A NOVEL ELECTRON GUN FOR OFF-AXIS BEAM INJECTION*

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Abstract

For certain type of electron accelerators injection from an off-axis cathode is required. This is the case of a race-track microtron (RTM), in which the beam passes several times through the accelerating structure, or of a high power standing wave electron linac, for which the lifetime of an on-axis cathode would be strongly reduced by the electron back-bombardment. The standard solution with the beam injection via a dipole magnet from an electron gun placed off-axis is too bulky, moreover in case of RTMs it requires special compensating dipoles. An annular ring cathode gun used in some accelerators leads to large beam emittance and divergence. As a new solution we describe a 3D on-axis electron gun with an off-axis cathode and a central hole for the beam passage. Results of the design optimization and performance of an electron gun built for a miniature 12 MeV RTM for medical applications are presented. We also discuss results of the beam parameters measurements and estimates of the beam emittance.

INTRODUCTION

A compact race-track microtron (RTM) with the maximal output energy 12 MeV is under construction at the Technical University of Catalonia in collaboration with the Skobeltsyn Institute of Nuclear Physics of the Moscow State University, CIEMAT and a few Spanish industrial companies and medical centers [1].

To implement a compact injection scheme for this RTM an on-axis electron gun of a novel design with cathode placed off-axis was suggested and studied in simulations, and its prototype version was successfully tested experimentally [2]. A schematic view of the gun geometry is shown in Fig. 1.

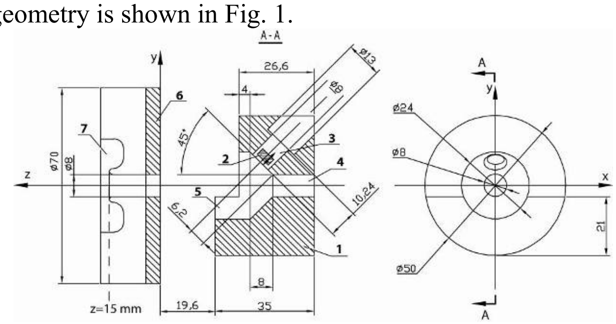


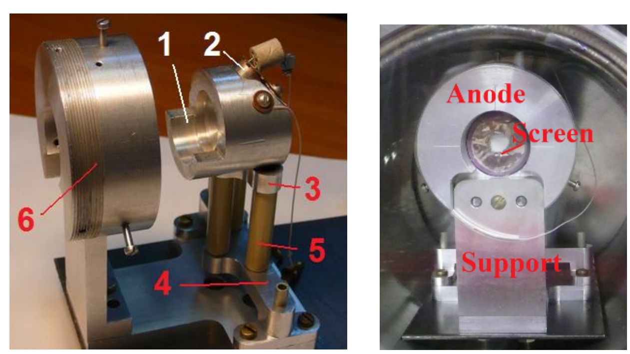
Figure 1: Electron gun geometry [2]. 1- focusing electrode, 2 – cathode, 3 – cathode seat hole, 4 – beam hole, 5 – beam directing bulge, 6 – anode plate, 7 – first linac cell.

The electron gun prototype was providing a 25-30 mA pulsed beam current at 25 kV with the beam radius at the entrance to the first linac less than 1 mm, as it is required by design specifications. However it could not be installed in RTM directly because a few issues had still to be resolved. First, because of a specific vacuum chamber design, inside which the electron gun must be placed, special high voltage isolating gun supports must be designed and built. Second, because of an asymmetry inherent to the gun geometry the beam had a highly asymmetrical halo which would produce an unwanted parasitic radiation during acceleration. Third, in order to get a sufficiently smooth approach of the beam to the linac axis the geometry of the gun electrode must be slightly modified. Finally, for beam dynamics simulation with realistic beam data measured values of the beam emittance estimation are required.

In the present paper we describe some aspects of the engineering design of the final version of the electron gun for the 12 MeV RTM and results of measurements of characteristics of the generated beam.

ELECTRON GUN DESIGN

The final engineering design of the electron gun was carried out in parallel to the RTM design. Its transverse and longitudinal dimensions were adjusted according to the beam trajectory and position of adjacent RTM elements. The final version of the electron gun is shown in Fig. 2(a). Its focusing electrode (1) with cathode (2) is precisely fixed via plate (3) at three ceramic isolating rods (5) attached to aluminium support (4). The support has fixing holes for its precise positioning on a common supporting platform at which all RTM elements are placed.



(a) (b)

Figure 2: (a) Electron gun test assembly; (b) Test assembly installed inside a vacuum chamber.

Gun operation and measurements of its characteristics were carried out at a special assembly also shown in Fig. 2(a). It includes the gun itself and test anode (6) both fixed at a common support. The anode diameter and the diameter of the anode beam hole are chosen to be the same as those of the RTM linac. The test assembly is placed inside a test vacuum chamber (see Fig. 2(b)) with a

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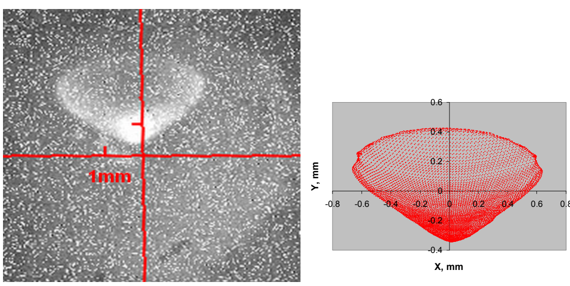
large glass window and a high voltage vacuum feedthrough. The chamber is also equipped with a 20 μm Ti foil to absorb the electrons which can be positioned at the beam axis at different distances from the anode edge to allow beam emittance measurements. The electric signal from the foil is received through a feedthrough. The foil side opposite to the impinging beam is covered by a phosphor layer sensitive to X-rays and can be viewed by a CCD camera. To feed the gun a high voltage modulator with the pulse length about 10 μs and repetition frequency varied in the range 1-50 Hz is used. It also provides the filament heating power. This regime of operation corresponds to that of the RTM.

ELECTRON GUN TUNING

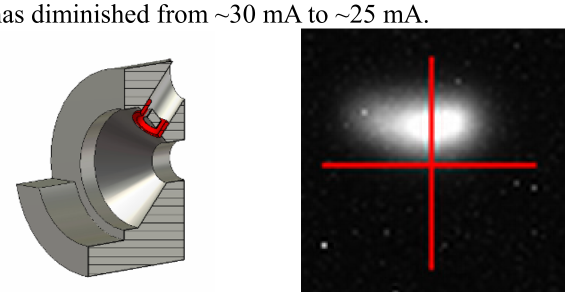
The geometry of the focusing electrode of the initial design and of the prototype version is shown in Fig. 1, the corresponding measured and simulated beam images are given in Fig. 3. As one can see, there is a considerable halo and the measured beam centre position is shifted upwards with respect to the axis for about 0.8 mm.



(a) (b)

Figure 3: Registered and calculated beam image.

As a result of computer simulations it was found that the beam halo can be eliminated by placing a cylindrical conducting insertion in the cathode seat hole (see Fig. 4(a)) which produces a field with a local axial symmetry with respect to the cathode axis. The beam image registered after the installation of the insertion and optimization of its dimensions is shown in Fig. 4(b). We would like to note that in this case, due to a decrease of the field strength at the cathode surface, the gun current has diminished from ~30 mA to ~25 mA.



(a) (b)

Figure 4: (a) Insertion in the cathode seat hole (shown in red). (b) Image of the beam from the gun with the insertion. The total length of each of the reference bars is 4 mm.

From computer simulations it was also found that to shift the beam position for 1 mm down towards the axis (see Fig. 3(a)) the length of the focusing electrode bulge must be decreased for about the same value. To check this we first cut the bulge for only 0.6 mm, as it is shown in Fig. 5(a). For a precise detection of the beam position shift the beam was generated at the maximal modulator repetition frequency which was sufficient for the beam to burn a hole in the foil (see Fig. 5(b)). The upper hole was burnt with the initial electrode design, the lower one after the bulge cut. As one can see, the beam position has shifted for about 0.6 mm well in accordance with the simulation prediction. After that the bulge has been cut for 0.2 mm more and the beam centre has set onto the horizontal axis.

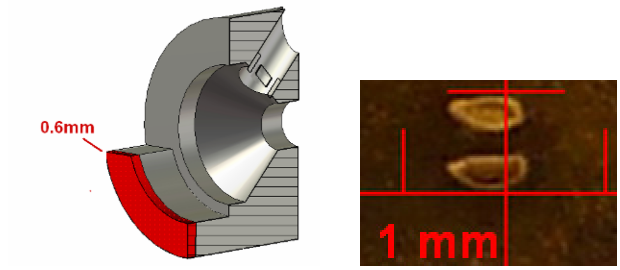


Figure 5: (a) Bulge cut which leads to the beam position shift downwards, (b) the holes burnt by the beam before and after the bulge cut.

BEAM PARAMETER MEASUREMENTS

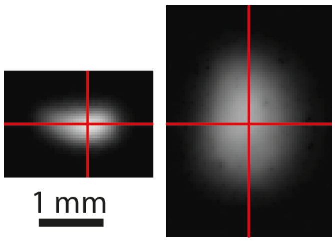
Estimates of rms beam parameters were done with the assumption that the beam had normal particle distribution in the horizontal and vertical transverse phase spaces and was described by rms ellipses and that the effect of the space charge forces on the free-space beam propagation was negligible.

Let $\beta_{x,0}, \alpha_{x,0}, \gamma_{x,0}$ be horizontal optical functions (ellipse parameters) at some point $z=z_0$ of the beam trajectory satisfying the standard relation $\beta_{x,0}\gamma_{x,0} - \alpha_{x,0}^2 = 1$. Then the rms beam size x_{rms} at some points z_i, $i=0,1,2..N$ satisfies

$$x_{rms}^2(z_i) = \beta_x(z_i)\varepsilon_{x,rms} = \\ = \varepsilon_{x,rms}\left[\beta_{x,0} - 2(z_i - z_0)\alpha_{x,0} + (z_i - z_0)^2\gamma_{x,0}\right] \quad (1)$$

(see, for example, [3]), where $\varepsilon_{x,rms}$ is the rms beam emittance in the x-plane. Similar equations can be written for the y-plane. By measuring the rms beam sizes at least at three points and solving system of equations (1) the rms ellipse parameters at z_0 and rms emittances can be obtained.

This procedure was applied by placing the Ti foil at z_0 = 15 mm, z_1=30 mm and z_2=45 mm from the anode edge. Note, that z_0 = 15 mm corresponds to the position of the entrance nose tip of the first accelerating cell of the RTM linac (Fig. 1) where the focusing force acting on the low energy injected beam is the strongest and where the minimal beam dimensions are required. In Fig. 6 filtered beam images registered at z_0 = 15 mm and z_2=45 mm are shown. The filtering was used in order to remove a noise from the CCD matrix defects. With the data in the image binary file the rms horizontal and vertical beam dimensions at the measurement points were determined and the rms emittances and rms ellipse parameters at z_0 = 15 mm were found. These results together with parameter values obtained in the computer simulation are listed in Table 1.



(a) (b)

Figure 6: Filtered beam images at the distance 15 mm (a) and 30 mm (b) from the anode edge.

Table 1: Measured and Simulated rms Beam Parameters

Parameter	Measured	Calculated
$\varepsilon_{x,rms}$ mm mrad	1.38	0.72
$\varepsilon_{x,rms,norm}$ mm mrad	0.44	0.23
$\alpha_{x,0}$	-0.23	1.87
$\beta_{x,0}$ mm/mrad	0.08	0.07
$\varepsilon_{y,rms}$ mm mrad	2.22	0.81
$\varepsilon_{y,rms,norm}$ mm mrad	0.71	0.26
$\alpha_{y,0}$	-0.36	1.31
$\beta_{y,0}$ mm/mrad	0.01	0.01

As one can see from Table 1 the measured normalized rms emittances are quite small, less than 1 mm mrad, however they are about 2-3 times larger than the calculated values. The main reason for the discrepancy between the measured and calculated emittances can be a strong deviation of the phase space distributions from the normal ones with the elliptical boundary. In addition, the distribution in the y-plane is highly asymmetric. These discrepancies suggest that the method of the emittance reconstruction used here is too rough. Nevertheless, from the obtained results we can conclude that both the measured and calculated emittances are small enough, that the crossover of the emitted beam is at the required point and that the beam dimensions at the crossover fully satisfy the RTM beam dynamics requirements.

After the completion of the tests the electron gun was installed on the supporting platform inside the RTM vacuum chamber, as it is shown in Fig. 7.

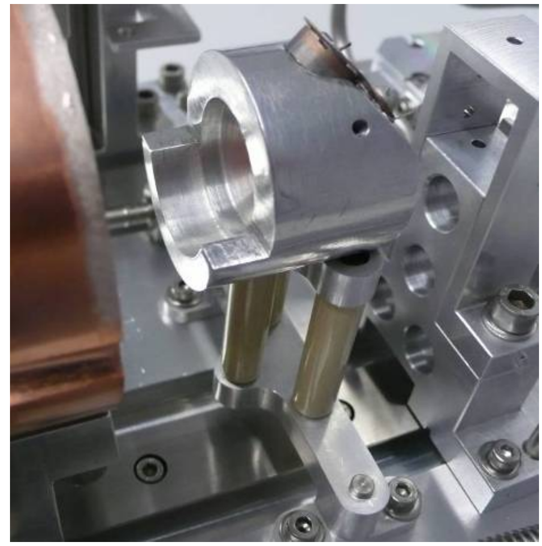


Figure 7: The electron gun installed on the RTM supporting platform.

CONCLUSIONS

The engineering design of the definite optimized version of the electron gun for the compact RTM has been carried out. Its parts were manufactured and the gun was assembled and tested at a special stand. The results of the tests show that the electron gun fulfills required specifications. Also the vertical and horizontal emittances and beam ellipse parameters at the position of the first linac cell entrance were measured. The experimental values differ considerably from the simulated ones, most likely due to a non-Gaussian character of the particle phase space distribution of the emitted beam. Finally, the electron gun was installed inside the vacuum chamber of the RTM.

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