ELECTRON STRING SOURCE OF HIGHLY CHARGED IONS: STUDIES AND THE FIRST TEST ON A SYNCHROTRON

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Abstract

Operation of an electron beam ion source (EBIS) in the reflex mode at certain conditions leads to formation of the so called electron string state of one component electron plasma, which similar to electron beam can be used for production of highly charged ions in Electron String Ion Source (ESIS). We describe the experiments and results on studies of electron string features, such as electron energy distribution and B-dependencies of string density and of ESIS ion output, obtained using 4 different EBIS sources since the EPAC '98 conference. The results of the first tests of ESIS "Krion-2" on acceleration of N^{7+} and Ar^{16+} ions in the LINAC injector LU-20 of JINR Nuclotron and of Ar16+ in Nuclotron to 1 GeV/nucl. are also presented.

1 INTRODUCTION

The modern studies of the reflex mode of EBIS operation are based on use of specially designed electron guns and electron reflectors [1], providing efficient accumulation of injecting electrons while they travel across strong solenoid magnetic field to the gun and reflector anodes, which serve as electron collectors. The most recent review and the current report on the studies one can find in Ref. [2, 3, 4]. In this paper we present the most significant results about electron string formation and its application for ion production and acceleration, obtained since EPAC '98, using the MSL Test EBIS, JINR Krion-2 and -3 and BNL EBIS Test Stand.

2 ELECTRON STRING FORMATION AND THE STRING FEATURES

Electron string formation is usually observed when electron pulses are injected into a drift tube structure of EBIS operating in the reflex mode. In figure 1 the process of the string formation is presented by an image current through a 50 Ω resistor, grounding the Krion-2 source drift tube structure. The oscillogram clearly shows, that string formation passes three phases in a sequence: quiet accumulation of electrons, instability and quiet accumulation again.

The kinetic energy distribution of the string electrons has been measured using the Krion-2 source by means of the Radiative Electron Capture (REC) method on Ar^{17+} ions. The distribution is rather broad with a width about 30% of the injected electron energy.

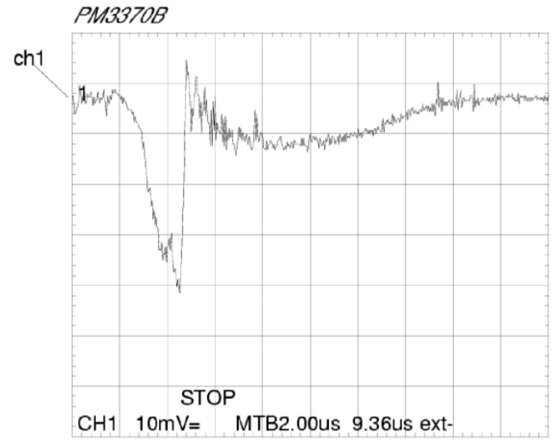

Fig. 1. Electron string formation after abruptly switching on electron injection.

The maximum number of electrons, which can be accumulated in electron strings increases rapidly with increasing solenoidal magnetic field of a source. It was shown with the sources Krion-2 and Krion -3, that this B-dependency has a nearly cubic power.

At the MSL EBIS Test Stand it was possible under certain conditions to detect a high frequency on the drift tube structure grounded via a 50 Ω resistor. The frequency corresponded to the single pass transit time of electrons through the structure and can be connected with the instability observed.

3 EXPERIMENTS AT THE BNL EBTS

Recently, at the Brookhaven National Laboratory (BNL) electron beam ion source test stand (EBTS), the reflex mode of operation was tested. The EBTS was built as prototype for an EBIS for the relativisitic heavy ion collider (RHIC) [5,6]. It has produced >60 nC ion charge when operating in a conventional EBIS mode with up to 10A electron beams. [7,8] Preliminary experiments indicate that special features of the EBTS might be useful for the development of the reflex mode operation in order to produce an axial electron string ion source (ESIS) capable of producing similarly high charge.

3.1 Experimental Setup

The EBTS uses a warm-bore, superconducting solenoid to generate an axial magnetic field in the 0.72 m ion confinement region. Two conventional solenoids provided axial magnetic fields of up to 0.35 T and 0.26 T in the gun and repeller regions, respectively during the reflex mode experiments. Five pairs of transverse coils, located along the axis from the gun to the repeller, provide magnetic steering of the electron beam. The drift tubes in the EBTS are typically 32 mm in diameter and can be operated with potentials exceeding 20 kV.

Electron gun and repeller assemblies (with 4mm inside diameter anodes) similar to those used at Krion-2 in Dubna were manufactured at JINR and installed in the midplanes of the gun and collector solenoids at the BNL EBTS. The magnetic field configuration is somewhat unusual from other sources in that there are minimums in the field between the main solenoid and auxiliary coils. In addition to demonstrating the robust nature of the reflex mode, operation in this configuration was chosen in order to:

- allow independent adjustment of the axial magnetic fields at the gun (Bg), the main region (Bm), the repeller (Br) and the corresponding ratios Bm/Bg and Bm/Br,
- provide differential pumping between the ultra high vacuum ionization region and the regions of power dissipation on the electron beam anodes,
- allow minimal reconfiguration of the BNL high current EBIS setup.

During these tests, the electron gun cathode and electron repeller could be operated between 0 and –4.5 kV and 0 and –10 kV, respectively. The anodes were held at ground through current measuring resistors of 100-1000 Ω. The drift tubes were operated up to +3 kV to provide an ion trap. The trap region was operated up to 2.5 kV and ions were extracted towards the repeller by rapidly lowering the voltage on the barrier drift tube.

3.2 BNL EBTS Results

The results reported in this paper the were obtained with main solenoid field strength Bm=4.6 T. To verify source alignment and find suitable starting values for the transverse correction coils a single-pass, 16 mA electron beam was propagated through the electron repeller to the faraday cup near the source exit with greater than 97 % transmission efficiency.

Oscillograms of electron string formation and decay are given in figure 2 and figure 3 for 7.2 nC and 10 nC electron strings, respectively. The maximum electron accumulation achieved in the trap region was 10 nC, which corresponds to a linear electron current density of 14 nC/m. This value was obtained with cathode voltage -4 kV, repeller –4.5 kV and magnetic field ratios Bm/Bg=16.1 and Bm/Br=18.5. The gun and repeller electron losses were 10 and 11mA respectively. (For the same electron energy, i.e., cathode and drift tube voltages, the EBTS operating in the normal mode would require ~0.65 A electron beam and would dissipate ~30 times the power). Formation of the electron string and rapid accumulation of electron charge in the 0.72 m long trap region was observed in times from 2-10 μs.

Ions were formed from continuous gas injection into the room temperature drift tube region. For 7 nC electron string charge in the trap region and a confinement time of 4ms, up to 4.8 nC of argon ion charge was observed during these trials. Of this 1.8 nC was transported to the Faraday cup and 3 nC was detected on the electron repeller electrode. In figure 4, an oscillogram showing 2.6 nC extracted Ar charge on the Faraday cup after a 4ms confinement period is displayed.

3.3 Discussion

Stable and reproducible reflex mode operation was obtained on the BNL EBTS. Electron strings with high linear electron space charge density, up to 14 nC/m, were produced. Extraction of ion charge corresponding to >50 % of the electron space charge was observed. The development of an axial ESIS to produce significantly higher accumulated electron and ion charge will necessitate the use of appropriately designed and cooled electron collecting surfaces (anodes), to handle the increased anode power dissipation. In these experiments it was demonstrated that an electron string can be extended axially by using auxiliary solenoids. Hence, electron collection can occur in a vacuum volume separated from the ion trap volume; thereby preserving the vacuum conditions required for high charge state ion production.

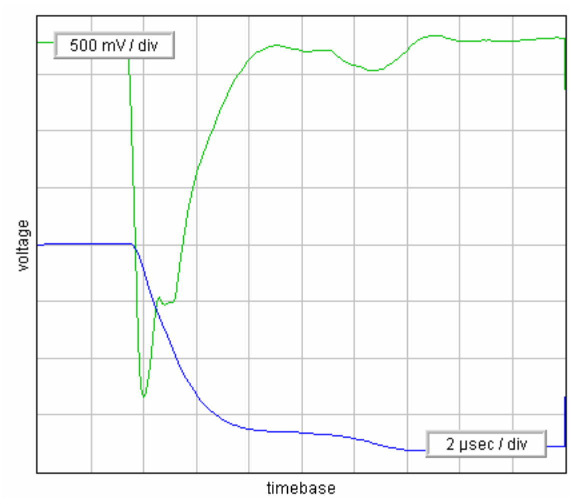

Fig. 2. Formation of a 7.2 nC electron string in the BNL EBTS. Upper trace: e-string accumulation current (vert. scale=0.5 mA/div). Lower trace: integrated charge (vert. scale=2 nC/div, horz. scale =2 μs/div)

4 KRION-2 IN THE STRING MODE: THE FIRST TESTS ON A SYNCHROTRON

In JINR, the electron string ion source "Krion-2" and all the necessary equipment were assembled, tested and used for production of Ar16+ ion beams and their acceleration in the linear accelerator LU-20 to energy 5 MeV/nucl. and in the superconducting JINR synchrotron "Nuclotron" to energy 1GeV/nucl. The slow extracted 1 GeV/nucl. beams of Ar16+ first were used for test physics experiments. In this first run on the accelerator facility the ESIS produced

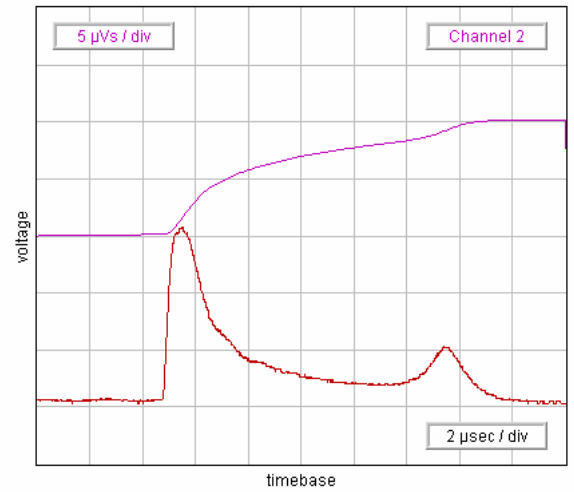

Fig. 3. Decay of a 10 nC electron string in BNL EBTS. Lower trace: e-string decay current (vert. scale=1mA/div) Upper trace: e-string decay charge (vert. scale=5 nC/div)

up to 150 µA of Ar^{16+} in a pulse of about 8 µs, suitable for a single turn injection into the synchrotron. The source beam emittance has not been measured, but it was shown that all the beam was injected into 15 mm LINAC aperture and accepted. The long term instability of Ar16+ beam was ~5% during the 96 hours LU-20-"Nuclotron" run. There was only one 45 min. scheduled interruption, for refilling the source with cryogenic liquids. A time-of-flight (TOF) charge state analysis of an ion beam produced from neutral Argon gas was made within the pre-injector acceleration tube. The TOF spectra showed that after a 400 ms confinement period in the electron string, the extracted ion beam consisted mostly of Ar^{16+}.

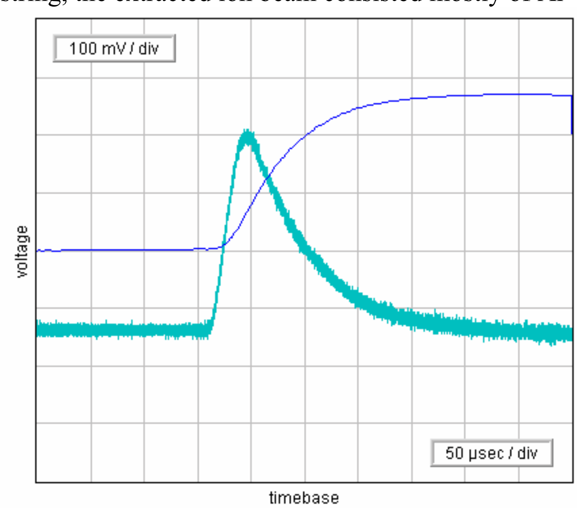

Fig. 4. 2.6 nC Ar ion signal extracted to the Faraday cup assembly at the BNL EBTS after a 4 ms confinement period. Lower trace: Ar current (vert. scale=10µA/div). Upper trace: Integrated Ar charge (vert. scale=1 nC/div))

The ESIS was also tested for production and acceleration in LINAC of N^{7+} nuclei beam. It provided up to 360 µA in a pulse after 200 ms confinement.

5 CONCLUSIONS

The present status of studies and the first test on a synchrotron show that Electron String Ion Source has become a new and useful tool for accelerator facilities.

6 ACKNOWLEDGMENTS

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