PIC SIMULATIONS OF ION DYNAMICS IN ECR ION SOURCES

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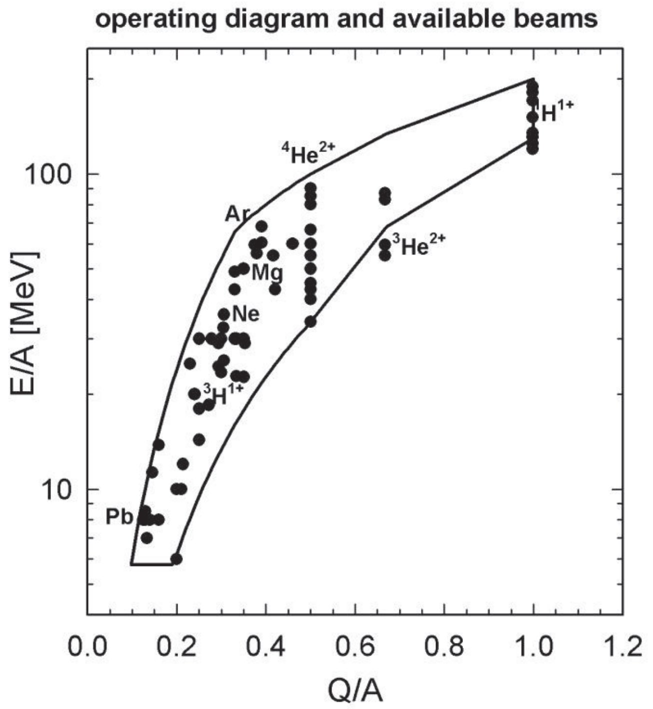
OUTLINE

- **ECR Ion Sources: layout and specific features**
- **Description of the physical model and PIC code**
- **Results of simulations**
- **Conclusions**

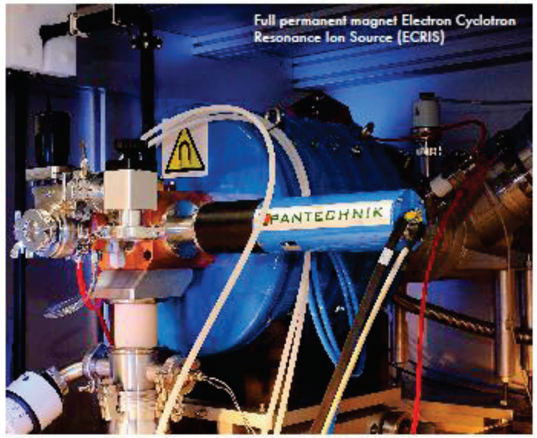
The central facility of KVI is AGOR (Accélérateur Groningen-Orsay), a superconducting K=600 MeV cyclotron for the acceleration of light and heavy ions.
The biggest experiment is TRIµP, meant for trapping radioactive ions produced with AGOR.
Also, the AGOR group has activities in the area of irradiations with the AGORFIRM-facility, an in-air beamline dedicated to irradiation of samples with high energy beams up to 190 MeV protons (solar spectrum) and up to 90 MeV/u Carbon.
The cyclotron is equipped with 3 external ion sources – multicusp proton source, SUPERNANOGAN, A-ECRIS.



SUPERNANOGAN

PANTECHNIK

Supernanogan



THE REFERENCE for Hadrontherapy

Supernanogan is an ECR ion source, reliable and with high performance, which the magnetic circuit is entirely made with permanent magnets both for the radial and longitudinal fields, so the total electrical power is extremely low. The source includes 220kg of permanent magnets and 300kg of lead protection. Its performance is the best of its category, allowing the production of beam currents of 200 eμA of Ar^{8+} and C^{4+}. Supernanogan can run with RF power up to 600W at 14.5 GHz depending on the element and charge state needed. The maximum extracting voltage is 30 kV. This ion source is working in several laboratories and is the reference source for Hadrontherapy, the ultimate cancer treatment method. Supernanogan can be used in any kind of accelerators, i.e. RFQ, LINAC, Synchrotrons, Cyclotrons, etc.

ion / Q	1	2	4	6	8	9	20	27
H	2000							
He	2000	1000						
C			200	2,5				
Ar	1000		250	200	200	90		
Xe	500				220		15	1
Au							20	6
Pb							10	1

Beam intensity for various charge states given in electric μA. This table indicates typical intensities for selected charge states.

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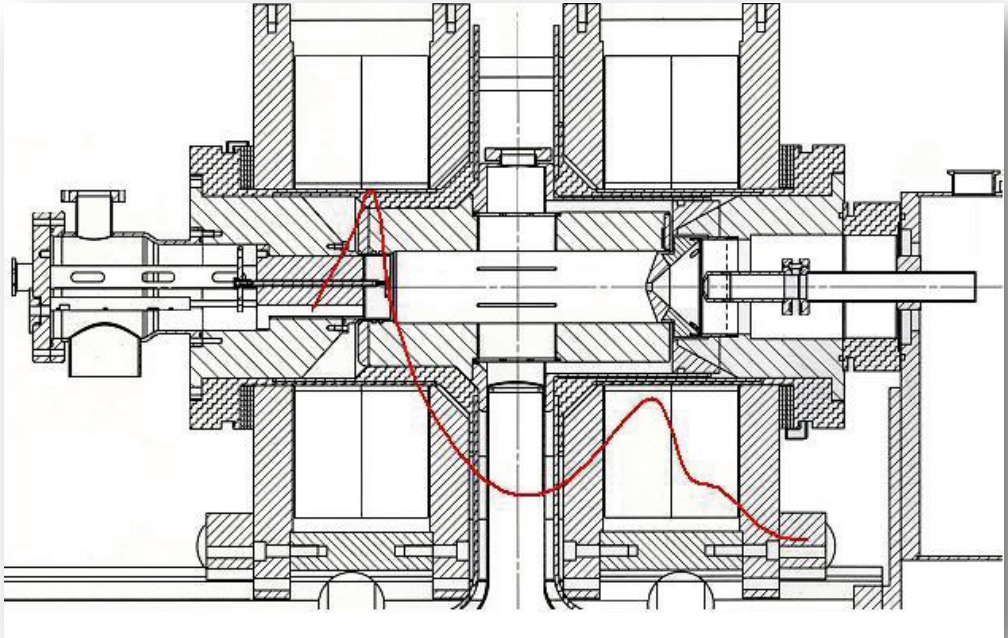
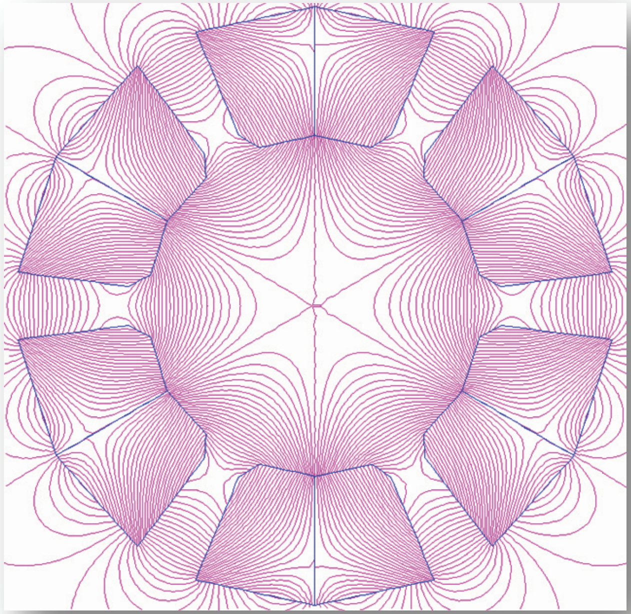
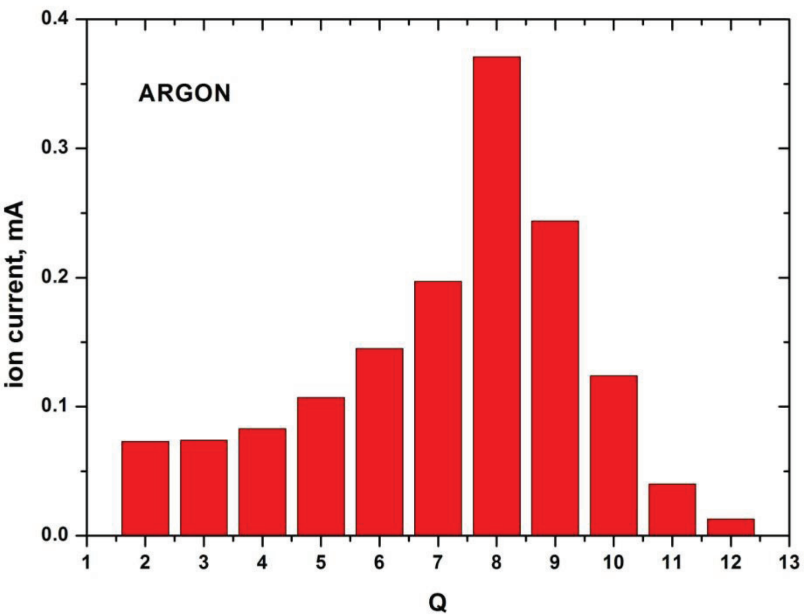
KVI-AECRIS

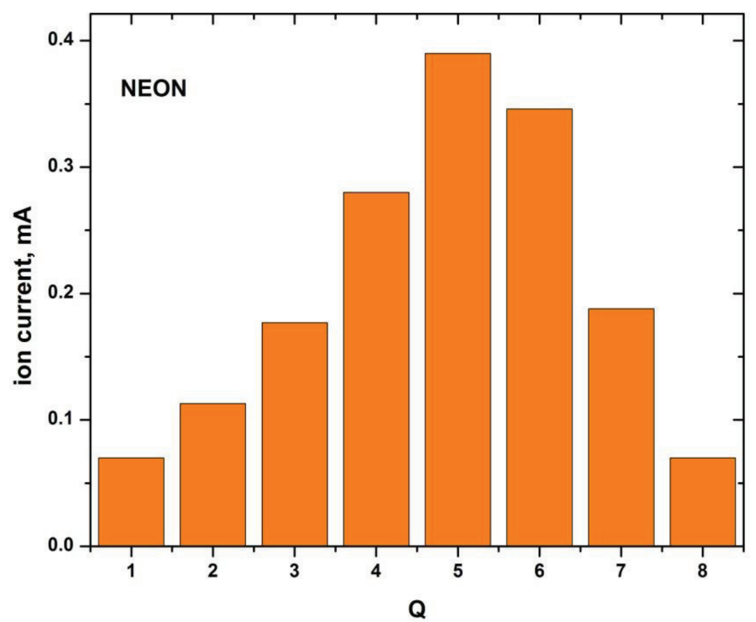




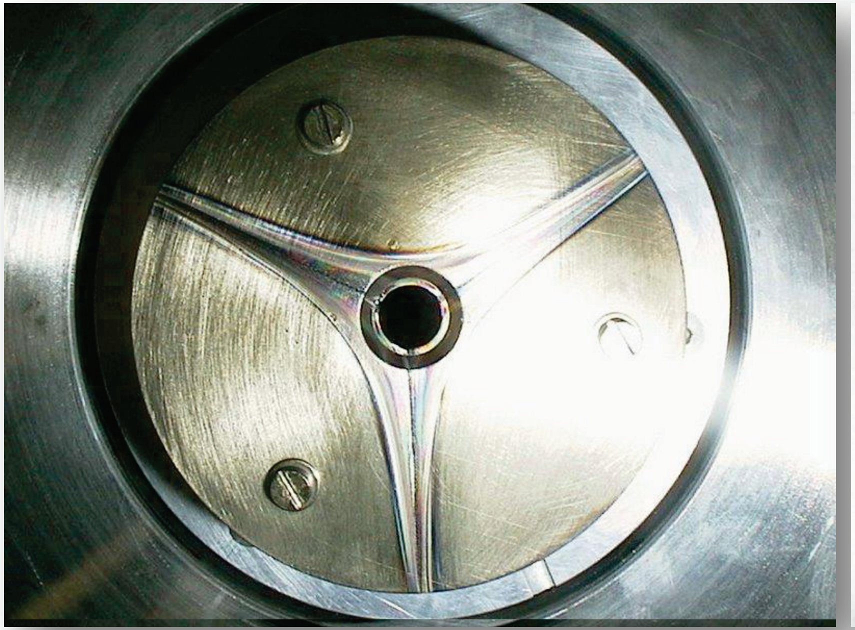
Al plasma chamber, hexapole with the slits for better pumping of the chamber.
RF frequency 14.1+(11-12.5) GHz
Binj=2.1 T, Bmin=0.36 T Bext=1.1 T, Brad=0.75 T
Chamber length 30 cm
Chamber diameter 7.6 cm
Extraction aperture 0.8 cm

Charge-state-distributions of the extracted currents - A-ECRIS

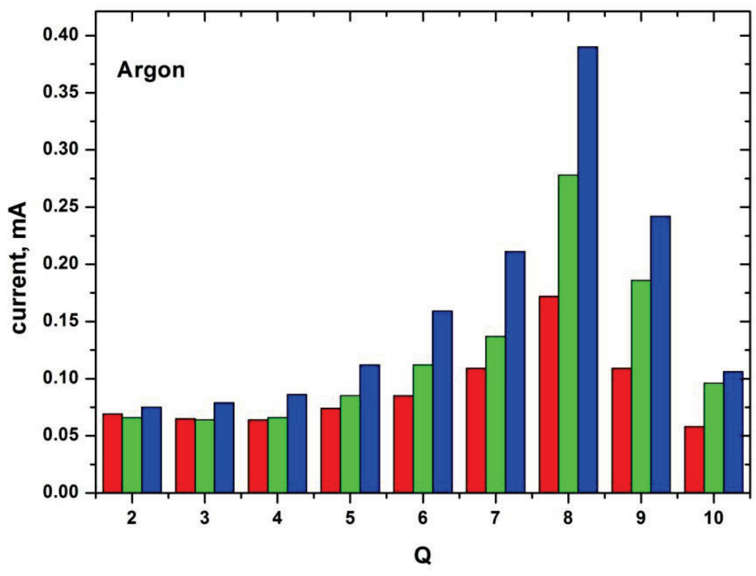


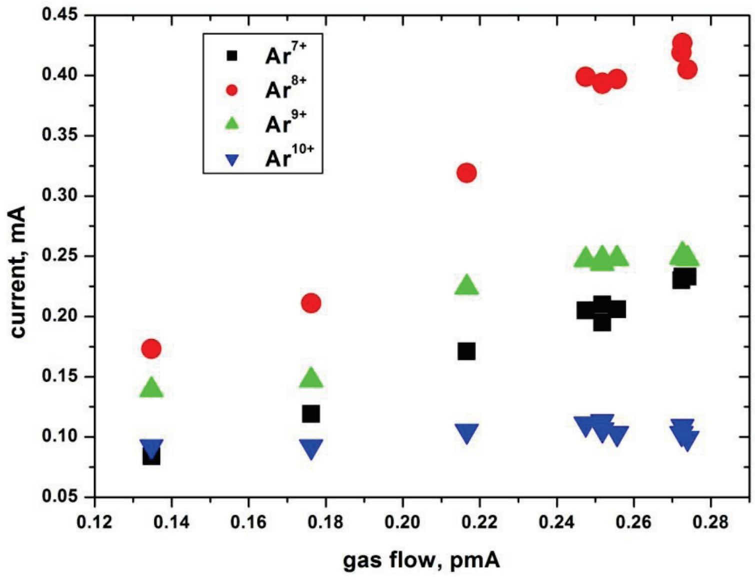


Sputtering of the extraction electrode

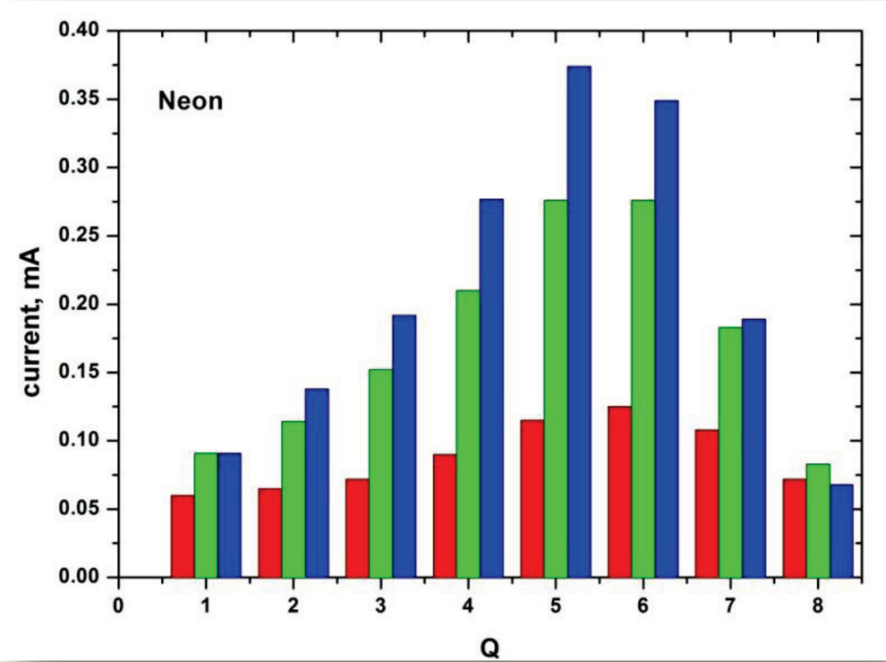


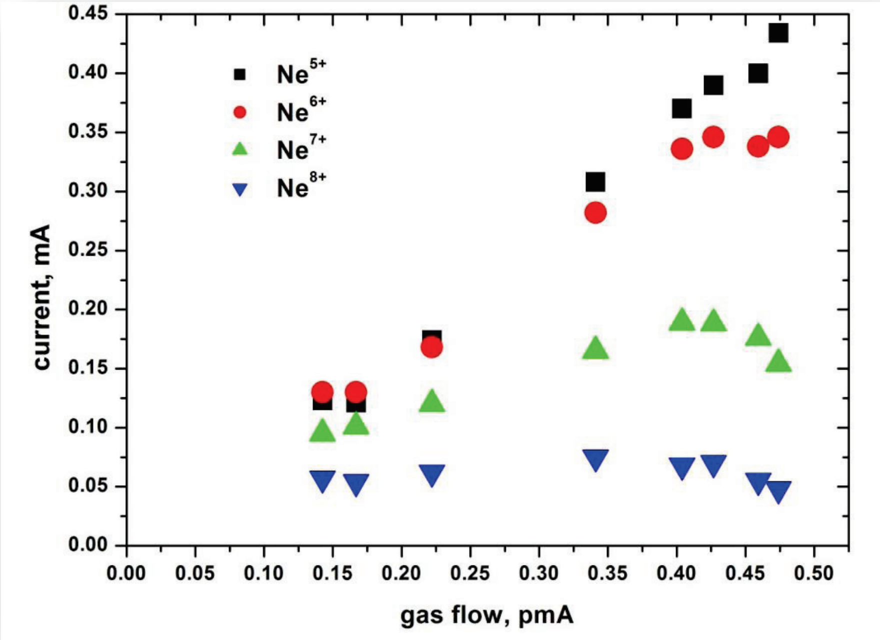
Gas-pressure dependencies



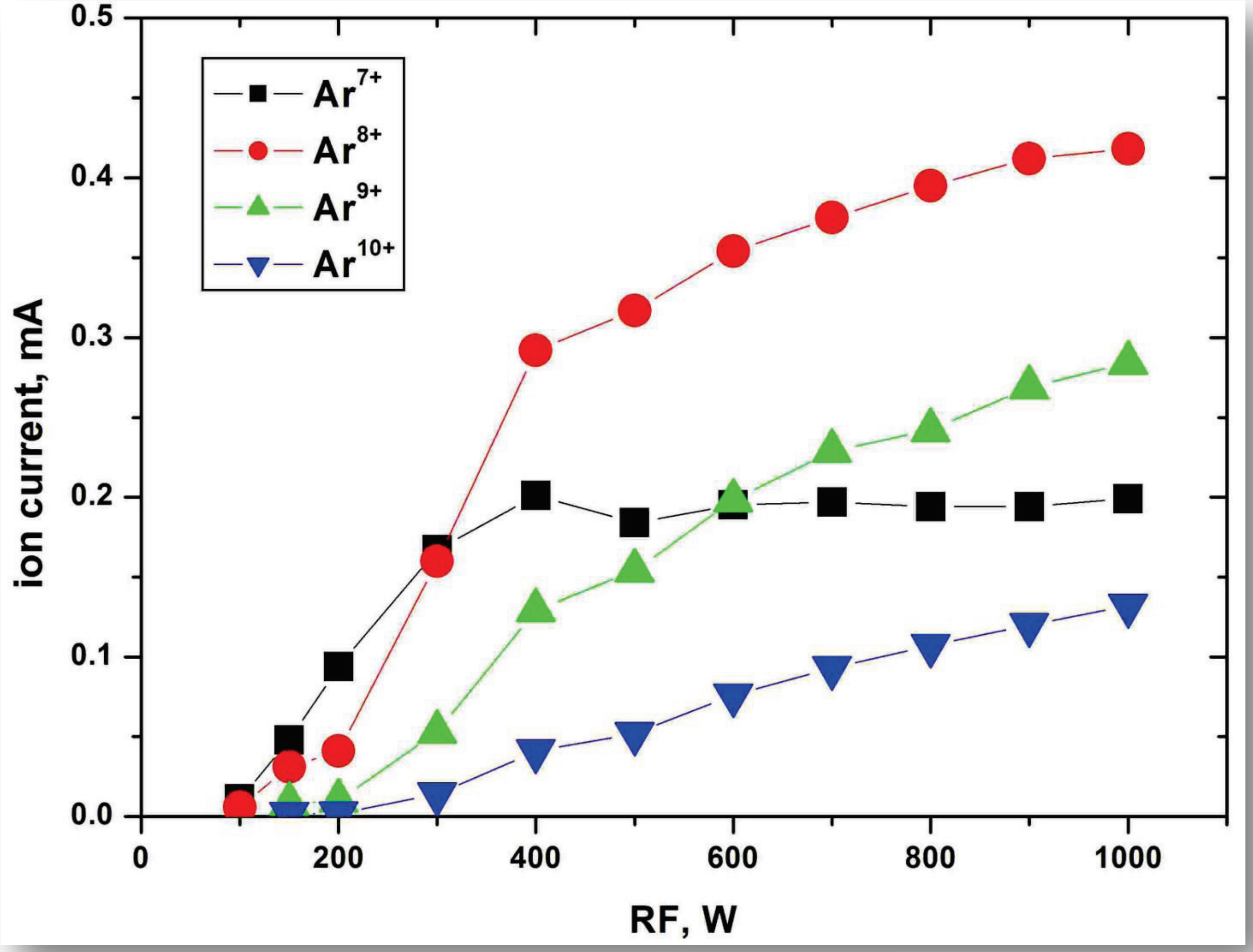


Gas-pressure dependencies

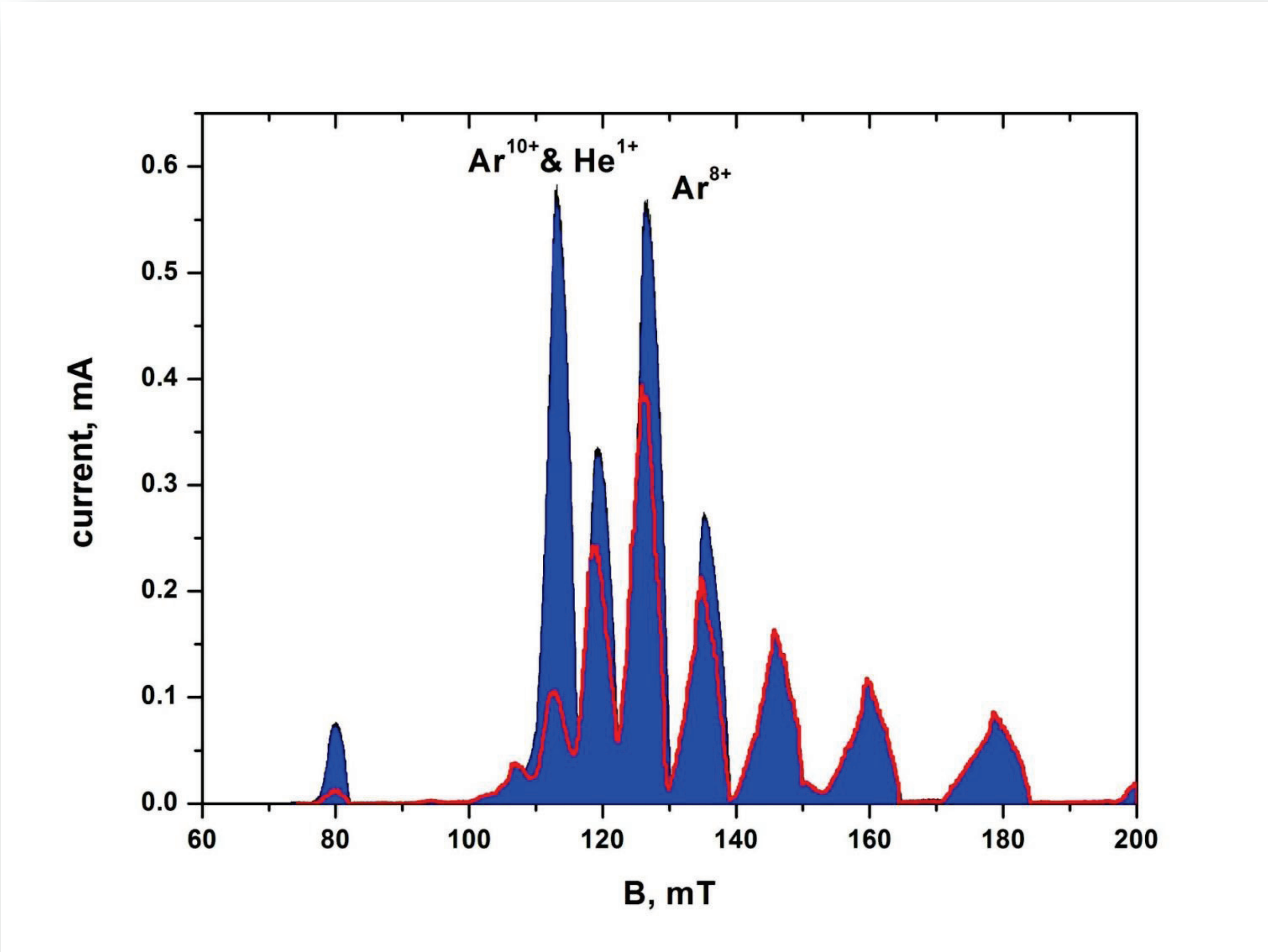




RF power dependence



Argon-helium gas mixing



Reasons for such peculiarities in ECRIS performance are not clear at the moment.

Response to the gas flow variations – charge-exchange collisions with the neutrals? Recombination? Loss of the ion confinement?

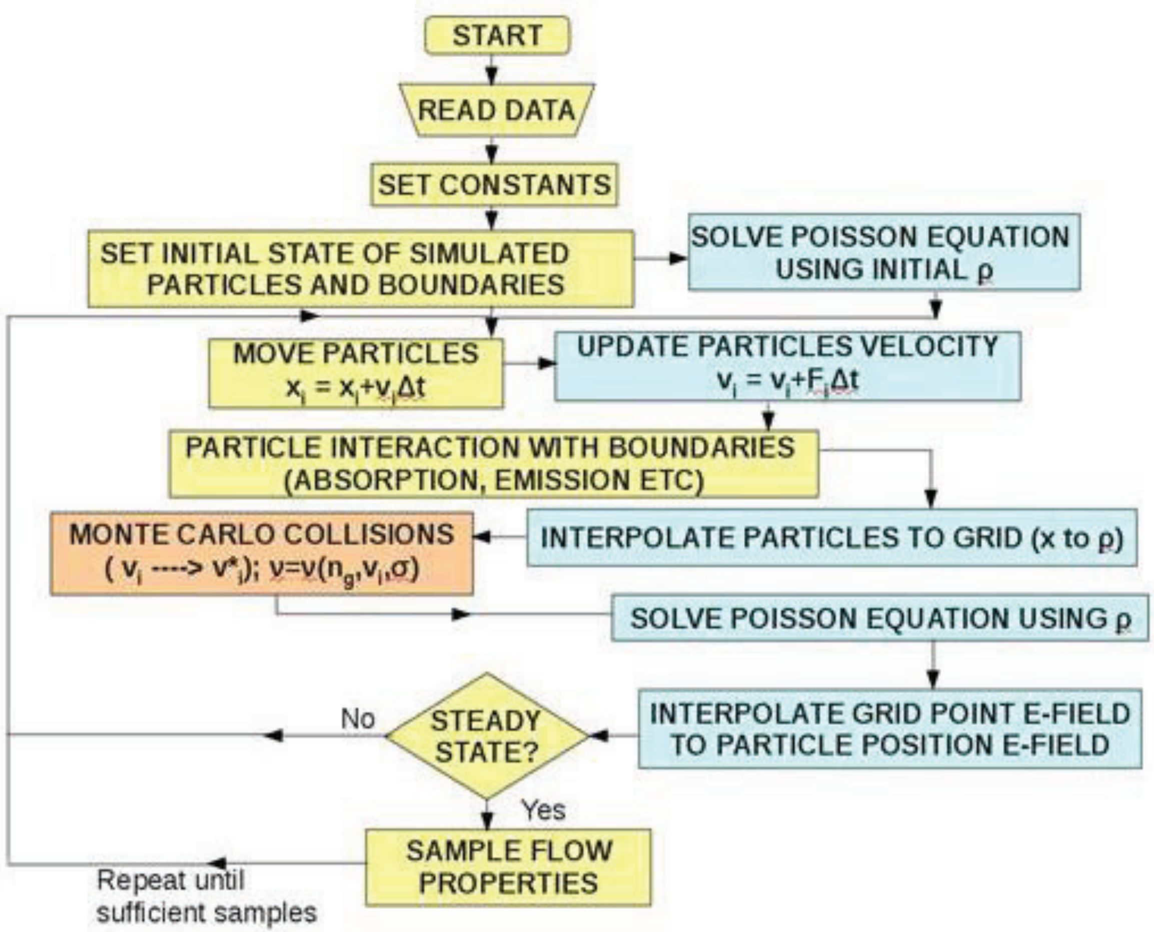
RF: bad coupling of microwaves to electrons, higher losses of electrons + instabilities?

Gas-mixing: evaporative cooling of heavy ion component? Improved ion confinement?

Why SUPERNANOGAN produces smaller currents compared to the AECRIS? Volume and magnetic field scaling?

- In order to better understand the source behavior, we develop the computer code that simulates the ion dynamics in the plasma, while taking the electron component parameters as free input into the code.
- Assumptions are unavoidable – can be checked *a posteriori*

Code description: Particle-in-Cell



Code description

- 3D rectangular mesh (39x39x64)
- Each super-particle represents 1e8-1e9 real atoms/ions
- Ion density in a cell = electron density ← charge neutrality
- Particles are colliding each other within a cell: elastic ion-ion collisions ←Takizuka-Abe method that conserves both energy and momentum

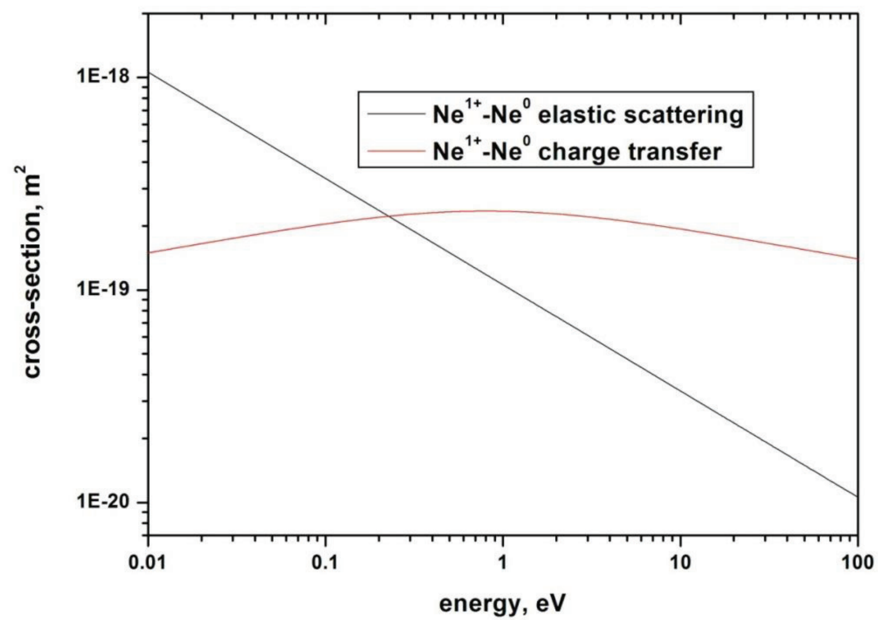
Important for correctly dealing with plasma diffusion across the magnetic field!

dure in the Appendix. The deflection angle θ_k for kth small-angle collision is given by [14]

$$\tan\frac{\theta_k}{2} = \frac{|q_\alpha q_\beta|}{4\pi\epsilon_0 \mu g^2 b}, \tag{5}$$

where q_α and q_β are the charges of the test particle and field particle, respectively, ϵ_0 is the permittivity of free space, μ is the mass of the test particle, and b is the impact parameter.

Charge-changing collisions between ions and atoms



Rates are from Phelps*, linear scaling with Q (ion charge). If the Q >=3, KER=10 eV → ion heating due to Coloumb explosion

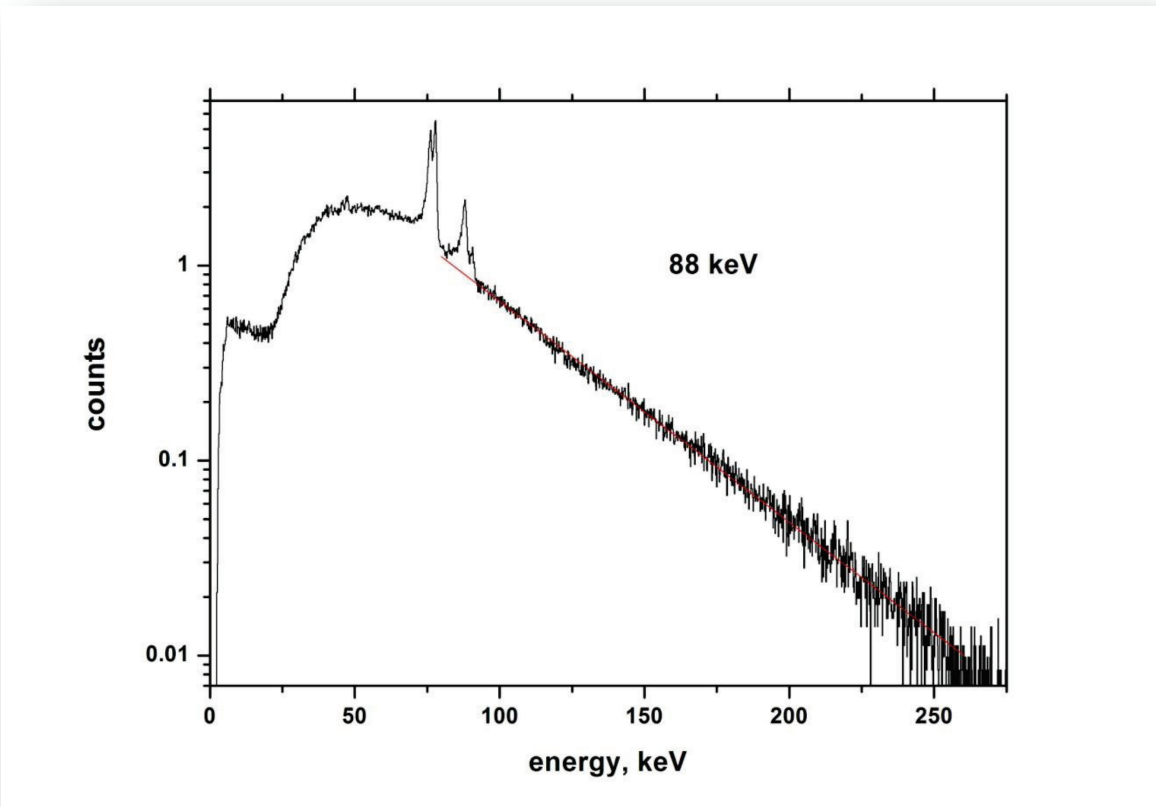
*****_http://jila.colorado.edu/~avp/collision_data/ionneutral/_

Electron-ion heating

T_e=1 keV everywhere, free parameter (Martin et al. X-ray spectroscopy of 14 GHz ECRIS, arXiv:0909.2393v1)

Each time step, kick the particle in a random direction.

$$V_{x,y,z} = V_{x,y,z} + \delta \times (n_e(ix,iy,iz) \times 15. \times dt \times Z^2 \times 6.11 \times 10^{-9} / m)^{0.5}$$



X-rays from AECRIS

Is the spectrum in contradiction with 1 keV electron temperature?

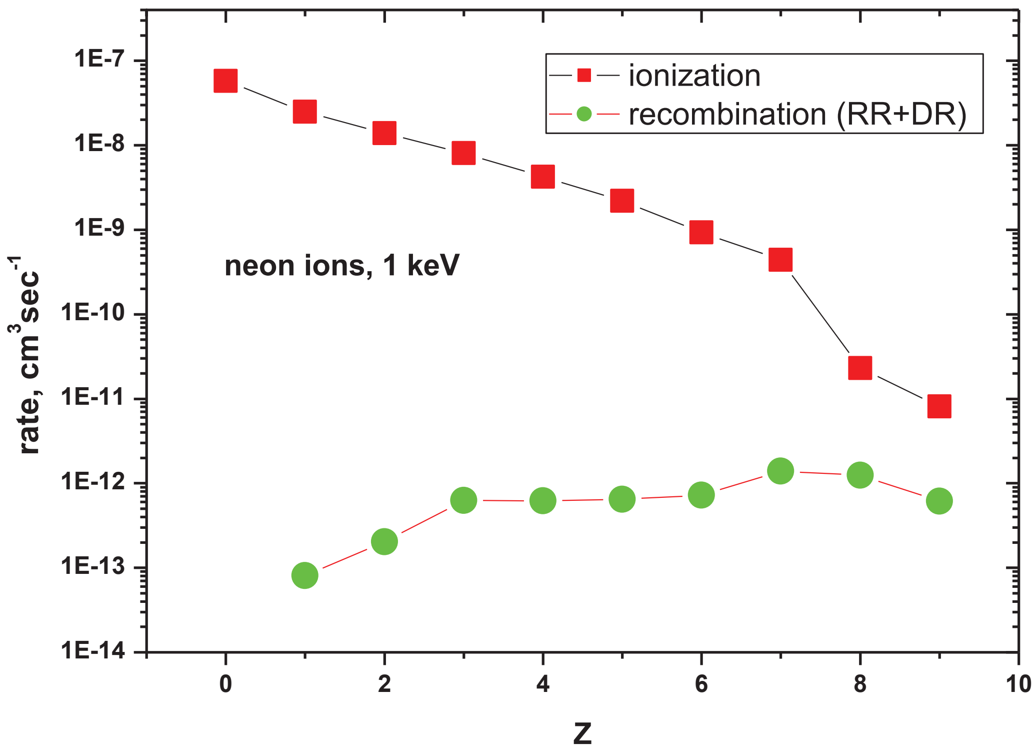
Ionization rates for 100 keV electrons are too small to reproduce the real ECRIS performance.

Hot electrons – just a tail carrying out most of RF power, but not contributing into the ion production.

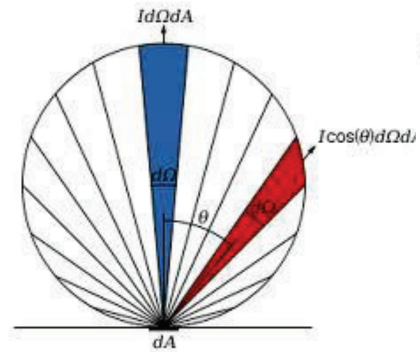
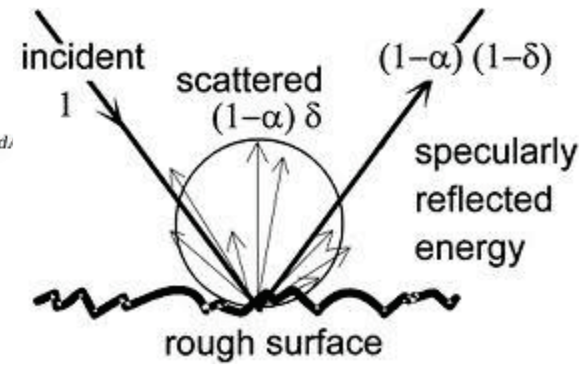
Ionization Rates

M Mattioli, et al. J. Phys. B: At. Mol. Opt. Phys. **40** (2007) 3569–3599

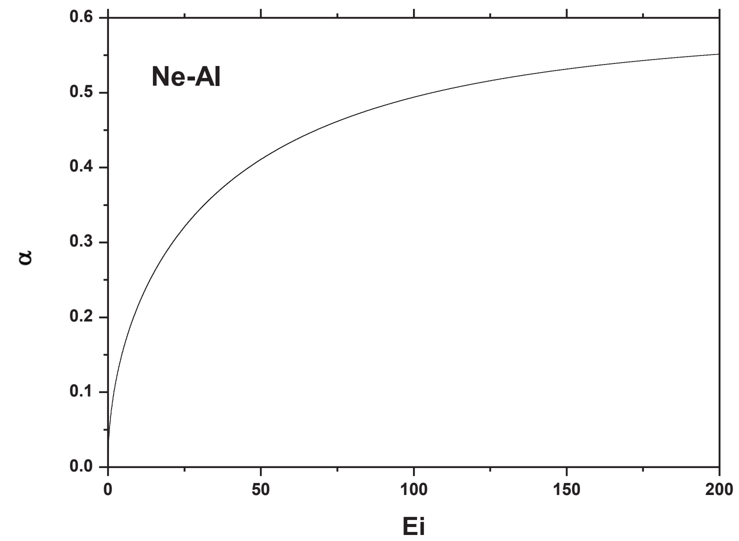
For argon, we should add the excitation-autoionization rates from K.B. Fournier, M. Cohen, M.J. May, W.H. Goldstein, Atomic Data and Nuclear Data Tables, Volume 70, Issue 2, November 1998, Pages 231–254



Atom scattering on walls

When ion hits the chamber wall, it is neutralized	Fraction of the backscattered singly charged ions is less than 1 %
If not in extraction aperture, ion is scattered back with an angular distribution according to the cosine-law (diffuse scattering)	 
Energy distribution of neutralized atoms is assumed to be around 80% of the ion initial energy (~Q*25 eV)	Maxwell-Boltzman distribution with the temperature of ~1.5*Q eV

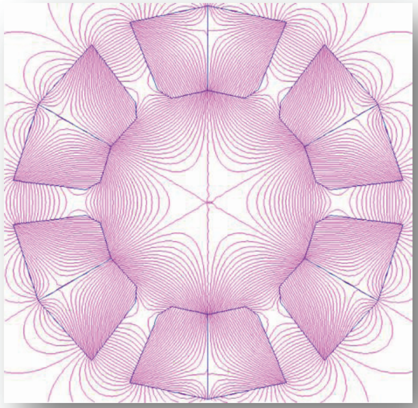
Atom scattering on walls

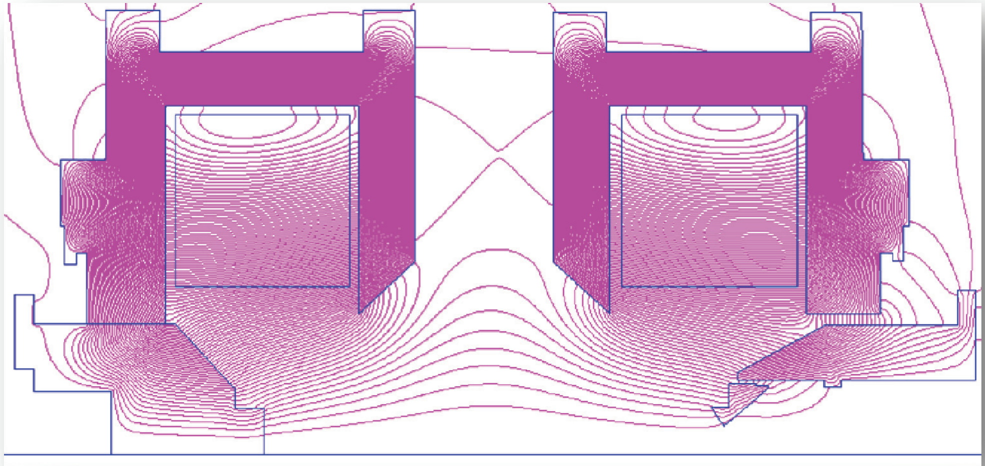
When atom hit the wall, it looses some energy. The thermal accommodation coefficient α	Es-Ei=α (Tw-Ei)
We use α(T) for Ne-Al (Ar-Al) surface collisions from *F.O.Goodman and H.Y.Wachman, J.Chem.Phys.* ***46****, 2376 (1967).* For small energies, α(T) is quite small → slow thermalization Not for all elements!	

Ion movement

Ions move in the static B and E fields defined analytically.

B field is from POISSON-SUPERFISH calculations for KVI-AECRIS + component for the Halbach hexapole (no edge effects)

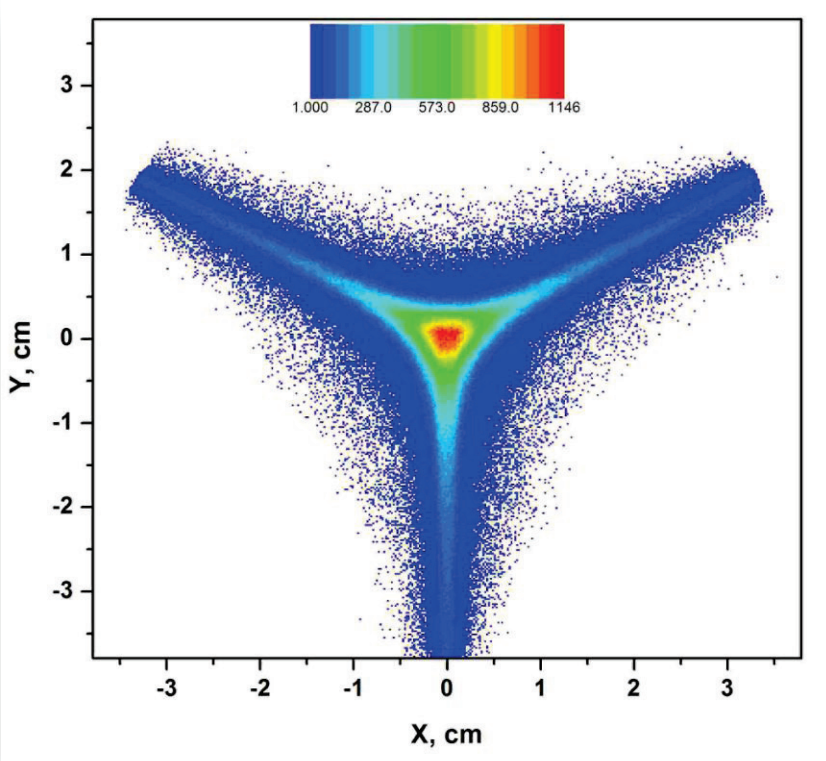


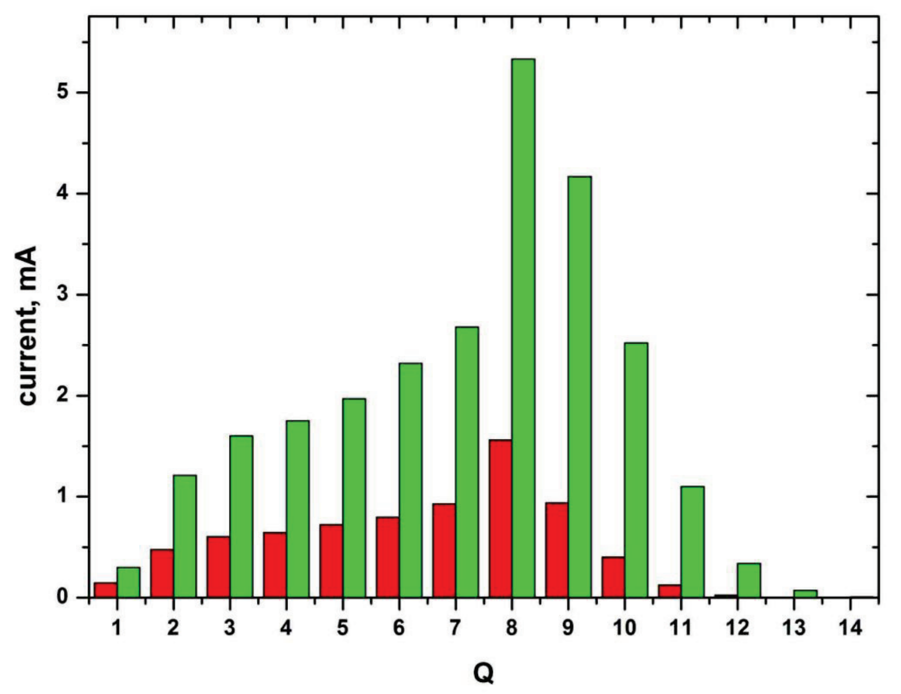


Start with some randomly selected spatial ion distribution and follow the ion dynamics until steady condition is reached

What if there are no electric fields?

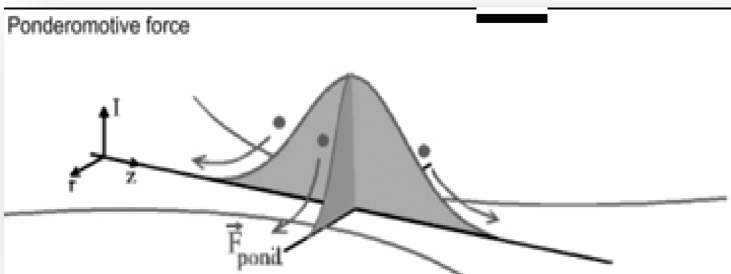
- Our first model: V. Mironov and J.P.M. Beijers, Phys. Rev. ST Accel. Beams **12**, 073501 (2009).





Assumption

- ECR plasma is confined by a potential barrier formed by expulsion of electrons from the regions with the high electric fields of microwaves (*ponderomotive force*)

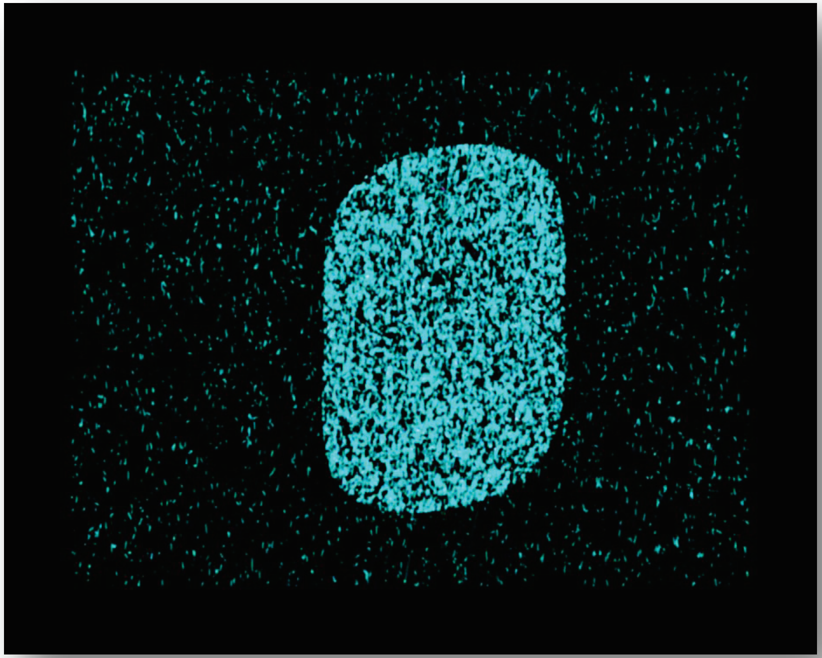


- The barrier is at Upper-Hybrid-Resonance layer

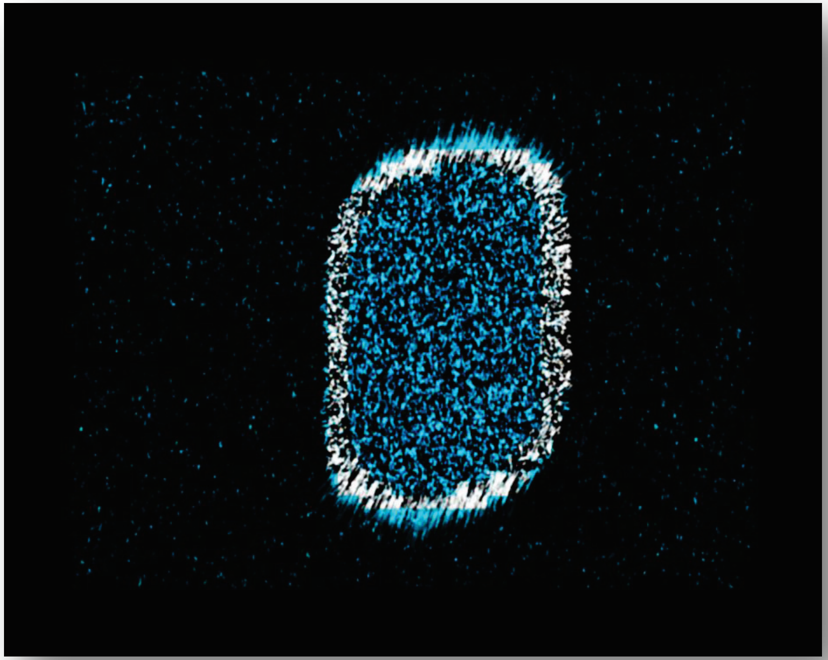
$$\omega^2_{RF}=\omega^2_p+\omega^2_c$$

with ω_{RF} the microwave frequency, ω_c the cyclotron frequency, and ω_p the plasma frequency

ECR and UHR zones



ECR zone → |B|=0.5 T



UHR zone shrinks when plasma density increases

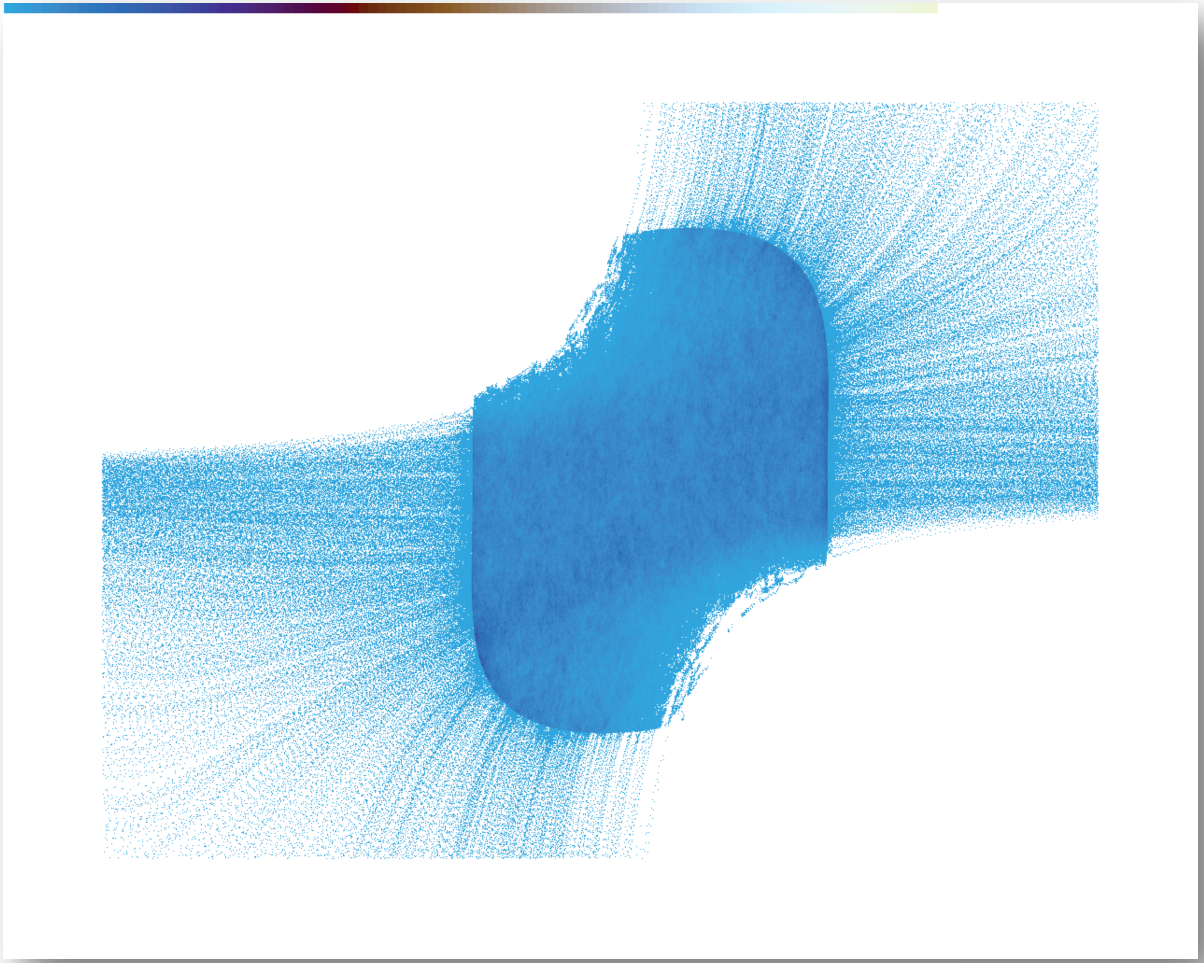
Electric field

Inside UHR zone the field is zero.

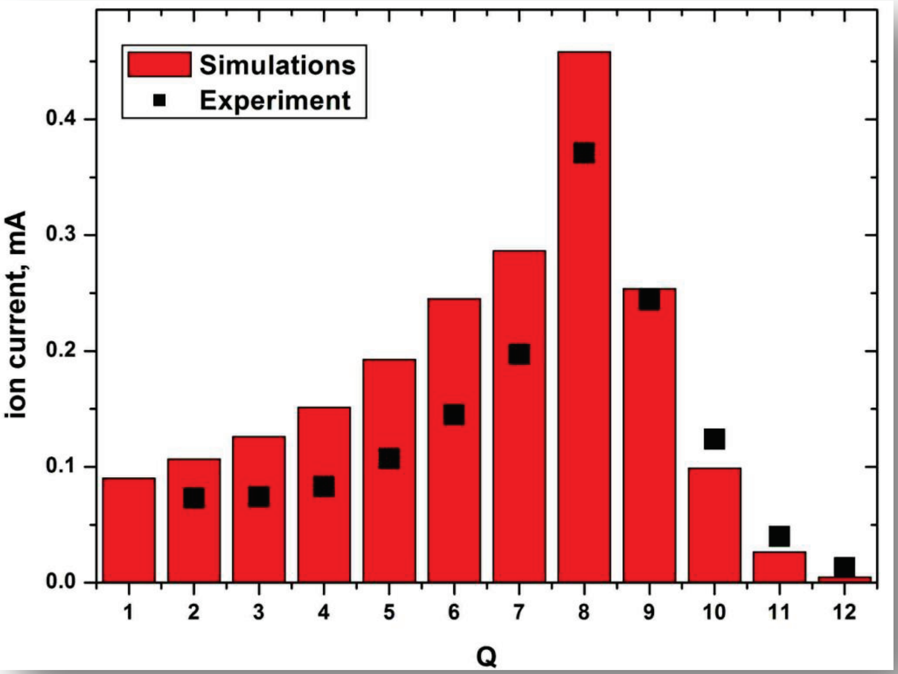
1 V/cm towards the walls outside the zone (pre-sheath). Can be varied in a wide range.

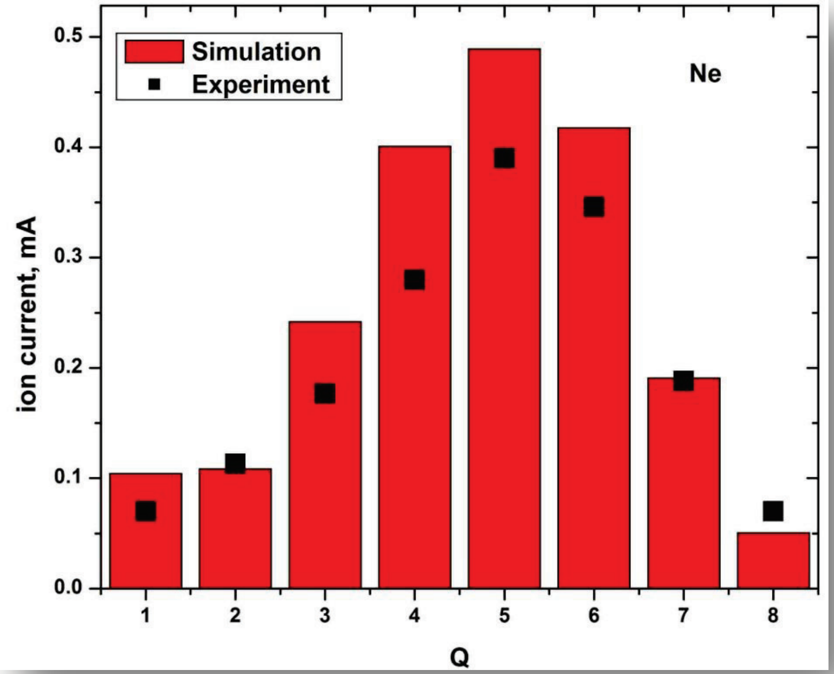
When ion crosses the UHR zone boundary, it is either accelerated to the walls, or it is reflected back if V<PB*$\sqrt{\ }$

PB is potential barrier height, free parameter in a range from 0 to a few Volts



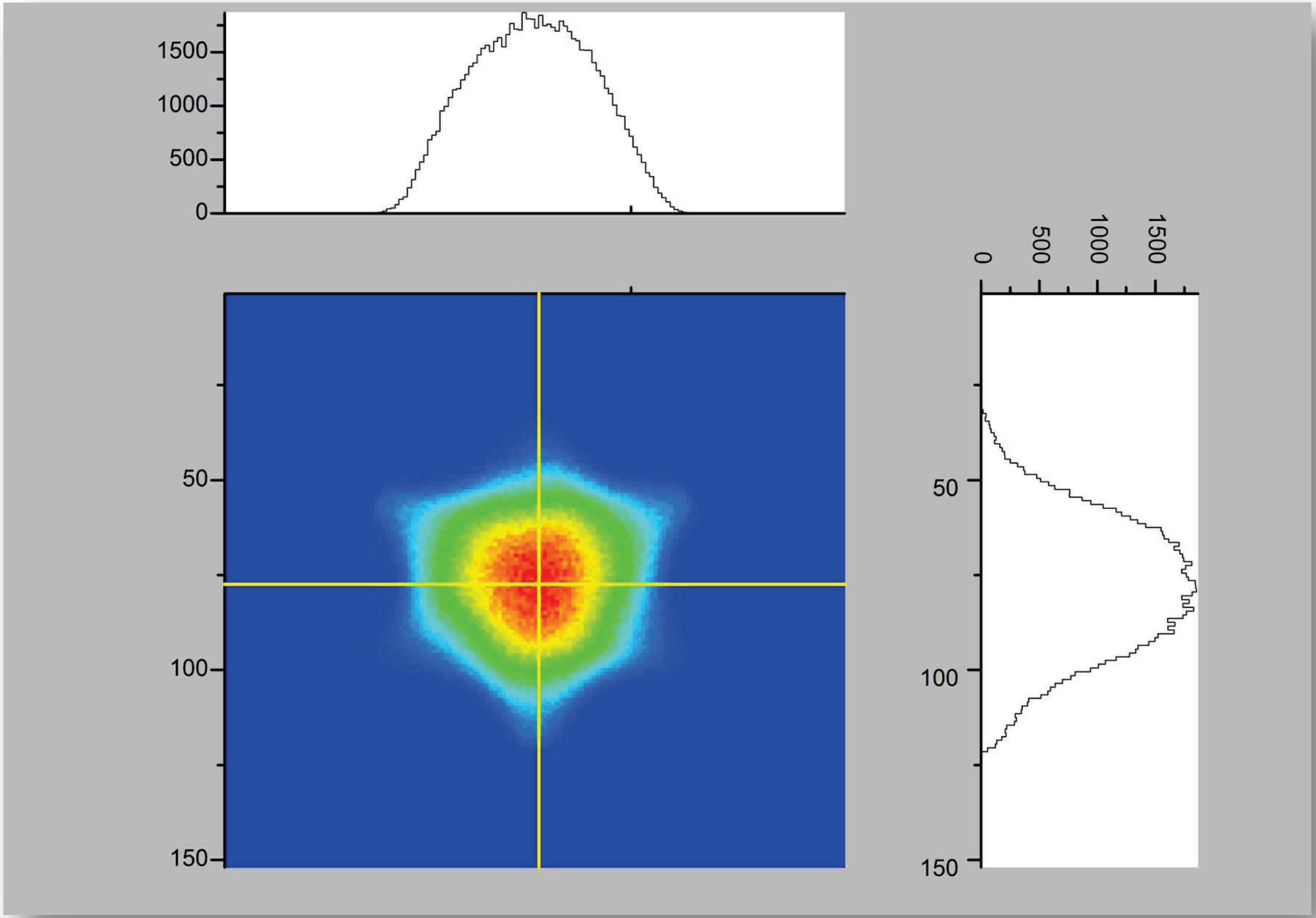
Results: charge-state-distributions



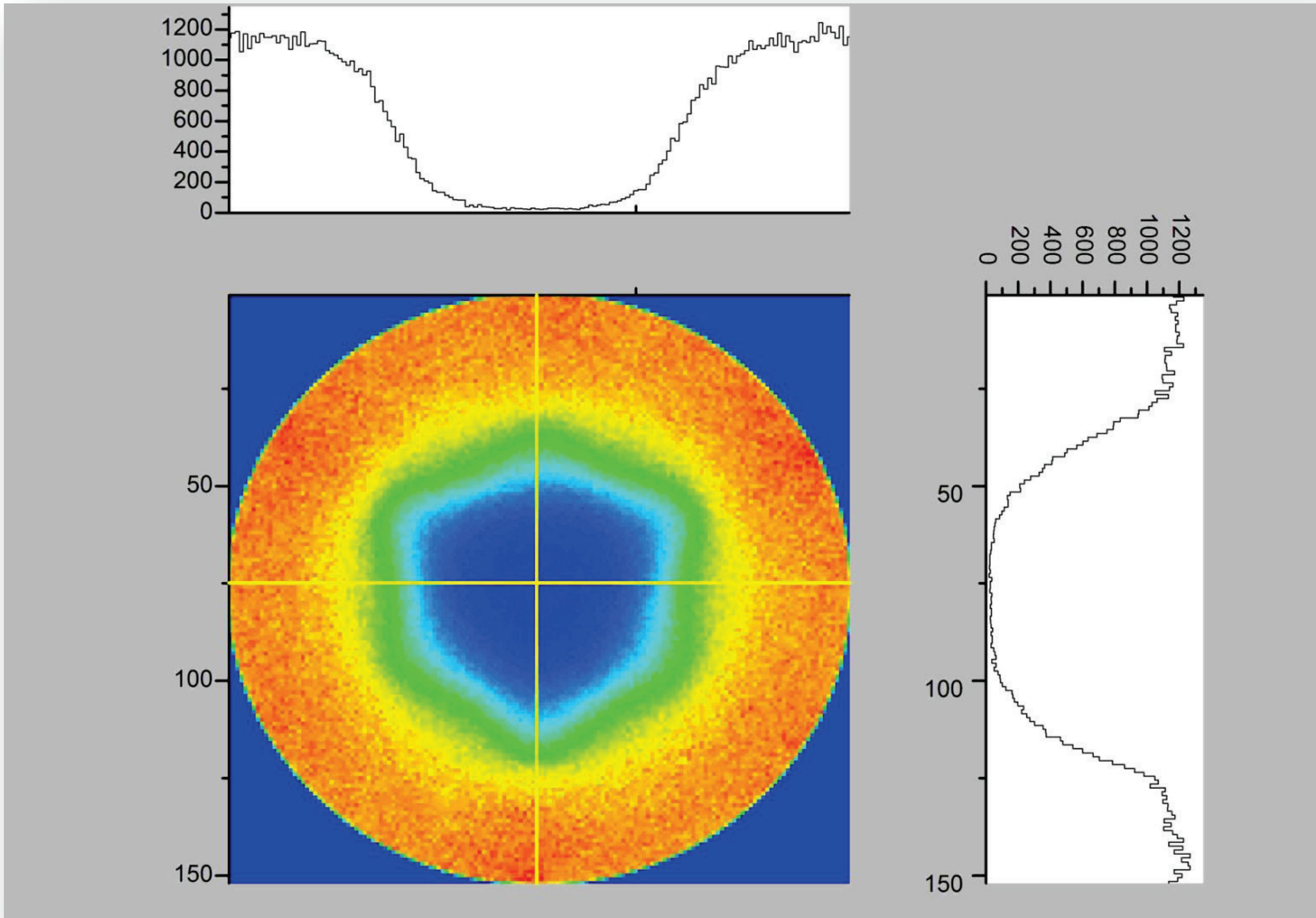


Argon **Neon**

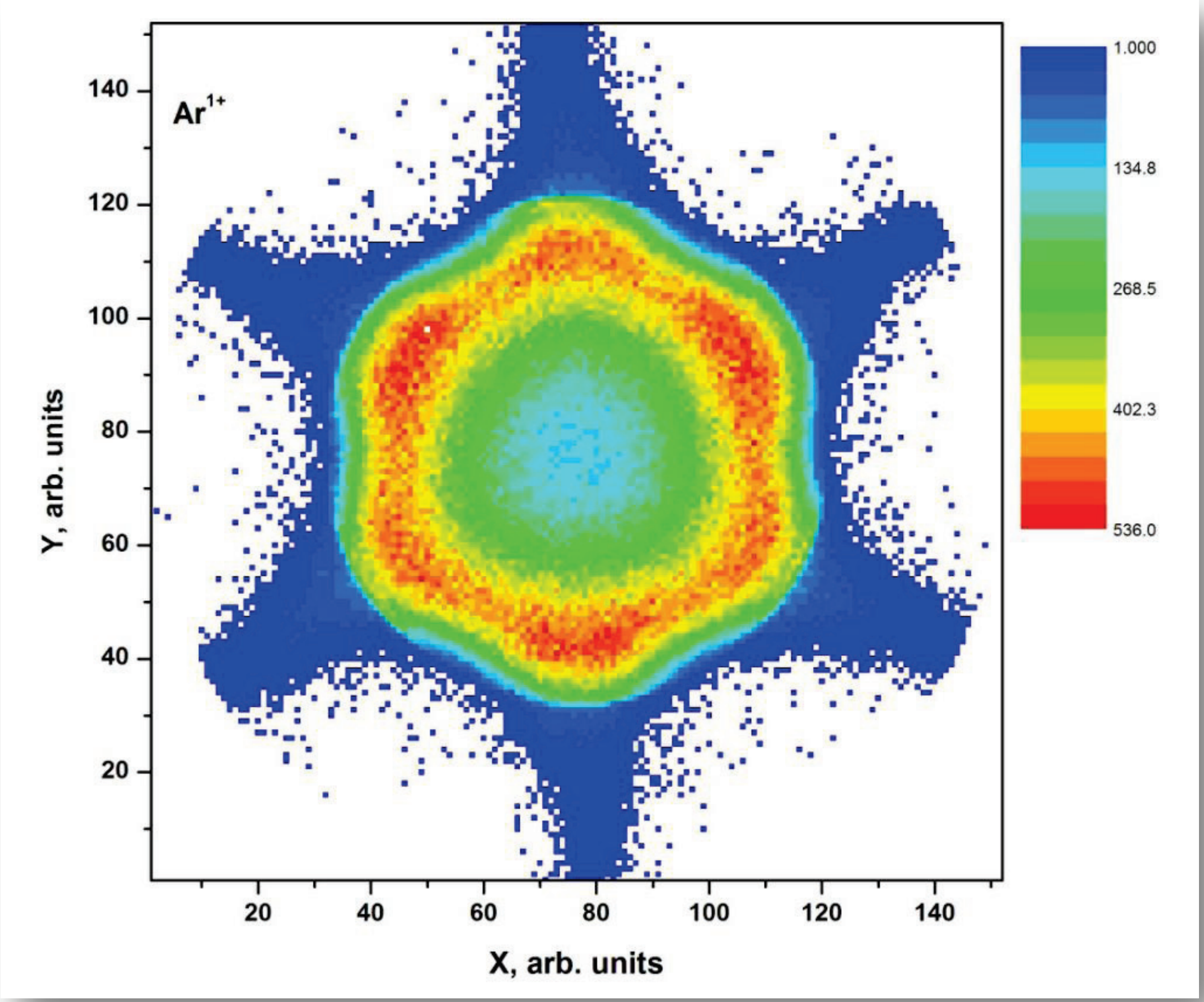
Spatial distributions: Ar8+



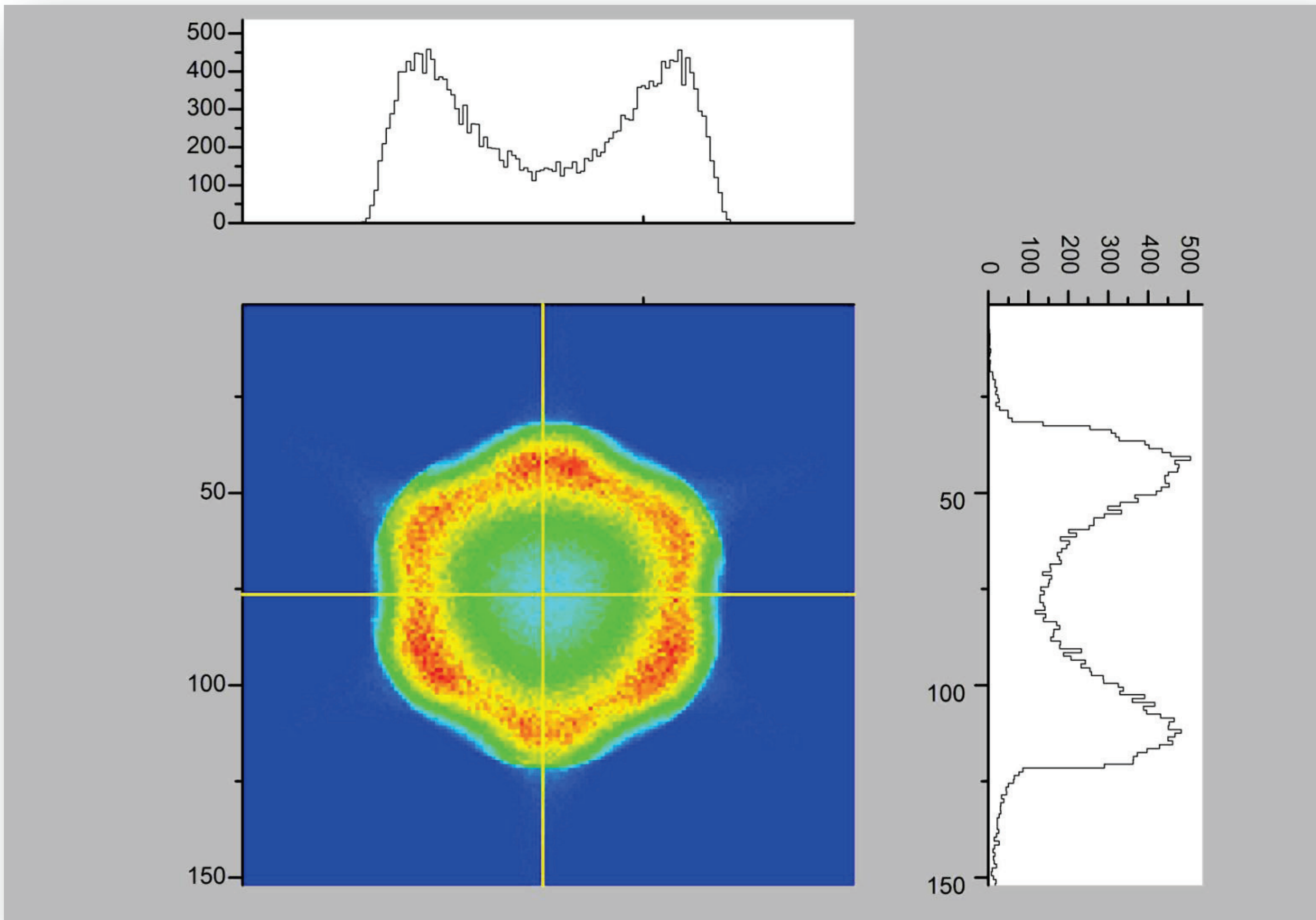
Spatial distributions: neutral Ar



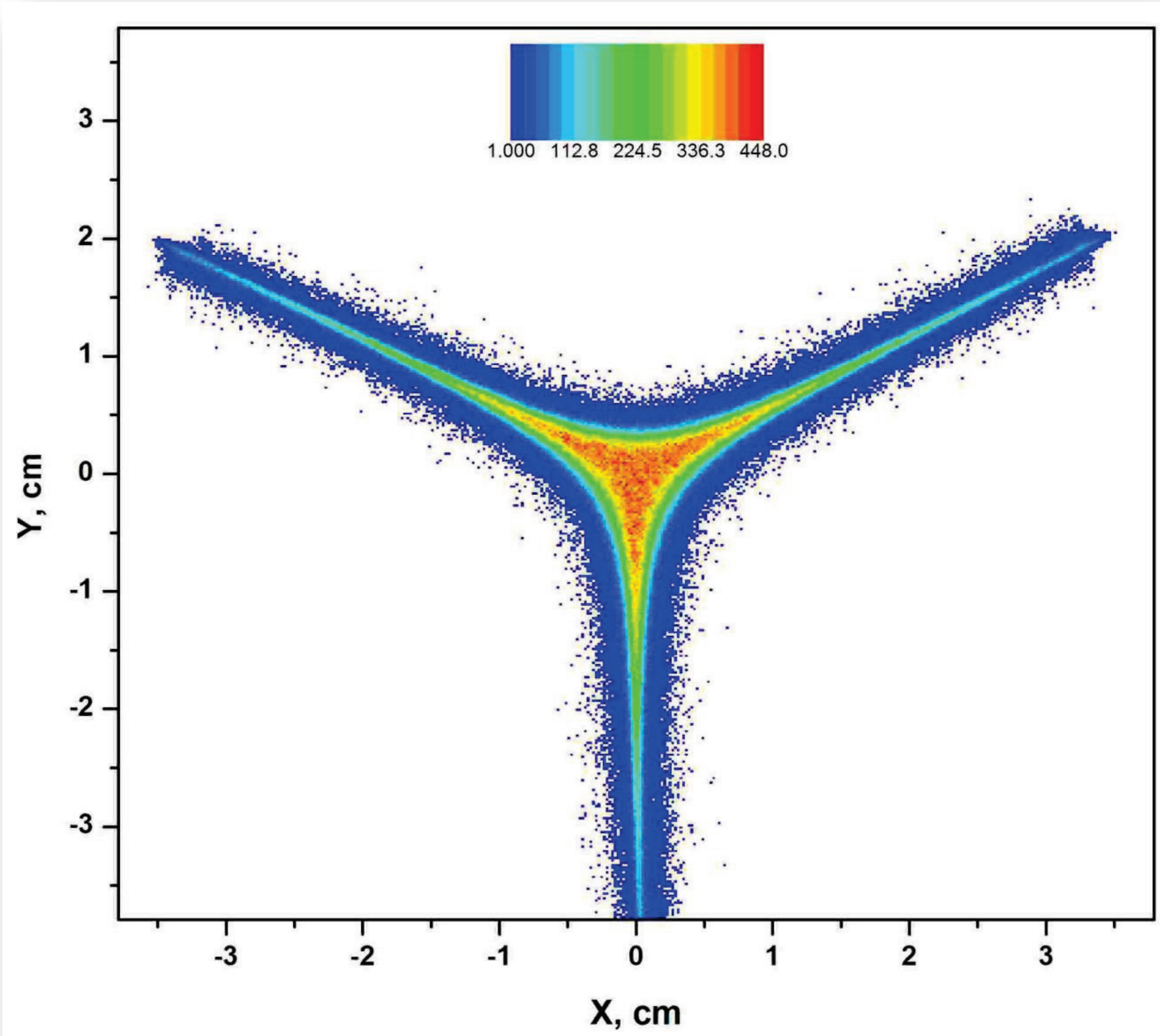
Spatial distributions: Ar1+



Spatial distributions: Ar1+



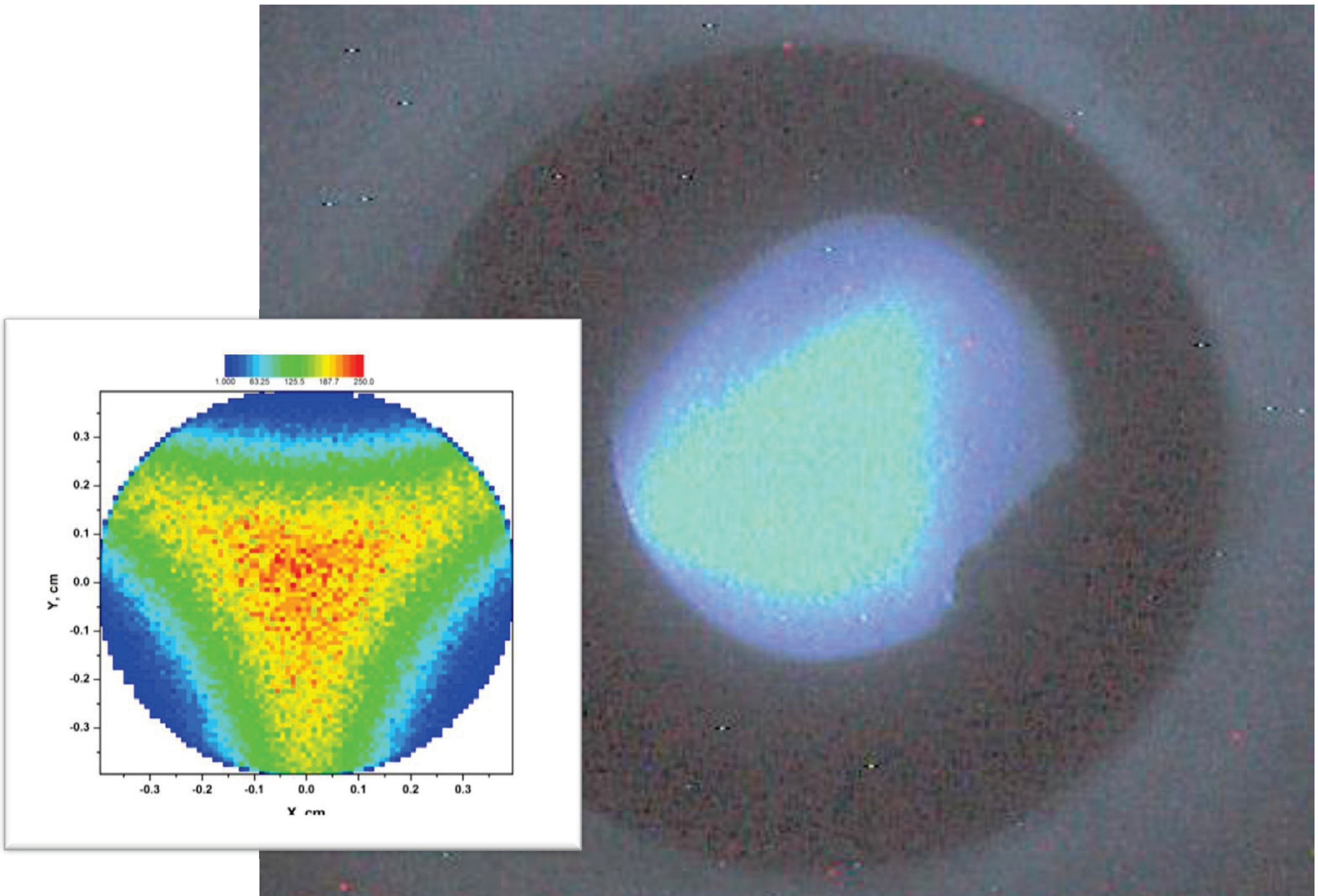
Ion losses at the extraction electrode



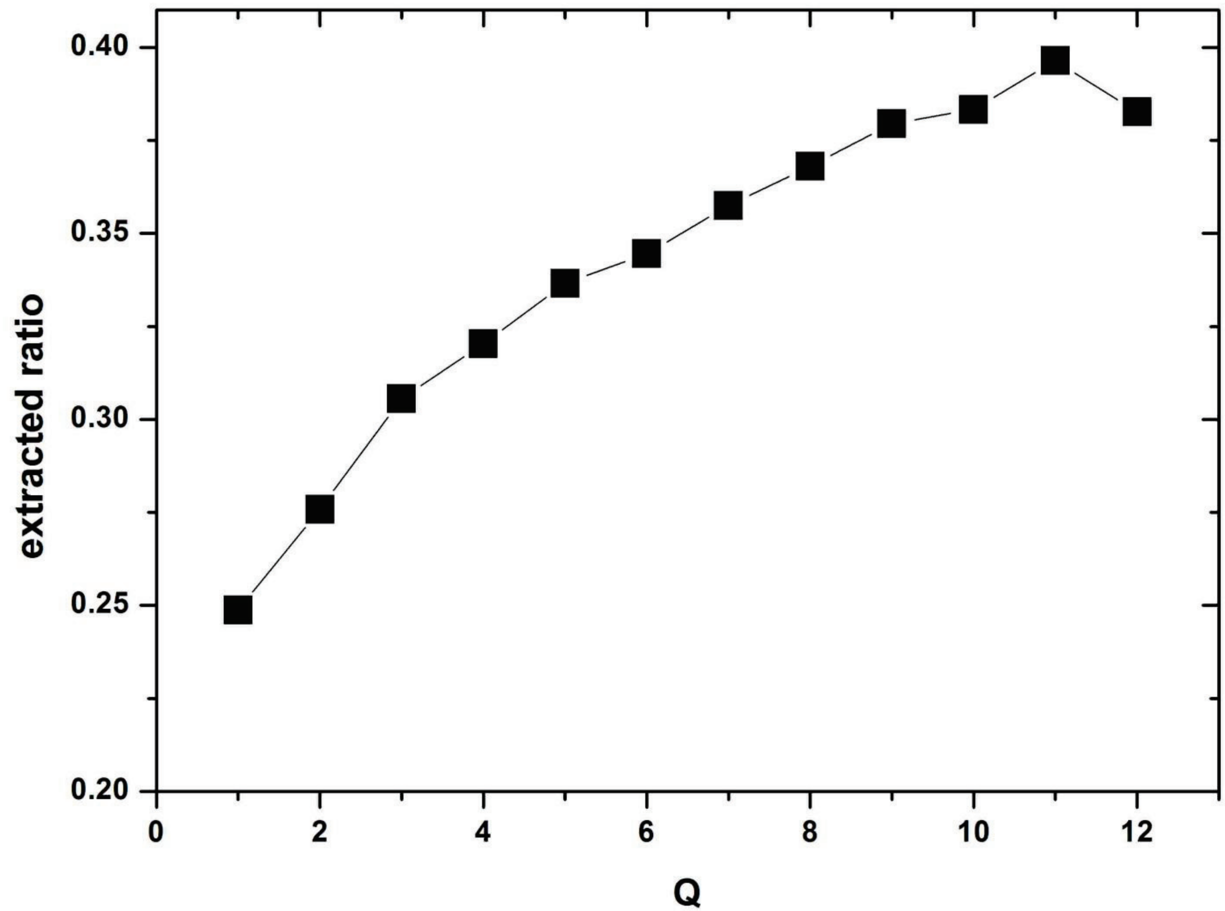
Ion losses at the extraction electrode

Ion losses at the extraction electrode

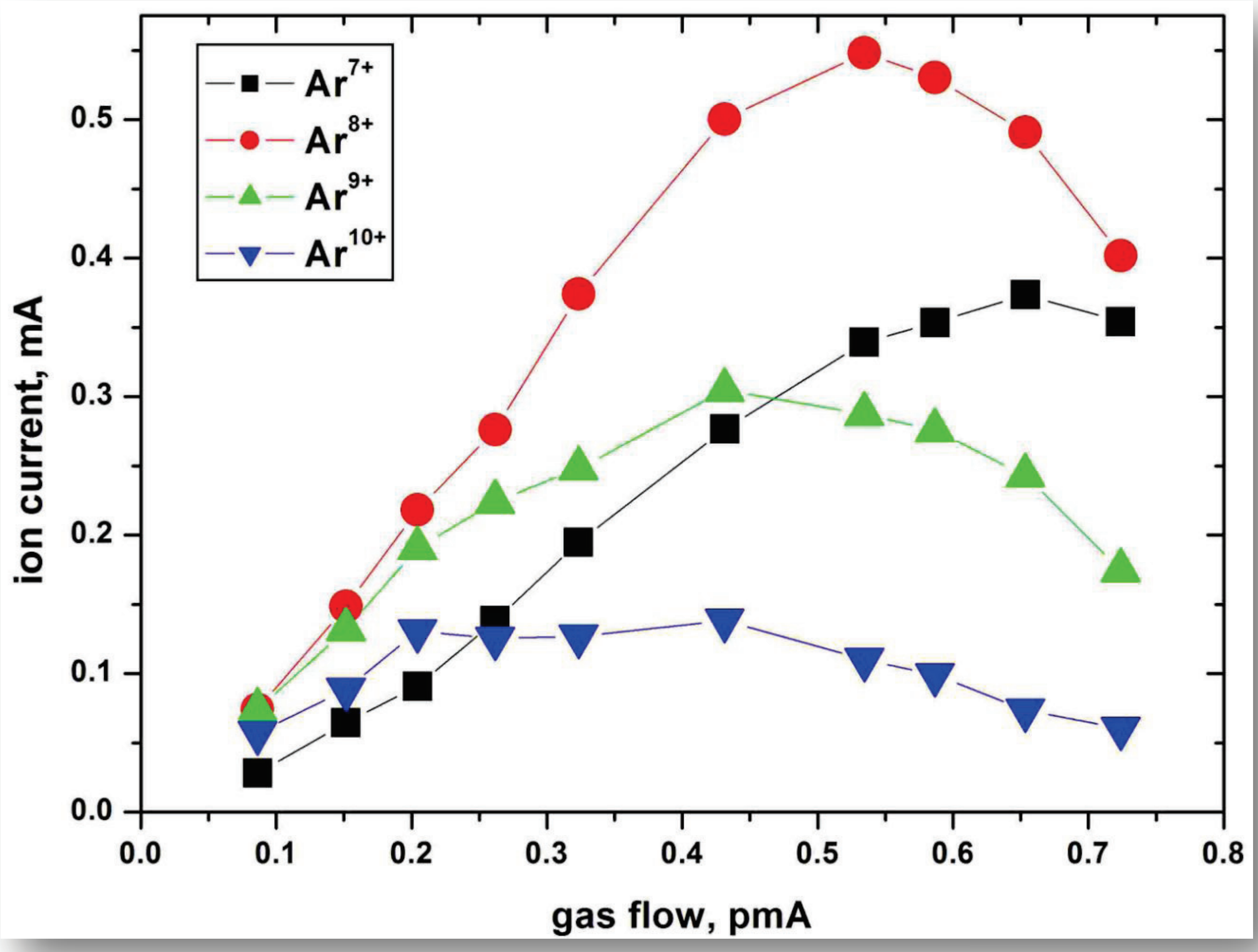
Helium beam on a viewing target



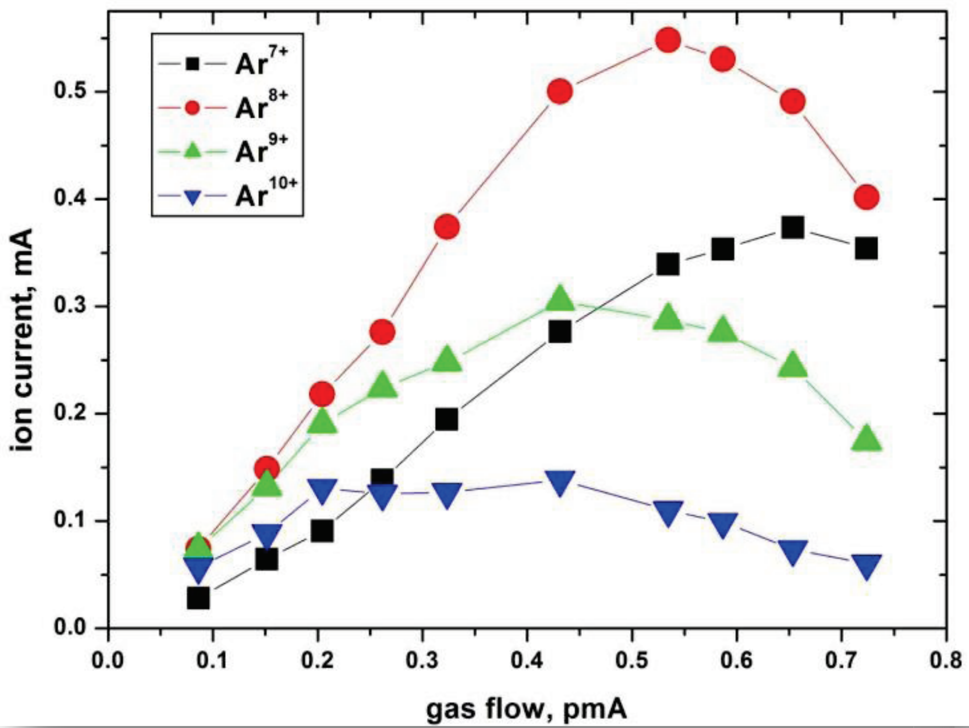
Ion flux to extraction aperture / flux to extraction electrode

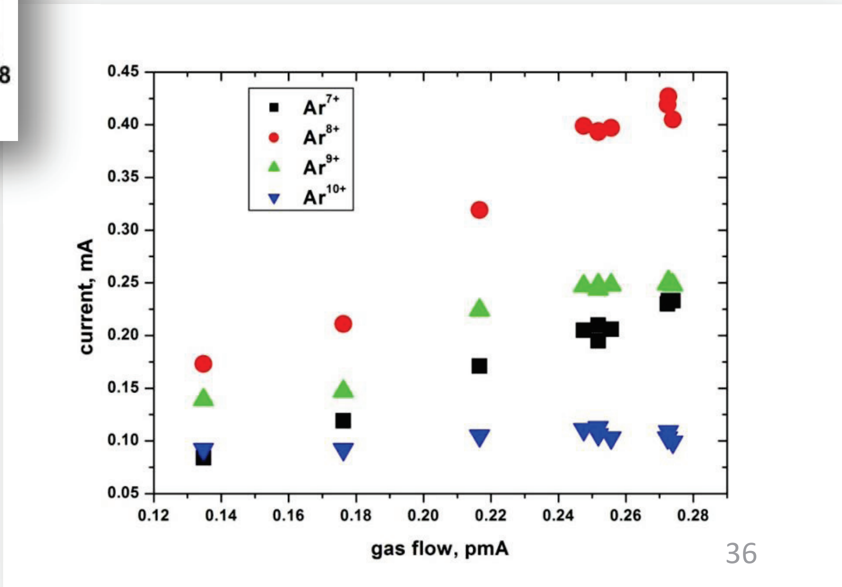


Gas-flow dependence

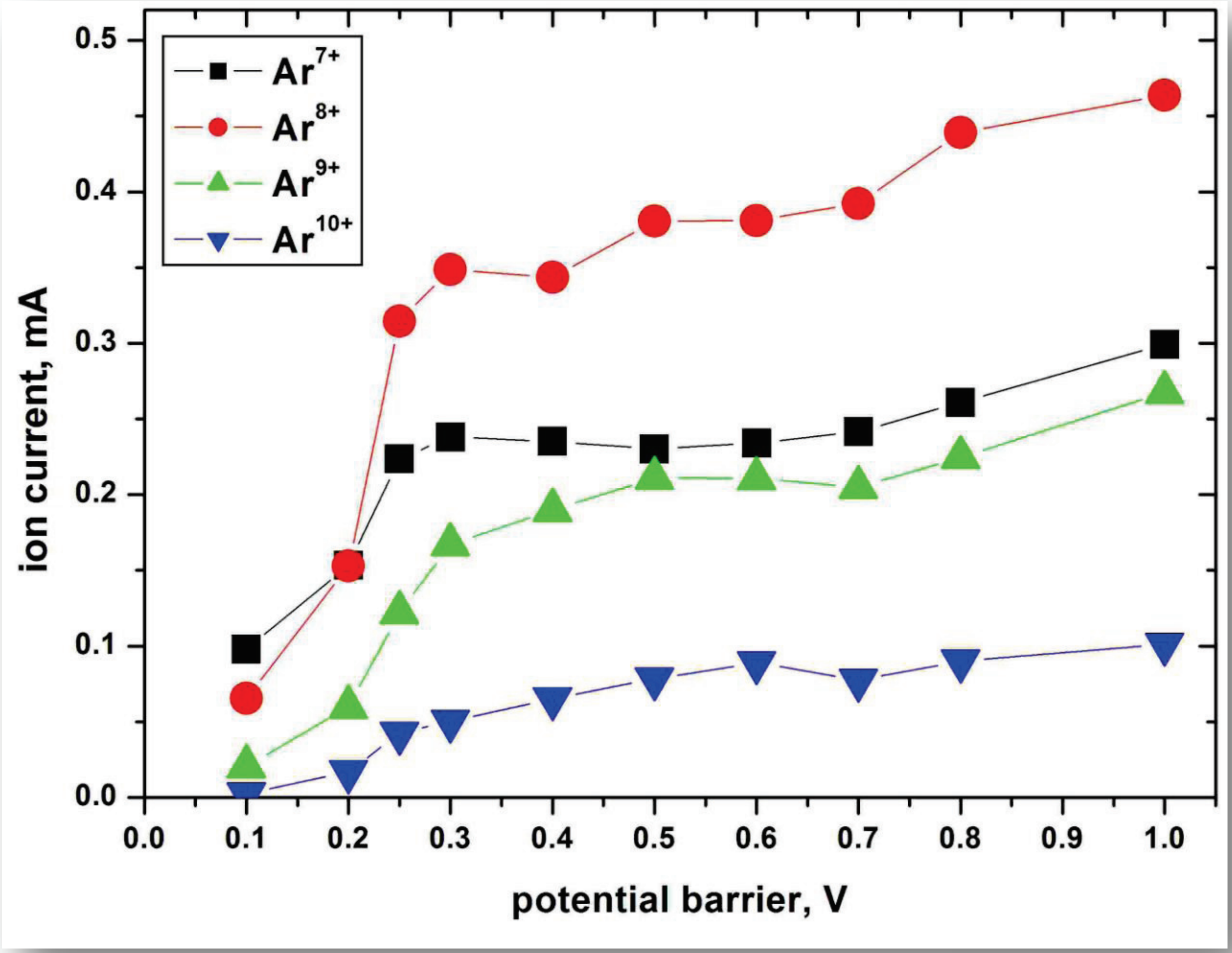


Simulations vs. Exp.





Dependence on the potential barrier height



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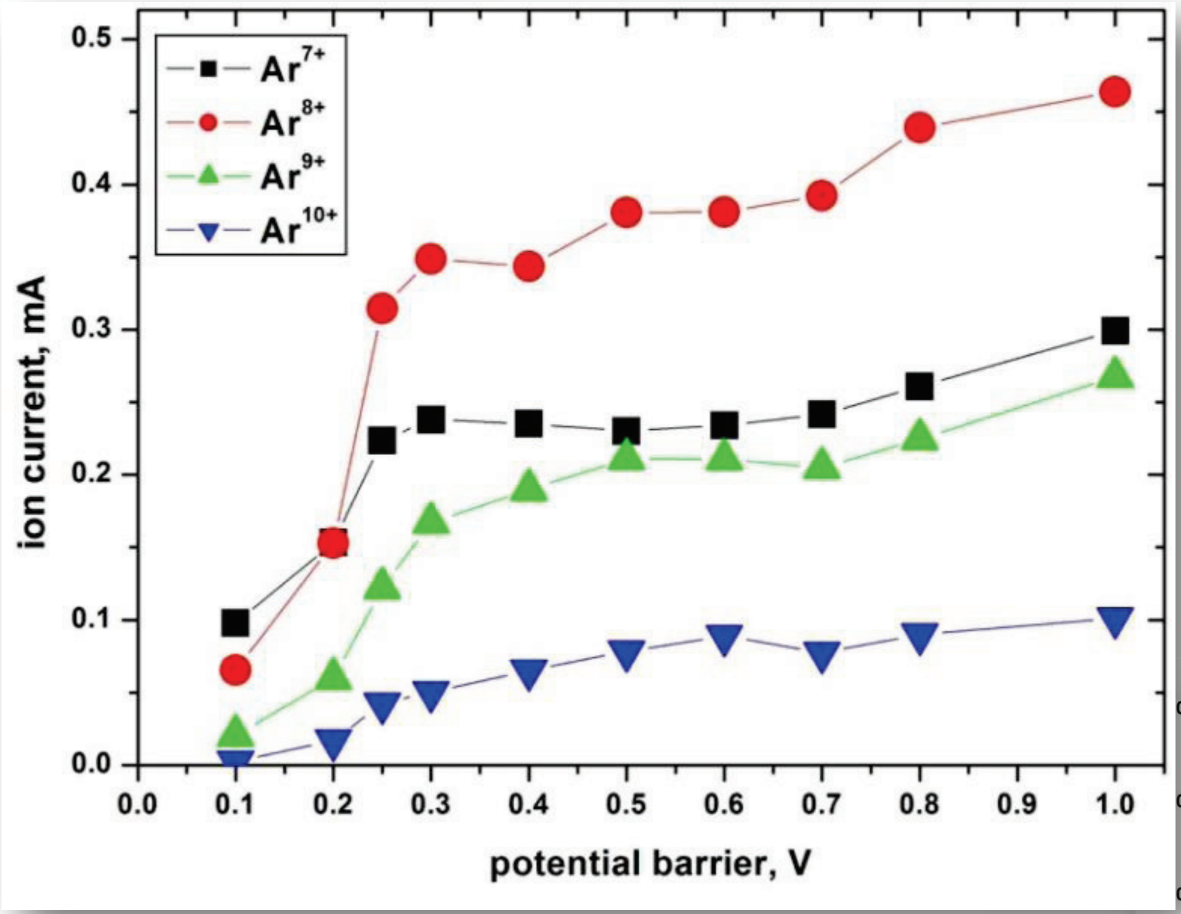
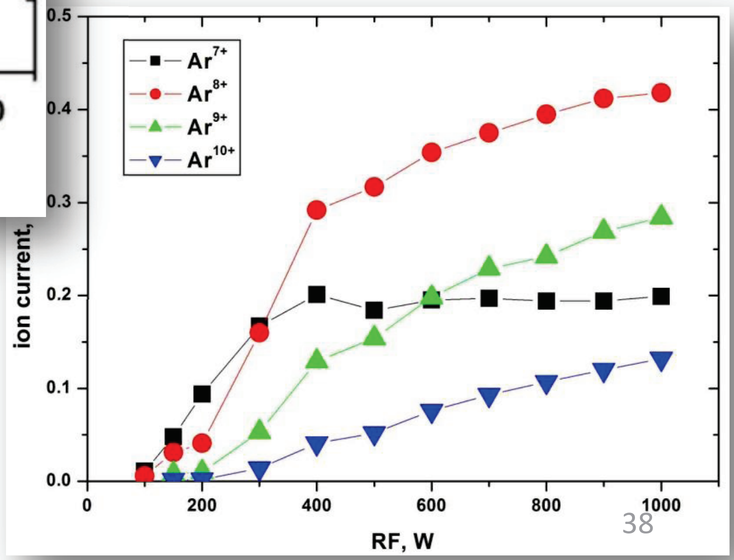
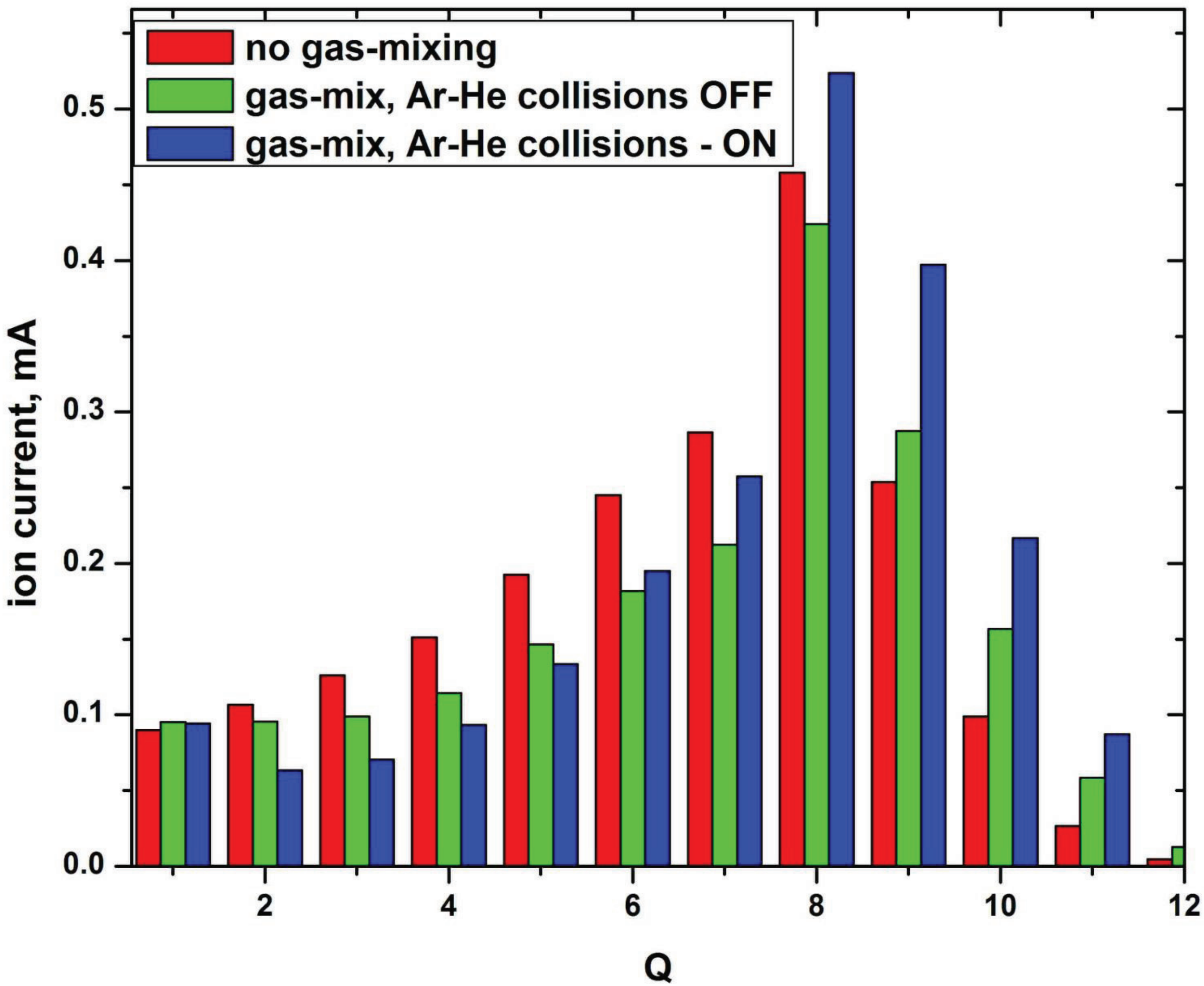




Gas-mixing: Ar+He



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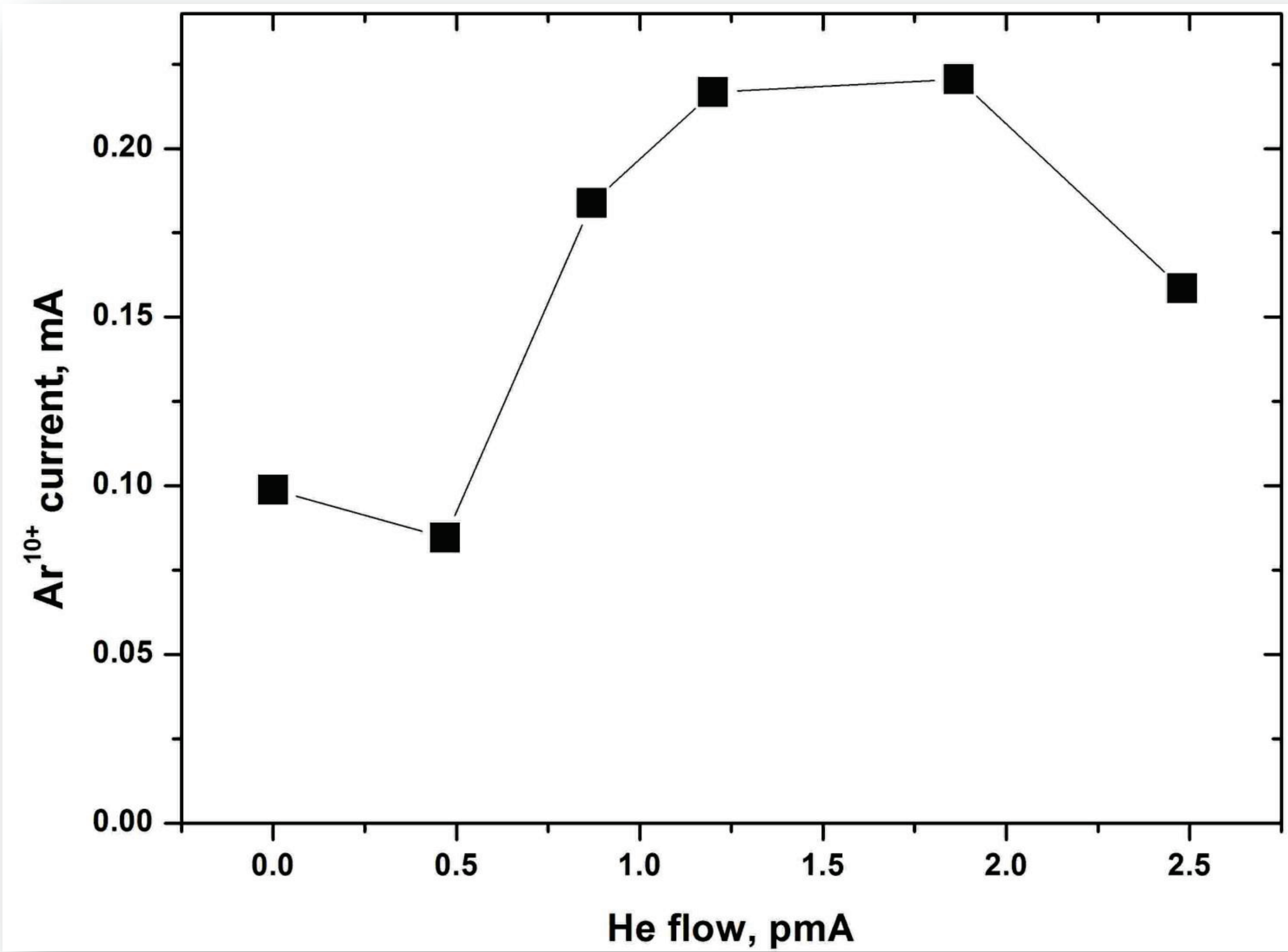
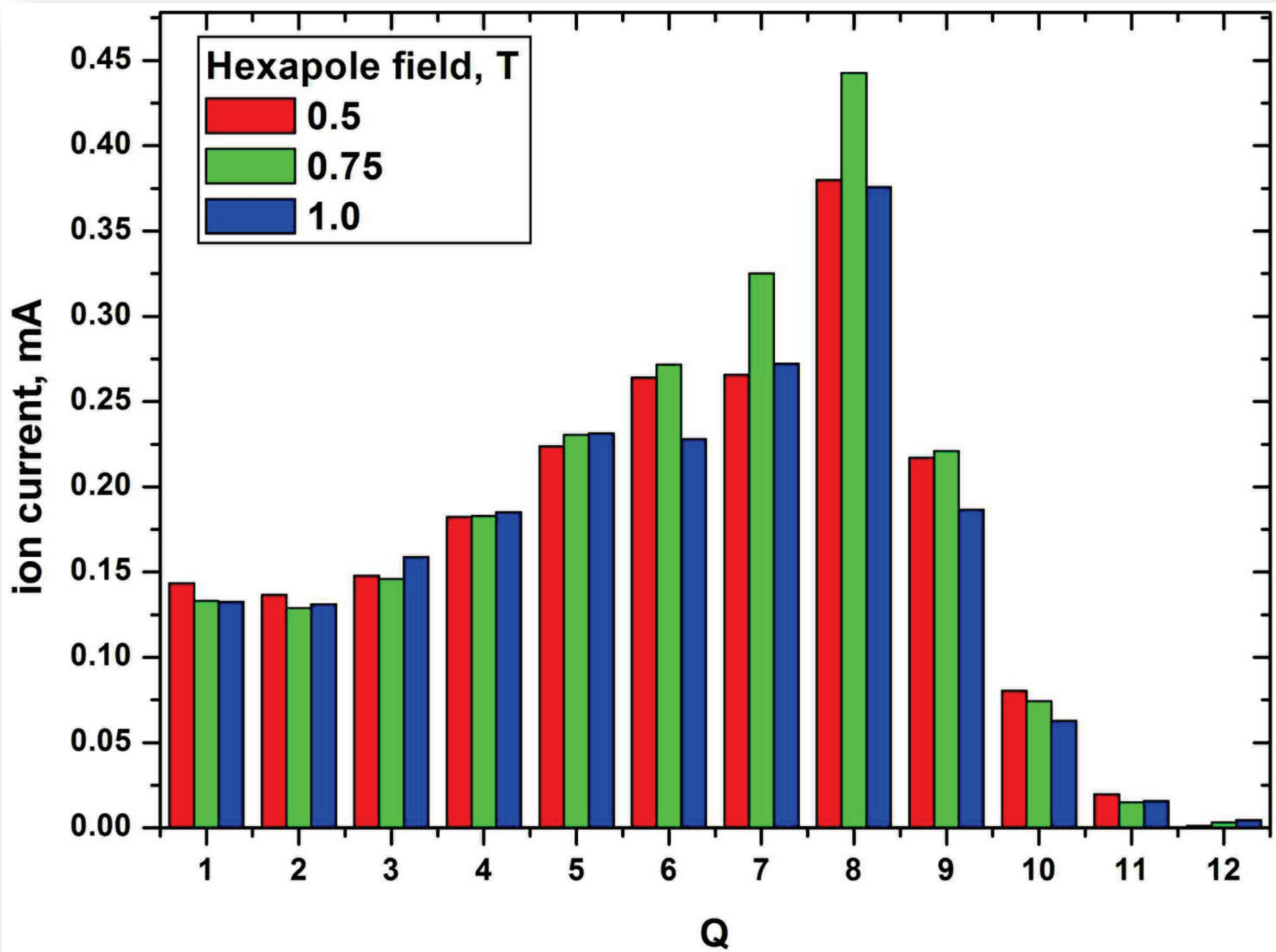
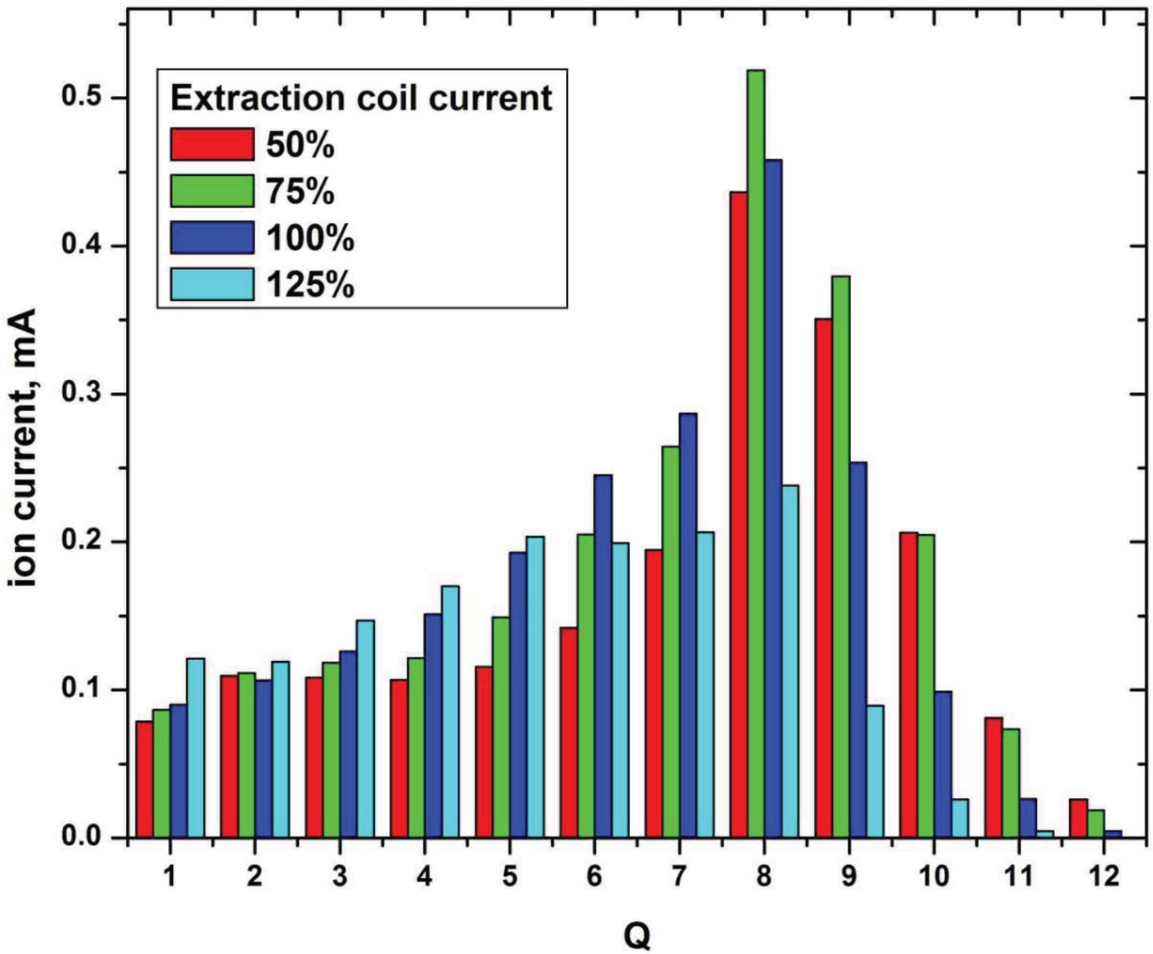


Hexapole field dependence



Extraction coil current



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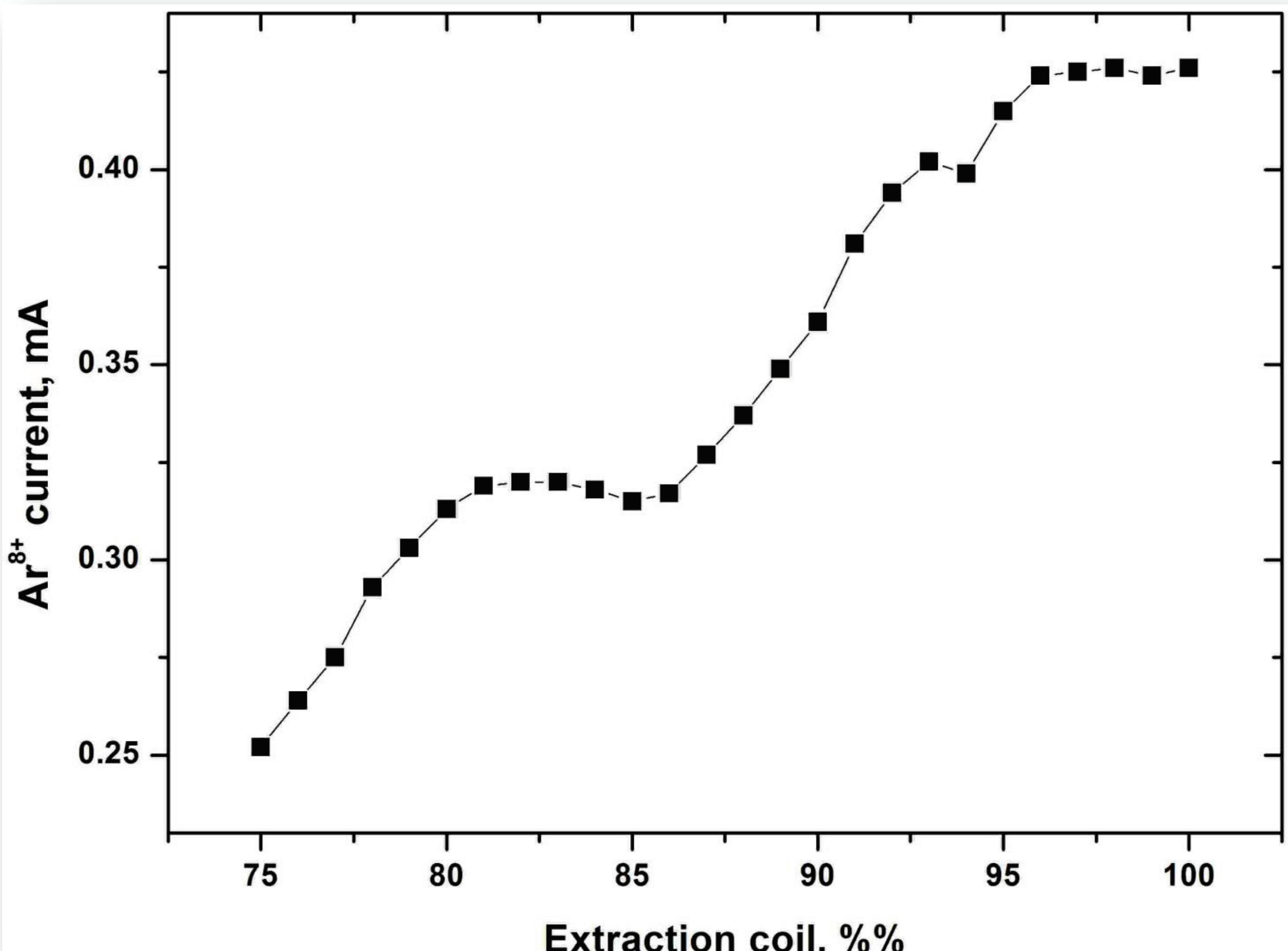

CONCLUSIONS

- The computational model described in this paper reproduces the main features of ECRIS performance. It is based on the assumption that ECR plasma is confined inside the upper-hybrid resonance zone by a potential barrier produced by the ponderomotive force.
- The simulated extracted ion currents are close to the experimental values.
- Responses of the source performance to variations in the gas flow and RF injected power are reproduced.
- The gas-mixing effect is also observed and found to be mainly due to the evaporative cooling of ions.
- Profiles of the extracted ion currents are obtained that can be used in the beam transport simulations.


Thank you