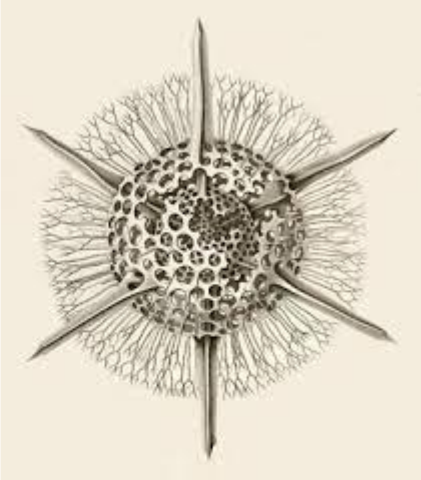
Numerical simulations of gas mixing effect in ECRIS

(http://arxiv.org/abs/1607.07230)



V. Mironov, S. Bogomolov, A.Bondarchenko,

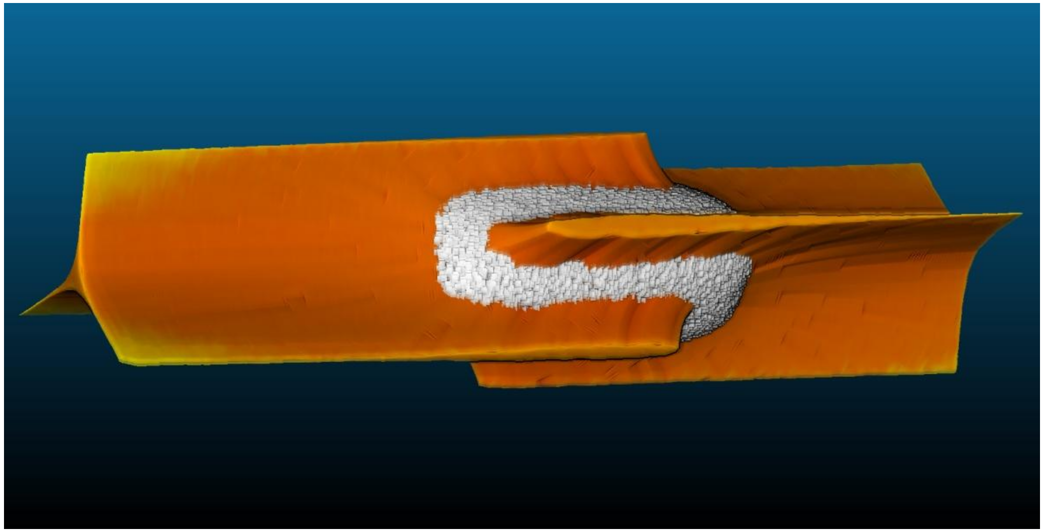
A. Efremov, V. Loginov

Joint Institute for Nuclear Research, Flerov Laboratory of Nuclear Reactions, Dubna

Basic assumptions

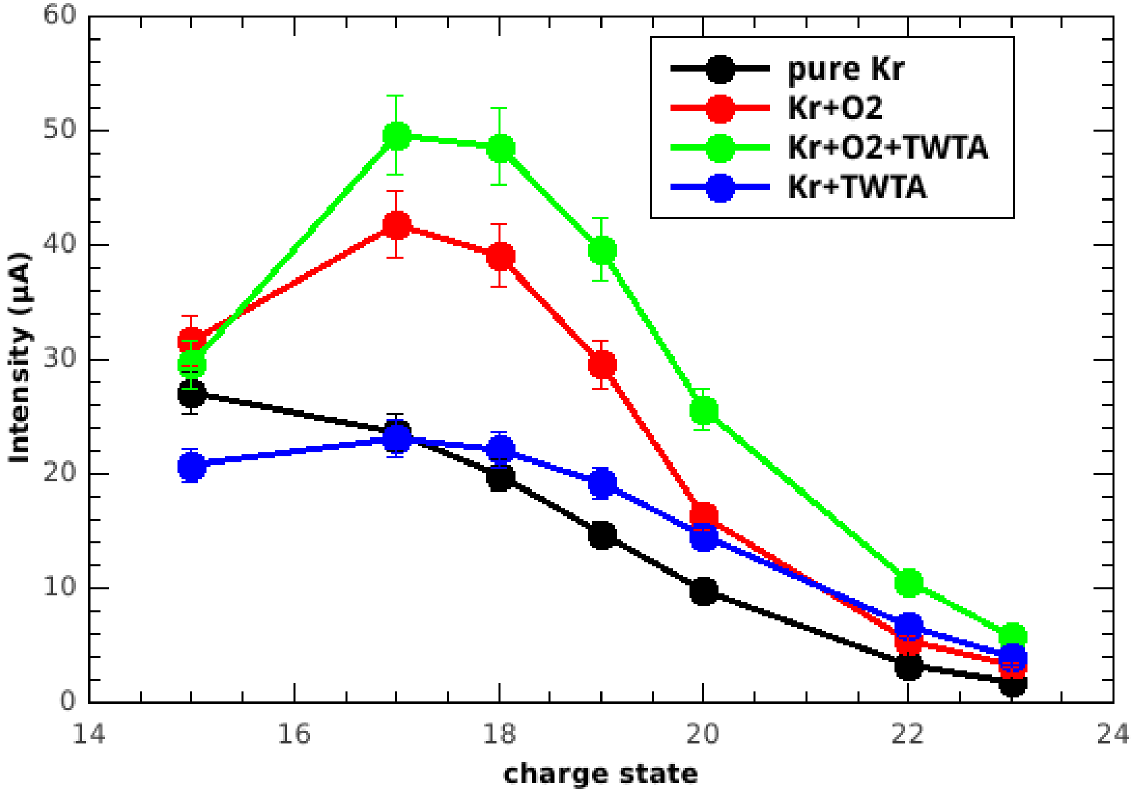
- ECRIS plasma is strongly localized inside the ECR volume;
- The electron and ion fluxes out of the zone are equal each other $$\tau_e = \tau_i$$
- Ion fluxes are regulated by a retarding potential Δφ at the ECR surface.

$$\tau_{iQ} = \frac{\sqrt{\pi} RL}{v_i} \exp\left(\frac{Q\Delta\varphi}{T_i}\right)$$



GAS MIXING EFFECT (A. Drentje, 1983)

When mixing two gases in the ECR discharge, currents of the highly charged heavy ions can be increased substantially.



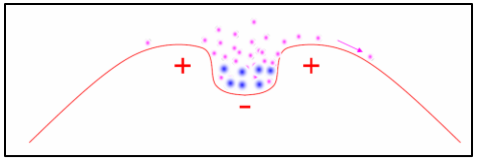
"Optimization of multiple-frequency heating and gas mixing in ECR charge breeders"

L. Standylo, H. Koivisto, O. Tarvainen, V. Toivanen, J. Komppula, T. Lamy, J. Angot, P. Delahaye, L. Maunoury, P. Gmaj, A. Galata, O. Steczkiewicz and J. Choinski

- Oxygen (esp. $^{18}O_2$) ← the best mixing gas;
- The effect depends on the surface conditions;
- Flux of the light element should be much higher than the heavy gas flux.
- Addition of small amounts of the heavy element decreases the extracted currents of the light element by order of magnitude.

Explanations:

- Evaporative cooling of ions in the plasma



$$\tau_{iQ} = \frac{\sqrt{\pi} RL}{v_i} \exp\left(\frac{Q\Delta\varphi}{T_i}\right)$$

- Decrease of the ion mean charge: slower ion heating in collisions with electrons + smaller electron scattering frequency → ion life time increases → ion densities are higher and extracted ion currents are increased.

$$\frac{dT_\alpha}{dt} = \sum_\beta \nu_e^{\alpha/\beta}(T_\beta - T_\alpha)$$

$$\nu_e^{\alpha/\beta} = 1.8\times 10^{-19} \frac{(m_\alpha m_\beta)^{1/2} Z_\alpha^2 Z_\beta^2 n_\beta \lambda_{\alpha\beta}}{(m_\alpha T_\beta + m_\beta T_\alpha)^{3/2}} \sec^{-1}$$

Why oxygen, not helium (hydrogen)? What about the potential barrier? Generally, is it possible to increase the ion confinement time with no changing the electron confinement time?

$$\tau_e^{-1} = \tau_i^{-1} = \tau_{i1}^{-1} + \tau_{i2}^{-1}$$

Model

V. Mironov, S. Bogomolov, A. Bondarchenko, A. Efremov, and V. Loginov, Phys. Rev. ST Accel. Beams **18**, 123401 (2015); http://dx.doi.org/10.1103/PhysRevSTAB.18.123401

- Particle-in-cell method on a rectangular mesh;
- Ion dynamics – movement in the magnetic field, collisions with electrons and other ions, with the chamber walls etc. Confinement by a potential dip;
- Electron density ← charge density of ions;
- Current of ions to the walls and into extraction → $\times\frac{3}{2}T_e$ → P_{RF}
- Total ion confinement time – averaging over the plasma volume

$$\tau_i = \frac{\sum_Q (Q \times \int_{ECR} n_{iQ}(x,y,z)dV)}{I_i}$$

- Charge-resolved ion confinement times $\tau_{iQ}^{-1} = \bar{n}_{eQ} k_Q \frac{I_{wall-Q}}{I_{ion-Q}}$

Electron confinement time

$$\nu_e = \tau_e^{-1} = g(R)(\nu_{ei} + \nu_{ee}) + \varepsilon(R, T_{ew}) \frac{P_{RF}}{V \langle n_e \rangle T_{ew}} + f(R, E_{\sec})\nu_{ion}$$

$$\nu_{ee} = 2.9 \times 10^{-12} \frac{\langle n_e \rangle}{T_{ew}^{3/2}} \lambda_{ee}; \nu_{ei} = 4.1 \times 10^{-12} \frac{\sum_Q \langle n_{iQ} \rangle \times Q^2}{T_{ew}^{3/2}} \lambda_{ei}$$

f=0.2-0.05

f=0.3 with no plasma potential (+25 V)

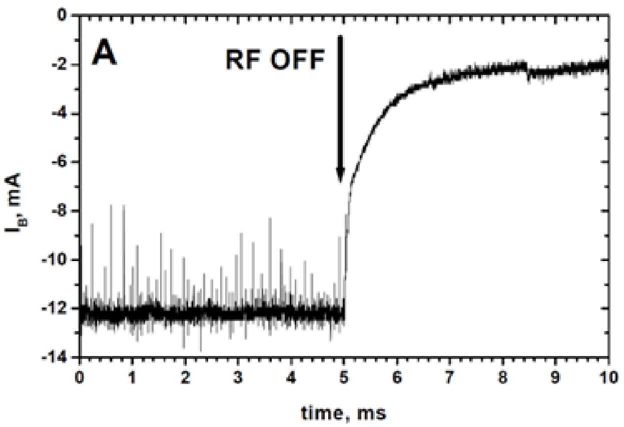
$$g(R) = \frac{R+1.5}{R-1} = 2.9$$

Post's electron confinement time

$$g_e(R) = \left[\frac{\sqrt{\pi}}{4} \sqrt{1 + \frac{1}{R}} \ln \left[\frac{\sqrt{1+1/R}+1}{\sqrt{1+1/R}-1} \right] \right]^{-1} = 0.8$$

Pastukhov's confinement time

$$\varepsilon(R, T_{ew}) = 0.32 \times (\frac{3}{2} T_{ew} / 4 \cdot 10^4)$$



RF diffusion into the loss cone

B.P. Cluggish, L. Zhao, J. Kim, Nucl. Instr. Meth. Phys. Res. Sect. A **631**, 111 (2011); http://dx.doi.org/10.1016/j.nima.2010.11.117

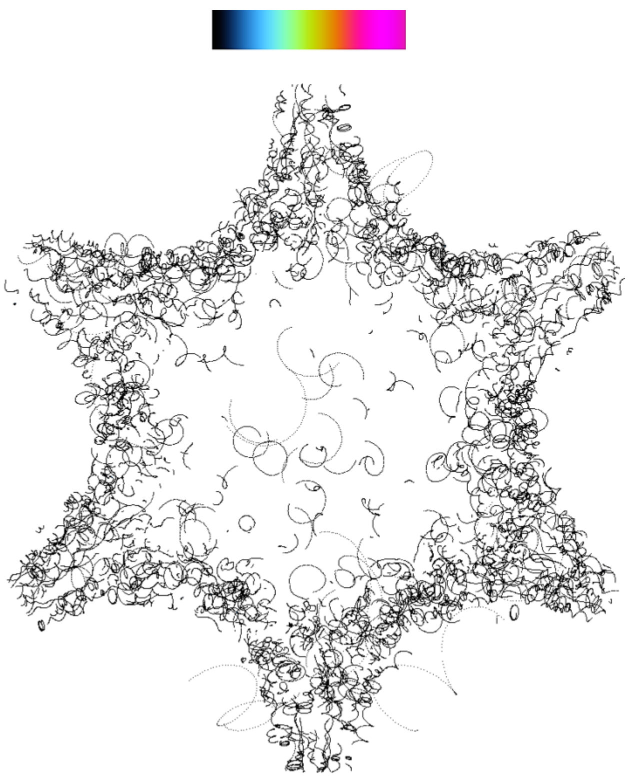
Molecular oxygen and nitrogen - ionization

	Reaction	k [10^{-8} cm^{-3}/sec]	KER per fragment [eV]
1	$O_2 + e \rightarrow O_2^{1+} + 2e$	5.5	0
2	$O_2 + e \rightarrow O + O + e$	3.34	1
3	$O_2 + e \rightarrow O + O^{1+} + 2e$	1.77	3.5
4	$O_2^{1+} + e \rightarrow O_2^{2+} + 2e \rightarrow O^{1+} + O^{1+} + 2e$	0.99	6.5
5	$O_2^{1+} + e \rightarrow O^{1+} + O^{1+} + 2e$	1.15	6.5
6	$O_2^{1+} + e \rightarrow O^{1+} + O + e$	1.77	3.5
7	$O_2^{1+} + e \rightarrow O + O$	1.0 (T_{ec}=5eV)	1
	$O + e \rightarrow O^{1+} + 2e$	1.4	0
8	$N_2 + e \rightarrow N_2^{1+} + 2e$	7.12	0
9	$N_2 + e \rightarrow N + N + e$	3.94	0.5
10	$N_2 + e \rightarrow N + N^{1+} + 2e$	0.93	3.2
11	$N_2^{1+} + e \rightarrow N_2^{2+} + 2e \rightarrow N^{1+} + N^{1+} + 2e$	1.55	5.9
12	$N_2^{1+} + e \rightarrow N^{1+} + N^{1+} + 2e$	0.59	5.9
13	$N_2^{1+} + e \rightarrow N^{1+} + N + e$	1.64	3.2
14	$N_2^{1+} + e \rightarrow N + N$	2.2 (T_{ec}=5eV)	0.5
	$N + e \rightarrow N^{1+} + 2e$	1.27	0

Atomic oxygen recombination in collisions with the walls -- 0.5 per collision; nitrogen – 0.01

Calculation flow-chart

Selection of the electron temperature and of the coupled RF power



Numerical weight of macro-particles and potential dip value

Confinement times for electrons and ions

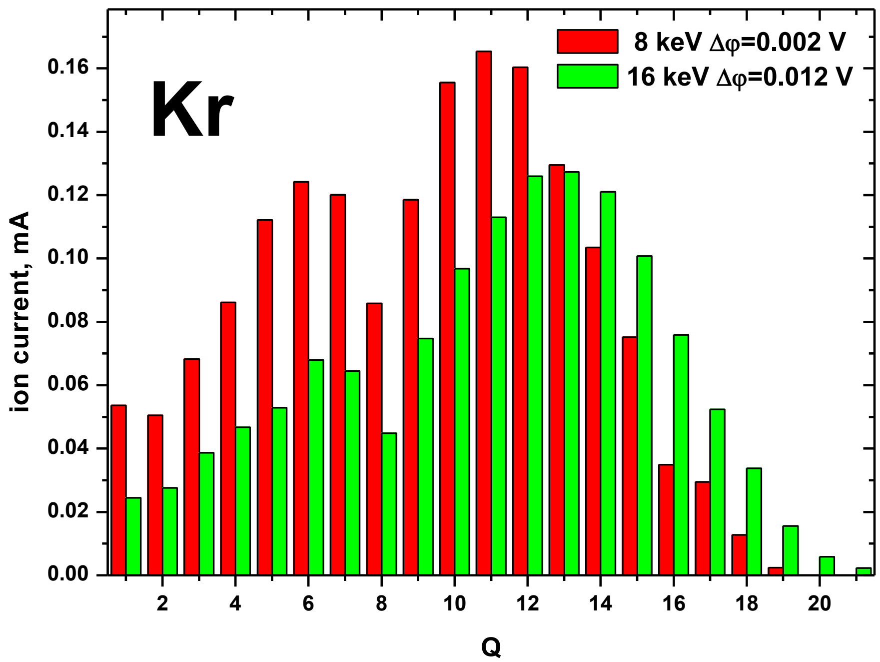
Stationary conditions

Extracted ion currents, gas flow into the chamber etc.

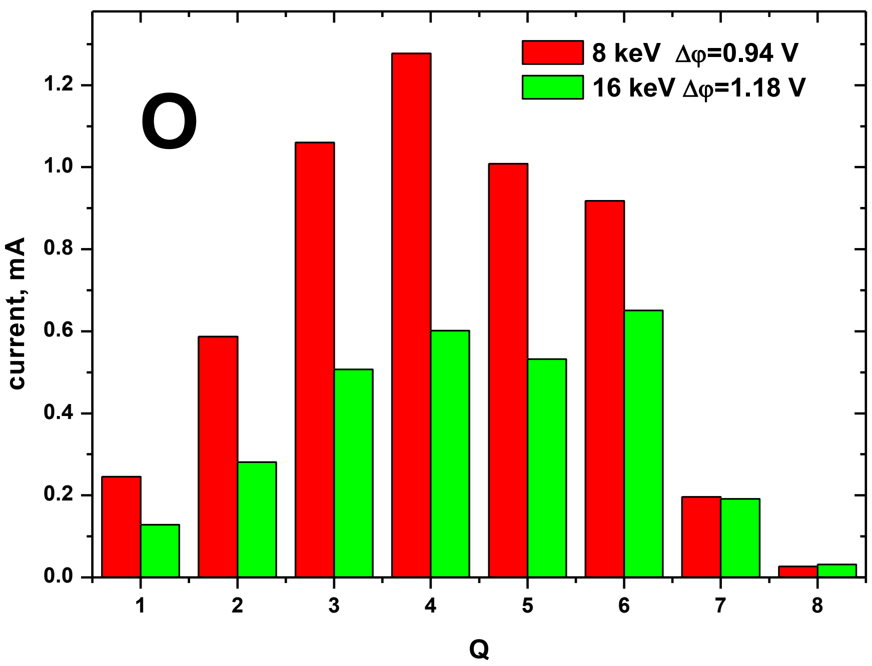
High electron temperature = small gas flow = small fluxes of ions/electrons out of the plasma;

Kr O_2 N_2 He Ne Ar

No Mix



Kr
8 keV Δφ=0.002 V
16 keV Δφ=0.012 V
ion current, mA
Q

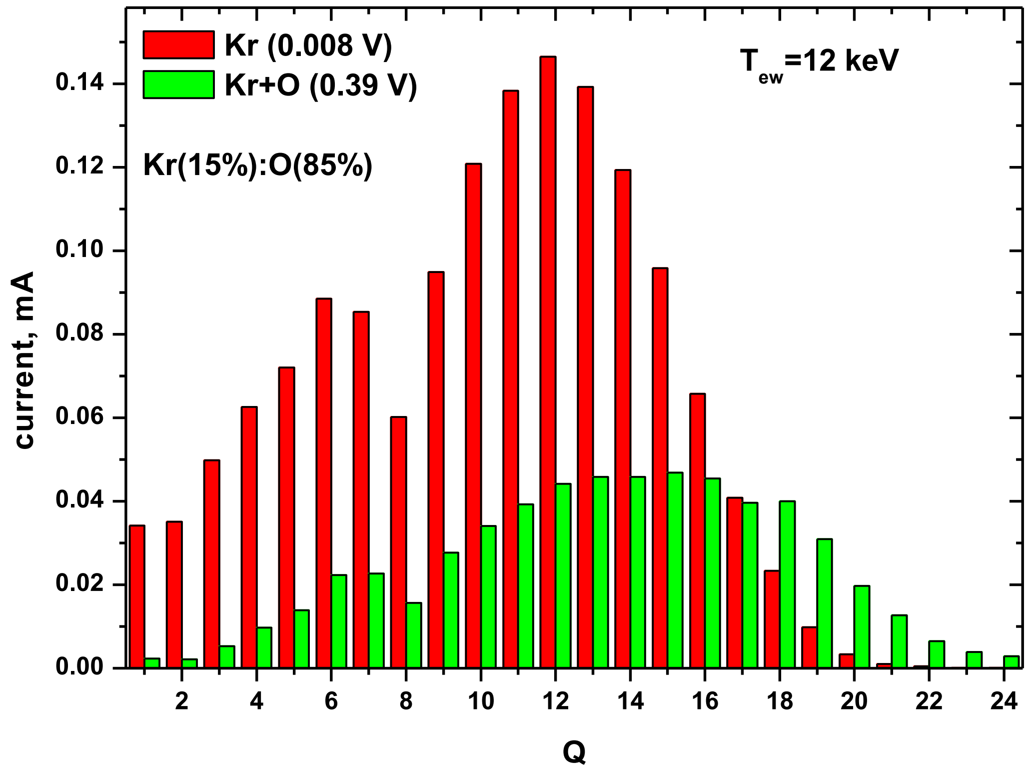


O
8 keV Δφ=0.94 V
16 keV Δφ=1.18 V
current, mA
Q

No Mix

Z	T_{ew}, keV	flow, pmA	$I_i(Q)$, μA	Δφ, V	τ_e, ms	T_i, eV	n_e,10^{12} cm^{-3}
Kr	4	0.77	221 (12+)	-0.017	0.14	0.24(12+)	0.8
Kr	8	0.33	160 (12+)	0.002	0.29	0.27 (12+)	0.82
Kr	12	0.25	146 (12+)	0.008	0.41	0.31 (12+)	0.81
Kr	16	0.2	126 (12+)	0.012	0.55	0.32 (12+)	0.77
O	4	3.0	894 (6+)	0.66	0.19	3.17 (6+)	1.06
O	8	1.74	918 (6+)	0.94	0.37	2.91 (6+)	1.19
O	12	1.2	816 (6+)	1.1	0.54	2.85 (6+)	1.25
O	16	0.9	650 (6+)	1.18	0.73	2.76 (6+)	1.25
He	4	8.45	7210 (2+)	0.22	0.23	0.4 (2+)	1.52
He	12	3.18	3170 (2+)	0.7	0.78	0.615 (2+)	1.75
Ne	4	2.84	1320 (6+)	0.04	0.19	0.57 (6+)	1.0
Ne	12	0.88	460 (6+)	0.2	0.54	0.71 (6+)	1.15
Ar	4	2.06	1450 (8+)	0.015	0.17	0.7 (8+)	0.93
Ar	12	0.6	500 (8+)	0.075	0.5	0.56 (8+)	0.97
N	4	3.48	2020 (5+)	0.6	0.19	2.4 (5+)	1.17
N	12	1.28	991 (5+)	1.0	0.58	2.35 (5+)	1.27

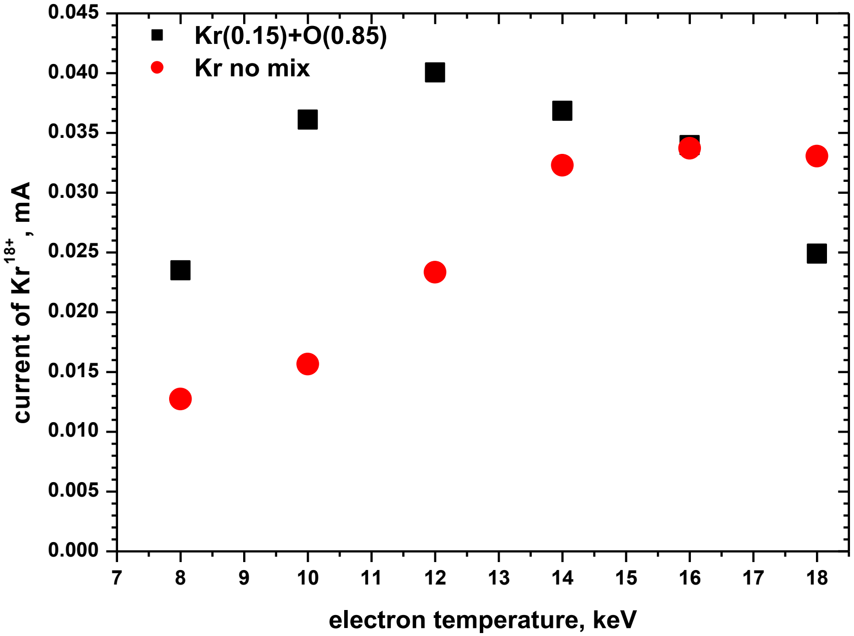
Mix of krypton and oxygen



Charge state distribution of the extracted krypton ions in the krypton discharge (red) and in the mix of krypton and oxygen (green): 15% of Kr and 85% of O atoms and ions of the total number of macro-particles in the chamber. Coupled power is 500 W

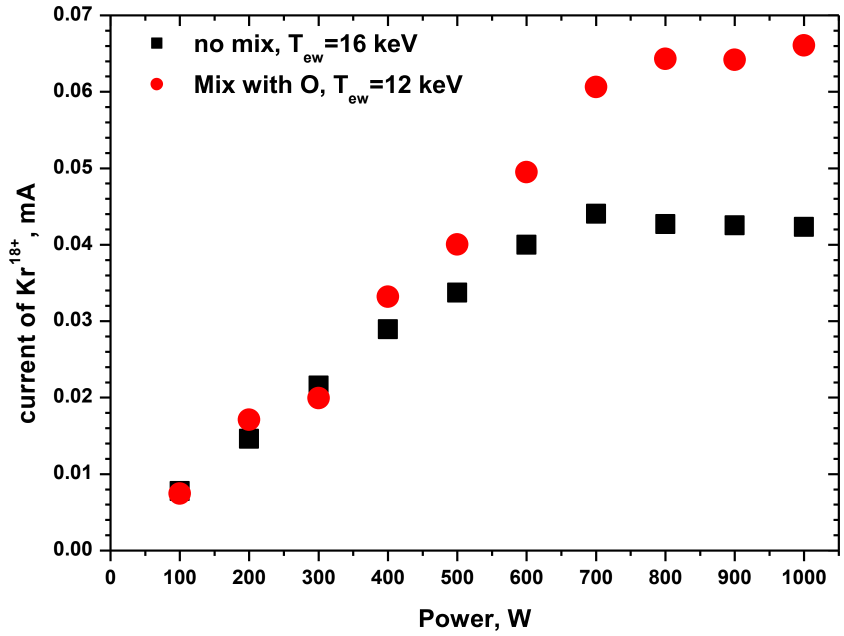
Mix of krypton and oxygen

GAS FLOW



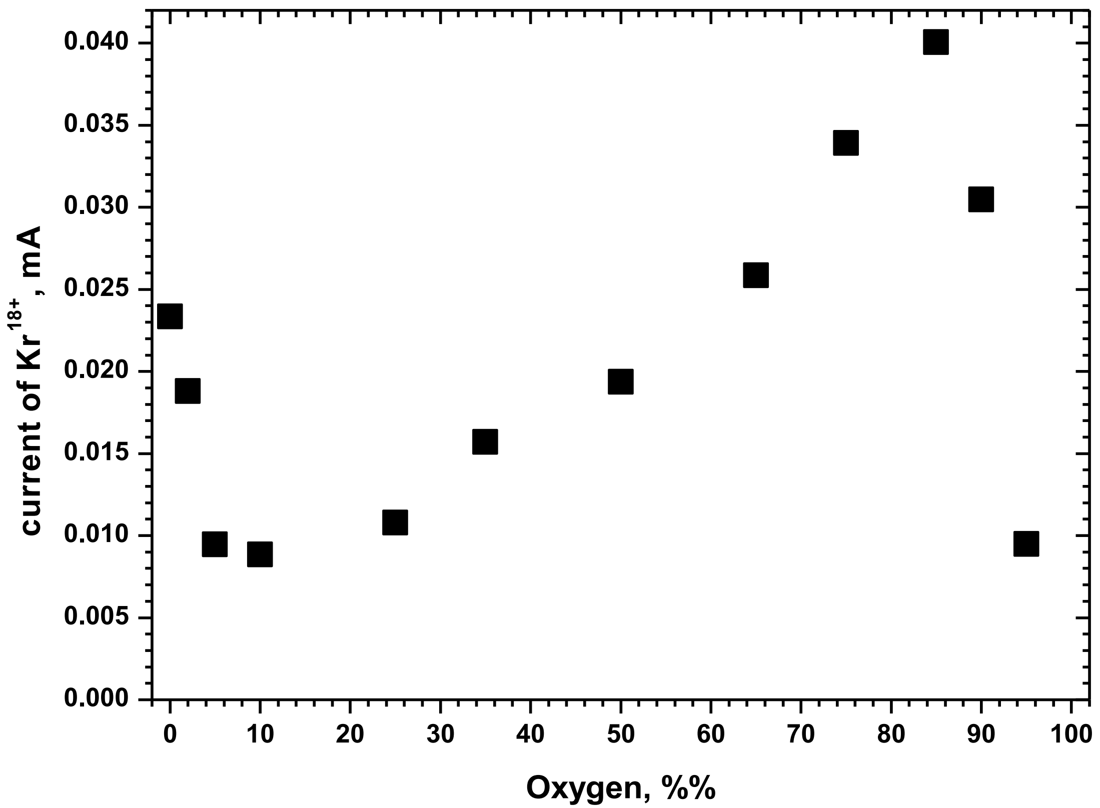
Current of the extracted Kr^{18+} ions as a function of the electron temperature in the krypton discharge and in the mix of krypton and oxygen (Kr=15%, O=85%).

MICROWAVE POWER



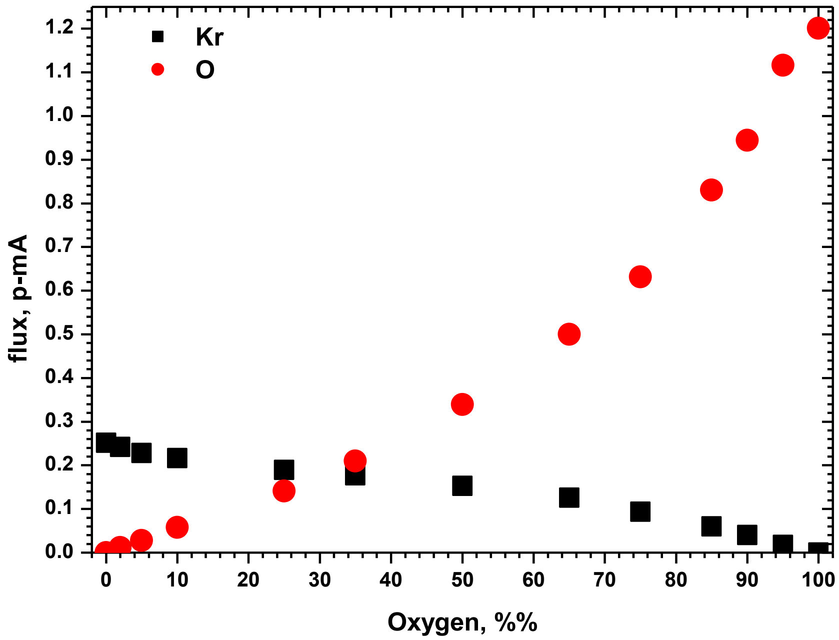
Extracted current of Kr^{18+} ions as a function of the coupled power for the krypton plasma (Tew=16 keV) and for the mix with oxygen Kr=15%, O=85%, Tew=12 keV.

Kr+O: different gas contents

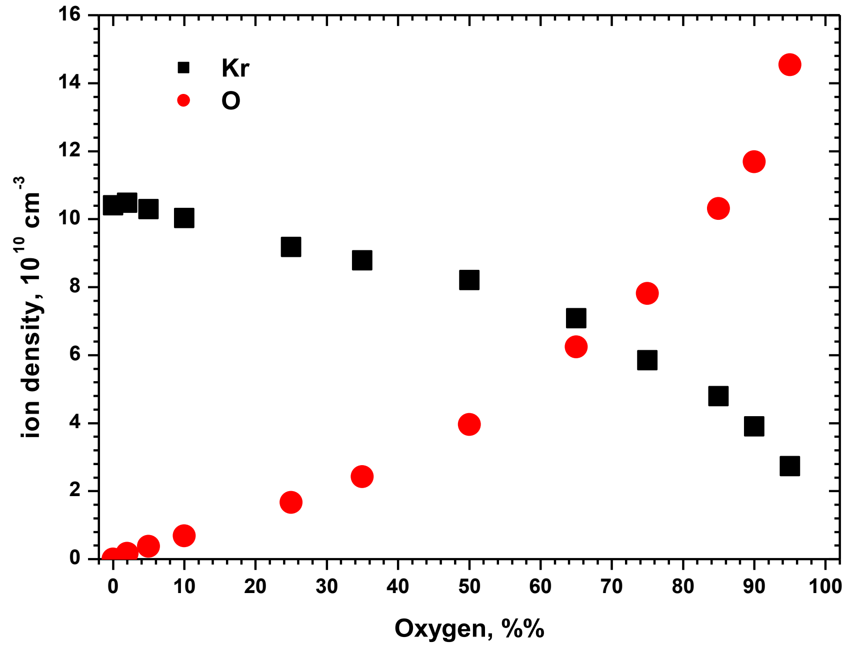


Extracted current of Kr^{18+} ions as a function of the oxygen content in the source chamber in percent of the total number of the macro-particles. P_{RF}=500 W, T_{ew}=12 keV.

Mix of krypton and oxygen

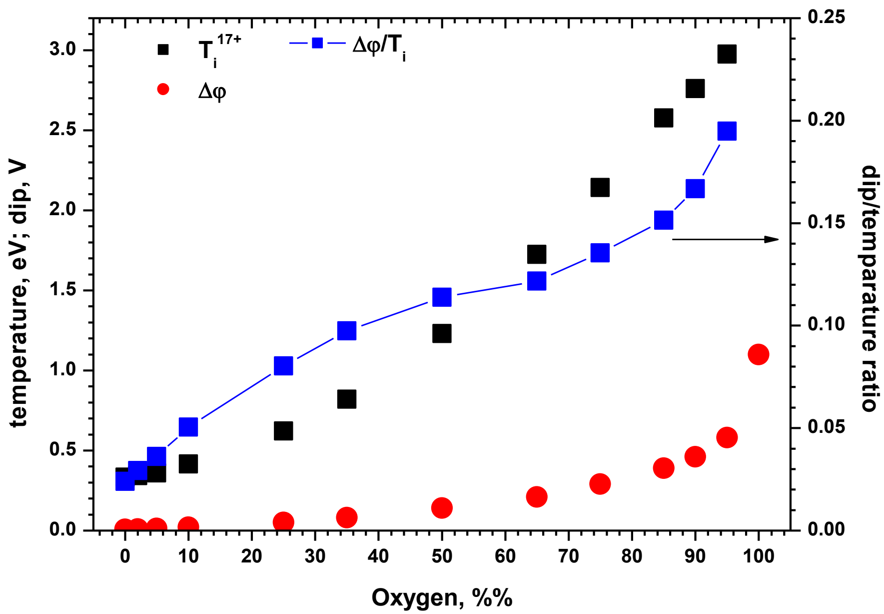


Fluxes of krypton and oxygen atoms into the source for different oxygen content. P_{RF}=500 W, T_{ew}=12 keV

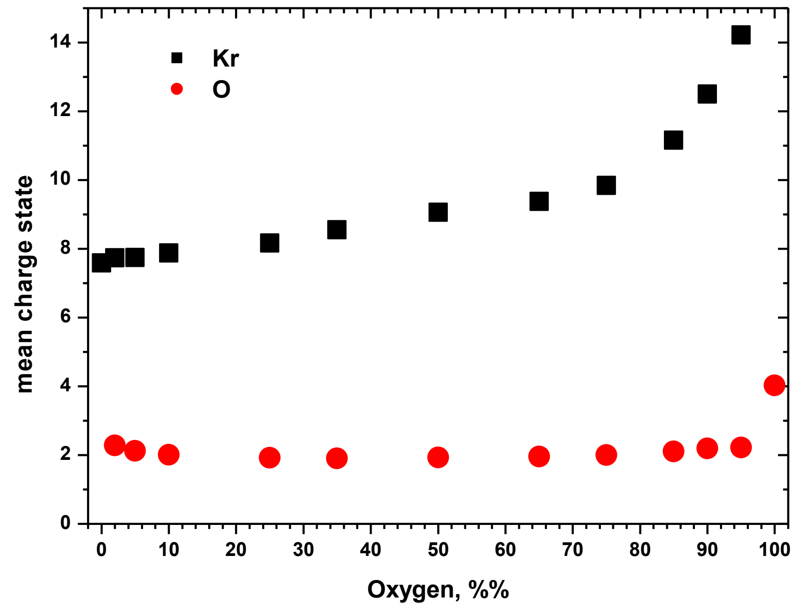


Total densities of krypton and oxygen ions averaged over the ECR volume for different oxygen contents.

Mix of krypton and oxygen

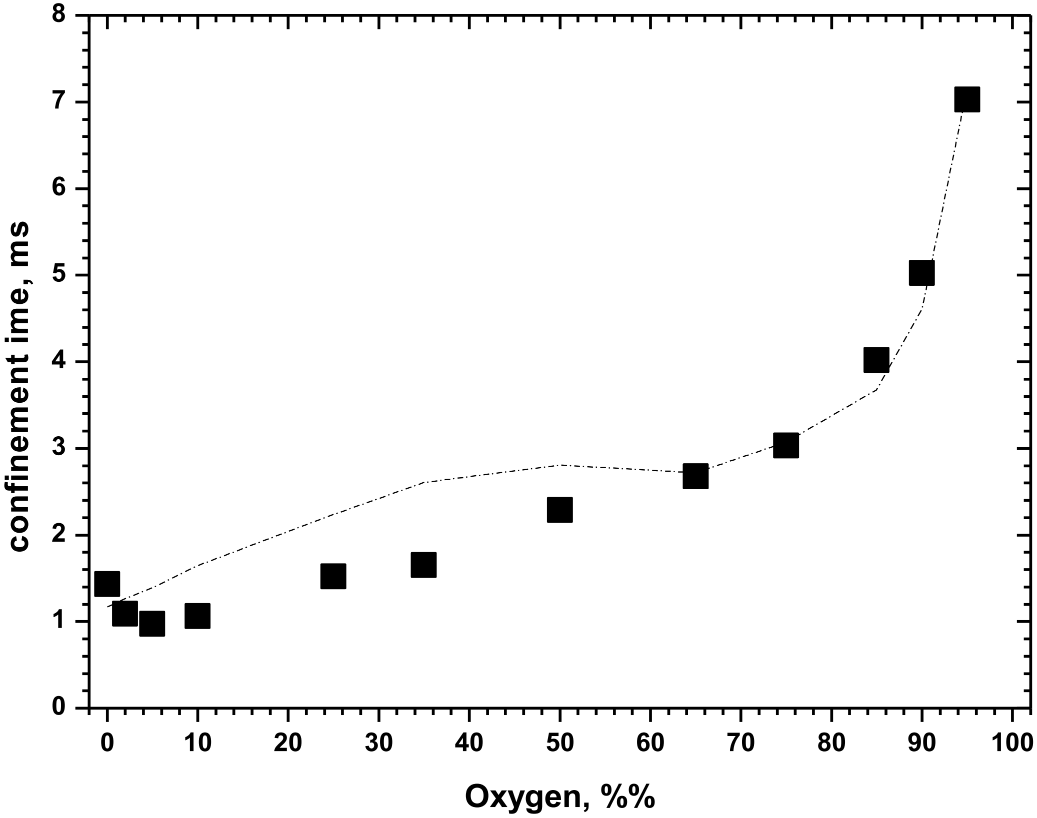


Dependence on the oxygen content of the potential dip Δφ (Volts, red circles, left scale), temperature of Kr^{17+} ions (eV, black squares, left scale) and the ratio between these values (blue squares, right scale).



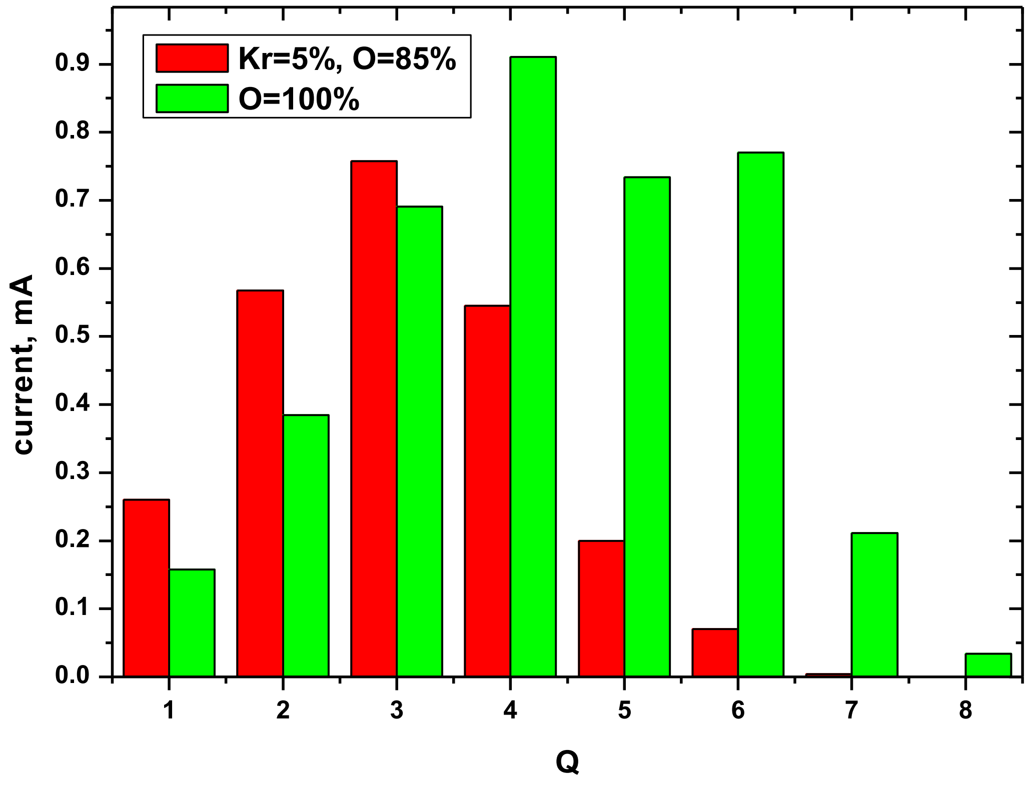
Mean charge state of the krypton and oxygen ions inside the ECR volume as a function of the oxygen content.

Mix of krypton and oxygen



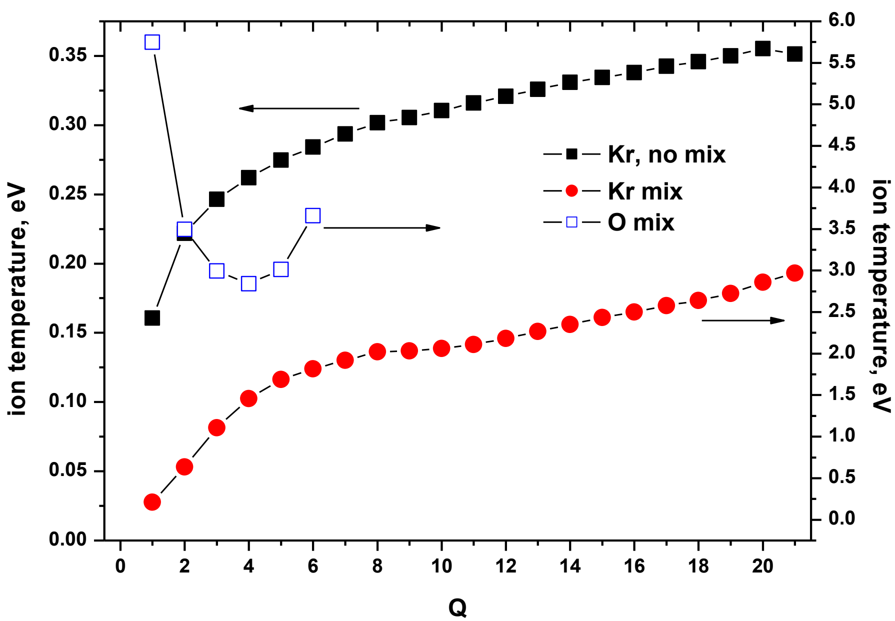
Confinement time of Kr^{17+} ions as a function of oxygen content

Mix of krypton and oxygen

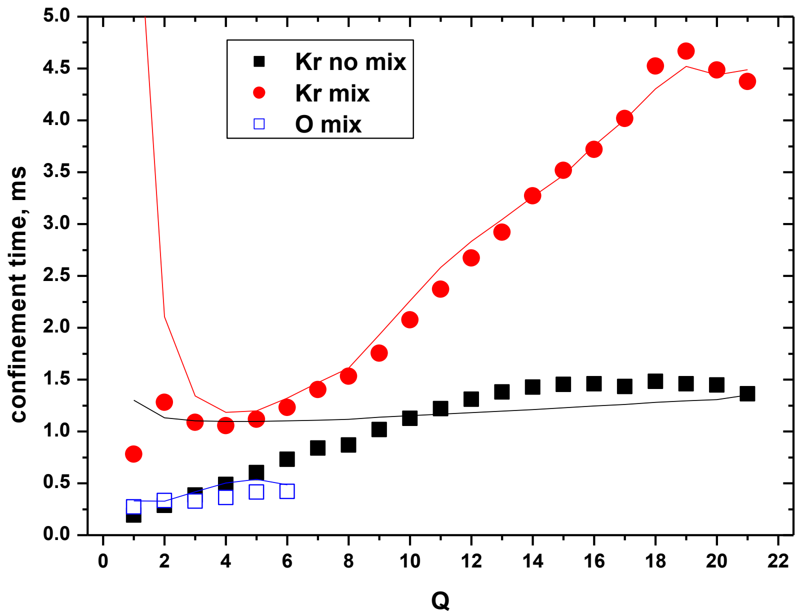


Charge state distribution of extracted oxygen ion currents for oxygen plasma and for the mix with krypton Kr=5%, O=95%. Electron temperature T_{ew}=12 keV, P_{RF}=500 W.

Mix of krypton and oxygen



Charge-state dependence of the ion temperature for krypton and oxygen ions in the pure krypton discharge (left scale, solid black squares) and in the mix of krypton and oxygen, Kr=15%, O=85% (right scale, red circles). Temperatures of oxygen ions are shown as open blue squares (right scale). T_{ew}=12 keV, P_{RF}=500 W



Confinement times of krypton ions for the krypton plasma Kr=100% (black squares) and in the mix with oxygen Kr=15%, O=85% (red circles) as a function of the ion charge state. Confinement times of oxygen ions in the mix are shown as the open blue squares. Fits with the Rognlien-Cutler times are shown as the lines. T_{ew}=12 keV, P_{RF}=500W

Mix of krypton and some gases

Z	flow (Kr), pmA	flow (mix), pmA	I_i (Kr^{18+}), μA	$I_i(Q)$, μA	Δφ, V	τ_e, ms	$T_i(17+)$, eV	$T_i(Q)$, eV	n_e, 10^{12} cm^{-3}	$n_e(Kr^{17+})$, 10^{12} cm^{-3}	$\tau_i(Kr^{17+})$, ms
^{16}O	0.06	0.83	40	28(6+)	0.39	0.46	2.64	3.66(6+)	0.73	0.44	4.0
^{18}O	0.06	0.79	38.5	32(6+)	0.39	0.47	2.68	3.52(6+)	0.72	0.45	3.9
N	0.054	0.87	33	63(5+)	0.3	0.48	1.93	2.48(5+)	0.69	0.40	5.1
He	0.074	1.23	12.4	285(2+)	0.022	0.45	0.2	0.21(2+)	0.75	0.79	2.6
Ne	0.051	0.70	19.9	198(6+)	0.05	0.50	0.36	0.38(6+)	0.83	0.57	3.2
Ar	0.047	0.48	13.4	342(8+)	0.06	0.48	0.55	0.54(8+)	0.89	0.62	2.4

Experiment:Mix Kr/Xe and $^{18}O/^{16}O$

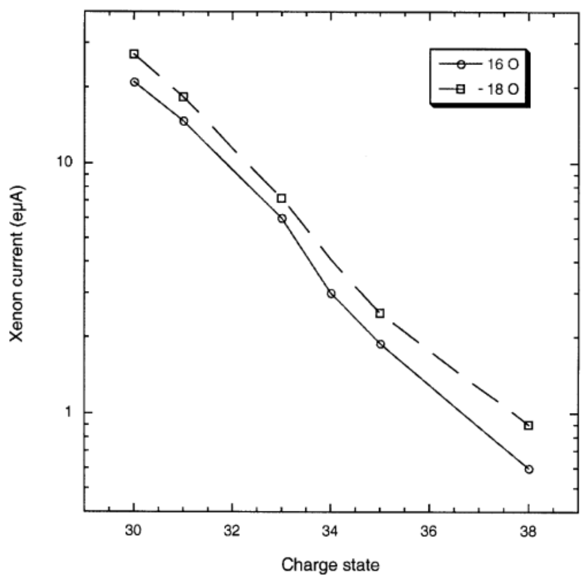


Fig. 1. Xenon current with different oxygen isotope as mixers.

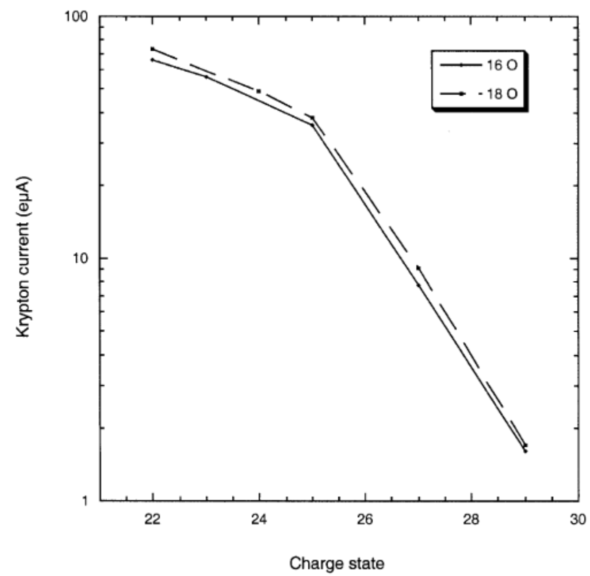


Fig. 2. Krypton current with different oxygen isotope as mixers.

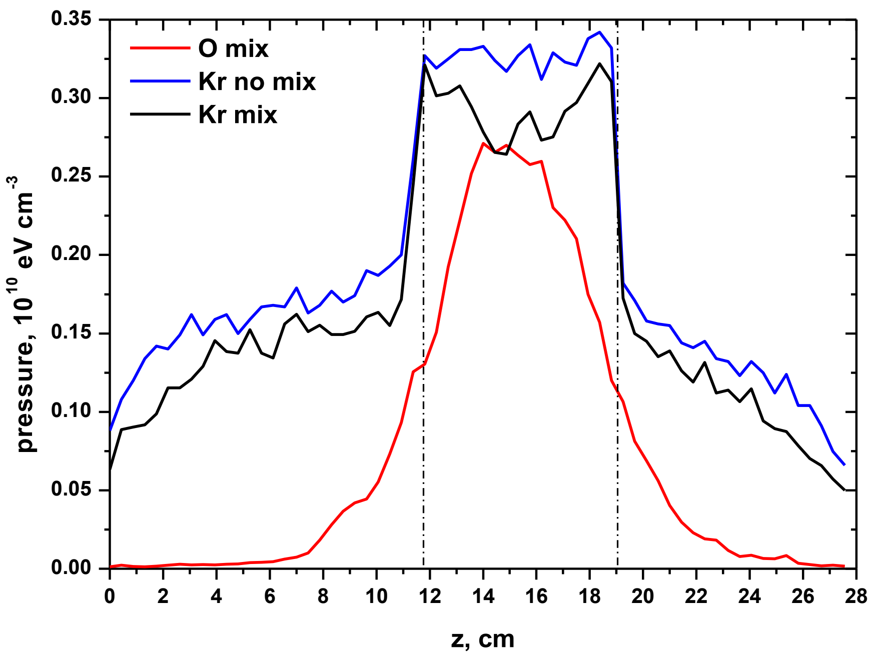
highly charged ions of heavy elements, up to values two or three times higher than any other ECR ion source. In future, more investigations will be car-

References

[1] A.G. Drentje, Proc. 7th Int. Workshop on ECR Ion Sources, Julich, 1986, p. 152, unpublished.

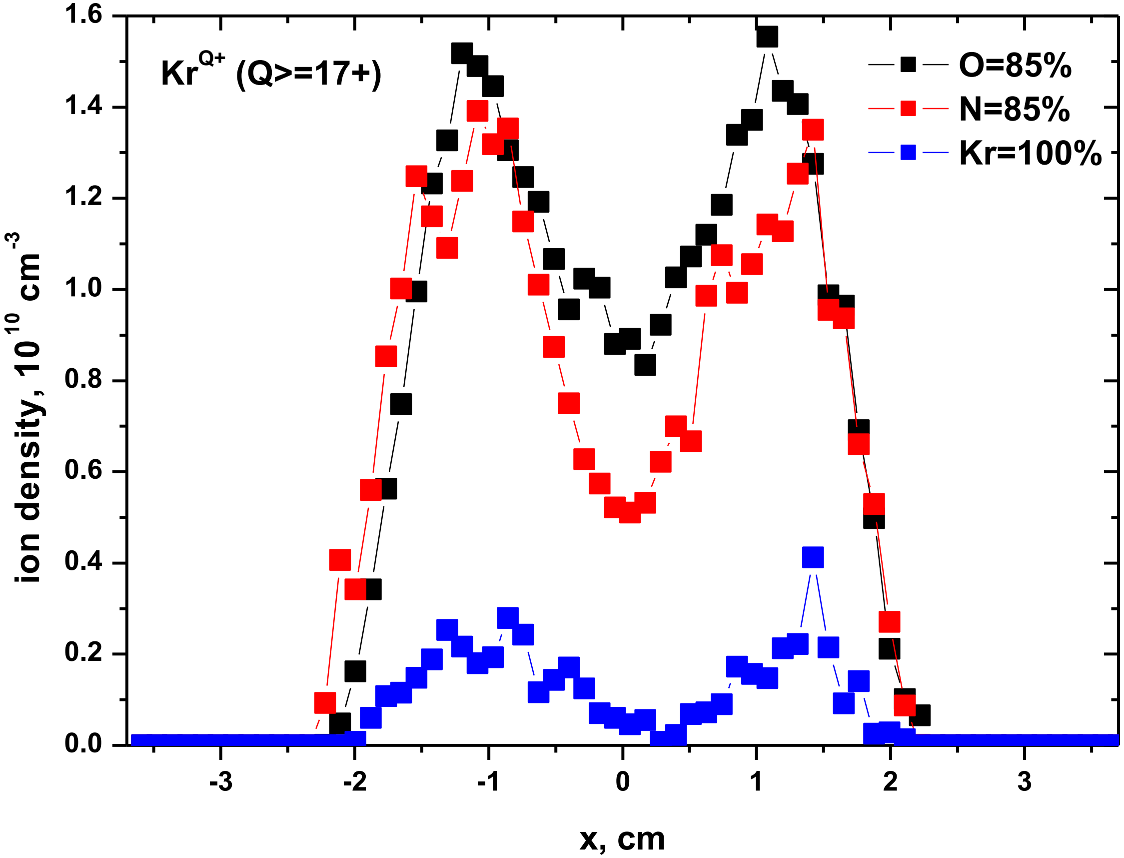
Conclusions

1. Gas-mixing effect is reproduced; the reasons are increase of the potential dip value and confinement times of the heavy highly charged ions due to the increased losses of the light ions.
2. Temperature of the heavy ions increases with injection of the light elements into the plasma.
3. Oxygen is the best mixing gas, energy of the oxygen ions is defined by molecular oxygen dissociation.
4. When injecting small fluxes of a heavy element, currents of the light elements decrease because of accumulation of the highly charged impurity ions in the potential trap of ECRIS plasma.



Ion pressure profiles along the source z-axis: pressure of oxygen ions (red), pressure of krypton ions at Kr=95%, O=5% (black), pressure of krypton ions at Kr=100% (blue). T_{ew}=12 keV, P_{RF}=500 W.

Mix of Kr, O and N



Density of the krypton ions with the charge states greater and equal to (17+) along x-axis in the middle of the source (z=14 cm) for the mix with oxygen (O=85%, black), nitrogen (N=85%, red) and with no mix (Kr=100%, blue). T_{ew}=12 keV, P_{RF}=500 W.