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Welcome

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The Child Langmuir Illusion

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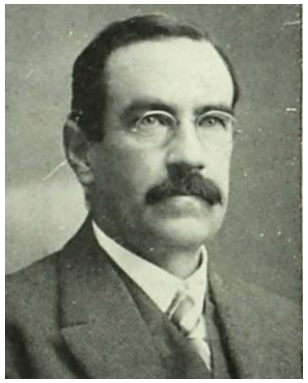
ICIS2023 Victoria, Canada
Sep 18, 2023

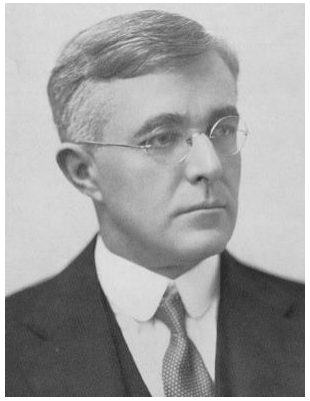
UNIVERSITY OF JYVÄSKYLÄ

Child Langmuir Law - Space charge limited extraction



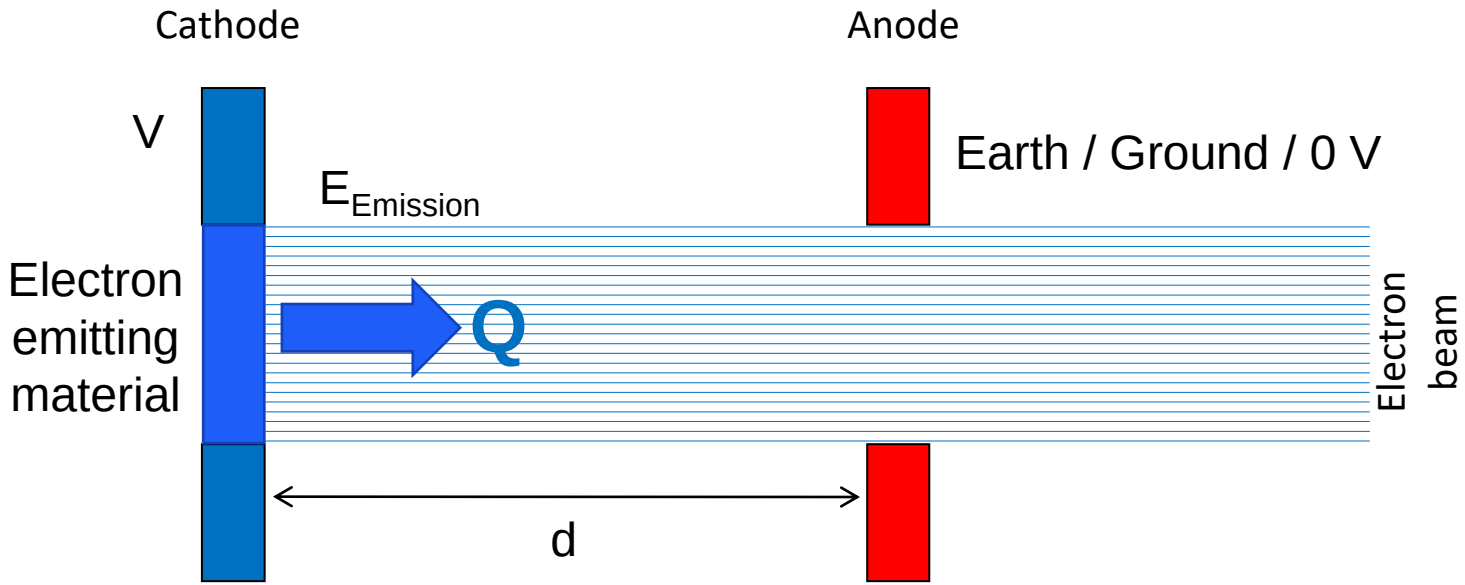
1911

Clement Dexter Child



1913

Irving Langmuir



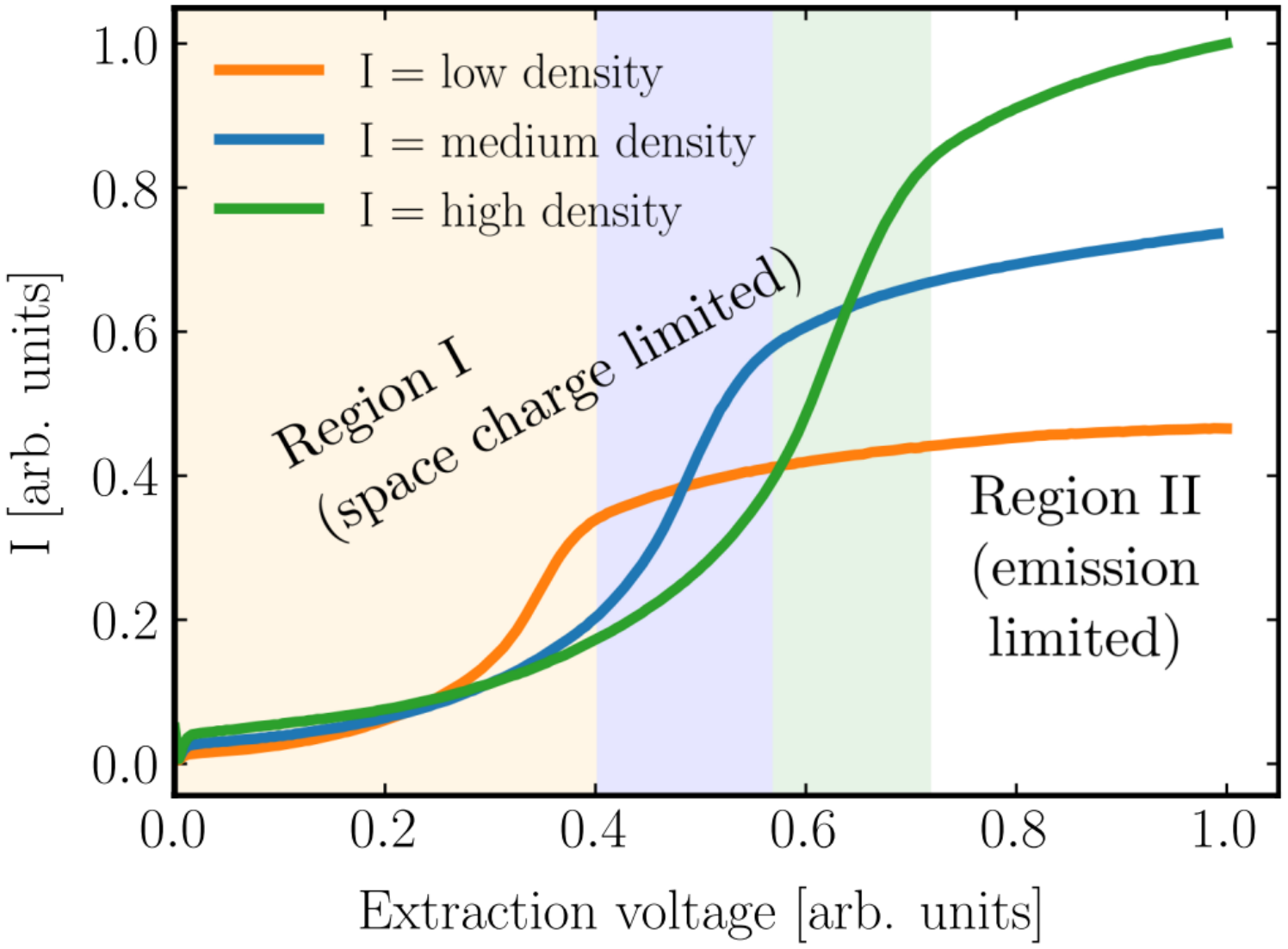
$$j = \frac{\frac{4}{9}\varepsilon_0\sqrt{\frac{2e}{m_e}}V^{\frac{3}{2}}}{d^2}$$

1 Dimensional

Assumptions

1. There are infinitely many particles available to be emitted. ✗
2. The emitted particles have zero initial velocity. ✗
3. The emitted particles have non-relativistic velocities. ✓
4. The electrodes are parallel and infinite in the plane normal to the beam. ✗
5. Constant spatial distribution of particles perpendicular to the direction of beam propagation. ✗
6. Zero electric field at the emitting surface. ✗

Accepted wisdom



As espoused by:

The physics and technology of ion sources 2nd Ed.
Brown I. 2004
(Wiley-VHC)

Theory and design of charged particle beams
Reiser M. 2009
(Wiley-VHC)

Particle Sources
Faircloth D. 2011-2023
(CERN Accelerator School)

… and many others

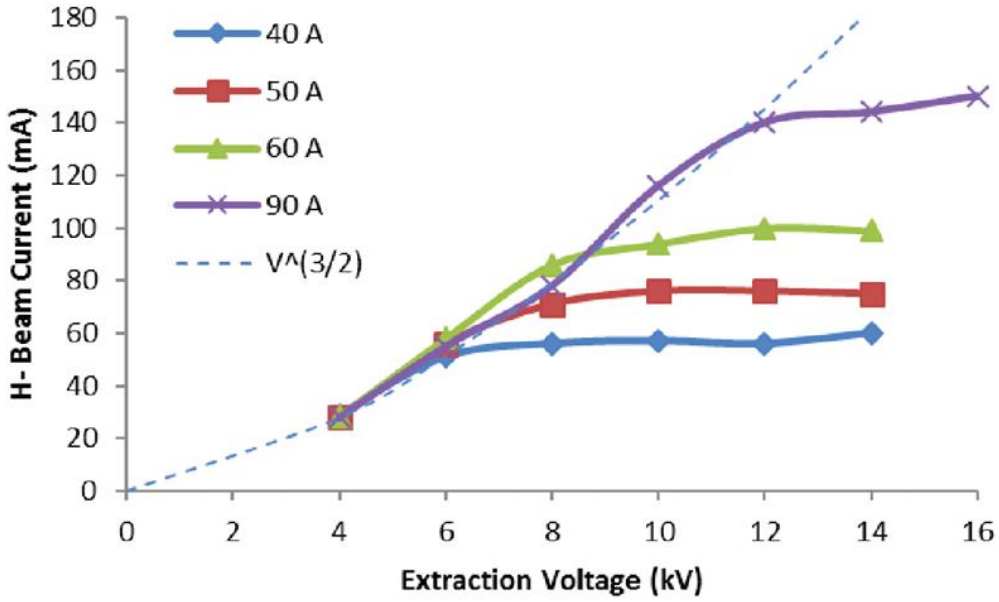
“In the space charge limited region, the extracted current varies as V^(3/2)”

I am guilty of fitting V^(3/2) curves to data from my extraction studies:

High current results from the 2X scaled Penning source

D. C. Faircloth, S. R. Lawrie, O. Tarvainen, T. Sarmento, M. O. Whitehead, J. Macgregor, R. Abel, T. Wood

AIP Conference Proceedings 2052, 050004 (2018)
https://doi.org/10.1063/1.5083758

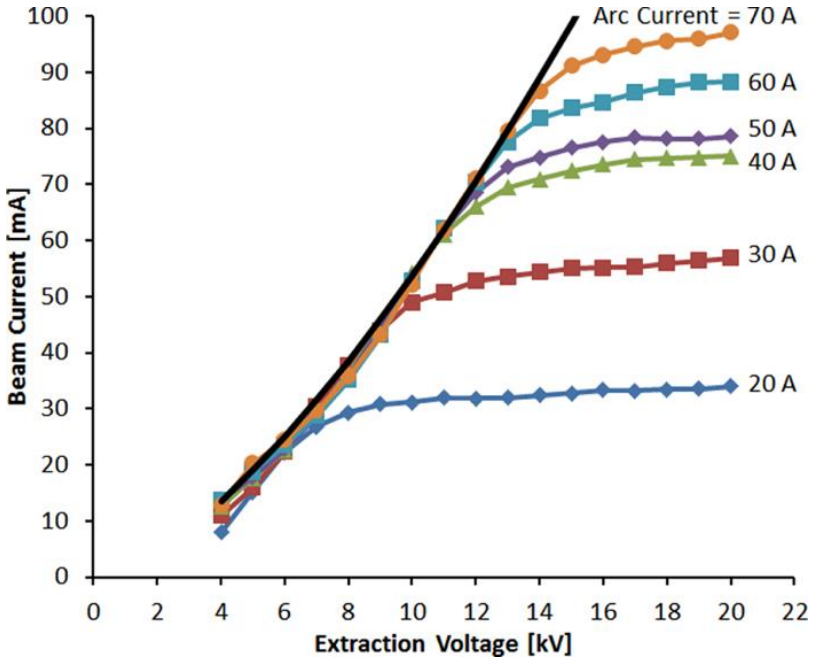


NIBS2018

Detailed beam and plasma measurements on the vessel for extraction and source plasma analyses (VESPA) Penning H⁻ ion source

S. R. Lawrie, D. C. Faircloth, A. P. Letchford, M. O. Whitehead, T. Wood

Rev Sci Instrum 87, 02B122 (2016)
https://doi.org/10.1063/1.4934580



ICIS2015

However…

The true cause of the observed power law is meniscus focusing and collimation on the extraction (puller) electrode

Recent Work

Critical assessment of the applicability of the Child-Langmuir law to plasma ion source extraction systems

S T Kosonen, T Kalvas, V Toivanen, O Tarvainen, D Faircloth

Plasma Sources Sci. Technol. **32** 075005
Published 12 July 2023
DOI 10.1088/1361-6595/ace0d7

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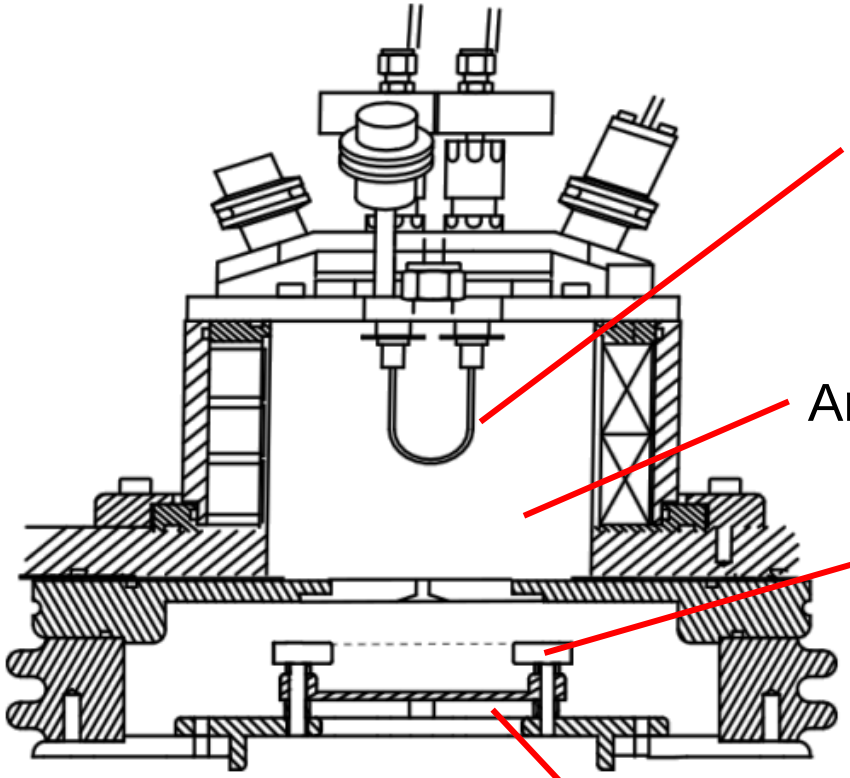
Experiments + Modelling = Confirmation that the observed power law is caused by meniscus focusing and collimation

Experiments

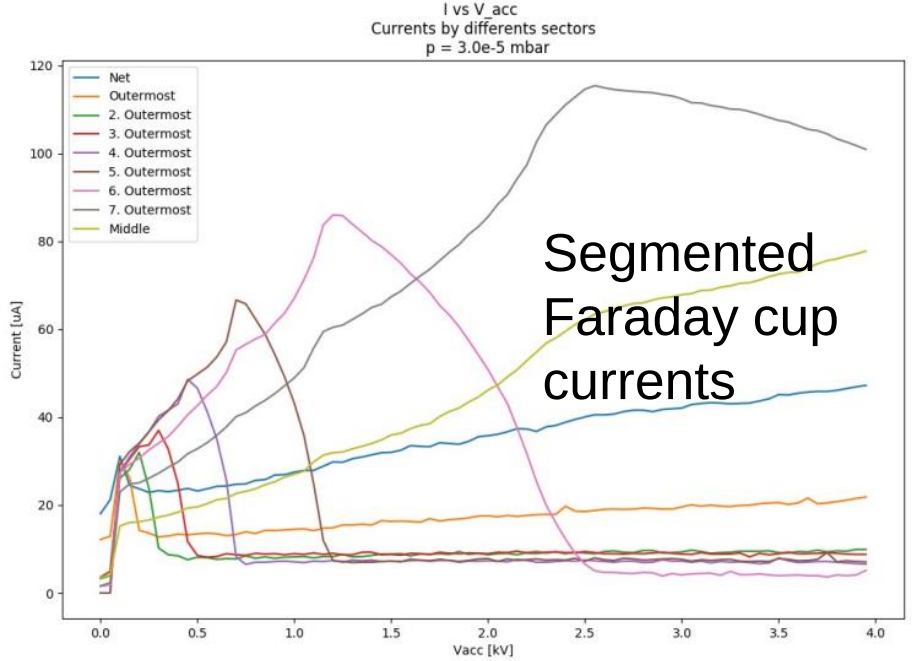


Simple filament source

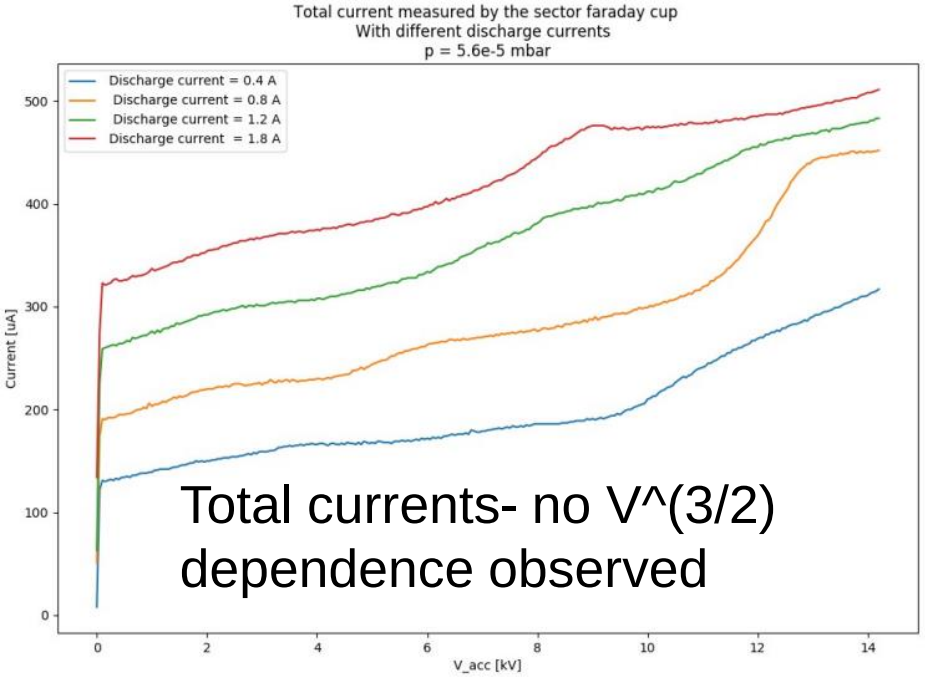
Argon plasma

Grid extraction (no collimation)

Concentric segmented ring Faraday cup



Segmented Faraday cup currents



Total currents- no V^(3/2) dependence observed

100 µA beams

Modelling options

Particle in Cell (PIC) codes

e.g.

VSim For Multiphysics Simulations XTech-X SIMULATIONS EMPOWERING YOUR INNOVATIONS

ONIX

KEIO-BFX

PICLas etc

Problem: High mesh density required to resolve the Debye length in plasma

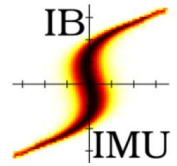
+

long extraction gap

vs

Tracking codes coupled with plasma equations

e.g.



IGUN etc

Problem: Do they truly reproduce the plasma dynamics?

The Combined Approach

Recent examples:

LINAC4 H- source

S. Nishioka, S. Abe, S. Mattei, J. B. Lallement, T. Kalvas, A. Hatayama, J. Lettry
https://doi.org/10.1063/1.5053372

KEIO-BFX + NINJA + IBSimu, TRAVEL

ELISE ion source

M Lindqvist, N Harder, A Revel, S Mochalskyy, A Mimo, R Nocentini, T Minea and U Fantz
DOI 10.1088/1741-4326/ac9c6f

ONIX+IBSimu

IB IMU

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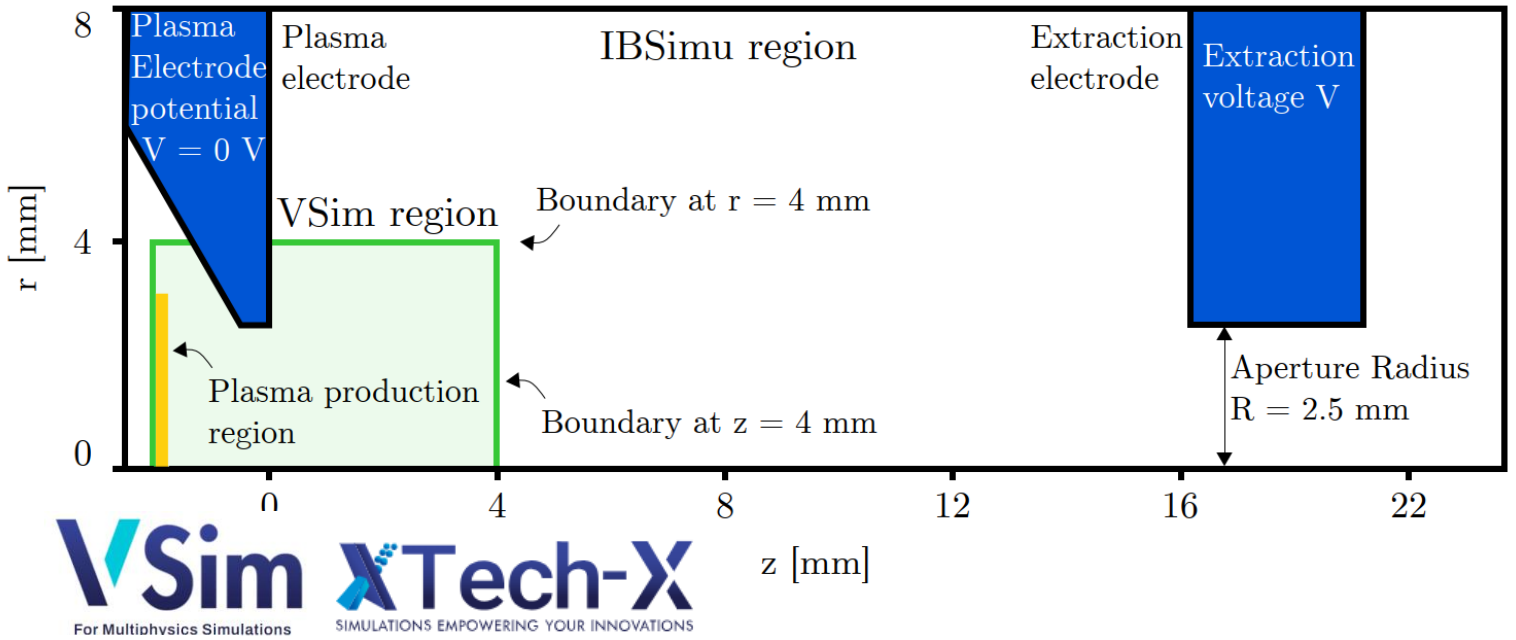
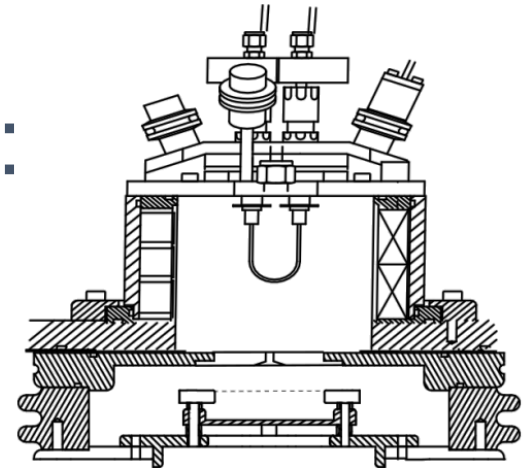


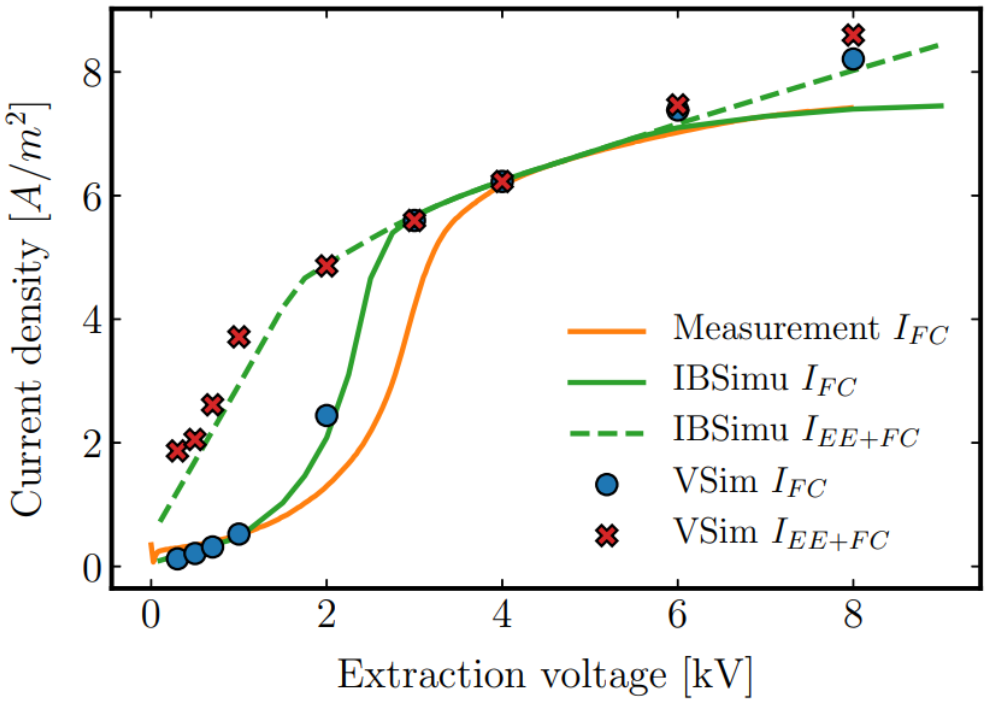
VSim For Multiphysics Simulations

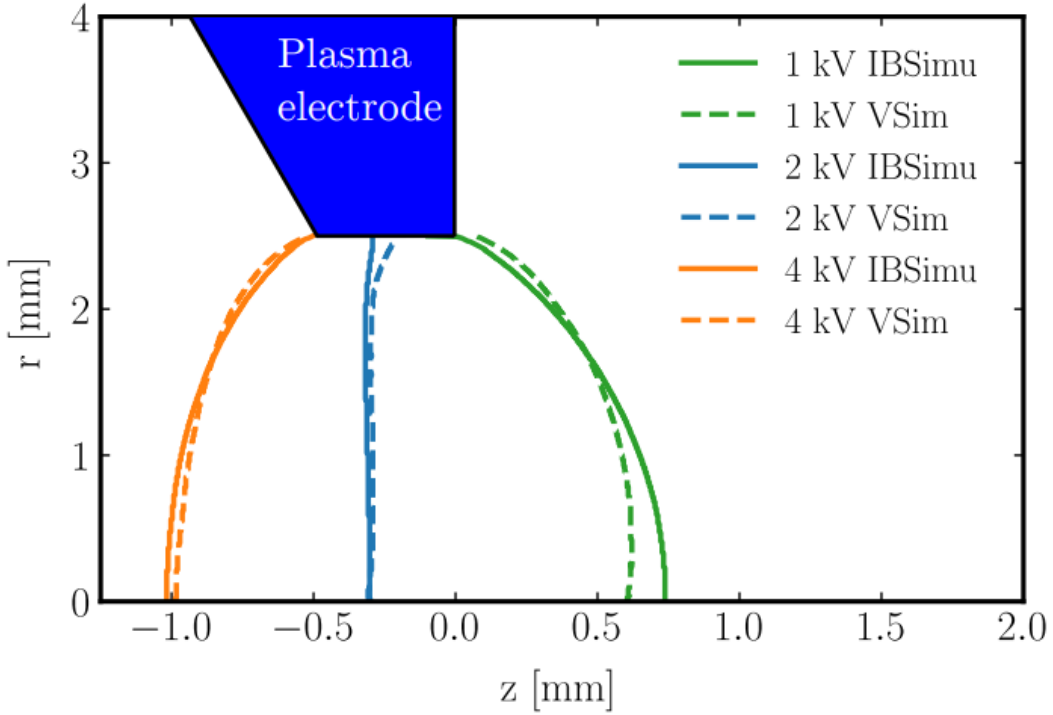
Tech-X SIMULATIONS EMPOWERING YOUR INNOVATIONS

Good comparison between:

- Experimental results *and*
- IBSimu + VSim *and*
- IBSimu

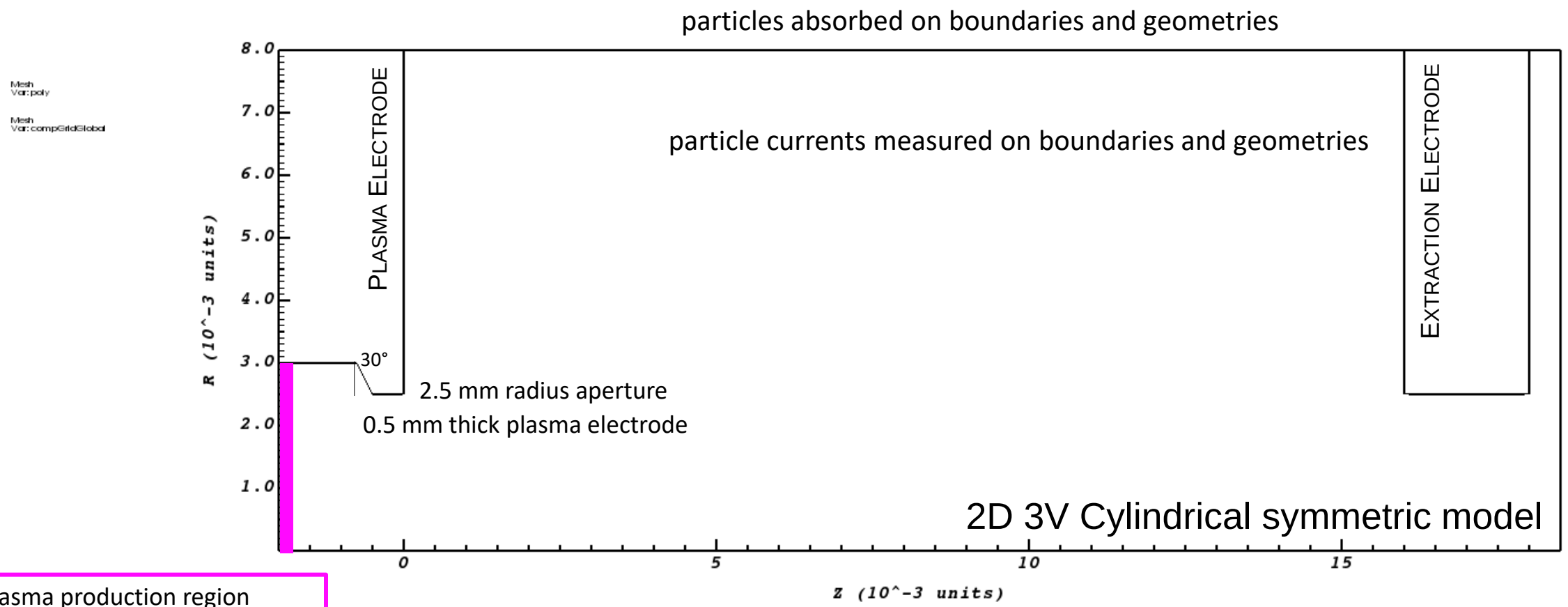






But doubts still exist when combining models…

A Single Model: PIC with a variable mesh density



plasma production region

3 mm radius, 0.2 mm thick disk

2.0 eV Gaussian electrons

0.1 eV Gaussian Ar^+ ions

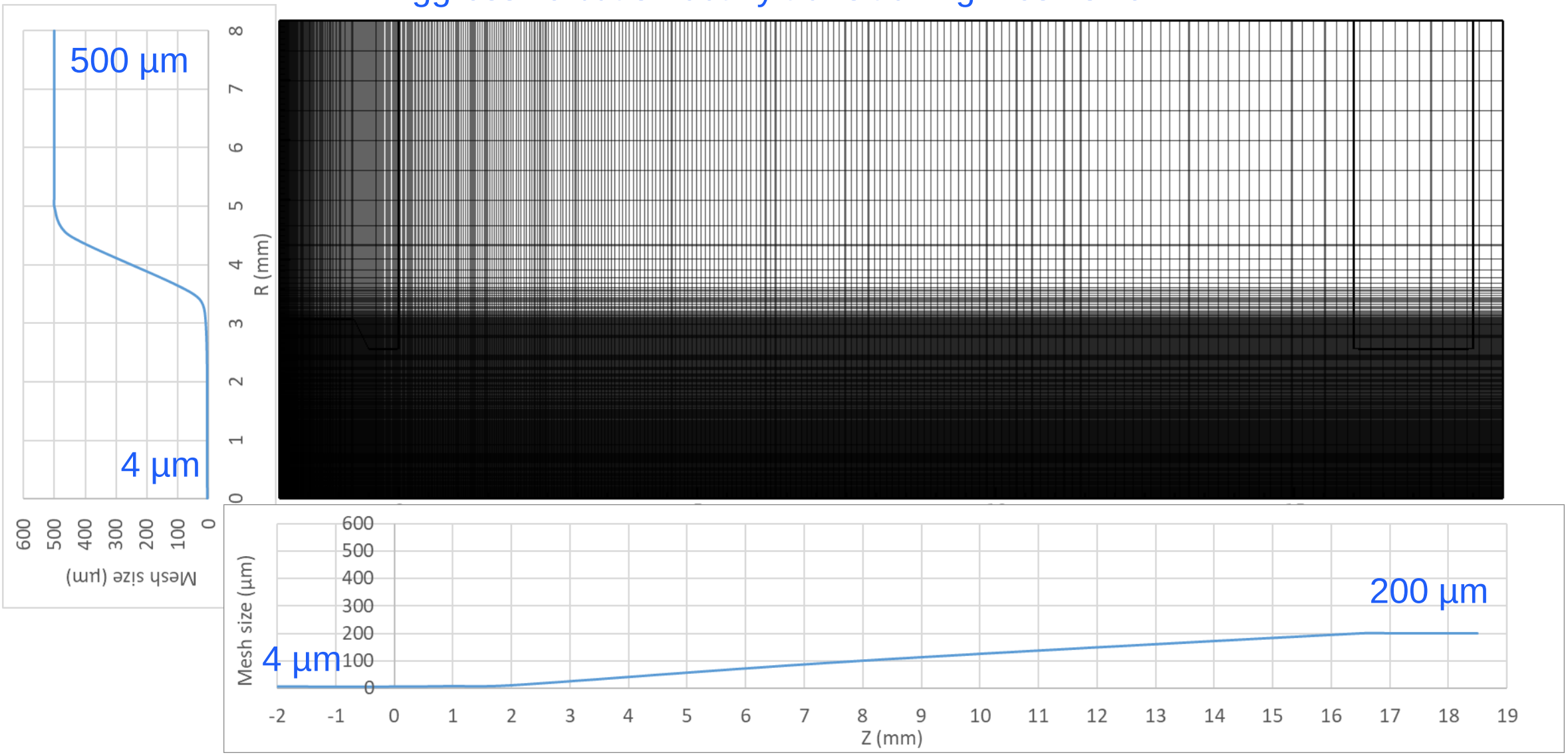
7.2×10^{23} $m^{-3}s^{-1}$ load rate

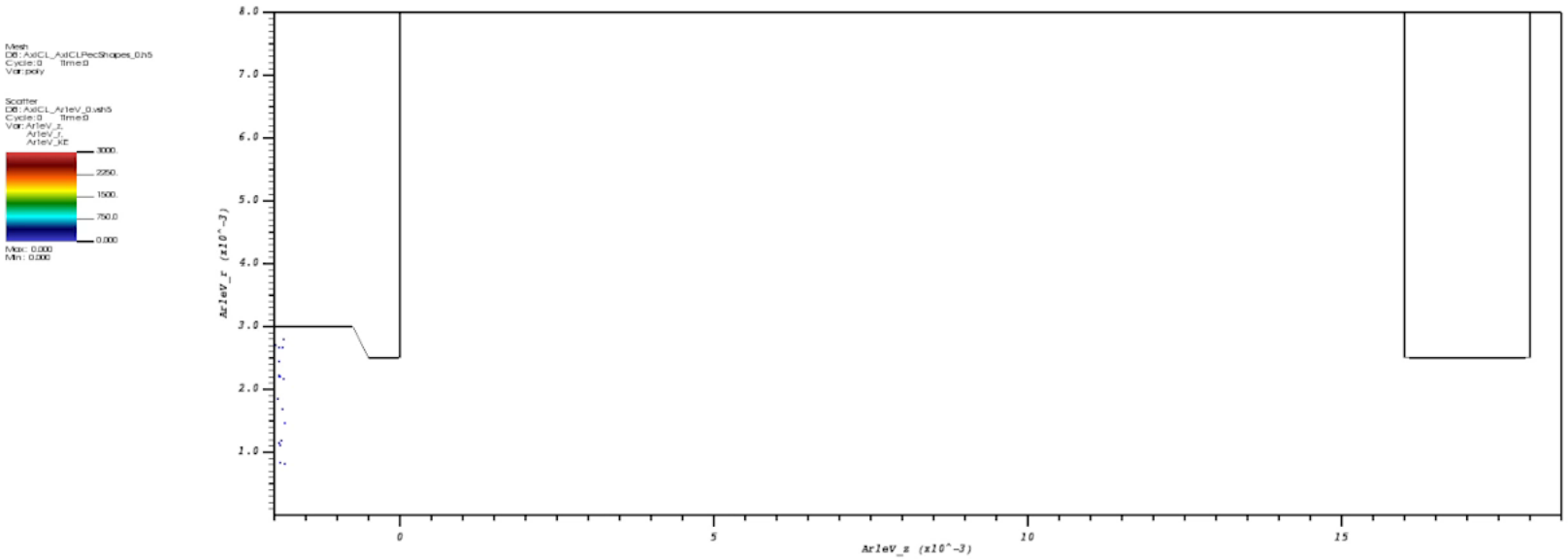
Load rate set to match experimental beam current at 4 kV extraction

A Single Model: PIC with a variable mesh density

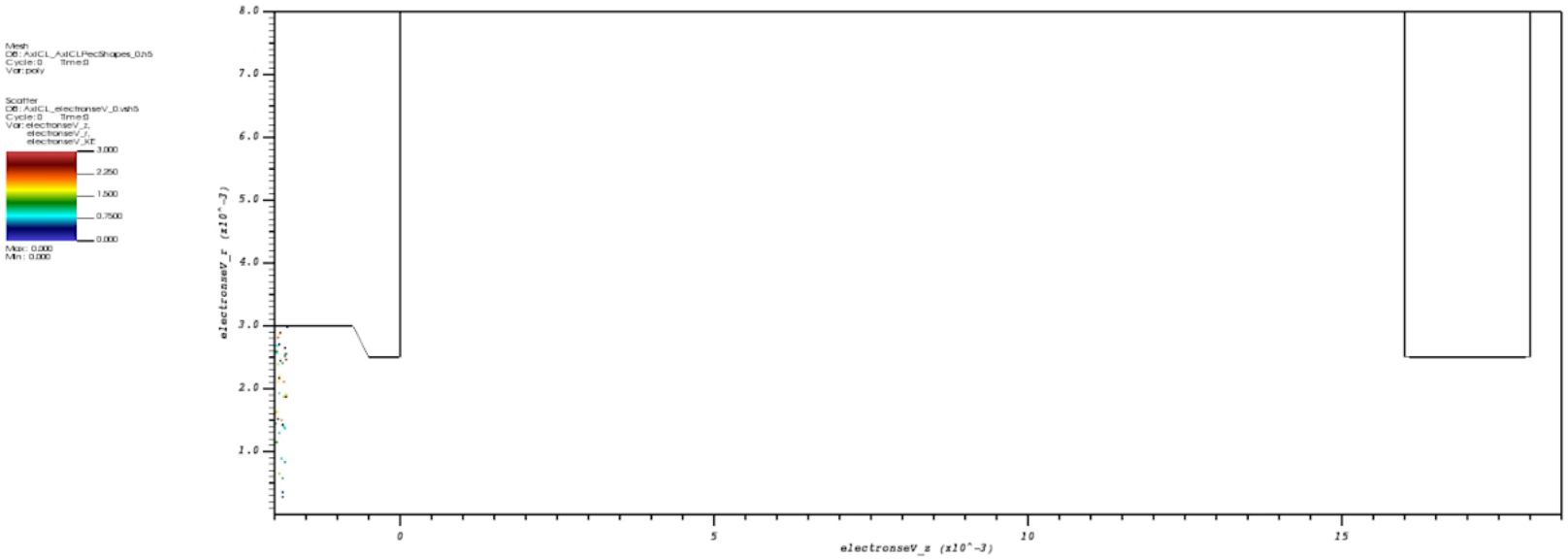
383 by 448 mesh cells

Aggressive but smoothly transitioning mesh size





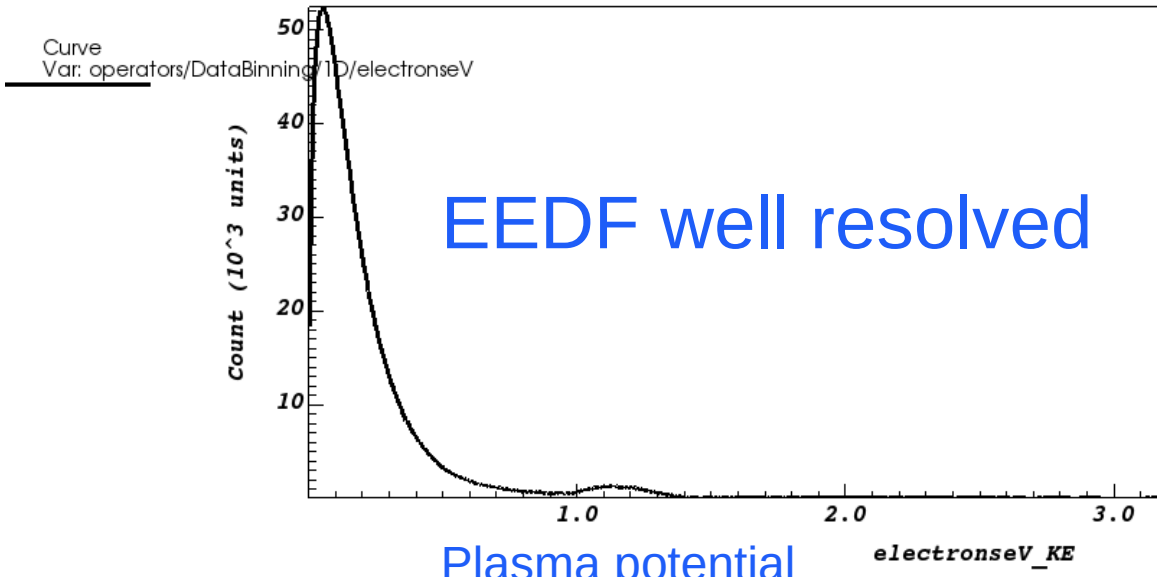
Ar+ Ions
3 keV colour scale



Electrons
3 eV colour scale

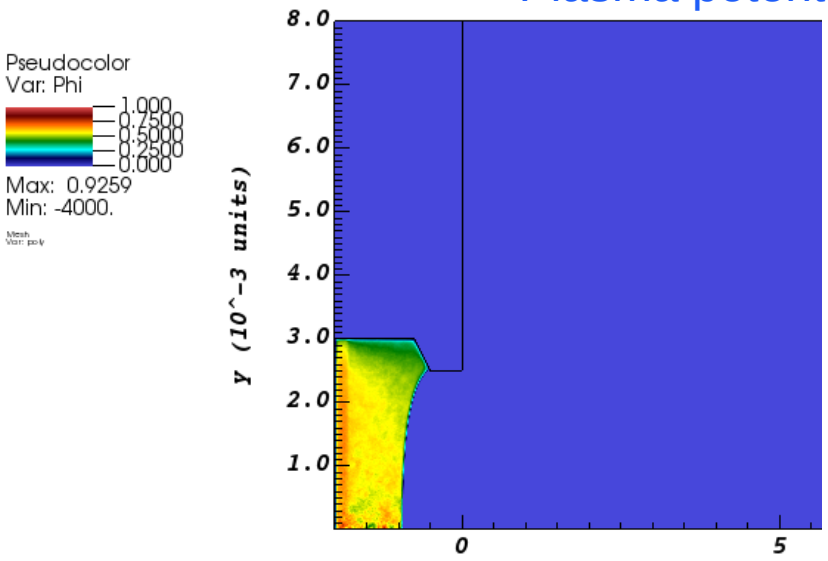
3 kV extraction voltage

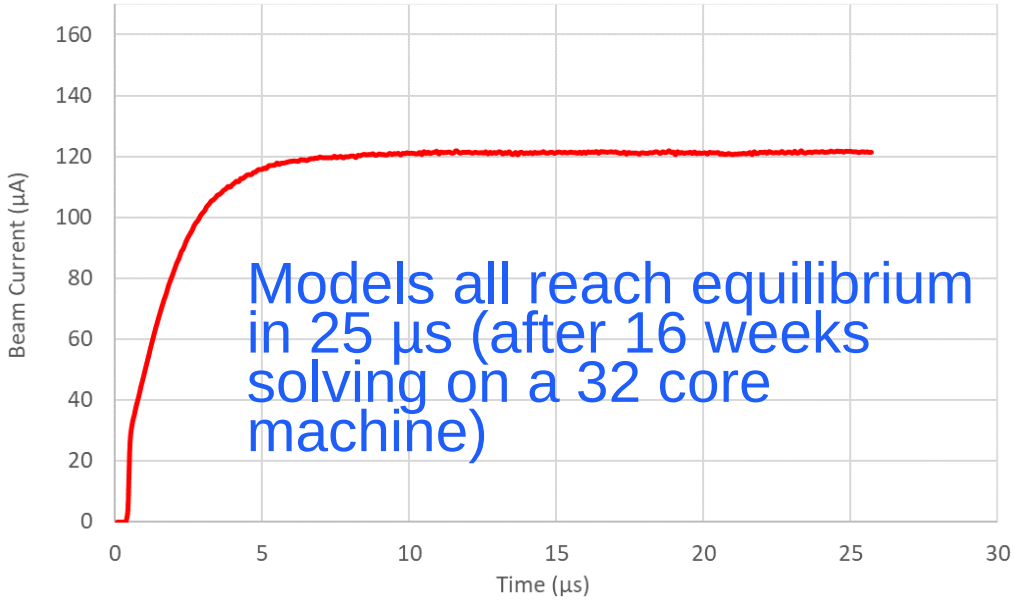
Run to equilibrium



EEDF well resolved

Plasma potential





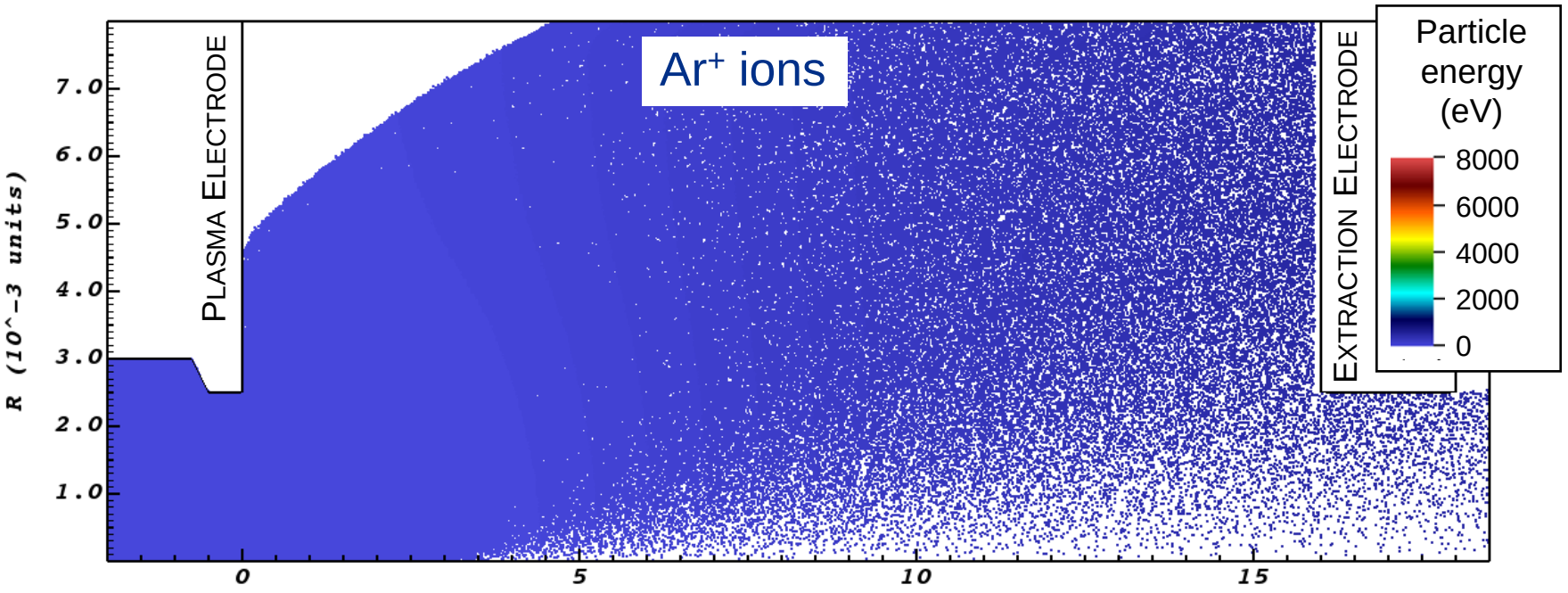
Models all reach equilibrium in 25 µs (after 16 weeks solving on a 32 core machine)

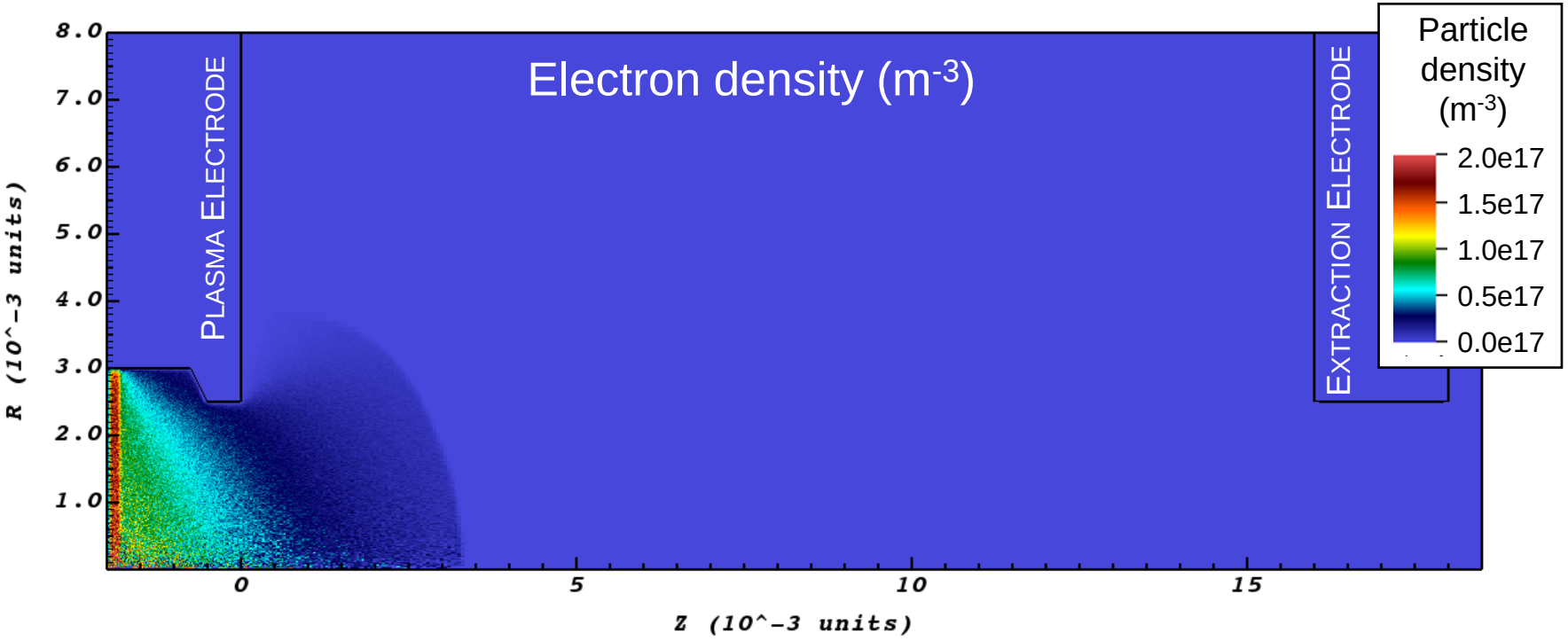
Record:

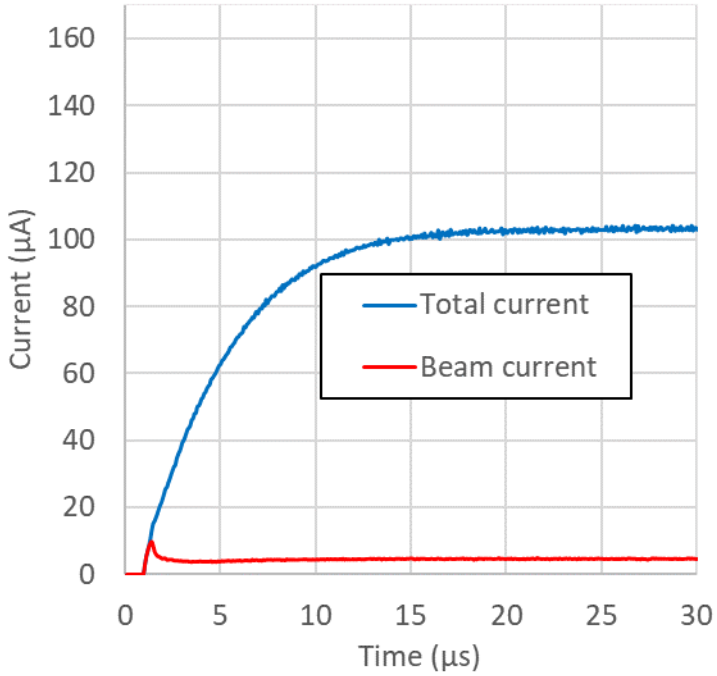
- total current
- beam current
- emittance (after extraction electrode)

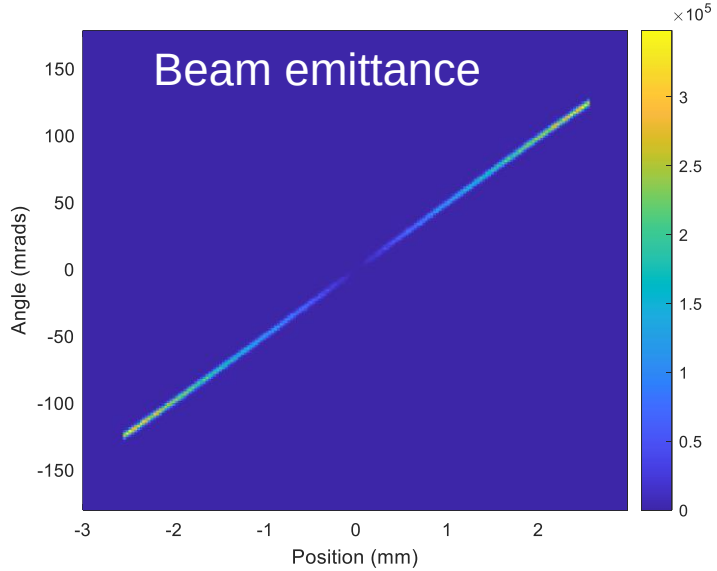
Repeat at different extraction voltages…

500 V Extraction Voltage

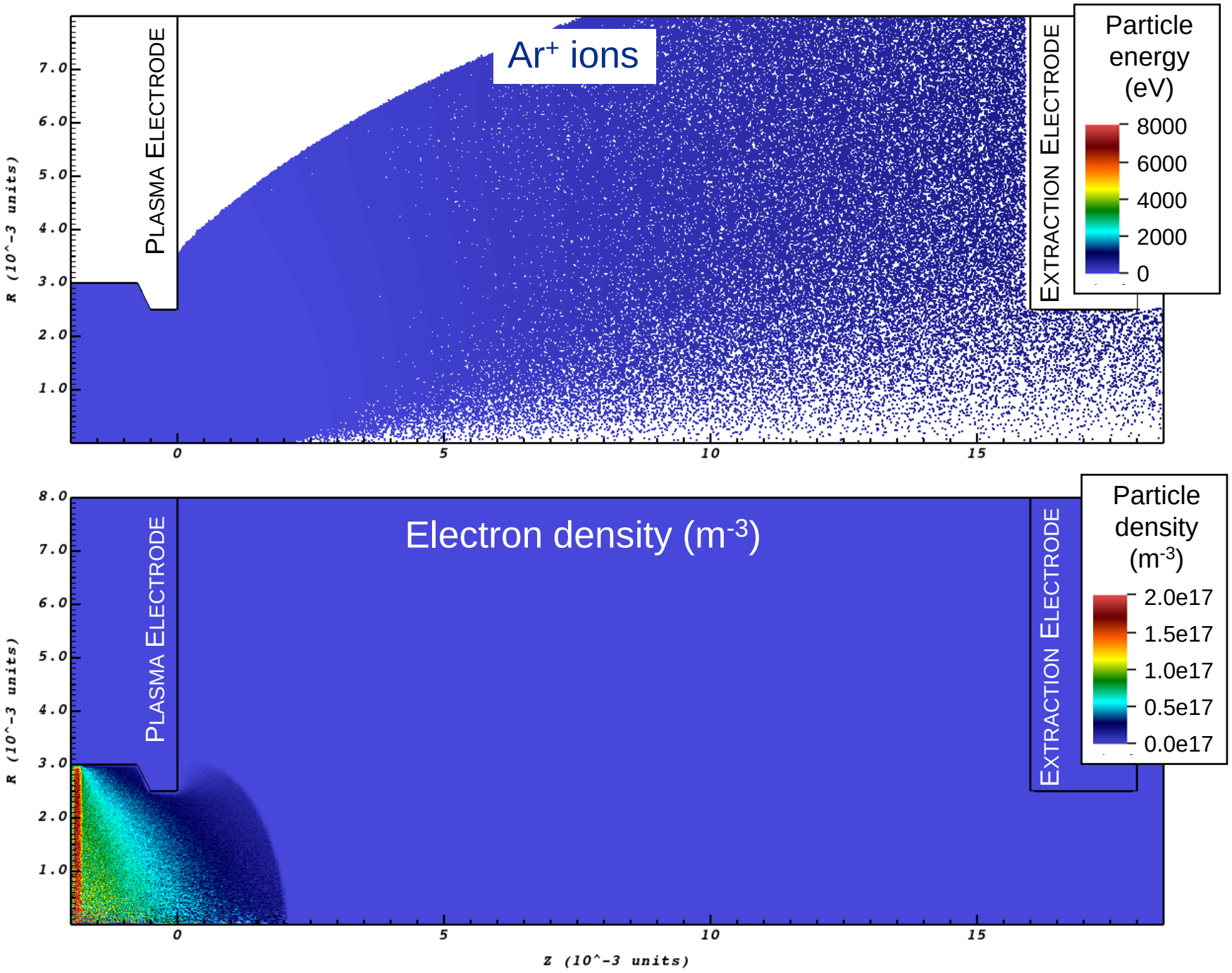


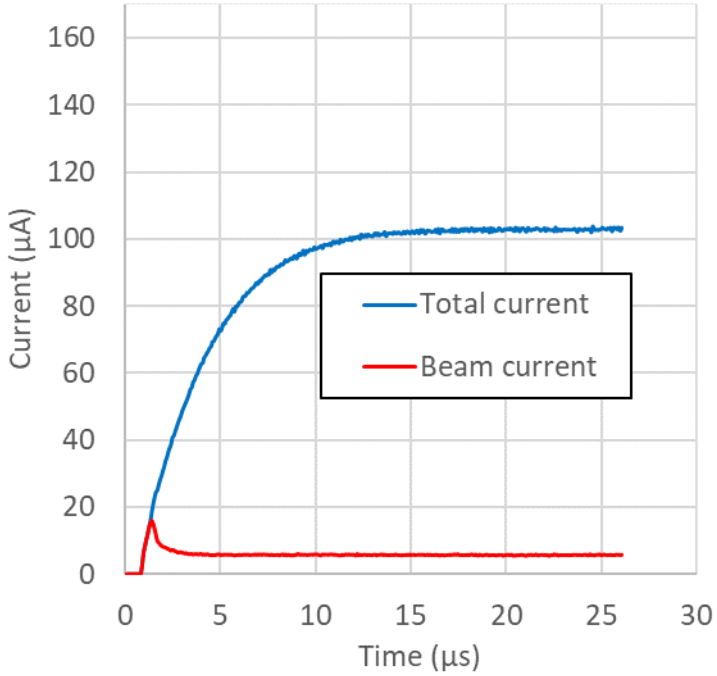


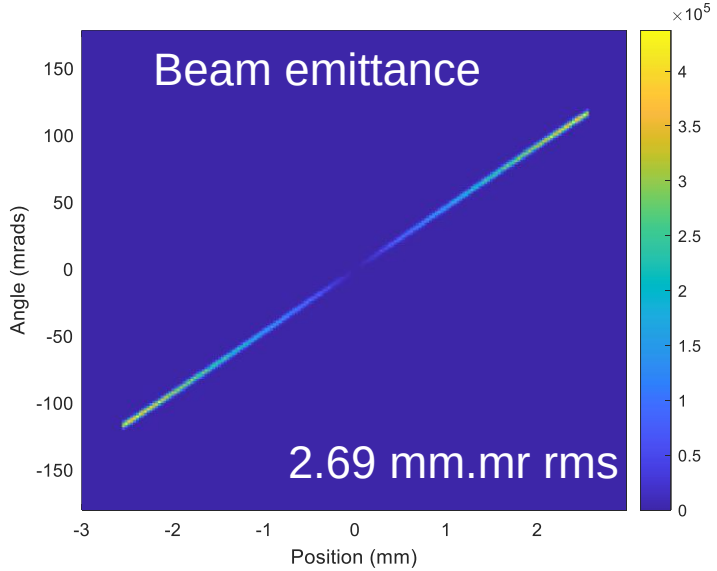




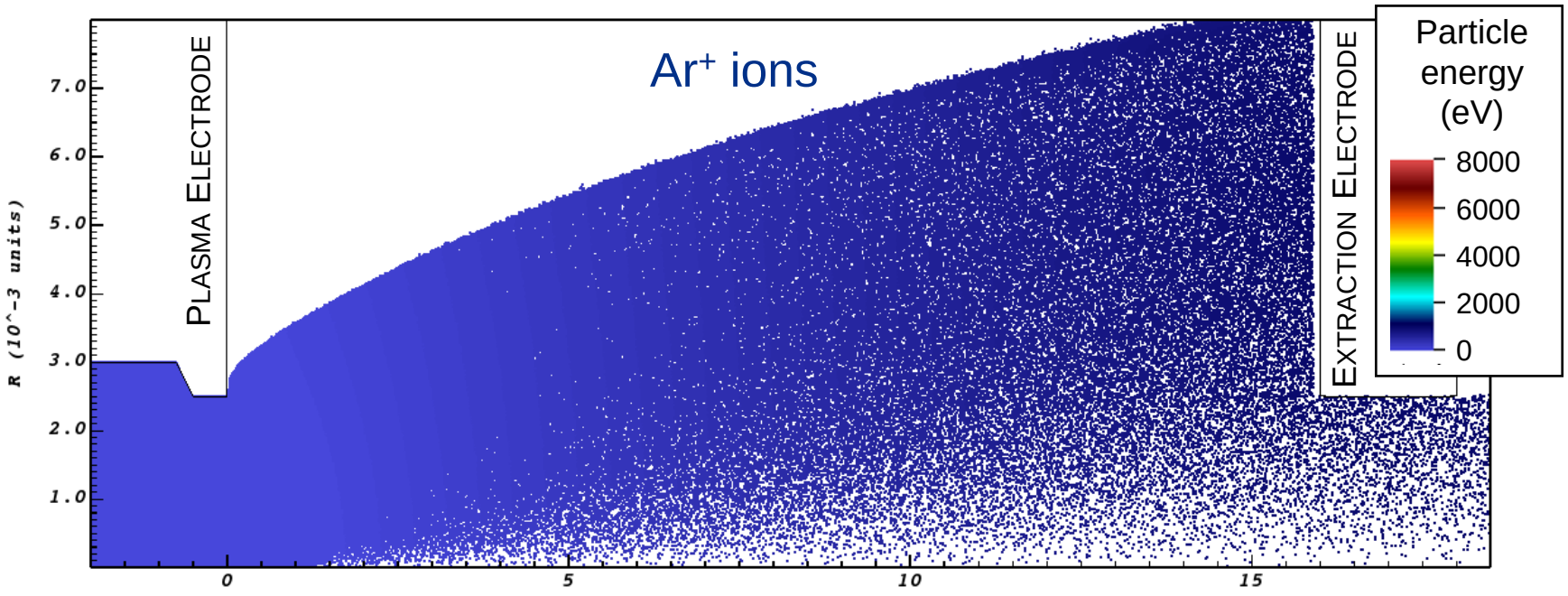
700 V Extraction Voltage

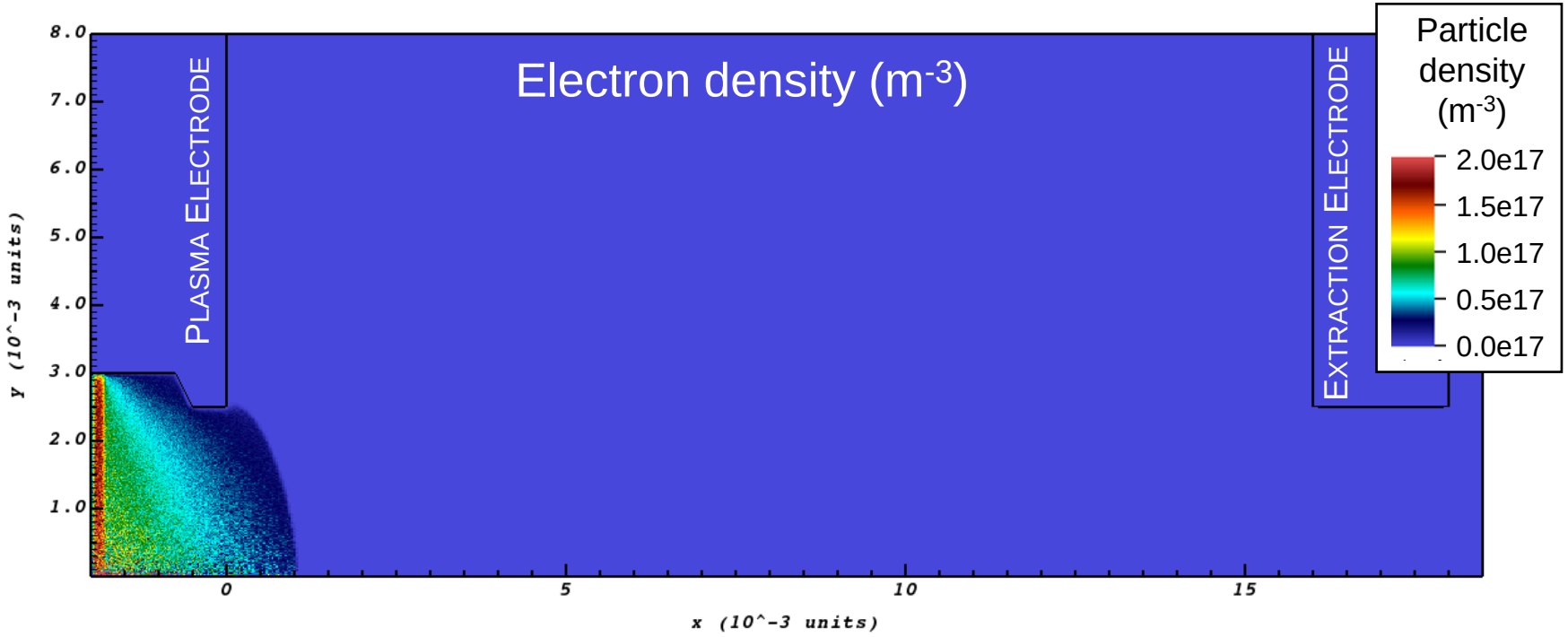


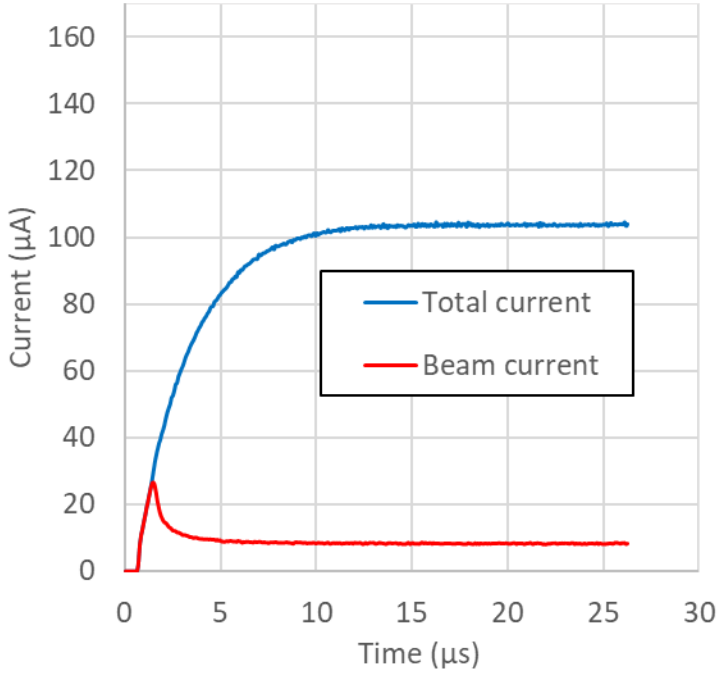


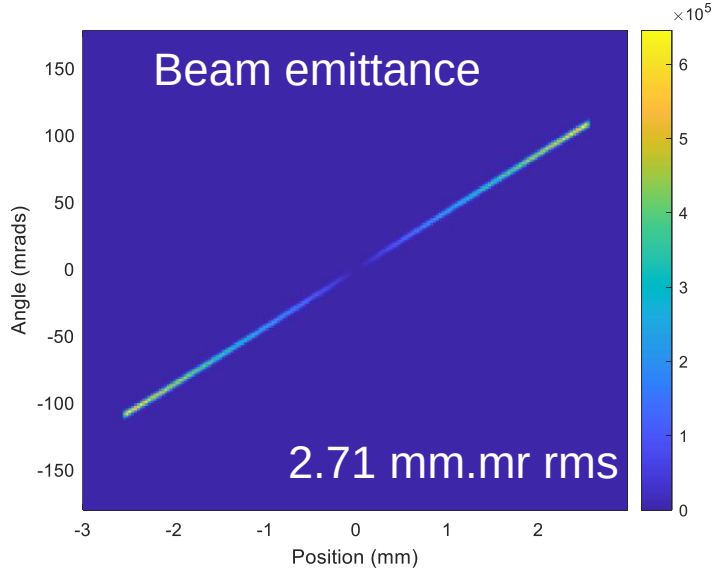


1 kV Extraction Voltage

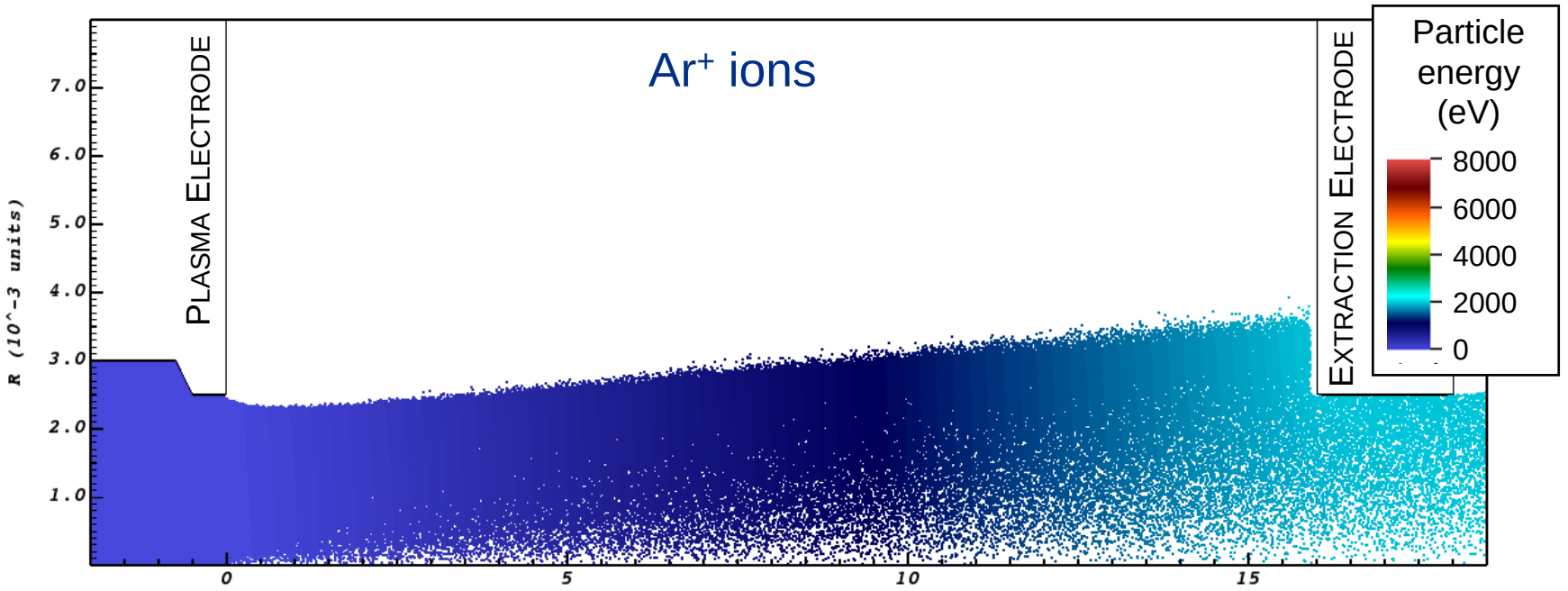


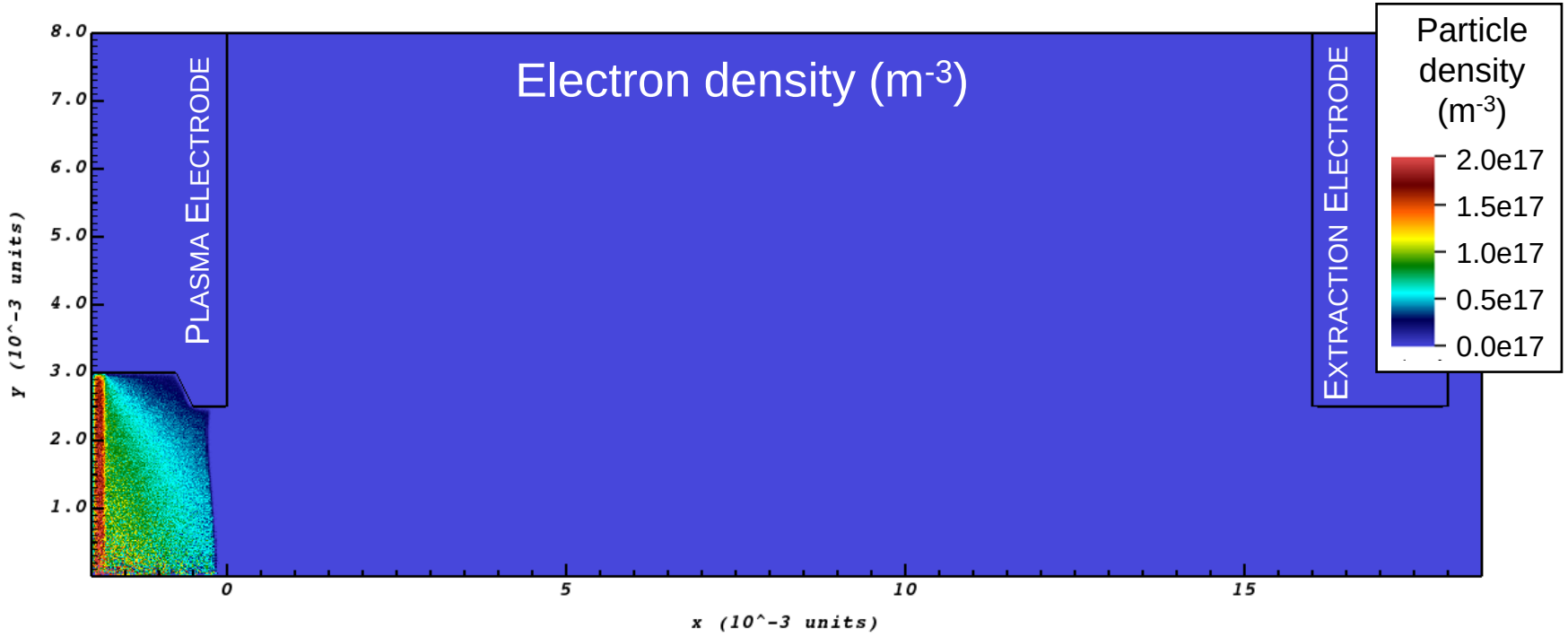


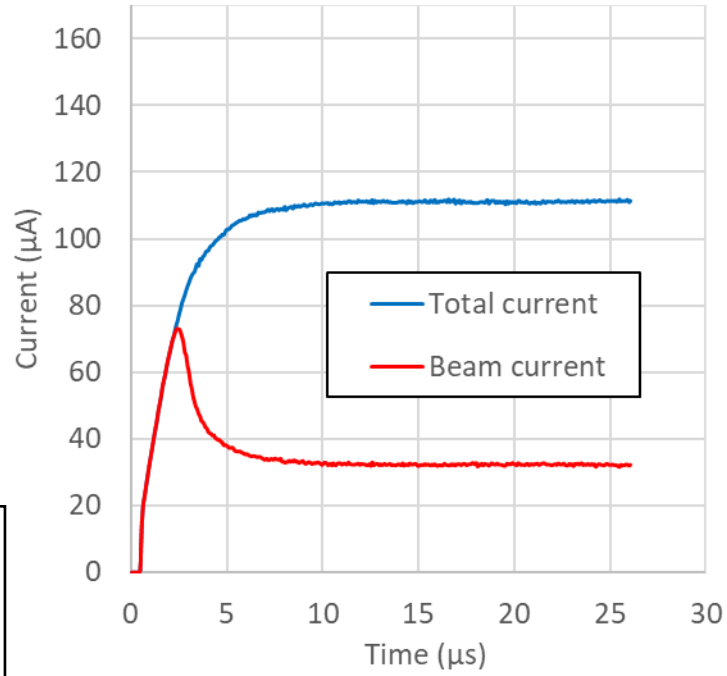


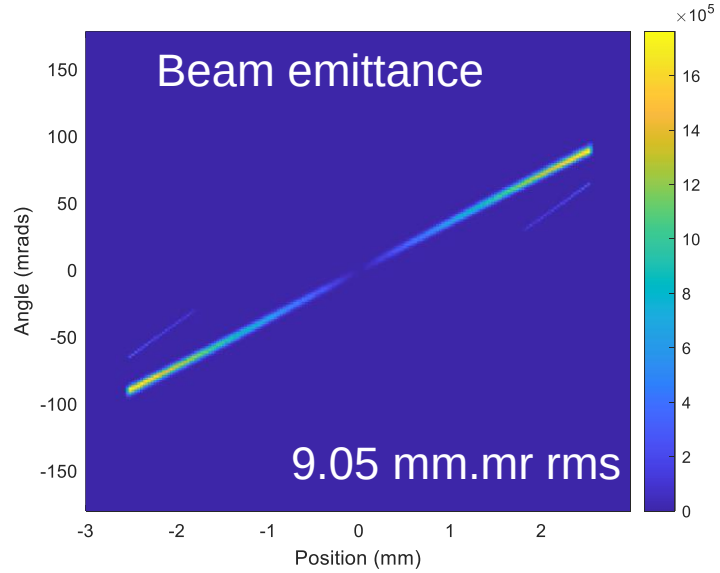


2 kV Extraction Voltage

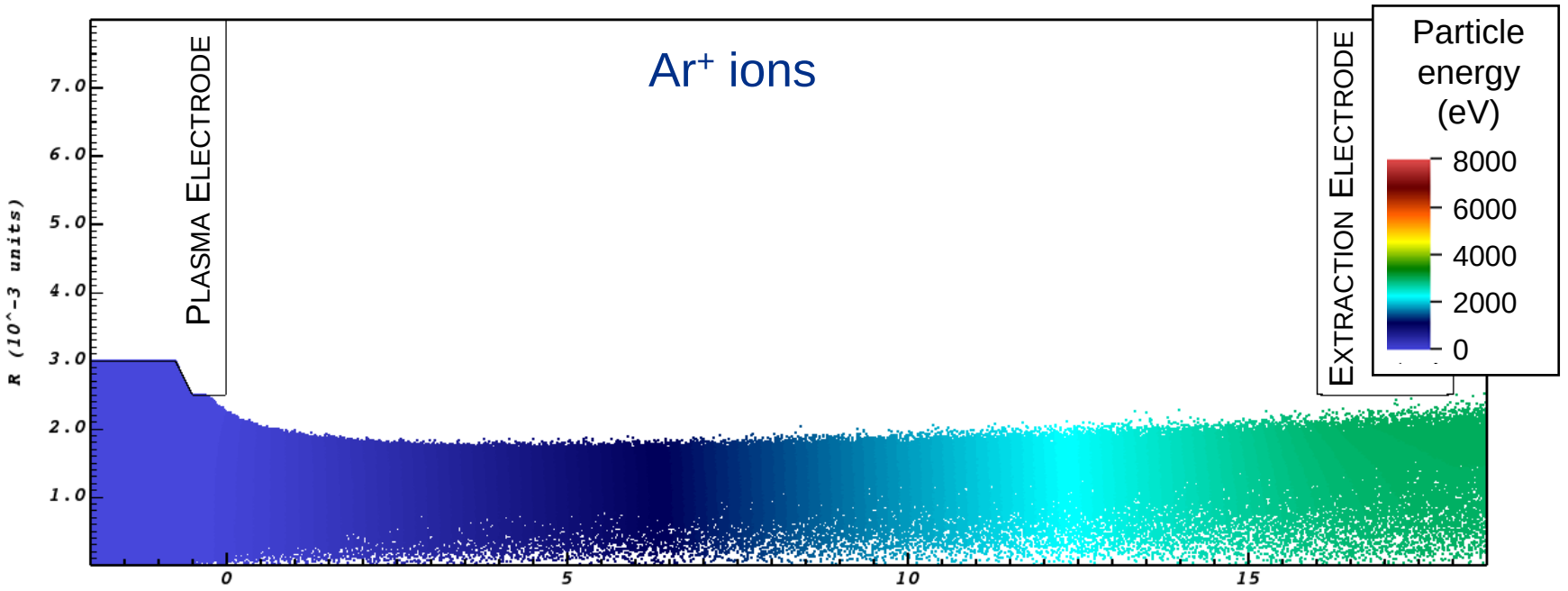


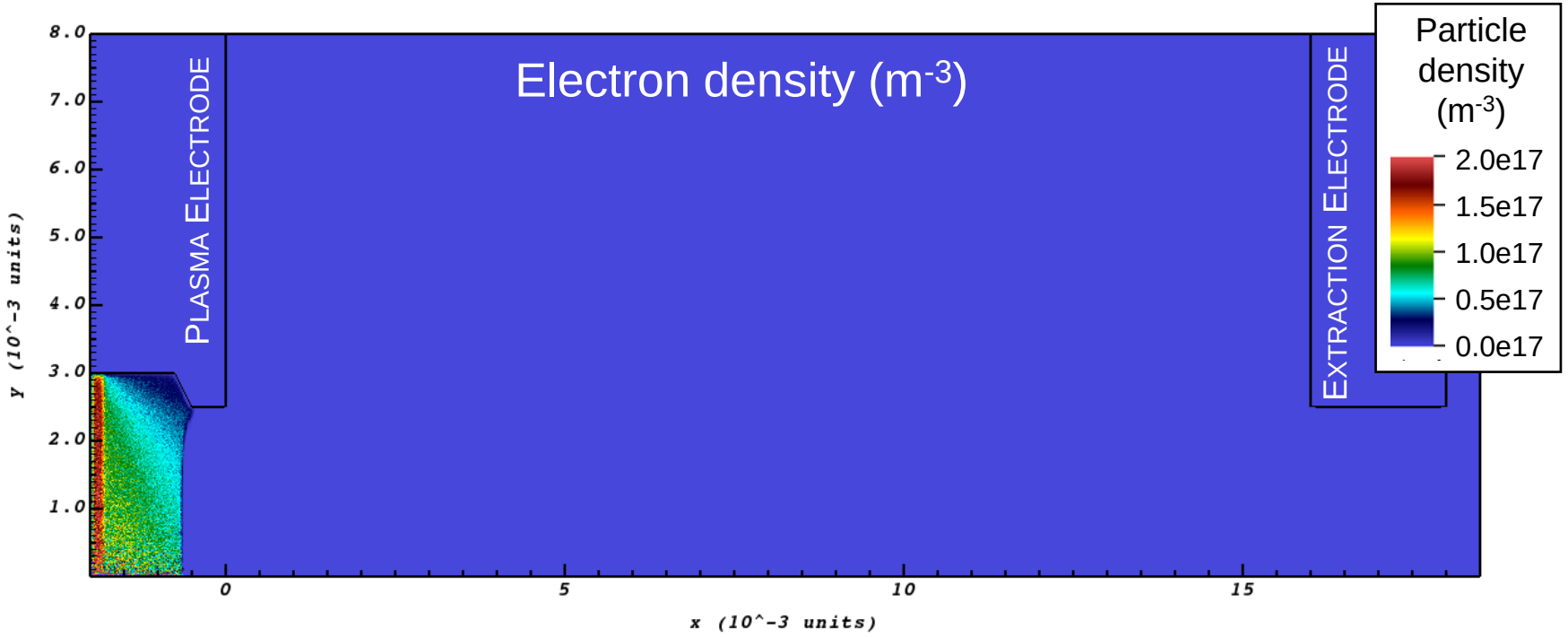


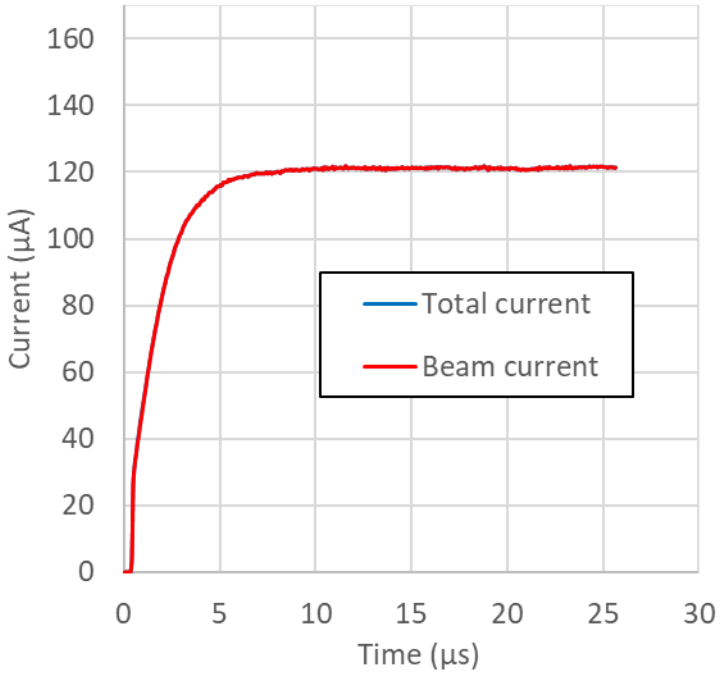


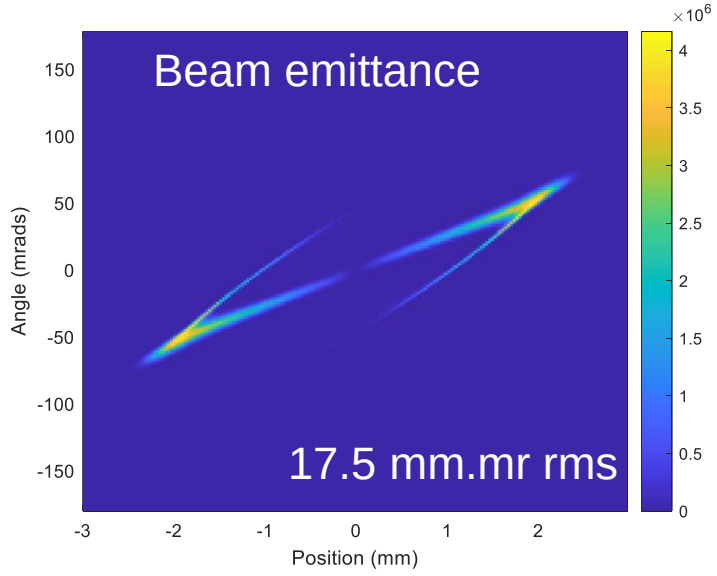


3 kV Extraction Voltage

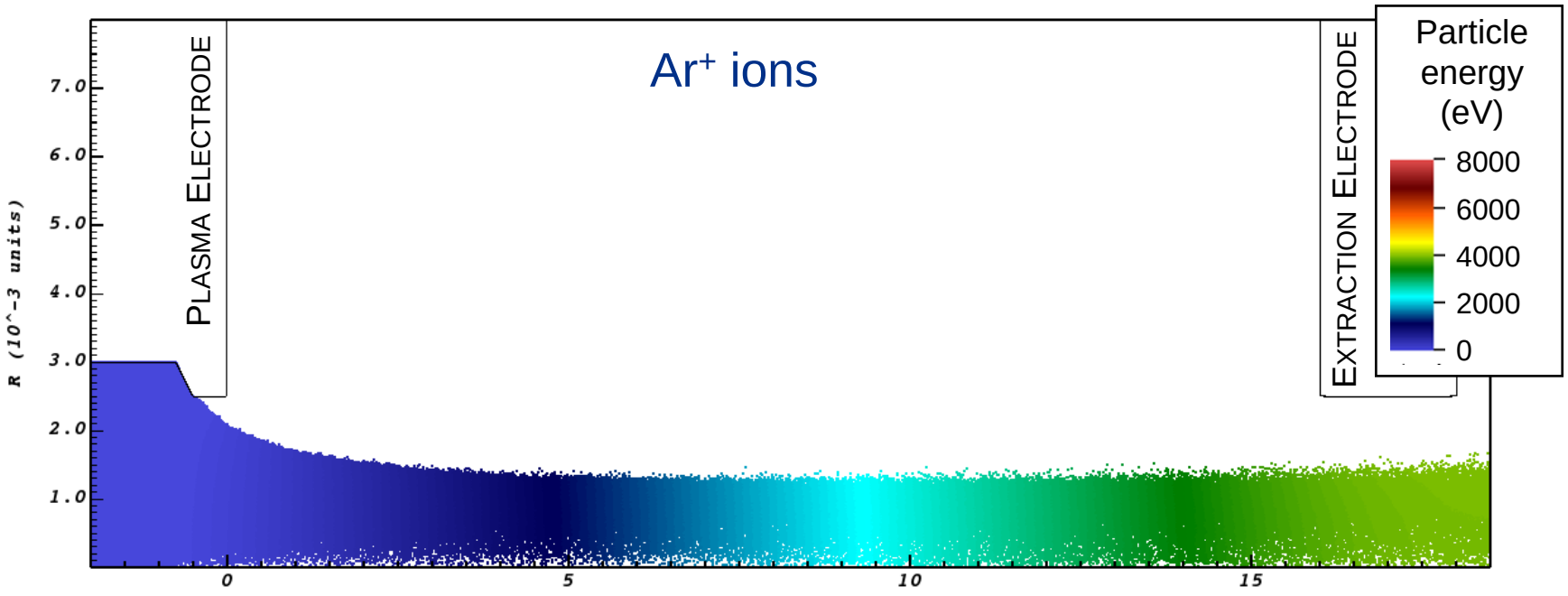


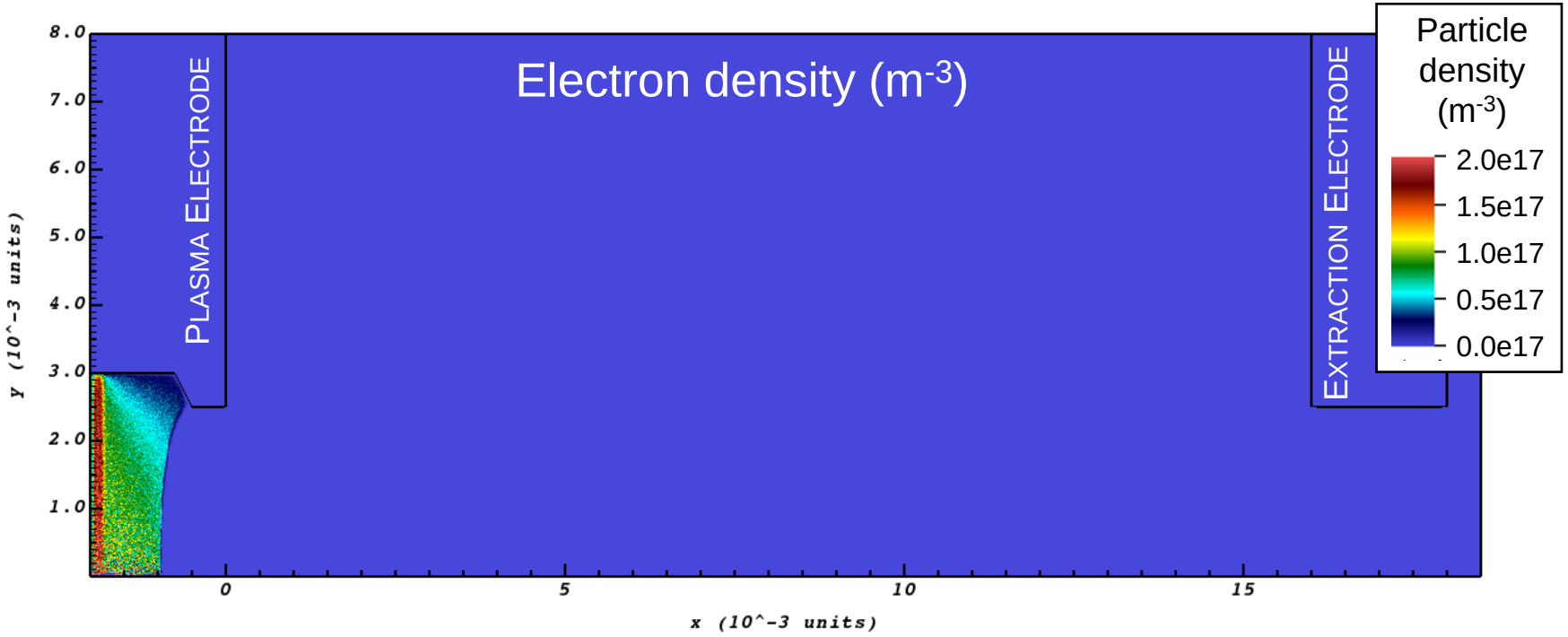


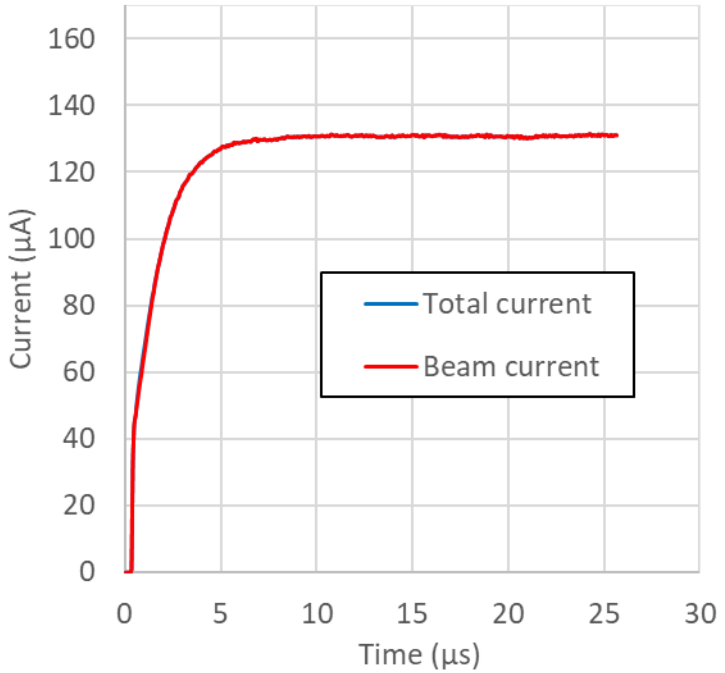


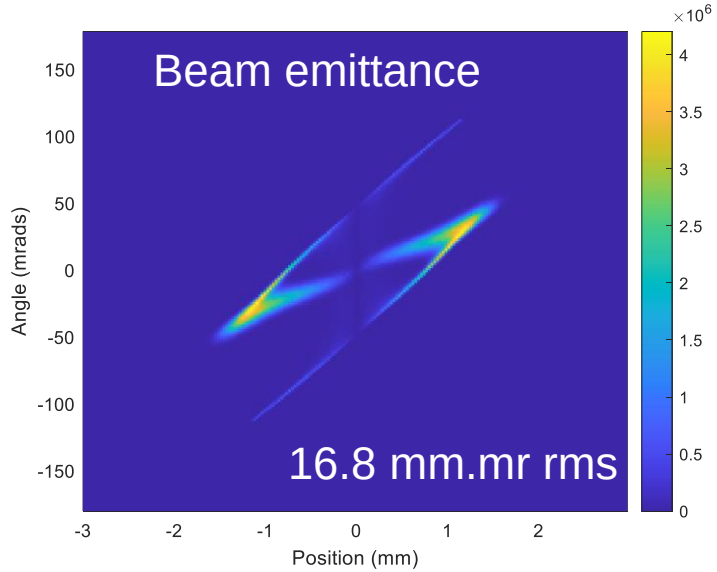


4 kV Extraction Voltage

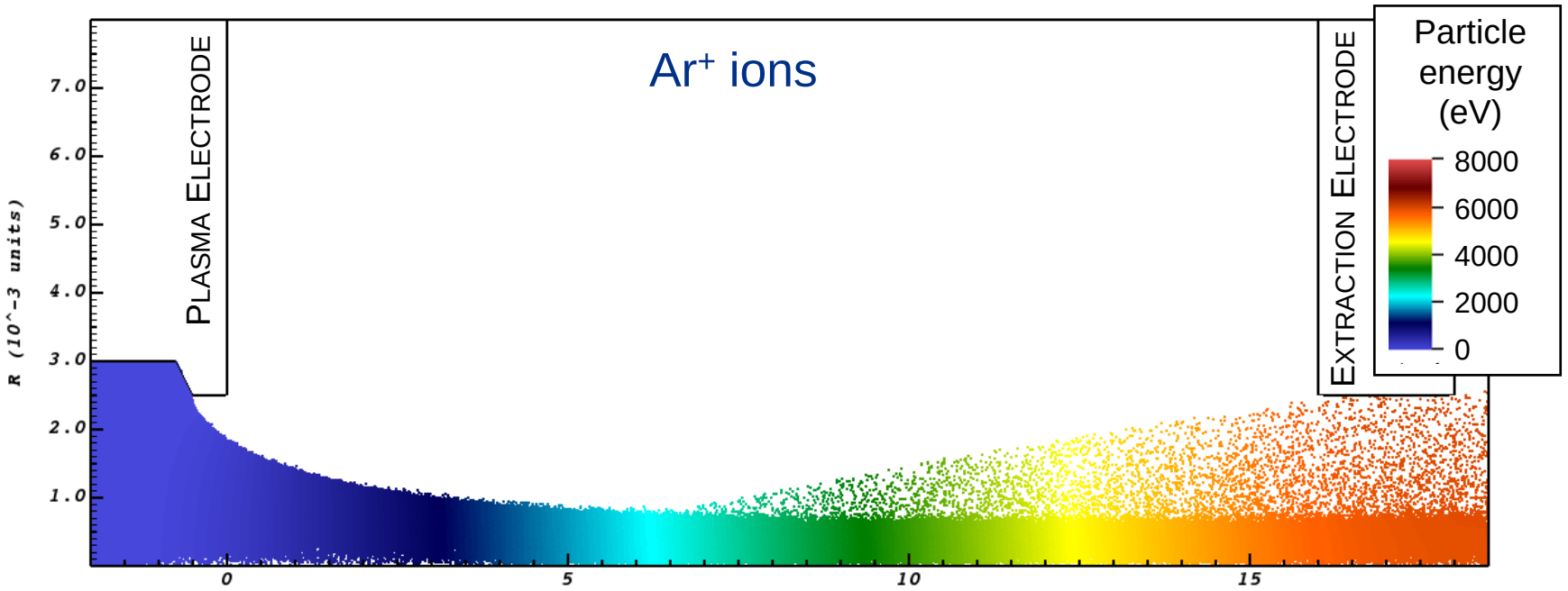


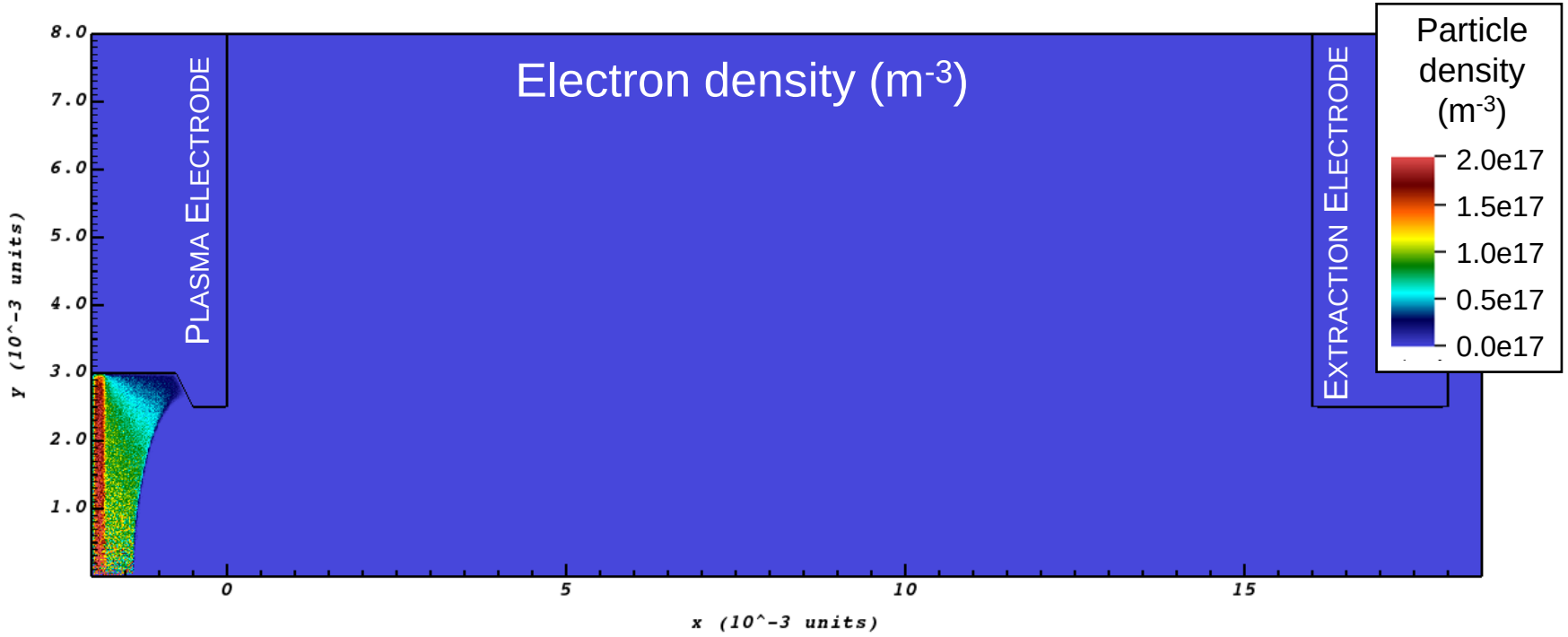


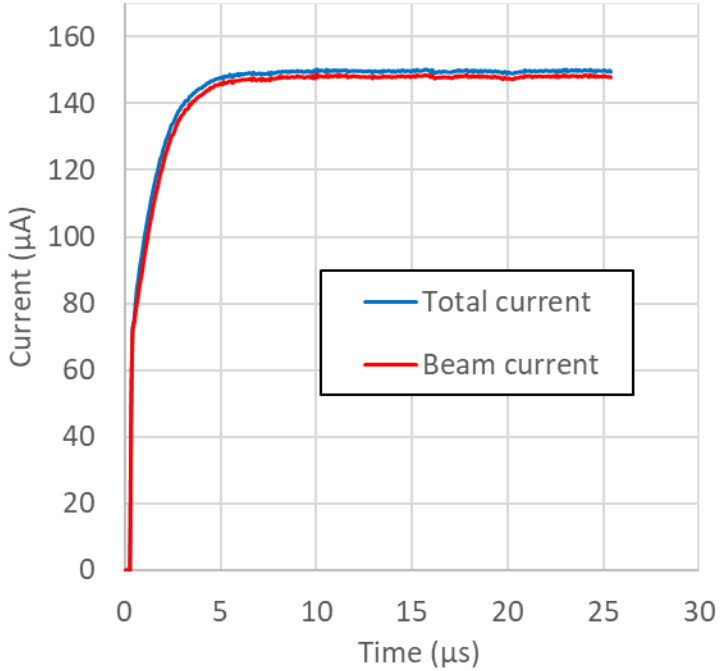


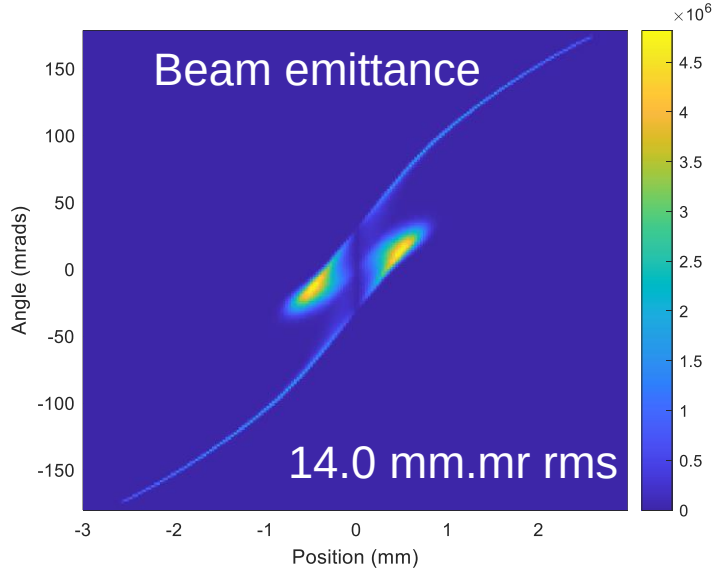


6 kV Extraction Voltage

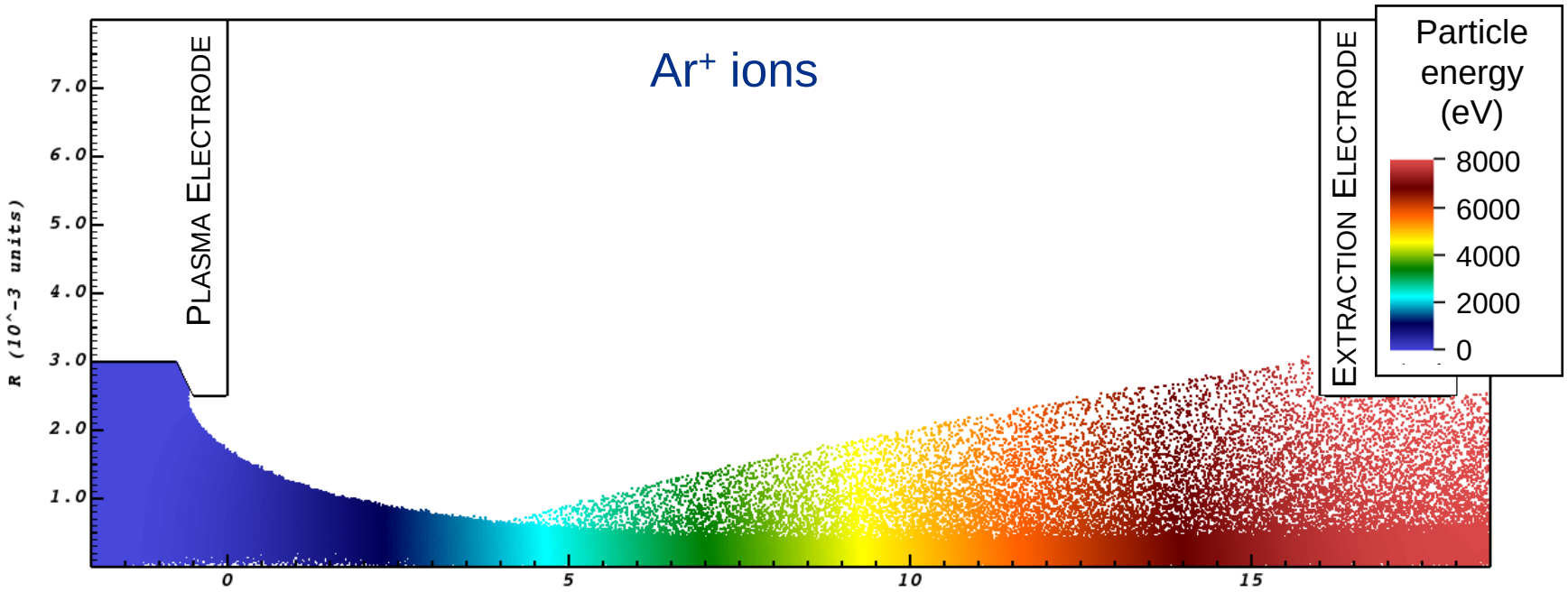


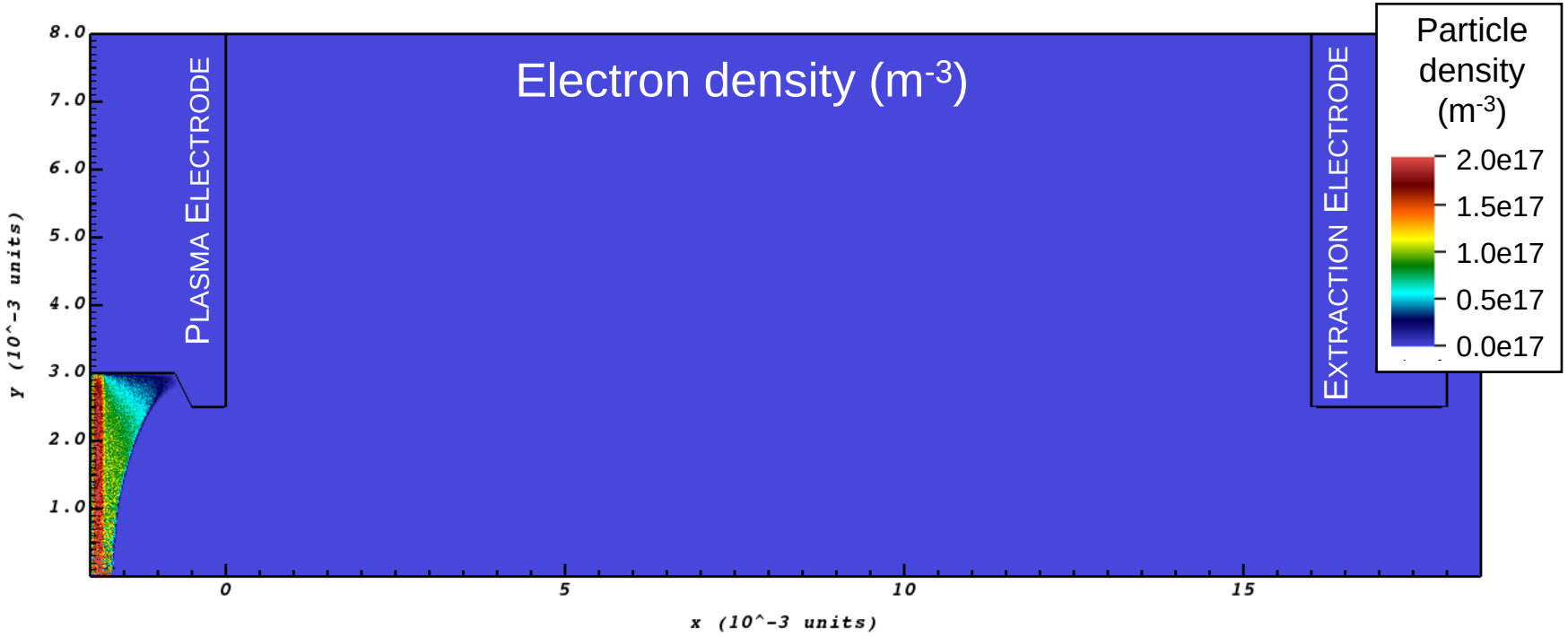


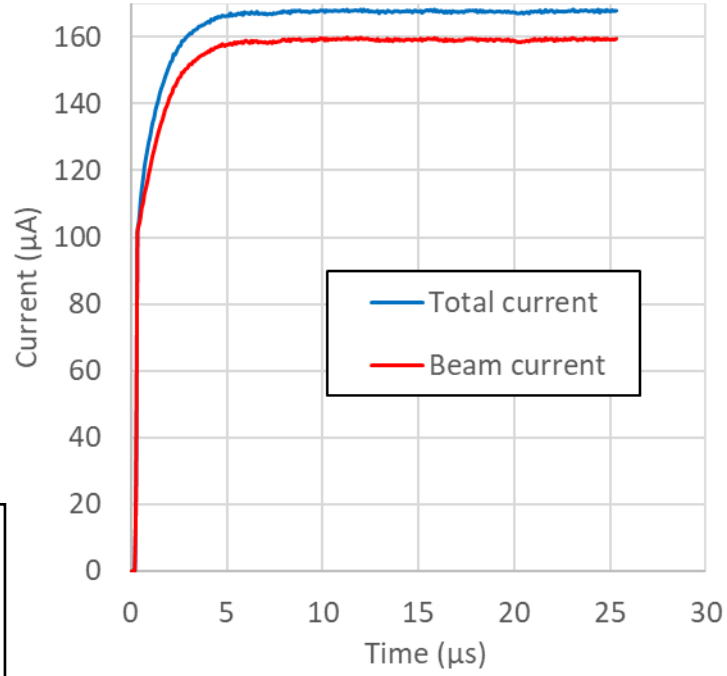


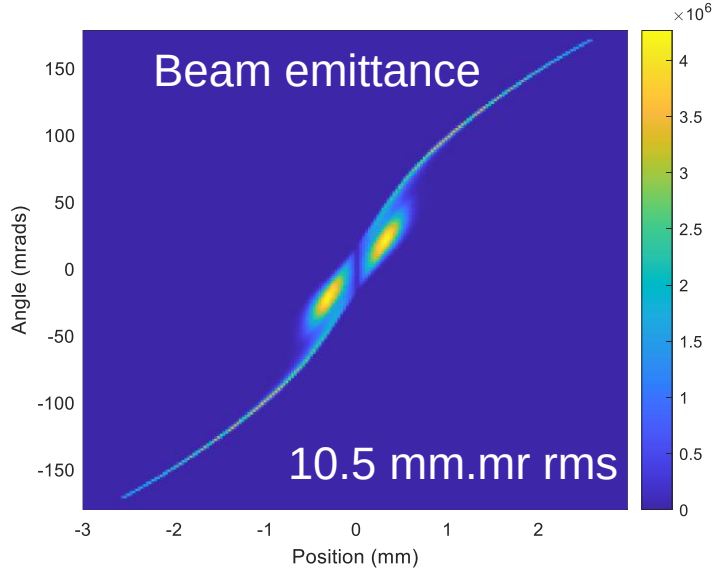


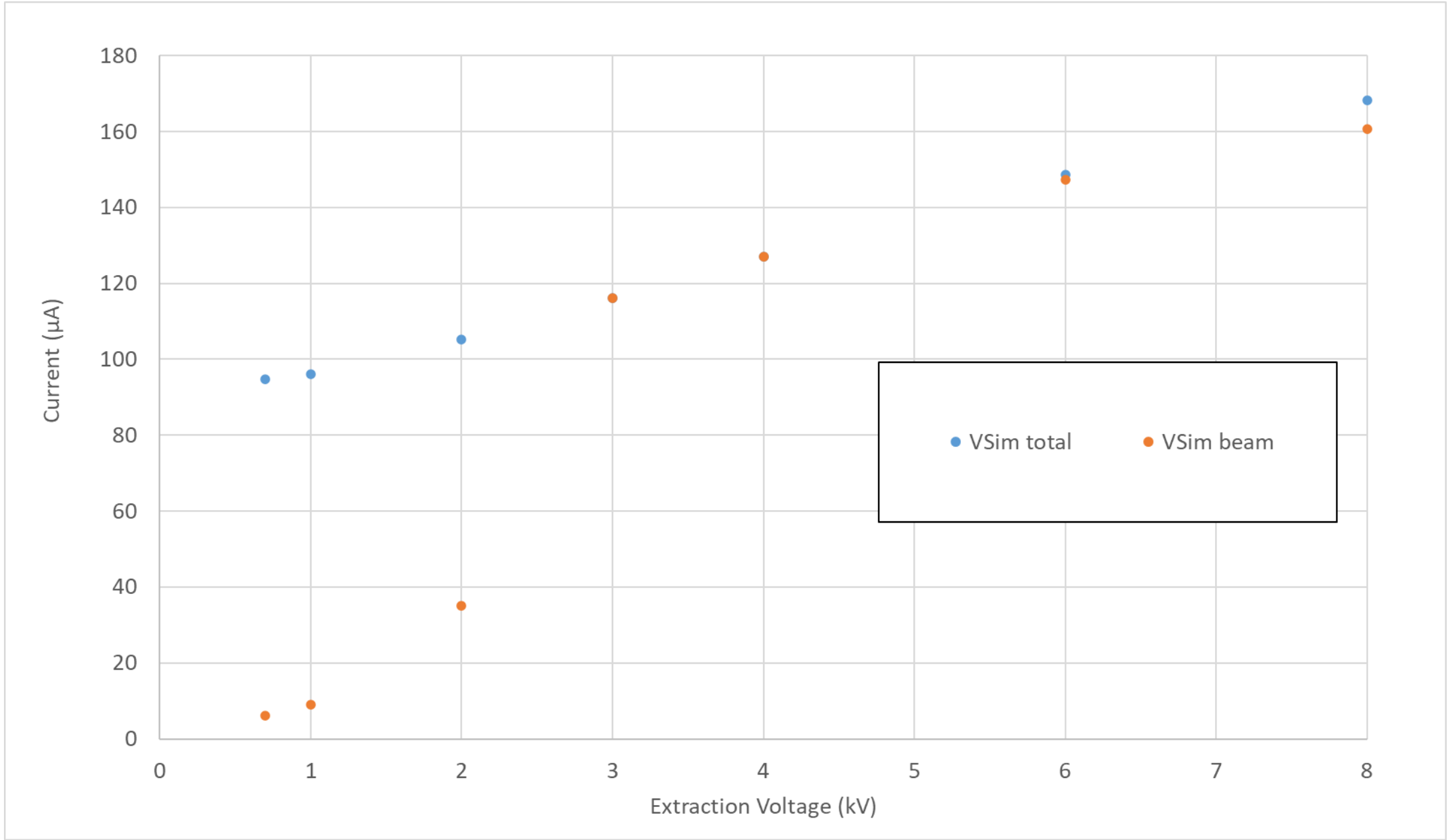
8 kV Extraction Voltage

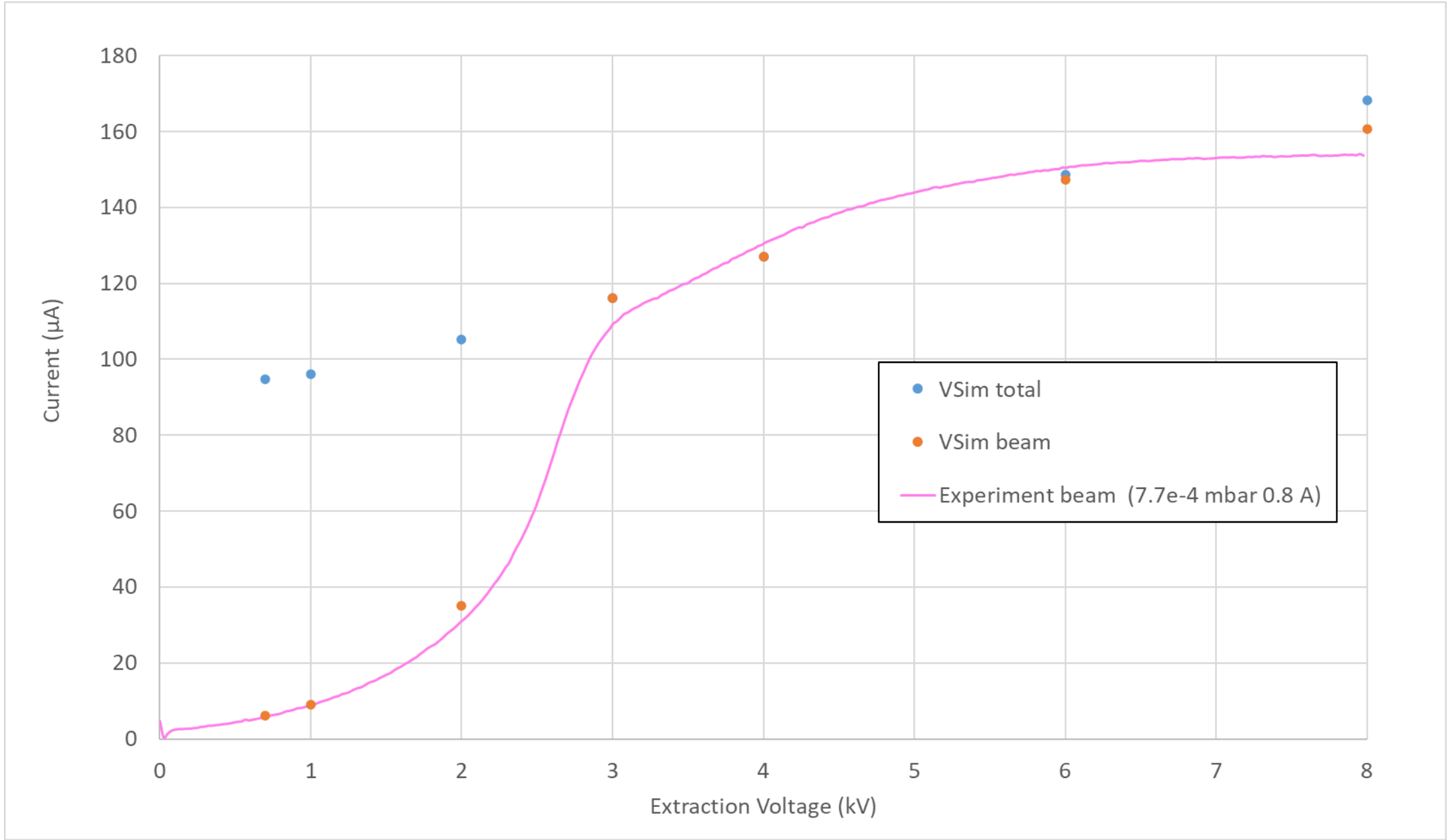


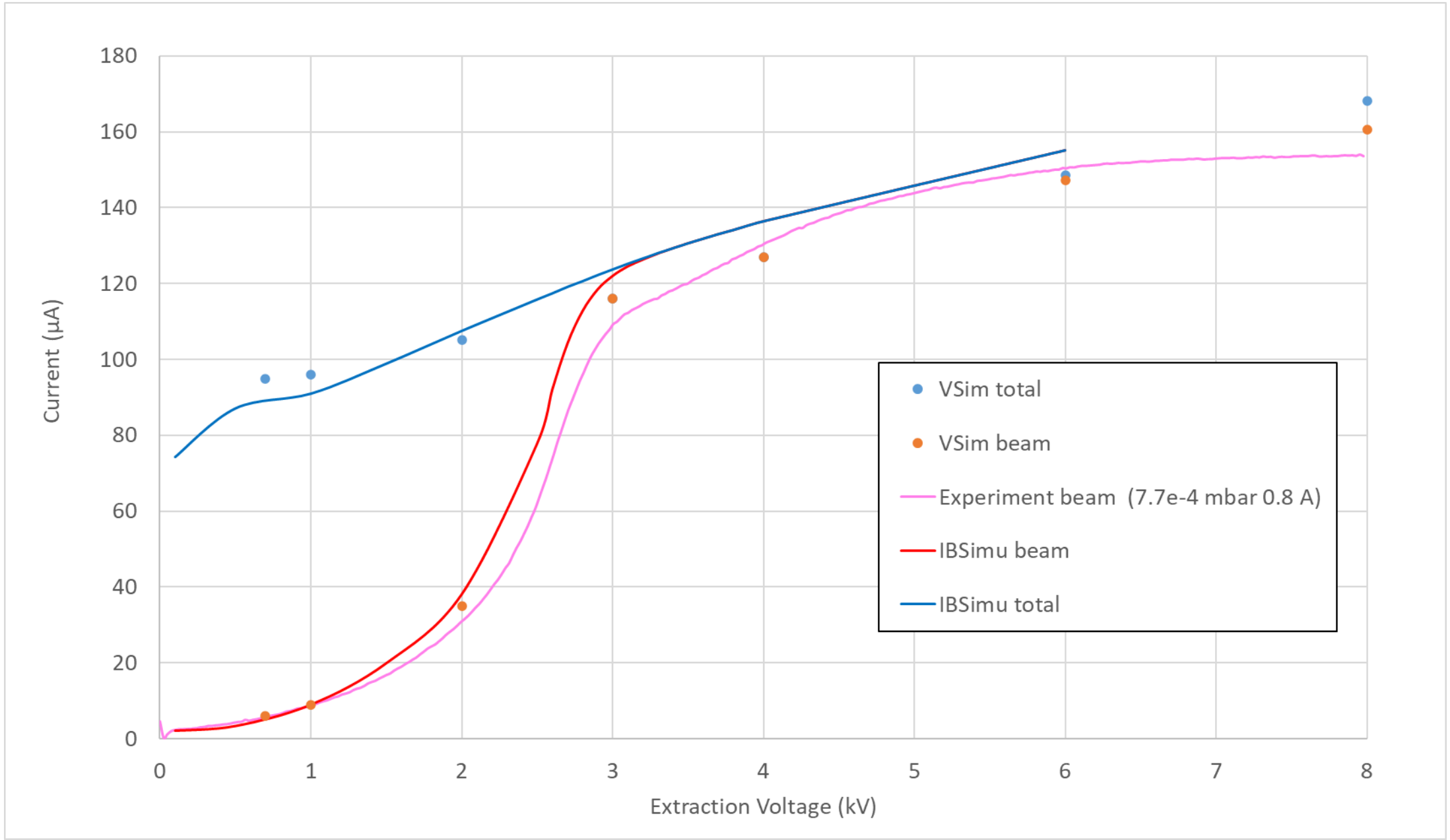


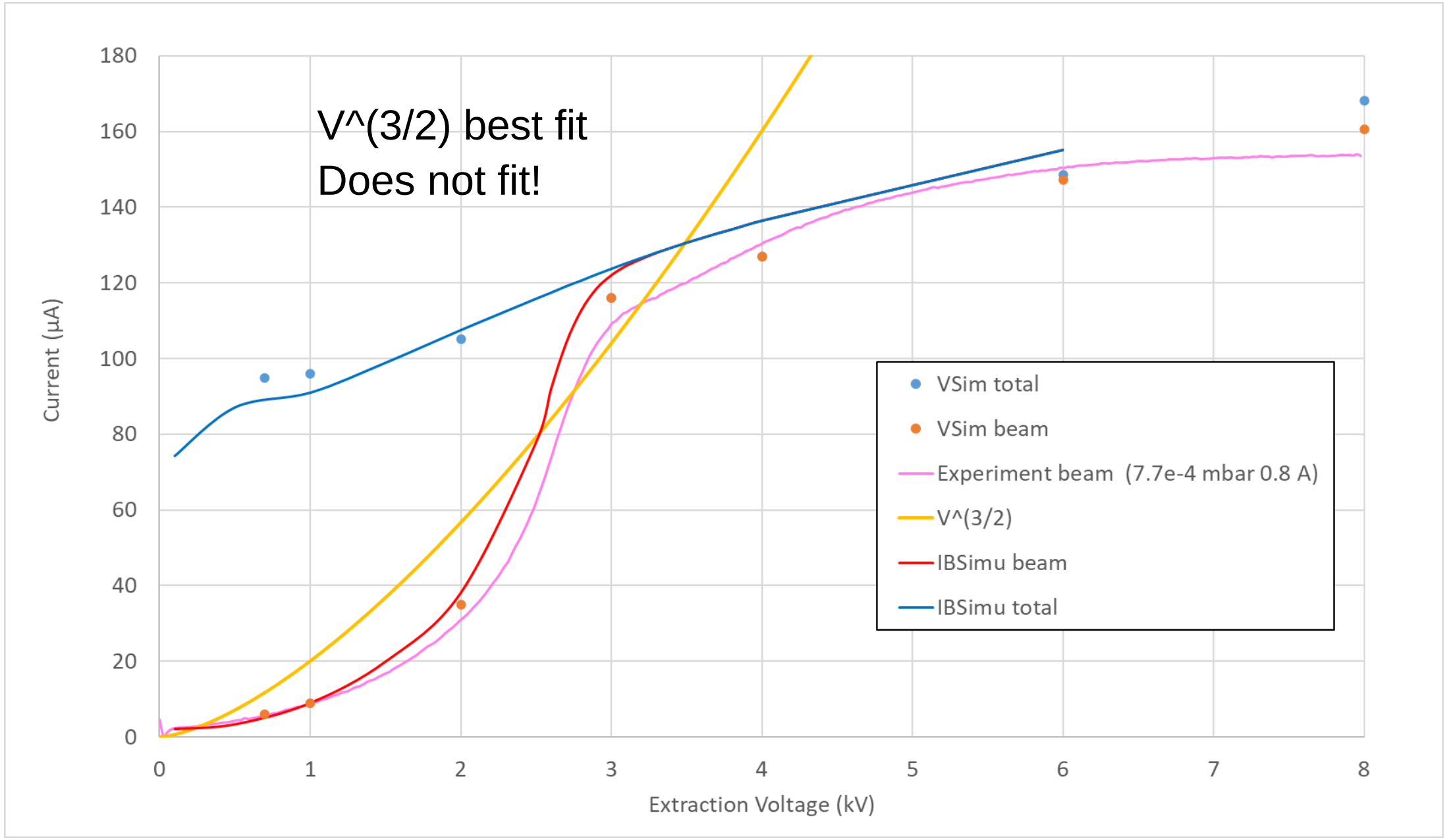





180
160
140
120
100
80
60
40
20
0
Current (μA)
0
1
2
3
4
5
6
7
8
Extraction Voltage (kV)
VSim total
VSim beam


180
160
140
120
100
80
60
40
20
0
Current (μA)
0
1
2
3
4
5
6
7
8
Extraction Voltage (kV)
VSim total
VSim beam
Experiment beam (7.7e-4 mbar 0.8 A)

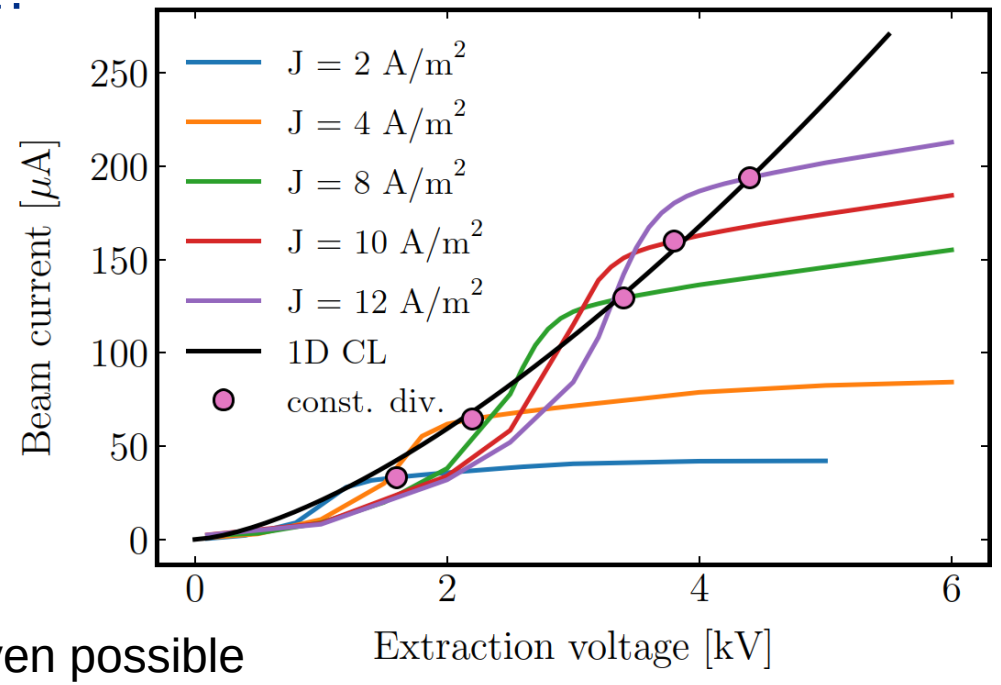

180
160
140
120
100
80
60
40
20
0
Current (µA)
0
1
2
3
4
5
6
7
8
Extraction Voltage (kV)
VSim total
VSim beam
Experiment beam (7.7e-4 mbar 0.8 A)
IBSimu beam
IBSimu total


V^(3/2) best fit
Does not fit!
Current (µA)
Extraction Voltage (kV)
0
20
40
60
80
100
120
140
160
180
0
1
2
3
4
5
6
7
8
VSim total
VSim beam
Experiment beam (7.7e-4 mbar 0.8 A)
V^(3/2)
IBSimu beam
IBSimu total

So how can we create a true perveance plot?

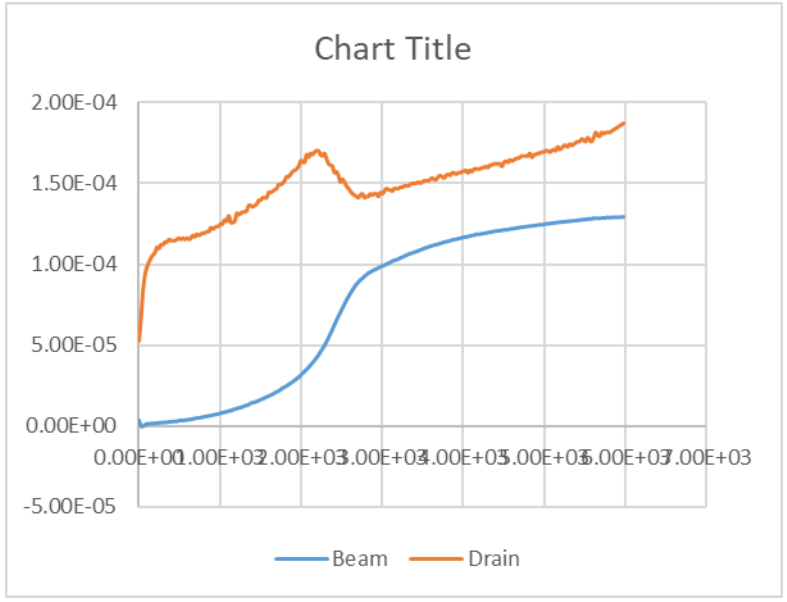
Simulations

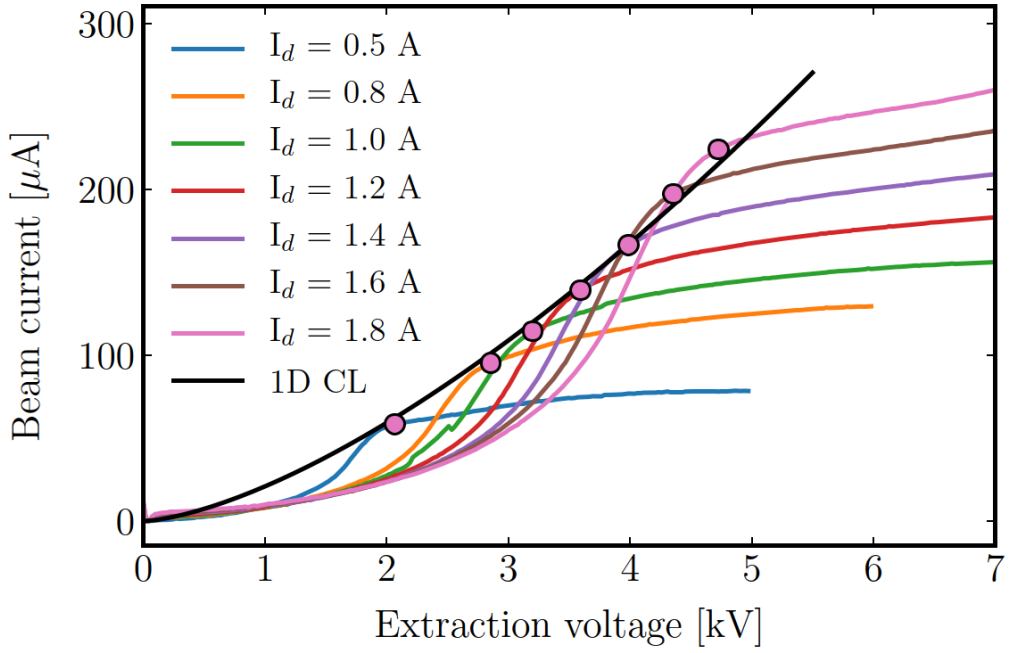
Constant meniscus
Constant divergence



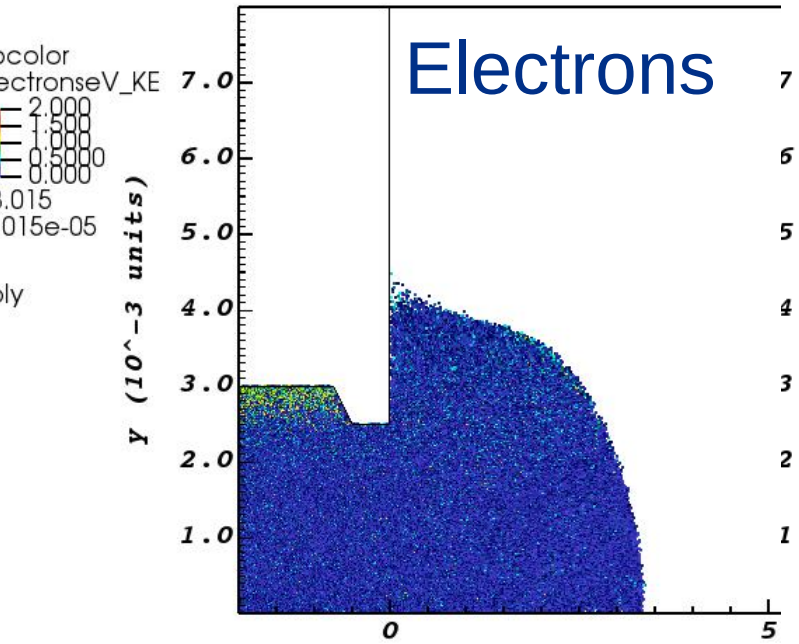
Experiment

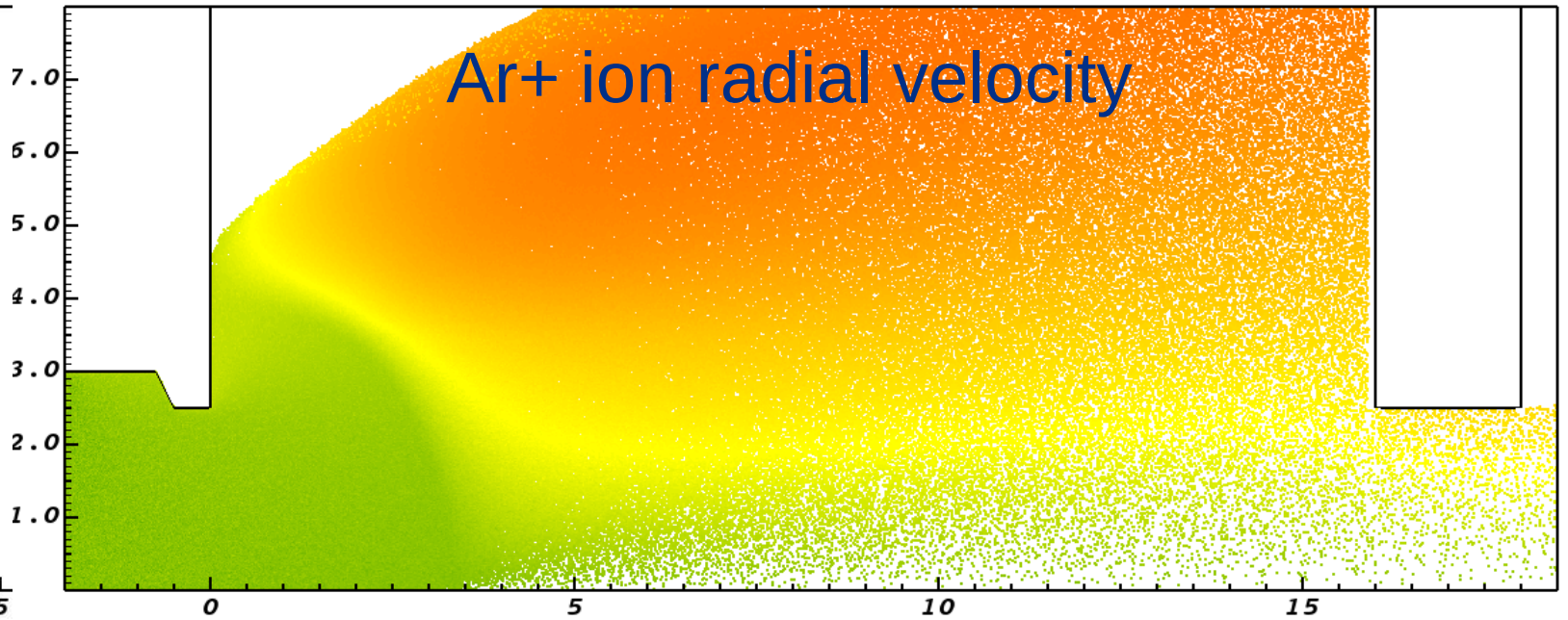
Find knee point- vague or not even possible



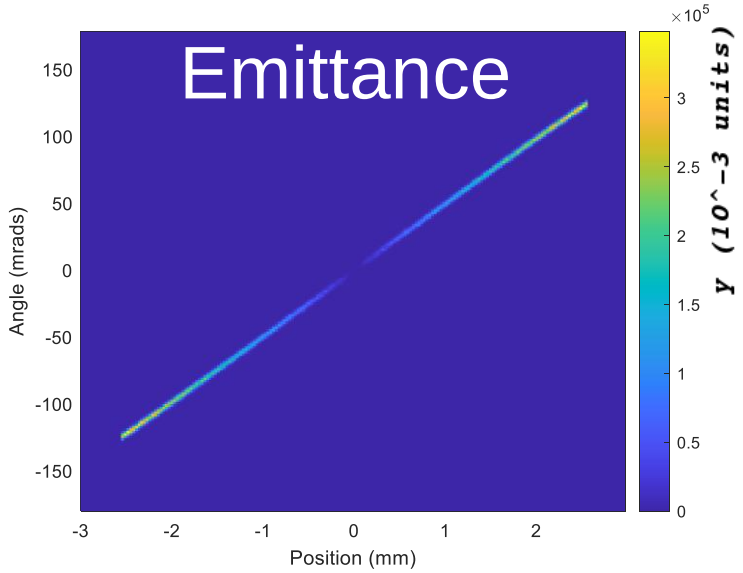


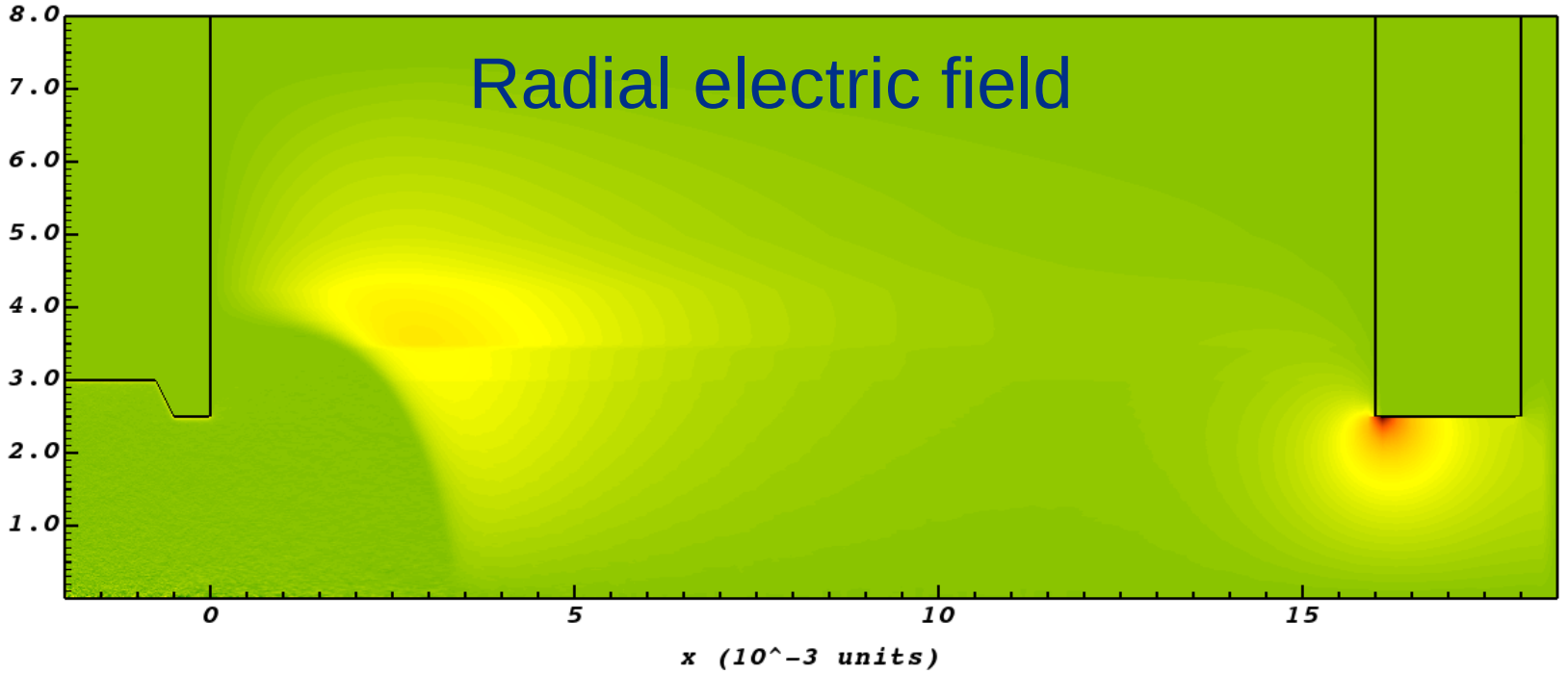
The emittance phase space ‘s’ shape



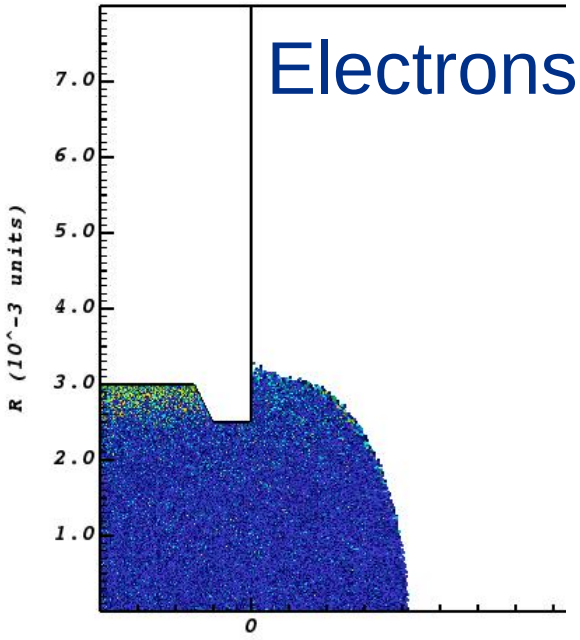


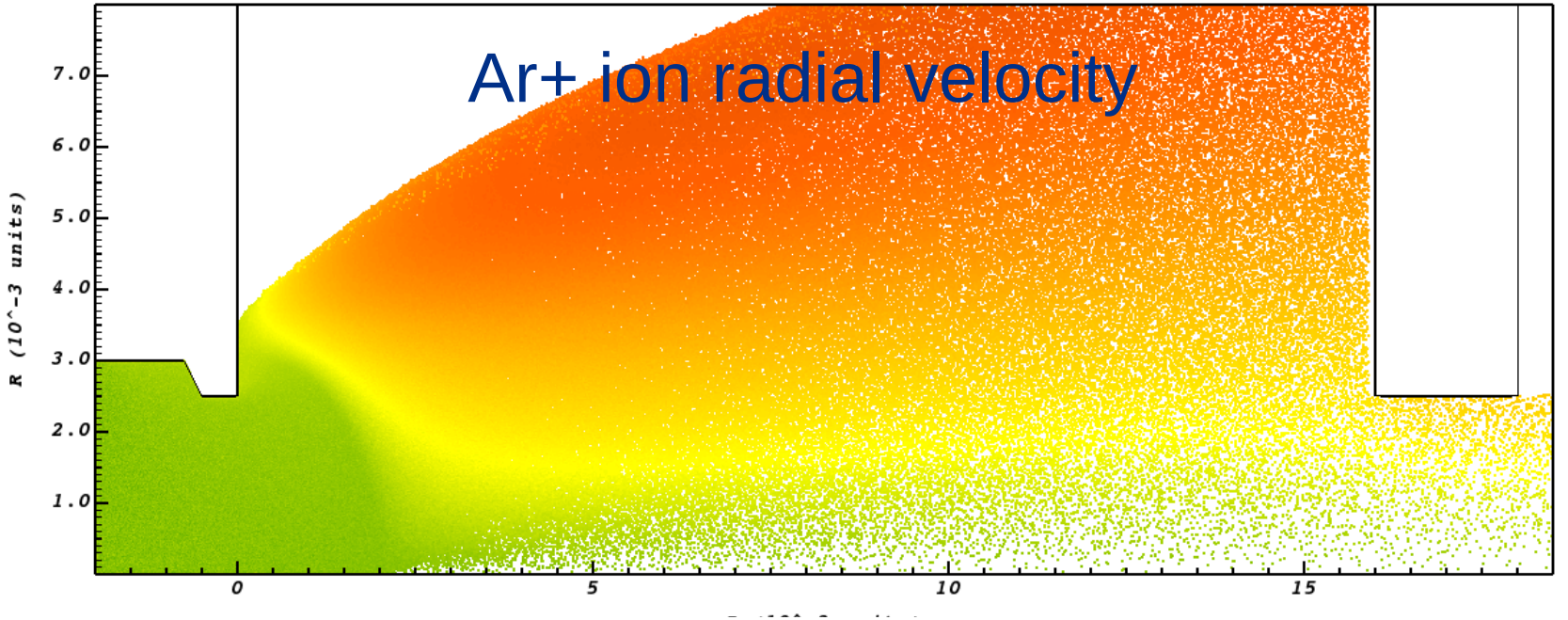
500 V extraction voltage

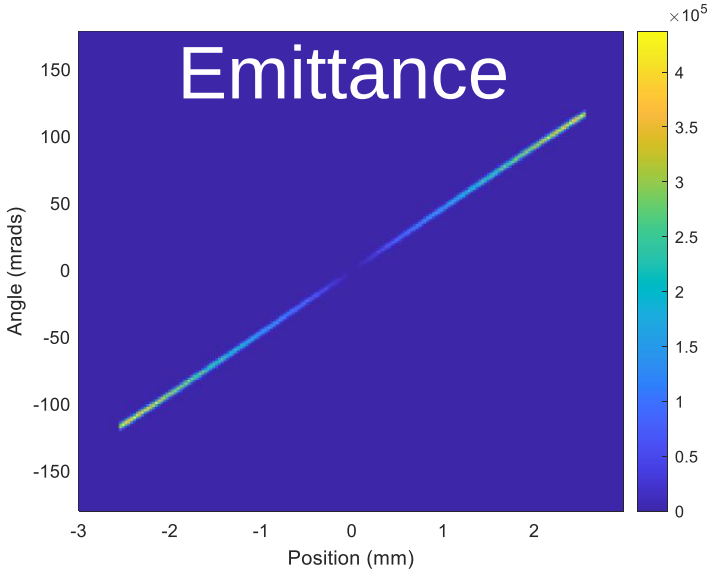


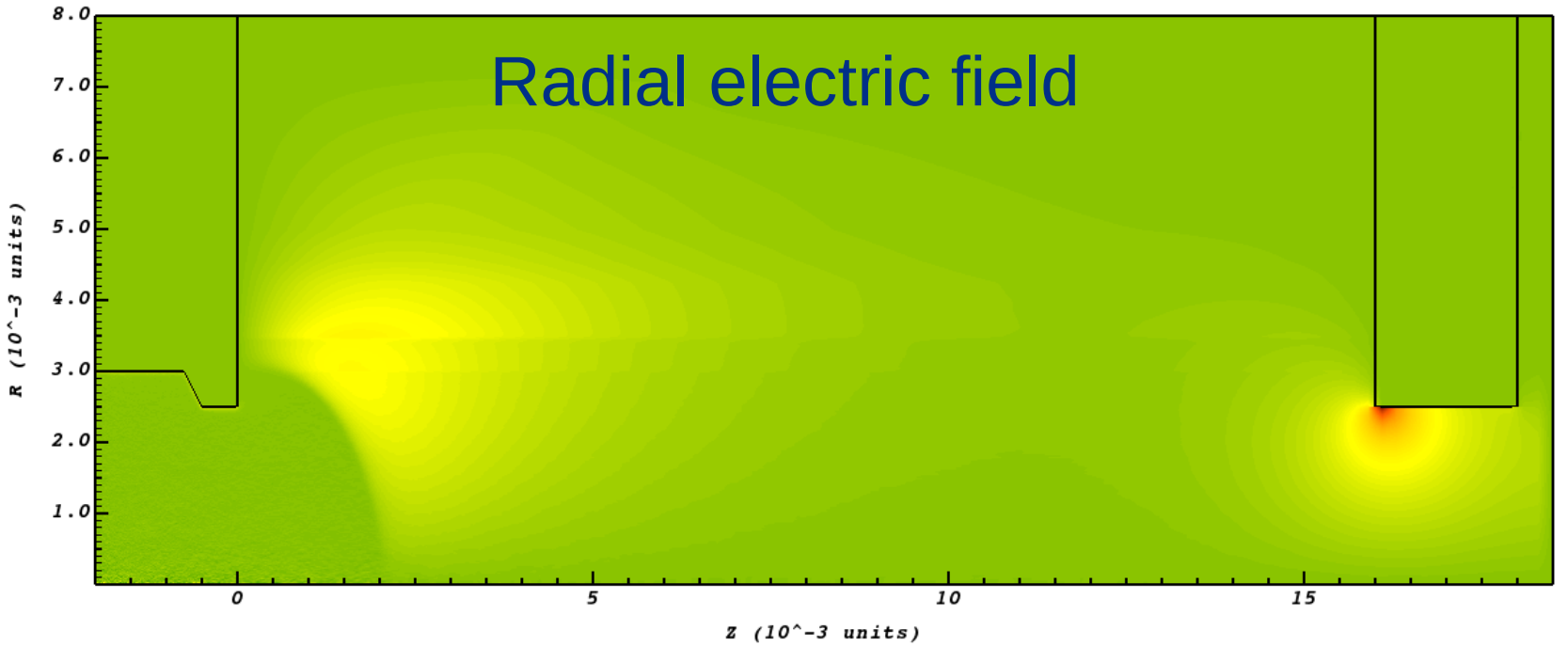


700 V extraction voltage

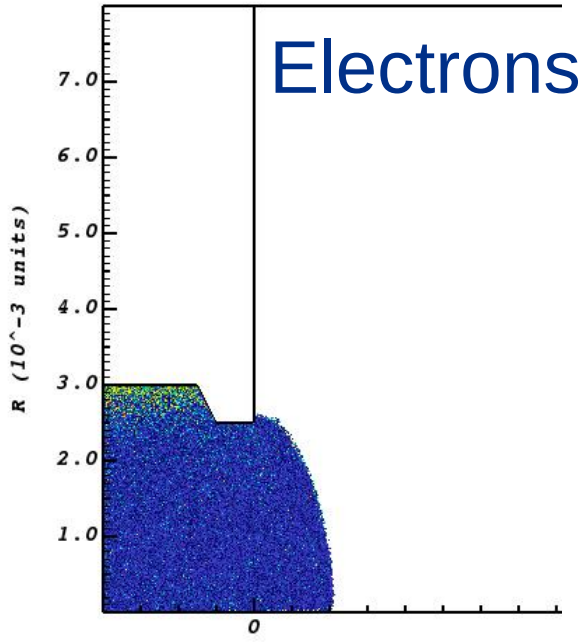


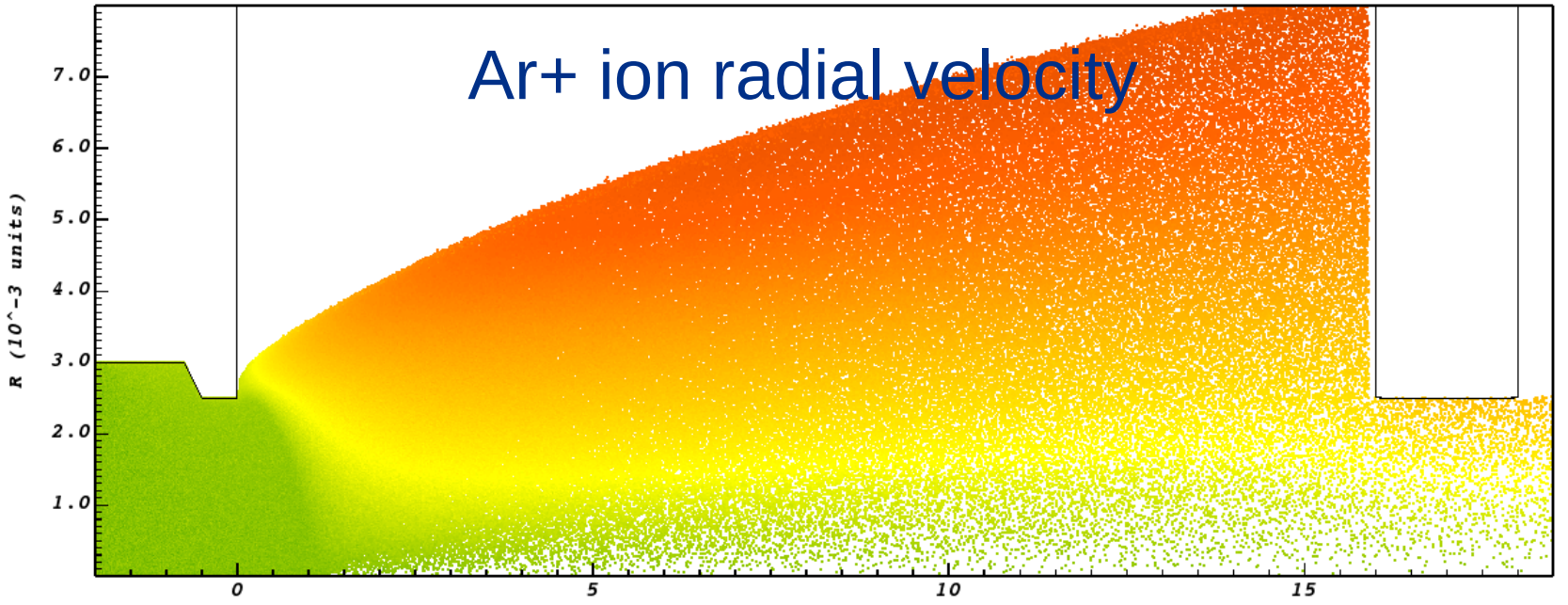


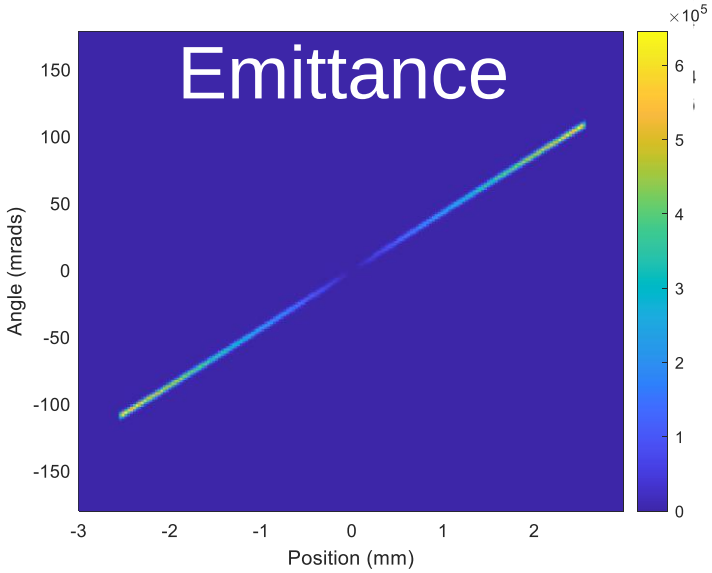


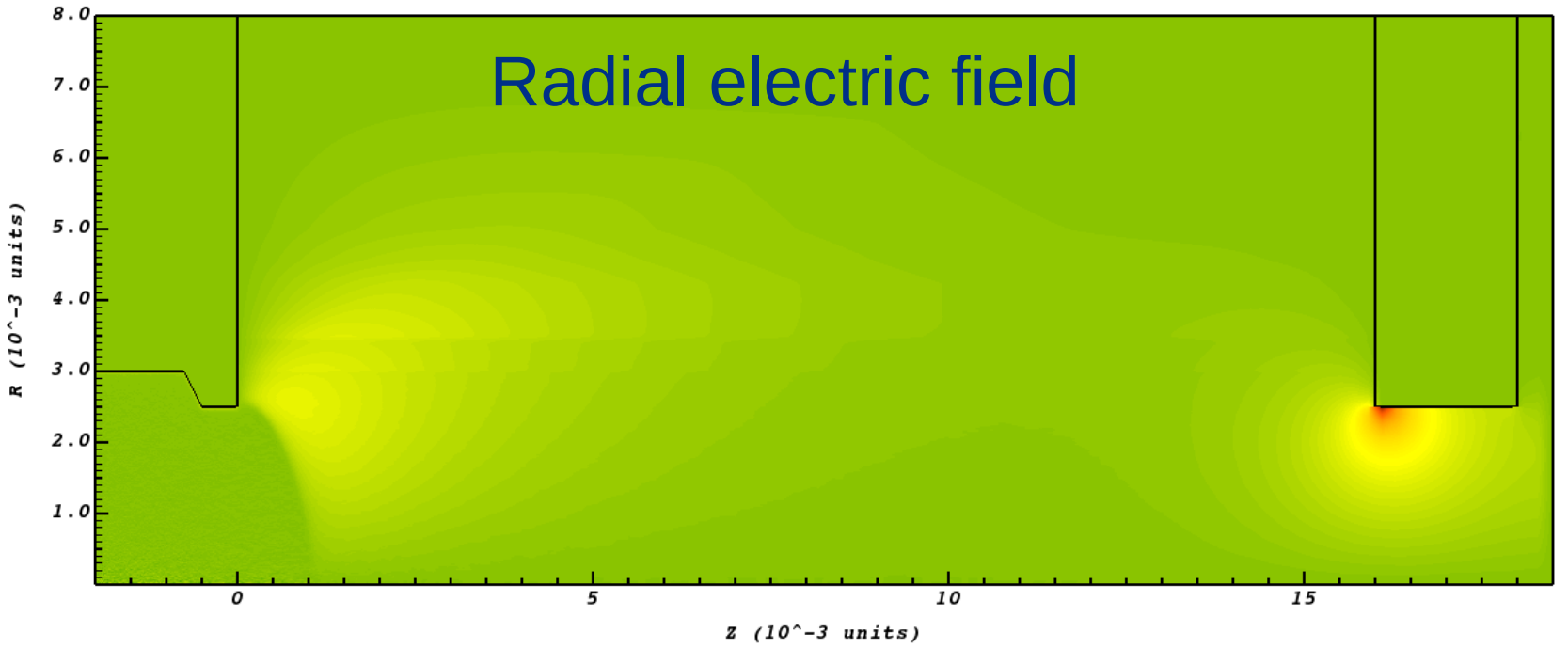


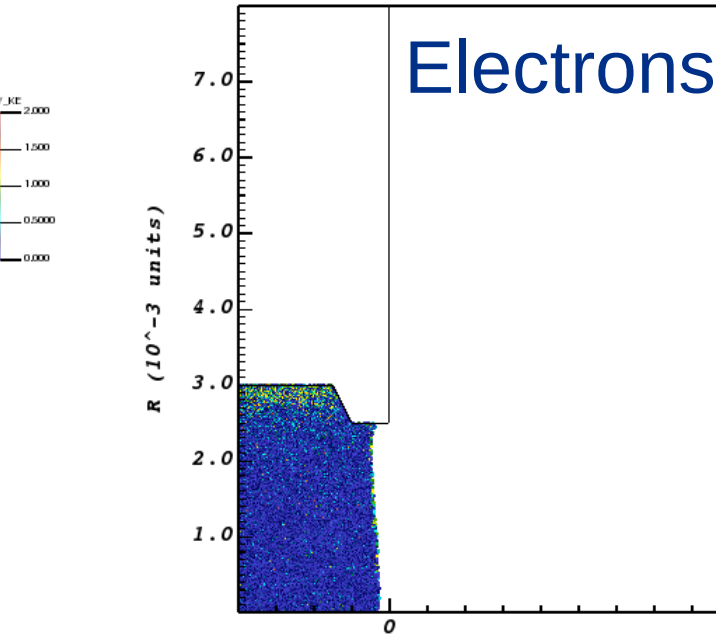
1 kV extraction voltage

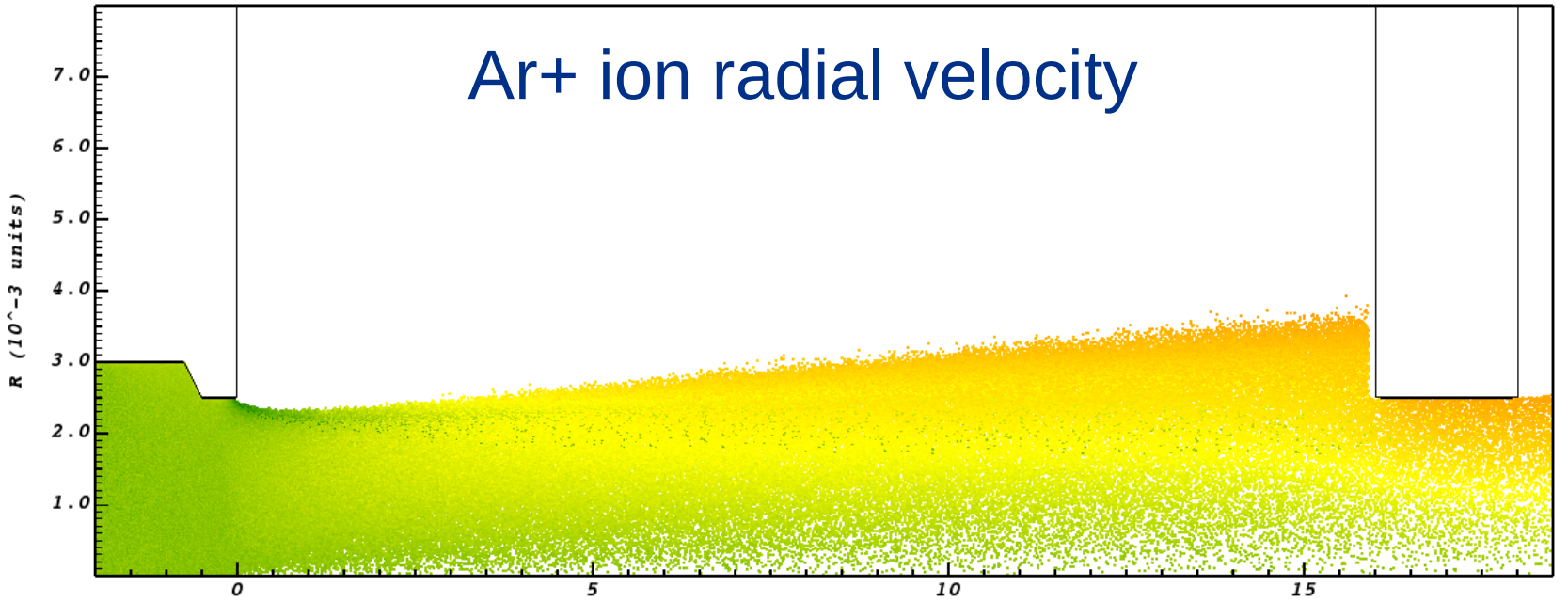




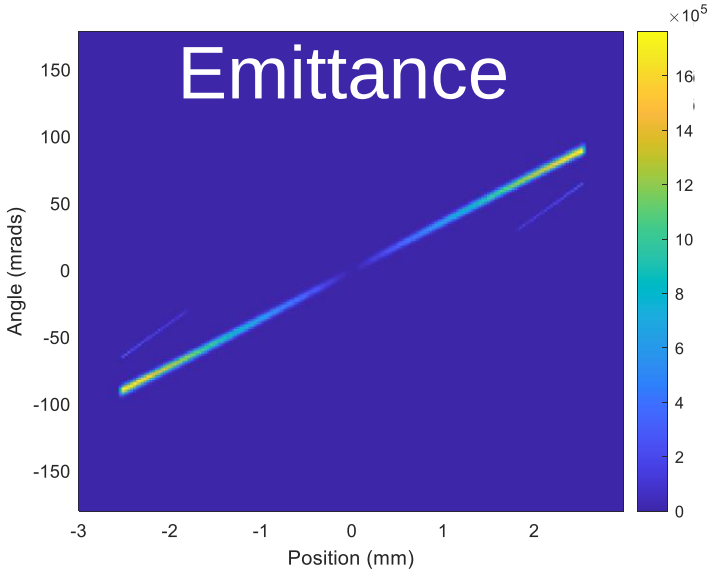


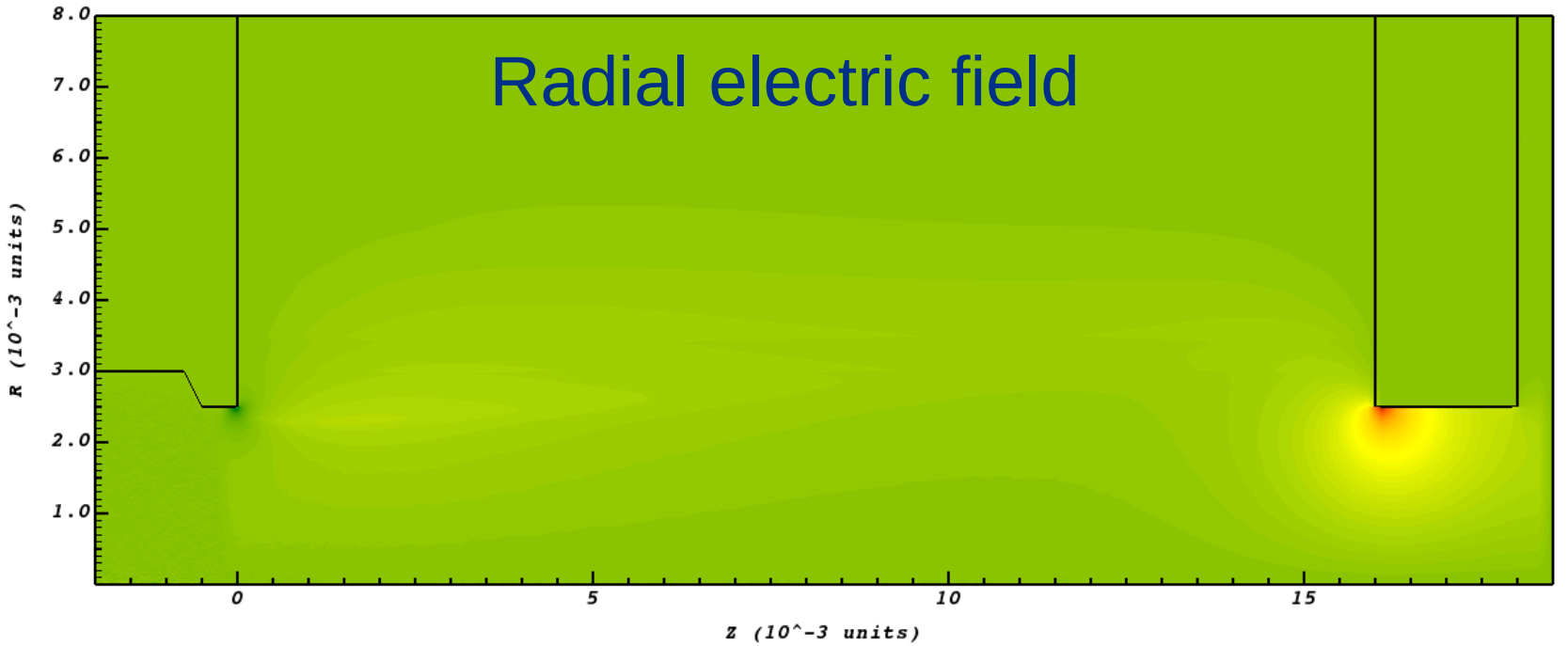


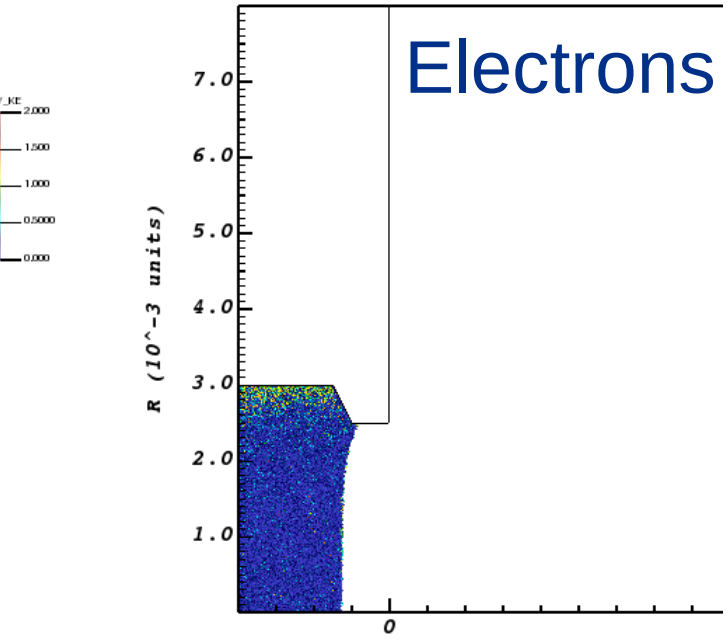


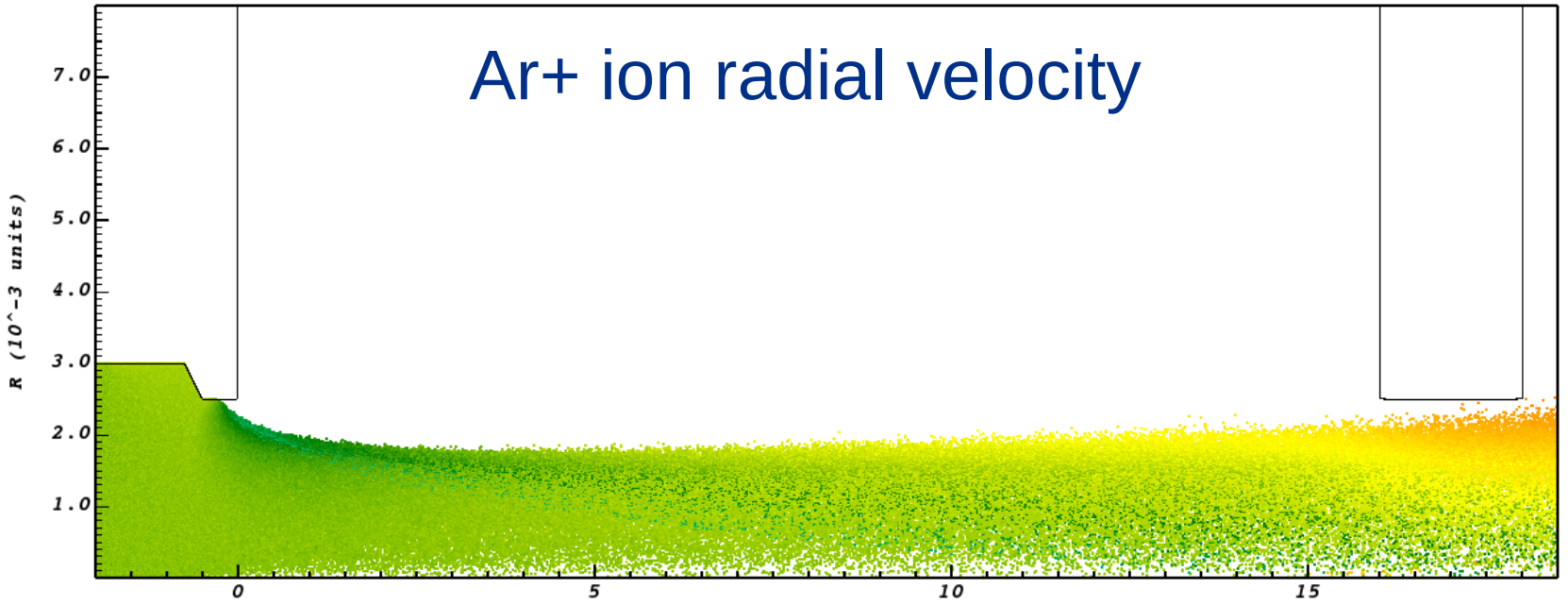


2 kV extraction voltage

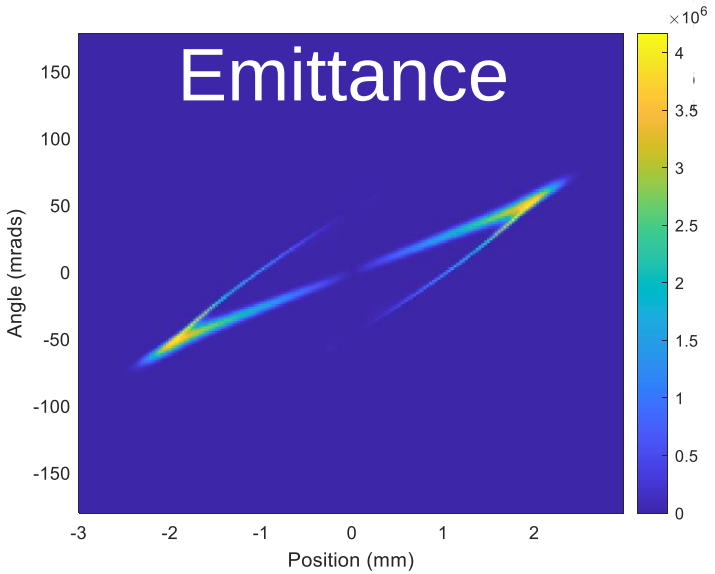


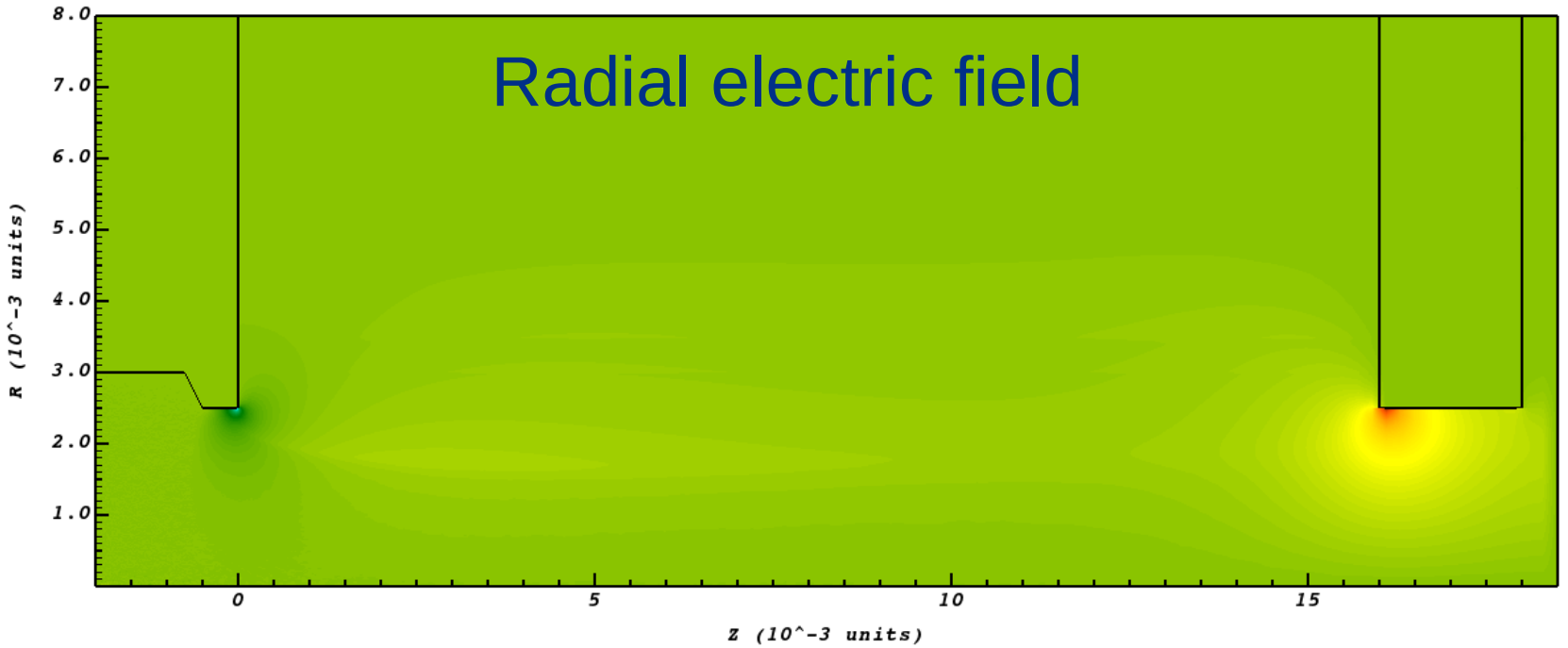


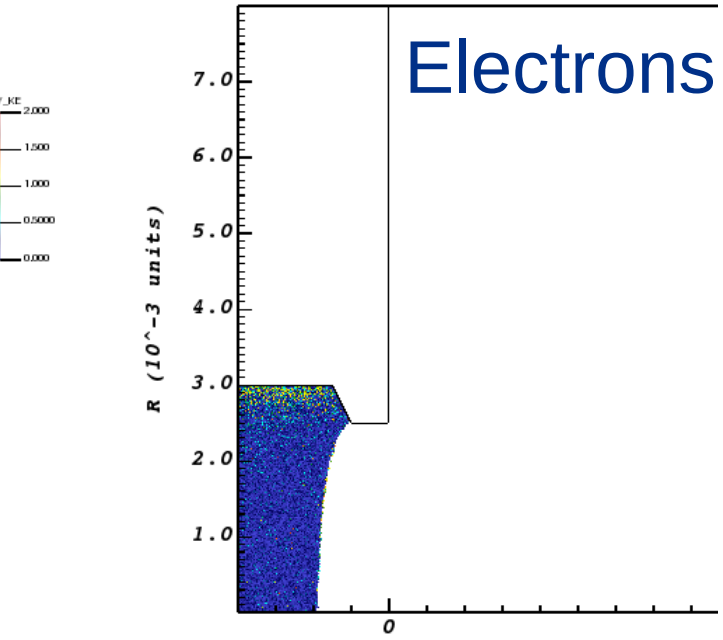


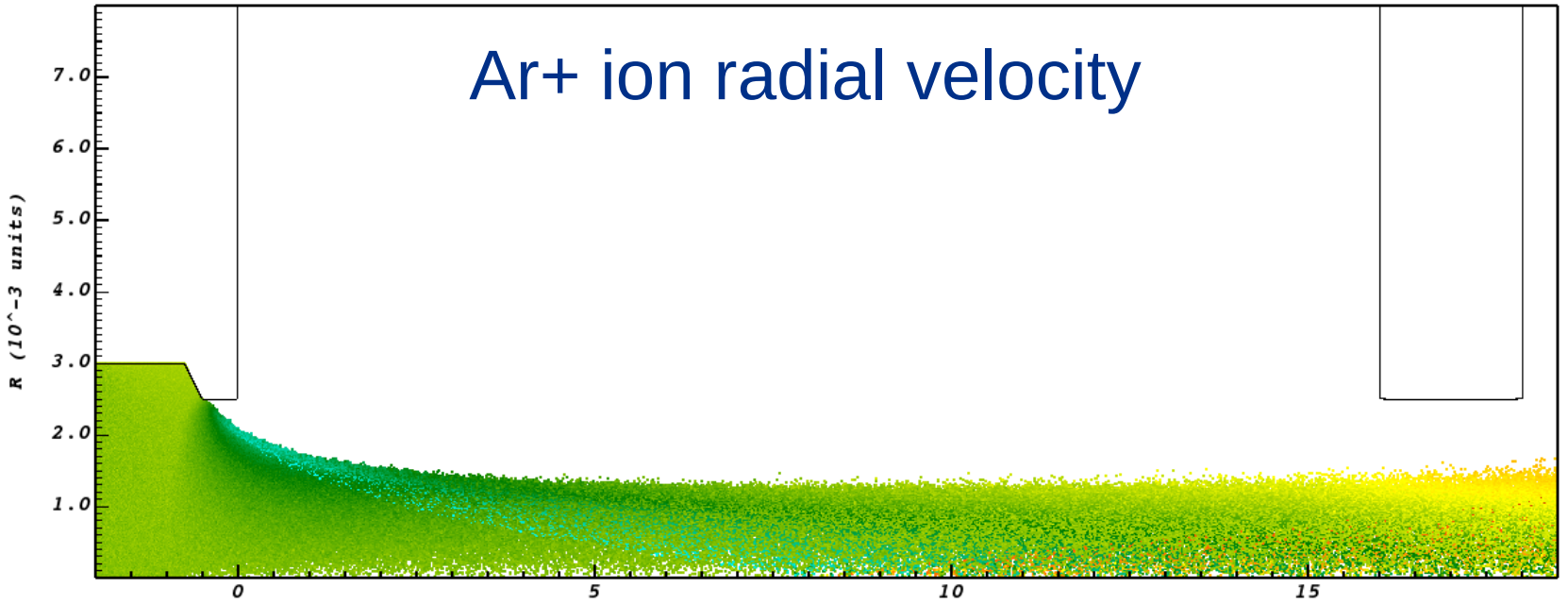


3 kV extraction voltage

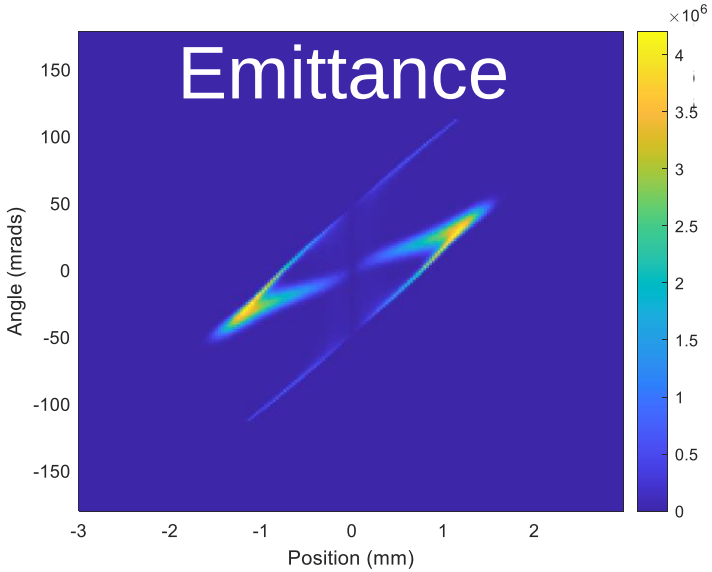


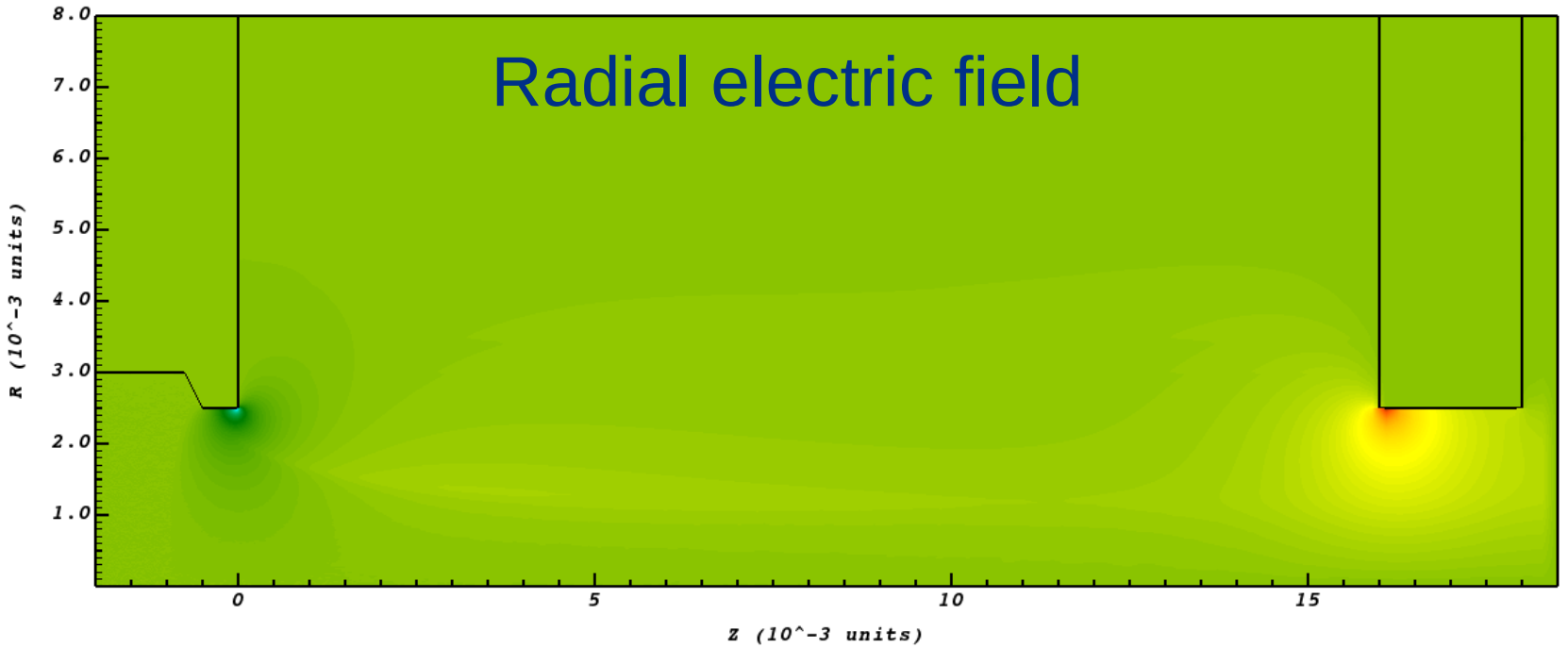


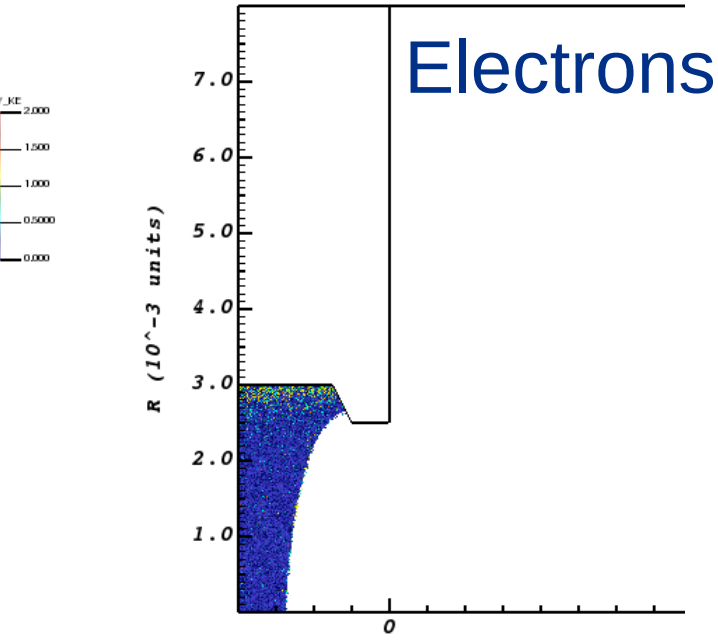


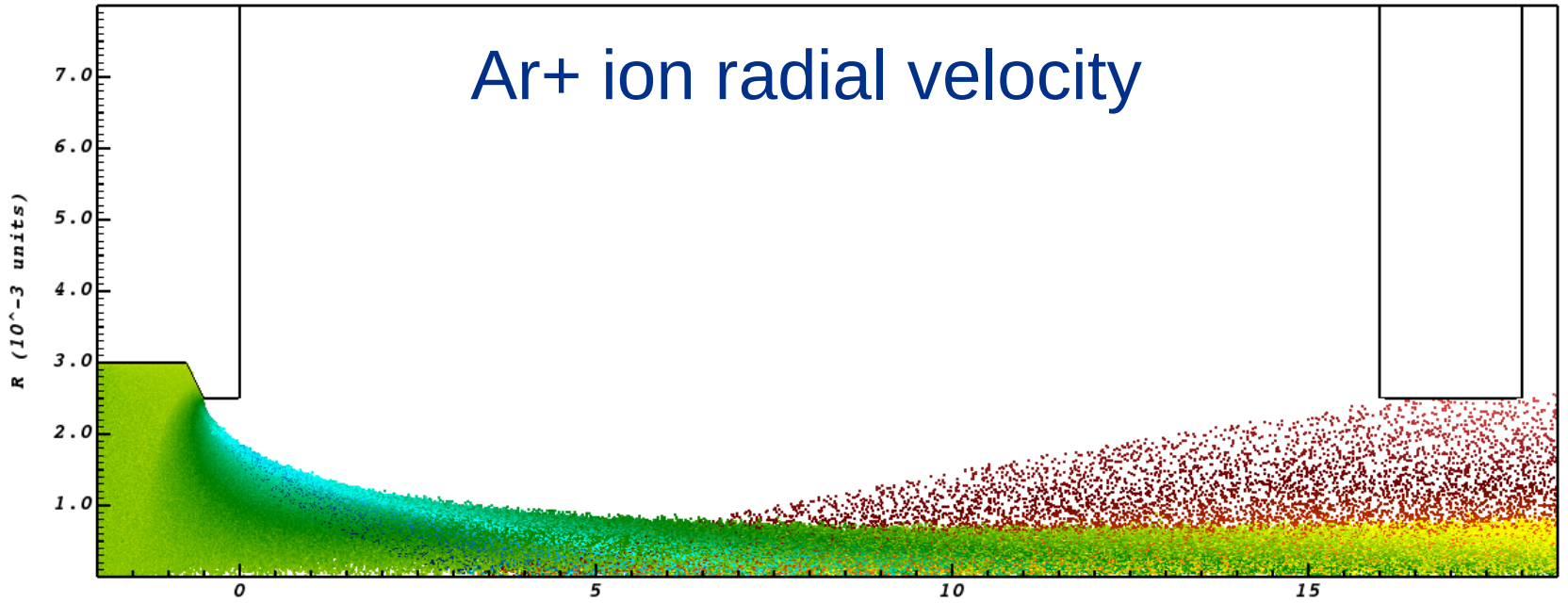


4 kV extraction voltage

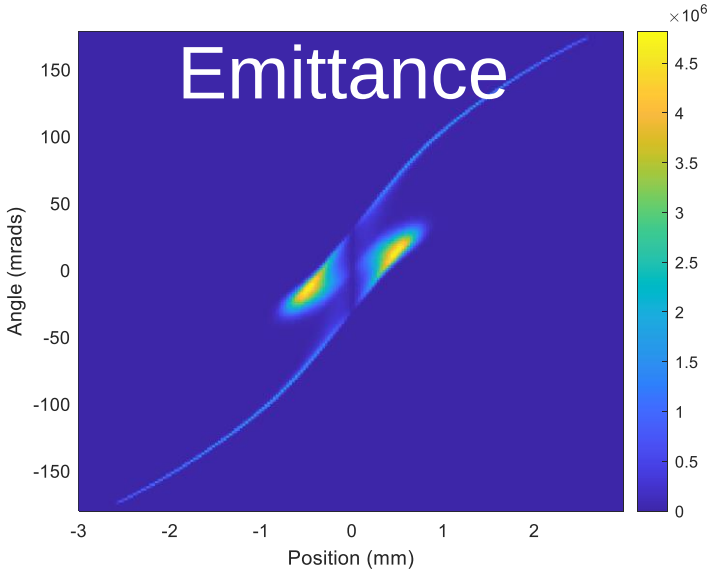


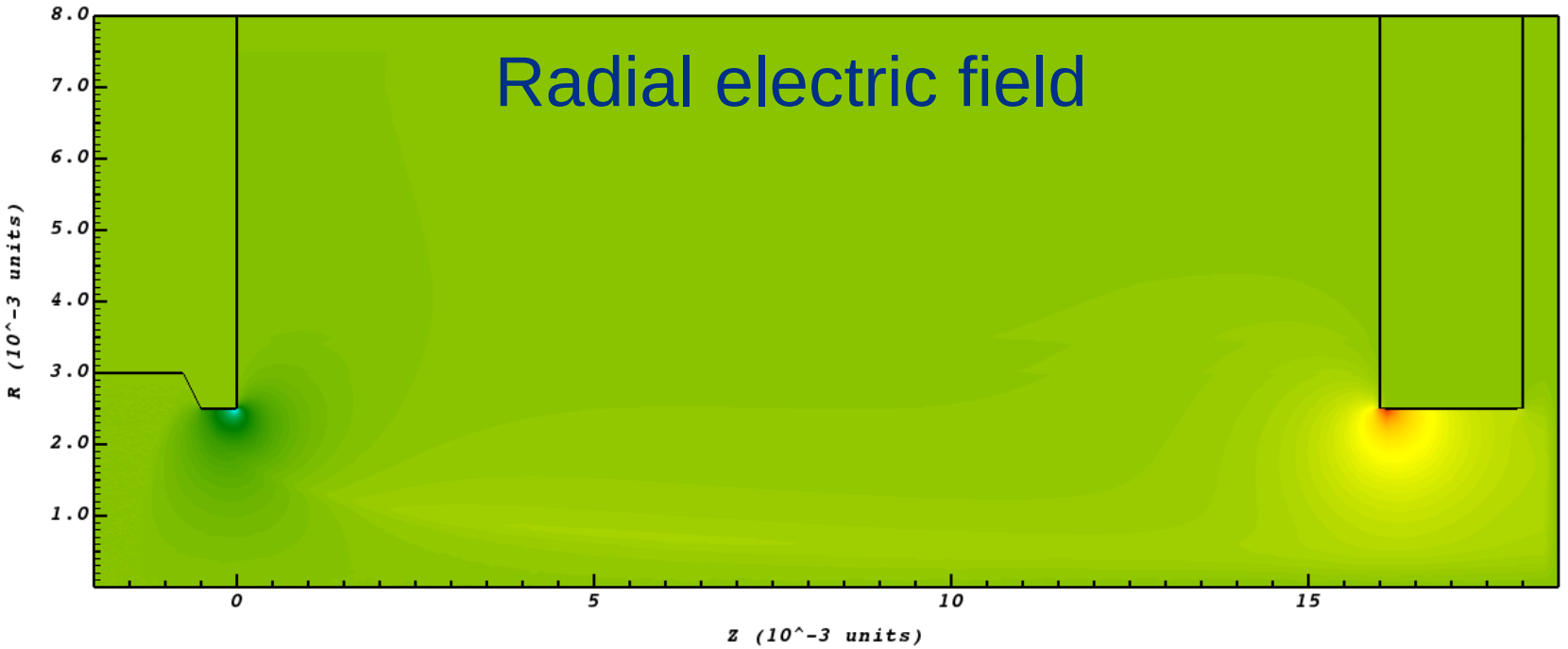


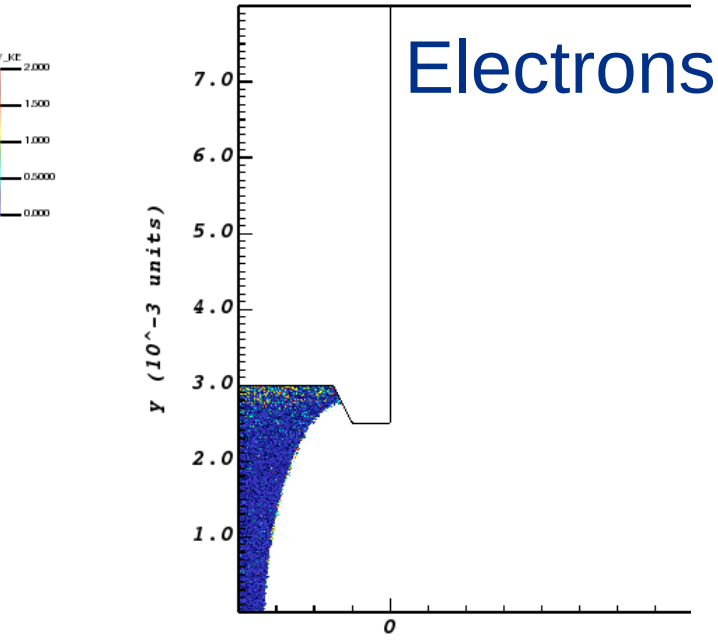


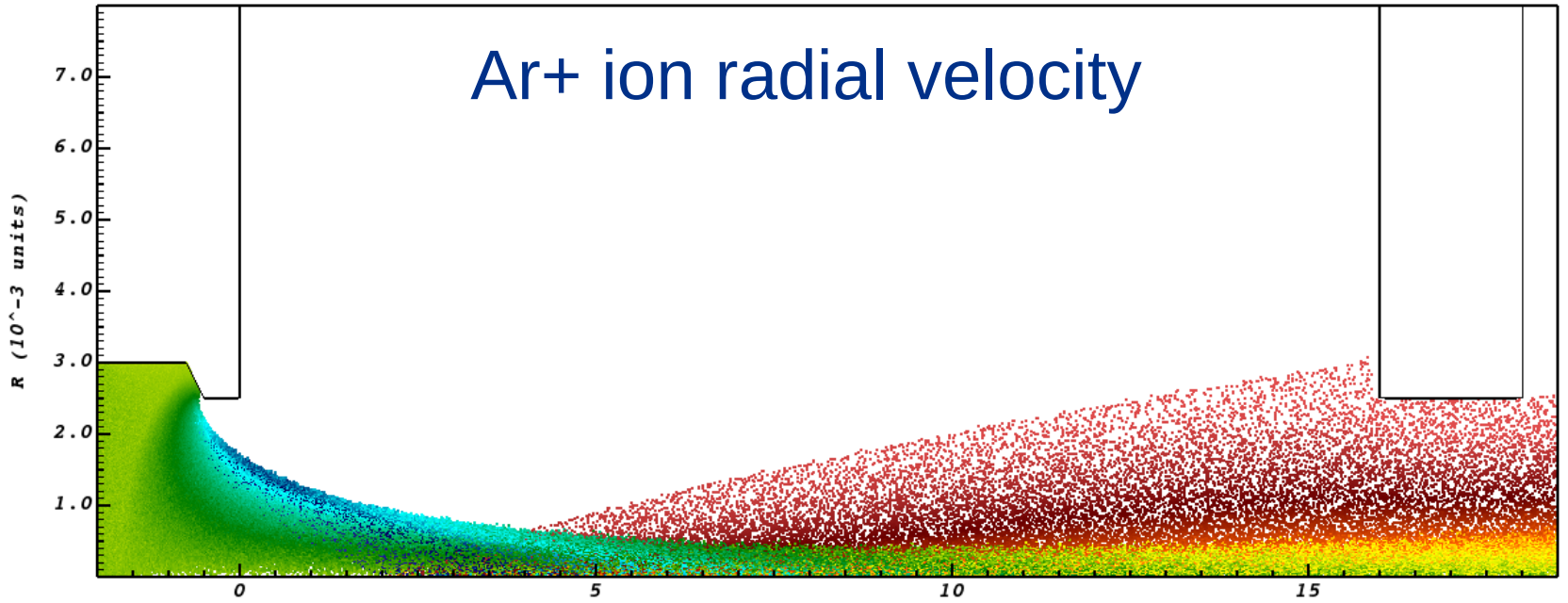


6 kV extraction voltage

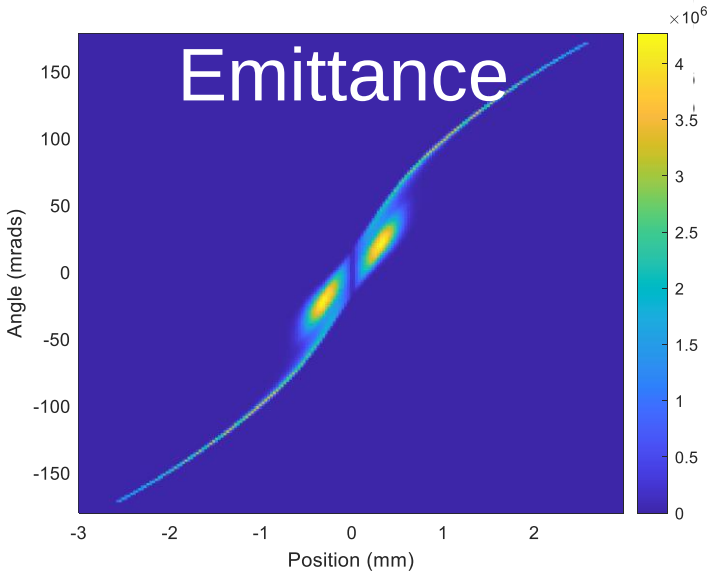


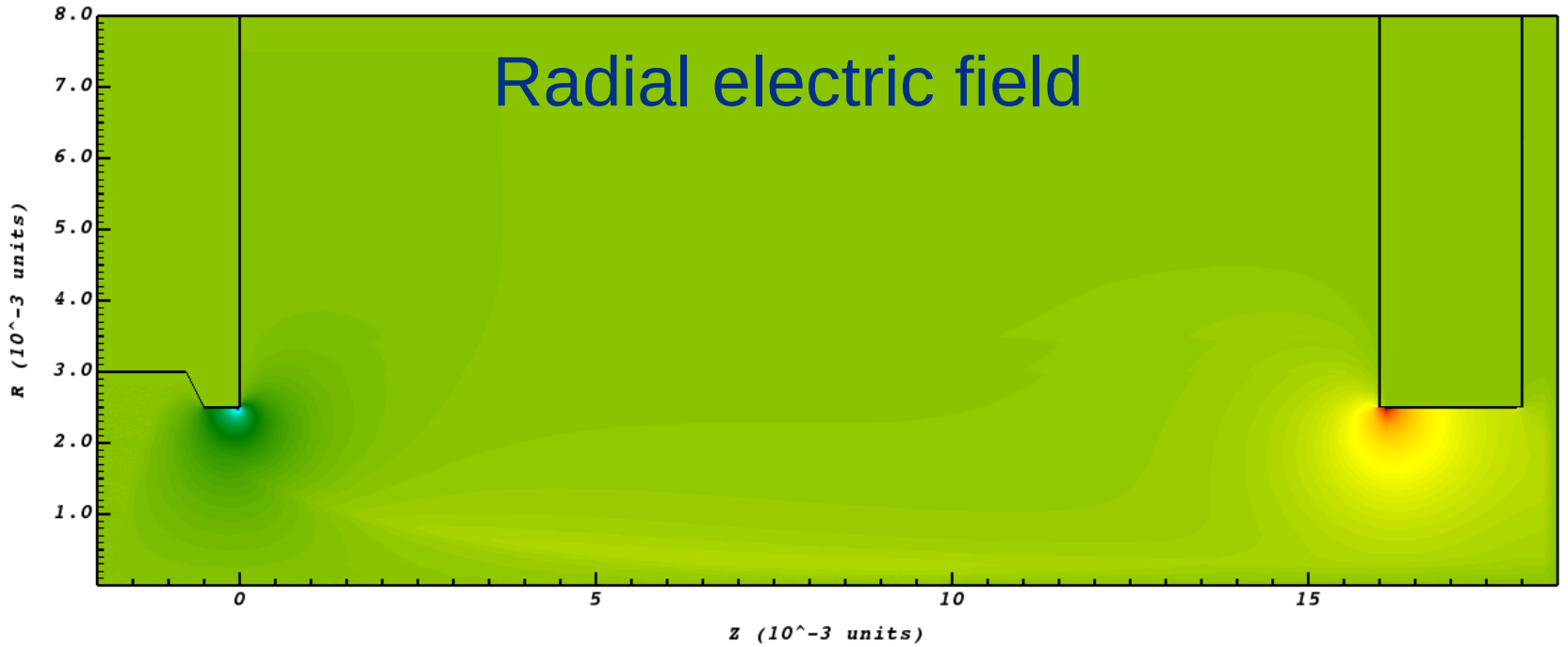




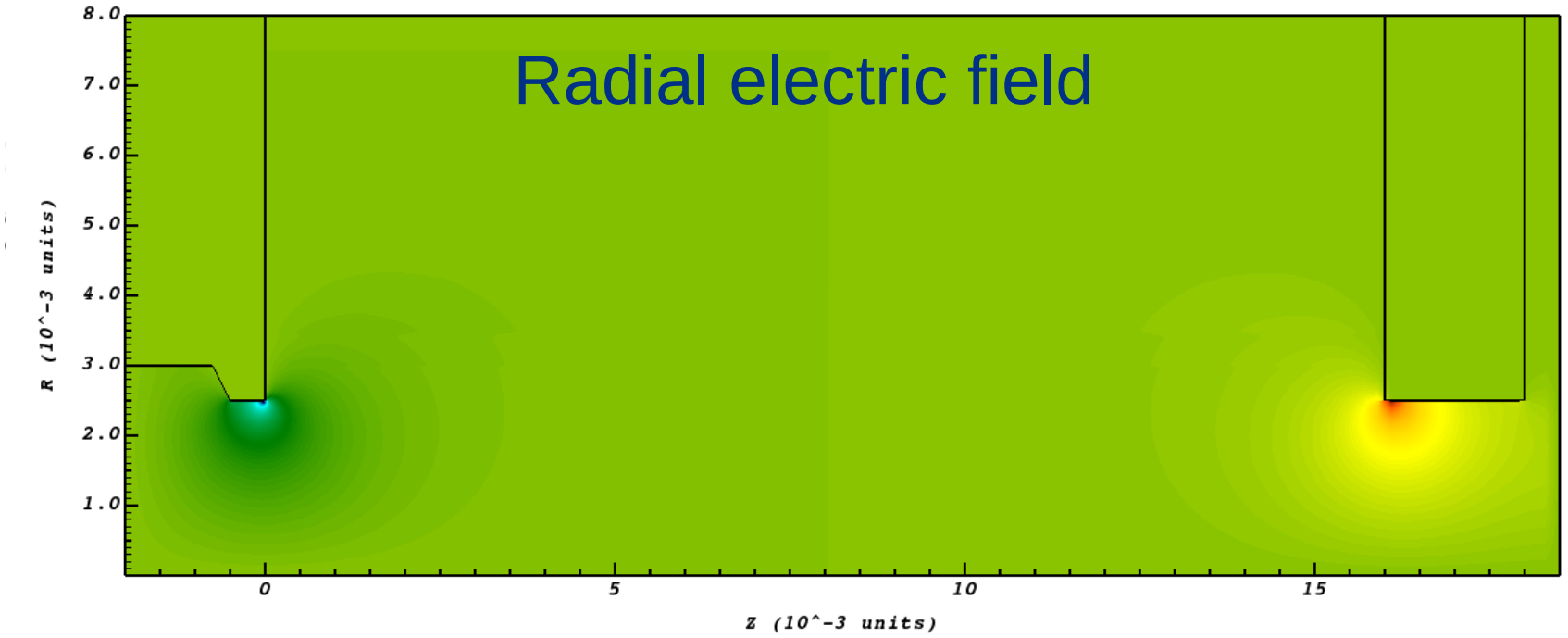


8 kV extraction voltage

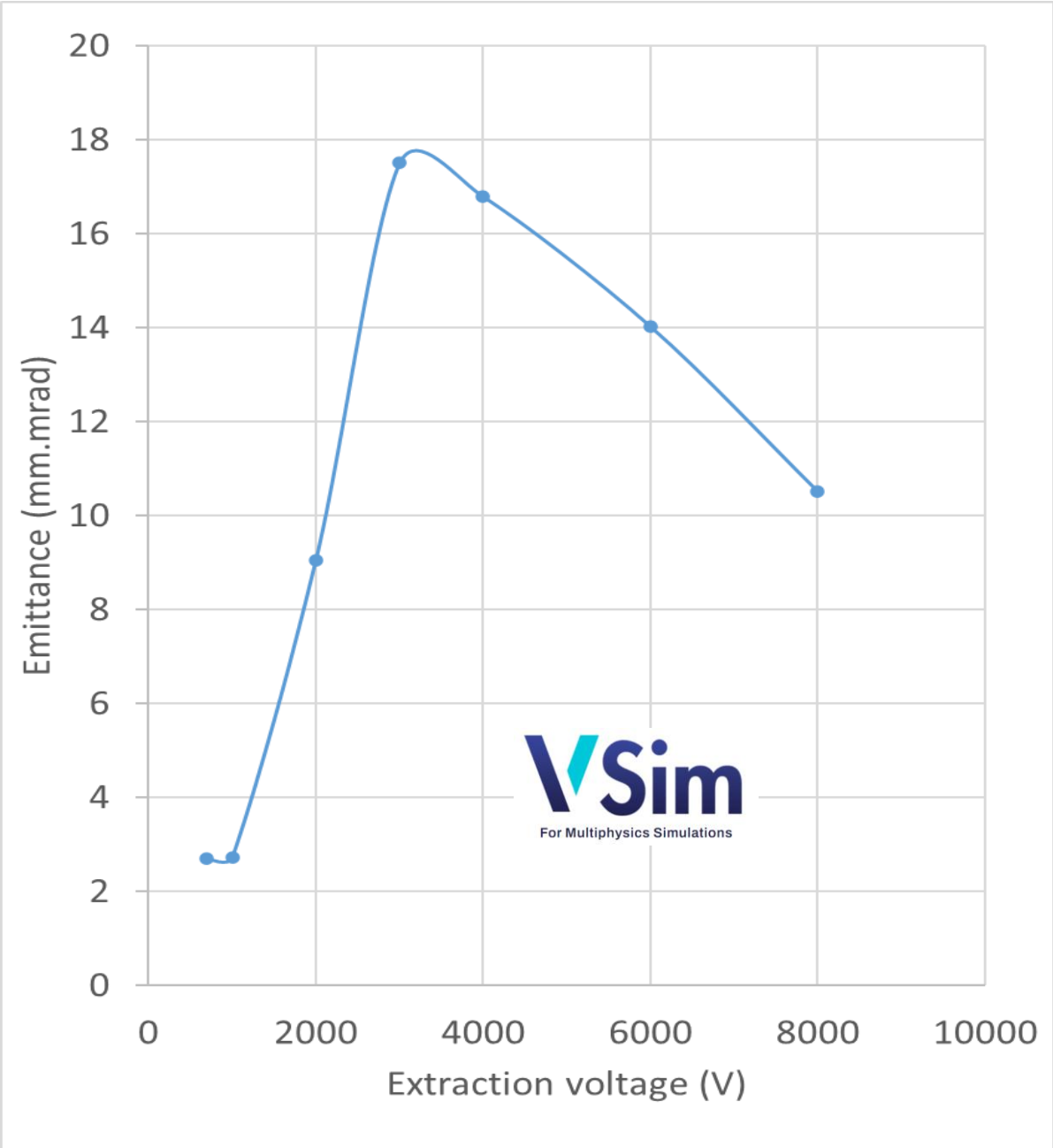


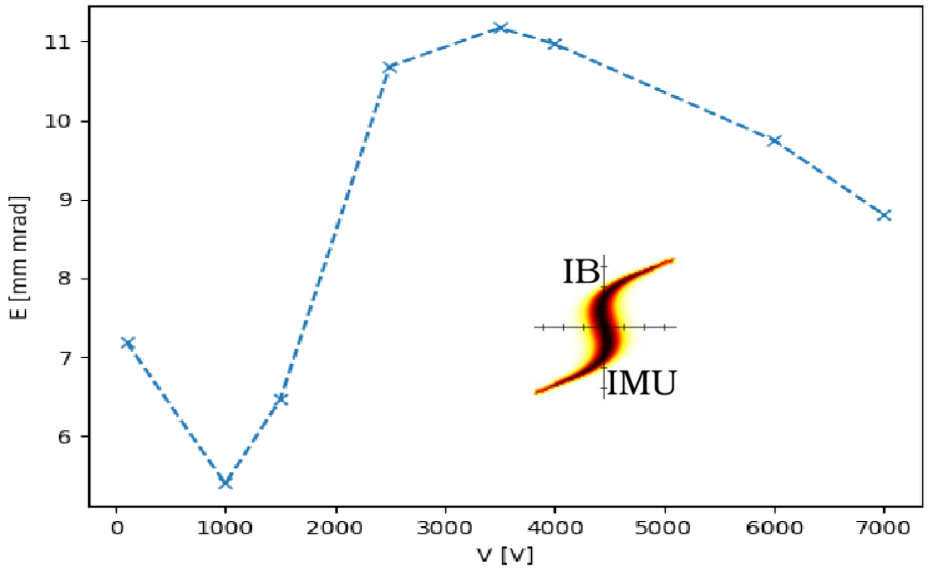


No plasma

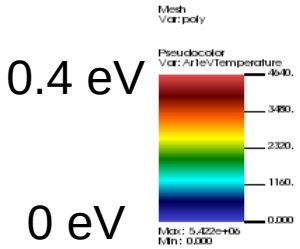

Radial electric field
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
R (10^-3 units)
0
5
10
15
Z (10^-3 units)

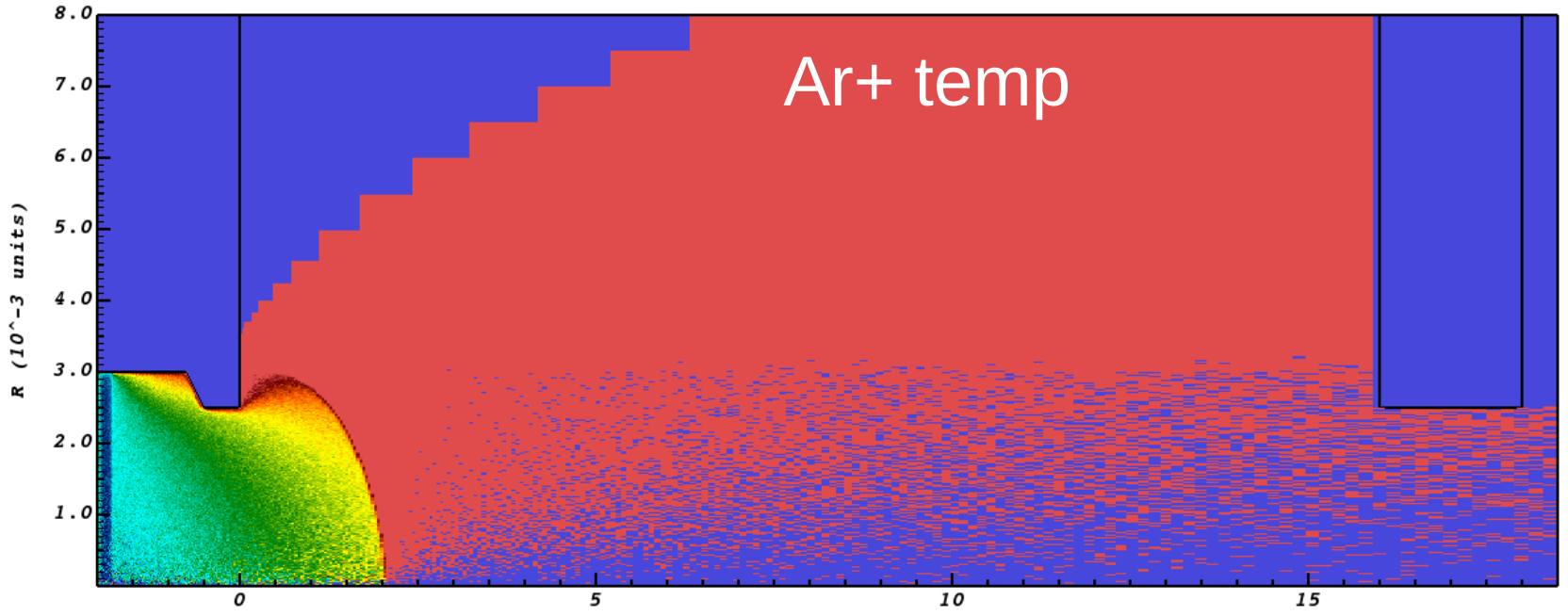
Emittance

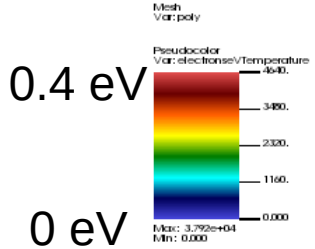

Emittance (mm.mrad)
Extraction voltage (V)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
VSim
For Multiphysics Simulations

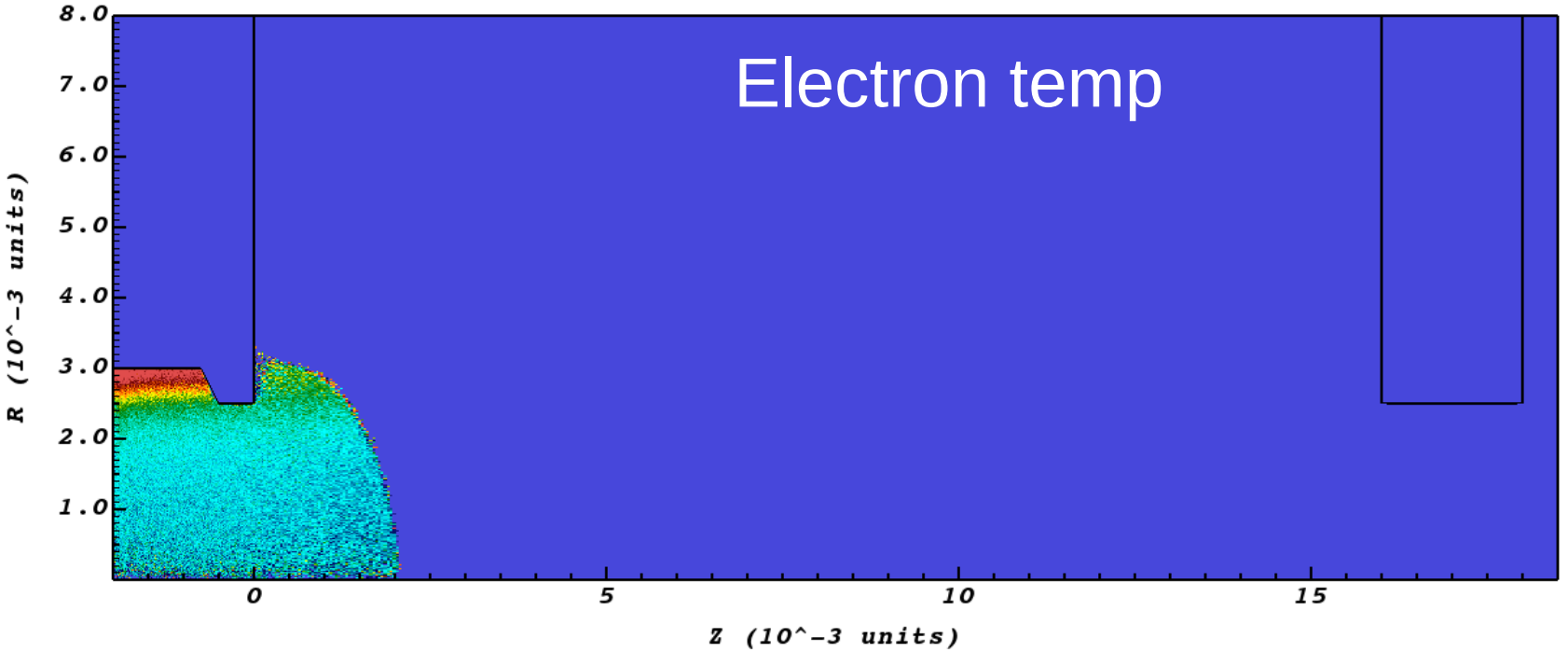

E [mm mrad]
V [V]
6
7
8
9
10
11
0
1000
2000
3000
4000
5000
6000
7000
IB
IMU

700 V extraction voltage

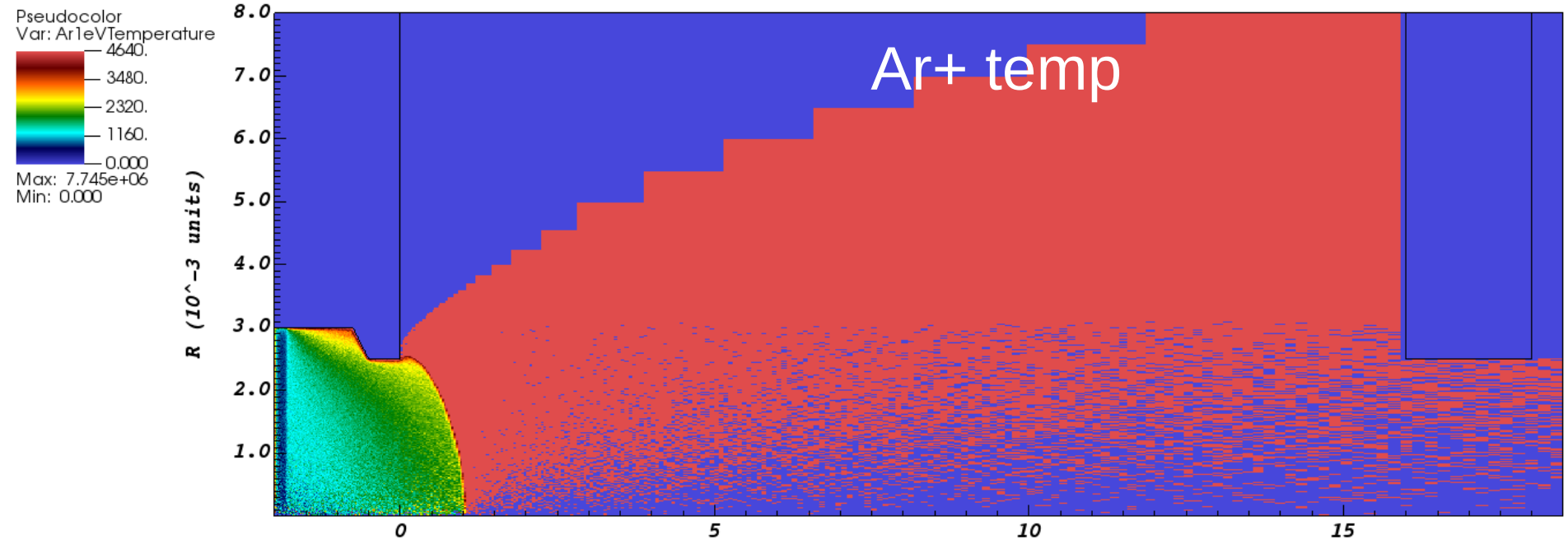


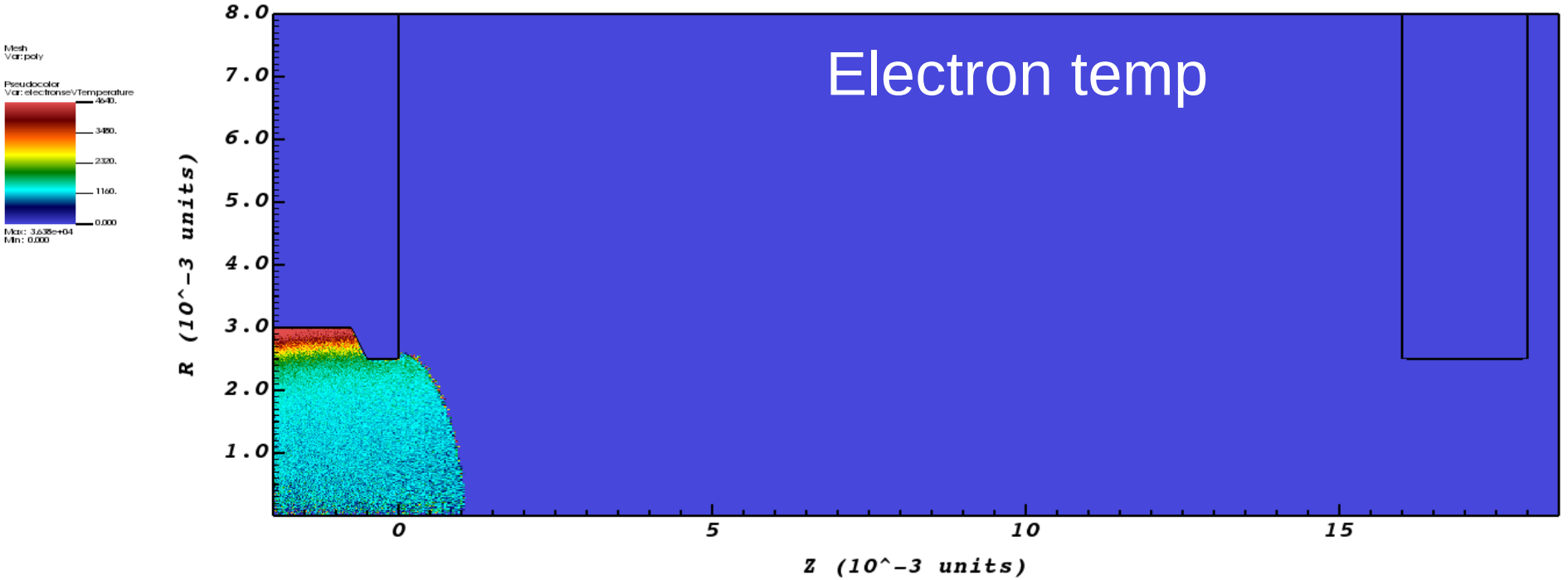






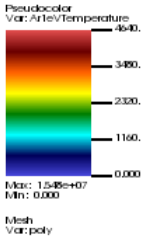
1 kV extraction voltage

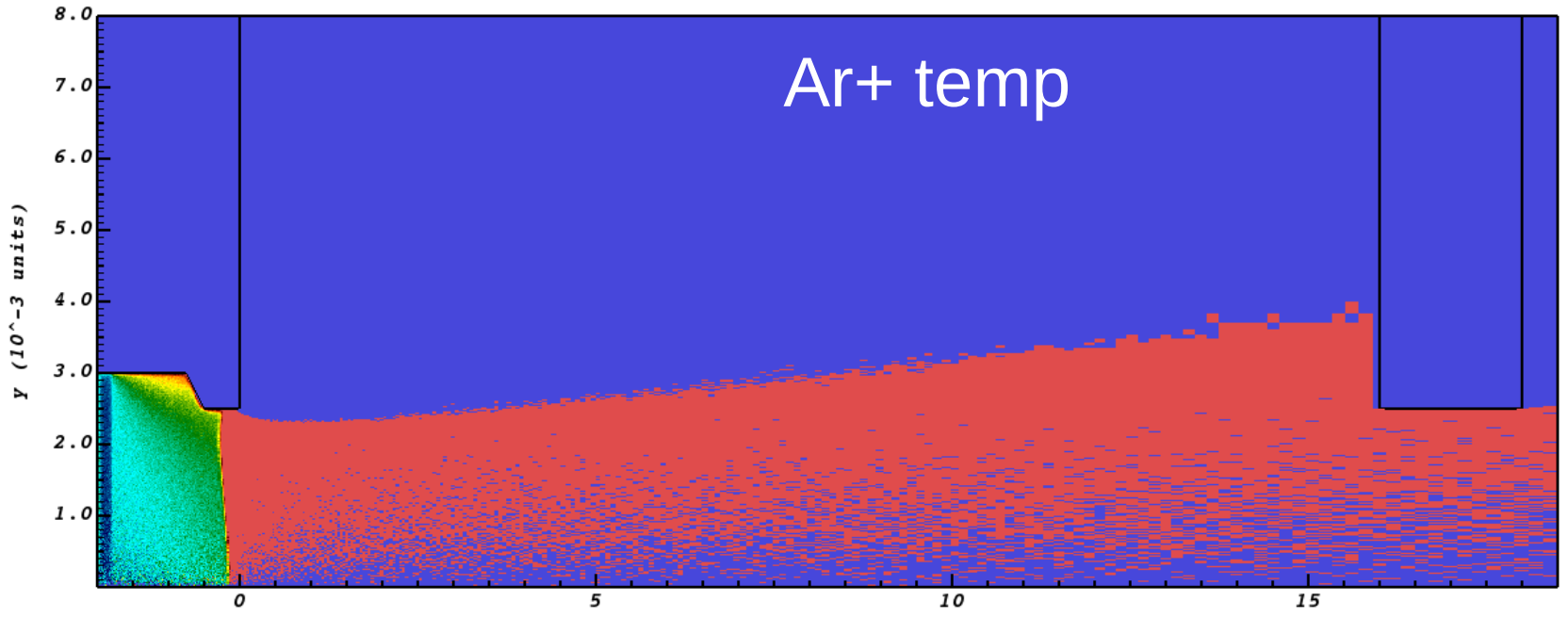


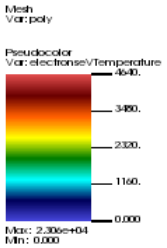


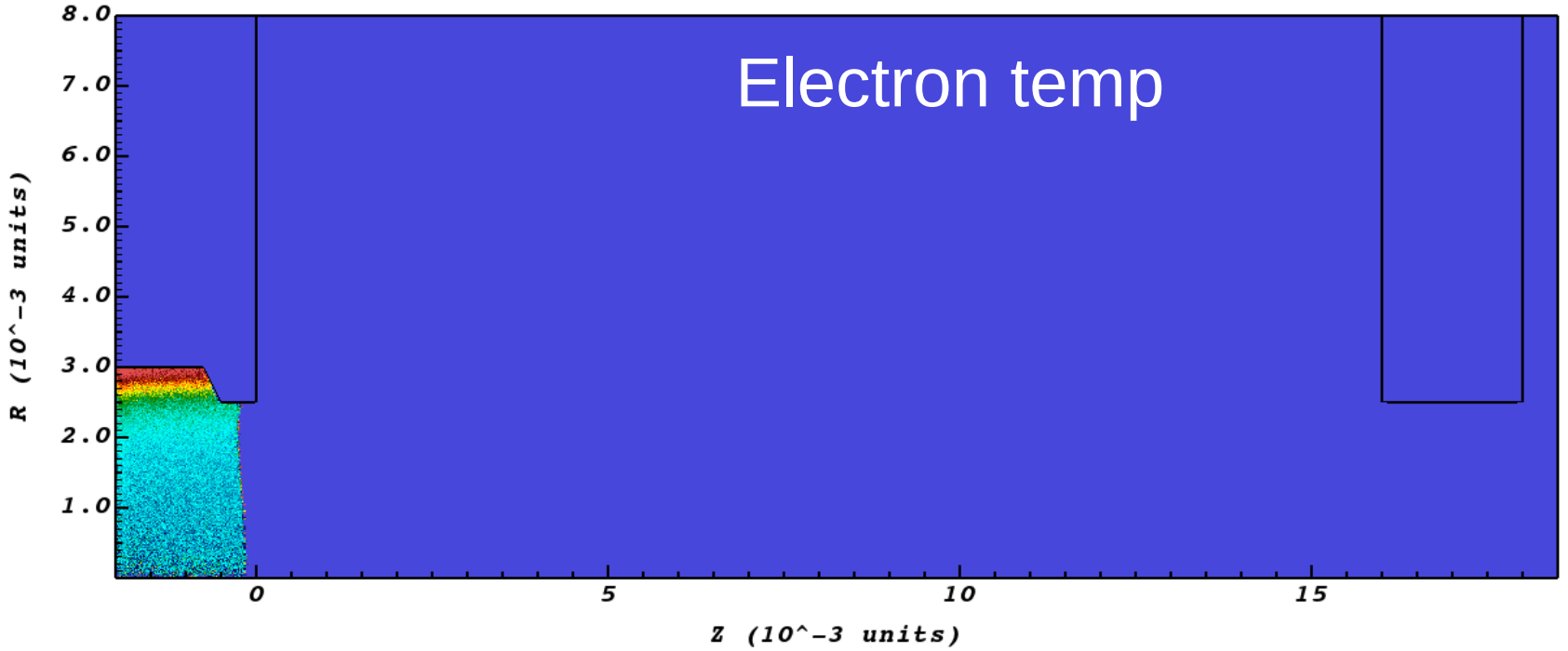
1000

2 kV extraction voltage

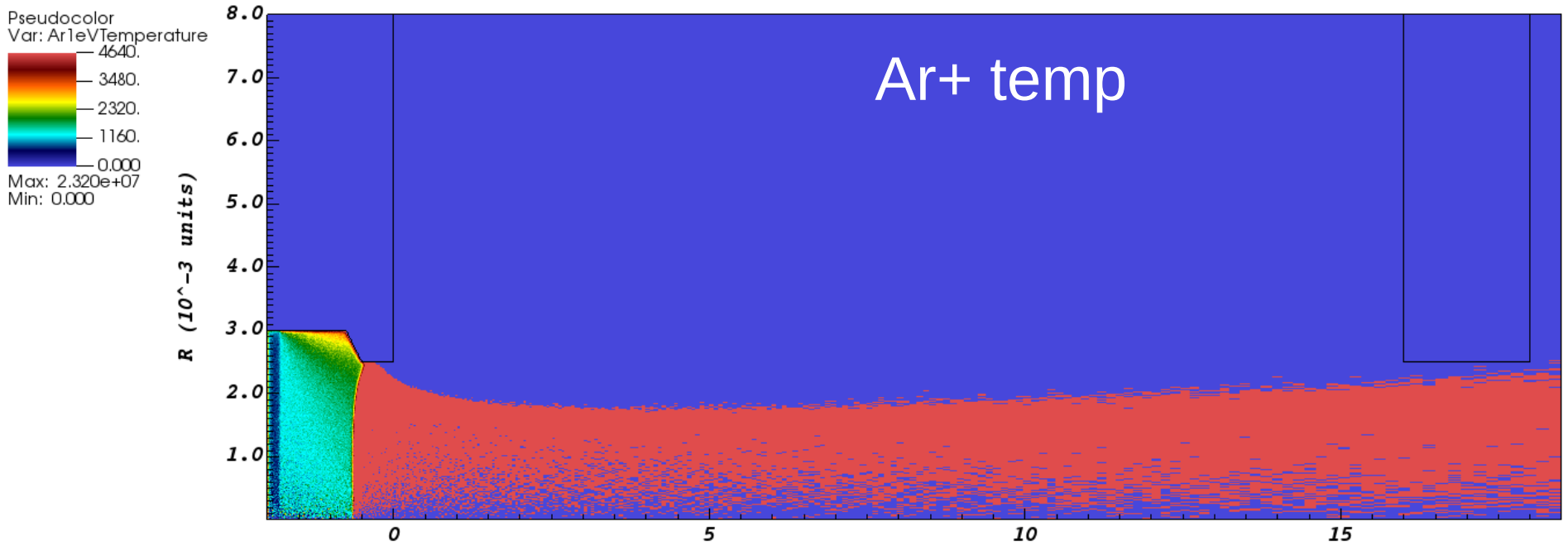


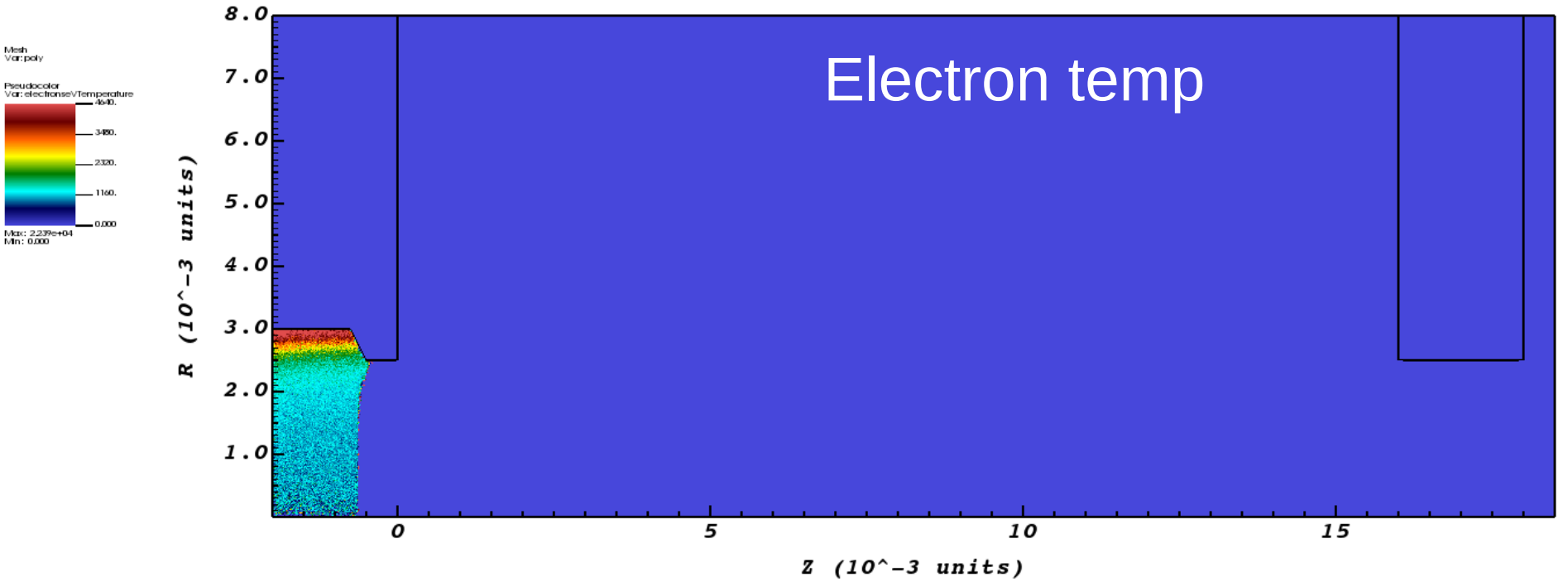




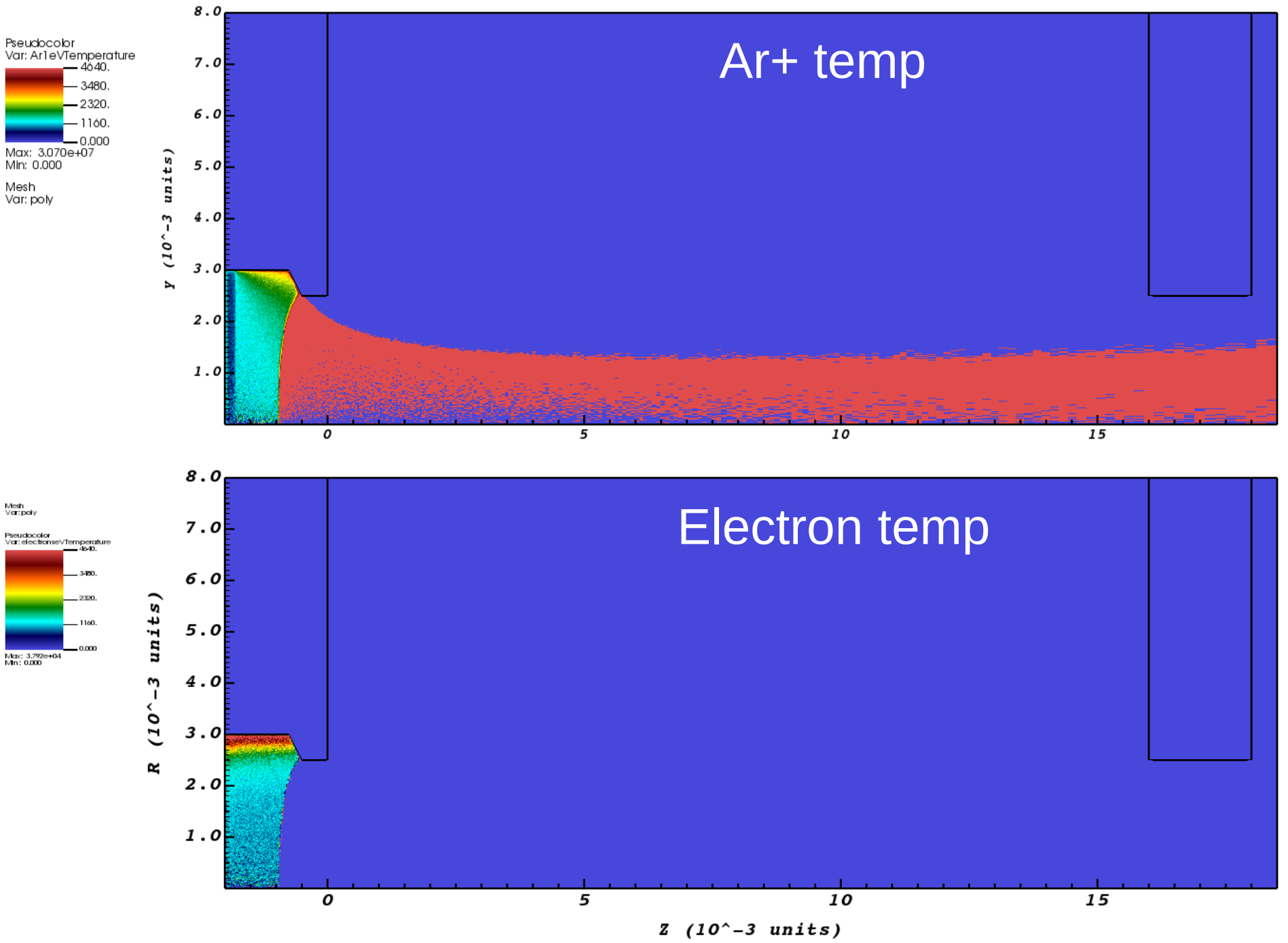


3 kV extraction voltage

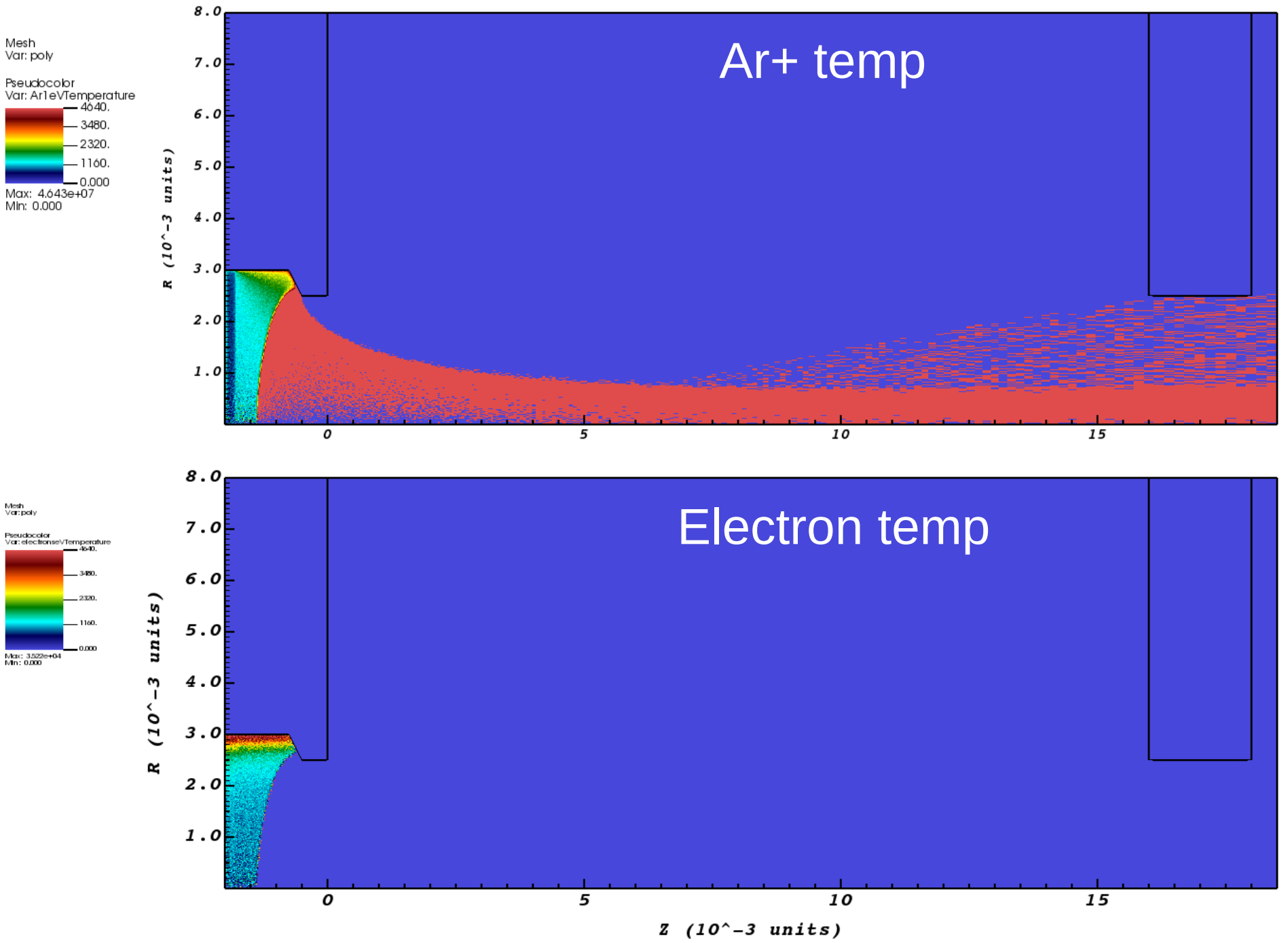




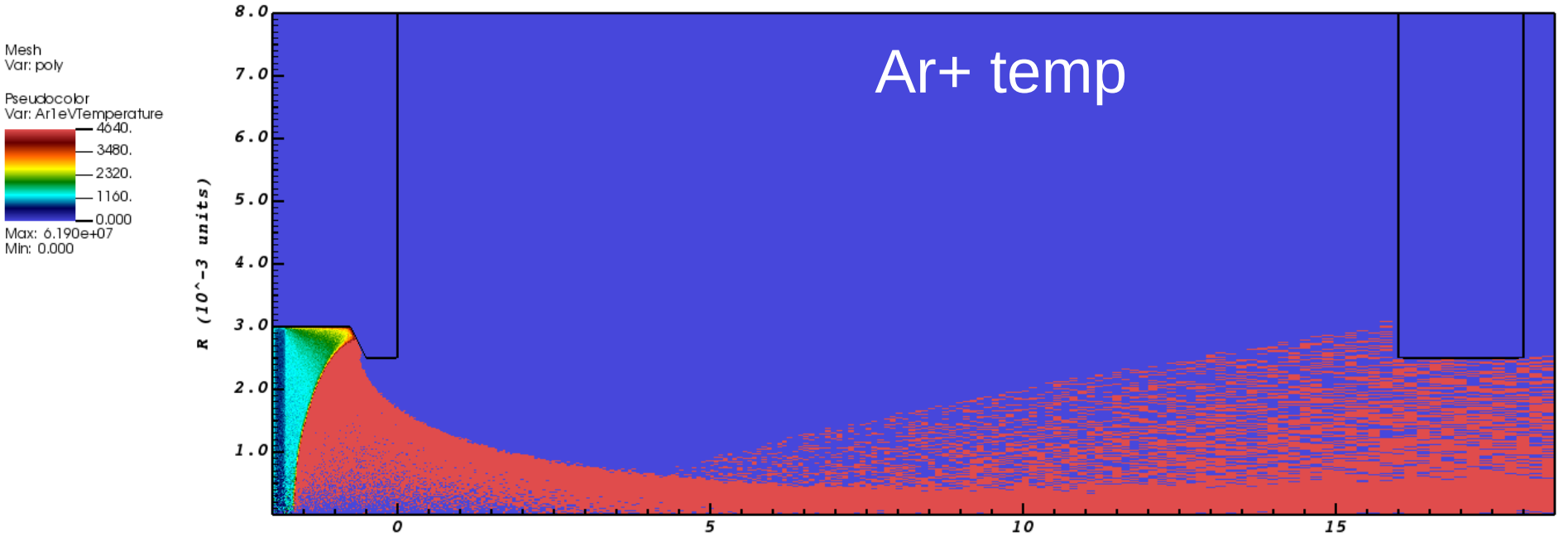
4 kV extraction voltage

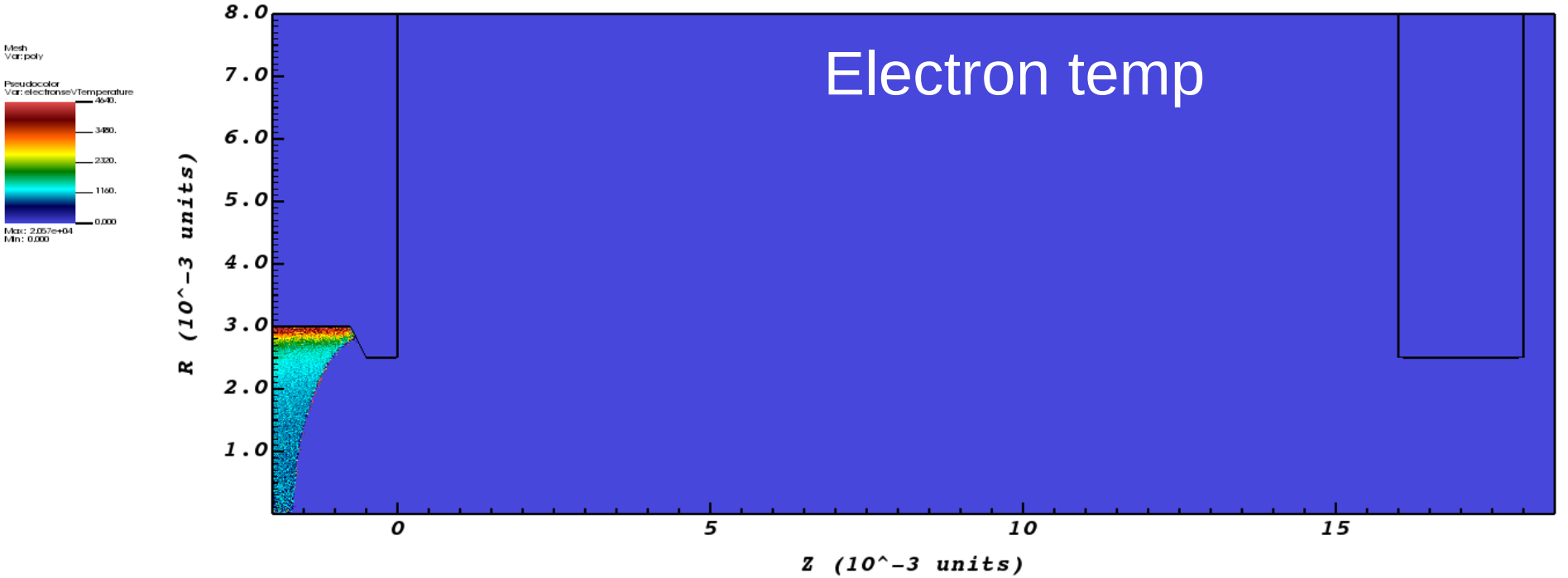


6 kV extraction voltage

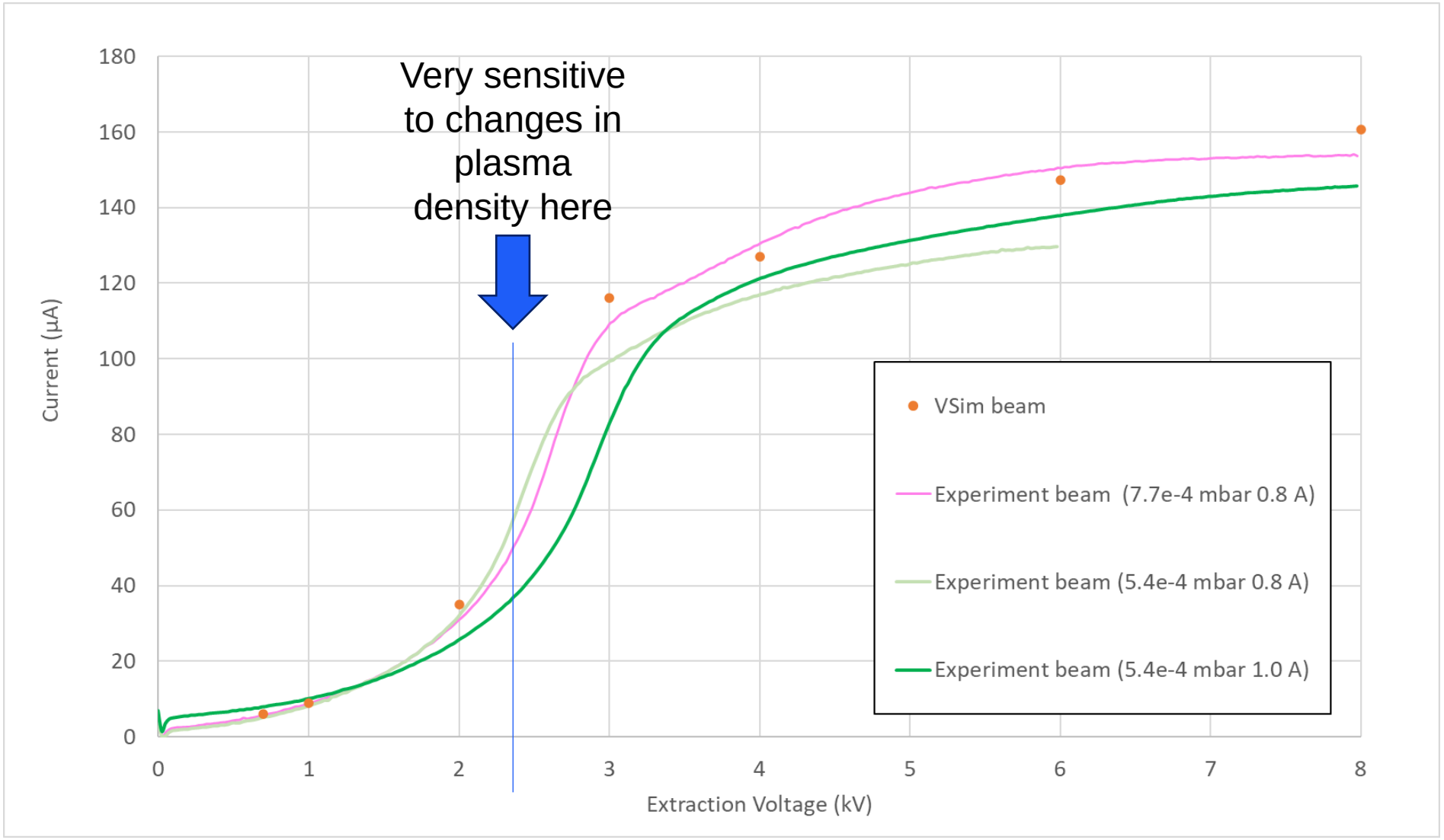


8 kV extraction voltage



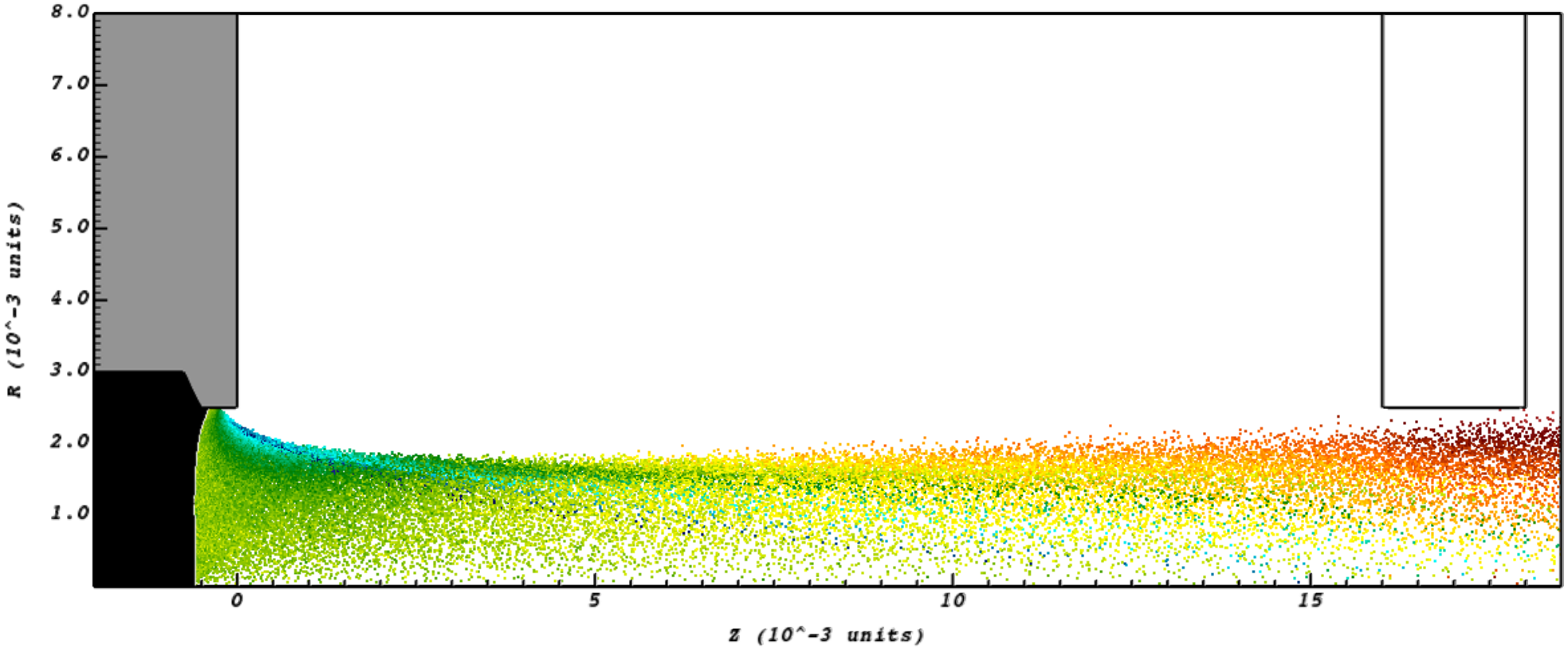


Vary Plasma Density



-30% plasma density

@ 2.3 kV extraction voltage

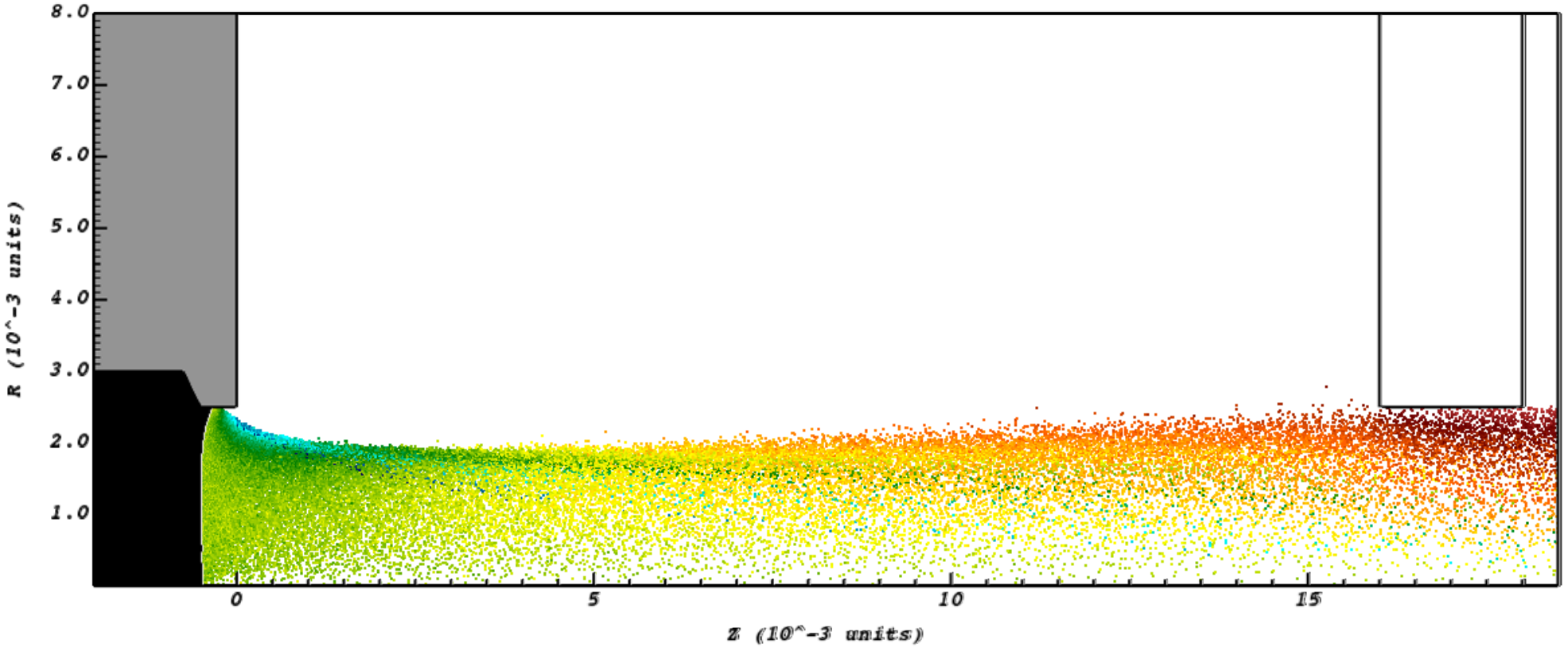


Colour scale
Ar+ radial velocity

81 µA beam current

-20% plasma density

@ 2.3 kV extraction voltage

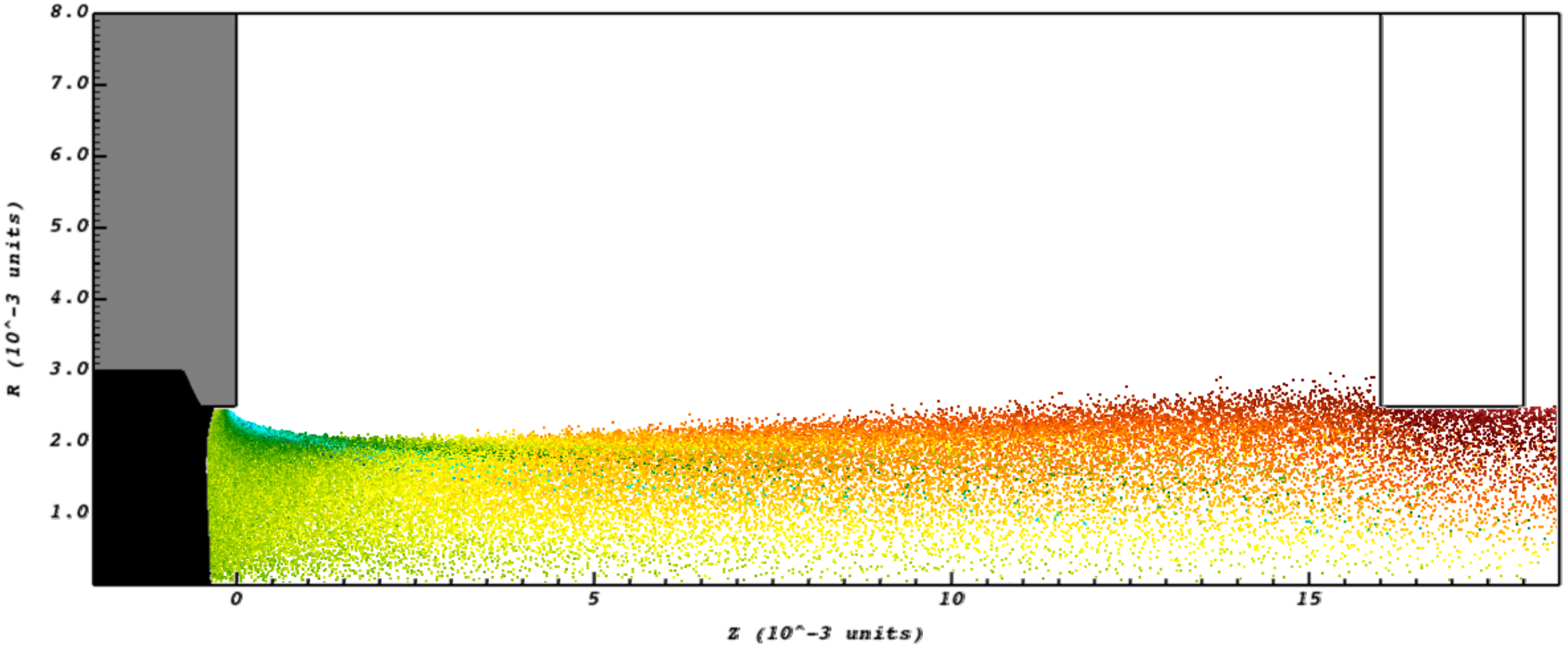


Colour scale
Ar+ radial velocity

86 µA beam current

-10% plasma density

@ 2.3 kV extraction voltage

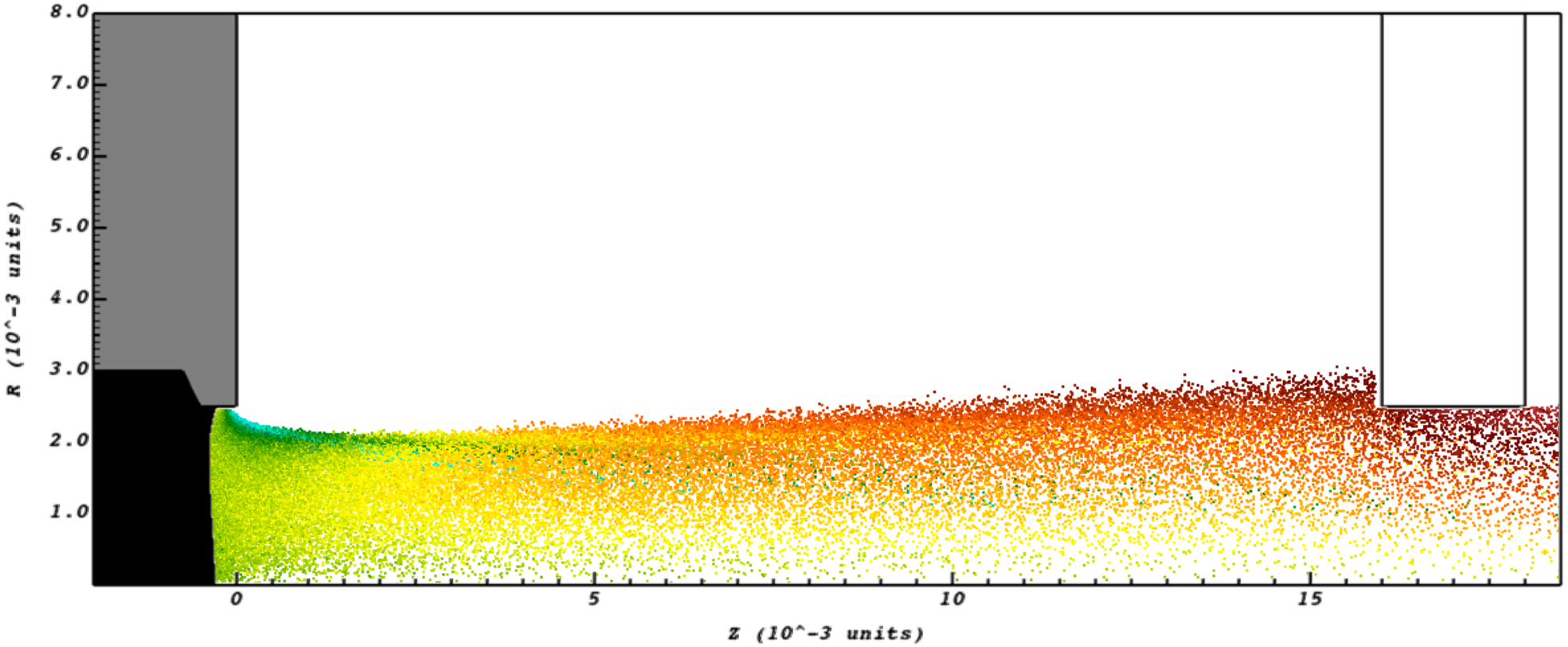


Colour scale
Ar+ radial velocity

86 µA beam current

-5% plasma density

@ 2.3 kV extraction voltage

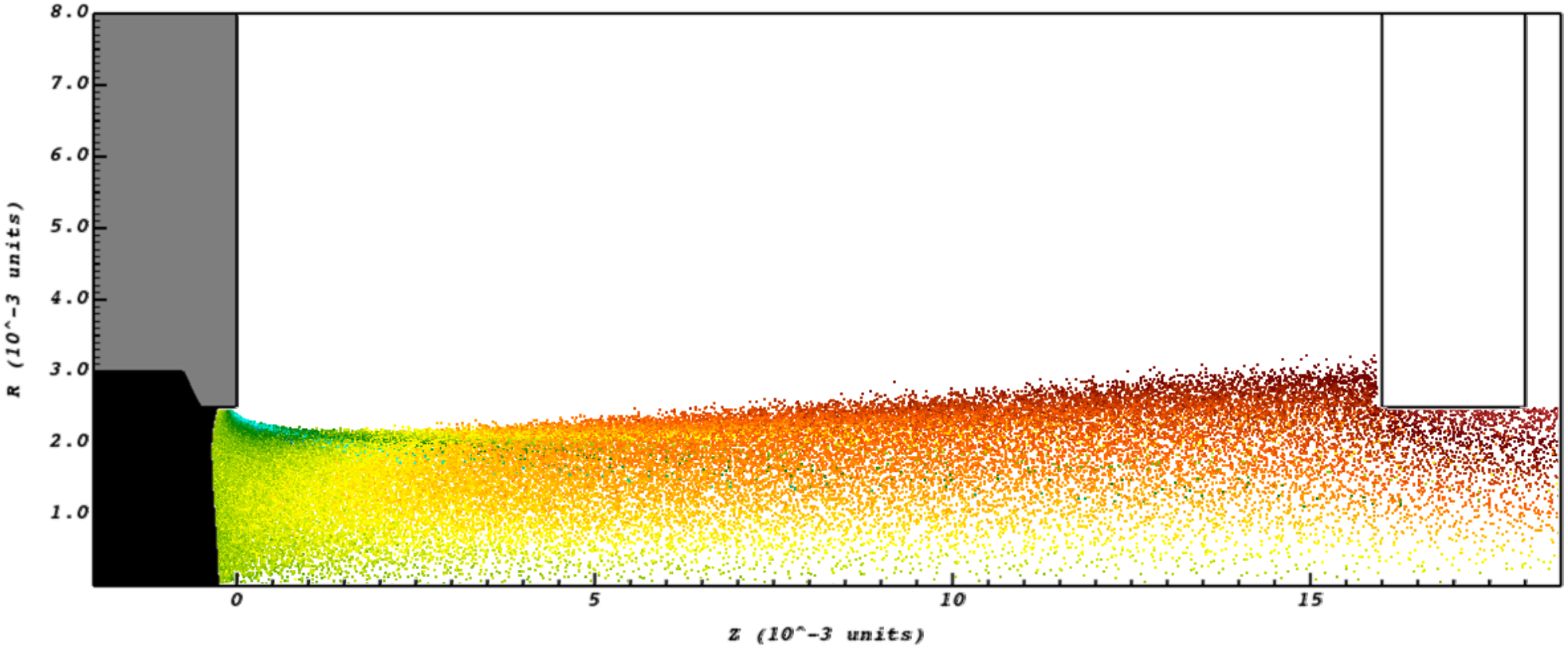


Colour scale
Ar+ radial velocity

58 µA beam current

Standard plasma density

@ 2.3 kV extraction voltage

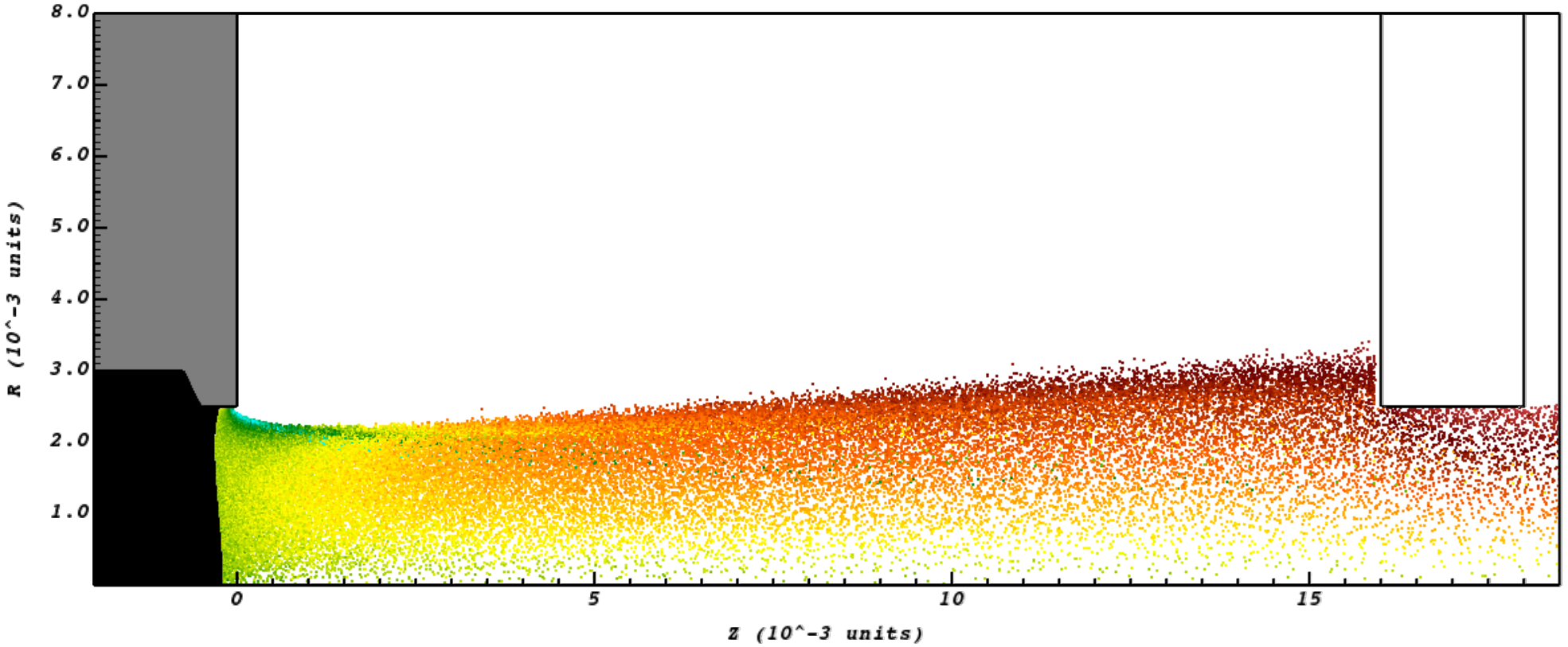


Colour scale
Ar+ radial velocity

52 µA beam current

+5% plasma density

@ 2.3 kV extraction voltage

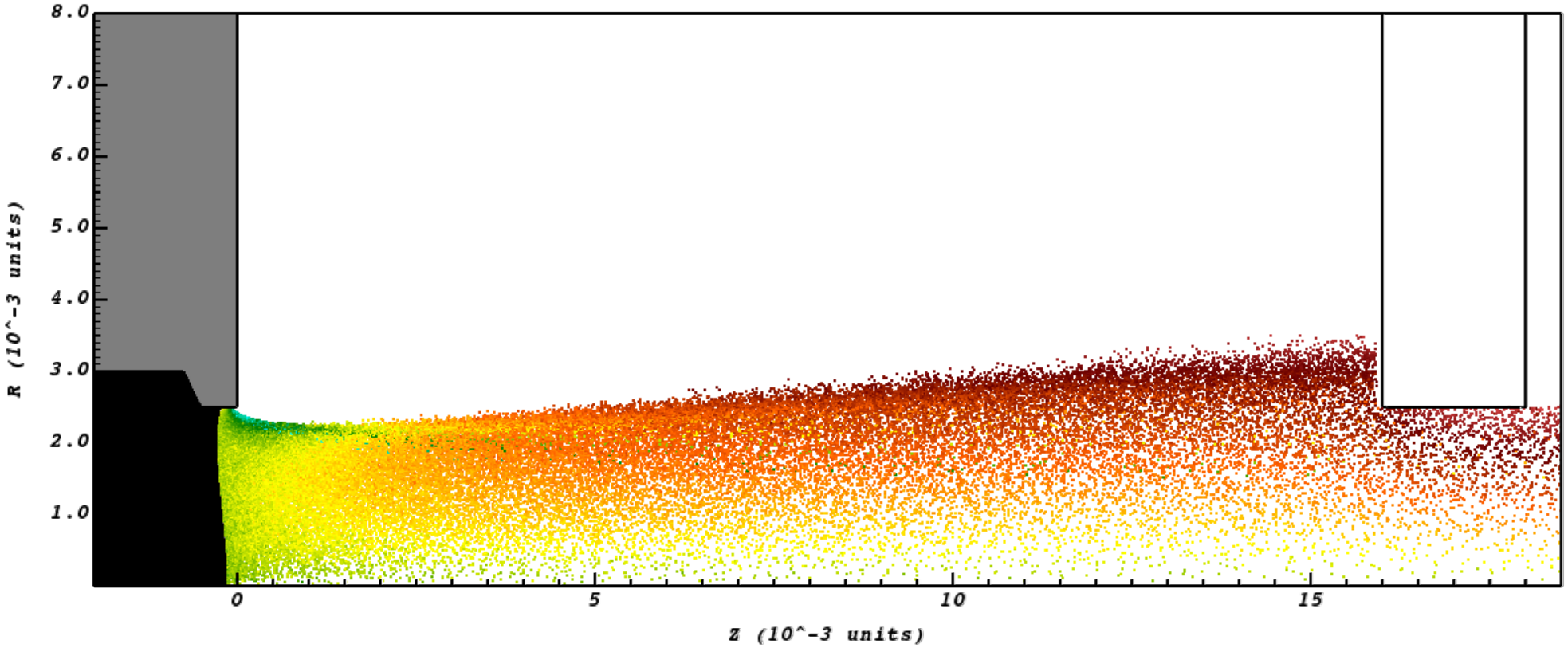


Colour scale
Ar+ radial velocity

48 µA beam current

+10% plasma density

@ 2.3 kV extraction voltage

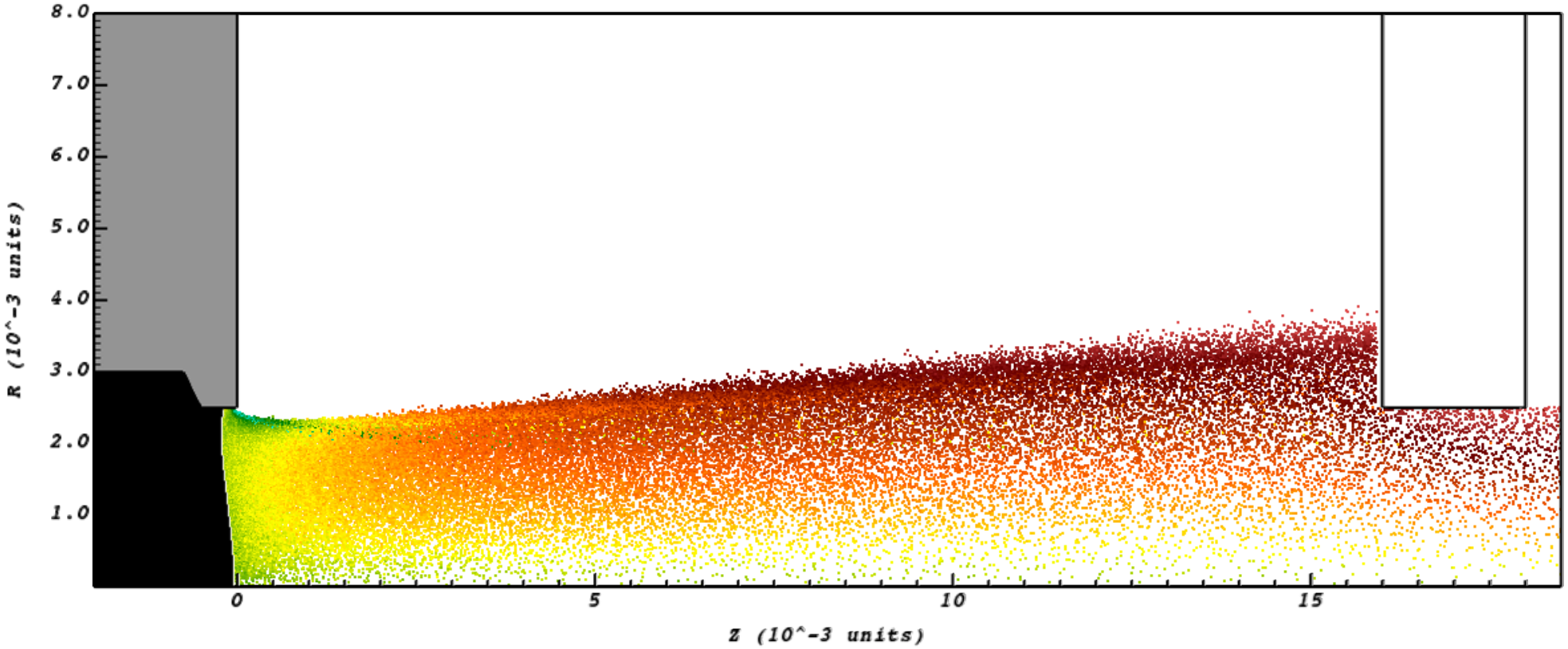


Colour scale
Ar+ radial velocity

44 µA beam current

+20% plasma density

@ 2.3 kV extraction voltage

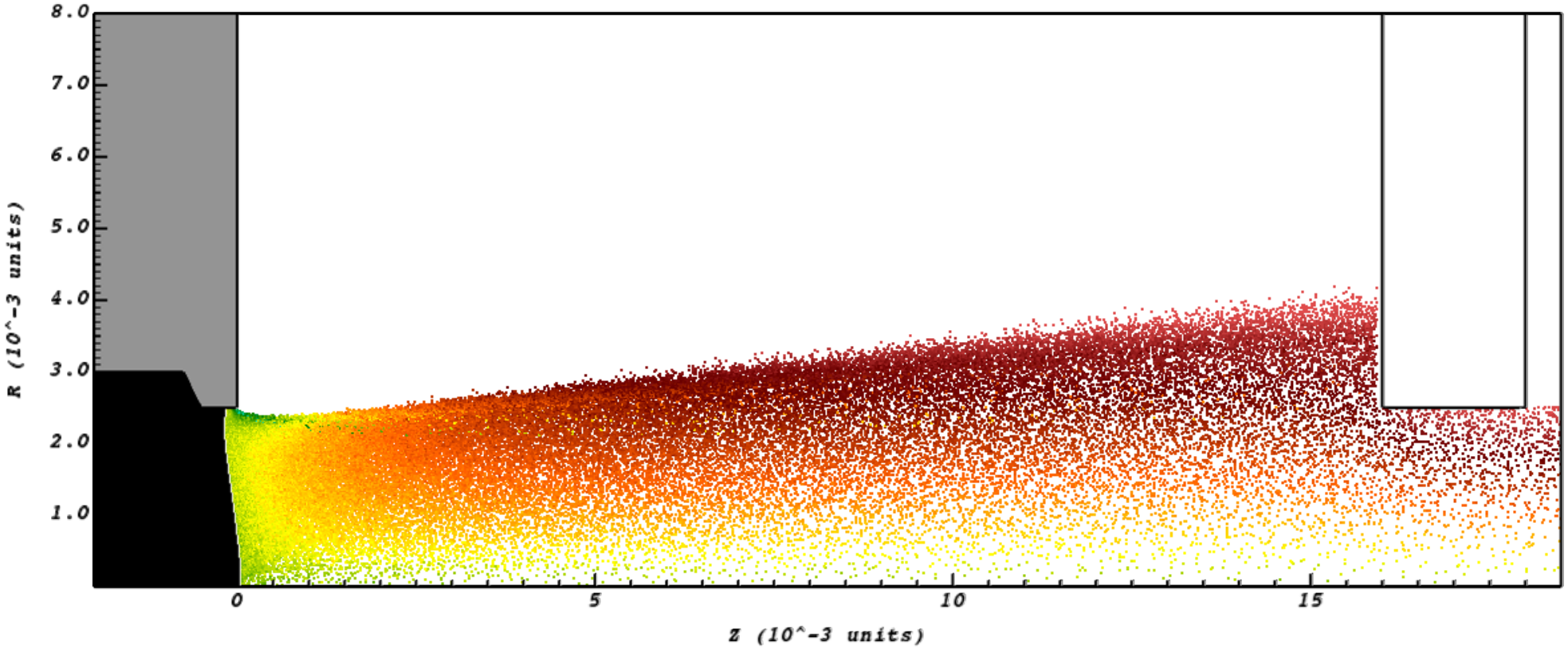


Colour scale
Ar+ radial velocity

40 µA beam current

+30% plasma density

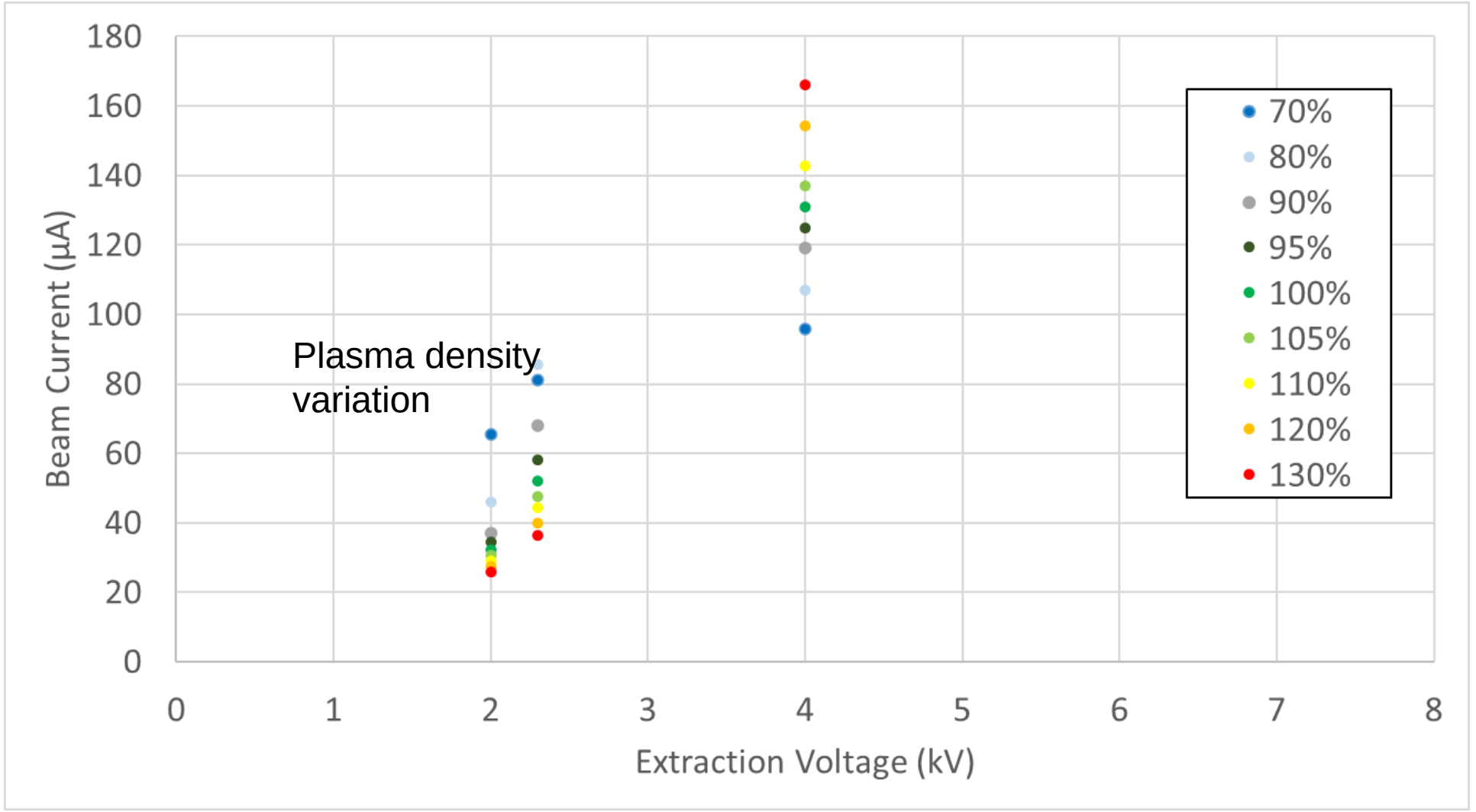
@ 2.3 kV extraction voltage



Colour scale
Ar+ radial velocity

36 µA beam current

Vary Plasma Density



Limit of 2D

- Beam current scales linearly with plasma density
- Debye length scales inversely with the square root of density.
- Increase of 100 in current requires an increase of 10 in grid resolution for each direction.
- So in 2D an increase of 100 in current requires an increase of 100 in number of cells.

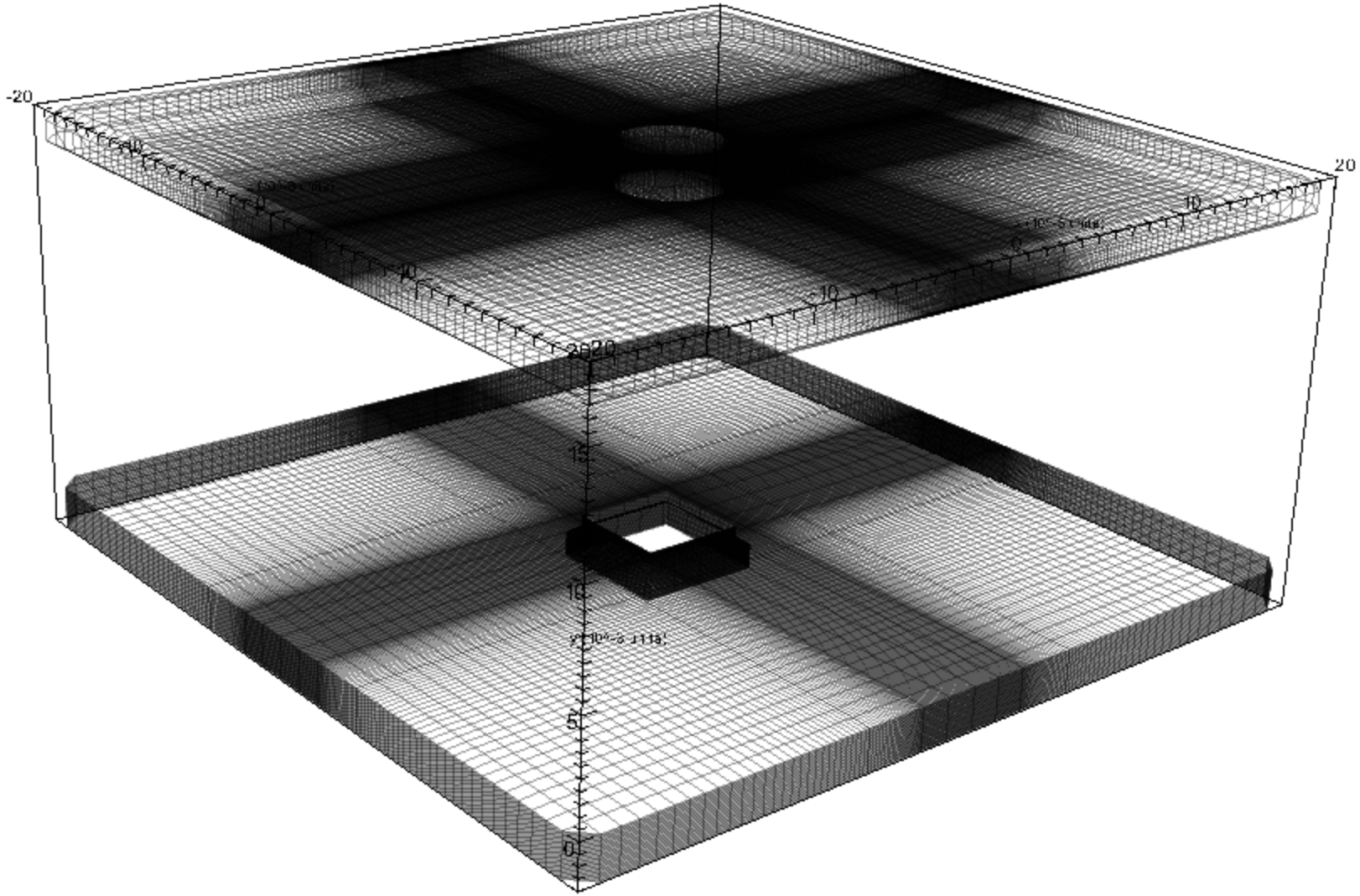
i.e., it scales linearly.

We currently have 4688 licenced cores
These models ran on 32 cores
4688/32 = 146.5 potential scaling

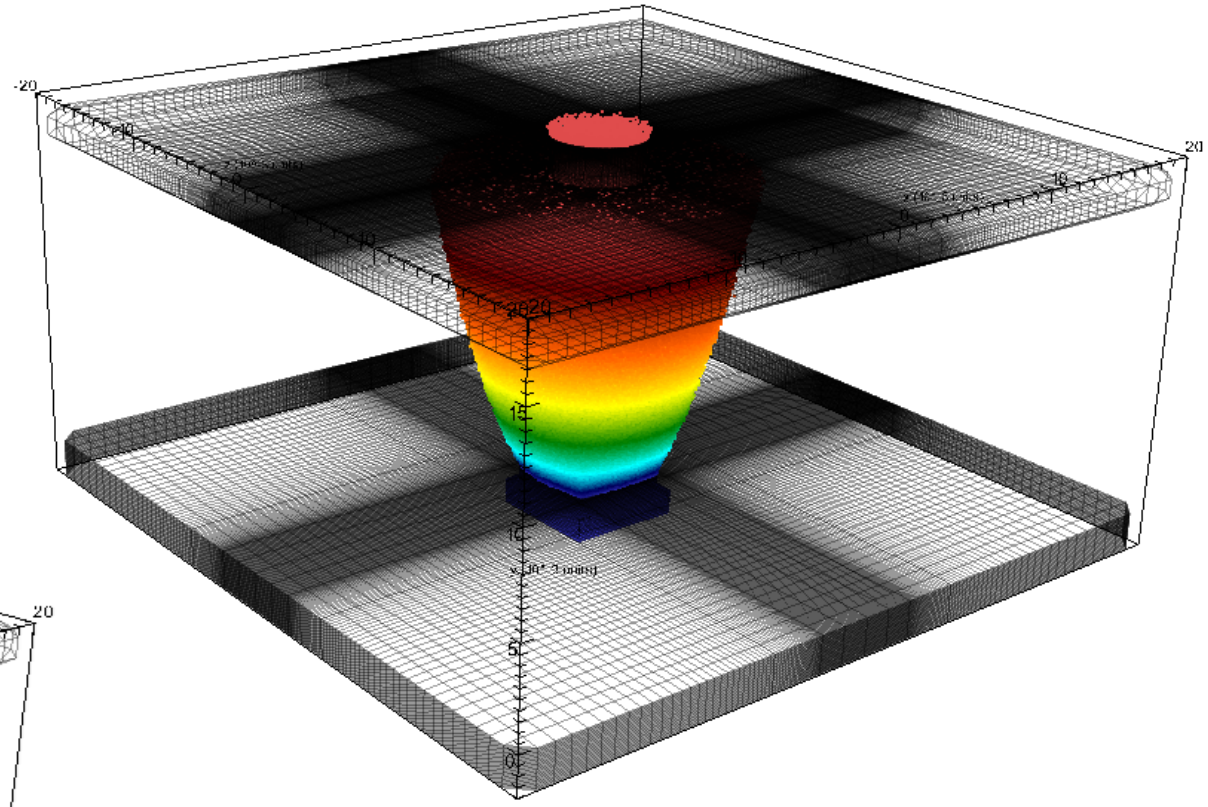
$\Rightarrow$ 150 µA can scale to **22 mA on 4688 cores**

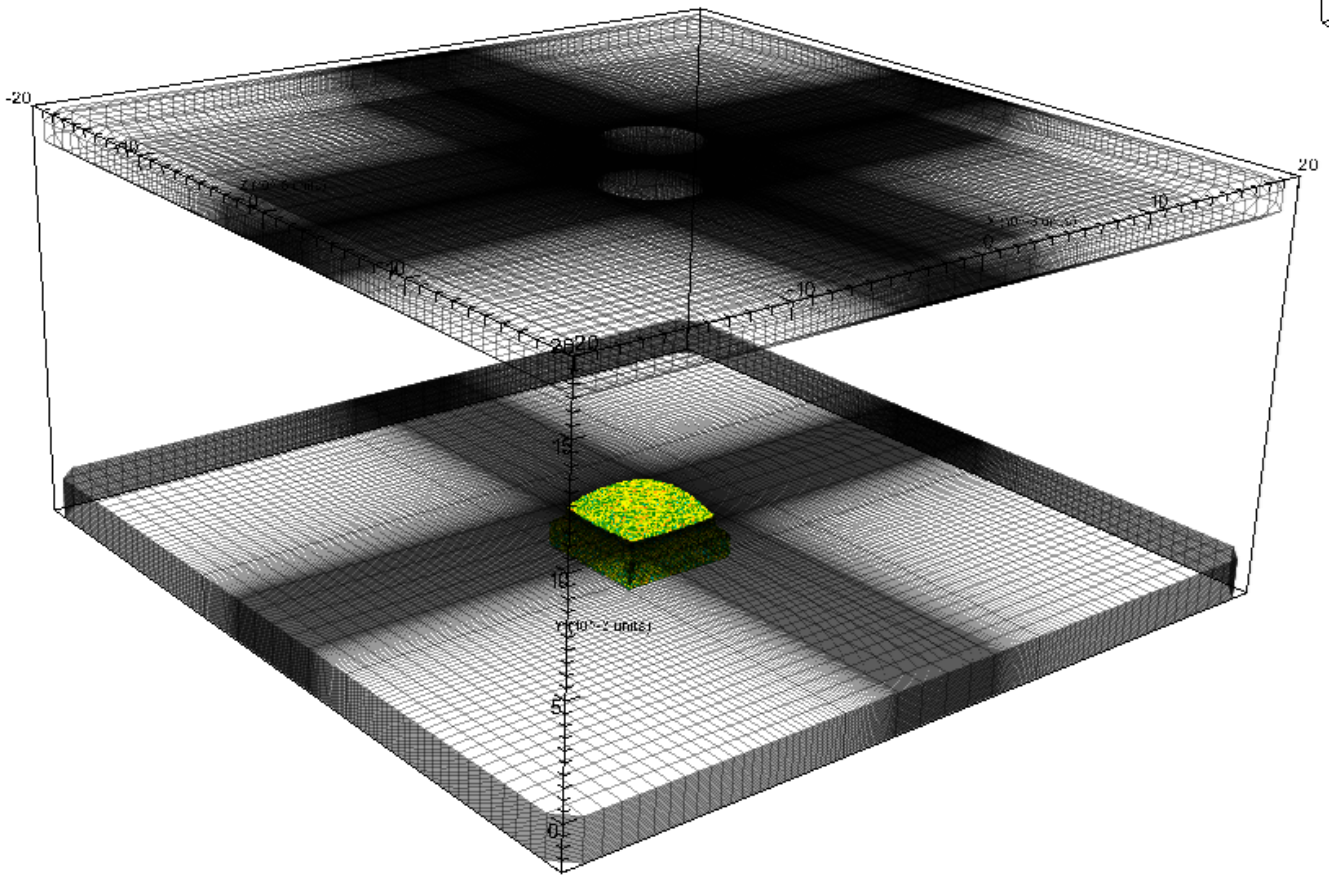
V12.2 Offers new domain decomp with x4 improvements

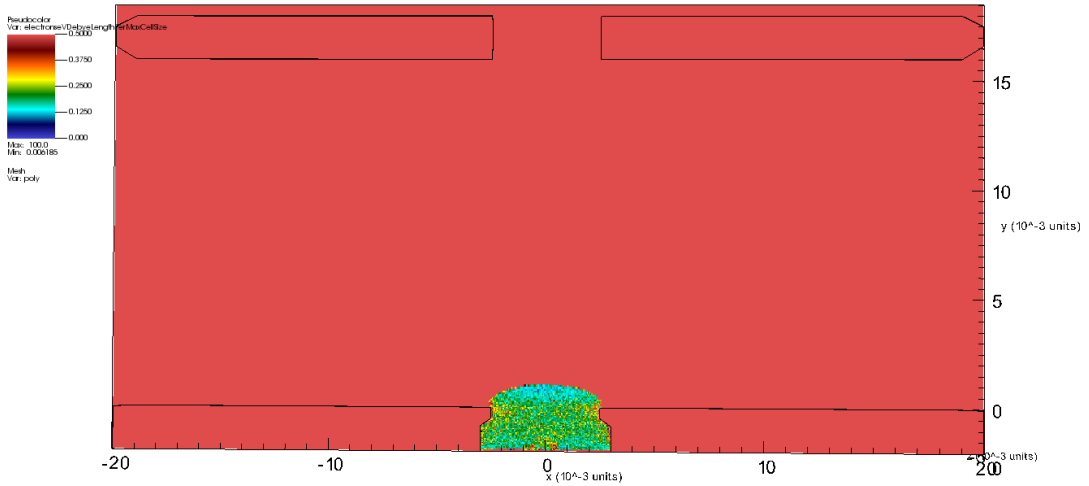
3D Variable Mesh



3D Model now up and running

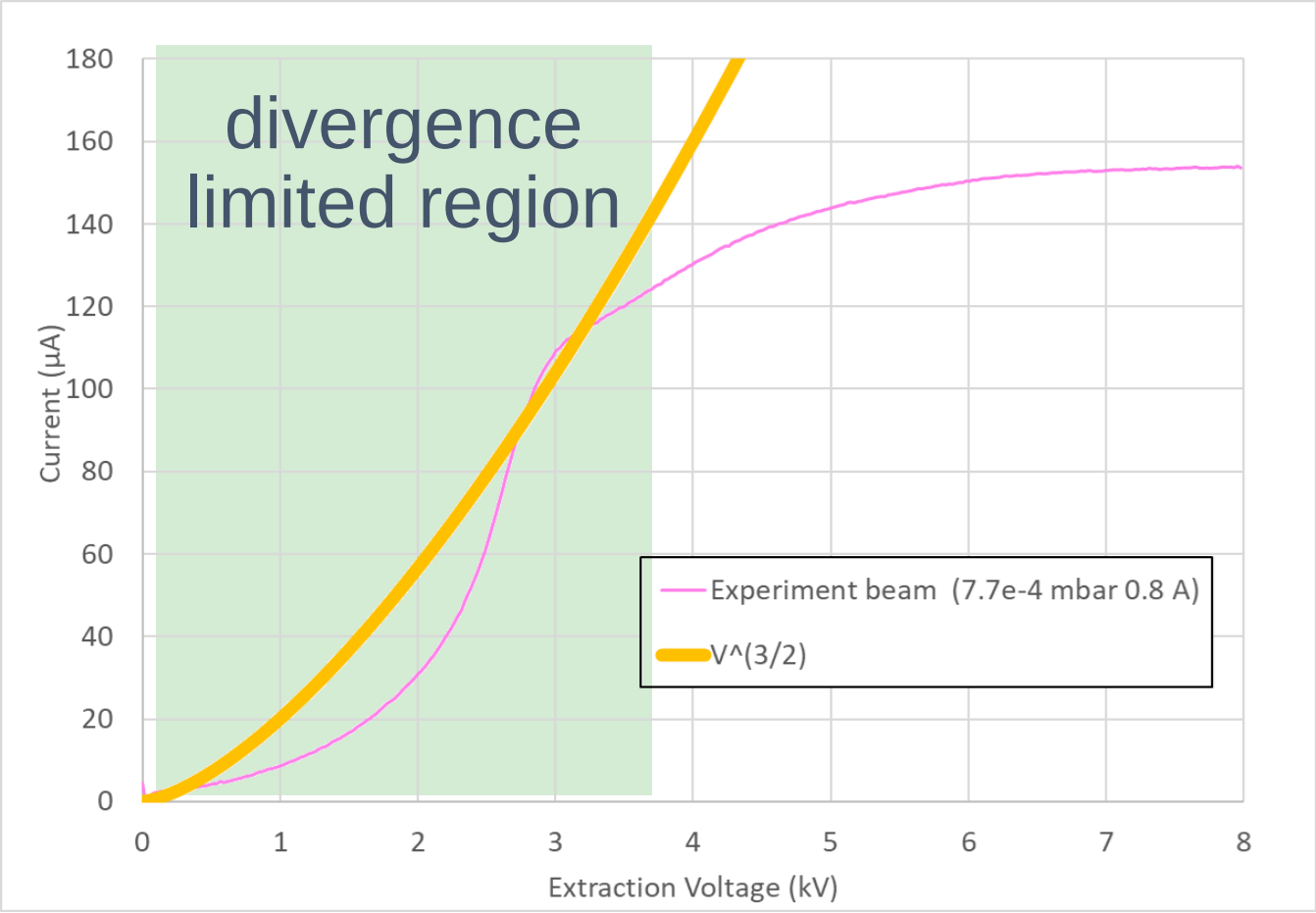






Summary

For a single extraction voltage sweep, the true cause of the “observed” power law is meniscus focusing and collimation on the extraction (puller) electrode



Next Steps

- Solve 2D and 3D on >4k cores at maximum density
- Detailed meniscus attachment studies:
  - PE thickness
  - PE hole external radius

- Reaction frameworks: H
- Modelling volume production
- ICP with electron fluid model

We're hiring!

Science and Technology Facilities Council

Senior Ion Source Physicist
UKRI Band E/F
£51,500- £65,450

Permanent position

2 Year Postdoc Researcher
UKRI Band D/E
£40,800- £56,650

Collaboration between UK and India to investigate space charge compensation and to develop ion source technology

STFC and DAE+BARC

Speak to myself or Olli Tarvainen for more details

Science and
Technology
Facilities Council

Questions?

UKRI Science and Technology Facilities Council

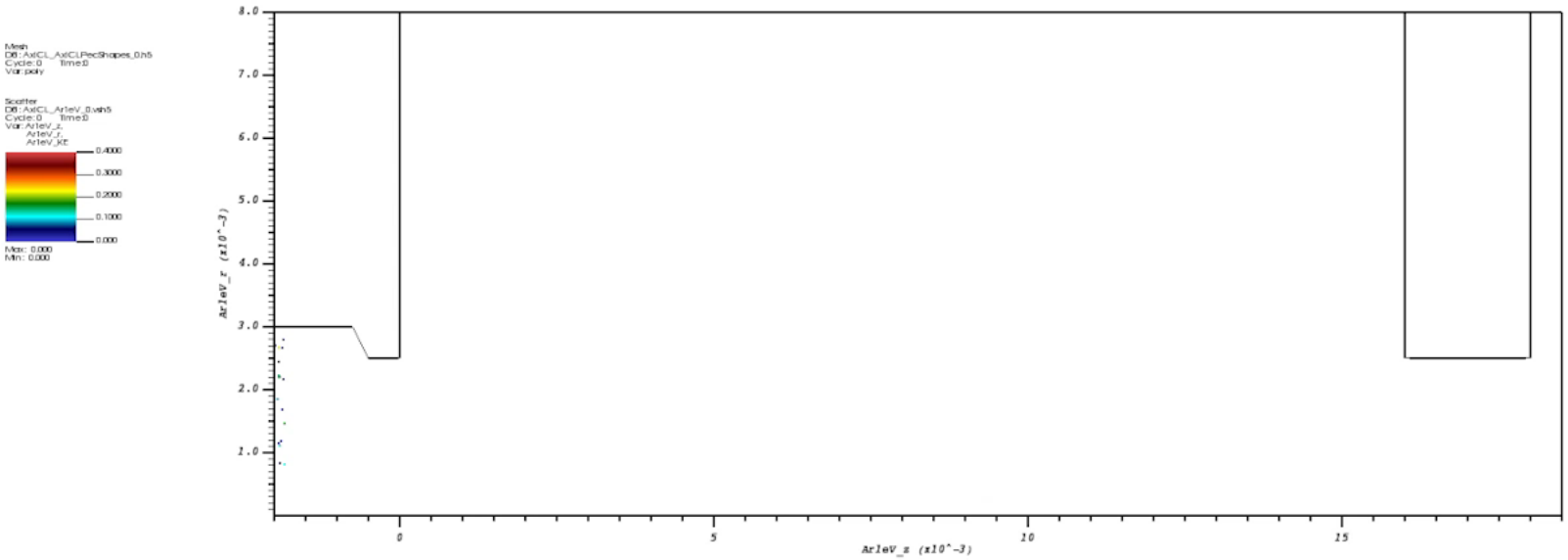
Thank you

Science and Technology Facilities Council @STFC_matters Science and Technology Facilities Council

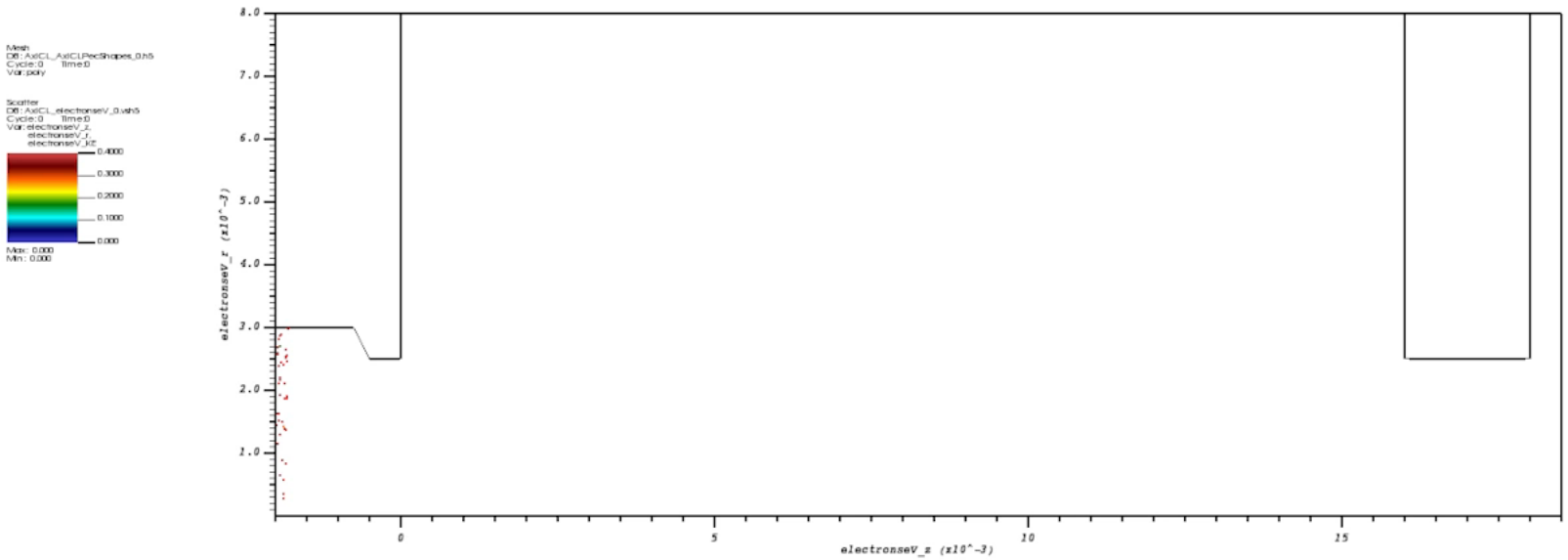
Additional slides

What happens at low extraction voltages?

This could be because the Debye length is not well resolved in the gap?

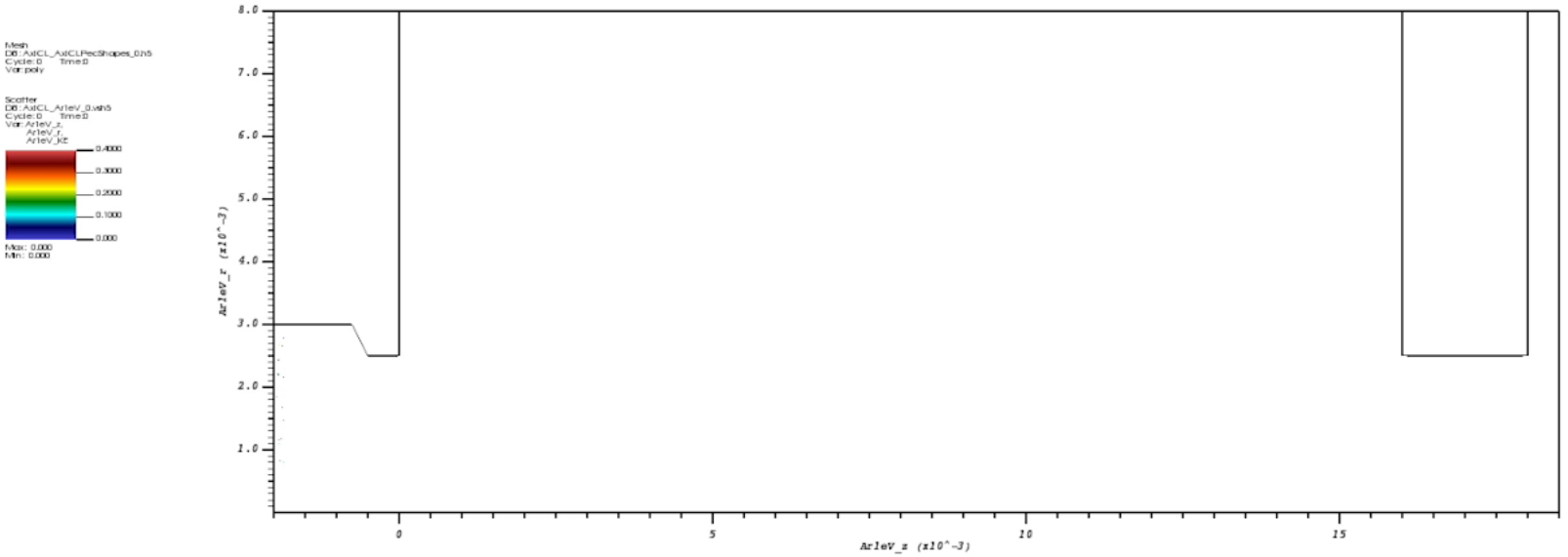


Ar+ Ions
0.4 eV colour scale

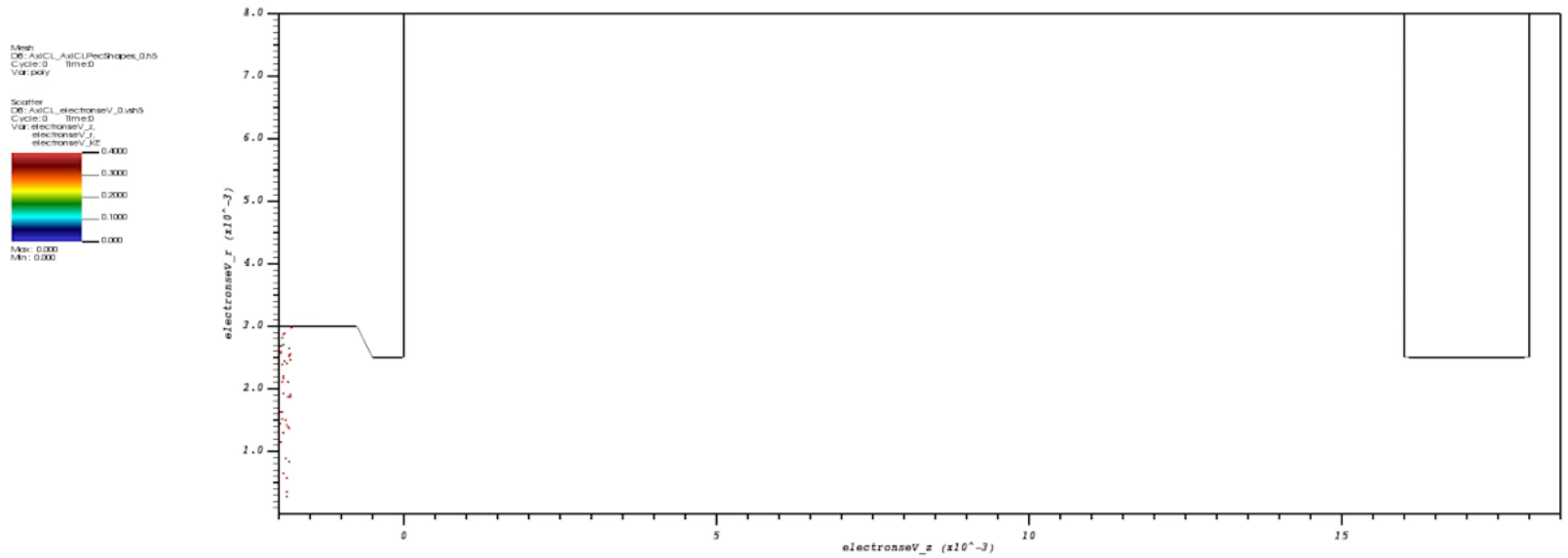


Electrons
0.4 eV colour scale

0 V extraction voltage



Ar+ Ions
0.4 eV colour scale



Electrons
0.4 eV colour scale

100 V extraction voltage