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Electron gun producing beams with controllable current density

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Abstract. The existing Brillouin-type electron gun at the TwinEBIS test bench is, according to Herrmann theory, capable of producing an electron beam with a current density of 3850 A/cm^2 in the 2 T solenoid. To control the electron beam current density and the magnetic flux inside the beam, the existing electron gun - now using purely electrostatic focusing - can be modified by permitting magnetic flux to reach the cathode. In such a configuration, the stabilizing magnetic flux inside the electron beam can be controlled by changing the current in the magnet coil surrounding the cathode. The radial oscillations of the electron beam, resulting from the increased magnetic field on the cathode, can be significantly reduced by employing a non-adiabatic magnetic field near the electron gun. This method has been recently developed and successfully used at REXEBIS at CERN. We present the computer simulations of such electro-optical system.

1. Introduction

The TwinEBIS device has an electron gun with magnetically shielded cathode and makes use of electrostatic compression in the cathode-anode gap [1]. With a very low magnetic field on the cathode (1.3 Gs), this gun produces practically a Brillouin beam with high compression, and the electron beam current density calculated with the Herrmann formula [2,3] reaches 3850 A/cm^2 in a magnetic field of 2 T for an electron current of 1.0 A. According to refs. [4,5], the stability of the electron-ion system in the ion trap of electron beam ion source (EBIS) depends on the density of electrons and ions, and on the length of the ion trap. Since the capacity of the EBIS is proportional to the length of its ion trap, stabilizing the electron-ion system in the trap by shrinking the ion trap length is not an option. The remaining free parameter to achieve a stable condition is the electron beam current density. For the very low enclosed magnetic flux within the Brillouin electron beam, the radius of the beam depends on the neutralization of the electron beam space charge and with high neutralization in the trap the electron beam current density increases by a factor $A=1/(1-f)$ [6], where f is a beam neutralization. Such a dynamic increase of the electron beam current density is not desirable in EBIS devices because it may trigger instabilities with subsequent loss of electron-ion overlap and significant degradation of the effective current density. A straightforward solution for reducing the electron beam current density and for preventing it from collapsing when it is neutralized is to permit some magnetic flux to reach the cathode. Such an electron gun, switchable between a Brillouin and magnetically immersed flow, by varying the magnetic field on the cathode with a magnetic coil has been proposed by R. Becker [7].

The goal of this study is not to calculate or simulate the stable ion trap conditions, but to find an optical solution for the electron beam formation in a range of magnetic field on the cathode. This solution should allow one to experimentally tune the magnetic field on the cathode with acceptable electron beam ripples, and provide an electron beam current density in a range of 300 to 1000 A/cm^2 in an ion trap with a 2 T magnetic field. Using this option, it would be possible to experimentally find the optimum EBIS conditions where the ion trap is stable and the electron beam has the maximum current density. Such desired flexibility presents a challenge for the design of the electro-optical system because deviating from the optimum Pierce gun parameters comes at a price of increased radial oscillations of the electron beam. Since these oscillations limit the maximum transmittable electron beam current, they should be minimized across the entire operating range of EBIS.

For suppressing the electron beam radial ripples we are planning to use the previously developed method employing a non-adiabatic magnetic field [8]. This method can be applied to a coherent beam by creating a local dip in the magnetic field on the descending phase of the electron cyclotron motion. Such dip can be produced either with a magnet coil or with an iron ring. The latter method is much simpler, but suffers from a limited range of the electron beam parameters.

2. Electron gun design.

The proposed electron gun for TwinEBIS has an electrostatic geometry similar to the previous version described in ref. [1]. Its spherical cathode has 12 mm diameter with a 10 mm radius of curvature. The perveance of the original gun is P=0.98x10 $^{-6}$ A/V$^{1.5}$ and it has not changed in the new design. The already existing magnetic coil around the cathode is planned to be used for controlling the exact magnetic field on the cathode surface. This coil has 16 turns and is made of Kapton-isolated copper wire. To accommodate a larger electron beam emitted by the cathode at the elevated magnetic fields, the diameter of the anode aperture will be increased from 2.4 mm to 5.4 mm. The main difference of the new gun design compared to the previous is a larger aperture in the magnetic shield around the gun: its optimized diameter was increased from 4.4 mm to 20.0 mm to allow magnetic flux to reach the cathode. The design of the proposed TwinEBIS electro-optical system is shown in Figure 1. This electro-optical system includes the electron gun and the iron ring positioned at optimum distance from the gun. The iron ring is positioned on the descending phase of the second cycle of the cyclotron oscillation.

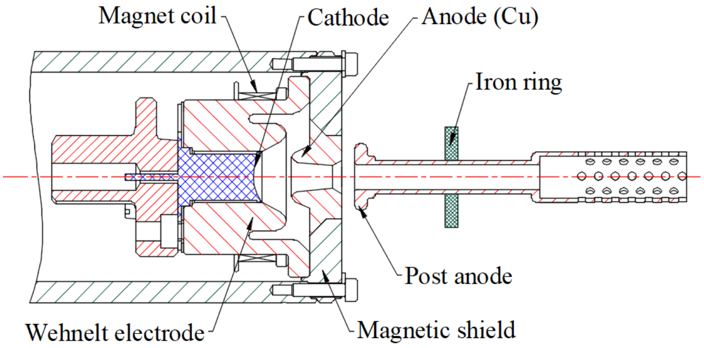

Figure 1. Design of the proposed TwinEBIS electron beam forming system.

3. Simulations

The simulations of the beam transmission with the proposed electro-optical system have been done with the software package TRAK [9] using the Child-Langmuir model for the cathode emission. Figure 2 shows the electron beam current density and the beam parameter K as functions of magnetic flux density on the cathode as computed with the Herrmann formula [2,3]. The parameter K is the ratio of the current density compression factor to the ratio of the magnetic fields on the cathode and inside the ion trap, i,e, K=(j_{trap}/j_{cath})/(B_{trap}/B_{cath}). In effect, the parameter K can be treated as a degree of magnetization of the electron beam and for a magnetic field higher than 30 Gs on the cathode, the magnetic flux within the electron beam in the ion trap is approximately constant and approaches the magnetic flux on the cathode. One can see that for the current density range 1000 to 300 A/cm^2, the required magnetic field on the cathode is between 17 and 58 Gs. The control over the magnetic field will be attained by tuning the cathode coil, which superimposes its field onto the residual flux from the main focusing field that penetrates through the widened aperture in the magnetic shield.

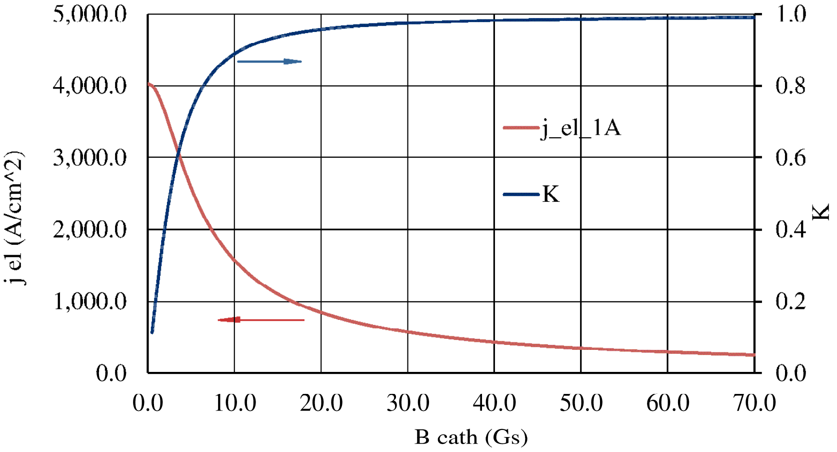

Figure 2. Electron beam current density in the ion trap region predicted with the Herrmann formula and evolvement of the parameter K (explanation in text) as function of the cathode magnetic field.

This magnetic field combination allows us to minimize the electron beam radial ripples at the elevated magnetic field on the cathode and to reduce the power dissipated in the coil, which does not have a water cooling. The dependence of the calculated cathode magnetic field on the coil current is presented in Figure 3. This dependence is very close to linear. If the coil is not energized, the magnetic field on the cathode is 14.9 Gs due to the magnetic flux leaking through the aperture of the gun iron shield.

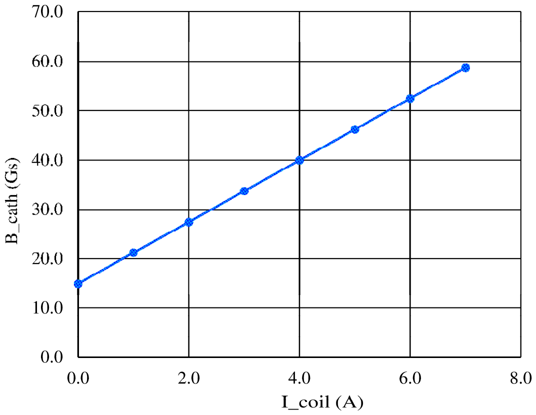

Figure 3. Dependence of the cathode magnetic field on the coil current.

Figure 4 presents a simulation of the electron beam and magnetic field for a case of 7 A current in the magnet coil, producing a magnetic field of 58.7 Gs on the cathode. The electron beam after the iron ring stays laminar with low amplitude of the radial ripples.

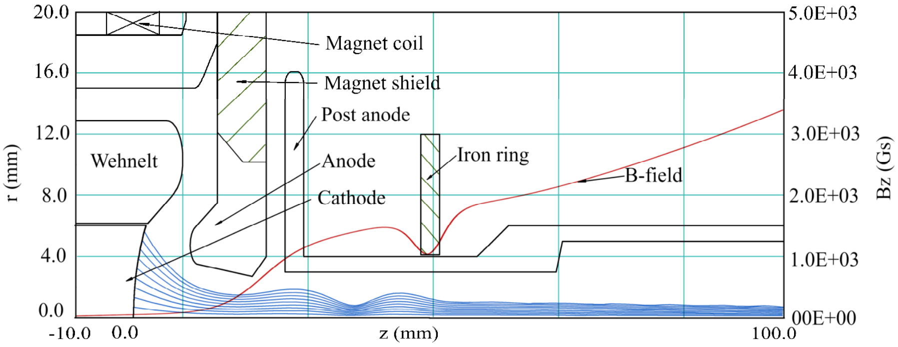

Figure 4. Simulation of the electron beam transmission with 58.7 Gs on the cathode. The electron current is 1.0 A, the cathode at -12 kV, post anode at 0 V and anode at -2 kV.

Figure 5 presents the beam envelopes for three different magnetic fields on the cathode. The beam envelope of the original electron gun is also shown as a dashed line for comparison.

Our simulations showed that the amplitude of the radial ripples depends on the electron energy and to minimize the ripples it is desirable to adjust the energy for each magnetic field on the cathode. The reason for such adjustment is the shift of the radial oscillation phase caused by the variations of the longitudinal electron velocity component at different magnetic fields on the cathode.

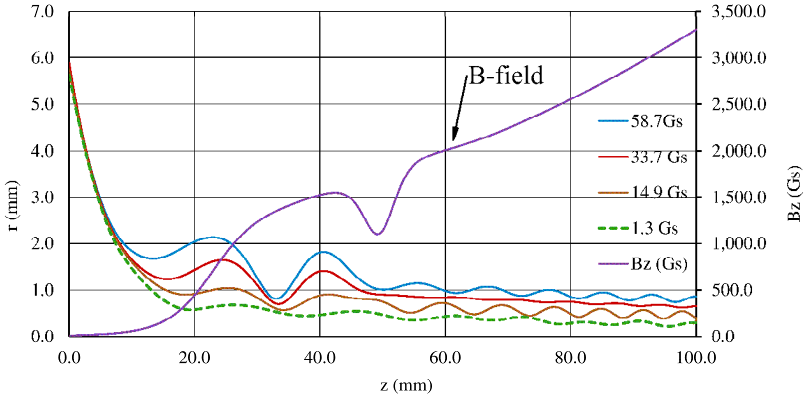

Figure 5. Beam envelope traces of electron beams with different magnetic fields on the cathode. The beam parameters are the same as in Figure 4.

In real devices, it is desirable to keep the voltages on the gun electrodes as stable as possible. To make the needed span of the optimization voltages small, the iron ring is positioned on the back-slope of the second radial oscillation. The iron ring does not eliminate the radial oscillations completely, but noticeably reduces them. The plots in Figure 6 illustrate the effect of this adjustment on the quality of the electron beam generated with a non-adiabatic magnetic field. The relative amplitude of radial beam oscillations is defined as $\frac{\Delta r}{r} = \frac{r_{max}-r_{min}}{r_{max}+r_{min}}$. We estimate the relative error of the simulated ripple amplitude to 5%.

From the left plot, one can see that the radial oscillation amplitude associated with a given magnetic field strength is energy independent for beam optics excluding the iron ring, whereas a pronounced minimum is observed if the magnetic field is modified by the presence of an iron ring. The right plot also shows that with optimized electron energy for each magnetic field on the cathode, the radial ripples of the electron beam remain lower than 10% for the most part of the cathode magnetic field dynamic range.

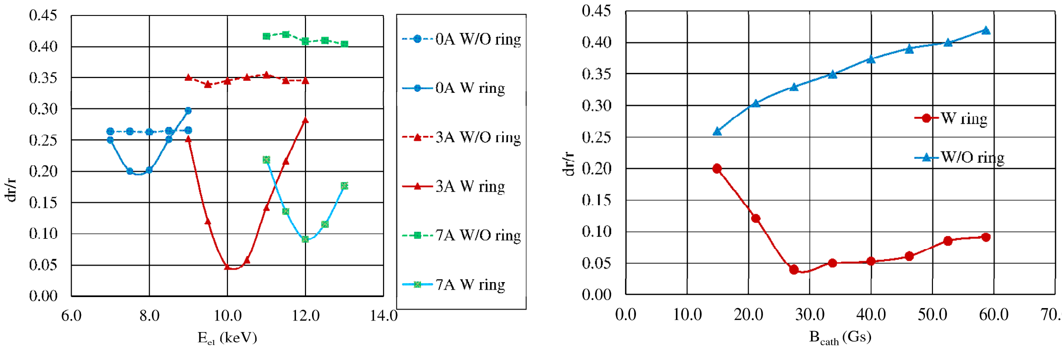

Figure 6. Left: Radial beam oscillation dependence on the electron energy, with and without iron ring present. The beam oscillations are given for three values of magnetic field on the cathode (0 A, 3 A and 7 A). Right: Dependence of radial oscillations on the magnetic field on the cathode. For the case with the iron ring, the electron energy has been optimized at each magnetic field value to achieve minimum oscillations

4. Conclusion

Our simulations demonstrate that the operating range of the magnetic field on the electron gun cathode can be extended to provide an electron beam density in the range of 300 to 1000 A/cm^2. A combination of a nonadiabatic magnetic field on the back slope of the radial beam oscillation and an adjustment of the electron energy allows us to attain an acceptable electron beam quality in a required range of current density in the ion trap.

5. Acknowledgement

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