

Electron beam tests for a slow positron spectrometer

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Preliminary tests for a future slow positron accelerator have been performed in order to find out the best setup for the electromagnetic and geometrical parameters used to confine, transport and accelerate the positron beam. This study combines the development of beam transport simulation models by IES LORENTZ EM software with beamline experiments, in order to improve the understanding of the properties of the extracted particles. The simulation of the beam extraction from an electron source is particularly challenging and interesting, as the initial density distribution at extraction is unknown. By combining magnetic field tracking, experimental measurements and beam diagnostics, we were able to predict beam patterns. Simulation results are in good agreement with the experimental observations. This powerful and sensitive spectrometer offers the possibility for the characterization of advanced materials, by putting in evidence open volumes, nanovoids or point defects concentration and type.

(Received July 30, 2012; accepted September 20, 2012)

Keywords: Electron beam, Slow positron accelerator, Positron Annihilation Spectroscopy

1. Introduction

Positron Annihilation Spectroscopy (PAS) is a nondestructive and noncontact spectroscopic technique that enables materials research studies, providing in some cases a higher sensitivity than electron microscopy [1–4]. Due to the continuous kinetic energy spectrum of the β^+ radionuclides, defects depth profiling of the samples can be made only by using monoenergetic positron beam with adjustable energy [5]. In order to reduce as much as possible the radiation level during the positron accelerator debugging period, we built an electron source. This source delivers electrons with a kinetic energy which can be adjusted between 0.1 and 12 keV. The idea of using an electron gun to debug a slow monoenergetic positron accelerator came from the fact that the behavior of the positrons emitted by a moderator material is similar to the one of the electrons originating from thermal emission of a tungsten filament [6, 7].

The positron beam diagnosis, especially for establishing the magnetic confinement parameters, is crucial for conducting PAS studies. Even if several slow positron accelerators are functioning worldwide [8, 9], our laboratory is the first and the only one in Romania to design and develop such a facility [10]. The main motivation for developing a PAS facility is represented by the high-tech materials characterization – detection of open volumes, nanovoids and the point defects. The electronic, optic and the electric properties of the advanced materials are sensible to the presence of point defects [11]. The investigation of these types of defects in metals,

semiconductors, polymers, mesoporous glasses, etc. is straightforward using PAS [12–14].

In this work, we used the IES LORENTZ EM computer program for modeling the effect of electric and magnetic fields on the motion of charged particles [15, 16]. The electron and positron beam transport was modeled and the resulting geometric and electromagnetic parameters are consistent with the experimental measurements carried out using a homemade electron source.

The developed spectrometer is a unique tool, intended to be used for detecting the nano-sized open volume defects present in different type of materials [17–20].

2. Experimental details

2.1 Electron source

The electron source consists of a tungsten filament and three electrodes: a Wehnelt cap (W), an accelerating electrode (A) and a convergent lens (L). The anode or the accel electrode is biased at 400 V, while the convergent lens or the decel electrode is held at 0 V, resulting in an accel – decel structure meant to keep the electron beam energy fixed at 100 eV. The shape of each electrode and the geometric arrangement were obtained using IES LORENTZ EM software. Ceramic muffs were used to insulate the three metallic rods which maintain the optimum distance between the electrodes and ensure their alignment. The electrons are emitted by a tungsten V shaped filament fixed into a ceramic cylinder which was

placed coaxially inside the stainless steel Wehnelt cap (Fig. 1).

For a preliminary beam diagnosis it was used a classic setup consisting in: a four-way stainless steel (316LN) cross (CABURN DN100CF), two cylindrical solenoid coils, power supplies, Keithley 6485 Picoammeter, a copper electron collector with manipulator and a vacuum system. One of the end-ports of the cross is closed by a metallic flange which holds the tungsten filament, all three electrodes and the multi-pins electrical feedthrough. A lateral port is used as the viewing port and the opposite one serves as a holder for the copper collector which is also electrically connected to the feedthrough. The pressure inside the cross is maintained at $\sim 5 \times 10^{-6}$ mbar using a turbomolecular pumping station.

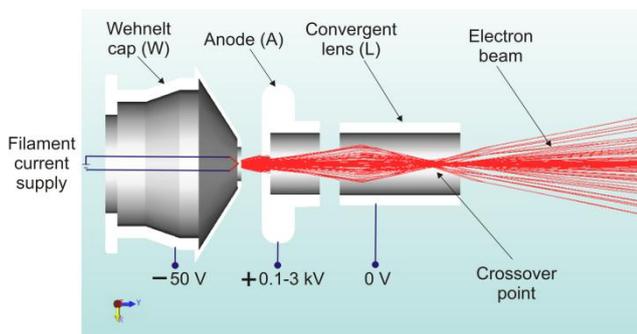


Fig. 1. Electron source schematic diagram and IES LORENTZ EM modeling for a 400 V voltage drop on the anode.

2.2 Structure modeling

The IES LORENTZ EM software is modern charged particles simulation software that can be easily used to calculate charged particle trajectories in the presence of electric and/or magnetic fields. The discretized model was used to generate field solutions as inputs to Ordinary Differential Equation solvers that compute the particles trajectories.

Child's law emission regime can be used for charged particles simulations in various fields as electron guns, ion sources and vacuum tubes. Subsequently, in the submitted simulation the Child's law emission regime has been chosen, neglecting, for simplicity in the calculations of Laplace equations solutions, the space charge effects. Therefore, the net space charge in our model was not affected by the charge of the emitted particles, otherwise the space charge distribution should be determined from electrons motion [16, 21].

The maximum current measured between the Wehnelt cap and the anode was $\sim 500 \mu\text{A}$. We have considered the Child's law which describes the current density of thermionic emission. The Child's Law important assumption is that the particles are initially accelerated from emitter's surface with zero velocity.

$$j = \frac{\varepsilon}{q\pi} \sqrt{\frac{2e}{m}} \frac{V^{3/2}}{d^2} \quad (1)$$

In the formula (1): $\frac{\varepsilon}{q\pi} \sqrt{\frac{2e}{m}} = 2.33 \times 10^{-6}$, j represents current density, V is the potential difference between anode and cathode, and d is the distance between anode and cathode.

In order to determine the crossover point for the electron beam, which gives the smallest beam spot diameter, we have defined an emitter structure (length ~ 4 mm), which mimics well enough the tungsten V shaped filament.

In the modeled structure all three electrodes (W, A and L – as defined in Fig. 1) are considered collectors in IES LORENTZ EM, resulting the electron absorption after collision with these parts of the system.

2.3 Experimental measurements

The beam current was measured on a copper collector which was mounted at a 345 mm distance from the emitting filament. The collector can be moved perpendicular to the beam axis by using a linear manipulator. In this way the electron beam profile was acquired (Fig. 2).

To avoid measuring the secondary electrons, a positive voltage (+45V) was applied on the Cu collector by a battery.

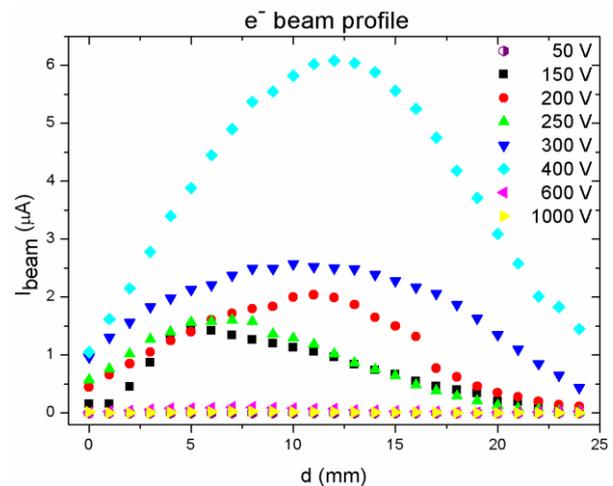


Fig. 2. Electron beam profiles measured at different anode voltages.

From Fig. 2 one can notice that the most efficient accelerating voltage, in the present electron source geometry is 400 V, for which we measured a maximum beam current of $\sim 6 \mu\text{A}$. Also an energy profile of an electron traveling between the tungsten filament and the first copper collector is presented in the Fig. 3.

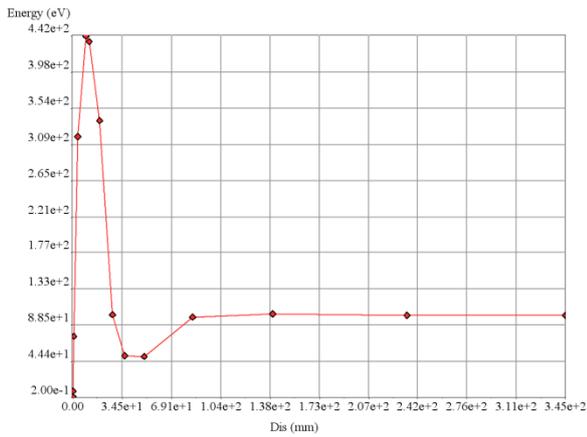


Fig. 3. IES LORENTZ EM energy profile of an electron versus the distance between the emission point (tungsten filament) and the first copper collector.

Building a slow positron accelerator requires a setup where the beam is bent at a certain angle, which proved to be 90° in our case (Fig. 4). The reason for this bending is the necessity to reduce as much as possible the background of gamma rays, emitted by the primary positron source, in the sample chamber area.

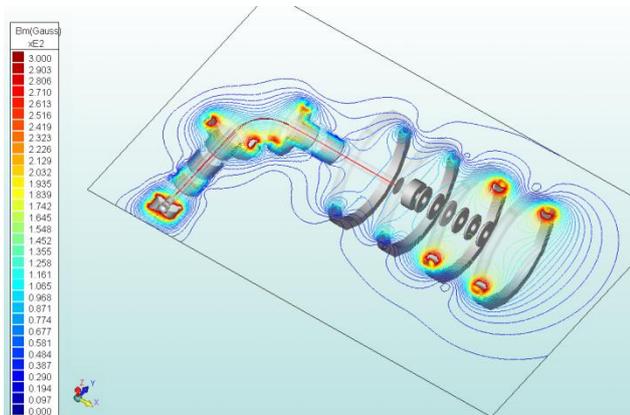


Fig. 4. Screenshot from the IES LORENTZ EM modeling for 90° electron beam bending, showing the equipotential lines of the magnetic flux density generated by ten coils guiding the electron beam (red curve).

For bending the electron beam, a perpendicular magnetic field was used [22]. To generate the magnetic field (~ 300 G) we used two Helmholtz pairs and six circular magnetic coils arranged in such a manner that the beam axis will pass through the center of each coil (Fig. 4). Equipotential lines for the magnetic flux density are also represented in the figure above together with a color scale.

A more detailed map of the ten coils is shown in the Fig. 5 where is also represented the location of the electron collector used to measure the beam current after bending.

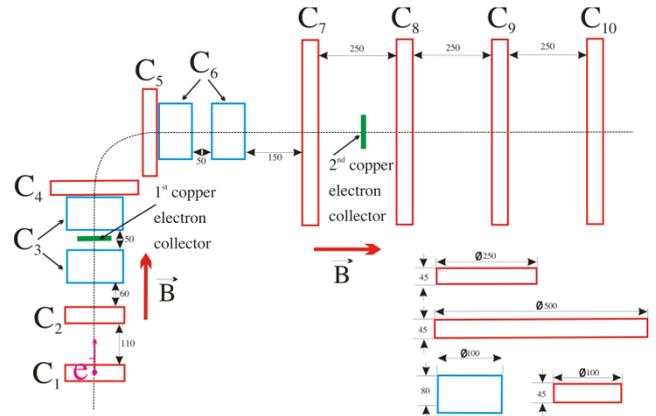


Fig. 5. Coils map schematics.

After carefully tuning the currents through the coils (Table 1), we recorded a $5 \mu\text{A}$ beam current on the second electron collector positioned between coil C_7 and coil C_8 (Fig. 4). C_3 and C_6 are two identical pairs of coils, each pair sharing the same power supply. Coils C_7 - C_{10} form two Helmholtz pairs.

We also performed an optical diagnosis of the electron beam by replacing the second copper collector with a plastic scintillator. One side of the scintillator was covered with a thin aluminum film (10 nm) and a metallic grid was placed in front of the film with respect to the electron beam propagation at a distance of 1 mm.

Table 1. The parameters of the solenoid coils.

Coil number	Radius (mm)	Length (mm)	Current (A)
1	50	45	5.5
2	50	45	3
3	50	80x2 coils	1
4	125	45	3.5
5	125	45	4.4
6	50	80x2 coils	2.2
7	250	45	3.5
8	250	45	4
9	250	45	5
10	250	45	5

By applying an electrical potential difference between the Al film and the metallic grid, the electrons gain energy in a uniform electric field up to 12 keV. The accelerated electrons can excite the scintillator which emits a blue light (Photo 1).

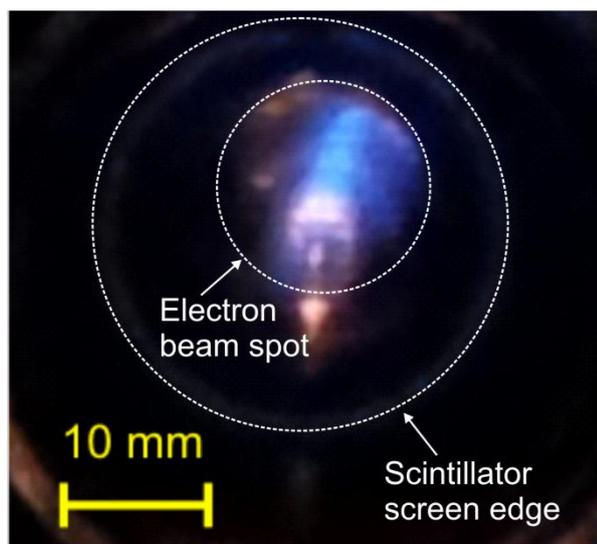


Photo 1. View of the electron beam spot ($E_e = 12 \text{ keV}$). The photograph is recorded from the plastic scintillator installed between coil C_7 and coil C_8 .

3. Results and discussion

A homemade electron source was developed to replace a primary positron source (^{22}Na , ^{18}F , ^{58}Co , etc) during the debugging period of the slow positron accelerator.

From Fig. 2 it can be seen that the maximum electron beam current was recorded for an accelerating voltage of about 400 V. Experimental measurements are in good agreement with the IES LORENTZ EM simulations, confirming that the electron beam spot (Photo 1) has a ~ 12 mm diameter. In the next stage, quadrupole magnets and einzel lenses will be installed for a better confinement of the electron beam. The replacement of the electron gun with a β^+ radioisotope opens many possibilities regarding the characterization of the advanced materials.

4. Summary and conclusions

In this paper, we report the installation, the beam confinement and guidance tests for a state-of-the-art slow positron accelerator. By carefully tuning the simulation parameters, we succeeded to determine the current values for the ten coils used for the electron beam guiding.

In the next stage, a pulsed beam for Positron Annihilation Lifetime Spectroscopy (PALS) [23-25] studies will be designed and implemented.

Acknowledgements

This work was carried out under POSDRU/88/1.5/S/56668 research project funded by the Romanian Ministry of Education and the UEFISCDI and under the COST action COINAPO MP 0902.

We are thankful to dr. Florin Constantin from the IFIN-HH for his valuable suggestions in the development of this slow positron beam facility.

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