Investigating Beam-Induced Electron Emission from Thin Wires in Proton Beams and Bias Voltage Influence

End of Internship Presentation

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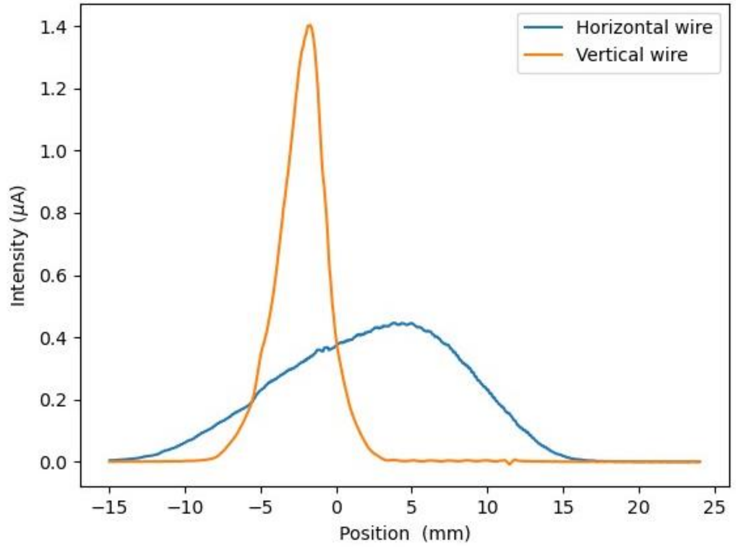
PSI, 16 December 2024

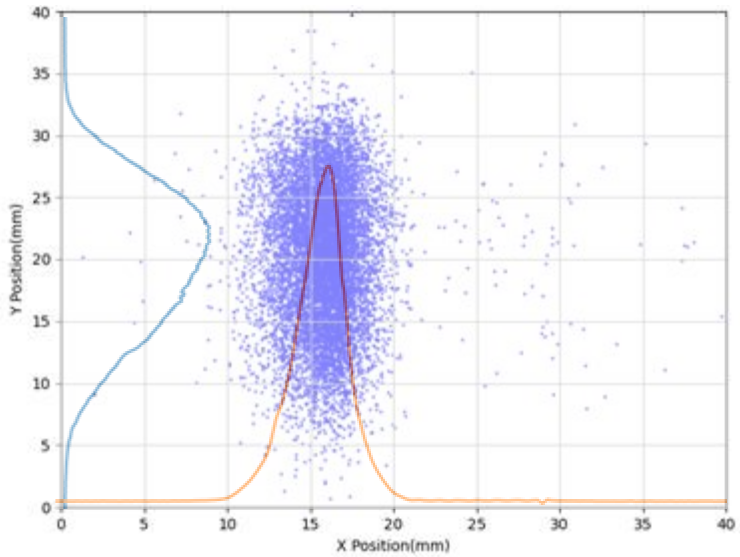
Presentation Outline

- Wire scanner overview
- Emission processes
- Previous results and analyses
- Recapture of low energy electron in presence of bias voltage
- Beam impact on the recapture
- Recapture of thermionic emission

Transverse Beam profile

- Information for efficient acceleration and particle delivery
- Obtain transverse beam intensity distribution
- Shape not always gaussian
- Scintillator screen, wire scanner, optical imaging system, Multi-Wire Proportional Chamber, IPM, SEM grids,…
- Wire scanner considered the most precise device





Wire scanner in brief

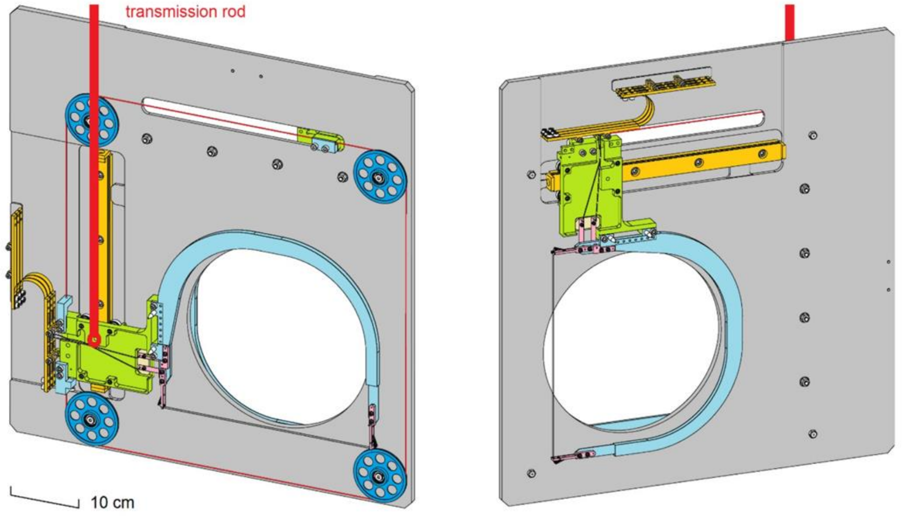
- Transverse beam profile by moving a thin wire through the beam and interact with it

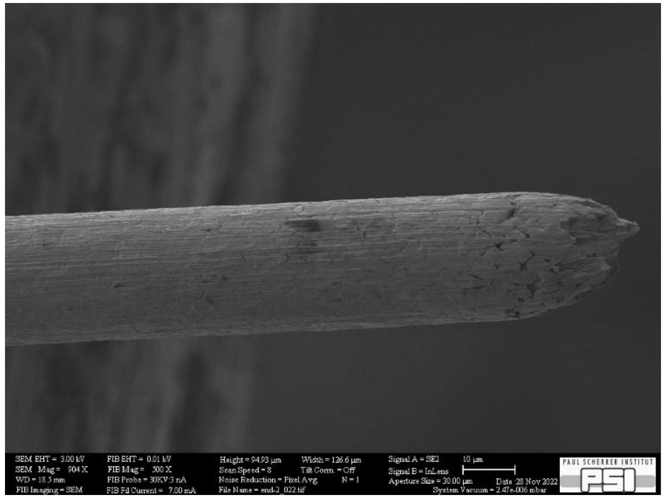
- Electrons escape the wire resulting in current

- Moving support rotational or linear

- Wire Thickness< 100 µm

- Wire material: tungsten, carbon fiber, Molybdenum..



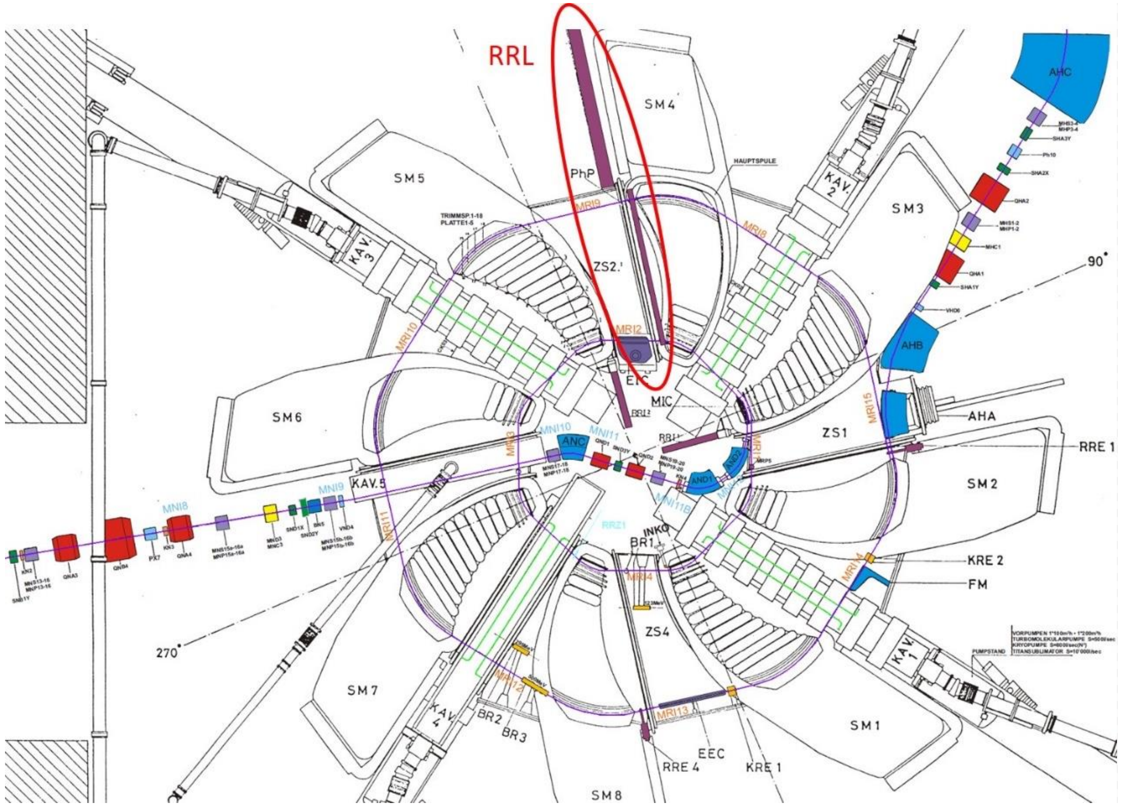


Broken Molybdenum wire with 25 µm of diameter

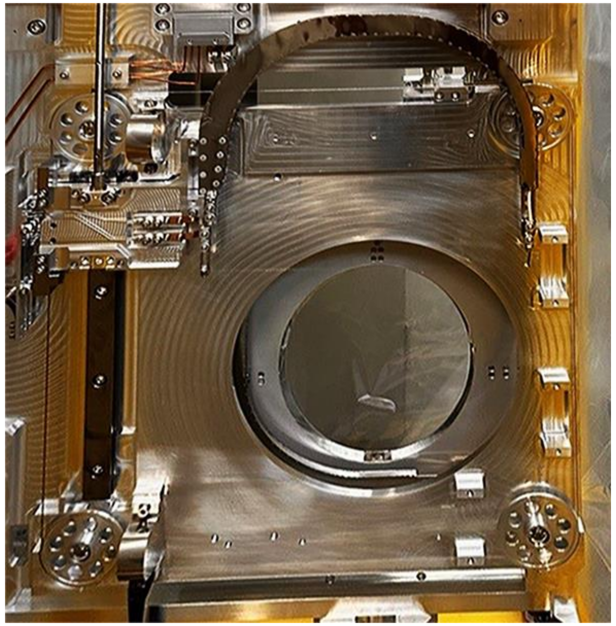
HIPA’s main ring

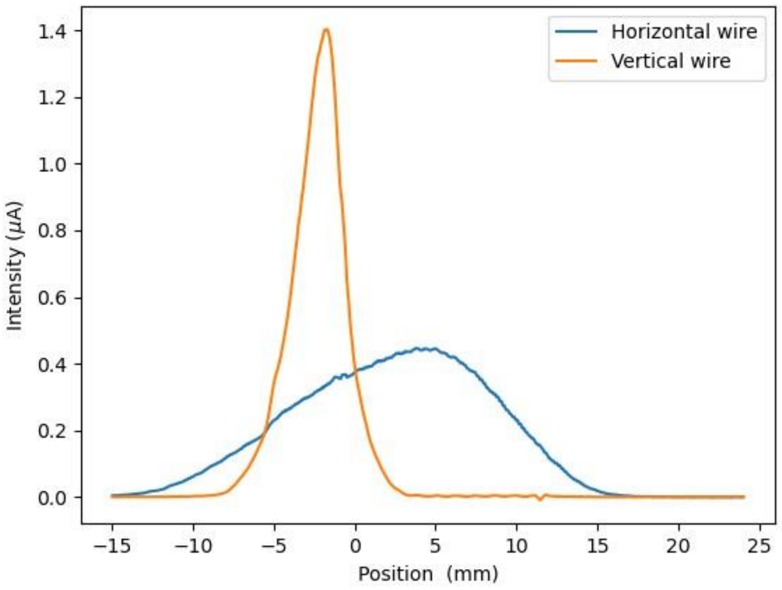
HIPA’s main ring properties:

- Energy:72-590MeV
- Number of turns:186
- Beam Intensity: few µA-2.2mA
- Longitudinal size: σ=0.2ns/every 20 ns (50MHz)



Wire scanner in both planes in UCN





- Energy:590 MeV
- Beam intensity: 2mA for 8 seconds every 5 minutes
- Flat beam

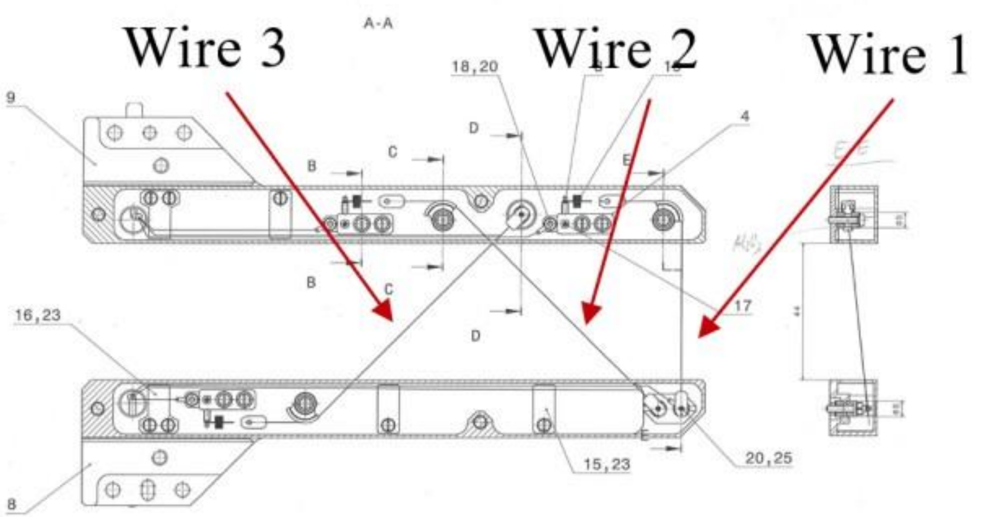
- Horizontal wire: Carbon nanotube wire
- Vertical wire: Molybdenum wire
- Motor speed:60 mm/s

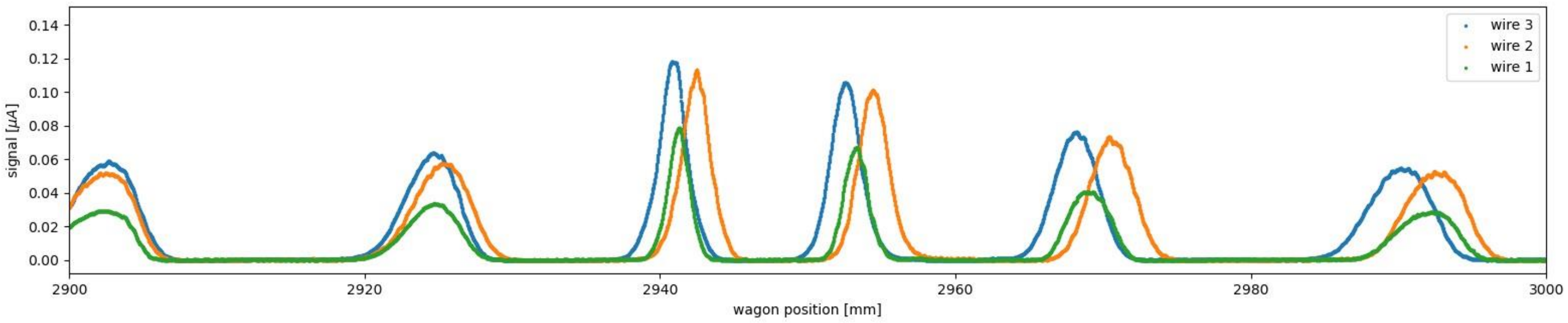
- Similar wire scanner in SINQ: 2 Molybdenum wires

Long Radial Probe(RRL)

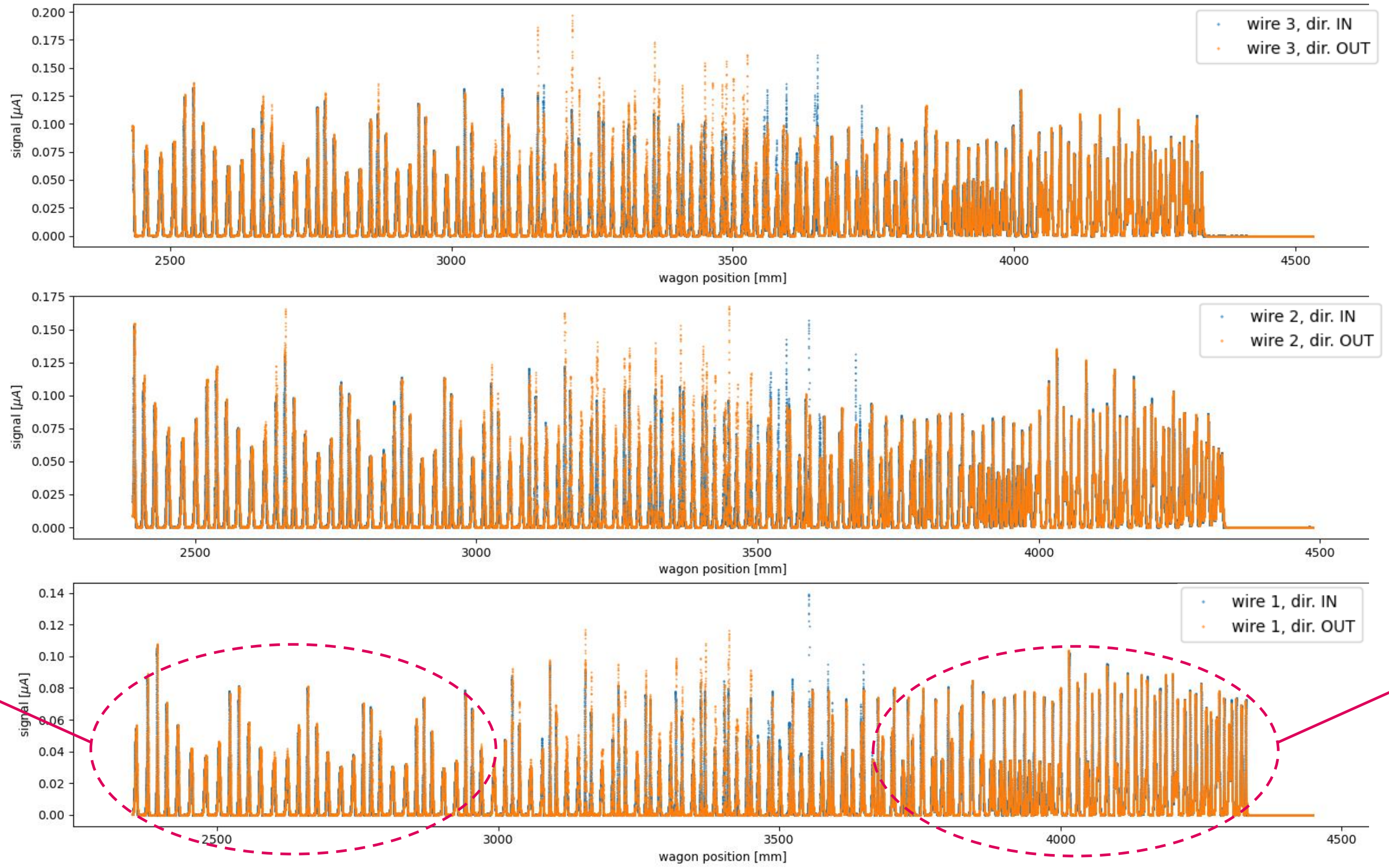
RRL properties:

- Radial probe in the main ring
- 3 wires: 2 titled (±45°)/ 1 vertical
- Carbon fiber wires (diameter: 33 μm)
- Motor speed:29.7 mm/s





Long Radial Probe(RRL)



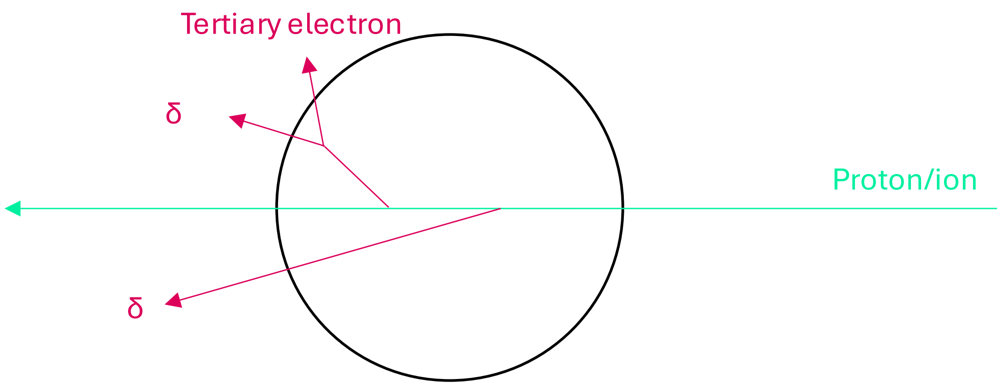
Orbit every 2cm in avg

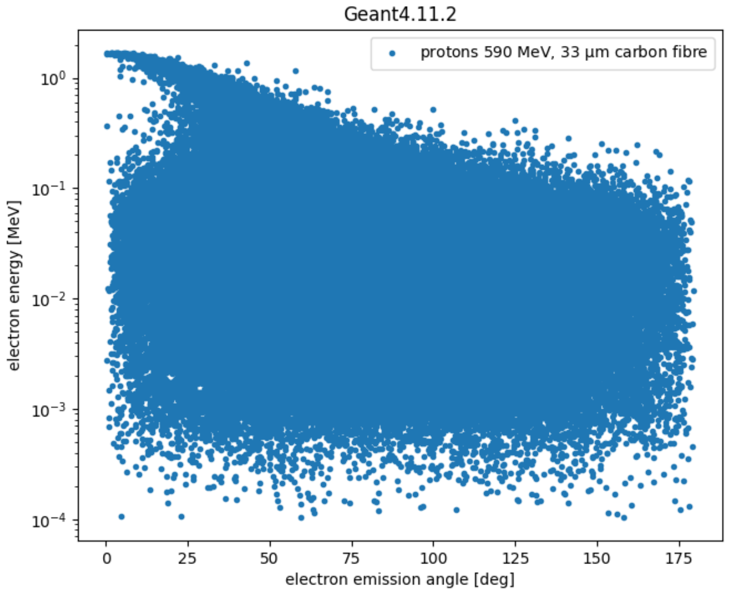
Orbit every 1cm in avg

72 MeV — Beam Energy → 590 MeV

Delta emission

- Binary interaction: Electrons scattered by proton/ion and escaping matter with low interaction and scattering (Tertiary electron)
- Describe as statistical process using Monte-Carlo simulation(proportional to beam intensity)
- High energy electrons: Avg energy of 92keV for RRL wire at 590MeV
- Decrease the energy deposited on the wire: Bethe-Bloch modified
- Impact in the signal is normally negligeable for wire scanner





Courtesy of Mariusz Sapinski

Low energy secondary emission

- Collective interaction

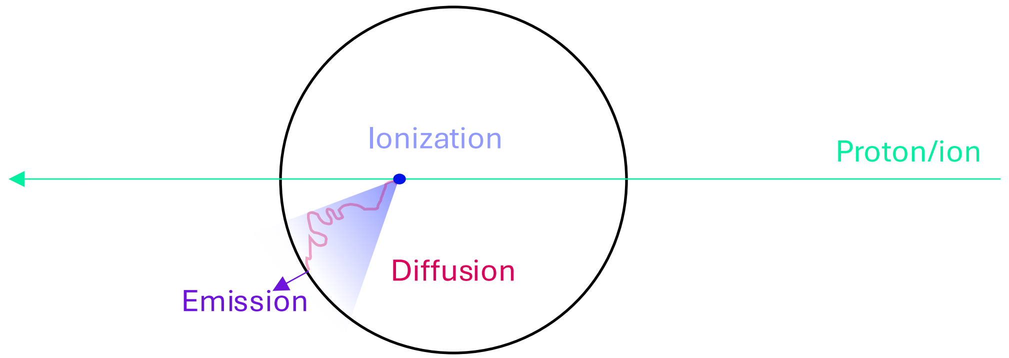
- 3 step process: Generation(ionization), Diffusion, Emission on the barrier

- Secondary emission yeld (SEY) described on Sternglass Formula :

$$SEY = 0{,}01.\,L_S \left.\frac{dE}{dx}\right|_{el}\left(1 + \frac{1}{1 + \frac{5{,}4.10^{-6}E}{A_p}}\right)$$

SEY values at 590 MeV: CF:1.14% Mo:4.19%

- Low energy electrons: <100 eV, avg energy 4-5eV



Thermionic emission

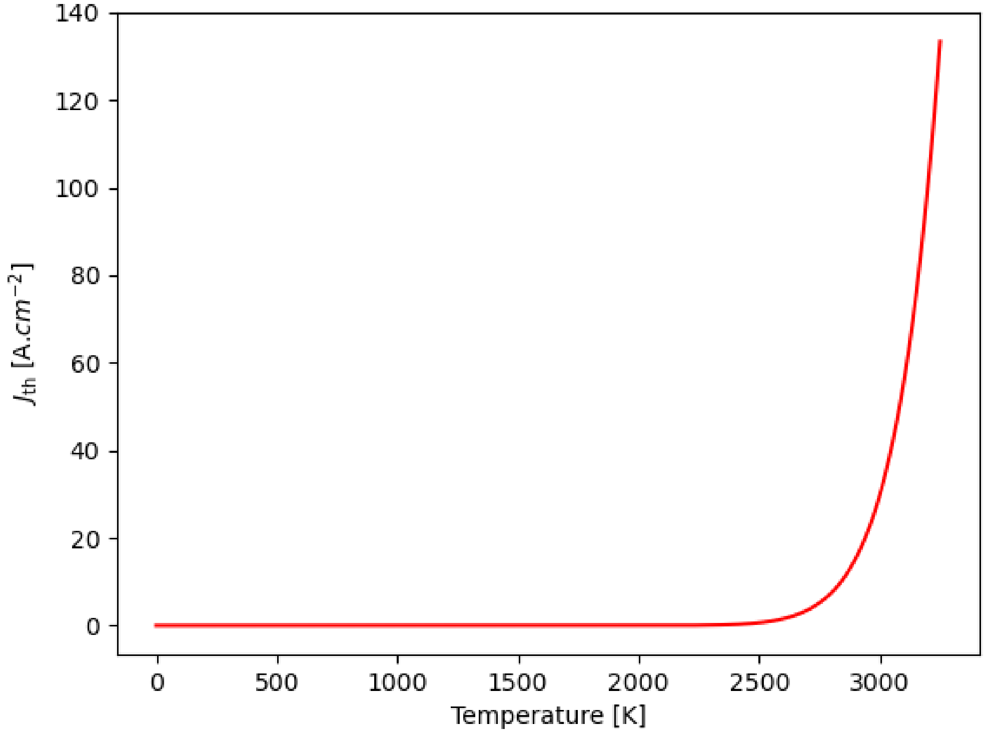
- electrons are emitted when their thermal energy becomes sufficient to overcome the wire's work function Φ

- Richardson-Dushman equation:

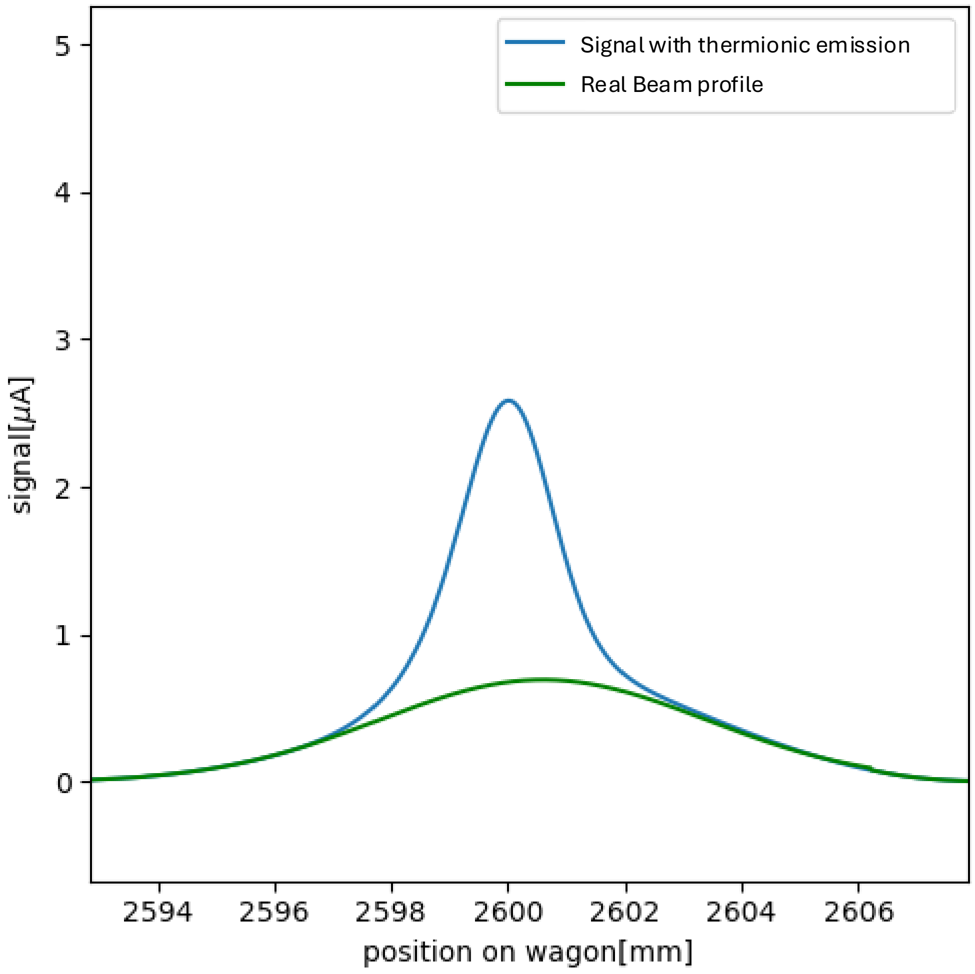
$$J_{th} = A_R.T^2.\exp\left(-\frac{\Phi}{k_B.T}\right)$$

- Cooling process for high temperature

$$\left(\frac{\partial T}{\partial t}\right)_{TC} = S.(\phi + \frac{2k_B T}{Q_e}) \cdot \frac{J_{Th}(T)}{\rho \cdot C_p(T) \cdot V}.$$

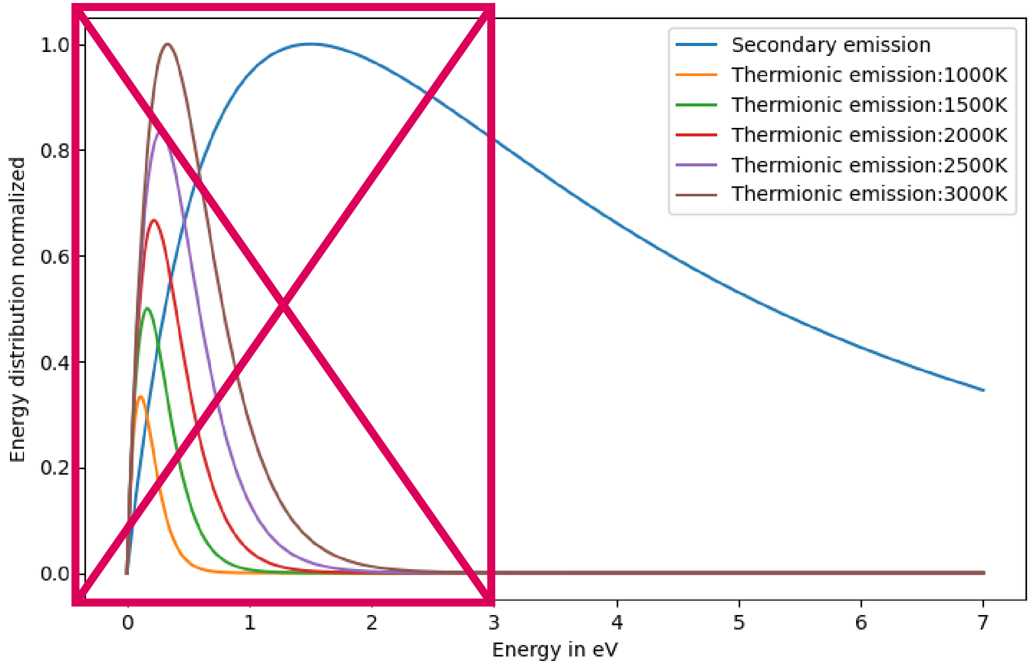


Thermionic emission: Disturbance



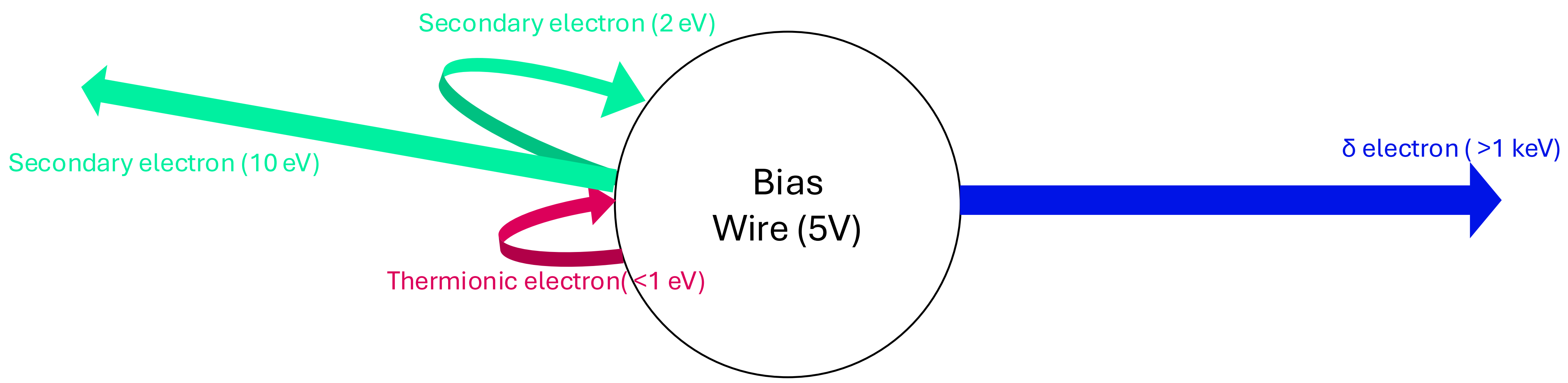
Energy distribution:

$$f_{th}(E) = \frac{E-\Phi}{1+\exp\left(\frac{E-\Phi}{k_B.T}\right)} H(E-\Phi)$$



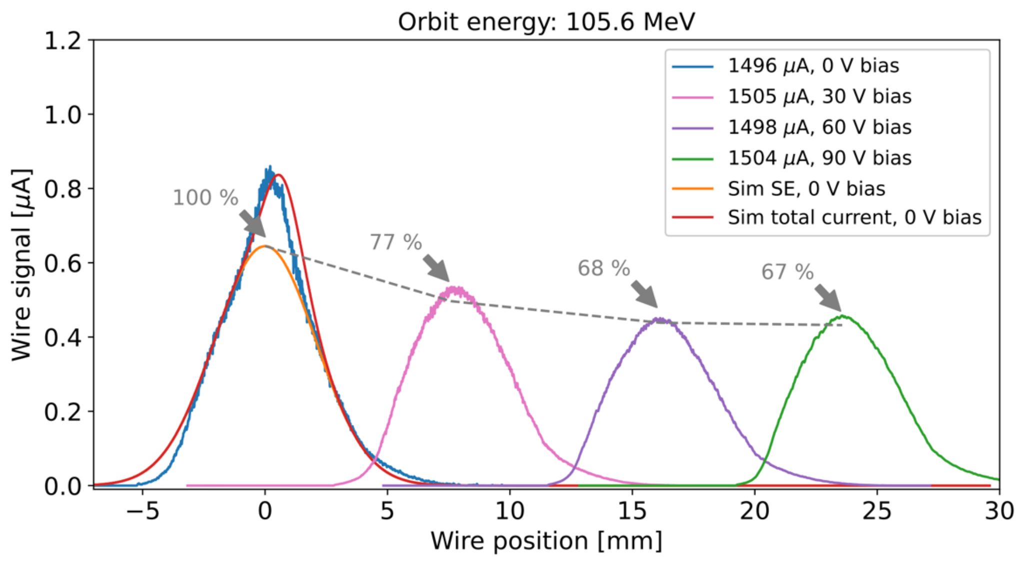
Bias Voltage

Emission processes in presence of biased wire

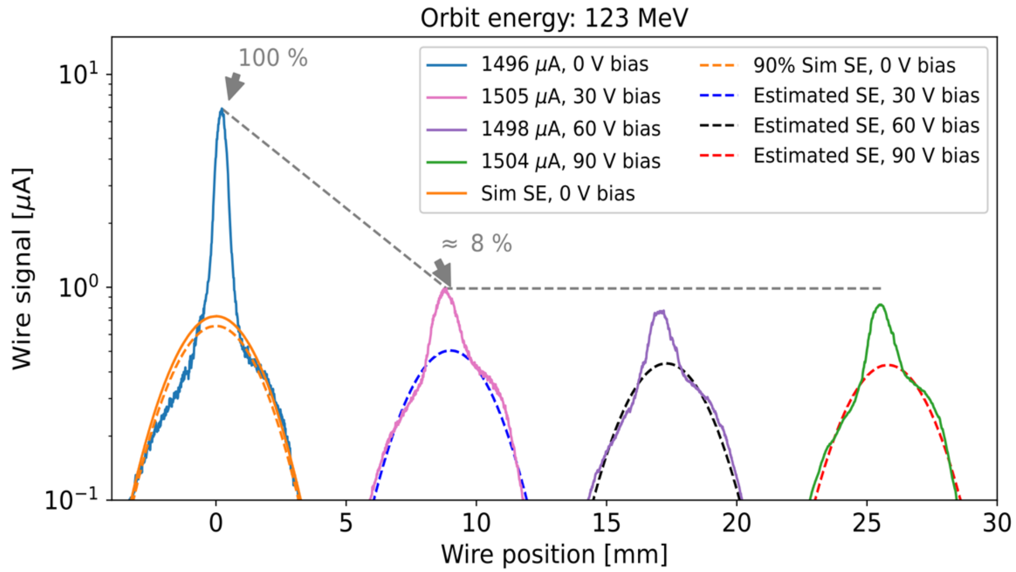


$$Signal = N_{sec,escaped} - N_{sec,recaptured} + N_{th,escaped} - N_{th,recaptured} + N_{\delta,escaped}$$

Previous results from Manon Boucard*

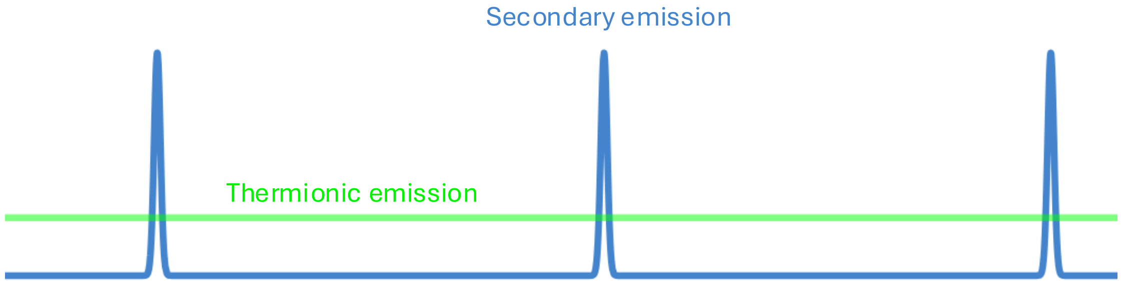


Remaining signal with increase of bias voltage



Thermionic emission seems to be not suppressed

Hypothesis:
Effect of Beam electric field that trap electrons



*Dealing with thermionic emission in wire scanners based on secondary electron emission, DOI:10.18429/JACoW-IPAC2023-THPL150

Experimental techniques

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- Log IV:

- 2kHz measurement
- Apply battery as bias voltage
-Logarithmic current amplifier
- Reading on Meson system

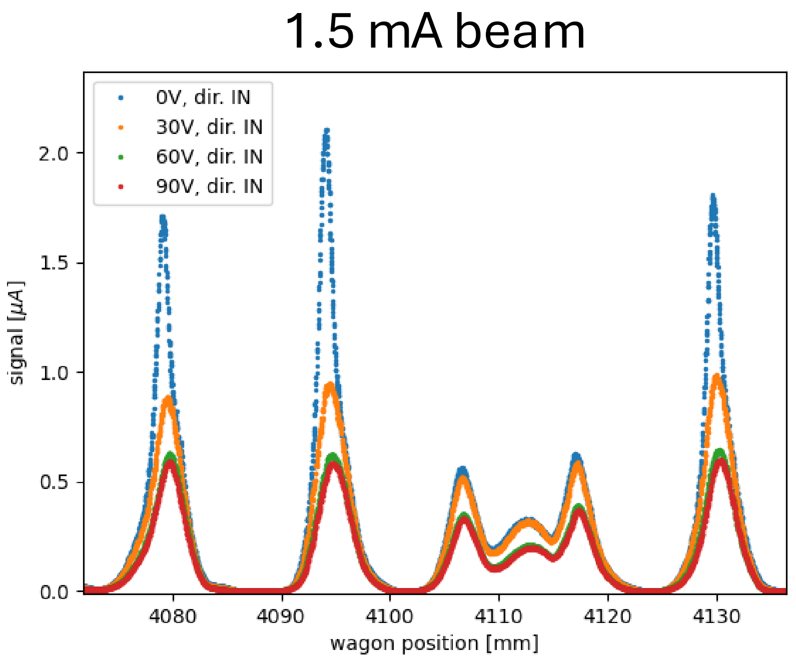
- Keithley 2400 source-meter:

- 10Hz measurement
- Voltage source and current meter
- Programmable using Labview scripts

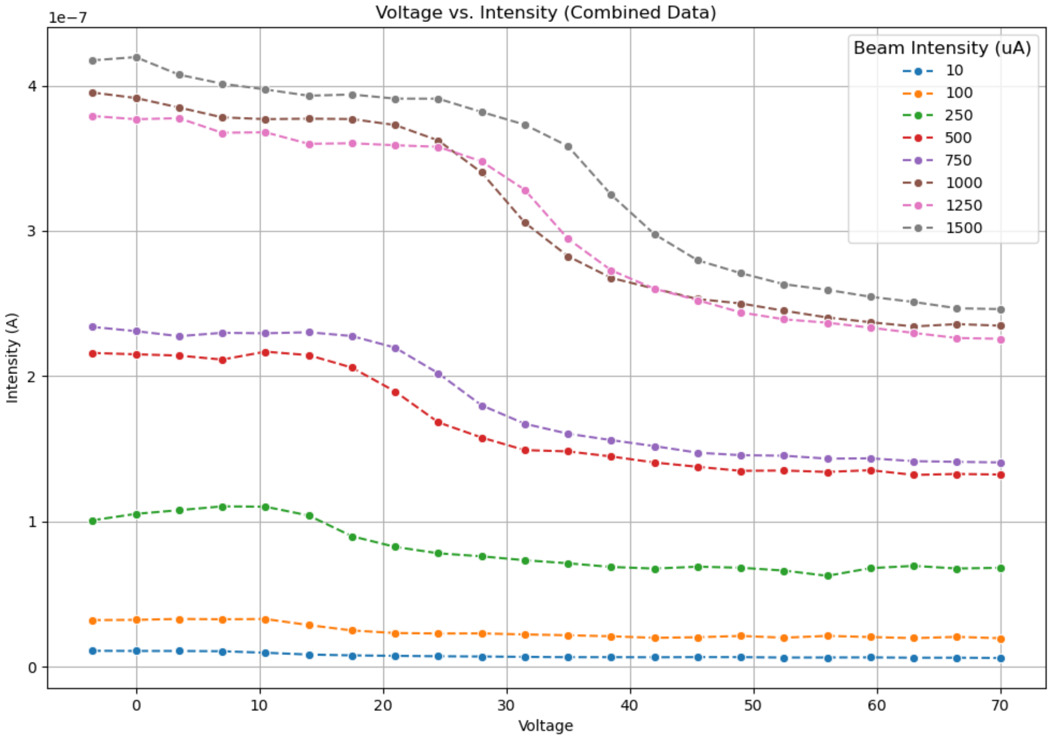
- Libera 4-channel current meter:

- 1kHz measurement
- Apply variable bias using Keithley

Recapture of secondary electron with bias voltage



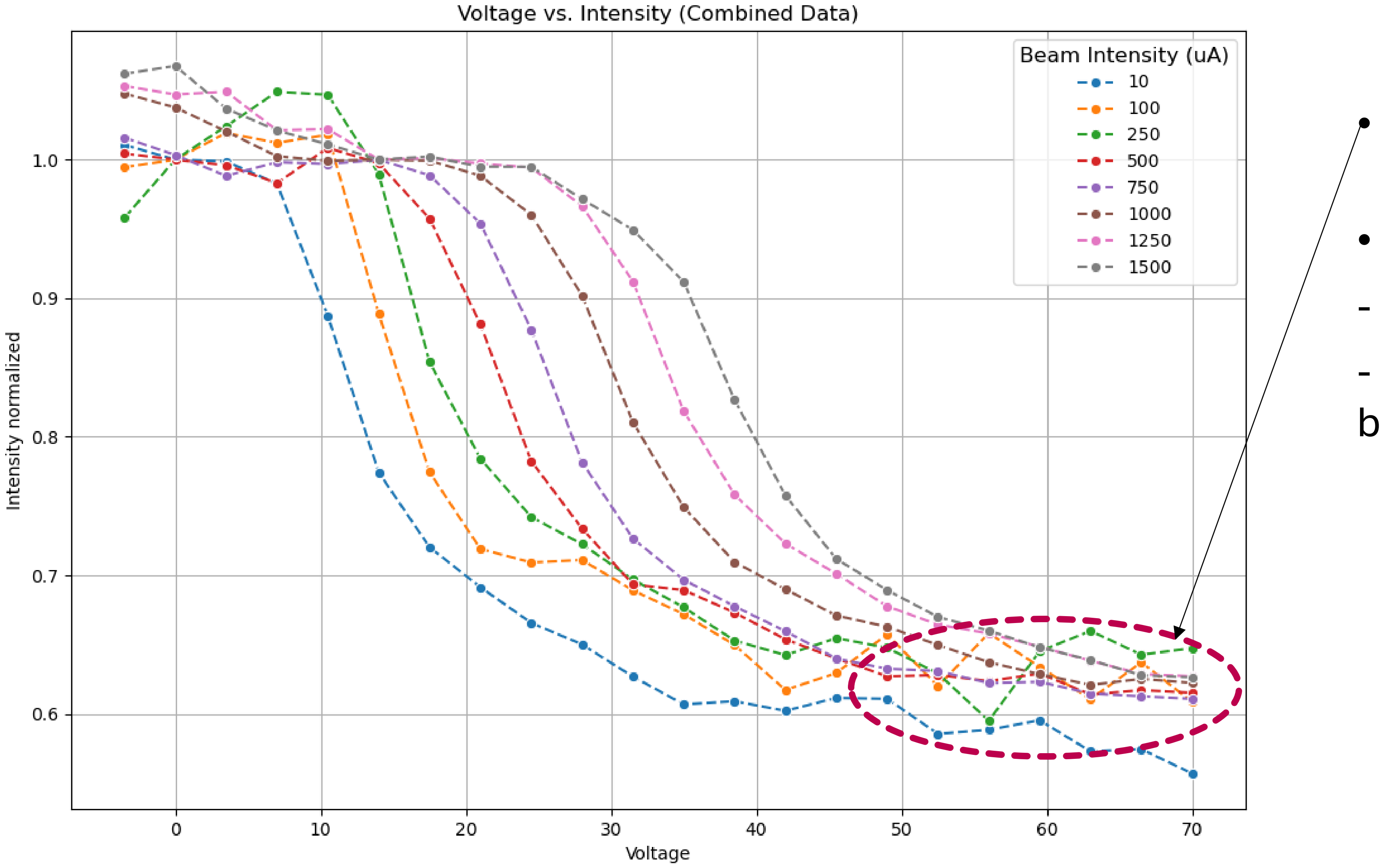
Scanning positions with constant biased voltage in RRL



Fixed Position with changing biased voltage in RRL

- Remaining signal proportional to the initial signal
- Partial recapture appears for all beam intensities

Recapture of secondary electron with bias voltage



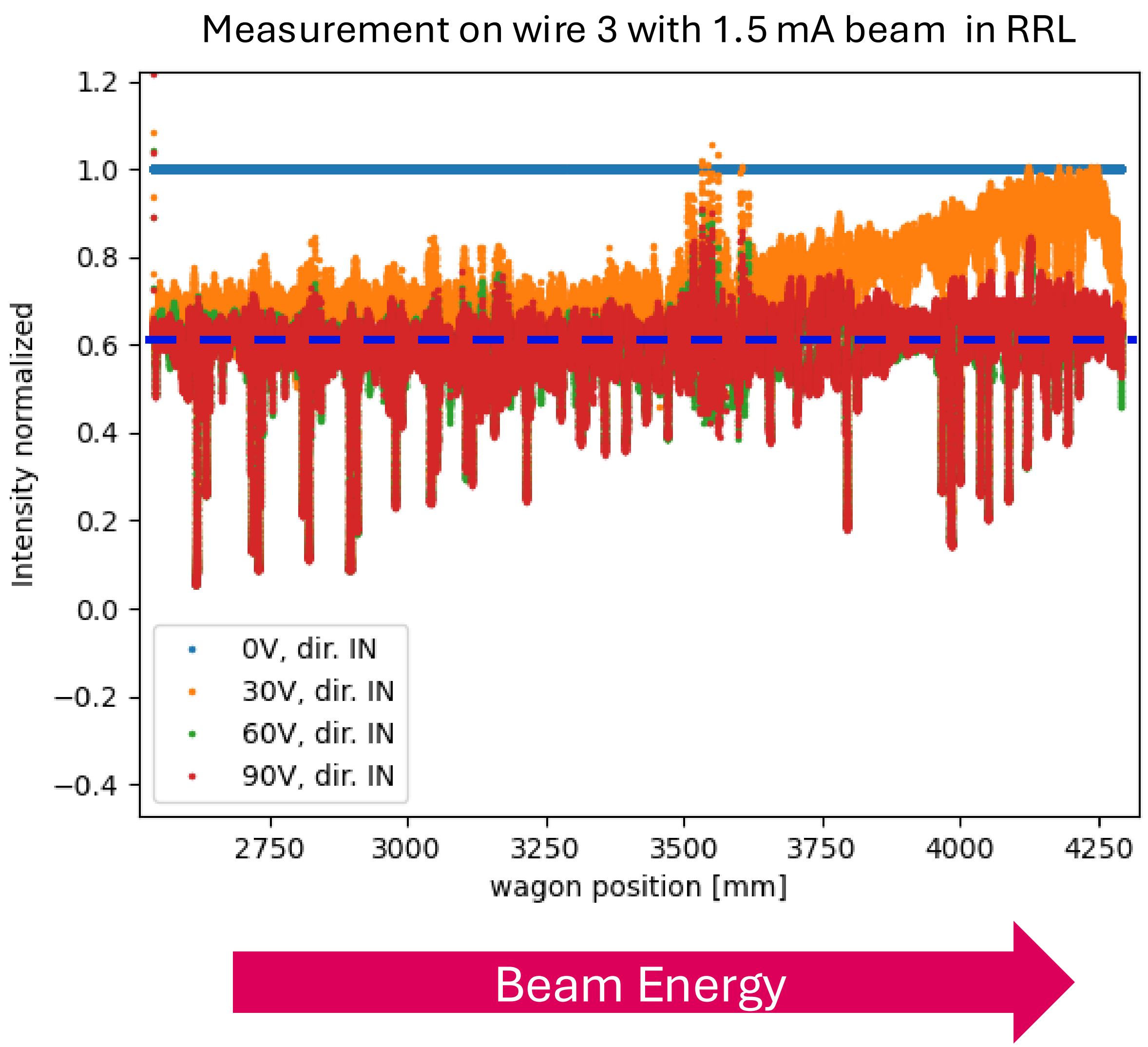
- Recapture of same ratio around 60%
- Possibilities:

- Higher delta-emission?

- Electron trapping by the beam?

Phenomenon dependent on energy?

- No dependency on energy



Phenomenon dependent on wire properties?

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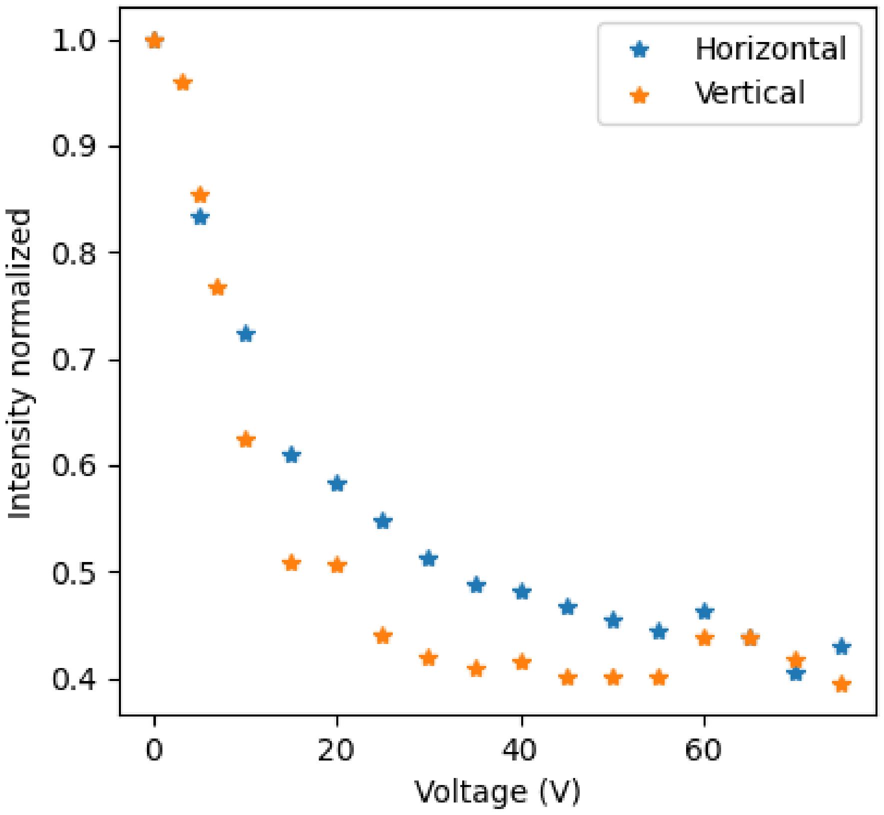
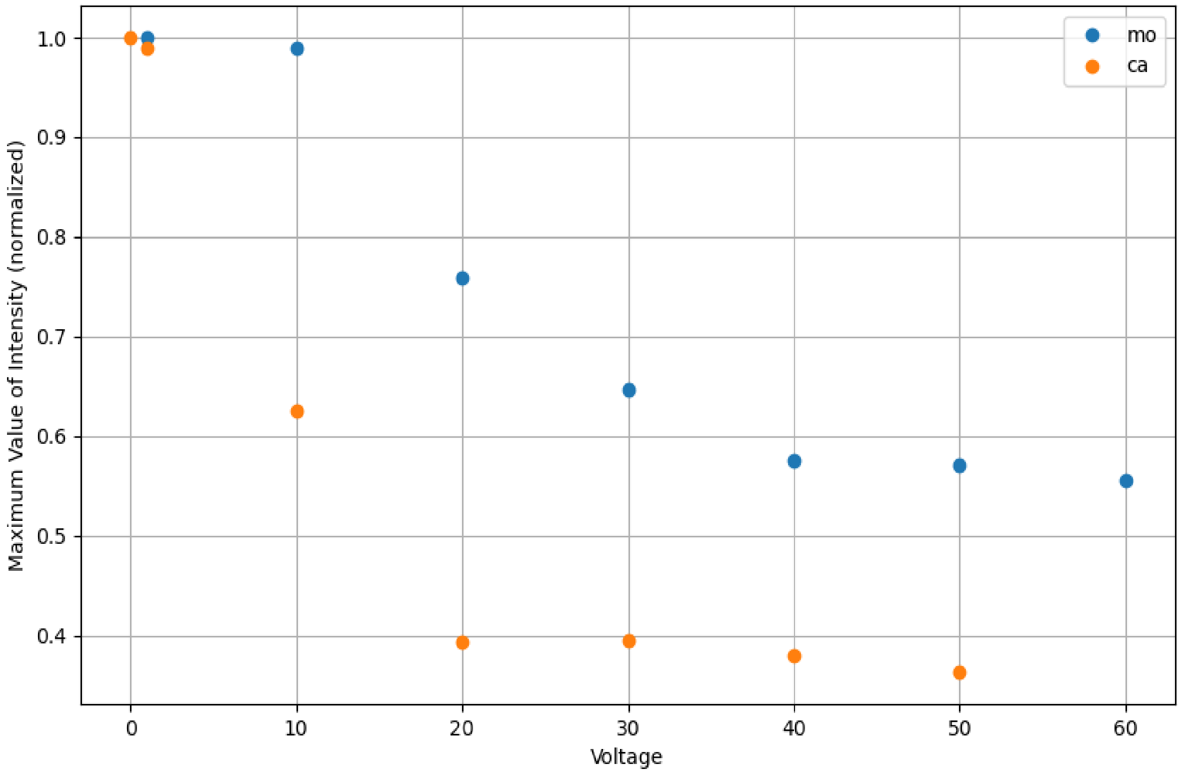


2 Molydbennum wires, 1.5 mA beam

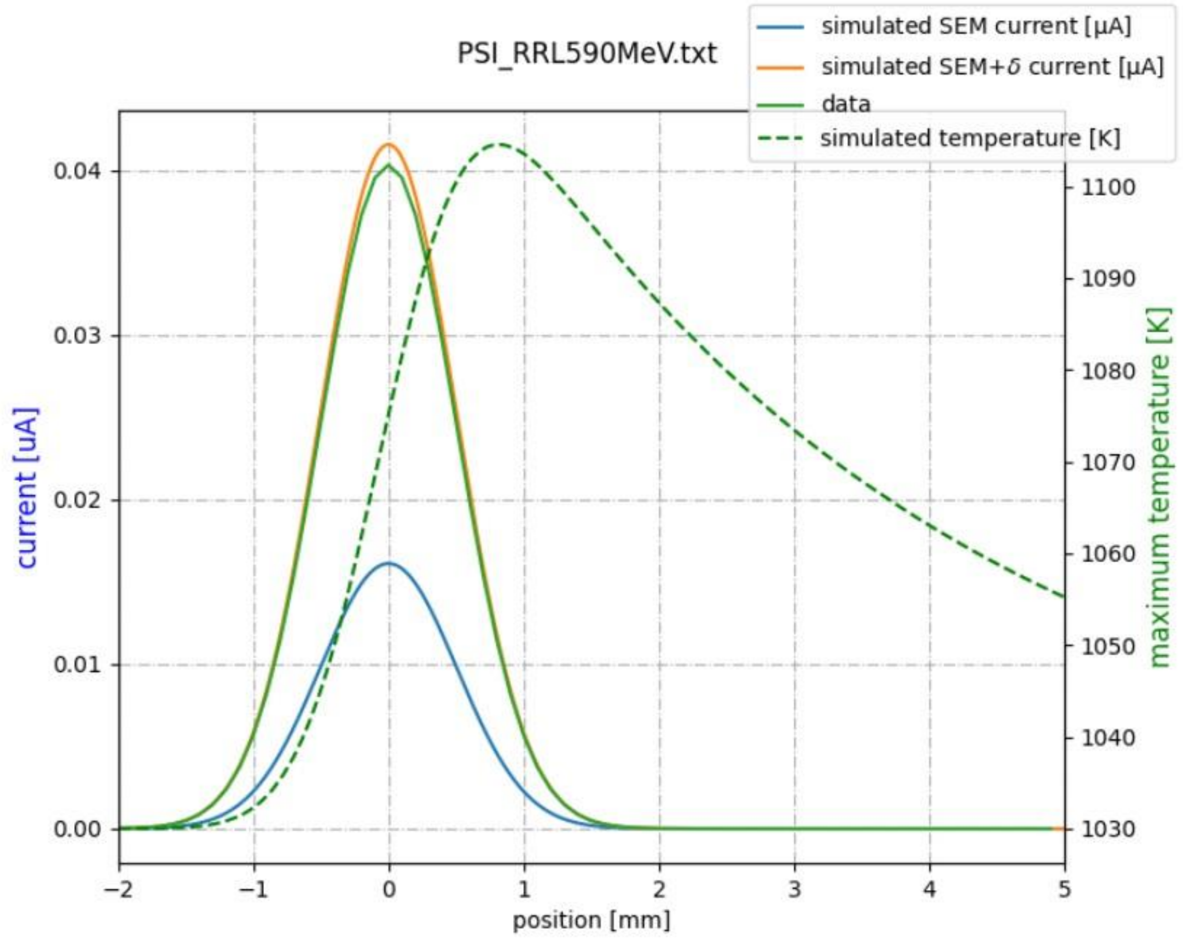
MBPT 1/2



1 molybdenum wire/ 1 carbon nanotube wire,2mA beam

- Dependency on wire properties!

Proportion of delta-emission higher than expected



Data from RRL (courtesy of M.Sapinski)

- Simulation using Geant 4 and Sternglass formula:

- Low Secondary emission only 40% of signal

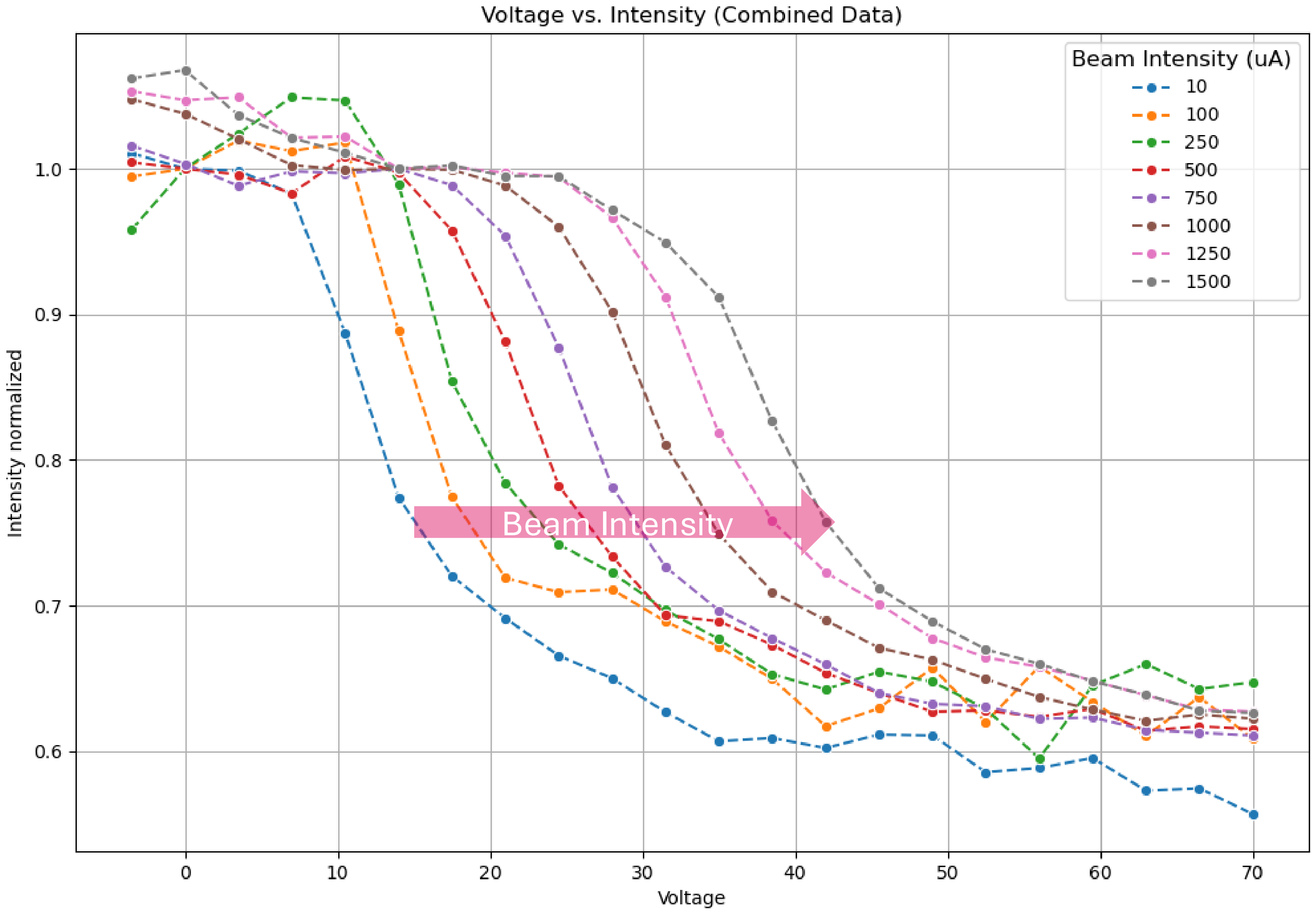
- Rest is delta-electron

Contribution of secondary emission in signal

Material	Energy (MeV)	Secondary emission contribution(%)	Diameter (µm)	Location	Experimental Value(%)
Carbon fiber	72	**36%**	33	RRL	**35-40**
Carbon fiber	590	**37%**	33	RRL	**35-40**
Carbon nanotube	590	?	40	UCN	**60-65** ?
Molybdenum	590	**59%**	25	UCN	**40-45**
Molybdenum	590	**59%**	25	SINQ	**55-60**

Beam impact on recapture

- Increase of the voltage required to recapture secondary electrons with increase of Beam intensity

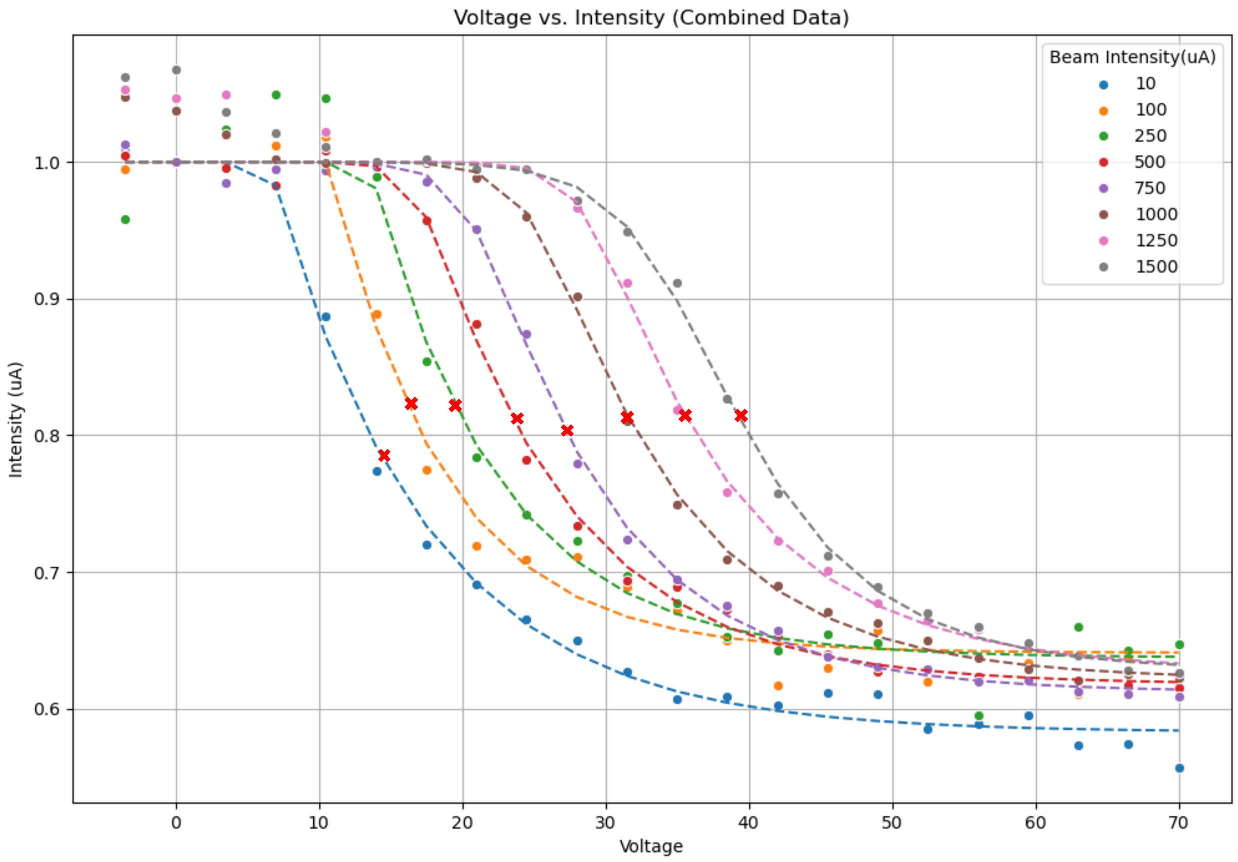


Data from wire 1 on RRL with low thermionic emission around 4105mm (500 MeV)

Beam impact on recapture

Fit of the previous curves with this sigmoid function:

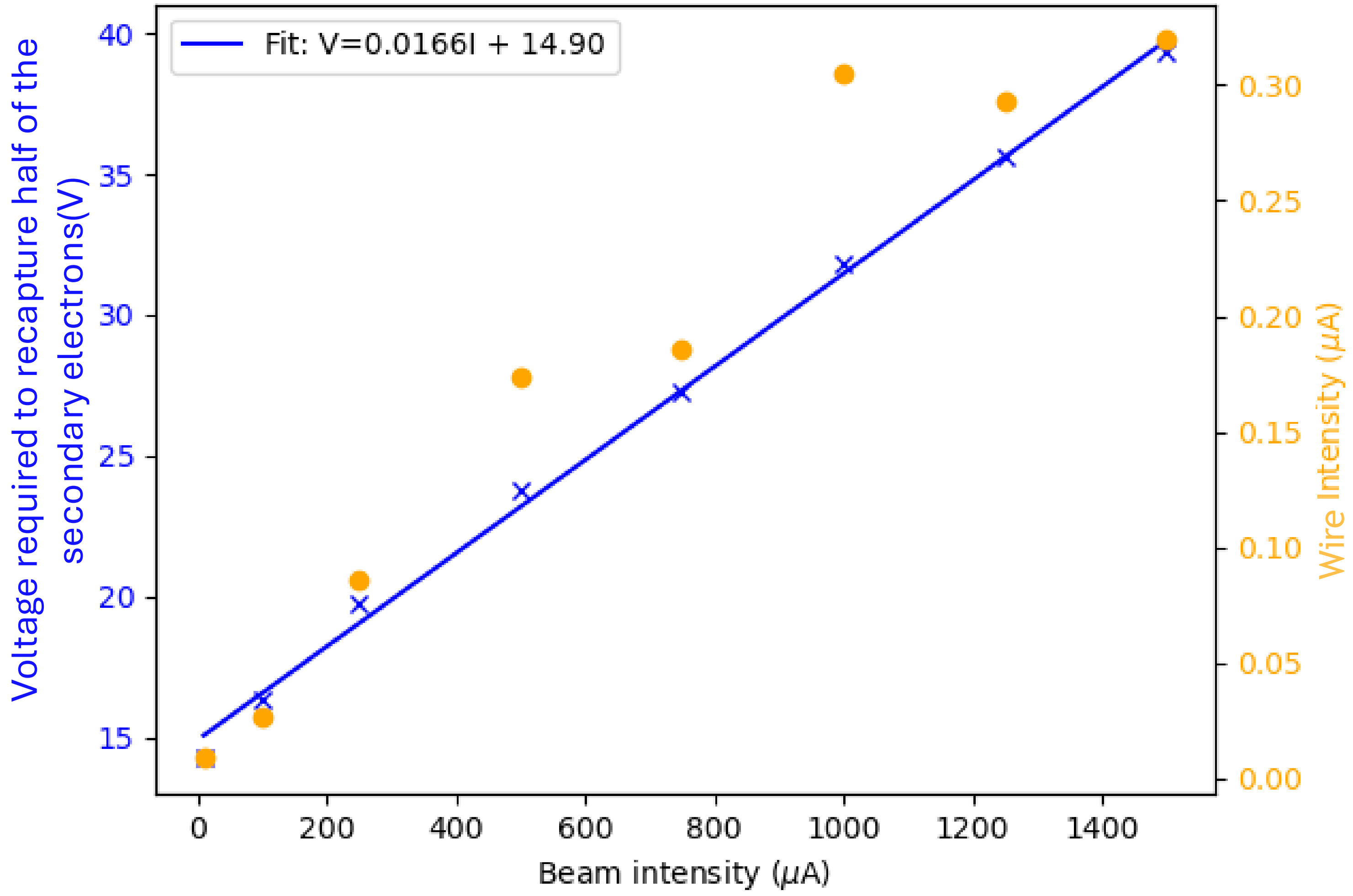
$$I(V) = \frac{1 - I_\infty}{(1 + e^{\alpha(V - V_0)})^\beta} + I_\infty$$



X: Voltage Required to Halve Final Intensity

Beam impact on recapture

- Linear tendency of the voltage required
- Wire intensity bit linear but at random place

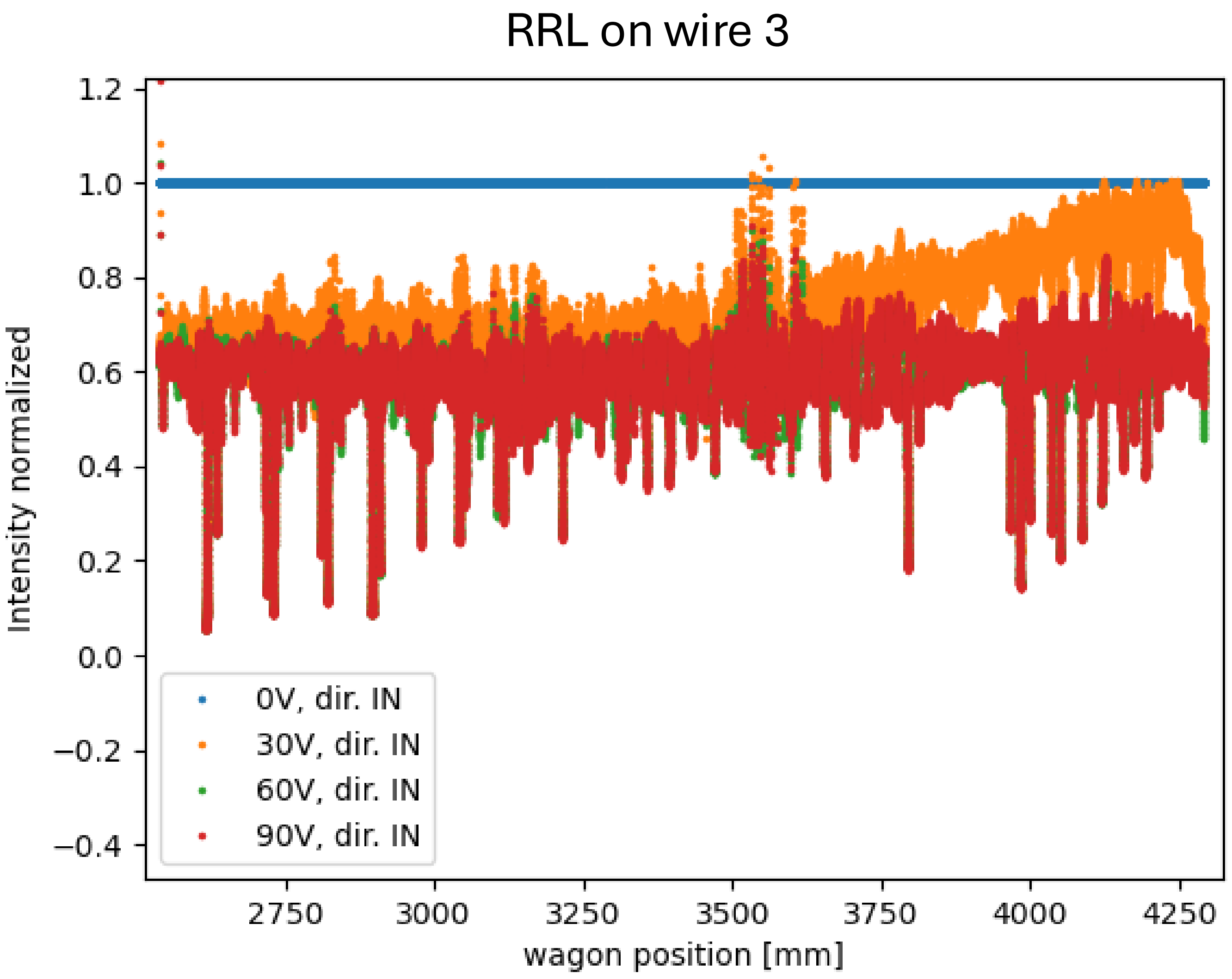


Voltage Required to Halve Final Intensity for Varying Beam Intensities compared to Wire Intensity at this voltage

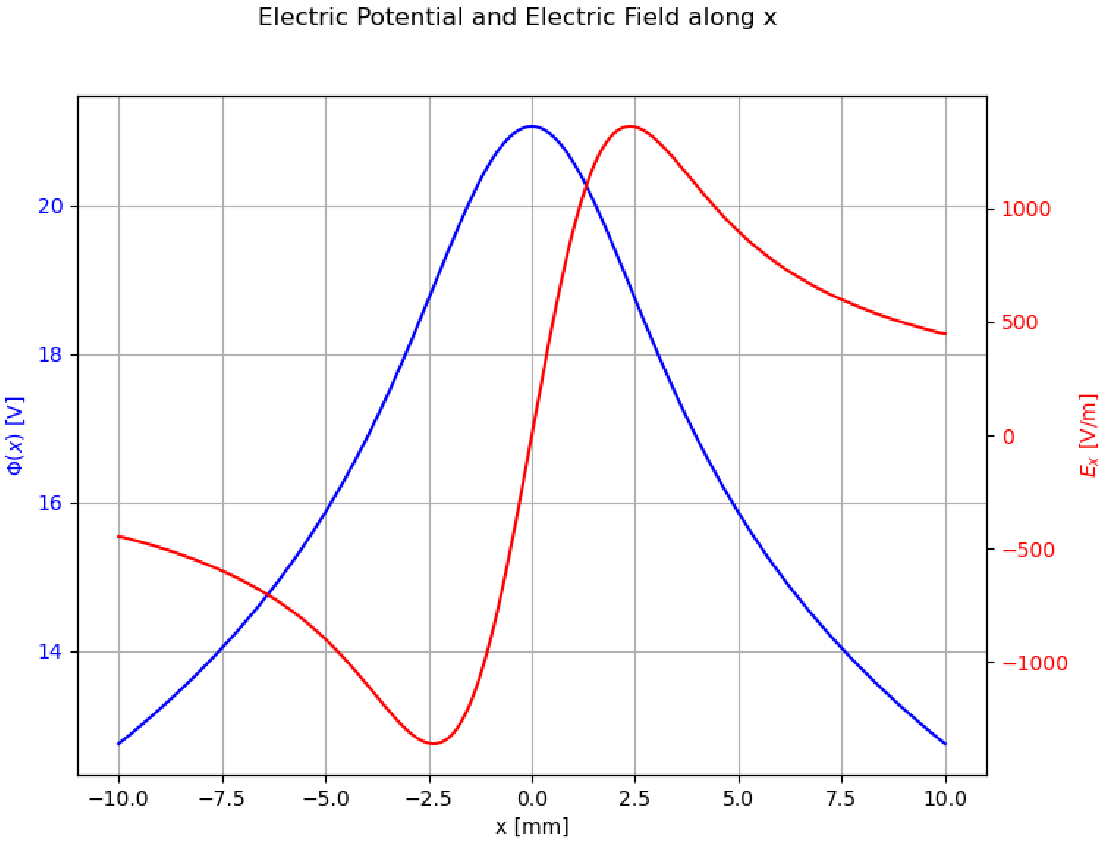
Beam impact on recapture

- **Increase of the voltage required to recapture secondary electrons**

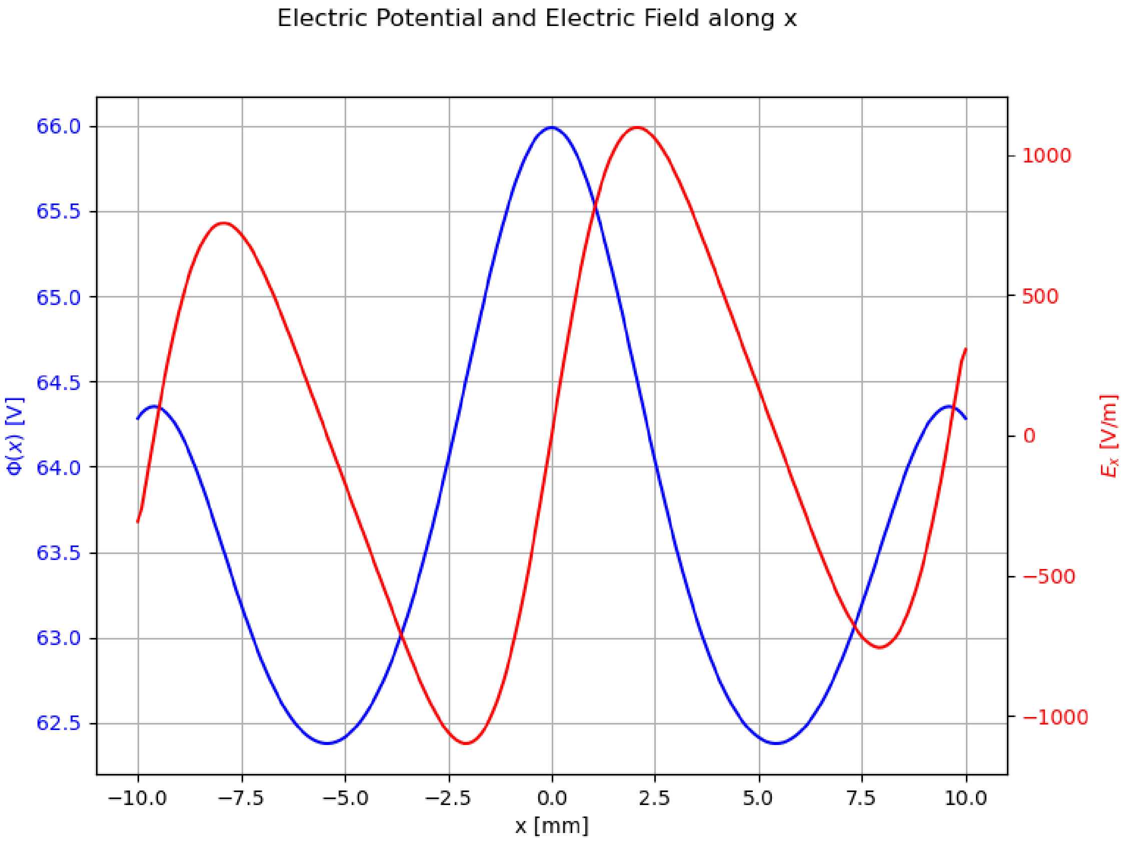
- **Dependence of orbit spacing (and energy) for recapture**



Beam electric field and potential



1.5 mA Beam alone at 590 MeV



1.5 mA Beam with two neighboring orbits spaced of 1cm on both sides at 590 MeV

Simulation softwares

- CST-Studio:

- Simulation of electromagnetic fields and particle tracking

- General tool for simulation

- PIC Solver: Particle tracking for both protons and electrons

- Matter interaction

- Long simulations

- Virtual-IPM*:

- Simulation of the electron/ion transport in Ionization Profile Monitors

- Particle tracking only for electrons

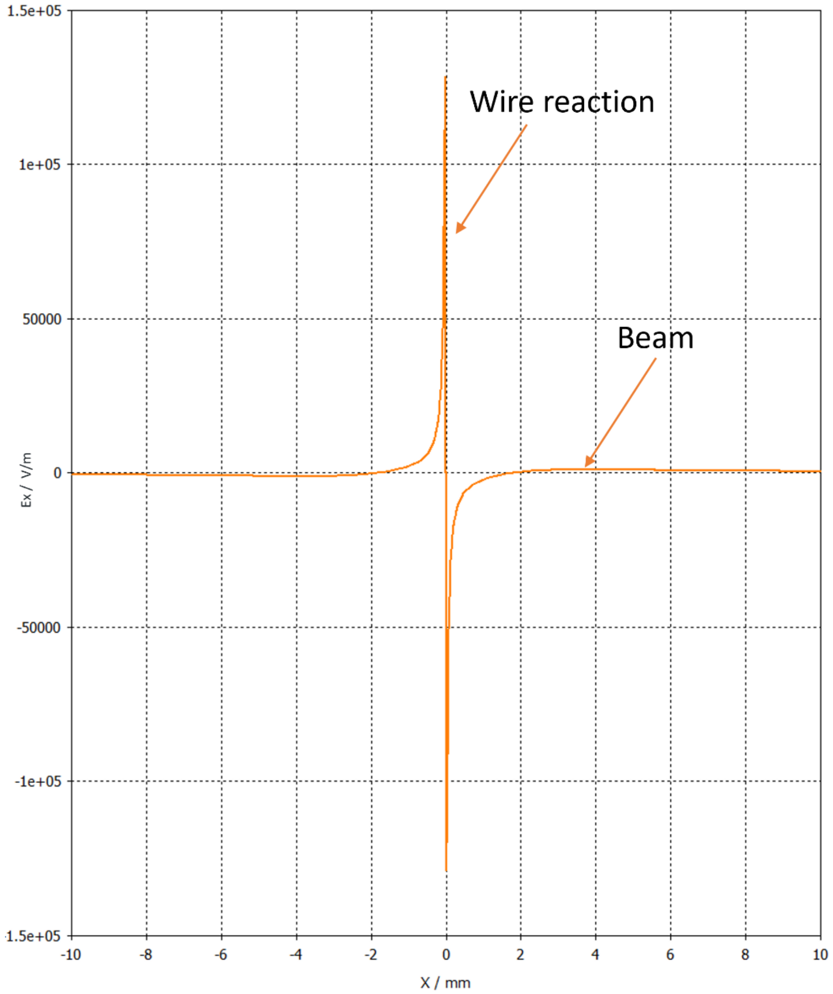
- No matter interaction

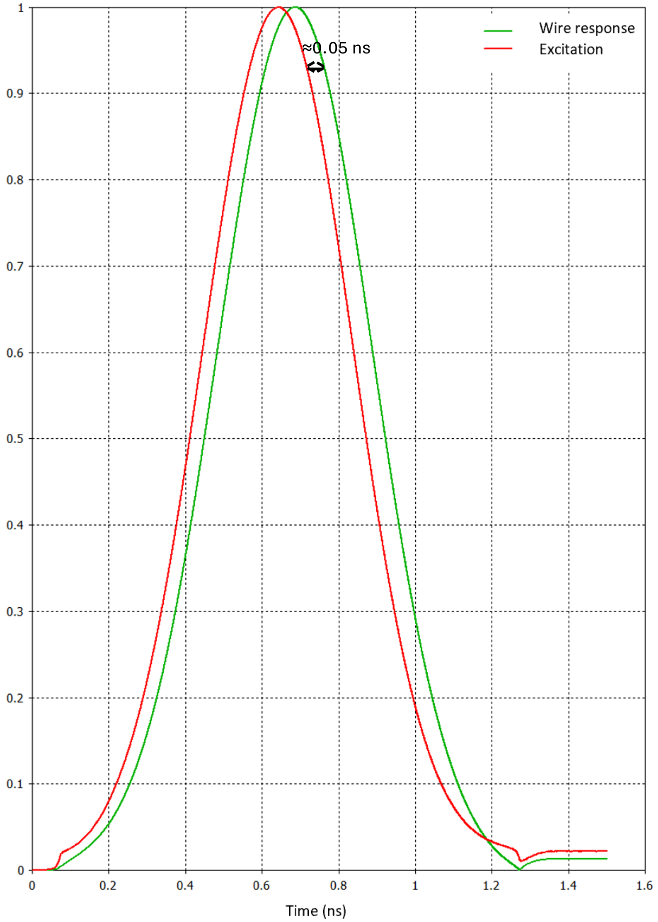
- Quick simulations

*D. Vilsmeier. “Virtual-IPM Python Package Index .”, Available: https://pypi.org/project/virtual-ipm

Electric field on wire (CST simulation)

- High Electric field from the wire
- Small size of the wire so high gradient





Wire in carbon fiber without bias (15µm radius / 1cm long)
1.5mm Gaussian shaped 590Mev beam at 1.5 mA

Reaction of the wire:

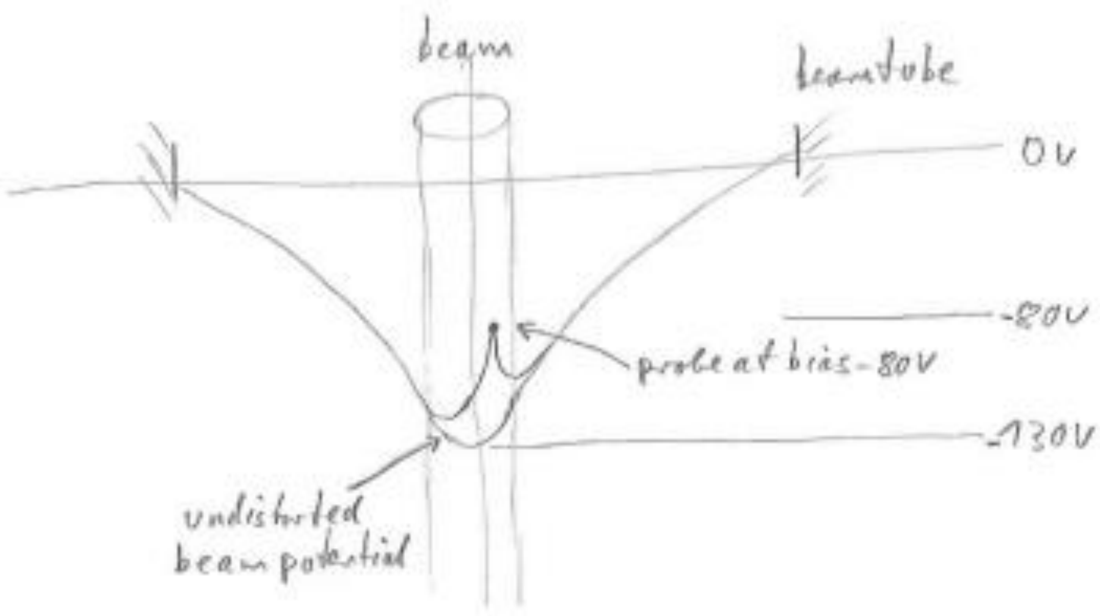


Illustration of the distortion of the bunch space potential by the probe wire.

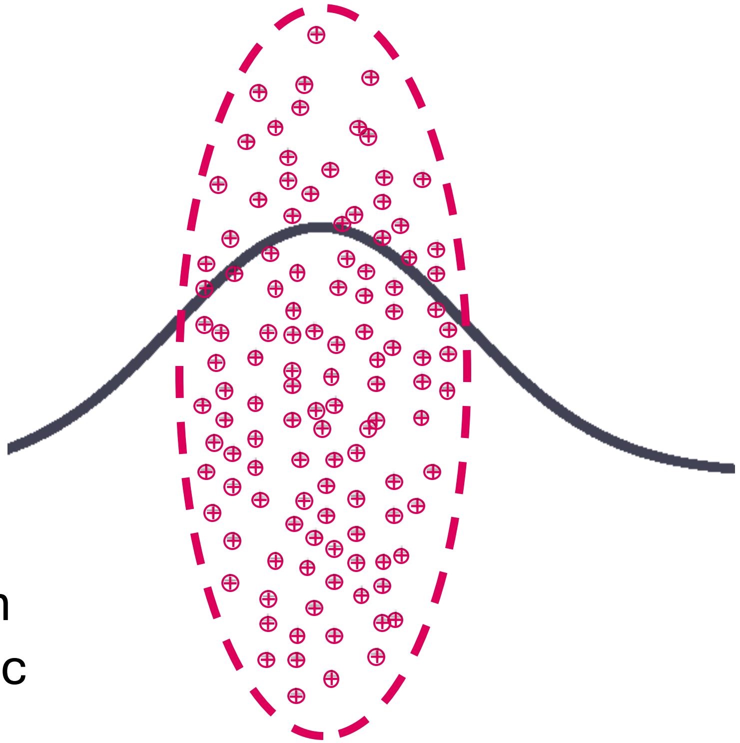
"The larger bunch potential results in a locally repelling electric field for the emitted electrons"

R. Doelling*, about wire scanners in CSNS-linac **

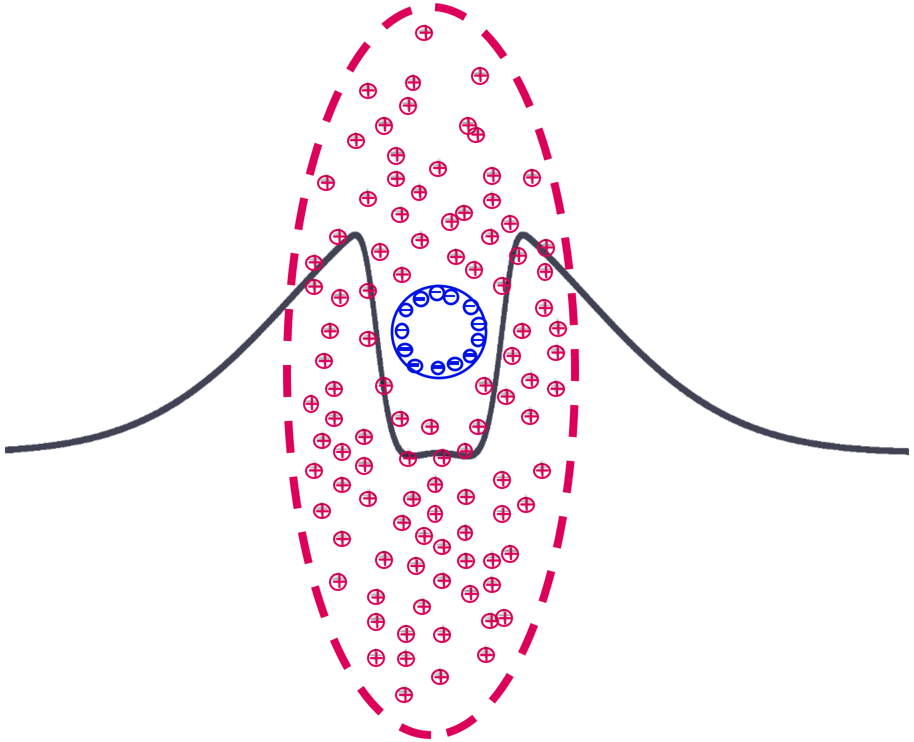
* Effect of bunch potential and bias voltage on wire monitor signal ,id:HIPA-DIAGNO-DR84-071.00-22.02.2022
** J. L. Sun et al., Study with wire scanner and beam loss monitors at CSNS-linac, IPAC2019, https://accelconf.web.cern.ch/ipac2019/papers/wepgw053.pdf

Electrostatic shielding

- Beam impact does not directly affect electrons
- Beam impact alters the surface charge distribution on the wire to counterbalance beam potential
- Wire is thin (few µm) compared to the beam (few mm) ,so a high gradient resulting in high electric field
- Resulting Electric field repels electrons from the wire



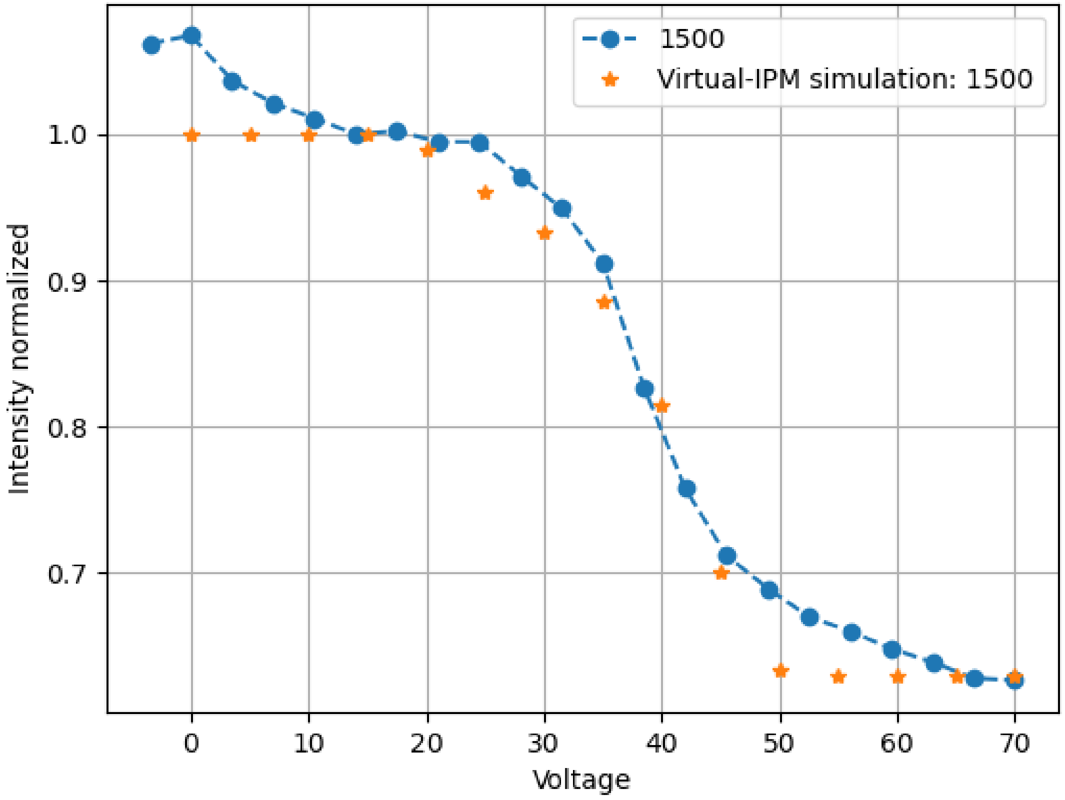
Beam potential without wire



Beam potential with wire

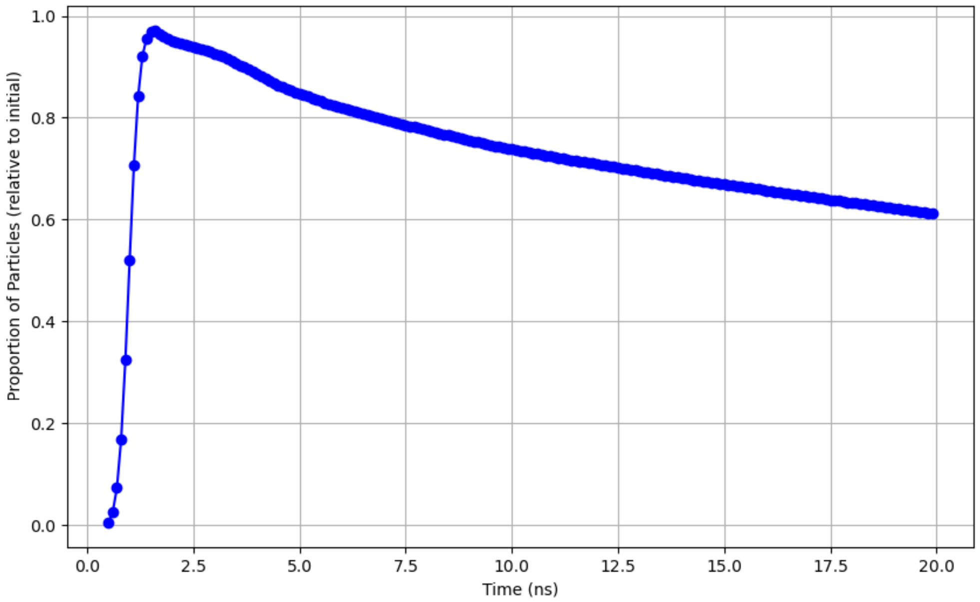
Simulations with Virtual-IPM

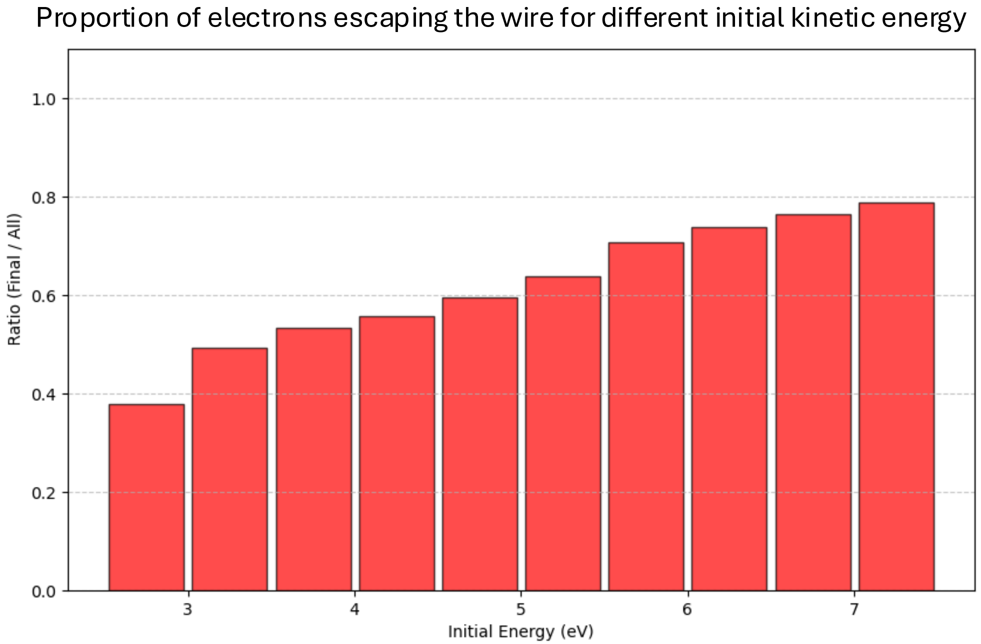
Settings:
- 1 neighboring orbit on both side spaced of 1 cm
- Beam at 590 MeV
- kinetic Energy of electrons: 5 eV (≈avg energy of secondary electrons)
- No time response
- Beam potential is entirely neutralized by the wire's surface charge distribution
-end of simulation: 17.5ns after the middle of the bunch(≈time between bunch:20ns)



- Observation of the impact of the beam
- Good agreement with data

Simulations with CST



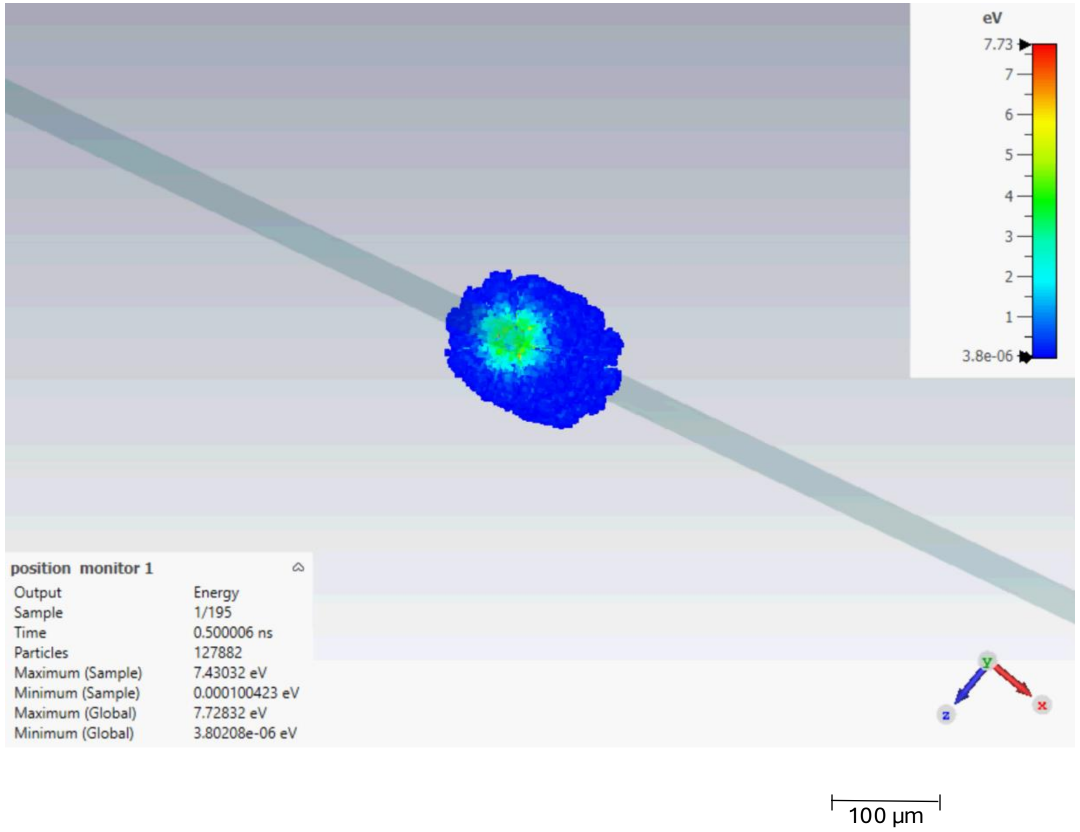


30V wire in carbon fiber (15µm radius / 8cm long)

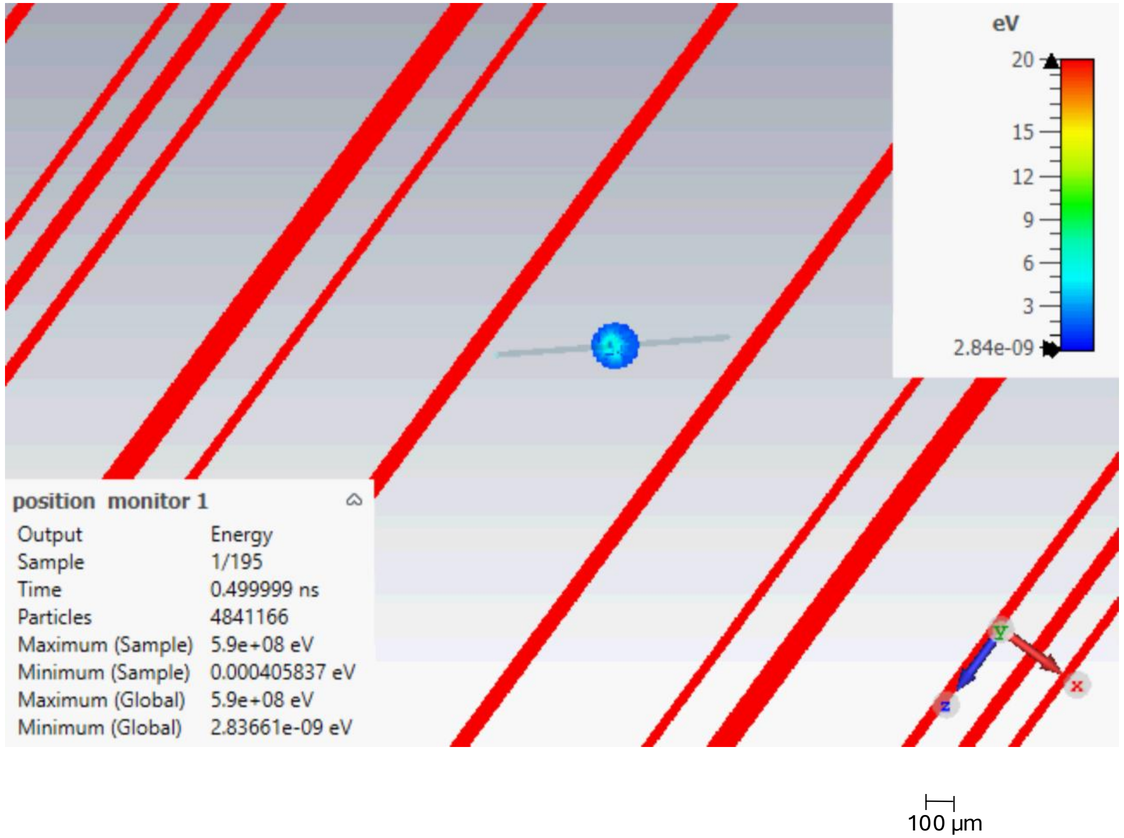
590Mev beam with 4 neighboring orbits (1cm)

Electron spectrum:2.5-7.5eV

Simulations with CST:Particle Tracking of electrons



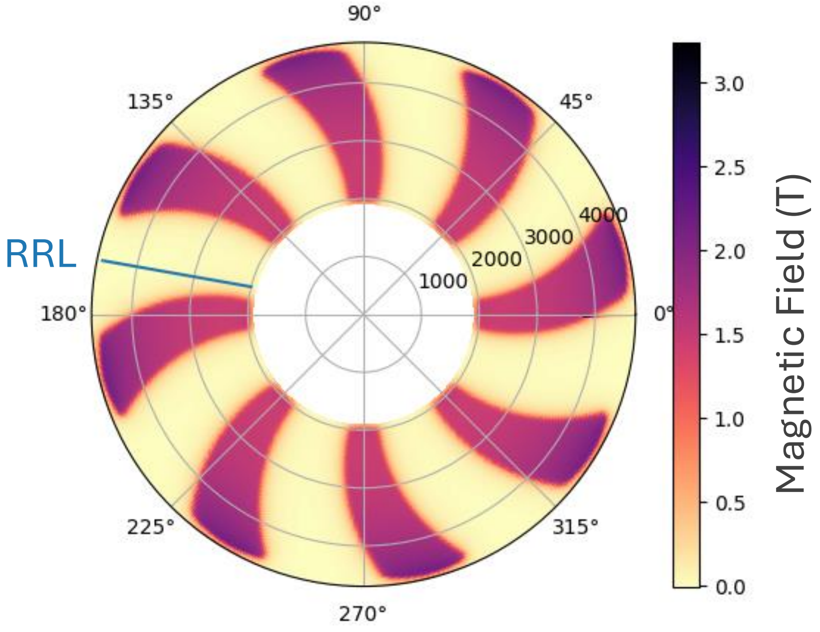
Without Beam



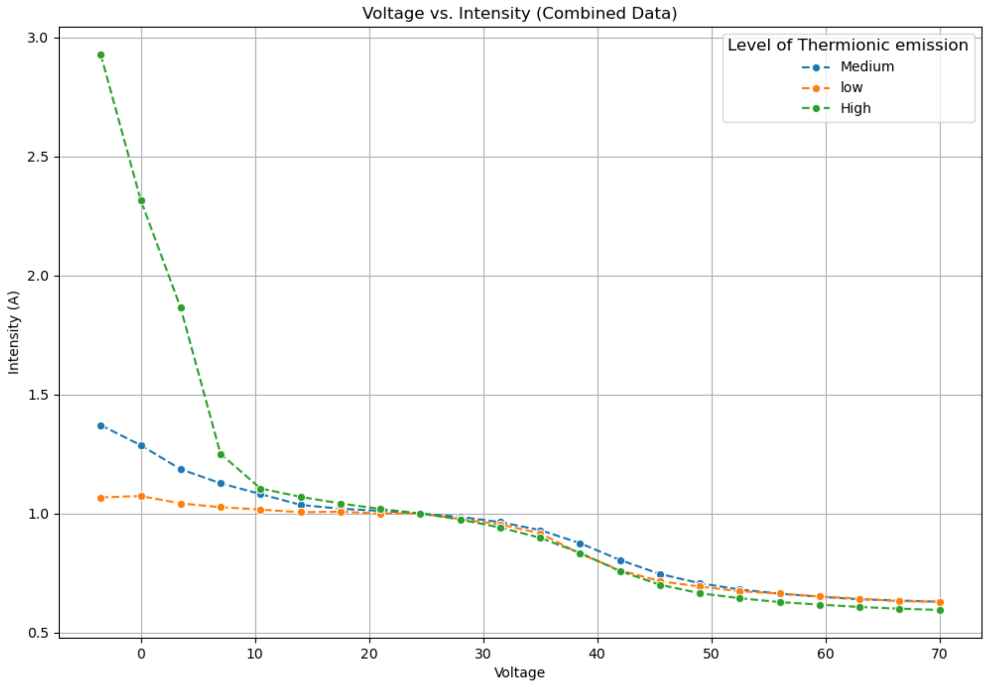
With Beam

Simulation issues

- High-speed of protons and low-speed electrons
- Uncertainty on wire properties
- Uncertainty on the spectrum of secondary emission
- Real geometry of the system (cavities/metal plate,...)
- Other sources as RF field and magnetic field
- Simulation time



Thermionic emission

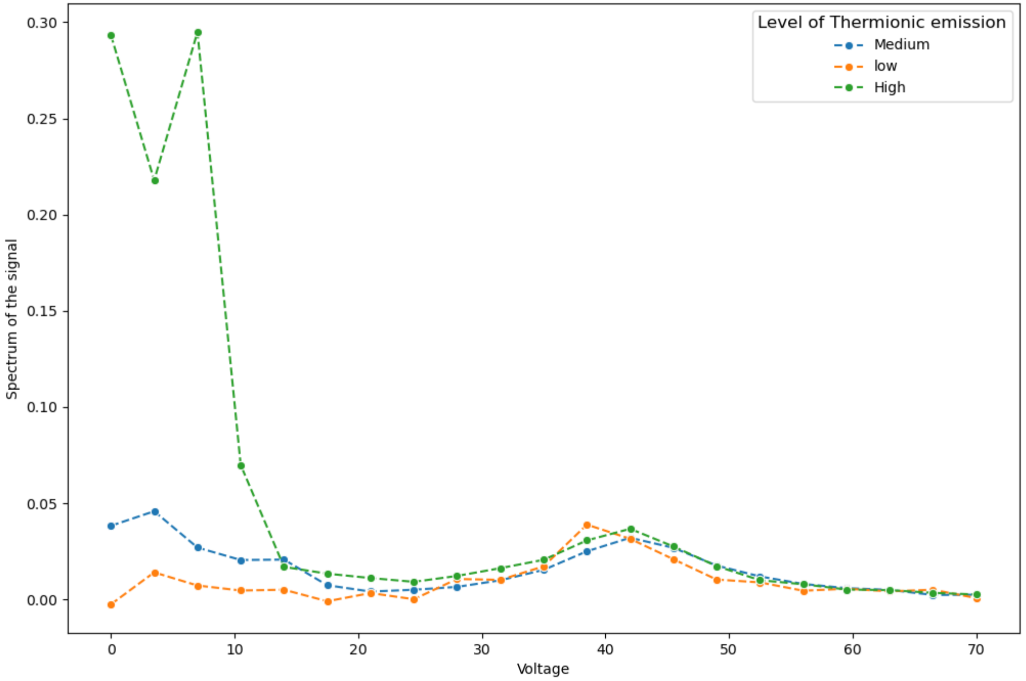


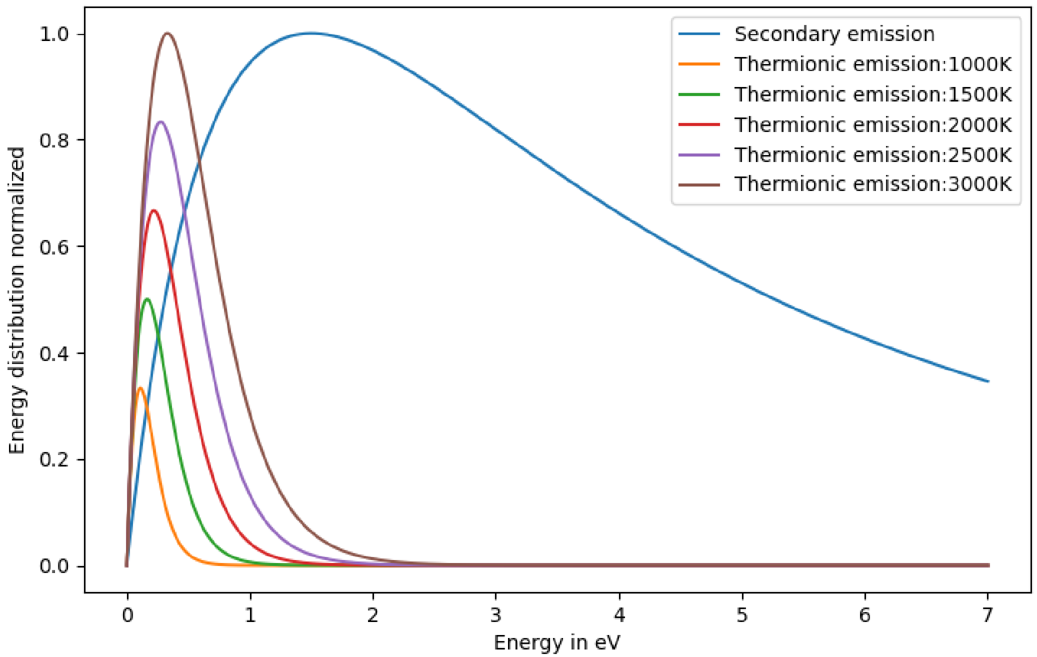
Different levels of thermionic emission at a similar fixed position with changing biased voltage in RRL for a 1.5 mA beam near 500 MeV

- < 10V/High decrease: Recapture of majority of thermionic emission
- 10V-35V/Small decrease: Recapture of thermionic electrons emitted closer to the beam
- >30V: Recapture of secondary electrons

Thermionic emission

1.5 mA beam



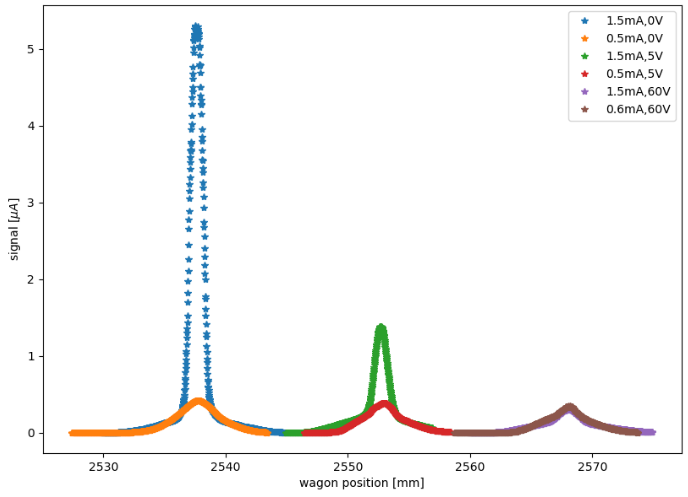


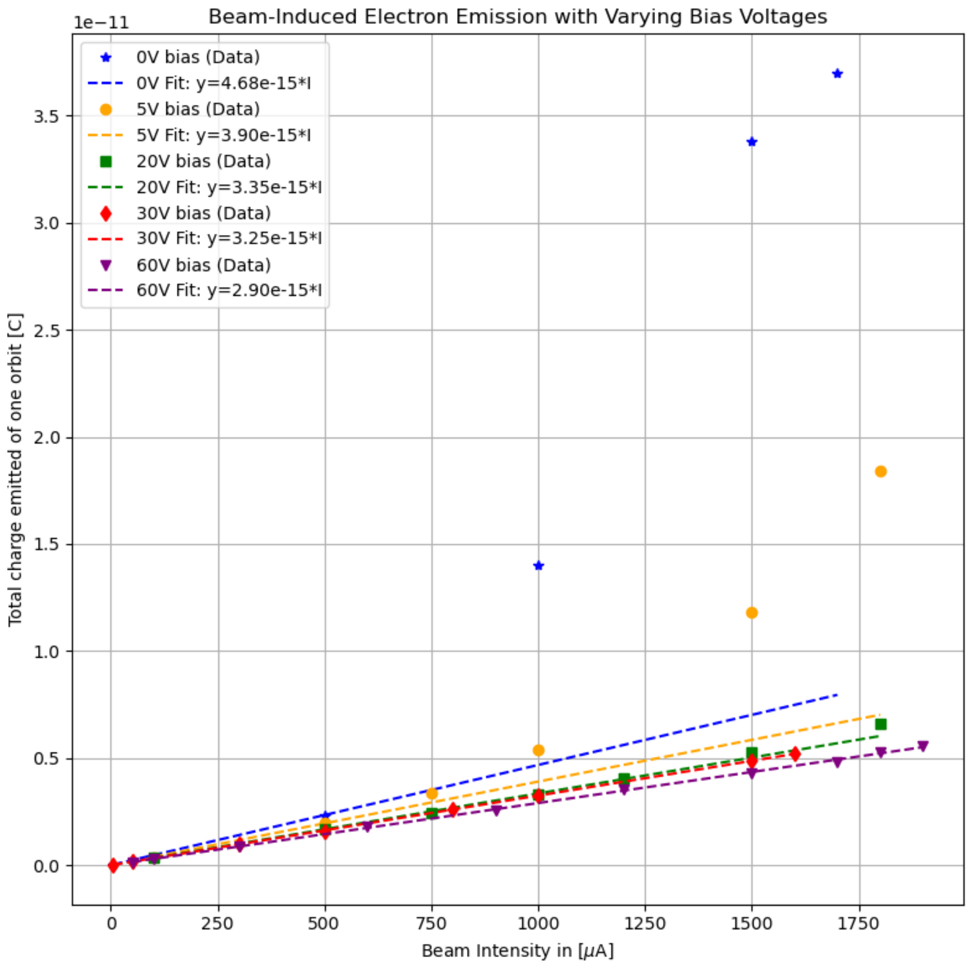
- < 10V/High decrease: Recapture of majority of thermionic emission
- 10V-35V/Small decrease: Recapture of thermionic electrons emitted closer to the beam
- >30V: Recapture of secondary electrons

- Higher spread of the spectrum

Thermionic electrons recaptured?

$$Q_{secondary} \propto Q_{Beam}$$

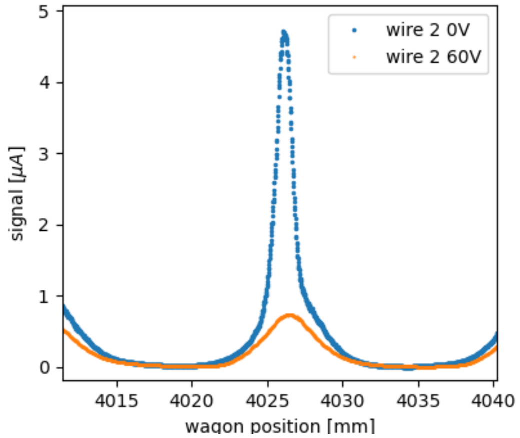


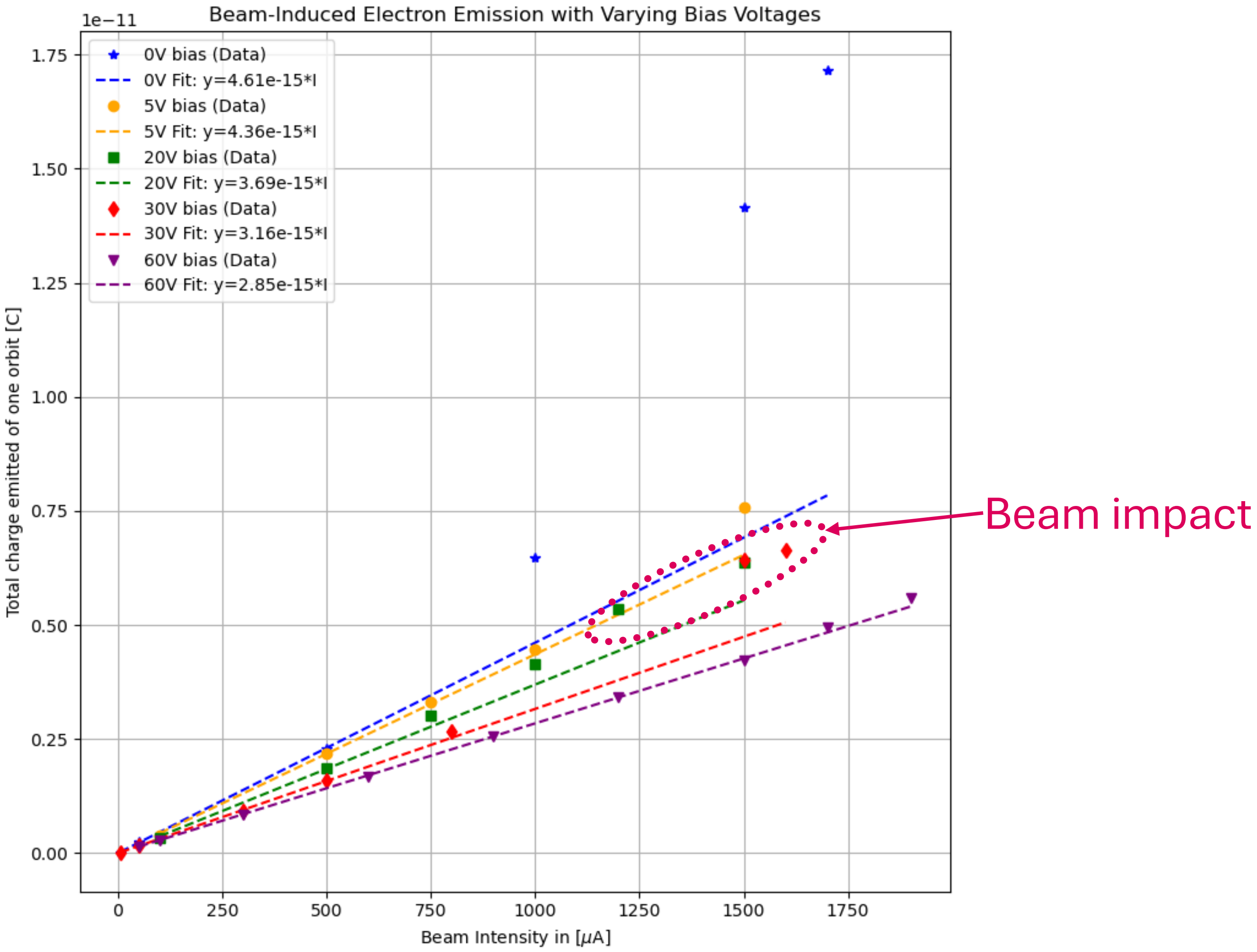


Position 2535mm: 123MeV orbit

Thermionic emission seems to be totally recaptured

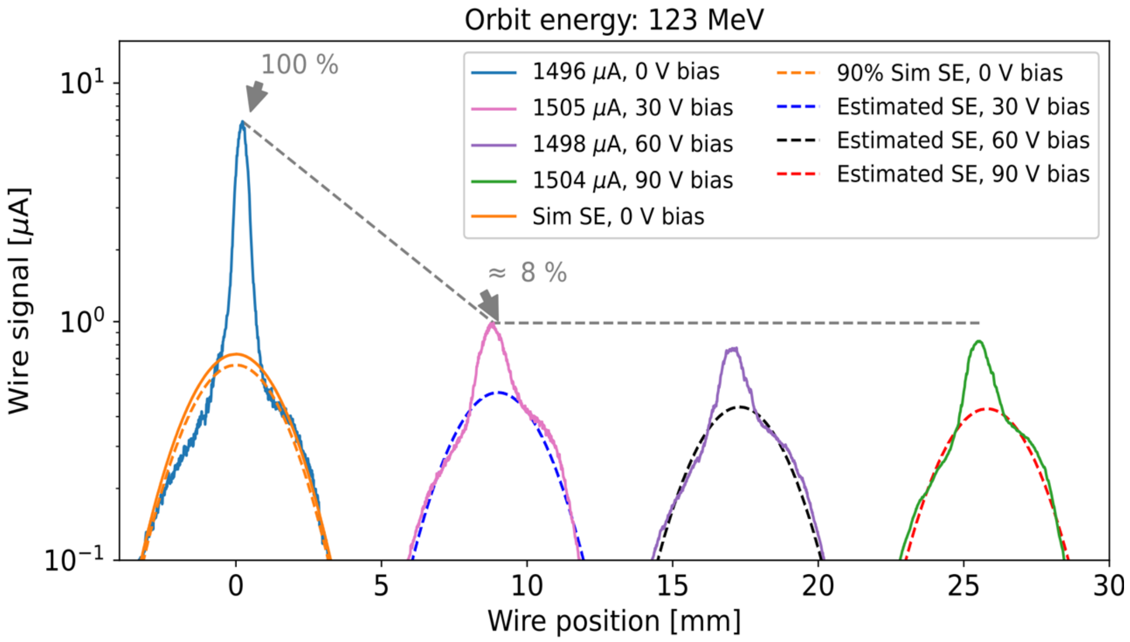
Thermionic electrons recaptured?



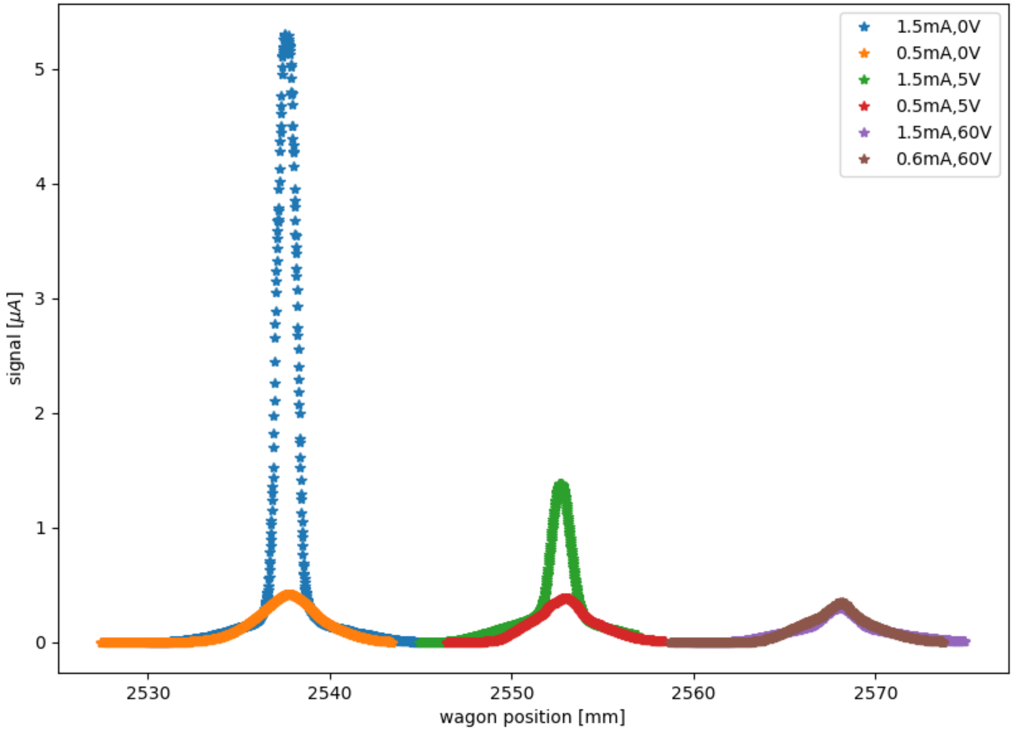


Position 4028mm: 489 MeV

Thermionic electrons totally recaptured?



Results of Manon Boucard



1.5mA beams rescaled/5V and 60V shifted, 123MeV

THANK YOU FOR YOUR ATTENTION

SPARE SLIDES

Material Properties

	Density $[g/cm^3]$	Strength [GPa]	Melting temp [K]	Heat cap [J/mol K]	Z
CF	1.8	3.1	3915	8.5	6
Be	1.8	0.8	1560	16.4	4
SiC	3.16	4.0	3100	1.1	12.6
Mo	10.3	2.1	2896	24.1	42
Ta	16.7	0.7	3290	25.6	73
W	19.3	3.4	3695	24.3	74
CNT	0.2	0.5	3915	7.2	6

Delta/Secondary contribution

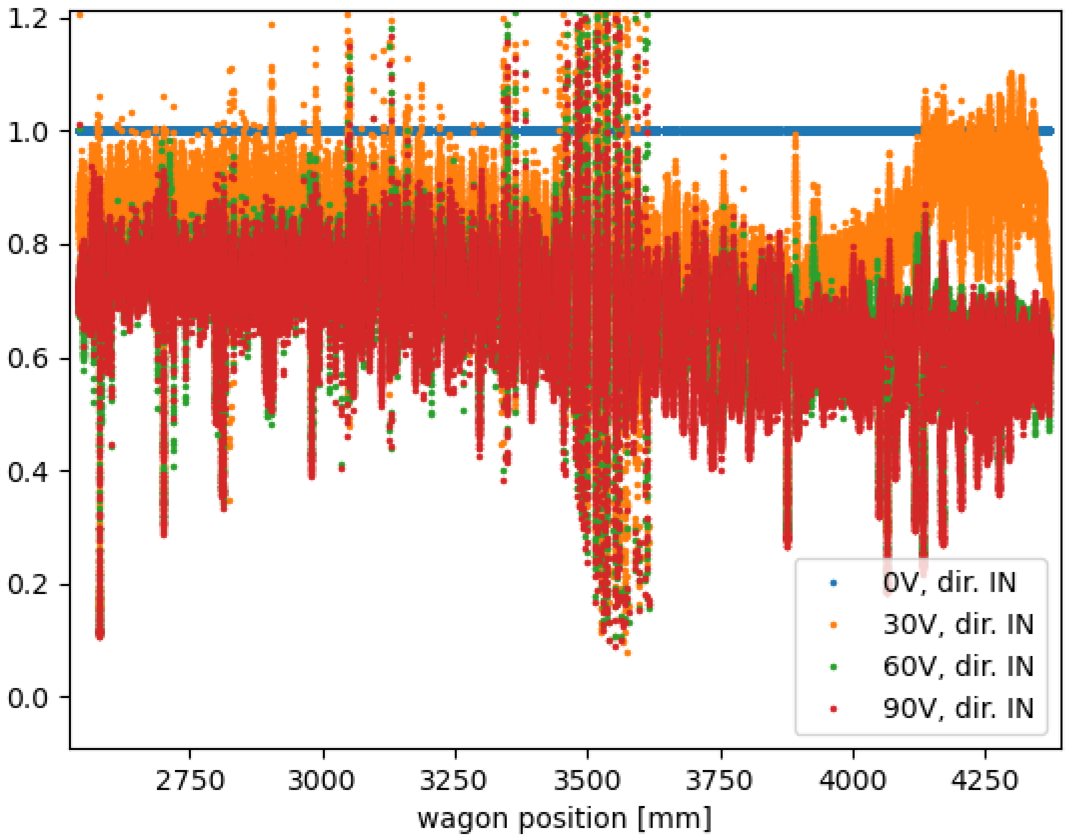
Table 1: Maximum and average energy of delta electrons for 33 μm carbon fibre.

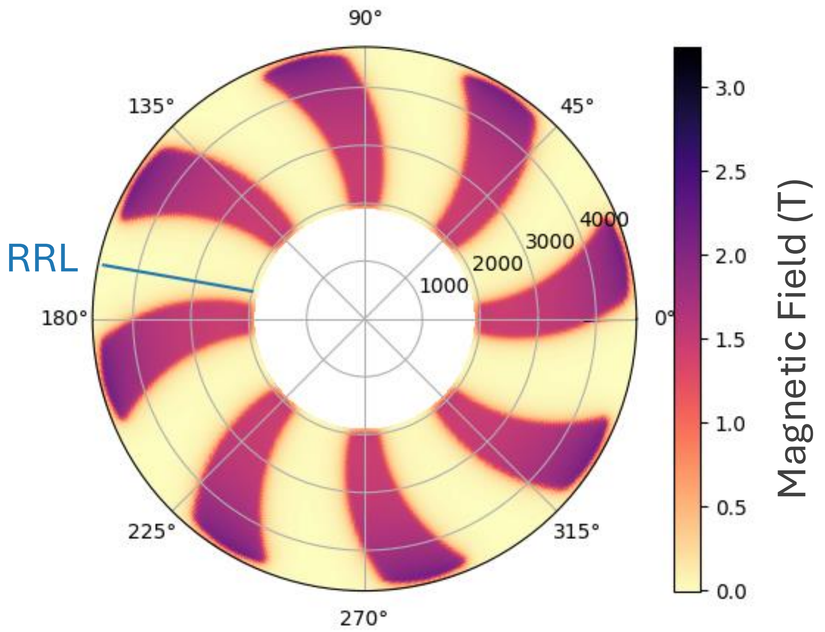
proton energy	T_{max}	emm.prob	E_{avg}
72 MeV	160 keV	7.34%	3 keV
590 MeV	1.69 MeV	1.93%	92 keV
3 GeV	17 MeV	1.34%	150 keV
450 GeV	155 GeV	1.29%	297 keV

Table 2: Secondary emission yield (SEY) assuming that the protons cross two surfaces (go through the target)

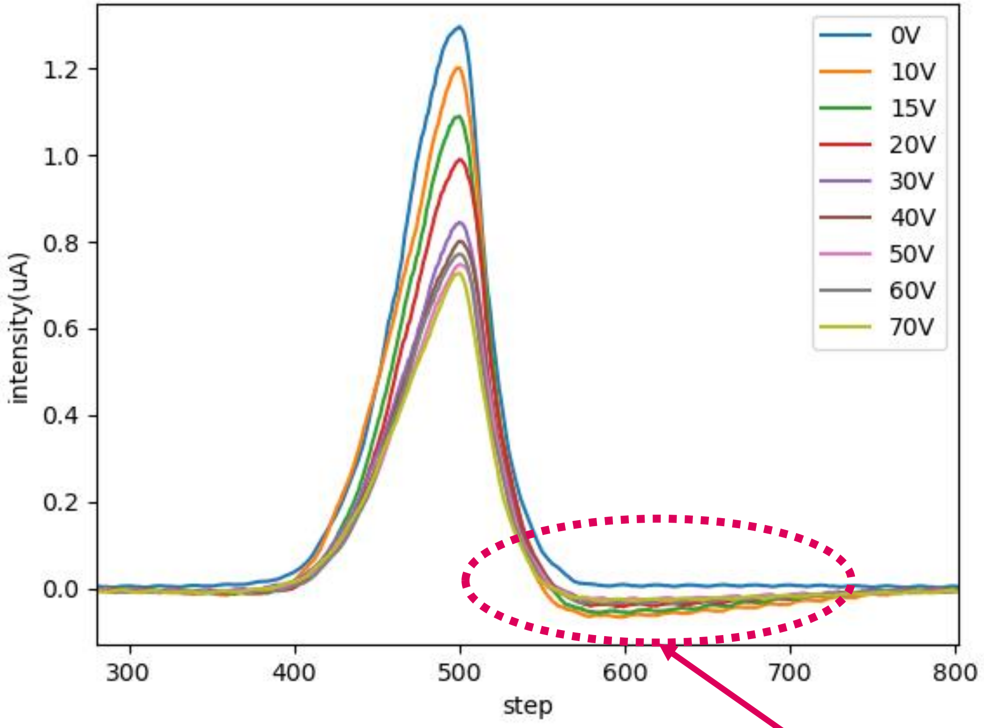
proton energy	Carbon	Mo	Tungsten
72 MeV	4.06%	14.87%	21.69%
590 MeV	1.14%	4.19%	6.11%
3 GeV	0.93%	3.42%	4.99%
450 GeV	1.66%	6.06%	8.84%

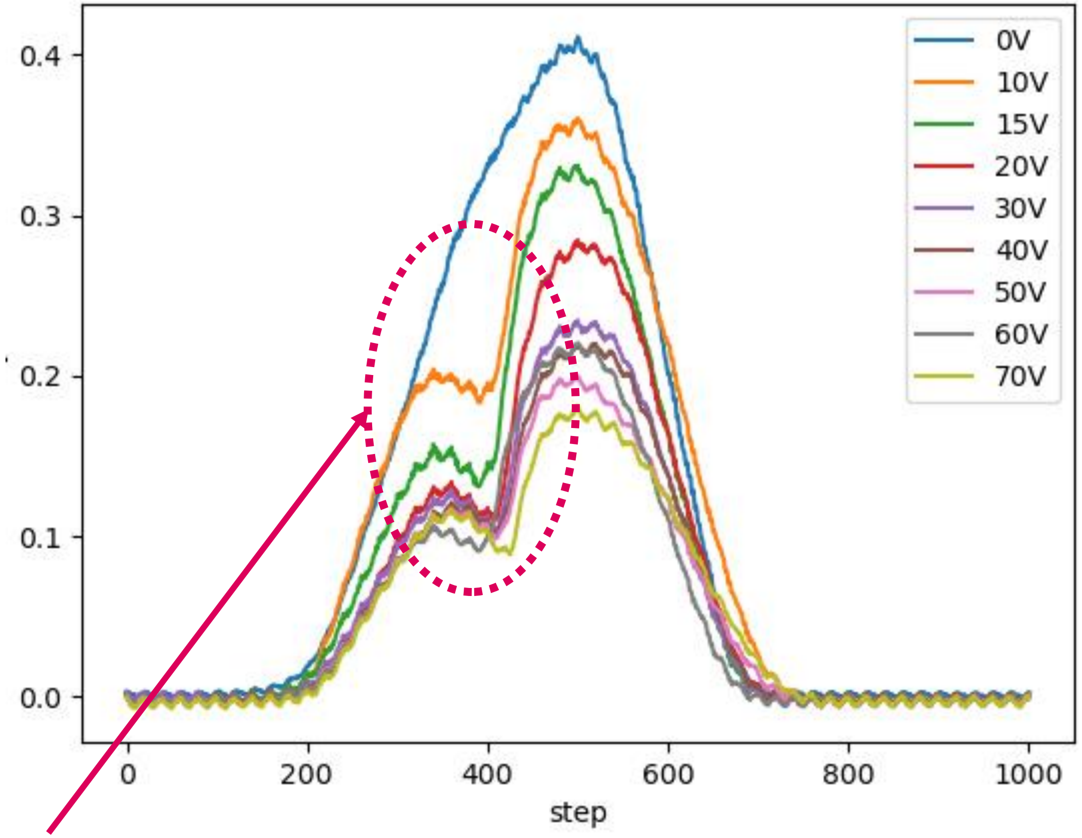
Possible impact of magnetic field





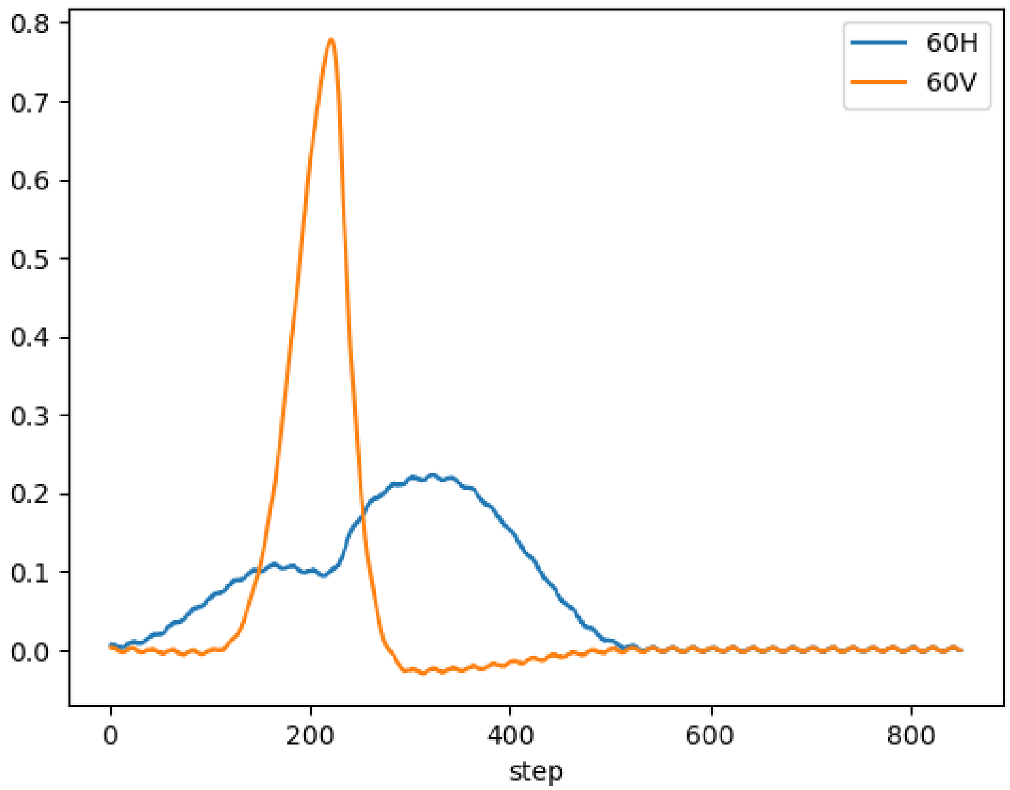
Limits on bias voltage

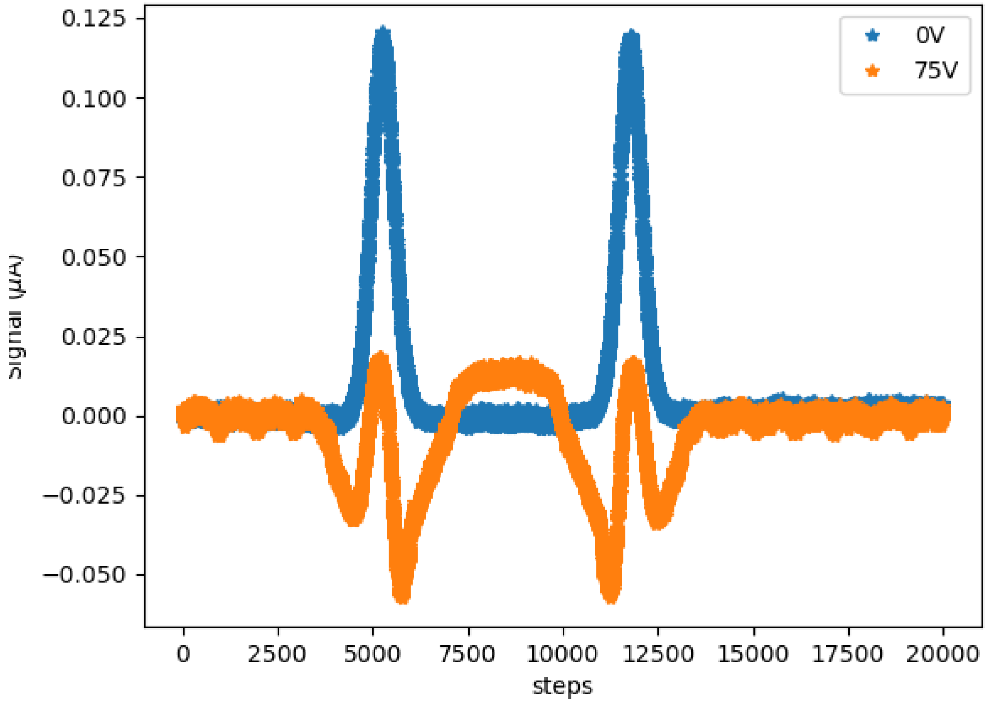




Disturbance of signal

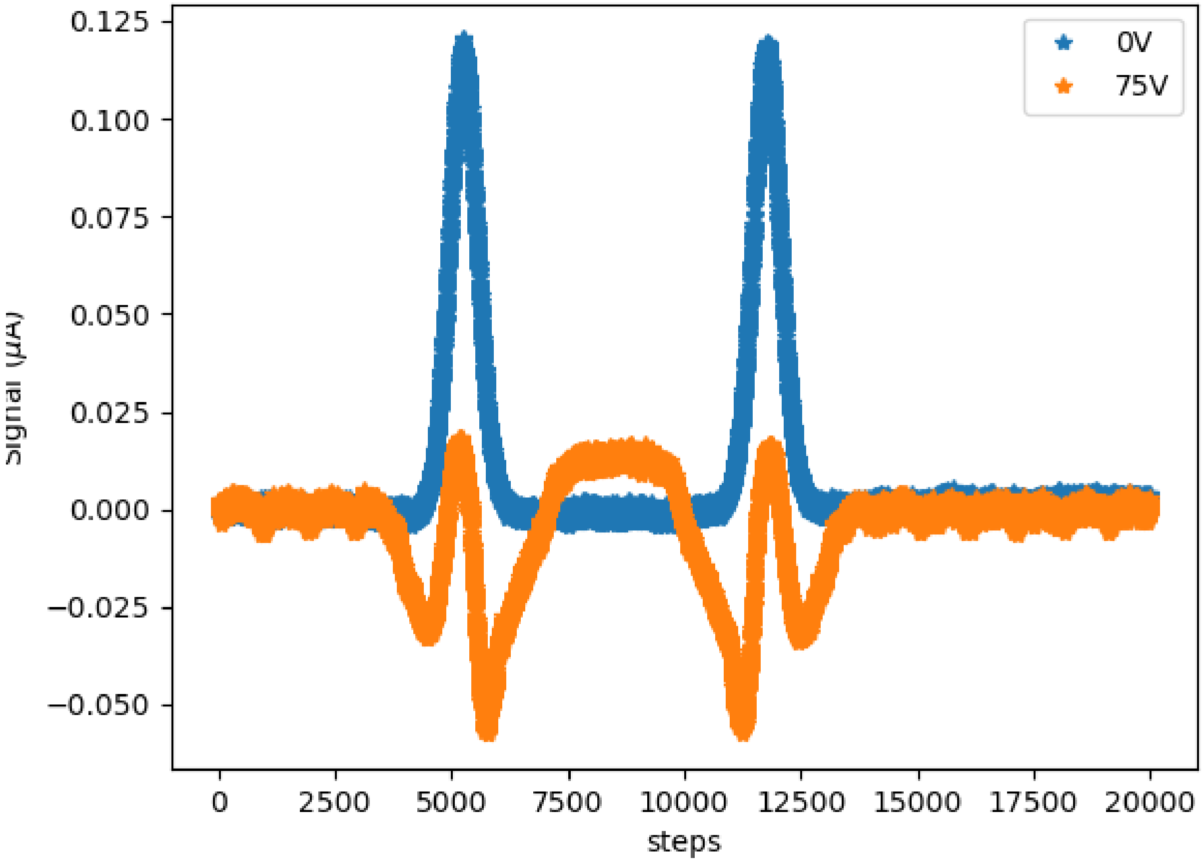
Limits on bias voltage: Cross-talk



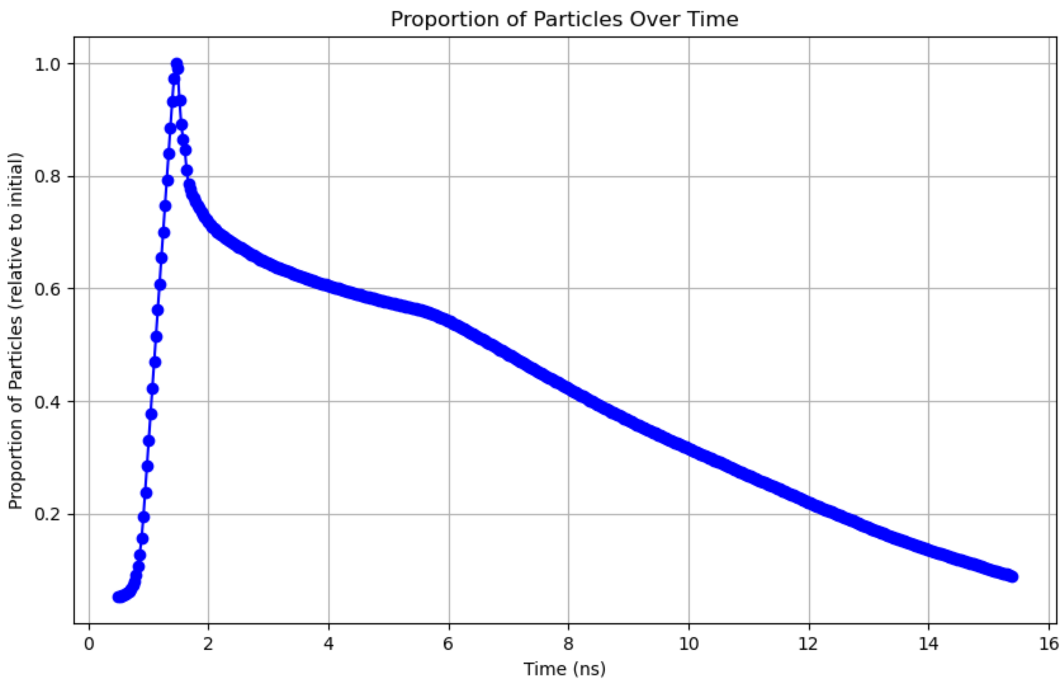


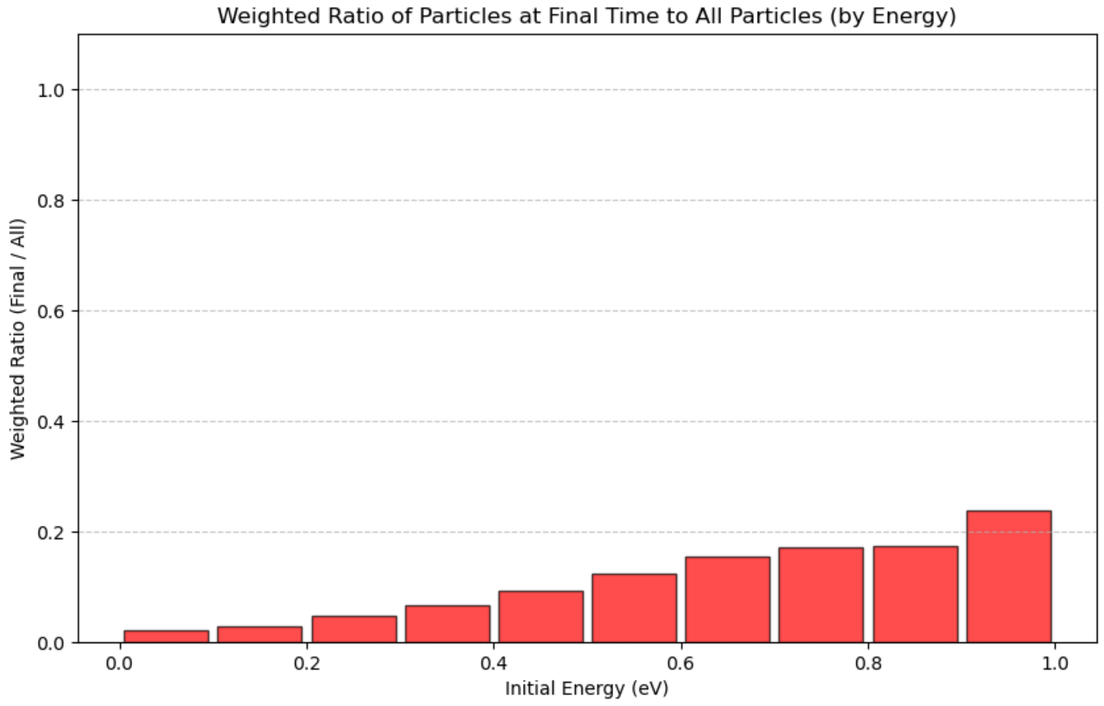
Limits on bias voltage

Recapture of electrons coming from other sources



Thermionic Emission : CST simulation





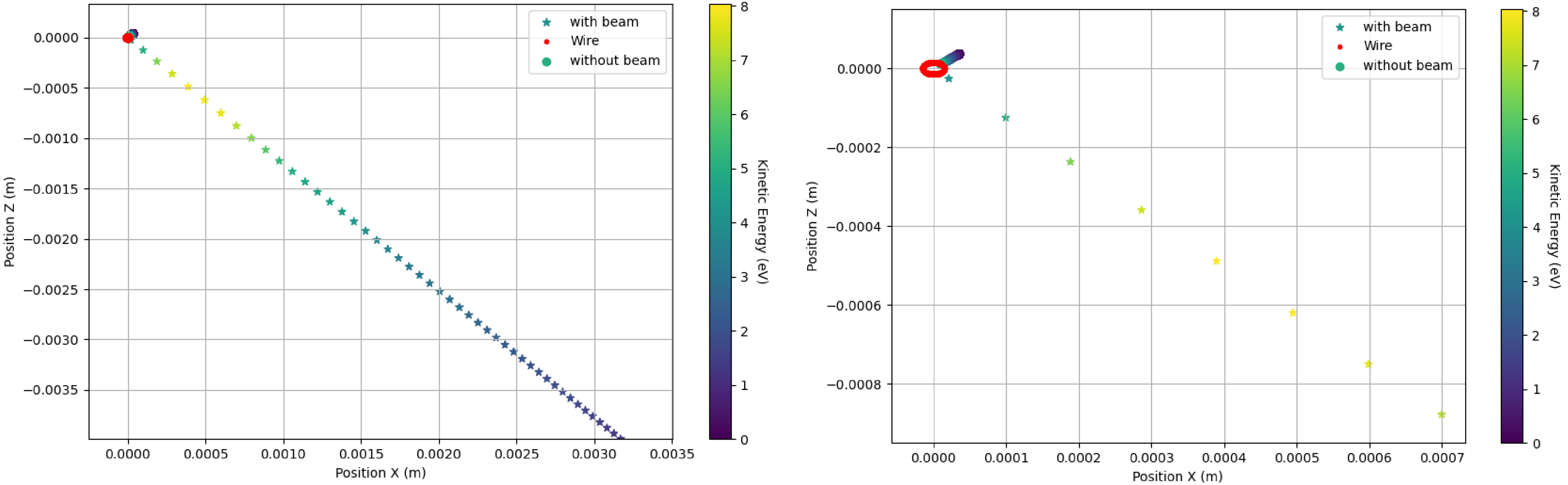
30V wire in carbon fiber (15µm radius / 8cm long)

590Mev beam with 4 neighboring orbits (1cm)

Electron spectrum: 0-1 eV

Simulations with CST

Particle Tracking of 5-eV electrons



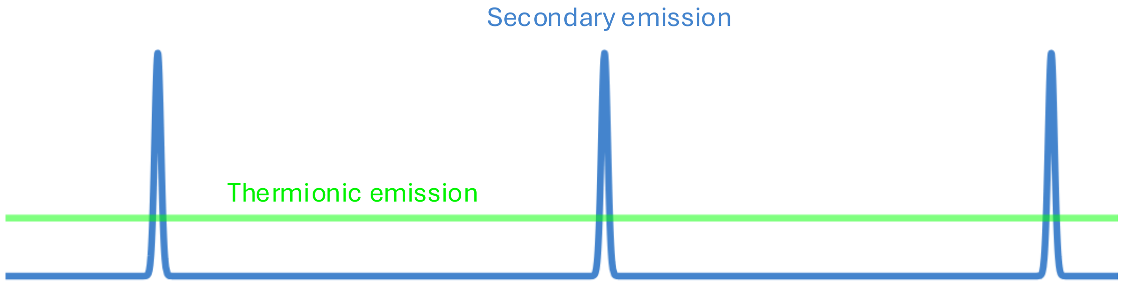
Perspectives on new method

- Idea:

Using the AC behavior of the signal to detect only secondary emission

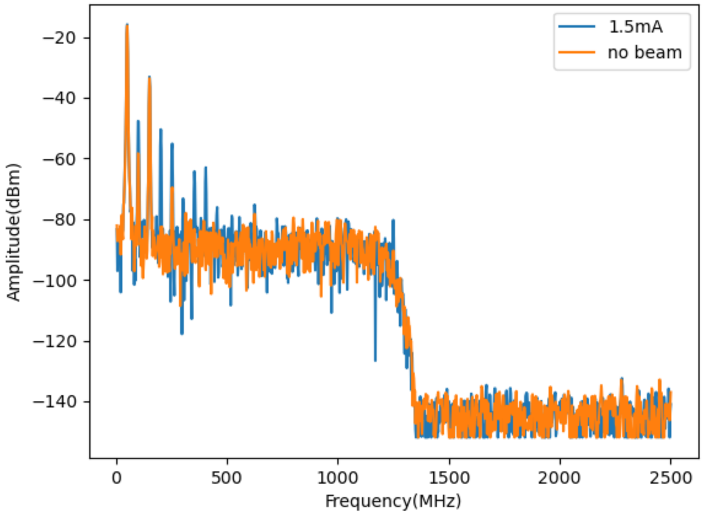
- Method:

Narrow-band filter



- Problems:

- Voltage Filter
- Low current
- High RF signal



Recap: Beam impact on electron recapture

Beam Electric Field → Charge redistribution on wire → High Electric Field near the wire → Repulsion of Electrons