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Analysis of magnetically immersed electron guns with non-adiabatic fields

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Electron diode guns, which have strongly varying magnetic or electric fields in a cathode-anode gap, were investigated in order to generate laminar electron beams with high current density using magnetically immersed guns. By creating a strongly varying radial electric field in a cathode-anode gap of the electron gun, it was demonstrated that the optical properties of the gun can be significantly altered, which allows the generation of a laminar, high-current electron beam with relatively low magnetic field on the cathode. The relatively high magnetic compression of the electron beam achieved by this method is important for producing electron beams with high current density. A similar result can be obtained by inducing a strong variation of the magnetic field in a cathode-anode gap. It was observed that creating a dip in the axial magnetic field in the cathode-anode gap of an adiabatic electron gun has an optical effect similar to guns with strong variation of radial electric field. By analyzing the electron trajectories angles and presenting the results in a gun performance map different geometries of magnetically immersed electron guns with non-adiabatic fields are compared with each other and with a more traditional adiabatic electron gun. Some advantages and limitations of guns with non-adiabatic fields are outlined. The tests results of non-adiabatic electron gun with modified magnetic field are presented.

1. Introduction

Some applications of magnetically immersed electron guns require electron beam having as low transverse energy as possible, such as the guns for electron coolers, guns for the electron lenses and electron beam ion sources (EBIS). In many of these applications a high compression of the electron beam cross-sectional area is achieved by injecting it into the high magnetic field of the superconducting solenoid with typical value 5 – 6 T. If the electron beam undergoes a magnetic compression, the electrons with velocity vectors outside of the acceptance cone turn back from the magnetic mirror [1-3]. This can result in a loss of electrons on the drift structure and the gun electrodes; sometimes it can result in excitation and bunching of the primary electron beam, vacuum degradation, etc. One way to reduce the reflection of electrons from the magnetic mirror is to improve the quality of the electron beam by reducing the transverse energy of electrons generated by the gun; i. e., to make it more laminar. The largest contributor of the transverse electron energy is usually the gun optics so we tried to find a way to reduce this contribution. A previous analysis [4] of several electrode configurations of the diode guns recommends a geometry with anode overlapping the cathode (coaxial diode), in which the simulation reveals the lowest transverse electric field within the cathode-anode gap of all 3 tested geometries. It is possible to generate a highly laminar electron beam for a given magnetic field using a more

complex electrostatic optics with 5 anodes [5] or even a more simple geometry, but the operational range of potentials on electrodes of such gun would be quite narrow. For electron gun configurations with adiabatic electric field in a case of uniform or slow varying magnetic field along the longitudinal axis the amplitude of beam radial oscillations decreases with increased magnetic field on the cathode. The required magnetic field on the cathode for an acceptable value of radial oscillations can be estimated as [6]:

$$B_c = 4.14 \cdot 10^3 \frac{\sqrt{U_a \cdot P}}{R_{osc}} \quad (1)$$

B_c – magnetic field on the cathode in Gauss,

U_a – anode voltage in Volts,

R_{osc} – amplitude of radial oscillations in millimeters and,

P - perveance of the gun ($P = \frac{I_{el}(A)}{U_a(V)^{1.5}}$),

However, in some cases this magnetic field on the cathode can be too high to achieve the desired areal compression of the electron beam.

Alternatively, the objective is to find gun geometry capable of producing a laminar electron beam with the required current and with as low as possible magnetic field on the cathode.

A theoretical analysis of origins of the electron gyromotion within the beam [7] states that for adiabatically varying magnetic and electric field no such motion should be expected, rather it arises when either an electric or a self-induced magnetic field varies sharply.

The electron gun on the Relativistic Heavy Ion Collider (RHIC) EBIS in its present form [8] has been morphed from the gun with geometry of a coaxial diode [9, 10] and retains similar optical properties. It has a spherical convex cathode with diameter 9.2 mm and the radius of curvature is 10 mm. It was adopted to generate a laminar high current electron beam with cathode magnetic field lower than required by equation (1). The geometry of this electron gun was used as a basis for our analysis.

2. Electron gun with non-adiabatic electric field.

Gyrotron technology utilized non-adiabatic electric fields for producing high-quality hollow electron beams [11, 12, 13]. We attempted with our simulations to generate an electron beam with small radial oscillations in low magnetic field by using non-adiabatic electric field in a cathode-anode gap of a diode electron gun producing a solid round electron beam. We call these strongly varying fields in a cathode-anode gap non-adiabatic because these variations take place on a distance, which is either shorter or comparable with the wavelength of Larmor electron motion. Unlike an adiabatic gun with spherical cathode, spherical Wehnelt electrode and overlapping anode, the non-adiabatic gun analyzed in this study, has flat opposing surfaces of Wehnelt electrode and anode. This shape of electrodes creates a strongly varying radial electric field in the cathode-anode gap. We also analyzed a hybrid gun, which produces a moderate variation of the radial electric field in the same region by combining geometries of adiabatic and non-adiabatic electron guns. All three electron gun geometries with axial distributions of the radial component of the electric field are presented in Fig. 1 a), b) and c).

Fig. 1. Geometries and axial distributions of radial electric field for an adiabatic a), a non-adiabatic b) and a hybrid c) electron guns. The electric field scans are taken at $r=3.0$ mm without electron beam space charge at gun voltages necessary to produce electron current $I_{el}=12.0$ A for each gun.

The axial components of the electric field have patterns similar to presented here radial components, although the scale of values is different. One can see that our adiabatic electron gun has relatively smoothly varying electric field in a cathode-anode gap and in a non-adiabatic gun these variations are much larger. A hybrid electron gun has variations of the radial electric field larger, than an adiabatic gun, but smaller, than the non-adiabatic gun.

The simulation model consists of electron gun with anode extending to the end of the model, which is immersed in an external magnetic field with uniformity of axial field distribution of $\frac{\Delta B}{B} = 3E-4$ within the simulation range to minimize fluctuations of the trajectory angles. The electron energy in this model is determined by the potential difference between the cathode and anode with correction for a space charge. The initial uniformity (without the electron beam space charge) of electric potential within the sampling range in our model was lower than $1E-6$ V. For the fields and trajectory simulations we used 2D program package from S. Humphries [14], which employs numerical method of emission calculations, satisfying the Child law. The procedure of these calculations is described in [15]. TRAK performs self-consistent simulations of particles trajectories with space charge of all particles involved. The output parameter of data processing we chose to be a maximum angle between the electron trajectory and the longitudinal axis of all electron trajectories for a given combination of the electron beam current and the external magnetic field, which is the same on the cathode and in the drift space. This analysis has been performed in a region downstream of the cathode-anode gap where both magnetic and electric fields are quite uniform on a distance of 250 mm: for each run only the largest angle of all electron trajectories independently of its radial position was picked and logged. The range of simulated beam current is $I_{el} = (1.0 - 14.0)$ A, and the corresponding range of the emission current density is $j_{emission} = (1.5 - 21.1)$ A/cm². Since the goal of this study is the analysis of the guns optical properties, we did not include in our simulations the energy broadening caused by the cathode temperature, cathode roughness etc. For easier comparison of different electron guns

with different beam currents and magnetic fields all maximum trajectory angles are given for fixed electron energy 25 keV.

The performance of electron guns can be presented as a map of maximum trajectory angles for different electron beam currents and magnetic fields. Such “map” of an adiabatic gun (Fig. 1 a) is presented in Fig. 2. The perveance of this gun is $2.88 \cdot 10^{-6} \text{ A/V}^{1.5}$.

	B_c, kGs																							
I_el, A	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40	1.50	1.60	1.70	1.80	1.90	2.00	2.10	2.20	2.30	2.40	2.50	2.60	2.70	2.80	2.90	3.00
2.0	5.07	4.17	4.17	3.32	2.50	2.32	2.48	2.52	2.36	2.13	2.01	2.03	2.09	2.10	2.05	1.99	1.95	1.96	1.97	1.97	1.95	1.92	1.92	1.92
3.0	6.35	5.82	5.56	5.02	4.20	3.24	2.70	2.68	2.84	2.90	2.74	2.51	2.35	2.29	2.36	2.41	2.41	2.36	2.29	2.25	2.24	2.25	2.27	2.27
4.0	8.02	6.77	6.39	6.11	5.51	4.72	3.75	3.11	2.91	3.07	3.19	3.17	2.97	2.74	2.59	2.55	2.61	2.65	2.68	2.63	2.59	2.52	2.50	2.49
5.0	9.92	7.87	7.06	6.79	6.51	5.85	5.02	4.04	4.04	3.12	3.26	3.40	3.43	3.31	3.08	2.87	2.75	2.75	2.82	2.88	2.90	2.85	2.81	2.75
6.0	11.86	9.21	7.86	7.34	7.10	6.69	6.03	5.20	4.22	3.56	3.31	3.44	3.61	3.66	3.54	3.34	3.10	2.95	2.91	2.95	3.02	3.07	3.06	3.02
7.0	13.79	10.68	8.72	7.93	7.65	7.37	6.85	6.10	5.21	4.27	3.71	3.50	3.65	3.80	3.87	3.77	3.55	3.33	3.15	3.09	3.08	3.15	3.22	3.24
8.0	15.72	12.12	9.76	8.56	8.11	7.91	7.50	6.91	6.12	5.16	4.25	3.74	3.72	3.81	4.00	4.05	3.94	3.73	3.50	3.31	3.22	3.23	3.29	3.35
9.0	17.59	13.64	10.88	9.24	8.55	8.30	8.04	7.54	6.86	5.97	4.95	4.22	3.84	3.86	4.03	4.18	4.22	4.11	3.89	3.66	3.48	3.38	3.37	3.42
10.0	19.25	15.11	12.03	10.01	9.06	8.67	8.48	8.13	7.50	6.75	5.79	4.84	4.22	3.97	4.04	4.23	4.35	4.37	4.24	4.01	3.77	3.62	3.51	3.50
11.0	21.06	16.60	13.23	10.91	9.55	9.05	8.86	8.57	8.05	7.37	6.49	5.51	4.67	4.20	4.08	4.22	4.43	4.51	4.48	4.33	4.11	3.88	3.70	3.62
12.0	22.06	18.12	14.44	11.78	10.17	9.47	9.17	8.95	8.60	7.95	7.16	6.23	5.26	4.57	4.22	4.26	4.41	4.60	4.65	4.62	4.44	4.19	3.96	3.82
13.0	23.78	19.41	15.56	12.67	10.83	9.88	9.52	9.33	8.99	8.41	7.72	6.88	5.90	5.01	4.50	4.32	4.44	4.62	4.75	4.78	4.68	4.47	4.27	4.06
14.0	24.76	20.84	16.77	13.64	11.47	10.32	9.85	9.63	9.37	8.89	8.26	7.50	6.50	5.54	4.86	4.46	4.43	4.60	4.78	4.89	4.89	4.76	4.52	4.29

Fig. 2. Dependence of maximum trajectory angle on the beam current and external magnetic field for adiabatic electron gun (Fig. 1 a) at fixed electron energy $E_{el}=25.0 \text{ keV}$. The angle is in degrees, magnetic field is in kGs and the electron beam current is in Amps.

One can see that the “map” is relatively smooth and does not have abrupt transitions. The maximum trajectory angle tends to reduce with increased magnetic field on the cathode and it increases with increased electron beam current for a fixed magnetic field. This gun has a large operating range in electron current and magnetic field.

A similar “map” for a non-adiabatic gun with cathode-anode gap $L=12.6 \text{ mm}$ and perveance $1.98E-6 \text{ A/V}^{1.5}$ (Fig. 1 b) is presented on Fig. 3.

		B, kGs																																			
I _{el} , A	0.7	0.75	0.8	0.85	0.9	0.95	1	1.05	1.1	1.15	1.2	1.25	1.3	1.35	1.4	1.45	1.5	1.55	1.6	1.65	1.7	1.75	1.8	1.85	1.9	1.95	2	2.05	2.1	2.15	2.2	2.25	2.3	2.35	2.4	2.45	2.5
1	3.32	3.14	2.82	2.32	1.80	1.27	0.88	1.19	1.54	1.78	1.92	1.94	1.87	1.72	1.52	1.30	1.11	0.97	0.92	1.09	1.26	1.39	1.44	1.43	1.39	1.30	1.22	1.12	1.08	1.03	1.02	1.10	1.17	1.24	1.26	1.25	1.23
2	3.22	3.74	4.05	4.18	4.14	3.93	3.60	3.17	2.63	2.09	1.59	1.16	1.32	1.72	2.02	2.27	2.41	2.46	2.44	2.34	2.20	1.99	1.78	1.54	1.36	1.23	1.17	1.26	1.45	1.64	1.74	1.82	1.83	1.81	1.76	1.67	1.59
3	2.36	3.03	3.69	4.22	4.57	4.77	4.79	4.69	4.48	4.12	3.68	3.12	2.60	2.04	1.56	1.29	1.61	2.01	2.31	2.56	2.72	2.81	2.83	2.79	2.68	2.51	2.31	2.06	1.87	1.63	1.49	1.37	1.34	1.46	1.66	1.85	1.98
4	3.86	2.66	2.96	3.70	4.29	4.79	5.08	5.25	5.29	5.19	4.99	4.66	4.24	3.71	3.18	2.63	2.14	1.63	1.44	1.79	2.16	2.50	2.75	2.95	3.06	3.12	3.11	3.04	2.92	2.75	2.55	2.31	2.10	1.86	1.70	1.58	1.50
5	5.67	4.24	3.05	3.07	3.73	4.44	4.94	5.38	5.60	5.72	5.73	5.59	5.37	5.00	4.61	4.08	3.53	3.00	2.50	1.94	1.58	1.74	2.10	2.47	2.76	3.01	3.19	3.32	3.39	3.36	3.32	3.18	3.03	2.83	2.64	2.39	2.18
6	7.55	5.81	4.49	3.18	3.24	3.92	4.59	5.16	5.60	5.92	6.06	6.10	6.04	5.85	5.59	5.24	4.81	4.23	3.71	3.15	2.65	2.11	1.70	1.79	2.13	2.54	2.85	3.13	3.31	3.48	3.56	3.59	3.57	3.51	3.38	3.19	3.03
7	9.00	7.47	5.88	4.49	3.27	3.49	4.12	4.83	5.38	5.84	6.19	6.38	6.44	6.41	6.28	6.02	5.74	5.32	4.85	4.25	3.75	3.19	2.70	2.15	1.76	1.92	2.26	2.66	2.97	3.27	3.46	3.64	3.74	3.80	3.79	3.75	3.65
8	10.47	8.80	7.35	5.71	4.39	3.40	3.73	4.42	5.08	5.66	6.12	6.45	6.63	6.73	6.62	6.43	6.13	5.76	5.27	4.80	4.17	3.68	3.13	2.65	2.11	1.84	2.10	2.44	2.84	3.13	3.44	3.63	3.81	3.93	3.99	3.99	
9	11.91	10.19	8.72	7.01	5.66	4.21	3.56	4.07	4.70	5.39	5.92	6.42	6.73	6.93	7.04	7.03	6.94	6.75	6.49	6.13	5.69	5.17	4.65	4.07	3.55	2.99	2.49	2.02	1.98	2.32	2.67	3.06	3.34	3.61	3.81	3.99	4.09
10	13.19	11.46	9.86	8.30	6.73	5.34	4.00	3.82	4.37	5.09	5.70	6.24	6.69	6.99	7.18	7.30	7.30	7.21	7.02	6.77	6.45	5.95	5.49	4.94	4.41	3.87	3.36	2.79	2.30	2.03	2.20	2.58	2.94	3.30	3.57	3.83	4.02
11	14.42	12.69	11.02	9.35	7.91	6.26	4.96	3.93	4.11	4.75	5.42	6.04	6.55	6.99	7.28	7.46	7.55	7.54	7.45	7.25	7.01	6.67	6.30	5.78	5.29	4.67	4.17	3.61	3.09	2.53	2.13	2.18	2.48	2.89	3.22	3.55	3.81
12	15.57	13.83	12.17	10.51	9.10	7.33	6.00	4.59	4.06	4.47	5.10	5.79	6.35	6.85	7.27	7.57	7.72	7.80	7.77	7.68	7.50	7.23	6.92	6.48	6.02	5.45	4.94	4.38	3.86	3.26	2.79	2.27	2.19	2.47	2.80	3.21	3.52
13	16.81	14.95	13.29	11.56	9.89	8.39	6.83	5.47	4.35	4.31	4.84	5.54	6.15	6.72	7.17	7.56	7.82	7.97	8.04	8.02	7.90	7.68	7.45	7.09	6.73	6.16	5.70	5.09	4.58	4.02	3.51	2.93	2.45	2.26	2.44	2.82	3.16
14	17.66	15.93	14.31	12.57	10.99	9.45	7.83	6.26	5.05	4.35	4.60	5.26	5.92	6.53	7.08	7.51	7.85	8.07	8.21	8.26	8.19	8.06	7.87	7.60	7.27	6.84	6.40	5.82	5.29	4.70	4.20	3.63	3.13	2.57	2.33	2.46	2.78

Fig. 3. Dependence of a maximum trajectory angle on electron beam current and magnetic field on the cathode for an electron gun with non-adiabatic electric field and the cathode-anode gap $L=12.6 \text{ mm}$, $E_{el}=25.0 \text{ keV}$.

As with an adiabatic electron gun, the maximum angle of electrons decreases with increasing magnetic field, as a general trend. On this “map” one of the areas with relatively small angles extends to low magnetic field. The dependence of optimum magnetic field on the electron beam current for this area can be expressed by a fitting formula with parameters, which are correct only for this particular gun:

$$B(kGs) = 0.468 \cdot [I_{el}(A)]^{0.343}$$

A graph of dependence of maximum trajectory angle on the magnetic field for different guns and different cathode-anode gaps of the gun with iron for a fixed electron beam current $I_{el}=12.0$ A is given in Fig. 4.

Fig. 4. Dependence of maximum electron trajectory angle on the magnetic field for different cathode-anode gaps of non-adiabatic guns with flat electrodes (Fig. 1 b), for an adiabatic gun (Fig. 1 a), and a hybrid gun (Fig. 1 c). The electron beam current $I_{el}=12.0$ A and the electron energy is 25 keV.

As a trend, for all simulated guns the maximum angle of the electron trajectory with longitudinal axis generally decreases with increased magnetic field. If an electron beam with current 12.0 A generated by an adiabatic gun is required to have this angle to be less than 5 degrees, the magnetic field on the cathode of this gun has to be higher than 1.9 kGs.

Our simulations of non-adiabatic gun show that for a particular cathode-anode gap and a fixed electron current the dependence of the maximum angle on the magnetic field has more than one minimum. The magnetic field, corresponding to the first minimum, is the lowest for electron gun with the largest cathode-anode gap. The hybrid electron gun generates electron beam at 12.0 A with smaller angles than the adiabatic gun for almost all simulated range of the magnetic field.

For non-adiabatic electron guns the range of maximum angles at fixed magnetic field during the current ramps also depends on the cathode-anode distance. Fig. 5 displays the dependence of maximum electron trajectory angle on the electron current during the current ramping at fixed

magnetic field. The value of the magnetic field for each curve corresponds to minimum angle at 12 A.

Fig. 5. Dependence of maximum electron trajectory angle on electron beam current (ramp curves) for a magnetic field corresponding minimum angle at 12 A and 25 keV for non-adiabatic electron guns with different cathode-anode gaps.

These two last plots demonstrate that the cathode-anode distance determines both the magnetic field with minimum trajectory angle and the range of the trajectory angles during the ramp. If the maximum magnetic field in the interaction region is 5 T and the magnetic field on the cathode is 1 kGs, the magnetic mirror transmission cone has angle of 8.1° , all electrons for all tested cathode-anode gaps of non-adiabatic guns should be transmitted through this mirror. The value of the magnetic field, which provides the smallest trajectory angle and the value of this angle at optimum magnetic field are the smallest of all tested gaps for the largest cathode-anode distance of 16.6 mm. These parameters improve with increasing this gap. However, the perveance of the gun decreases with increasing this gap and at cathode-anode distance 16.6mm the gun perveance is $P=1.29E-6 \text{ A/V}^{1.5}$ for our cathode size.

Curiously, it appeared that in a range of magnetic field lower than 0.5 kGs this electron gun exhibits another stable area with minimum angles similar to what it has in a range around 1 kGs (Fig. 6:

	B, kGs																				
I_{el}, A	0.3	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.4	0.41	0.42	0.43	0.44	0.45	0.46	0.47	0.48	0.49	
1	2.57	2.38	2.00	1.73	1.44	1.16	0.93	0.94	1.15	1.36	1.54	1.69	1.80	1.88	1.93	1.94	1.93	1.89	1.82	1.73	
2	4.13	4.18	4.18	4.13	4.01	3.87	3.69	3.48	3.23	2.94	2.63	2.34	2.04	1.76	1.49	1.24	1.11	1.28	1.49	1.69	
3	3.97	4.19	4.45	4.61	4.72	4.79	4.80	4.77	4.71	4.61	4.47	4.32	4.09	3.81	3.55	3.27	2.95	2.65	2.38	2.08	
4	3.32	3.65	4.08	4.37	4.64	4.87	5.03	5.16	5.25	5.29	5.29	5.25	5.18	5.08	4.93	4.77	4.55	4.29	4.02	3.76	
5	2.82	3.02	3.48	3.85	4.22	4.59	4.87	5.12	5.36	5.50	5.60	5.68	5.73	5.75	5.72	5.63	5.54	5.41	5.24	5.03	
6	3.77	3.23	3.06	3.33	3.73	4.11	4.47	4.81	5.11	5.35	5.61	5.80	5.94	6.02	6.09	6.11	6.10	6.05	5.97	5.88	
7	5.23	4.59	3.70	3.21	3.32	3.64	4.02	4.40	4.76	5.09	5.39	5.65	5.89	6.07	6.24	6.33	6.40	6.44	6.45	6.42	
8	6.50	5.82	4.98	4.20	3.53	3.41	3.63	3.99	4.35	4.75	5.09	5.43	5.70	5.95	6.21	6.38	6.52	6.61	6.69	6.72	
9	7.86	7.14	6.10	5.44	4.58	3.90	3.56	3.69	3.99	4.38	4.73	5.11	5.46	5.76	6.02	6.29	6.51	6.71	6.83	6.92	
10	8.99	8.49	7.33	6.45	5.78	4.97	4.24	3.79	3.78	4.04	4.38	4.75	4.27	5.50	5.82	6.10	6.38	6.62	6.84	6.97	
11	10.19	9.46	8.56	7.64	6.71	5.90	5.29	4.50	3.98	3.91	4.11	4.46	4.82	5.19	5.56	5.88	6.18	6.51	6.73	6.97	
12	11.34	10.61	9.48	8.76	7.85	6.94	6.12	5.49	4.73	4.17	4.05	4.22	4.53	4.90	5.26	5.64	5.99	6.31	6.57	6.84	
13	12.37	11.68	10.58	9.63	8.91	8.01	7.11	6.29	5.66	4.89	4.34	4.19	4.35	4.64	5.00	5.34	5.74	6.08	6.41	6.69	
14	13.40	12.67	11.55	10.67	9.77	9.06	8.13	7.27	6.41	5.79	5.03	4.48	4.35	4.47	4.75	5.09	5.44	5.85	6.16	6.50	

Fig. 6. Dependence of maximum trajectory angle on the electron current and magnetic field for cathode-anode gap 12.6 mm for low magnetic fields. Electron energy is 25 keV.

This stable “road” is narrower, than for a 1 kGs range and it would require both careful tuning and stability of magnetic field and electron current to operate the gun in this range of magnetic field. The trajectory angles are similar to what this gun exhibits at 1 kGs. Since the ratio of magnetic field in the main superconducting solenoid (5T) to the optimum cathode field for 12.0 A (400 Gs) is 125, which is much higher than for magnetic field 1.0 kGs, the acceptance cone is smaller for this lower magnetic field range than for 1 kGs. The maximum angle, which can penetrate the magnetic mirror with 5T field, is 5.12° . This means that for the cathode-anode gap 16.6 mm the maximum simulated angle on a ramp for electron beam current 4 A is 6.1° and one should expect some reflected electron flux on the ramp with pulsed operation. However, DC operation at such low fields seems possible and a non-adiabatic electron gun with such high compression can provide a very high current density electron beam in the interaction region with high magnetic field. If the maximum magnetic field on the electron beam’s path is 2T, the acceptance cone is 8.1° and there are no problems with transmitting such beam in all regimes.

Our simulations of non-adiabatic gun without the electron space charge demonstrated, that for the same potential distribution on the gun electrodes and the same magnetic field the electron trajectories have visibly smaller amplitude of radial oscillations and therefore the trajectory angles are smaller. We think that analysis of such guns neglecting the electron space charge would be not correct.

3. An electron gun with locally modified magnetic field

We decided to complement a relatively uniform magnetic field in a region of our originally adiabatic electron gun with a highly non-uniform magnetic field in a cathode-anode gap hoping that by adjusting the shape of this additional field we can find favorable combinations of the electric, magnetic fields and electron beam parameters, when the beam is laminar. The initial goal was to create a radial component of the magnetic field on the surface of the cathode. Such field shape can be produced by reducing the main magnetic field in a near-cathode region. We found that a simplest way to create such shape of the magnetic field is to replace a non-magnetic stainless steel as a material for a conical part of the anode funnel in our original adiabatic electron gun with soft iron, which would draw in a part of the magnetic flux and therefore would reduce the magnetic field in a gap between the cathode and the anode.

The electrode structure of the electron gun with iron tip is presented in Fig. 7. The simulated axial magnetic field distribution is plotted together with electrode's geometry.

Fig. 7. Geometry of the electron gun electrodes and axial magnetic field distribution for external field of $B = 1.50$ kGs for an “optimum” cathode-anode distance.

The value of the gun perveance with spherical cathode for an “optimum” cathode-anode distance as in Fig. 1a is $P_{\text{Optimum}}^{\text{gun}} = 3.09\text{E-}6 \text{ A/V}^{1.5}$, which is somewhat larger than the perveance of our adiabatic gun ($P_{\text{adiabatic gun}} = 2.6\text{E-}6 \text{ A/V}^{1.5}$) because the cathode-anode gap is 2 mm shorter.

If a non-magnetic material of the conical tip of the anode in this gun is replaced with soft iron, the magnetic field distribution within this gun changes dramatically and the “map” acquires area with small angles in a low magnetic field region, which looks like a “road” and extends from a low electron beam current to high current continuously (Fig. 8). This table is for the same electrostatic geometry as for adiabatic gun, and the iron tip on the anode is the only difference. We will call this gun with iron tip an “optimum” gun.

	B_cath, kGs																																							
I_el, A	0.70	0.75	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20	1.25	1.30	1.35	1.40	1.45	1.50	1.55	1.60	1.65	1.70	1.75	1.80	1.85	1.90	1.95	2.00	2.05	2.10	2.15	2.20	2.25	2.30	2.35	2.40	2.45	2.50			
2.0	5.58	3.58	1.80	2.48	3.51	4.23	4.71	4.96	4.98	4.79	4.48	4.09	3.59	3.06	2.55	2.13	1.86	1.75	1.83	1.99	2.12	2.25	2.35	2.37	2.38	2.35	2.32	2.27	2.20	2.14	2.11	2.07	2.06	2.05	2.04	2.05	2.05			
3.0	10.97	8.59	6.48	4.47	2.62	2.36	3.52	4.40	5.03	5.41	5.69	5.74	5.56	5.33	4.98	4.52	4.03	3.49	2.95	2.50	2.19	2.03	2.04	2.15	2.32	2.44	2.58	2.67	2.72	2.74	2.70	2.66	2.62	2.54	2.49	2.44				
4.0	22.77	13.75	10.59	8.46	6.34	4.40	2.56	2.68	3.86	4.76	5.42	5.88	6.18	6.27	6.29	6.06	5.75	5.44	4.95	4.43	3.88	3.35	2.86	2.53	2.28	2.22	2.26	2.40	2.56	2.69	2.84	2.95	2.98	3.00	3.00	2.98	2.96			
5.0	27.53	25.04	15.51	12.01	9.74	7.68	5.65	3.74	2.05	3.30	4.40	5.34	5.95	6.38	6.74	6.77	6.62	6.29	5.95	5.55	5.10	4.56	3.98	3.47	3.00	2.66	2.45	2.36	2.43	2.59	2.74	2.86	3.01	3.13	3.20	3.24				
6.0	31.94	28.96	26.40	16.62	13.04	10.69	8.57	6.56	4.58	2.81	3.04	4.19	5.13	5.95	6.53	6.88	7.14	7.22	7.22	7.05	6.70	6.40	5.98	5.50	4.96	4.41	3.86	3.38	3.01	2.72	2.57	2.54	2.63	2.80	2.96	3.07	3.21			
7.0	33.83	32.68	30.06	26.81	16.96	13.64	11.31	9.23	7.07	5.16	3.33	2.78	3.99	5.05	6.00	6.65	7.05	7.38	7.57	7.60	7.54	7.32	6.98	6.69	6.26	5.78	5.26	4.69	4.15	3.65	3.23	2.94	2.73	2.68	2.73	2.85	3.02			
8.0	34.49	35.39	33.03	30.83	26.02	17.19	13.94	11.70	9.57	7.42	5.51	3.67	2.76	3.97	5.09	6.05	6.71	7.28	7.59	7.84	7.95	7.95	7.81	7.54	7.25	6.86	6.44	5.95	5.40	4.84	4.28	3.79	3.40	3.07	2.86	2.80	2.83			
9.0	36.18	36.77	36.83	33.50	31.32	23.50	16.76	14.10	11.74	9.64	7.64	5.69	3.83	2.86	4.07	5.23	6.11	6.86	7.50	7.85	8.15	8.29	8.31	8.25	8.05	7.70	7.37	6.94	6.48	5.99	5.46	4.90	4.39	3.88	3.51	3.19	2.99			
10.0	36.48	37.44	37.73	36.58	33.96	31.46	21.36	16.55	13.98	11.79	9.67	7.67	5.71	3.88	3.01	4.24	5.40	6.27	7.05	7.69	8.05	8.43	8.57	8.62	8.62	8.43	8.10	7.75	7.42	7.01	6.47	6.00	5.42	4.87	4.36	3.87	3.51			
11.0	37.60	38.68	39.38	39.76	36.42	34.25	29.41	19.61	16.22	13.77	11.60	9.57	7.52	5.61	3.78	3.19	4.43	5.60	6.45	7.30	7.91	8.28	8.65	8.83	8.91	8.91	8.74	8.49	8.16	7.85	7.36	6.93	6.37	5.89	5.31	4.76	4.28			
12.0	38.26	38.55	39.66	40.21	39.21	36.56	34.35	25.34	18.46	15.77	13.61	11.42	9.33	7.31	5.39	3.64	3.48	4.67	5.87	6.72	7.54	8.07	8.54	8.92	9.10	9.20	9.18	9.04	8.81	8.46	8.17	7.76	7.31	6.80	6.29	5.71	5.15			
13.0	38.61	39.37	40.62	41.56	41.97	38.67	36.42	32.56	21.87	17.85	15.38	13.13	10.98	8.94	6.98	5.11	3.42	3.85	5.00	6.10	7.02	7.77	8.33	8.78	9.17	9.36	9.40	9.40	9.32	9.06	8.77	8.45	8.09	7.61	7.09	6.62	6.03			
14.0	38.99	40.11	41.31	42.47	43.03	41.33	38.50	35.88	27.82	20.48	17.22	14.91	12.71	10.66	8.60	6.66	4.81	3.21	4.21	5.37	6.40	7.36	8.06	8.63	9.04	9.39	9.61	9.69	9.72	9.59	9.34	9.05	8.72	8.37	7.93	7.43	6.87			

Fig. 8. Dependence of maximum trajectory angle on the electron beam current and the external magnetic field for an “optimum” electron gun. The horizontal axis is magnetic field (kGs) and the vertical axis is electron beam current, A. The energy of the electron beam is 25 keV.

The difference between the smallest and the largest angles on a map of this “optimum” gun becomes much larger than for an adiabatic gun and the transitions between them became steeper.

The position of this “road” on the “map” depends on the cathode-anode distance: the smaller is this gap, the more the “road” on a “map” with small trajectory angles is shifted to the left (to area with lower magnetic field) and vice versa. Fig. 9 displays scans of such maps for different cathode-anode gaps and for a fixed electron beam current $I=12.0$ A. It also shows scans for a adiabatic electron gun and for iron-tipped gun with flat cathode and for a thin iron tip (50% of “optimum” gun iron cone thickness).

Fig. 9. Dependence of a maximum trajectory angle on a cathode magnetic field for different gun configurations. Electron beam current $I= 12.0$ A, electron energy 25 keV.

It follows from our simulation that for the described gun configuration with iron tip the cathode-anode distance determines the position of the area with minimum angles on the “map”. Within the simulated range of parameters, the smaller the cathode-anode distance, the lower the magnetic field at the minimum of the angle-magnetic field dependence. The curves in Fig. 4 may have a second minimum at higher magnetic field and the trajectory angle at this minimum is smaller than at a first minimum at lower field. Apparently, the shape of the cathode, whether spherical with radius 10.0 mm or flat, does not change the striped pattern of the “map” and the dependence of the trajectory angle on the magnetic field for a flat cathode looks very similar to a

gun with spherical cathode and with somewhat larger cathode-anode distance. However, the flat cathode shifts the optimum magnetic field of an area with laminar beam to higher values compare to a gun with spherical cathode with the same geometry and dimensions of other electrodes. It also appears that for a gun with modified magnetic field in a cathode-anode gap the cathode-anode distance has a strong effect on the value of the optimum magnetic field, but its effect on the value of the maximum electron trajectory angle in the first minimum of the curve is not so strong for all cathode-anode gaps, which have been simulated. Unlike for the previously described guns with electrostatic non-adiabatic field, the guns with strongly varying magnetic field have opposite dependence of optimum magnetic field on the cathode-anode distance: the optimum field reduces with reduced gap.

The “road” on the “map” with small trajectory angles is attractive because of laminarity of the beam, but as with guns with non-adiabatic electric field it comes at a price of visibly increased angles in adjacent areas compare to an adiabatic electron gun. This feature is a drawback for all simulated non-adiabatic guns because it can limit application of such guns for some pulsed operation, where the beam current changes from zero to maximum value and back to zero at a fixed magnetic field. Changing the magnetic field in the cathode region during the front of the current pulse, so that it follows the beam current and maintains the working point on a “road” does not seem practical for most pulsed applications. Fig. 10 illustrates the dependence of maximum trajectory angle on electron beam current for fixed magnetic field 1.5 kGs for some gun configurations.

Fig. 10. Dependence of the maximum trajectory angle on the electron beam current at electron energy $E_{el}=25.0$ keV and magnetic field 1.5 kGs for different guns (ramp curves).

The gun with an iron tip (“optimum” gun) generates large angles on ramps but has smaller angles at optimum current-field combinations than the adiabatic gun has at highest simulated magnetic fields. This non-adiabatic gun with iron tip has advantage for DC applications or some pulsed

applications where the fronts are fast or the beam properties on the fronts are not important for operation.

If with “optimum” gun we need to compress the electron beam by increasing the magnetic field from 1.5 kGs on the cathode to 50 kGs in the interaction region, which is typical magnetic field for superconducting solenoid, the magnetic mirror acceptance cone is 9.9° . It means, that during the ramp at 1.5 kGs to 12.0 A the electron beam generated by the “optimum” gun still penetrate the magnetic mirror with a margin of 2.7° . This margin increases with increased magnetic field on the cathode.

By controlling the depth of the magnetic field modification one can control the pattern of the “map” and the contrast between the minimum and maximum trajectory angles. The simulation shows that reducing the thickness of the iron cone by half makes variations of maximum trajectory angle smaller, positioning this gun between the adiabatic and “optimum” guns (Fig. 10, violet trace). For electron beam current $I_e=12.0$ A and magnetic field $B=1.5$ kGs the minimum value of the trajectory angle in this gun is larger than for an “optimum” gun, but the maximum value is smaller. Reducing the magnetic permittivity of the iron tip makes the magnetic field modification in the cathode-anode region shallower and therefore changes the pattern of the map similar to a gun with thinner iron tip.

Our simulation shows that a similar effect on the trajectory angle can be achieved with a magnet coil located within the volume of the anode cone of the gun. The ability to control the degree of field modification would make this concept much more flexible. It would be convenient to locate the iron tip or the field-modifying coil outside of the vacuum enclosure for easy access.

4. Experimental test of non-adiabatic electron gun with soft iron tip

In order to create a non-adiabatic magnetic field in a cathode-anode gap of the gun shown above in Figure 7, the anode tip was manufactured from a soft steel 1006. The steel tip was annealed in vacuum furnace at 1050°C for 10 minutes, held at 900°C for an hour and then slowly cooled. The tip is mounted on its holder with a thread (Fig. 11) to avoid creating a non-uniformity of magnetic structure during brazing or welding.

Fig. 11. Anode of the electron gun with iron tip. Outside diameter of the anode cone is 64 mm.

This non-adiabatic electron gun with iron tip has been tested in RHIC EBIS with optimum magnetic field on the cathode for each electron current value.

This electron gun has been used to produce electron beam pulses with current $I_{el}=8.0$ A and duration $T_{el}=200$ ms. Ion beams of Fe^{20+} , suitable for use by the NASA Space Radiation Laboratory (NSRL) were generated using this electron beam. In addition, pulse trains of 12 pulses at 5 Hz, with electron current $I_{el}=8.0$ A and duration $T_{el}=35$ ms were produced with a magnetic field on the cathode of $B=1.2$ kGs. These are the electron beam parameters for generating ion beams Au^{32+} for RHIC. Maximum stable electron beams with current 12.0 A have been produced with magnetic field of 1.4 kGs on the cathode. The electron gun has been successfully tested on RHIC EBIS but without the ability to directly measure the electron trajectory angles. It was observed that the electron beam at optimum magnetic field appeared to have a wider operational range of parameters, than away from of this calculated field value. The estimated electron beam current density in the EBIS ion trap region with this electron beam was 645 A/cm^2 . Traces of pulses of the mentioned electron beams are presented in Fig. 12.

Fig. 12. Traces of electron beam pulse with current 12.0 A (a) and of a 12 pulses train with current 8.0 A (b).

Our concern was the electron beam current loss on the anode caused by the reflected component of the electron beam. The anode current on the top of the pulse for maximum current did not exceed our measurement sensitivity of $50 \mu\text{A}$ (fig. 13):

Fig. 13. Trace of current loss on the anode for electron beam with current $I_{el}=12.0$ A.

Our typical EBIS operation employs “seed” ion injection into an electron beam with current about 40 – 50% of its full value on the top of the pulse during ion confinement and ionization. The electron beam should therefore have a front ramp sufficient for ion injection, which requires traversing the sub-optimal area of the “map” during the ramp time. We did not have accurate measurements of the current load on the anode during the ramps because of strong contribution of the current required to charge the electrodes and circuit effective capacitance. The relatively long rise and fall ramp times (4-5 ms) were tolerated, which is sufficient for EBIS operation with “fast” mode of ion injection. The electron gun, which was used before this experiment, operated with typical magnetic field 1.6 kGs for electron beam current 8-9 A. The new electron gun allowed us to bring this field down to 1.2 kGs for the same electron current with current density in the ion trap increased proportionally. As expected, higher magnetic compression of the electron beam resulted in a reduction of the confinement time needed to produce ions with the required charge states.

5. Effect of electron beam space charge

To determine the effect of the electron beam space charge we simulated the beam transmission both with space charge included in a self-consistent simulation and in the absence of the space charge, with only the external electrostatic and magnetostatic fields included. This simulation has been done for electron gun with electrostatic non-adiabatic field presented in Fig. 1b with distance between the cathode and anode 14.6 mm. The electron beam current was 12.0 A and the magnetic field at the cathode position and in the drift space was 1.05 kGs. This is an “optimum” magnetic field for this electron current, where the maximum detected trajectory angle was the smallest. The result is presented in fig. 14 (a) and (b).

Fig. 14. Simulated electron trajectories for electron gun with flat electrodes and a cathode-anode distance 14.6 mm. The electron current is $I_{el}=12.0$ A, magnetic field $B=1.05$ kGs. (a) – electron space charge is not included in simulation, (b) - space charge is included in self-consistent simulation.

One can see that without the electron space charge, when the electron motion is determined by the external fields, the electron trajectories display very similar phases. The inclusion of the

electron space reduces the amplitude of radial oscillations of the electrons and completely neutralizes the effect of the external field at some radius, where the electrons practically do not oscillate radially. Above this equilibrium radius the electrons start their oscillation with increasing amplitude, and the phase of this oscillation is reversed compare to electrons with radius smaller than the equilibrium radius reflecting a reversed action of the combined field.

6. Conclusion

The analysis of magnetically immersed electron guns with non-adiabatic electric and magnetic fields in a cathode-anode gap demonstrates that such guns may have operating range of magnetic field on the cathode substantially lower than the guns with adiabatic fields. The non-adiabatic guns are not as “broadband” as are the adiabatic guns and they have limited operating range in a low magnetic field area. For the presented gun geometries both the optimum magnetic field required for producing a laminar electron beam and the variations of the electron trajectory angle can be defined by selecting the length of the cathode-anode gap and by selecting the degree of variation of either electric or magnetic field in the same region. All other geometrical parameters, such as radius of the cathode sphere, shape of electrodes, and a shift of magnet shim with respect to the anode front surface in a gun with iron tip also have effect on the optimum magnetic field and on the minimum value of the trajectory angle and therefore should be optimized for a specific geometry. Our experimental test of the electron gun with iron tip confirmed, that such gun can operate in a low magnetic field region according to simulations and produce stable high-current electron beams.

The simulations confirm that the electron beam space charge is a crucial source of transverse field component contributing to the balance of forces determining the transverse motion of the beam electrons. In our opinion it is not unfeasible to generate a gun geometry in which the transverse forces are neutralized across the entire electron beam for optimum magnetic fields.

Our future plans regarding non-adiabatic electron gun include building and testing an electron gun with electrostatic non-adiabatic field because it may allow obtaining higher electron current density than our present gun with iron tip can deliver.

We demonstrated, that non-adiabatic electron guns allow achieving higher electron current densities than adiabatic guns. A combination of electrostatic and magnetostatic non-adiabatic fields can be an interesting study with new opportunities.

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