Laser Ablation Plasma Injection into the Frankfurt 14 GHz ECRIS

V.Mironov[§], O.Hohn[†ó], S.Runkel[†ó], L.Schmidt[†], G.Shirkov[§], K.E.Stiebing[†],
H. Schmidt-Böcking[†], A.Schempp[ó]

[†]*Institut für Kernphysik der J. W. Goethe-Universität, August Euler Straüe 6, D60486 Frankfurt am Main, Germany*
[ó]*Institut für Angewandte Physik der J. W. Goethe-Universität, Robert Mayer Str. 4-6, D60056 Frankfurt am Main, Germany*
[§] *Joint Institute for Nuclear Research, PPL, Dubna, Moscow Region, 141980, Russia*

1. Introduction

The laser ablation technique to evaporate solid materials into the plasma of an electron cyclotron resonance ion source (ECRIS) has already been tested [1,2,3]. By this method dense fluxes of neutral atoms can be injected into the ECRIS plasma by illuminating a solid target, mounted in the ECRIS vacuum chamber close to the plasma. If the laser beam intensity exceeds certain threshold values, specific for the target material, the laser driven evaporation resembles a local explosion forming laser ablation plasma in the direct proximity of the target surface; after that, the plasma rapidly expands. At moderate laser beam intensities the cooling and neutralisation during this expansion leads to a flux of particles, which consists to a high level of neutral atoms at sufficiently large distances from the target surface. When crossing the ECR plasma, these particles have a high chance to be ionised by electron impact ionisation, captured in the ECR discharge and transformed into highly charged ions by subsequent ionisation.

2. Experimental set-up

We have used this method at the Frankfurt 14GHz-ECRIS to explore the properties and mechanisms of the ECRIS plasma. A Q-switched YAG:Nd^{+3} laser with a power of 30 mJ, 15 nsec pulse duration and a wavelength of λ=1.064 μm was used for this purpose. For this laser system the total number of atoms emitted from a Zinc target is about 10^{15} particles released in a pulse of 10 μsec duration at 5cm distance from the target [4]. The atoms gain an average velocity of 10^6 cm/sec, which corresponds to kinetic energies of 20 eV.

The main features of the 14GHz Frankfurt ECRIS are described elsewhere [5,6]. For the tests described here, Argon, Oxygen, Helium and Xenon working gases were used to sustain the main ECR discharge. Gas pressures were in the range of 1-5×10^{-7} mbar measured at the microwave injection side of the source. Microwave powers up to 500 W were used. The extraction voltage was 25 kV. The source was equipped with movable biased disk made from stainless steel. The laser beam was introduced into the vacuum chamber through one of six vacuum ports, which enter into the plasma chamber from the microwave injection side with an inclination of 17° with respect to the source axis. The laser beam was focused by a 120-mm lens onto the surface of the metal target, which was tilted by 60° relative to the laser beam such that the atomic fluxes were tablets were used during these experiments. The repetition rate of laser was restricted to 1 shot per 15 seconds.

We have run the laser system in two modes. Maximum laser power was used for the production of highest currents of metal ions and to study the pulsed release of working gas ions. For the purpose of plasma diagnostics, the laser beam energy was reduced by approximately a factor of 3, to minimise the influence of the atomic fluxes onto the main ECR discharge.

2. Metal ion beams

At the first preliminary run with a Cd-target, we have measured up to 250 enA of Cd^{18+}-ions. It takes about 15 msec for the current to reach its maximum. It then decreases slowly during the next 30 msec. Lower charge states are produced much faster. For example, Cd^{9+}-ions need only 2 msec for their breeding.

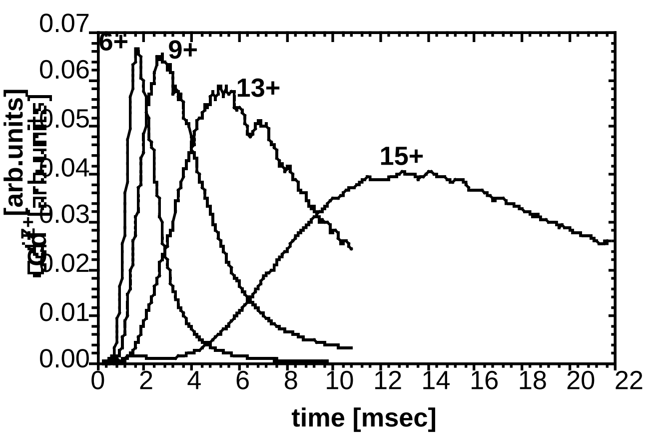

Fig.1 Time structure of Cd ion currents. The laser ablated Cadmium atoms are injected into Argon plasma with the reduced laser beam power.

When the laser beam energy is reduced, the time scale for the highest charge states becomes longer, which is probably connected to the better confinement in the less disturbed plasma of the main discharge. The ion currents for this mode of operation are presented in Fig.1 for Cd. The dependencies are similar when Zn is used as target material (Fig.2). Note that in contrast to Fig.1, these dependencies are normalized.

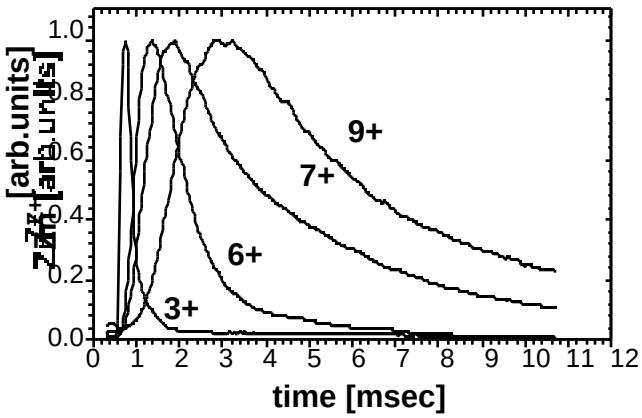

Fig.2 Time structure of Zn ion currents with the reduced laser beam energy. Zinc injection into Argon ECR plasma

In order to fit the experimentally determined shapes we have performed numerical simulations of ionic pulses of Cd and Zn ions injected into Argon plasma, which was considered to be non-disturbed. The code, used for this purpose, solves a set of non-linear differential balance equations for the ions, electrons and neutrals in the respective two-element mixture [7].

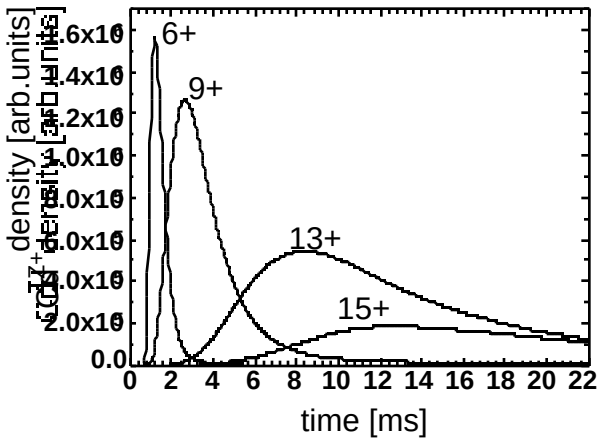

Fig.3 Numerical simulation of Cd ion currents under the Cd injection into Ar plasma. Electron density of Ar plasma is $n_e=5\times10^{11}$ cm^{-3}, electron temperature $T_e=750$ eV, ion confinement time $\tau_I=10$ msec for all charge states.

Good correspondence to the measured low charge state dynamics is achieved, if an electron density of $n_e=5\times10^{11}$ cm^{-3} in the Argon plasma with an electron temperature of $T_e=750$ eV is assumed. Fig.3 presents these results for Cd, and Fig.4 for Zn injection. In order to describe the fall times of the ion currents, the confinement time for the highest charge state has to be set to 10 msec.

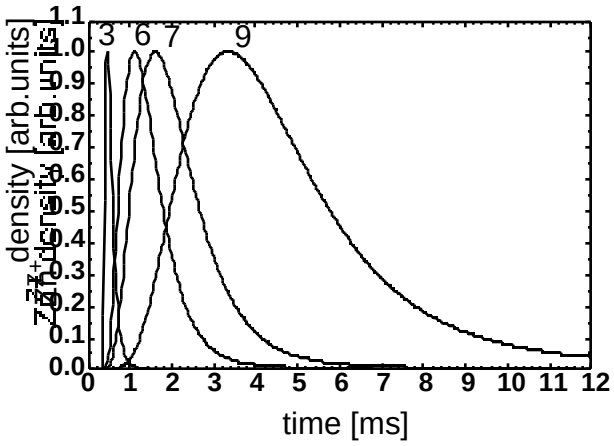

Fig.4 Numerical simulation of Zn ion currents under the Zn injection into Ar plasma. The same parameters of Ar plasma as in Fig.4.

The time to reach the maximum of the specific ion density is very sensitive to variations of the electron density and the electron temperature. The hotter and denser the plasma, the faster is this time. We have measured therefore the time position of the maximum amplitude for Zn^{7+} ions varying the microwave power and the Argon partial pressures (Figs.5 and 6).

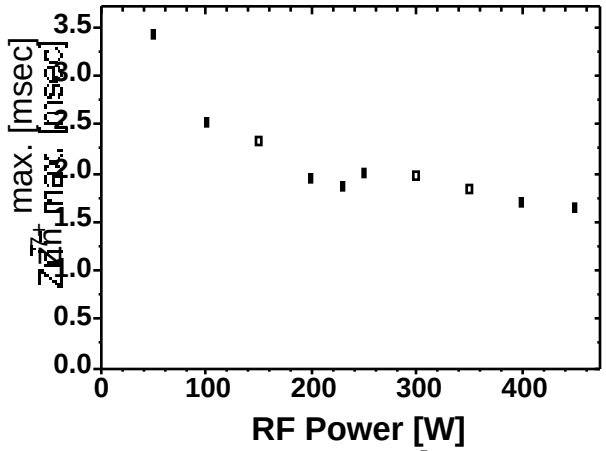

Fig.5 Time position of the peak for Zn^{7+} current as a function of microwave power. Argon pressure - 1.4×10^{-7} mbar.

It was observed that the time position of the Zn^{7+}-peak shifts to the shorter values when the microwave power or the Argon partial pressure are increased. While the influence of the Ar gas pressure on the rise times of the metal ion pulse seemed to be quite weak, it had a strong influence on the extracted Ar ion currents. The optimal values for Ar^{8+} were obtained at 1.4×10^{-7} mbar, whereas the Ar^{8+} currents were much lower (by the factor of 3) already at 1×10^{-7} mbar. It should also be noted that the shift of the time position of the metal ion pulse saturated at microwave powers higher than 200 W. The biased-disk voltage influenced the amplitudes of the ion currents significantly, but no changes of the time structure of the ion pulses were observed.

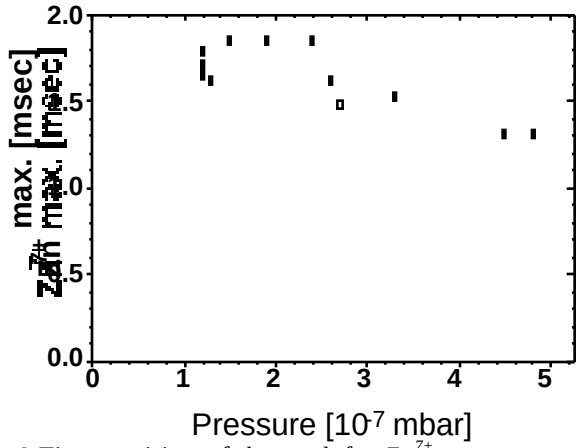

Fig.6 Time position of the peak for Zn^{7+} current as a function of Ar pressure. The microwave power - 400 W.

3. Argon and Xenon ion beams under the injection of neutrals.

The ion beams of the working gas elements were changed drastically when the laser ablation plasma was injected into the source. The typical dynamics is presented in Fig.7. Here, currents of Ar^{8+}-ions are plotted for two different Ar gas pressures in arbitrary units as a function of time after the creation of the Zn ablation plasma (laser pulse). The dashed horizontal lines indicate the DC levels of ion currents extracted from the unperturbed Ar-plasma. The maximum laser beam power was used, providing the highest possible atomic fluxes into the ECR plasma.

Immediately after the injection of the pulse of Zn atoms, the output current for Argon is decreased by factor of 2 followed with some delay by a pulsed release of Ar ions. This release lasts for approximately 1 to 2 msec. After this, the extracted currents slowly (within 20 to 50 msec) recover to their previous DC levels (Fig.8). This behaviour is essentially the same for all Ar charge states.

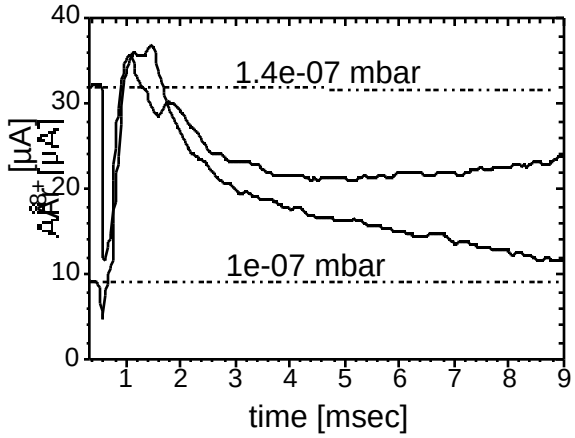

Fig.7 Early stage of Ar^{8+} currents under the Zn injection for two Ar pressures: 1.4×10^{-7} mbar (optimal for Ar^{8+} production) and 1×10^{-7} mbar.

While the amplitudes of the pulse remained almost the same for gas pressures in the range between 1 and 2×10^{-7} mbar, the ratio of the ionic pulse to it's respective DC level, depends clearly on the pressure. At the ratio is about 3-5, at the optimised gas pressure it is only about 1-1.5.

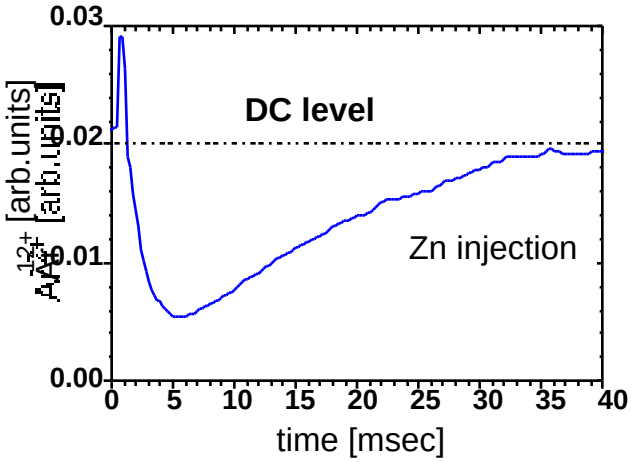

Fig.8 The recovery of the Ar^{12+} ion current after the Zn atom injection into ECRIS.

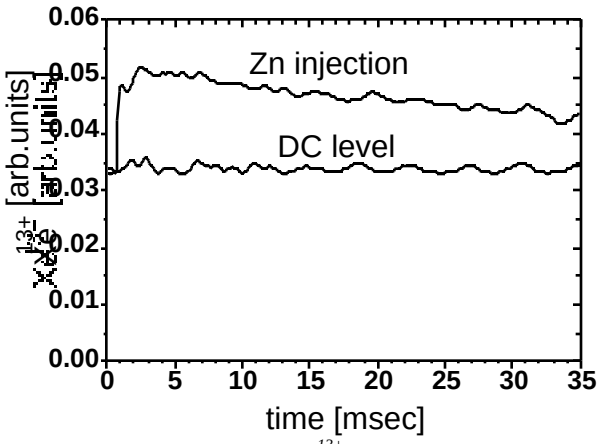

Fig.9 Time development of Xe^{13+}-ion currents under the injection of laser ablated Zn atoms into the ECRIS plasma optimised for the Xe^{13+} production.

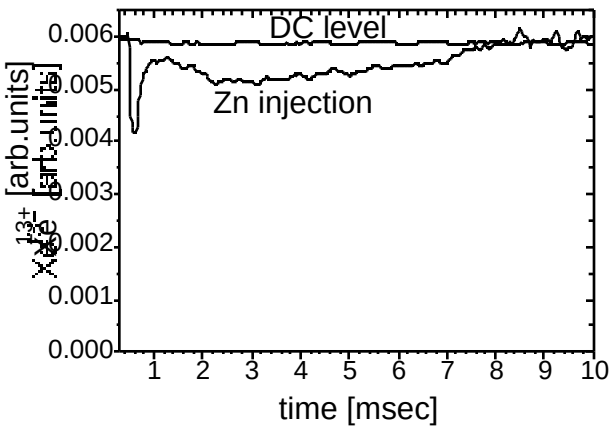

Fig.10 Xe^{13+} ion current under the $Xe+O_2$ gas-mixing and Zn injection.

For Xenon as working gas, these dynamics differ clearly from Argon case. In the pure Xe discharge the addition of metal atoms results in the prolonged increase of Xe ion currents, which lasts much longer than the Argon ionic pulses. This is shown in Fig.9, where the

DC level of the Xe^{13+} -ion currents is exceeded by factor of 1.5. This situation changes drastically when Oxygen is added to the discharge. By optimising the source performance in the "gas-mixing" mode of operation the DC currents of Xe^{13+}-ions could be increased by factor of almost 8. In this case the prolonged pulsed increase due to the injection of laser ablated Zn-ions could not be observed, and only the short pulse of ionic currents was observed (Fig.10).

4. Conclusion

The addition of metal atoms to the discharge changes the plasma potential by means of non-balanced creation of ions and electrons. Starting with neutral atoms and with an initially positive plasma potential of 50-100 eV [8], one can expect a rapid decrease of the plasma potential by the ionisation of the initially neutral metal ions, releasing electrons to compensate the plasma potential, whereas some energetic metallic ions leave the plasma. This probably explains the first fast drop of the extracted ion currents shortly after the injection of the neutral atoms. At the same time the metallic ions start to become collisionally thermalised from their initial energies (about 10 eV) down to values typical for an ECRIS (few eV [8]) by heating simultaneously the working gas ions. At this stage the electron losses from the plasma grow, whereas a built-up plasma potential trap decreases the losses of sufficiently slow ions allowing to create highly charged metal ions by means of successive electron impact ionisation (see Fig. 1). This whole process should result in the strongly oscillations of the plasma potential until the system will come back to its initial non-disturbed conditions. One could expect the additional release of ions during the transitional period. Highly charged Ar ions, which already exist in the plasma, will preferably be expelled in this process, since they have higher q/m ratios in comparison with Zn or Cd ions. The time scale and dynamics of the relaxation depends on the working gas pressure and the plasma parameters.

As we have measured almost the identical amplitudes of the pulsed release of Ar^{8+}-ions, we suggest that the total Ar ion content in the plasma is essentially at the same level for the two gas pressures presented in Fig.7. These observations should be combined with the measurements of the breeding times for Zn^{7+} as a function of the gas pressure (Fig.6). However, quite different DC currents were measured. This then has to be ascribed to the different rates of ion production/loss processes for the two cases of different flow of neutral Argon atoms into the plasma. It is interesting to see the parallels between these observations, afterglow effects [8] and the increase of the currents under the operation of a pulsed biased disk [6].

The case of the injection of Zn atoms into the pure Xe discharge can be explained in terms of pulsed gas-mixing, where the metal ions, being lighter than the working gas now, serve as supporting (mixing) gas. Its dynamics is different from pure Ar+Zn(Cd) and Xe/O_2+Zn cases. The effect develops quite fast and continues for the relatively long period of time, which is roughly in the order of the dwelling time of the metal ions in the Xe plasma. In gas-mixing with O_2+Xe, the Zn influence diminishes completely within 10 msec, which is the time typical for the plasma potential disturbance shown in analysis of these observations may provide more information about the gas-mixing and afterglow effects.

Acknowledgements

The work is supported by a grant of "wissenschaftliche technische Zusammenarbeit mit Rußland" (WTZ), Bundesministerium für Forschung und Technologie (BMBF), Grant Number: RUS-669-97. Valuable discussions with S. Biri are gratefully acknowledged.

Literature

[1] R.Harkewicz, P.J.Billquist and R.C.Pardo, in *Proc. of 12th Int.Workshop on ECR Ion Sources*, 1995, RIKEN, ed. by M.Sekiguchi and T.Nakagawa, INS-J-182, 19 (1995)

[2] P.Yuan, Z.W.Liu, X.Z.Shang and X.H.Guo, in *Proc. of 12th Int.Workshop on ECR Ion Sources*, 1995, RIKEN, ed. by M.Sekiguchi and T.Nakagawa, INS-J-182, 232 (1995)

[3] L.Bex, P.Lehérissier and J.F.Hamet, Nucl.Instrum.and Meth., **A 365**, 564 (1995)

[4] V.Mironov, G.Shirkov, O.Strekalovskiy, N.Tokareva, Rev.Sci.Instrum., **69(**2), 1129 (1998)

[5] K.E. Stiebing, H. Streitz, L. Schmidt, A. Schremmer, K. Bethge, H. Schmidt-Böcking, A. Schempp, U. Bessler, P. Beller, in *Proc. of the 12th Int. Workshop on ECR Ion Sources*, 1995, RIKEN, ed. by M.Sekiguchi and T.Nakagawa, INS-J-182, 122

[6] S.Runkel et al., these Proceedings

[7] G.Shirkov, report CERN/PS 94-33 (HI) (1994)

[8] R.Geller, "Electron Cyclotron Resonance Ion Sources and ECR Plasmas" (IOP Publishing, Bristol), 434 p. (1996)