PERFORMANCE OF A HIGH-PERVEANCE ELECTRON GUN WITH A CONVEX CATHODE

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Abstract

Strongly magnetized electron gun with a convex cathode can provide the homogenous transverse current density distribution in a low temperature electron beam with the high perveance of 5-10 μA/V$^{3/2}$. Such a gun was successfully tested with currents up to 10 A at the prototype set-up for beam-beam compensation in the Tevatron collider. In this article we present the test results. Electron guns of this type can be used in electron cooling and beam-beam compensation devices.

1 INTRODUCTION

On of the most important characteristics of an electron gun is its perveance $P = \frac{I}{U_a^{3/2}}$, where I is the beam current and U_a is the anode potential with respect to the cathode. For guns with flat or concave cathodes, current density inhomogeneity becomes large when the perveance exceeds the value of 1 – 2 μA/V$^{3/2}$. However, electron beams with higher perveance are needed in number of applications where charge or current density is a key parameter. One example is a set-up for compensation of beam-beam effects in high energy colliders [1] where a high-current electron beam needs to be modulated with high duty factor. Another example is electron cooling at low energies, where an increase of beam current at a fixed energy increases cooling rate (see, for instance, [2]). For these and similar cases, where the gun has to be immersed into a strong longitudinal magnetic field, the perveance can be increased by usage of a convex cathode [3]. Prototype of the gun was tested at the “Tevatron Electron Lens” (TEL) prototype set-up at Fermilab [4]. The paper presents results of the gun tests.

2 GUN DESCRIPTION

The mechanical schematic of the gun is shown in Fig.1 and its main parameters are listed in Table 1.

The gun employs a spherical dispenser cathode made by HeatWave (Watsonville, California). A so-called control electrode around the cathode (an analog of the Pierce electrode) is insulated from the cathode and is used for adjusting of the shape of the beam current density distribution. The anode profile is optimised for the maximum smoothness of the radial electric field E_r.

Table 1: Main parameters of the tested gun

Beam diameter in the gun	10	mm
Anode voltage, max	15	kV
Beam current, DC, max	3	A
Beam current, pulsed, max	10	A
Magnetic field on cathode	0.5- 2	kG
Control electrode voltage (with respect to the cathode)	0 - -15	kV
Gun perveance, max	6	μA/V$^{3/2}$

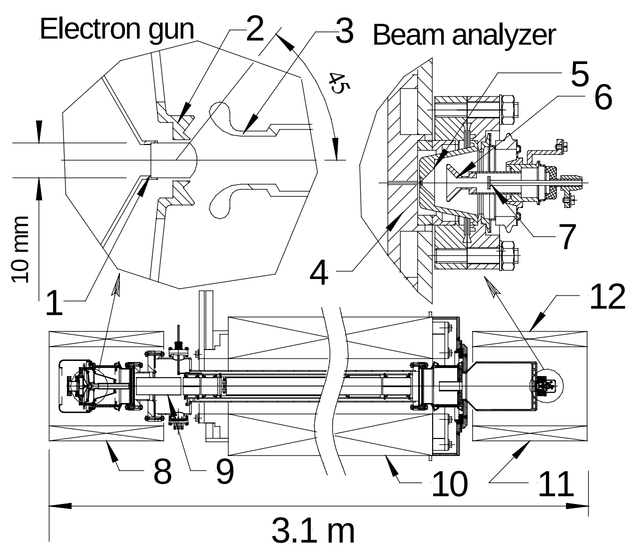

Figure 1: Mechanical schematic of the test bench. Electron gun and the beam analyzer are shown in detail. 1- cathode, 2- control electrode, 3- anode, 4- water-cooled collector bottom with a 1mm hole in the center, 5- diaphragm with 0.6 mm hole, 6- retarding electrode, 7- analyzer collector, 8- gun solenoid, 9- drift tube, 10- main solenoid, 11- collector solenoid.

3 GUN SIMULATION

The gun was simulated and optimised using SSAM code [5] in order to have current density distribution uniform within 10% at gun perveance of 5 μA/V$^{3/2}$. Another important gun parameter is the value of the electron velocity $\vec{V}_t$ transverse to the magnetic field. It is convenient to split the velocity into two components:

$$\vec{V}_t = \vec{V}_d + \vec{V}_c \quad . \tag{1}$$

Here $\vec{V}_d = \frac{\overrightarrow{E_r} \times \vec{B}}{B^2} c$, where B is the strength of the longitudinal magnetic field in the gun and c is the speed of light, $\vec{V}_d$ denotes the drift velocity, and $\vec{V}_c$ is the cyclotron component. In a drift tube, modules of both components are constant while V_t oscillates with the cyclotron frequency. In this case the value of V_d is determined by beam parameters only:

$$V_d = \frac{2Ic}{vRB}, \tag{2}$$

where I is the beam current, v is average z-component of electron velocity, and R is the beam radius. On the contrary, the cyclotron component is a sum of electron thermal velocities and an excitation in a gun, which depends on the gun optics. Peculiarity of the convex cathode gun, an angle α between the magnetic field and the normal to the cathode surface, results in an additional increase of the component by [6]

$$V_s = 4\pi \frac{mc^2}{e} \cdot \frac{j \sin\alpha}{B^2}, \tag{3}$$

where m and ($-e$) are electron mass and charge, and j is the cathode current density.

Results of the simulation are shown in Fig.2. The drift velocity decreases with the magnetic field strength as $1/B$, while the value of V_c drops faster and is close to the estimation by (3). Because the drift velocity can not be eliminated in the gun, it is a natural unit to characterize quality of the gun optics. At $B > 1$ kG, $V_c < V_d$, and the optics does not determine the effective value of beam transverse velocities.

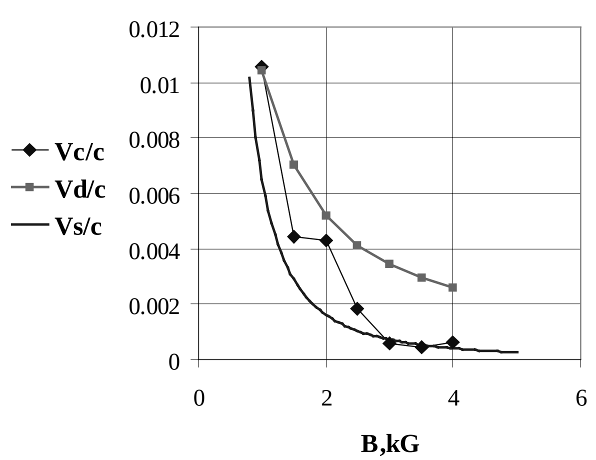

Figure2: Results of simulation of the drift and cyclotron components at U_a= 10 kV, I= 5A without taking into account electron thermal velocities. The curves represent maximum values throughout the beam in the drift tube.

4 TEST BENCH

Gun characteristics were measured at a test bench (Fig.1) used at Fermilab for prototyping of TEL elements [4]. The test bench consists of the gun immersed into longitudinal magnetic field B_{gun} of 1- 2 kG generated by a gun solenoid, a drift tube with diagnostics placed inside 4 kG, 2 m long main solenoid, and a collector, also inside a separate solenoid. The collector is equipped by a beam analyzer, similar to ones described elsewhere [6]. A small (∅ 0.6 mm) hole in the collector bottom cuts from the electron beam a narrow part, which passes through a retarding electrode and is absorbed by an analyzer collector. To measure the current density distribution, the beam is moved with respect the hole by steering coils placed inside the main solenoid, and the analyzer collector current I_{ac} is recorded as a function of the beam transverse position

If the potential of the retarding electrode with respect to the cathode U_r is close to zero, only electrons with a high enough longitudinal momentum $P_{\parallel}$ reach the analyzer collector. Derivation of the measured function $I_{ac}(U_r)$ gives an electron distribution over a “longitudinal energy” $E_{\parallel} = \frac{P_{\parallel}^2}{2m} - eU_r$.

5 RESULTS OF MEASUREMENTS

Except high perveance, the gun is not much different from a planar cathode gun. The beam current follows the Child’s law with a good precision (Fig.3).

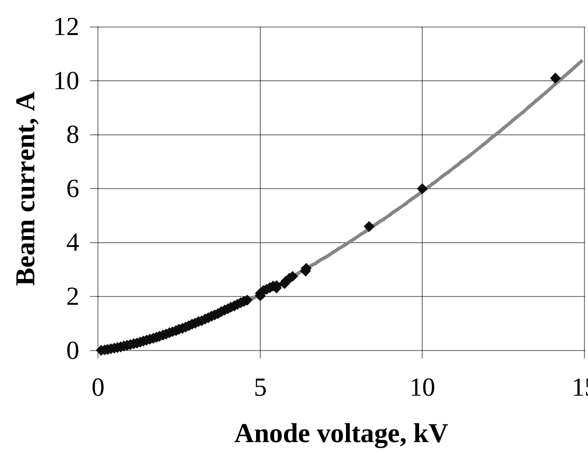

Figure 3. Beam current as a function of the anode voltage. Magnetic field is 2 kG, $U_{ce} = 0$. Diamonds represent experimental points, and the solid curve shows the fit with $P = 5.9 \mu A / V^{3/2}$.

For the TEL project it is important to control a current density distribution. The distribution needs to be adjustable preferably from nearly uniform to a bell-like shape [1]. One can do it by regulation of the control electrode voltage U_{ce} (Fig.4). At equal control electrode and cathode potentials ($U_{ce} = 0$), the measured gun perveance of 5.9 is slightly higher than 5.0 found in the simulation. Edge peaks in the current density profile indicate, and computer simulations confirm, that the reason is some 0.4 mm protrusion of the emitted surface from the control electrode with respect to its optimum position. The shift occurs because of either uncertainty in the thermal expansion of the cathode or mechanical error. Probably, a slight current distribution asymmetry, seen in Fig.4, is because of an asymmetric misalignment.

The effect can be corrected by applying a small negative voltage to the control electrode. With the perveance decreased to its nominal value, the current density variation in the beam is about 10 %. With further increase of the absolute value of U_{ce}, the beam profile approaches to bell shape.

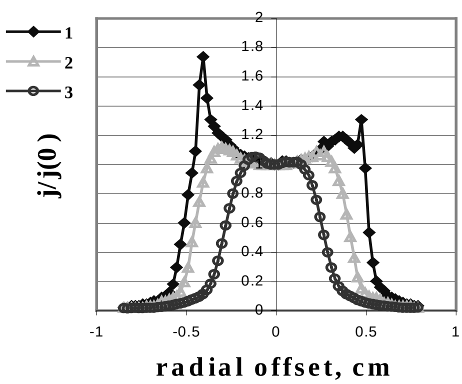

Figure 4: Current density distributions for three control electrode voltages: 1- $U_{ce} = 0$, I= 1 A; 2- $U_{ce} = -0.3$ kV, I= 0.6 A, 3- $U_{ce} = -1.2$ kV, I= 0.16 A. U_a= 3 kV, magnetic field in all solenoids 2 kG.

Measured distributions of the longitudinal energy of electrons are close to the Gaussian one:

$$\frac{dI_{ac}}{dE_{\|}} = \frac{1}{\sqrt{2\pi}} \cdot \frac{I_{ac0}}{\delta W} \cdot \exp\{-\frac{(E_{\|} - E_0)^2}{2\delta W^2}\}, \quad (3)$$

where I_{ac0} is the maximum value of the analyzer collector current typically measured at the potential of the retarding electrode equal to 100 V with respect to the cathode. The energy spread δW, measured in the beam center, depends on the beam current in a good accordance with known formulae, describing relaxation in the beam [8], in the entire range of measured beam currents (see Fig.5).

At currents below 0.2 A, the measurements of E_0 were performed also near the beam periphery. The results were equal to ones obtained in the beam center within precision of measurements, which was about 1 V. The fact implies that the possible “transverse energy” acquired in the gun was below 1eV.

To prevent thermal problems at the irradiated surface, profile and temperature measurements were done in the DC regime only at currents below 0.5 A. The maximum current in the DC operation, 3 A, was reached in the regime with a decreased collector magnetic field and was limited by the collector cooling system. The gun behaviour at higher currents was investigated in a pulsed regime with the pulse width of 0.2-1 μs. No significant deviation from results of simulations and DC measurements was found.

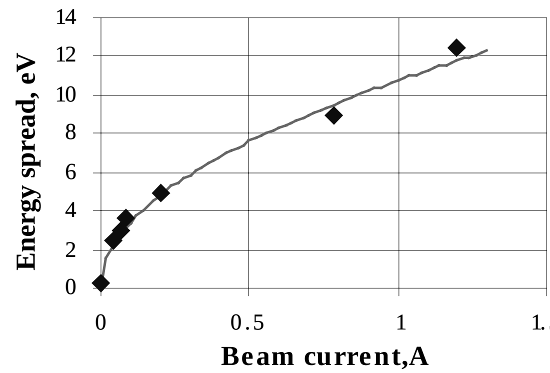

Figure 5: Energy spread as a function of the beam current. Magnetic field is 2 kG, solid line corresponds to the fit $\delta W[eV] = 10.8 \cdot \sqrt{I[A]}$.

6 CONCLUSION

Results of simulations and measurements show that the gun with a convex cathode emits a homogeneous beam with perveance of about 5 $\mu A/V^{3/2}$. The gun perveance changes less than 5% in the range of beam currents of 0.1-10 A at the magnetic field strength of 2 kG. Additional transverse temperature because of the specific cathode geometry does not exceed 1 eV at the beam current of 0.2 A and field strength of 2 kG.

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