Analysis of a Possible 20A Electron Gun and Collector Design for the RHIC EBIS[†]

Alexander Pikin, James G. Alessi, Edward N. Beebe, Ahovi Kponou, Krsto Prelec, John Ritter, Louis Snydstrup

Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract. Successful operation of the BNL EBIS with electron current up to 10 A provides optimism that EBIS operation with even higher electron current should be possible. We are now considering key aspects of the design for an EBIS operating with electron current 20 A. Several technical problems need to be resolved, including generation of a 20 A electron beam and dissipation of this electron beam power on the electron collector. Since we already have a tested concept of electron beam generation with the gun immersed in a magnetic field and subsequent purely magnetic compression of the electron beam, it makes sense to develop the new electron gun with immersed cathode but with higher perveance. To distribute the electron beam power on the surface of the electron collector more evenly, the emission current density from the cathode can be made bell-shaped with minimum close to zero on the periphery of the electron beam. With the already high requirements to the emission current density, and since such shaping of the electron beam makes these requirements even higher, perhaps the only available cathode material that can satisfy these requirements is IrCe. The problems of power dissipation on the electron collector (EC) include heat removal with cooling water and fatigue of the EC material. The first step in the EC design was electron beam transmission simulation with the goal to reduce "spikes" of power density on EC surface as much as possible. With the geometry of EC thus defined, the conditions of heat exchange for several modes of EBIS operation have been analyzed and cooling parameters, which provide adequate heat removal were found. The last step was stress analysis of several EC materials with ANSYS to find the material suitable for this application. Details of the 20 A electron gun and collector are presented.

INTRODUCTION

To reach the design parameters of RHIC EBIS [1] it is required to increase the ion trap length relative to the Test EBIS, since effective ion confinement and ionization on Test EBIS has been demonstrated in operation with electron current up to 10A [2-4]. This goal can be achieved with longer solenoid and central vacuum chamber. Nevertheless it would be desirable to have a safety margin with electron beam current for reliable EBIS operation at 10 A and some prospects for increase of output ion intensity in the future. At this time we are considering increase of electron current in RHIC EBIS to 20 A. This current increase will have several implications on EBIS performance including higher outgassing from electron collector, stronger beam – wall interaction, etc. Only electron beam generation and dissipation are covered in this study.

[†] Work performed under the auspices of the U.S. Department of Energy.

ELECTRON GUN

The existing electron gun of Novosibirsk design [5-6] produces a laminar electron beam, which allows operation in a wide range of electron current, potential and magnet field distribution. It also allows substantial deceleration of the electron beam in the ion trap and electron collector regions. This is a gun with cathode immersed in a magnetic field of approximately 0.14 T and has an inverted magnetron geometry. The cathode has a convex spherical shape. The perveance of this gun is $1.2\cdot10^{-6}$ A/V$^{3/2}$ and maximum anode voltage is limited to approximately 55 kV by feedthroughs.

The diameter of the convex cathode is 9.2 mm and the radius of the sphere is 10 mm. Material of this cathode is IrCe, which can provide emission current density 40 A/cm^2 with expected lifetime of several thousand hours [7]. To reach electron current of I_{el}=20 A with existing 40 kV anode power supplies the perveance of the gun should be doubled. Partial shielding of the cathode periphery with a Wehnelt electrode compensated the effect of increased electron emission on the periphery of the cathode from the decreased cathode-anode distance. The design of this gun is presented in Figure 1.

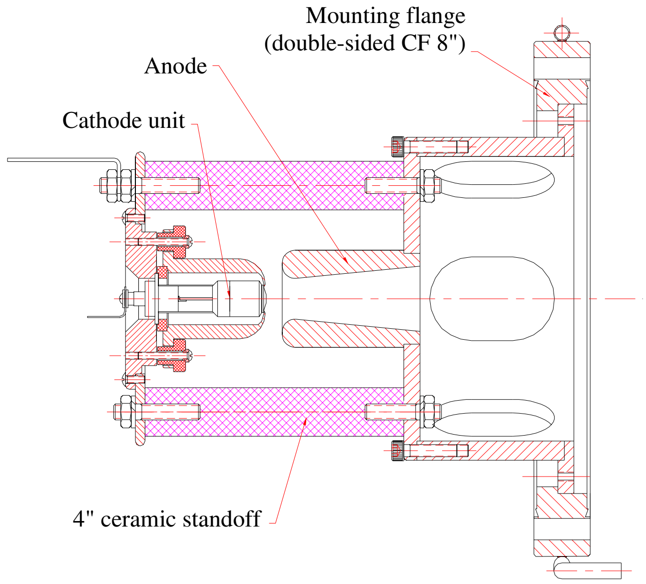

FIGURE 1. RHIC EBIS electron gun design.

This gun will be mounted on a unit separated from the rest of RHIC EBIS with two gate valves. This configuration allows replacing of the whole electron gun unit mounted on a platform with another one without venting the gun, but only the small buffer chamber between two valves. The replacement of the electron gun can then be done in a matter of several hours. Schematic of this replaceable electron gun unit is presented in Figure 2.

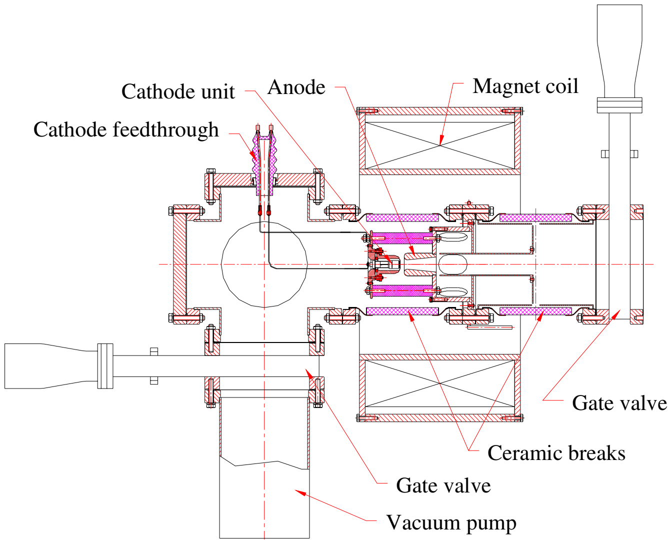

FIGURE 2. Schematic of the replaceable electron gun unit.

The cathode shielding effect by the Wehnelt electrode at zero voltage with respect to the cathode is sufficient to suppress electron emission on the cathode periphery to virtually zero. The benefit of such bell-shaped current density distribution is expected to be a more homogeneous power density distribution on the electron collector with reduced peak from the peripheral part of the electron beam. The price of such bell shaping is increased requirement to the emission density of the cathode and somewhat increased aberrations on the periphery of the electron beam. Current emission from the periphery of the cathode can be controlled by applying different voltages on the isolated Wehnelt electrode similar to the Fermilab electron gun [8]. Figure 3 presents radial distributions of the emission current density from the cathode.

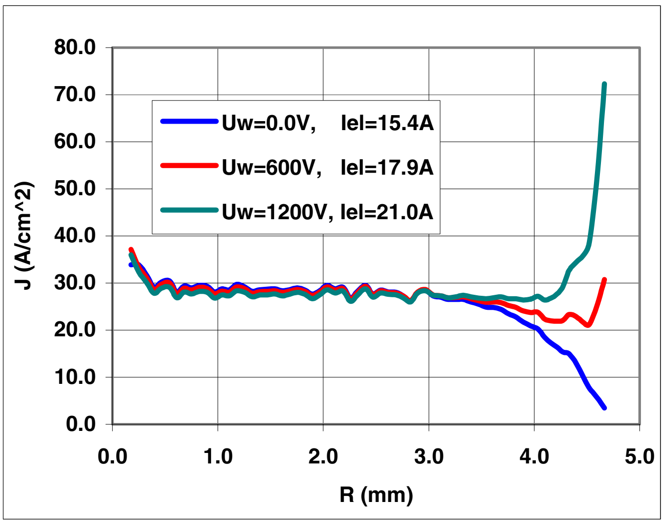

FIGURE 3. Radial distributions of the emission current densities from the cathode of electron gun at anode voltage U_{an}=32700 V and different voltages on Wehnelt electrode with respect to cathode.

ELECTRON COLLECTOR

The electron collector (EC) is designed to dissipate power of electron beam with current up to 20 A and energy of electrons on EC surface up to 15 keV. This energy of electron beam is found by assuming that the operating perveance of RHIC EBIS will be the same as it is on the existing Test EBIS. Maximum duty factor in our calculations is assumed to be 50% with electron beam 50 ms ON and 50 ms OFF. To produce ions Au^{34+} with electron beam 20 A the confinement time should not exceed 25 ms, therefore the electron beam pulse length used in EC calculations is more than two times longer than it is necessary for Au^{34+} ions production and is used to guarantee reliable EC operation and the possible future RHIC EBIS upgrade.

The design of RHIC EBIS EC is based on the geometry proposed by the Novosibirsk team [5,9] and was later optimized to reduce peaks in power density distribution. Considering that the peripheral part of the electron beam is responsible for the highest power density on EC surface, the emission from the peripheral part of the electron gun cathode is suppressed by the extended Wehnelt electrode. The design of RHIC EBIS EC is presented in Figure 4.

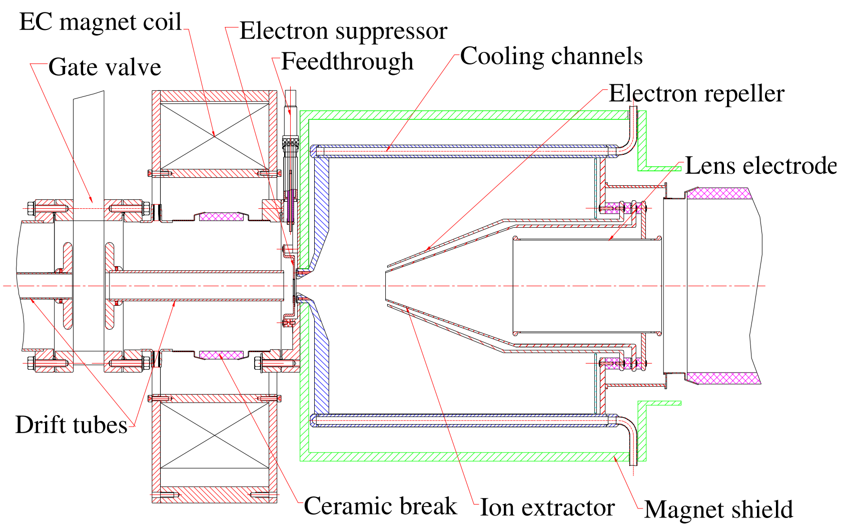

FIGURE 4. Schematic of RHIC EBIS electron collector.

Electron beam transmission in the electron gun and electron collector regions has been simulated using program TriComp of Stanley Humphries, Jr. [10]. The results of simulation for I_{el}=21.1 A and two values of the electron energy on EC surface (E_{el}=15 keV and Eel=10 keV) are presented in Figure 5. Calculated distributions of power density on EC surface for these two cases are presented in Figure 6. At 10 keV the power density is lower in part because the beam is dissipated over larger area than at 15 keV. It is worth mentioning that at 10 keV the lowest potential on the beam axis is 3.9 kV, which is more than sufficient for electron beam propagation. It is obvious that reducing the electron beam energy on EC would be very beneficial for both the cost and operating conditions of EBIS, and electron beam quality can be one of the solutions.

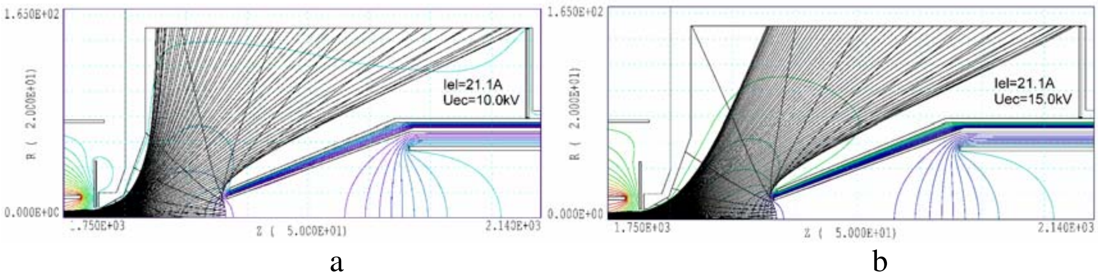

FIGURE 5. Simulation of the 21.1 A electron beam transmission inside the electron collector for potential difference between cathode and collector 15.0 kV (a) and 10 kV (b).

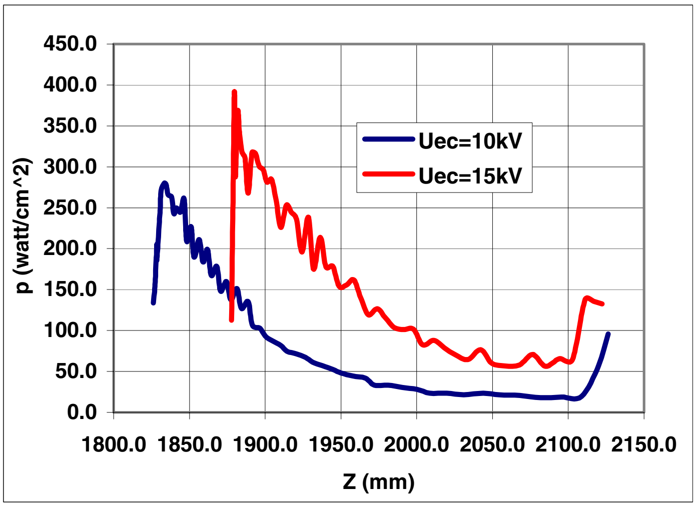

FIGURE 6. Axial distributions of the electron beam power density on the electron collector surface for electron beam current 21.1 A and potential difference between cathode and collector 15.0 kV (red) and 10 kV (blue).

The electron optics, cooling structure and material of the electron collector were optimized to reduce both the average temperature of EC surface and amplitude of its variations during the operation cycle.

There are 60 cooling channels with diameter 9 mm in the cylindrical part of EC, which has inner diameter 300 mm and is 15 mm thick. Each 6 channels are connected in series and these 10 groups are connected in parallel for water flow. The flow rate of cooling water through each channel is planned to be 0.25 l/s with 20 bar pressure. The critical heat flux to the cooling water for these conditions was calculated using Bowring correlation [11] and is found to be 790 watt/cm$^{2.}$ This value is twice higher than we expect at the peak of power density distribution.

The ANSYS simulations of temperature and stress distributions have been done for the electron energy 15 keV and current 20 A with mentioned above 50% duty cycle. Figure 7 presents temperature distribution in EC at the end of ON cycle when the temperature is highest. The material is Beryllium Copper, Alloy 3 of Brush Wellman Inc. Temperature variation at the hottest node of EC surface during the operation cycles is presented on Figure 8. In this case the average temperature has reached its equilibrium.

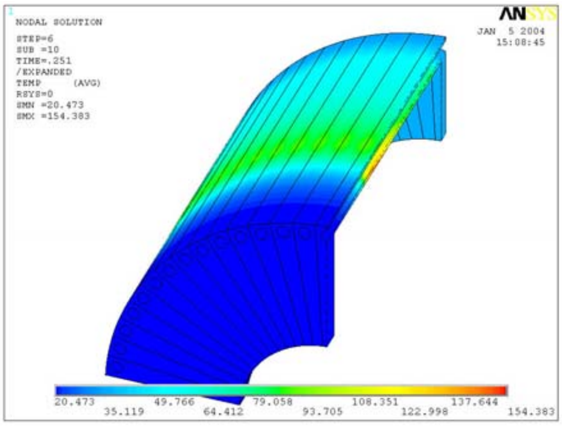

FIGURE 7. Simulated temperature distribution in the body of electron collector at the end of ON cycle. The regime is 50 ms ON and 50 ms OFF. I_{el}=20 A, U_{EC}=15 kV.

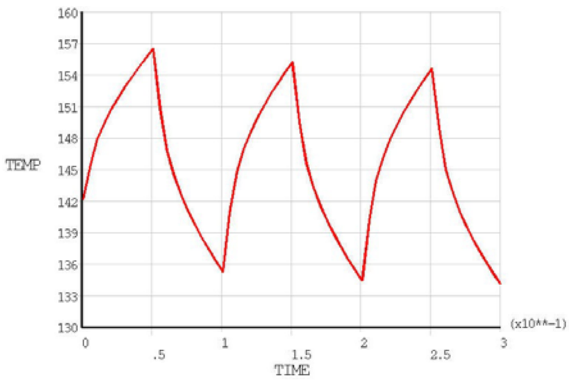

FIGURE 8. Temperature variations at the hottest node of electron collector during three operation cycles with electron beam parameters I_{el}=20 A, U_{EC}=15 kV. Time units: seconds, temperature: ^{0}C.

Figure 9 presents dynamics of the average hottest node temperature. One can see that it takes approximately 10 minutes to reach the equilibrium if start with initial room temperature.

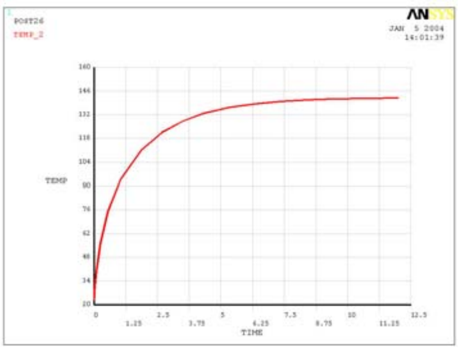

FIGURE 9. Dynamics of the average temperature at the hottest node from the start with room temperature. Electron beam parameters I_{el}=20 A, U_{EC}=15 kV, 50 mc ON, 50 ms OFF.

This thermal analysis was used to determine the expected number of electron beam load cycles before EC failure. Using the Modified Goodman Diagram [12] it was determined that for the described electron beam the stresses developing during operating cycles provide operation of the EC before the fatigue failure for at least 10^8 cycles. Similar result was obtained with the same 20A, 15 keV electron beam and operation cycle 300 ms ON and 700 ms OFF.

CONCLUSION

Experimental results obtained on BNL Test EBIS with electron current up to 10 A, accumulated know-how and computer simulations provide a reason for optimism that the goal of doubling the electron current to 20 A and increasing the operation frequency from 1 Hz to 5 Hz can be reached.

REFERENCES

1. K. Prelec, J. Alessi, and A. Hershcovitch, Proceedings of the 1994 European Particle Accelerator Conference, World Scientific Publishing, London, 1994, pp.1435-1437.
2. J. G. Alessi, E. Beebe, D. Graham, A. Kponou, A. Pikin, K. Prelec, J. Ritter, V. Zajic, Proceedings of PAC-2003, Portland, OR , IEEE, Piscataway, NJ, 2003, pp. 89-91.
3. E.N. Beebe, J.G. Alessi, O. Gould, D. Graham, A. Kponou, A. Pikin, K. Prelec, and J. Ritter, *Rev. Sci. Instr.,* 65, No. 2, 2002, pp. 699-701.
4. A. Pikin, J.G. Alessi, E. Beebe, O. Gould, D. Graham, A. Kponou, K. Prelec, J. Ritter, and V. Zajic, Proceedings of 8-th European Particle Accelerator Conference (EPAC-2002), published by EPS-IGA, Geneva, 2003, pp. 1732-1734.
5. A. Kponou, E. Beebe, A. Pikin, G. Kuznetsov, M. Batazova, M. Tiunov, *Rev. Sci. Instr.,* 69, 1998, pp. 1120-1122.
6. Gennadiy I. Kuznetsov, Marina A. Batazova and Michael A. Tiunov, Proceedings of Electron Beam Ion Sources and Traps and Their Applications: 8th International Symposium, in AIP Conf. Proceedings **572**, 2001, pp. 43-47.
7. G. Kuznetsov, *Nuclear Instruments & Methods in Physics Research* A **340**, 1994, pp.204-208.
8. X. Zhang et al., Proceedings of 2003 Particle Accelerator Conference, pp. 1781-1783.
9. Gennadiy I. Kuznetsov, Marina A. Batazova and Michael A. Tiunov, Proceedings of Electron Beam Ion Sources and Traps and Their Applications: 8th International Symposium, in AIP Conf. Proceedings **572**, 2001, pp. 143-154.
10. http://www.fieldp.com/
11. J.Collier, J. Thome, Convective boiling and condensation, Third edition, Oxford Engineering Science Series, No 38, Clarendon Pr., 1997, pp. 353.
12. Jacobson, and Schmidt, Fundamentals of Machine Elements, Hamrock, McGraw-Hill, 1999, p.282.