# $H^-$ beam formation and electron dumping strategies

Taneli Kalvas

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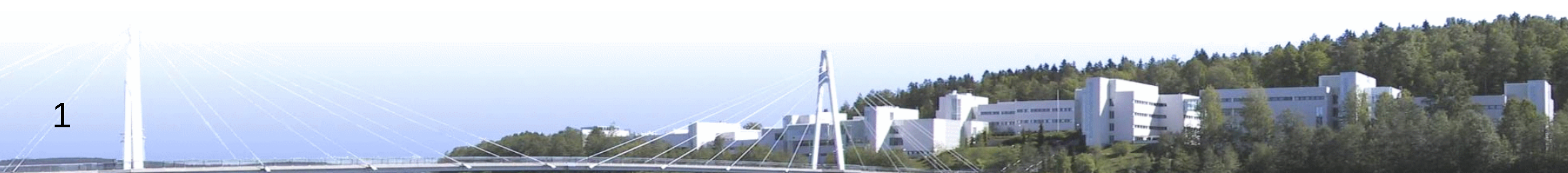
5.9.2018, 6th International Symposium on
Negative Ions, Beams and Sources, Novosibirsk



# Outline

- Introduction to negative ion plasma extraction codes
- Beam formation studies with the PELLIS ion source
- CERN Linac4 $H^{-}$ simulations
- Deviation of model and potential corrections
- Outlook

# Background

Development of $H^-$ extraction systems:

- Plasma modelling, PIC-MCC
- Extraction codes
- Experimental work

# Background

Modelling negative ion extraction from plasma volume

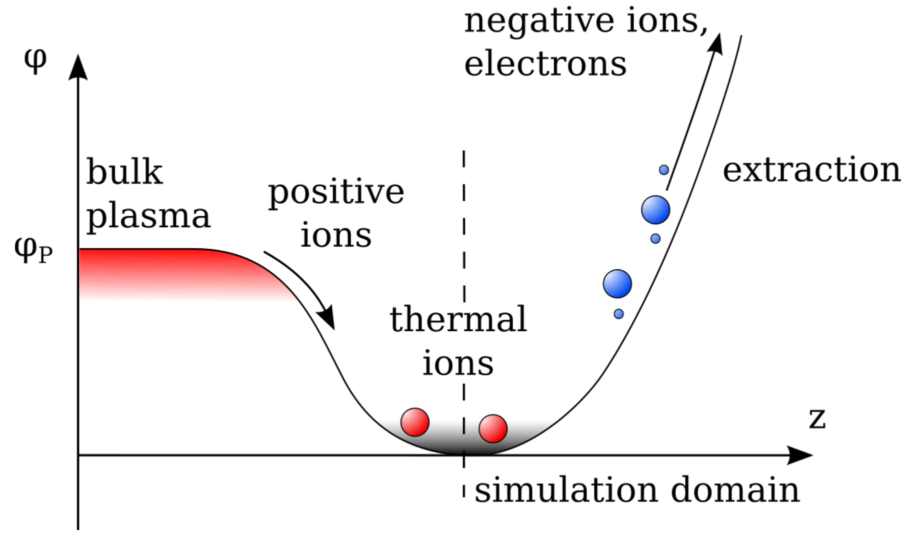
Assumption: $\phi$ = 0 V near the extraction:

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

$$\rho_{th} = \rho_{th0}\exp\left(\frac{-e\phi}{kT_p}\right)$$

$$\rho_f = \rho_{f0}\left(1 - \mathrm{erf}\left(\frac{\phi}{\phi_P}\right)\right)$$

$$\vec{F} = q\left(\vec{E} + \vec{v}\times\vec{B}\right)$$



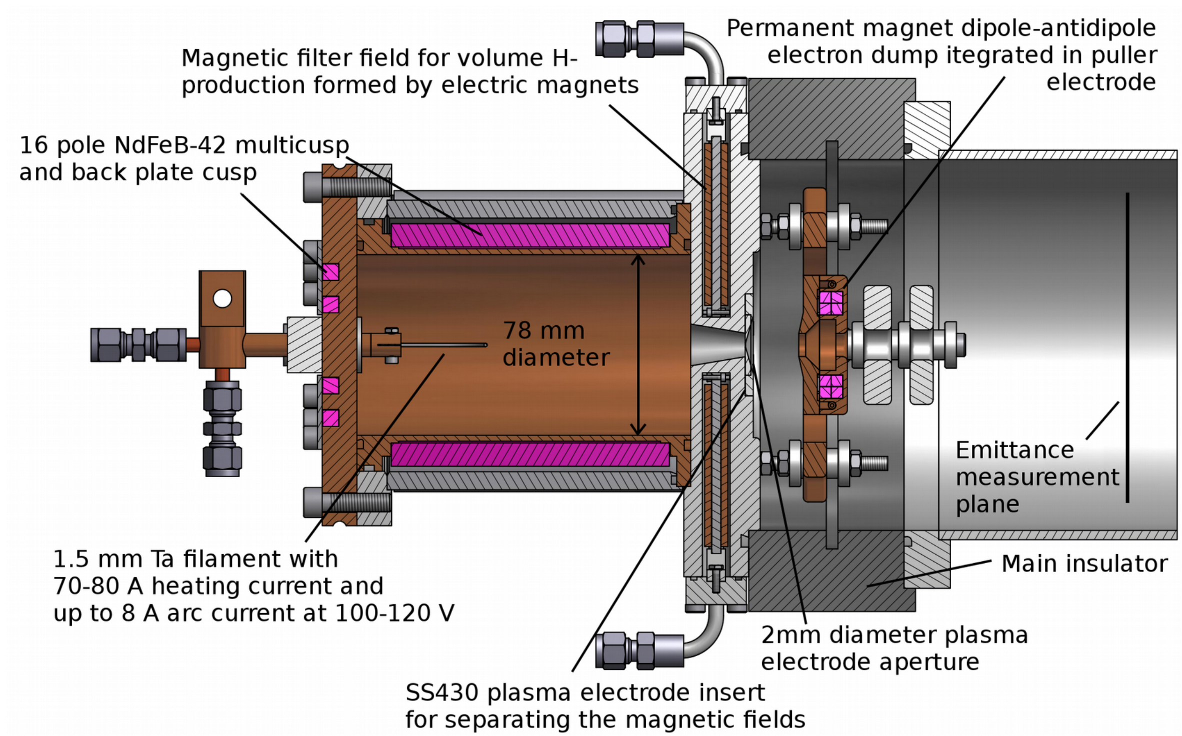

Very simplified but allows systematics to be done due to fast computation (~1 h for $10^7$ node 3D problem), which is not possible by PIC methods.

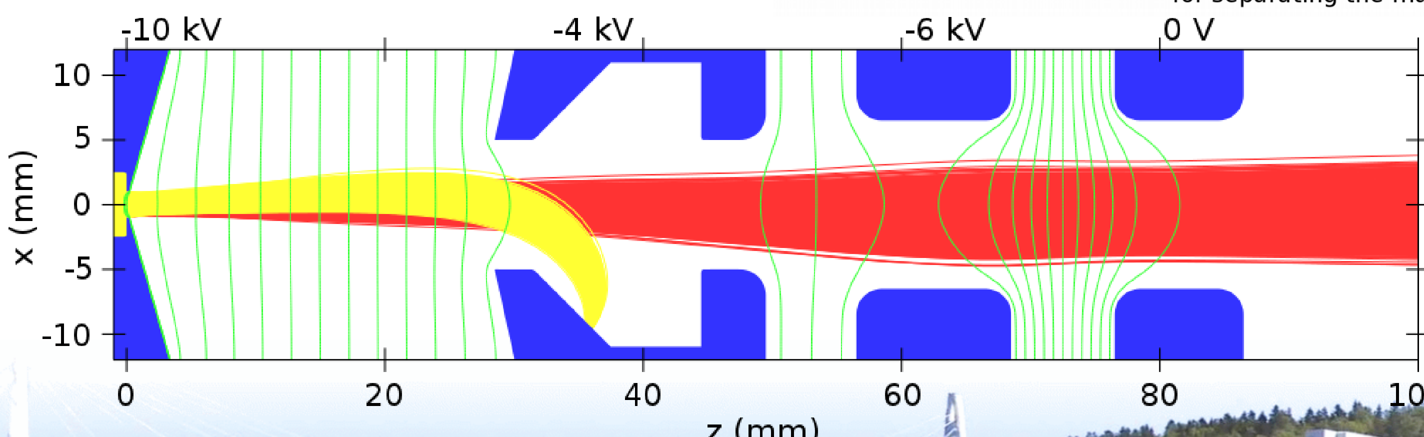

R. Becker, Rev. Sci. Instrum. 75, 1723 (2004) and
R. Becker, AIP Conf. Proc. 763, 194 (2005).

# JYFL PELLIS ion source

Filament-driven H⁻ ion source

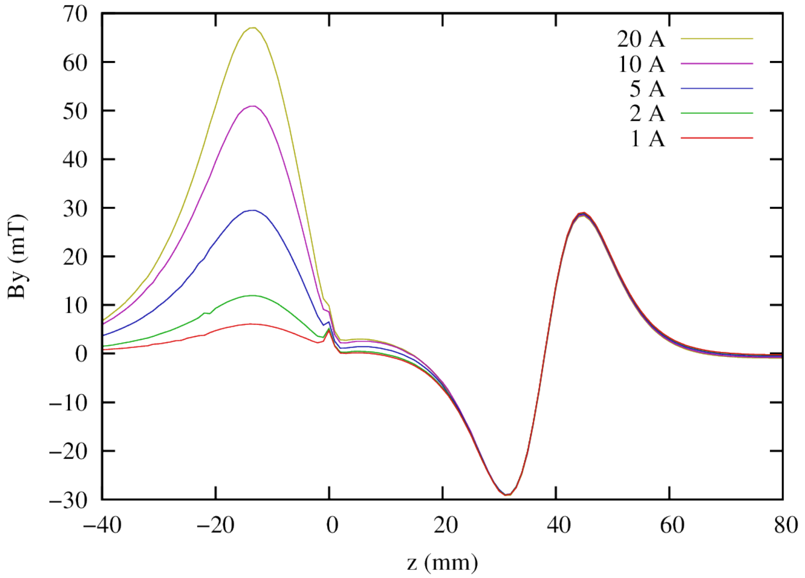
- CW volume production
- Low-emittance beams <100 µA
- ⌀2 mm plasma aperture
- Low aberrations, low space charge forces

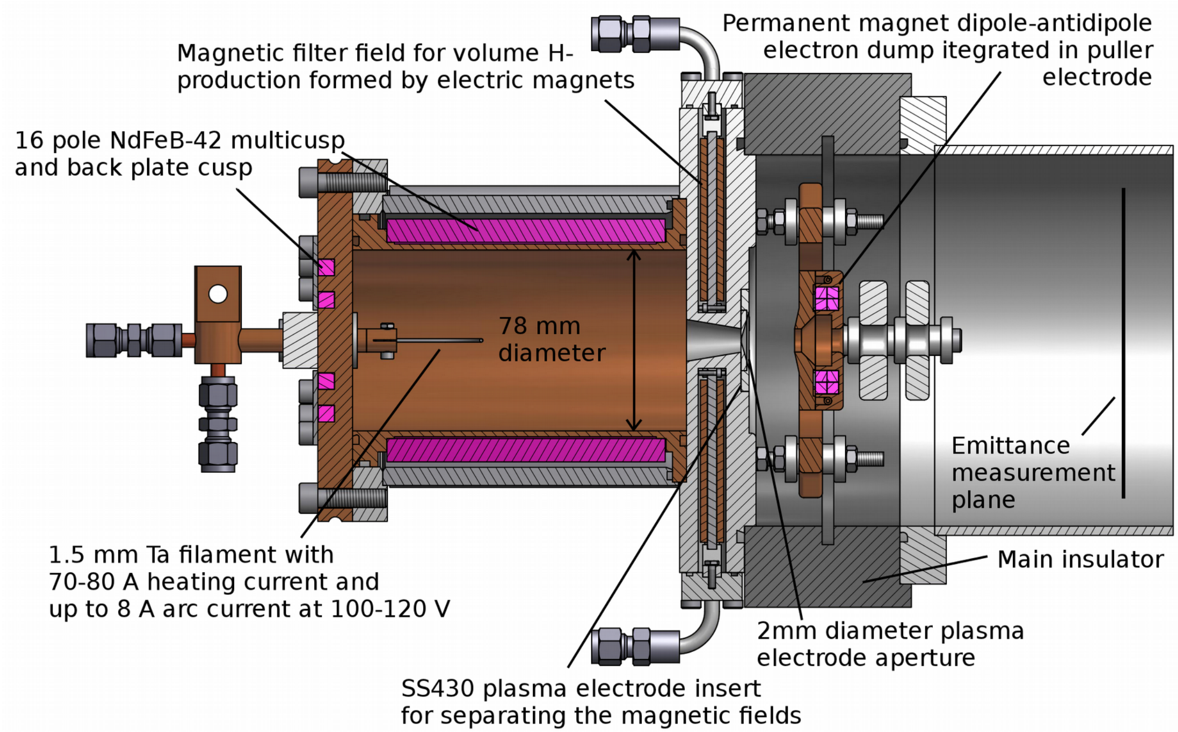


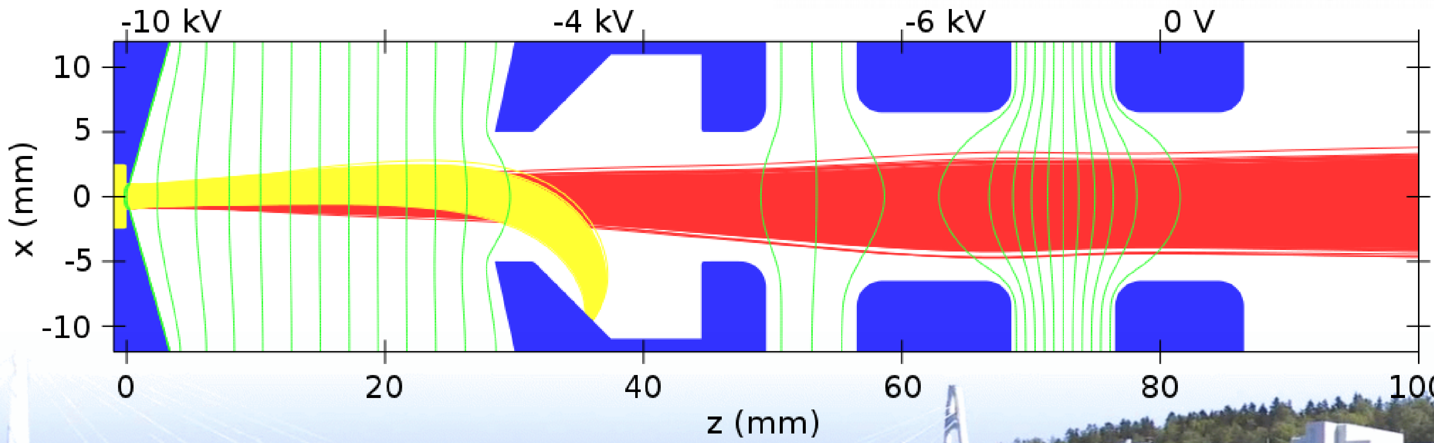



# JYFL PELLIS ion source

## Filament-driven $H^-$ ion source



# Effect of filter magnet

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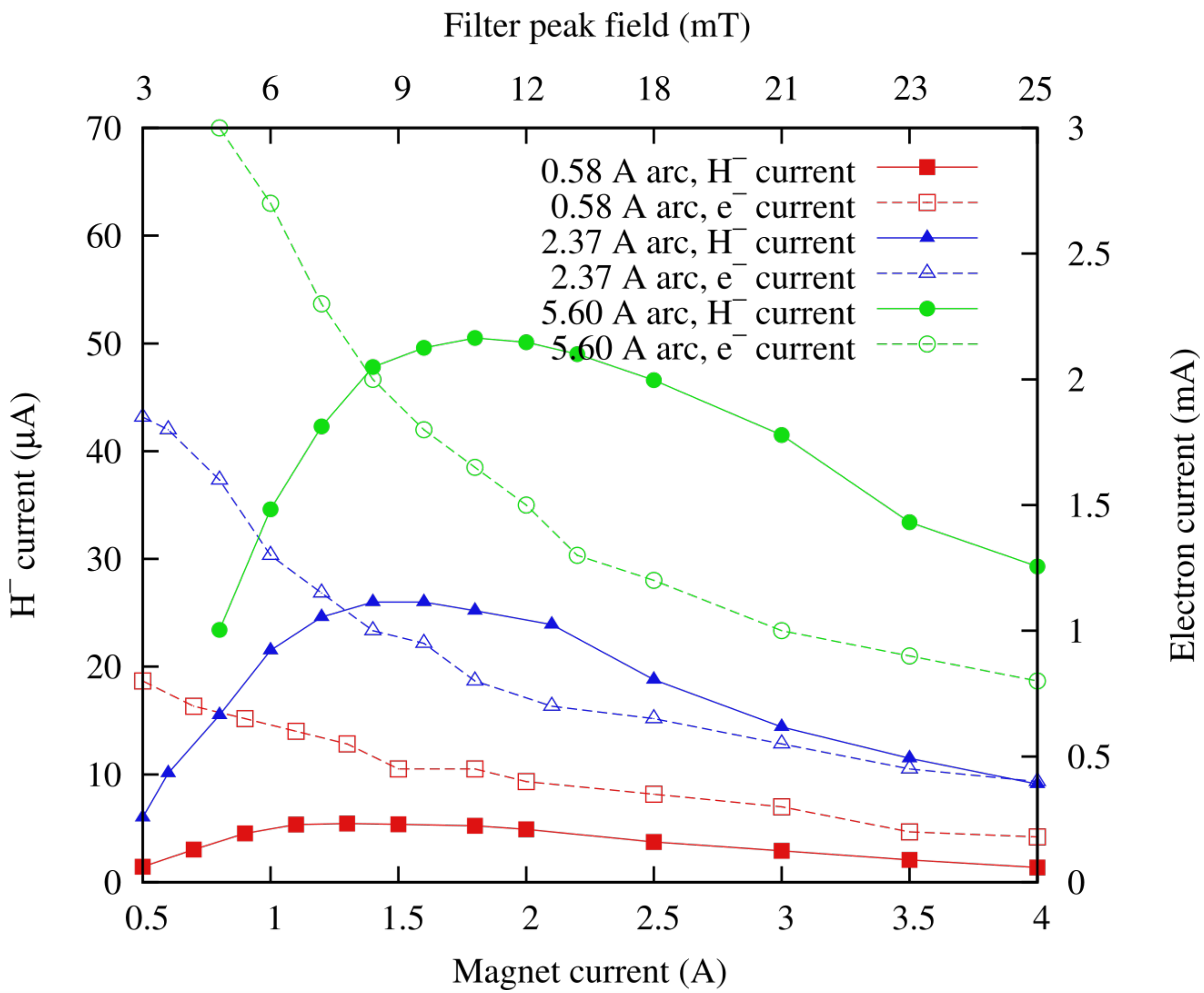
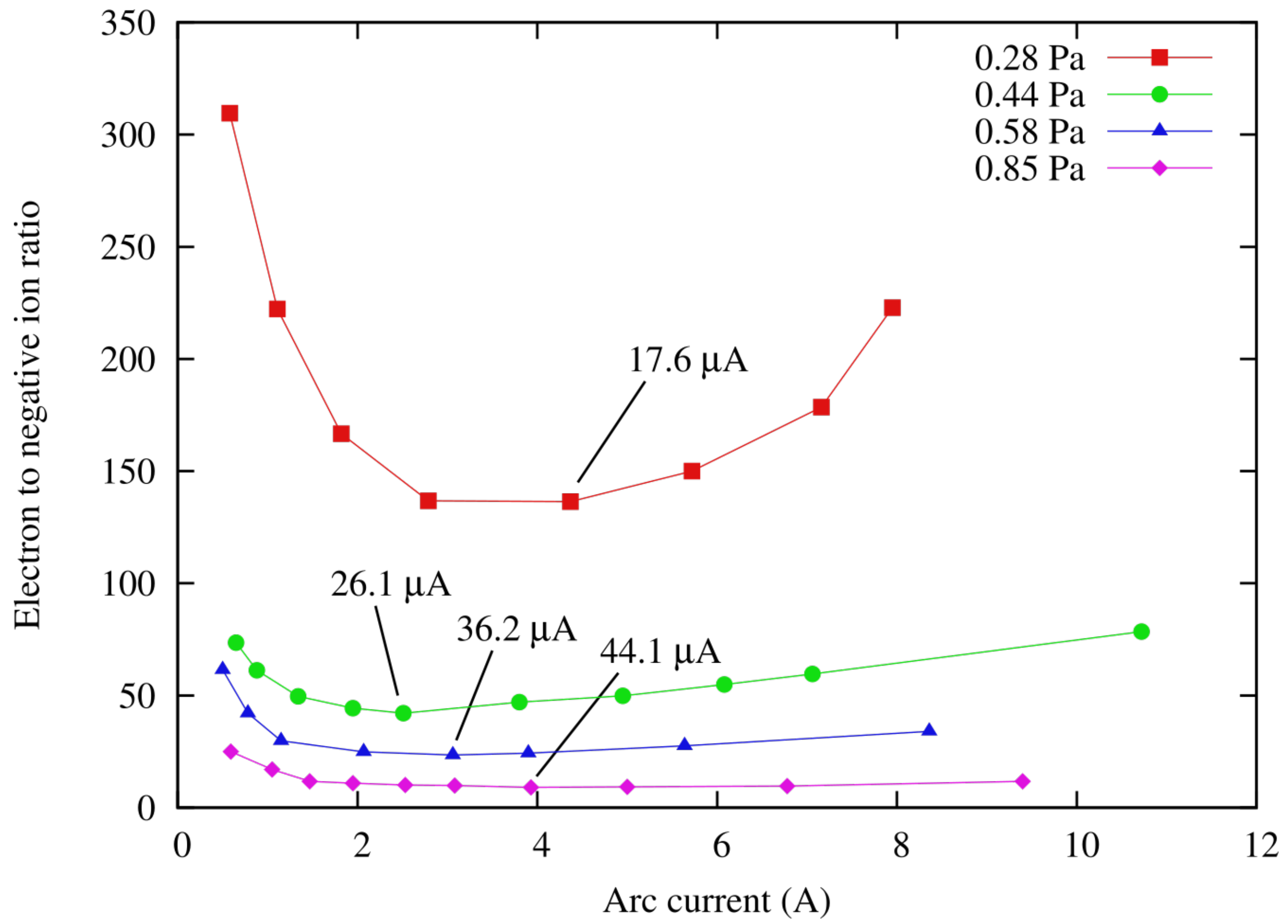
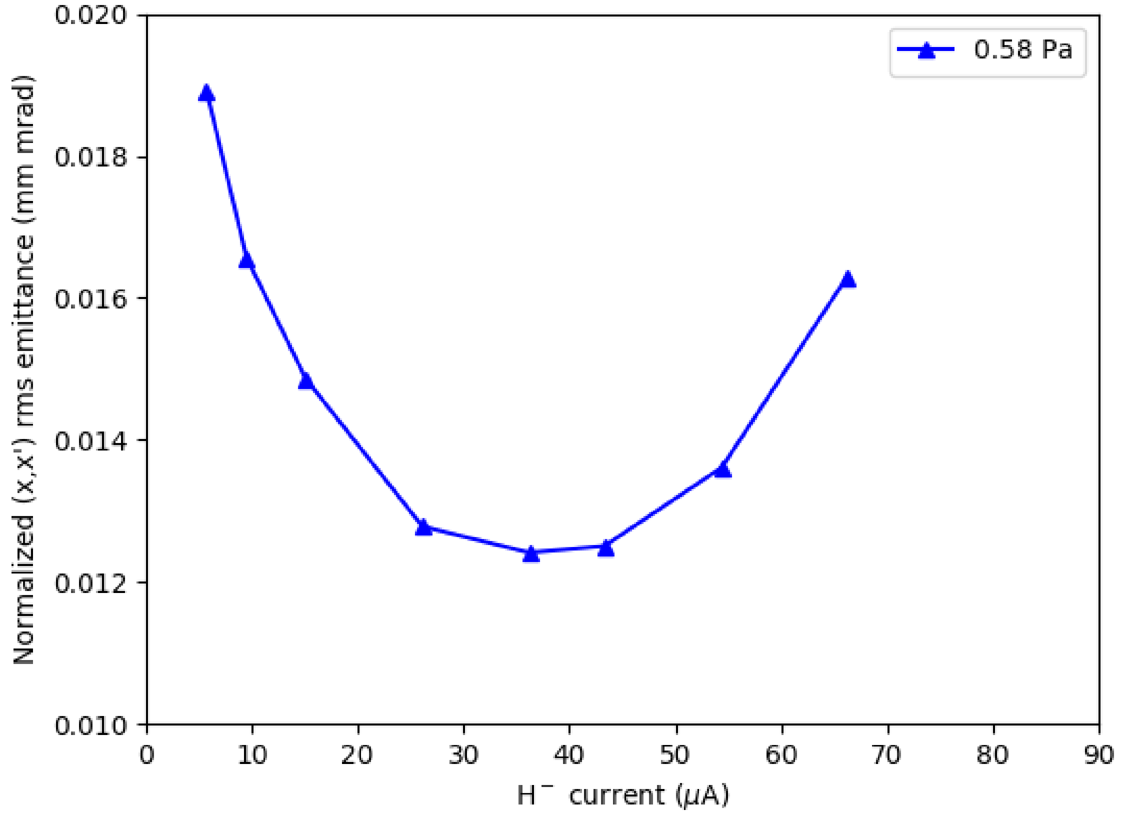


# Effect of pressure

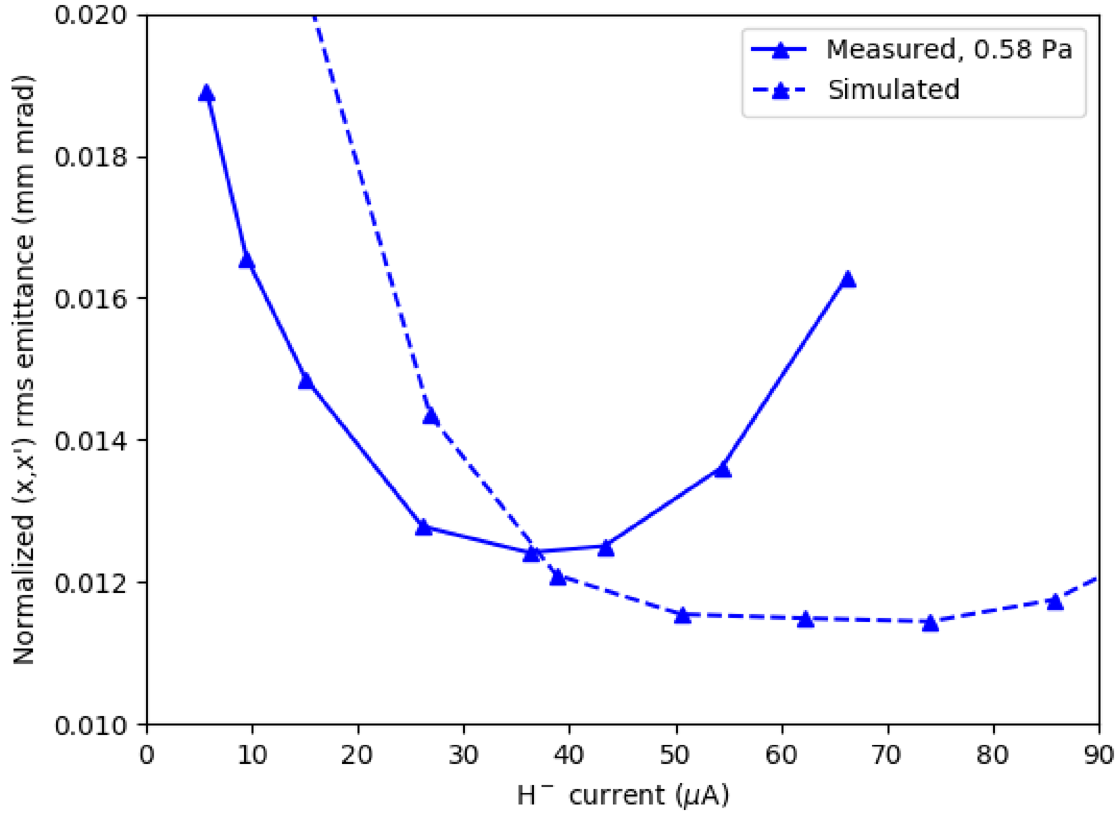


# Measured emittance curve




5 kV plasma to puller electrode voltage
Filter magnet at 1.8 A, e/$H^-$ ratio ~ 20

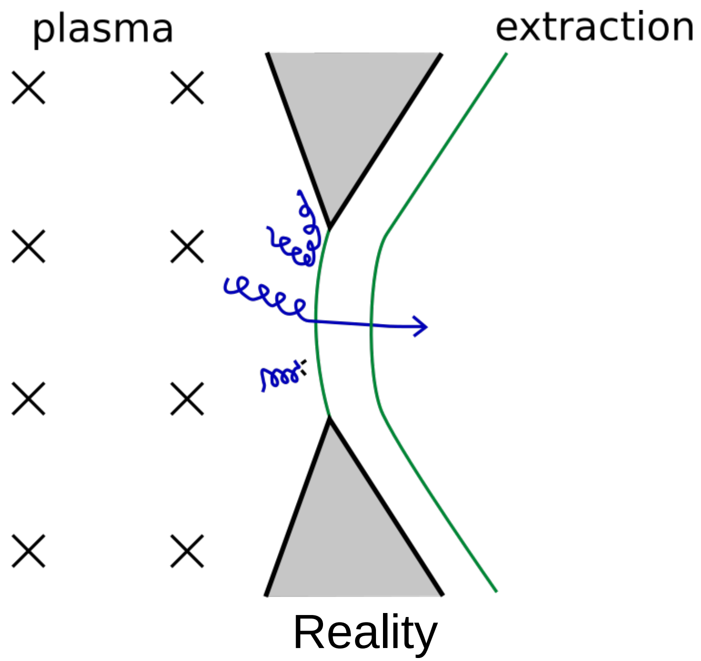
# Measured emittance curve

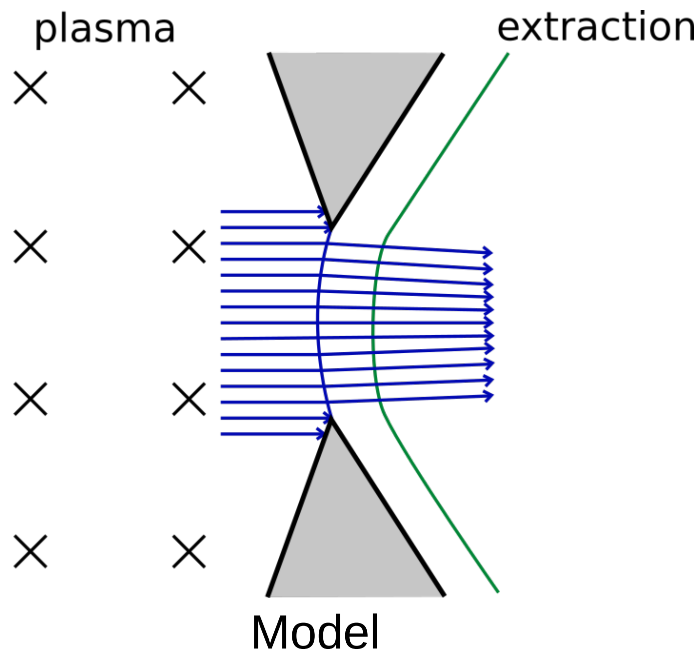



5 kV plasma to puller electrode voltage
Filter magnet at 1.8 A, e/$H^-$ ratio ~ 20

# Plasma model failure

Modelling of ions ~ok
For electrons, physical processes are not properly modelled



# Plasma model failure

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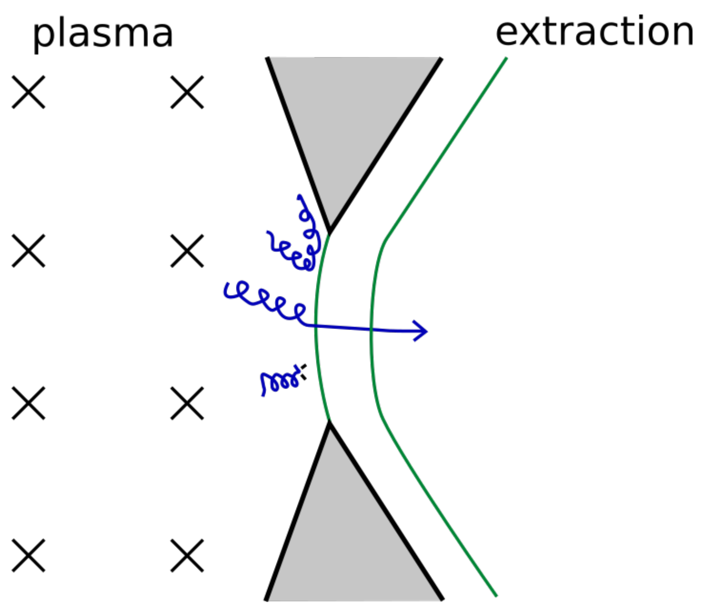
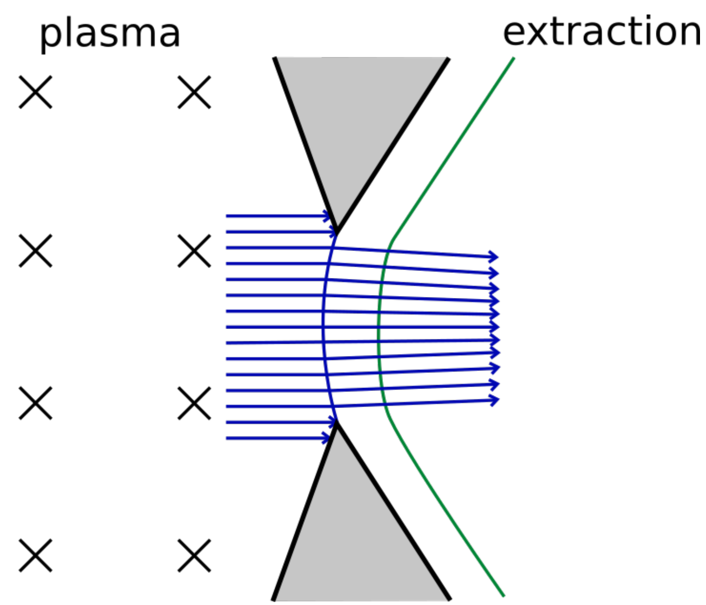
Modelling of ions ok
For electrons, physical processes are not properly modelled




Reality

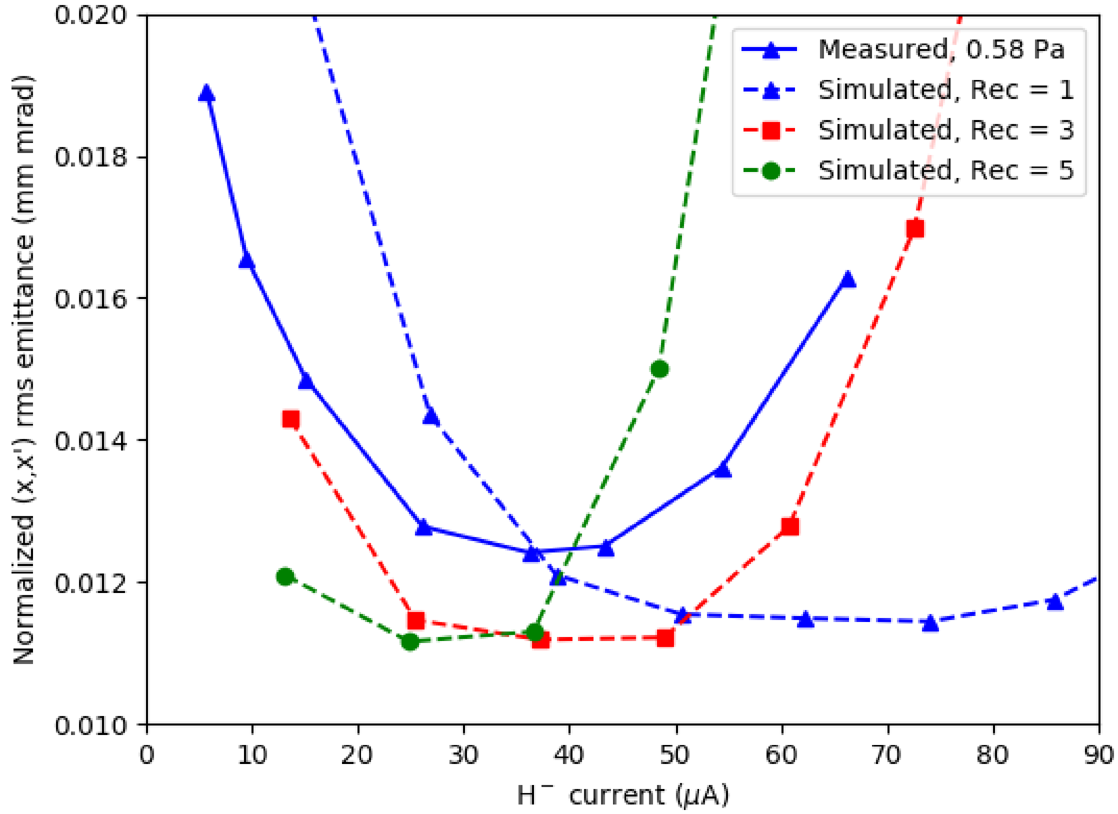
$$\rho_e \neq \frac{J_e}{v_e}$$




Electron density coefficient $R_{ec}$

Correction: $\rho_e = R_{ec} \frac{J_e}{v_e}$ at $\phi < 2\phi_P$

# Electron coefficient to match experiment




5 kV plasma to puller electrode voltage
Filter magnet at 1.8 A, e/$H^-$ ratio ~ 20

# $H^-$ equal current

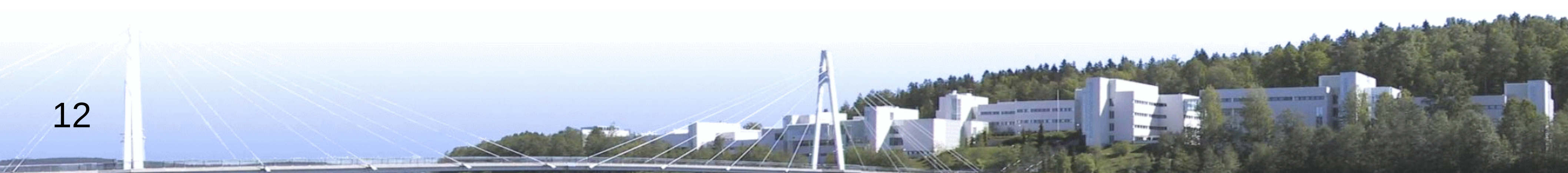
$$\rho = \frac{J}{v} \qquad v = \sqrt{\frac{2qU}{m}}$$

$$\rho_{\text{tot}} = \rho_{H^-} + \rho_e = \frac{J_{H^-}}{v_{H^-}} + \frac{J_e}{v_e} \qquad J_e = R_{ec} J_e^* = R_{ec} R_{ei} J_{H^-}$$

$$\rho_{\text{tot}} \propto J_{H^-} \left(1 + R_{ec} R_{ei} \sqrt{m_e / m_{H^-}}\right)$$

$$\sqrt{m_{H^-} / m_e} \approx 43$$

$$I_{\text{eq}} = I_{H^-} + R_{ec} I_e^* \sqrt{m_e / m_{H^-}}$$



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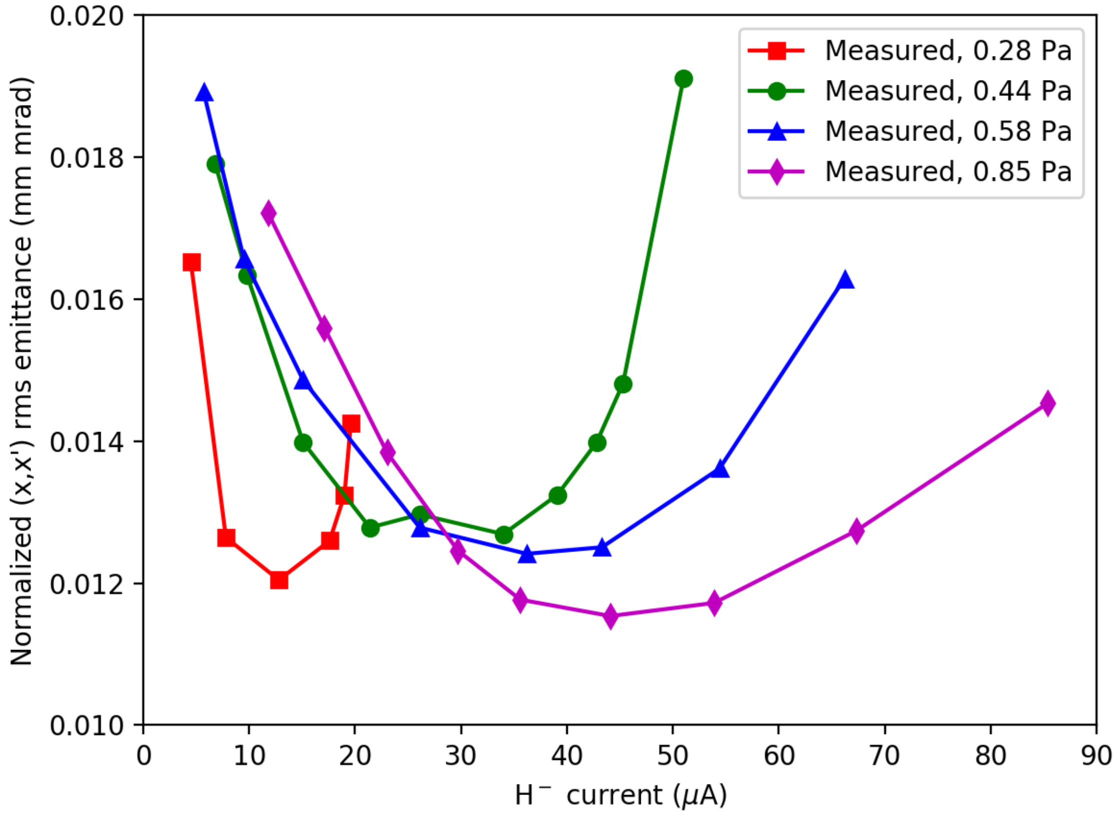
# Emittance measurements




5 kV plasma to puller electrode voltage
Filter magnet at 1.8 A

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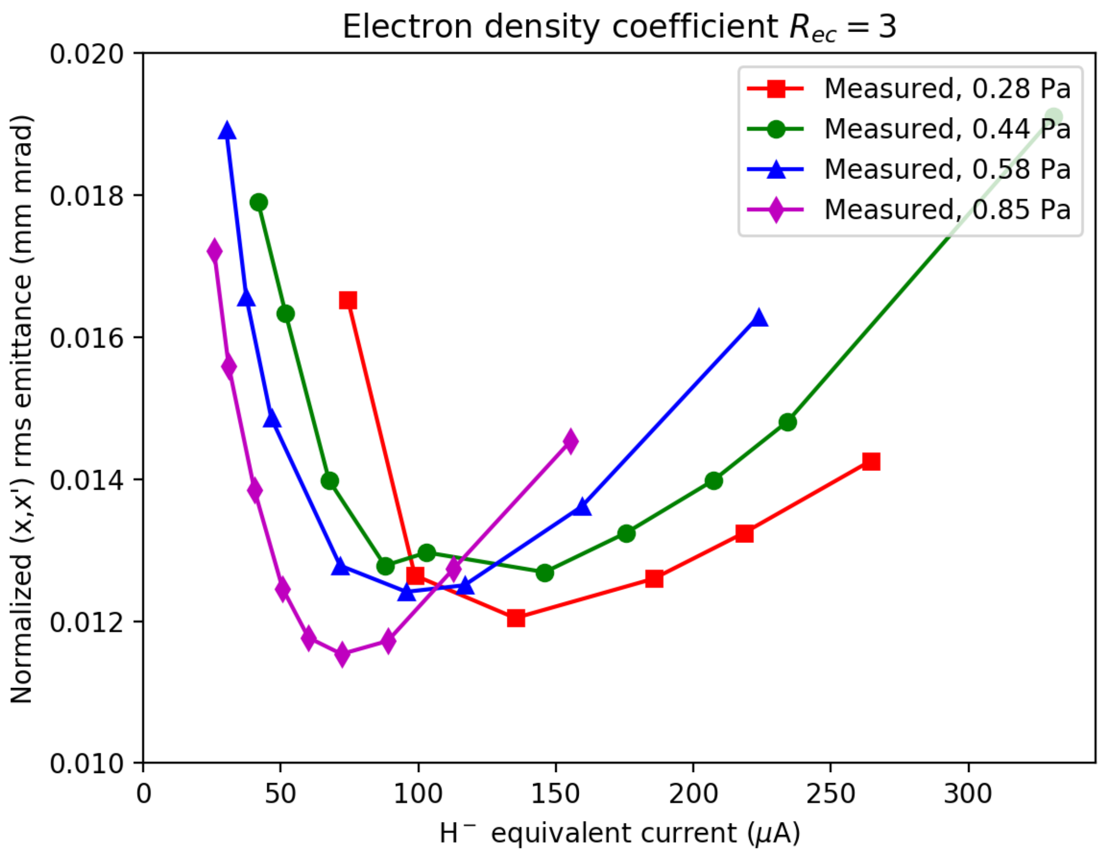
# Emittance measurements

$$I_{eq} = I_{H^-} + R_{ec} I_e^* \sqrt{m_e / m_{H^-}}$$

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# Emittance measurements

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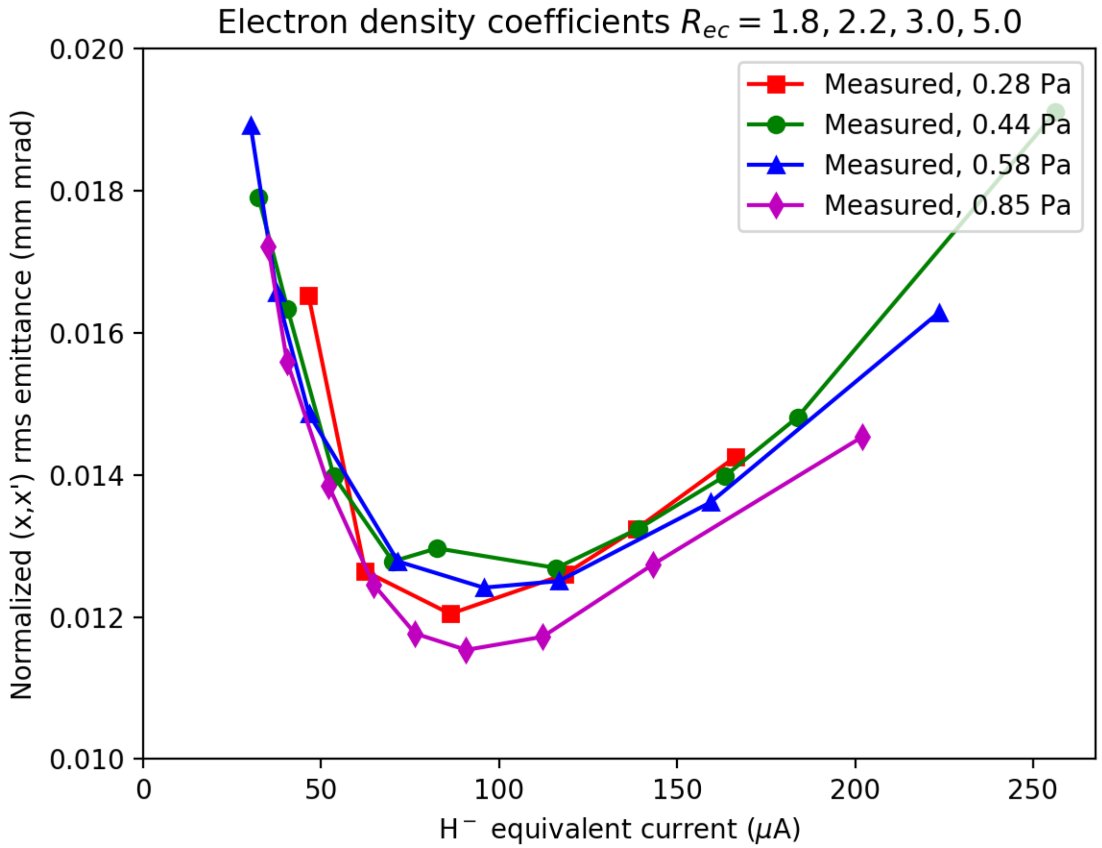
$$I_{eq} = I_{H^-} + R_{ec} I_e^* \sqrt{m_e / m_{H^-}}$$

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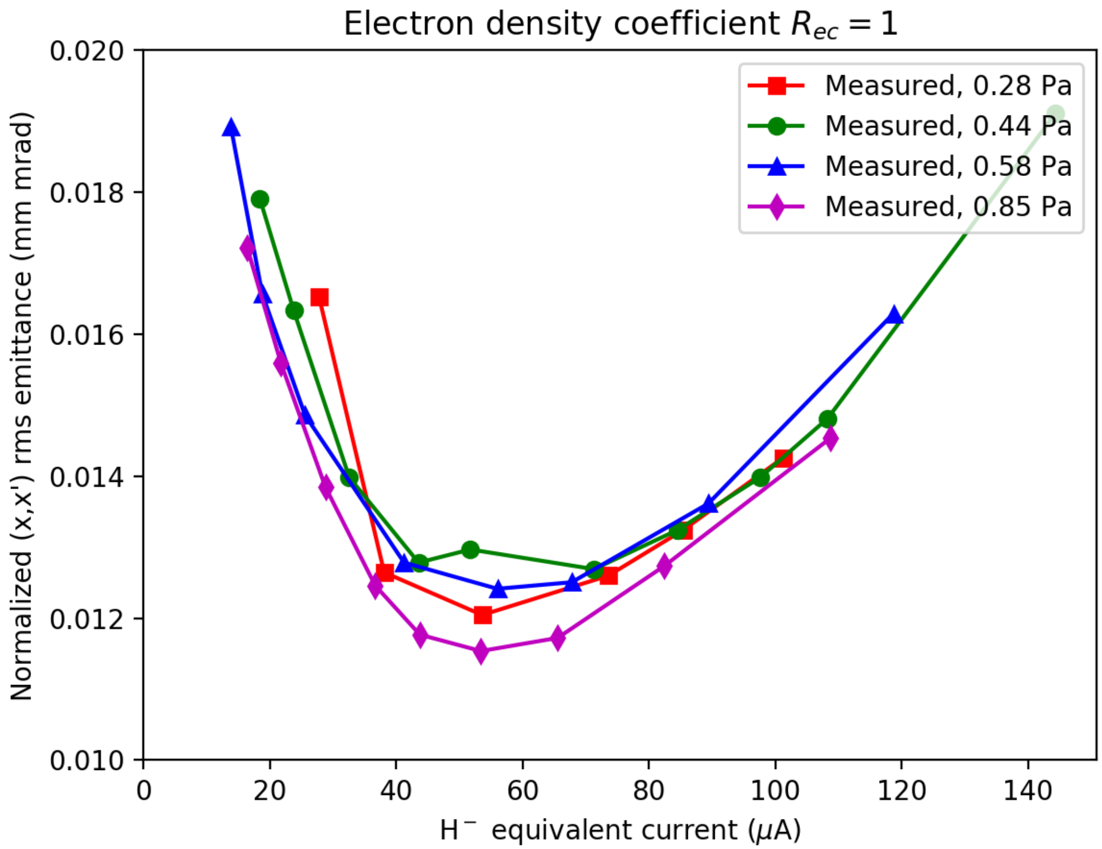


5 kV plasma to puller electrode voltage
Filter magnet at 1.8 A

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# Total effect on space charge

$$\rho = \frac{J}{v} \qquad v = \sqrt{\frac{2qU}{m}}$$

$$\rho_{\text{tot}} = \rho_{H^-} + \rho_e = \frac{J_{H^-}}{v_{H^-}} + \frac{J_e}{v_e} \qquad J_e = R_{ec} J_e^* = R_{ec} R_{ei} J_{H^-}$$

$$\rho_{\text{tot}} \propto J_{H^-} \left(1 + R_{ec} R_{ei} \sqrt{m_e / m_{H^-}}\right)$$

$$\sqrt{m_{H^-} / m_e} \approx 43$$

$$I_{\text{eq}} = I_{H^-} + R_{ec} I_e^* \sqrt{m_e / m_{H^-}}$$

$$R_{\text{tot}} = \frac{\rho_{\text{tot}}}{\rho_{\text{tot}}^*} = \frac{J_{H^-}\left(1 + R_{ec} R_{ei} \sqrt{m_e / m_{H^-}}\right)}{J_{H^-}\left(1 + R_{ei} \sqrt{m_e / m_{H^-}}\right)}$$

$$R_{ei} = 20, R_{ec} = 3 \rightarrow R_{\text{tot}} = 1.6$$

# Stripping?

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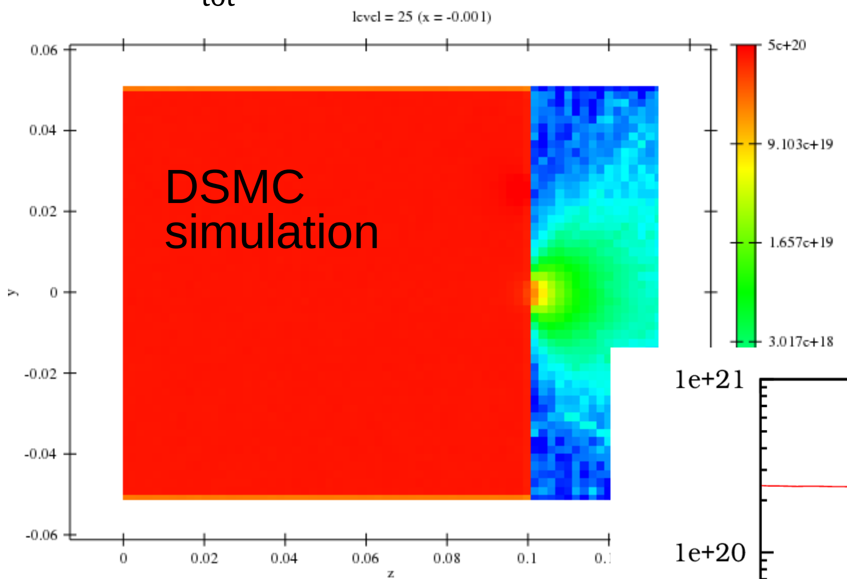
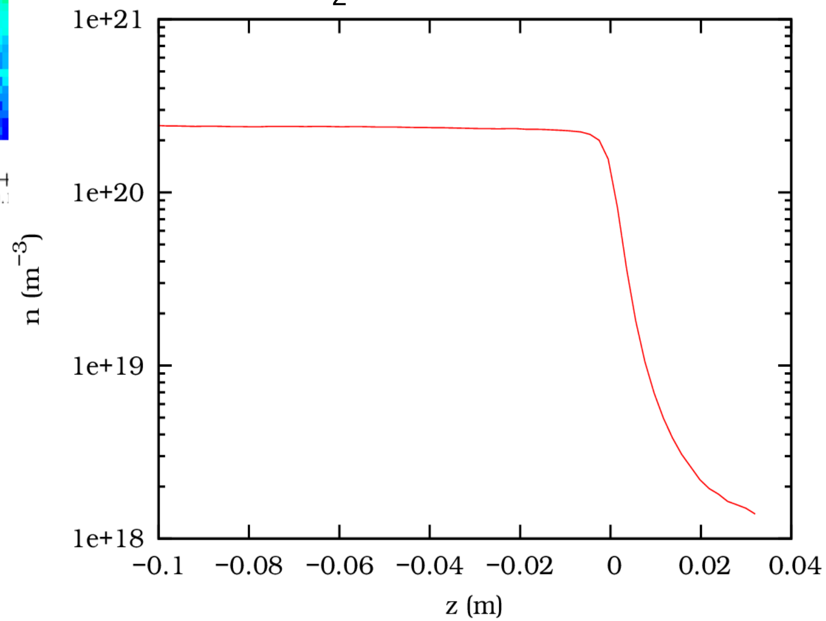
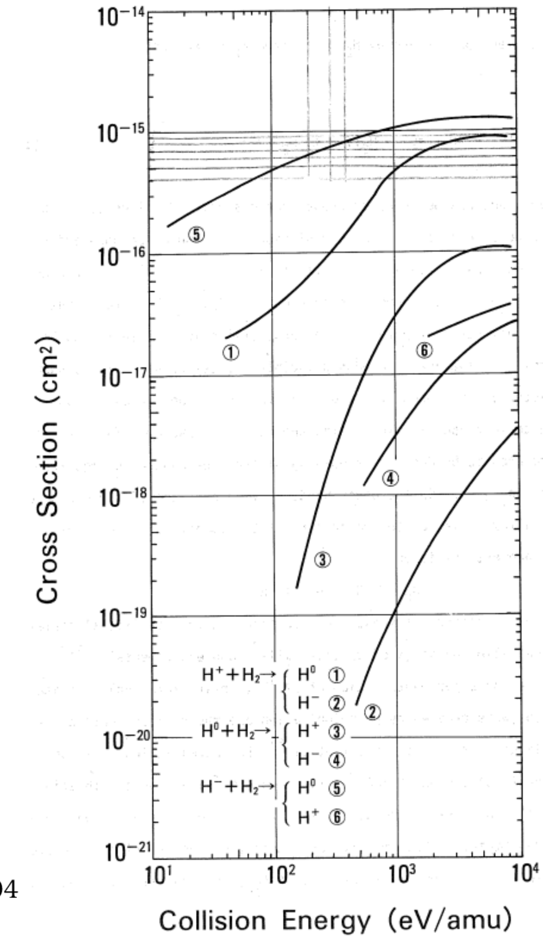
Why $R_{tot} = 1.6$ ?




$H_2$ density on axis



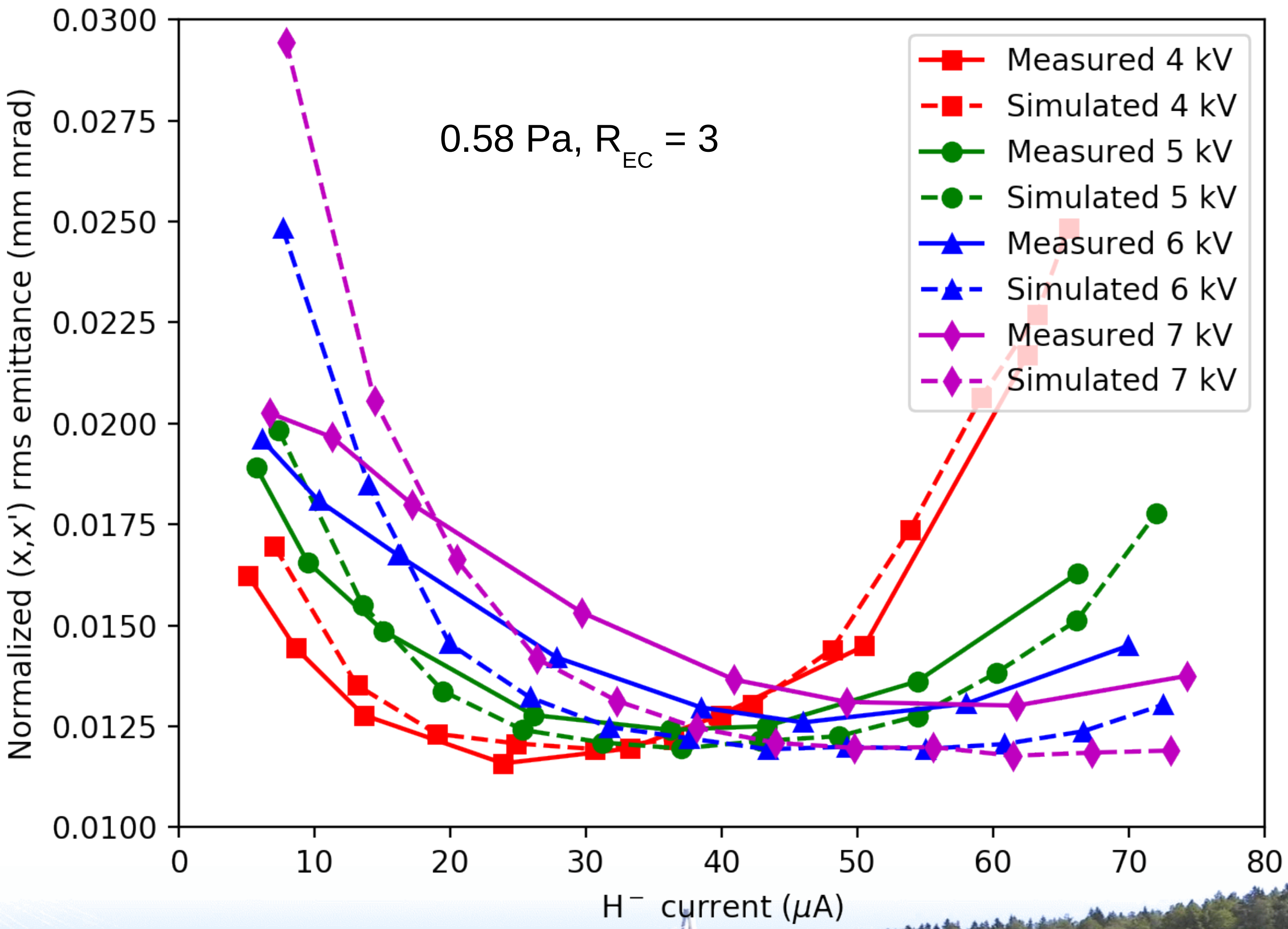

H. Tawara, “Atomic data involving hydrogens relevant to edge plasmas”, IPPJ-AM-46, 1986

$P = 0.5 - 0\,\mathrm{Pa}$

$z = 10\,\mathrm{mm}$

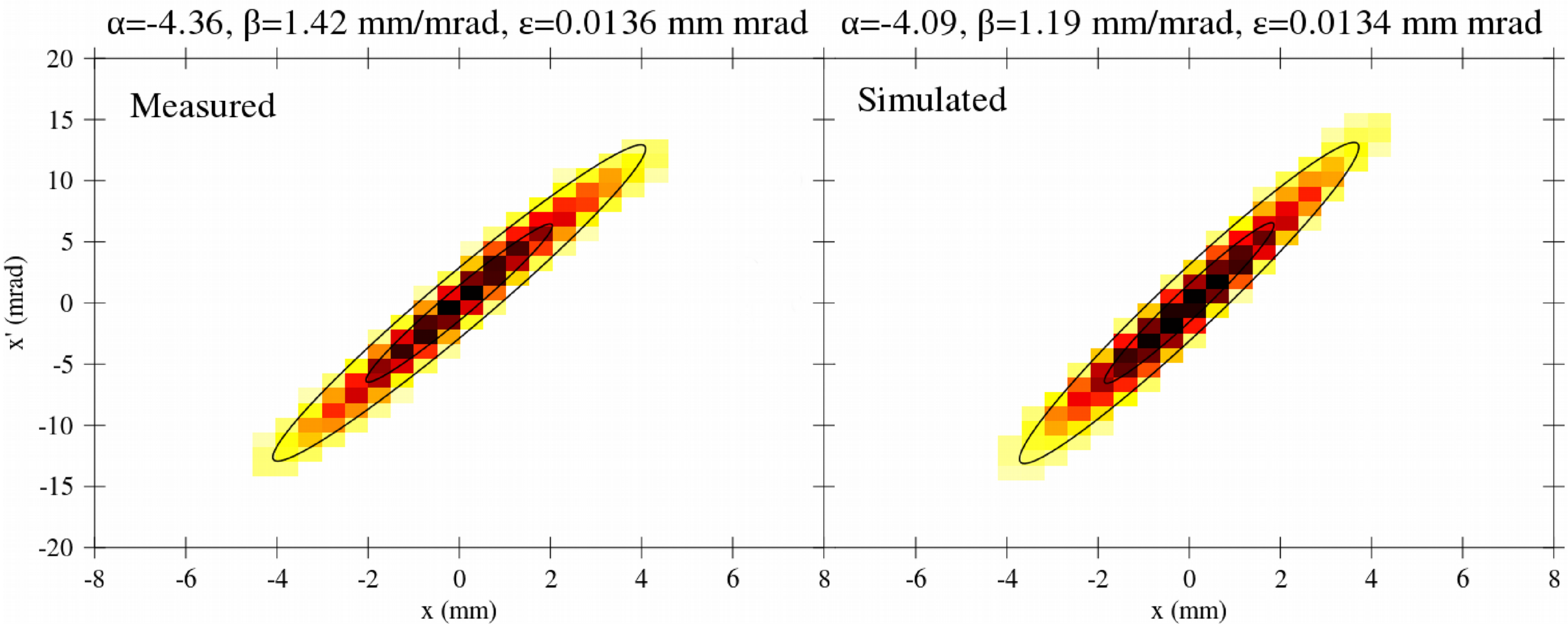
$I/I^* = \exp(n\sigma z) = 1.13$

# Emittance measurements



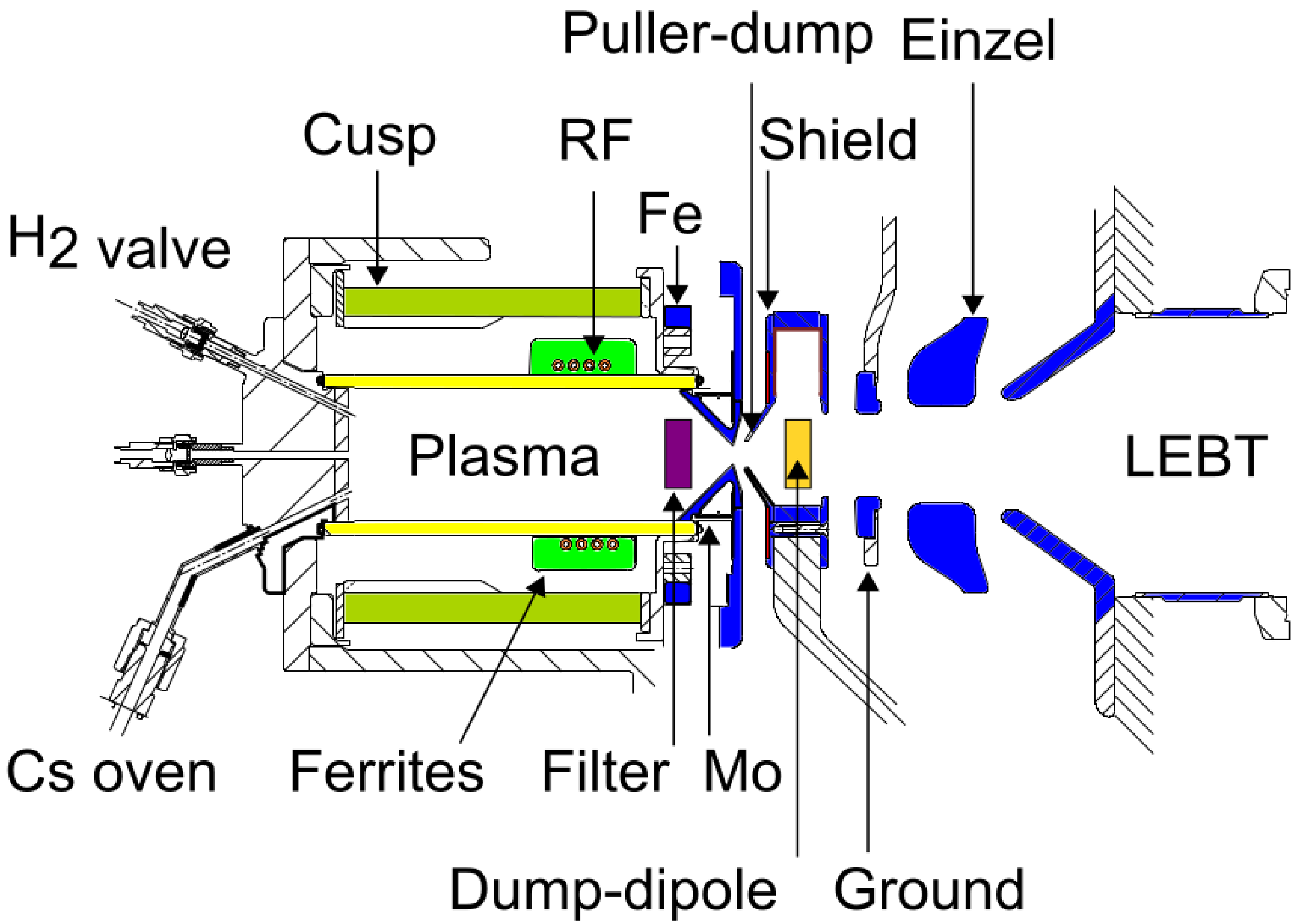
# Phase space distribution

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



# CERN Linac4

Striving for 50 mA $H^-$ at 45 keV with 0.25 mm mrad rms-emittance normalized



# CERN Linac4 paper

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Nuclear Inst. and Methods in Physics Research, A 904 (2018) 179–187

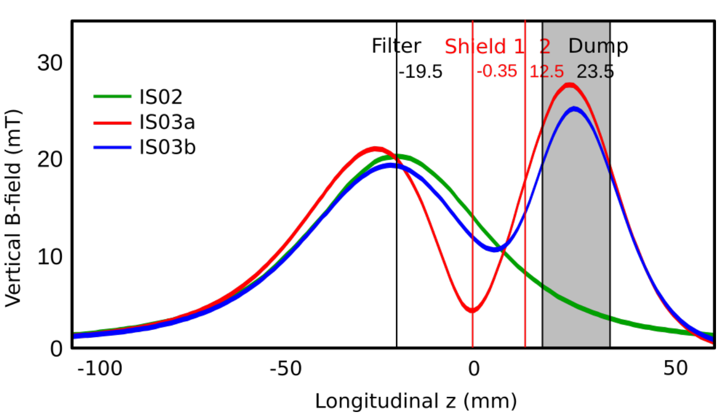
Contents lists available at ScienceDirect

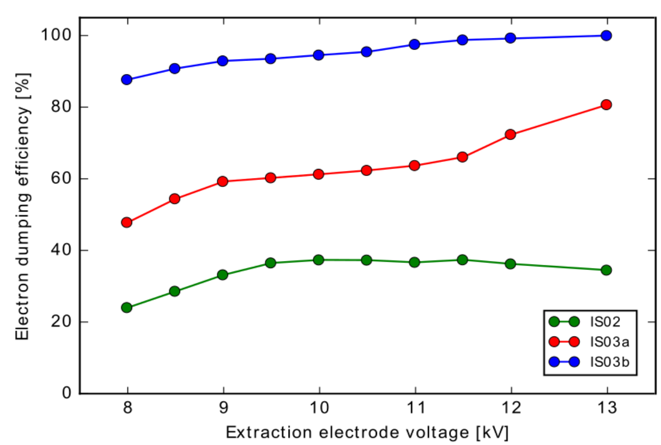
Nuclear Inst. and Methods in Physics Research, A

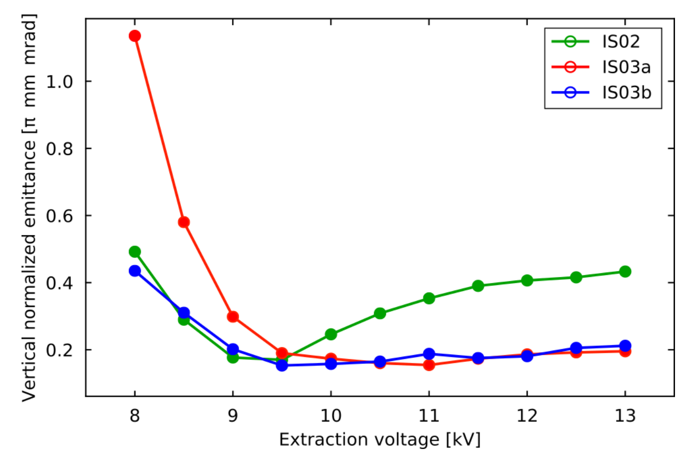
journal homepage: www.elsevier.com/locate/nima

## H⁻ extraction systems for CERN’s Linac4 H⁻ ion source

D.A. Fink [a,*], T. Kalvas [b], J. Lettry [a], Ø. Midttun [c], D. Noll [a]

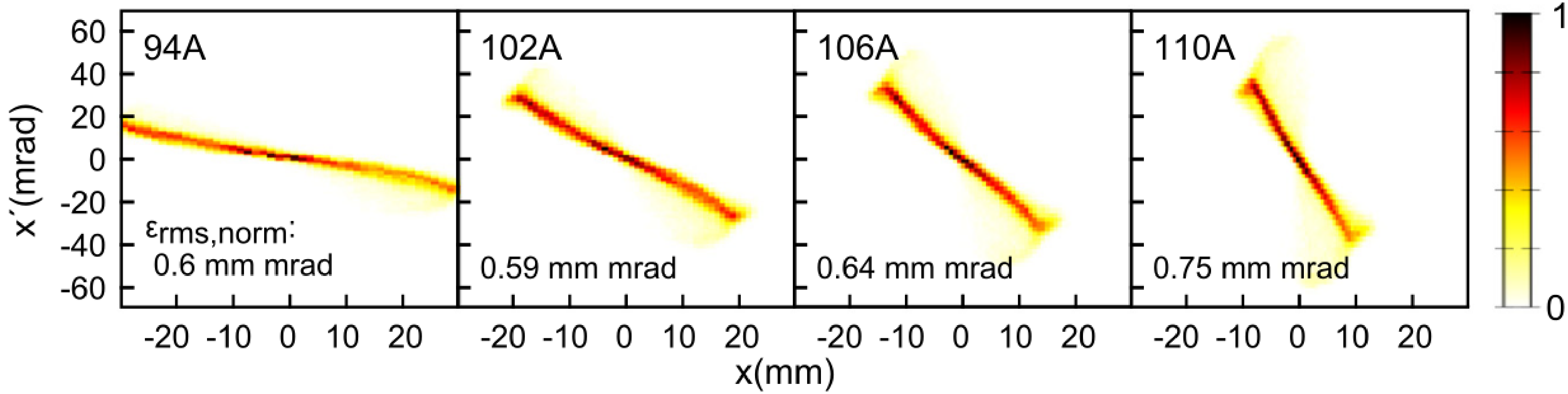


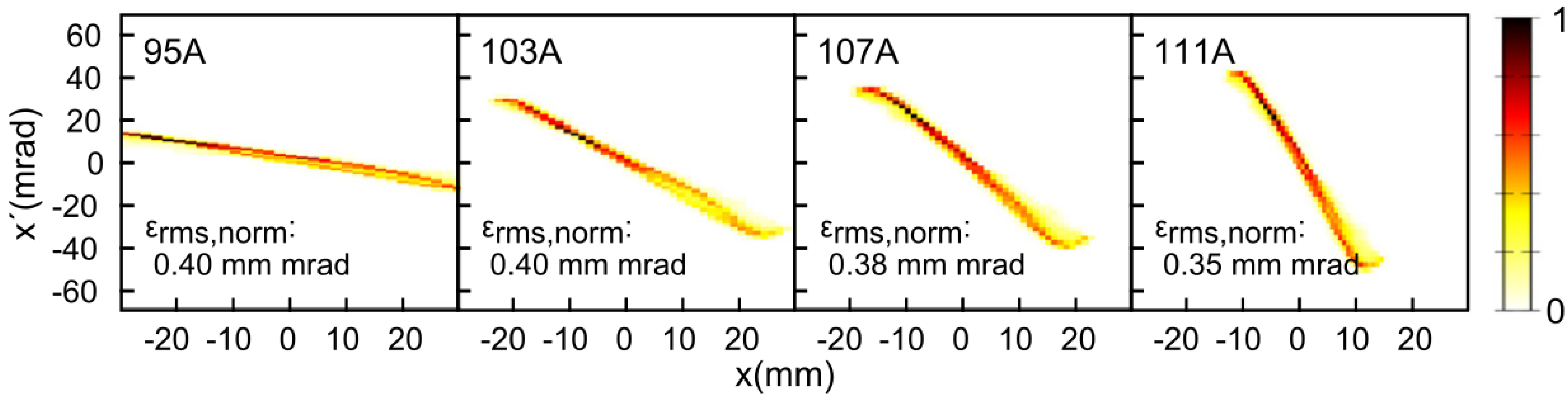




# Emittance comparison

Measurements Linac4 teststand:




Simulations IBSimu:




ISO03b, 50 mA $H^-$ ⌀6.5 mm aperture

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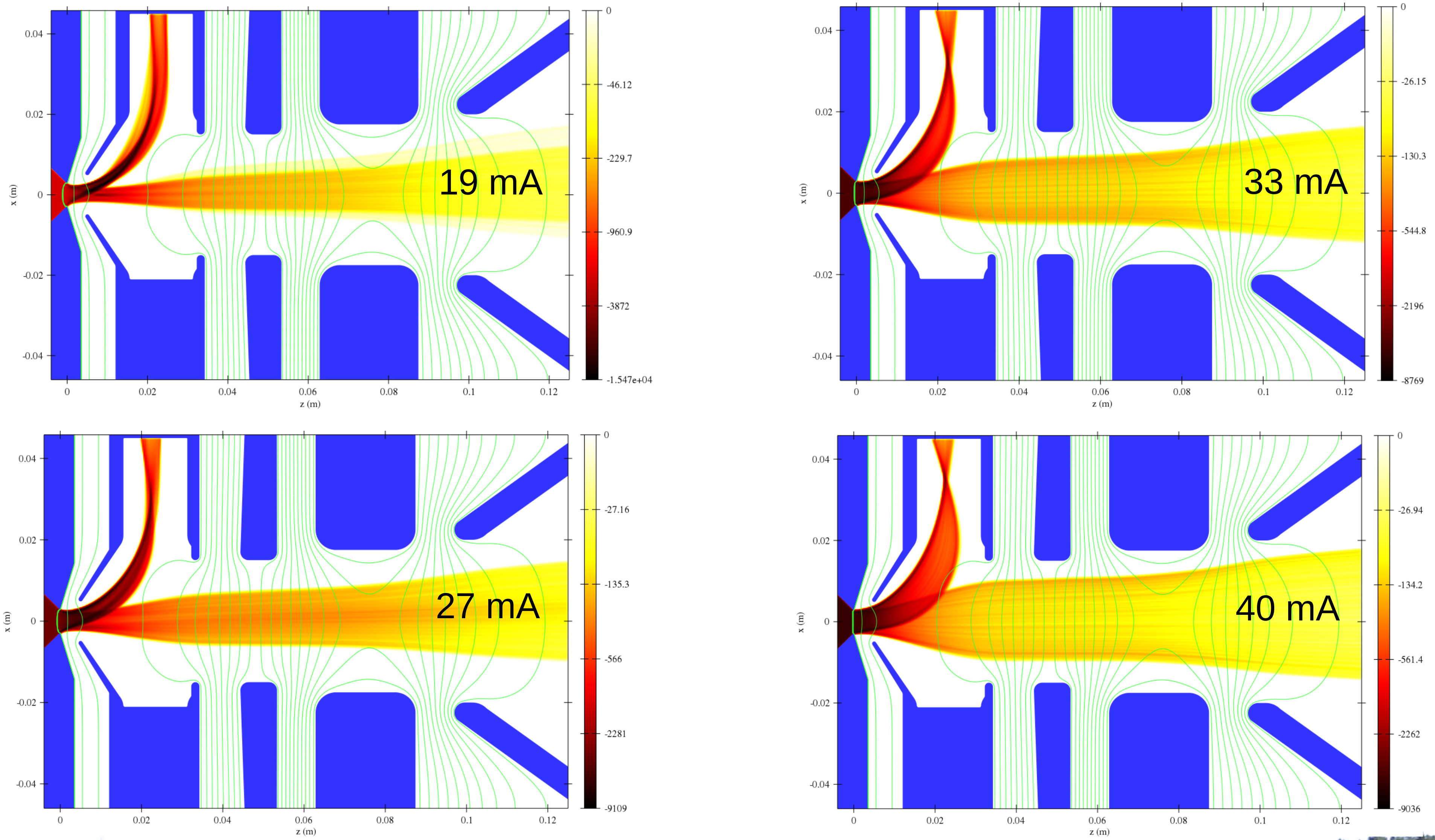
# Contributions to emittance



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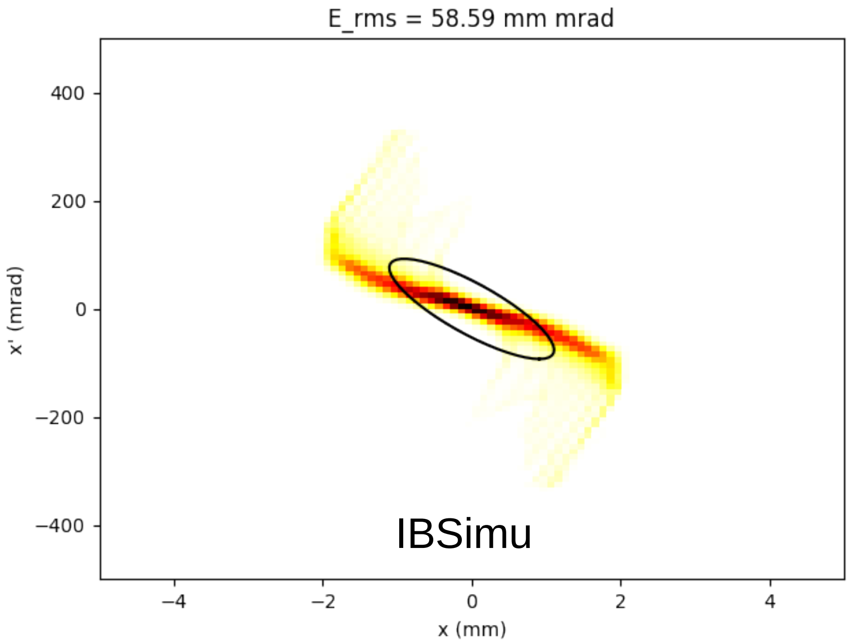
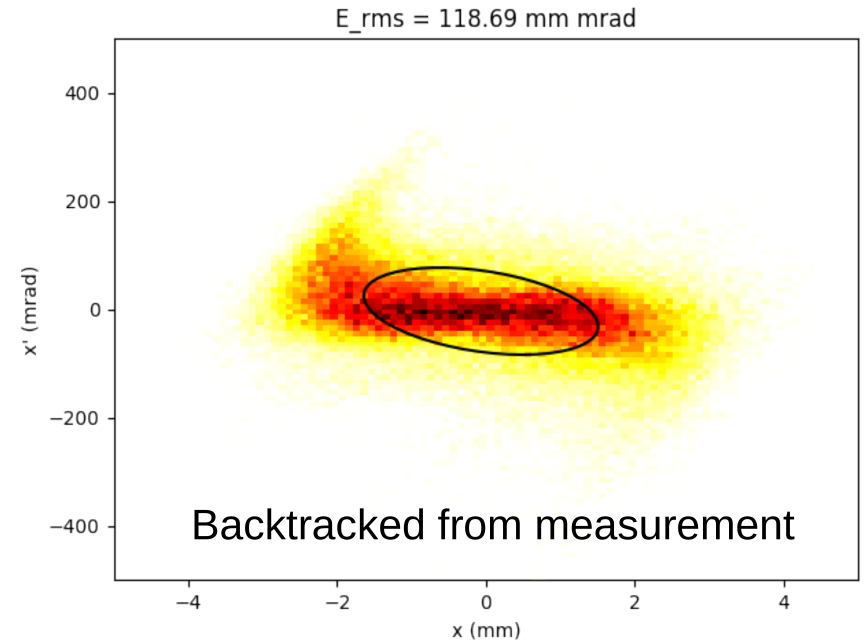
# Backtracked phase space at z=3 mm

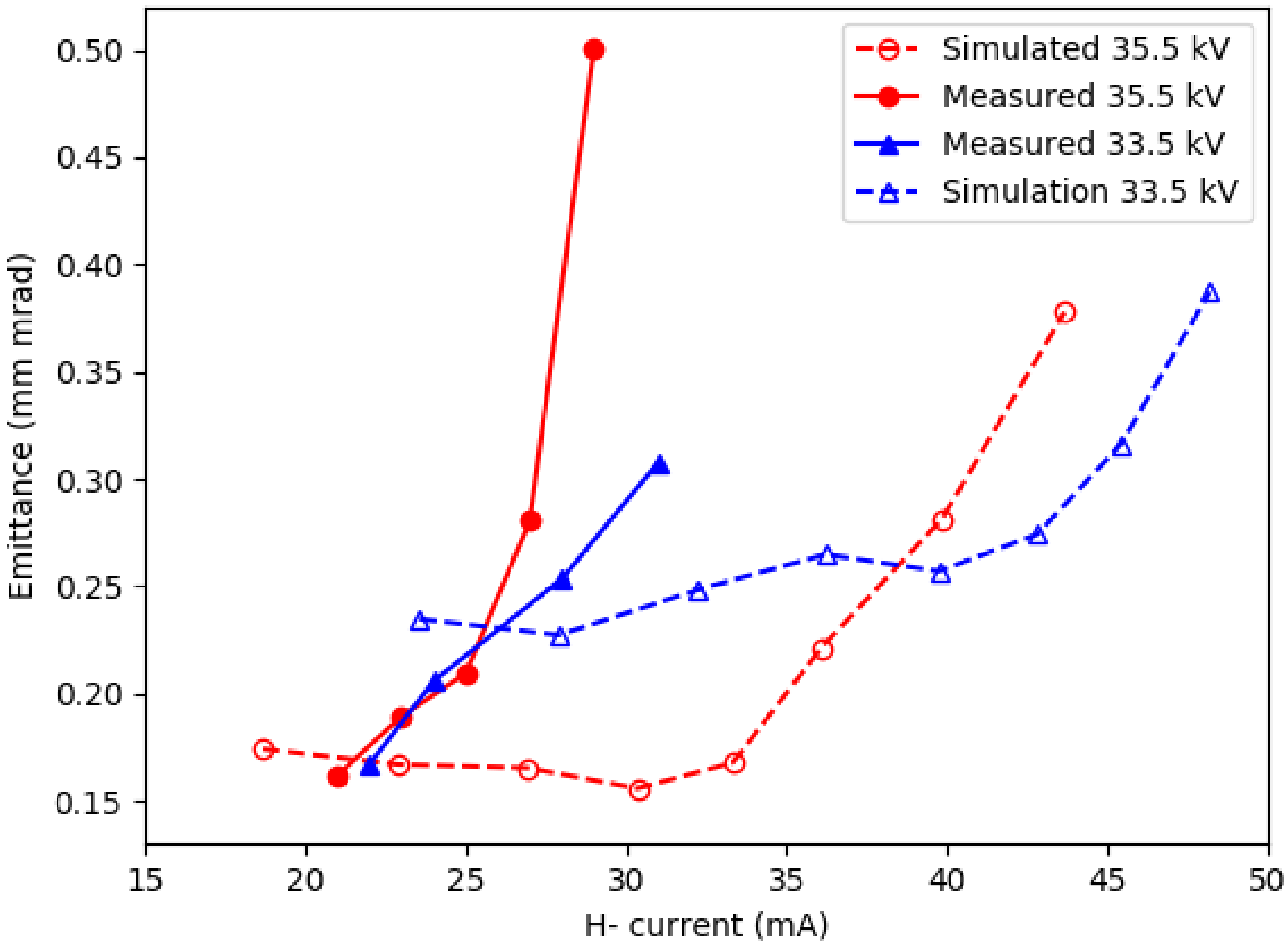
Uncesiated IS03c: 20 mA $H^-$, $e^-/H^-$ ratio 15–20



# Emittance curves

Beam emittance as a function of current for IS03b ⌀5.5 aperture



# Backtracking of measured distributions

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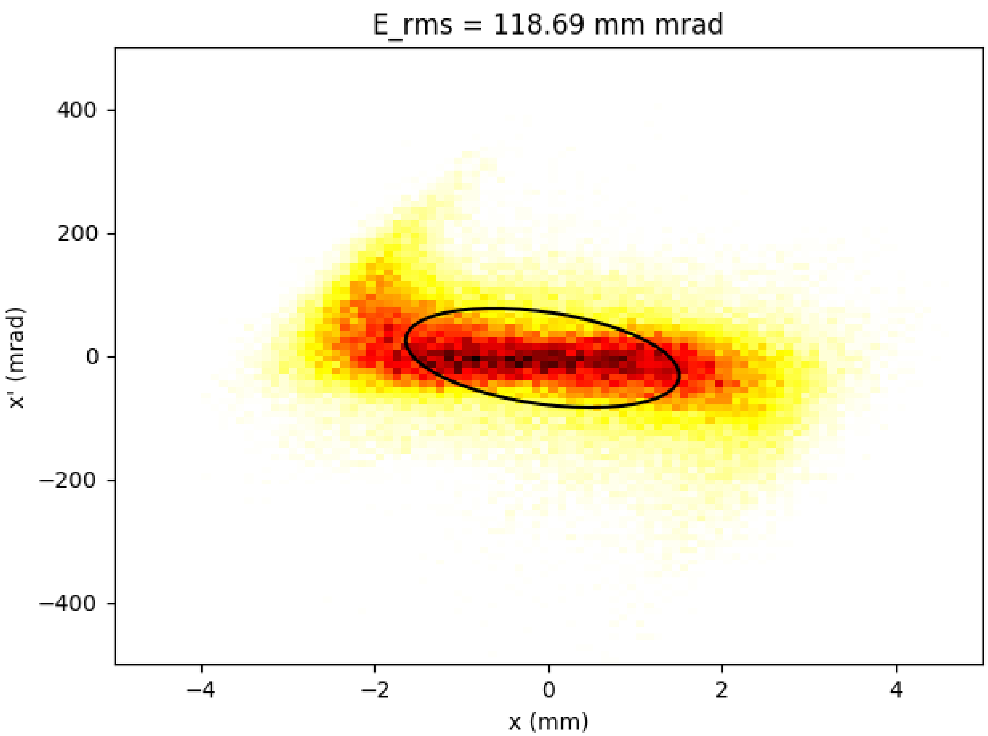
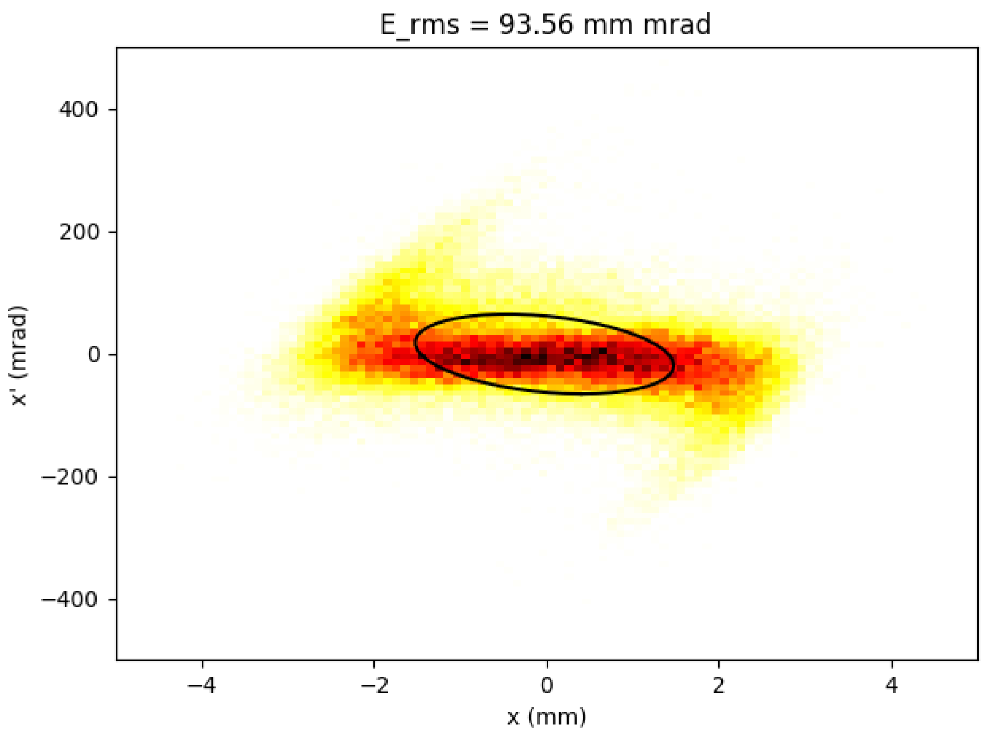
CERN Linac4 IS03c: phase space data backtracked to z=3 mm



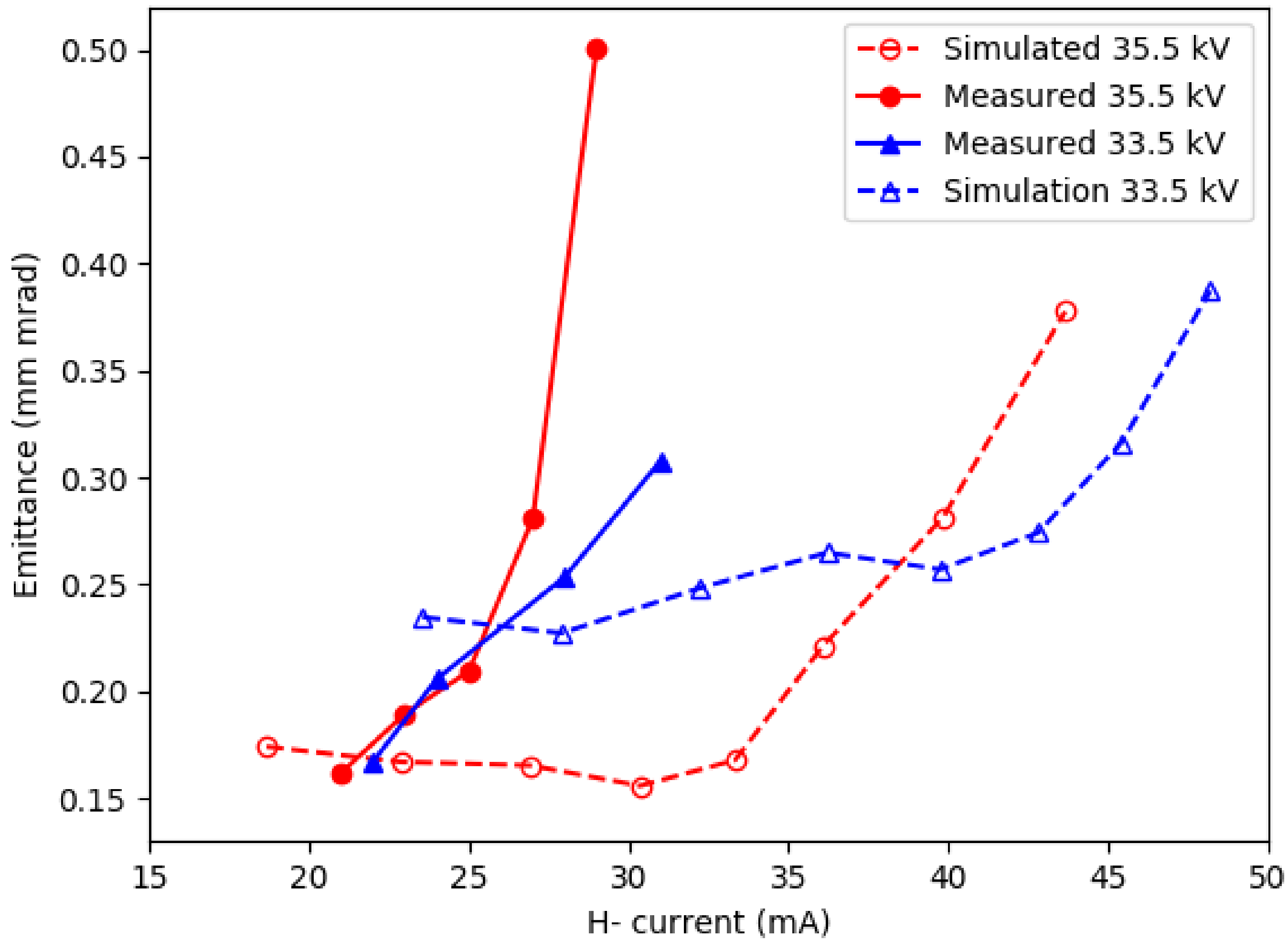

Uncesiated source: 20 mA $H^-$
$e^-/H^-$ ratio 15

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

D. Noll, "Linac4 source extraction and LEBT study", ICIS2017

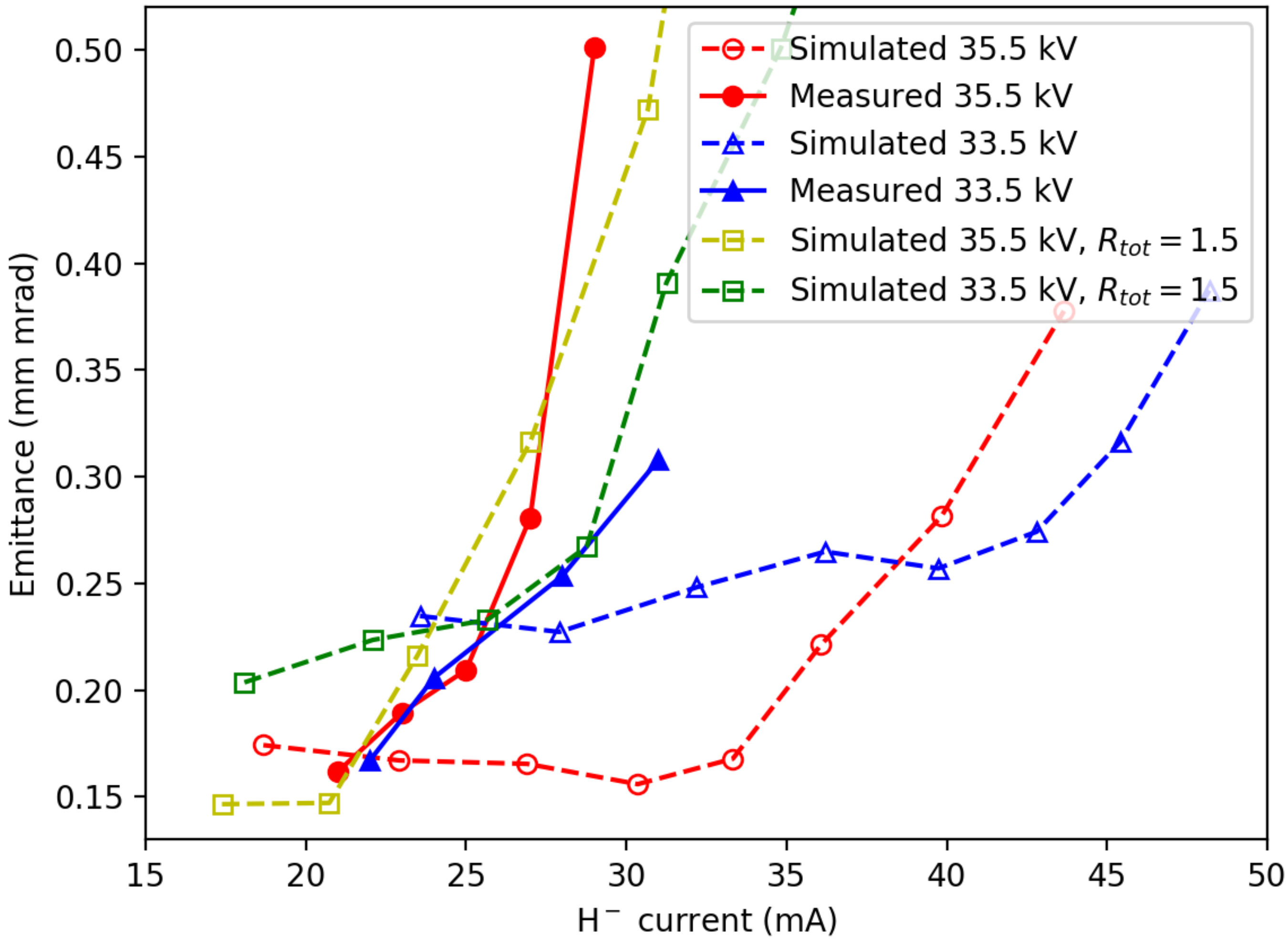
# Emittance curves

Beam emittance as a function of current for IS03b ⌀5.5 aperture



# Emittance curves

Emittance curves for total space charge coefficient $R_{tot}$=1.5, Rei = 2.5 ➔ Rec = 10

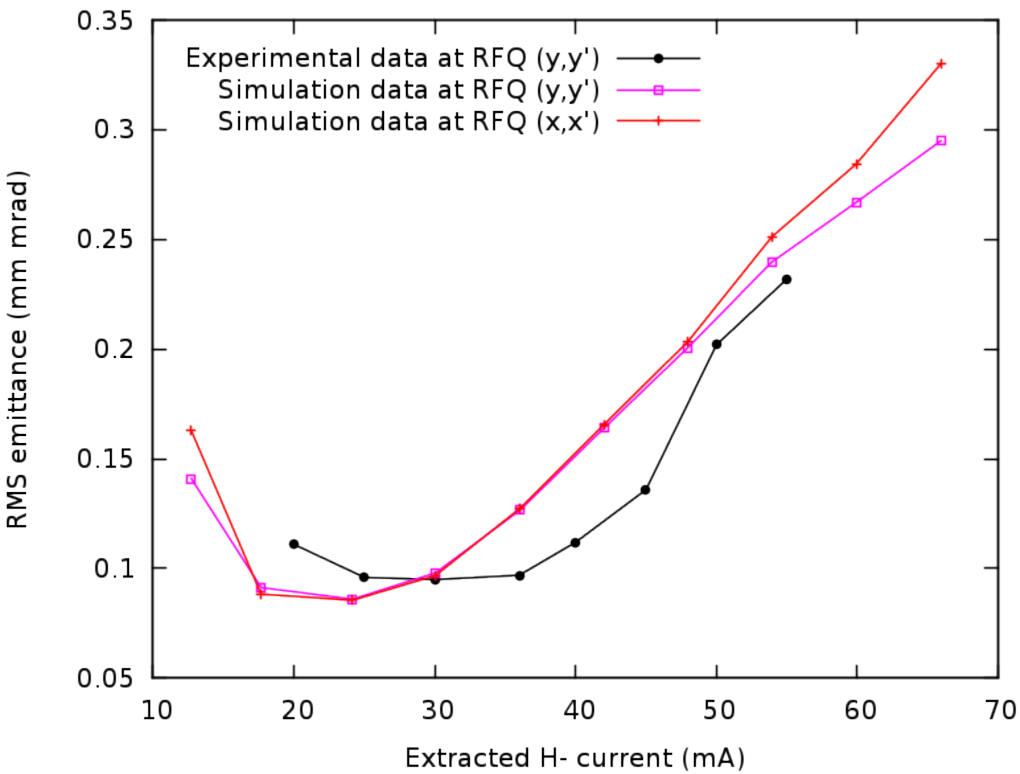


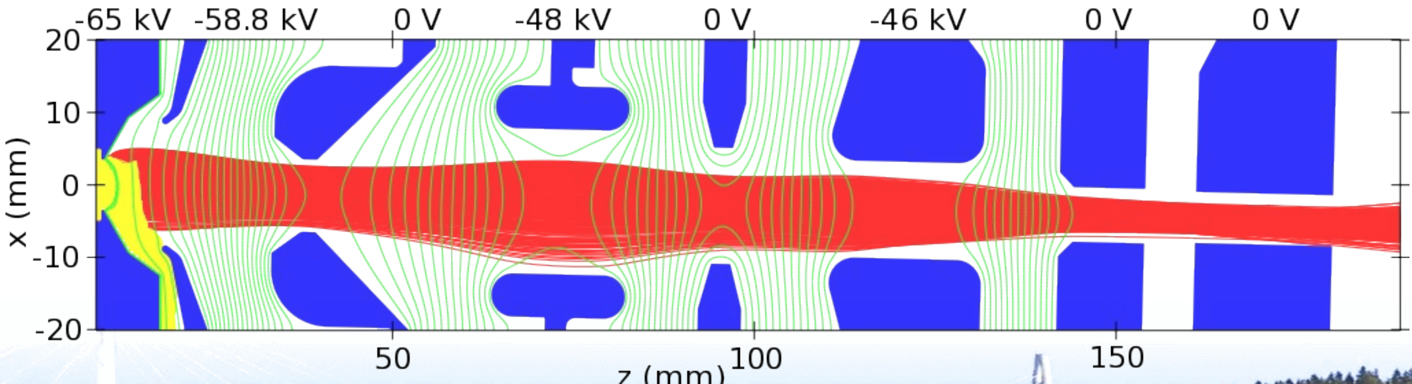
# Emittance comparison for SNS



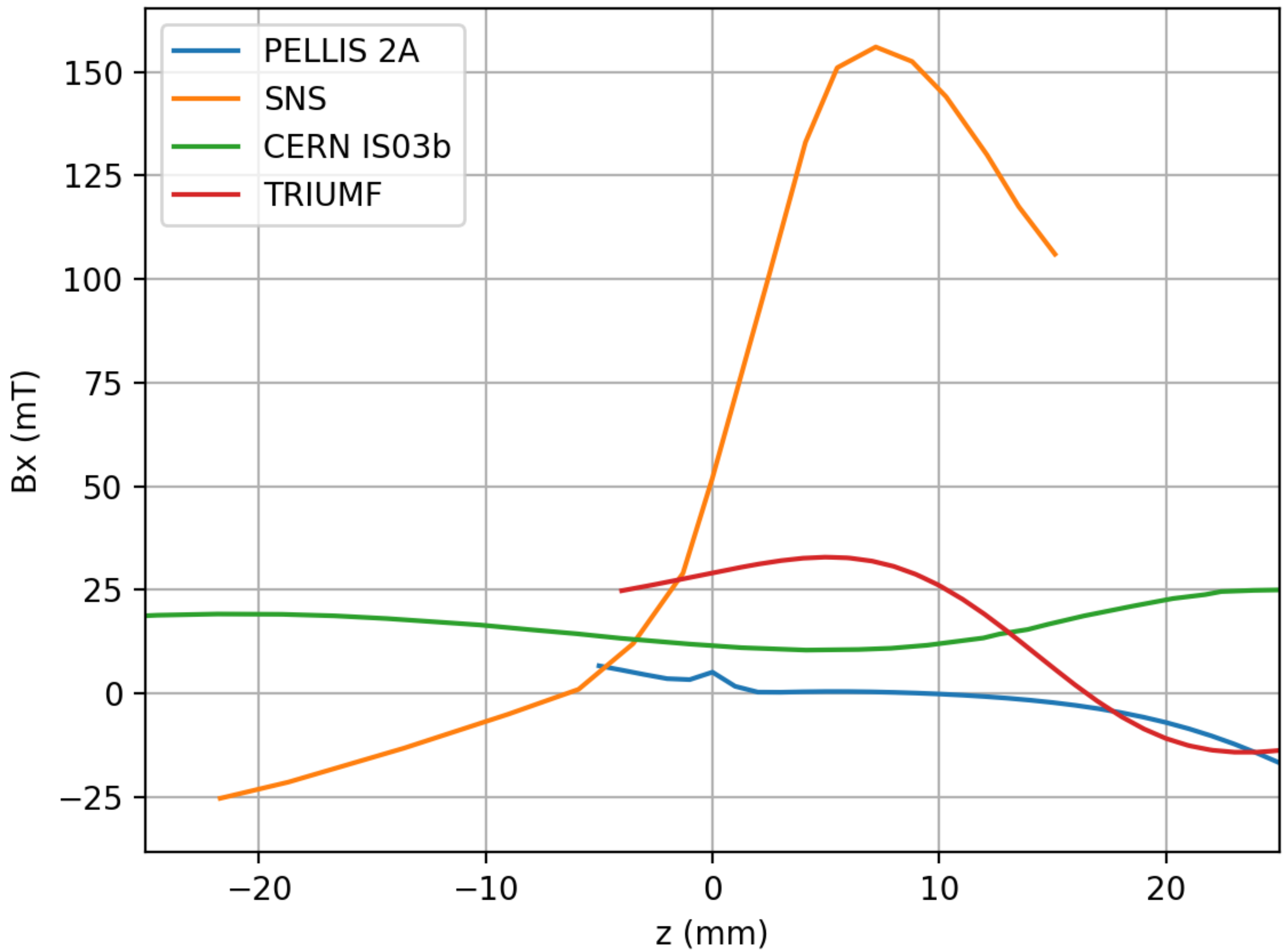
SPALLATION NEUTRON SOURCE

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



# Magnetic field comparison



# Linac4 IS03b, higher extraction field?

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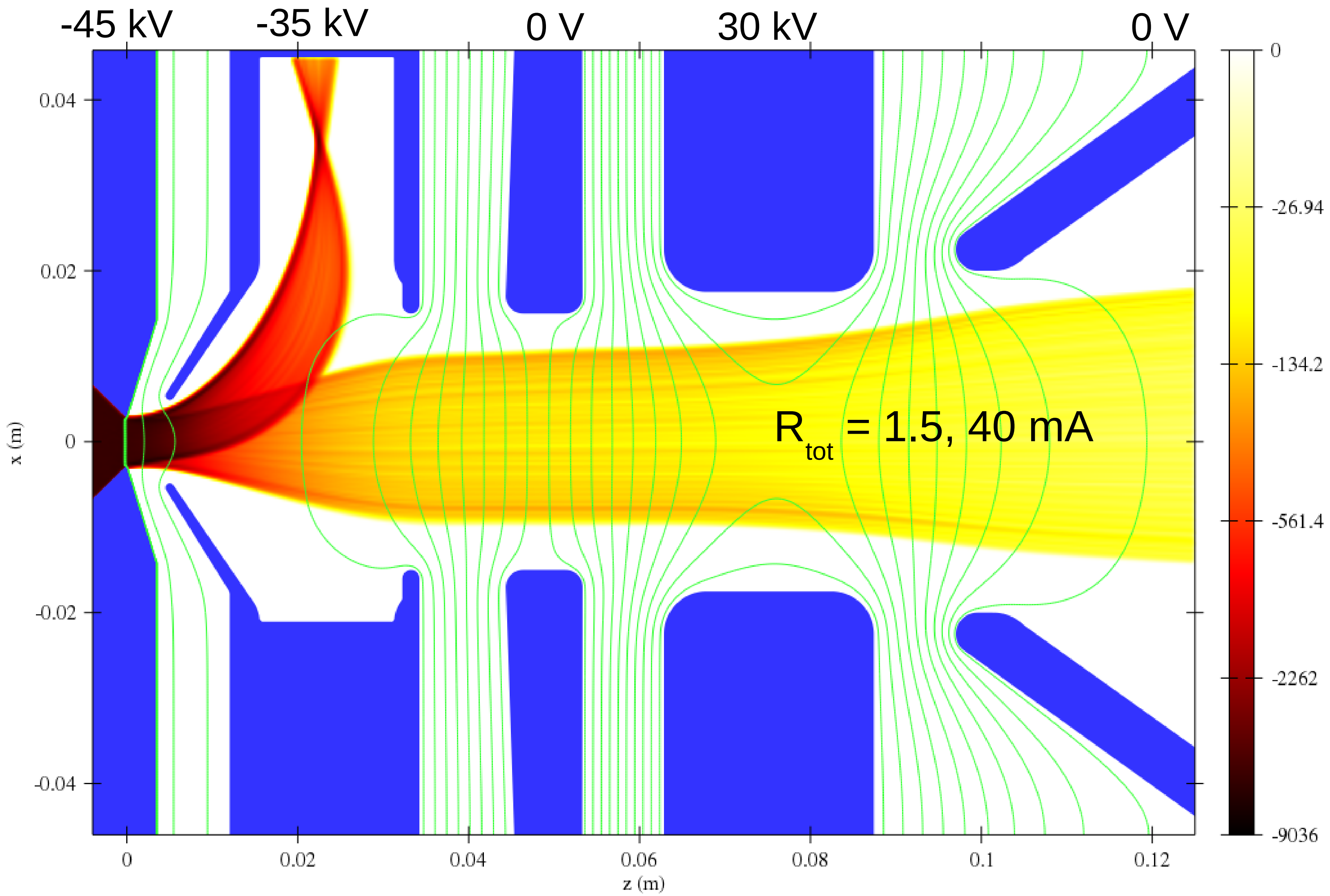

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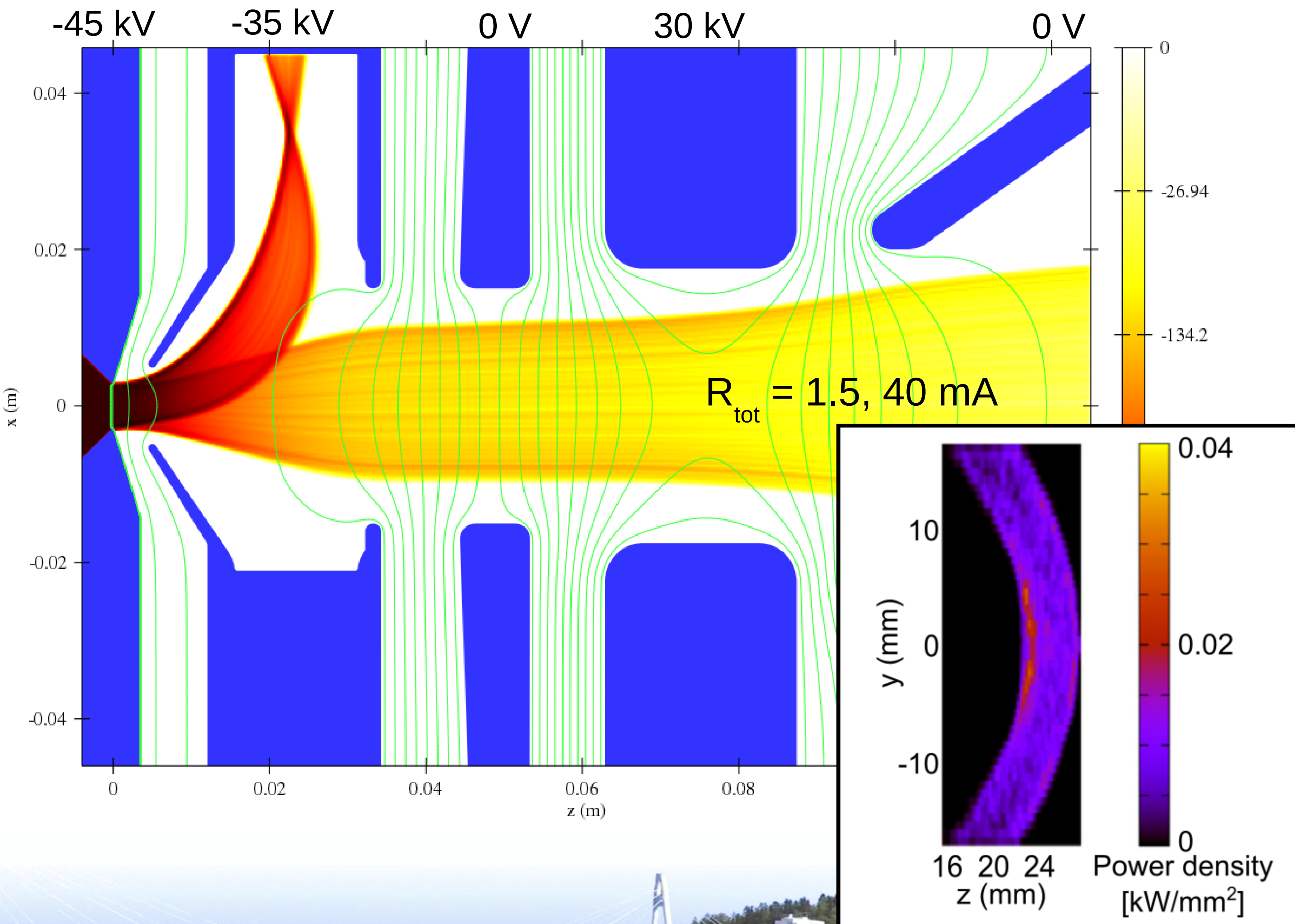
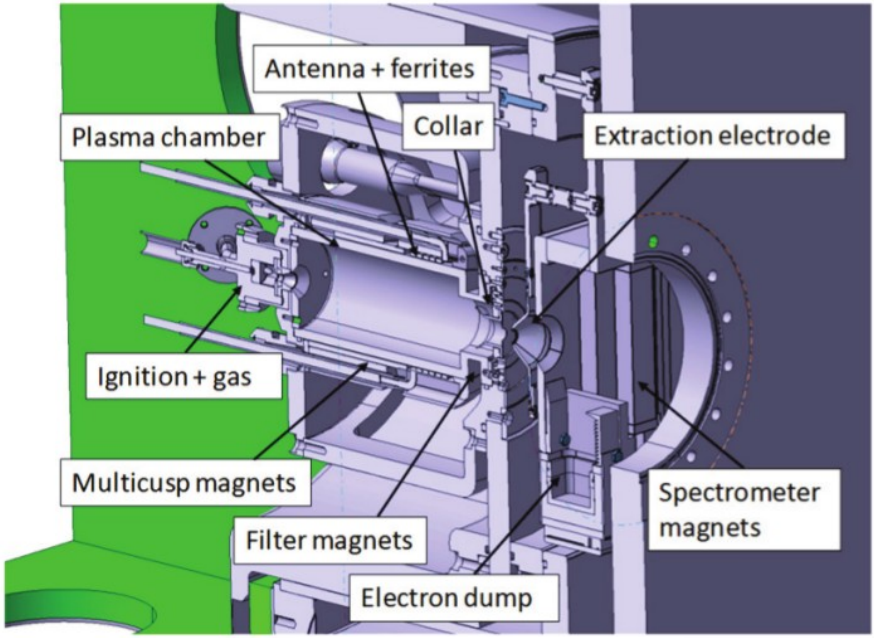
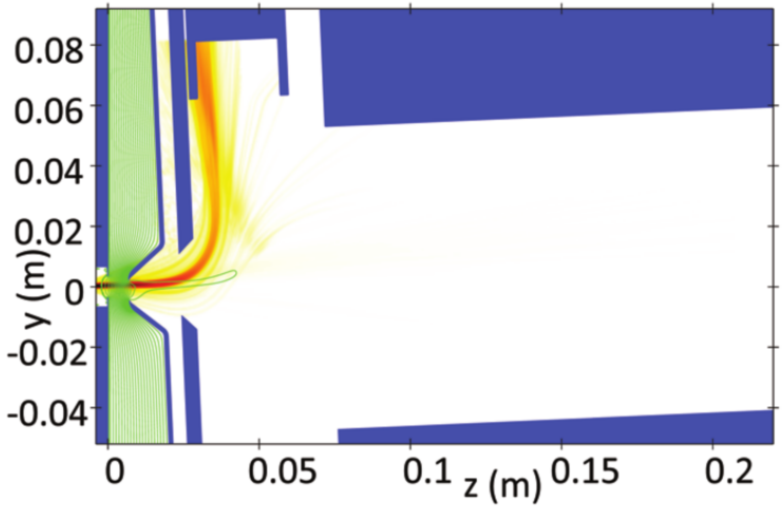
# Linac4 IS03b, higher extraction field?

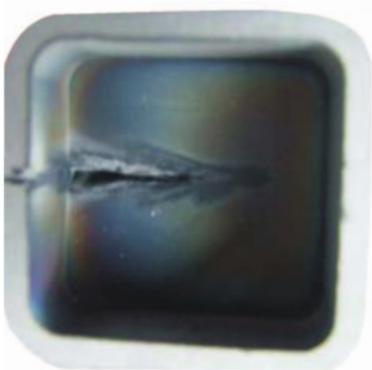


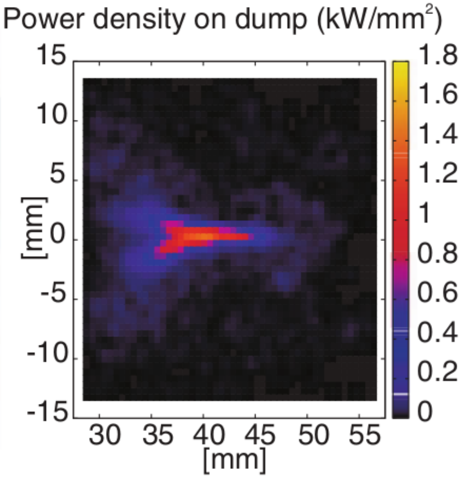
# Linac4/DESY

DESY source at 45 keV producing ~23 mA H⁻ and >1 A of electrons



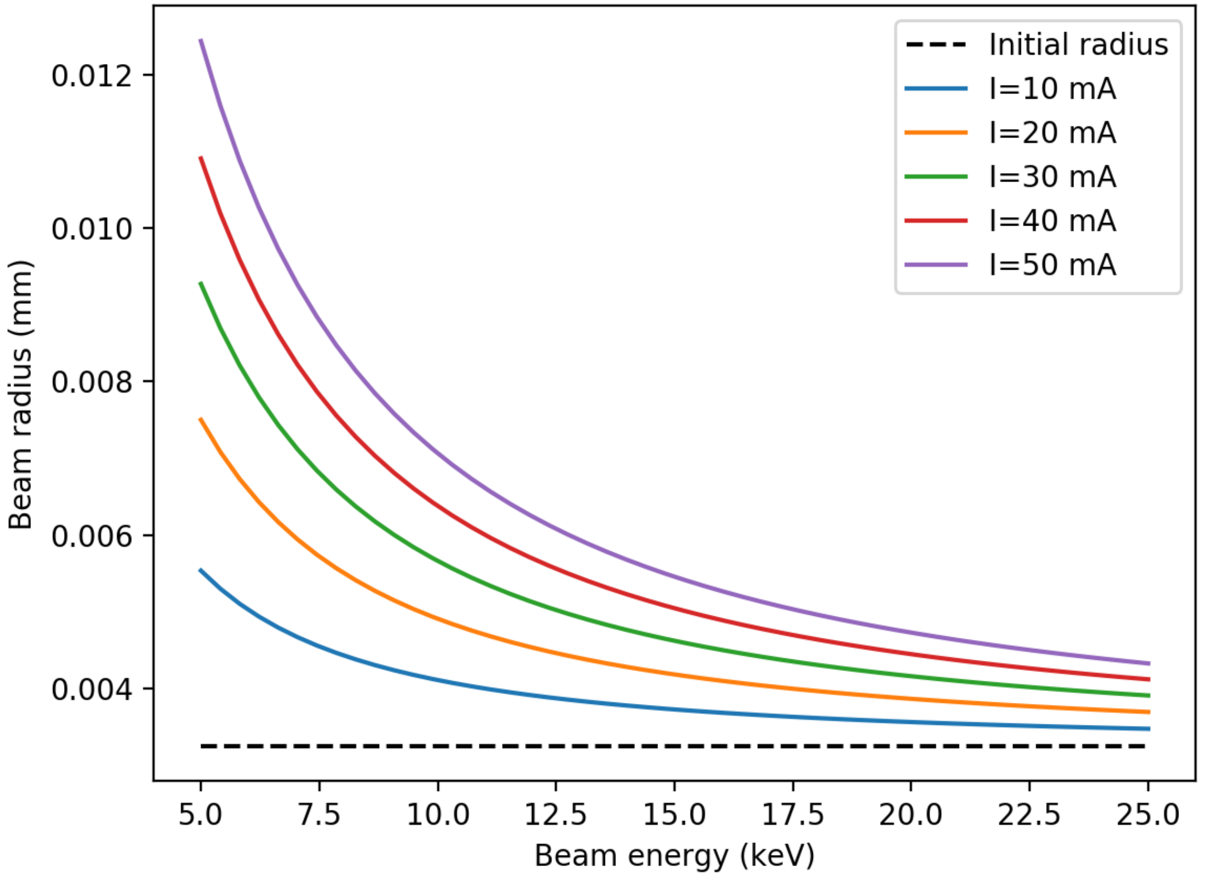






O. Midttun, Rev. Sci. Instrum 83, 02B710 (2012)

# Space charge blowup

Using the paraxial approximation for calculating beam size after electron dump at z=30 mm



# 20 keV electron dump design

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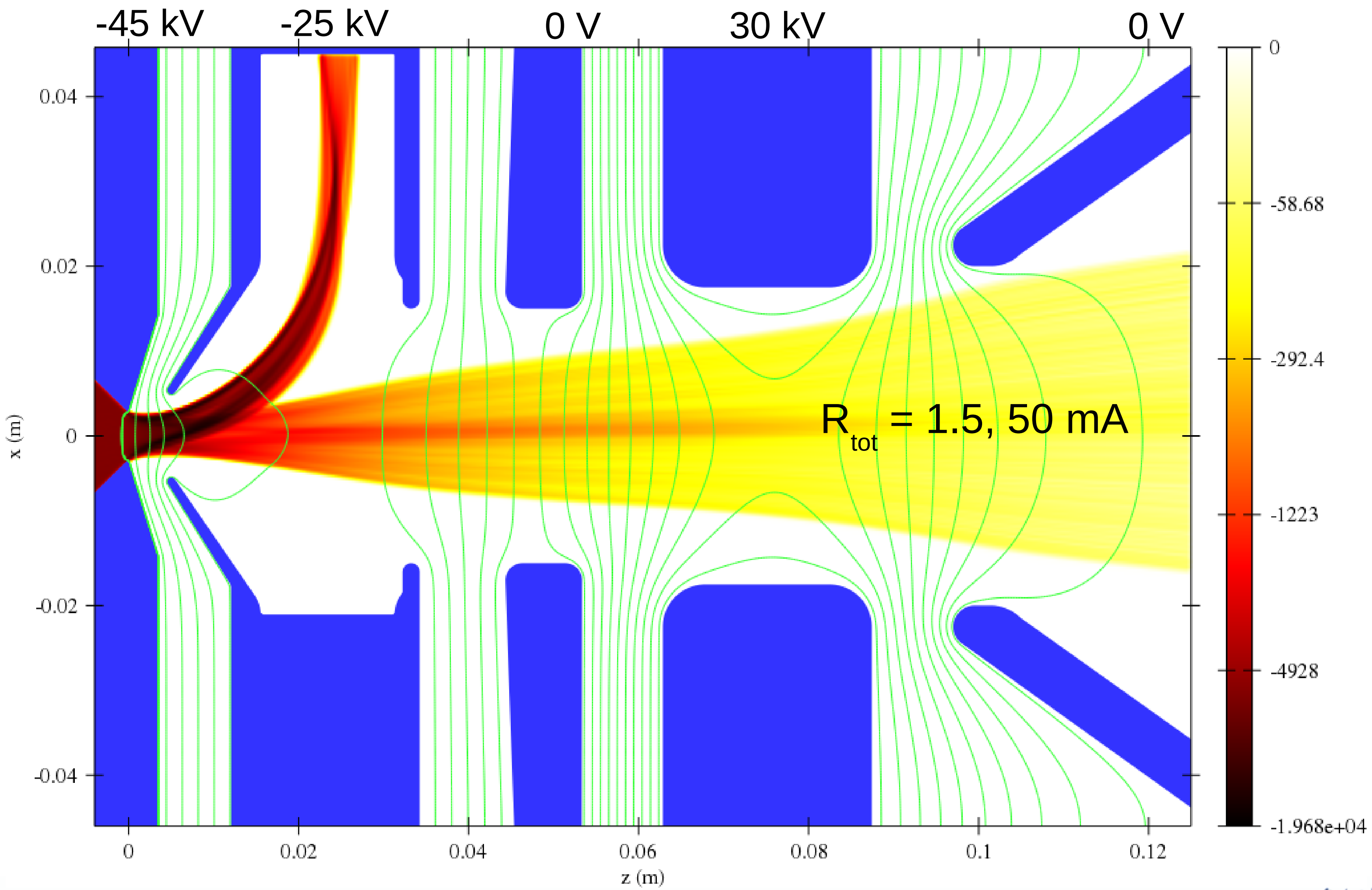

# Sight towards the horizon

**Studies on IBSimu plasma model**

- Further studies with PELLIS:

  - Effect of magnetic field on the beam formation optimum?

- Data from PIC-codes

- Further studies on beam formation at CERN and RAL

**Roadmap for Linac4**

- A way towards lower emittance:

  - Better predictive power on IBSimu
  - Higher energy dumping and/or larger plasma apertures