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Some Physical and Engineering Aspects of High Current EBIS.

1. Introduction

Some applications of an Electron Beam Ion Source (EBIS) require intensities of highly charged ions significantly greater than those which have been achieved in present EBIS sources. For example, the ion source for the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) must be capable of generating $3x10^9$ ions of Au^{35+} or $2x10^9$ ions of U^{45+} per pulse [1]. In this case, if the fraction of ions of interest is 20% of the total ion space charge, the total extracted charge is ~ 5×10^{11}. It is also desirable to extract these ions in a 10 μs pulse to allow single turn injection into the first synchrotron. Requirements for an EBIS which could meet the needs of the LHC at CERN are similar (~ 1.5×10^9 ions of Pb^{54+} in 5.5 μs). This charge yield is about an order of magnitude greater than that achieved in existing EBIS sources, and is what is meant here by "high current". This also implies, then, an EBIS with a high electron beam current.

The scope of problems in a high current EBIS is broad, and includes generating a sufficient total charge of electrons in the volume of the ion trap, achieving a stable electron beam (without high frequency oscillations), preventing ions in the trap from acquiring too much energy (which can lead to a high rate of ion loss and increase in the emittance of the extracted ion beam), injection of metal ions into the ion trap, and achieving the appropriate vacuum in the ionization region. Development of the Electron Beam Test Stand (EBTS) at BNL addresses these problems, and is an attempt to develop the technologies relevant to a high current EBIS. The final goal of this development is to build an EBIS for RHIC. The general description of this project is published in [2]. In this chapter the discussion is limited to the handling of a high perveance electron beam and to vacuum issues.

2. Electron beam

2.1 Electron beam requirements

One can calculate approximately the necessary electron beam parameters from the required intensity of extracted ions. Assuming 50% compensation of electron space charge by ions in the trap, and 20% abundance in the charge state of interest, one finds that to reach intensity $3x10^9$ ions of Au^{35+} per pulse, a total space charge of electrons in ion trap has to be $Q_{el}=1.1x10^{12}$ elementary charges. This charge is simply related to EBIS parameters according to the relation:

$$Q_{el} \approx 10^{13} \cdot I_{el} \cdot L_{trap} / \sqrt{U_{el}}$$

where I_{el} is the electron beam current (A), L_{trap} the trap length (m), and U_{el} the electron beam energy (eV). If the length of the ion trap is L_{trap} =1.5 m and electron beam current is I_{el}=10 A, the average energy of electrons should be U_{el}=21 keV. In electron beam optics one of the major parameters, characterizing an electron beam is perveance (p), defined as:

$$p=I_{el}(U_{el})^{3/2}$$

The perveance of this electron beam in the trap region is $p=3.3\times10^{-6}$ A/V$^{3/2}$, which is unusually high compared with the perveance in any other existing EBIS. In fact, the high perveance of the electron beam determines specifics of a high intensity EBIS, which are discussed in this chapter.

2.2 Electron beam formation

The primary requirement for a high electron space charge in the trap region can be satisfied for the case of a straight single pass electron beam if, for example, electrons from the gun are extracted at a high energy, determined by the required current and perveance of the electron gun, and later, in a strong magnetic field, are adiabatically decelerated to the minimum possible energy. If the potential of the drift space is below a certain critical value, electrons with minimal energy reflect back, making the potential in this region even lower so that all of the electron beam eventually reflects back. This phenomenon is called "virtual cathode formation". To be able to effectively decelerate the electron beam in the region of the ion trap to the minimum possible potential, without virtual cathode formation, the electron beam should be sufficiently laminar, i.e. its transverse fraction of velocity should be relatively low. The requirements to the laminarity of electron beam can be even stricter if one wants to collect electrons at a lower potential than in the ion trap region. Such retardation is important to reduce the power load on the electron collector, but has its difficulties: some electrons of the primary beam, those with the lowest longitudinal velocity, can be reflected back from the minimum potential. These electrons can make their way back towards the cathode, and can raise the pressure in the source due to bombardment of the drift tubes and elements of the gun. These electrons could also act as an element of positive feedback, boosting electron-ion two-stream instability [3].

The requirements of laminarity and stability of the electron beam over a wide range of EBIS parameters (current, energy, current density, and magnetic field) can be satisfied with an electron gun concept proposed by G. Kuznetsov [4]. In this concept the electron beam is primarily formed in a narrow region near the cathode surface with the shape of electric field well defined by the surface of the cathode, as it is in a coaxial diode with magnetic insulation. Such an electron gun design for the EBTS contains a spherical convex cathode with a diameter of 8.3 mm, a spherical radius of 10.6 mm, and a spherical convex focusing electrode, inside a coaxial anode. Simulated with the program SAM, extraction of the electron beam inside this gun, with perveance p_{gun}= 1.69×10^{-6} A/V$^{3/2}$, is presented in (Fig.1) [4]. After the electron beam leaves the gun region, it is compressed radially in the field of the main solenoid. A separate solenoid at the electron gun allows control of the magnetic field on the cathode independent of the main solenoid, and thus controls the degree of compression of the electron beam inside the main solenoid.

Some important relations for a magnetically focused electron beam are illustrated with simulations of the EBTS electron beam. There are limits on the retardation of the electron beam for the needed compression of the beam cross section and for the given magnetic field of the main solenoid. One of these limits is imposed by the radial component of electron velocity which arises if beam scalloping develops. As shown in Fig.2a [4], the higher the radial beam compression (lower field at the cathode), the less axial retardation is possible. The azimuthal component of electron velocity (which is a part of the transverse component) also contributes to the limit of retardation of the electron beam. In Kuznetsov's design of the electron gun this azimuthal component is effectively minimized by the proper shaping of the convex cathode and focusing electrode. The dependence of the electron beam current density in the ion trap on the magnetic field at the cathode, for conditions as in Fig.□2a and a magnetic field in the trap of 5 T, is presented in Fig.□2b [4]. One sees that the current density decreases with increasing magnetic field on the cathode: it is inversely proportional to this field for the fixed magnetic field in a trap.

2.3 Effect of space charge on the potential distribution

For a high perveance electron beam as required in the BNL EBIS, the space charge of the beam has a significant effect on the potential on the axis of the drift tube structure. This will cause an additional deceleration of the electron beam beyond that from the potential applied □□□the drift tubes. A simulation was done of the transmission of a 13.6 A electron beam through the drift structure having an axial potential distribution on the electrodes such as to produce an ion trap. The electron optical structure, and □□□□potential distribution on the drift tubes and on the axis of □□□□electron beam, are presented in Figs.3a and 3b. The depth of the radial potential well inside the drift tubes in the ion trap region is $\Delta U \approx 14$ kV for □ potential □□ the drift tubes with respect to the cathode of U_{dt}=25 kV. The potential on the axis of the electron beam in this case is thus only U_{axis}=11 kV, which is even lower than the 21 kV value required to provide the necessary electron charge in the volume of the ion trap.

The ion space charge in the trap is expected to be ~50% of the electron charge, so in the process of filling the trap with ions, during their confinement, or while emptying the trap, the depth of the potential well will vary significantly. This causes a variation in the energy of the primary electrons in the trap region, and therefore of the electron charge in the trap. Thus, to maximize the ion space charge in the trap, the potential of the drift tubes in the trap region should be controlled such that the potential of the bottom of the well stays constant during the whole process.

The varying diameter of the electron beam in the EBIS due to the change in the magnetic field from 0.16 T in the cathode region to 5 T in the center of the solenoid, results in a non-homogeneous axial potential distribution inside the drift tube structure with fixed inner diameter. One can see from Fig. 3 that the difference of potential on the axis of the electron beam between drift tube 1 and the edge of the trap (gap between tubes 4 and 5) is about □□□□□□4.5 kV (for fixed inner diameter and potential of drift tubes). In such a configuration the ion trap is defined not by the central tubes with minimum potential (tubes 5-8), but by the point with maximum potential on the low barrier side of the trap and the point with the same potential on the other side of this trap. All ions generated between the maxima of the axial potential distribution will be directed by the electric field to the central part, and the region external to the main trap region will serve as an additional source of background ions, increasing the vacuum requirements in this region. Also, as a result of such a nonuniform potential distribution, relatively shallow but "permanent" ion traps are created in the drift structure. Ions in these traps will stay as long as the electron beam is running. In principle, to straighten the axial potential distribution one could maintain the ratio r_{dt}/r_{eb} constant over the full structure by the proper shaping the inner diameter of the drift tubes. This proves to be difficult, however, so alternatively one can attempt to maintain this ratio constant at least within each drift tube, and then build a flat potential distribution on the axis of the drift tubes with the electron beam running by applying relatively small variations to the potential of neighboring drift tubes, on a top of common applied potential. However, strictly speaking, the axial potential distribution can be built flat for a certain radial compression of □□□□electron beam but will not be flat for another compression. Instead of building a flat potential distribution, it is preferable to build one with a continuous decline in potential outside the ion trap over the full range of compression ratios of the electron beam. In this case all ions generated outside the ion trap will either be directed to the cathode of electron gun or to the electron collector.

3. Vacuum

The most rigorous vacuum requirements in an EBIS are imposed by the need to have a low influx of background ions into the ion trap, because through the process of ion-ion collisions these ions can replace the injected ions. Since background ions are typically lighter than injected ions, there can be some positive effect from these background ions in that one can get a cooling of the injected ions. However, it is advantageous to be able to inject cooling ions into the electron beam in a controlled way, in which case the pressure of background ions has to be significantly lower than the pressure of cooling gas. Requirements on the pressure of residual gas in the electron gun region are dictated primarily by the need for proper conditions for operation of cathode, and in the electron collector by the need for stable transmission of the electron beam without plasma excitation. Normally, the pressure in the regions of electron gun and electron collector can be higher than in the ionization region, provided there is efficient vacuum separation between the sections.

3.1 Vacuum requirements for the ionization region

We can find, using the graph of Donets [5], that the ionization factor (product of electron beam current density j and confinement time τ), required to generate U^{45+} is $j\tau \approx 23.8$ A•s/cm^2. Assuming that ions spend only 50% of the time inside the electron beam, for an electron beam with a current density j=600 A/cm^2 the confinement time should be τ_{conf}=79 ms. With this figure in mind we can estimate requirements on the pressure of residual gas.

An estimate of the time necessary to compensate electron space charge (τ_{comp}) with nitrogen ions (residual gas component) has been made by E. Donets [6]. This estimate is made under the assumption that all nitrogen ions are singly charged. In the ion trap residual gas ions can reach high charge states, (up to fully stripped), if they are not lost. On the other hand, through the process of ion-ion collisions these background ions (typically with lower charge state than injected heavy ions) will acquire energy from the heavier ions and escape from the trap before they reach such a high charge state. These phenomena work in opposite directions in terms of the charge state of residual ions and their total space charge. For a residual gas pressure $P=1\times10^{-10}$ Torr, and electron beam energy of E_{el}=10 keV, one estimates [6] that τ_{comp} = 4.5 s. This is 57 times longer than the expected confinement time in our EBIS. This would mean that if pressure of residual gas is $P=1\times10^{-10}$ Torr, less than 2% of the ions accumulated in the trap will be background ions. This is, however, only a rough estimate of the requirements, which become more stringent if higher charge states of background ions are produced.

3.2 Outgassing

In most existing EBISes the superconducting solenoid has a cold bore, which provides cryopumping of the trap region. The BNL superconducting solenoid bore, however, is at room temperature. This allows a shorter time between the exposure of the EBIS to atmosphere and the start of the next experiment, compared to a "cold" EBIS. The trade-off is that one then has a serious problem in providing sufficiently high vacuum in the ionization region while the high current electron beam is running. The main sources of outgassing in a "warm" EBIS are:

1. thermal outgassing of surfaces in vacuum at room temperature,
2. outgassing of hot surfaces (electron gun, Ti sublimation pump),
3. outgassing of surfaces under bombardment by the electron beam and X-rays (electron collector),
4. outgassing of surfaces bombarded by ions (inner surfaces of drift tubes, ion beam focusing electrodes).

In the following, we evaluate the contribution of each of these components to the total pressure of residual gas.

3.2.1 Thermal outgassing

Thermal outgassing of surfaces in the central vacuum chamber at room temperature is estimated to be $Q_n=1.3\times10^{-8}$ Torr l/s, after preliminary vacuum firing and baking in situ at 300^0 C. With our eventual pumping speed of S=2000 l/s, we can then expect this mechanism to lead to a pressure in this part of the EBIS of $P_n=6.5\times10^{-12}$ Torr. On our experimental bench, a pressure of $P=4\times10^{-11}$ Torr was reached in the central vacuum chamber with more limited baking (5 hours at 200^0 C), followed by 5 days of pumping with a Ti sublimation pump (1000 l/s) and a turbopump (180 l/s). The dominant component of residual gas in the central vacuum chamber (without the electron beam) was hydrogen.

3.2.2 Outgassing of hot surfaces

There are two main regions that are hot in the EBIS, and that generate considerable gas load: the electron gun and the Ti sublimation pumps. Other hot elements - cathodes of vacuum gauges and cathode of mass spectrometer - are much smaller gas sources.

3.2.2.1 Electron gun

The LaB_6 cathode operates at a temperature $T_c \approx 1700^0$C, and its heating power is 110 W. The main outgassing component is CO. The outgassing rate decreases with time of conditioning of the gun, and there is no efficient procedure for preliminary outgassing of the cathode unit. The anode of our electron gun does not have efficient cooling, and reaches an equilibrium temperature $T_a \approx 350^0C$ when the cathode of the gun is hot. The main outgassing component is H_2. The anode can be vacuum fired to reduce this outgassing.

On our electron gun test bench, equipped with a Ti sublimation pump (S=1000 l/s) and ion pump (S=20 l/s), the pressure of residual gas in the gun chamber was $P=3x10^{-9}$ Torr with the electron gun hot. The main components of residual gas were CO (70%) and H_2 (25%), and the rest was primarily CH_4.

3.2.2.2 Ti sublimation pump

The Ti sublimation pump outgasses only when it is hot, i.e. in the standby mode and during sublimations (1-2 min). The main component of outgassing is methane (CH_4), which Ti layers do not pump. After a 1 month training, the contribution of the Ti sublimator, operating in standby mode, to the total outgassing in electron gun chamber will be much smaller than that of the gun itself.

3.2.3 Outgassing of surfaces under bombardment by the electron beam

This source of outgassing is the heaviest for a high current EBIS. At the collector, the 10 A, 10 keV electron beam hits with a flux of around 30 mA/cm^2, releasing gases from the surface via electron stimulated desorption (ESD). Studies of this phenomena [7,8] indicate that the coefficient of ESD, η_g, (the number of molecules released from the surface per one incident electron) for copper reduces with time of training, and reaches a stable value which depends on conditioning of the surface. The minimum value of this coefficient, reached in [7] was $\eta_g=2.5x10^{-7}$ molecules/electron for 300 eV electrons on copper, after a bakeout at 300^0C and glow discharge treatment (Ar+10% O_2) with a dose of $6x10^{18}$ ions/cm^2. Baking and subsequent beam training without glow discharge treatment gave $\eta_g=2.5x10^{-4}$ molecules/electron. The main components of residual gas were H_2, CO and CO_2. At an electron energy of 2 keV this coefficient is higher by approximately a factor of 2, and the further increase with energy is slow. Our maximum total electron flux on the electron collector is expected to be $6.3x10^{19}$ electrons/s (10 A beam). After baking and the recommended glow discharge cleaning of the surface of the electron collector, we can expect the total number of molecules desorbed by the electron beam to be $N_{desorp} \approx 4x10^{13}$ molecules/s or $Q_{ec} \approx 1.2x10^{-6}$ Torr l/s. If the effective pumping speed in the electron collector chamber is $S_{ec}=1000$ l/s, a minimum equilibrium pressure $P_{ec}=1.2x10^{-9}$ Torr can be achieved in the electron collector chamber. This value is close to the pressure achieved experimentally in the EBTS gun chamber.

3.3 Separation of volumes with different outgassing rates.

In an EBIS with a "cold" drift structure the ionization volume is automatically separated from the side regions through cryogenic pumping by the cold surfaces of the central region. In a "warm" EBIS, if no special measures are taken, the pressure in all regions of the EBIS will be close to each other because of a normally high vacuum conductance between different parts of the ion source. However, if those parts of the EBIS which outgas heavily (electron gun and electron collector) are mounted in well-pumped chambers that have limited vacuum conductance to the ionization region, the vacuum in this central part can be considerably better than in the side chambers. This vacuum solution is implemented in the BNL EBTS (Fig.4). Chambers containing the electron gun and electron collector are connected to the central part only through the channels for transmission of the electron beam, having a total estimated vacuum conductance $F_{eg}+F_{ec}$ =86 l/s (H_2, 300^0C). Each of these chambers is equipped with a Ti sublimation pump (S=1000 l/s). Based on the measured pressure of residual gas in the gun chamber on the test bench of $P_{gun}=3x10^{-9}$ Torr (with hot cathode), and assuming a similar pressure in the electron collector chamber, the gas flow into the central chamber should be $Q_{side} \approx 2.6x10^{-7}$ Torr l/s. The central chamber has a Ti sublimation pump and a cryopump, each with a total pumping speed of S_c=1000 l/s. The contribution of the side chambers to the pressure in the central chamber is thus calculated to be $P_c \approx 1.3x10^{-10}$ Torr. This contribution is larger than that from thermal outgassing Q_n, but is acceptable for achieving a sufficiently long compensation time. If electron bombardment of the drift tubes in the central region is excluded and the only source of outgassing is a thermal outgassing, then the pressure difference (ΔP) between the center of the drift tube structure and the outer central vacuum chamber is estimated to be $\Delta P \sim 1x10^{-11}$ Torr.

The pressure in the central part of EBIS can be improved by implementing additional pumping with non-evaporative getters (NEG). The only inconvenience with NEGs is their limited gas capacity. To regenerate NEGs one has to periodically bake them for approximately 1 hour.

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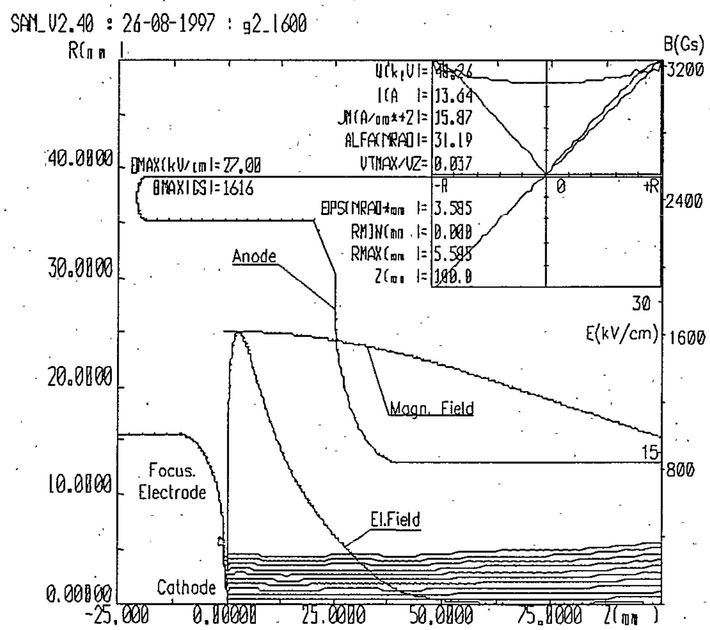
Figure Captions.

Figure 1. Simulation of extraction of the electron beam with current 13.64 A.

Figure 2. a: Critical drift tube potential (solid line) and corresponding potential on the axis of a 13.64 A electron beam (broken line) for virtual cathode formation vs. magnetic field on the cathode. The main solenoid field is 5 T. b: Minimum and maximum of average current density – due to beam modulation in the center of the trap region, as a function of magnetic field on the cathode for the same conditions, as in 2a.

Figure 3. a: Electron optical system of the BNL EBTS, b: Axial potential distribution on EBTS elements with a constant drift tube inner diameter of 31 mm (solid line), and on the axis for a 13.64 A electron beam (fine line).

Figure 4. Schematic showing the vacuum separation of the central region of the EBTS from the regions of the electron gun and electron collector. F_{eg} and F_{ec} are the vacuum conductivities of the electron gun chamber and electron collector chamber, respectively, to the central chamber.



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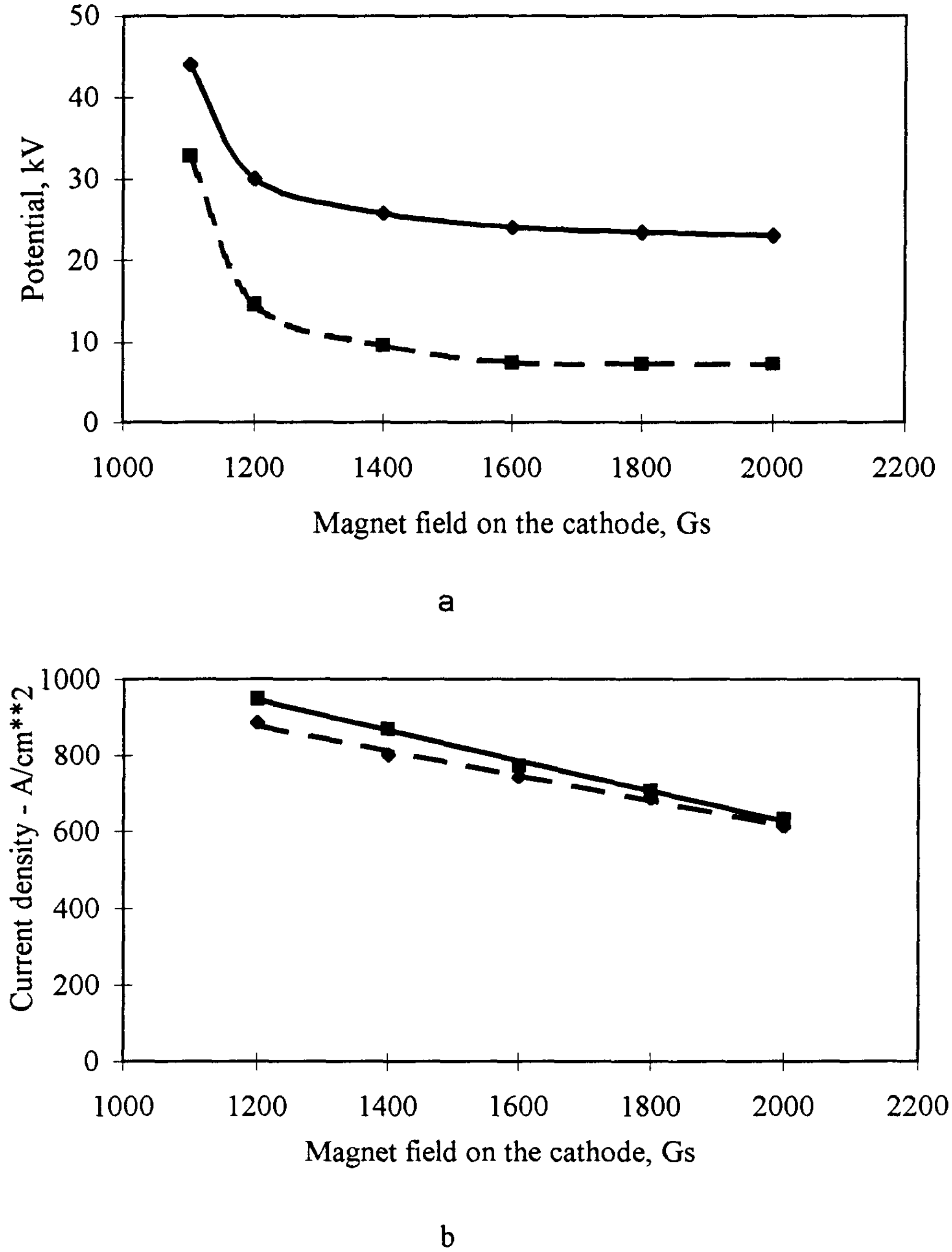
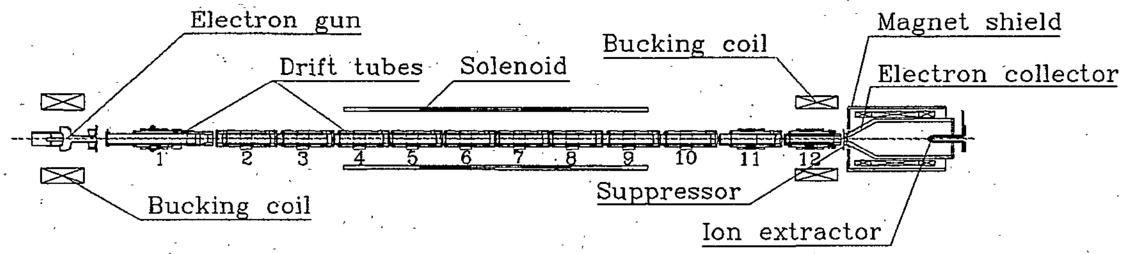


Fig. 2 a: Critical drift tube potential (solid line) and corresponding potential on the axis of a 13.64 A electron beam (broken line) for virtual cathode formation vs. magnet field on the cathode. The main solenoid field is 5 T. b: Minimum and maximum of the average current density – due to beam modulation in the center of the trap region, as a function of magnet field on the cathode for the same conditions as in 2a.



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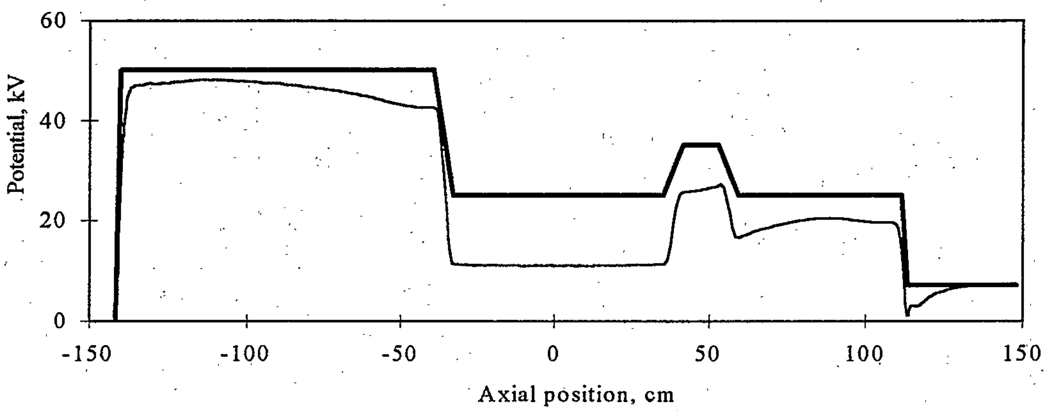

b

Fig. 3. A: Electron optical system of EBTS, b: Axial potential distributions on EBTS elements with constant drift tube inner diameters of 31 mm (solid line), and on the axis of a 13.64 A electron beam (fine line).

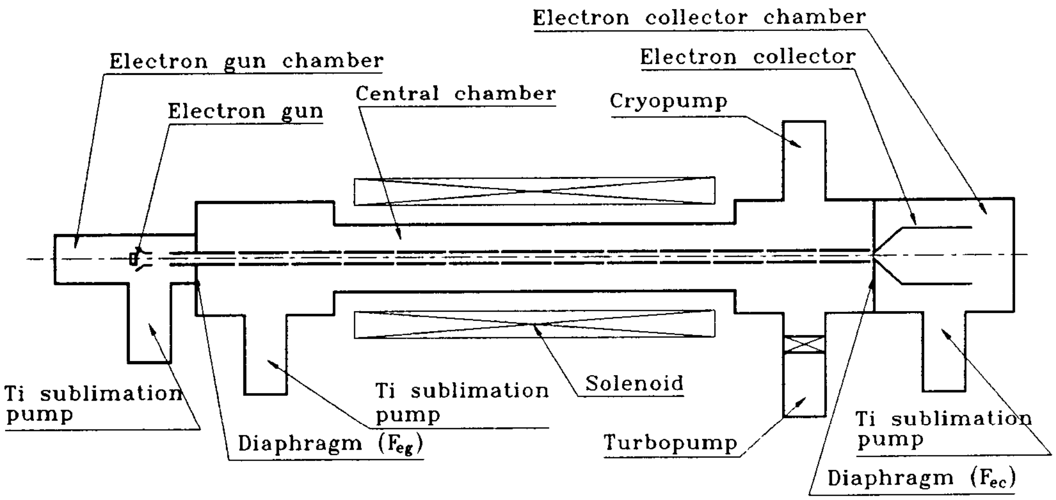

Fig. 4. Vacuum separation of the central region of the EBTS from the regions of the electron gun and electron collector. F_{eg} and F_{ec} are the vacuum conductivities of the electron gun chamber and electron collector chamber, respectively, with the central chamber.