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Ionization of polarized $^3He^+$ ions in EBIS trap with slanted electrostatic mirror*

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Abstract. Methods of producing the nuclear polarized $^3He^+$ ions and their ionization to $^3He^{++}$ in ion trap of the electron Beam Ion Source (EBIS) are discussed. Computer simulations show that injection and accumulation of $^3He^+$ ions in the EBIS trap with slanted electrostatic mirror can be very effective for injection times longer than the ion traversal time through the trap.

Keywords: Polarized ^{3}He, electron beam ion source
PACS: 30, 80

1. INTRODUCTION

An Electron Beam Ion Source is shown schematically in Figure 1. At one end an electron beam is produced, and then compressed to high density as it enters a strong solenoidal magnetic field. The beam passes through the solenoid, is decelerated, and then stopped in the electron collector. The EBIS trap region is a series of cylindrical electrodes in the main solenoid. Electrostatic barriers for ions are produced on the ends of the trap region by applying positive voltages on the end electrodes. Ions are confined radially by the space charge of the electron beam. The trap is seeded either by injecting neutral gas of the desired species, or by axial injection and trapping of singly charged ions produced in an external ion source. As the ions are held in the trap, they are step-wise ionized, until the desired charge state is reached, at which time the voltage on one end electrode is reduced and the ions are extracted. They pass axially through the electron collector and into a beam transport line.

The first ion injection from an external ion source into EBIS trap has been done in France on Dione EBIS [1]. This ion source delivered highly charged ions for the SATURNE-II accelerating facility for several years using external ion injection.

The same group used Dione for accumulation and ionization of polarized ions Li^{+1} [2]. Bare nuclei Li^{3+} were extracted from EBIS in short pulses with current 20 μA and had polarization $P_{zz} \approx 80\%$. The injected ions did not lose their polarization during axial injection into a 5T field of superconducting solenoid, confinement in a trap for several milliseconds and extraction.

It is possible to produce polarized $^3He^{+2}$ ions in EBIS by injecting the polarized ^{3}He gas in the ionization region of EBIS [3,4]. Injection of He gas into EBIS was tested at BNL EBIS with unpolarized ^{4}He. Nevertheless considering use of RHIC EBIS as a

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universal ion source running for several applications in a time-share mode, when running a cycle with species other than He, the residual He gas can reduce intensity of working ions because of its substitution with residual ions (memory effect). The charge-state spectra of ions extracted from EBIS with gas injection usually have a low-charge tail caused by continuously incoming neutral atoms, and for He this tail is $^{3}He^{+}$ ions. With fixed capacity of the ion trap for a given electron current the tail results in a reduced output intensity of $^{3}He^{+2}$ ions.

2. BNL EBIS

The existing BNL Test EBIS [5-8] operates with electron current up to 10 A and produced highly charged ions with gas injection and with external ion injection from different ion sources [9-10]. Schematic of Test EBIS is presented in Fig. 1.

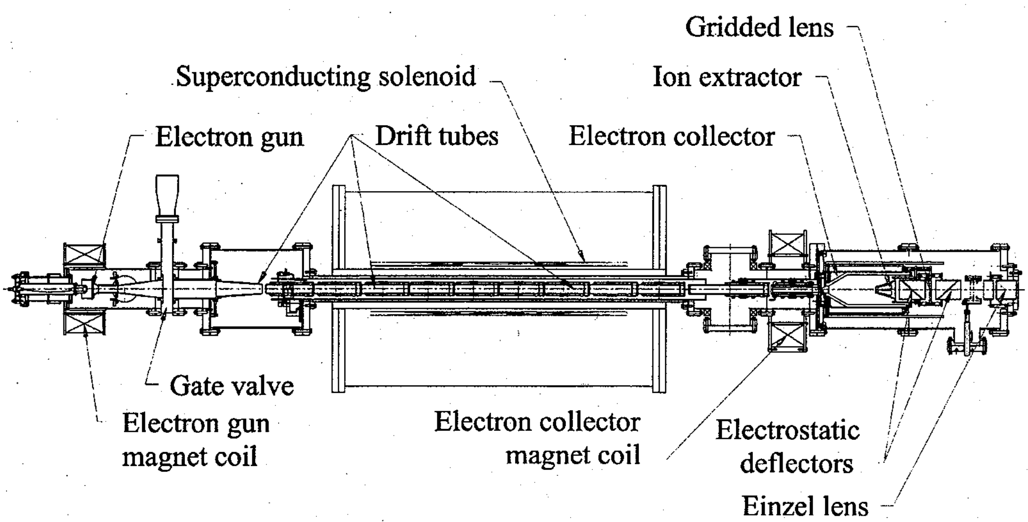

FIGURE. 1. Schematic of BNL EBIS Test Stand

Ion injection from an external ion source is used routinely on BNL Test EBIS for injection of metallic and gaseous ions. Its main advantage is absence of memory effect and ability to change species with required time structure by controlling electrostatic deflectors connecting different ion sources to the main injection line. Charge state spectra with pulsed ion injection are free of low-charge tail.

2. PRODUCTION OF POLARIZED $^{3}He^{+}$ IONS

There is a possibility to produce a single-charge polarized $^{3}He^{+}$ ion beam in the process of optical pumping of the triplet $^{3}S_{1}$ metasable atoms and subsequent selective ionization of metastable states in collision process [Murnick, 11]. The advantages of this technique in comparison with polarized gas injection might be higher nuclear polarization of $^3He^{++}$ ion beam and universality of the ionization scheme with the other ions.

Murnick's proposal is based on optical pumping of triplet metastable $^3He(^3S_1)$ fast atomic beam (produced in the neutralization of $^3He+$ ion beam of a 0.75 keV energy in the sodium vapor cell). The optical pumping by circular polarized laser light of a 1080 nm ($^3S_1$ – $^3P_1$) transition is used to transfer all atoms to the (F, m_F) , (3/2, 3/2) state which is 100% polarized m_I = ½. The required laser power (of about100 mW/mm^2) can be easily achieved with the use of contemporary lasers developed for the "metastability exchange" polarization technique of He-3 gas in the cells. The He-3 metastable state level diagram and transitions used for "optical pumping" are presented in Figure 1 [11]. Two narrow band laser beams are required for pumping of both F=3/2 and F=1/2 states.

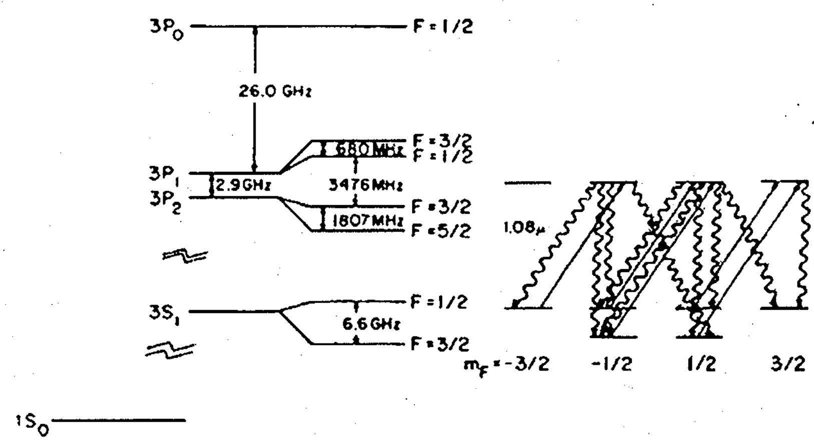

FIGURE 2. Diagram of He-3 metastable state and transition used for "optical pumping".

Selective ionization of the highly polarized metastable atoms in collisions with N_2, H_2 or other atoms in gaseous ionizer cell can be used for production of polarized $^3He^+$ ion beam for injection to the EBIS ionizer. At 0.5 keV beam energy the ionization efficiency of metastable atoms is about 50 times higher than ionization from ground states [12].

3. EXISTING METHODS OF EXTERNAL ION INJECTION INTO EBIS

In the EBIS ion trap ions are confined with electron beam space charge in radial direction and with two potential barriers on the side drift tubes in axial direction. There are two known methods of injection the ions produced outside EBIS into EBIS ion trap: "fast" injection and "slow" injection. Both methods are described below assuming that the electron beam is running from the electron gun on the left to the electron collector on the right and the primary ions are injected from the external ion source moving from right to the left.

With “fast” ion injection the primary ions (ions, which came from the external ion source) are coming in through the aperture in the electron collector and traversing the trap region when the axial potential barrier on the injection side (downstream barrier) is down and the potential barrier on the opposite side (upstream barrier) is up (Fig. 3a). When ions enter the trap region they are decelerated and acquire additional axial energy spread because part of ion initial longitudinal energy (depending on their radial position) translates into transverse components due to interaction with radial electric field of the electron beam and with magnetic field. For this reason axial density of ions in the trap region reaches maximum after certain time determined by the ion axial energy spectrum and the length of the trap. For Dione and BNL Test EBIS this time is approximately 200 μs. After this period of time the downstream barrier turns up, the primary ions from the outside ion source can not go over it as well as ions in a trap region and all ions between the two barriers get trapped (Fig. 3b).

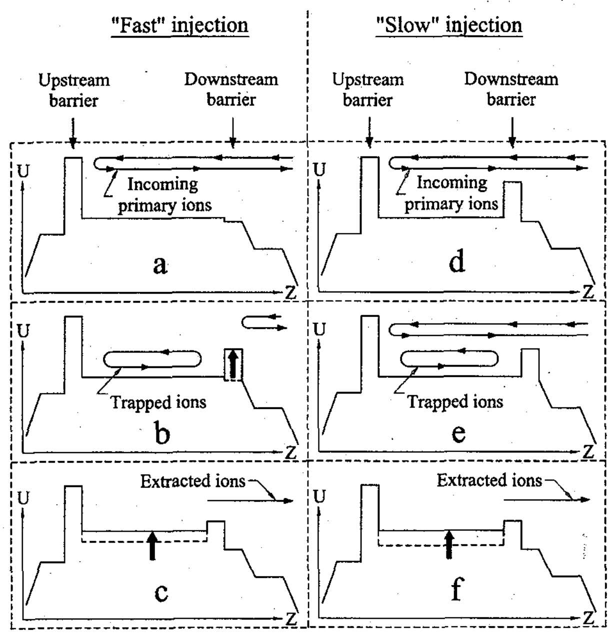

FIGURE 3. Illustration of methods of ion injection. a, b and c – axial potential distributions for ionization cycle with “fast” ion injection. d, e and f - axial potential distributions for ionization cycle with “slow” ion injection.

These ions get ionized by the fast electrons of the beam and their charge state increase. Ions can be confined in a trap as long as it takes to reach the required charge state distribution and after this time they can be extracted. One can extract ions either by lifting the “bottom” of the trap (rising the potential of the drift tubes in the trap between the two barriers) (Fig 3c) or simply by lowering the downstream barrier. Both methods can be used simultaneously for faster ion extraction.

With “slow” injection the primary ions have sufficient energy to go over the downstream barrier but not enough to go over the upstream barrier. Ions are traversing the trap region with both barriers up (Fig. 3d). Most ions go over the downstream barrier, get reflected from the upstream barrier and return back passing the downstream barrier without being trapped. Those ions, which reduce their longitudinal energy per charge as a result of energy exchange with molecule or another ion, or as a result of ionization, do not have enough energy to cross the downstream barrier on the way back and get trapped (Fig. 3e). When ions reach the require charge state they can be extracted in the same fashion as in a cycle with fast injection (Fig. 3f).

The efficiency of capturing the primary ions into the EBIS trap with "fast" ion injection was measured on CRYSIS [13], Dione [14] and REXEBIS [15] and the reported value has a range of 14.5%-58.8%. With relatively high efficiency of this type of ion injection it is limited to pulsed beam structure and can not take advantage of pulses longer than it takes for reaching the equilibrium. The only possible way to increase the number of injected ions is to increase current of the primary ion beam, which is not always possible. Also, the higher ion current usually results in larger emittance of the primary ion beam and therefore lower trapping efficiency.

4. ION INJECTION WITH SLANTED ELECTROSTATIC MIRROR

The electron beam propagating inside the drift tube creates a radial potential well with its space charge. For cylindrically symmetric case and uniform electron space charge density its depth is:

$$\Delta U_t = \Delta U_b \times [1 + 2\ln(\frac{r_t}{r_b})] \qquad (1)$$

ΔU_t – potential difference between the axis of the electron beam and the drift tube wall,
r_t - inner radius of the drift tube,
r_b – radius of the electron beam,
ΔU_b – potential difference between the axis of the electron beam and its boundary:

$$\Delta U_b = \frac{I_{el}}{4\pi\varepsilon_0\sqrt{\frac{2e}{m}E_{el}}} \qquad (2)$$

I_{el} – current of the electron beam,
E_{el} – electron beam energy.

For electron beam current I_{el} =1.0 A and electron energy E_{el} = 10.0 keV the potential well within the electron beam boundary is ΔU_b = 151.6 V and the full potential well inside the drift tube according to (1) can be several times larger.

Such radial ion confinement inside electron beam presents an opportunity to reduce longitudinal ion energy by transferring part of it into the transverse components and yet not to lose ion radially on the drift tube wall. The proposed method [16] of such transformation is based on a property of a slanted electrostatic mirror to reflect ions asymmetrically, so that after reflection on such mirror the ratio of longitudinal component to the transverse components of ion velocity changes. The schematic diagram of such mirror is presented in Fig. 4.

One can see from this diagram that with mirror normal (AB) tilted with respect to the longitudinal axis (AC), the ions with angles of impact 0 - 90^0 will have part of their transverse energy transferred to longitudinal and will have their longitudinal energy increased (Accelerating region). If the angle of impact is -90 – 0^0 the ions will have their longitudinal energy decreased because of transferring part of it into transverse component (Decelerating region).

The existing electrostatic mirror in EBIS, which is formed by the drift tube of the upstream potential barrier and next to it trap drift tube traditionally is axially symmetric and concentric with other drift tubes and electron beam. Its reflecting equipotential surface is practically perpendicular to the axis of the trap and therefore has very little effect on the ratio between longitudinal and transverse components of ion velocity. Slanting this mirror can change angle of ion velocity vector with respect to the longitudinal axis.

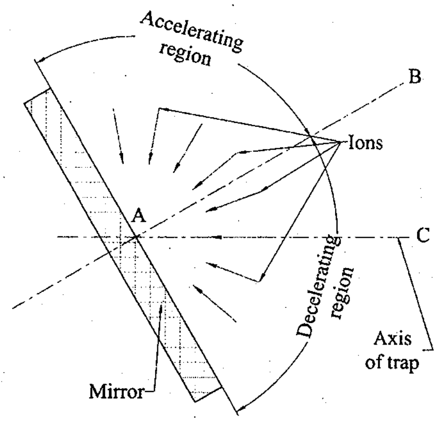

FIGURE 4. Schematic diagram of slanted electrostatic mirror. AC – longitudinal axis of the trap, AB – normal to the mirror.

Ion injection with such mirror can be done with both upstream and downstream barriers up. Substantial fraction of incoming primary ions will lose part of their longitudinal energy after reflection on the slanted mirror and get trapped. 3D simulations demonstrated that up to 60% of the incoming ions can be trapped with this mechanism. The maximum injection time can be limited by factors such as the ion source repetition rate or the ability of the electron collector to dissipate power of electron beam. With efficiency of ion injection 60% the required current of ions $^3He^{+1}$ to fill the full capacity of the RHIC EBIS ion trap ($1.1 \cdot 10^{12}$el. ch.) is < 10 μA. The accumulated charge of polarized $^3He^{+1}$ should be sufficient to fill RHIC to its space charge limit ($2.5 \cdot 10^{11}$ ions $^3He^{+2}$).

A source of polarized $^3He^{+1}$ ions can be installed on an injecting beam line along with other primary ion sources (Fig. 5).

Injection of polarized $^3He^{+1}$ can be done by switching electrostatic benders so that only ions from the beam line containing the source of polarized $^3He^{+1}$ are directed in a LEBT chamber and further into RHIC EBIS.

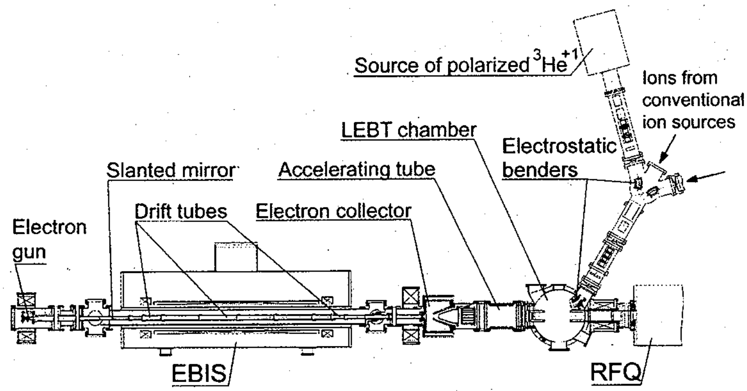

FIGURE 5. A layout of a proposed combination of RHIC EBIS and a source of polarized $^3He^{+1}$.

REFERENCES

1. J. Faure, B. Feinberg, A. Courtois, R. Gobin, NIM 219, 449, (1984)
2. Courtois, J. Faure, R. Gobin, P. A. Leroy, B. Visentin, P. Zupranski, Rev. Sci. Instrum. 63 (4), 2815, (1992)
3. R. Milner, This conference
4. Zelenski A., Alessi J., ICFA Beam Dynamics Newsletter 30, 39, (2003).
5. A. Pikin, J. Alessi, E. Beebe, A. Kponou, K. Prelec, G. Kuznetsov, M. Tiunov, AIP Conf. Proc. 572, 3, (2001)
6. E. N. Beebe, J. G. Alessi, O. Gould, D. Graham, A. Kponou, A. Pikin, K. Prelec, J. Ritter, Rev. Sci. Instrum., 73 (2), 699 (2002)
7. J. G. Alessi, E. Beebe, D. Graham, A. Kponou, A. Pikin, J. Ritter, V. Zajic, Proceedings of PAC-2003, 3, 89 (2003)
8. A. Pikin, J. G. Alessi, E. N. Beebe, A. Kponou, K. Prelec, Rev. Sci. Instrum., 77, 03A910 (2006)
9. E. N. Beebe, J. G. Alessi, D. Graham, A. Kponou, A. Pikin, K. Prelec, J. Ritter, V. Zajic, "Proceedings of the 9-th International Symposium on Electron Beam Ion Sources and Traps" in Journal of Physics: Conference Series (Japan), 2, 164 (2003)
10. A. Pikin, J. Alessi, E. Beebe, A. Kponou, K. Prelec, Conference Proceedings of Italian Physical Society, 72, 47 (2000)
11. D. E. Murnick, AIP Conf. Proc. 131 (1), 73, (1985)
12. H. B. Gilbody et al., J. Physics B, 3, 1105 (1970)
13. E. Beebe et al, NIM B93, 378, (1994)
14. B. Visentin, P. Van Duppen, P. A. Leroy, F. Harrault, R. Gobin, NIM B101, 275, (1995)
15. F. Wenander, P. Delahaye and R. Scrivens, Rev. Sci. Instrum., 77, 03B104, (2006)
16. A. Pikin, A. Kponou, J. G. Alessi, E. N. Beebe, K. Prelec, D. Raparia, Rev. Sci. Instrum. 79 (1), 3088, 2008