Electron String Phenomenon: Physics and Use

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Abstract. Electron string phenomenon arises as a result of phase transition of a state of multiply reflected electron beam to this new discovered state of one component electron plasma and can be easily observed in the reflex mode of EBIS operation. The transition goes via a strong instability, which causes considerable electron energy spread, which in its turn suppresses the instability. Electron string state is a stationary state of hot pure electron plasma, which is heated by injected electron beam and cooled because of electron loses. Electron string is quiet in broad regions of experimental parameters, so that it is used for confinement and ionization of positive ions by electron impact to highly charge states similar to electron beams in EBIS.

Application of electron strings instead of electron beams for ion production allows to save about 99% of electric power of electron beam and simultaneously to improve reliability of an ion source considerably. The JINR EBIS “Krion-2” in the string mode of operation is used for production of N7+, Ar16+ and Fe24+ ion beams and their acceleration to relativistic energies on the facility of the JINR super conducting one turn injection synchrotron “Nuklotron”.

The tubular electron string possibly can exist and it is under study now theoretically and experiments are prepared now. Estimations show that a Tubular Electron String Ion Source (TESIS) could have up to three orders of magnitude higher ion output then a Linear one (LESIS). In frames of nuclear astrophysics electron strings can be used for research of fusion nuclear reactions at low energies in conditions when both beam and target nuclei do not carry orbital electrons. The project NARITA – Nuclear Astrophysics Researches in an Ion Trap Apparatus is proposed. Polarization effects also can be studied.

INTRODUCTION

The so-called reflex mode of Electron Beam Ion Source (EBIS) operation is under intense studies both experimentally and theoretically during the last decade in the Laboratory of High Energies of the Joint Institute for Nuclear Research (Dubna, Russia) in collaboration with Manne Siegbahn Laboratory (Stockholm, Sweden), the Institute fuer Angewandte Physik (Frankfurt/M, Germany) and Brookhaven National Laboratory (Upton, USA). The interest to the reflex mode of EBIS operation was motivated first by the attractive possibility to decrease in hundreds times a power of the electron beam, preserving simultaneously the same ion yield. Indeed, the power of the electron beam in a direct mode can reach many hundreds kW that causes a lot of serious technical obstacles for successful realization. The first tests of the reflex mode of EBIS operation were performed in the late 70-th in the Laboratory of High Energies and in the Institute fuer Angewandte Physik [1, 2]. The results obtained were not
looked like prospective ones and the experimental studies were terminated. In 1994 in the Laboratory of High Energies the studies were renewed with use of the special design of the electron gun and the electron reflector [3] in the EBIS “Krion-2” and soon the new phenomenon has been observed called electron string [4-6].

**ELECTRON STRING: OBSERVATION AND PHYSICS**

The electron string can arise if the number of electrons stored in the source drift tube space exceeds some threshold value. This threshold value depends on various parameters such as electron injection energy, the applied magnetic field strength, the magnetic compression of the injected electron beam and so on [5-8]. The oscilloscope pictures, which illustrate the electron accumulation under 4 various values of the electron injection current are presented in Fig. 1 (a, b, c, d) (injection current increases from a to d). Electron injection is switched on at the beginning of the each process presented on the oscillograms. The measurement has been done in such a way that the total area of the signals, situated below zero level is proportional to the total number of the stored electrons. Under the relatively low electron injection current (Fig. 1 a) (usually it is about of 1-5 \(\mu A\)) some stable equilibrium between the injected and lost electrons is fixed at the same number of the stored electrons (pulse 1 at the oscillogram). If the injection electron current is gradually increased, usually up to 20-100 \(\mu A\), the stationary unstable state arises after the first pulse of electron accumulation (region 2 on Fig. 1 b, c). This unstable state was called pre-string state and it looks like oscillations on the oscillogram. Physically this oscillation behavior means that each period of electrons accumulation in a whole drift space is replaced by the following period of the electrons ejection. One can see that the oscillation frequency increases with increasing of injection electron current. It was found experimentally that electrons eject in the longitudinal direction along the magnetic axis and the total number of the accumulated electrons is equal to the number of the ejected electrons during each oscillation in the pre-string state. And finally, if the electron injection current exceeds some threshold value, usually 150-200 \(\mu A\) (Fig. 1 d) the electron string is formed (region 3 in Fig. 1 d). One should stress the electron string state arises after the system passes successively first relatively week electron accumulation (1) and the unstable pre-string state (2). And then the pre-string state instability is self-suppressed and the stable electron string state is formed with the accompanied powerful second electron accumulation pulse (3).

The electron energy distribution in the electron strings has been measured experimentally with use of two various methods: 1) the control electron string decay method, and 2) the spectrometry of the characteristic X-rays, produced by the highly charged ions in the radiative recombination of the ions with the string electrons. In this second method we used Ar17+ ions, produced in the string investigated. The knowledge of the electron energy distributions has importance for a phenomenological description of the electron string state and for the applications. The string electron energy distribution has a maximum in average at the level of 20 % below the electron injection energy and moreover, these distributions are wide enough (about 20 % at the half-height level) and there is in it a tail with energy higher than the injection one. On
our understanding namely this shape of the string electron energy distribution is mainly responsible for the suppression of the instabilities, which often develop in a system of the mono energetic electrons.

It was found experimentally [7] that the maximum total number of the electrons accumulated in the electron strings grows as third power of the applied confining magnetic field, that also has a physical explanation. One can also suggest that this strong dependence on the applied magnetic field was one of the reasons why the electron string phenomenon was not discovered early, say in 60-th. In fact, the problem of the electrons accumulation, inspired by the controlled nuclear fusion problem, was under the intense investigation in many laboratories around the world in that time. However, the applied magnetic fields were relatively low in all these studies in order to recognize the electron string formation. Note, the magnetic field of the super conducting solenoid in the “Krion-2” source is about 3 Tesla and one can observe an electron string formation at low magnetic field, say at 0.7 T, only in slow change of the field to this level from the much upper one.

FIGURE 1. Oscilloscope pictures of electron accumulation processes in the drift space of “Krion-2” ion source: a – injection current $5 \mu A$; b – injection current $20 \mu A$; c – injection current $50 \mu A$; d – injection current $300 \mu A$. 
PRODUCTION OF HIGHLY CHARGED IONS IN ELECTRON STRINGS

The next step is studies of the ion confinement in a space charge of the electron string and production of highly charged ions. One has to mention, that the processes of electron accumulation and string formation, described above, have been performed under the super high (~ $10^{-12}$ Tor.) vacuum conditions in order to exclude the influence of the residual gas ions. In principle, the injection of the working material ions into the electron string is equivalent to the studies of the electron string physics under the conditions of a high vacuum (~ $10^{-8}$ Tor.) that could be restrict the frames of the electron string stability, caused by the presence both electrons and ions in the system. However the experimental results are occurred to be favorable for further use of electron strings for the ions production. It was experimentally found that the frames of the electron strings stability are not restricted by the ions. Moreover the ions space charge provides the decreasing of the electron losses that leads to the electron string formation at the lower electron injection currents. The additional electrons, which appear due to ionization, do not have detectable influence on the string physics. It is explained by their fast heating and incorporating to the energy distribution of the electron string. In general, the processes of the ions injections into the electron strings, their containment and evolution up to the highest charge states, and the further ions extraction from the electron strings in a longitudinal direction are in a complete analogy with those characteristics for the case of electron beams. Namely, the ions charge state spectra are narrow enough and can consist on the single line if the electron injection energy is fine tuned according to the binding energy of the electron on the corresponding atomic shell and ion-ion cooling mechanism is easily observable (see Fig.2, where the charge state spectra of Ar ions are presented, obtained in the

![FIGURE 2. Charge state distribution of Argon ions after 300 ms confinement (a) and 500 ms confinement (b) in an electron string of “Krion-2” source, obtained with time-of-flight method.](image-url)
electron string regime of “Krion-2” source); the emittances of extracted ion beams are almost negligible since the extracted ions get sufficient axial velocities still being confined in a focusing electron string space charge electric field; this focusing electric field allows to realize a fast (during a few µs) ions extraction from the Electron String Ion Source (ESIS) that gives to ESIS a highest priority for their using on the one–turn injection synchrotrons.

As usual in JINR we use dc injection of neutrals and electronically controlled pulse injection of low charge states ions, produced from the neutrals in the beams or the strings. There is the, so called, injection section of the drift tube structure in the source “Krion – 2”. This section usually is thermally connected to 79 K terminal. For production of gaseous ions, which were only produced in this source in the past, we put a weak gas flow via the low thermal conductivity pipe. Recently the technology of ferrocene (FeC₁₀H₁₀) vapor injection was developed for the “Krion – 2” source. Now the section has the low thermal conductivity supports, separating it from the terminal of 79 K. The section carries the container with ferrocene, which is connected with the internal part of the section by means of narrow canal with low gas conductance. During production of Fe ions the section and therefore the container were heated to a necessary temperature using the resistor heater belts by means of the Joule heating. The working temperature was controlled and stabilized applying technology based on the proportional – integral method of regulation. Efficiency of ferrocene vapor ionization was near 100 %, providing a long term (about a year) use of several mg ferrocene stored in the container.

In Fig. 3 one can see the charge state distribution of Fe ions, obtained in the string mode of operation of “Krion-2” source.

![FIGURE 3. Charge state distribution of Iron ions after 700 ms confinement (a) and after 1100 ms confinement (b) in an electron string of “Krion-2” source, obtained with time-of-flight method.](image)

The estimations of an effective electron stream current density in electron strings, interacting with ions for their successive ionization show about 200 A/cm².

The maximum number of positive elementary ion charges obtained up to now, accumulated in electron string is 6.2*10¹⁰/m at about 50 W of the electron beam power dissipated in the ESIS. Taking into account the cubic B-dependency of the number of
accumulated electrons in a string and expecting 100 % compensation of electron space charge by ion space charge, one can to compare existing and expected ion outputs for EBIS and for ESIS. The comparison data are presented in the Table 1, where the existing data are bold printed. The data for ESIS presented include also expected ion outputs of a version of electron string ion source in a tubular configuration. In the Laboratory of High Energies the works are in progress at present time on a generation of a tubular electron string [9] as well as on its further use for production of highly charged ions.

| N_\text{e}/m | EBIS | ESIS |
|------------|------|------|
| 10^{11}   | 10 kW | 50 W |
| 10^{12}   | 200 kW | 200 W |
| 10^{13}   | 5000 kW | 2 kW |
| 10^{14}   | 20 kW | |
| 10^{15}   | 200 kW |

One can see that limiting numbers for Tubular ESIS exceeds the EBIS data on two-three orders of magnitude.

**APPLICATION OF ELECTRON STRINGS**

In spite of the physics of electron string is not completely studied and understood electron strings already found their use in production of highly charged ions and we can foresee several others interesting and unique applications.

**Electron String Ion Source on a Synchrotron Facility**

The “Krion-2” ion source in the string mode of operation successfully has been used twice, in June 2002-nd [10] and in June 2003–rd in the “Nuclotron” runs and the high ionization efficiency as well as the reliability and stability of “Krion-2” ESIS in an automatic regime of it’s work have been demonstrated. “Krion-2” ESIS has provided a high pulse intensity of the highly charged ion beams during these runs: Ar^{16+} - 200 \mu A, Fe^{24+} - 150 \mu A in 8 \mu s pulses. In this runs the ion beams Ar^{16+} and Fe^{24+} were first accelerated on the “Nuclotron” up to the relativistic energies and used for the physics researches. Increase of ESIS ion output we connect with application of higher magnetic fields and with realization of the tubular version of electron string ion source [11], which is under study now.

**Nuclear Astrophysics Researches in an Ion Trap Apparatus – NARITA Project**

Realization of Electron String Ion Source and especially Tubular Electron String Ion Source (TESIS), if it will be done, open new exciting perspectives on studies of nuclear fusion reaction at the very low energies (in the deeply under barrier region) [12]. These researches directly relate to the Standard Solar Model verification and to
the Solar neutrino problem and therefore they should be performed in condition when both beam and target particles are bare nuclei. Because of very low interaction energy it is impossible to have such the conditions in usually used methods of cross-section measurements. To solve the problem NARITA project was recently proposed in JINR-RCNP collaboration. The BeTa (Beam-Target) apparatus is a core of the installation, dedicated to the cross-section measurements. It is proposed to produce beam particle (bare nuclei) and also target nuclei inside of an electron string at two different potential levels, axially separated from each other. This difference of the potential levels would be variable, providing a necessary nuclei beam energy in bombardment of a nuclei target. It is proposed to study first the fusion \( d+d \) reaction with relatively large cross-sections, then \( d+^3He \) and after that, possibly \( ^3He+^3He \) with cross-sections in region \( 10^{-36} \text{cm}^2 \) at the interaction energy of interest. And if the BeTa apparatus will be combined with some others, several others fusion reactions with exotic nuclei can be also studied in frame of NARITA project. For example, effects of polarization in fusion reactions could be studied.

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