Simulation and experimental characterization of the extraction of a focused broad ion beam from an inductively coupled plasma source

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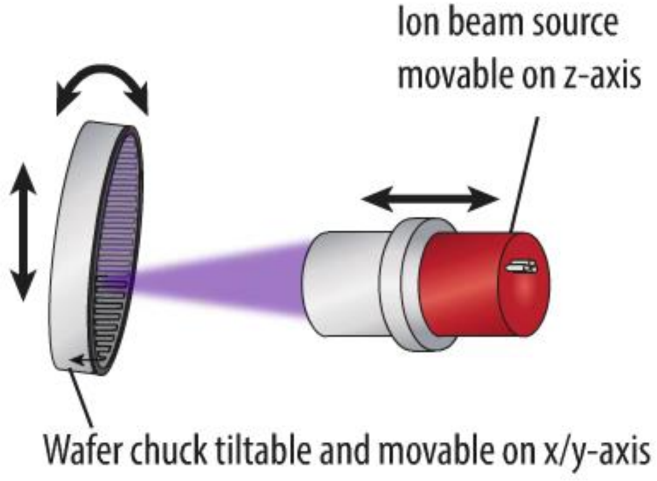
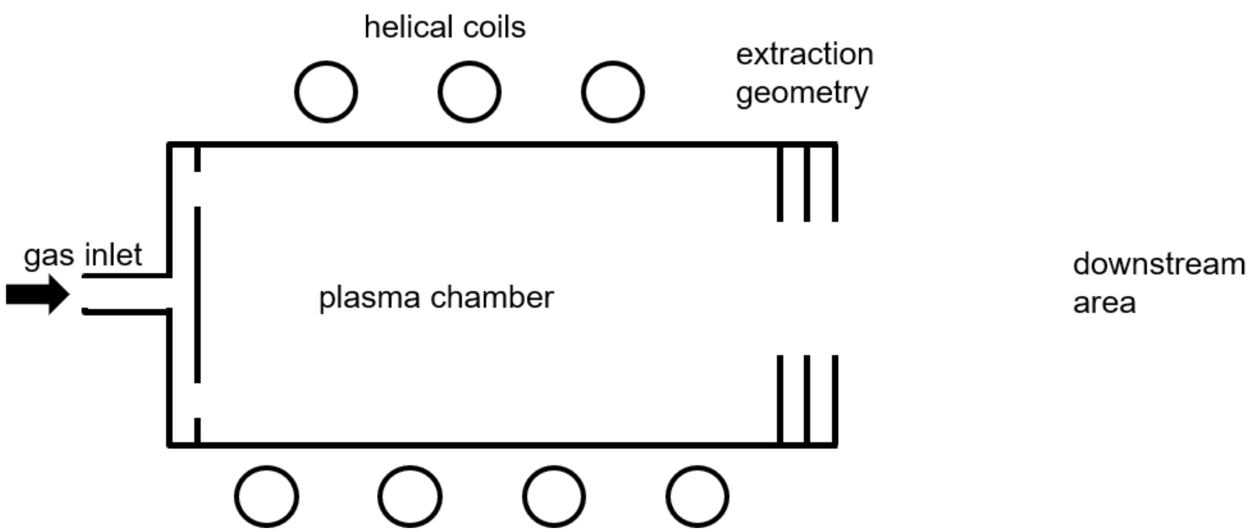
Application – Ion Beam Trimming

- Focused broad ion beam for ion beam trimming (IBT) applications
- Ion beam width needs to match the applications topography error to be corrected
- Assist and accelerate the characterization, optimization and development of ion beams sources with simulations



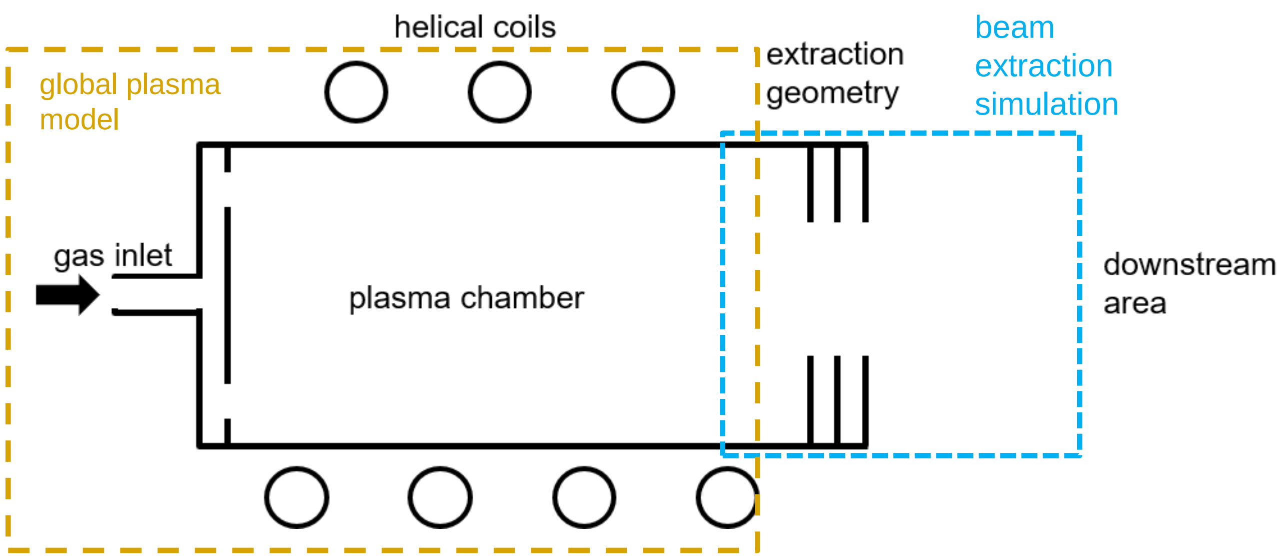
Inductively coupled plasma chamber

- Inductively coupled plasma (ICP) inside the plasma chamber
- Potential difference in grid electrodes accelerates ions from the plasma towards the downstream area



Simulation approach

- Inductively coupled plasma (ICP) inside the plasma chamber
- Potential difference in grid electrodes accelerates ions from the plasma towards the downstream area
- Plasma parameters calculated for the source geometry and operation conditions by a global plasma model
- Numerical simulation of the beam extraction from the plasma in equilibrium state



Global plasma model for gridded ICP

- Analytical model for determination of plasma parameters for ICP sources [1]
- Solving ordinary differential equations (ODE) for species densities and temperatures:
  - Particle balance of ions:

$$\frac{dn}{dt} = nn_{\mathrm{g}}K_{\mathrm{iz}} - nu_{\mathrm{B}}\frac{A_{\mathrm{eff}}}{V}$$

  - Particle balance of neutrals:

$$\frac{dn_{\mathrm{g}}}{dt} = \frac{Q_0}{V} + nu_{\mathrm{B}}\frac{A_{\mathrm{eff,ion}}}{V} - nn_{\mathrm{g}}K_{\mathrm{iz}} - \Gamma_{\mathrm{g}}\frac{A_{\mathrm{g}}}{V}$$

  - Neutral power balance:

$$\frac{d(\frac{3}{2}n_{\mathrm{g}}k_{\mathrm{B}}T_{\mathrm{g}})}{dt} = 3\frac{m_{\mathrm{e}}}{M}k_{\mathrm{B}}(T_{\mathrm{e}} - T_{\mathrm{g}})nn_{\mathrm{g}}K_{\mathrm{el}} - \frac{1}{4}Mu_{\mathrm{B}}{}^2nn_{\mathrm{g}}K_{\mathrm{in}} - \kappa(\frac{T_{\mathrm{g}}-T_{\mathrm{g0}}}{\Lambda_0})\frac{A}{V}$$

  - Electron power balance

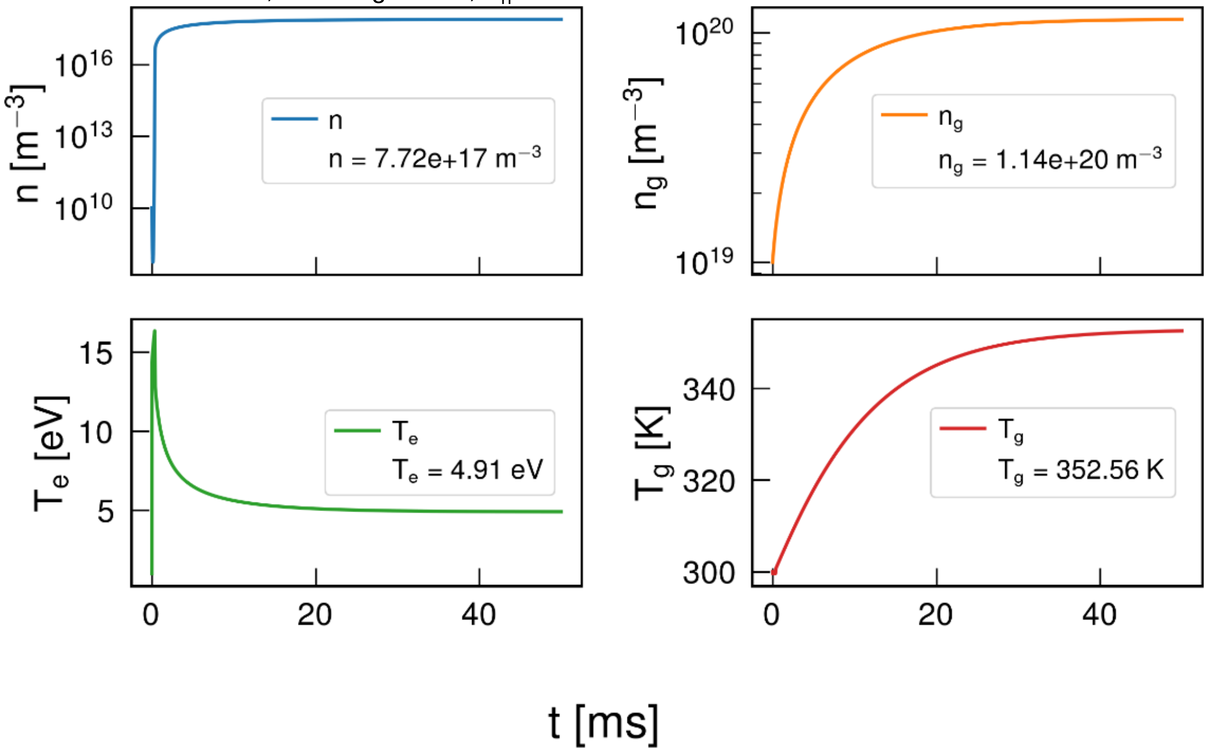
$$\frac{d(\frac{3}{2}n_{\mathrm{e}}k_{\mathrm{B}}T_{\mathrm{e}})}{dt} = P_{\mathrm{abs}} - P_{\mathrm{loss}}$$

1: P. Chabert et al. Phys. Plasmas 19**,** 073512 (2012).

Global plasma model for gridded ICP

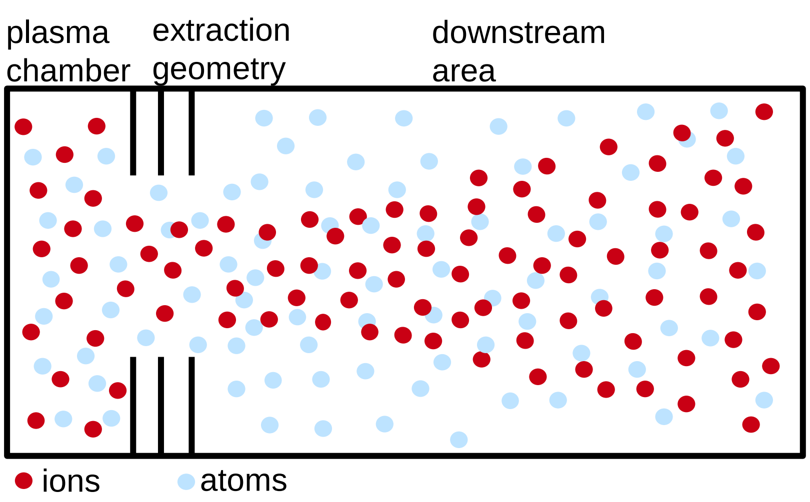
- Physical constants and properties of the inert gas
- Plasma chamber geometry (chamber, grid and coil geometry; grid transparency)
- Operation condition (gas flow rate; radio frequency (rf) power)

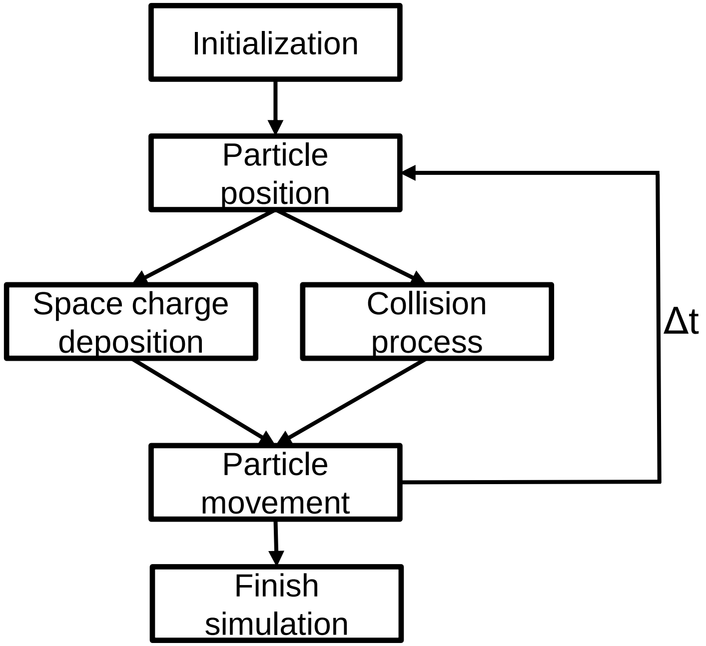
Example - cylindrical chamber: d = 37 mm, l = 35 mm, extraction grid with d = 10 mm, 1 sccm gas flow, P_{rf} = 100 W



PIC-DSMC approach

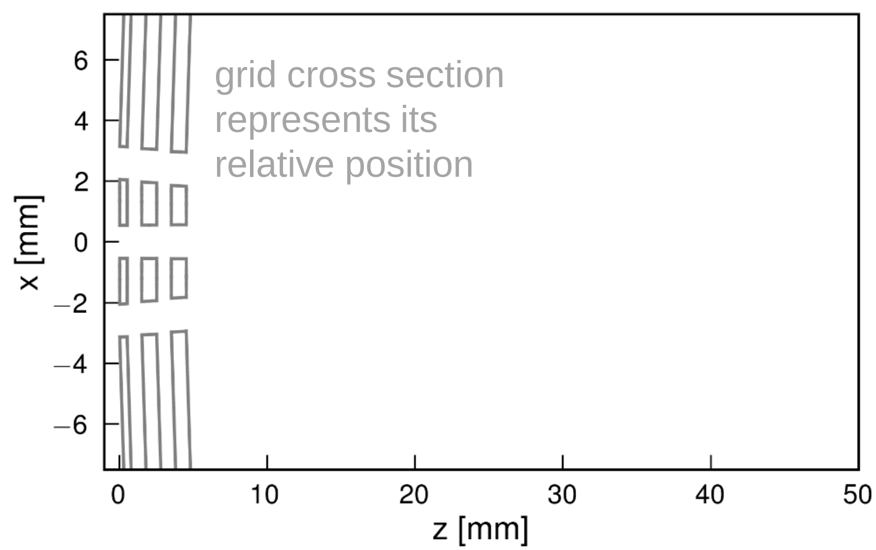
- Particle-in-cell and direct-simulation Monte-Carlo (PIC-DSMC) approach
- Time dependent macro-particle movement in E- and B-fields
- Multiple charged and neutral plasma species for coherent physical modeling
- Modeling of electron population in the plasma and the ion beam (for space charge compensation, SCC) via Boltzmann relation

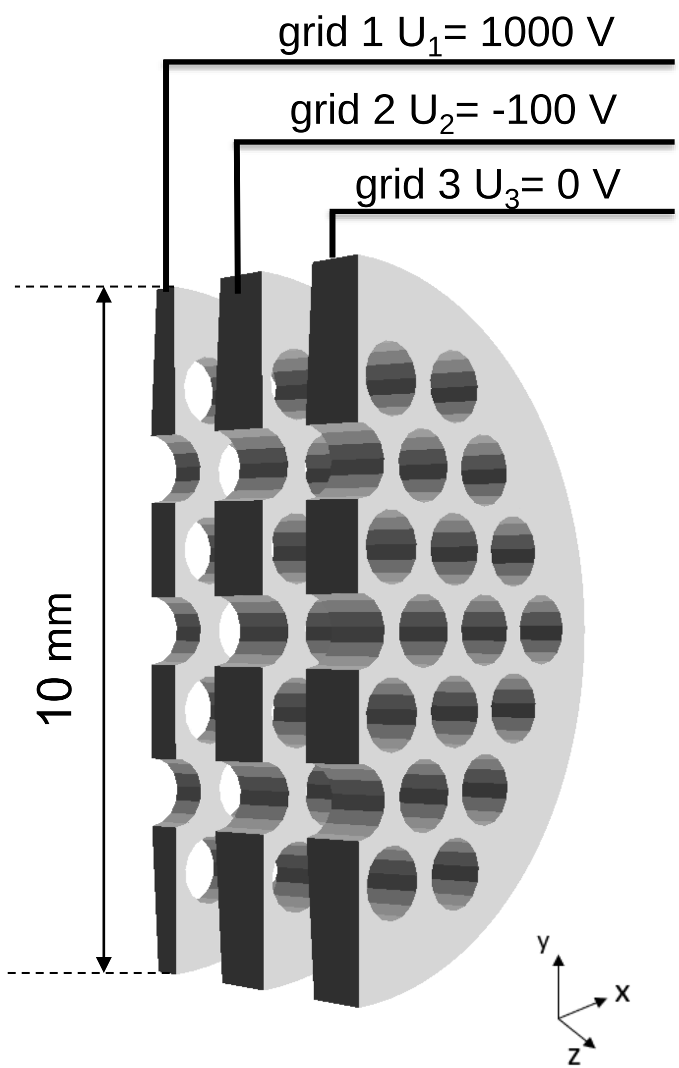




10 mm extraction grid

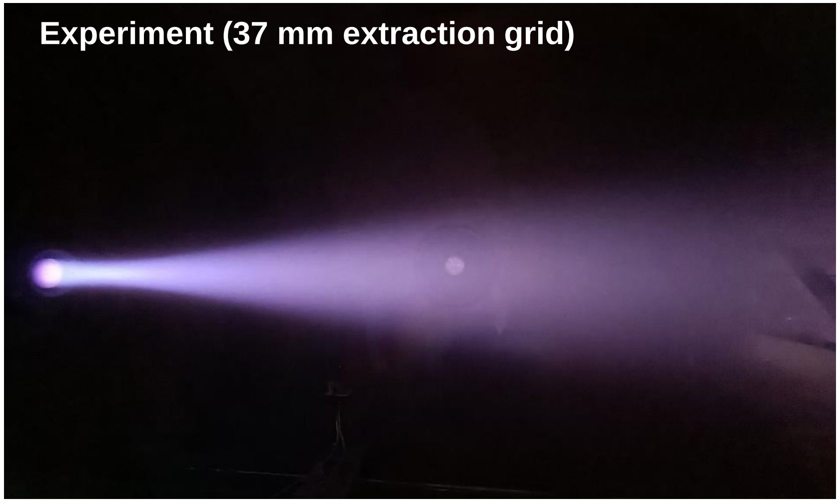
- Multi-aperture three-grid extraction system
- Curved grids for geometric focus made from graphite with thicknesses of 0.5 and 1 mm
- Modeling of grids with 10 mm and 37 mm diameter and single-aperture systems with a diameter of 1 mm



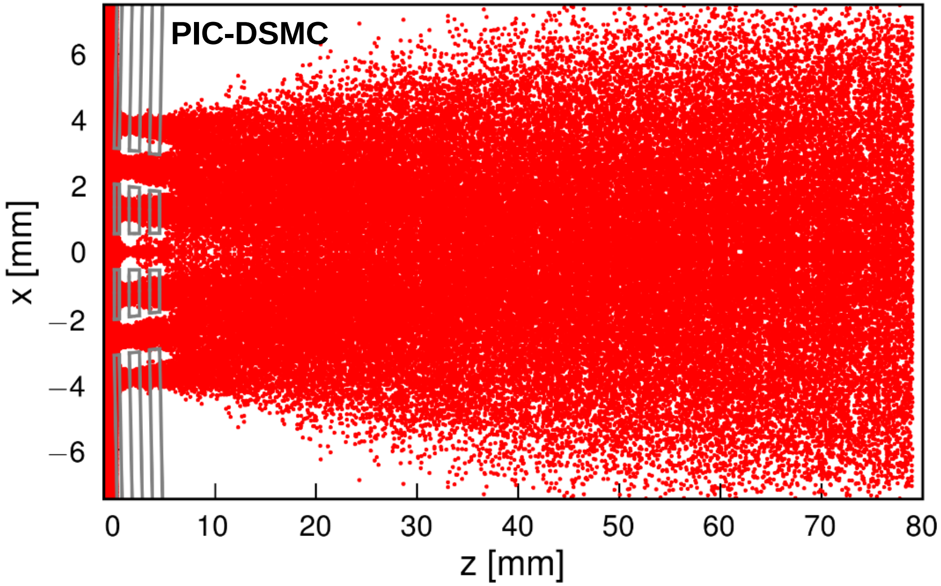


10 mm extraction grid

- Projection of 3D simulation only containing the position of ions (red)
- Full ion beam is interpolated from a simulation of a 30° piece of the full geometry (symmetry of the system is exploited to reduce the calculation time)
- Focus point visible after further examination

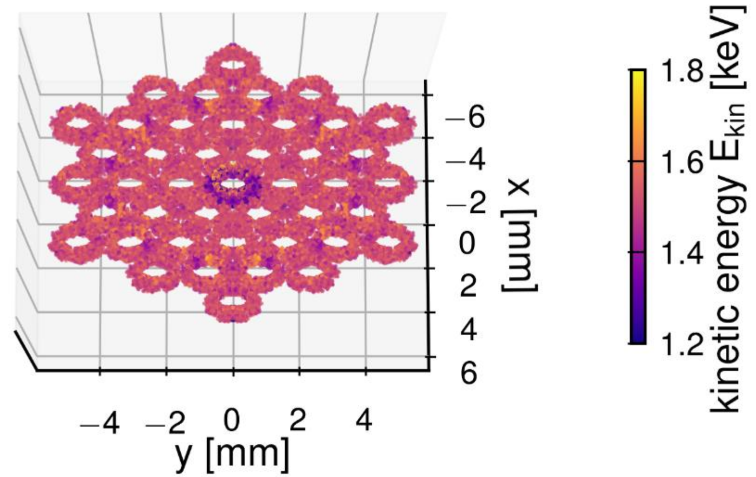


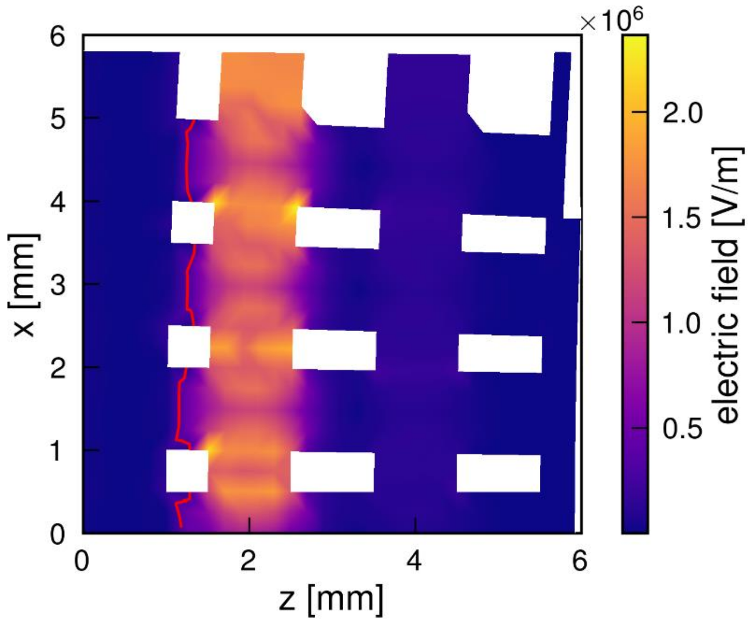
Projection of particle positions in x-z-plane

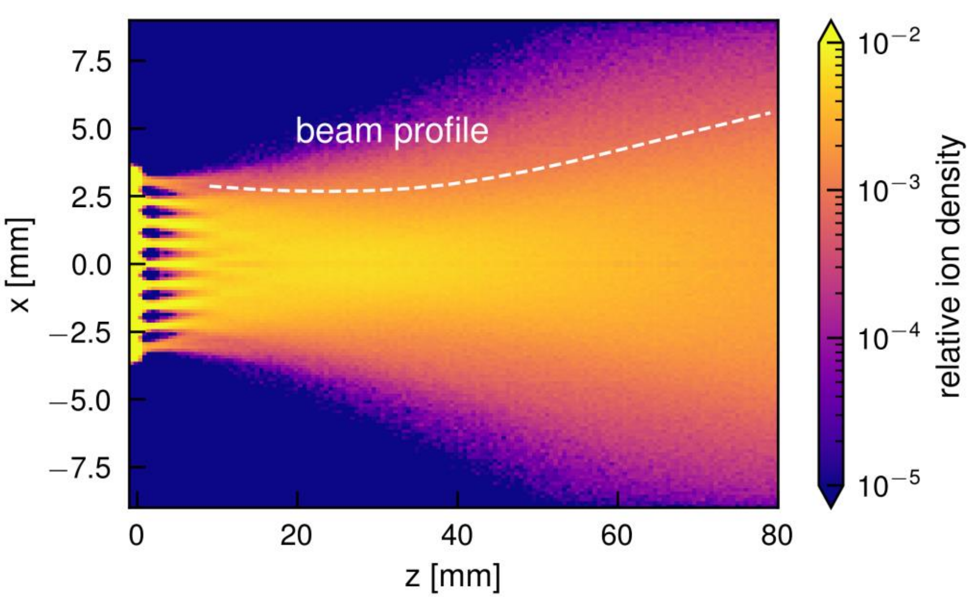


10 mm extraction grid

- Prediction of grid erosion and resulting changes in the extracted ion beam properties
- Evaluation of plasma properties at the extraction geometry → plasma sheath
- Characterization of the extracted ion beam



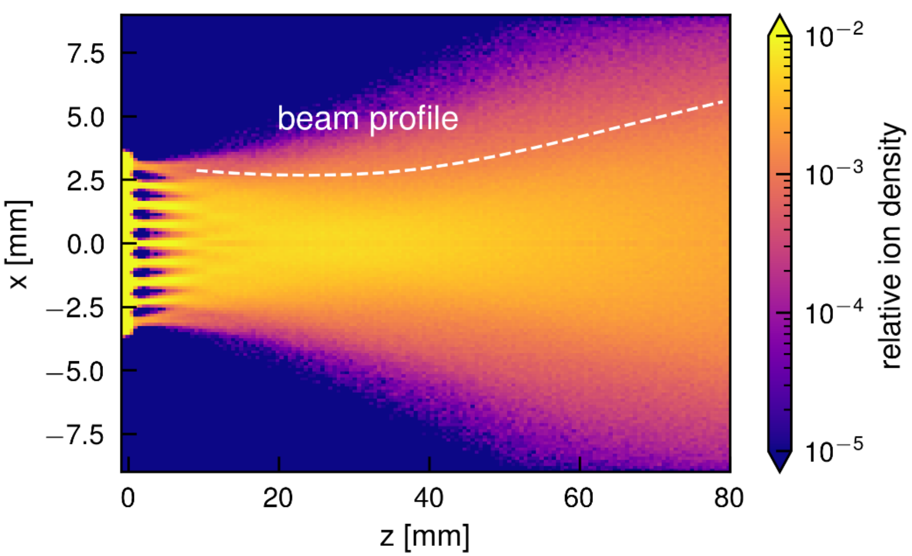


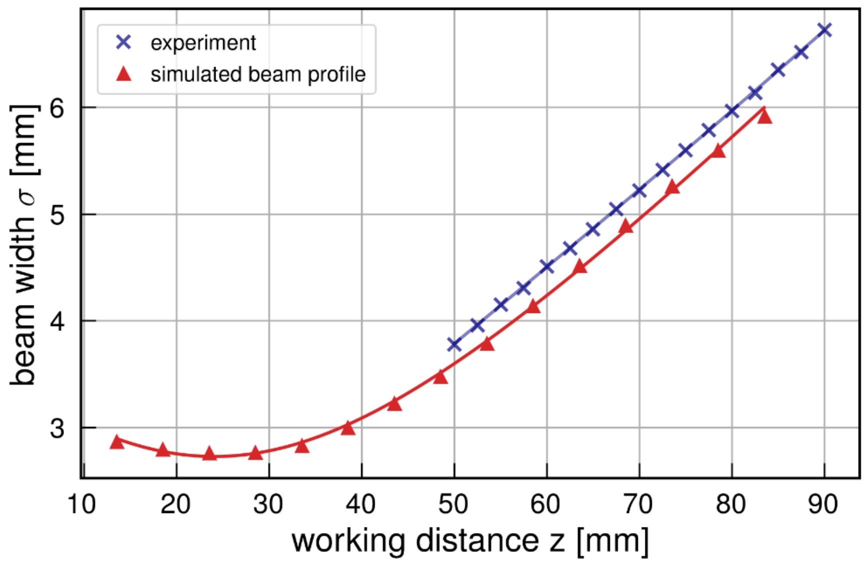


Comparison Experiment - Simulation

- Using the same operation conditions for simulation and experiment (10 mm extraction grid, 100 W rf power, 1 sccm Ar-gas flow, 1.5 keV beam extraction)
- Evaluation of the beam width at various distances z from the ion source
- Fit of Gauss function at each beam cross section: standard deviation σ corresponds to beam width

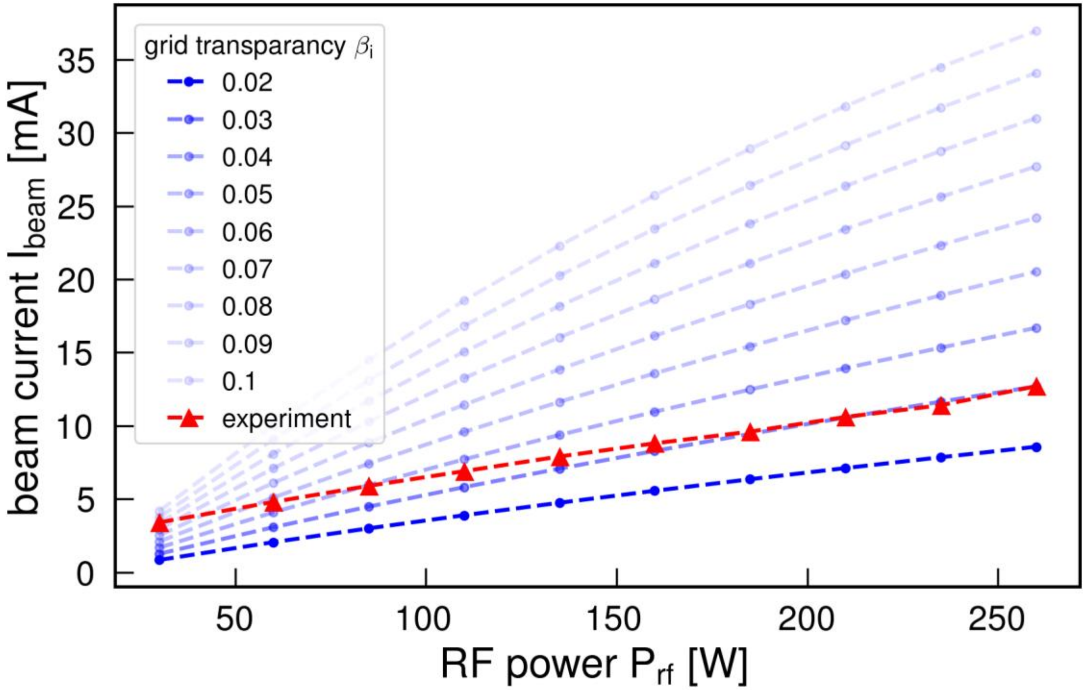
➢ Investigation of a larger set of parameters: variation of rf power





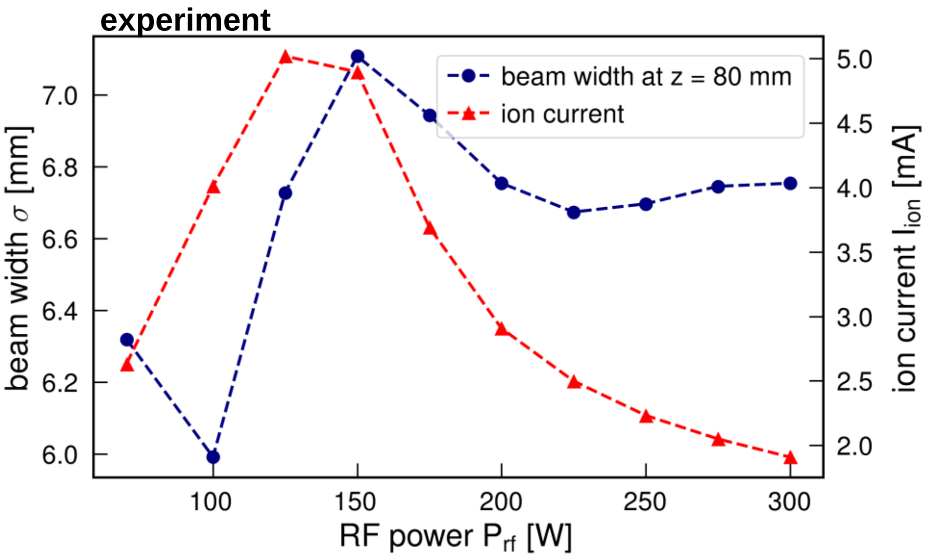
Comparison Experiment - Simulation

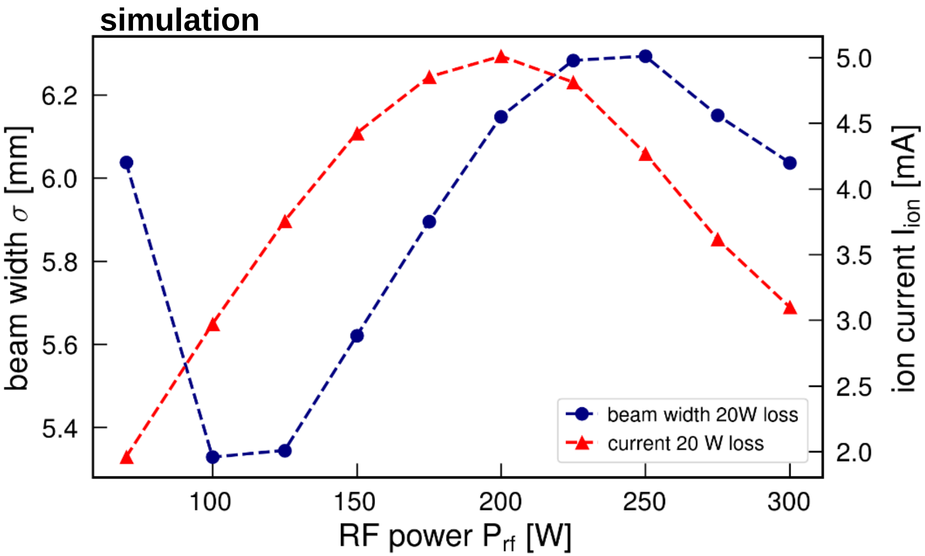
- Two critical aspects for a comparison between experiment and simulation:
  - Power loss in the experimental configuration
  - Variable grid transparency for ions during power variation in global ICP model
- Accordance of beam current (current extracted through first extraction grid) only by considering variable transparencies for different applied rf powers



Comparison Experiment - Simulation

- Variation of rf power in experiment and simulation
- Evaluation of the beam width and ion current at a distance of z = 80 mm from the plasma source
- Consideration of variable grid transparency and constant power loss of 20 W

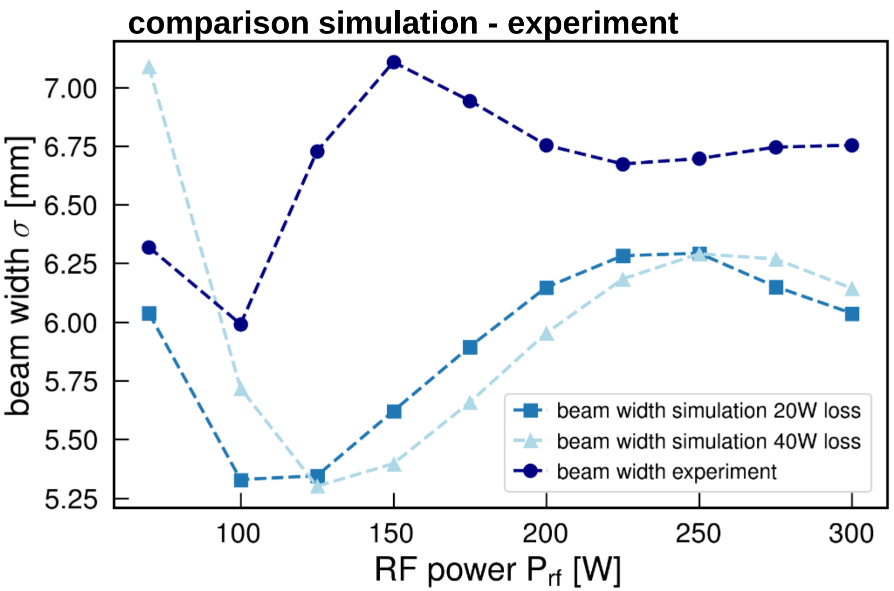


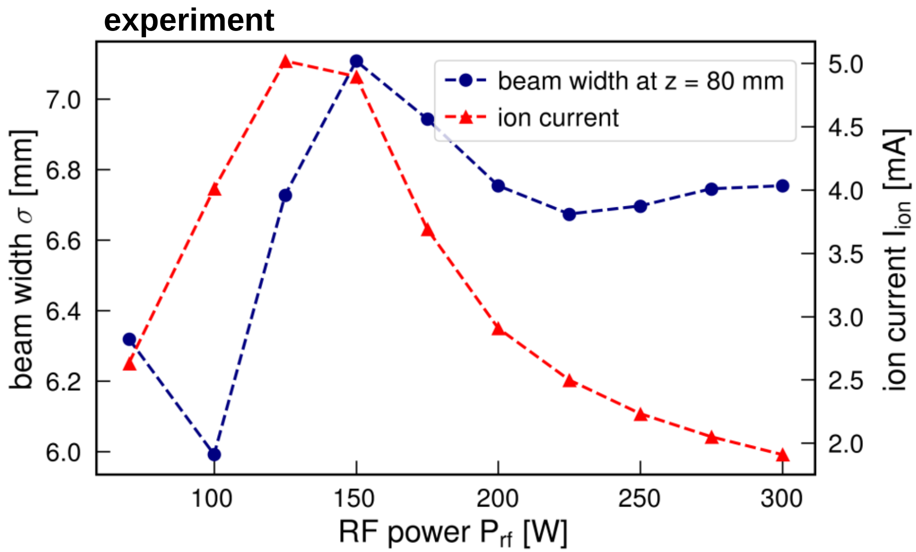


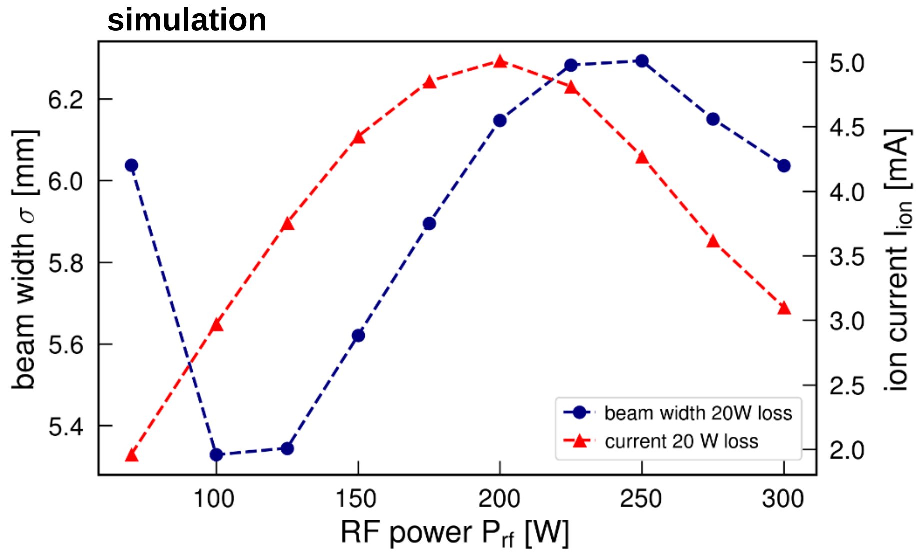
Comparison Experiment - Simulation

- Beam width comparison with constant 20 W and 40 W power loss
- Minor deviations in total beam width while differences in the trend are correct

➢ correct power scaling required

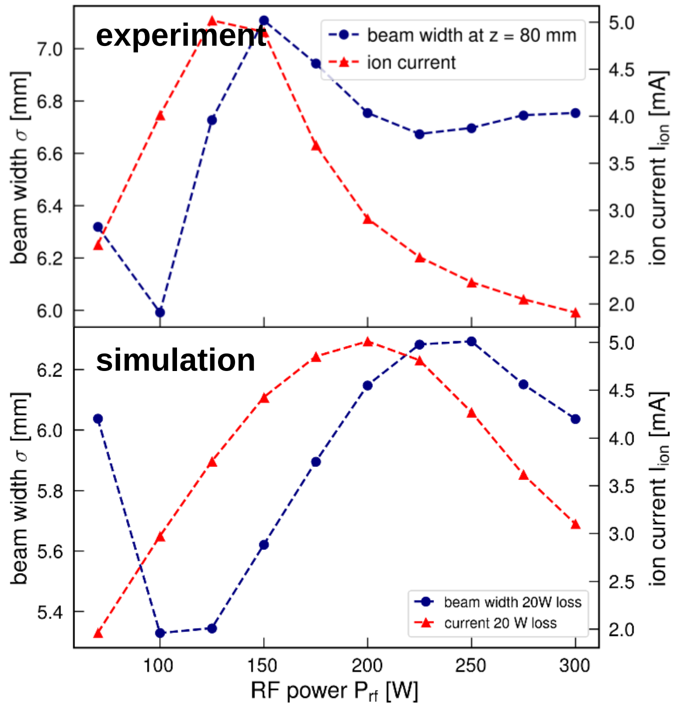






Conclusion and Outlook

- Theoretical model to predict ion beam properties based on source geometry and operation conditions
  - Global model for ICP to determine plasma parameters of the system
  - Numerical PIC-DSMC simulation of the beam extraction through a three-grid system
- Good agreement between experimental data and simulated ion beams



Experimental setup of the ion source → Operation conditions → Global model for ICP → Plasma parameters → Numerical PIC-DSMC simulation scia systems

Conclusion and Outlook

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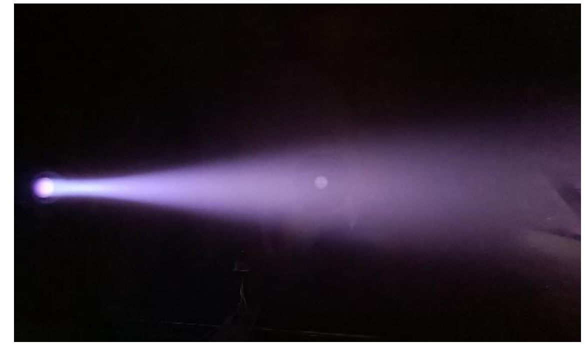
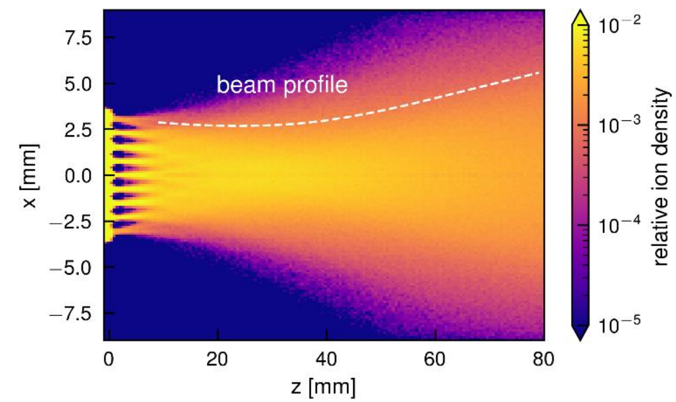
- Further experimental investigation of the system
  - Examination of the actual power loss
  - Measuring plasma parameters in the chamber and in the beam for verification
- Improvement of the model to include a self consistent calculation of the grid transparency for ions
- Using the model for optimizations and further development of new ion sources





Thank you!

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