PH1
Computational Ion Optics with IBSimu

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FL114

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https://ibsimu.sourceforge.net/jss2015

Participants

Lecturer:

Taneli Kalvas, `taneli.kalvas@jyu.fi`

Course tutors:

Risto Kronholm, `risto.j.kronholm@student.jyu.fi`

Janne Laulainen, `janne.p.laulainen@student.jyu.fi`

Who else?

The course

- First week: Introductory part (1 ECTS)
  - Lectures 3×2 hours
  - Demonstrations 3×2 hours

- Second week: Main part (3 ECTS)
  - Lectures 2×2 hours
  - Demonstrations 5×2 hours
  - Homework!

Schedule

Schedule

Introductory part

Wed 5.8. 10–12, 14–16

Thu 6.8. 10–12, 14–16

Fri 7.8. 10–12, 14–16

Main part

Mon 10.8. 10–12, 14–16

Tue 11.8. 10–12, 14–16

Wed 12.8. 12–14

Thu 13.8. 12–14

Fri 14.8. 12–14

Contents

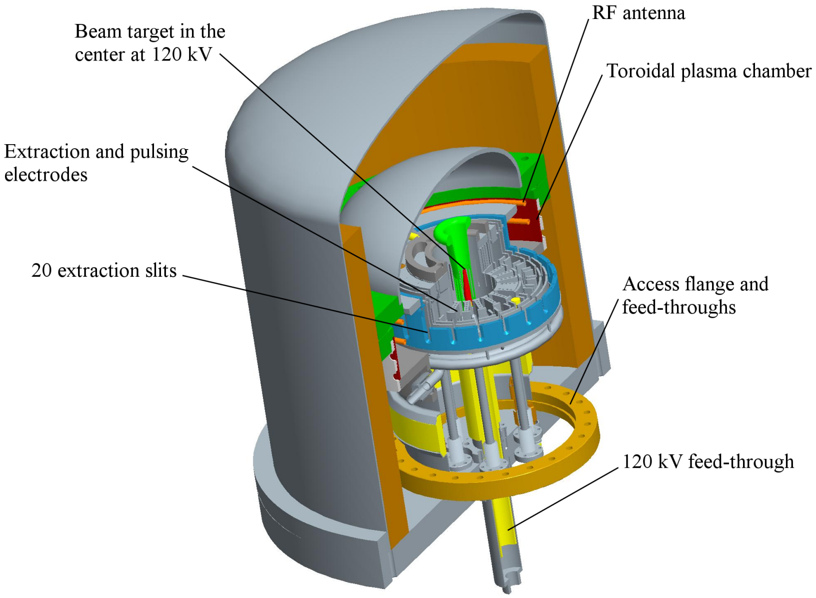
Main part

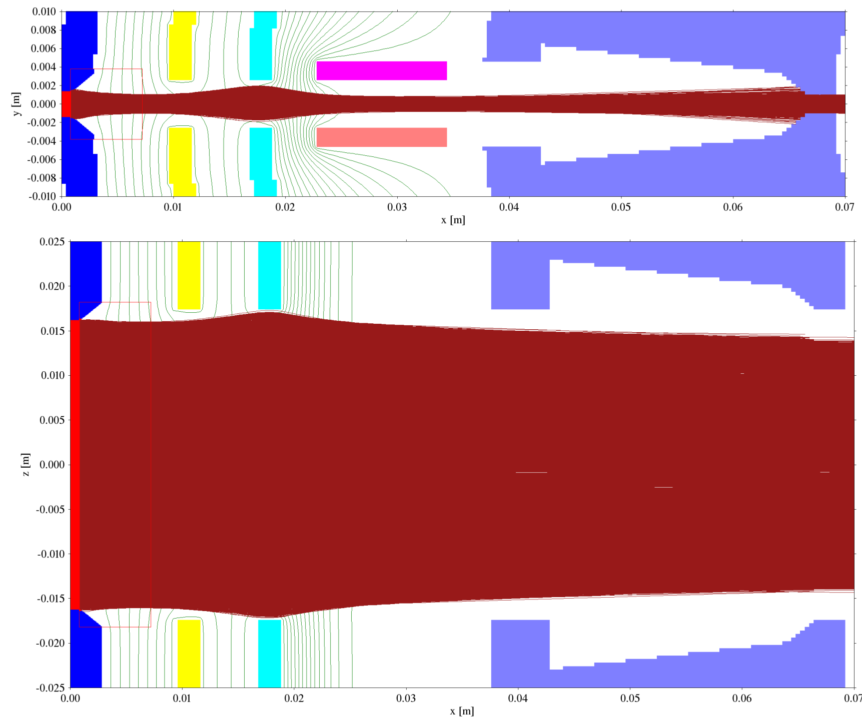
- What can IBSimu do?
- Full-scale examples
- Error-analysis

What can IBSimu do?

Start of development

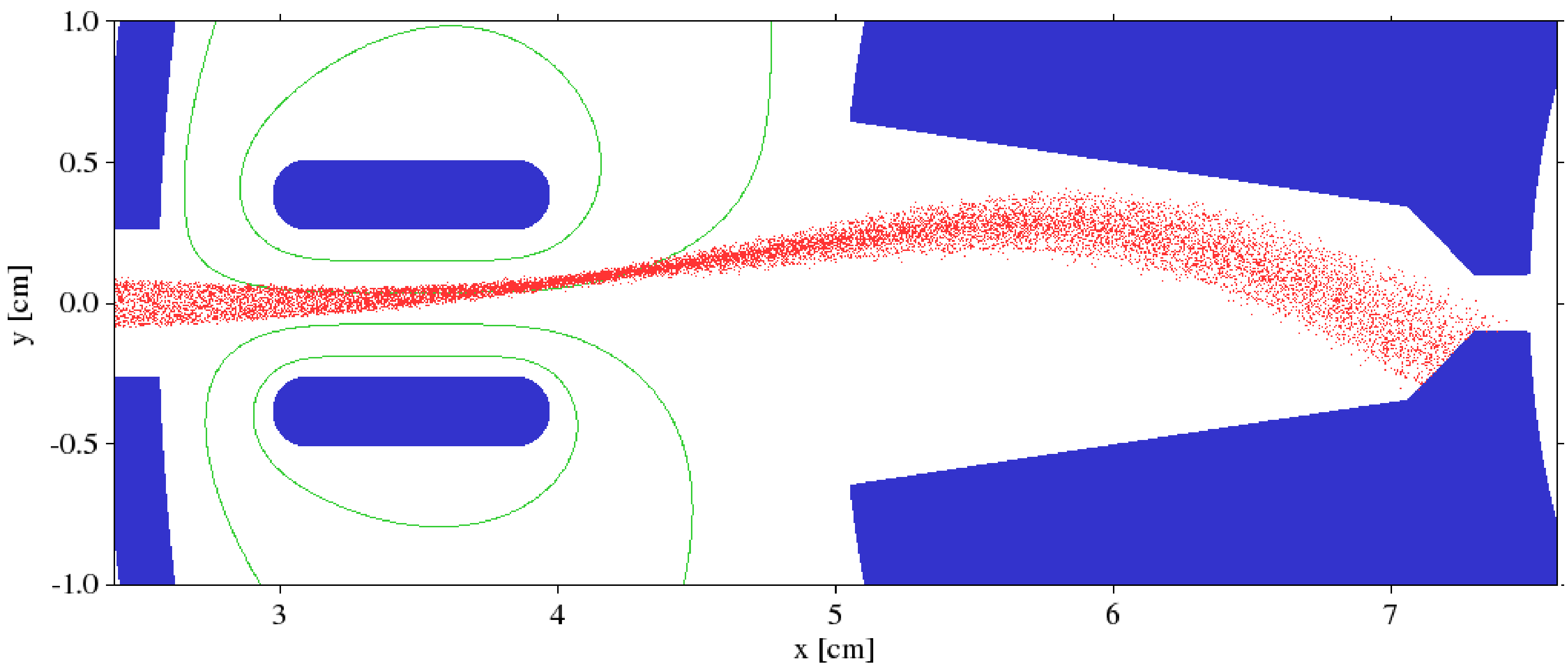
Work with IBSIMU started at LBNL in 2004 when designing a slit-beam neutron generator with nanosecond scale beam chopping.





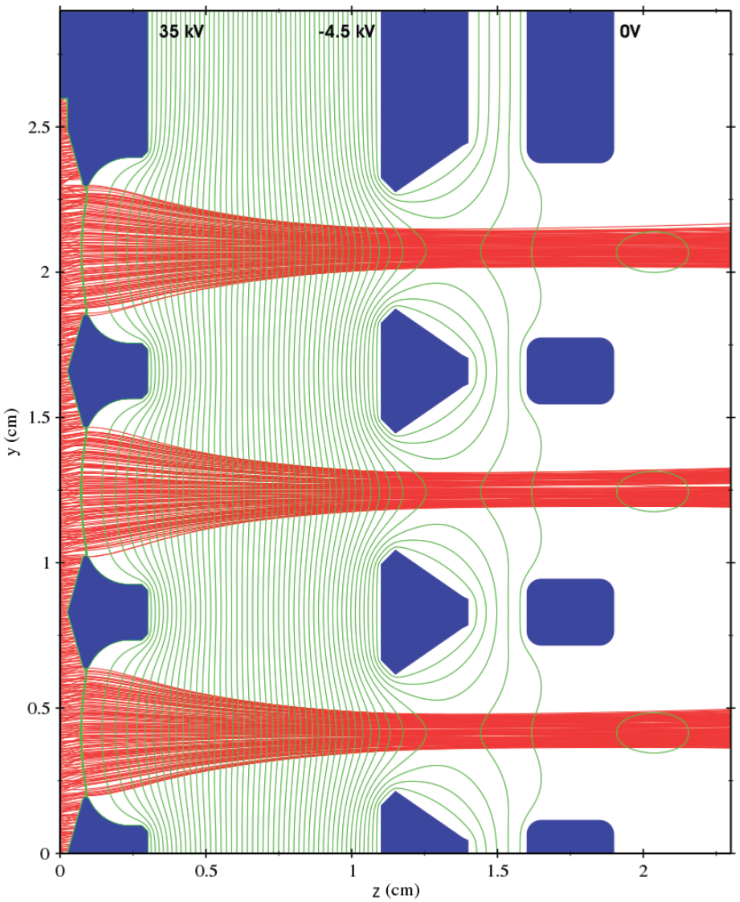
Start of development

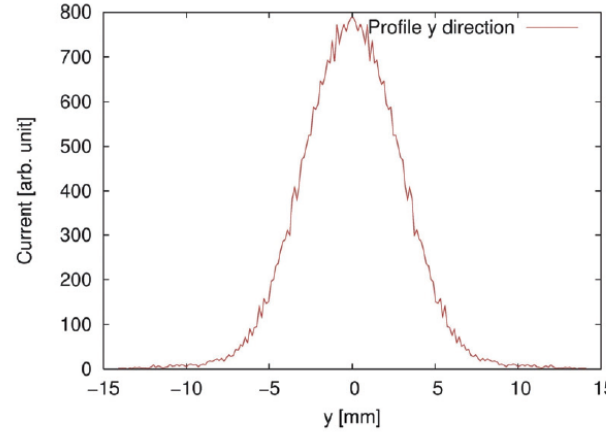
Particle-in-cell modelling of chopped beam was an important part of the original work. Such capability does not exist currently, but may be implemented with little effort.

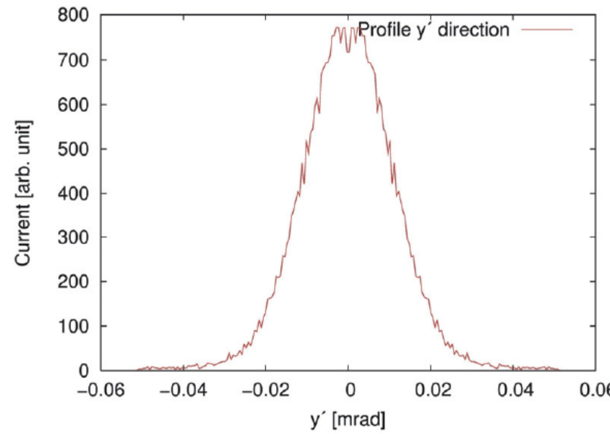


Positive plasma model

A positive ion extraction plasma model was added and other difficult three dimensional problems were modelled, for example a slit-beam system for PPPL.





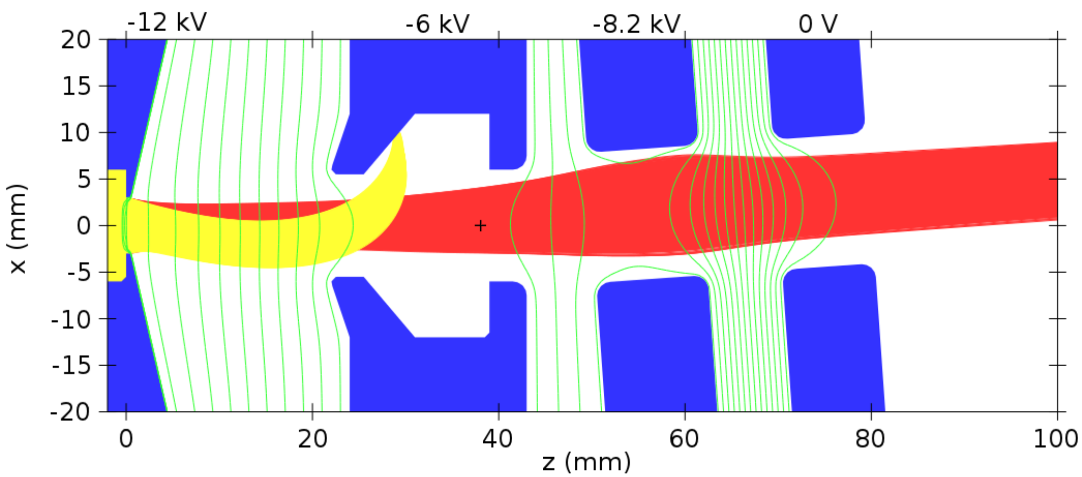


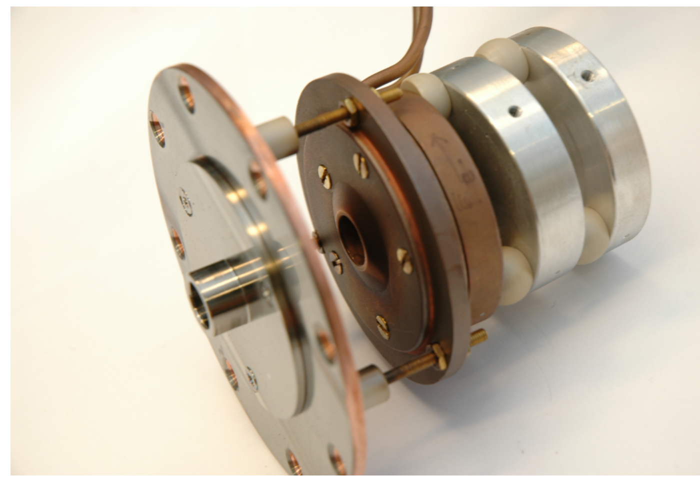
ICIS 2007, J. H. Vainionpaa, et. al., Rev. Sci. Instrum. **79**, 02C102 (2008)

Negative plasma model

Negative ion extraction model was developed and used with several designs over the years

Texas A&M 1 mA H^-/D^- ion source extraction design

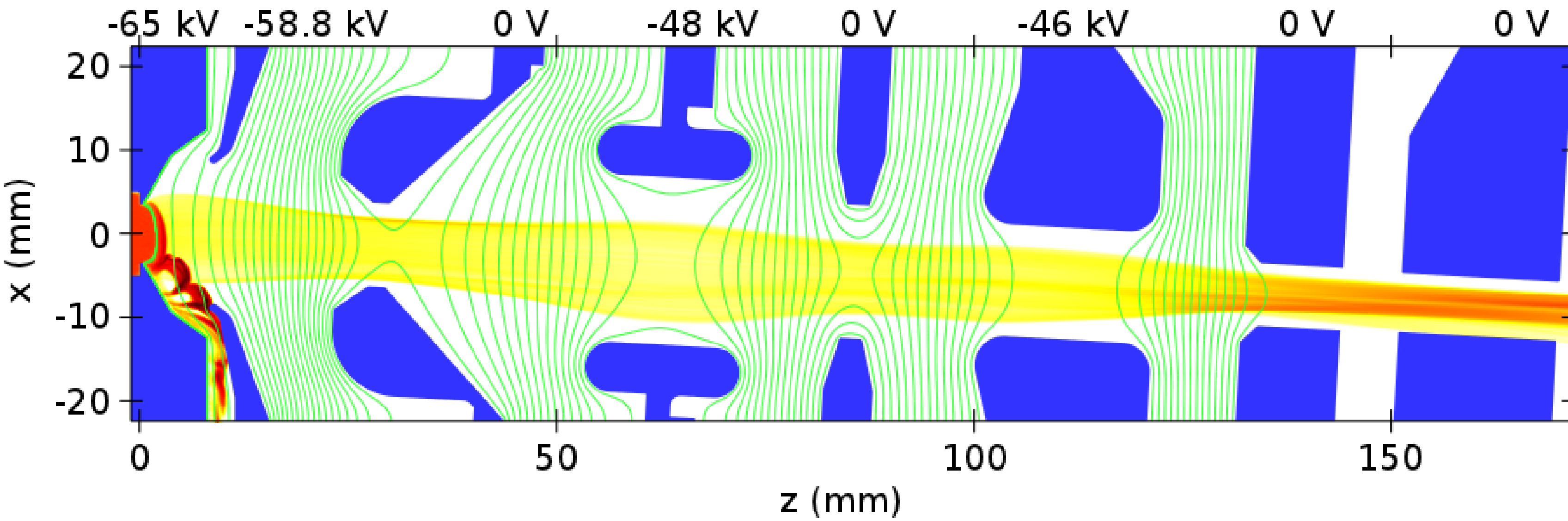


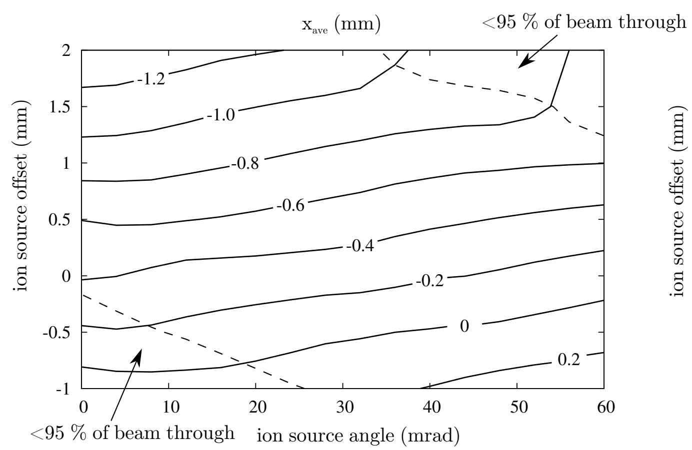


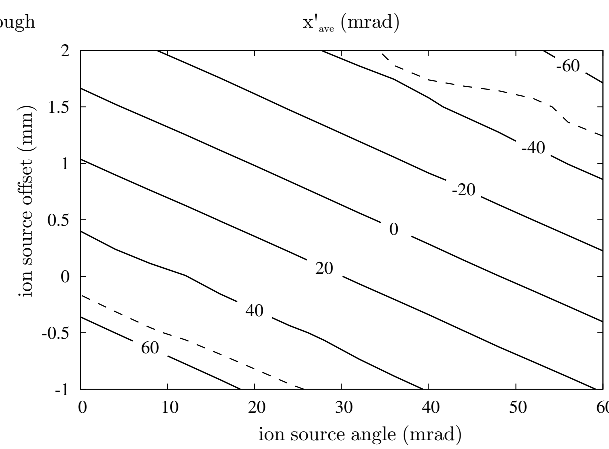
NIBS 2010, T. Kalvas, et. al., AIP Conf. Proc. **1390**, 150 (2011)

Negative plasma model

SNS Baseline 38 mA H^- ion source extraction modelling



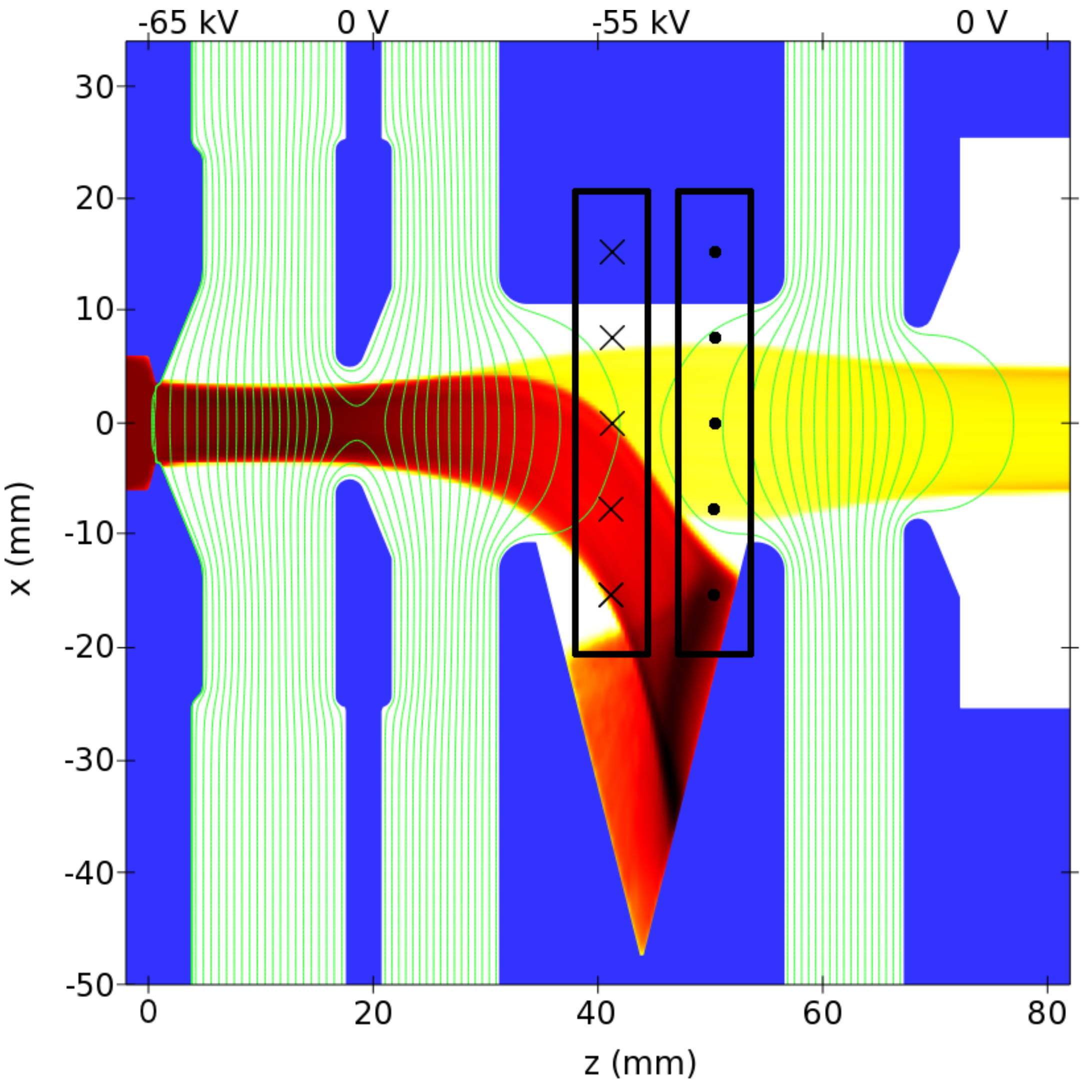




ICIS 2011, T. Kalvas, et. al., Rev. Sci. Instrum. **83**, 02A705 (2012)

Negative plasma model

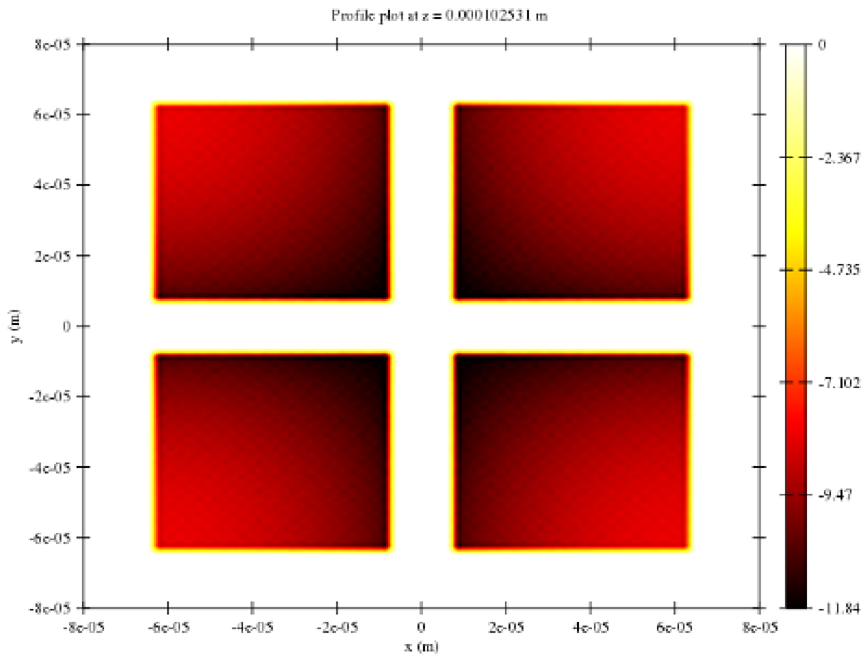
Proposed new extraction for SNS (100 mA H^-, 1 A e^-)

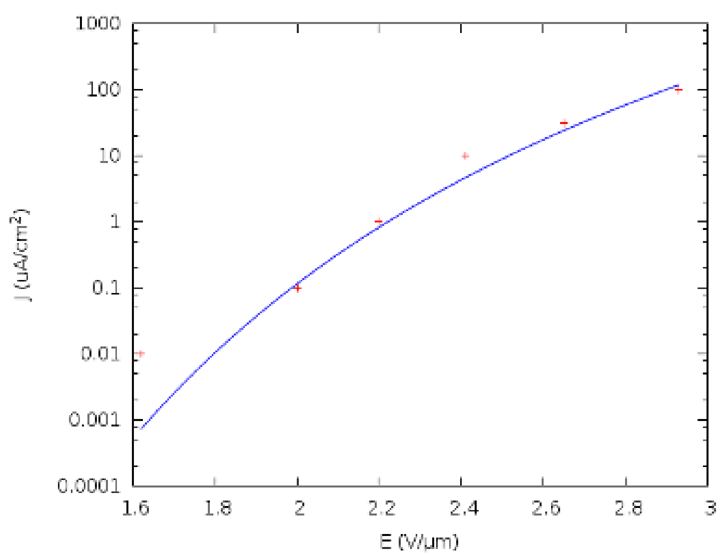


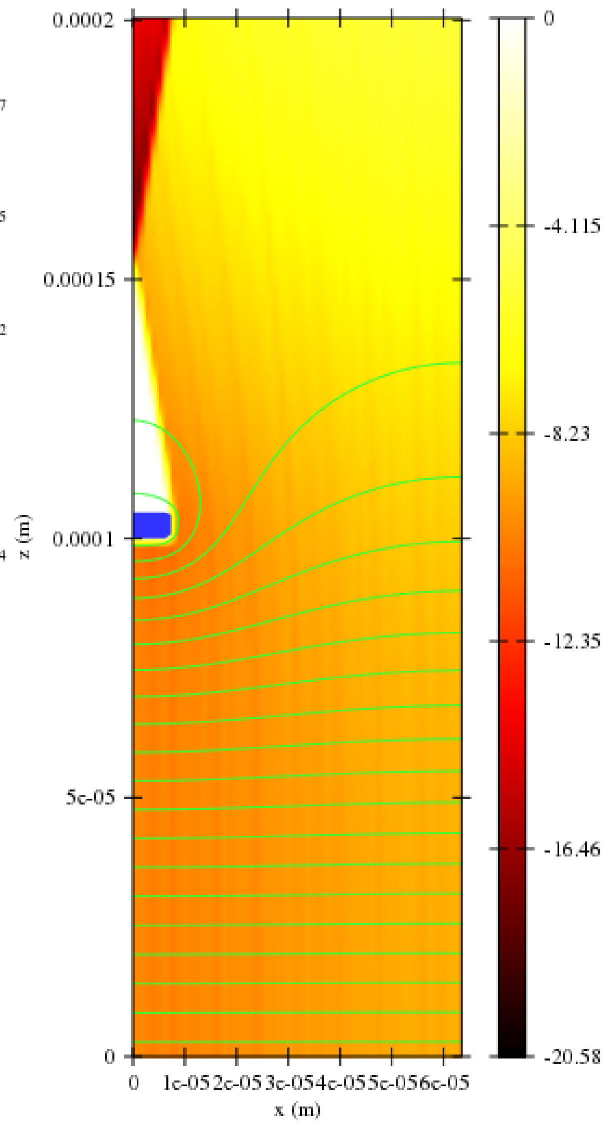
ICIS 2011, T. Kalvas, et. al., Rev. Sci. Instrum. **83**, 02A705 (2012)

Surface emission

Surface electron emission simulation for nanographite e-gun







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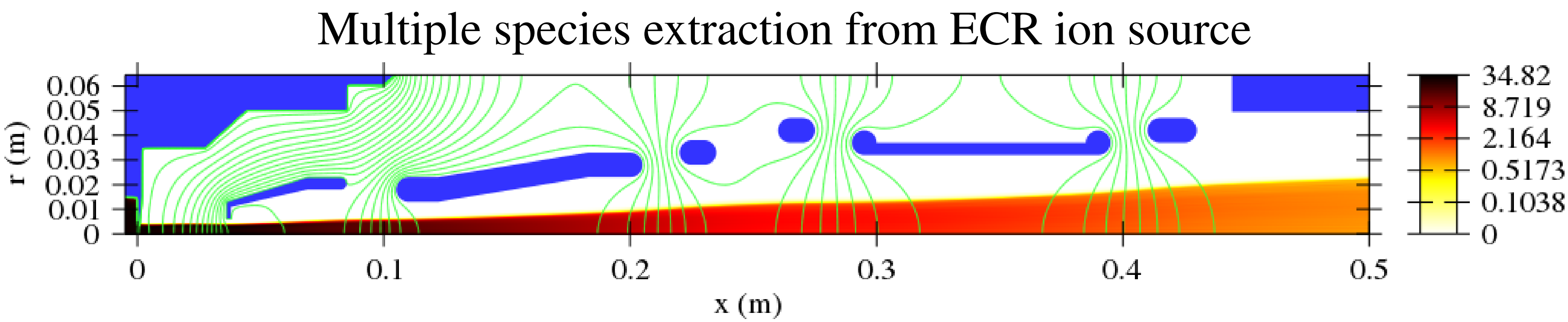
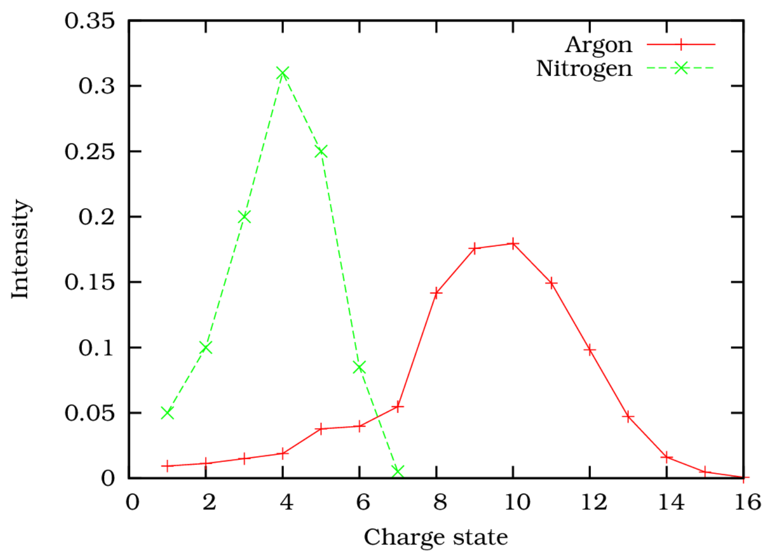
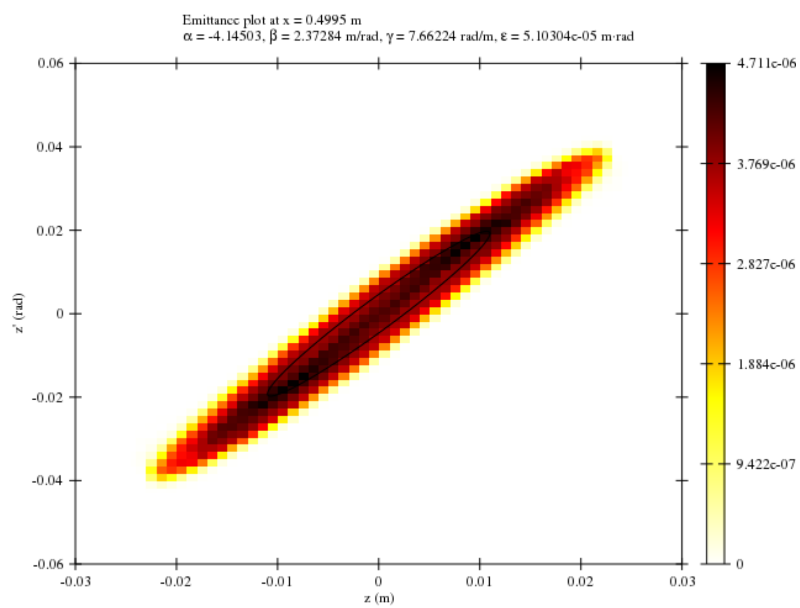
14 GHz ECR extraction





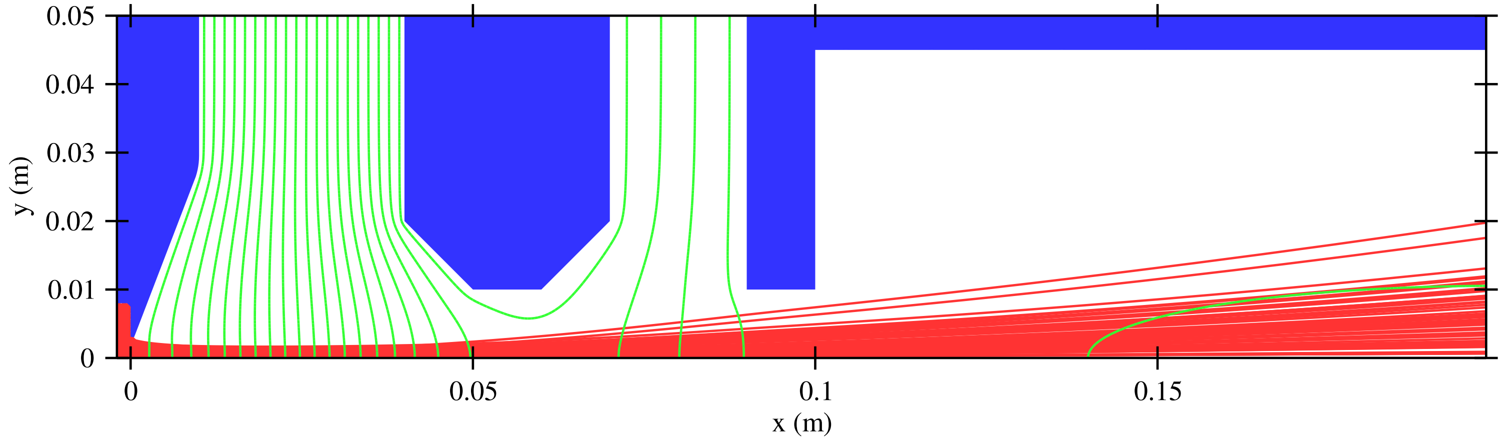


Full scale examples

Slit-beam triode extraction

- 30 mA/cm^2 H$^+$ ions from 3 mm slit
- 2D approximation first, 3D effect studied next
- Triode electrode system for blocking electron back-flow
  - Enables beam space charge compensation
- Choosing simulation parameters, introduction to discrete effects
- Optimizing geometry and voltages for emittance

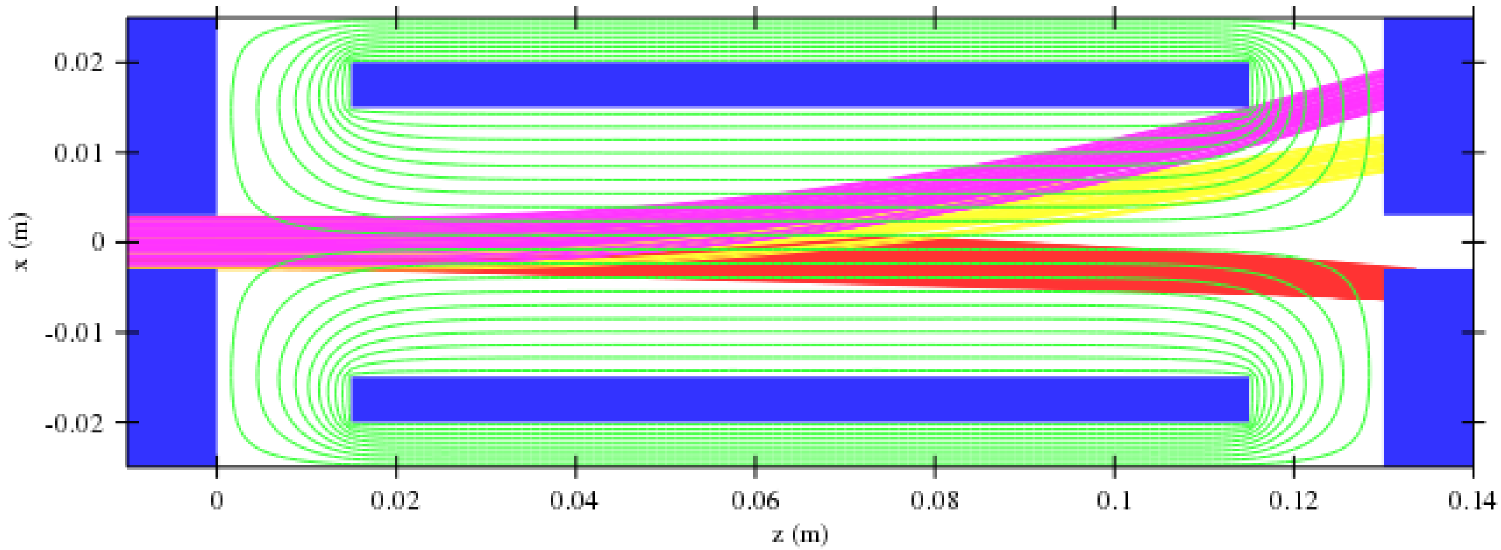
Slit-beam triode extraction

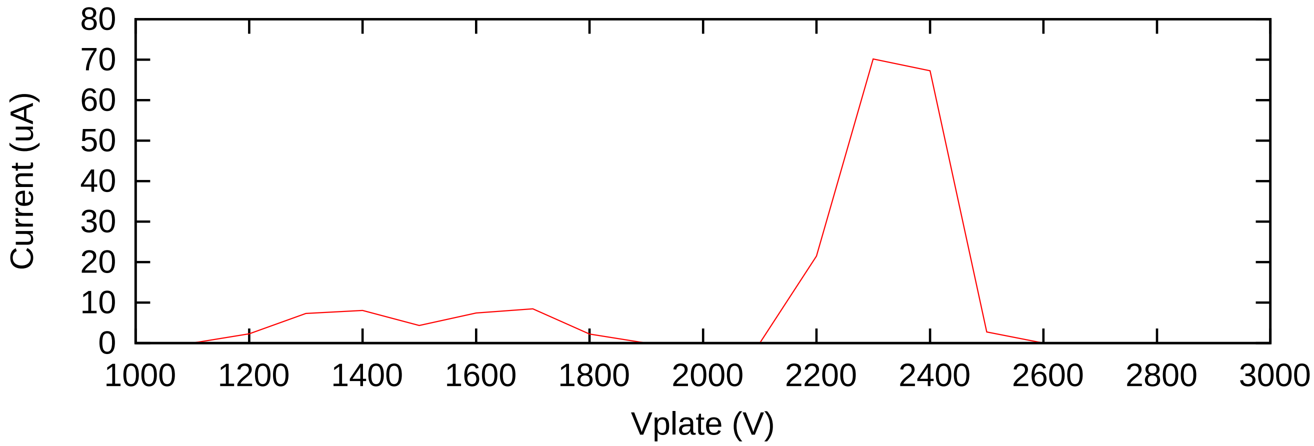


Wien filter

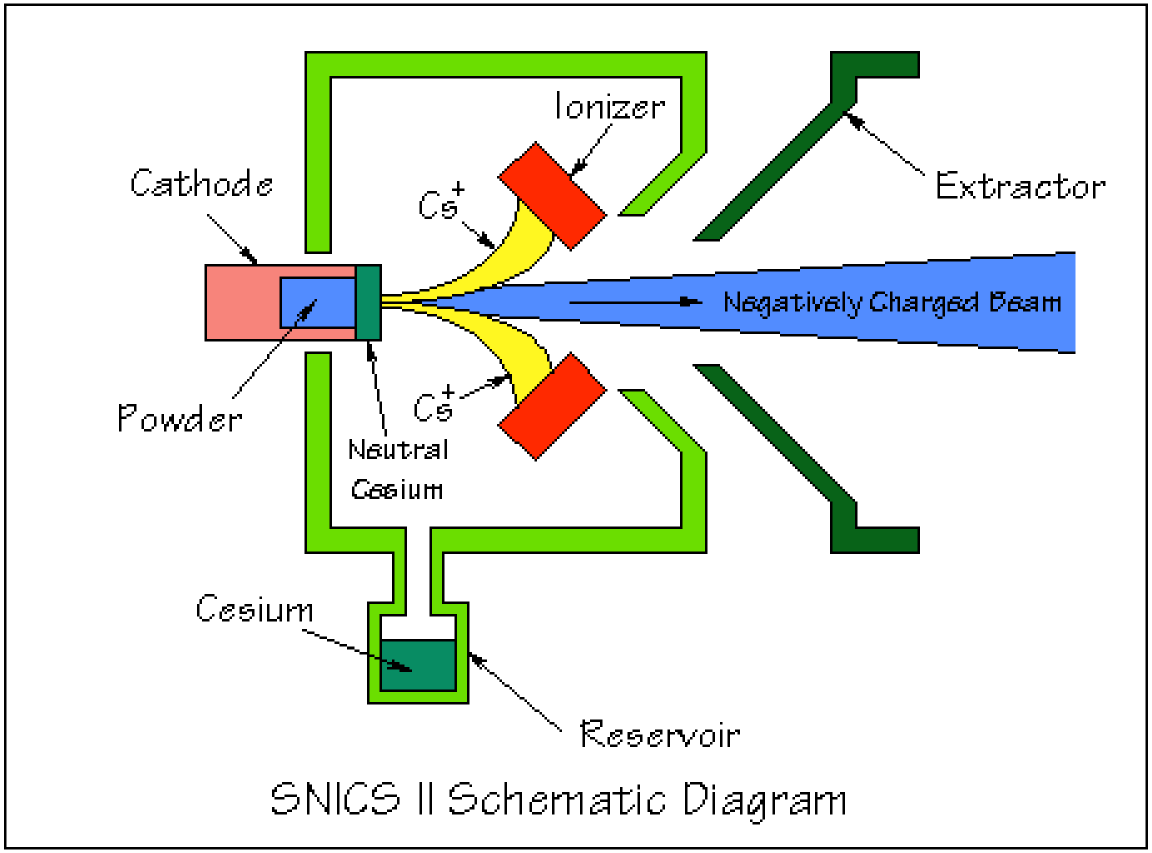
- Velocity filter using crossed B and E-fields, 3D problem
- Construction of simple geometry with FuncSolids
- Automation: use of plotting tools and diagnostics

Wien filter


0.02
0.01
0
-0.01
-0.02
x (m)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
z (m)

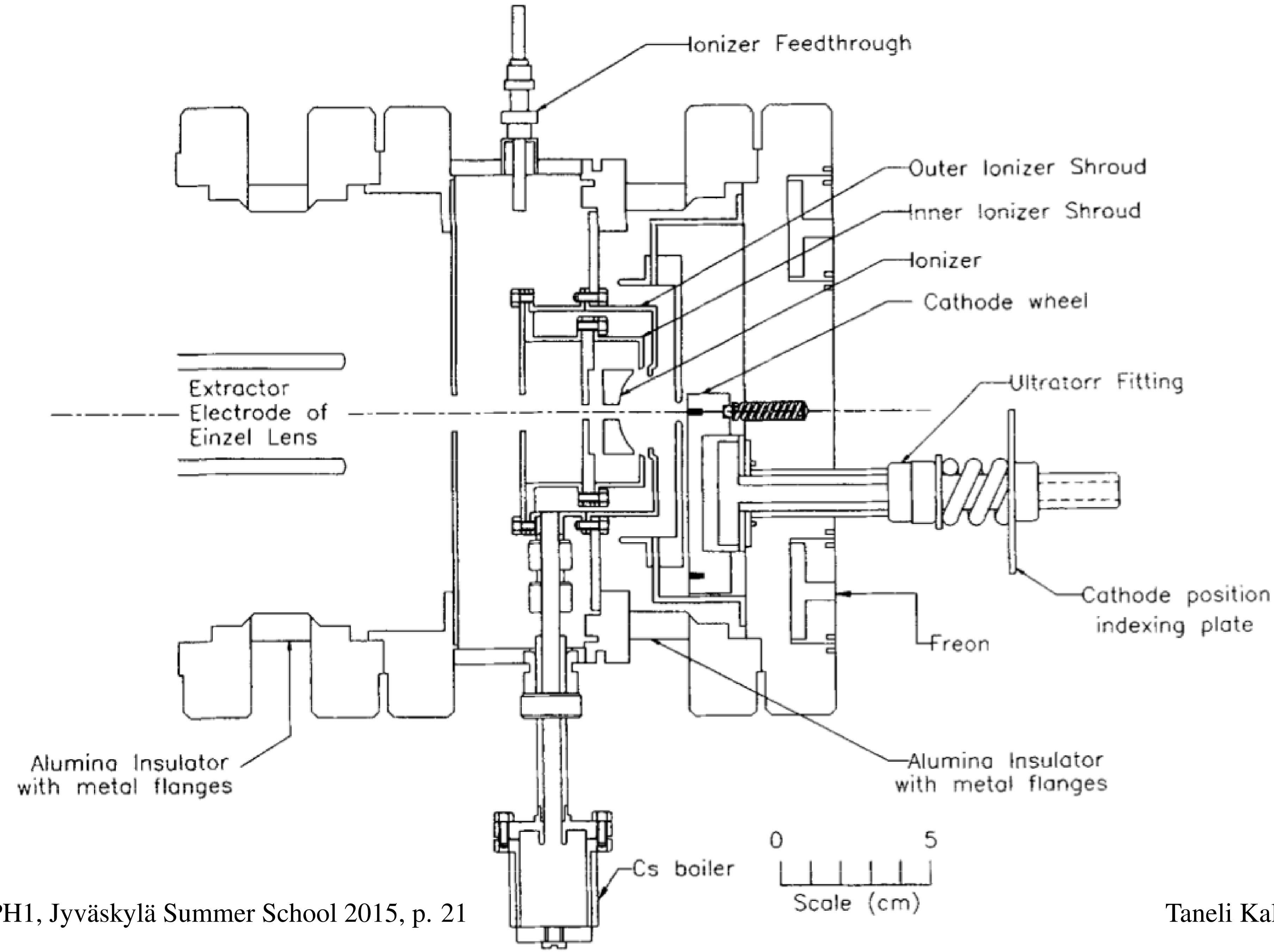

80
70
60
50
40
30
20
10
0
Current (uA)
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Vplate (V)

Cesium sputter ion source



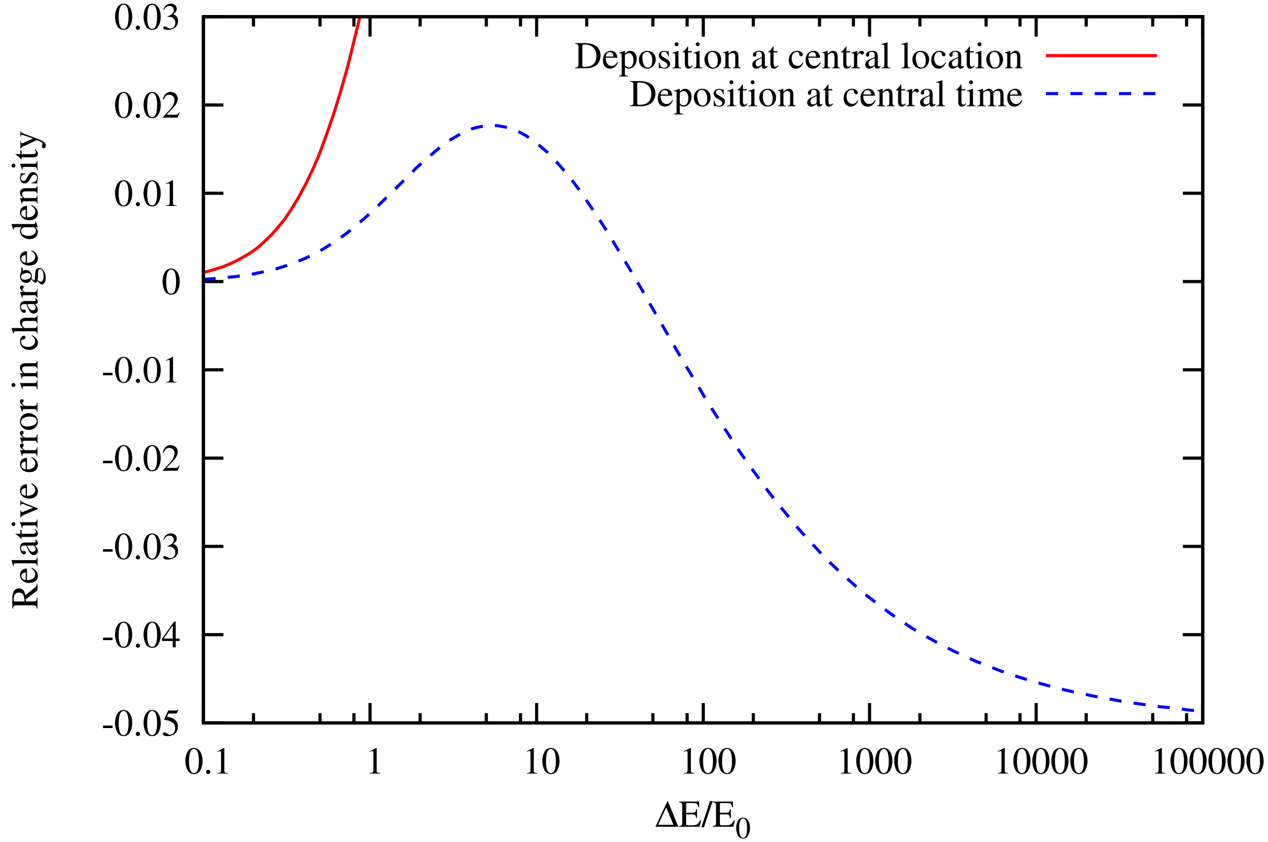
Cesium sputter ion source

I.S. Iyer et al. / Nucl. Instr. and Meth. in Phys. Res. A 381 (1996) 1–3



Cesium sputter ion source

- Beam starting with low energy causes convergence problems: $\rho = J/v$
- Fixed J is not a valid solution (space charge limited emission in reality)
- Space charge limited emission not implemented yet in IBSimu



Volume production H^- ion source LIISA

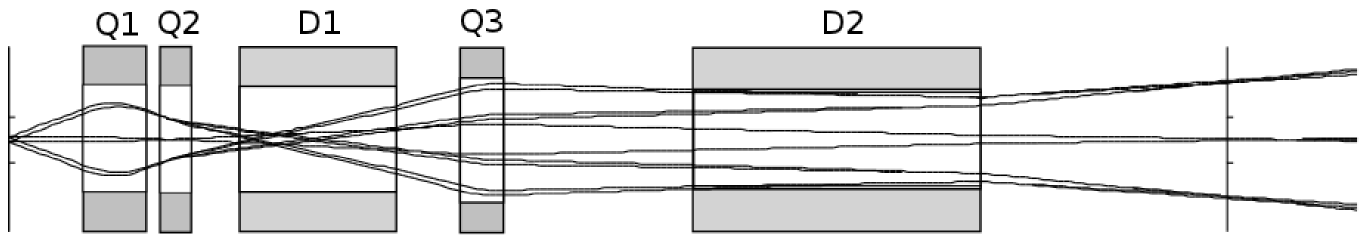
- 1 mA H^- ions and 5 mA electrons
- 3D problem with magnetic field
- Geometry cylindrically symmetric
- Effects of magnetic field, dumping of electrons

14 GHz ECR at JYFL

- Quick cylindrically symmetric simulation
- Full charge state distribution of N-15
- Emittance growth due to magnetic field
- Analysis using saved binary data, plotting using IBSimu tools

Matrix coefficients for beam transport programs

Traditional transfer matrix optics



Treats ion-optical elements (and drifts) as black boxes with transfer matrices describing the effect to trajectories. In TRANSPORT $X = (x, x', y, y', l, \delta p/p)$

$$X_i(1) = \sum_j R_{ij} X_j(0) + \sum_{jk} T_{ijk} X_j(0) X_k(0) + \cdots$$

Ideal 1st order quadrupole:

$$R = \begin{pmatrix} \cos kL & \frac{1}{k}\sin kL & 0 & 0 & 0 & 0 \\ -k\sin kL & \cos kL & 0 & 0 & 0 & 0 \\ 0 & 0 & \cosh kL & \frac{1}{k}\sinh kL & 0 & 0 \\ 0 & 0 & k\sinh kL & \cosh kL & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Traditional transfer matrix optics

- The whole system can be described with one matrix:

$$R_{\text{system}} = R_N \cdots R_2 \cdot R_1$$

- Can also transport elliptical envelopes in addition to trajectories:

$$\sigma_1 = R\sigma_0 R^T, \text{ where}$$

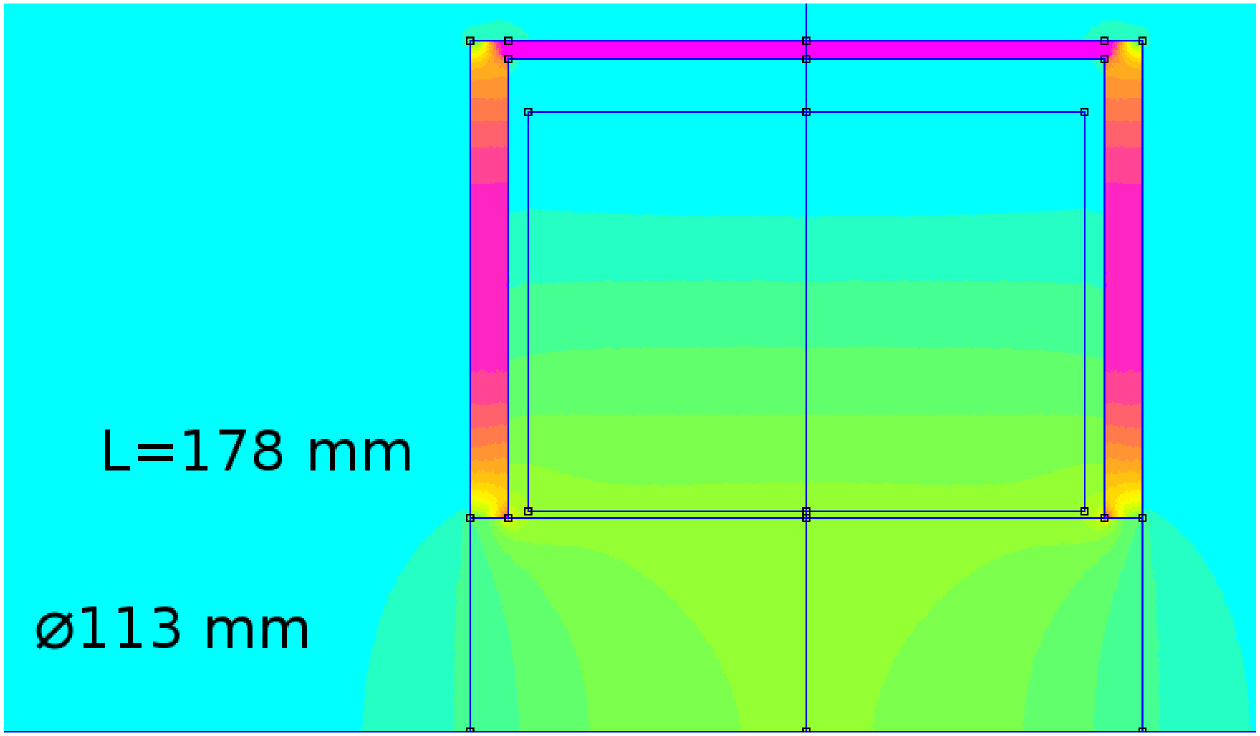
$$\sigma = \epsilon \begin{pmatrix} \beta & -\alpha \\ \alpha & \gamma \end{pmatrix}$$

- Advantage: calculation is fast (automatic optimization, etc)
- May include additional space charge induced divergence growth for beam envelopes and/or rms emittance growth modelling for particle distributions.
- Matrices arise from analytic formulation, numerical integration of fields or **fitting to experimental/simulation data**.

Solenoid fitting example

JYFL injection line solenoid

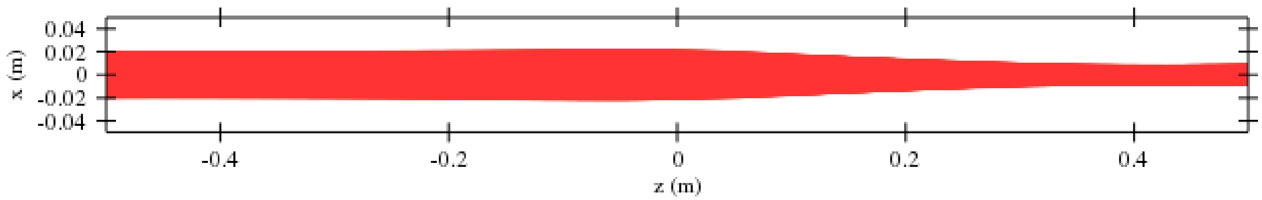
- Modelled with FEMM for 100 A induction current



Grid data output (using MATLAB script) within $z \in [0, 350]$, $r \in [0, 50]$
Data mirrored to fill $z \in [-350, 350]$.

Solenoid fitting example

IBSimu simulation to track particles through the magnetic field



Linear fitting to $(x_0, x'_0, y_0, y'_0) \rightarrow (x_1, x'_1, y_1, y'_1)$ produces a matrix

$$R = \begin{pmatrix} -0.16945 & 0.272915 & -0.169915 & 0.268352 \\ -1.75785 & -0.172501 & -1.72776 & -0.165878 \\ 0.169905 & -0.268383 & -0.169429 & 0.272935 \\ 1.72775 & 0.165847 & -1.75778 & -0.172471 \end{pmatrix}$$

This is a transfer matrix for drift + solenoid + drift.

Solenoid fitting example

Goal: coefficients L and B_0 for linear solenoid model $R_{\text{sol}} =$

$$\begin{pmatrix} \cos(\phi)\cos(\phi) & \sin(\phi)\cos(\phi)/K & \sin(\phi)\cos(\phi) & \sin(\phi)\sin(\phi)/K \\ -\sin(\phi)\cos(\phi)K & \cos(\phi)\cos(\phi) & -\sin(\phi)\sin(\phi)K & \sin(\phi)\cos(\phi) \\ -\sin(\phi)\cos(\phi) & -\sin(\phi)\sin(\phi)/K & \cos(\phi)\cos(\phi) & \sin(\phi)\cos(\phi)/K \\ \sin(\phi)\sin(\phi)K & -\sin(\phi)\cos(\phi) & -\sin(\phi)\cos(\phi)K & \cos(\phi)\cos(\phi) \end{pmatrix},$$

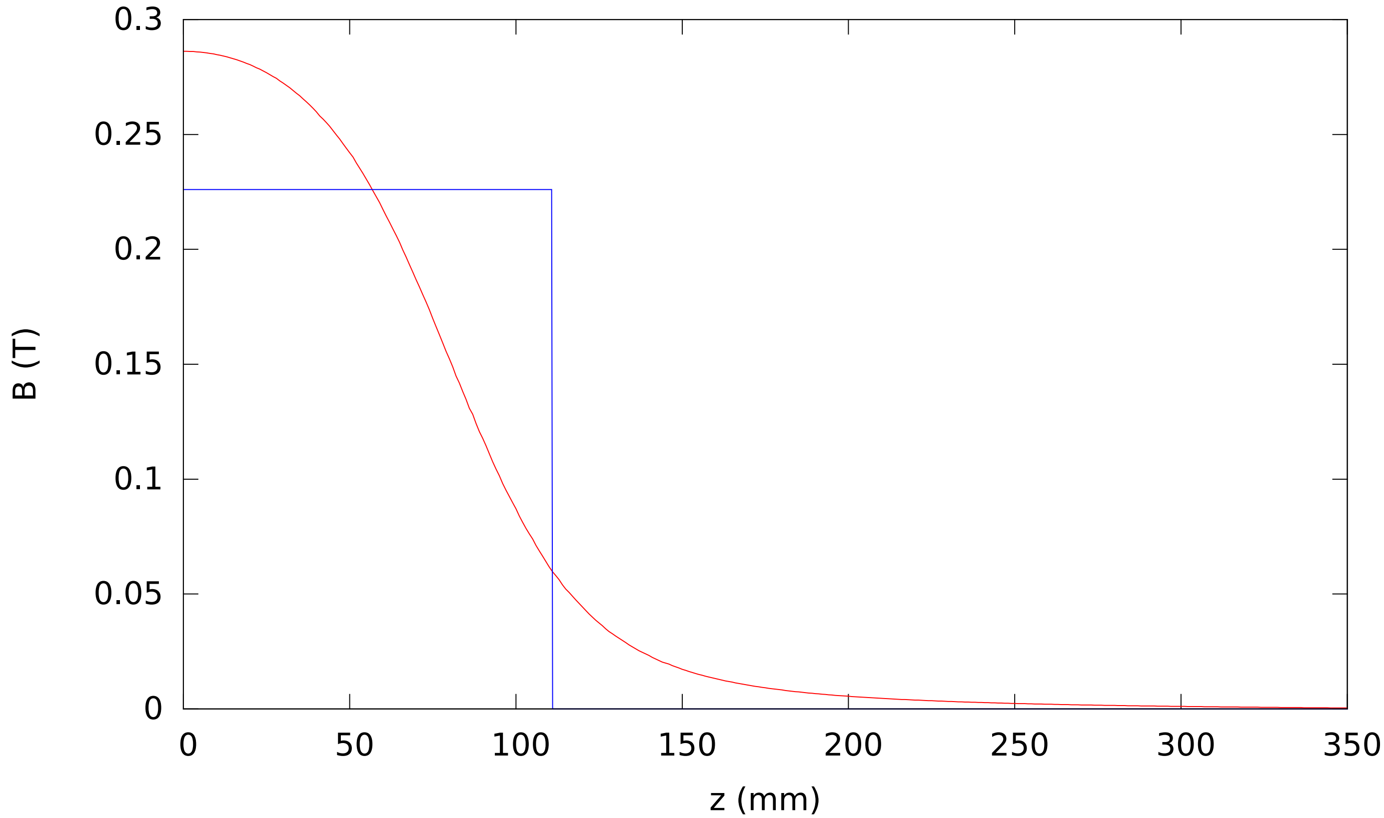
where $\phi = \frac{1}{2}B_0L/B_r$ and $K = \phi/L$.

Fitting of drift$(0.5\ \text{m} - 0.5L)$ + sol(B_0, L) + drift$(0.5\ \text{m} - 0.5L)$ produced coefficients

$B_0 = 0.226$ T
$L = 0.222$ m

Solenoid fitting example

Resulting linear solenoid model vs. real field on axis



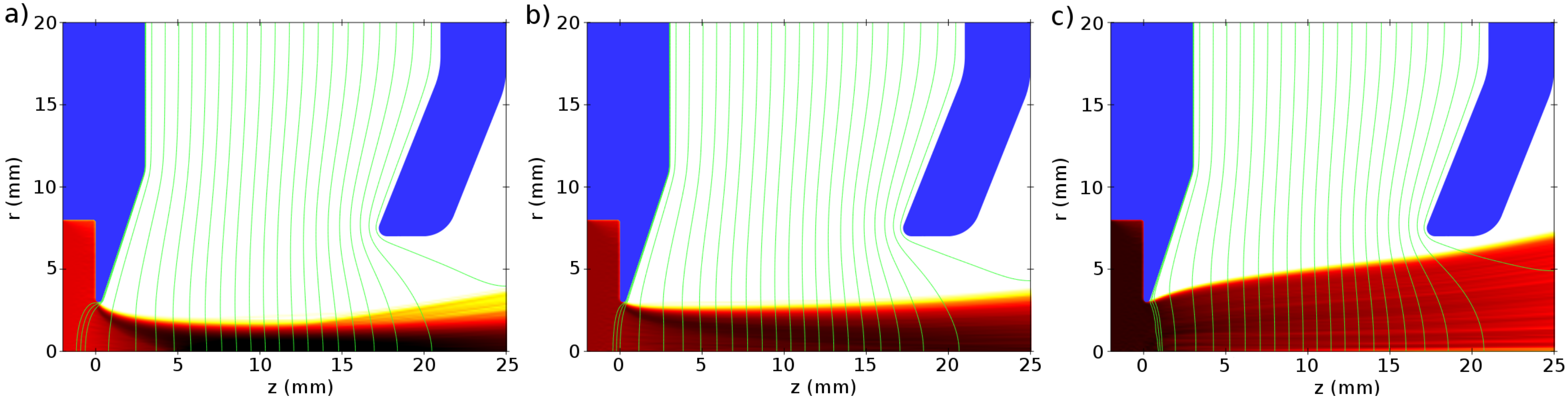
Negative ion extraction from plasma

Effect of plasma parameters in simulation

Homework:

How do negative ion extraction plasma model parameters J, $R_e i$, T_t, R_f, ϕ_P, E_0 and T_p affect the solution in IBSimu?

Emittance as a function of beam current

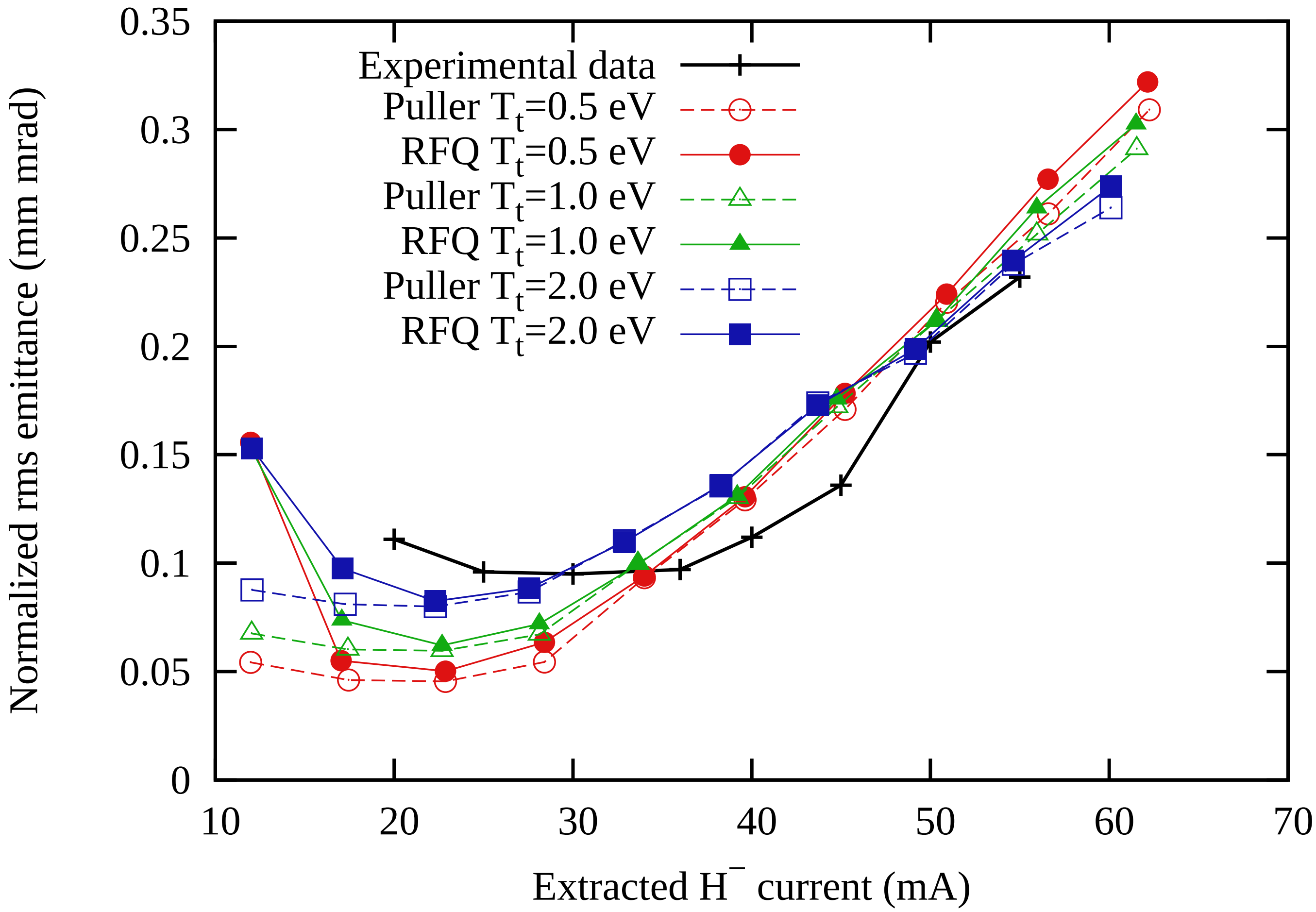


low J
high ϵ

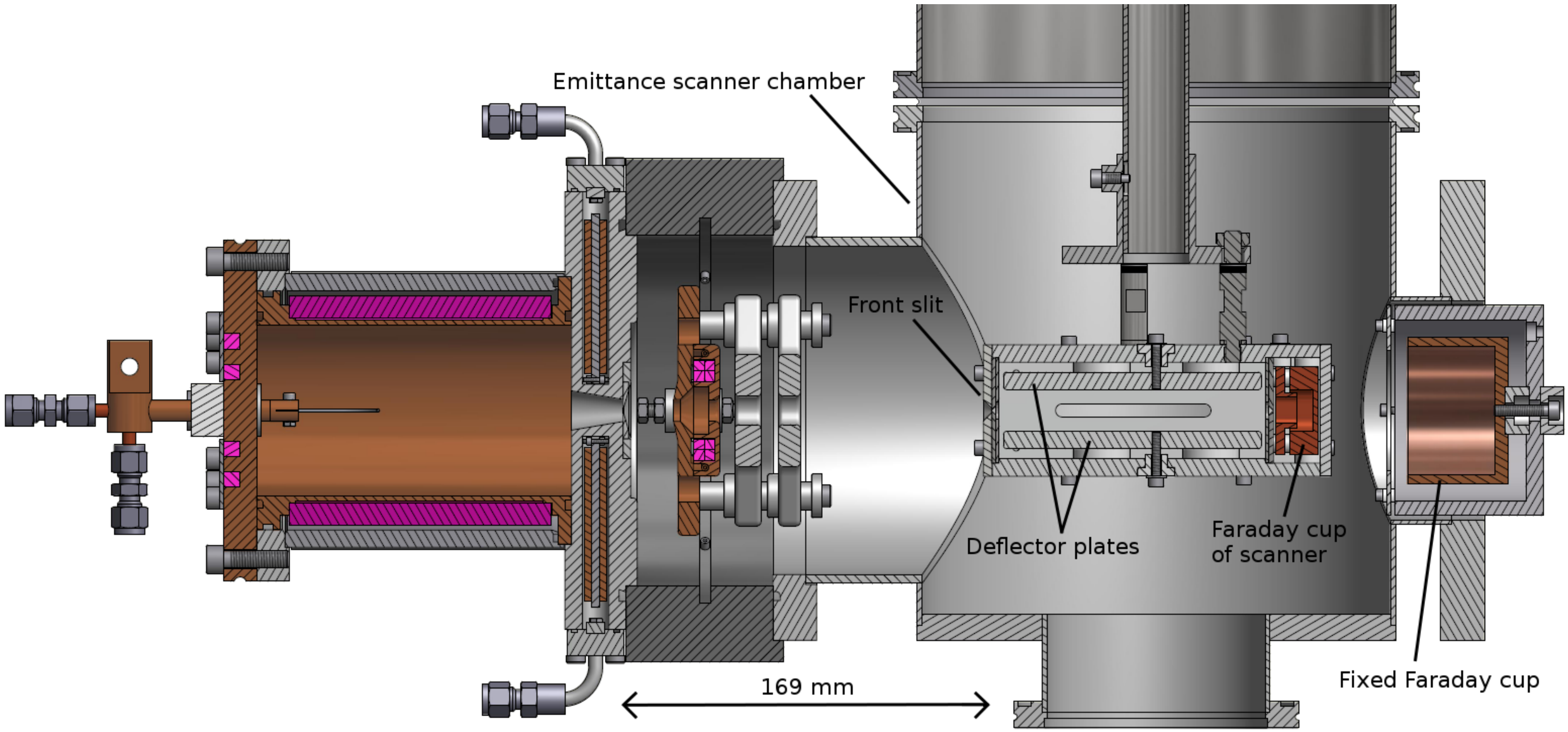
medium J
optimum ϵ

high J
high ϵ

SNS extraction



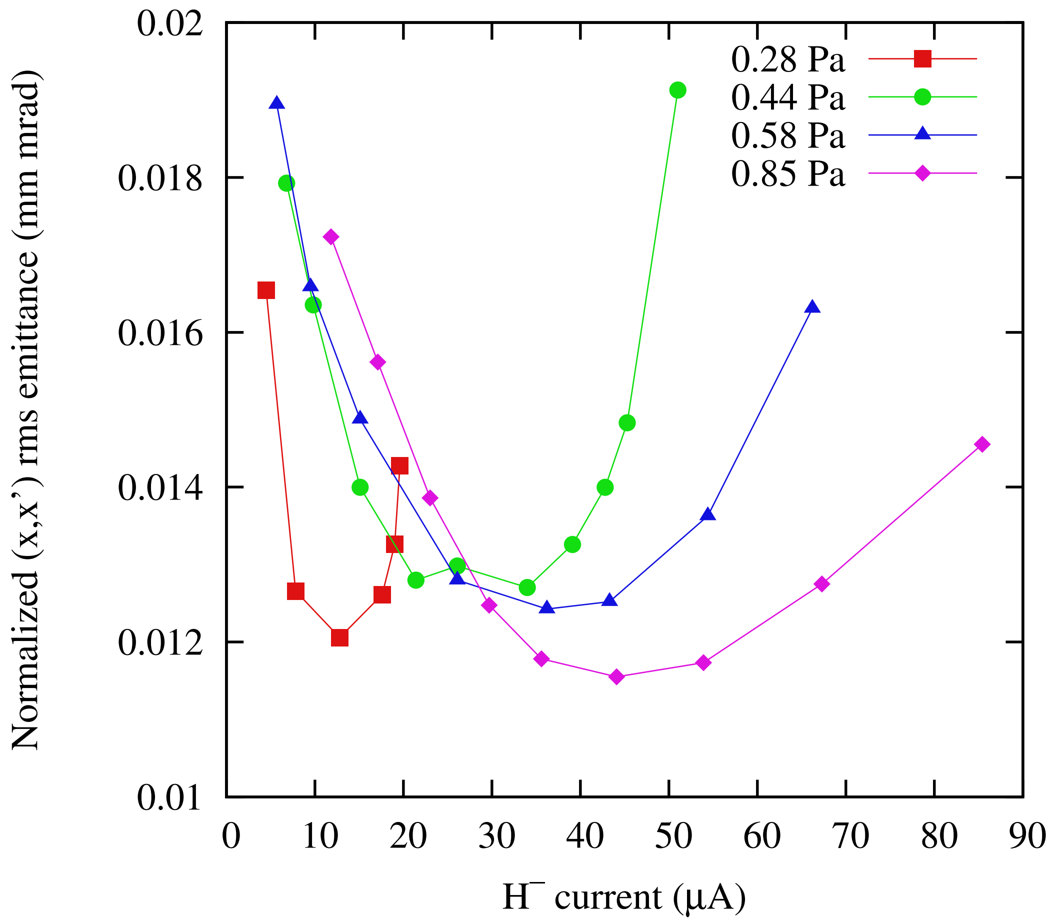
Emittance as a probe for plasma sheath



PELLIS ion source at JYFL Pelletron accelerator

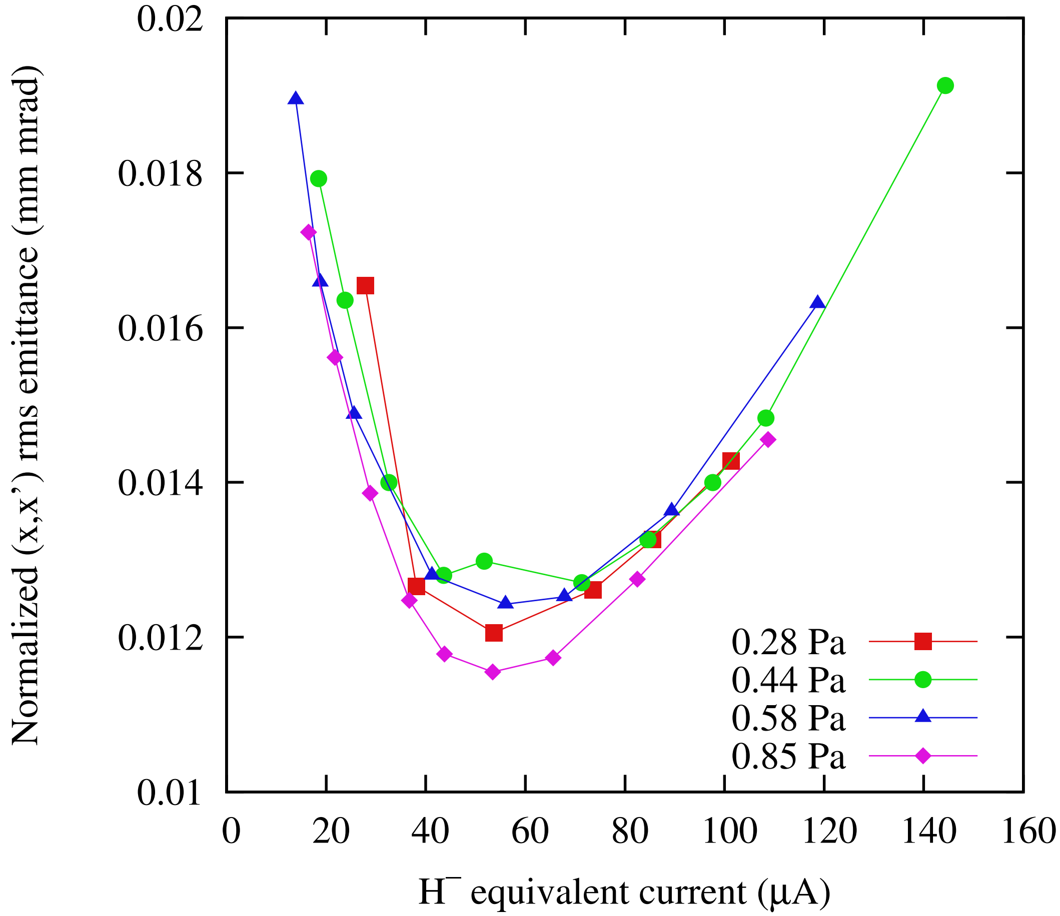
Experimental emittance

Varying source pressure and filament power



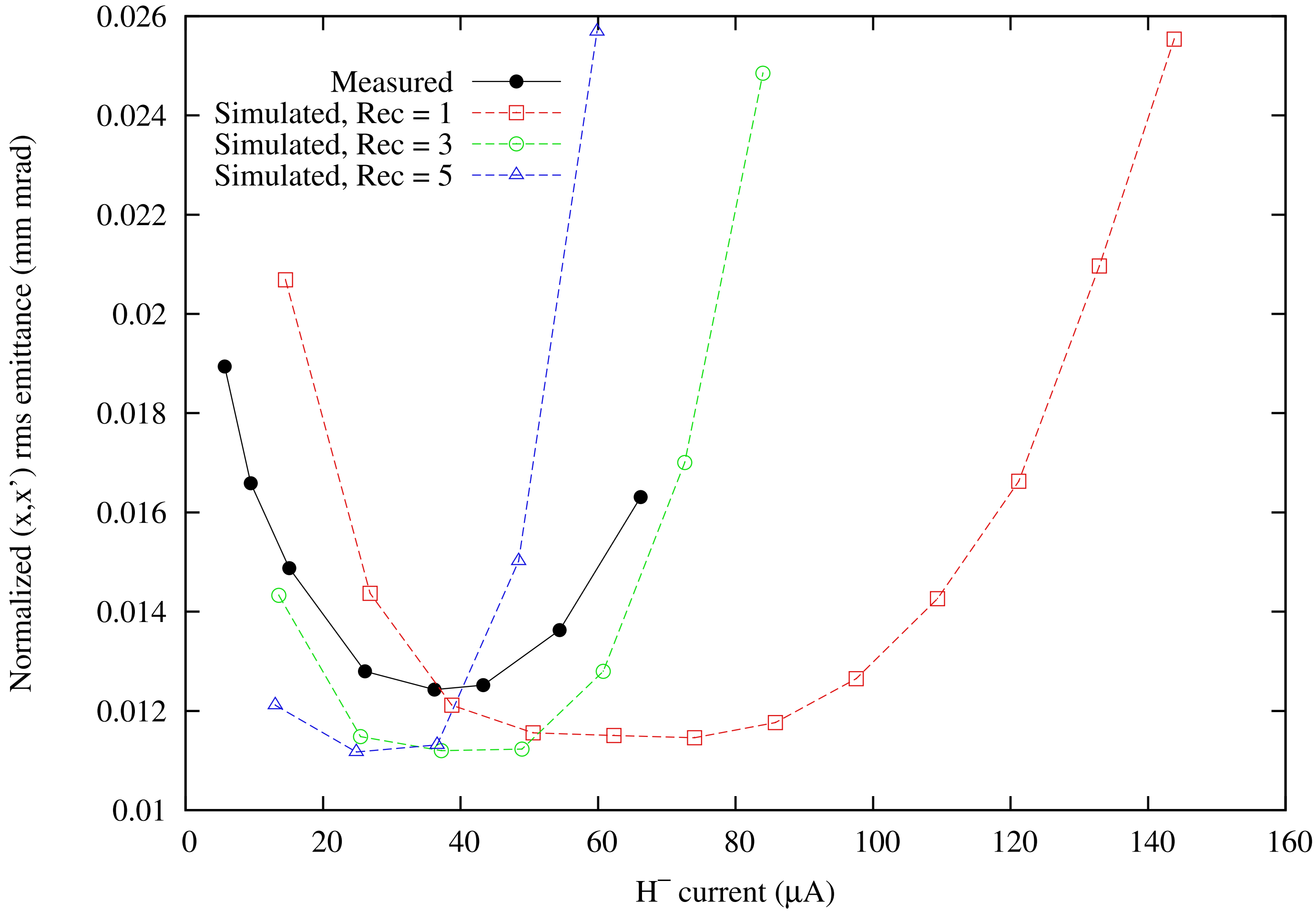
Experimental emittance

Varying source pressure and filament power



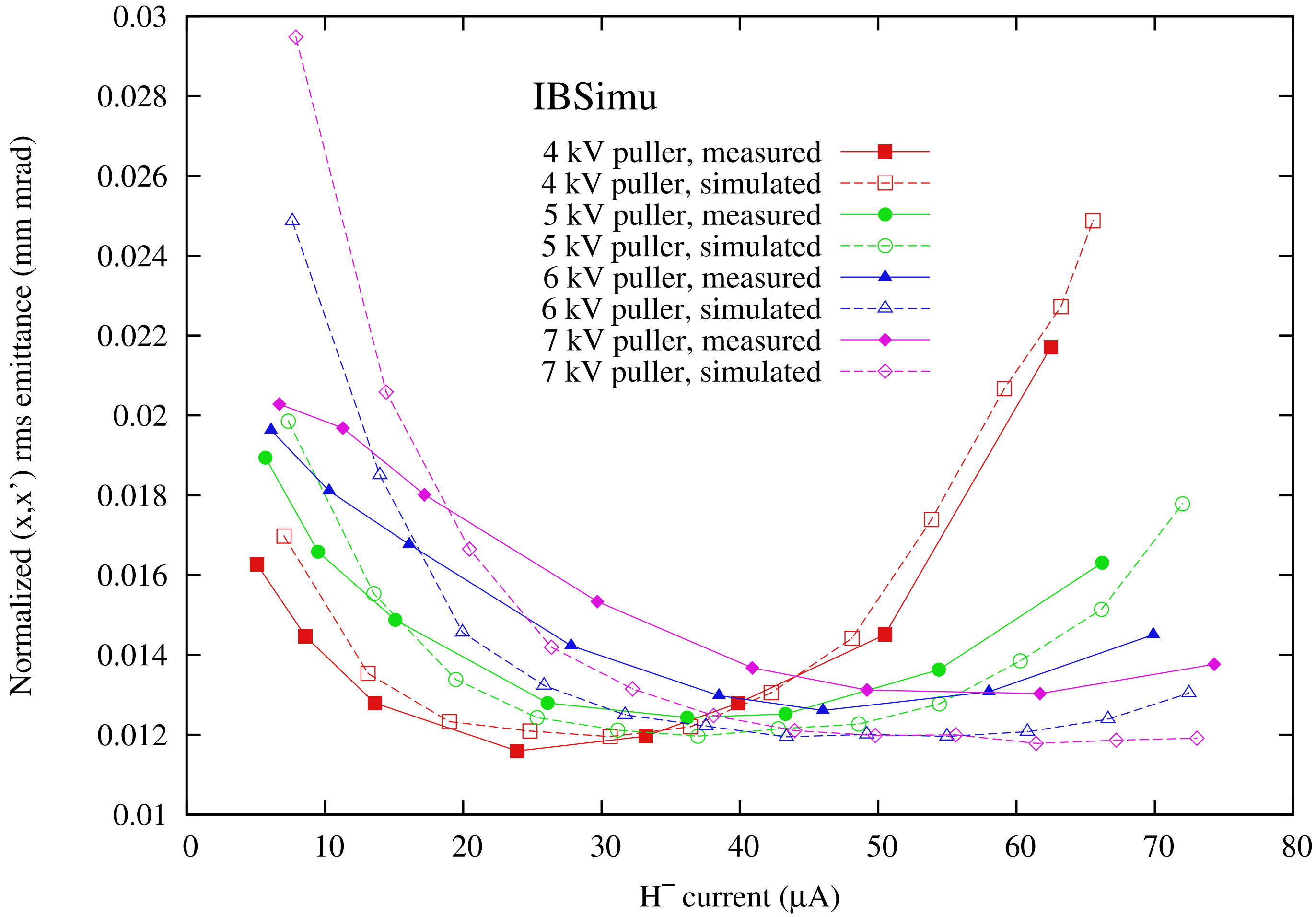
Equivalent current is $I_{H^-} = I_e \sqrt{m_e/m_{H^-}}$

Experiment vs. simulation



There seems to be higher charge density at the plasma sheath than what can be calculated from the beam current.

Emittance vs. simulation



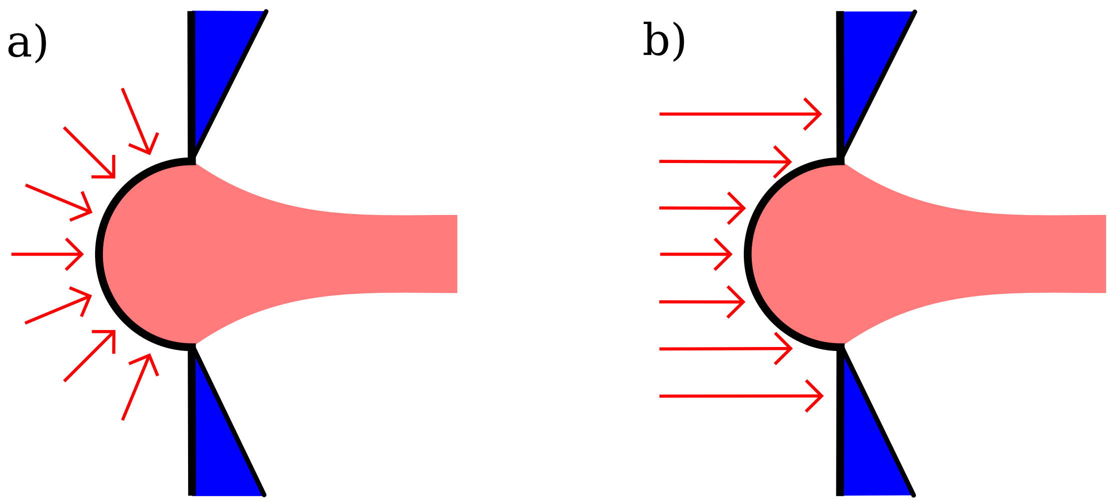
Fitting produced $R_{ec} = 3$ and $T_t = 0.75$ eV. Rest of parameters from literature.

Other artefacts of plasma model

The flux direction at sheath edge

a) In reality

b) In simulations



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