TANDEM EBIS*

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Abstract

A method to increase the ion beam intensity of RHIC EBIS by extending its ion trap into magnetic field of an additional superconducting solenoid is described. The strong axial support of the cold masses in these solenoids is required to place them on a common axis close to each other. Such configuration of solenoids allows to produce a long EBIS with a single electron gun, electron collector and injection system. Preliminary calculations of magnetic forces, magnetic field and potential distributions are presented along with proposed structure of the ion traps.

INTRODUCTION

RHIC EBIS supplies the RHIC accelerating facility with highly charged ions from He2+ to U39+. The design of this ion source and its main components can be found in [1-9] and the results of its experimental study and commissioning on RHIC accelerating facility can be found in [10-13]. The total ion charge, which can be accumulated in the ion trap of the Electron Beam Ion Source (EBIS) is limited by the charge of the electrons within the axial ion trap. Usually some factors like an insufficient ion injection, not full axial trapping, and contamination of the trap with the residual gas ions result in a reduction of the accumulated charge of working ions below this maximum value. For electron current 10.0 A, electron energy 20 keV, and the trap length 1.5 m the project value of the RHIC EBIS ion capacity is 177 nC or $1.1*10^{12}$ el. ch. with the charge of working ions constituting 50% of the electron charge. It has been experimentally proven that the extension of the ion trap beyond the limits of the uniform magnetic field results in an increased accumulated ion charge at a cost of some reduction of the effective electron beam density [14]. No disruption of the EBIS operation has been observed. The reduction of the effective current density of the ion trap extended into a low magnetic field area requires some longer confinement time to produce the required charge state of the working ion specie compare to a trap with uniform magnetic field.

THE CONCEPT OF TANDEM EBIS

One way to increase the intensity of the extracted ion beam from EBIS is an axial extension of the ion trap, making it longer. The capacity of the ion trap is proportional to the length of the trap if the radial depth of the potential well remains the same in any axial position of the trap. The extension of the ion trap requires an additional area with an acceptable value of the magnetic field, which is concentric with the existing one. Extending the magnetic field by building a longer superconducting solenoid or placing two solenoids in the same cryostat seem not practical. It is proposed to use an additional superconducting solenoid of the same length and a “warm” inner diameter (ID) as the existing one to extend the magnetic structure and the ion trap of the existing RHIC EBIS creating a longer Tandem EBIS (Fig. 1) with a single electron gun, a single electron collector and a common vacuum system. For the presented geometry the preliminary PerMag simulations give the value of the minimum magnetic field in a gap between two solenoids of 2.1 kGs for magnetic field in the center of each of two superconducting solenoids 4.8 T. This value of minimum magnetic field is quite sufficient for the electron beam transmission in the transition region between both magnets.

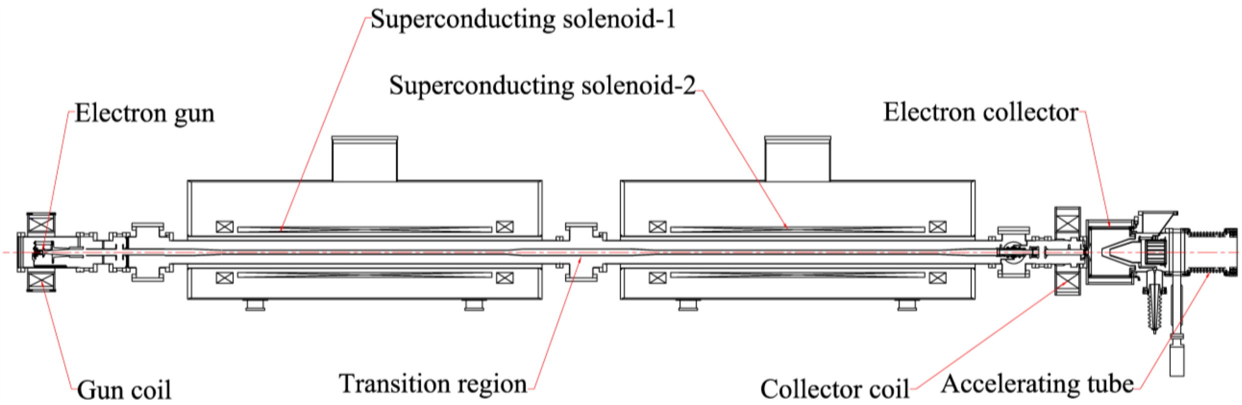

Fig. 1. Schematic of the Tandem EBIS.

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According to the PerMag simulations, the axial force acting on each of the cold masses is approximately 1200 kg if both magnets have the magnetic structure of our ACCEL solenoid.

A possible sequence of axial potential distributions for one ionization cycle in a Tandem EBIS with one injection trap and two pre-extraction traps is presented in Fig. 2.

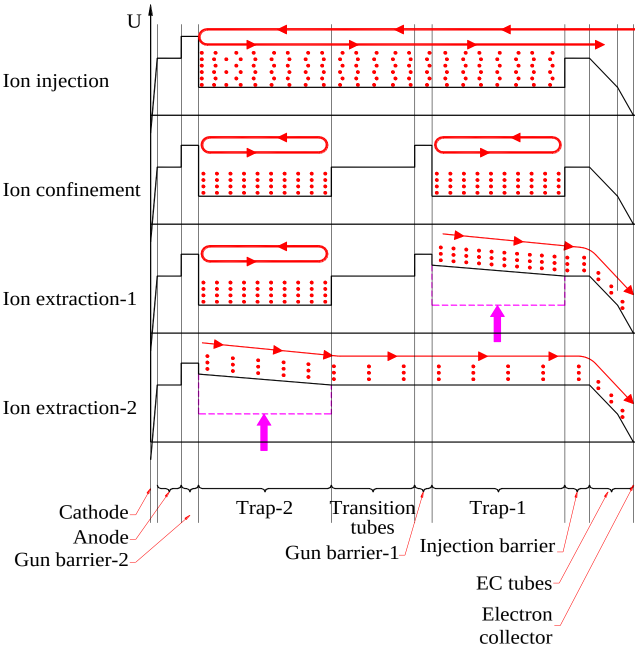

Fig. 2. Ionization cycle diagram for Tandem EBIS with two pre-extraction traps.

DRIFT TUBE STRUCTURE OF TANDEM EBIS

To provide access for ions to all parts of the trap during the ion injection one needs to keep uniform the potential on the axis. In a "conventional" EBIS the magnetic field distribution within the ion trap is usually uniform and so is the ID of the drift tubes. The idea of extending the ion trap into the regions with lower values of the magnetic field seems attractive because it promises increase of capacity of the ion trap and therefore the intensity of the extracted ion beam. However, the variations of the magnetic field within the ion trap have several consequences, which need to be taken into account on a design stage of such EBIS. If all the drift tubes have uniform ID the extending of the ion trap into regions with lower magnetic field would result in a radial potential well having different depth within the drift tubes located in a gradient of magnetic field. These drift tubes would have radial potential wells varying according to the magnetic field values. The potential well is deeper in a high magnetic field region and more shallow in a low magnetic field region.

The potential difference between the axis of the electron beam and the drift tube ΔU can be expressed as:

$$\Delta U = \frac{q/l}{4\pi\varepsilon_0}\cdot\left[1+2Ln\left(\frac{r_t}{r_b}\right)\right] \qquad (1)$$

q/l – total linear electric charge density (includes electrons and ions),
ε_0 – vacuum permittivity,
r_t – drift tube radius,
r_b – electron beam radius,

For an electro-optical system with an immersed electron gun the average radius of the electron beam changes with magnetic field as:

$$r_b(z) = r_c\cdot\sqrt{\frac{B_c}{B(z)}} \qquad (2)$$

$r_b(z)$ - electron beam radius in a point with axial coordinate z,
B_c – magnetic field on the cathode,
B(z) – magnetic field in a point with axial coordinate z.

One can maintain the value of r_t/r_b the same within the drift tube if the inner radius of this tube changes with magnetic field according to (3).

$$r_t(z) = r_{t,0}\cdot\sqrt{\frac{B_0}{B(z)}} \qquad (3)$$

$r_t(z)$ - drift tube inner radius in a point with axial coordinate z and magnetic field B(z) ,
$r_{t,0}$ – inner radius of the drift tube in the point with magnetic field B_0

In an ideal case with uniform value of r_t/r_b in all drift tubes in the trap one can maintain a uniform potential distribution in the trap with the same potential on all drift tubes involved because the value of the radial potential well remains the same. In this case the "flat" potential distribution on the axis does not change with the degree of the electron beam neutralization. For practical reason a complicated shape of the drift tubes inner surface defined by (3) can be substituted with simple conical shapes, which will cause small variations of axial potential within one drift tube, which are much smaller than the radial potential well and therefore can be acceptable.

If the magnetic field variations within the extended ion trap are too large, maintaining the same value of r_t/r_b becomes impractical because of space limitations and one has to change the value of r_t/r_b for some tubes. The different values of this ratio would require different potentials to be applied to the drift tubes to maintain the axial potential distribution for a not-neutralized electron beam "flat". Keeping the axial potential distribution without bumps in the middle is important for distributing ions over the whole trap during the ion injection, especially for breeders with small number of ions and small final neutralization. Ion charge build-up during the confinement reduces the radial potential well and with full neutralization a uniform potential distribution on the drift tubes within the trap is needed. One consequence of having different values of r_t/r_b within the ion trap is different rate of ion losses in such drift tube structure with higher losses in the drift tubes with lower value of r_t/r_b, which have the minimum depth of the radial potential well.

The Tandem EBIS layout presented in Fig. 1 has a crude drift tube structure with two values of inner diameter and only one drift tube in a transition region between the superconducting magnets. Such structure can provide a relatively uniform potential distribution on the axis for over 5 m long ion trap with a not neutralized electron beam, it is presented in Fig. 3.

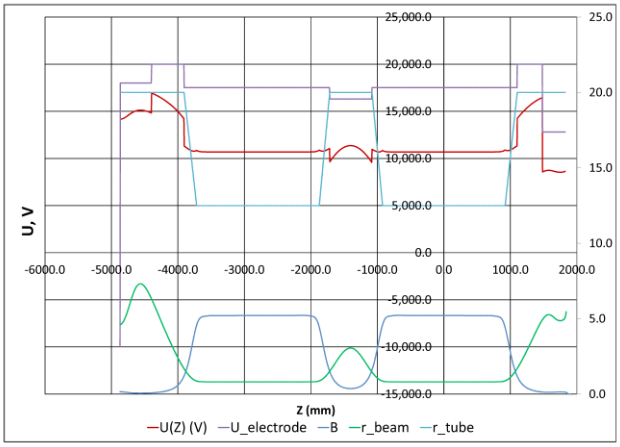

Fig. 3. Axial distributions of magnetic field, electron beam radius, drift tube radii and potential distributions on the drift tubes and on the axis with “flat” bottom in the Tandem EBIS for electron beam with current 10.0 A and energy 20 keV for a single injection trap.

The presented axial potential distribution includes the electron space charge but it does not take into account a mutual penetration of potentials in the adjacent drift tubes gaps, which makes the actual potential distribution smoother.

The long drift structure of the Tandem EBIS is flexible and allows different configurations of ion traps at different periods of the ionization cycle. There can be one or two ion traps with the required time structure of the extracted ion pulses. For the RHIC EBIS application the ion injection can be done into a single ion trap for the entire length. After the injection is completed, the potential on the transition section, which is located in a low magnetic field area, can be raised and two axial potential traps can be created. This transition should be done adiabatically for ions with respect to their axial oscillations, so the ions from an initial single trap are distributed between the two new traps with minimal losses. At the end of the ionization cycle the highly charged ions can be extracted with the time pattern optimized for the best RHIC performance.

It may be possible to extend the ion traps into areas with magnetic field much lower than in the centers of solenoids (around 5T), probably to as low as 1.5 kGs. The electron beam current density in these areas is much lower than in the center, so the main contributors to the ionization process remain the central areas of the both solenoids, and the peripheral regions can be used for increased trap capacity. Such trap extension will result in some increase of the confinement time compare to the “conventional” trap with uniform magnetic field, but it will have increased total accumulated ion charge. For a trap with length 5.2 m and electron current 10.0 A the average current density is j_{aver} =385 A/cm^2, as compare to 487 A/cm^2 for a trap with uniform magnetic field and the length of 1.5 m in a central region of each solenoids.

A gap between two solenoids is used for high voltage feedthroughs and vacuum pumping. It is preferred not to have in-line gate valves between the two central chambers inside the both solenoids to avoid detrimental axial potential well due to penetrating of a ground potential in a valve’s gap.

CONCLUSION

The Tandem EBIS concept is a relatively low-cost modification of the existing RHIC EBIS if two superconducting magnets with sufficient axial supports are available. It has potential to double the EBIS intensity using the existing units: electron gun, electron collector, extraction/injection ion optics, and ion injection system. One of problems, which require addressing in Tandem EBIS for RHIC application, is a fast ion extraction from a long trap. The longitudinal energy spread and a possible transverse emittance growth resulting from a fast ion extraction need to be minimized for effective injection into RFQ.

The increased ion trap capacity is not the only possible benefit of EBIS structure with two solenoids and a single electron beam. For the radioactive ion beam (RIB) breeder with continuous ion injection one of two traps can be used as an accumulator with low current density and a large acceptance. The accumulated ions can be transferred in a short bunch into the second trap for the final ionization. At the end of the ionization cycle the highly charged ions can be extracted over the operating accumulating trap. An efficient vacuum separation between two regions allows use of gas in one trap either for injection of the working gas or for ion cooling.

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