EXPERIMENTAL STUDY OF ENERGY SPREAD IN A SPACE-CHARGE DOMINATED ELECTRON BEAM *

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Abstract

Characterization of beam energy spread in a space-charge dominated beam is very important to understand the physics of intense beams. It is believed that coupling between transverse and longitudinal direction via Coulomb collisions will cause an increase of the beam longitudinal energy spread. At the University of Maryland, experiments have been carried out to study the energy evolution in such intense beams. To measure the energy spread, a high-resolution retarding field energy analyzer has been developed. In this paper, we present the initial experimental results using this energy analyzer. The temporal beam energy profile along the beam pulse has been characterized at the exit of the electron gun. It is the first time that we measure the energy profile of the head and tail of the bunched beams in the experiment. The measured mean energy variation along the beam pulse is in excellent agreement with direct measurement of the cathode-grid pulse waveform. The measured rms energy spread is very close to the theoretical prediction of Coulomb scattering.

1 EXPERIMENTAL SETUP

The experimental setup as shown in Figure 1, consists of a gridded thermionic electron gun, a solenoidal magnetic lens and a diagnostic chamber. The energy analyzer is located in the diagnostic chamber after a solenoid. The solenoid is used to control the beam current into the energy analyzer. The distances of the solenoid and energy analyzer from the gun are 11 cm and 24 cm, respectively. The magnetic fringe field extends less than 10 cm from the solenoid center, so magnetic field has no influence inside the energy analyzer and electron gun.

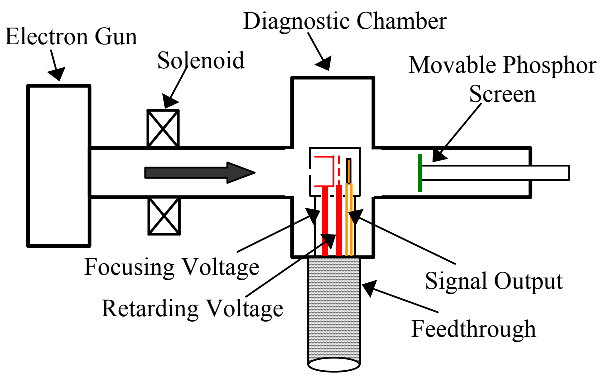

Figure 1. Experimental Setup

The energy analyzer as shown in Figure 2 is cylindrical with a focusing electrode that is insulated with the retarding mesh. The focusing voltage on the focusing cylinder is independently adjustable to provide proper focusing strength to overcome the defocusing force due to space-charge force and beam trajectories etc. A collector is located downstream of the retarding mesh. We developed a computer-controlled automated system. By automatically controlling the retarding voltage and oscilloscope this system can take the energy analyzer data with very fine step. The smallest step to change the retarding voltage is 0.16 V on top of several kilo volts. In the ground shielding there is a 2mm diameter pinhole at the front for beam entry. With a diameter of 5.1 cm and a length of 4.8 cm, this energy analyzer can be easily inserted at any place in the beam line. The energy analyzer can be aligned by a linear feedthrough with three connectors for retarding voltage, focusing voltage and output signal respectively. We also have the ability to insert a movable phosphor screen into the plane of the energy analyzer so that we may obtain an image of the beam at that axial position.

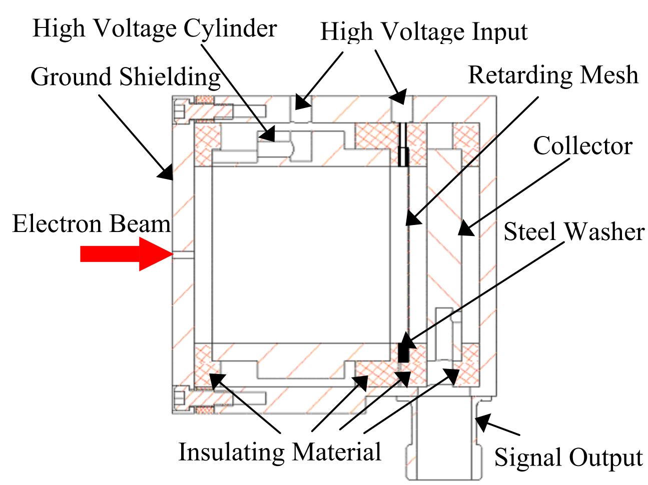

Figure 2. Schematic of the energy analyzer with variable-focusing cylindrical electrode

2 EXPERIMENTAL RESULTS AND ANALYSIS

In the experiment, the nominal beam energy is 5 keV and beam current is 135 mA with pulse width 100ns and

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rise time 2ns. Figure 3 shows different signal profiles corresponding to different retarding voltages. For a given retarding voltage, 16 current pulses are sampled and averaged to remove noise effect. The signal from the energy analyzer (~10mV) is deliberately generated by a small injected beam current (~ 0.2mA) to avoid the space-charge effect in the energy analyzer [1,2]. The focusing voltage is set to 120V to measure the optimum energy spread [2]. The wiggles on the waveform may be related to the oscillation of the virtual cathode formed in the energy analyzer and other effects.

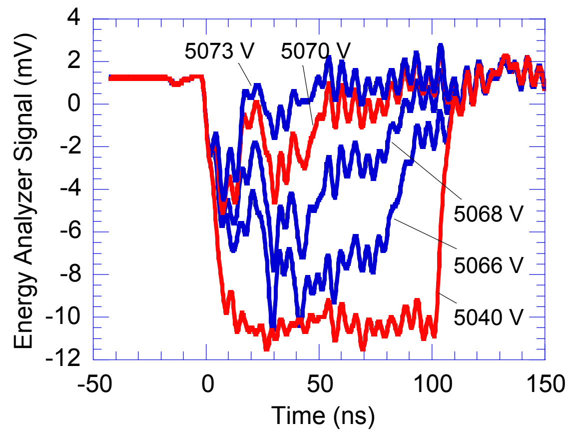

Figure 3. Energy analyzer outputs at different retarding voltages

By differentiating the energy analyzer output with respect to the retarding voltage, we can get the beam energy profile information at a given time in the pulse. Figure 4 shows the energy distribution function curve taken at mid-pulse. From the energy distribution function, we can get temporal mean energy and rms energy spread along the beam pulse.

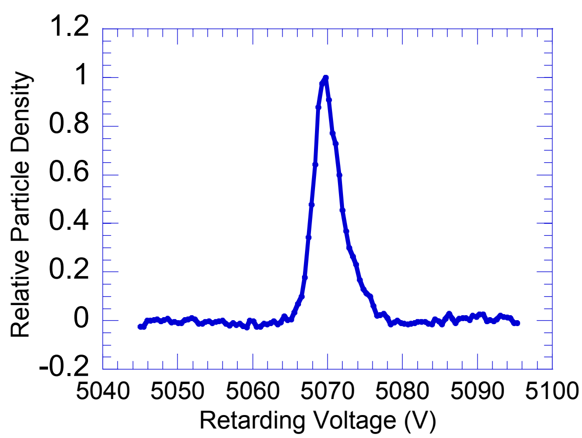

Figure 4. Beam energy spectrum for a beam with energy of 5 keV and current of 135 mA. The rms energy spread is 2.2 eV

Figure 5 shows the measured mean energy as a function of time along the beam pulse. The measured mean energy of the main beam is about 5070 eV. This is 50 eV higher than the beam energy from the gun. It is believed that this DC energy shift is due to the use of mesh and focusing voltage in the energy analyzer. The head of the beam with a length of about 6 ns has a higher mean energy, up to 5200 eV. The tail of the beam with about the same 1ength has a lower energy, down to 4940 eV. The head and the tail of the beam are caused by the longitudinal space-charge effect in the bunched beam [3]. It is the first time that we clearly observed the temporal mean energy information including the head and tail along the beam pulse in the experiment.

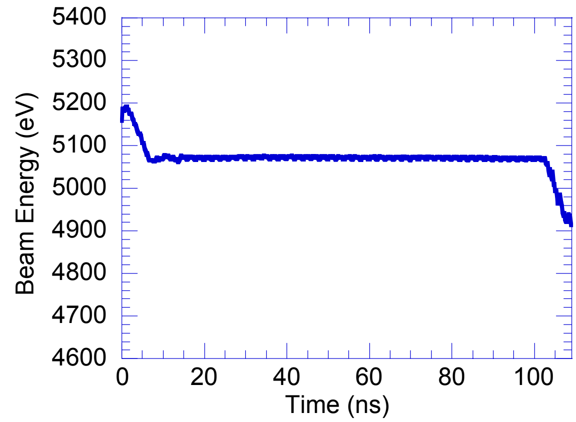

Figure 5. Mean energy along the beam pulse for a beam with energy of 5 keV.

When we zoom out to see the Figure 5, we note the mean energy of the beam has an about 4 eV droop from 30 ns to 100 ns in time region as shown in Figure 6 in the solid line. This is due to the droop in the cathode-grid pulse, as shown in Figure 6 in the dotted line, when we directly measure the pulse waveform between cathode and grid in the electron gun. Although the measured pulse waveform has some noise due to high voltage probe's resolution, we still can see the excellent agreement using two experimental methods. The energy analyzer has better resolution (<0.25eV) than the high voltage probe when measuring beam mean energy.

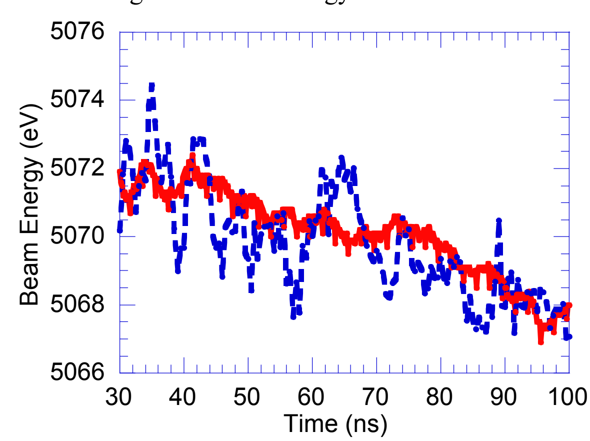

Figure 6. Zoomed mean energy along beam pulse (red solid line) compared with pulse voltage between cathode and grid of the electron gun (blue dotted line).

Figure 7 shows the measured energy spread as a function of time along the aforementioned beam. It is clear that there is higher energy spread at the beam head. The energy spread decreases from ~12 eV at the head to ~

2.2 eV at the main beam, then goes up at the tail of the beam. The wiggle in the head of the beam may be caused by plasma oscillation with a plasma period of ~ 5 ns. When beam energy and other experimental condition are kept the same except that the beam current reduced to ~ 13 mA by decreasing the aperture size in the electron gun, the temporal energy spread of the beam drops from ~10 eV at the head to ~ 1.7 eV of the main beam as shown in Figure 8. We note there is no wiggle in the small current case.

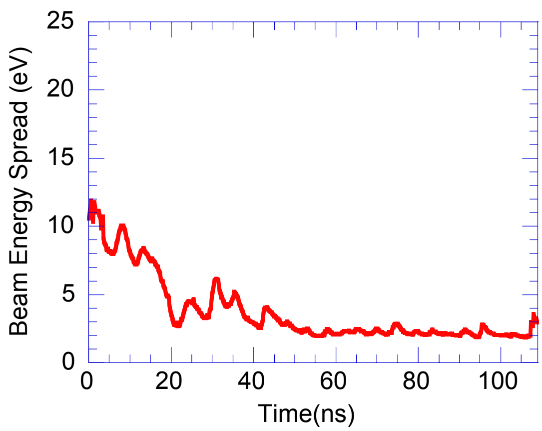

Figure 7. Beam Energy Spread Along Beam Pulse for a beam with energy of 5 keV and current of 135 mA. Average energy spread of the main beam is 2.2 eV

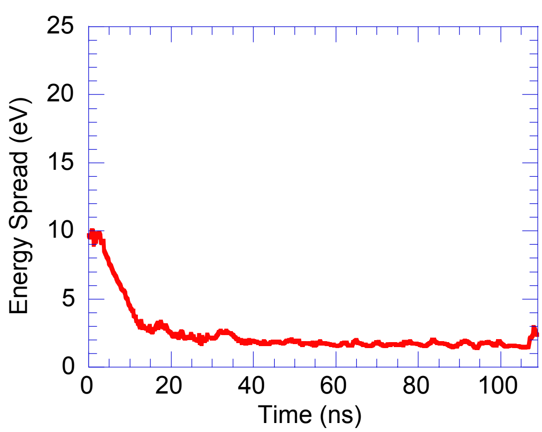

Figure 8. Beam Energy Spread Along Beam Pulse for a beam with energy of 5 keV and current of 13 mA. Average energy spread of the main beam is 1.7 eV

It is very interesting to compare the measured energy spread with theoretical prediction considering the longitudinal-longitudinal effects and the Boersch effect [4,5,6]. According to the theoretical prediction, the rate of evolution of energy spread depends on the current density of the beam. A Higher current density makes energy spread in the longitudinal direction increase faster via Coulomb collisions and other effects after the beam is accelerated. In our experiment, beam energy is 5 keV and beam current is 135 mA. Current density of the beam can be varied by changing the focusing strength of the solenoid. When we use weak focusing, the measured energy spread is ~2.2 eV, which is very close to theoretical prediction, ~2.0 eV. However, when we use strong focusing and get high current density, the measured energy spread increases to ~2.5 eV, also very close to theoretical prediction, ~2.6 eV. We also measured the energy spreads with beam energies of 3 keV and 4 keV. Beam current is 70 mA for the 3 keV beam and 100 mA for the 4 keV beam. Figure 9 shows the measured energy spread compared with the theoretical prediction for different beam energies for both weak and strong focusing of the beam. Triangles with solid line are the theoretical values for weak focusing. Diamonds with dotted line are the theoretical values for strong focusing. Circles are the measured energy spreads for weak focusing and squares are for strong focusing. Error bars added on the measured energy spread are determined by the resolution of the energy analyzer [2].

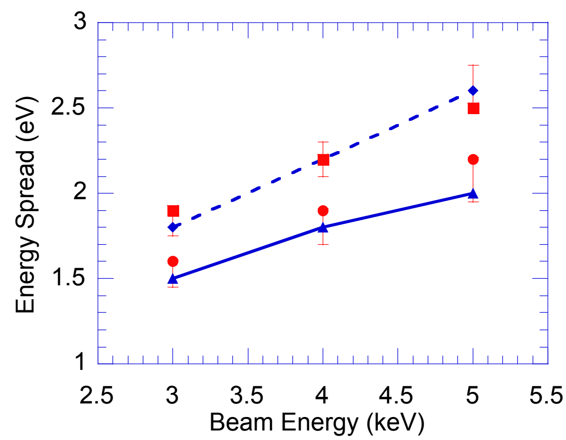

Figure 9. Measured beam energy spreads are compared with the theoretical predictions for different beam energies.

3 FUTURE WORK

We already characterized the energy profiles of the beam at the exit of the electron gun for different energy and different beam current. We will set up a long transport line with a length of 2 m to study the energy spread evolution and other interesting physics.

4 REFERENCES

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