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New challenges in ion beam extraction modelling

Taneli Kalvas

Department of Physics, University of Jyväskylä

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Outline

- Introduction to plasma extraction codes
- Previous application of the negative ion extraction model
- CERN Linac4 H^- simulations
- Breaking the extraction model
- Possible modelling solutions
- Similar problems with ECRIS modelling

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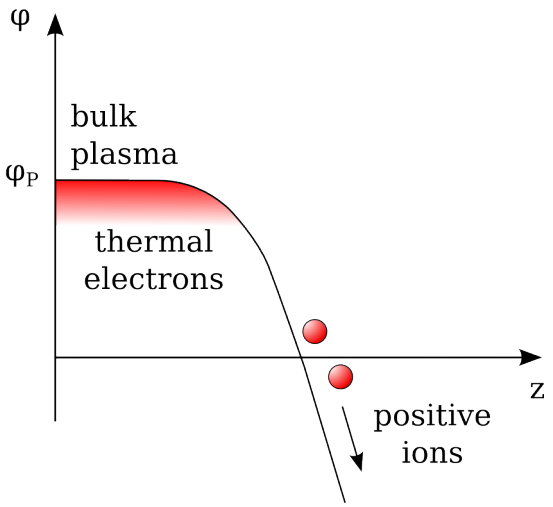
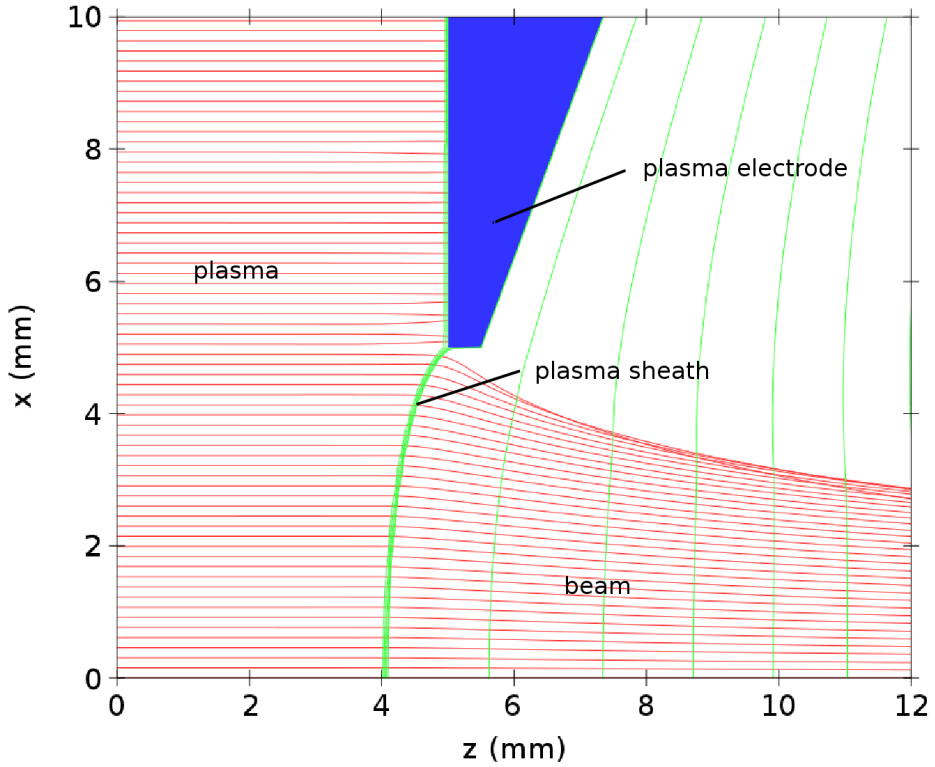
Background

Positive ion plasma extraction model

$$\nabla^2\phi = -\frac{\rho}{\epsilon_0} = -\frac{\rho_{beam}+\rho_e}{\epsilon_0}$$

$$\rho_e = \rho_{e0}\exp\left(\frac{e(\phi-\phi_0)}{kT_e}\right)$$





S. A. Self, Phys. Fluids 6, 1762 (1963).
J. H. Whealton, Rev. Sci. Instrum. 48, 829 (1977).

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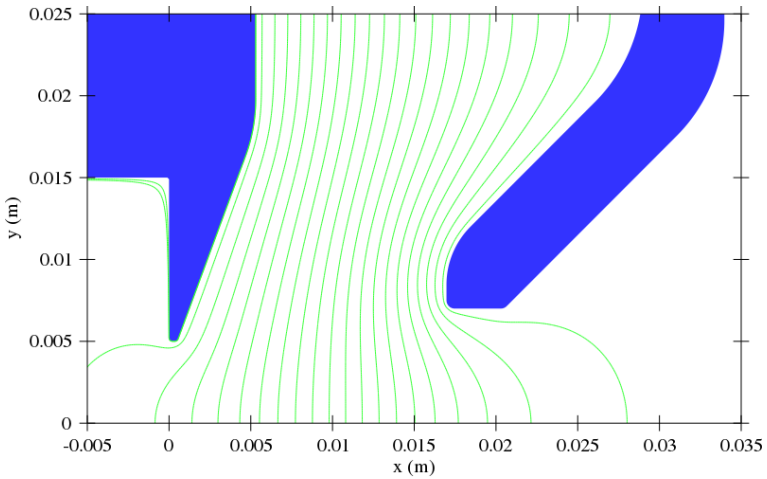
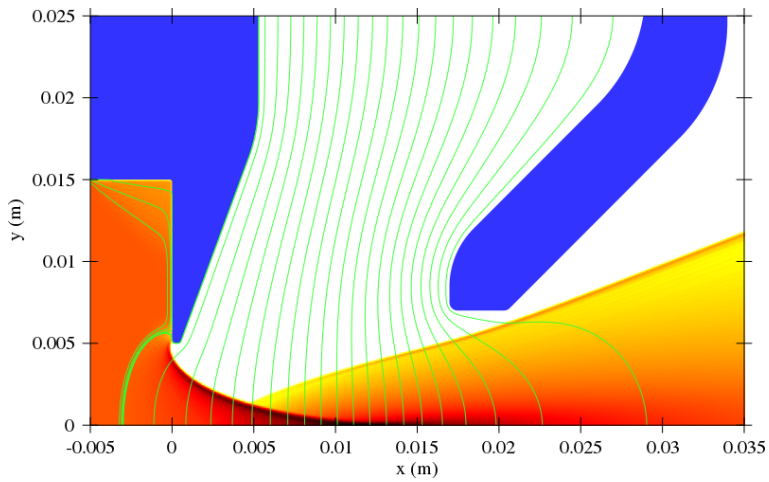
Background

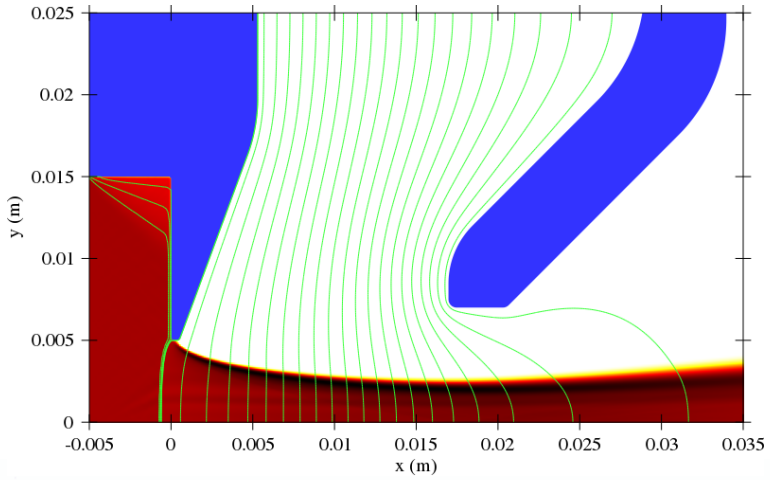
Vacuum



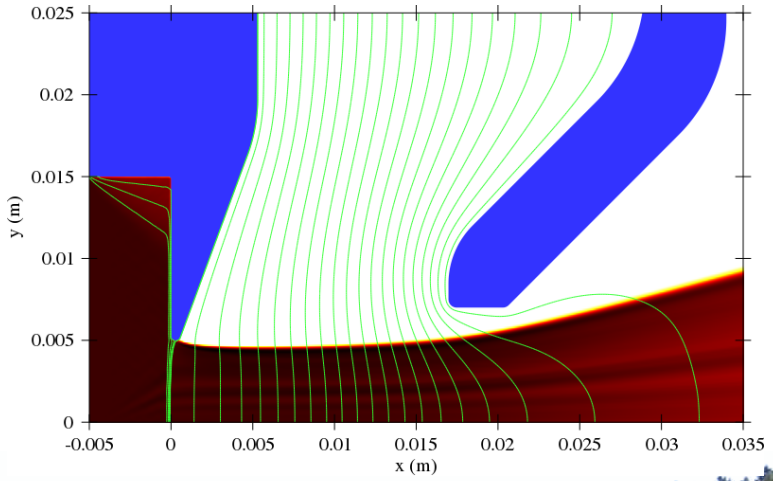
J=100 A/m^2



J=500 A/m^2



J=900 A/m^2



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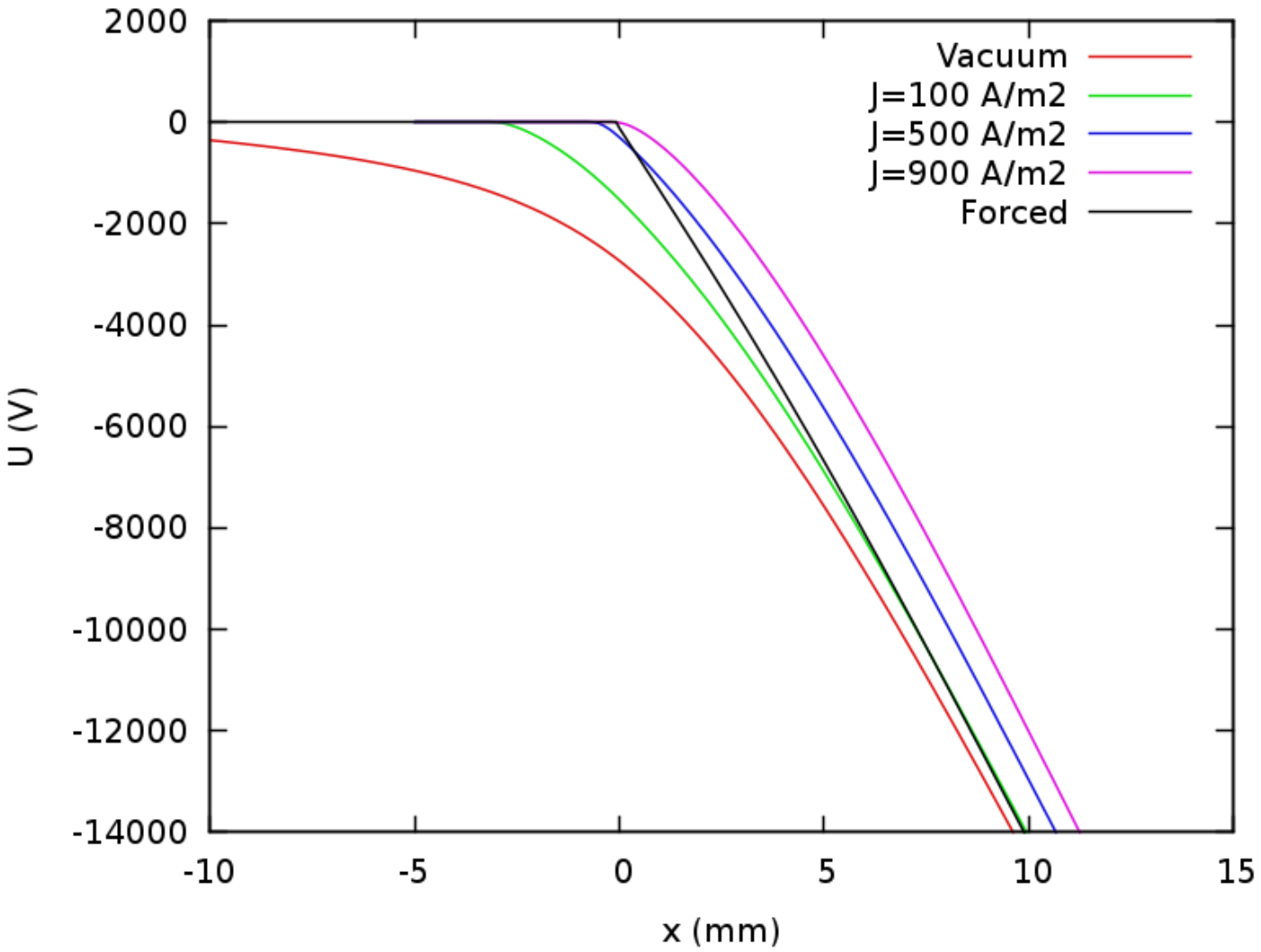

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Background

Negative ion extraction from plasma volume

- Plasma at positive potential
- Extraction potential is positive
- Plasma electrode at 0 V

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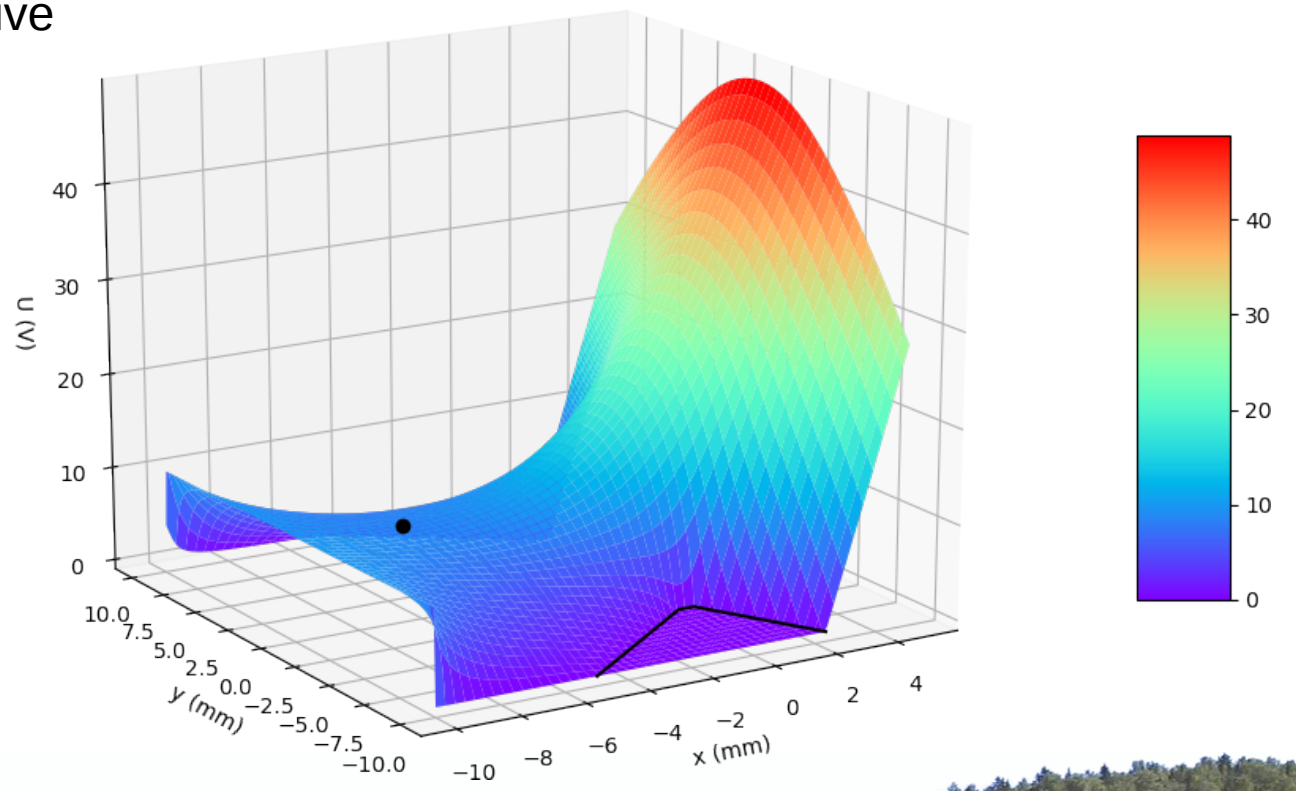
Background

Negative ion extraction from plasma volume

- Plasma at positive potential
- Extraction potential is positive
- Plasma electrode at 0 V
- Species: H^-, H^+, e^-

Saddle-shaped potential



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Background

Negative ion extraction from plasma volume

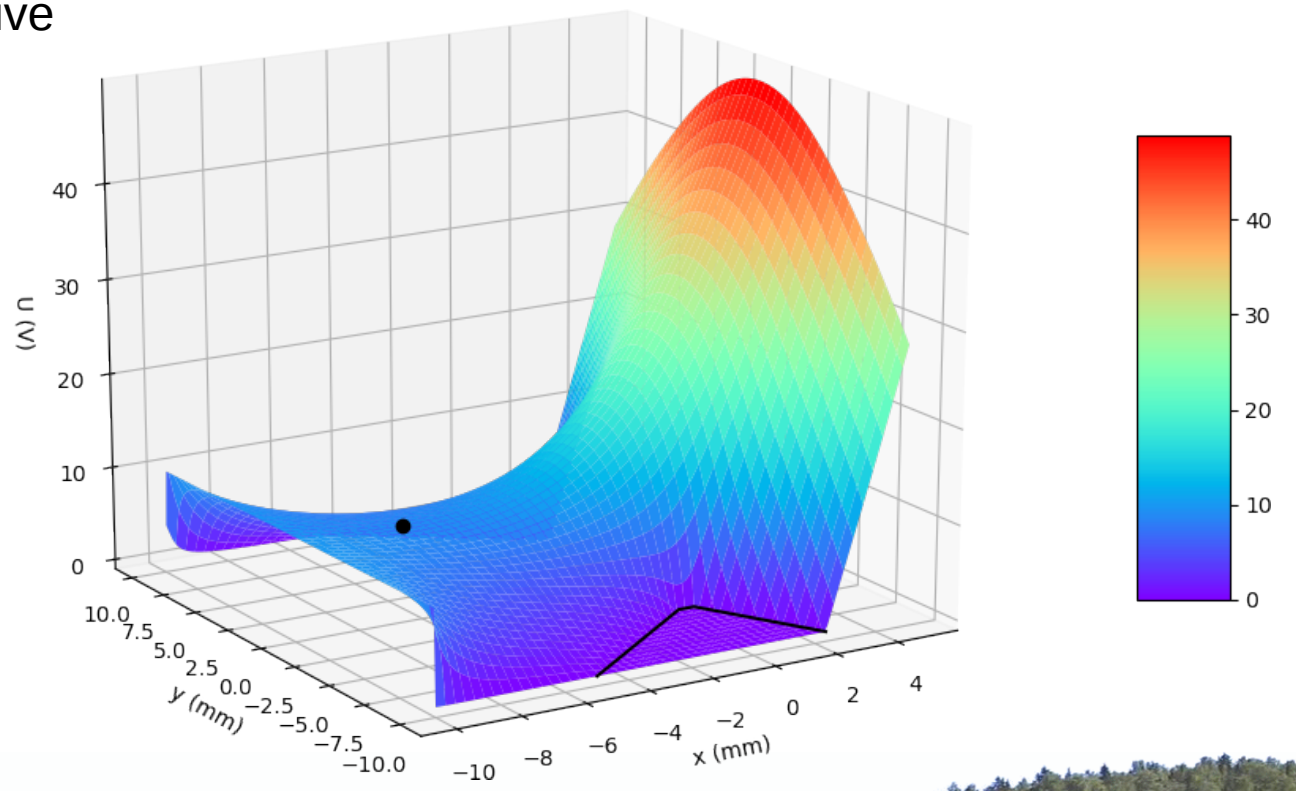
- Plasma at positive potential
- Extraction potential is positive
- Plasma electrode at 0 V
- Species: H^-, H^+, e^-

Extracted $I_e/I_{H-} < 100$:

$\rho_e/\rho_{H-} << 1$

Plasma only slightly positive near the extraction

Saddle-shaped potential



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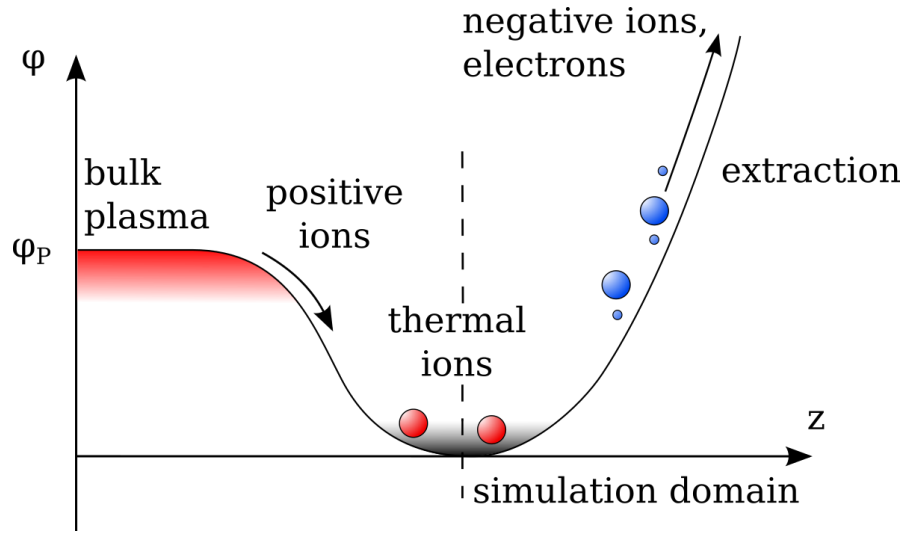
Modelling negative ion extraction from plasma volume

Approximation: ϕ = 0 V near the extraction:

$$\nabla^2\phi = -\frac{\rho}{\epsilon_0} = -\frac{\rho_{H^-} + \rho_e + \rho_f + \rho_{th}}{\epsilon_0}$$

$$\rho_{th} = \rho_{th\,0}\exp\left(\frac{-e\phi}{kT_p}\right)$$

$$\rho_f = \rho_{f\,0}\left(1 - \mathrm{erf}\left(\frac{\phi}{\phi_P}\right)\right)$$



Very simplified but allows systematics to be done due to fast computation (~1 h for 10^7 node 3D problem), which is not possible by PIC methods.

R. Becker, Rev. Sci. Instrum. 75, 1723 (2004) and
R. Becker, AIP Conf. Proc. 763, 194 (2005).

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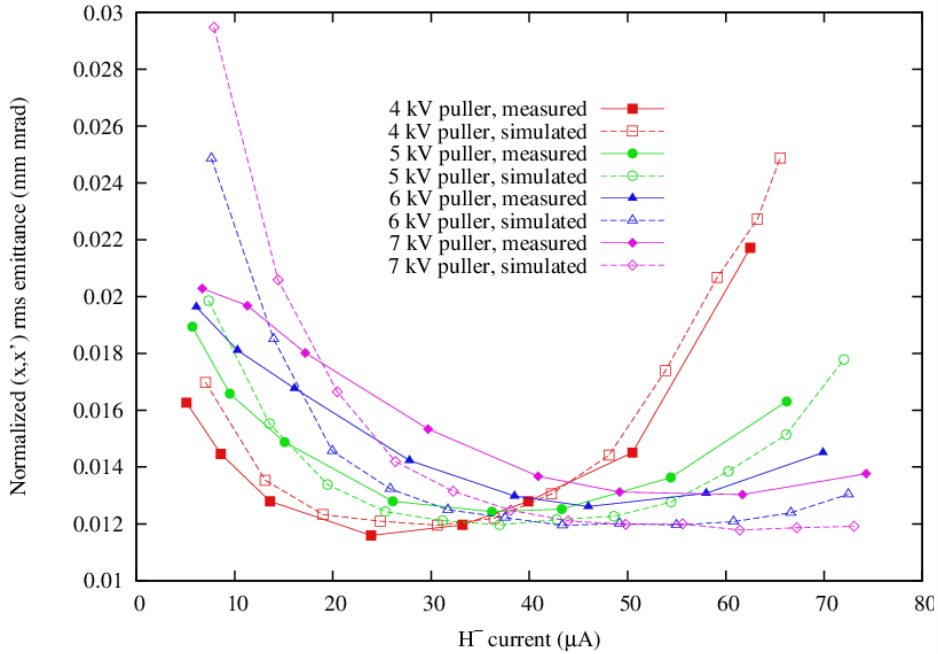
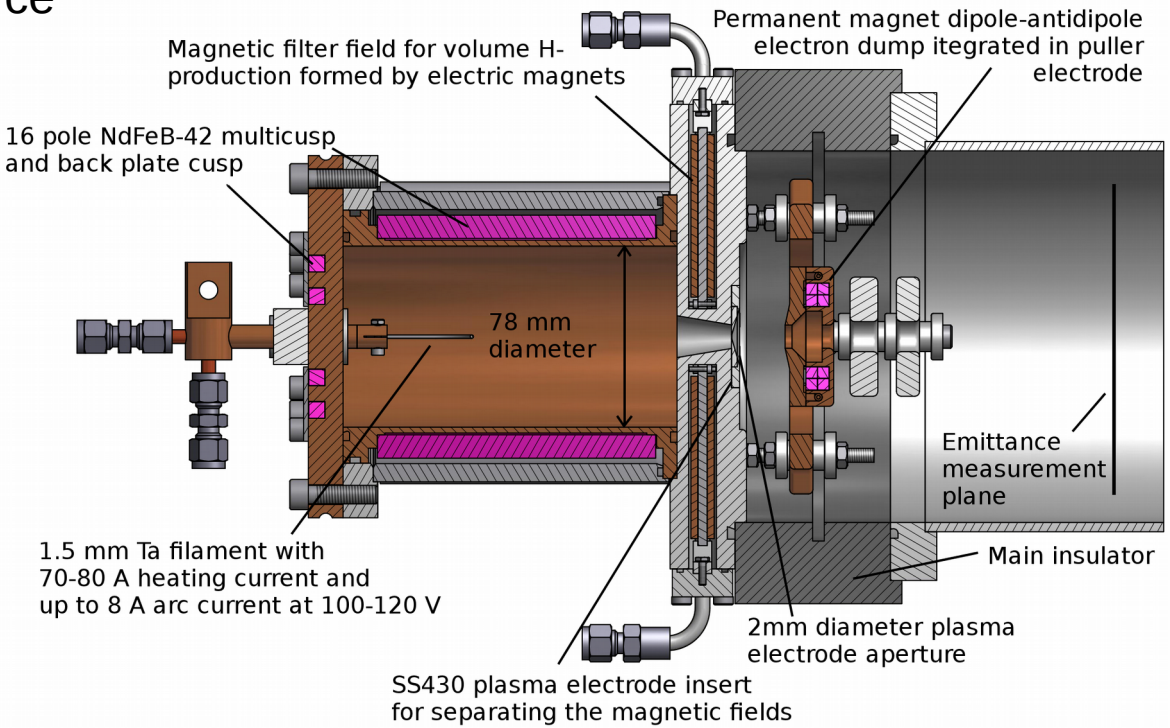
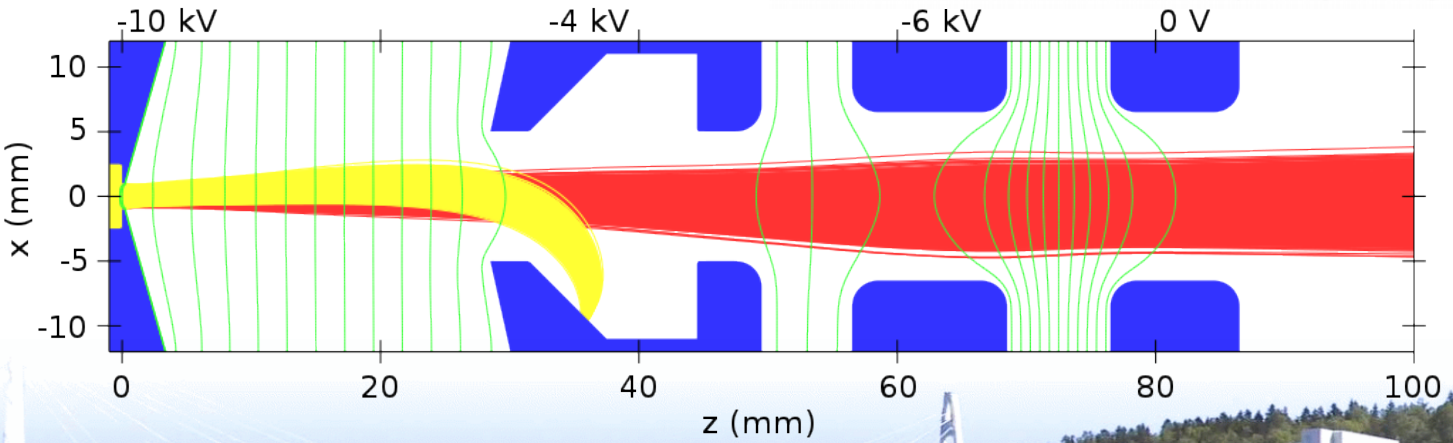
Application of the model

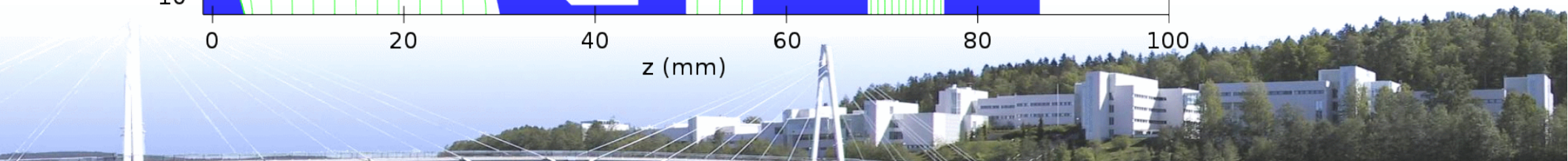
JYFL PELLIS filament-driven H^- ion source







e-/H- ratio 20



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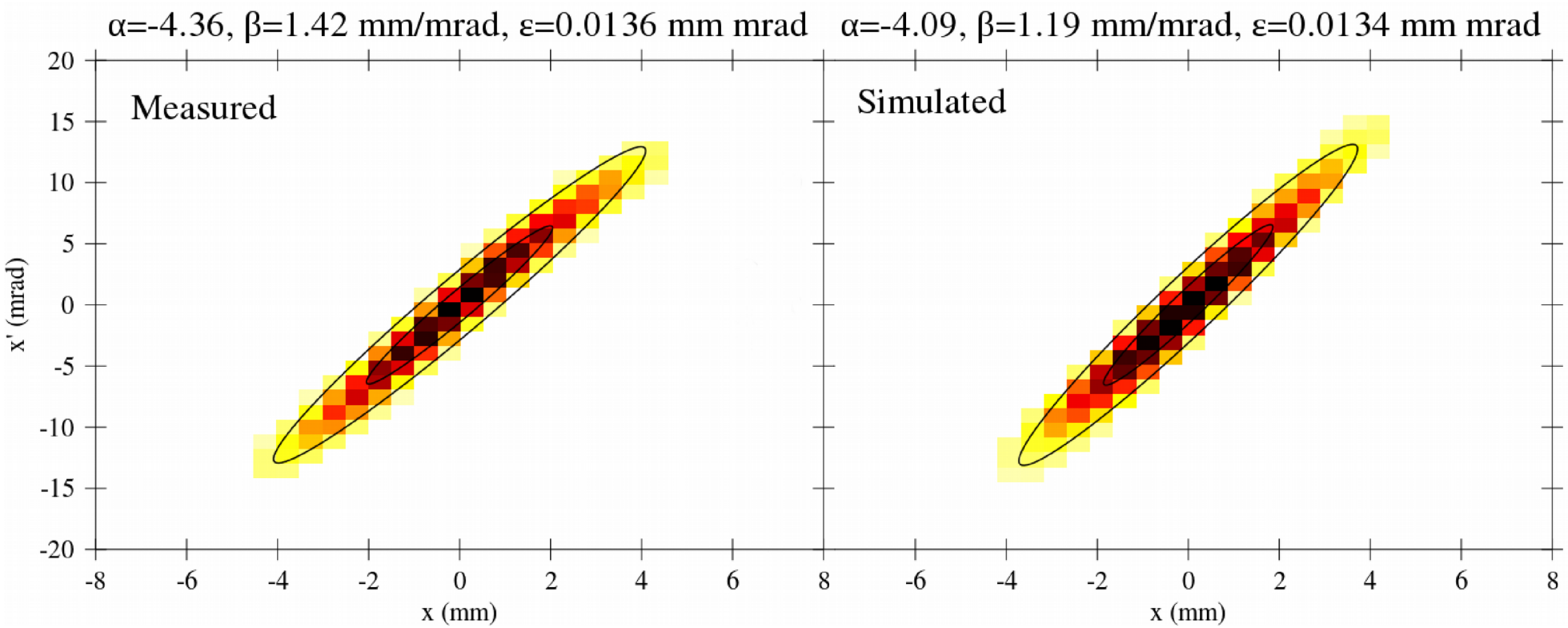
Application of the model

Measured and simulated (x,x') phase space patterns for 40 μA extracted H^- beam with 5 kV puller voltage



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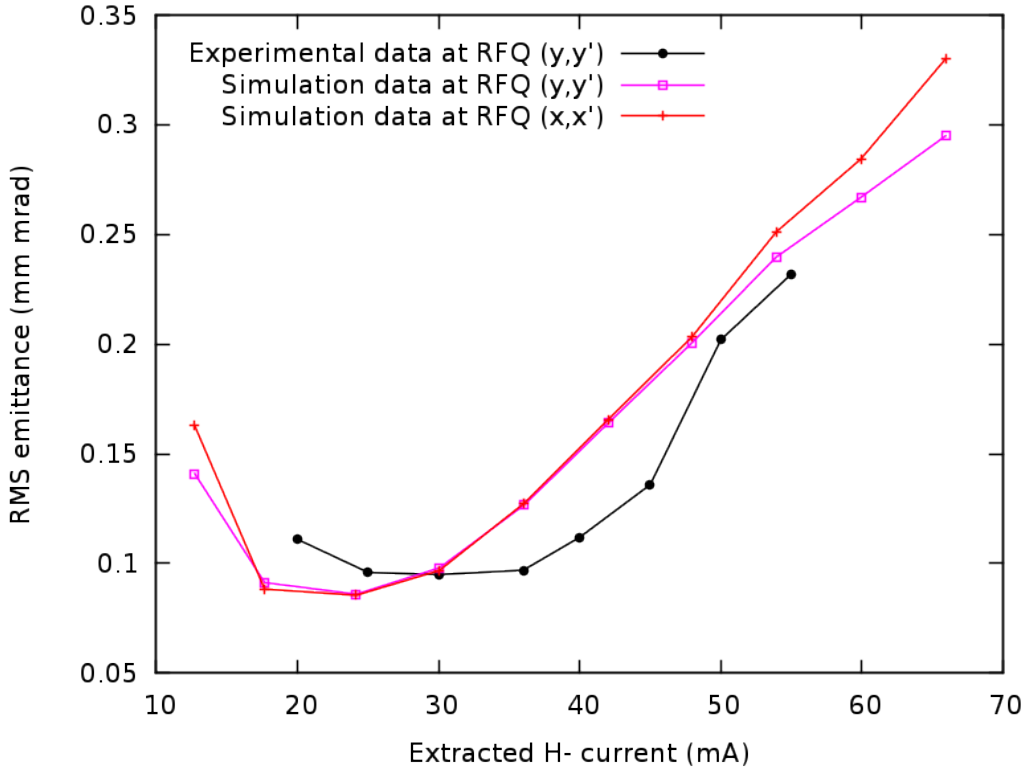
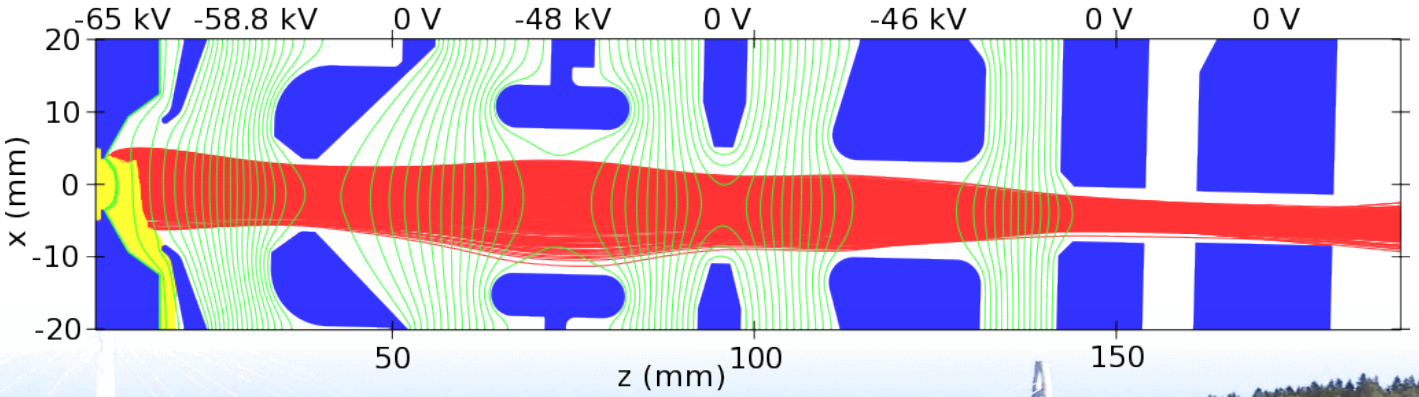
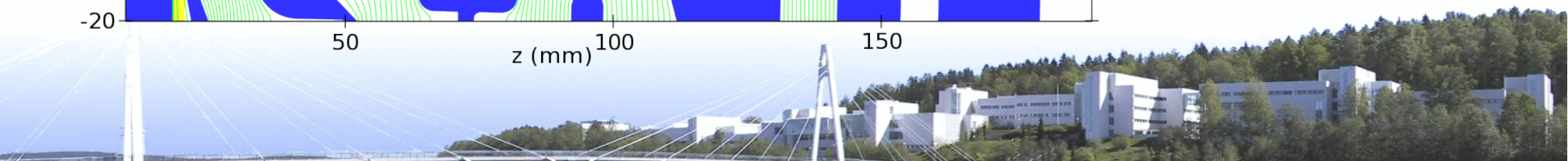
Application of the model



T. Kalvas, R. F. Welton, O. Tarvainen, B. X. Han and M. P. Stockli, Rev. Sci. Instrum. 83, 02A705 (2012).





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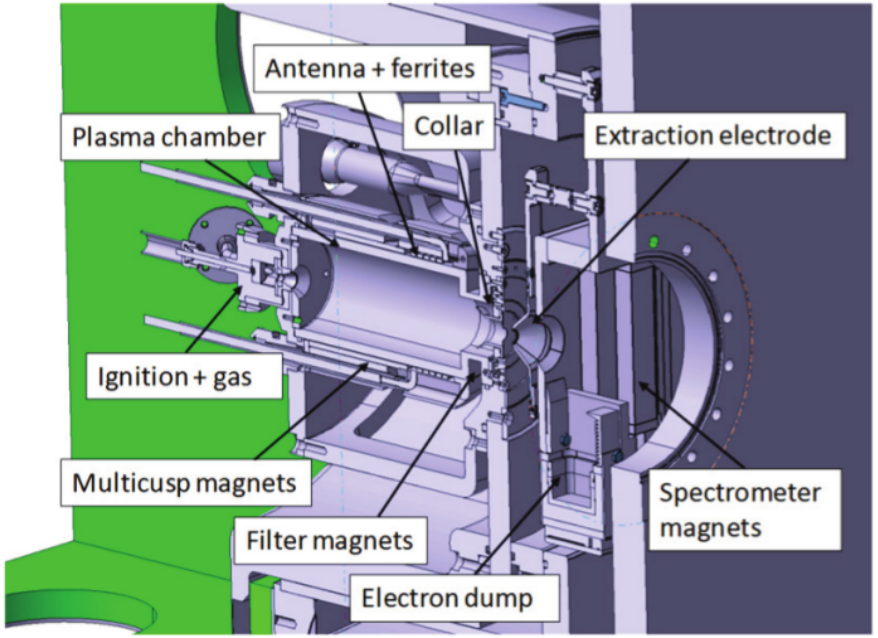
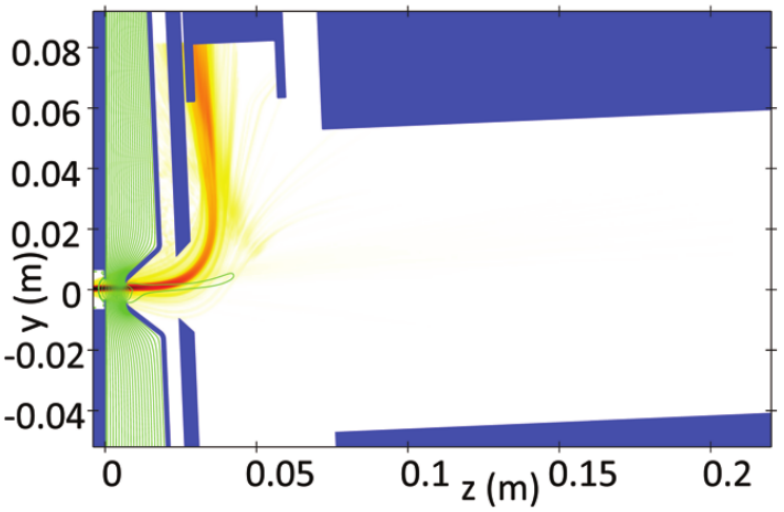
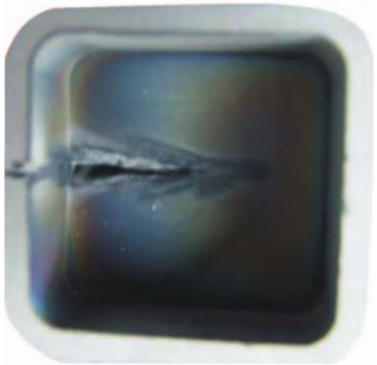
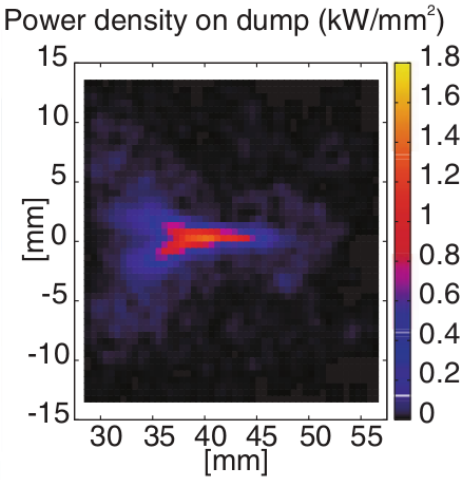
CERN Linac4 / DESY

DESY source at 45 kV producing ~23 mA H^- and >1 A of electrons









O. Midttun, Rev. Sci. Instrum 83, 02B710 (2012)

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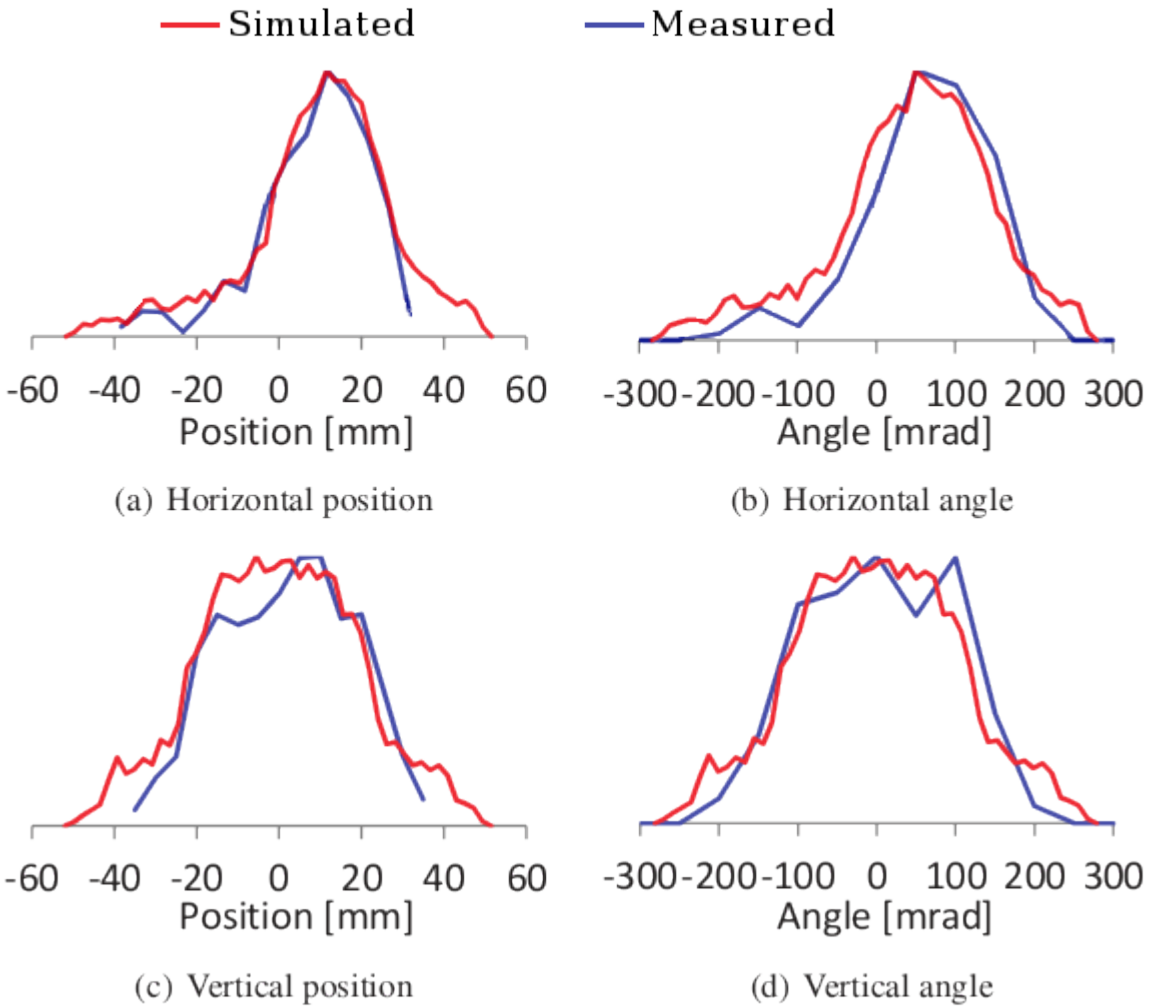
CERN Linac4 / DESY

H⁻ beam profile comparison



O. Midttun, “Improved beam extraction for a negative hydrogen ion source for the LHC injector chain upgrade, Linac4”, Ph. D. thesis, University of Oslo 2014.

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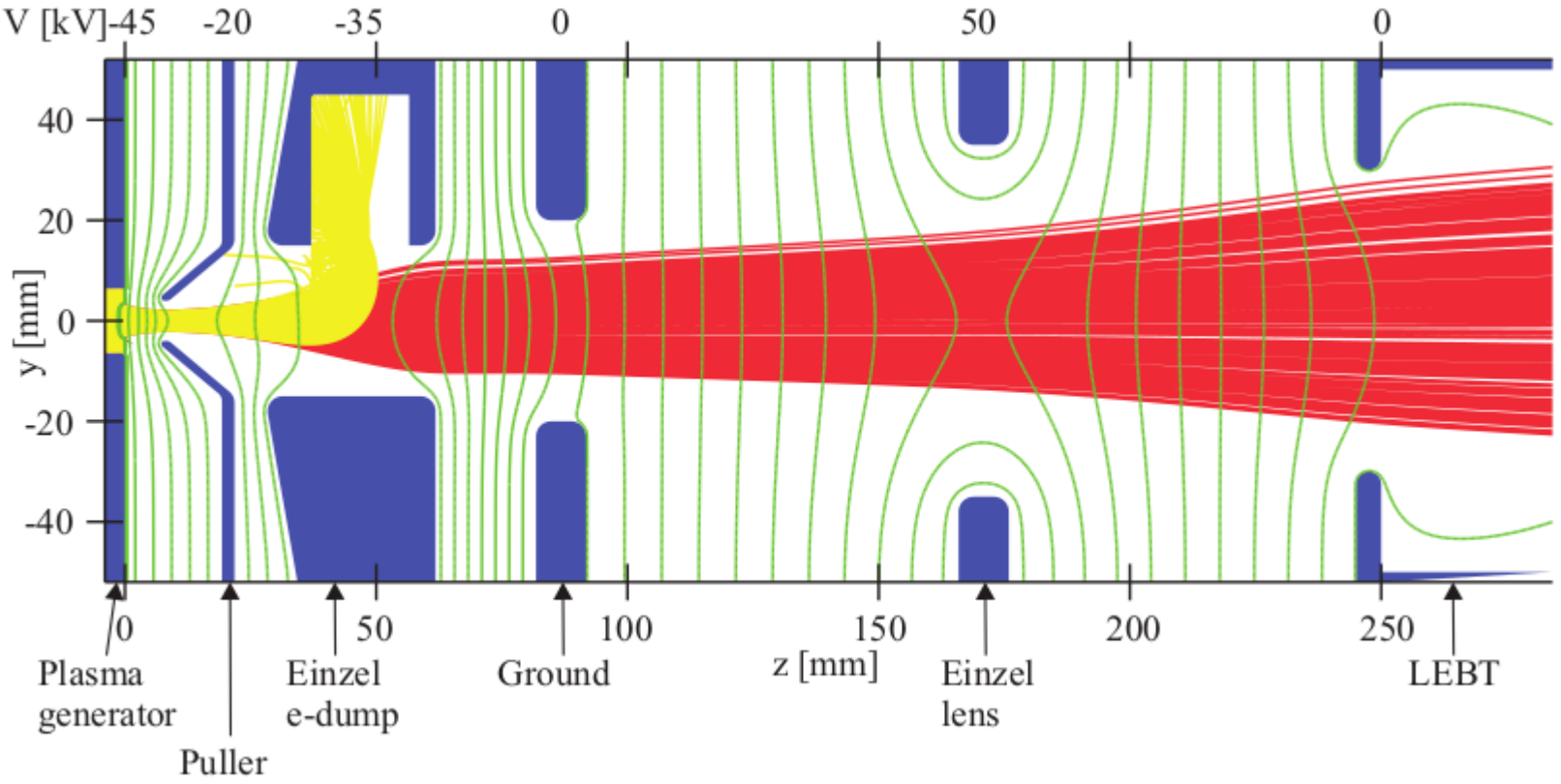
Linac4 IS01

Volume production, electron dumping at lower energy



O. Midttun, AIP Conf. Proc. 1515, 481 (2013)

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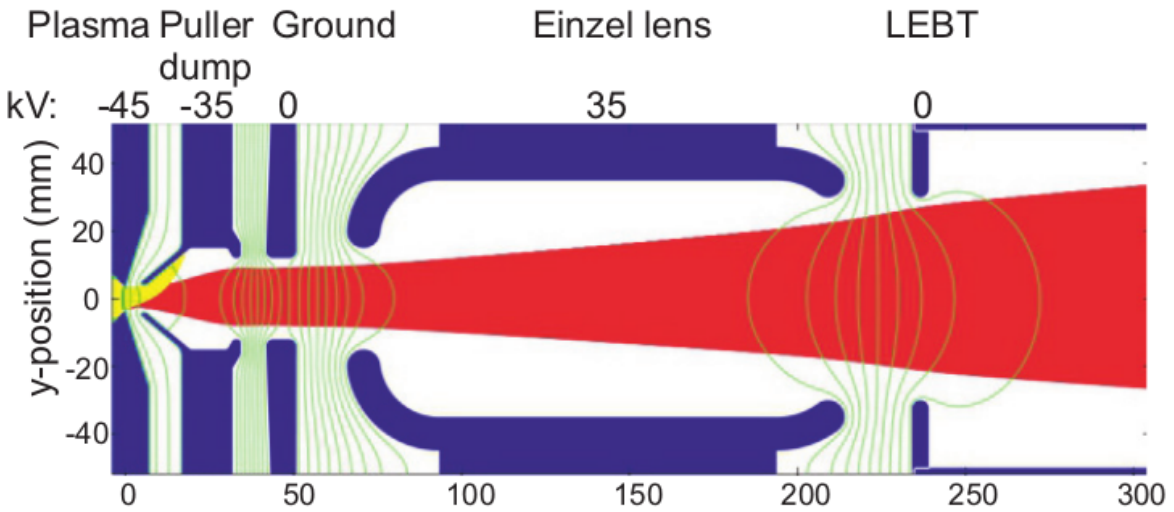
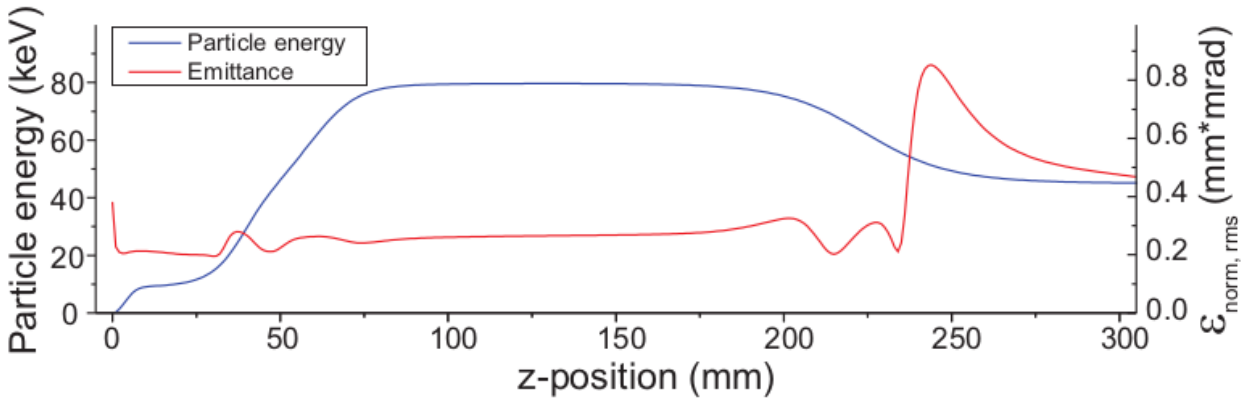
Linac4 IS02

Cesiated source to increase H^- production and to reduce e^-/H^- ratio





D. Fink, AIP Conf. Proc. 1655, 030006 (2015)

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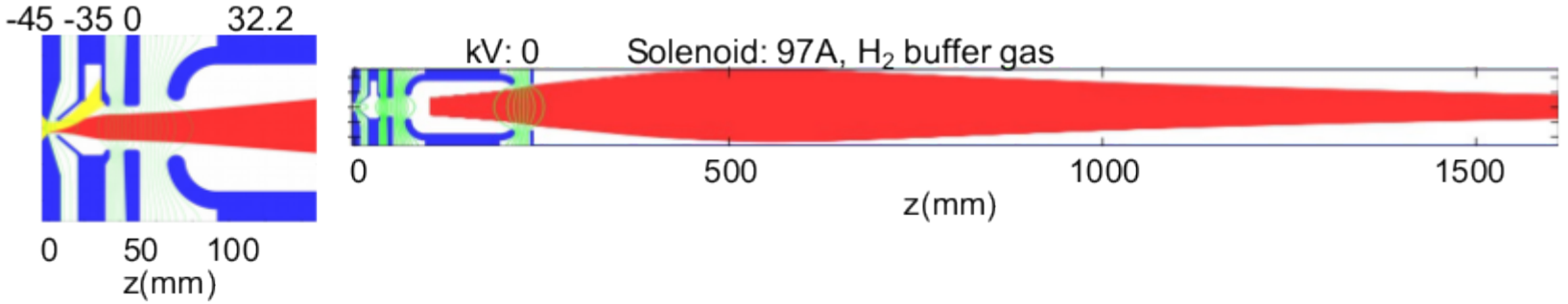
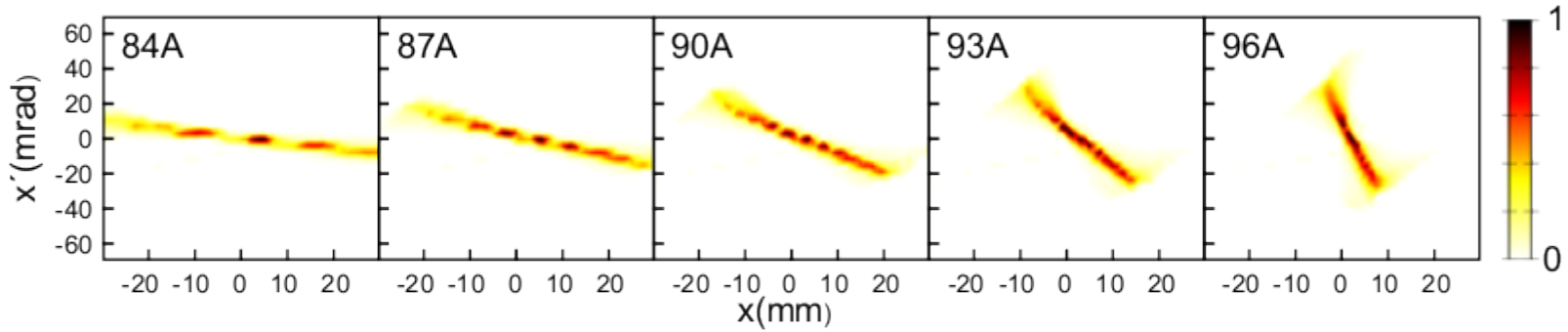
Linac4 IS02

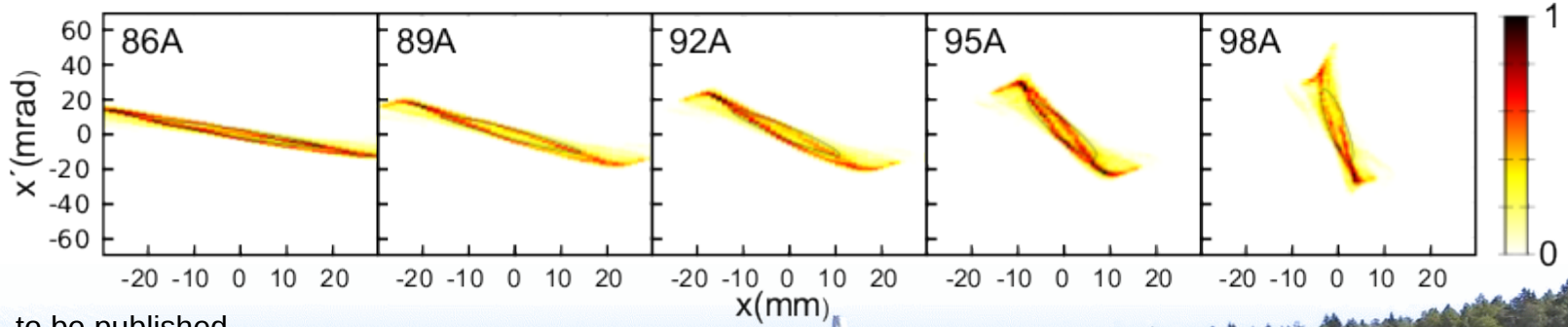
46 mA H^-, e^-/H^- ratio of ~1, full compensation in LEBT



Measurements Linac4 teststand:



Simulations IBSimu:



D. Fink, to be published

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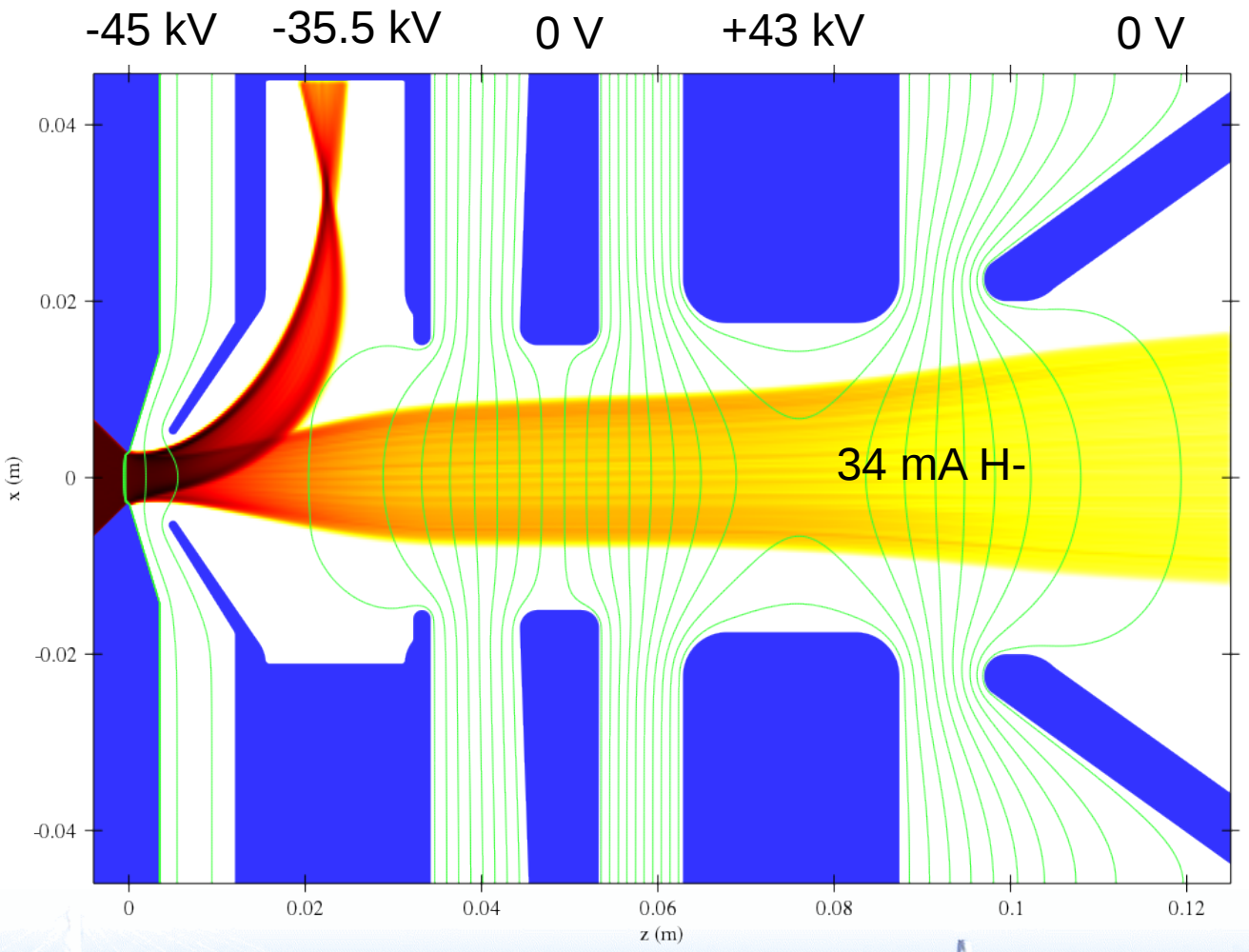
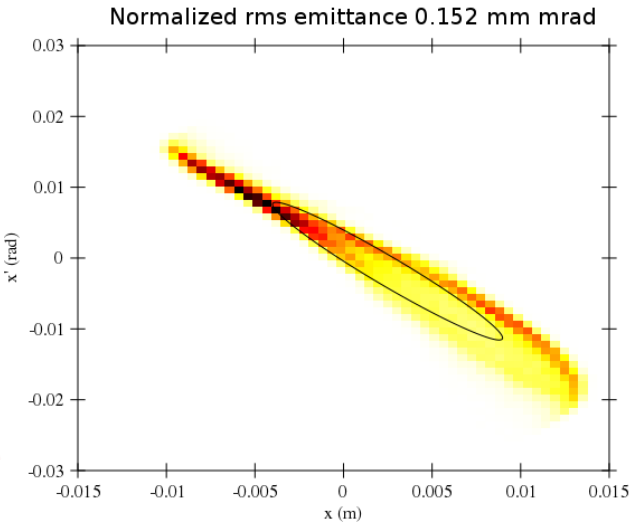
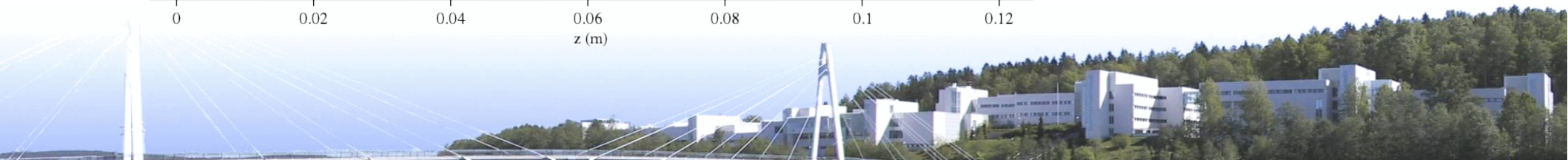
Linac4 IS03b

IS03a, IS03b optimized the filter field, fixed the electron dump leakage and reduced the emittance growth in the extraction einzel lens.







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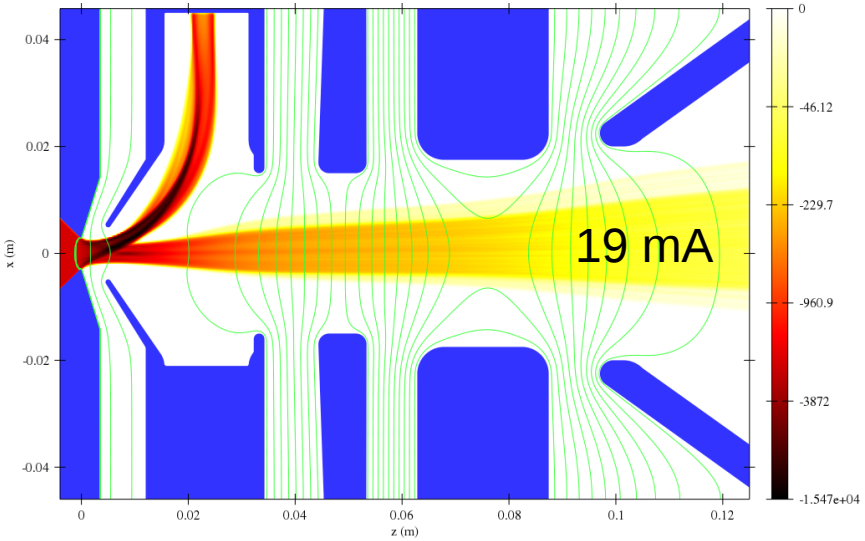
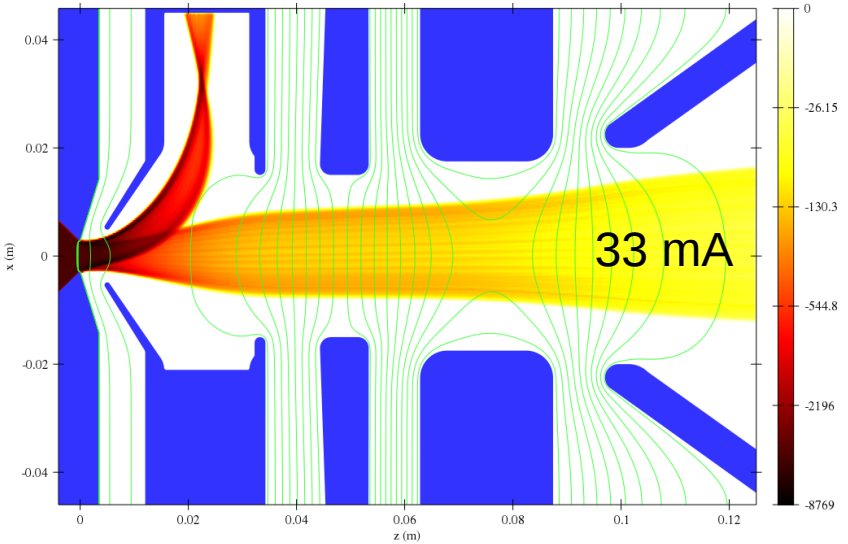
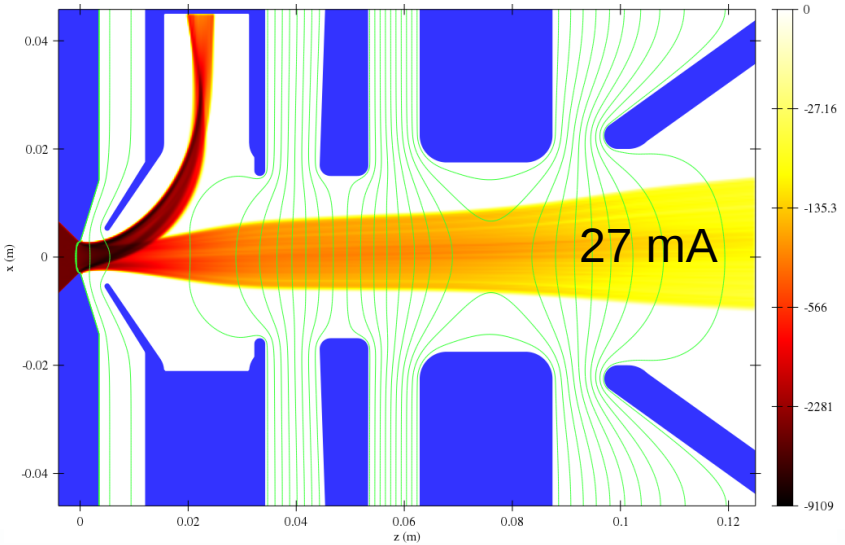
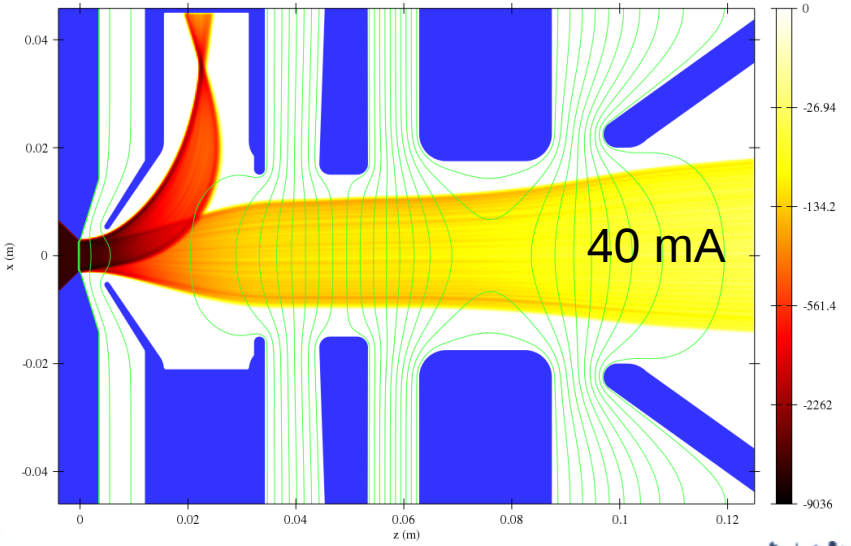
Linac4 IS03b









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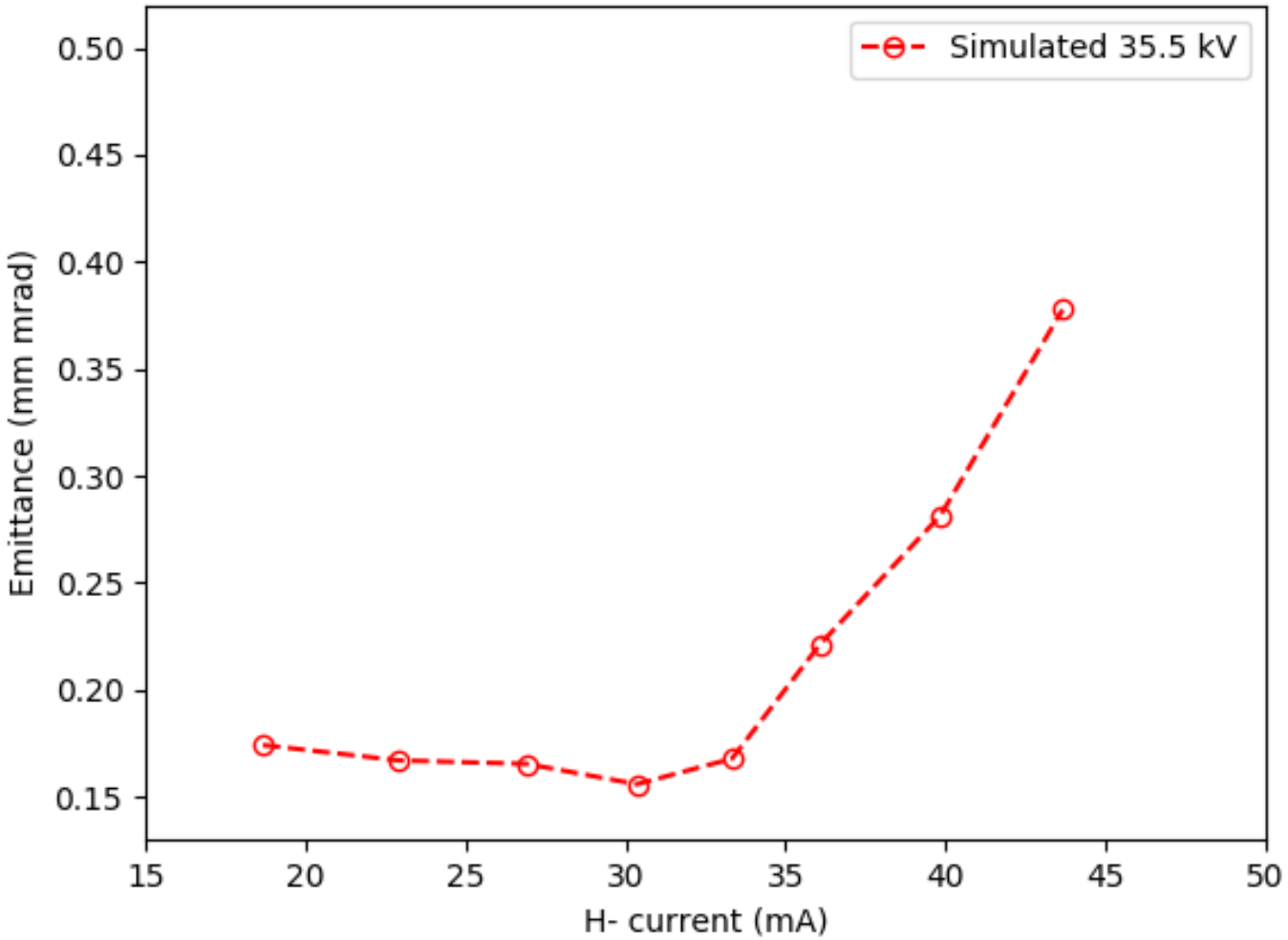
Linac4 IS03b

Beam emittance from the source



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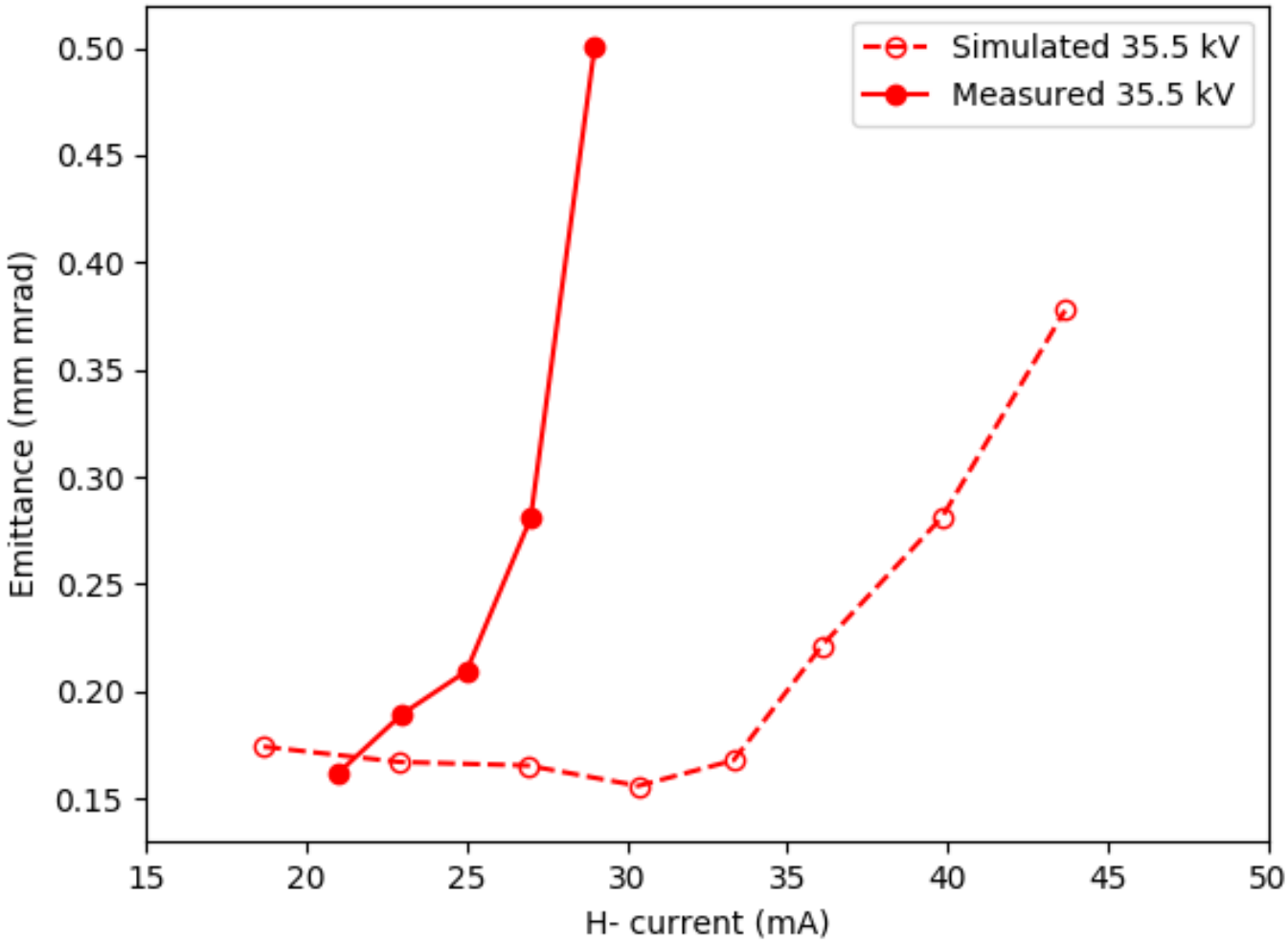
Linac4 IS03b

Beam emittance from the source



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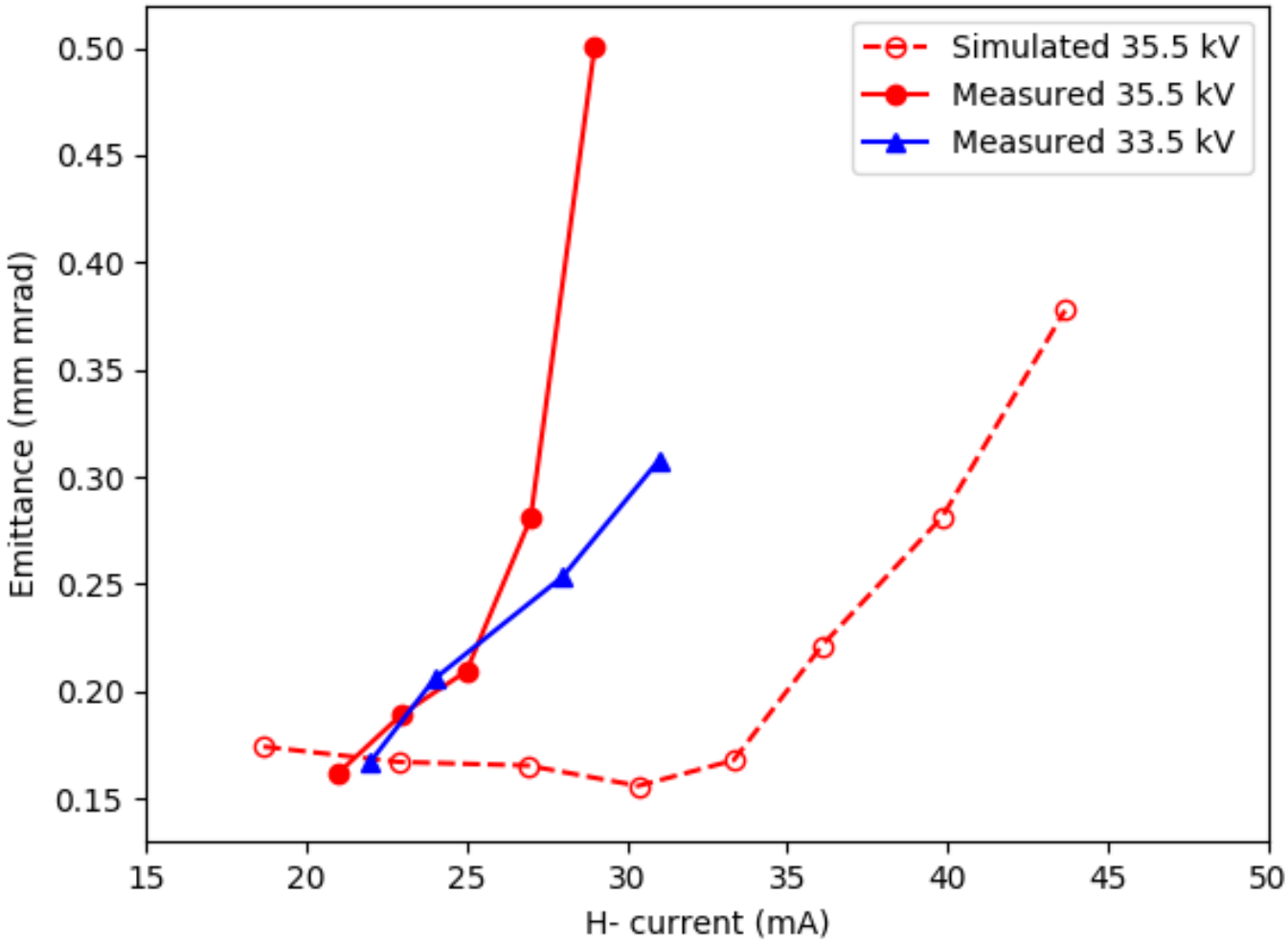
Linac4 IS03b

Beam emittance from the source



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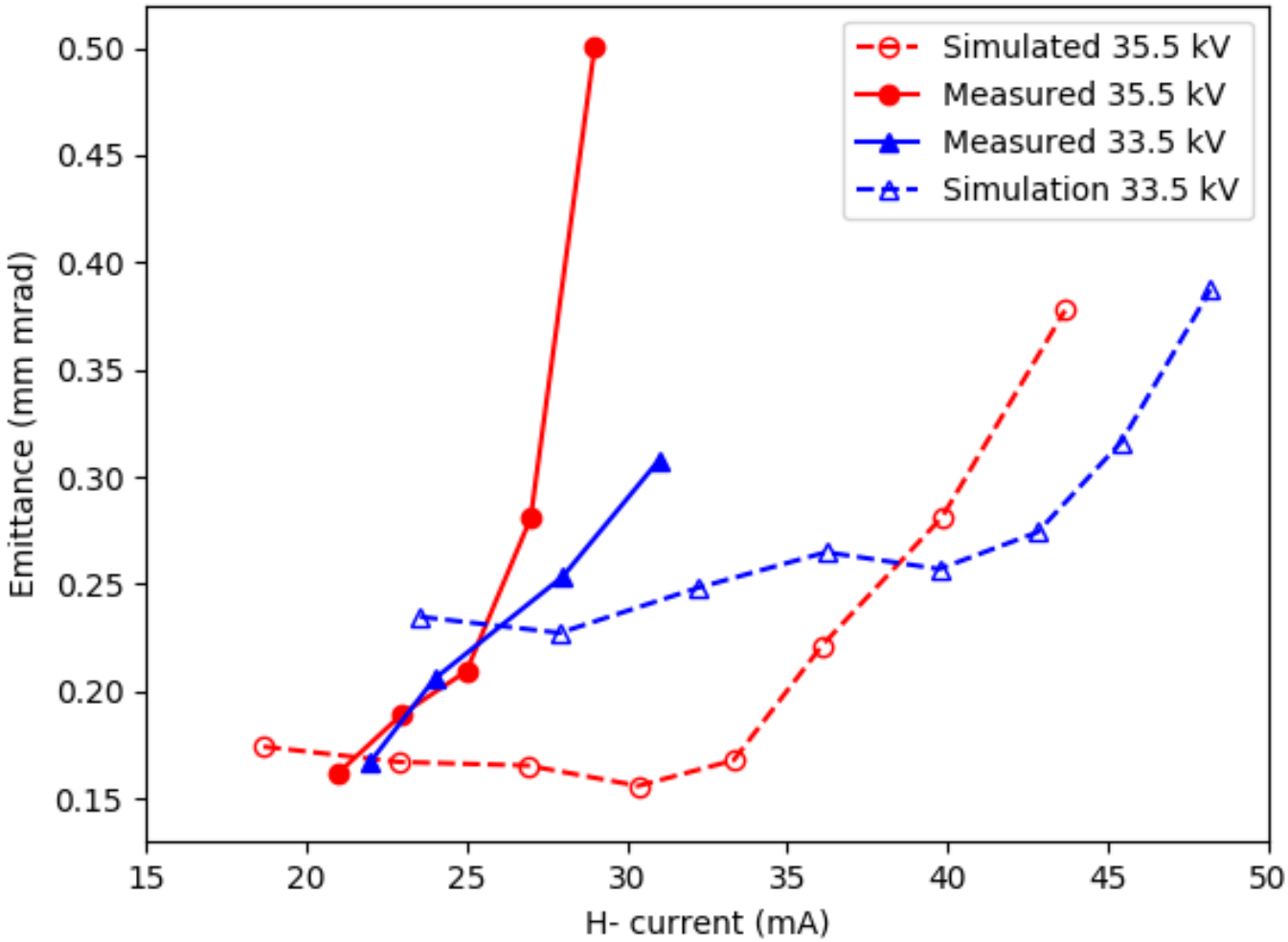
Linac4 IS03b

Beam emittance from the source



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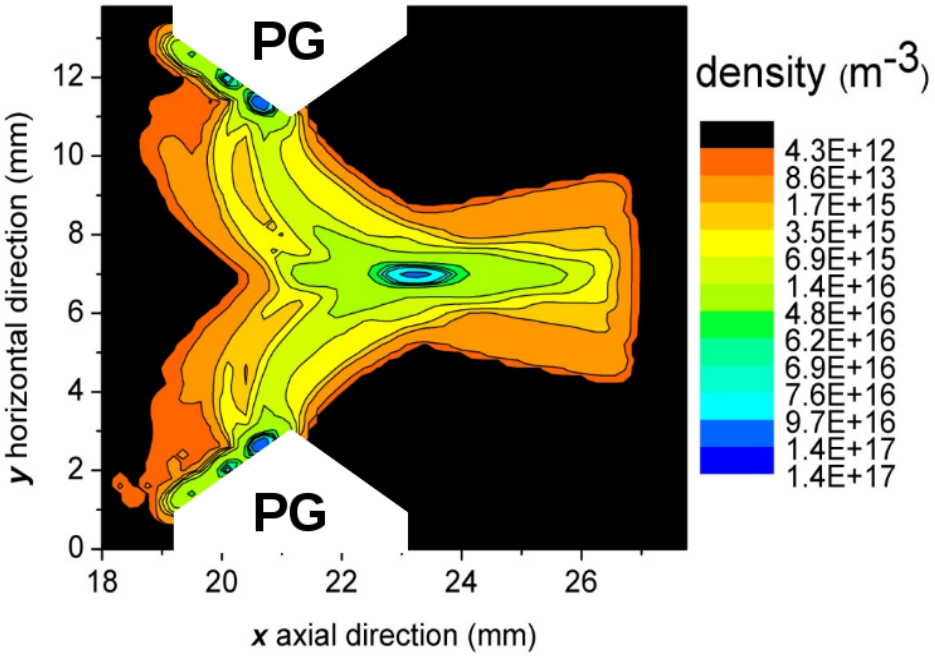
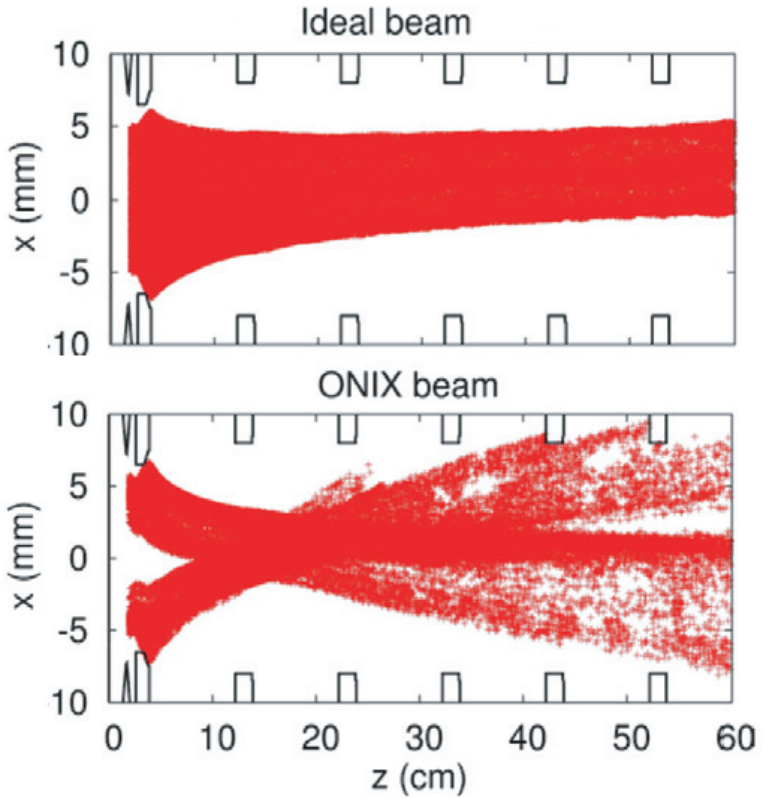
Surface production effect?





S. Mochalskyy, ICIS2013 and
A. Revel et al., Nucl. Fusion 53, 073027 (2013)

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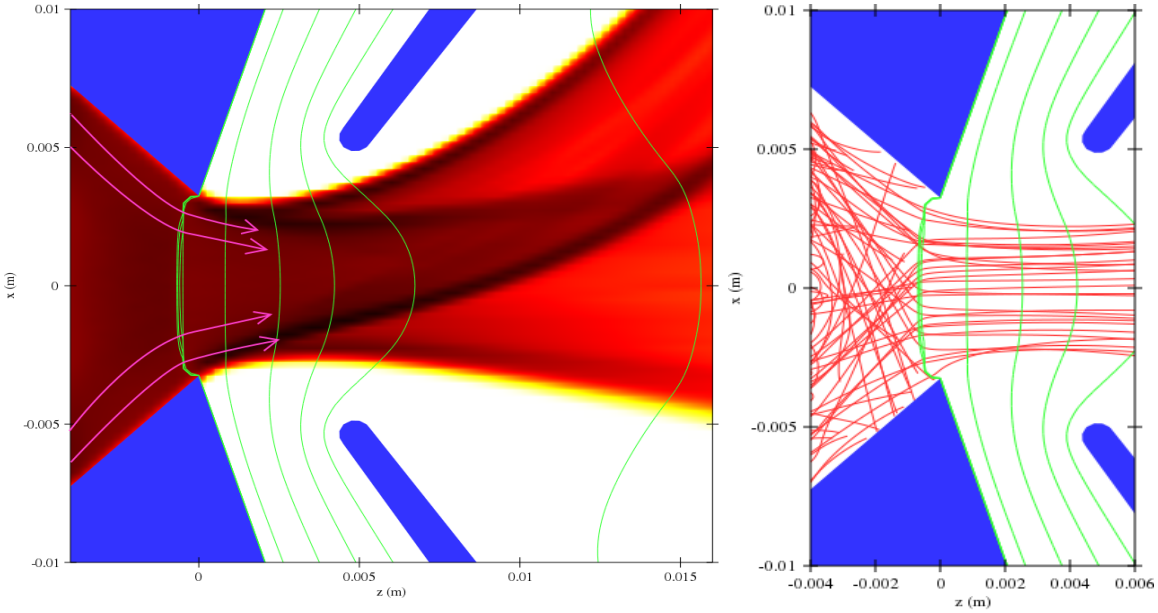
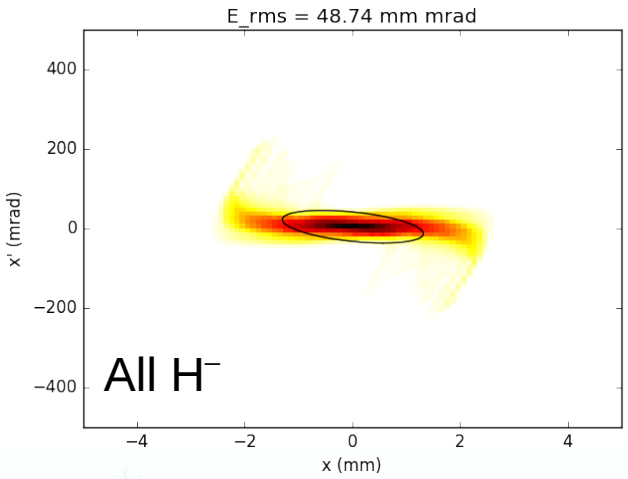
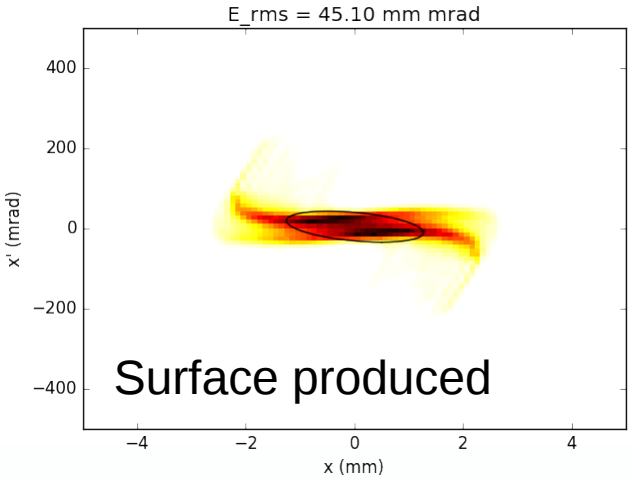
Surface produced H^- in tracking codes?

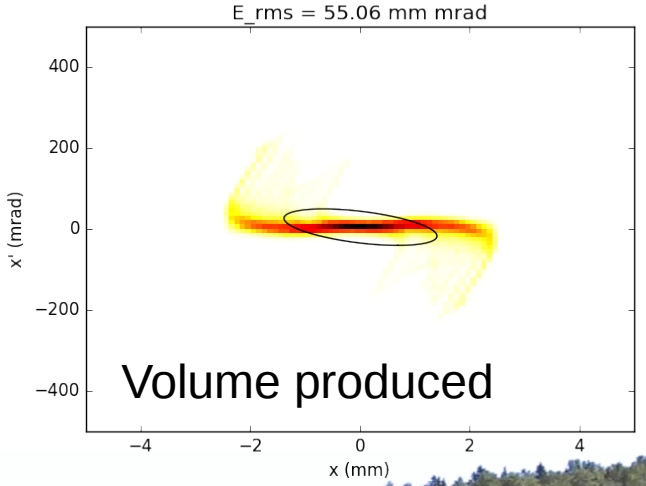
Test with additional surface species:

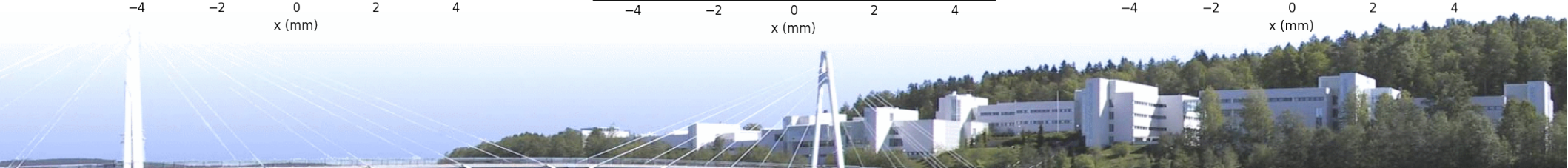
- 40 mA total
- 20 mA surface produced
- 80 mA electrons











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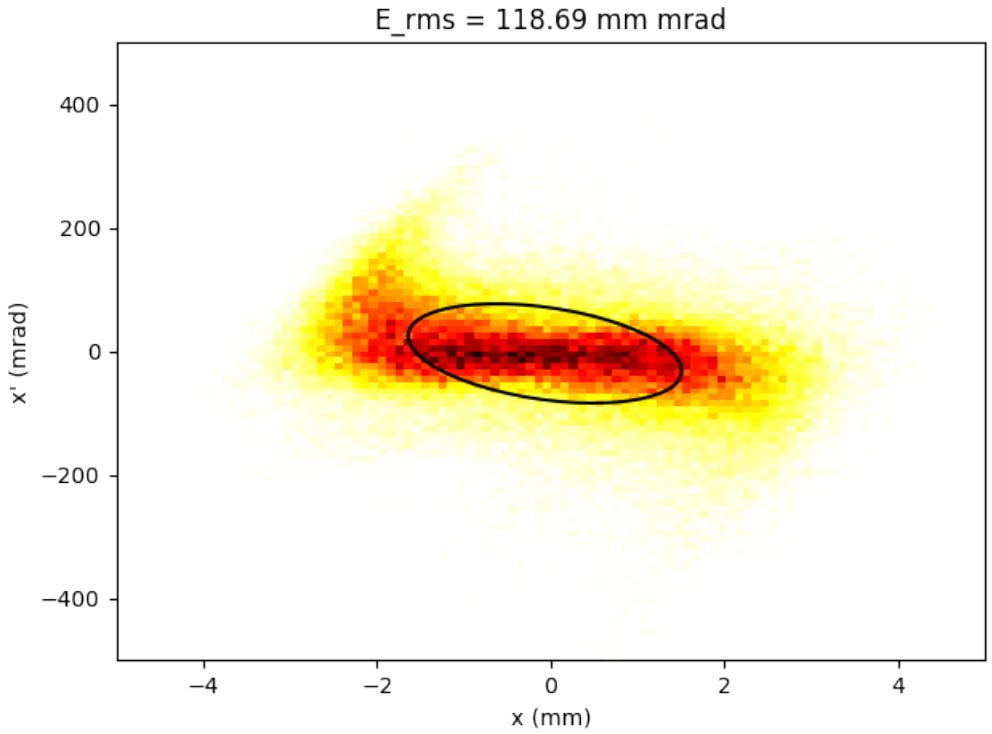
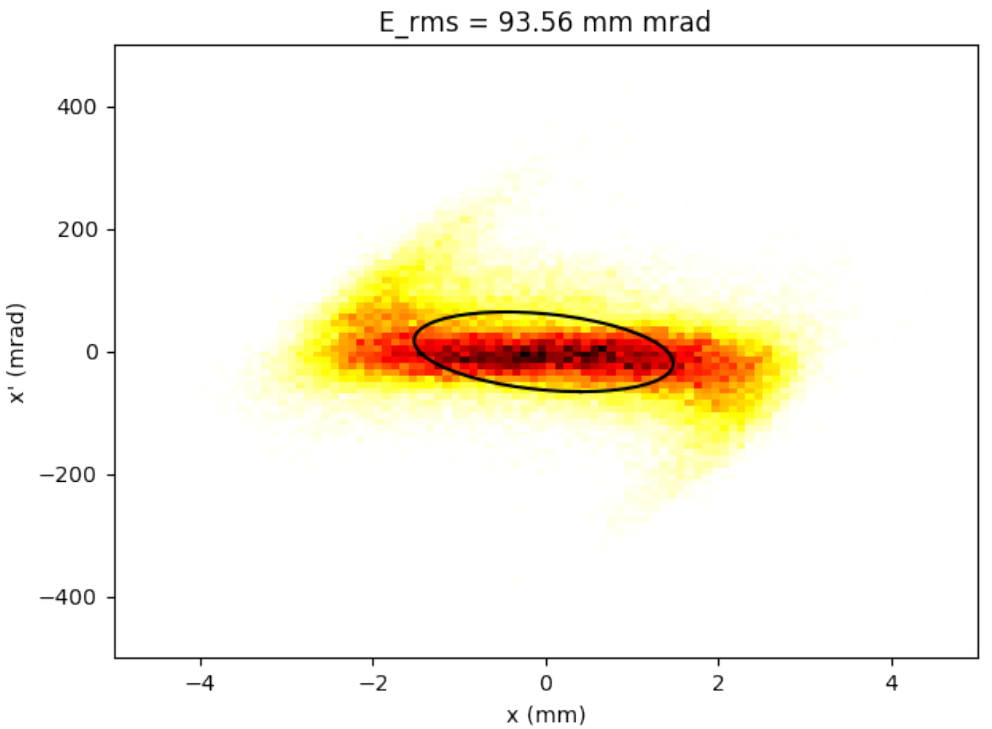
Backtracking of measured distributions

CERN Linac4 IS03c: phase space data backtracked to z=3 mm

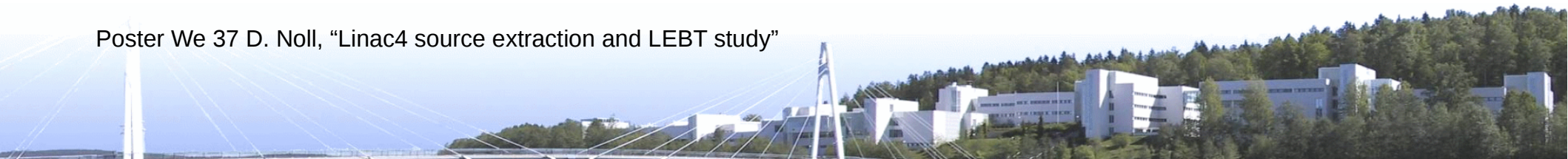




Uncesiated source: 20 mA H^-
e^-/H^- ratio 15

Cesiated source: 21 mA H^-
e^-/H^- ratio 2

Poster We 37 D. Noll, “Linac4 source extraction and LEBT study”



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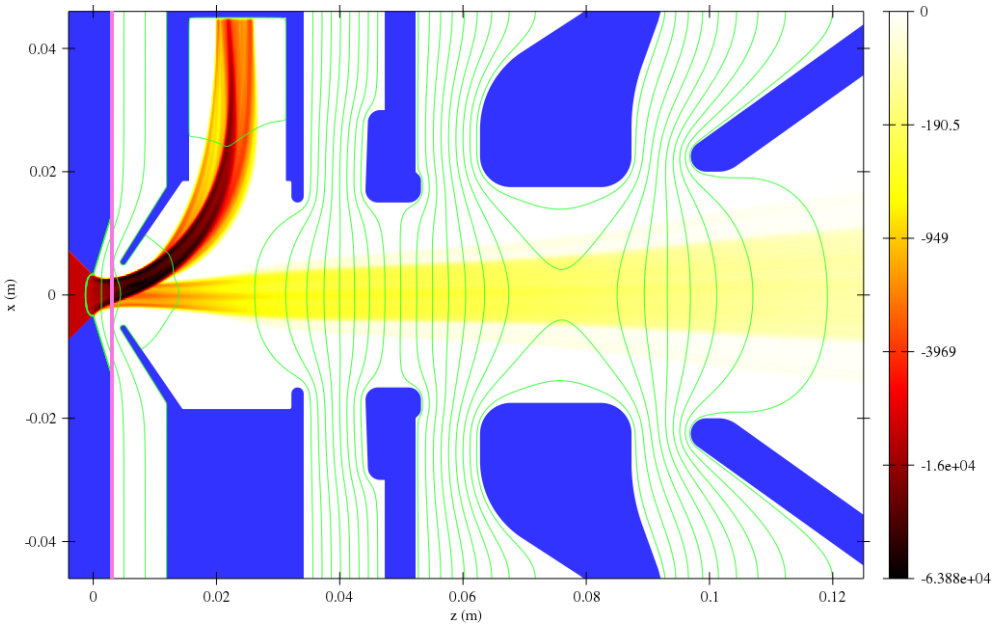
Coupled PIC extraction + tracking code

Collaboration with Keio University:

1. IBSimu calculation with plasma and beam → Potential at z=3 mm, boundary for PIC calculation.



Coupled PIC extraction + tracking code

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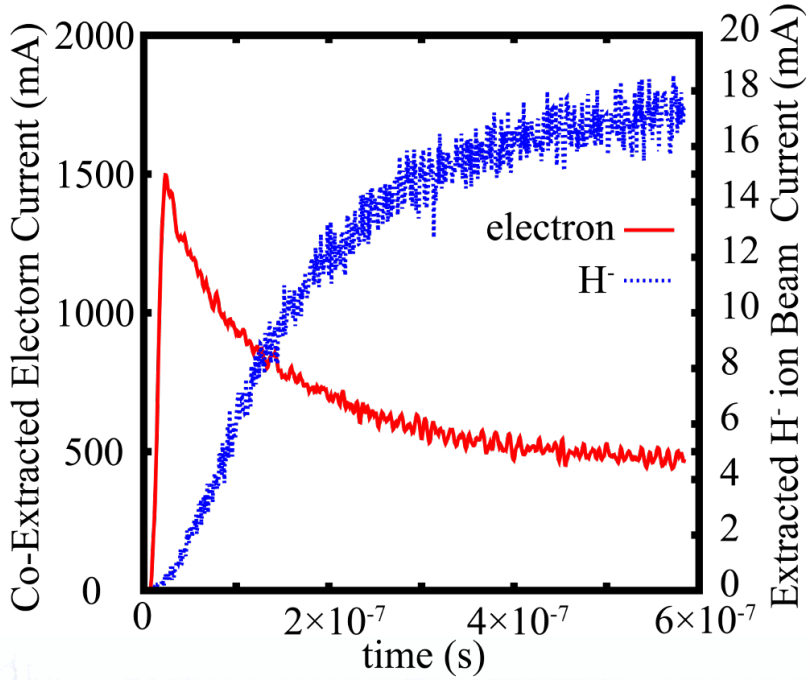
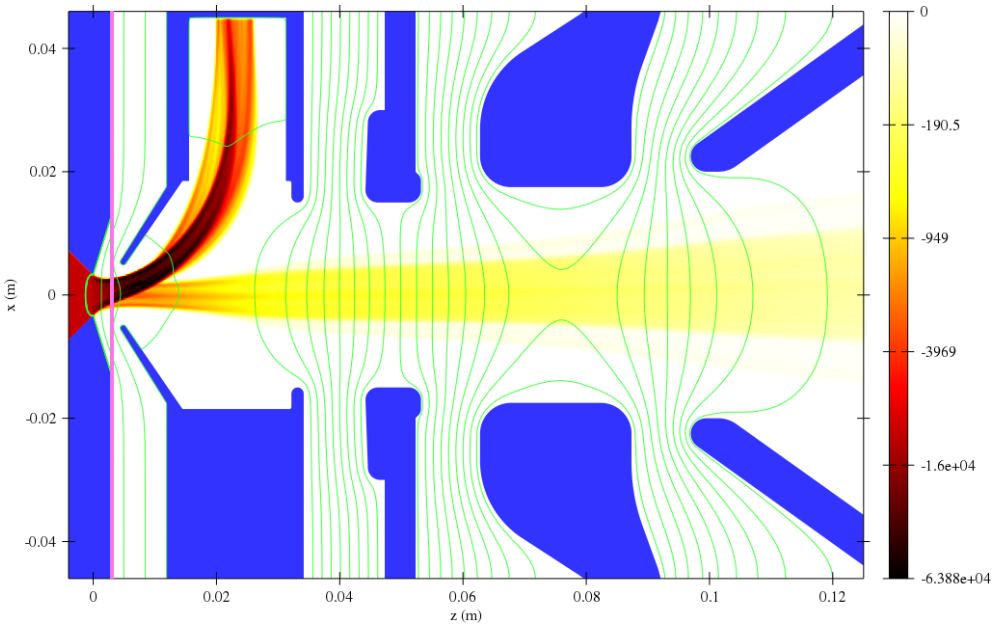
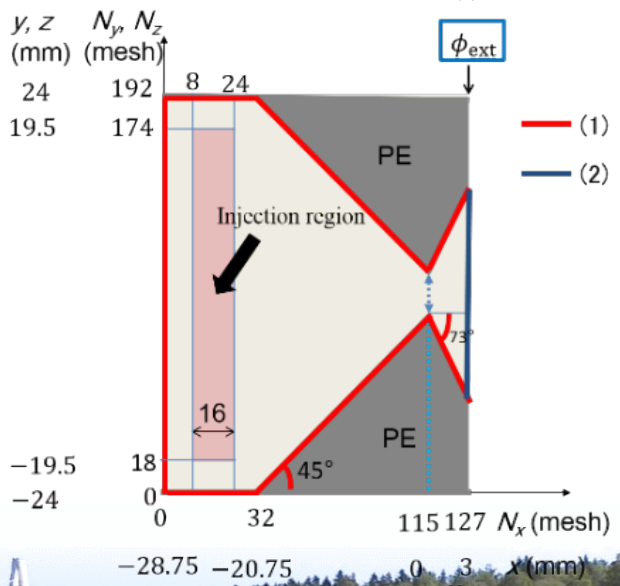
Collaboration with Keio University:

1. IBSimu calculation with plasma and beam → Potential at z=3 mm, boundary for PIC calculation.

2. KEIO-BFX PIC calculation using the potential map.







Poster We 17 S. Nishioka, “Integrated modeling of the beam formation and extraction in the Linac4 hydrogen negative ion source”

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Coupled PIC extraction + tracking code

Collaboration with Keio University:

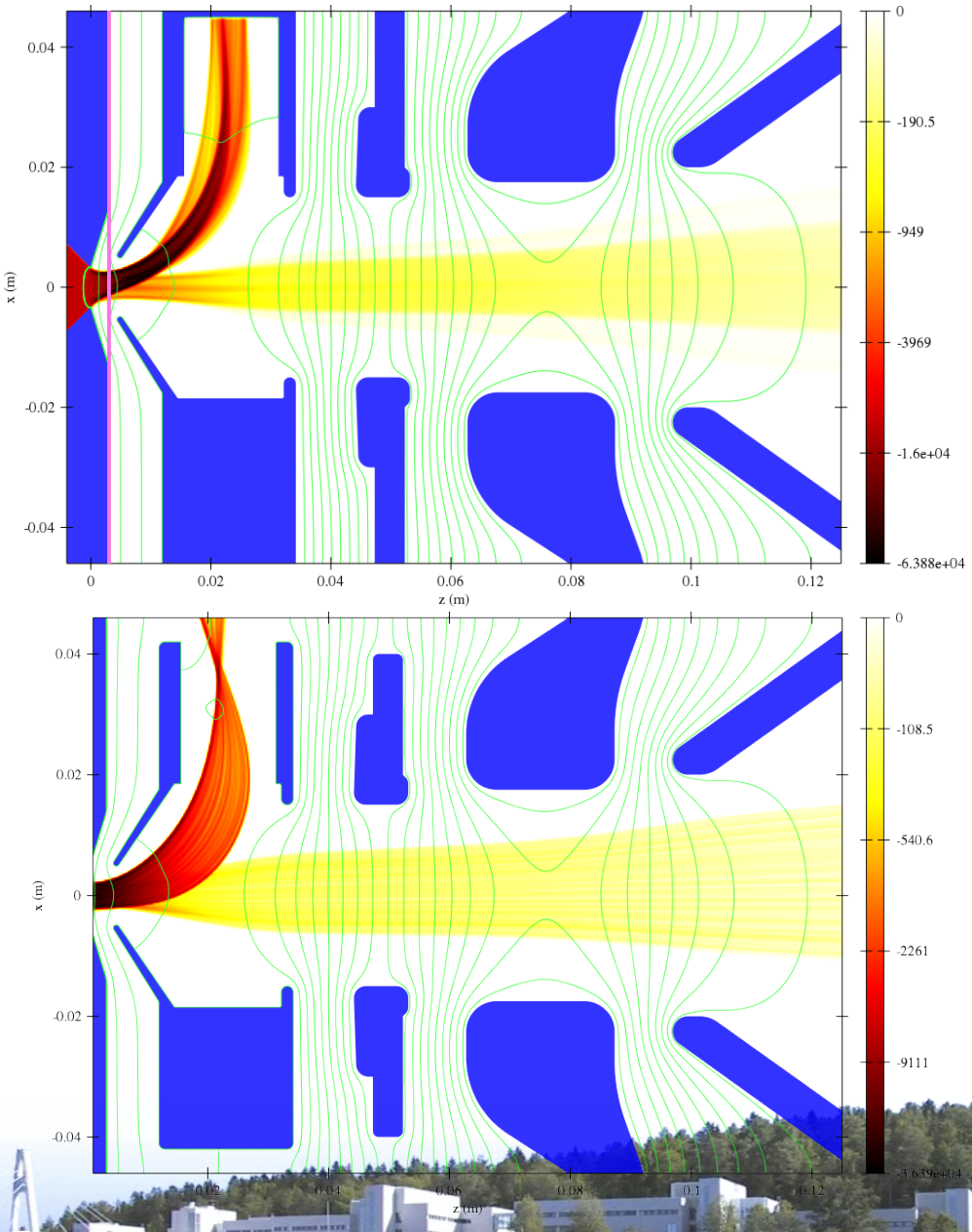
1. IBSimu calculation with plasma and beam → Potential at z=3 mm, boundary for PIC calculation.

2. KEIO-BFX PIC calculation using the potential map.

3. Potential and particle data exported at z=1 mm.

4. IBSimu calculation using the data from KEIO-BFX

Case shown here:
~20 mA, e^-/H^- ratio ~20



Poster We 17 S. Nishioka, “Integrated modeling of the beam formation and extraction in the Linac4 hydrogen negative ion source”

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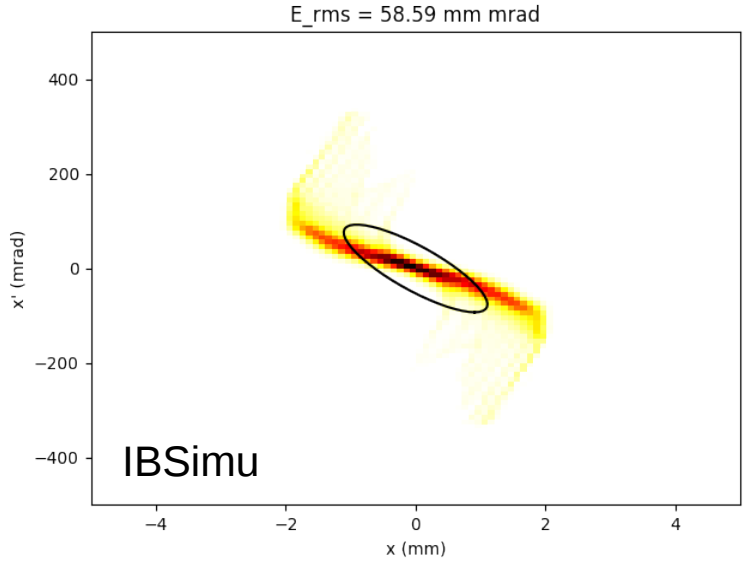
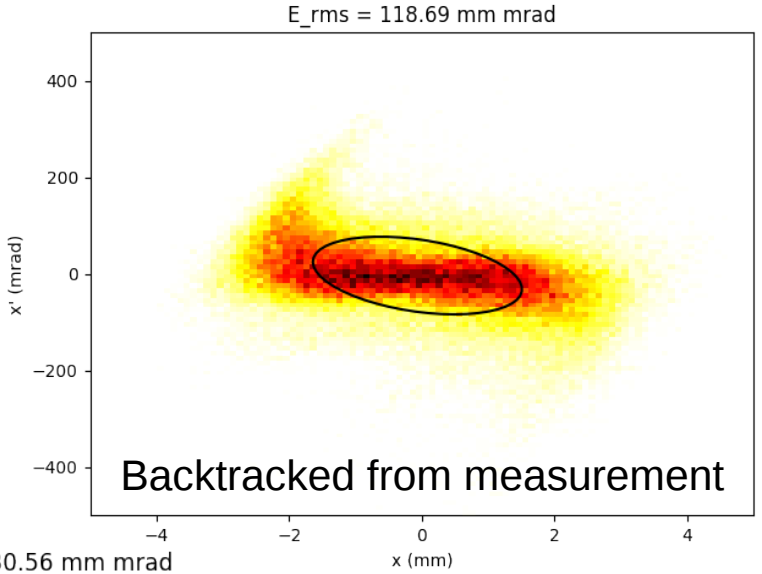
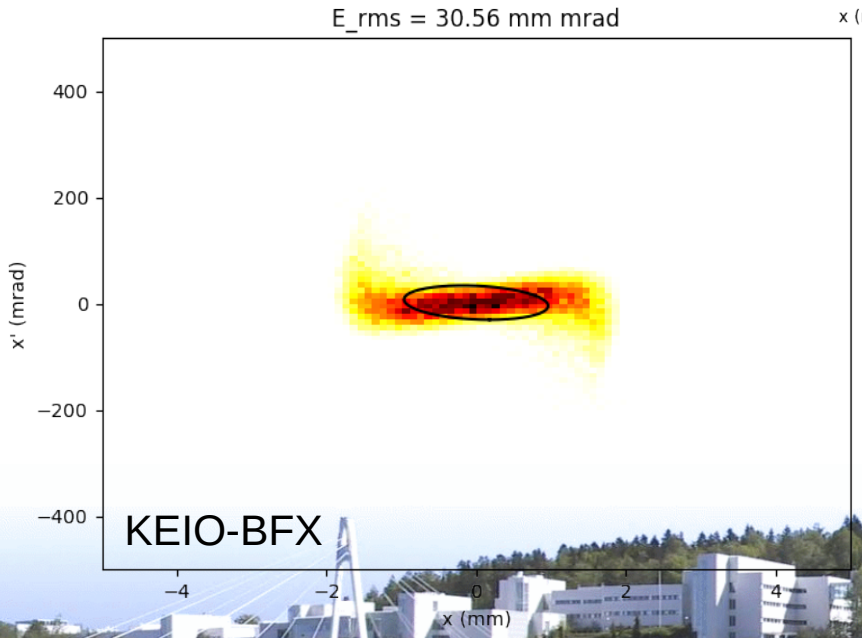
Phase space distributions at z=3 mm

Uncesiated IS03c: 20 mA H^-, e^-/H^- ratio 15–20







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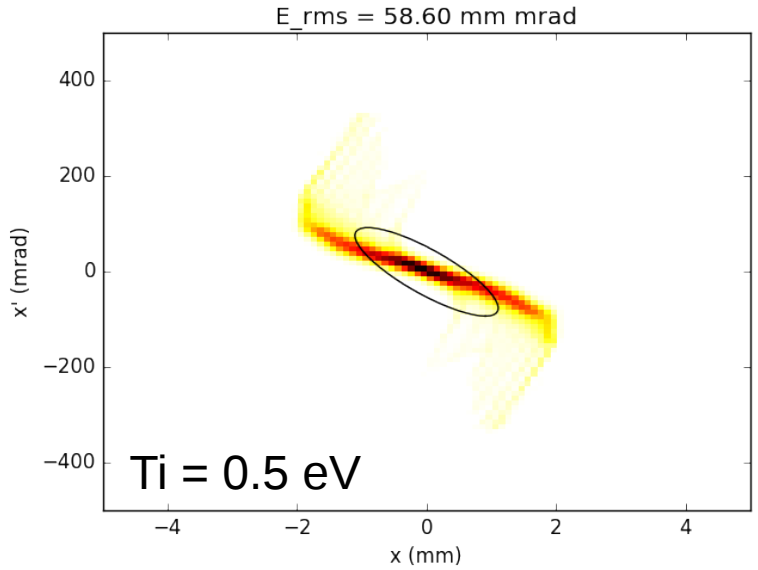
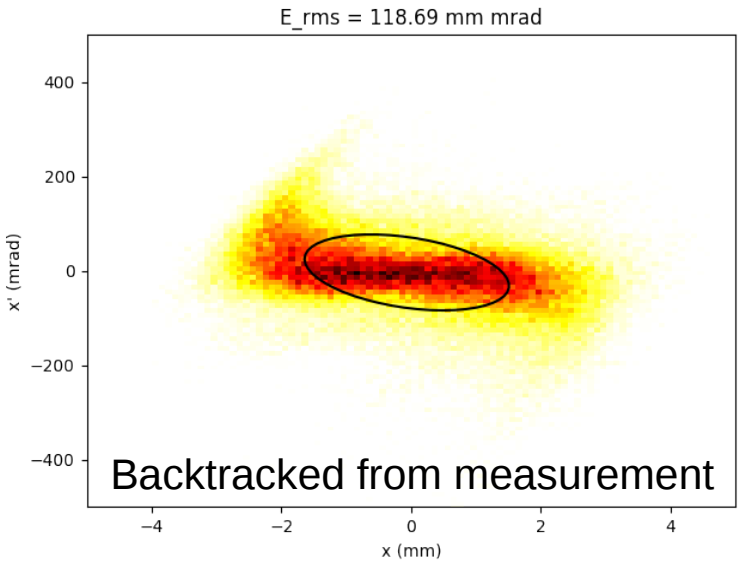
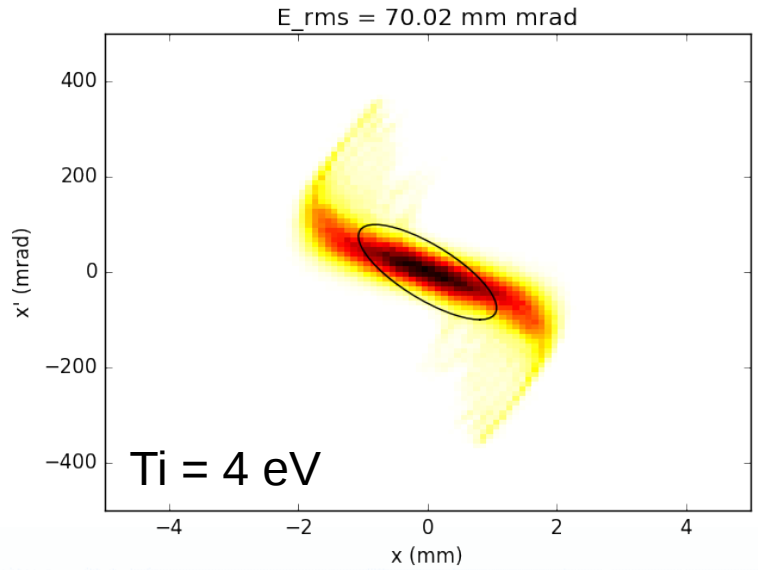
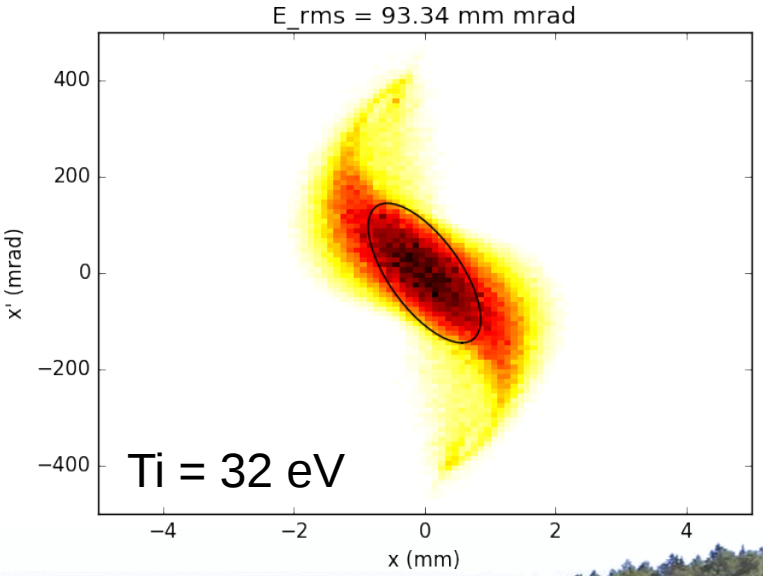
Effect of ion temperature









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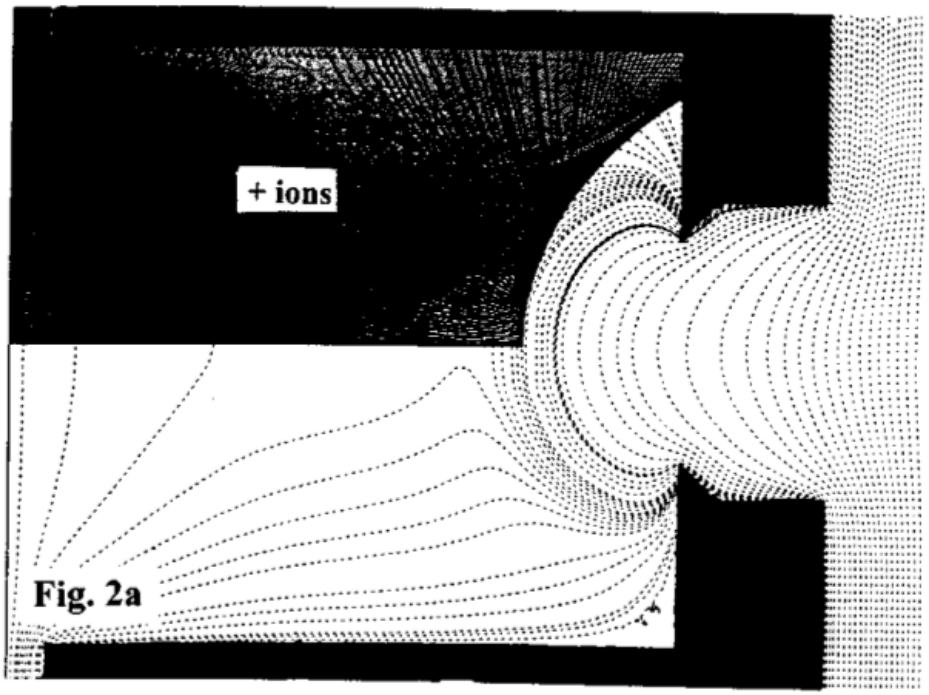
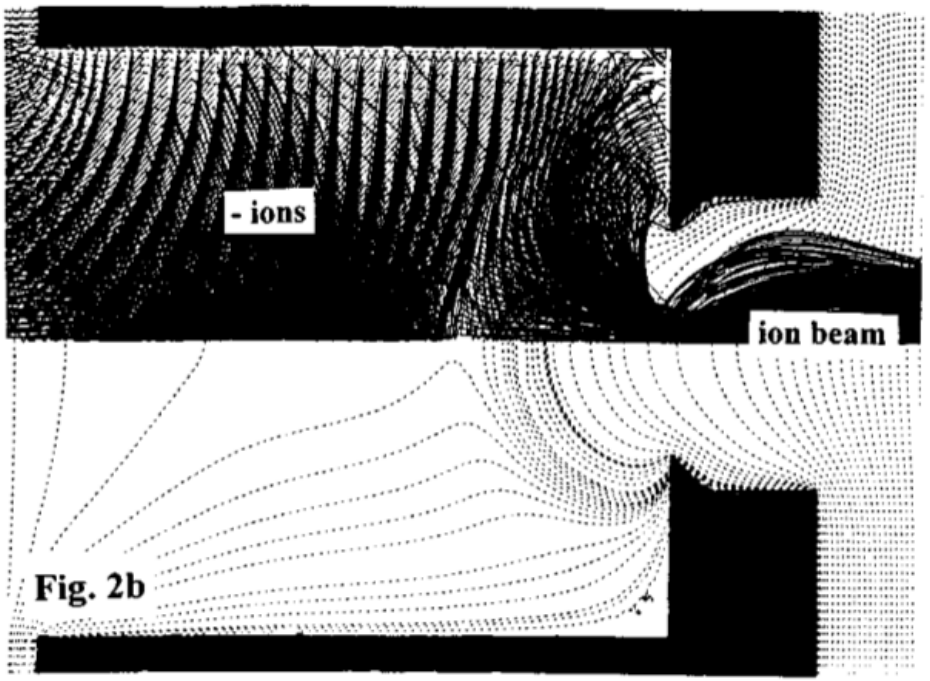
Better tracking code H^- plasma model?

J. H. Whealton, J. Appl. Phys 64, 6210 1988 and Rev. Sci. Instrum. 69, 1103 (1998):





- Much more complicated than current negative extraction model
- Still simpler and especially faster than PIC

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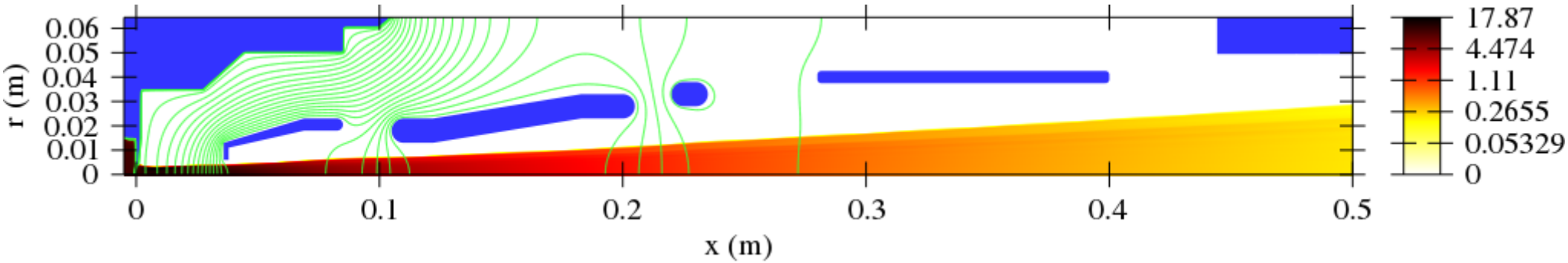
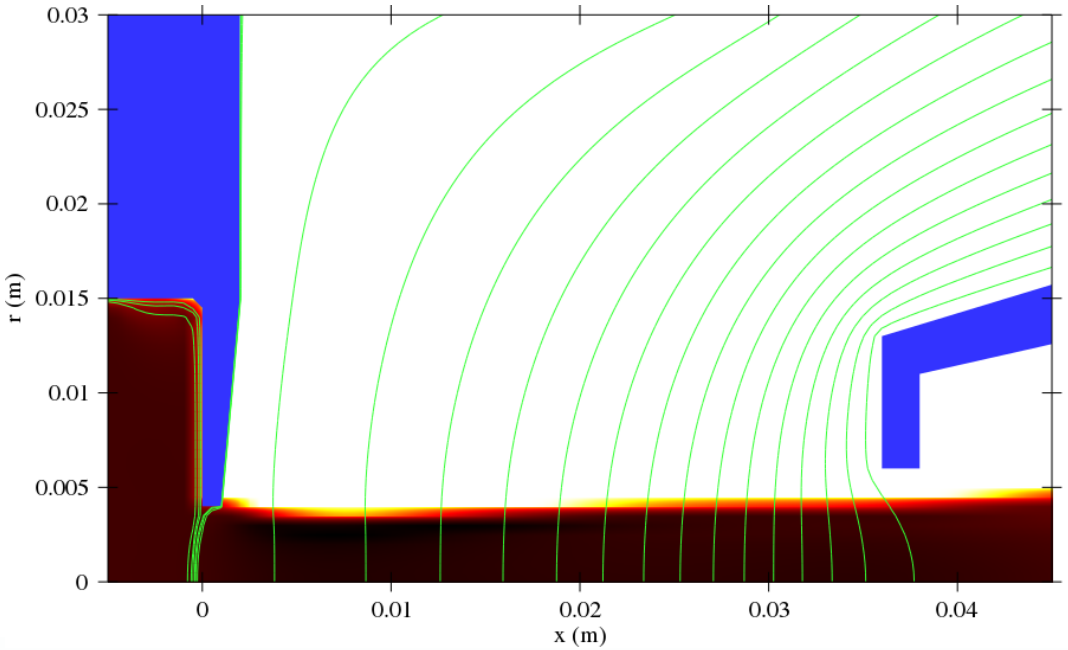
ECRIS modelling

Use of classic exponential model for ECR plasma extraction: JYFL 14.1 GHz





V. Toivanen, T. Kalvas et al., JINST 8 P05003 (2013)

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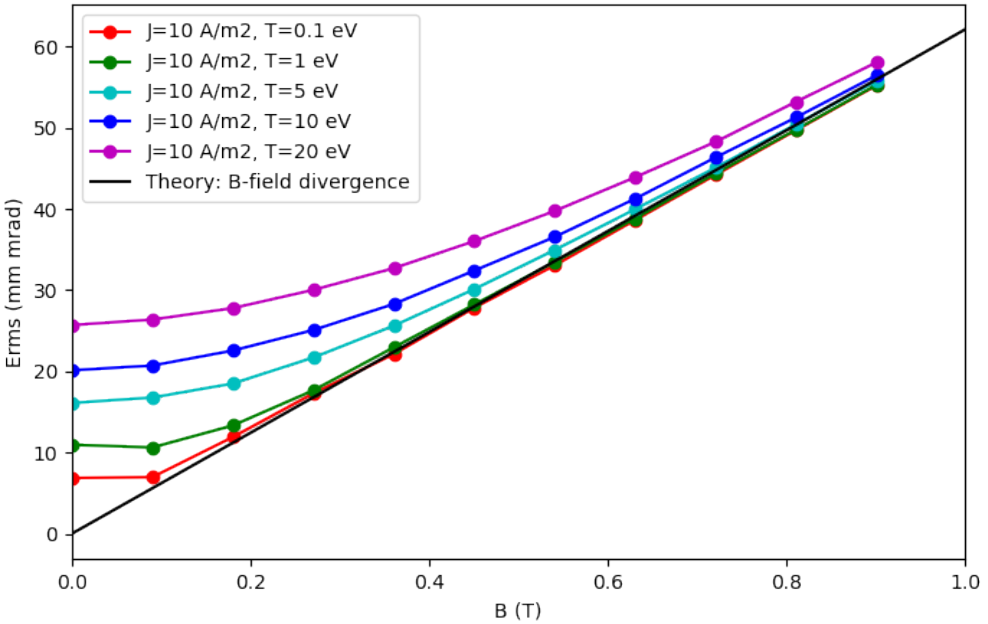
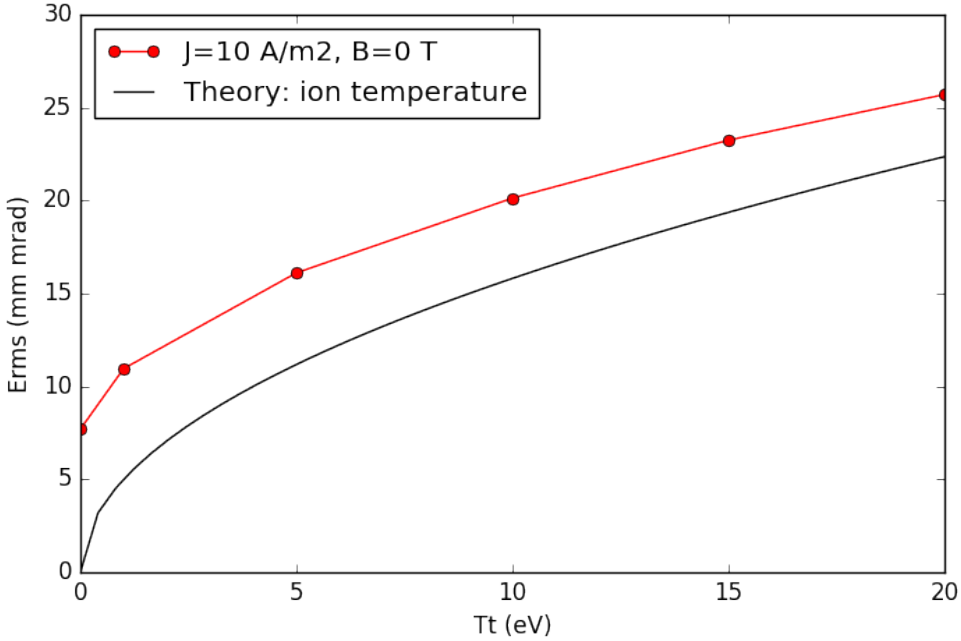
ECRIS modelling

Argon 8+:

$$\epsilon_{B,rms} = \frac{qB}{10\,mc} r^2$$



$$\epsilon_{T,rms} = \frac{1}{2}\sqrt{\frac{kT}{m}}\frac{r}{c}$$



Contributions to emittance:
1. Ion temperature
2. Magnetic field divergence
3. Extraction aberrations

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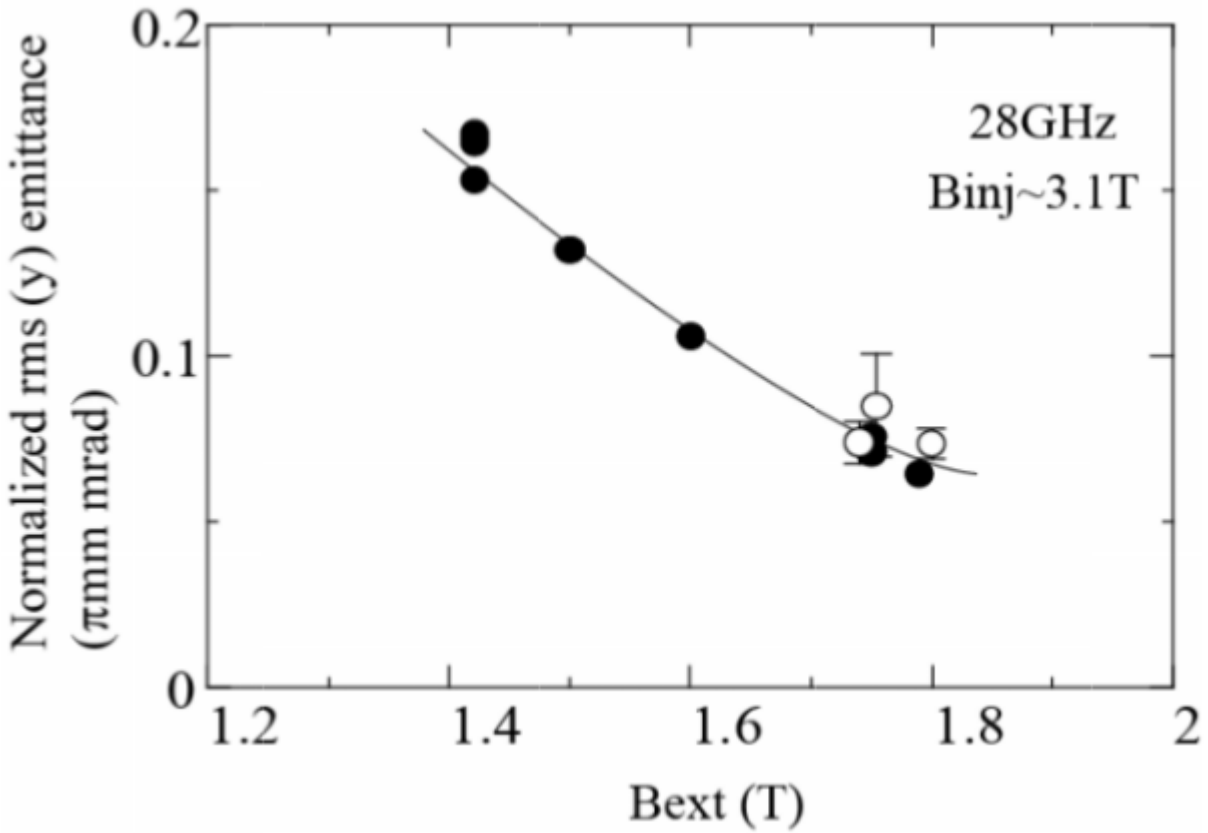
ECRIS modelling



Higurashi, et al., Proceedings of ECRIS-2014, Nizhny Novgorod, Russia

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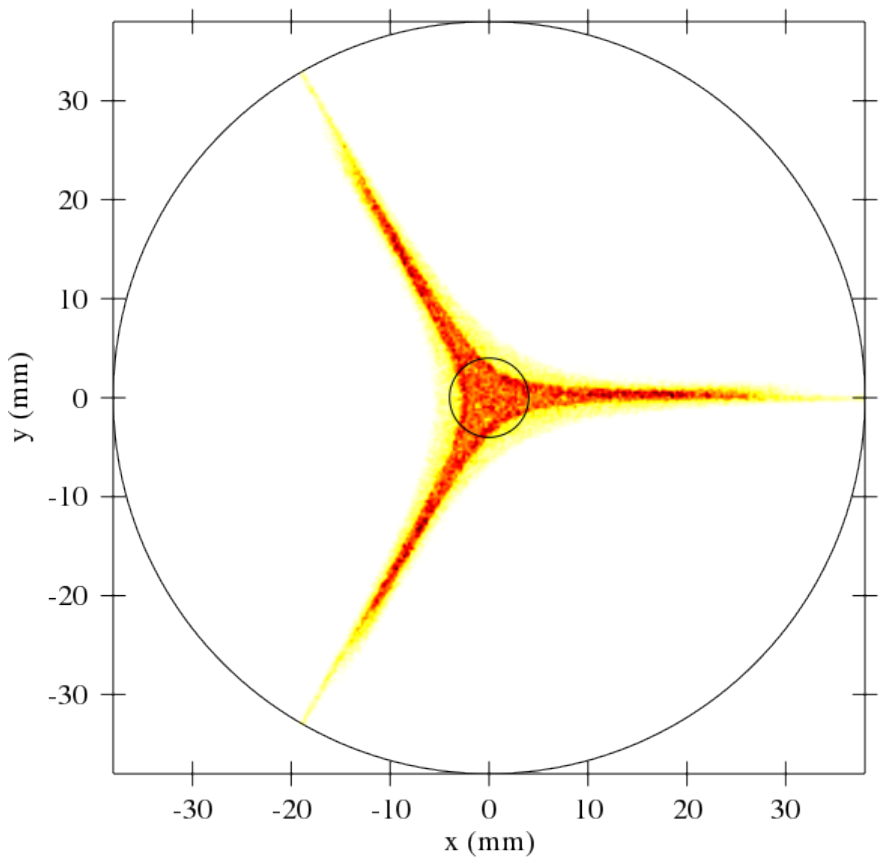
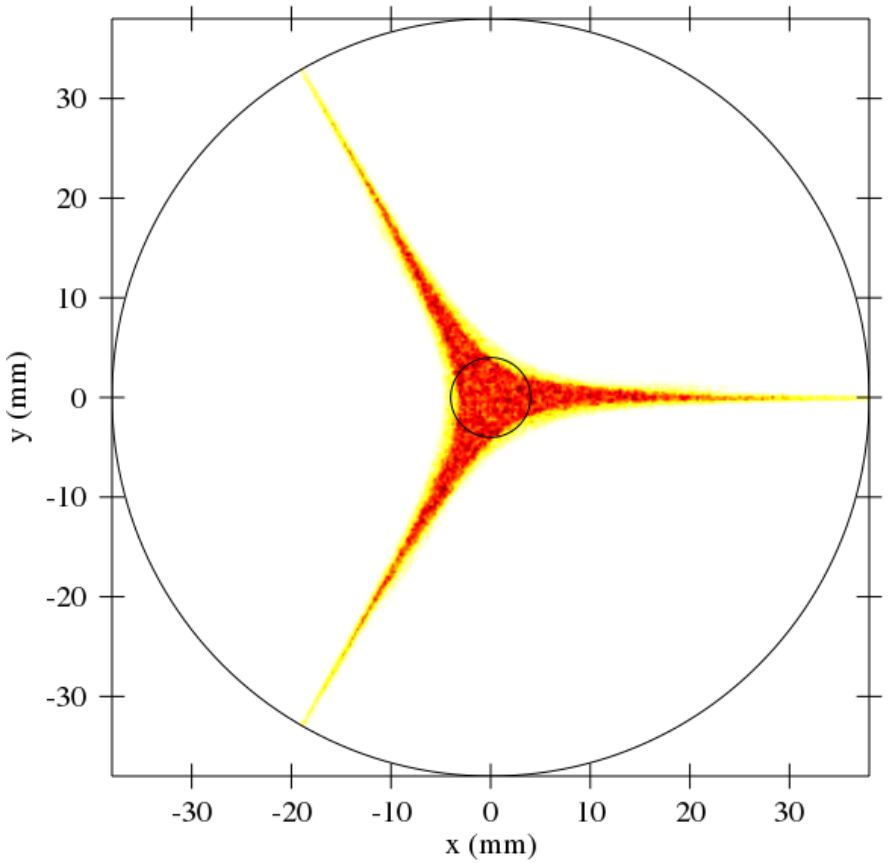
ECRIS modelling

Electron loss patterns for JYFL 14.1 GHz ECRIS



500 A / 500 A



600 A / 600 A

S. Biri, P. Spädtke, et al., “Combination of two ECRIS calculations...”, ECRIS-2014, Nizhny Novgorod

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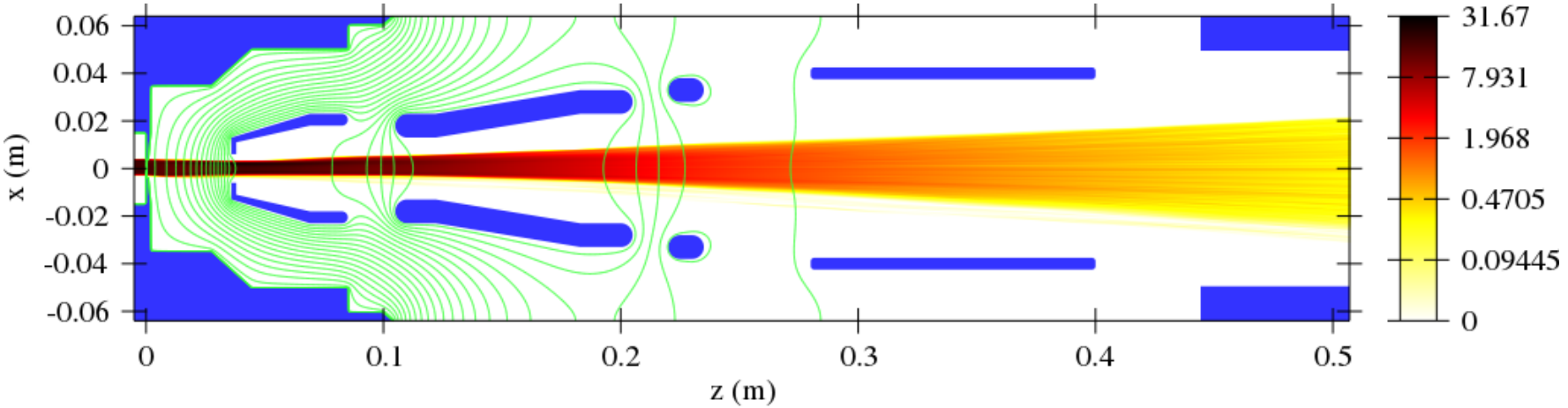
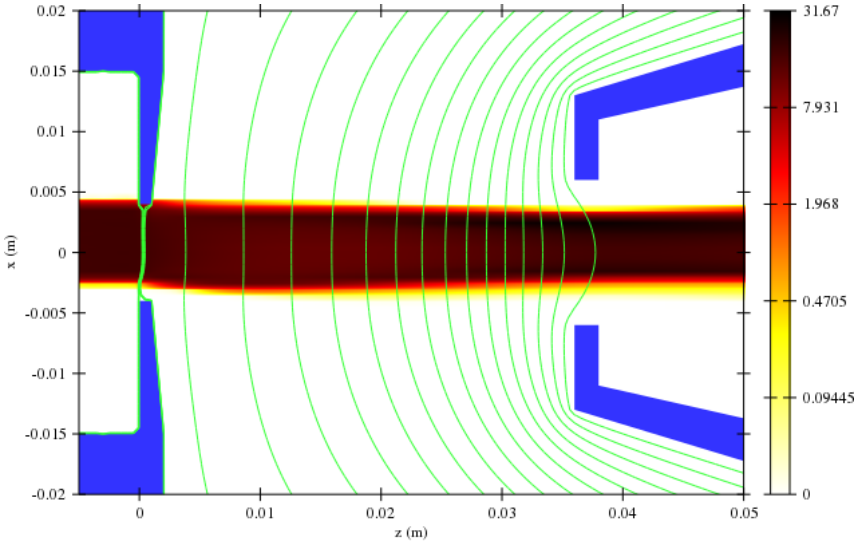
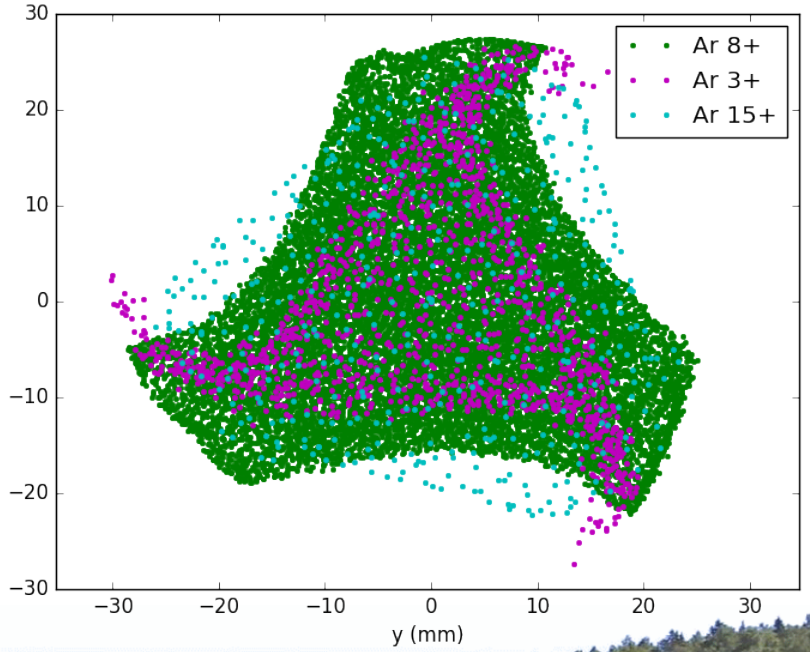
ECRIS modelling







Poster We 04 V. Mironov “On optical properties of ion beams extracted from ECRIS

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