STATUS REPORT ON DEVELOPMENT OF TUBULAR ELECTRON BEAM ION SOURCE (TEBIS)#

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Abstract

The tubular version of EBIS with the off-axis injection and extraction of ions was proposed recently [1,2] to make possible a sufficient increase number of interacting electrons and ions compare to the usual linear version and for all that to conserve a small ion beam emittance peculiar to EBIS. Here we describe the results of a conceptual computer simulation of TEBIS in the direct current and in the reflex modes of operation with use of IGUN code [3]. Simulations show that the effective electron current can reach more than 100 *A* under a beam current density of about 300 – 400 A/cm^2 and the electron energy in a region of several *KeV* with a corresponding increase of a source ion output. The first results of simulation of a slow ion extraction from TEBIS in the off-axis mode are also presented.

1 THEORETICAL ESTIMATIONS

The idea of using of Tubular version of Electron Beam Ion Source was put forwarded in order to obtain sufficient increase of ion outputs, comparable with those for ECR sources, saving charge states and small ion beam emittance, usually provided by EBIS.

1.1 Limiting Currents

Indeed, if a source length and gun voltage are chosen, ion output is determined by the electron beam perveance, which is limited from above by a virtual cathode.

It is well-known, that in the case of a solid cylindrical beam the value of a limiting current Υ depends on ratio of the tube radius R to the radial beam size r_0 and Υ reached maximum if $r_0 \approx R$. If we consider tubular beam of a radial size a with the same energy, propagating longitudinally between two coaxial cylindrical tubes of radiuses R-$a/2$ and $R+a/2$ ($a<<R$), its limiting current J also depends on the ratio R/a, but not on their absolute values.

In fact, estimating ratio of limiting currents for the tubular and solid beams of the same energy one gets

$$J/\Upsilon \geq R/a \qquad (1)$$

increase of the limiting electron current for a tubular beam. Note, this estimations valid for the reflex mode of EBIS operation, which provides, due to a possible electron string formation, electron accumulation on a level, more or less approaching to the virtual cathode limit [4]. Indeed, electron beam perveance in the reflex mode is just determined by a perveance of the drift tube structure, which is more times bigger than an electron gun perveance [5]. In the direct current mode a limiting current is bounded from above by an electron gun perveance, and in this case the ratio of a limiting currents is estimated simply as a ratio of the emitter squares : $J / \Upsilon = 2Ra/r^2_0 = 8\ R/a$, if $r_0 = a/2$.

1.2 Stability of a Tubular Beam

It is well-known fact in plasma physics that diocotron and filamenation instabilities are, in general, peculiar for both kinds of tubular beams, travelling inside a drift tube with (tubular beam) or without interior tube (it calls hollow beam). The mentioned instabilities were one of the main objections for using tubular beams for ion production.

However, as it was discussed in [2], the theory predicts that tubular beams should be stable under the following conditions:

- Thin beam $a << R$;
- Negligible gaps between beam edges and tube walls;
- Strong applied magnetic field $\Omega >> \omega$.

Standard definitions for cyclotron frequency $\Omega = eB/mc$ and electron plasma frequency $\omega^2 = 4\pi e^2 n/mc$ (e, m - electron charge and mass, B – applied magnetic field, n – electron density, c – speed of light) have been introduced.

2 TEBIS APPARATUS; OFF-AXIS ION EXTRACTION

The schematic view of a Tubular Electron Beam Ion Source, suitable for the reflex mode of operation is presented in Fig.1.

The electron gun has an annular electron emitter, surrounded by interior and exterior dummy cathodes and focusing electrodes, and anodes. The electron reflector is similar in geometry to the gun and its annular electron repeller has one or several orifices at definite azimuthal angles for ion extraction. The gun and the reflector are situated axisymmetrically in respect to the magnetic field of the solenoid on its opposite ends fringe field where $B_{gun} = B_{reflector}$ = 1/20 B_{max}. The drift tube structure consists of several interior and exterior sections, having shapes of the similar to each other figures of rotation, situated along the corresponding surfaces bounding the definite constant magnetic flux of a solenoid.

Injection of atoms or ions of working materials into the tubular electron beam/string, their ionization and confinement in an electrostatic ion trap are performed

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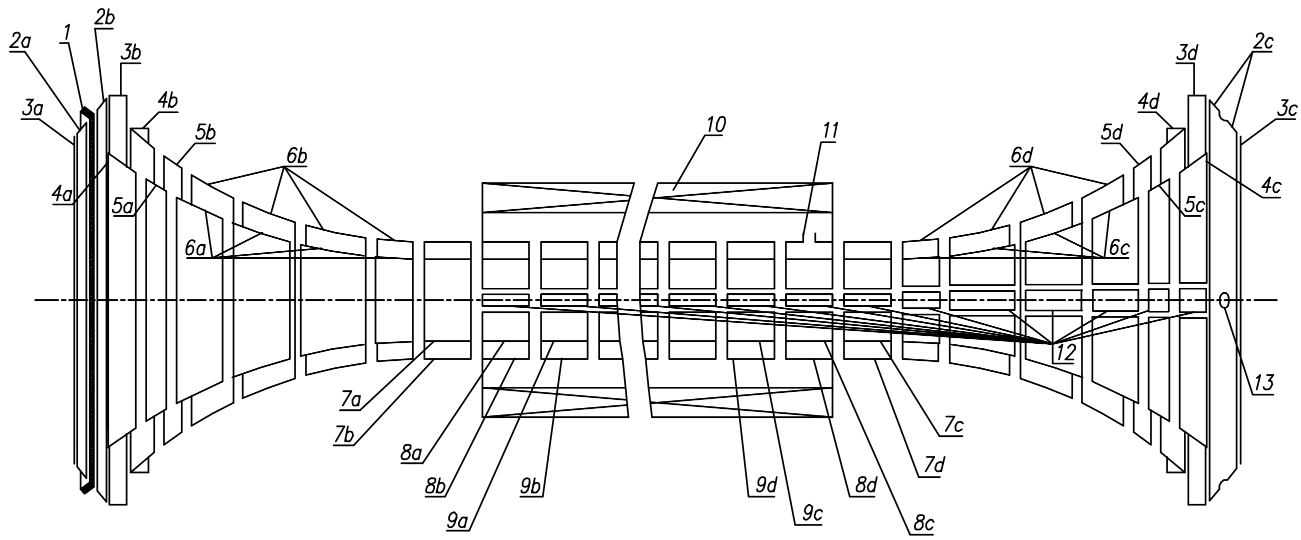

Figure 1. Schematic view of Tubular Electron Beam Ion Source. TEBIS is axially symmetric apparatus except off-axis extraction system, which is shown in the projection. 1 – annular electron emitter; 2a-b – interior and exterior dummy cathodes; 3a-b – interior and exterior gun focusing electrodes; 4a-b – interior and exterior anodes of the gun; 5,6 – interior (a,c) and exterior (b,d) drift tube sections in the fringe magnetic field regions; 7,8,9 – end sections of drift tube structure; 10 – solenoid; 11 – working gas inlet; 12 – biplate extraction system (shown in the projection to the drawing plane; it is projected to the axis since the azimuthal angle, directed orthogonal to the drawing plane was chosen for the off-axis extraction system arrangement); 13 – orifice for ion extraction (projection).

similar to those in the usual linear EBIS. Moreover, tubular apparatus has some other advantages which allow to use it effectively in a such novel area as a nuclear astrophysics researches [6].

In order to extract ions, additionally to the drift tube structure the biplate extraction electrode system is installed on the certain azimuthal angle (coinciding with the orifice on the repeller) along the corresponding generatrix lines of the tubular drift tube structure surfaces. As a result, ion extraction goes along the magnetic flux line at the certain azimuthal angle to the region of a weak magnetic field, where they can be picked up electrostatically and further accelerated. It is the main point of the off-axis ion extraction proposal [1,2], which allows to preserve small value of ion beam emittance. Migration of ions from all the tubular space toward the extraction biplates happens naturally due to their azimuthal drift motion in a longitudinal magnetic field and radial electric field of an electron beam space charge. As usual for EBIS, there can be the fast and slow ion extraction [2]. We will consider further only slow ion extraction in our numerical simulations, which can lasts any time, providing low temperature of the extracted ion beam.

In the direct current (beam) mode of TEBIS operation the electron repeller has to be removed and electron collectors (exterior and interior) have to be installed in a low magnetic field. Self-consistent simulation of off-axis ion extraction and electron beam capturing by the collector requires effectively 3-dimensional numerical codes and this problem is not considered here.

3 SIMULATION OF TUBULAR BEAMS

We have used IGUN code [3], which allows to simulate axisymmetric problems of a charged beam propagation in an external electric and magnetic fields, also taking into account beam space charge. The code has been additionally modified for tubular beam simulations.

Magnetic system of the operational Krion-2 source (JINR) was used for modeling of a tubular system. This magnetic system consists only on a superconducting solenoid of 120 *cm* length with its winding rectangle thickness 1.2 *cm*, center of the winding rectangle is situated at r=3.1 *cm* out of the magnetic axis. This solenoid admits maximal magnetic field 3.3 *T*.

3.1 Tubular Electron Beams

Similar to usual linear version of EBIS we used Pierce-angle electron gun with an annular emitter of a radial thickness a=0.32 *cm*, immersed into the solenoidal fringe magnetic field approximately orthogonal to the magnetic flux lines at R=3.36 *cm*, that corresponds to B_{total} =1/20 B_{max} at the center of the emitter, B_{max} = 3 *T*. . Drift tube sections are arranged along the magnetic flux lines such that in the uniform magnetic field the internal tube has radius r=0.67 *cm* and the external tube r=0.87 *cm*.

On Fig.2 thr tubular electron beam is presented, obtained as a result of IGUN simulation with use of the Child low emission under the cathode-anode voltage 10 *kV*.

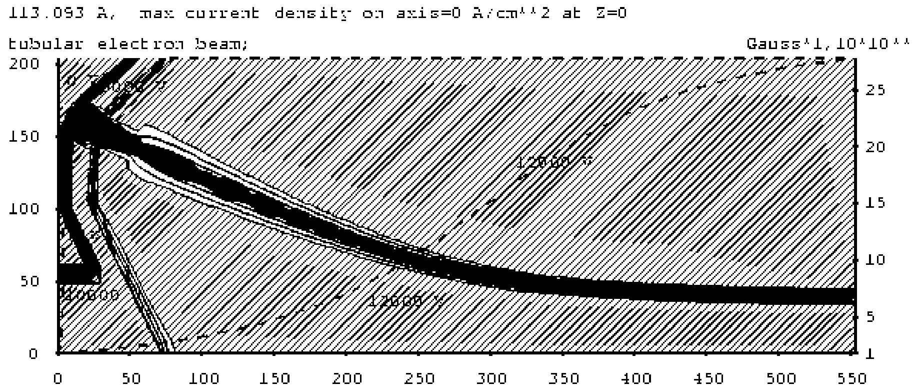

Figure 2. Tubular electron beam: I=113 *A*, cathode voltage 0 *V*, gun anode voltage +10 *kV* and the drift tube voltage +12 *kV;* dashed line – magnetic field on the axis in *kGauss* (right vertical scale); length scale: 100 *units* = 2.0 *cm.*

The resulting electron beam of a current I=113 *A* propagates smoothly along the magnetic flux lines into the region of the uniform magnetic field B_{max}=3 *T*, where the current density reaches 320 A/cm^2 as a result of the magnetic compression.

Electron trajectories data from the run, presented at Fig.2, has been used further to simulate self-consistently (taking into account beam space charge) the beam exit to the fringe magnetic field at the other side of the solenoid, its reflection and propagation back to the uniform magnetic field. The results are presented on Fig.3.

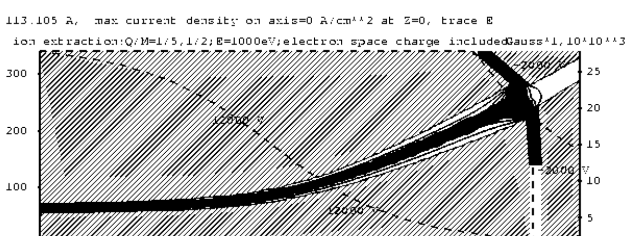

Figure3. Beam reflection. Drift tube voltage +12*kV*, reflector voltage –2*kV*; length: 100 *units* = 1.25 *cm.*

This simulations gives a reasonable background for experimental using of the reflex mode of TEBIS operation due to the simulated smooth propagation of intense electron beams along the magnetic flux lines.

3.2 Slow Off-Axis Ion Extraction

Unlike electrons, ions with a reasonable extraction energies do not follow, in general, magnetic flux lines in a fringe magnetic field region. On a Fig.4a trajectories of test ions (no ion space charge) with two different q/m ratio, extraction voltage 1 *kV,* are presented. It demonstrates that some electrostatic correction is needed.

However, the space charge of the electron beam provides a radial confinement for ions, extracting along the central part of the electron beam, that corresponds to a slow ion extraction. In Fig.4b one can see trajectories of the same ions, propagating in the electric field of the reflected electron beam (Fig.3) towards the extraction orifice in the reflector. Note, the azimuthal drift of the confined ions is negligible and it makes this axially symmetric simulation equivalent to simulation of the considered off-axis ion extraction.

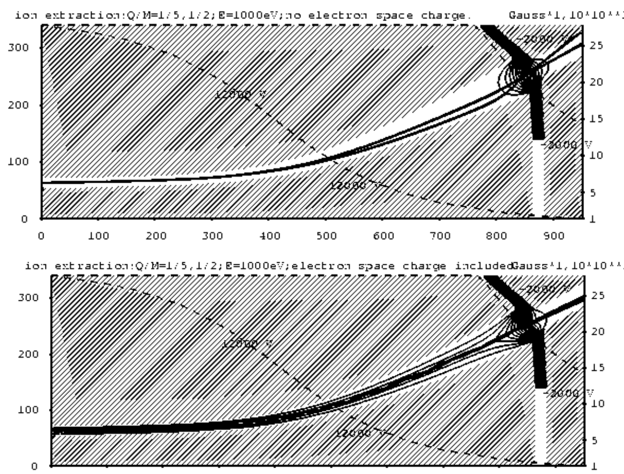

Figure 4: a) (top), b) (bottom). Off-axis ion extraction: q/m=1/5 and q/m=1/2; a) – no space charge; b) – in the electron beam space charge; length: 100 *units* =1.25 *cm*

To summarize: our simulations confirm that in a tubular source the electron beam current can reach more than 100 *A*. The electron beam and ion beams, confined in the central part of the electron beam, can propagate smoothly along the magnetic flux lines in the fringe field region hence providing the desired small values of the ion beam emittance, peculiar for the linear EBIS.

4 REFERENCES

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