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First Test of BNL Electron Beam Ion Source with High Current Density Electron Beam

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Abstract.

A new electron gun with electrostatic compression has been installed at the Electron Beam Ion Source (EBIS) Test Stand at BNL. This is a collaborative effort by BNL and CERN teams with a common goal to study an EBIS with electron beam current up to 10 A, current density up to 10,000 A/cm^2 and energy more than 50 keV. Intensive and pure beams of heavy highly charged ions with mass-to-charge ratio < 4.5 are requested by many heavy ion research facilities including NASA Space Radiation Laboratory (NSRL) at BNL and HIE-ISOLDE at CERN. With a multiampere electron gun, the EBIS should be capable of delivering highly charged ions for both RHIC facility applications at BNL and for ISOLDE experiments at CERN. Details of the electron gun simulations and design, and the Test EBIS electrostatic and magnetostatic structures with the new electron gun are presented. The experimental results of the electron beam transmission and of the first experiments with extracted ions are given.

INTRODUCTION

The successful operation of the electron beam ion source (EBIS) on the Relativistic Heavy Ion Collider (RHIC) facility of the Brookhaven National Laboratory (BNL) [1,2,3] demonstrated high performance and reliability of EBIS technology for accelerator application where EBIS is a primary source of highly charged ions. A sufficiently large acceptance of EBIS for externally injected ions [4], high ionization efficiency and ability to generate highly charged ions with low and controllable contamination makes it an attractive choice for charge breeders in facilities exploiting re-acceleration of radioactive ions. Using EBIS for charge breeding of radioactive ions requires high electron current density because of the sometime short life-time of these isotopes. The acceptance and therefore the efficiency of ion injection into EBIS charge breeder, is determined by the electron linear charge density, which is proportional to the electron current. Development of such EBIS with both high electron current and high current density can bring benefits to charge breeders of radioactive ions at ISOL facilities, such as for the planned upgrade of ISOLDE at CERN [5,6]. Other accelerator application where EBIS is a primary source of multi-charged ions, like RHIC EBIS, would also benefit because it would be capable of delivering ions with higher charge state within the available confinement time, which can be accelerated to higher energy.

One way to generate high-current density electron beam is to utilize an electron gun with electrostatic compression of the electrons and with near-zero magnetic field on the cathode. Previous simulations [7] resulted in a design and construction of the electron gun, which has been installed on the BNL Test EBIS.

ELECTRON GUN DESIGN

The general overview of Test EBIS with the new electron gun is shown in Fig. 1:

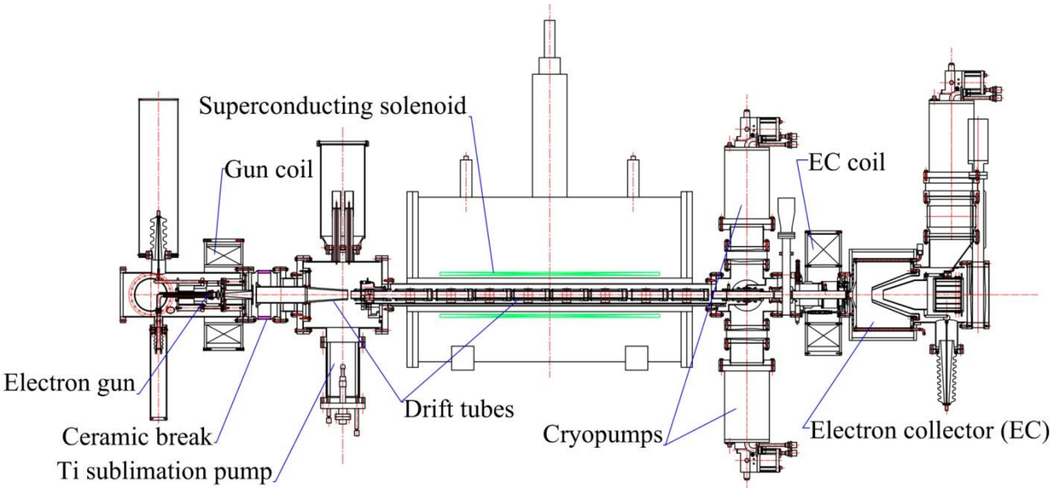

Fig. 1. Test EBIS assembly with new electron gun.

As one can see from Fig. 1, the vacuum chamber with the new electron gun is mounted on the Test EBIS with a ceramic break. The entire gun chamber is electrically isolated from the grounded parts of the Te4st EBIS. The purpose of this arrangement was to test a method of suppressing the magnetron discharge inside a gun chamber by eliminating the radial electrostatic field between the gun electrodes and the vacuum chamber walls.

The magnetic structure of this assembly includes three solenoidal coils with individual controls: the gun coil, the superconducting solenoid and the electron collector (EC) coil. The axial magnetic field distribution between the gun and collector has two minima between coils, where the electron beam expands [8]. The existing Test EBIS magnetic structure also includes transverse correcting dipole coils between the mentioned solenoidal coils and over the central vacuum chamber inside the superconducting solenoid. These coils are used for steering the electron beam in the existing magnetic environment affecting the position of the Test EBIS magnetic field axis.

The design of the electron gun is presented in Fig. 2. The diameter of the HeatWave dispenser cathode is 20 mm and the radius of the spherical emitting surface is 16 mm. The maximum electron beam current for this gun is 10 A because the maximum emission current density from the cathode surface should stay below 5 A/cm^2.

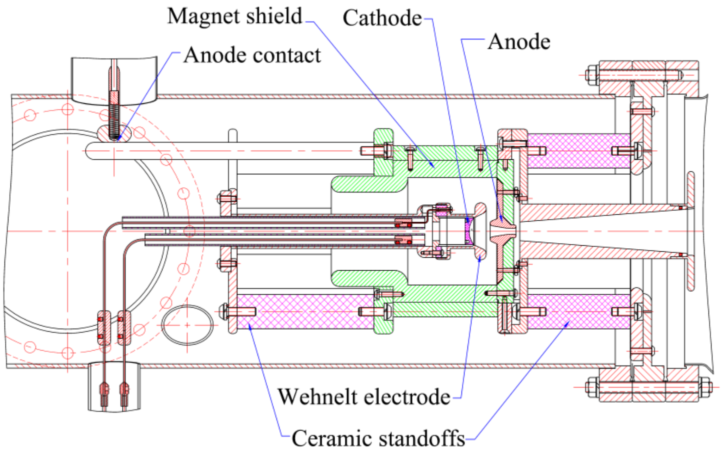

Fig.2. Electron gun structure inside vacuum chamber.

The magnetic field in the cathode-anode gap is defined only with a magnetic shield, which screens the external magnetic field within its volume. This external magnetic field is generated by the combination of the gun coil located outside the vacuum chamber and the superconducting solenoid, with dominating contribution of the gun coil. No additional correcting coils for magnetic field forming have been used used primarily because of complexity of such arrangement. The simulated magnetic field distribution is shown in Fig. 3.

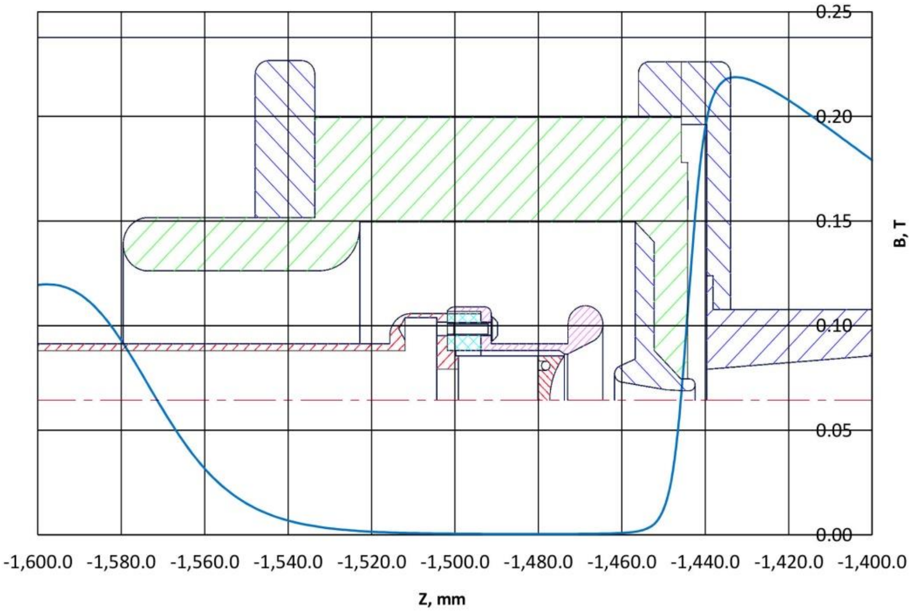

Fig. 3. Axial magnetic field distribution within electron gun simulated with PERMAG.

This magnetic field distribution is optimized for a 10 A electron beam current. At the design stage, the choice of the injection magnetic field value and therefore the electrostatic optics of the gun have been selected based on an operational value of the existing gun coil current. The magnetic shield does not cancel the magnetic field on the cathode entirely and a residual field of 2-4 Gs is present on the cathode surface depending on the external magnetic field. The plot of simulated trajectories of 10 A electron beam for optimized geometry and magnetic field is given in Fig. 4.

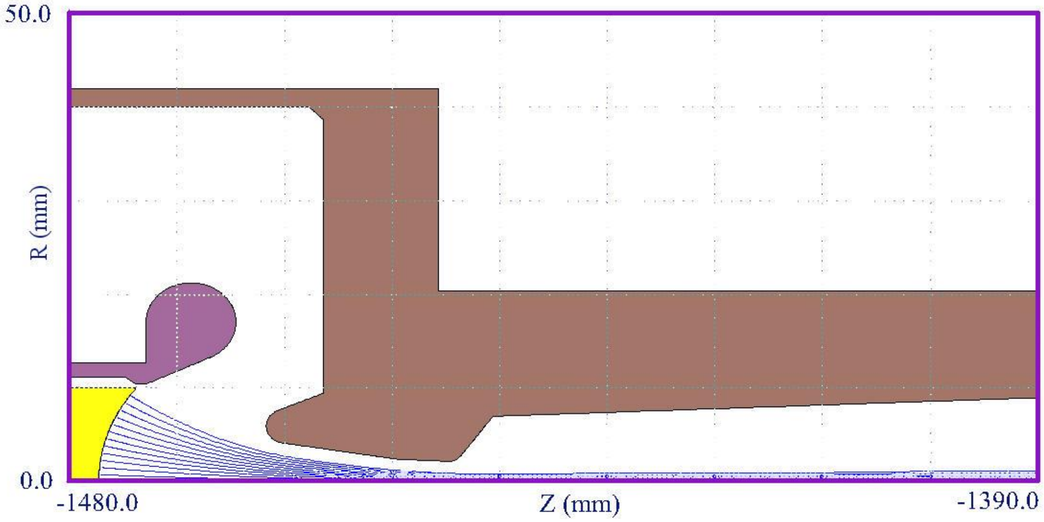

Fig. 4. Simulated 10 A electron beam transmission in a gun region with optimized parameters.

The minimum relative amplitude of the radial oscillations for the optimized geometry and magnetic field is 3% for an electron beam current of 10 A. For smaller currents and optimized magnetic field it stays at approximately at the same level. The simulations demonstrate that the amplitude of radial oscillations for each electron beam current is a function of the injected magnetic field (magnetic field right outside of the vertical wall of the magnetic shield), i.e. each electron beam current has an optimum magnetic field, which provides minimum amplitude of radial oscillations.

EXPERIMENT

The magnetic structure of the Test EBIS, its vacuum system, control and diagnostics used in these experiments were the same as with Test EBIS operation using our immersed high-current electron gun. The general schematic of the power supplies and the electron current measurements is presented in Fig. 5.

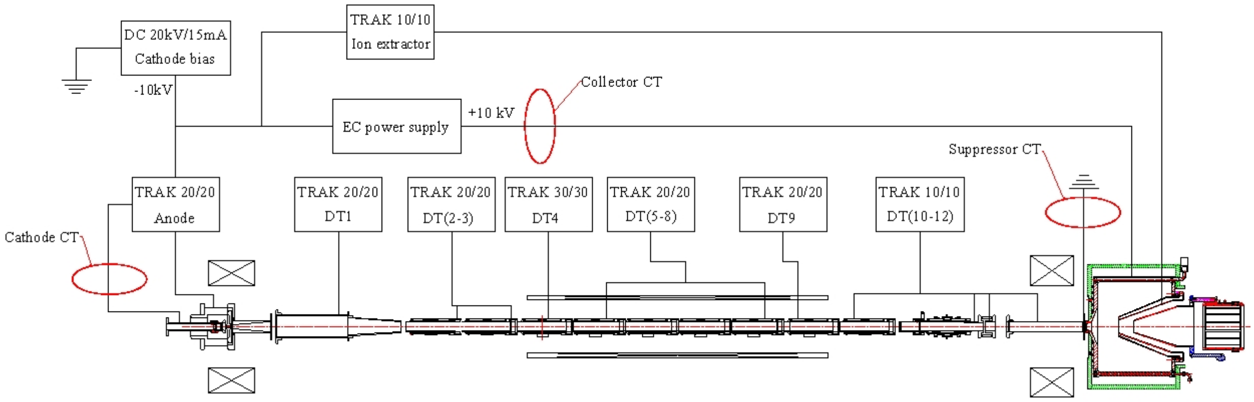

Fig. 5. General schematic of the Test EBIS electrical connections. CT - current transformers.

The electron gun power supplies (PS) including the cathode heater PS and the anode PS, also the ion extractor PS and the electron collector (EC) PS are mounted on a cathode platform, which can be energized with a cathode bias PS. Since Test EBIS operates in a pulsed mode, for the voltage control of the drift tubes the fast TREK amplifiers with output voltages of 10 and 20 kV are used.

During experiments the pressure inside the gun chamber was $2\cdot10^{-8}$ Torr and in the gun-transition chamber connected with central chamber it was $1\cdot10^{-8}$ Torr with cathode hot and electron beam running. Such vacuum conditions were considered acceptable for experiments with the electron beam. The typical electron pulse length was 10 -16 ms and the frequency 1 Hz.

The cathode is biased to -10 kV and the drift tubes in the central chamber were at their highest potential of 20 kV. However, the drift tubes in a transition between the gun and the central solenoid were held at the potential close to zero or even slightly negative.

The maximum electron beam current transmitted to the electron collector was 1.7 A. The waveform of the electron beam pulse on the electron collector is presented in Fig. 6.

Waveforms, setup, and screen image saved to A:\ALL0020

Fig. 6. Waveform of the electron beam pulse (Scale: 1V=1A).

The perveance of the electron gun measured with sufficient cathode heating power was P_{gun} $=0.93\cdot10^{-6}$ A/V$^{1.5}$, which is within accuracy of our measurements the same as the simulated value.

The limiting factor in transmitting higher electron current was load on the gun anode. The TRAK amplifier used for the anode modulation had maximum output current of 20 mA.

The strongest effect on the electron beam transmission had the magnetic field generated by the gun coil. The simulated dependence of the radial electron beam oscillations on the gun magnetic field can hardly explain the observed effect of the anode current loss on the gun coil. Nevertheless, the range of optimum values of the injected magnetic field was close to simulated values. The potentials on the drift tubes in the gun-transition region proved to be also critical. We noticed some effect of the electron collector (EC) coil on the anode current.

We tried to detect RF oscillations in a range of 10-100 MHz in a gun-transition region, but so far did not detect any signal.

SUPPRESSION OF THE MAGNETRON DISCHARGE

The magnetron discharge can be a serious factor affecting vacuum conditions in the electron gun chamber and other areas, where appropriate crossing electrical and magnetic fields (ExB) exist. A photo of such discharge in our RHIC EBIS electron gun is shown in Fig. 7.

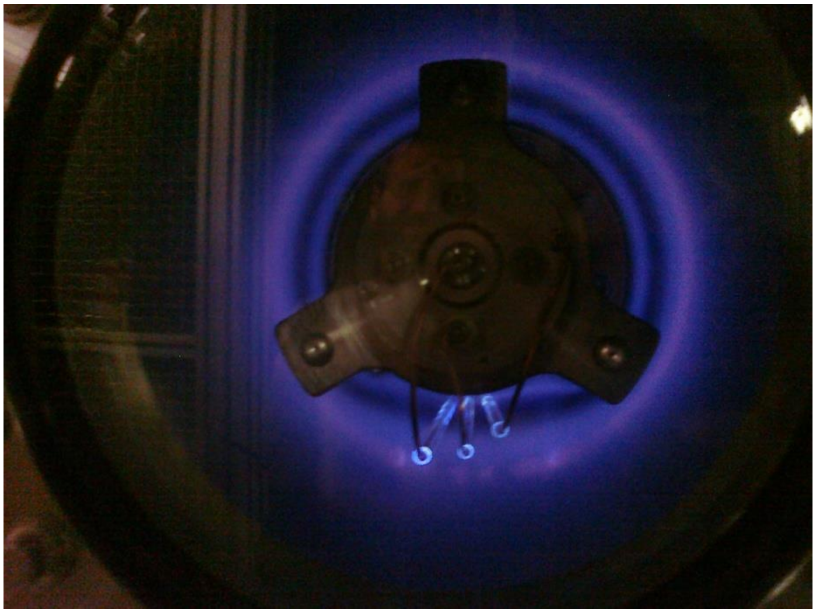

Fig. 7. Magnetron discharge in RHIC EBIS electron gun chamber.

Once started, the discharge stays as long as the potentials on the gun electrodes and the magnetic field exist simultaneously. Over training time the intensity of this discharge reduces and the vacuum improves, but the discharge can restart again very intensively if a pressure spike occurs. Since EBIS is very sensitive to the pressure of the background gas, we decided to eliminate magnetron discharge by reducing or eliminating the radial electric field.

In our experiments the gun vacuum chamber was electrically isolated from the rest of EBIS, the gun chamber turbo vacuum pump and its vacuum gauge with ceramic breaks. The gun chamber can be connected either to the cathode of the gun, to the anode or to the high voltage power supply for independent voltage control, it also can be grounded. When the gun chamber was connected to the Spellman power supply, we found, that with nominal magnetic field of 2 kGs, it was sufficient to have only 2 kV difference between the gun and the chamber to start the discharge and to increase the pressure in the gun chamber by a factor of 2-3. The discharge intensifies with increased potential difference between the gun and wall. In the course of our experiments with electron beam transmission the gun chamber was normally connected to the cathode.

Since both the cathode and anode of the gun are isolated, we also tested a regime when the gun chamber was connected to the anode. The concern was an increased stray capacitance of the anode circuit, which could decrease the anode pulse rise time. The test showed that the effect of this configuration on the anode rise time was minimal and the rise time was on the order of 100 µs.

The tested method of suppression the magnetron discharge is effective and simple. It can also significantly simplify the gun design if either the anode or the cathode of the gun is connected to the vacuum chamber. The downside of this approach is a need to provide electrical isolation of the gun chamber from the gun coil in atmosphere. In our case it was not a problem

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SUMMARY AND ANALYSIS

1. An electron gun with electrostatic focusing has been tested on BNL Test EBIS. An electron beam with maximum 1.7 A current has been transmitted to the electron collector. Loss of electron beam has been detected only on the anode of the gun. The anode power supply current of 20 mA limited further increase of the transmitted electron beam current.

A possible reflection of some of the electron beam from the magnetic mirror created by the main solenoid can be a reason of the observed anode load. The electron beam quality can be affected by not optimum position of the cathode with respect to the magnetic shield to the anode as a result of thermal expansion of the gun parts. An additional contribution to the beam degradation can be electron emission from cathode edge [9] and the side of the dispenser cathode. The simulated emission from this area is shown in Fig. 8.

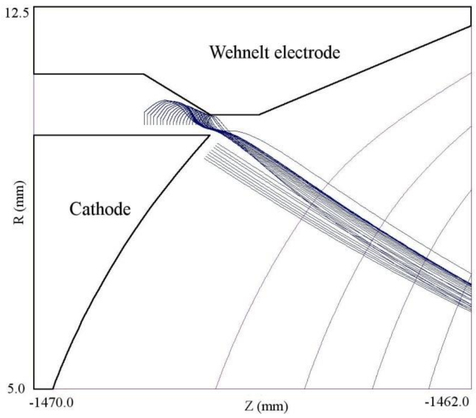

Fig. 8. Simulated electron emission from the edge and the side of the cathode.

Since the Wehnelt electrode was internally connected to the cathode in our experiments, we could not suppress the peripheral emission.

Based on this analysis, we are planning to disconnect the Wehnelt electrode from the cathode and have it energized independently, to suppress electron emission from the cathode side and to make the axial position of the cathode adjustable during testing using linear or rotating feedthrough.

2. Testing of suppressing the magnetron discharge inside the gun chamber by eliminating the radial electric field was quite successful. We are planning to apply this method to RHIC EBIS electron gun.

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