ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC25-THPS083

INVESTIGATING BEAM-INDUCED ELECTRON EMISSION FROM THIN WIRES IN PSI PROTON BEAMS

M. Sapinski*, J. Touguet, PSI Center for Accelerator Science and Engineering, Villigen, Switzerland

Abstract

The emission of electrons induced by beam interaction with thin targets is a phenomenon used to measure various properties of particle beams. The main processes of electron emission are: secondary emission, delta electron production and thermionic emission. The last one is not desired, because the intensity of thermionic electrons is not directly related to beam density profile. A common technique to suppress thermionic emission employs bias potential on the wire, which allows for recapturing of low energy electrons. This study investigates the effectiveness of the bias voltage method for high-brightness proton beams of the HIPA accelerator. Through experiments and simulations, the study aims to better understand the emission spectra, the suppression of thermionic emission, and the effects of beam fields on electron dynamics.

INTRODUCTION

Transverse beam profile measurements are essential components of beam diagnostics. One of the most widely used instruments for this purpose is the wire scanner, in which the interaction of the proton beam with the wire generates detectable electron emission. Secondary and δ-electrons are emitted with a probability proportional to the local beam particle density, and the resulting electron current, measured synchronously with the wire position, enables the reconstruction of the beam profile.

In contrast, thermionic emission originates from wire temperature and is independent of the beam's spatial distribution. Therefore, it is undesirable component to the signal. This study focuses on the suppression of thermionic electron contribution by means of wire biasing.

The experiments were conducted using the Long Radial Probe (RRL) [1], a diagnostic device deployed in the Main Ring Cyclotron of the HIPA facility [2]. The RRL operates in a harsh environment, in the presence of intense RF fields and low-density plasma. It is difficult to assess impact of those phenomena on the electron emission processes. Nonetheless, it was selected for this investigation because it suffers most from measurement distortion and understanding the impact of bias voltage would be the most helpful.

Figure 1 shows the map of magnetic field in the central plane of the Main Ring Cyclotron. A blue line represents position of the RRL. Notably, when the beam is at its lowest energy and located near the cyclotron center, the RRL is positioned close to the sector magnet. In this region, the magnetic field strength reaches approximately 0.1 T, an important factor in interpreting the electron dynamics observed in this study.

* mariusz.sapinski@psi.ch

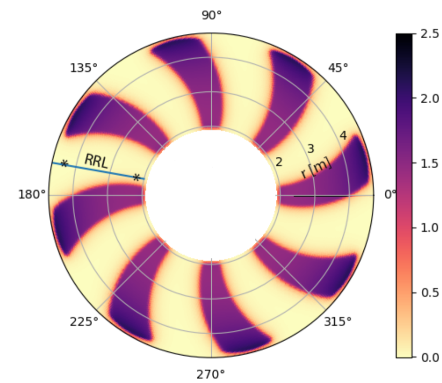

Figure 1: The map of the Main Ring Cyclotron magnetic field (courtesy of C. Baumgarten) and the location of the RRL. The two stars designate the approximate locations of the measurements (see text).

ELECTRON EMISSION MECHANISMS

When a thin wire is placed in a proton beam, several distinct electron emission processes are triggered [3]:

- Delta Electrons: High-energy electrons ejected via binary collisions between incident protons and electrons within the wire material. These electrons typically carry significant kinetic energy (keV).
- Secondary Electrons: Low-energy electrons produced as a result of inelastic interactions and ionization processes initiated by the primary delta electrons or directly by the beam. Their energies are typically below 20 eV, and they are more likely to be influenced by local electric and magnetic fields.
- Thermionic Emission: Electrons emitted due to thermal excitation. These electrons carry very low energy (< 2 eV) but differ from secondary electrons - their emission is governed by the wire temperature, not by direct particle interactions.

EXPERIMENTAL SETUP AND METHODOLOGY

The RRL probe features 3 carbon fibers (one vertical and two tilted by $\pm 45°$) used as targets, which move through about 186 turns of the cyclotron. The total distance traveled is about 2.5 meters and the speed of the carriages which support the wires is about 3 cm/s [4].

As the first step various bias voltages were applied to the wires during routine scans. In the preceding report [5] only

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC25-THPS083

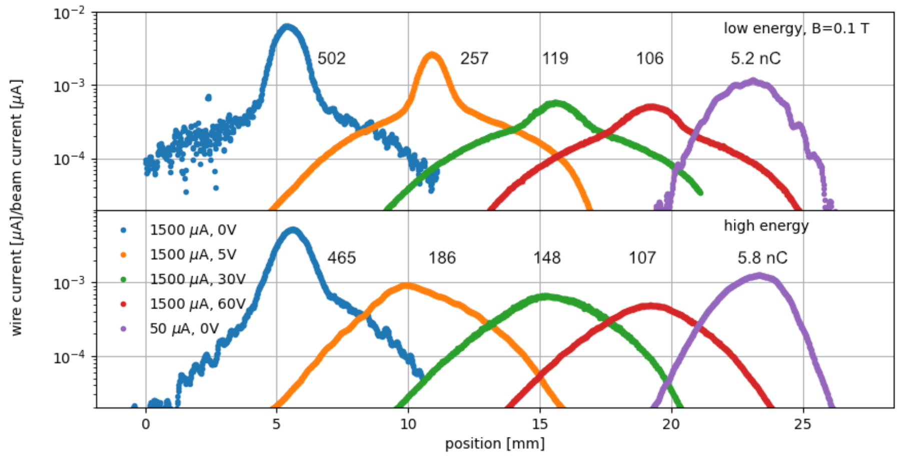

Figure 2: Comparison of the orbit profile measurements performed using a 45° tilted wire (wire 2) with various applied bias voltages. Strong thermionic emission is clearly visible when no bias is applied. The numbers next to the peaks represent the integrals in [nC].

the low energy orbits were analyzed. This was motivated by the fact that at low energies the orbits are well-separated and the presence of magnetic field was not considered. In contrast, the present work extends the study to high-energy orbits and finds insights revising the previous conclusions.

Full wire scans can be performed using a limited set of bias voltages. To enable more detailed analysis, additional measurements were performed in which the wire was held stationary at specific positions near the beam center. At these fixed locations the signal was recorded while sweeping the bias voltage in range between −20 V to 70 V in steps of 3.5 V. The measurement was repeated for beam currents in range from 10 µA to 1.6 mA.

It should be noted that the position of orbits varies with the beam current, therefore the wire position was slightly adjusted to maximize the signal. This adjustment procedure was carried out quickly to minimize the heating of the wire and its support due to strong RF fields [4].

The measurement were performed using a Keithley 4020 electrometer, with data acquisition fully automated via a dedicated LabVIEW program. For each bias voltage setting, a sequence of 20 current measurements was recorded at an acquisition rate of 10 Hz. After completing a full bias sweep, the beam current was increased, the wire position was readjusted, and a new scan was initiated.

RESULTS AND DISCUSSION

Figure 2 shows the profiles for a low-energy orbit (at a radius of approximately 2502 mm) and a high-energy orbit (r = 3990 mm). The upper plot which resembles the profile shown in Ref. [5], indicates that even a high bias voltage is insufficient to suppress the thermionic emission bump from the registered profile. It was previously hypothesized that the bunch field, which can reach about 1.5 kV/m [6] carries away low energy thermionic electrons. However at high energy orbit, where bunch fields are of comparable magnitude, shows that even a small bias voltage is effective in completely eliminating the thermionic emission.

In order to better understand this behavior, the bias scans were conducted at low and high-radius positions with the wire held stationary near (though not exactly on) the previously discussed orbits. In both locations the measured current decreases at positive bias in one main step. This behavior is well-represented by an S-curve, suggesting a threshold-like suppression of low-energy electrons as the retarding potential increases. An additional slope (L_1) is included in the fit function is:

$$I(U_{bias}) = \frac{L_1 * U_{bias} + L_0}{1 + exp(-k * (U_{bias} - U_0))} + C \qquad (1)$$

The U_0 parameter represents the inflection point. Analysis of these fits to the bias-current data reveal a very different behavior between the two measurement locations.

Bias Voltage Scan at Around 500 MeV

The results are visualized in Figs. 2 and 3 where the signal was normalized to zero bias. This decrease of the signal with increasing bias voltage reflects the fact that about 40% of the signal (see Table 3 in Ref. [3]) originates from δ-electrons, which possess sufficient energy to remain unaffected by bias voltage.

The inflection point clearly increases with the beam intensity, indicating an influence of the bunch fields on the dynamics of low energy electrons. Higher beam intensity facilitates the escape of the electrons from the the wire vicinity. At a beam current of 1.5 mA a bias of about 50 V is needed to recapture low energy secondary electrons.

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC25-THPS083

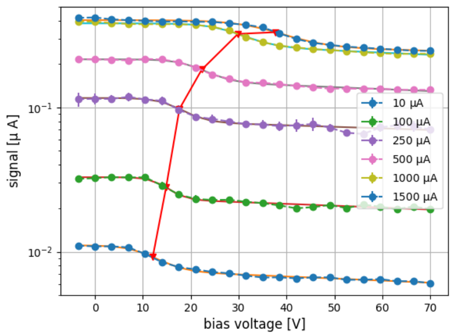

Figure 3: Vertical wire current registered for various bias voltages and for various beam intensities at beam energy of about 500 MeV. The red line represents the position of the inflection point. In this measurement no contribution from thermionic emission is present.

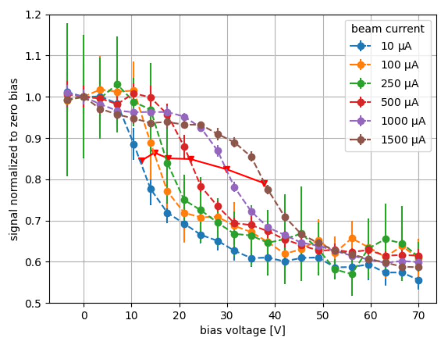

Figure 4: Wire current from Fig. 2 normalized to the current measured at zero bias voltage.

Bias Voltage Scan at Around 100 MeV

The effect of the bias voltage is different in the second measurement location at low beam energies. In this case, the analysis is based on data from the tilted wire (wire 2), as data from the vertical wire were not available. As shown in Fig. 4, the beam intensity does not affect the inflection point of the bias-current curves. Instead, a pronounced dependence is observed in the linear coefficient (L_1). This suggests that in the presence of a magnetic field, the slope of the electron current response is more sensitive to beam conditions than the threshold-like behavior captured by the inflection point.

Virtual-IPM [7] simulations confirm a strong impact of the 0.1 T field on electron trajectories. The gyroradius of 2 eV electrons is 48 μm, indicating that the thermionic electrons can be recapture. However the tilted geometry of the wire, presence of bias voltage, bunch fields and the RF fields from nearby cavities make the understanding of the electron reabsorption a complex task. Figure 6 shows trajectories of 2 eV electrons emitted normal to the wire surface in 16 directions. Trajectories are confined by magnetic field. In the absence of bias most electrons escape. In case of even low bias, most of the electrons come back to the wire.

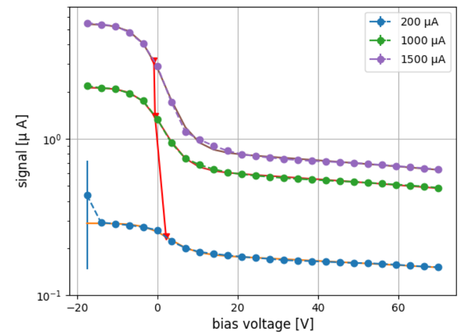

Figure 5: Wire current registered for various bias voltages and for three different beam intensities at beam energy of about 100 MeV and in presence of vertical magnetic field of about 0.1 T. For clarity only selected data are presented. Here, the 1.5 mA data contain thermionic emission component as the current at negative bias is higher than expected.

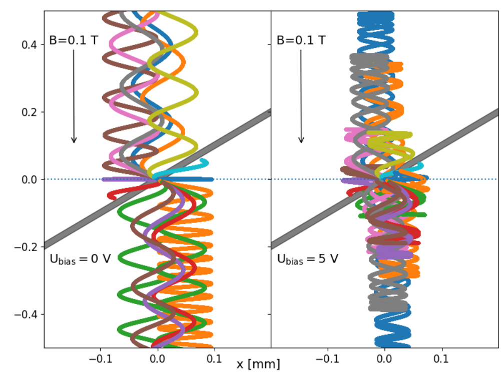

Figure 6: Virtual-IPM simulations op electron trajectories emitted from tilted wire in vertical magnetic field without (left plot) and with (right plot) 5 V wire bias. An impact of the bunch field on electron trajectories was also observed.

CONCLUSION AND PERSPECTIVES

This study explores how the electrons emitted from wires are affected by the bunch field, bias voltage and a magnetic field. It demonstrates the role of bias voltage in suppressing thermionic emission and discusses it limits.

Future work will include additional measurements, particularly at low energy orbits, and simulations, to fully understand the discussed phenomena. It will aim to determine the minimum bias voltage required to fully suppress thermionic emission and to explore alternative mitigation strategies.

ACKNOWLEDGMENTS

Authors would like to thank R. Doelling for initiating this study and D. Vilsmeier for updating the Virtual-IPM with wire-generated field.

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC25-THPS083

REFERENCES

[1] M. Sapinski, R. Dölling, and M. Rohrer, "Commissioning of the renewed long radial probe in PSI ring cyclotron", in *Proc. 11th Int. Beam Instrum. Conf. (IBIC'22)*, Kraków, Poland, Sep. 2022, pp. 76–79. doi:10.18429/JACoW-IBIC2022-MOP19

[2] M. Seidel *et al.*, "Production of a 1.3 MW proton beam at PSI", in *Proc. 1st Int. Part. Accel. Conf. (IPAC'10)*, Kyoto, Japan, May 2010, pp. 1309–1313, https://accelconf.web.cern.ch/IPAC10/papers/tuyra03.pdf

[3] M. Sapinski, "Secondary, thermionic and delta electron emission from thin targets", in *Proc. 11th Int. Beam Instrum. Conf. (IBIC'24)*, Beijing, China, Sep. 2024, pp. 653–660. doi:10.18429/JACoW-IBIC2024-FRAT1

[4] M. Sapinski, M. Rohrer, R. Martinie, and S. Lindner, "Experience with PSI's main ring cyclotron long radial probe", in *Proc. 11th Int. Beam Instrum. Conf. (IBIC'24)*, Beijing, China, Sep. 2024, pp. 310–314. doi:10.18429/JACoW-IBIC2024-WEP28

[5] M. Boucard and M. Sapinski, "Dealing with thermionic emission in wire scanners based on secondary electron emission", in *Proc. 14th Int. Part. Accel. Conf. (IPAC'23)*, Venice, Italy, May 2023, pp. 4820–4823. doi:10.18429/JACoW-IPAC2023-THPL150

[6] J. Touguet,"Investigating beam-induced electron emission from thin wires in proton beams and bias voltage influence", EPFL, Lausanne, Switzerland, EPFL report, Feb. 18, 2025, unpublished

[7] Virtual-IPM, https://ipmsim.gitlab.io/