Theory and Simulation of a Tubular EBIS

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Abstract. In this paper the theoretical estimations and numerical simulations of tubular beams are presented. Steady-state of a tubular beam is described analytically in a thin-beam approximation and stability properties of tubular beams are studied in a framework of the magnetic hydrodynamics. The idea of the off-axis ion extraction is illustrated with 3-D numerical simulations.

INTRODUCTION

The idea of using a tubular version of the electron beam ion source (TEBIS) was put forward recently\(^1,2\) in order to obtain a considerable increase of ion outputs, comparable with those in ECR sources, but with the high charge states and small ion beam emittance, usually provided by EBIS.

In fact, the number of the produced ions \(N_i\) is proportional to the number of the electrons \(N_e\) in the source and for a given source length it is proportional to the beam cross-section area. It is clear, the ratio of the stored ions/electrons in the tubular \(N_{\text{tub}}\) and in the solid cylindrical beams \(N_{\text{solid}}\) of the same length (with use of the same cryomagnetic system)

\[
\frac{N_{\text{tub}}}{N_{\text{solid}}} \propto \frac{S_{\text{tub}}}{S_{\text{solid}}} = \frac{\pi (r_e^2 - r_i^2)}{\pi a^2} \equiv \frac{R_e^2 ((1+x)^2 - (1-x)^2)}{a^2} \equiv \frac{4R_0}{a}; \quad x \equiv \frac{a}{R_0} \ll 1;
\]

where \(a\) is the radial beam thickness and \(R_0\) is the main radius for the tubular beam. Moreover, the beam perveance is limited from above by a virtual cathode and this limit for a tubular beam is in \(R_0/a\) times greater than for a cylindrical beam\(^3,4\).

Electrons propagate along the magnetic flux lines hence the drift tube structure should also follow the magnetic flux lines in a fringe field regions having shape of a corresponding figures of rotation. It was shown\(^3,4\) numerically that for tubular sources the effective electron current can reach more than 100 \(A\) with a beam current density of about \(300 - 400 \, A/cm^2\) and the electron energy in the region of several \(KeV\) with a corresponding increase of ion output. The tubular beam steady-state is described in the next Section and stability properties of tubular beams are studies in third Secton.

The method of the off-axis ion extraction from the TEBIS was proposed\(^1,2\) in order to get the usual solid extracted ion beam of a small emittance. This method is illustrated with use of 3-D numerical simulations in the last Section.
BASIC EQUATIONS AND DEFINITIONS

Let us assume a tubular electron beam of a radial thickness $r_e - r_i = 2a$, $(r_i$ and $r_e$ are inner and outer beam radii) which propagates longitudinally with an average axial velocity $v_z$. It is considered also the beam is enclosed between two coaxial conducting drift tube walls of a radii $R_i$ and $R_e$. The applied uniform magnetic field $\vec{B}_0 = (0,0,B_0, \equiv B_0)$ is directed along the beam symmetry axis $(z)$.

A so-called thin-beam approximation will be considered further which admits a dimensionless small parameter $1 / 0 \ll \equiv R_0 x R_i R_e \Rightarrow x = a / R_0 \ll 1$, $n \geq 1$, $nx \ll 1$. (1)

Second dimensionless parameter, $n$ is introduced to describe the gap between the beam edges and the drift tubes in relative units: $n = 1$ corresponds to the gap absence, $n = 2$ means the gap is equal to the beam half-thickness and so on…

In the thin-beam approximation one can consider the electron density is constant inside the beam:

$$n_e (r) = \begin{cases} 
\pi e, & r_i \leq r \leq r_e; \\
0, & R_i \leq r < r_i, \quad r_e < r \leq R_e. 
\end{cases}$$

The corresponding solution of the (relevant) radial part of the Poisson’s equation

$$\frac{1}{r} \frac{\partial}{\partial r} r \frac{\partial}{\partial r} \varphi_0 (r) = 4 \pi e \rho_e (r),$$

which is supposed to be smooth at the inner and the outer beam edges, can be obtained in terms of a series expansion in respect to the small parameter $x$:

$$\varphi_0 (r) = \begin{cases} 
\kappa (-4 R_0^2 \ln \left( \frac{R}{R_0} \right)) x + \frac{2 R_0^2 (-6 n^2 + (1 + 3 n^2) \ln \left( \frac{R}{R_0} \right)) x^2}{3 n} + \frac{2}{3} R_0^2 x^3 + O(x^4), \\
\kappa (r^2 - R_0^2 - 2 R_0^2 \ln \left( \frac{R}{R_0} \right)) + \frac{2 R_0^2 (3 n (1 - 2 n) + (1 - 3 n + 3 n^2) \ln \left( \frac{R}{R_0} \right)) x^2}{3 n} + O(x^4), \\
\kappa (4 R_0^2 \ln \left( \frac{R}{R_0} \right)) x + \frac{2 R_0^2 (-6 n^2 + (1 + 3 n^2) \ln \left( \frac{R}{R_0} \right)) x^2}{3 n} - \frac{2}{3} R_0^2 x^3 + O(x^4)), 
\end{cases}$$
where the top expression is valid at the region \( R \leq r \leq r^*_i \), middle – at the region inside the beam \( r^*_i \leq r \leq r^* e \), and the bottom – at the region \( r^* e \leq r \leq R^* e \). It was assumed also the inner and outer drift tube walls are at ground potential and \( \kappa = \pi |e| n_e \). The distribution (3) has a potential well shape hence ions could be confined electrostatically similarly to the usual cylindrical solid electron beam. The radial electric field vanishes at the point of the local minima \( r_{E0} \):

\[
-(\partial \varphi_0(r)/\partial r)|_{r_{E0}} = 0, \quad r_{E0} = R_0 \sqrt{1 - \frac{(1 - 3n + 3n^2)x^2}{3n} - \frac{(3 - 10n^2 + 15n^4)x^4}{90n}} + O(x^6).
\]

(4)

For further analysis it is useful to introduce the electron cyclotron (\( \Omega_e \)) and the electron plasma (\( \omega_{ep} \)) frequencies (\( \omega_{ep} \to (1 - f)\omega_{ep} \) if the beam is filled with ions, \( f \) – the compensation level: \( 0 \leq f \leq 1 \)), which are characterizations of an applied magnetic field and an electron beam density correspondingly:

\[
\Omega_e \equiv \frac{|e|B_0}{m_e c} \simeq 2.8 \times 10^7 \mathrm{Hz}; \quad \omega_{ep} \equiv \sqrt{\frac{4\pi e^2 n_e}{m_e}} \simeq 8.98 \sqrt{n_e} \times 10^3 \mathrm{Hz},
\]

(5)

where \( m_e \) is a mass of electron and \( c \) – speed of light. The electron beam density \( n_e \) can be expressed in terms of the main beam data (\( I_e \) – total electron beam current, \( v_e \) – averaged beam axial velocity, \( S_b = \pi (r^2 e - r^2_i) \) – beam cross-section area) as:

\[
n_e \equiv \frac{6.3 \times I_e [\Omega] \times 10^{18}}{v_e [\mathrm{cm/s}] \times S_b [\mathrm{cm}^2] \times \left[ \frac{1}{\mathrm{cm}^3} \right]}.
\]

(6)

The Hamiltonian for the considered magnetized beam electrons has a standard form, written in a cylindrical \((r, \theta, z)\) coordinate system:

\[
H_e = \frac{p_r^2}{2m_e} + \frac{p_\theta^2}{2m_e} + \frac{1}{2m_e r^2} (p_\theta + e|A_\theta(r)|)^2 - e|\varphi_0(r)|; \quad A_\theta(r) = \frac{rB_0}{2}.
\]

(7)

Note that in the case of an axially symmetric magnetic systems the vector potential has a non-vanishing component \( A_\phi \) only; in the fringe magnetic field regions it becomes a function of both \( r, z \) coordinates \( A_\phi (r, z) \). However, for now we consider an infinite length \((z\text{- independent})\) system in an uniform magnetic field \( B_0 \). The Hamiltonian (7) admits 3 conserved integrals of motions:
\[
E = \frac{1}{2m_e} \left( p_r^2 + p_z^2 + \rho_\theta^2 \right) - e \varphi_0 (r) \equiv U_0; \quad (\rho_\theta \equiv m_e r^2 \theta, \quad \cdot \equiv \frac{\partial}{\partial t}) \quad (8.1)
\]

\[
p_\theta = m_e r^2 \theta \cdot - e B_0 \equiv \frac{e B_0}{2} \equiv \rho_\theta, \quad (8.2)
\]

\[
p_z = m_e v_z \equiv P\ z_0. \quad (8.3)
\]

- the energy, the canonical angular momentum and the axial momentum correspondingly. The equations of motion for the beam electrons in the transverse \((r-\theta)\) plane are strongly nonlinear

\[
\begin{align*}
\dot{r} &= \frac{\omega_{rp}^2}{2} (1 - \frac{r_0^2}{r^2}) r - \Omega_e r \dot{\theta}; \\
\dot{\theta} &= \frac{1}{m_e r} \left( \frac{\rho_{\theta 0}}{r} + \frac{m_e \Omega_e r}{2} \right); \\
r|_{t=0} = \bar{r}_0 \equiv r_0, \quad \dot{r}|_{t=0} = 0; \quad \theta|_{t=0} = 0; \quad \rho_{\theta 0} = -\frac{m_e \Omega_e}{2} \bar{r}_0^2,
\end{align*}
\]

(9)

however, they can be solved in the thin-beam approximation (1) by making use of a linearized version of (9). Indeed, assume that the deviation \(\delta r(t)\) of the electron radial position from the its initial value \(\bar{r}_0\) is a small perturbation:

\(r(t) = \bar{r}_0 + \delta r(t); \quad \delta r(t) \ll \bar{r}_0\), since \(a/R_0 \ll 1\). The linearized system (9) has a form

\[
\begin{align*}
\delta r(t) + \omega_r^2 (\bar{r}_0) \delta r(t) &= -\frac{\omega_{rp}^2}{2 \bar{r}_0^2} (r_0^2 - \bar{r}_0^2); \\
\dot{\delta r}(t) &= -\omega_{rp}^2 (1 + \frac{r_0^2}{\bar{r}_0^2}) \delta r(t); \quad \delta r|_{t=0} = 0, \quad \delta r|_{t=0} = 0,
\end{align*}
\]

(10)

and it is integrable in terms of elementary functions that finally gets:

\[
\begin{align*}
r(t) &= \bar{r}_0 - \frac{\omega_{rp}^2 (r_0^2 - \bar{r}_0^2)}{2 \bar{r}_0^2} \left[ \frac{1 - \cos(\omega_r (\bar{r}_0) t)}{2} \right] \quad \delta \theta(t) = \Omega_e \left[ \frac{1 - \frac{r_0^2}{\bar{r}_0^2}}{2 \omega_r^2 (\bar{r}_0)} \right] = t;
\end{align*}
\]

(11)

One can see that the beam electrons oscillate radially with a betatron frequency \(\omega_r (\bar{r}_0)\) around \(\bar{r}_0\) \((\forall \bar{r}_0; \bar{r}_0 \in [r_l, r_u])\) and rotate azimuthally with an averaged (oscillating part of the radial perturbations is neglected) angular frequency
Electrons with \( r_0 = r_{E0} \) do not rotate whereas the electron layers with \( r_i \leq r_0 < r_{E0} \) and \( r_{E0} < r_0 \leq r_e \) rotate in an opposite directions that is determined by the sign of the radial electric field \( E_r = -(\partial \varphi_e(r) / \partial r) \).

To summarize: the obtained expressions (2-4), (8), (11-12) self-consistently describe a steady state of a tubular electron beam in the thin-beam approximation (1).

**STABILITY PROPERTIES OF A TUBULAR BEAM**

In this Section we discuss stability frames of a tubular electron beam in a magneto-hydrodynamics approximation. In this approximation the electron beam motion should be assumed laminar, that means one must neglect the radial electron oscillations in (11). This approximation is valid if the amplitude of the radial oscillations is much smaller than the beam radial half-thickness \( a \). It is true for the typical EBIS conditions in the beam mode of operation (strong magnetic field and a moderate beam density):

\[
\begin{align*}
\frac{\omega_{ep}^2}{\Omega_e} &< \frac{\varphi_e(r_0)}{r_0} \ll 1; \\
\Rightarrow \nu^0(r) = & \begin{cases} 

r(t) = r_0; & \nu^0_\nu(r) = \dot{\nu}(t) = 0; \\

\nu^0_e(r) / r = \omega_{eb}(r) \equiv \frac{\omega_{ep}^2}{2\Omega_e} \left(1 - \frac{E_0^2}{r^2} \right); \\

\nu^0_\varphi(r) = \nu_\varphi = \text{const}; 
\end{cases}
\end{align*}
\]

Note, the obtained azimuthal drift velocity \( \nu^0_\varphi(r) = r \omega_{eb} \) in the (13) is a solution of the radial force balance equation
\[
m_e r \omega_{eb}^2(r) = \left[ \varphi_e(r) \right] \equiv \left[ \varphi_e(r_0) - r_0 \omega_{eb}(r) \right] \]

for each electron layer at the orbit with \( r_i < r \leq r_e \).

So, we consider the steady-state solution for a thin tubular beam (1), described by the equilibrium values \( n_e(r) \) (2), \( \varphi_e(r) \) (3), \( \mathbf{B} = \mathbf{B}_0 = (0, 0, B_0) \) and \( \nu^0(r) \) (13), which are solutions of the equation of motion and the discontinuity equation for the electron fluid as well as the Poisson’s equation:

\[
\begin{align*}
(\partial / \partial t + \mathbf{v} \cdot \nabla) n_e \mathbf{v} = -e[\mathbf{\nabla} \varphi + \mathbf{v} \times \mathbf{B} / c]; \\
\frac{\partial}{\partial t} n + \nabla \cdot (n \mathbf{v}) = 0;
\end{align*}
\]
Neglecting the self-magnetic fields effects let us consider small electric perturbations \( \delta \Phi_j(x,t) \): \( \Phi_j(x,t) = \Phi_j^0(r) + \delta \Phi_j(x,t) \); \( \Phi_j^0(r) \equiv (n_e, \varphi_0, \nu_r^0, \nu_\theta^0, \nu_z^0) \) of the relevant background quantities \( \Phi_j^0(r) \) and make their Fourier decomposition according to

\[
\delta \Phi_j(x,t) = \delta \Phi_j(r) \exp(-i \omega t + i l \theta + i k z),
\]

where \( l \) is the azimuthal harmonic number and \( \omega \) is the (complex) eigenfrequency; eigenfrequencies with \( \text{Im} \omega > 0 \) signal on the exponentially growing instability.

Additionally we assume perturbations with very long wavelength \( (k_z^2 R_0^2 \ll 1) \) and, hence, approximate \( k_z = 0 \) in the Eq. (15). Substituting Eq. (15) into the system (14) and leaving with the first order perturbed terms only after straightforward algebraic manipulations one gets a single equation for the perturbed electric potential \( \delta \varphi(r) \):

\[
\left( \frac{1}{r} \frac{\partial}{\partial r} r \frac{\partial}{\partial r} - \frac{l^2}{r^2} \right) \delta \varphi(r) = - \frac{l \delta \varphi(r)}{r^2} \frac{\omega_{ep}^2 (\delta(r-r_i) - \delta(r-r_e))}{\Omega_e (\omega - l \omega_{eb}(r))},
\]

where \( \delta(r-r_i) \) and \( \delta(r-r_e) \) are Dirac delta-functions. The solution of this equation which vanishes at the drift tube walls \( r = R_i, r = R_e \) and is continuous at the beam edges \( r = r_i, r = r_e \) is expressed as:

\[
\delta \varphi(r) = \begin{cases} 
\frac{(A_r^{2l} + C)(r^{2l} - R_i^{2l})}{r^l (r_i^{2l} - R_i^{2l})}, & R_i \leq r \leq r_i; \\
Ar^l + Cr^{-l}, & r_i \leq r < r_e; \\
\frac{(A_r^{2l} + C)(R_e^{2l} - r^{2l})}{r^l (R_e^{2l} - r_e^{2l})}, & r_e \leq r \leq R_e;
\end{cases}
\]

where \( A \) and \( C \) are free integration constants. These constants can be related by the integration of the Eq. (16) across the discontinuities at \( r = r_i \) and \( r = r_e \) that gives:

\[
\begin{align*}
Ar_i^l \left( \frac{r_i^{2l} + R_i^{2l}}{r_i^{2l} - r_i^{2l}} + 1 + D_1 \right) + Cr_i^{-l} \left( \frac{r_i^{2l} + R_i^{2l}}{R_i^{2l} - r_i^{2l}} - 1 + D_1 \right) &= 0; & (D_1 = \frac{\omega_{ep}^2}{\Omega_e (\omega - l \omega_{eb}(r_i))}); \\
Ar_e^l \left( \frac{r_e^{2l} + R_e^{2l}}{R_e^{2l} - r_e^{2l}} + 1 + D_2 \right) + Cr_e^{-l} \left( \frac{r_e^{2l} + R_e^{2l}}{R_e^{2l} - r_e^{2l}} - 1 + D_2 \right) &= 0; & (D_2 = \frac{\omega_{ep}^2}{\Omega_e (\omega - l \omega_{eb}(r_e))}).
\end{align*}
\]
The system of equations (18.1-18.2) is a homogeneous linear system in respect to the $A$ and $C$, hence the untrivial solution exists only if the corresponding determinant is equal to zero. This existency condition is a (transcendental) equation which determines the desired eigenfrequencies $\omega$. However in the thin-beam approximation (1) one can get an analytical solution for the eigenfrequency $\omega$ in terms of series expansions on $x = a / R_0 \ll 1$ as follows:

$$\sigma_{tub} = \text{Re}(\omega) = \frac{l \omega_{ep}}{2} \left( \frac{\omega_{ep}}{\Omega_e} \right) (n^2 - 3n - 1) \left( \frac{a}{R_0} \right); \quad \gamma_{tub} = \text{Im}(\omega) = \frac{l \omega_{ep}}{\Omega_e} \sqrt{\frac{n-2}{n}} \left( \frac{a}{R_0} \right);$$

(19)

where $l=1,2,3…<< R_0 / a$; $\omega_{ep}$ and $\Omega_e$ are defined in (5-6), and according to the (1):

$$r_i = R_0 (1 - x), \quad r_e = R_0 (1 + x), \quad R_i = R_0 (1 - nx), \quad R_e = R_0 (1 + nx),$$

$$x \equiv a / R_0 << 1, \quad n \geq 1, \quad nx << 1.$$

It is instructive to compare the obtained expression for the increment $\gamma_{tub}$ (19) with those $5,6$, obtained for the hollow electron beam without internal drift tube wall ($\gamma_{b1}$) and for the hollow electron beam without both drift tube walls ($\gamma_{h2}$):

$$\gamma_{b1} = 2l \omega_{ep} \left( \frac{\omega_{ep}}{\Omega_e} \right) \sqrt{(n-1)(l-1)} \left( \frac{a}{R_0} \right)^{3/2}; \quad \gamma_{h2} = \omega_{ep} \left( \frac{\omega_{ep}}{\Omega_e} \right) \sqrt{l(l-2)} \left( \frac{a}{R_0} \right).$$

(20)

The key formula (19) gives us the frames of a tubular beam stability: indeed, if $1 \leq n \leq 2$ the eigenfrequency $\omega$ does not have an imaginary part, hence all initially small perturbations do not grow with time and only oscillate with a real frequency $\sigma_{tub}$. Note, according to (20) the hollow beam is stable only if $n = 1$: the gap between the outer beam edge and the external drift tube wall should vanish for stability.

As a result: in framework of the magnetic hydrodynamics approach thin tubular electron beams are stable in respect to the considered electrostatic perturbations if the gaps between the beam edges and the drift tube walls do not exceed the radial beam half-thickness: $1 \leq n \leq 2 \Rightarrow a \leq (r_i - R_i, R_e - r_e)$. However, if $n > 2$ in the formula (19), the instability exists and it is useful to estimate its growth rate for some physically motivated configuration, related to the TEBISes. Let us analyze stability of a tubular electron beam which is foreseen to get with use of the Stockholm Test EBIS: $r_i = 0.34cm; \quad r_e = 0.37cm; \quad R_i = 0.3cm; \quad R_e = 0.41cm; \quad \Rightarrow \quad R_0 = 0.355cm; \quad a = 0.015cm; \quad x = a / R_0 = 0.0423; \quad n = 3.6626 > 2$!! For the cathode-anode voltage $U = 500V$ one gets self-consistently: $I_e \equiv 0.87A; \quad \nu \equiv 1.2 \times 10^9 cm/s$; $\Rightarrow \pi_e \equiv 6.7 \times 10^{10} cm^{-3}; \quad \omega_{ep} \equiv 2.3 \times 10^9 Hz$; and the beam electrons time-of-flight $\tau_f = L / \nu$, where $L[cm]$ is the source working length; $\Omega_e \equiv 2.8 \times B_0 (Tesla) \times 10^{10} Hz$. After substituting the all relevant data into the Eqs.(19) one gets that each unstable mode $\delta_r \varphi(r)$ of the electric field perturbations, labeled by the azimuthal harmonic number $l=1,2,3,4…<< R_0 / a \equiv 23.6$ grows up during time-of-flight by the factor $\lambda$ as:
One can see, the instability is strongly suppressed if the magnetic field $B_0 \geq 1T$ hence the electron tubular beam should propagate smoothly without any detectable deviation from its steady-state ($\lambda > 15$ is definitely out of the considered linear regime) and a further nonlinear regime of the instability development should lead to the breakdown of the beam annular shape, caused by the beam bunching at some randomly chosen azimuthal position (note, the unstable modes are labeled by the azimuthal number $l=1,2,3\ldots$). It opens a possibility to detect the instability experimentally with use of an azimuthally sectioning electron collector. The instability in nonlinear regime also should lead to the appearance of the beam energy spread and to the anomalous electron radial drift across the magnetic field, caused by the breakdown of the steady-state energy (8.1) and the canonical angular momentum (8.2) conservation.

We studied (19) a so-called diocotron instability which is mostly the result of the steady-state angular velocity shear (13). In the case of more dense beams (if $eep\approx\omega$) and filamentation (finite axial length effects, $k \neq 0$ in the Eq.(15)) instabilities could be studied on this way additionally to the diocotron instability. This work is in progress now and the results will be reported elsewhere.

**OFF-AXIS ION EXTRACTION FROM THE TEBIS**

In order to extract ions from the TEBIS and save a low beam emittance the only way is extraction of ions along magnetic flux lines until a weak magnetic field region. However, in order to get a solid extracted ion beam, one should pick up all ions in a narrow extraction channel which should be arranged at the proper azimuthal angle along the magnetic flux line. This extraction channel should start at uniform magnetic field region and finish somewhere in a weak magnetic field region where ions could be confined and further accelerated electrostatically.

Migration of in the azimuthal direction happens naturally due to their azimuthal drift motion. Indeed, for the ions with the charge-to-mass ratio $(Z/A)$ the averaged
azimuthal drift frequency in the tubular electron beam space charge field (3) and longitudinal uniform magnetic field can be estimated similarly to (11-12):

$$\omega_i \equiv \dot{\theta}_i(t) \equiv \frac{(1 - f) \omega_{pe}^2 \Omega_c}{\Omega_p^2 + (1 - f) \omega_{pe}^2} \left( \frac{a}{R_0} \right); \quad \eta \equiv \frac{(Z/A)}{(m_p/m_e)} \equiv \frac{(Z/A)}{1836.12},$$  \hspace{1cm} (22)

where $f$ is the compensation level. As a result the ion drift azimuthal rotation on $2\pi$ angle lasts $\tau_{drift} \approx 5 \times 30 \times 10^{-6}$ s for various reasonable values of $(Z/A)$, $\omega_{pe}$, $\Omega_c$, $f$, $a$, $R_0$, that is a reasonable time in order to get both slow and fast ion extraction.

The basic principles of the off-axis ion extraction from the TEBIS are illustrated on the Figure 1, which is the result of a self-consistent (space charge of the electron and ion beams is taken into account) 3-D numerical simulation (OPERA 3-D code).

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**FIGURE 1.** Off-axis extraction of the ion beam from the TEBIS. A tubular ion beam (1) in the uniform magnetic field has the initial extraction energy which is not enough to penetrate through the electrostatic barrier. As a result, the ions are reflected back except those which are captured in the extraction channel (2), where the electrostatic barrier has lower height. The obtained solid ion beam (3) is extracted along the extraction channel up to the weak (1/20 $B_0$) magnetic field region (4) and then is accelerated electrostatically. The electron beam is not displayed here but its space charge is taken into account.
CONCLUSIONS

The theoretical estimations and numerical simulations, presented in this paper, give a reasonable background for the experimental studies of basic principles of the TEBIS operations. It is expected the first experimental tests of Tubular EBIS Krion-2 in the reflex mode of operation (JINR, Dubna) should start during summer 2004. The beam mode of TEBIS operation is planned to study with use of Stockholm Test EBIS (MSL) at the end of 2004.

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REFERENCES

1. Donets, E. D., Donets, D. E., and Donets, E. E., Russian Federation Patent RU 2 205 467, 22.06 (2001); Bull. “Izobretenia” 15, Moscow (2003).
2. Donets, E. D., Donets, D. E., and Donets, E. E., Rev. Sci. Instrum. 73, 696-699 (2002).
3. Donets, E. D., Donets, E. E., and Becker, R., in: Proceedings of EPAC-2002, Paris, 2002, pp. 1703-1705; http://accelconf.web.cern.ch/accelconf/02/papers/thpri017.pdf.
4. Donets, E. D., Donets, E. E., Becker, R., Liljeby, L., Rensfelt, K.-G., Beebe, E. N., Pikin, A. I., Rev. Sci. Instrum. 75(5), (2004), in press.
5. Uhm, H. S., and Siambis, J. G., Phys. Fluids 22, 2377-2381 (1979).
6. Davidson, R. C., Uhm, H. S., and Mahajan, S. M., Phys. Fluids 19, 1608-1620 (1976).