A STUDY OF ELECTRON STRINGS AND THEIR USE FOR EFFICIENT PRODUCTION OF HIGHLY CHARGED IONS

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Abstract

The electron beam ion source in reflex mode (REFEBIS) and its use for effective ion production is investigated[1] jointly by JINR, Dubna, IAP, Frankfurt, SRPC, Friazino and MSL Stockholm. This paper presents a study of the energy spread in the electron string performed at "Krion-2" at JINR, Dubna, string production in PITEBIS at IAP, Frankfurt and studies of the effect of repeller position at the test EBIS, MSL, Stockholm.

1 INTRODUCTION

Electron beam ion sources (EBIS) produce the highest ion charge states among all ion sources. The ionization is achieved by accelerated electrons colliding with atoms or ions, removing bound electrons. The electron beam is dumped on a collector after one pass.

Several advantages e.g. saving power can be gained if the electrons are not lost on a collector but used repeatedly oscillating between the cathode and a reflecting electrode. Under certain conditions the multiply reflected stored electrons exhibit properties typical for a phase transition in a one component plasma. This transition leads to a stepwise increase of the number of stored electrons. It was first studied in Dubna [1] and named "electron string".

This project aims at investigating and exploring this new feature of the electron beam ion sources in reflex mode. With 5 mA initial electron current pulses of 500 μA Ar^{16+}, 8 μs long, have been achieved. The progress of the project has been reported at several occasions [1-6].

2 ELECTRON ENERGY DISTRIBUTION

2.1 Background

The electron energy distribution is believed to give important information about the properties of electron strings. It was already found that string electron energy spectrum is not mono-energetic [3-6]. The "repeller voltage string decay control" (RVSDC) method, used in [4-6] can, in principle, give the total energy distribution in pure electron strings. In ionisation processes, however, the kinetic energy distribution is important. To measure these distributions we produced Hydrogen-like Argon (Ar^{17+} - ions) in electron strings and measured the radiative recombination (RR) X-Ray spectra, emitted in capture of string electrons into the ^1S state of Ar^{16+}. As RR is not a resonance process these spectra in general represent the string electron energy distributions shifted to higher energies on the binding energy of electrons in the ^1S state of the ion, which is 4.12 keV. To get the actual electron energy distribution one has to take the dependence of the RR cross-section of the electron energy into account. This was done using the Rrq[2] code by O.Brinzanescu and Th. Stöhlker based on [7].

2.2 Experimental Set-up

The experimental set-up, used for the studies was the same as in [3], and was based on the EBIS "Krion-2" (JINR, Dubna), reconstructed for the reflex mode of operation and X-Ray detection. The principal design of the gun (EG) and the reflector (ER) is clear from Fig. 1 and its caption. EG and ER are situated on the magnetic

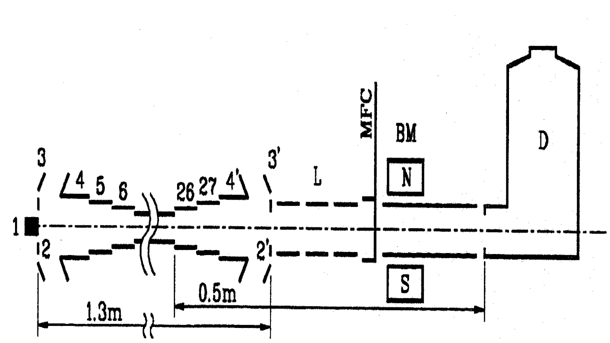

Figure 1: Schematic view of the experimental set-up. 1 - electron emitter; 2 - dummy cathode; 2' - repeller; 3,3' -focusing electrodes EG and ER; 4,4' - anodes of EG and ER; 5,6,...,27 - drift tube structure; L - einzel lens; MFC - movable Faraday cup; BM - bending magnet; D - Si-Li X-ray detector.

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[2] The code was kindly given to us by Dr Th Stöhlker

axis of a 3 T superconducting solenoid in positions where B=1/20 B_{max}. The potential of the repeller was usually 200 - 300 V more negative than the potential of the emitter and the dummy cathode. In the string mode the electron current, that is usually less than 1 mA, is collected on the anodes of EG and ER. Electron strings appear spontaneously, when the number of multiply reflected electrons reaches a definite value, which depend on the different parameters of the source. The manipulations with ions were the same as in the normal mode of EBIS operation. In these experiments for formation of electron strings beams of 5.0 keV and 5.3 keV electrons were used. As the electron gun was designed for voltages less than 4.5 keV we lifted up the potential of the trap region drift tube structure up to 1 keV.

2.3 Experiment and results

As the binding energy of the ^{1}S electron in Ar^{17+} is 0.3 keV larger than in Ar^{16+} measures had to be taken not to produce detectable amounts of Ar^{18+}. To provide such a condition we used a continuous injection of Argon into the string and controlled the Ar ion charge state distribution by the pressure of Argon in the source trap space on a value around $6\cdot 10^{10}$ mbar [8]. The trap was cleaned by ion extraction every second. Various X-ray spectra, emitted by Ar ions of various charge states were observed. With the pressure in the trap less than 10^{-9} mbar X-Rays of energy above 8 keV were detected. Background X-Ray spectra were obtained with the Argon valve closed. In Fig. 2 the high energy parts of the Ar^{17+} RR X-Ray spectrum and the background X-Ray spectrum are presented.

The string was formed with electrons of 5.3 keV energy. With 5.0 keV electron energy the high energy limit of the RR X-Ray spectrum shifted 0.3 keV down. In Fig. 3 the electron energy distribution in the string for

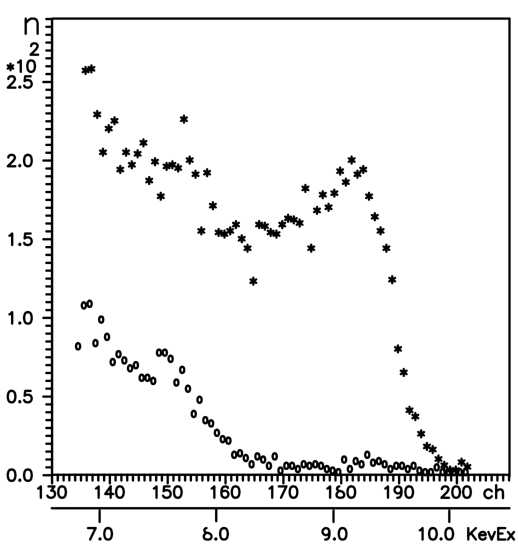

Figure 2: High energy part of X-ray spectra. * - with Ar in the string; o - without Ar in the string.

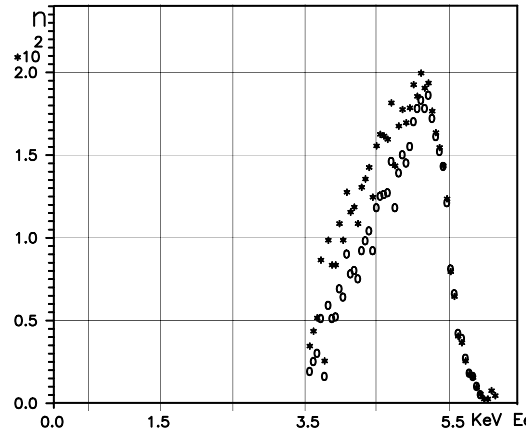

Figure 3: Energy distributions of electrons in the electron string, formed by electrons with 5.3 keV injection energy. * - the electron energy dependence of RR cross-section not taken into account, o - taken into account.

5.3 keV electron injection energy is shown. It was obtained from the data of Fig. 2 subtracting the background and taking the electron energy dependence of RR cross section into account. Unfortunately the high background level made the energy range below 3.6 keV not accessible. However, one can see that the main feature of the distribution confirms the results, obtained earlier with the RVSDC method [4].

3 ELECTRON STRING IN PITEBIS

Using the Frankfurt PITEBIS [9] (Penning Ion Trap EBIS) transition to the string state has been achieved. The gun had a fully immersed cathode of 0.5 mm diameter. An electrode similar to the dummy electrode in Fig. 1 controls the emission. When the bias is decreased the emission increases. At a certain point the DC ion current increases substantially though the electron current decreases. This can be interpreted as a filling of the axial space charge with oscillating electrons that at a certain stage undergo the transition to the string state.

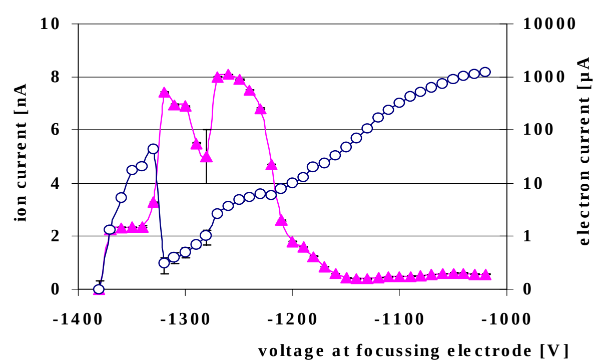

Figure 4: Ion current (triangles) from rest gas ionisation and electron current (open circles) as function of dummy cathode voltage.

4 REPELLER POSITION

At MSL a test EBIS has been built as part of another project. The solenoid is superconducting with a maximum field of 2 T and a room temperature bore. An electrode structure similar to the one shown in Fig. 5 has been built. Besides the gun and reflector parts so far only three electrodes have been used to produce the potential well for ion production, the central one fully in the constant field region.

After the set-up was made operational almost one year ago a number of measurements have been performed. Most of the properties of the reflected electron beam found at "Krion-2" have been verified. The strong increase of total ion production at the transition to the string state has also been seen but so far only for rest gas ions. Here we report the first results on varying the position of the reflections by using different electrodes as repeller.

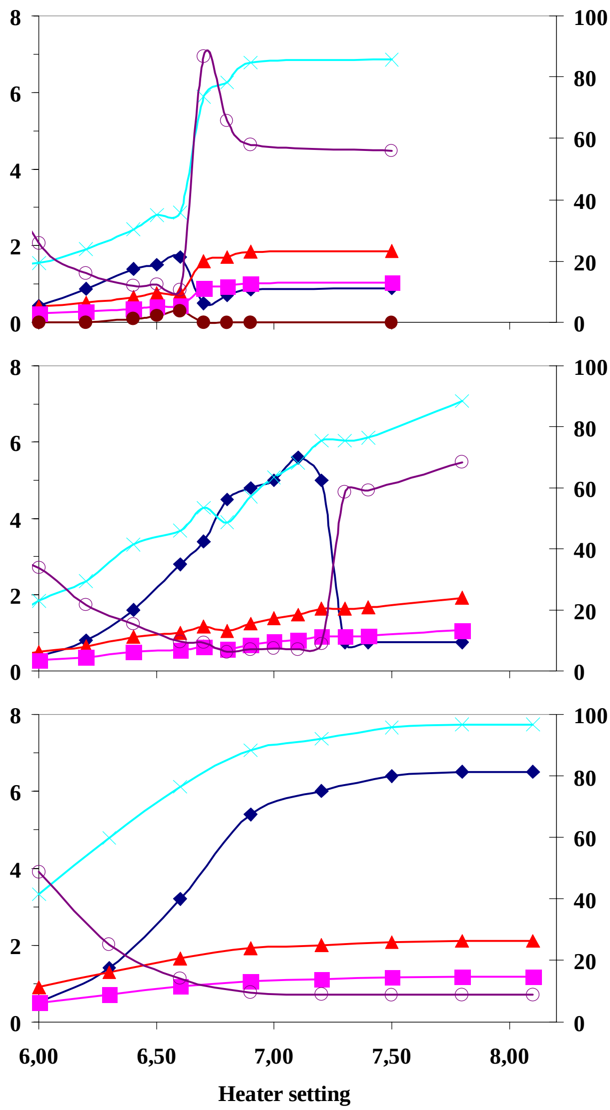

Figure 5: The dependence of the repeller position on the gun anode current (mA, tilted squares), reflector anode current (when relevant, (mA, filled circles), charges in structure (nC, triangles), perveance (µP, squares), current density (A/cm^2, crosses) and number of reflections (open circles, right scale). Top diagram: ordinary configuration, middle: repeller voltage connected to reflector anode, bottom: to reflector barrier.

The gun was placed where the axial field is about 1/17 of the maximum central field, in these measurement 2 T, and the reflector somewhat closer to the midpoint of the solenoid. This is referred to as the ordinary set-up in Fig. 5, top diagram. The cathode voltage was 1335 V and repeller voltage 1910 V. The emission was controlled by the heater setting and pulsed with the dummy cathode voltage as described in [3]. The cathode supply could deliver up to 50 mA electron current. For the middle diagram of Fig. 5. the reflector anode was used as repeller, the position was almost the same but the shape differed from the ordinary. The transition occurs then at a higher emission. Finally the reflector barrier was used as repeller, bottom diagram. The reflections were than made in the constant axial field region. As can be seen in Fig. 5 it was not possible to produce a transition with the available emission in this case.

5 CONCLUSIONS

The experimental results described above represent several new steps in collection of knowledge about the electron string phenomenon. For its use for production of highly charged ions it is interesting to know what determines the maximum numbers of negative and positive charges, which can be accumulated in strings. A natural limit can appear due to a virtual cathode formation in the accumulation space. It is possible that the rapid decrease of ion current with increase of injected electron current in Fig. 4 and some other similar effects in experiments on "Krion-2", MSL test EBIS and Frankfurt EBIS are the first signs of a virtual cathode formation. These studies will continue.

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