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Eliminating unwanted electrons in EBIS devices[a)]

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In electron beam ion sources step-wise ionization to high charge states is accomplished by magnetically confined electron beam. Electron space charge and high voltage electrodes confine the ions. The relativistic heavy ion collider (RHIC) ion source Debye length meets requirements for instabilities with free source of energy to grow. Electrons stripped from ions provide energy for a variety of microinstabilities to grow. Possible solution is to remove these electrons from the trap to a drift tube biased to higher Voltage than the other tubes between the gate and the collector. If needed a split drift tube for bleeding these electrons to ground is added.

I. INTRODUCTION

In principle, an electron beam ion source (EBIS), which was invented by Donets[1,2], device has a very simple mode of operation: an electron beam propagating through a gated ion trap step-wise ionizing trapped ions to high charge states. The electron beam, which is confined by an extremely large magnetic field, is injected from an electron gun through the trap into an electron collector. The ions are confined by the electron beam space charge radially and by high voltage electrodes (gates) axially.

Any instability requires a free source of energy to grow. The electron beam moving through the trap structure is, potentially, a free energy source. Electron - trap structure RF generation and electron beam interaction with the ions have been extensively analyzed and were found not to be a problem for the relativistic heavy ion collider (RHIC) EBIS.

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Diocotron instability[3] (a.k.a. slipping stream instability) is a plasma instability created by two sheets of charge slipping past each other. Energy is dissipated in the form of two surface waves propagating in opposite directions, with one flowing over the other. This instability is the plasma analog of the Kalvin-Helmholtz in fluid mechanics. Stripped electrons can be a source of free energy for the diocotron instability by providing a slipping stream.

A variety of microinstabilities due to axial positive slope gradients in configuration and velocity space are also possible[4,5]. Stripped electrons can accumulate in the positively biased gates and facilitate these instabilities[6] by providing a source of free energy.

Therefore, it's prudent to eliminate the stripped electrons from the trap.

One option is to install a drift tube between the gate and the collector biased to higher positive Voltage than the other tubes; and, if necessary bleed these electrons to ground in an additional split drift tube inserted downstream from the highest Voltage tube. **Preliminary analysis** of this idea is presented.

II. THE BASIC IDEA

EBIS[1,2] is primarily used to produce highly stripped ions, as high as fully stripped xenon and helium-like uranium. In a typical EBIS, a high current density electron beam is launched along the magnetic axis of a high field solenoid. Coaxial with the magnetic axis are positively biased cylindrical electrodes, which together with the magnetic field form a gated ion trap. Low charge state ions (or in some cases neutral atoms) are introduced into the trap and are then subjected, by the electron beam, to successive ionization by electron impact. These ions are confined radially by the negative potential well due to the electron beam space charge, and axially by an appropriate potential distribution impressed on the electrodes. When the desired ion charge state is reached, the axial trap potential is modified as to expel the ions from the source, i.e., the gate on the ion extractor side is opened. Throughout the whole cycle, the electron beam is continuously injected into one end of the trap, and collected at the electron collector located before the ion extraction region outside the opposite end of the trap.

Figure 1 is a generic EBIS diagram, to which an additional high Voltage drift tube was added after the downstream (with respect to the electron flow) gate drift tube. In principle this tube should solve the stripped electrons problem. If needed, following the high Voltage drift tube, a split tube can be inserted, which when biased, its electric field is perpendicular to the magnetic field to

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generate an **EXB** drift for bleeding stripped electrons to ground.

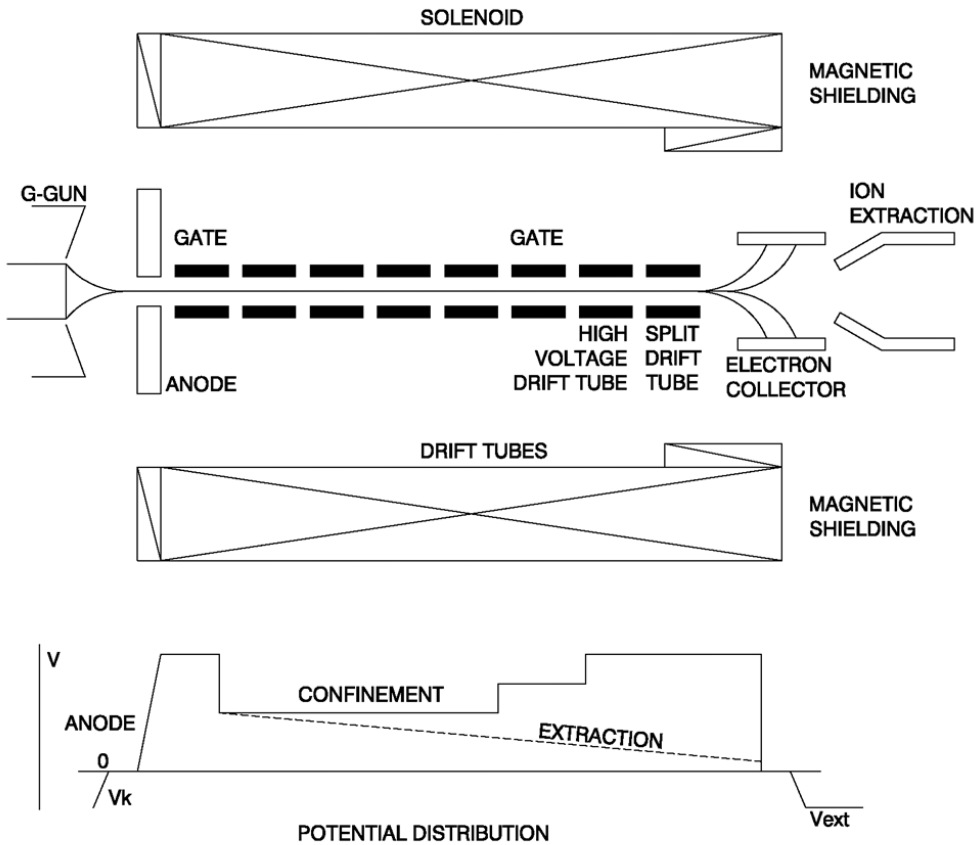

FIG. 1. Schematic of EBIS modified for bleeding stripped electrons

Also shown in figure 1 is the EBIS potential distribution during confinement (solid line) and extraction (broken line) cycles.

Although this scheme for removing undesired electrons from an EBIS trap is applicable to almost any EBIS or electron beam ion trap (EBIT) device, analysis is performed based on RHIC EBIS parameters.

III. RHIC EBIS PARAMETERS

Present BNL EBIS[7] is part of a heavy ion preinjector that supplies beams for the Relativistic Heavy Ion Collider and the National Aeronautics and Space Administration Space Radiation. This EBIS, which has a base pressure of 10^{-10} Torr is designed to produce milliampere level currents (in 10s µsec pulse lengths) of all ion species, with q/m= 1/6−1/2. Among the major components of this source are a 5 T, 2-m long, 204 mm diameter warm bore superconducting solenoid, an electron gun designed to operate at a nominal current of 10 A. Although the RHIC EBIS can generate high charge state ions of practically any species, its primary output[8] is that of Au^{+32} and Fe^{+20}.

Relevant to this paper subject matter are the parameters[8] of the downstream section of the trap, i.e. the last three drift tube, to the collector entrance. The last three drift tubes (12 – 14) have (in downstream direction) lengths and inside diameters of L=233.3 mm, ID=30.5 mm; L=35 mm ID=30 mm; L=245mm, ID=34.5. magnetic field between the last drift tube (#14) and the collector entrance varies between 1.6 kG to 1.1 kG.

Although the electron gun was design to operate with a current of 10 A, its routine operation is at currents of 6 – 8 A. The electron beam energy is 24 kV; inside the trap, the electron beam radius is 1.5 mm. Energy spread of electron in not known exactly. Other parameters relevant to the below analysis are not known, but can be estimated. The minimum energy spread of the electron beam can be estimated to be roughly the same as the potential well inside the beam, which is 500 – 800 eV. This energy spread might be larger due to other effects.

IV. STRIPPED ELECTRON ELIMINATION

Based on the above parameters, basic calculations with analytical formulas[9,10] are performed for exploring the feasibility of extracting stripped electrons from the trap during confinement time. Basic question is whether stripped electrons are attracted to the high Voltage drift tube downstream from the gate?

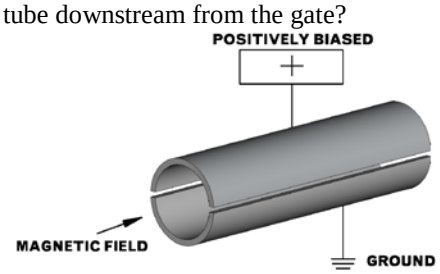

FIG. 2. Rough sketch of the split drift tube designed to bleed off electron with ExB drift.

Correspondingly, are stripped electrons shielded or exposed to the high Voltage electrode potential? Answer depends on plasma Debye length that is calculated from the RHIC EBIS parameters: electron beam velocity: $V_{drift}=5.9x10^7E^{1/2}$ cm/sec, where E is the electron energy. At 24 keV $V_{drift}= 9x10^9$ cm/sec. Electron beam radius is 1.5 mm → electron beam cross section area A is 0.07 cm^2. Hence electron beam density n can be calculated from $J=I/A=qnV_{drift}$, therefore, n = $7.9x10^{10}$ cm^{-3} for 8 A electron beam.

Debye length λ_D is given by $7.43x10^2T^{1/2}n^{-1/2}$, assuming electron energy spread of 1 keV, yields $\lambda_D = 0.08$ cm (for and electron beam current of 6 A $\lambda_D = 0.09$ cm), i.e. Debye length is smaller than the electron beam radius. Therefore, stripped electrons inside the electron beam are shielded from external potentials. But, collisions can facilitate stripped electron diffusion to outer radii and out of the electron beam. This diffusion is enhanced by radial potential well space charge, which with the axial magnetic field generates $\mathbf{E_rXB_z} = \mathbf{V_\theta}$ i.e. an azimuthal drift that enhance collision step size. Additionally the potential in the EBIS trap is negative, which drives ions radially inward; while causing stripped electrons to drift outward (beam electrons are not affected due to the extremely short dwell time in the trap). Enhancement to this phenomenon comes from column rotations that drive light particles (i.e. electrons) to outer radii while heavy particles (i.e. ions) remain radially inward. The later was even explored for isotope separation.

Collision frequency for electrons with singly charged ions, which will cause electron to diffuse, is given by $f_c = n_i\sigma_{e,i}V_{the}$ where n_i is the ion density, $\sigma_{e,i}$ is the collision cross section and V_{the} is the stripped electron thermal velocity, which is given by $V_{the}=4.19x10^7T^{1/2}$ cm/sec, which for stripped electrons having an energy corresponding to the median potential well energy (potential well is between 500 and 800 volts) of about 650, $V_{the}= 1x10^9$ cm/sec. Total cross section $\sigma_{e,i}$ for such interaction with gold atoms[11] (it's most likely higher with ions) is 10^{-15} cm^2. Therefore, the collision frequency with gold ions is at least $f_c = 3.4x10^5$ Hz. But, the collision frequency increases a Z^2, where is Z the ion charge state. During confinement time the average gold charge state is more than 16, and $f_c > 9x10^7$ Hz, while for iron average charge state is more than 10; hence $f_c > 3.4x10^7$ Hz. Essentially during a confinement time stripped electrons with undergo much more than 10^6 collisions. Therefore, collisions can be an effective mechanism for stripped electron diffusion outside the beam envelope, where the plasma density is too low to shield gates or high Voltage drift tube potentials. Furthermore, conjectural evidence exist[6] that stripped electrons accumulate in the gates.

During confinement, potential difference[8] between the trap and gates is 7 kV. Biasing the HV drift tube of figure 1 to 8 kV above the trap, should attract the stripped electron to this drift tube. Once stripped electrons oscillate about drift tube, it's very likely that all plasma free energy sources are removed from the EBIS trap (no slipping streams and gradients of positive slopes in velocity space).

If HV drift tube collection is insufficient, split drift tube bleed of stripped electron can be utilized to bleed electrons[12] to ground, possibly utilizing semiconducting glass[12] between the spilt semi-cylinders of figure 2. But, since the stripped electron energy[8] is unknown, exact dimension of this tube cannot be calculated (measurements and/or simulations needed; beyond the scope of this paper). Biased part of that tube and its ID are assumed to be 8 kV and 3.5 cm respectively. Hence, the electric field $E=2.3x10^5$ V/m. At a magnetic field of 1.6 kG, drift velocity $V_{EXB}=\mathbf{EXB/B^2}=2x10^6$ m/s, which would take a charged particle 16.7 µsec to travel 3 cm. The 24 keV electron beam would be deflected 0.067 cm (placing this tube at 1.1 kG results in 0.047 cm deflection). Simulations can determine if an additional split tube is needed to correct for this deflection.

V. DISCUSSION

Preliminary analysis indicates that an additional drift tube outside an EBIS trap, biased to a higher Voltage than the gates, can remove stripped electrons from the trap and gates. Collisions can cause stripped electrons to diffuse to the outer radius of the electron beam, from where these electrons will be attracted to the highest positive potential. But, simulations are needed to determine the diameter of the high Voltage tube, based on the electron beam size.

Stripped electrons attracted to the high Voltage drift tube of figure 1 will most likely remove any of the free energy sources from the EBIS trap. No gradients of positive slopes in velocity space will remain in the trap; and, in the lower magnetic field their density will be diluted, slipping stream should not lead to instability.

Essentially, this concept for improving EBIS devices, deserve more serious consideration.

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