STATUS REPOTR ON PHYSICS RESEARCH AND TECHNOLOGY DEVELOPMENTS OF ELECTRON STRING ION SOURCES OF MULTICHARGED IONS

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Abstract

Electron String Ion Source (ESIS) "Krion-2" (JINR) is the first and now only ion source of such type in the world. ESIS is a sophisticated modification of Electron Beam Ion Source (EBIS) working in a reflex mode of operation under very specific conditions. Using the results of the research and the technology development the following main results were achieved in JINR with Krion-2 ESIS during recent years: Au^{54+} ion beams with intensity $5x10^7$ particle per pulse were first produced and ion-ion cooling technology was demonstrated to prove its efficiency for a thermal ion loss reduction; Krion-2 was used for production and injection of Xe^{42+} ion beam into LINAC injector of JINR synchrotron Nuclotron, where the beam was first accelerated to relativistic energy in March 2010 [1-3].

At the present time an essential progress was achieved in construction of the new 6 Tesla ESIS, which is expected to be the full scale prototype of a highly charged ion source for NICA - the new JINR accelerator complex. It is foreseen in the NICA project that new ESIS will provide Au^{32+} beams with the ion yield about $2x10^9$ ppp. However, a project parameters of new Krion-6T(esla) ion source allow to expect production of even more highly charged states of heavy elements, up to Au^{69+} in terms of gold. In this case the new Krion-6T ESIS may be used on operating JINR "Nuclotron" facility in near future for experiments with an extracted accelerated gold ion beams on a fixed target.

INTRODUCTION

Electron string phenomenon occurs during the reflex mode of EBIS operation. The interest in the studies of reflex mode operation was motivated by an attractive possibility to decrease the power of the electron beam by a hundred times while simultaneously preserving the same ion yield. Indeed, the power of the electron beam in a direct mode can reach many hundreds of KW that provides serious technical obstacles for a successful realization.

The study of the reflex mode of EBIS operation was initiated in JINR in 1994. These research were performed with use of JINR EBIS Krion-2. The reflex mode of EBIS operation is realized by using the specially designed electron gun and electron reflector that allows multiple use of beam electrons. The electrons do not reach electron collector after one pass through the drift space of the source (1.2 m long). Usually emitter has a negative voltage of few KV, anodes and drift tube structure are at ground potential, and the reflector has negative voltage few KV lower than the emitter. As a result, the emitted electrons after one path are reflected back towards the emitter side and then are reflected again in a vicinity of the emitter and so on. The emitter and reflector are placed in a fringe magnetic field (in a region of about 1/20 of a maximal magnetic field) hence each electron reflection is accompanied by some transformation of the longitudinal electron velocity to the radial/azimuthal velocity. As a result, the electrons are accumulated in a drift tube space of the source. The stored multiply reflected electrons can be used for highly charged ions production similarly to the beam electrons.

An unknown phenomenon was unexpectedly observed in JINR in 1994, which became a key physics ingredient of the proposed EBIS development in the reflex mode of operation. It was found that under certain conditions one component pure electron plasma, which consists of the multiply reflected electrons, confined in a strong solenoid magnetic field, exhibits a stepwise increase of the confined electron plasma density in a new steady state called "electron string". The transition usually goes via an unstable pre-string state in which the electron energy spectrum expands, which further suppresses the instability.

The electron string can arise if a definite number of electrons which exceeds some threshold value is stored in the source drift tube space. This threshold value depends on various parameters such as the electron injection energy, the applied magnetic field strength, the magnetic compression of the injected electron beam and so on. Electron strings are occurred to be stable in a certain frames that allows to use them for an effective production of highly charged ions in Electron String Ion Sources (ESIS), similarly to electron beams in EBIS.

An interesting observed feature of electron strings is a high energy tail in a total electron energy distribution. For example, for electrons with injection energy 3 KeV, this tail extends up to 5 KeV , see [1] and refs therein.

HIGHLY CHARGED ION BEAMS PRODUCED WITH KRION-2

Kr and Xe Highly Charged Ions

Production of highly charged Kr and Xe ion beams has been done in a framework of preparing Krion-2 ESIS for the Nuclotron run. Nuclotron – superconducting synchrotron which includes Linac LU-20 as a part of its injection complex. LU-20 accepts highly charged ions

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with charge to mass ratio $q/A \geq 1/3$ which determines lower boundary of charge states for all possibly accepted ions; for example q = 28+ for ^{84}Kr and q = 41+ for ^{124}Xe. Binding energy of the external electron for Kr^{27+} ion is equal to 3,2 KeV and for Xe^{40+} ion – 3.0 KeV.

Because of technical limitations of injected electrons energy only up to 5,0 KeV the well known for EBITs energy recuperation mode was proposed and used first in Electron String Ion Source. In order to realize the method of energy recuperation, main part of the Krion-2 drift tube structure was lifted up to +1.5 KV. Electrons which are injected by the electron gun with injection energy, say, 4.5 KeV, get additional acceleration in a gap between gun anode sections (at ground potential) and first drift tube section which is at +1.5 KV potential. So, string electrons should get energy about 6,0 KeV along the ion trap. After one pass through the drift tube structure electrons decelerate down to the energy 4.5 KeV at the gap between the last drift tube section (at +1.5 KV voltage) and the reflector anode, which is also at ground potential.

As a result, accumulated string electrons, being multiply reflected from the repeller and the gun electrodes, have energy on 1.5 KeV higher at the ionization trap region. It was shown experimentally that electron strings retain all their main features under such conditions, hence energy recuperation could be efficiently used in electron string mode of ESIS operation. Moreover, electron strings with energy recuperation are stable and can be used for highly charged ions production during long confinement time.

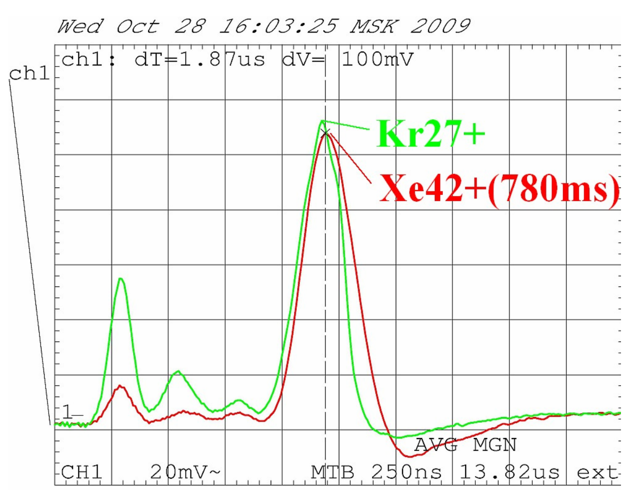

Figure 1: TOF spectra (arb. units) of Xe (natural mixture of isotopes) and Kr highly charged ions, produced with Krion-2 ESIS during 780 ms of ionization.

We used purely separated isotope ^{84}Kr in this experiments that allowed us to get enough resolution to identify definite charge states. During the experiments we did not have purely separated Xe isotope so a natural mixture of Xe isotopes was used. As a result, definite Xe charge state lines have not been resolved. We used TOF calibration based on the identified ^{84}Kr charge state lines positions. TOF spectrum for natural mixture of Xe isotopes is presented on Fig.1 together with ^{84}Kr spectrum, obtained at the same conditions. One can see that the maximum intensity corresponds to Xe^{42+} charge state. This charge state has been chosen for further acceleration by Nuclotron. Note, ionization time for Xe ions to get Xe^{42+} charge state was about 750 ÷ 950 ms that is acceptable for Nuclotron acceleration regime.

One can summarize ion yield produced by Krion-2 ESIS on HV platform of the Linac during Nuclotron run at February-March 2010 as follows:

- $^{84}Kr^{28+}$ $3.5\cdot10^7$ ions per pulse 7 µs duration,
- **$^{84}Kr^{29+}$ $3.2\cdot10^7$** ions per pulse 7 µs duration,
- $^{84}Kr^{30+}$ $3.0\cdot10^7$ ions per pulse 7 µs duration,
- $^{124}Xe^{41+}$ $3.0\cdot10^7$ ions per pulse 7 µs duration,
- **$^{124}Xe^{42+}$ $3.0\cdot10^7$** ions per pulse 7 µs duration,
- $^{124}Xe^{43+}$ $2.7\cdot10^7$ ions per pulse 7 µs duration,
- $^{124}Xe^{44+}$ $1.5\cdot10^7$ ions per pulse 7 µs duration.

Au Highly Charged Ions

The scheme of internal injection of gold atoms into the working space of the Krion-2 ESIS is based on evaporation of Au atoms from the surface of tungsten wire by pulse electric current heating. We used a gold plated tungsten wire of 0.05 mm in diameter. The wire was installed in the specially designed cell in the vicinity of the working space of the ESIS, few mm away from the axis. The cell volume was separated from the drift tube space by the stainless steel grid with 70 % transparency.

As it was noted before the electron injection energy in Krion-2 ESIS can not be more than 5,0 KeV because of technical reasons. So, Au^{51+} was a maximal charge state reachable at such conditions. There is a considerable gap in binding energies between the last electron in N-shell (2.96 KeV for Au^{51+}) and the next M-shell: 4.89 KeV for Au^{52+}, 5.04 KeV for Au^{53+}5.32 KeV for Au^{54+} et cetera…

We still had no possibility to increase the electron injection energy higher than 5.0 KV, however, it became possible to overcome this limit by lifting the drift tube structure up to +1.5 KV and using the energy recuperation mode of operation.

These experiments have been done during December 2009. Electron injection energy was 4.8 ÷ 5.0 KV and the drift tube structure was lifted up to 1.5 KV as well. Typical TOF spectrum of gold ions after 1500 ms of ionization is presented in Fig.2, where mean charge state in its maximum corresponds to $Au^{54.17+}$ [1].

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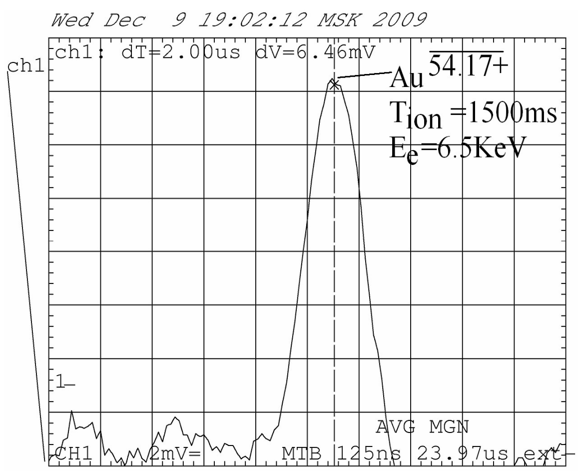

Figure 2: TOF spectrum (in arbitrary units) of the gold HCI beam extracted from Krion-2 ESIS after 1500 ms of the ionization. Mean charge state is equal to 54,17+.

In the Table 1. the parameters and the sorts of produced ions of existing ion source Krion-2 are listed.

Table 1: Krion-2 parameters and produced ions

	Fe^{24+} Nuclotron 2003	Au^{32+} stand	Au^{51+} stand 2007	Au^{54+} stand 2010	$Xe+^{42}$ Nuclotron 2010
Binding energy E_b, keV	2.05	1.21	2.96	5.32	3.07
Electron injection energy, keV	4.0	4.0	5.0	6.5	6.5
Ionization time τ, s	1.5	2×10^{-2}	1.0	1.5	1.5
Repetition rate, Hz	0.5	40	1.0	0.67	0.67
Extraction time t, 10^{-6} s	8	8	8	8	8
N_i per pulse	1×10^8	5×10^8	1×10^8	1×10^7	3×10^7

PULSE INJECTION OF GASEOUS SPECIES IN E-STRING

A specially designed cryogenic cell has been elaborated and successfully tested for pulse injection of gaseous species. The cell consists of a cylindrical chamber which is situated in the vicinity of the working space of the ESIS, 1 cm away from the axis. The chamber is placed at 78 K temperature terminal. This provides an efficient reflection of CH_4,N_2,O_2, and CO molecules and of Ar, Kr, Xe, and possibly Rn atoms from the chamber walls. The chamber has two orifices: one is being opened in order to load the portion of working gas from the outside, and the second one is always opened and it is designed to connect the chamber with the working space of ESIS through a thin pipe of 0.5 mm diameter and of 3.0 mm length. The pipe is kept at 78 K for an efficient transportation of gases.

The key element of the cell is the copper rod of 2.5 mm diameter and of 90 mm length, located on the axis of the chamber and connected to 4.2 K terminal of the ion source. The rod is supported with thermoinsulated flanges of the cell cylinder. The rod has the sandwich-type electroinsulating-conducting layers so that the conducting one may be heated by a current pulse. The cell operates as follows. A working or coolant gas portion, transported from the outside, is frozen on the rod surface. Due to electric pulse the rod surface is heated during 1–2 ms from 4.2 K up to 40–60 K and all the frozen gas leave the rod surface. The resulting gas pressure at this temperature provides penetration of about 10^{10} molecules or atoms into the drift tube space of the ESIS during 2–5 ms. After switching off the electrical current through the conduction layer the temperature of the rod surface is relaxed down to the 4.2 K during a few milliseconds as well and all the rest gas is frozen again at the rod surface. Then the injection pulses can be repeated with necessary repetition rate.

The cell construction was simulated and optimized numerically with use of all available information about the material properties versus temperature in the range of 4.2–78 K where all these dependencies are very strong. Experimentally it was proven that for nitrogen the elaborated cryogenic cell provides pulse injection with the shortest pulse duration equal to 3 ms and for methane 5 ms [2]. The cell has been successfully tested and used for pulse injection of CH_4, N_2, Ar, Kr, and Xe in e-string of the ion source. As an example in Fig. 3, the Ar ion current pulse is presented [3].

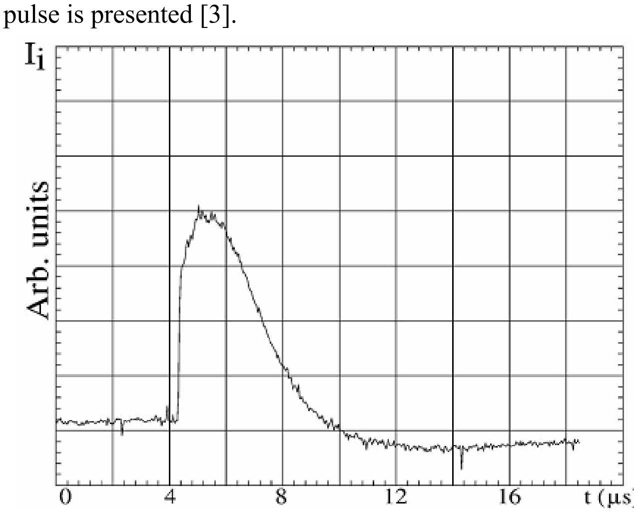

Figure 3: Ar ion current pulse obtained using the cryogenic cell.

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CONVERSION EFFICIENCY OF GASEOUS SPECIES TO ION BEAM

There can be cases, when conversion efficiencies of gaseous species to ion beams are of a great importance. Conversion efficiency of radioactive $^{11}CH_4$ to $^{11}C^{4+}$ ion beam is one of the cases. Development of the cell for gas pulse injection allowed us to measure this efficiency for Krion-2 using non-radioactive methane. The efficiency appeared to be rather high, but inexplicable spread of results from 4.2% to 19% in various experiments requires a further research [3].

ION-ION COOLING

We consider ion-ion cooling technology as a powerful mean for decreasing of ion losses during ionization. There fore, we began systematic studies of the cooling with a goal to find the best coolant for various heavy ions. The first pair was Kr injected from the described above cryogenic cell and continuously injected CH_4 – the lightest coolant. In Fig. 4 we show the rather large effect of ion–ion cooling in production Kr^{27+} during 155 ms confinement [3].

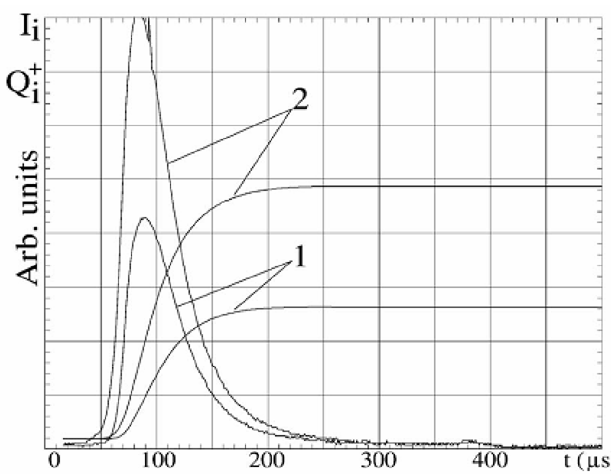

Figure 4: Kr^{27+} ion pulses: 1 – cooling "off"; 2 – cooling "on."

For Au^{51+} ions we have tried first CO, desorbing from the gold plated tungsten wire, as the gas for coolant ions. Fig. 5 illustrates the benefit of the ion-ion cooling in terms of ion yield under various time of coolant gas injection. Total ionization time is T_i=700 ms. The injection time for cooling gas, as shown on corresponding curves, T_c =150 ms, T_c =450 ms, T_c =550 ms, and T_c =650 ms.

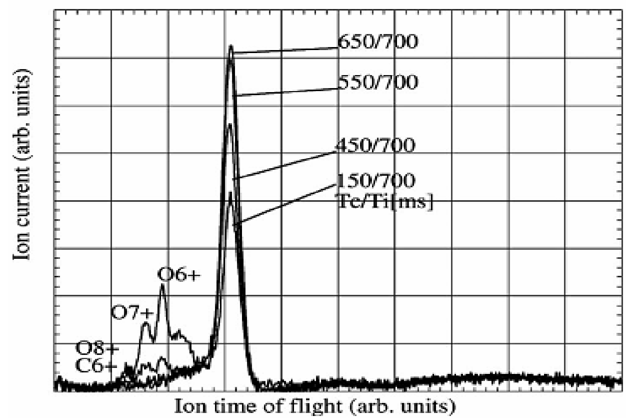

Figure 5: Au ion yield and TOF spectra for various injection time of the cooling CO gas.

The ion yield has been measured in the Faraday cup, located behind the last section of the TOF spectrometer. Because of several grids along the spectrometer only some fraction about 40% of the total ion beam was passed through the spectrometer structure and was measured. The measured fraction of ion yield is definitely proportional to the total produced ion yield. Hence Fig. 5 gives an adequate impression on a benefit of the ion-ion cooling. The total maximal number of the produced Au^{51+} ions was about 10^8 per pulse [2].

CONSTRUCTION OF NEW 6 TESLA ESIS: CURRENT STATUS

The ion source of ESIS-type, named Krion-6, is expected to be one of the ion sources JINR NICA project. Krion-6 is currently under construction with the following project parameters: 6 T superconducting solenoid of 1,2 m length and electron injection energy range of up 25.0 KeV. Expected main parameters of new ion source are presented in the Table 2.

Table 2: Krion-6 expected main parameters in terms of Au^{31+} ions, planned for NICA injector.

Working element/charge state	Au^{31+}
Expected ion yield N_i (number of $^{Au31+}$ ions in pulse)	$2 \div 4 \times 10^9$
Repetition rate	50 ÷ 60 Hz
Extraction time form the ESIS	$8 \div 30 \times 10^{-6}$ s
RMS emittance	0.6 π mm mrad (for 8 x 10^{-6} s extraction time); 0.15 π mm mrad (for 30 x 10^{-6} s extraction time).
Peak current in pulse	up to 10 mA

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We expect to get 2 ÷ 8 times increased ion yield with our new Krion-6T ESIS in comparison to Krion-2 ESIS. Our optimistic expectations (8 times) on ion yield increase are inspired by the observed earlier ion yield N_i growth in ESIS $N_i \sim B^3$, where B is an applied solenoid magnetic field of the ion source. This almost cubic dependence on the magnetic field was measured in a range 2.8 ÷ 3.3 T with Krion-2 ESIS and we hope this growth will continue up to 6 T magnetic field as well.

The vacuum system of the source was constructed and tested. The winding device to manufacture 6 T solenoid of a perfect symmetry magnetic field was constructed and three test solenoids of 20 cm length have been manufactured to proof the manufacturing technology. We have reached 7.15 T, 7.4 T and 7.8 T maximal magnetic field correspondingly for these test solenoids, tested in a liquid helium filled cryostat. The obtained currents/magnetic fields are occurred to be just in a short vicinity (and even exceeded) of the corresponding critical currents for short pieces according to the superconducting wire manufacturer data.

The full-scale solenoid for Krion-6 facility was manufactured in JINR and its field symmetry test is done. The test was performed at room temperature with current about 100 mA. Magnetic field sensors was installed near the ends of the solenoid, where the symmetry of the field is worse than in the middle part of the solenoid. The maximal asymmetry in different azimuthal positions on the first side was 0,23%, on the second side 0.16%. This asymmetry past to the sufficient magnetic field quality needed for the ion source operation. The symmetry in the middle part is much better then at the ends.

The solenoid and a passive quench protection system were installed and cryomagnetic tests were done. Maximal reached magnetic field was 5.44 T using the current 105 A at October 04, 2012. After assembling of an active quench protection system further tests at higher magnetic field up to 6 T and more, we hope, will be possible.

As we already noted, it is foreseen in the NICA project that new ESIS will provide Au^{31+} beams with ion yield about $2x10^9$ ppp. However, a project parameters of new Krion-6T(esla) ion source allow to expect production of even more highly charged states of heavy elements, up to Au^{69+} in terms of gold. In this case new Krion-6T ESIS is planned to be used on operating JINR "Nuclotron" facility in near future for experiments with an extracted accelerated gold ion beams on a fixed target.

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