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EBIS for high intensity stable beams

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Abstract: Electron beam ion sources technology made significant progress since 1968 when this method of producing highly charged ions in a potential trap within electron beam was proposed by E. Donets. Better understanding of physical processes in EBIS, technological advances and better simulation tools determined significant progress in key EBIS parameters: electron beam current and current density, ion trap capacity, attainable charge states. Greatly increased the scope of EBIS and EBIT applications. An attempt is made to compile some of EBIS engineering problems and solutions and to demonstrate a present stage of understanding the processes and approaches to build a better EBIS.

1. Introduction

A source of highly charged ions based on multistep ionization of ions confined in a closed potential trap within an energetic electron beam was proposed by Evgeniy Donets in 1968 [1]. First observation of ions Au¹⁹⁺ injected by pulsed thermal evaporation from a light bulb tungsten filament inside EBIS was decisive confirmation of this method [2]. Since then EBIS technology made large advances and the EBIS application field expanded greatly. One of the largest advantages of EBIS over other plasma ion sources is separate energy and density distributions of electrons and ions and therefore absence of plasma polarization. The electrons are produced by the electron gun and can have independently controlled current and energy. The ability to control the potential distribution inside the ion trap makes possible a flexible control of the ionization cycle in EBIS from ion injection to ion extraction. By controlling the voltage ramping of the extraction barrier one can choose the extraction time and therefore can control the ion current, which makes this kind of ion source unique and very attractive for synchrotrons with a single-turn injection: EBIS can produce high currents of highly charged ions for extraction time of few microseconds. Even that the capacity of the accumulated total ion charge in EBIS is limited to the electron space within the ion trap, which is $1.4 \cdot 10^{12}$ el. charges for RHIC EBIS, the instantaneous current can reach several mA and exceeds that of its close competitor ECRIS.

The first applications of EBIS on accelerator was accelerating of light highly charged ions (C⁺⁶, N⁺⁷, O⁺⁸ and Ne⁺¹⁰) from KRION-1 on Dubna Synchrophasotron in 1977 [3]. Later on KRION-2 the electron current density was substantially increased by pulling the electron gun in a lower magnetic field [4]. The next application of EBIS on synchrotron was Dione ion source on Saturn II [5]. Unlike Russian EBISes, which used magneto-immersed electron guns, Dione had an electron gun with electrostatic focusing, which was capable of producing Brillouin electron beams with very high current density. It also operated at higher electron current (0.48 A) [6] and remained an EBIS champion until Saturn II was closed down in 1997. Unlike KRIONs with internal gas injection Dione used externally produced singly charged ions, including metals for charge breeding inside the ion trap [7]. It also was a first EBIS for producing polarized ions Li⁺³ injected into the ion trap as singly charged ions from the external ion source [8]. A first French built EBIS CRYEBIS [9], which was discarded as non-usable for Saturn II and replaced by Dione, by an odd twist of faith has been upgraded

and used routinely and reliably for highly charged ion injection on CRYISIS accelerator at Manne Siegbahn Institute in Stockholm [10].

At this time the most powerful EBIS operating on accelerator is RHIC EBIS, which supplies all required multicharged ion species with charge to mass ratio $q/M \geq 1/7$ except of Hydrogen isotopes for accelerator facility of Brookhaven National Laboratory starting September of 2010 [11] with electron current up to 10 A and ion trap length of 1.8 m.

This review presumes that the reader is familiar with principles of EBIS operation and its basic structure. Good introduction to EBIS physics one can find in reviews [12, 13, 14, 15].

To successfully operate EBIS one needs to have:

- electron beam with sufficient current and current density,
- high enough magnetic field for the beam compression and transmission with adequate length for a required trap capacity, sufficient transverse correcting coils,
- good vacuum to retain ions in a trap for sufficiently long time with low contamination from the residual gas,
- fast and flexible control system with adequate power supplies,
- in case of using external ion injection, one also needs low-aberration ion optics with fast switching from one regime to another.

The complexity of a powerful EBIS illustrates an interconnecting of physical processes with sometimes positive feedback: like electron beam loss, electrical discharge and vacuum.

2. Electron beam generation

Presently there are two methods of generating the electron beam for EBIS: using a magneto-immersed electron gun and using an electron gun with electrostatic compression and subsequent magnetic compression, which produces a Brillouin electron beam.

The first method is simpler and much less critical to matching the electrostatic and magnetic fields.

a. Magneto-immersed guns.

For magneto-immersed electron beams the magnetic flux through the beam cross-section conserves, therefore the beam radius at any point with axial coordinate z can be calculated as

$$r(z) = r_{cath} \cdot \sqrt{\frac{B_c}{B(z)}} \quad (1)$$

r_{cath} – cathode radius

B_c – magnetic field on the cathode

B_z – magnetic field at point with axial coordinate z .

The beam radius of the magneto immersed beam as we see does not depend on the beam current and energy or the degree of the electron beam neutralization by ions. The electron beam current density is determined by the cathode emission current density and by the magnetic compression. It makes sense to design an electron gun with cathode diameter providing the required current at maximum emission current density for a reasonable lifetime. The typical ion confinement times are in a millisecond range, which are considered “long” pulses for cathodes and one needs to pick a cathode material based on emission current density for DC operation. Of all known to date commercial cathode materials only the high-temperature cathodes operating in temperature range of (1600 – 1800)°C can provide long time operation with continuous emission current density of 10 -18 A/cm². The RHIC EBIS electron gun generates electron beams $I_{el}=10$ A with cathode diameter 9.2 mm ($j_{em}=15.0$ A/cm²). This electron beam in the ion trap with magnetic field $B_{trap}=5.0$ T have current density of 500 A/cm².

The most popular cathode materials are hexaborides (LaB6 and CeB6) and IrCe, which is superior, but is difficult to buy.

Designing the electron gun one needs to take into account a Larmor motion at low magnetic field. The best gun should generate a laminar electron beam with nominal parameters at minimum required magnetic field. The electron guns with adiabatic electrostatic field, developed at Budker Institute of Nuclear Physics (BINP) (16, 17) is a reliable no-thrill approach, but does not allow using it with maximum emission current density at magnetic field on the cathode lower than $B_{\text{cath}} = 0.15$ T due to unacceptably large radial beam oscillations. Using electron guns with non-adiabatic fields allows extending operating range of the gun into much lower magnetic fields [18], which should allow reaching current densities close to 1000 A/cm^2 . On the down side, the operating range of such guns is smaller than of the adiabatic guns: it has optimum combinations of electron current and magnetic field in the gun, where the beam is laminar.

b. Guns with electrostatic compression

Electron guns with electrostatic compression produce electron beams, which in magnetic field $B_{\text{trap}} = 5$ T may have current density of $j_{\text{el}} = 5 - 20 \text{ kA/cm}^2$. However, it requires careful matching of electric and magnetic field and good axial symmetry of electrodes and the main magnetic field to get a beam with low radial oscillations.

Dione EBIS on Saturn-II, which was equipped with Brillouin electron gun. It operated with electron current 486 mA and with magnetic field in the trap $B_{\text{trap}} = 5$ T the apparent electron current density varied from 1300 A/cm^2 at very low electron beam neutralization to 700 A/cm^2 for neutralization of 75% [5].

At present time, there are no EBIS or EBIT devices with Brillouin electron gun, which can generate highly charged ions with effective current density higher than 1000 A/cm^2 and operating with electron current higher than 0.5 A. The existing EBIT devices have electron current density in a range of 5000 A/cm^2 , but typically operate with even lower electron beam current; they have a short ion trap, and are hardly suitable for high-intensity ion beam production. Nevertheless, the efforts to build a high-current EBIS with Brillouin electron gun continue at BNL [19, 20] and at CERN [21].

c. Reflex EBIS

In 1996 E. Donets proposed a version of EBIS with electron beam oscillating between the cathode and reflecting electrode in a confining magnetic field [22, 23]. Such oscillating electron system appears to stabilize within a few microseconds after start and E. Donets named it “electron string”. The electrons are used for ionization and ion confinement many times and such electron string saves substantial electron beam power. The Dubna EBIS KRION-2 modified for string operation has been successfully used on Nuclotron for accelerating light bare ions and Fe24+ [24]. The ion capacity of KRION-6T is still no match for RHIC EBIS but it has a decent current density of several hundred A/cm^2 . This concept of ion source has some advantages over traditional EBIS and has a good potential for development.

d. Electron current limitation and mitigation

The maximum attainable current on EBIS and EBIT devices is usually limited by excessively high current loss on the anode of the electron gun and some other electrodes in

the transition regions. This loss seems to be caused by the electrons reflected from the magnetic mirror [25, 26, 27] and to less extent, by electrons reflected from the electron collector area. The electrons reflected from partial virtual cathode caused by slow electrons can also cause this loss. The reason of reflecting the electron from the magnetic mirror is excessive transverse energy, which makes the trajectory angle of this electron larger than the acceptance cone of the magnetic mirror. Electrons reflected from the magnetic mirror oscillate between the cathode and the mirror and can bunch and modulate the primary electron beam when their density exceeds certain threshold [28]. Such bunched electron beam makes operation of EBIS unstable. The main contributing components to the electron transverse energy are optics of the gun, non-coaxiality of the electric and magnetic fields, non-uniform cathode emission.

The gun optics makes a major contribution to the energy of electron Larmor motion. It is advisable to operate the gun with specific current in a magnetic field, where this Larmor motion makes the maximum trajectory angle of the electron beam significantly smaller than the magnetic mirror acceptance cone. The parameters affecting the gun anode load with electron loss are:

- transverse and axial position of the gun with respect to the main solenoid,
- transverse correcting magnetic fields in the EBIS transition regions and in the main solenoid,
- electron energy in the transition region between the gun and the main solenoid.

The ability to move the electron gun axially and transversely together with ability to adjust the transverse magnetic fields are of primary importance for transmitting the maximum electron beam with minimum loss. Independent control of the magnetic field on the gun allows decoupling of the electron beam size in the ion trap from the phase of axial oscillations of the reflected electrons. It would be also advantageous to control the magnetic field distribution in the transition region gun/main solenoid with an independent coil.

3. Electron beam collector

The electron collectors (EC) in EBIS serve a simple purpose: to collect the primary electrons and let the incoming and outgoing ions in and out. However, there are several aspects, which require approaching this simple task carefully.

- **Optics:** EC should not restrict the EBIS acceptance for the incoming ion beam. Usually its geometrical acceptance is much larger than the EBIS acceptance, but it would be prudent to simulate the ion injection in this region. The ion extractor electrode, which some people call also electron repeller should not restrict the path of ions extracted from EBIS even for the maximum current and lowest ion energy. Also, it should not trim the incoming ion beam. The electron beam should be distributed on the water-cooled cylindrical surface with maximum uniformity and its density in the centre should be minimal to minimize the flow of electrons reflected from the electron repeller back into EBIS. In most EBIS EC with electron repeller the pattern of electron flux inside EC has a “folding” structure with two maximum power density regions: one is at the beginning of axial power distribution and the other one is at the end of it. The first one is caused by higher total electron current on the electron beam periphery and the second one is a result of overlap when the beam “folds”. A good solution for magnetic field control in EC is magnetic shielding, which helps to expand the electron beam inside EC rapidly. This magnetic shielding also does a good job in trapping the backscattered electrons inside EC and not letting them out. Without such shielding and with residual magnetic field of few hundred Gauss the

backscattered electrons can spiral back into EBIS along the magnetic field lines. The most probable energy of electrons backscattered from copper is 80% of their initial energy.

- **Thermal:** depends on power regime of EC. It appears, that pulsed operation of EBIS can bring additional complication to the EC design and to the choice of its material, even that the average power is smaller than the peak power. The electron beam power causes temperature gradient and mechanical stress in the EC wall. For safe operation of EC the deformation caused by this stress should be within elastic margin and this consideration determines a choice of materials with appropriate combination of heat conductance and strength to avoid damage by fatigue. In powerful EC to prevent collapse of the heat exchange between the wall and cooling water, which can result in a wall melting one needs to perform analysis of the critical heat flux. Since some electron beam power dissipates on the front surface of the powerful EC as well, it also should be cooled with water. Useful toolbox for analysis of a powerful EC can be found in [29, 30].
- **Vacuum:** high power deposition by the electron beam in EC determines heavy outgassing of its surfaces, which makes EC a major gas source for EBIS. With strict requirement to the residual gas pressure in the ion trap all efforts should be made to reduce the gas flux from EC into the EBIS central volume. Apart of standard vacuum treatment of internal surfaces the design of EC should:
 - ✓ Provide a good vacuum conductance from the internal EC volume to the nearby vacuum pump,
 - ✓ Have vacuum connection of the internal EC volume with the rest of EBIS only through the EC entrance aperture and have this aperture as small as possible, just sufficient for transmission of the electron beam. Magnet coil at the EC entrance can provide the necessary magnetic field for controlling the electron beam size in this area. It would be advantageous to have the EC water-cooled cylindrical surfaces to serve as a vacuum envelope. In this case the EC has to be electrically isolated from the rest of EBIS, from the ion beam line and from the vacuum pump.
 - ✓ Effective vacuum separation between EC and the central vacuum chamber can reduce the gas flux from EC by a factor of 10 or more.

4. Drift tubes

The primary purpose of the EBIS drift tubes (DT) is axial ion control in an ionization cycle. In a classic EBIS the DT system should provide a gun-side potential barrier, a trap region and an extraction barrier: all of them with individual potential control. There are several aspects to consider when designing the drift tubes.

- **Inner diameter** (ID) of the trap DT should be large enough, so that the ratio of the drift tube radius to the electron beam radius is the largest in the electron beam path. In this case the electron beam components, which constitute the beam loss will be trimmed off on other electrodes, where this ratio is smaller. Apart of direct electron loss the ion loss during confinement should be also considered: small ID is equivalent of insufficient axial potential trapping: ions with energy higher than the potential distance from the beam axis to the wall will be lost. Study of ion loss rate on CRYEBIS with DT ID 5 mm and 10 mm [31] shows that ion loss rate during confinement with ID 10 mm is substantially smaller than for ID 5 mm.
- **Trap length.** If necessary, the ion trap may extend into area with magnetic field beyond traditionally accepted margin of magnetic field non-uniformity of few percent. Experiments demonstrated almost proportional increase in ion intensity with extending the ion trap into low-magnetic field area [32]. It would be prudent to retain

the radial potential well created by the electron beam uniform along the drift tube structure by increasing the DT ID in low-magnetic field areas.

- **Shape.** A cylindrical DT structure inside the long ion trap may require several drift tubes if a fast ion extraction is required. R. Becker suggested using for the central DT a system of two interleaving tubes which provide a linear electrostatic gradient in the centre if different potentials are applied to both tubes [33]. This approach can help reduce the number of drift tubes and to provide the necessary uniform axial extraction gradient for fast ion extraction.
- **Material.** There is no consensus on the best material for drift tubes. EBIT devices operate with copper drift tubes. KRION-1 had its first copper DT structure excited by the electron beam and this excitation disappeared after replacing the copper tubes with stainless steel ones, which also had increased capacity between each other.

5. Vacuum

Vacuum is a key parameter for EBIS: it determines the achievable ion charge state, the intensity of the extracted working ion beam and the stability of EBIS operation. A good target for the residual gas pressure in the ion trap region for “warm” EBIS would be $P=1 \cdot 10^{-11} - 1 \cdot 10^{-10}$ Tor with electron beam running (RHIC EBIS range). It can be even lower for the “cold” EBIS.

The main sources of the gas load are thermal outgassing, electron collector, electron gun and discharges. Thermal outgassing can be reduced with conventional vacuum procedures, like using low-outgassing materials, NEGs [34, 35, 36], vacuum firing and bakeout. For “warm” EBIS it is essential to have vacuum conductance from the ion trap to vacuum pumps as large as possible even if NEG materials in the ion trap region are used. In this case the vacuum pumps can still provide acceptable vacuum when the NEG materials are partially or completely saturated. The gas load from the electron gun and EC can be reduced with vacuum separation.

The electrical discharge can be a dominant source of gas inside EBIS. P. A. Redhead [37] proposed a model for calculating the condition for magnetron discharge. Usually, the most probable areas with magnetron discharge are regions with low magnetic field and high radial electric field. The most efficient method of reducing this kind of discharge is eliminating the radial electric field by using a grounded drift tube. If this is not possible, adding an axial electric field to drain the carriers away by making the concentric opposite surfaces conical rather than cylindrical may help.

6. Cold bore or warm bore?

There is no lack of consensus regarding a choice of solenoid for the powerful EBIS: it has to be superconducting to provide magnetic field in the trap region in a range of 5-6 T. A choice of internal drift structure (cold or warm) is debatable with good arguments on both sides. There are good working solutions for both approaches. The main argument against cold structure is the so-called memory effect: the gas molecules, which are condensed on the internal surfaces of the drift tubes can be desorbed by the trap components and contaminate the ion content of the trap. Such contamination normally is not desirable in EBIS, which works as an ion source for the accelerator because the contaminants substitute the working ions and effectively reduce their intensity. First EBISes used for accelerators (KRION, CRYEBIS and Dione) had cold drift structure and the main inconvenience with it was a long turnaround time determined by the warming/cooling cycle of the large mass of solenoid and

its cryostat. But the turnaround time for a “warm” EBIS is not shorter because of pumping/baking cycle, which also carries a risk of leak and damage. With “cold” drift structure one can provide vacuum separation between different EBIS regions using cold drift tubes. Availability of cryogenic temperatures allows a pulsed ion injection with continuous gas injection for a broad range of gases. This kind of ion injection is routinely used on all KRION ion sources in Dubna. A good compromise between the “warm” and “cold” bores can be a “warm” bore with drift structure cooled with independent cold head. Such structure is independent on vacuum in the cryostat of the solenoid and its turnaround time can be shorter than for a classic “cold” bore EBIS, or for classic “warm” EBIS.

7. Prospects of EBIS intensity increase

So far the main progress with EBIS intensity increase has been made primarily by increasing the electron beam current. Presently in RHIC EBIS the electron current is 8-10 A at the beam energy of 22 keV. One way to increase the capacity of the ion trap and therefore the ion beam intensity is to increase the electron beam current using electron gun with larger cathode. One more approach in boosting the ion trap capacity is increasing the length of the ion trap. The first step in increasing the RHIC EBIS ion trap length by 25% has been done by extending the ion trap into area with lower magnetic field (80% of the maximum). The next step will be done by chaining two superconducting solenoids together [38, 39].

8. Conclusion

Building EBIS is not a simple task, especially building a powerful one. The accumulated experience with Test EBIS, with RHIC EBIS and with KRION generations found solutions for many aspects of the powerful EBIS design and operation, which seemed unsolvable in the past. At the present stage, EBIS has a good potential for further increase of the intensity of highly charged ions.

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