RECENT DEVELOPMENTS AND ELECTRON DENSITY SIMULATIONS AT THE ATOMKI 14.5 GHz ECRIS

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Abstract

The 14.5 GHz ECR ion source of ATOMKI is a standard, room-temperature ECRIS for plasma diagnostic studies, for atomic physics research and also serves as a low-energy particle source with wide range of elements for surface treatments. Recently the original NdFeB hexapole was exchanged by a new one and, consequently, new iron plugs were calculated, designed and installed at the injection side of the source. The resulted stronger magnetic trap has shown significant effect on the beam intensities and on the charge states distributions. The new magnetic configuration was re-calculated by the TrapCAD code developed by our group. The spatial positions and energy structure of 3 million electrons were calculated. A post-simulation energy filtering carried out on the non-lost (plasma) electrons reveals numerous interesting and important information in 3D.

INTRODUCTION

The 14.5 GHz ATOMKI ECR ion source celebrates its 20 years anniversary in 2012 because the basic financial contract was signed in 1992. The first plasma was generated in 1996 and the ion source delivers beams since 1997. During the past two decades continuous technical developments characterize the source itself and its surroundings called ECR Laboratory [1].

In a recent paper the status in 2011 and the special features of our ECRIS were shown in full detail [2]. Since then the magnetic trap was significantly strengthened by exchanging the hexapole magnet and the iron plugs. The computer control system was also changed and the new one is being tested and developed promisingly. All these technical upgrades are summarized in the first part of this paper.

The new magnetic trap significantly changed the structure of the magnetic field inside the plasma chamber. The magnetic system was re-calculated and then the electron cloud in the new trap was simulated by our TrapCAD code [3, 4]. Meanwhile TrapCAD itself was also slightly upgraded. The results of the simulation are shown in the second part of the paper.

UPGRADED MAGNETIC TRAP

The mechanical, electrical and microwave structures of the ATOMKI-ECRIS are not fixed: depending on the actual experiment they have several configurations. In Fig. 1 the basic (most frequent) setup is shown. The magnetic trap consists of two identical room-temperature solenoid coils with 5 cm thick iron yoke and of a permanent magnet hexapole. The coils-generated axial magnetic field peak values are 0.95 Tesla at both sides without the optional soft iron plugs at the injection side.

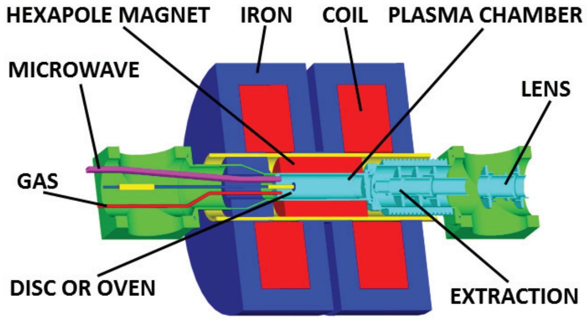

Figure 1: The most frequent mechanical and magnetic configuration of the ATOMKI-ECRIS.

In 2012 the 15 years old hexapole was exchanged by a new one. Table 1 summarizes the geometrical and magnetic features of the original and new hexapoles. The radial pole field of the old hexapole at the plasma chamber internal wall (R=29 mm) was 0.95 Tesla at the beginning and this value gradually decreased between 1996 and 2007 year by year by a yearly factor of about 2%. In 2008 however, a sudden and still un-understable big decrease occurred resulting a much weaker magnetic field strength of 0.7 Tesla at R=29 mm. Between 2008 and 2012 the ECRIS mainly operated at lower frequencies with the weakened hexapole in order to reach an acceptable mirror ratio. In 2012 the hexapole was exchanged by a new one. Its external diameter could be enlarged by a small re-designing of the surrounding pieces. Now the magnetic field in the plasma chamber is about 1.2 Tesla i.e. much stronger than ever it was with the old hexapole.

When the new hexapole was installed the soft iron magnetic plugs at the injection side had to be re-designed, manufactured and installed. The goal of this change was double. We wanted to increase the peak magnetic field at the injection side inside the plasma chamber as high as possible. The second gal was to minimize the force to the plugs and thus to minimize the opposite direction force to the basic structure of the ion source. Both goals were achieved and now the peak axial magnetic field at the injection side is almost 1.3 Tesla while it remained less

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ISBN 978-3-95450-123-6

than 1 Tesla at the extraction side. One of our next plans within the development activities is to design and install iron plugs to the extraction side, as well.

	Old hexapole	New hexapole
Material	NdFeB (490i/400i)	NdFeB (N45H)
Segments	24	24
Lengths (mm)	200	200
ID (mm)	65	65
OD (mm)	135	155
B-field at R=29 mm (Tesla)	0.95 (0.7)	1.2

Table 1: Summary of the two hexapoles. R=29 mm is the internal radius of the plasma chamber.

The new hexapole and iron plugs (see Fig. 2) significantly effected on the charge state distribution of the plasma. So far the effect was tested mainly for oxygen and argon and a prompt 10-50 % increase was observed for all charge states. The beam tests will be continued for other elements.

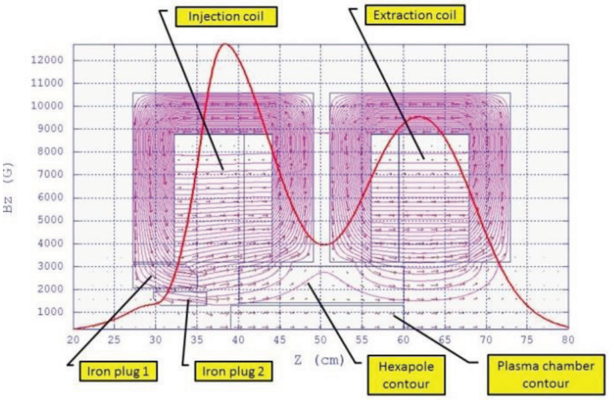

Figure 2: The upgraded magnetic system (Superfish calculation) with field lines and with the axial magnetic field distribution.

The ion choice of the ATOMKI-ECRIS recently increased due to new the requirement from our users. Gold and calcium beams were produced by the sputtering method using oxygen base plasma. While the peak intensities for both elements are not high yet (1-2 microampere) the CSD for gold is satisfactory. The highest peak was 20+ and charge states up to 26+ were observed in the first experiment.

The old computer control system (Pentium-1 motherboard, Windows-95) served well during the last 15 years. Recently a new NI-PXI hardware was installed. The development of the Labview-based control software is under way. At that moment all the functions operated under the old control system work at the same level or better in the new configuration. The final goals are to include majority of the ECRIS setting tools (digital and analogue inputs/outputs, GPIB and RS232 interfaces, stepping motors etc.) and to shorten the tuning and beam transport times.

PLASMA ELECTRONS SIMULATIONS

The modifications in the magnetic system involved that the simulation of the plasma in the upgraded magnetic trap is the next logical and useful step to understand the operation of our ECRIS. For the simulations the TrapCAD code was used which is described in details elsewhere [3, 4]. TrapCAD was made to visualize the magnetic trap of ECR and other ion sources and to follow the paths and the energy evolution of the electrons in this magnetic trap by including the electron-cyclotron-resonance phenomena. The magnetic field distribution is calculated by freeware or commercially available pre-processing codes (e.g. PoissonSuperfish). TrapCAD is a “limited-3D” code, the magnetic system must have some regularities (cylindrical axial field, multipolar radial field), but the resulting motion is implemented in 3D.

The spatial and energy structure of the non-lost electrons in the new magnetic trap of the ATOMKI-ECRIS were calculated. TrapCAD was used within a timescale such that the particle–particle interactions are neglected. A high number of independent electrons are energized by stochastic resonance heating process. All the initial particles were located at the resonance surface. A recent small upgrade in TrapCAD resulted that the initial electron density on the surface of the resonance zone (RZ) is more equal than before. Another modification accelerated the running time of the code. Now the simulation of one million electrons is possible in reasonable time (a few tens of hours CPU time on a PC with i5 processor). In the simulation the initial conditions were as follows.

- **Geometry.** Calculation took place in the cylindrical plasma chamber of the ATOMKI-ECRIS, diameter is 58 mm, length is 210 mm.
- **Magnetic field.** As described in the previous section, calculated by PoissonSuperfish. Mesh size is 1 mm in each directions.
- **Electrons**. 3 million electrons were placed with equal density into a thin layer developed by the resonance field (B=5200 gauss closed magnetic surface for 14.5 GHz microwave frequency). The basic condition was that the magnetic field can differ by less than 100 gauss from the resonance value. Electrons thus started from positions where the magnetic field was between 5100 and 5300 gauss. This corresponds to a layer with about 0.6 mm thickness. The starting energy of the electrons was a random value between 1 and 100 eV for both (parallel and perpendicular) components.

- **Microwave**. A circularly polarized plane wave propagates along the plasma chamber axis. The electric vector of this type of wave is rotating in the perpendicular plane. The initial phase difference between the rotating electric field and velocity vector of the particle is a random value. Thus the electrons are heated up by stochastic resonance heating process. In this calculation 14.5 GHz frequency and 1000 watt power were applied.
- **Simulation time.** In order to neglect the electron-electron and electron-ion collisions (not included in TrapCAD) the simulation time was chosen to be 200 nanoseconds. In real (CPU) time the calculation lasted for 127 hours.
- **Overall result.** At the end of the simulation 49% (1.46 million) of the electrons were still remained in the plasma and 51% lost on the chamber wall. The average energy of the non-lost (plasma) electrons increased from 100 eV up to 3330 eV by the ECR heating process. In Fig. 3 the energy distribution curve of the non-lost (plasma) electrons is shown.

  According to our recent study [5] the electron component of the plasma may artificially be grouped into sub-populations (see Fig. 3):
    - E<200 eV: cold electrons.
    - 200 eV < E < 3 KeV: intermediate electrons.
    - 3 KeV < E < 10 KeV: warm electrons.
    - E>10 KeV: hot electrons.

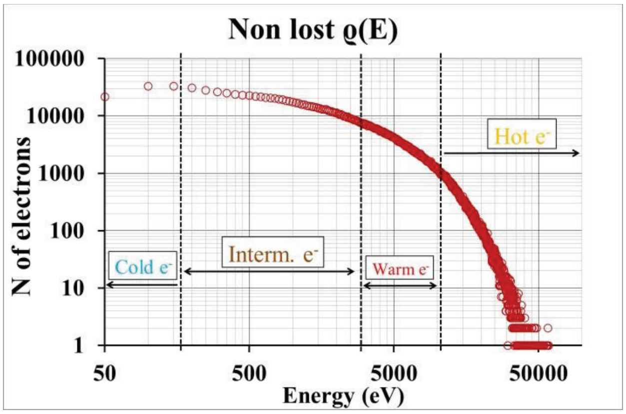

Figure 3: Simulated energy distribution curve of the non-lost electrons in the Atomki-ECRIS.

For the point of view of HCI production, the most important group is the warm electrons. In [5] was shown that for the case of argon plasma mainly the 3-10 KeV energy (warm) electrons carry out the step-by-step ionization. By comparing the simulation results with X-ray photos of argon ions the spatial positions of these two particle clouds were very similar. Based on this result, any spatial information to be obtained for the warm electrons from this simulation, can be used (with some limitations) for the plasma ions.

After 200 nanosecond simulation time the final energy and positions of all the electrons are saved. The non-lost electrons are filtered by their energies according to Fig. 3.

The electron density distribution along the plasma chamber axes demonstrates the significant difference between the electron populations. In Fig. 4 cold electrons are found all along the plasma chamber – according to the many visual observations (cold electrons excite atoms which emit visible light photons). The warm (ionizing) electrons concentrate much more around the resonance zone (RZ). They are two order of magnitude less near the chamber end-plates (z=1 and z=20) than the cold electrons. The ion density should also much higher near the RZ than at the ends. It does not mean of course, there are no electrons or ions close to or at the end-plates. The well-known triangles are always formed from both low charged and higher charged lost ions as it was shown in [6]. The density of the hot electrons outside the RZ is more than 3 orders of magnitude less than near the RZ. For all energy components however a general conclusion is valid: the electrons separate into a high density inner plasma (developed by the RZ) surrounded by a lower density halo. The same observation was found and proved in [7].

To get 3D-impression on the main components of the plasma it is useful to visualize "plasma-slices" along the Z-axes. In Fig. 5 one centimetre thick plasma-slices of three electron populations (intermediate, warm, hot) are shown. These populations are the most interested in the point of view of ions. Z=11-12 cm means the middle plane of the plasma chamber; here the plasmas consist of 6 identical clouds in the 6 magnet gaps. The Z=8-9 and 14-15 cm positions are at the two ends of the RZ. The transformation of the 6-pole structure gradually changes into triangles toward both directions. The differences between the 3 populations at the same axial position are also well visible. Note the different intensity scale for each sub-pictures (and for Fig. 6 and 7, later on). In the most right column the superposition of all the plasma slices are shown. The warm electrons sub-picture is very much similar to those X-ray plasma photos. Figure 6 shows the projection of the cold, intermediate, warm and hot electrons from side directions.

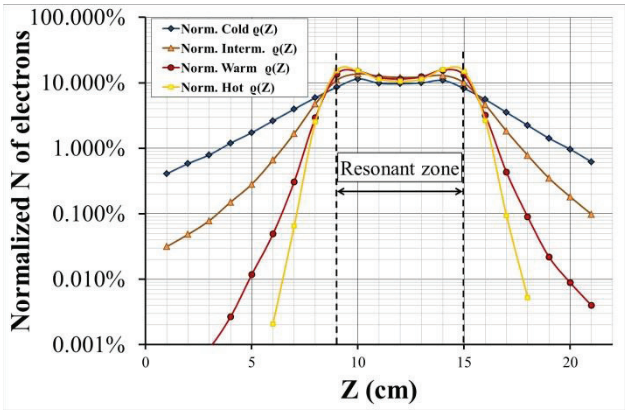

Figure 4: Normalized electron density distributions along the plasma chamber axes (z-axes).

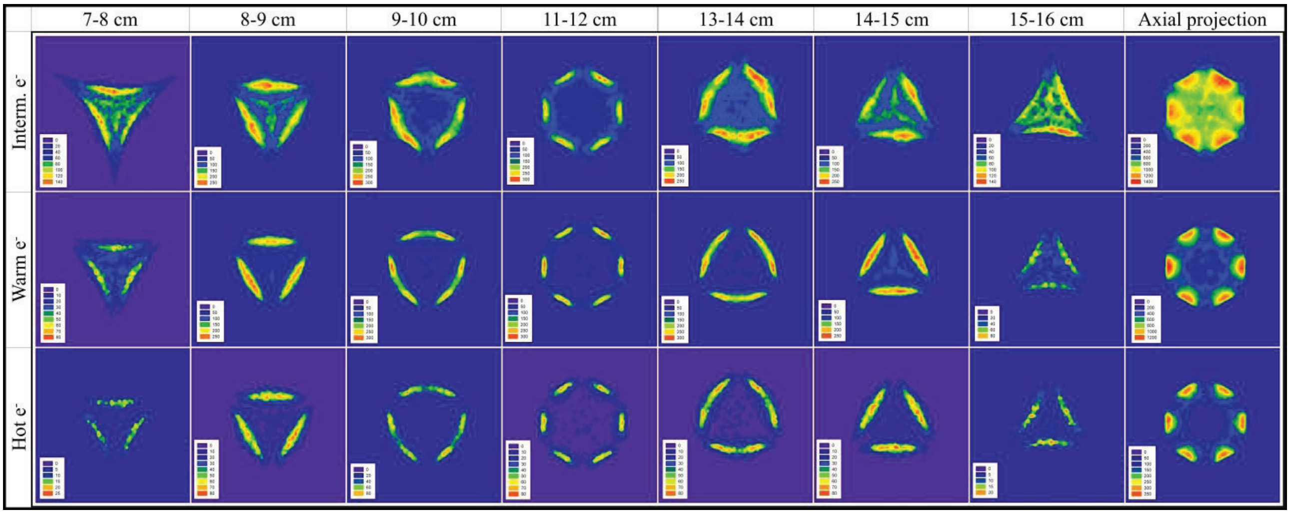

Figure 5: Plasma slices formed by electrons with different energy. In the right column: the superposition of all electrons from axial view.

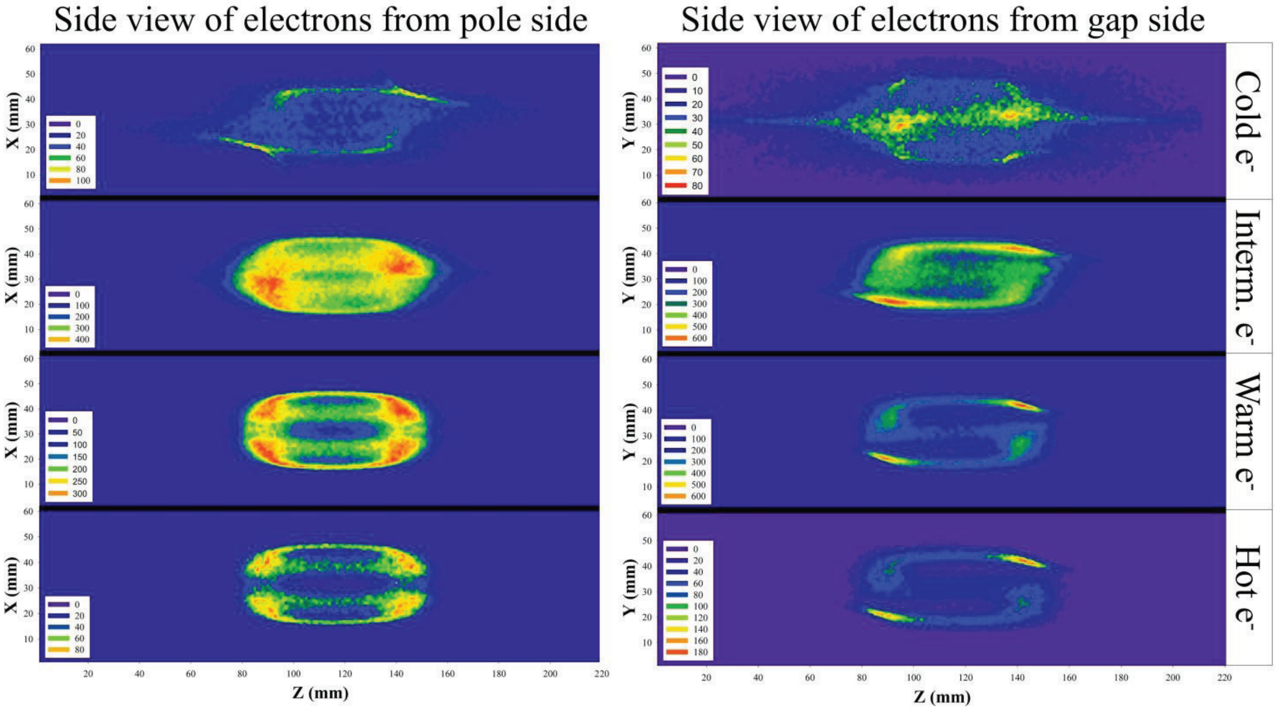

Figure 6: Side view projections of the cold, intermediate, warm and hot electron parts of the plasma from pole (left) and gap (right) direction.

In Fig. 7 the spatial distribution of the 3-10 KeV warm electrons are drawn in the extraction "third" of the plasma chamber (z-positions: 13-21 cm). Assuming that extraction of ions mainly takes place from these regions this double filtering may serve as starting data for extraction simulation codes (see e.g. [8]). In these extraction codes individual ions can be started from the appropriate x-y-z coordinates where the ion density (i.e. warm electron density) is the highest. Another way might be to construct a 3D density matrix by the TrapCAD output files (number of electrons in each cubic mm) and to use these position-dependent density values for the ions extraction simulations.

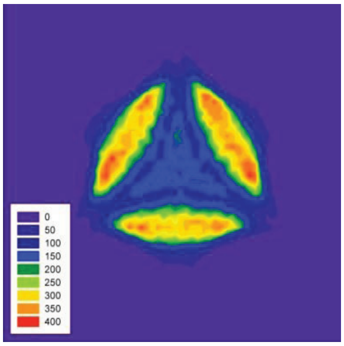

Figure 7: Axial projection of the warm electrons in the extraction side of the plasma chamber.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Union Seventh Framework Program FP7/2007-2013 under Grant Agreement n° 262010 - ENSAR. The EC is not liable for any use that can be made on the information contained herein. This work was also partly supported by the Hungarian TAMOP 4.2.1./B-09/1/KONV-2010-0007 project which is co-financed by the European Union and European Social Fund.

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