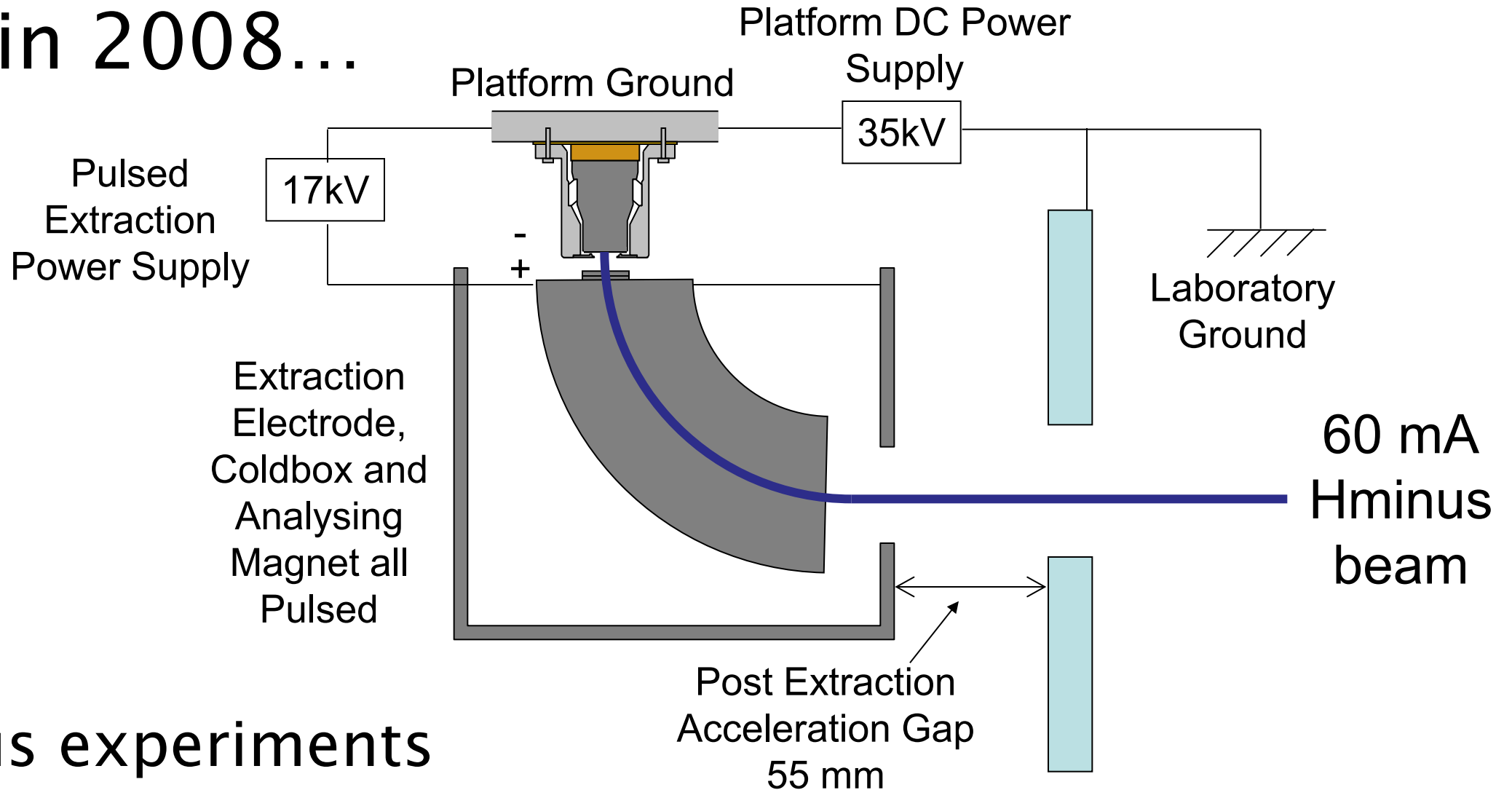
Olli Tarvainen¹, Erin Flannigan¹, Kiran Jonathan², Benzi John²
(ISIS¹ and STFC Scientific Computing Department²)

Back in 2008...

The 1st International Symposium on Negative Ions, Beams and Sources
9–12 September 2008
Aix-en-Provence (France)



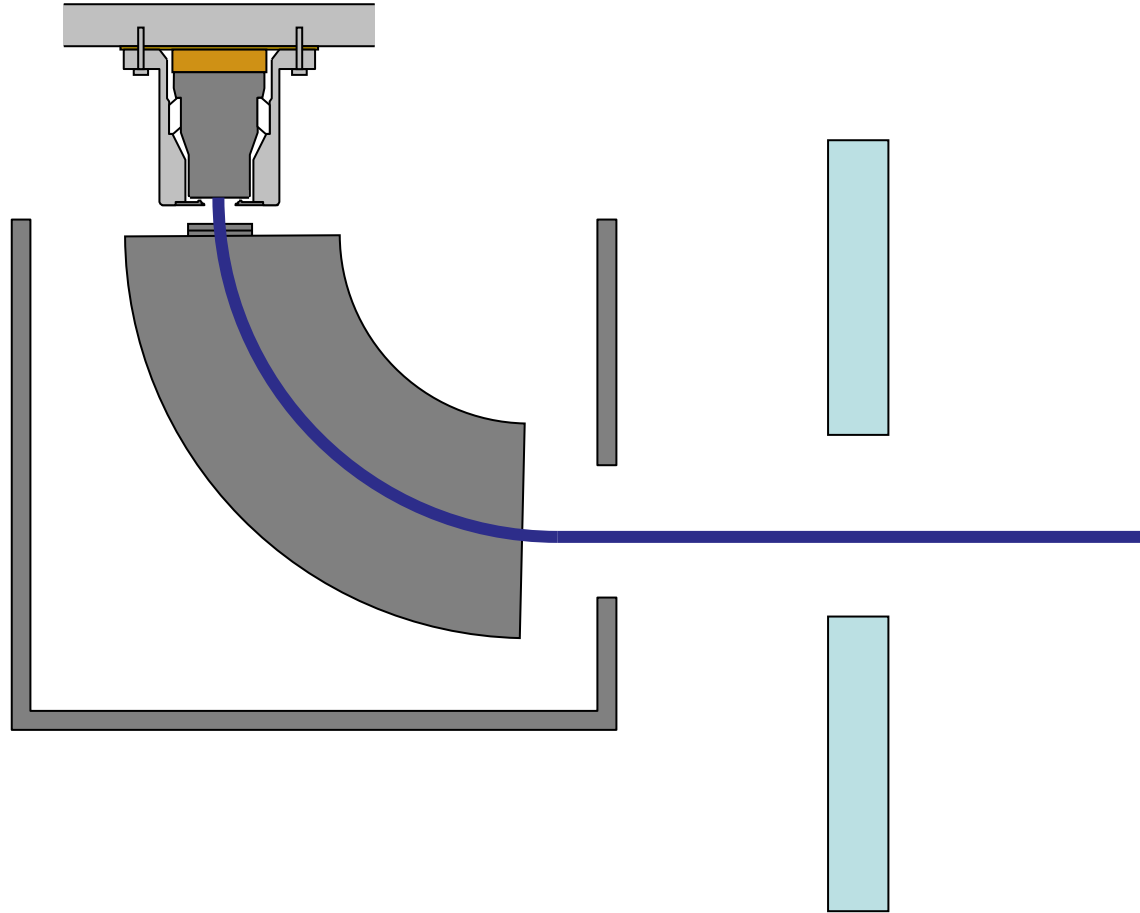
Back in 2008...



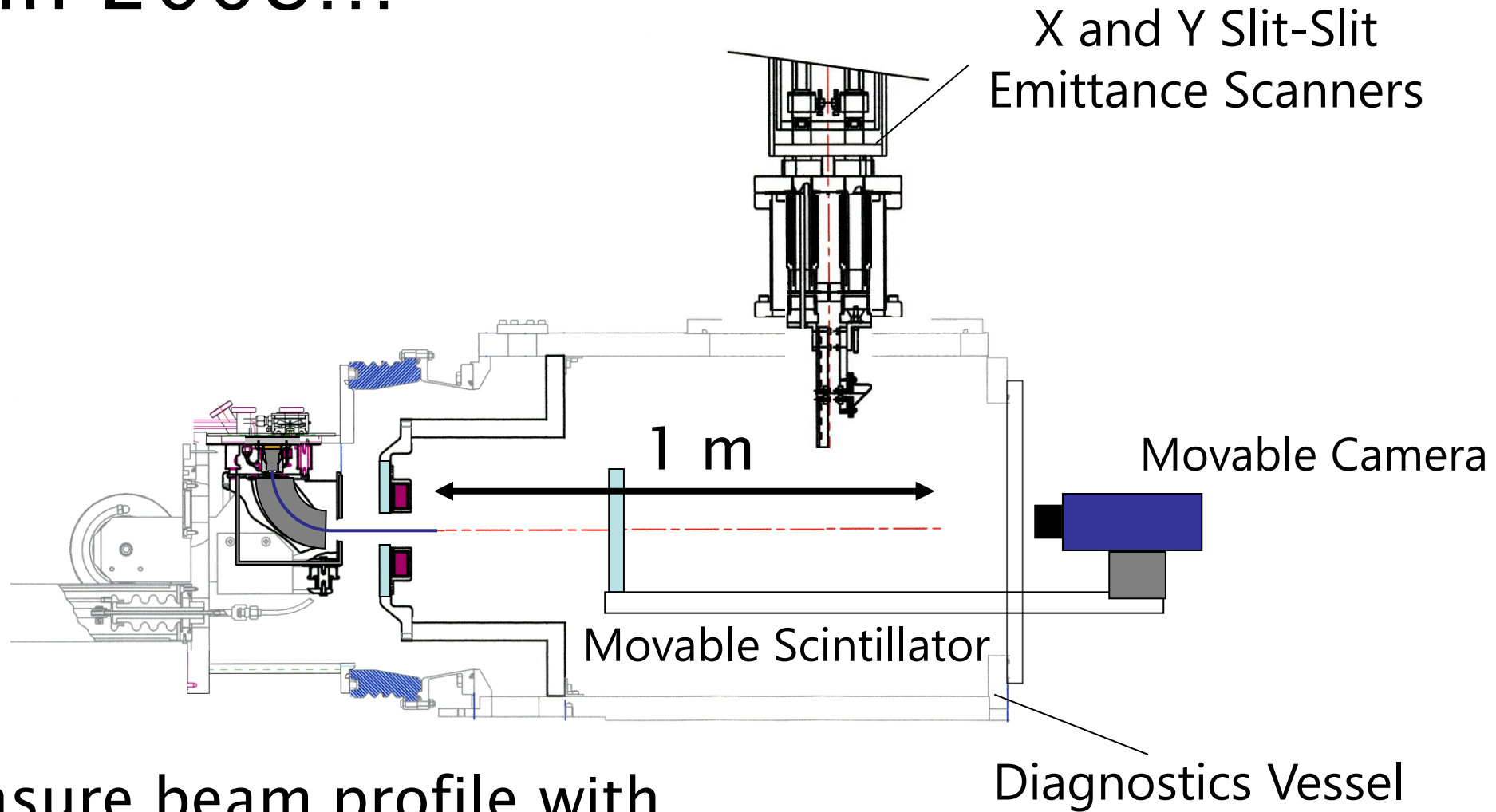
Hminus experiments with the ISIS Penning Surface Plasma Source



Back in 2008...



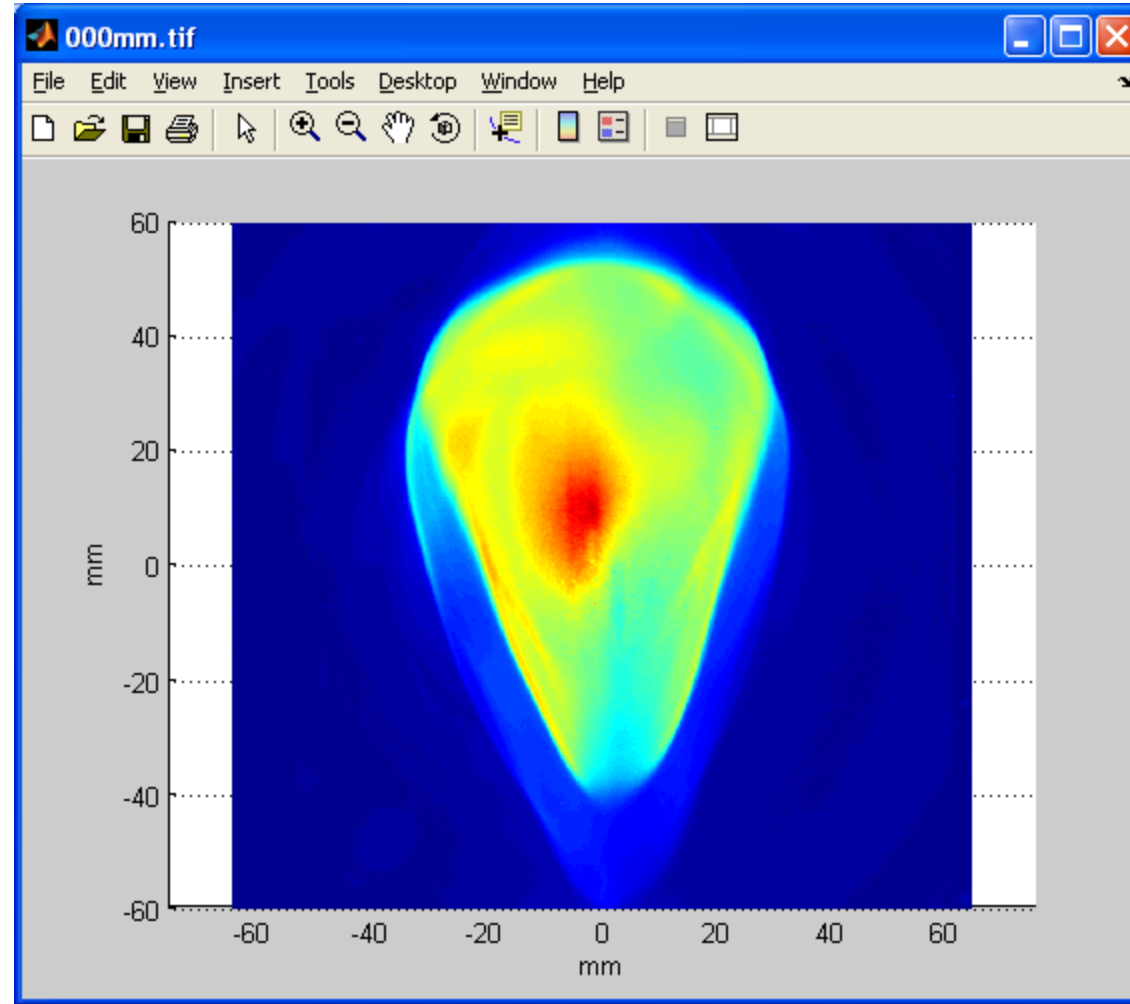
Back in 2008...



Measure beam profile with
scintillator at different z positions

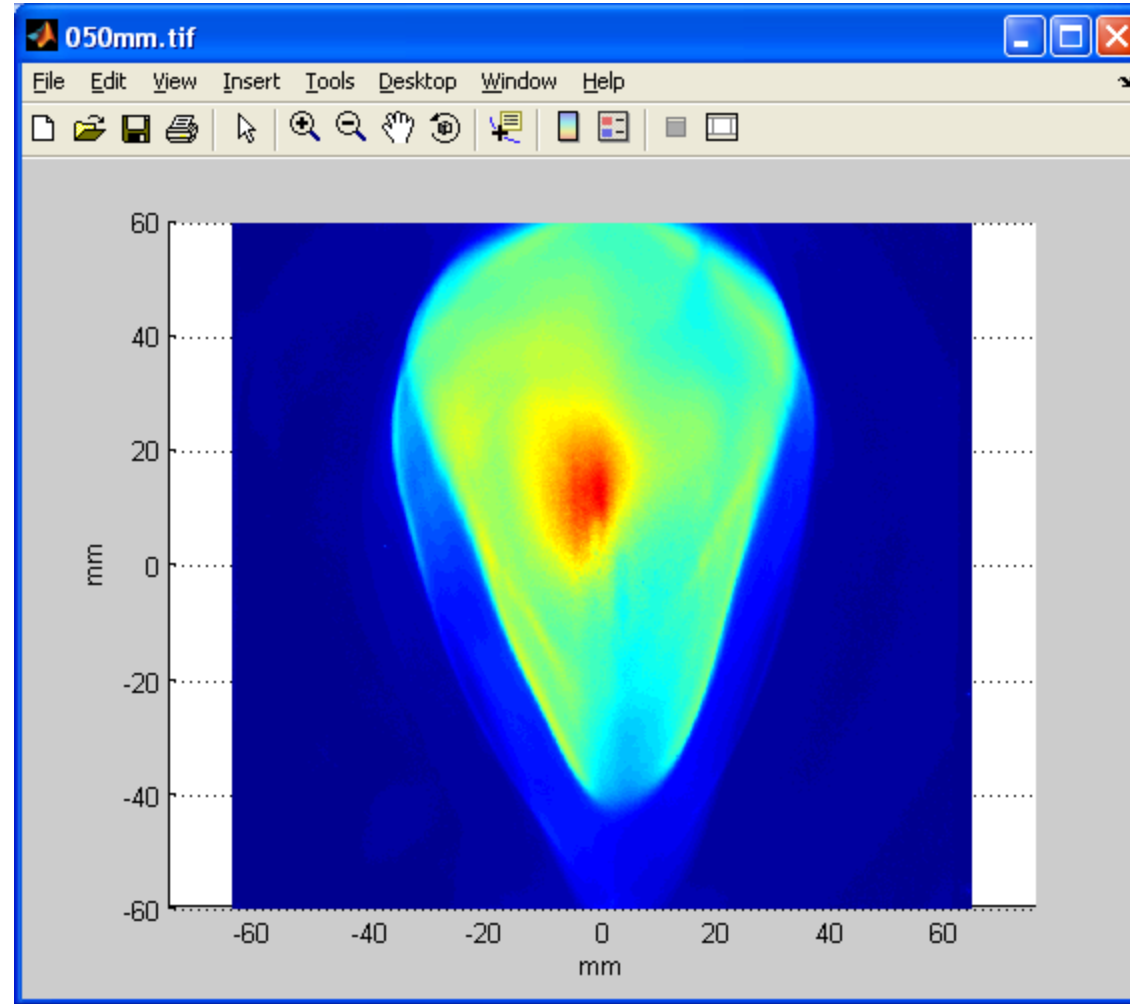
Back in 2008...

Hminus
density
profile
measured at
 $z + 0$ mm



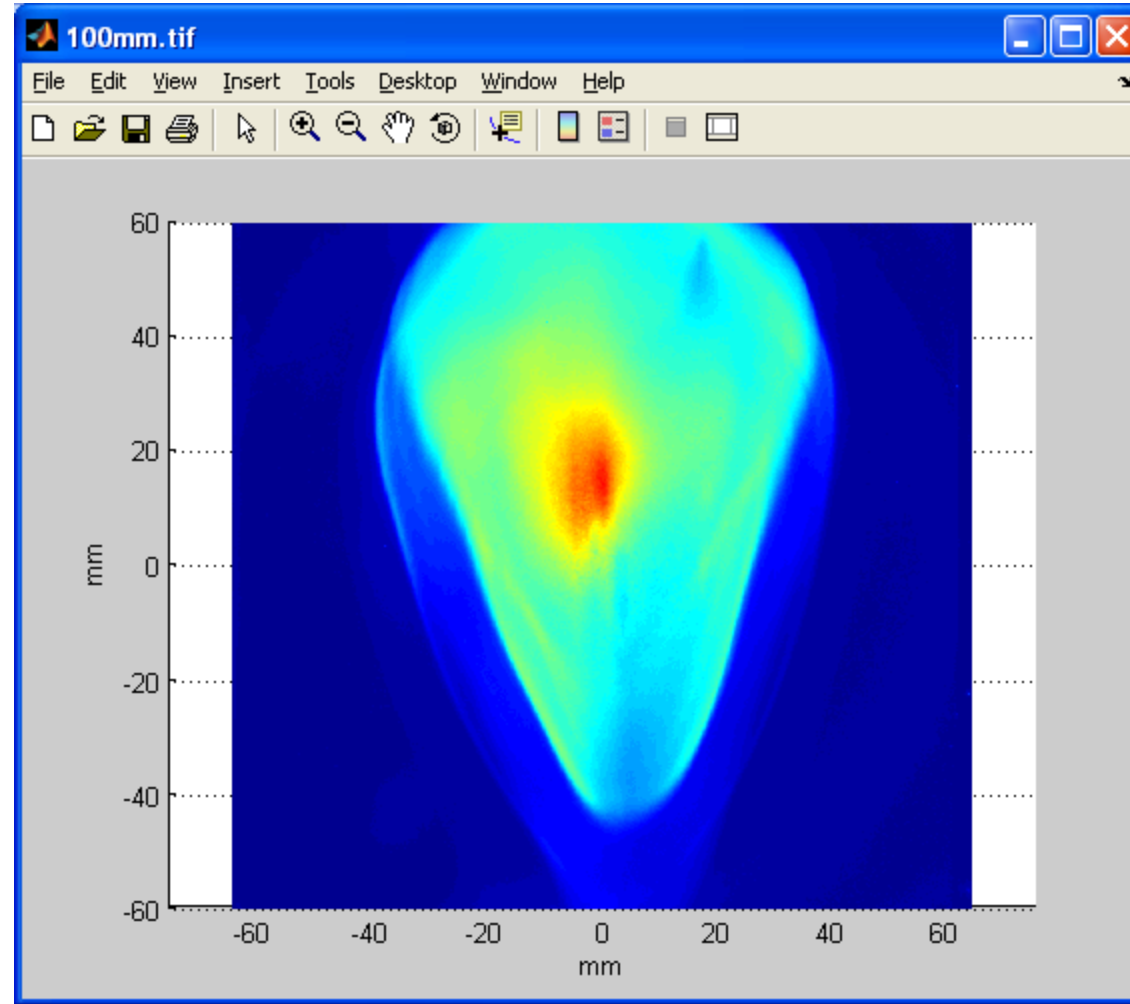
Back in 2008...

Hminus
density
profile
measured at
 $z + 50$ mm



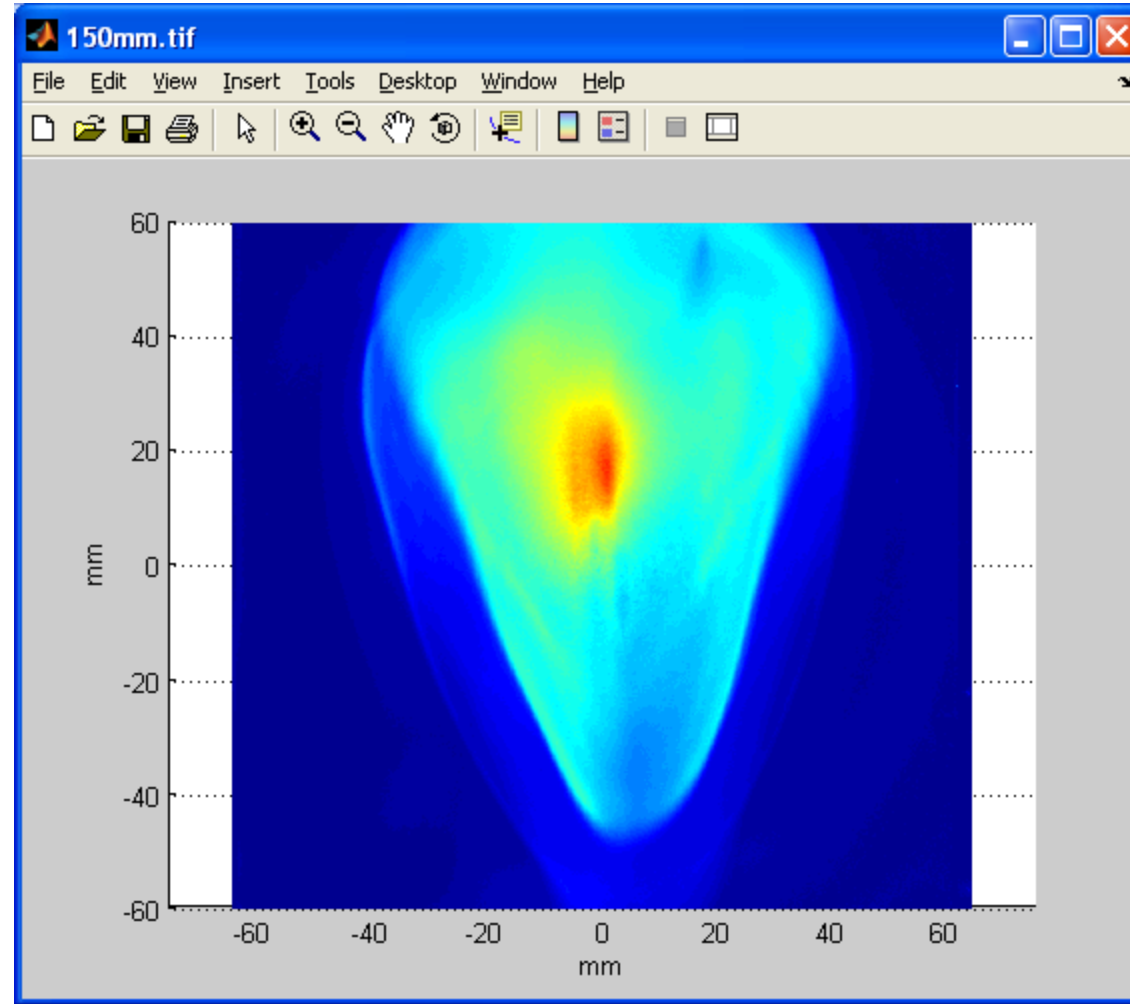
Back in 2008...

Hminus
density
profile
measured at
 $z + 100$ mm



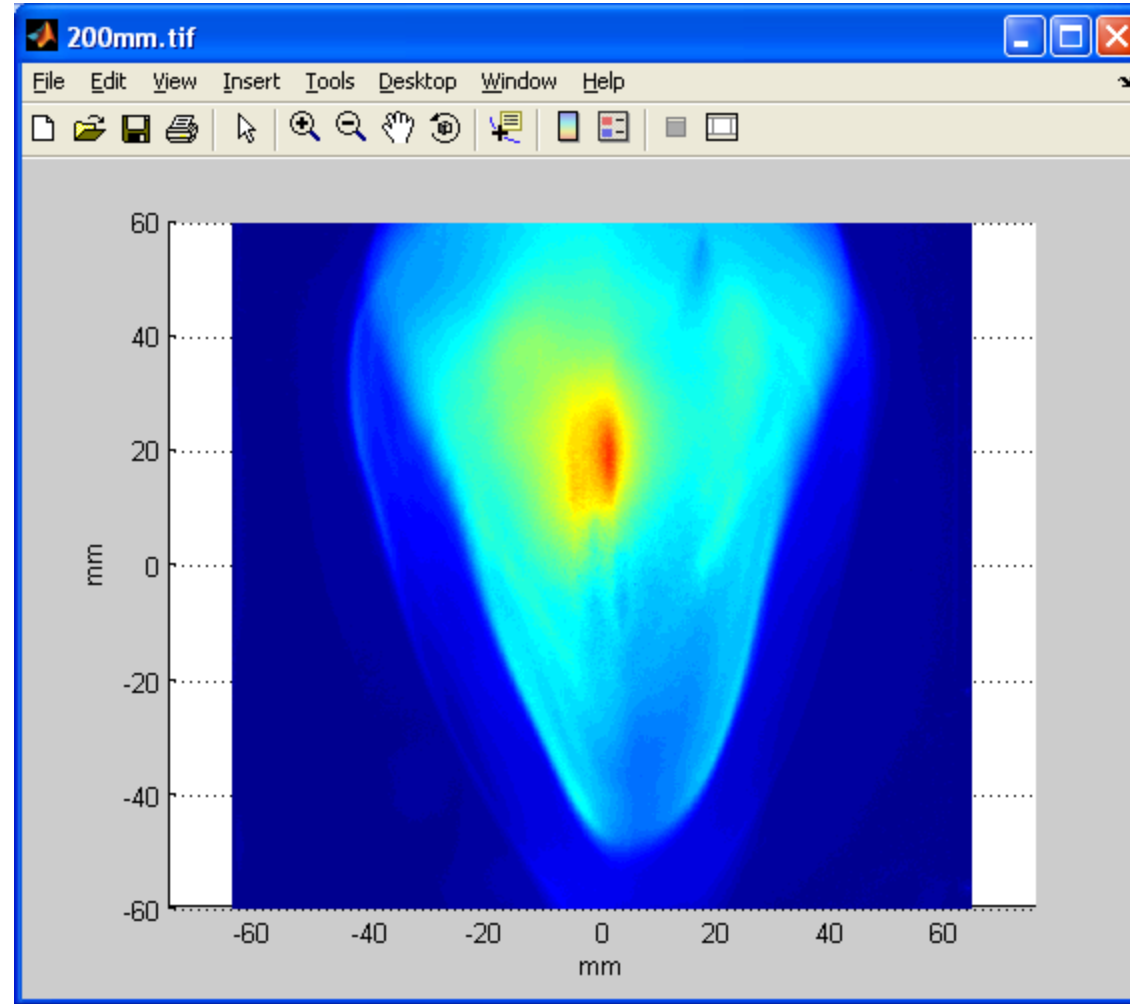
Back in 2008...

Hminus
density
profile
measured at
 $z + 150 \text{ mm}$



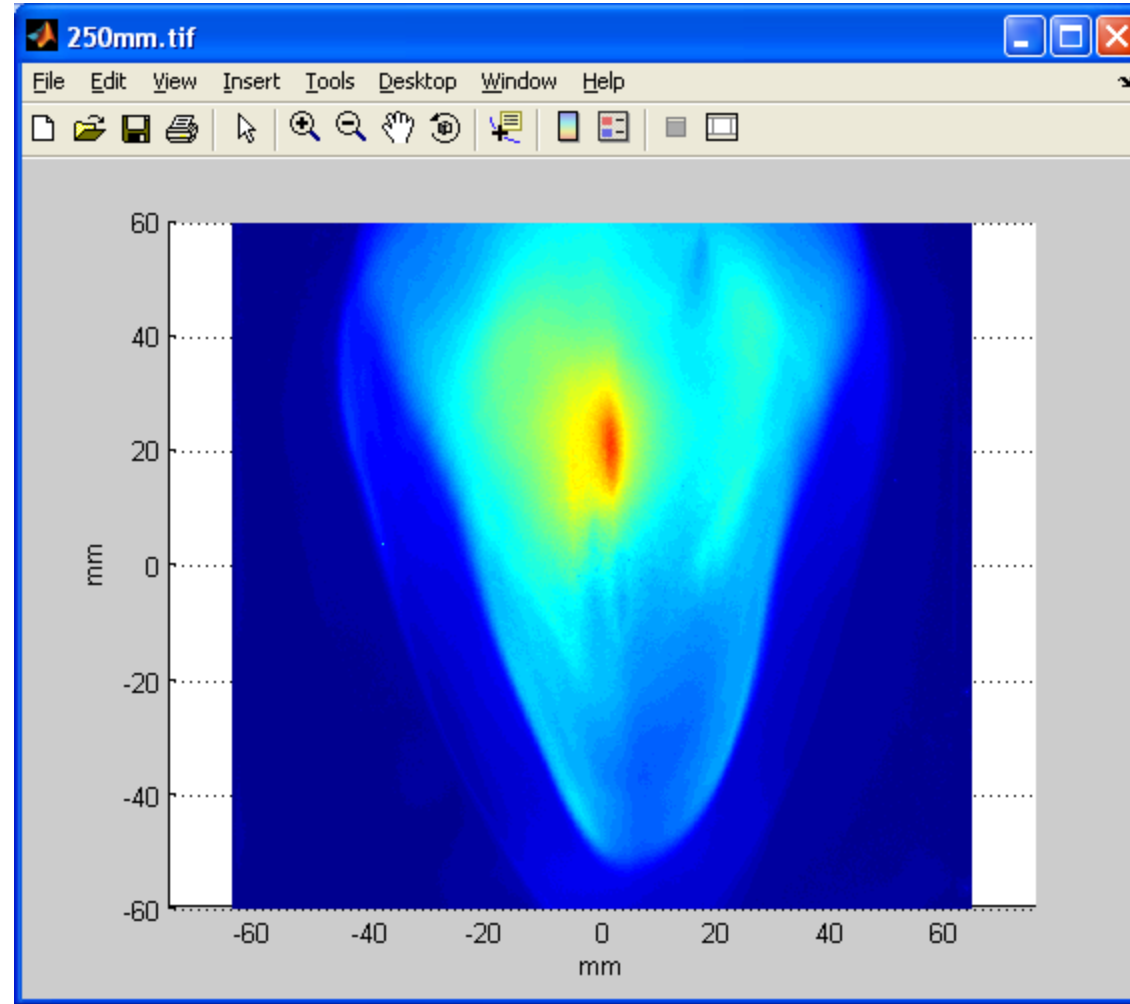
Back in 2008...

Hminus
density
profile
measured at
 $z + 200$ mm



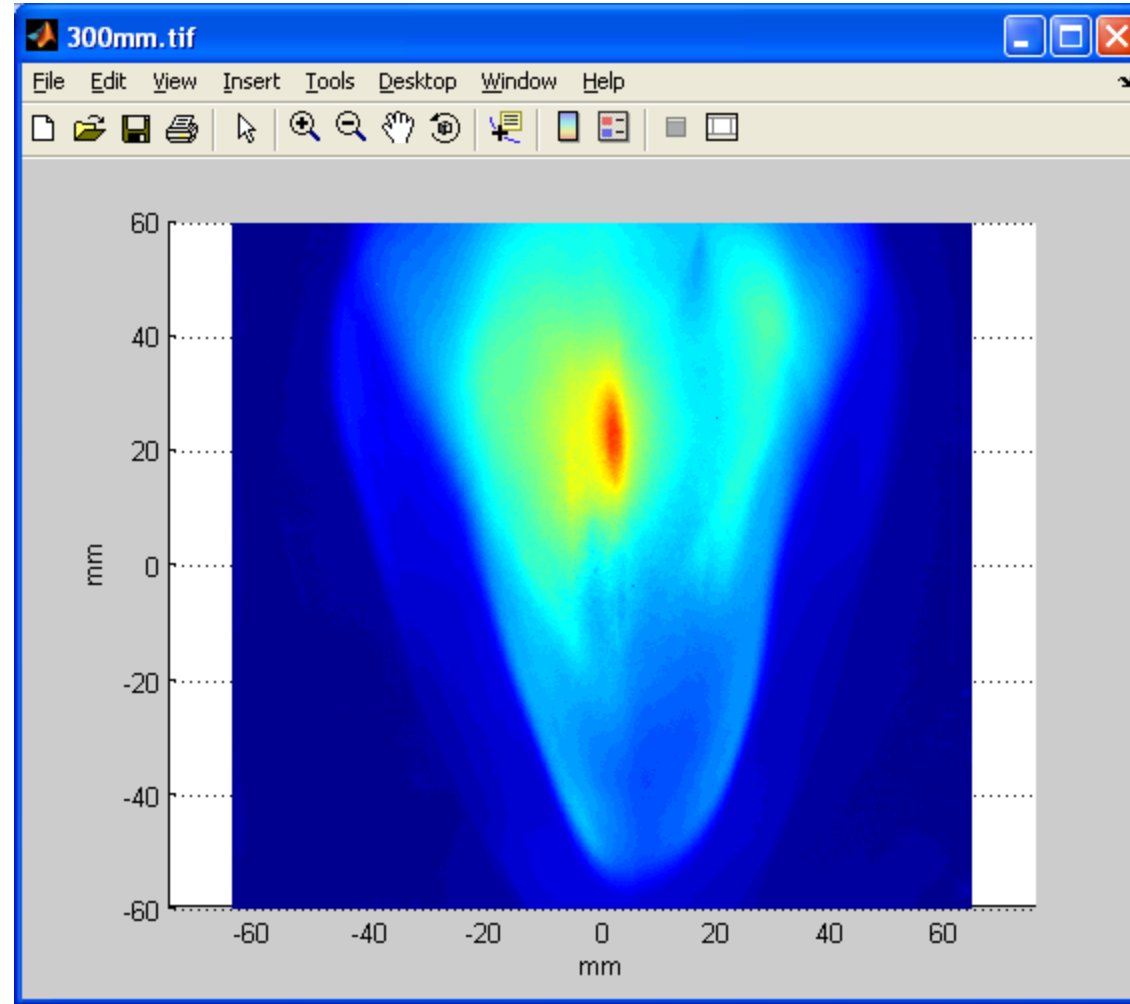
Back in 2008...

Hminus
density
profile
measured at
 $z + 250$ mm



Back in 2008...

Hminus
density
profile
measured at
 $z + 300$ mm



experiments
revealed a
dense core is
present at all
z-positions

But why?

Life moved on...



Science & Technology
Facilities Council

Life moved on...

...then in 2025

Develop Particle-In-Cell (PIC) models of the Low Energy Beam Transport (LEBT) to study space charge compensation using VSim and PICLas

Space Charge Compensation Reactions

H₂ ionisation by H⁻ impact: $\text{H}^- + \text{H}_2 \rightarrow \text{H}^- + \text{H}_2^+ + \text{e}$

Electron detachment in collision with H₂: $\text{H}^- + \text{H}_2 \rightarrow \text{H}(\text{fast}) + \text{H}_2 + \text{e}$

Electron impact detachment of H⁻: $\text{e} + \text{H}^- \rightarrow \text{H} + 2\text{e}$

Electron impact ionisation of H₂: $\text{H}_2 + \text{e} \rightarrow \text{H}_2^+ + 2\text{e}$ or $\text{H}^+ + \text{H} + 2\text{e}$

Model Parameters

128x128x1024 mesh cells

Uniform mesh cell size: 0.8 mm

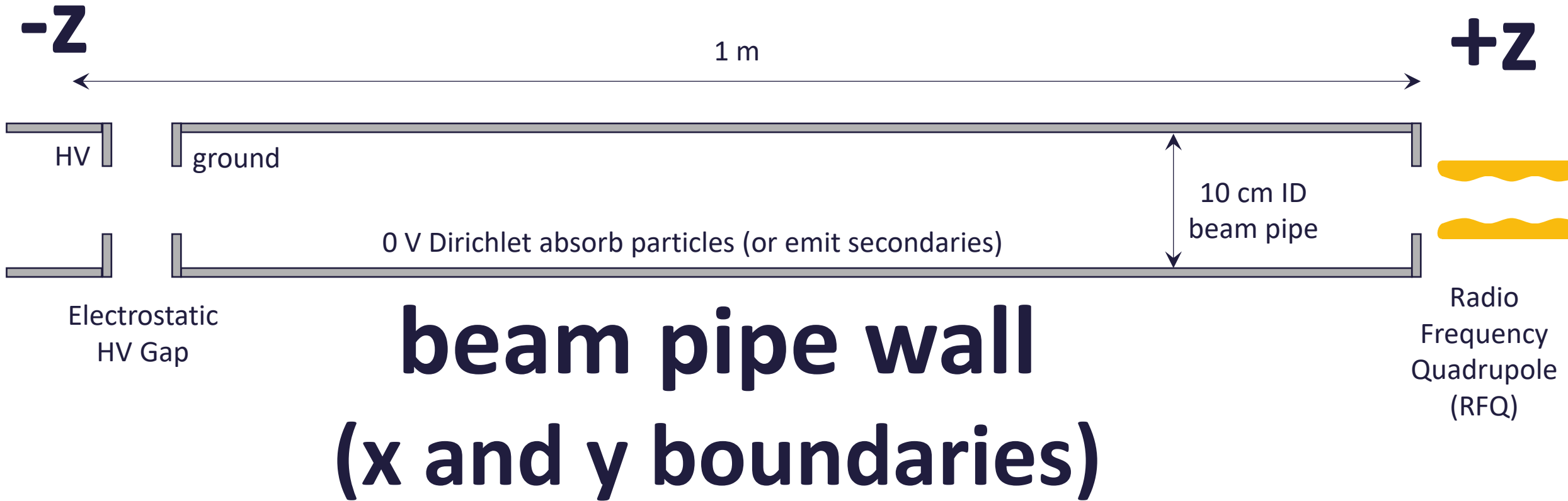
Time step: 1E-10 s

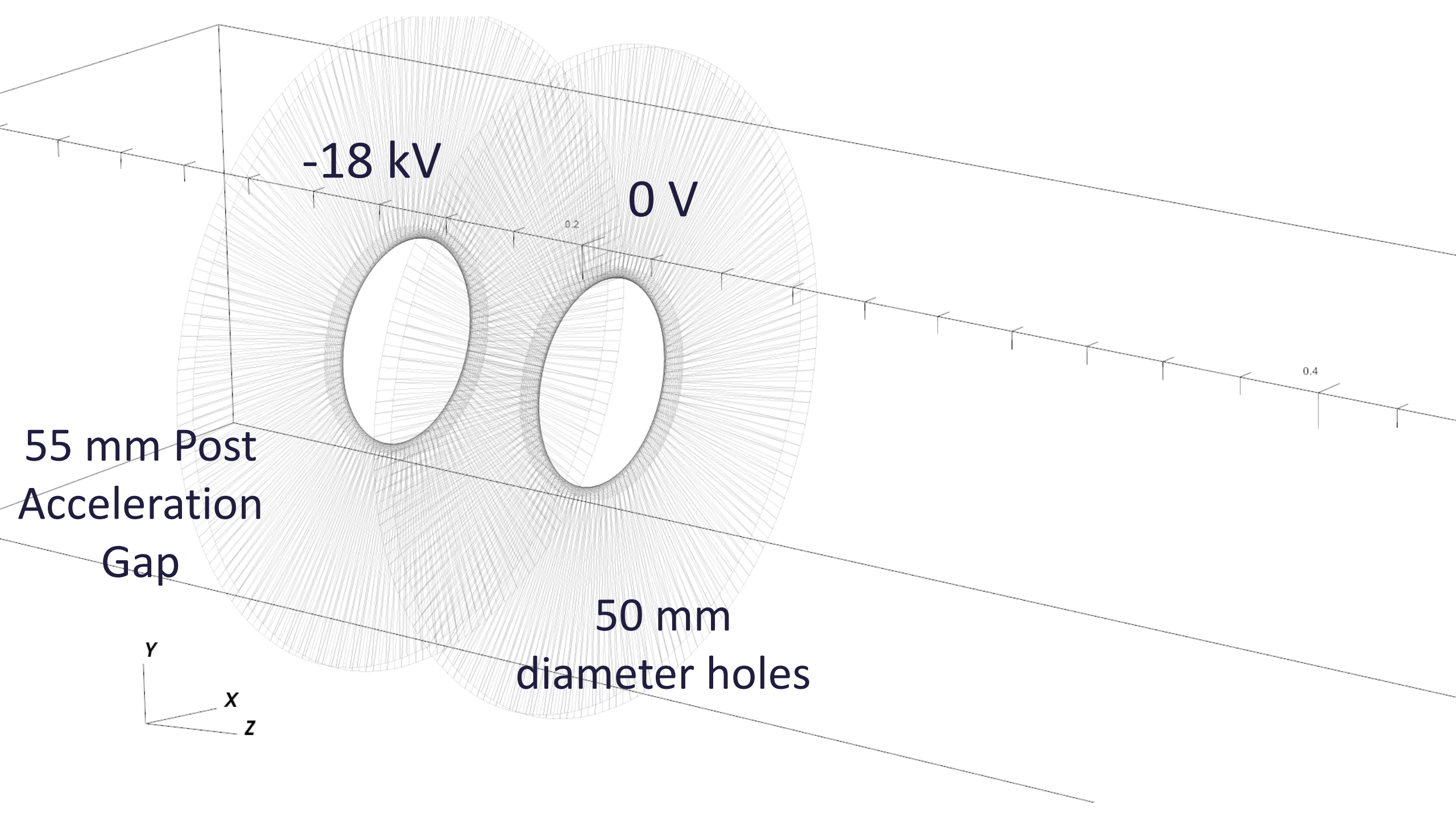
Equal constant particle weights:

Up to 60 million macro particles in the primary Hminus beam

Runs on 192 or 512 cores for up to 6 weeks

What are the boundary conditions of the LEBT?





-18 kV

0 V

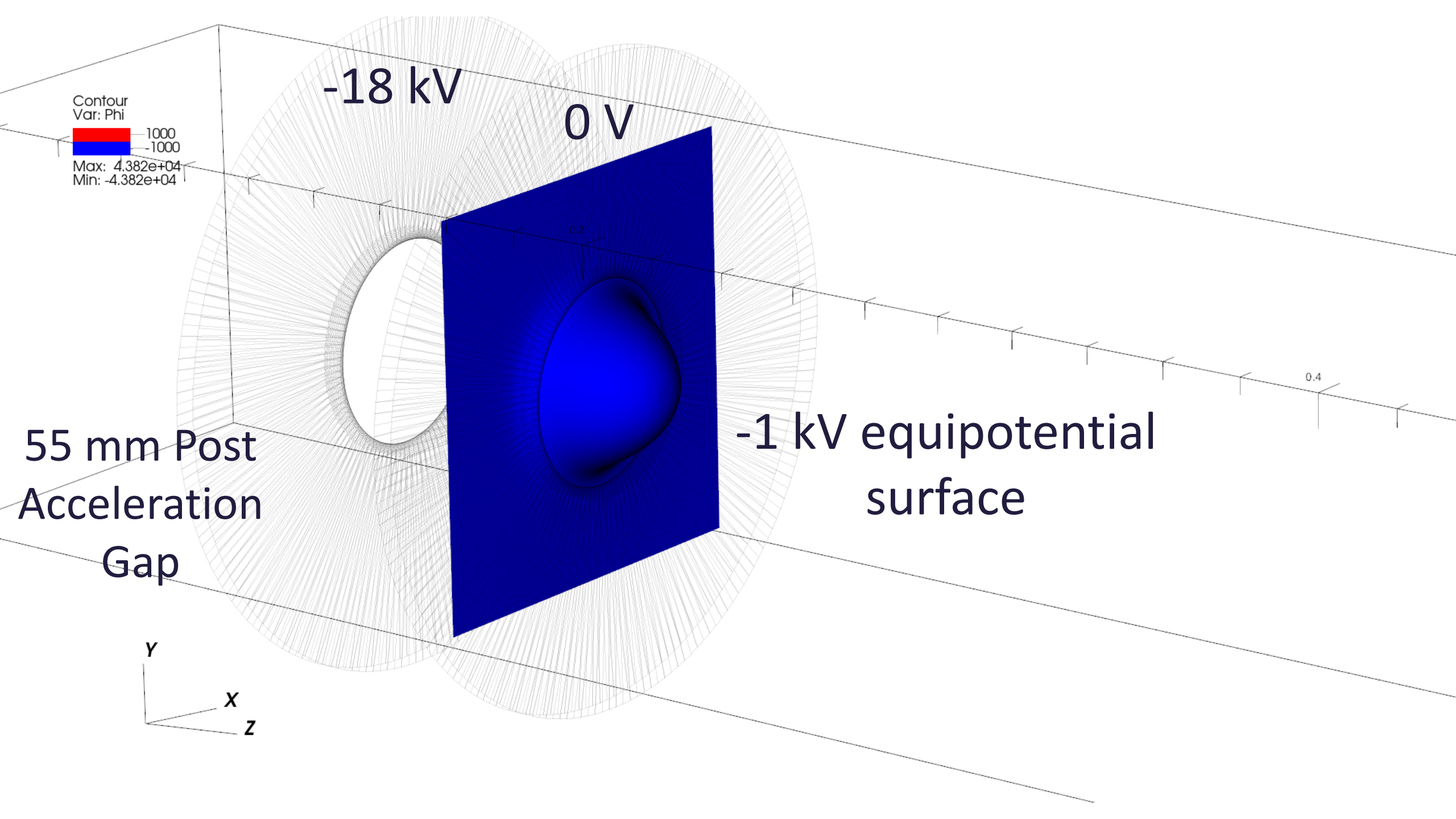
0.2

0.4

**55 mm Post
Acceleration
Gap**

**50 mm
diameter holes**

y
x
z

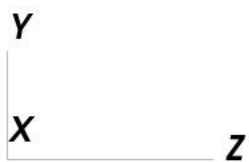


-18 kV

0 V

-z boundary

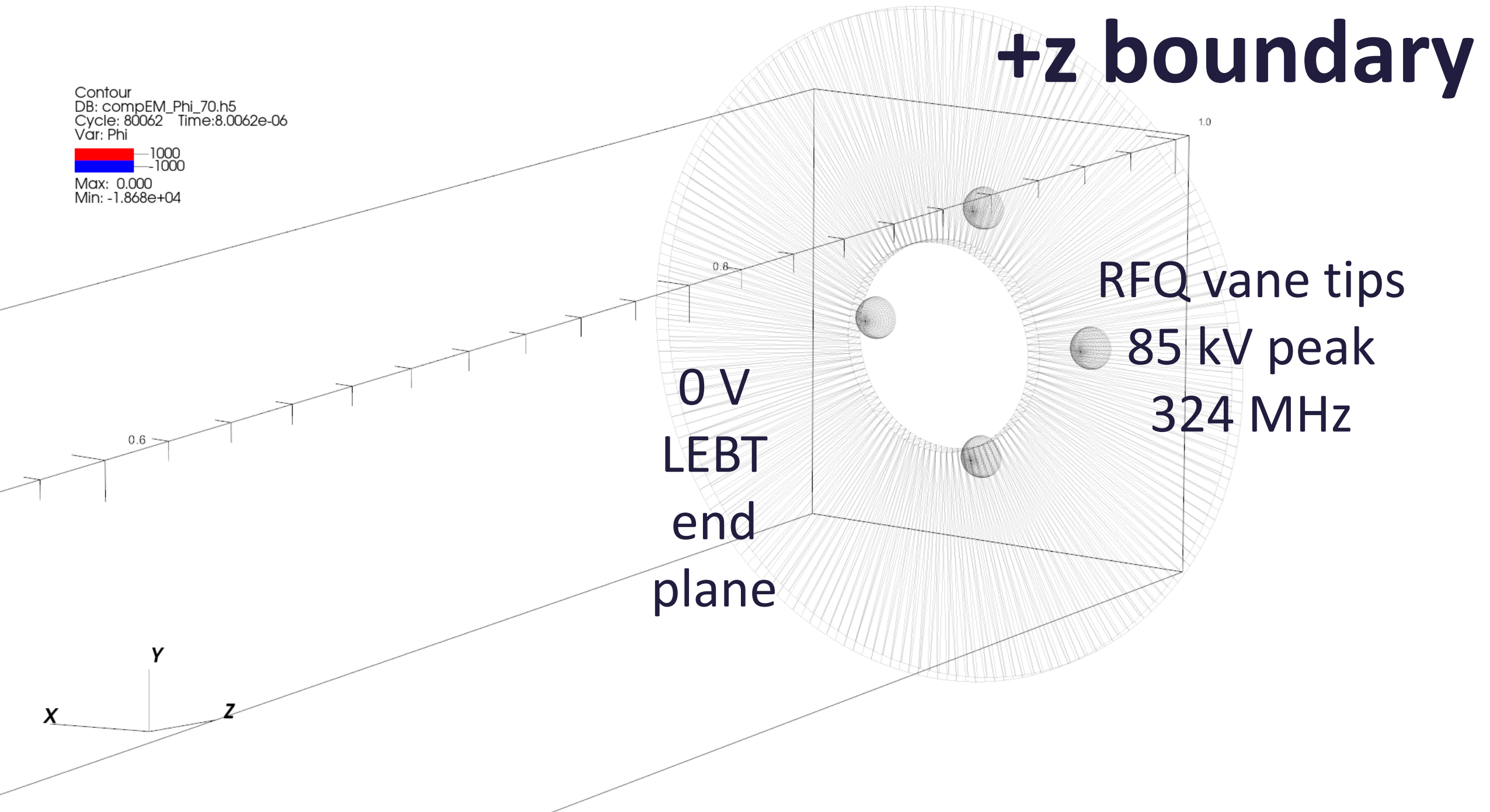
-1 kV equipotential
surface



Contour
DB: compEM_Phi_70.h5
Cycle: 80062 Time: 8.0062e-06
Var: Phi

1000
1000
Max: 0.000
Min: -1.868e+04

+z boundary



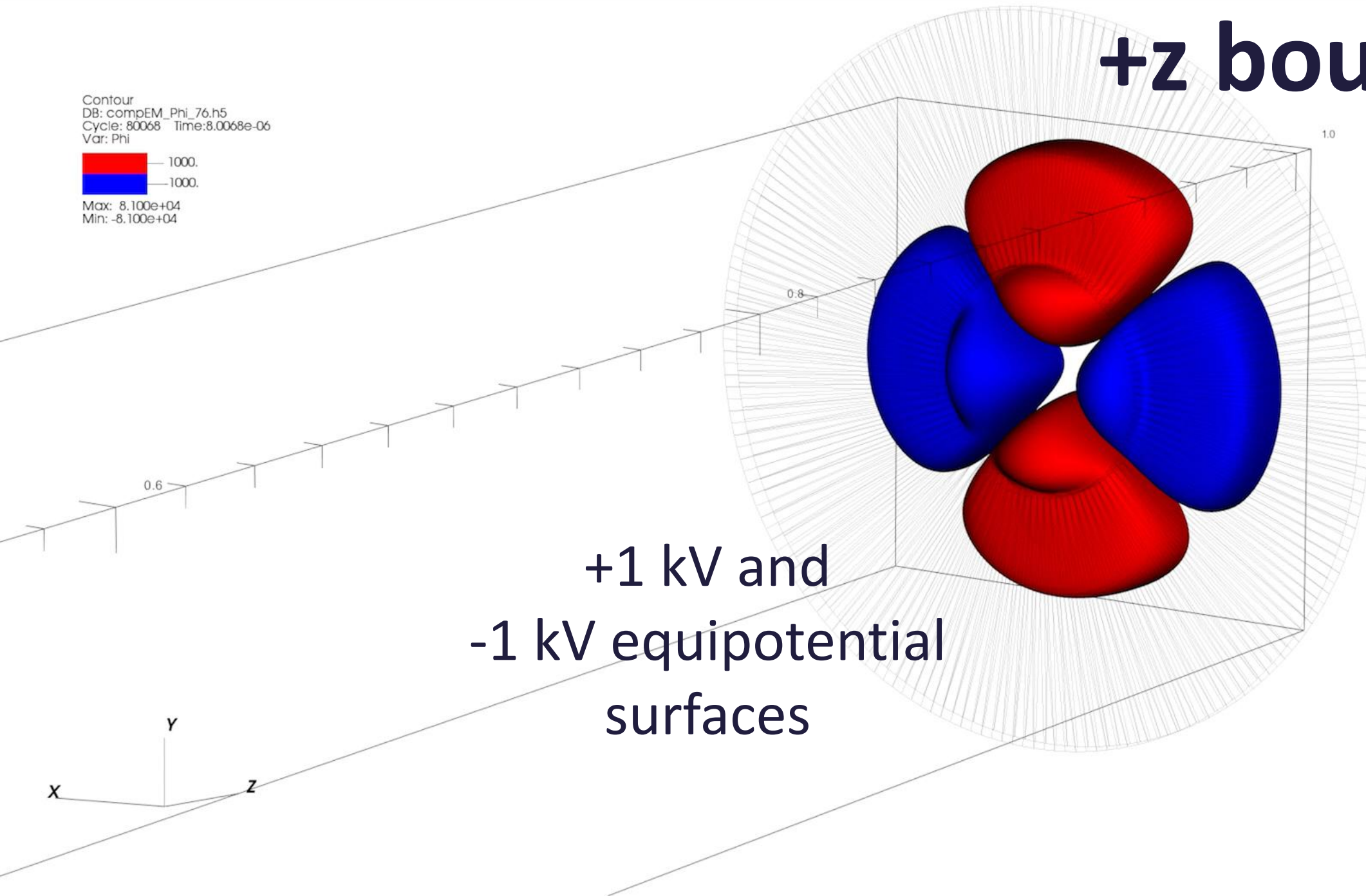
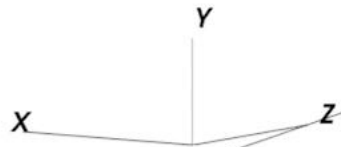
+z boundary

Contour
DB: compEM_Phi_76.h5
Cycle: 80068 Time: 8.0068e-06
Var: Phi



Max: 8.100e+04
Min: -8.100e+04

+1 kV and
-1 kV equipotential
surfaces

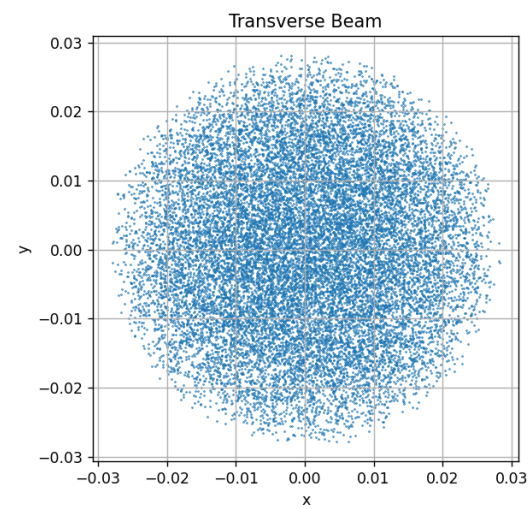
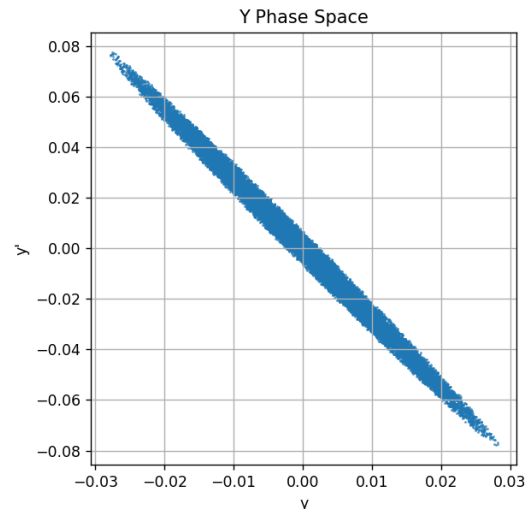
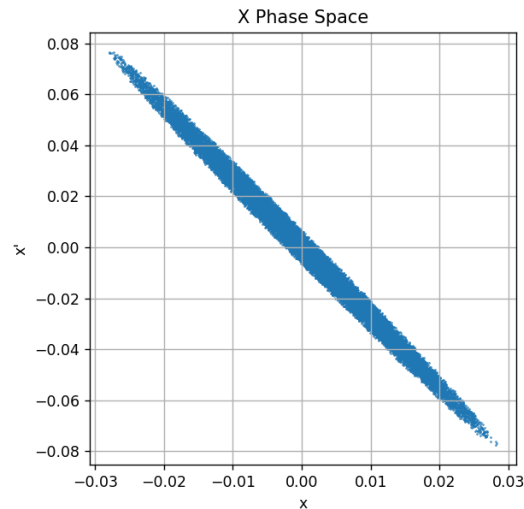


Launching the beam

Electrostatic
HV Gap

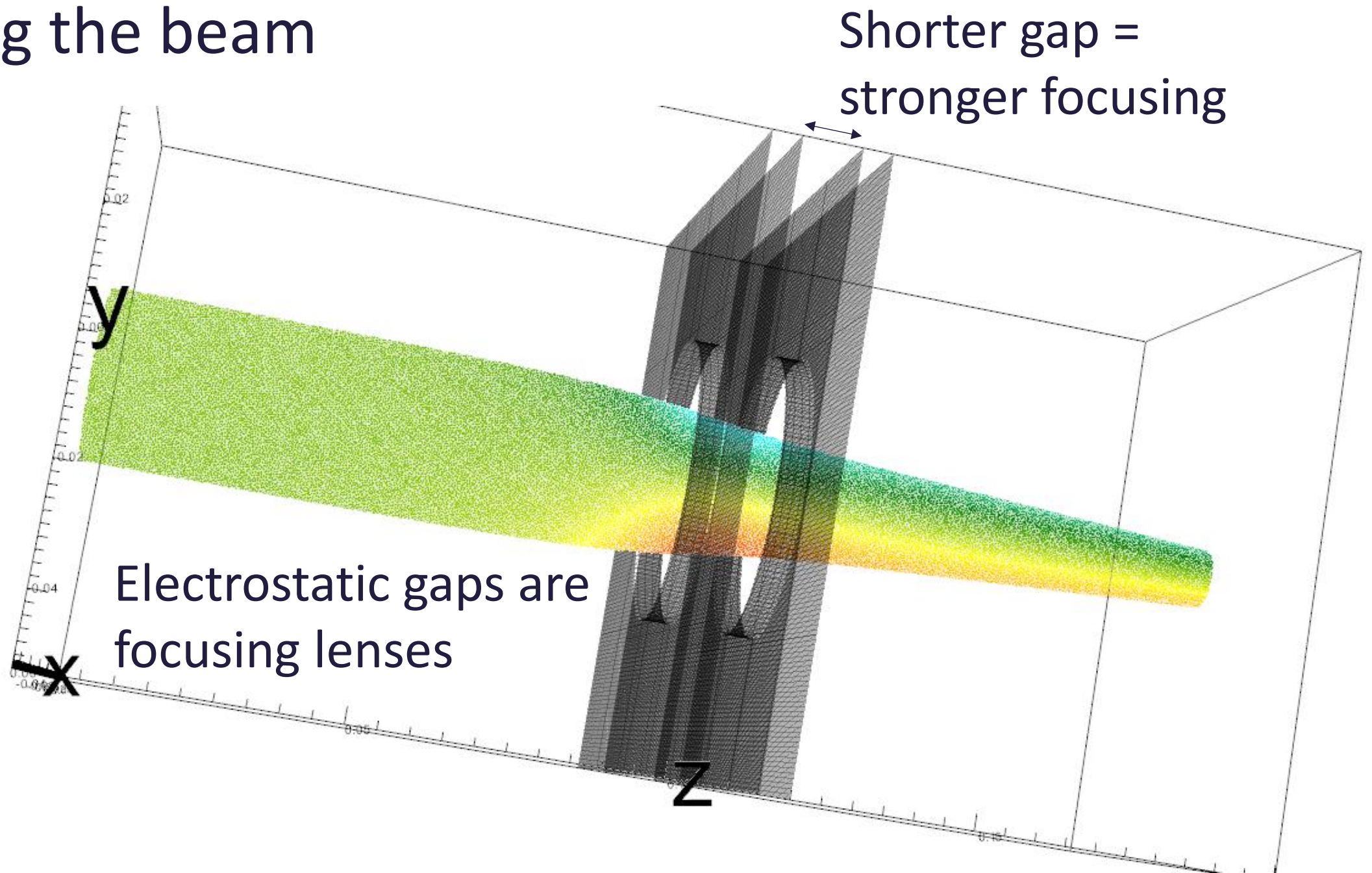
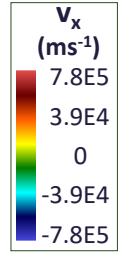


Load a
waterbag
distribution
every
timestep



Radio
Frequency
Quadrupole
(RFQ)

Aiming the beam



Aiming the beam

Key assumption:

You can design beam optics for high current beams by assuming a high percentage space charge compensation

i.e. design the optics using a low current beam

Aiming the beam

Use a test beam:

- low current ($3\ \mu\text{A}$) – minimise space charge
- symmetrical beam – keep things simple
- low emittance ($1/1000$) – see effects clearly
- medium diameter (14 mm) – avoid chromatic aberration

Vary Twiss Alpha parameter until a parallel beam is formed in the LEBT

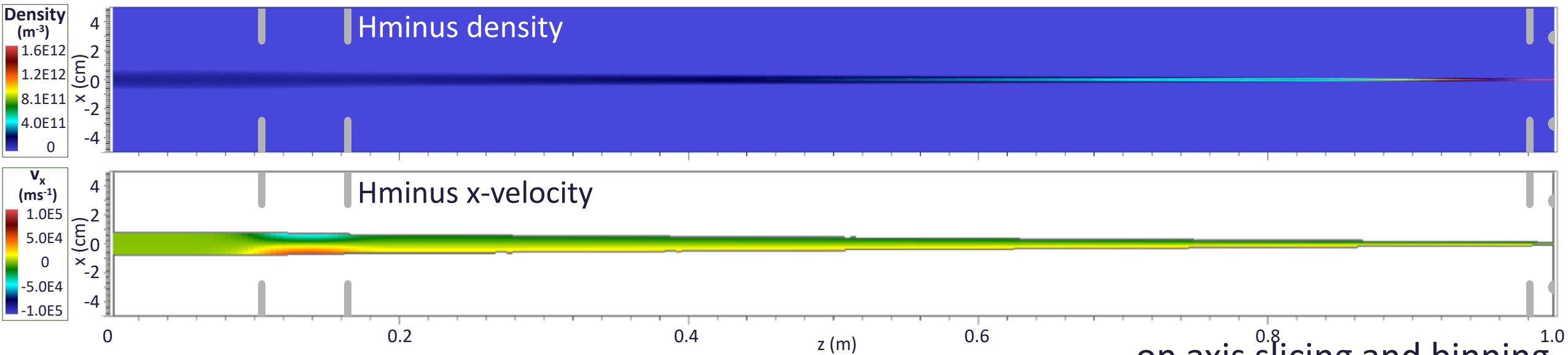
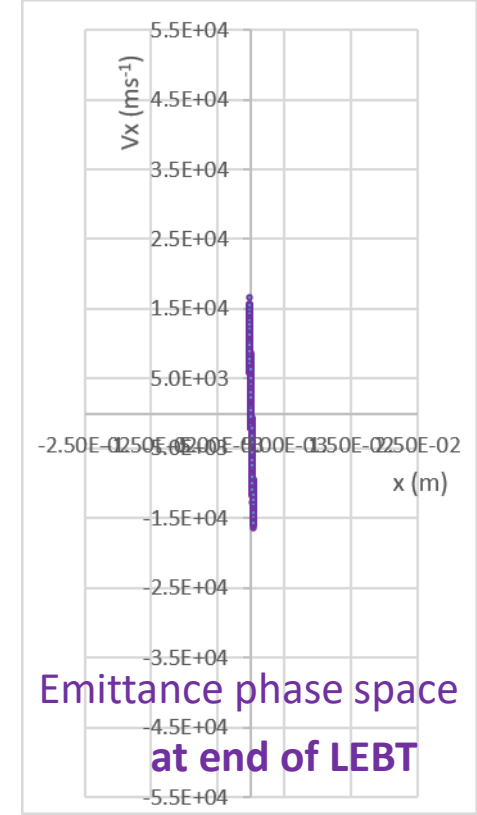
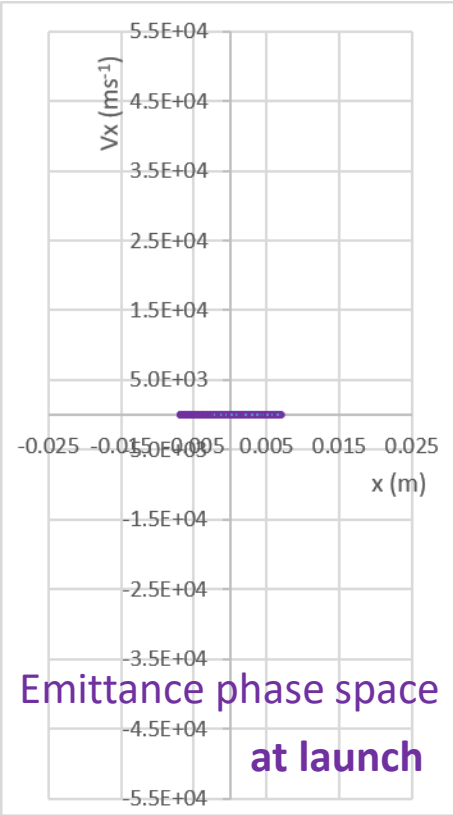
Aiming the beam

Twiss Parameters at launch:

Alpha 0

Beta **250**

Emit **0.034** mm.mrad



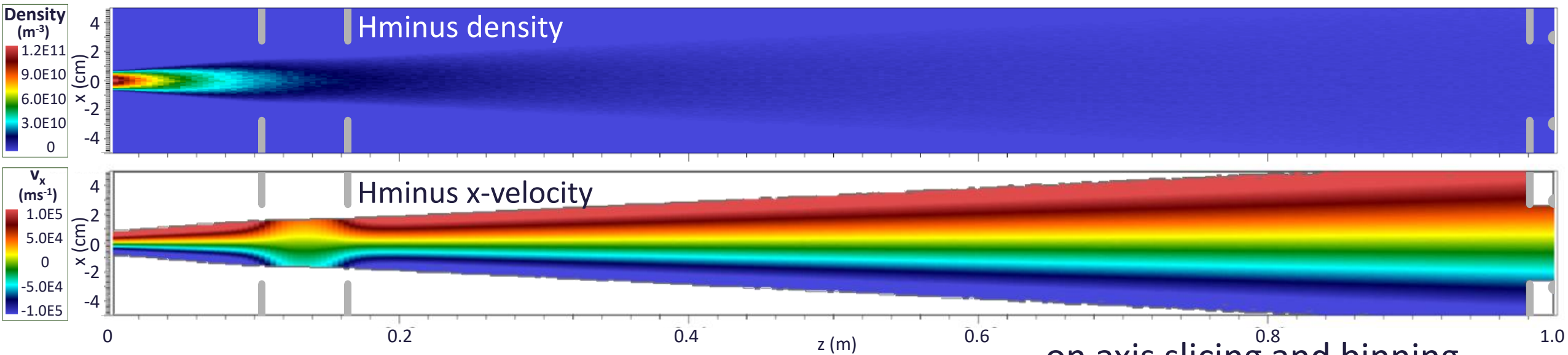
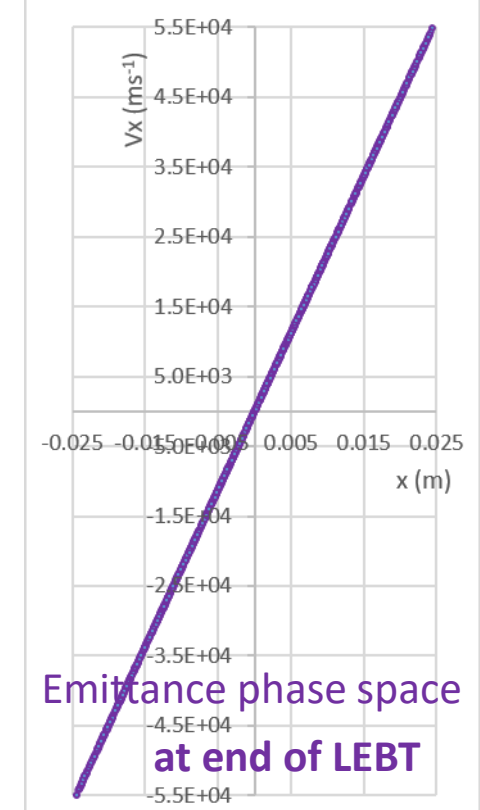
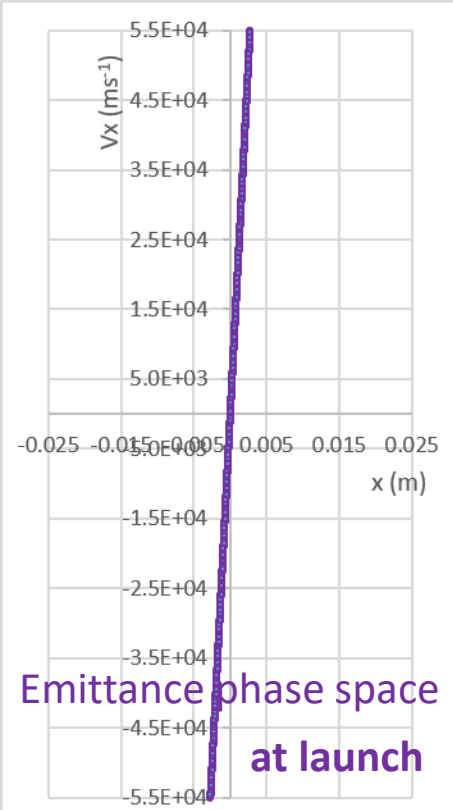
Aiming the beam

Twiss Parameters at launch:

Alpha 2800

Beta **250**

Emit **0.034** mm.mrad



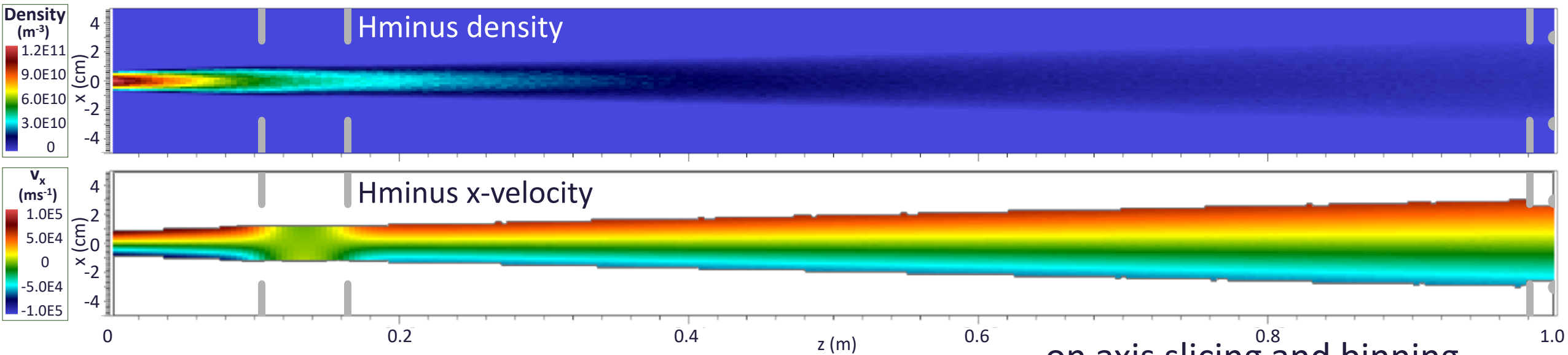
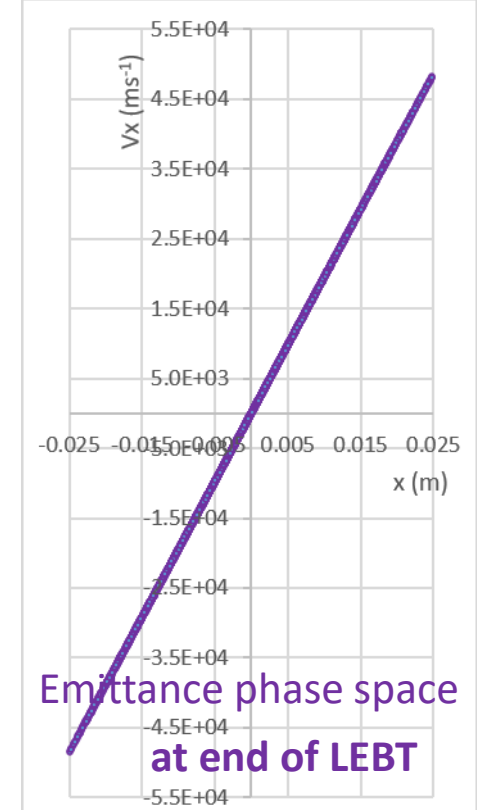
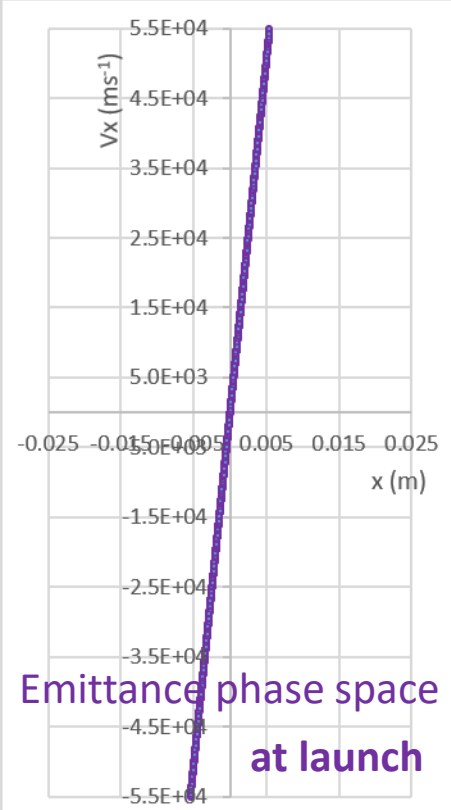
Aiming the beam

Twiss Parameters at launch:

Alpha 1400

Beta **250**

Emit **0.034** mm.mrad



on axis slicing and binning

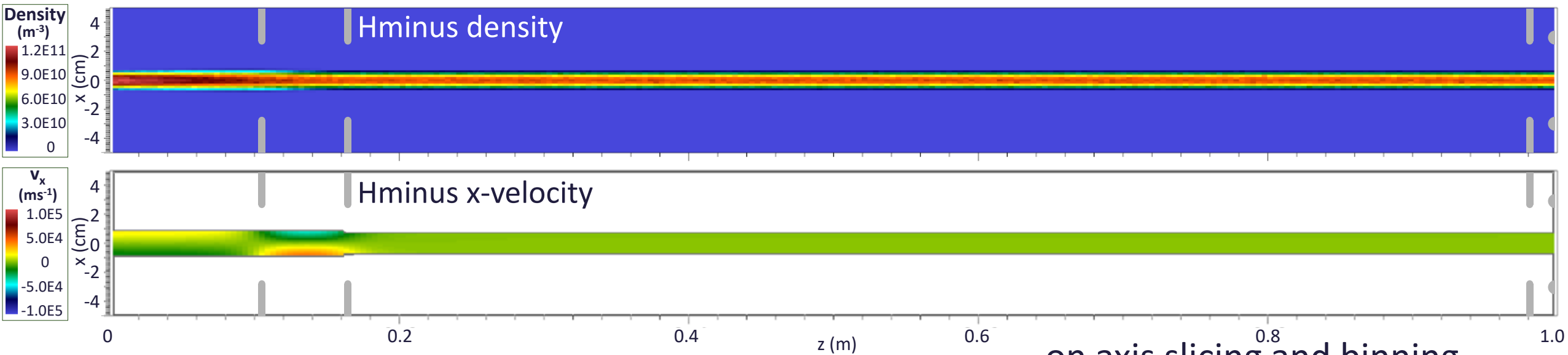
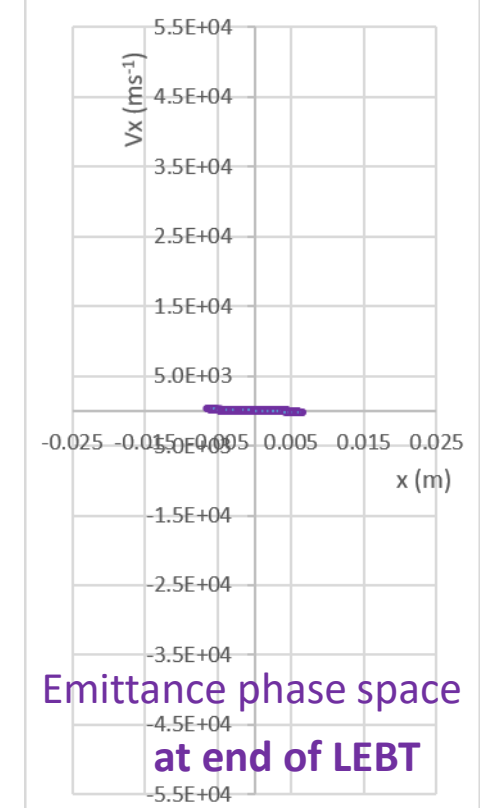
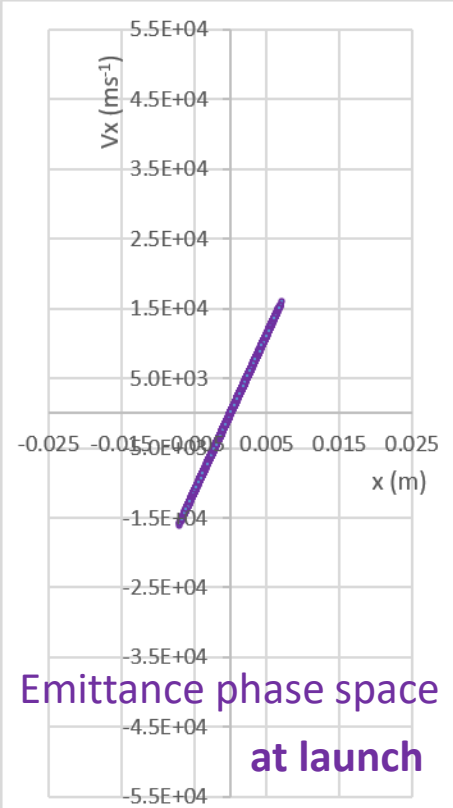
Aiming the beam

Twiss Parameters at launch:

Alpha 313

Beta **250**

Emit **0.034** mm.mrad

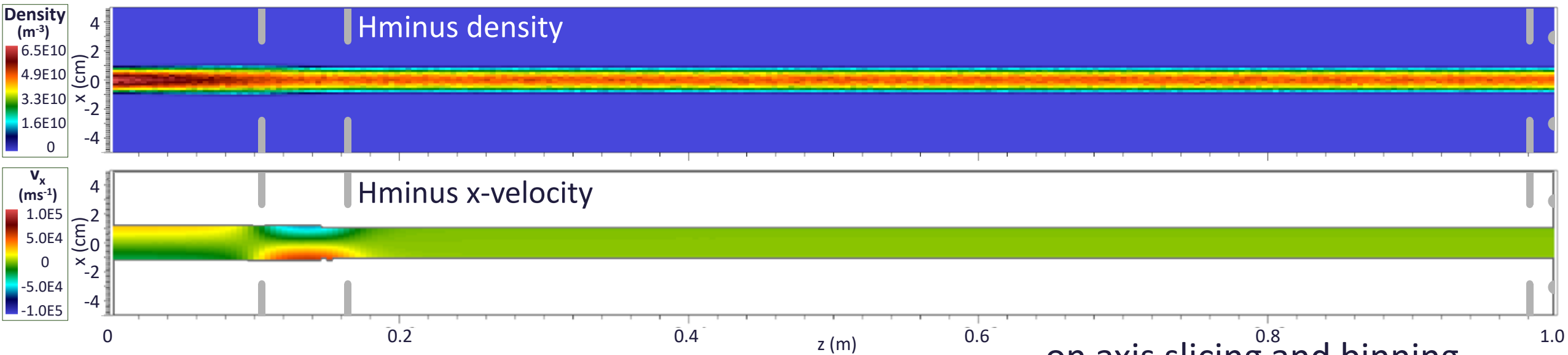
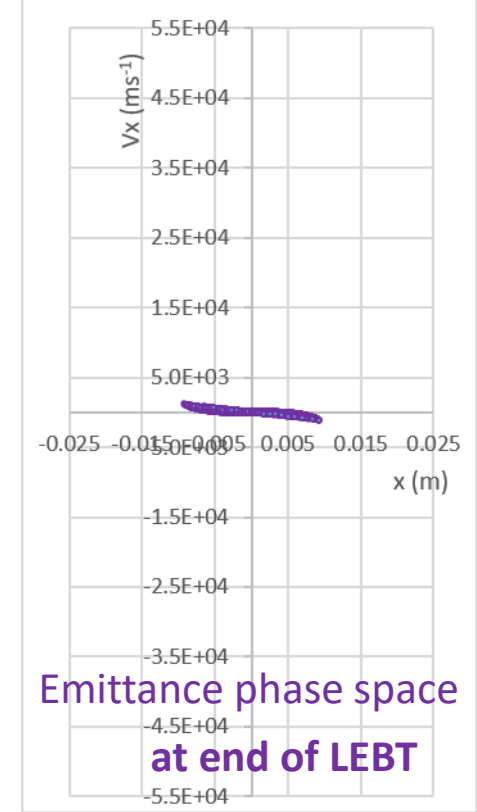
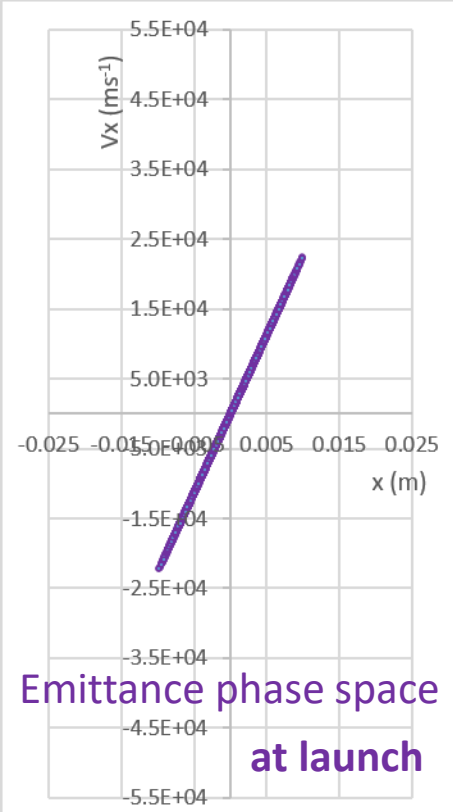


Increase the beam diameter

Twiss Parameters at launch:

Alpha **313** } **X2**
Beta **250**

Emit **0.034** mm.mrad

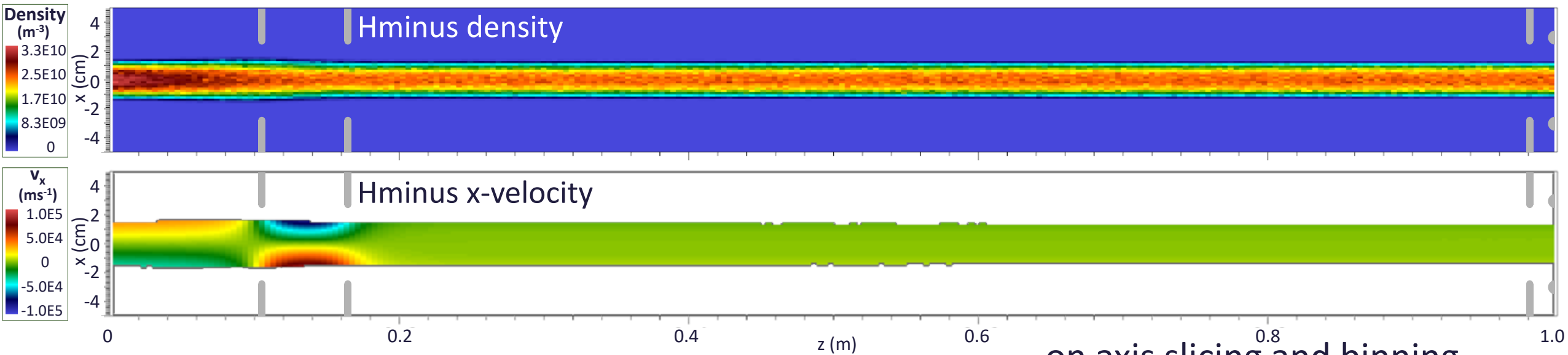
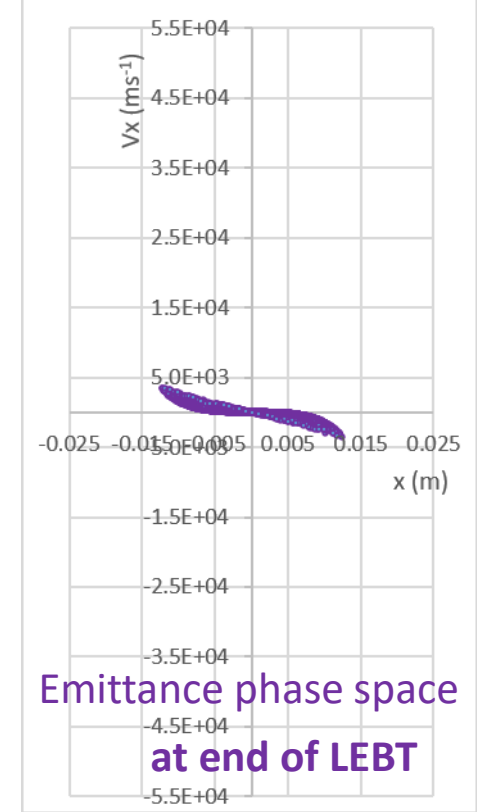
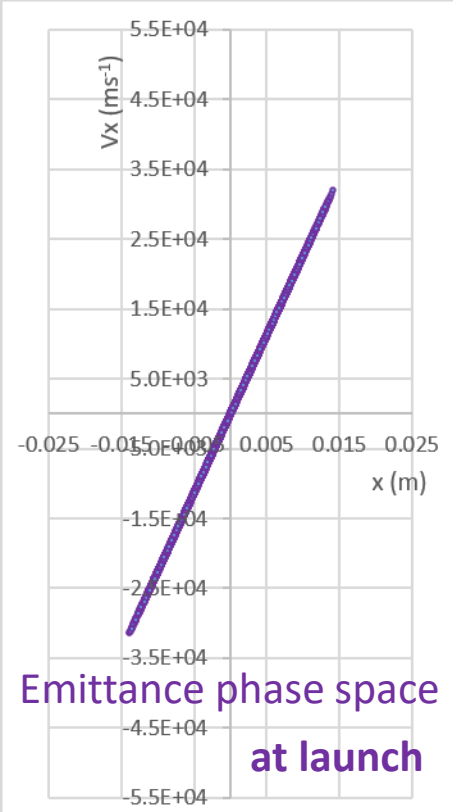


Increase the beam diameter

Twiss Parameters at launch:

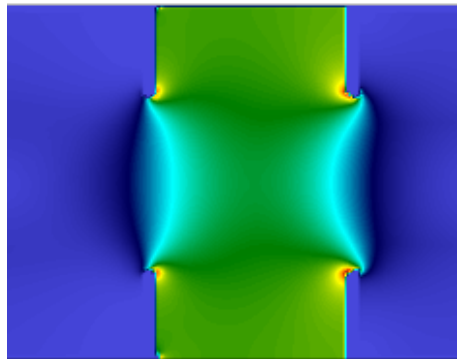
Alpha **313** } **X4**
Beta **250**

Emit **0.034** mm.mrad



Increase the beam diameter

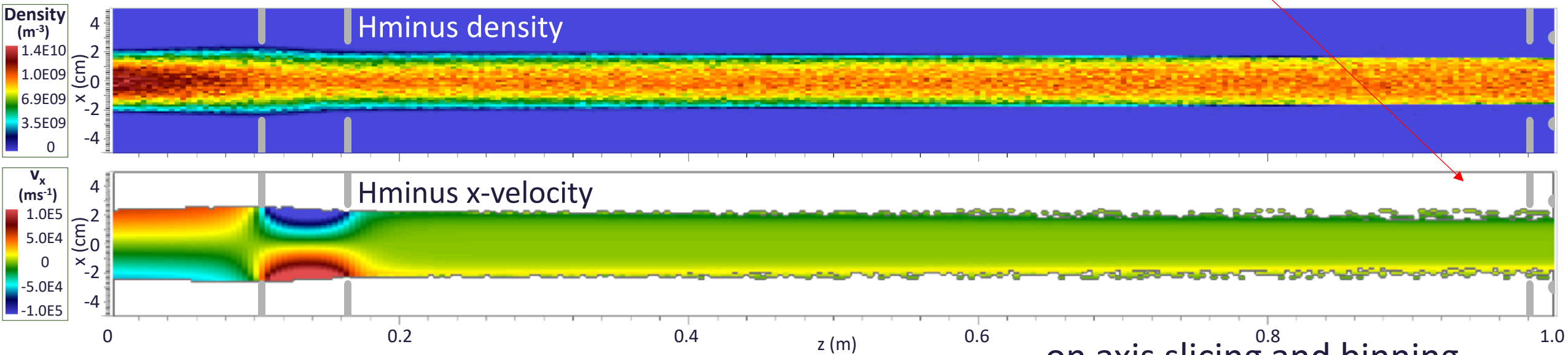
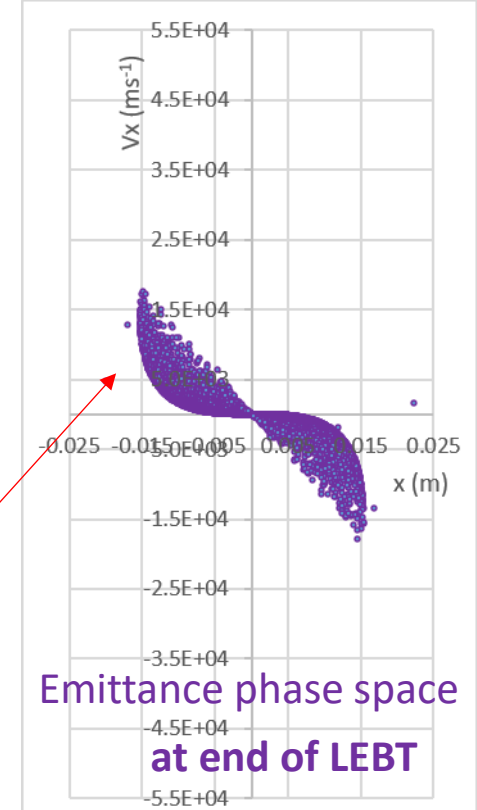
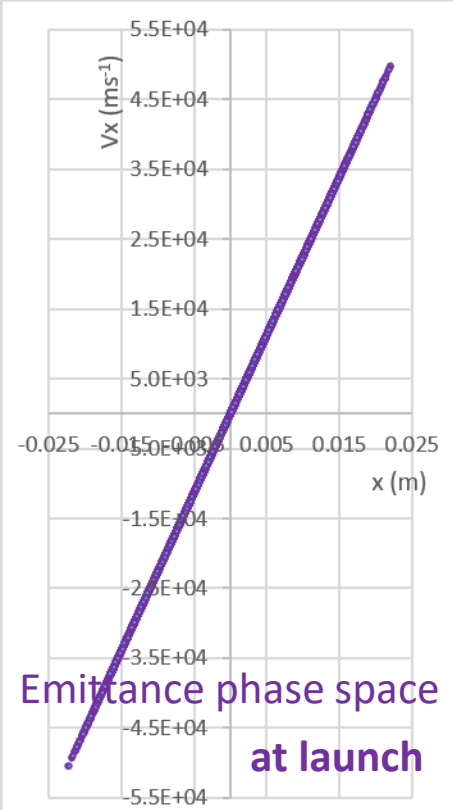
electric field in acceleration gap



Twiss Parameters at launch:

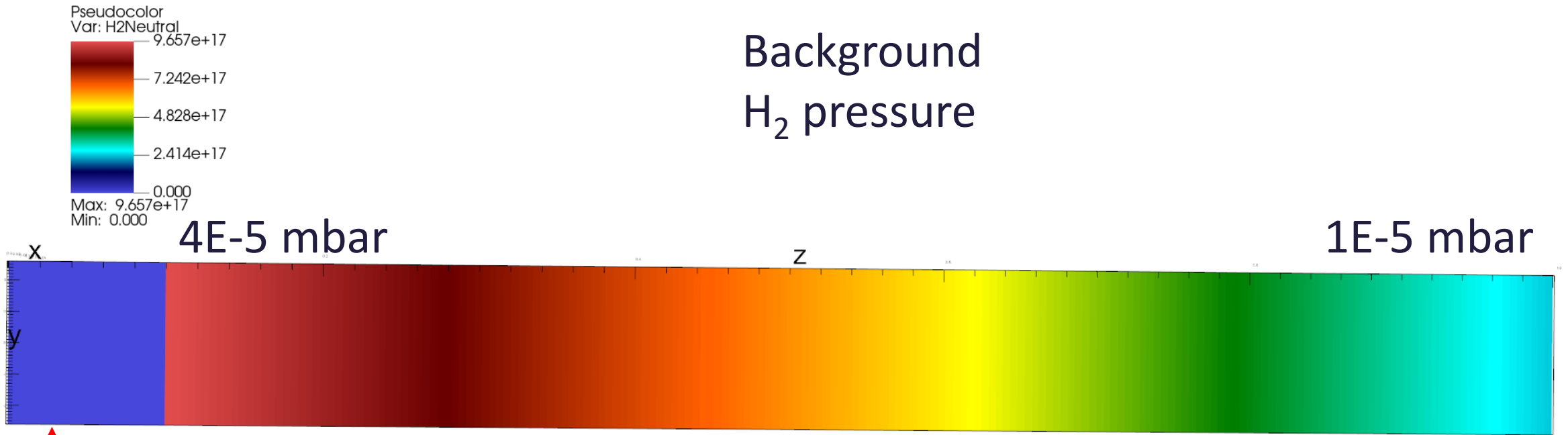
Alpha **313**
Beta **250** } **x8**
Emit **0.034** mm.mrad

chromatic aberration visible

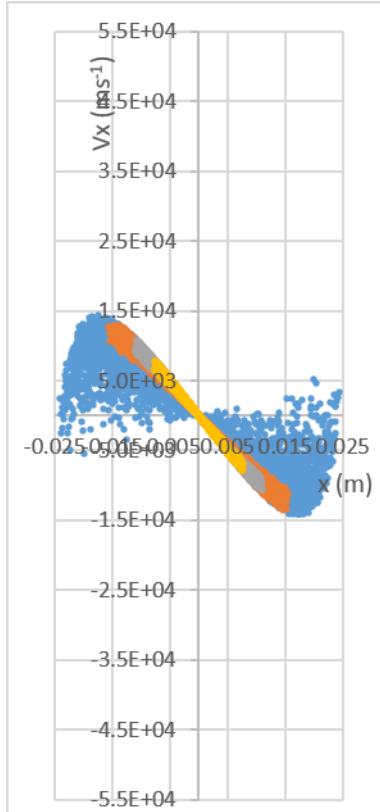
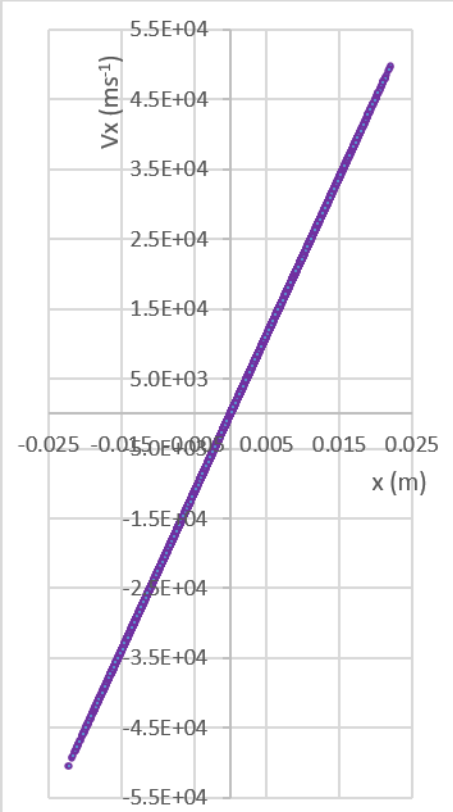


on axis slicing and binning

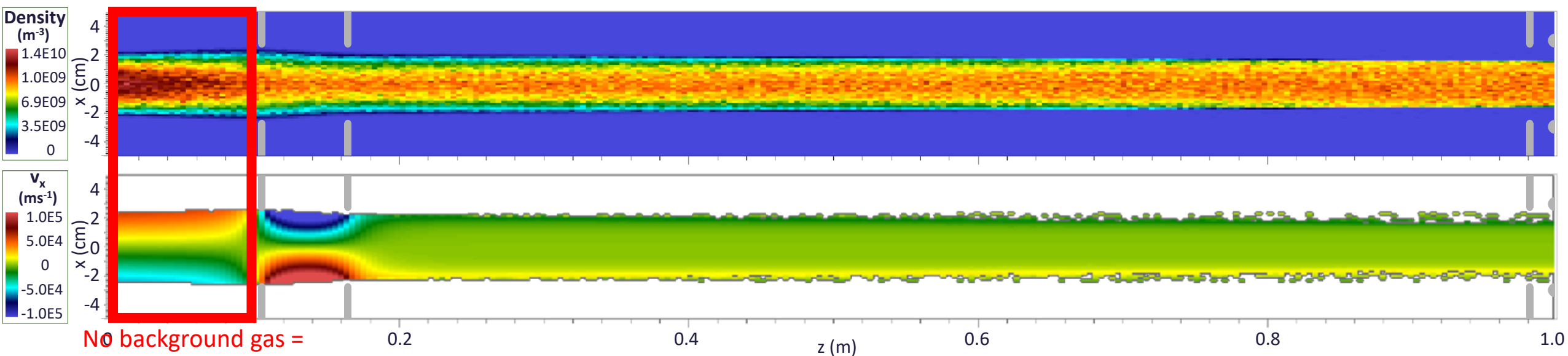
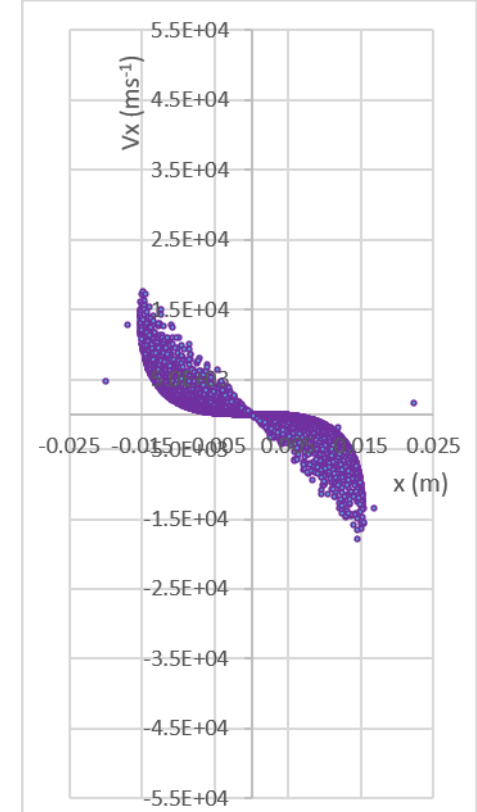
What is the pressure in the LEBT?



The launch region is not the area of interest so drop the pressure to zero for computational efficiency

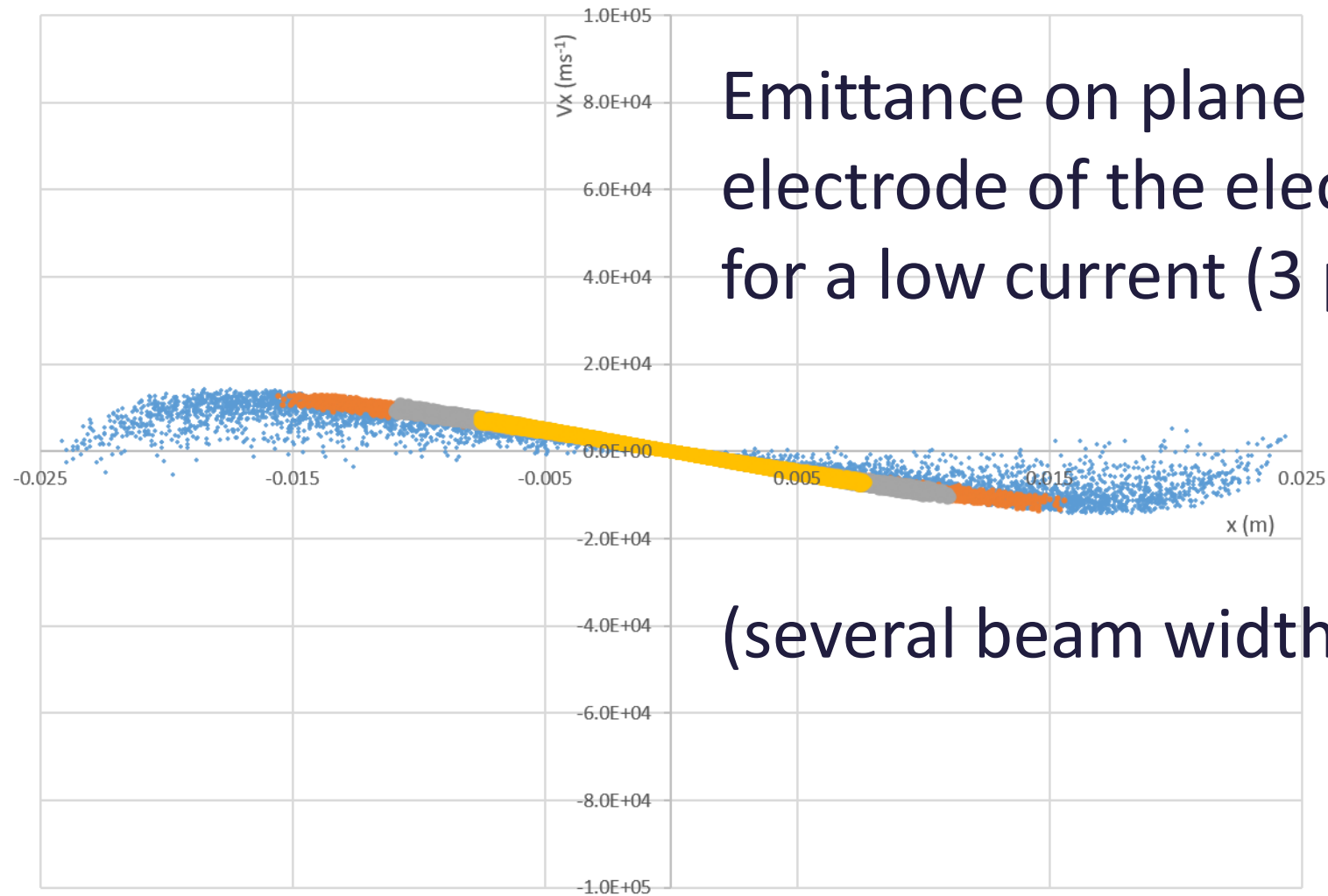


So we must aim a high current beam to the entrance of the electrostatic gap and then assume that it will fully compensate to a “low current” beam



No background gas =
No compensation

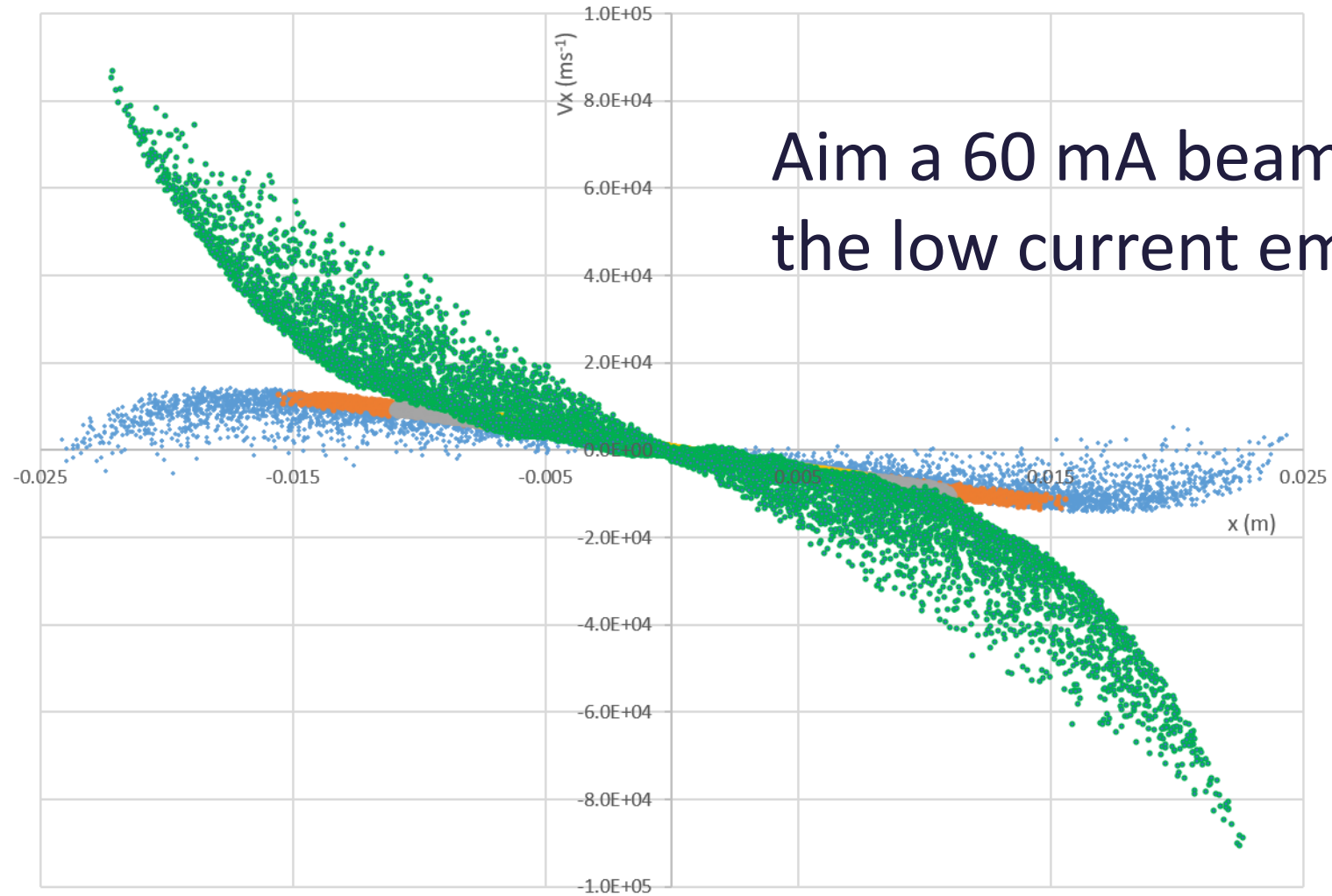
Aiming the Beam



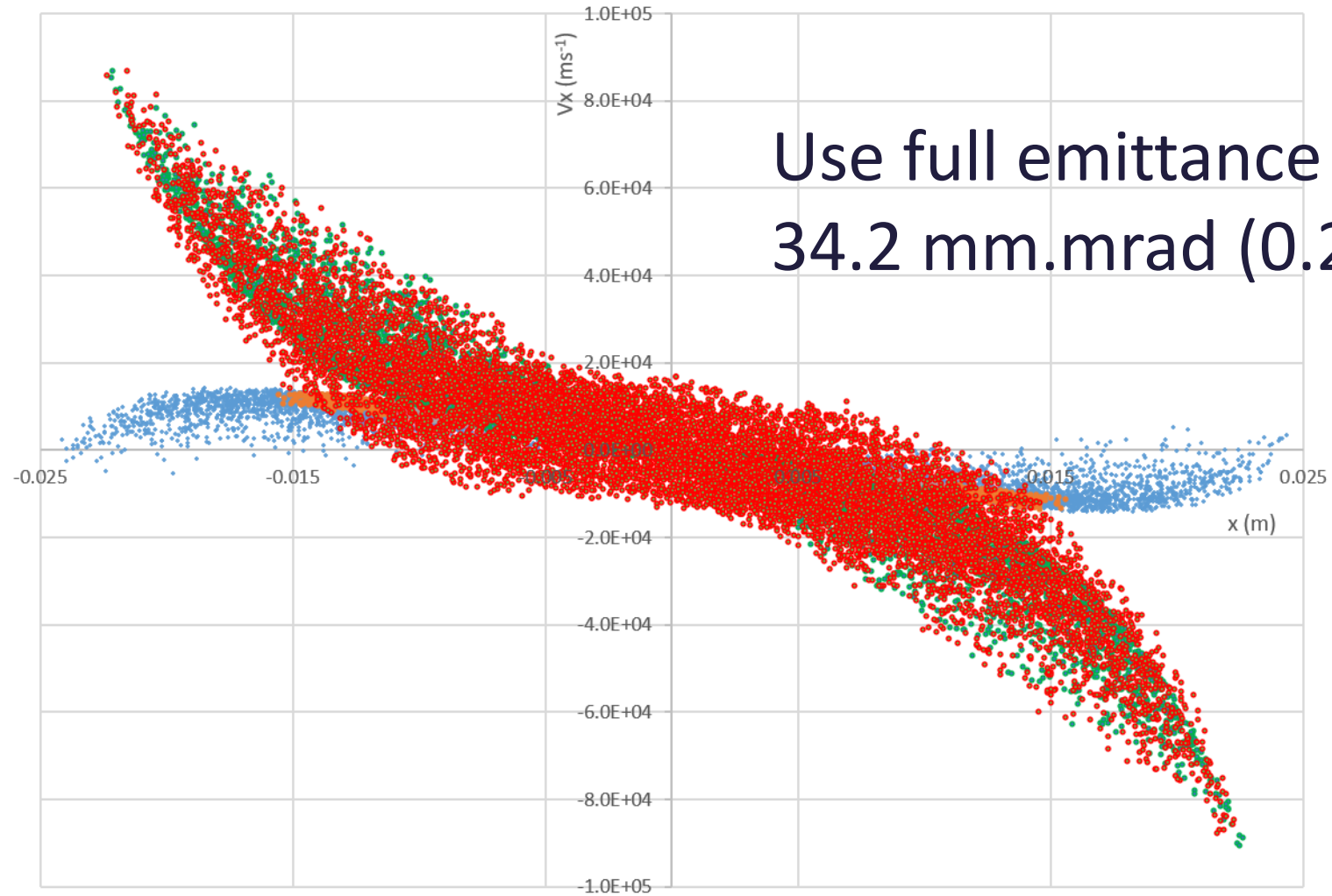
Emittance on plane of the first electrode of the electrostatic gap for a low current ($3 \mu\text{A}$) beam

(several beam widths are shown)

Aiming the Beam

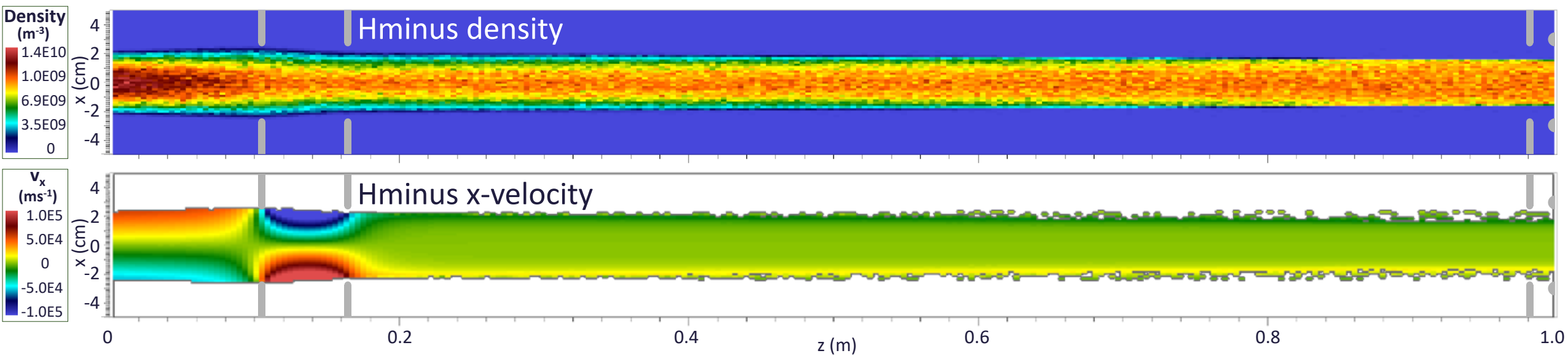


Aiming the Beam



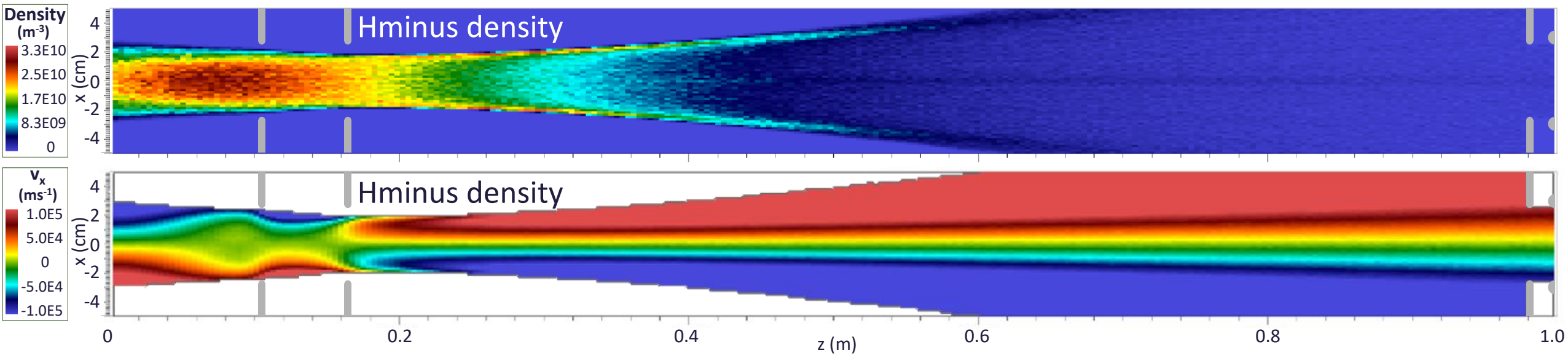
Use full emittance
34.2 mm.mrad (0.21 rms norm)

Low current parallel beam

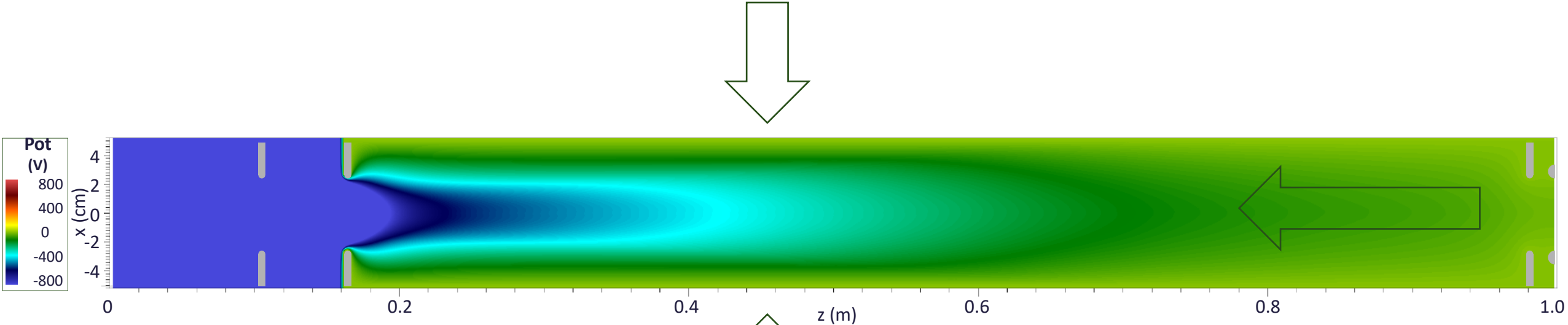


Aimed 60 mA beam

@ 1 μs



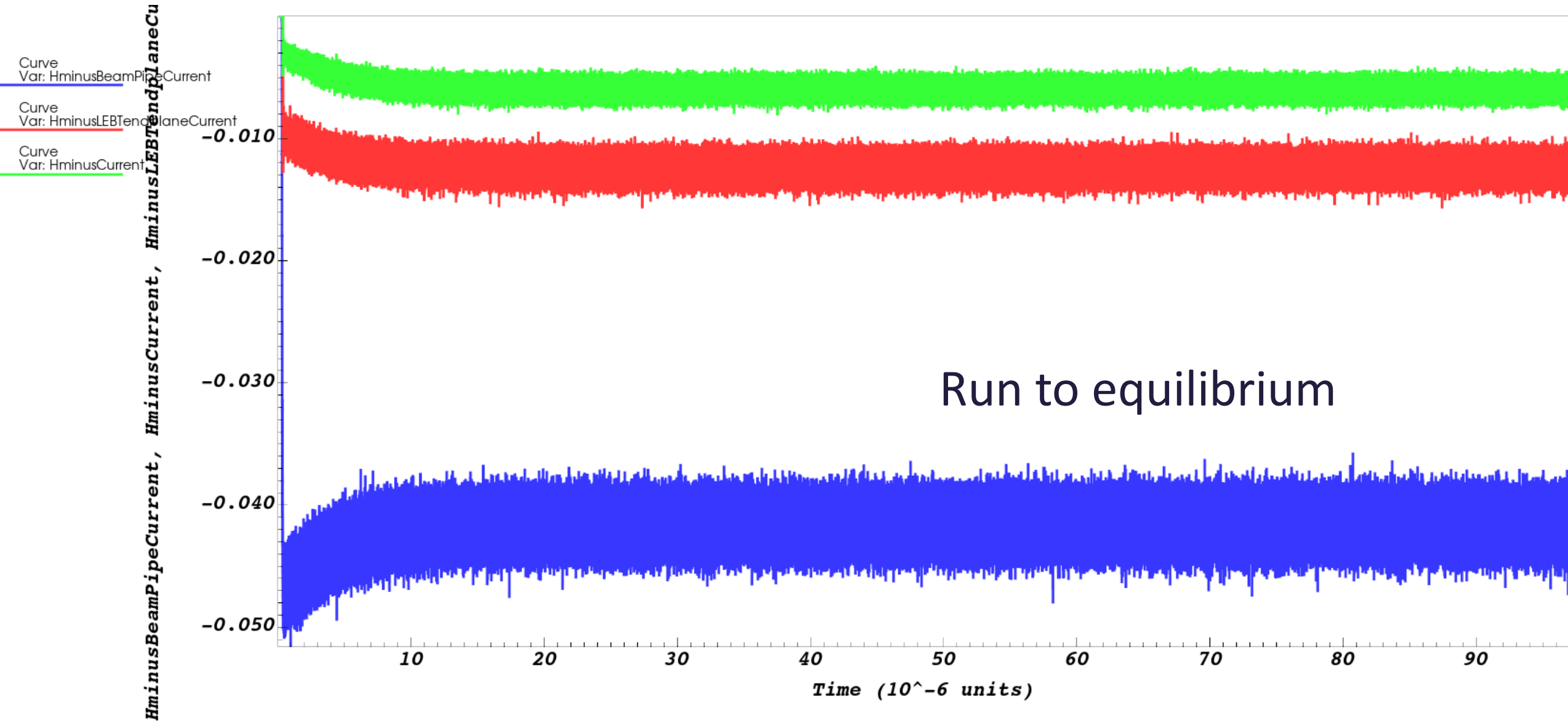
Beam Potential

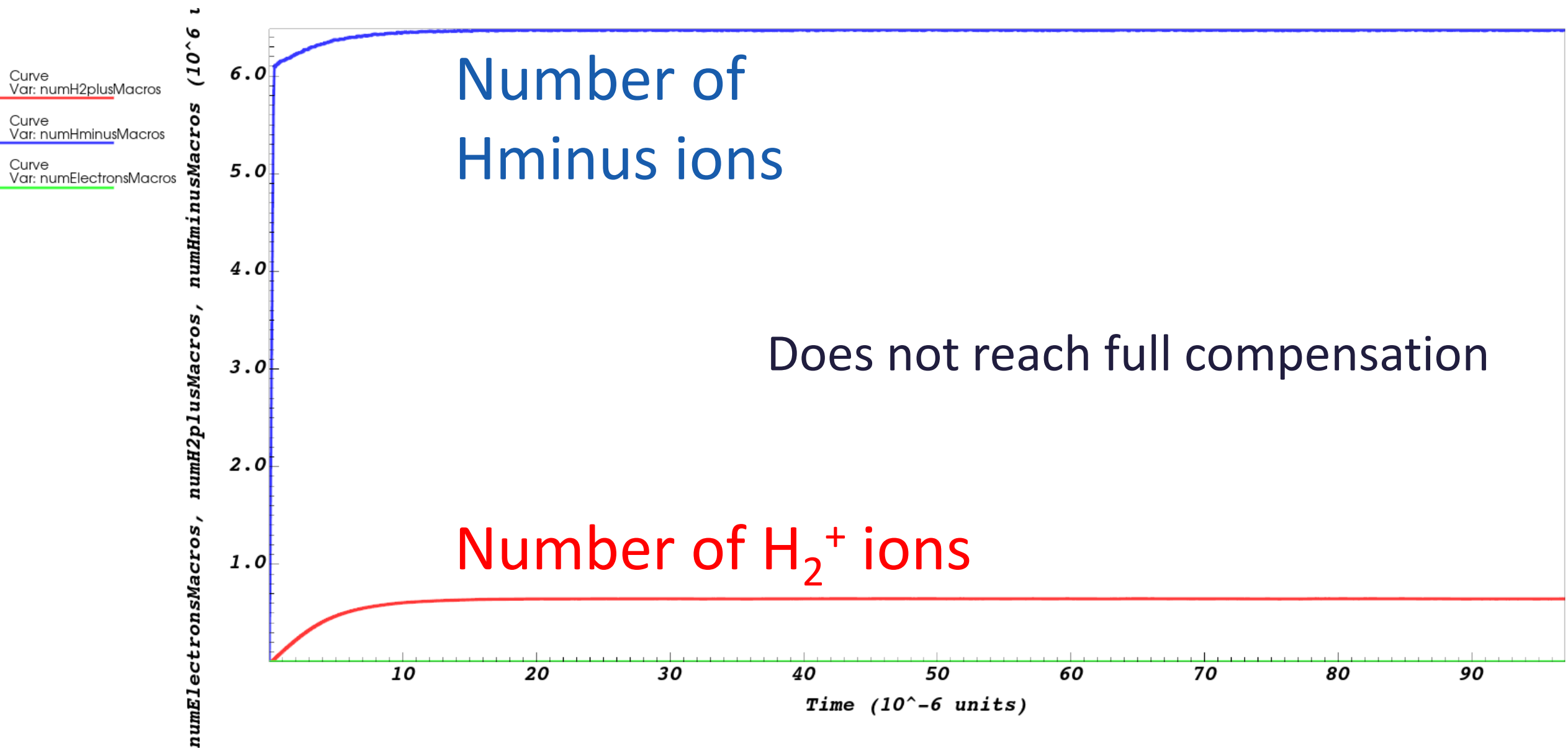


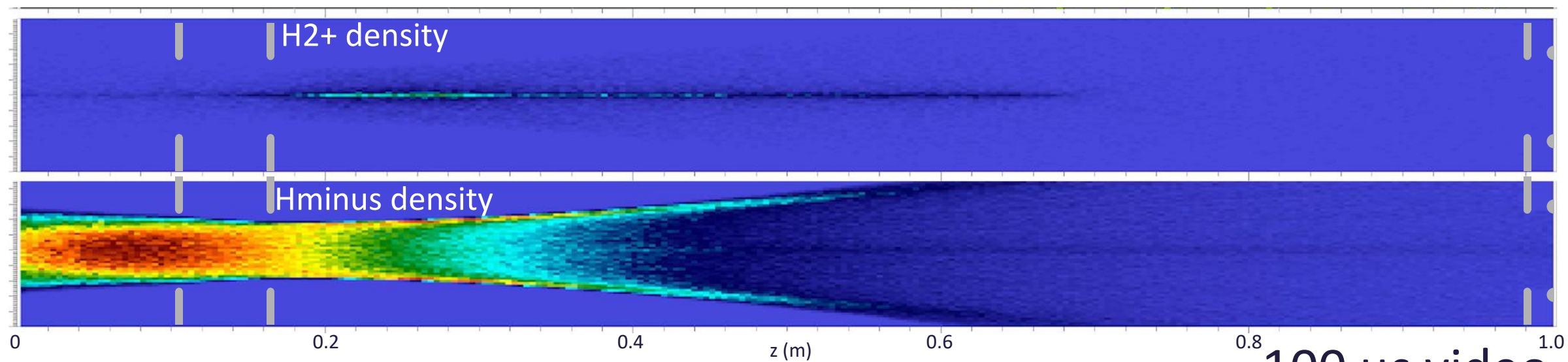
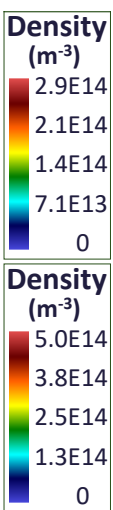
The negative beam potential pulls the H_2^+ compensating particles into the centre of the beam

The diverging beam causes a gradient in the beam potential in the z direction, pulling the H_2^+ compensating particles back along the beam

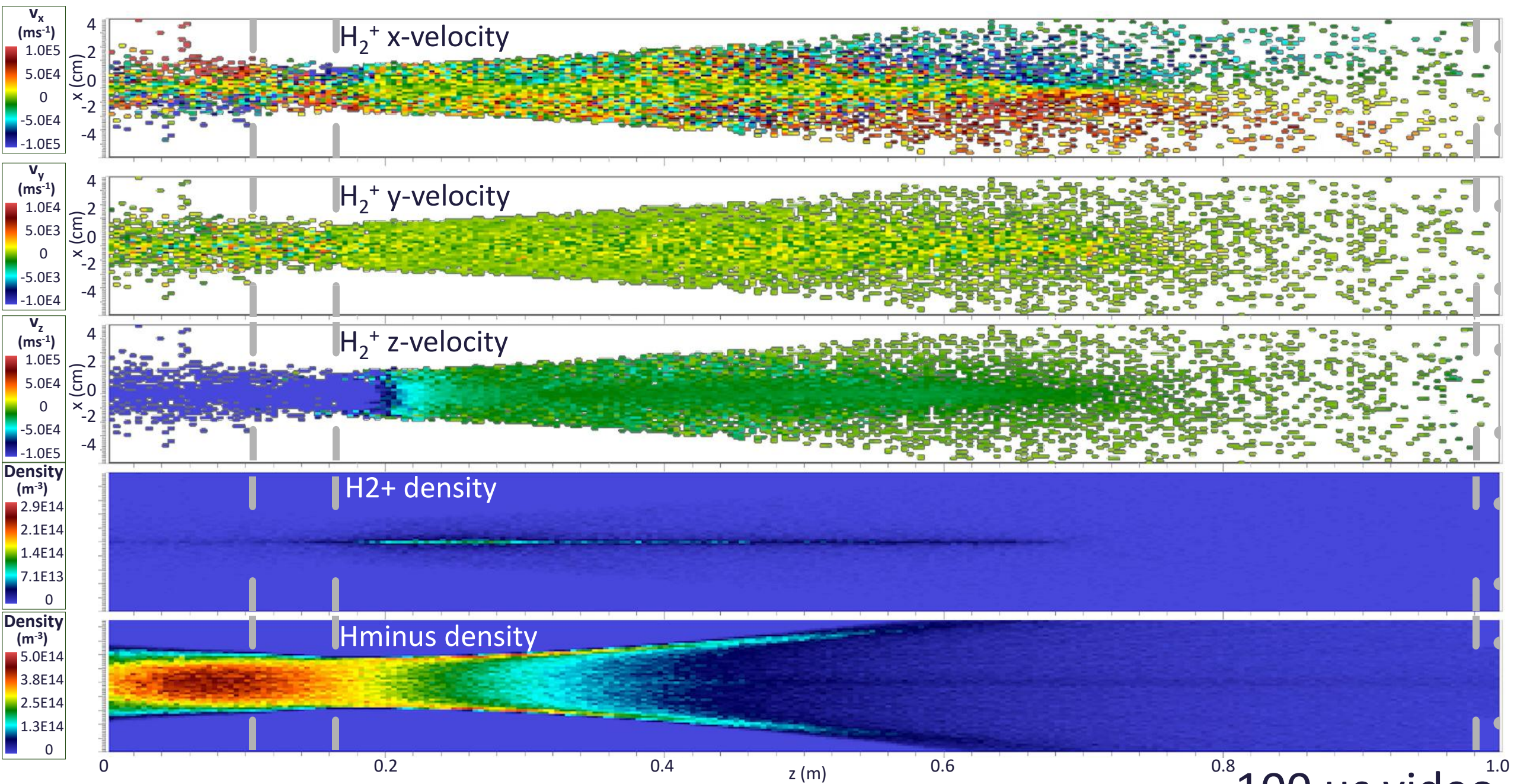
60 mA run to 100 μ s







100 μs video



100 μs video

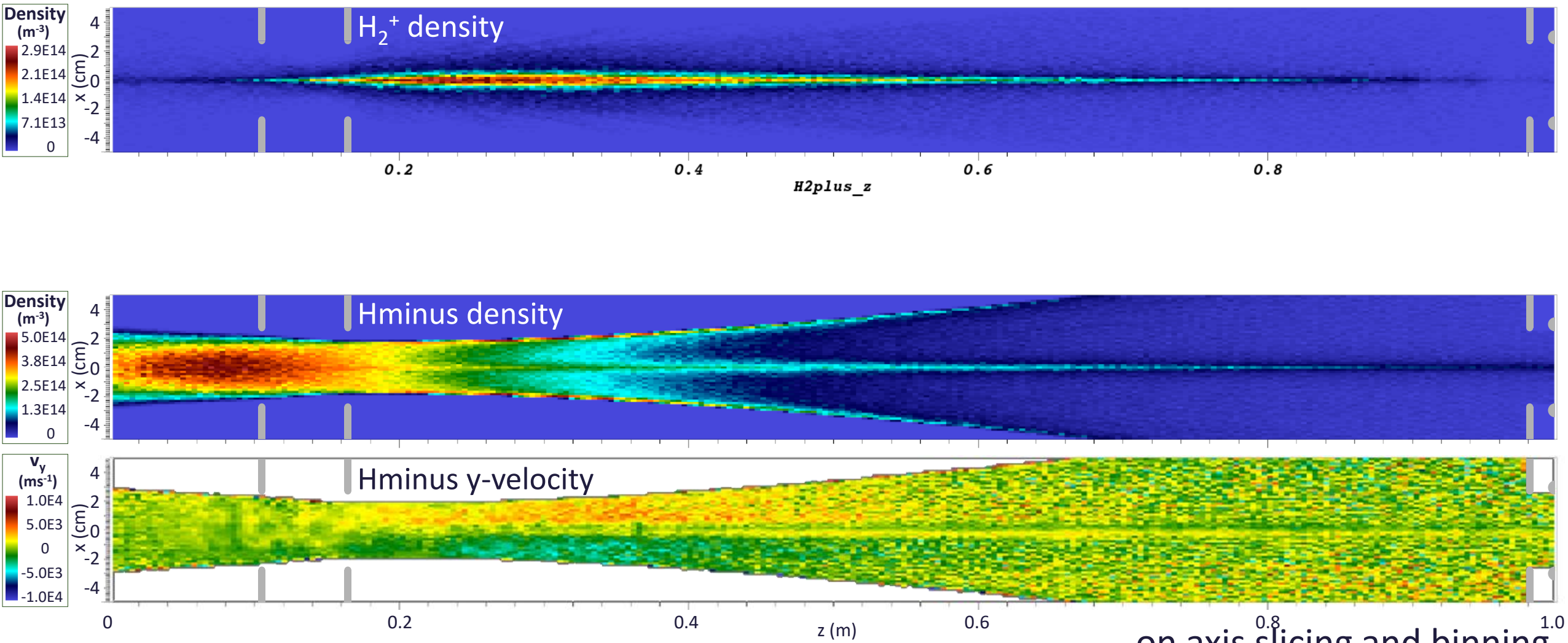
What happens to these vortex-like, space charge structures if the emittance is increased?

Effect of beam emittance

60 mA beam

Scale emittance 34.6 mm.mrad (0.21 rms norm.) **X 0.1**

Slice @ 20 μ s

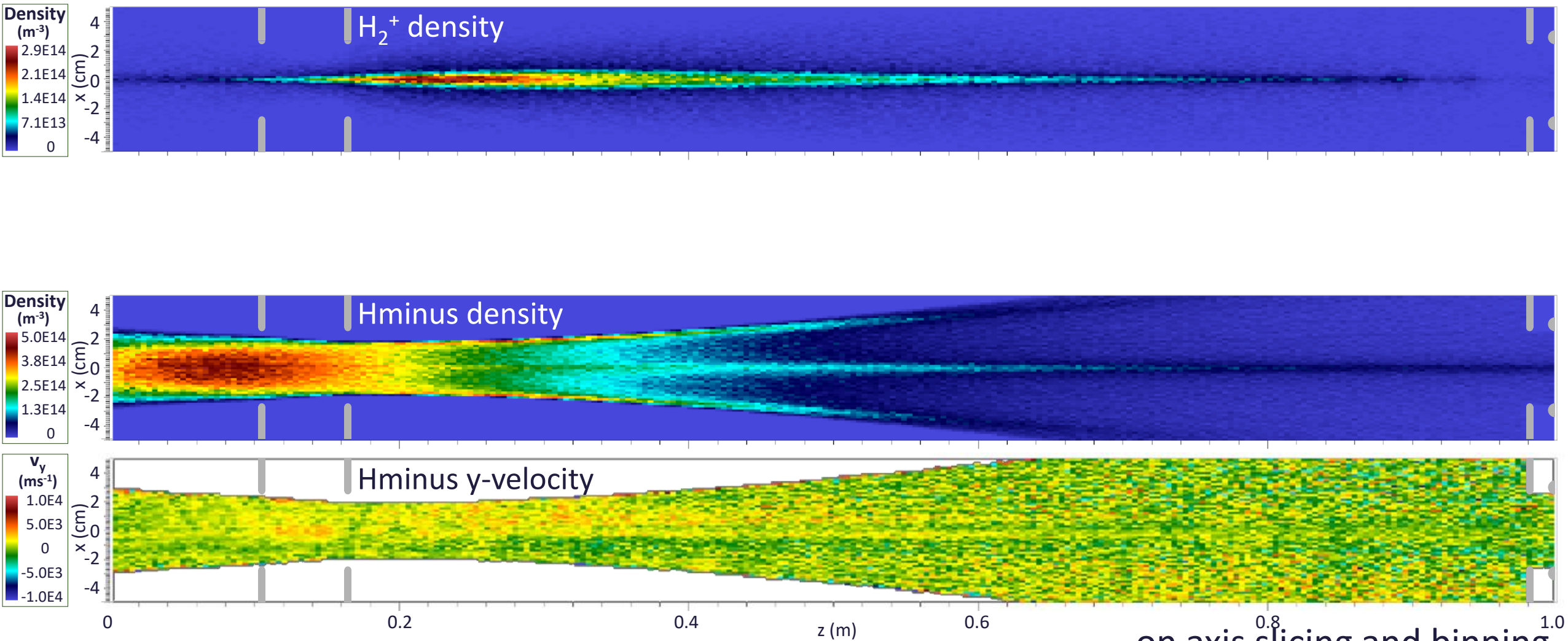


Effect of beam emittance

60 mA beam

Scale emittance 34.6 mm.mrad (0.21 rms norm.) **X 1**

Slice @ 20 μ s

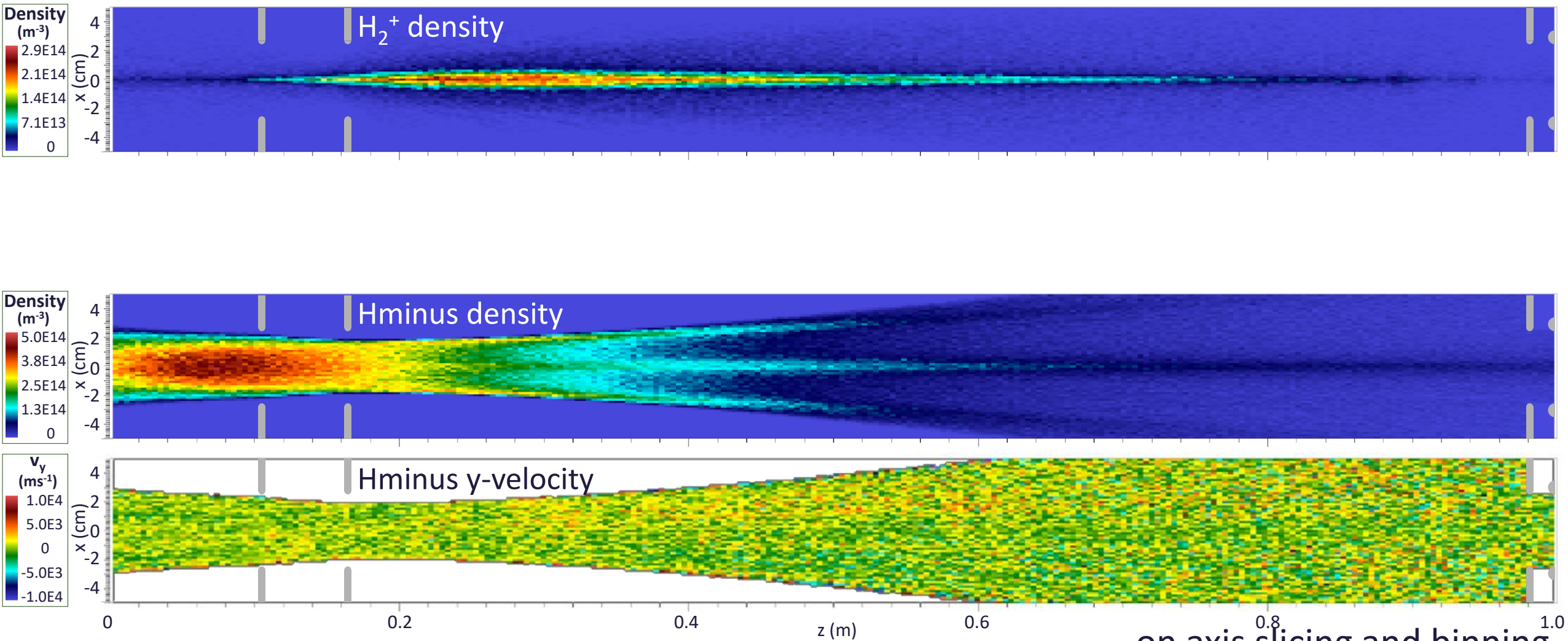


Effect of beam emittance

60 mA beam

Scale emittance 34.6 mm.mrad (0.21 rms norm.) **X 2**

Slice @ 20 μ s

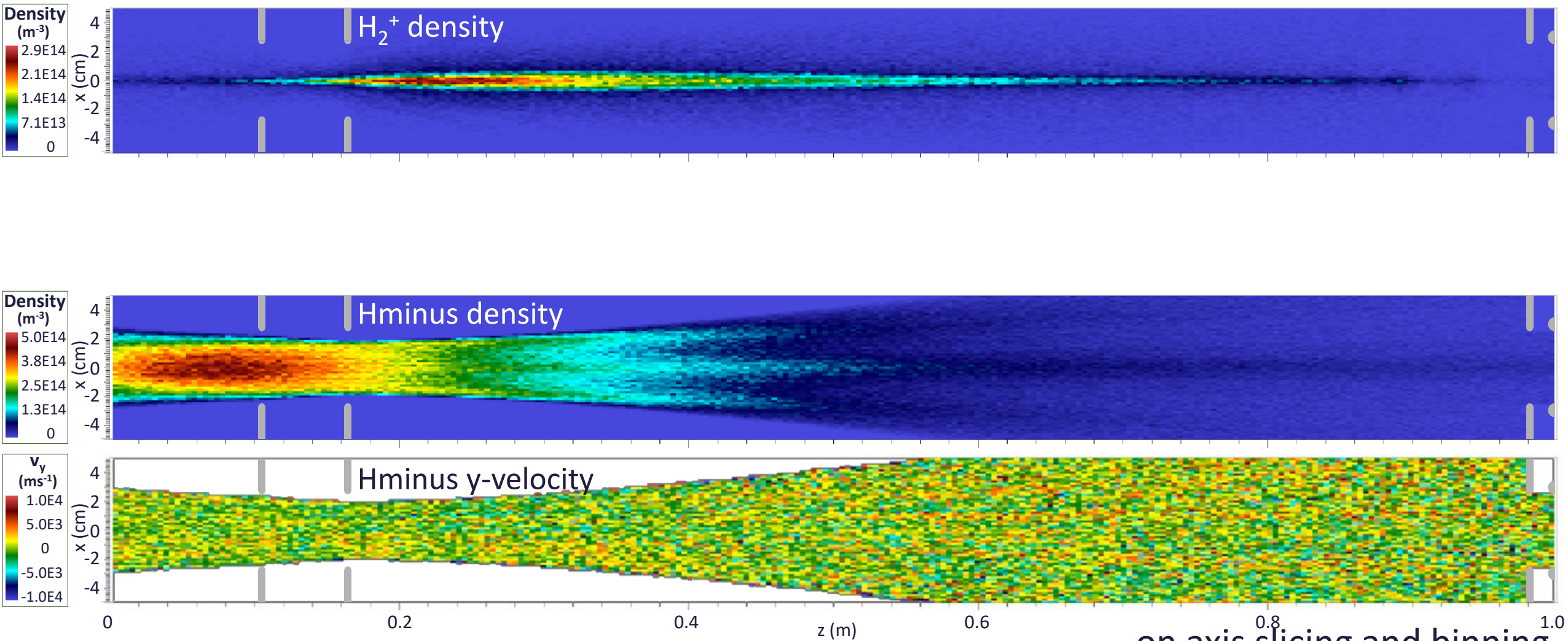


Effect of beam emittance

60 mA beam

Scale emittance 34.6 mm.mrad (0.21 rms norm.) **X 4**

Slice @ 20 μ s

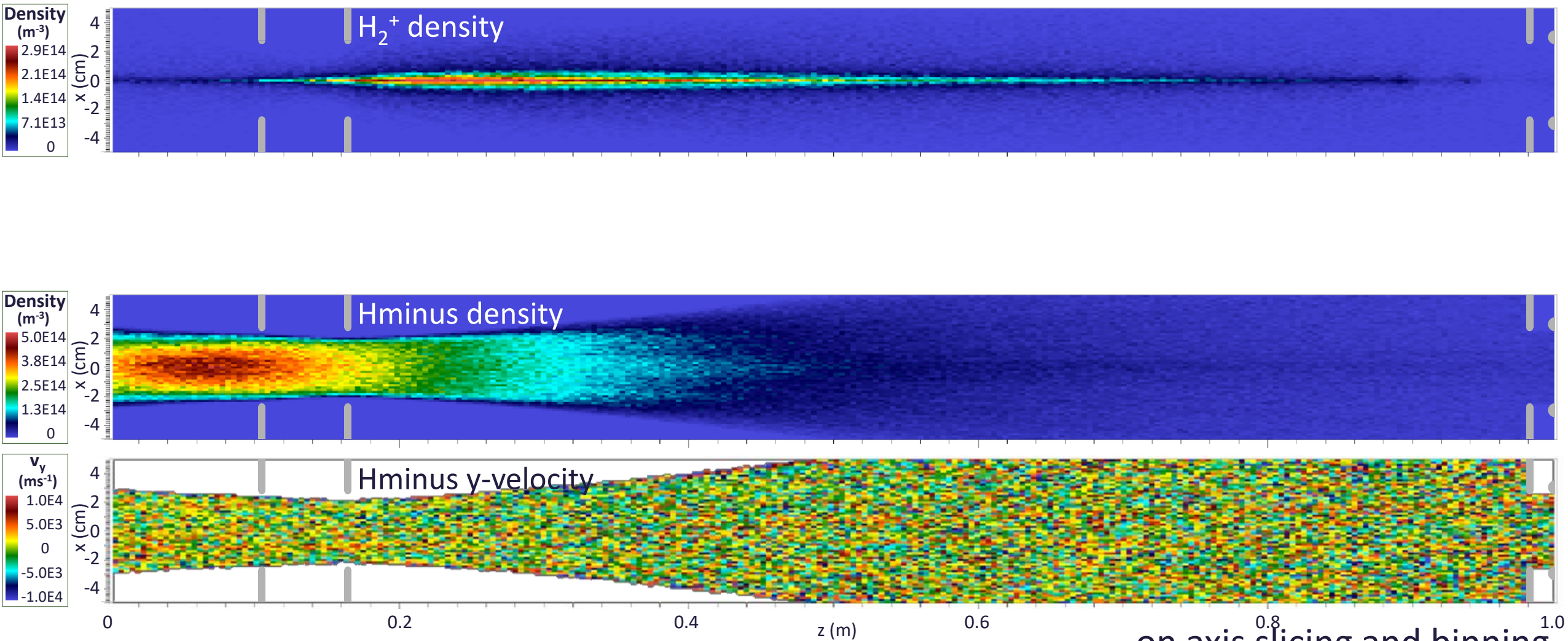


Effect of beam emittance

60 mA beam

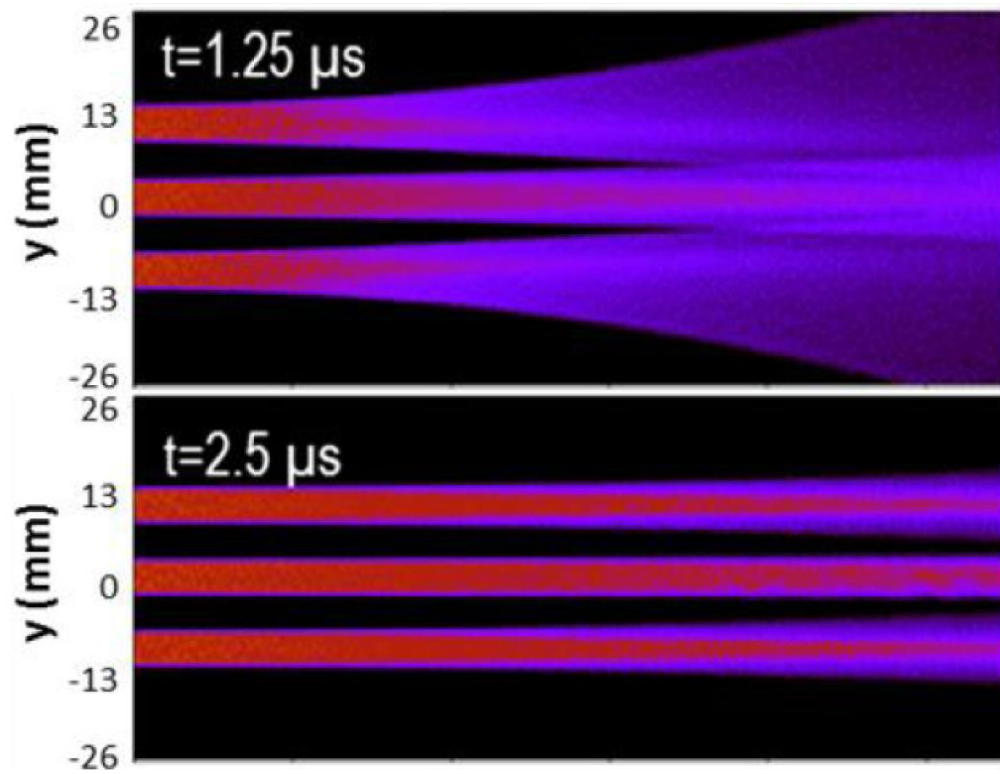
Scale emittance 34.6 mm.mrad (0.21 rms norm.) **X 8**

Slice @ 20 μ s



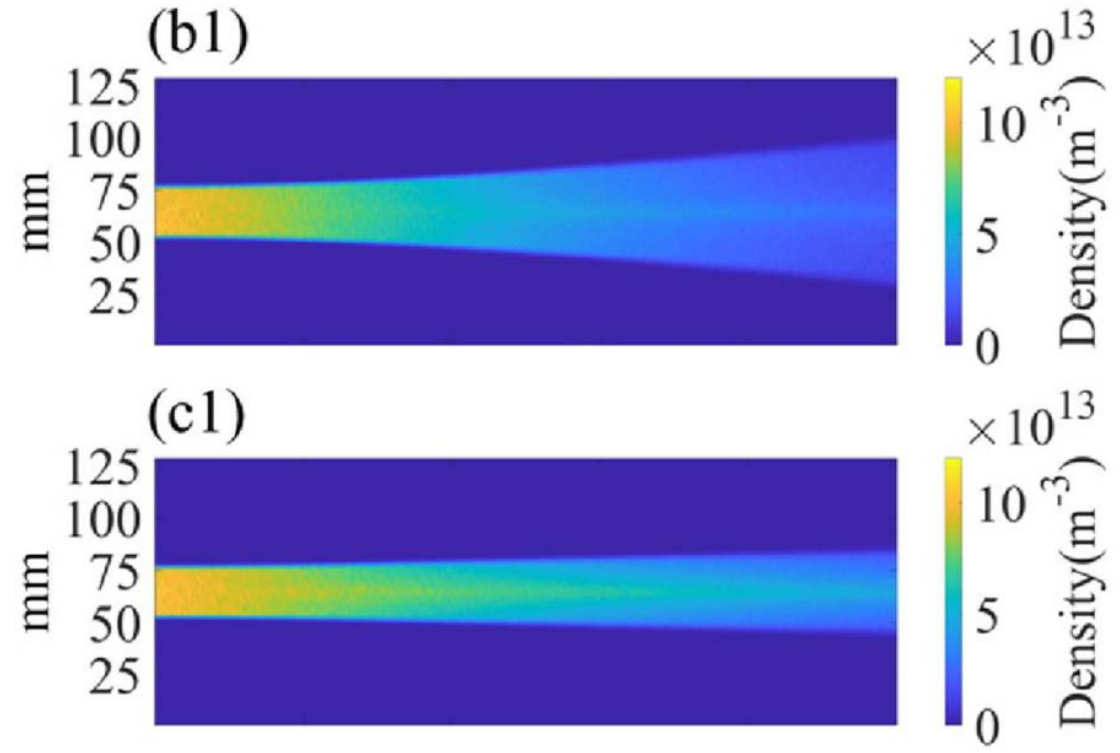
Other researchers have published PIC results with a dense core

(Higher pressure background)



1 μs

3 μs



Sartori et. al. "Simulation of space charge compensation in a multibeamlet negative ion beam"

REVIEW OF SCIENTIFIC INSTRUMENTS 87, 02B917 (2016)

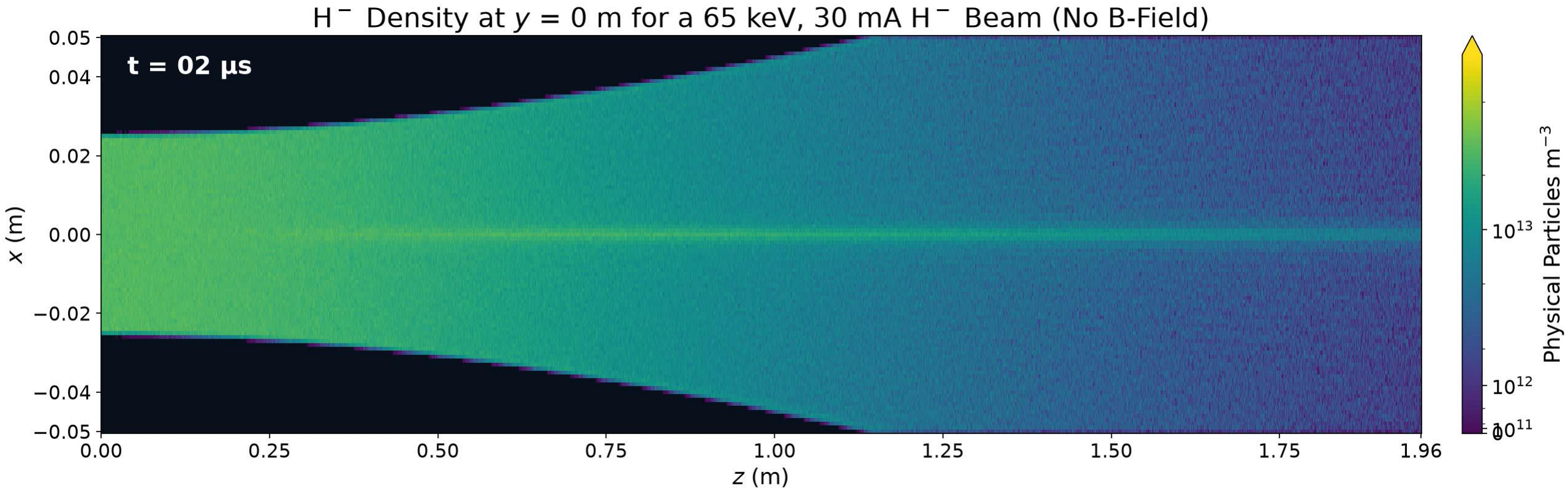
<https://doi.org/10.1063/1.4933252>

Li et al, "Transport process and space charge compensation of negative hydrogen ion beams in neutralization chambers"

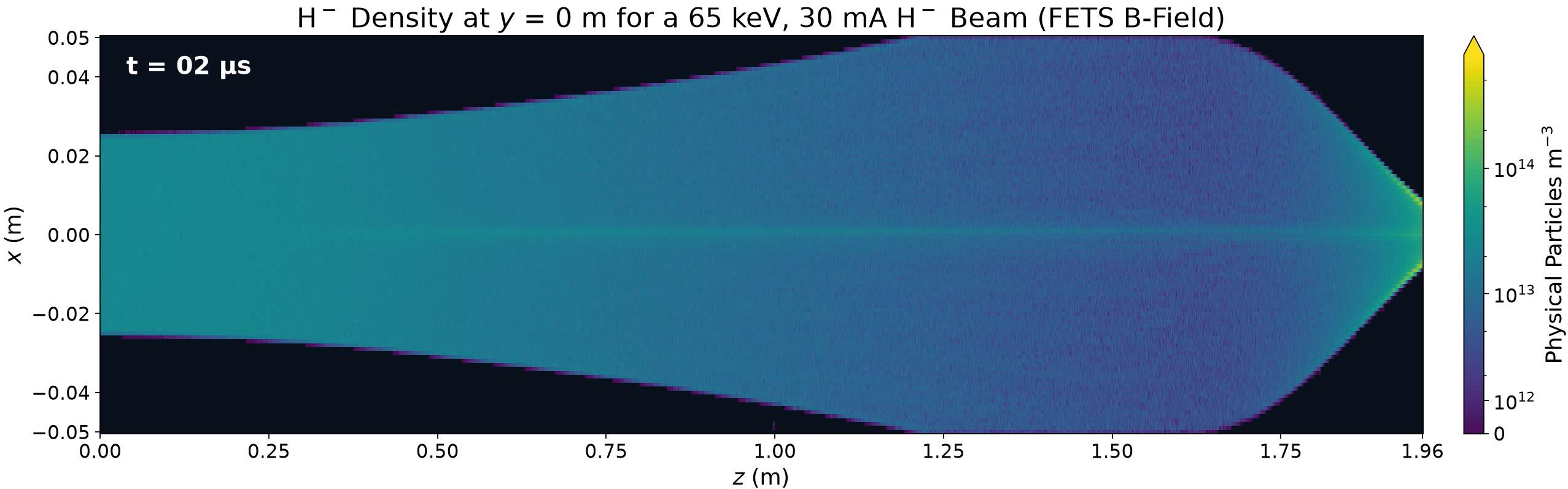
Plasma Phys. Control. Fusion 68 (2026) 045050

<https://doi.org/10.1088/1361-6587/ae60a5>

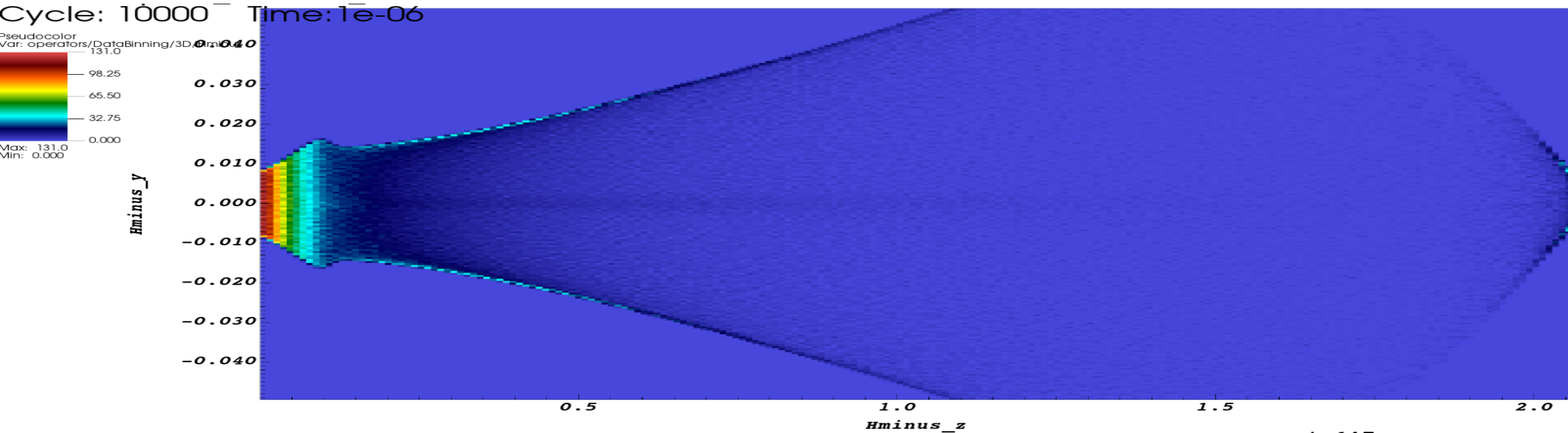
STFC Scientific Computing



STFC Scientific Computing

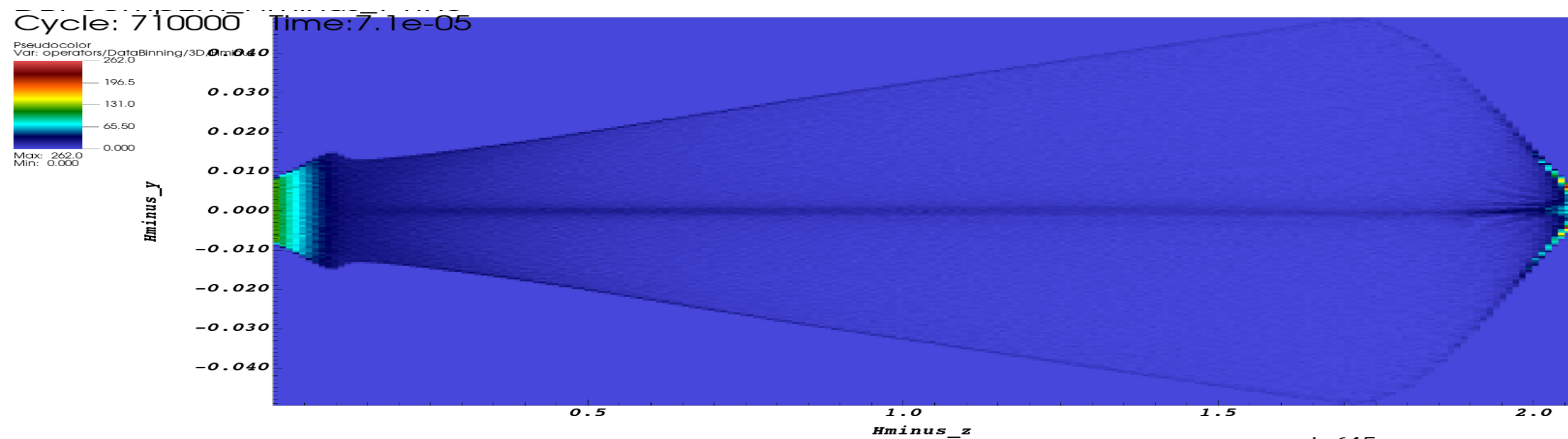


Hminus density 30 mA solenoids on



@ 1 μ s

Hminus density 30 mA solenoids on



@ 71 μ s

Curve
Var: HminusCurrent

30 mA transported

HminusCurrent

-0.005

-0.010

-0.015

-0.020

-0.025

-0.030

compensation time
comparable to
experiment

10

20

30

40

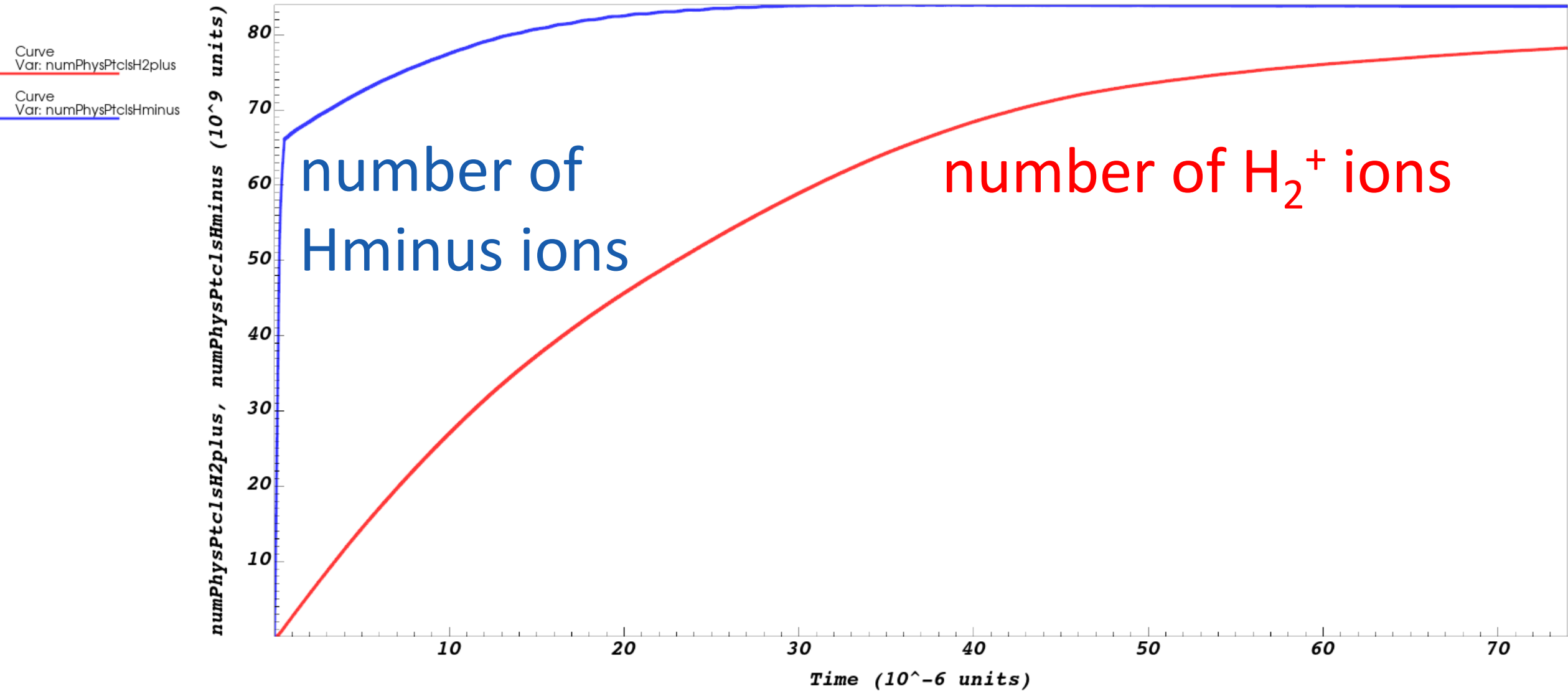
50

60

70

Time (10⁻⁶ units)

Does not reach 100% compensation



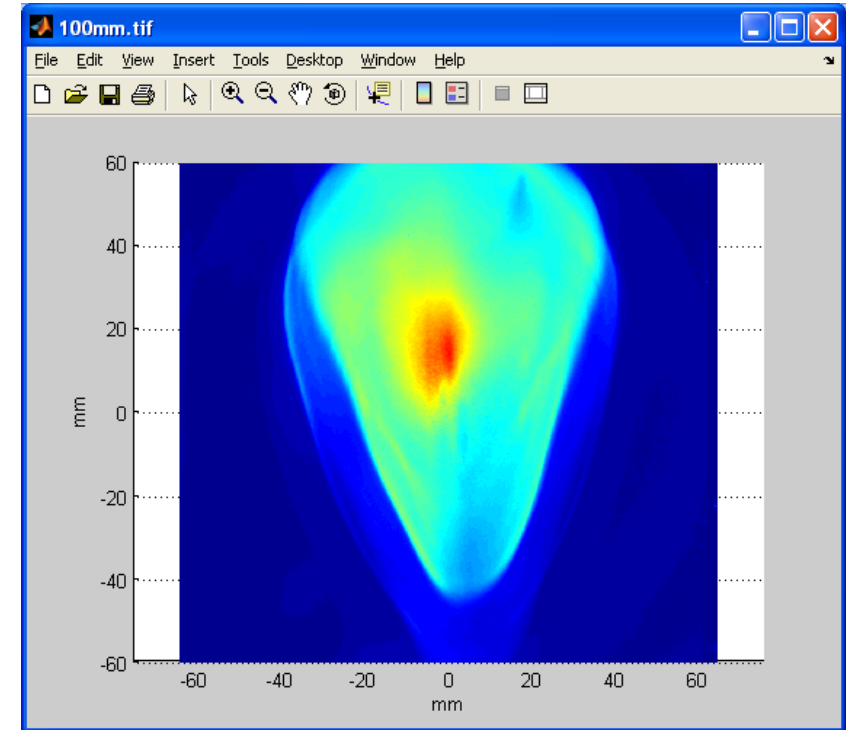
Aside- proton beams

The compensating behaviour is very different for positive beams
The mobility of the compensating particle is important.
Positive beams require a suppressor electrode to compensate fully

The dense core phenomenon
does not occur in proton beams

Conclusions

- The space charge from H_2^+ ions falling into the beam potential form on-axis, vortex-like, space charge structures that cause a twisting motion in the Hminus beam, creating a dense core
- The core becomes less pronounced as the emittance of the beam increases
- The dense core is transient:
 - if the beam is too defocused
 - if the beam reaches 100% SCC





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Thank you



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@STFC_matters



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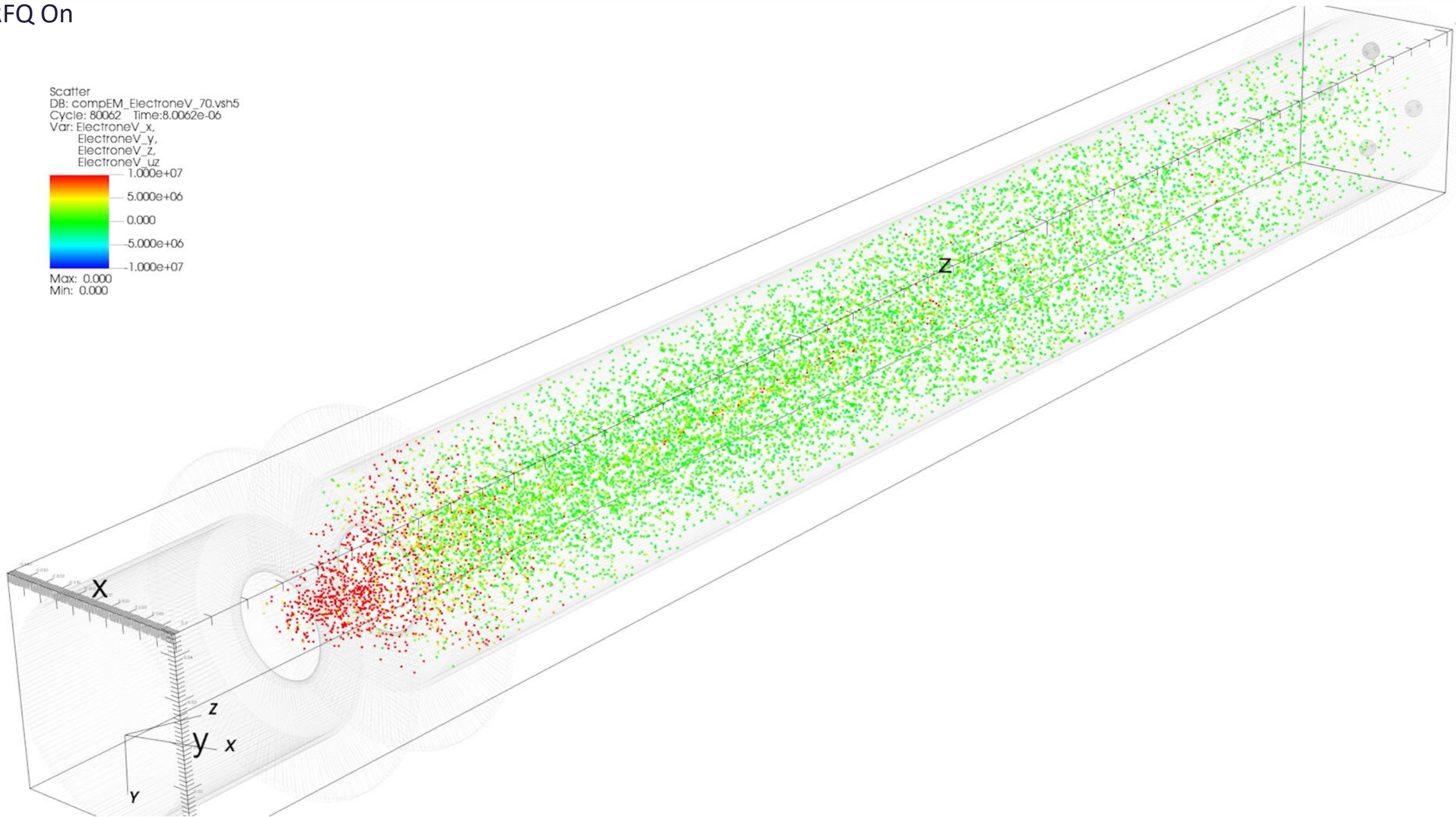
The background features a large blue rectangle on the right side, which is partially overlaid by a series of blue lines forming a complex, abstract geometric pattern. This pattern includes several nested, right-angled shapes and lines that create a sense of depth and movement. The overall color scheme is dominated by orange and blue.

Questions?

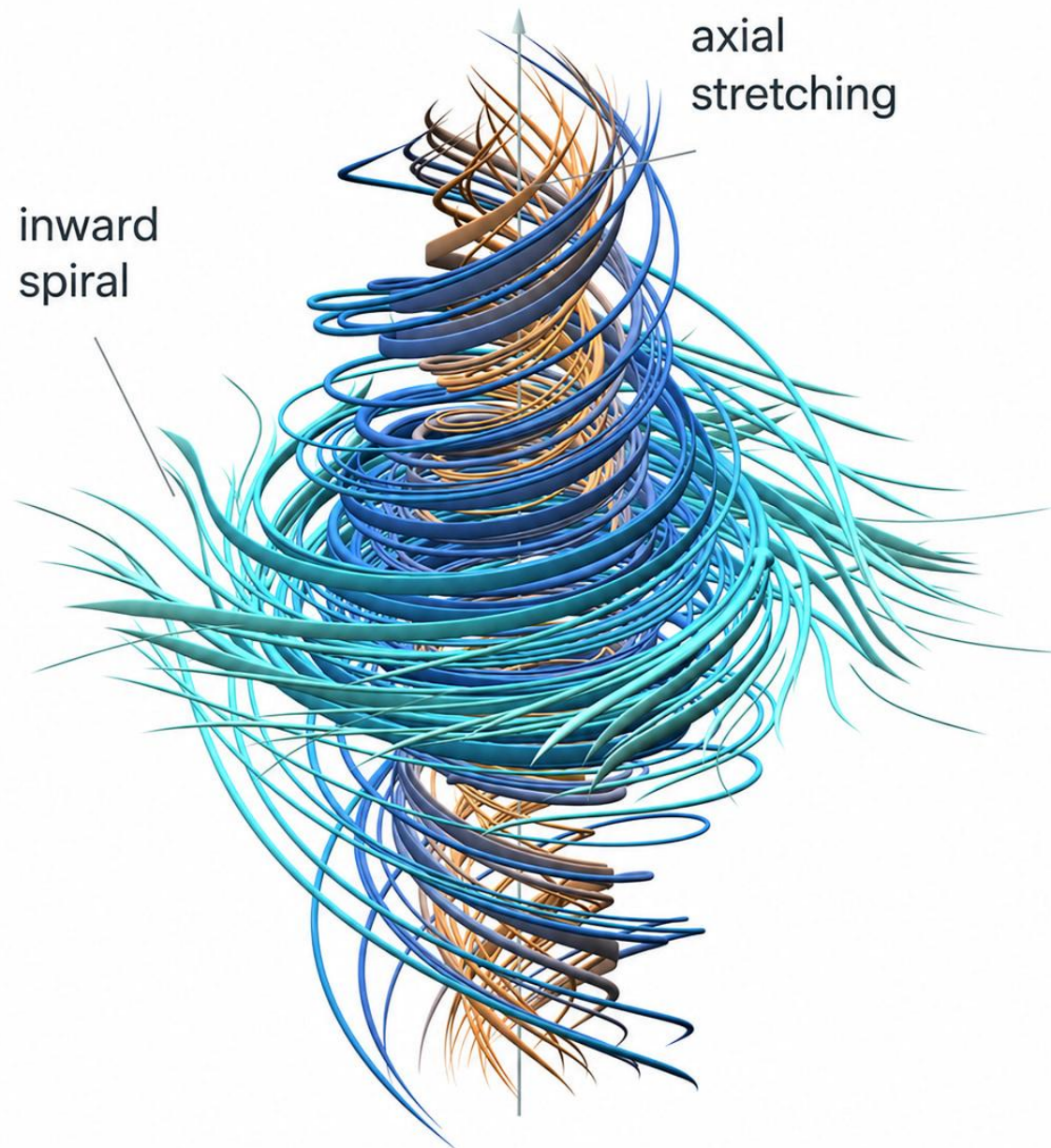
Additional slides
Electron motion

RFQ On

Scatter
DB: compEM_ElectroneV_70.vsh5
Cycle: 80062 Time: 8.0062e-06
Var: ElectroneV_x,
ElectroneV_y,
ElectroneV_z,
ElectroneV_uz
1.000e+07
5.000e+06
0.000
-5.000e+06
-1.000e+07
Max: 0.000
Min: 0.000



Additional slides
Is this just maths?



DB: compEM_Hminus_6.h5
Cycle: 60000 Time: 6e-06

Pseudocolor
Var: operators/DataBinning/3D/Hminus

1.005e+04
7539.04
5025.
2512.
0.0000.02
Max: 1.005e+04
Min: 0.000

Hminus_y

0.00

-0.02

-0.04

0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8
Hminus_z

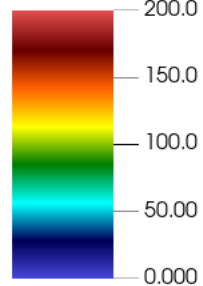
H⁻ ion density

Try super
high
resolution
mesh on axis
(10 μm)

10 μm mesh

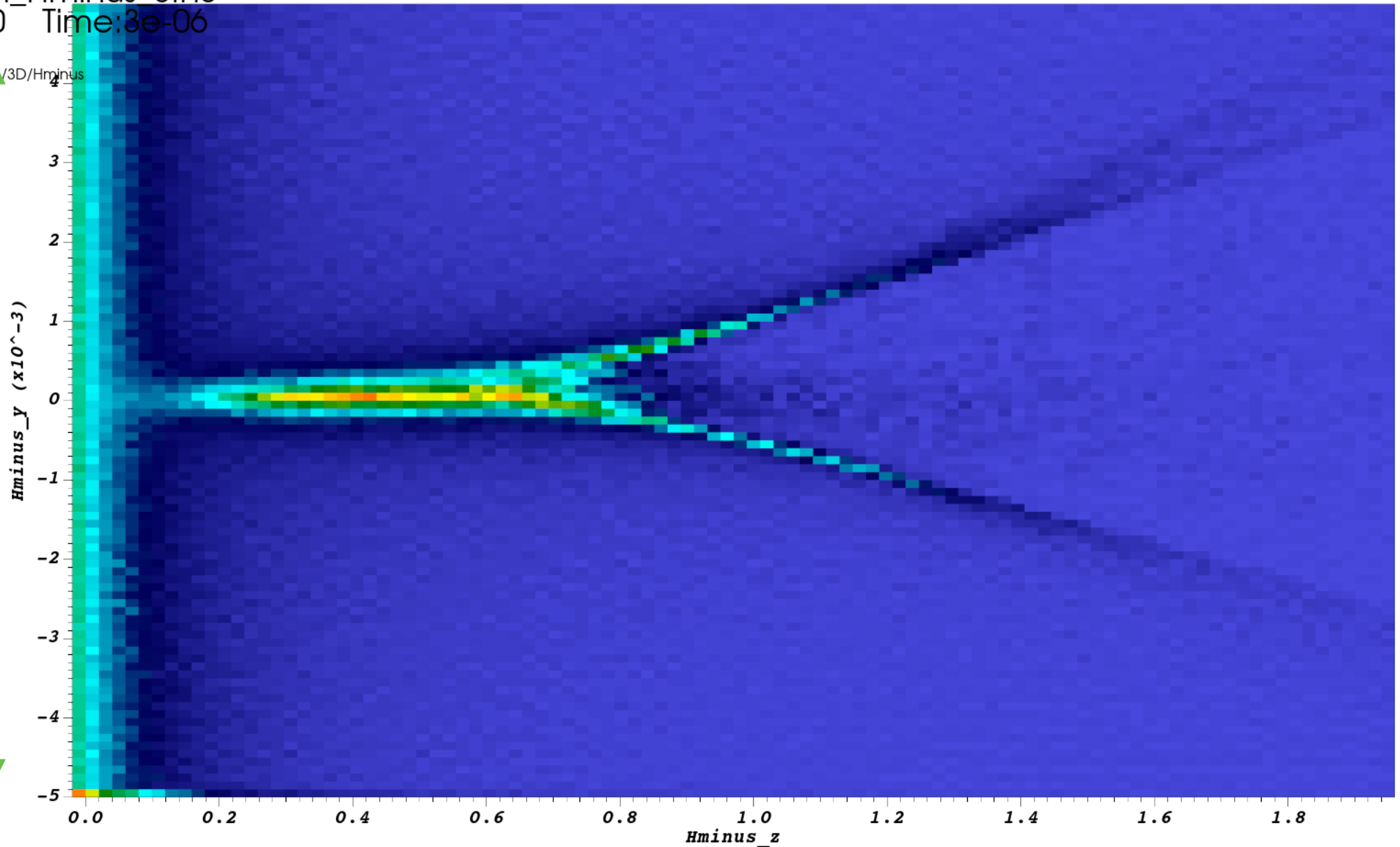
DB: compEM_Hminus_3.h5
Cycle: 30000 Time: 3e-06

Pseudocolor
Var: operators/Data/3D/Hminus



H⁻ ion
density

1 cm
zoom



Infinites can be created for zero emittance beams!

user: dcf45
Mon Sep 22 12:50:30 2025