PSI

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EMISSION OF SECONDARY, THERMIONIC AND DELTA ELECTRONS FROM THIN TARGETS

13th International Beam Instrumentation Conference

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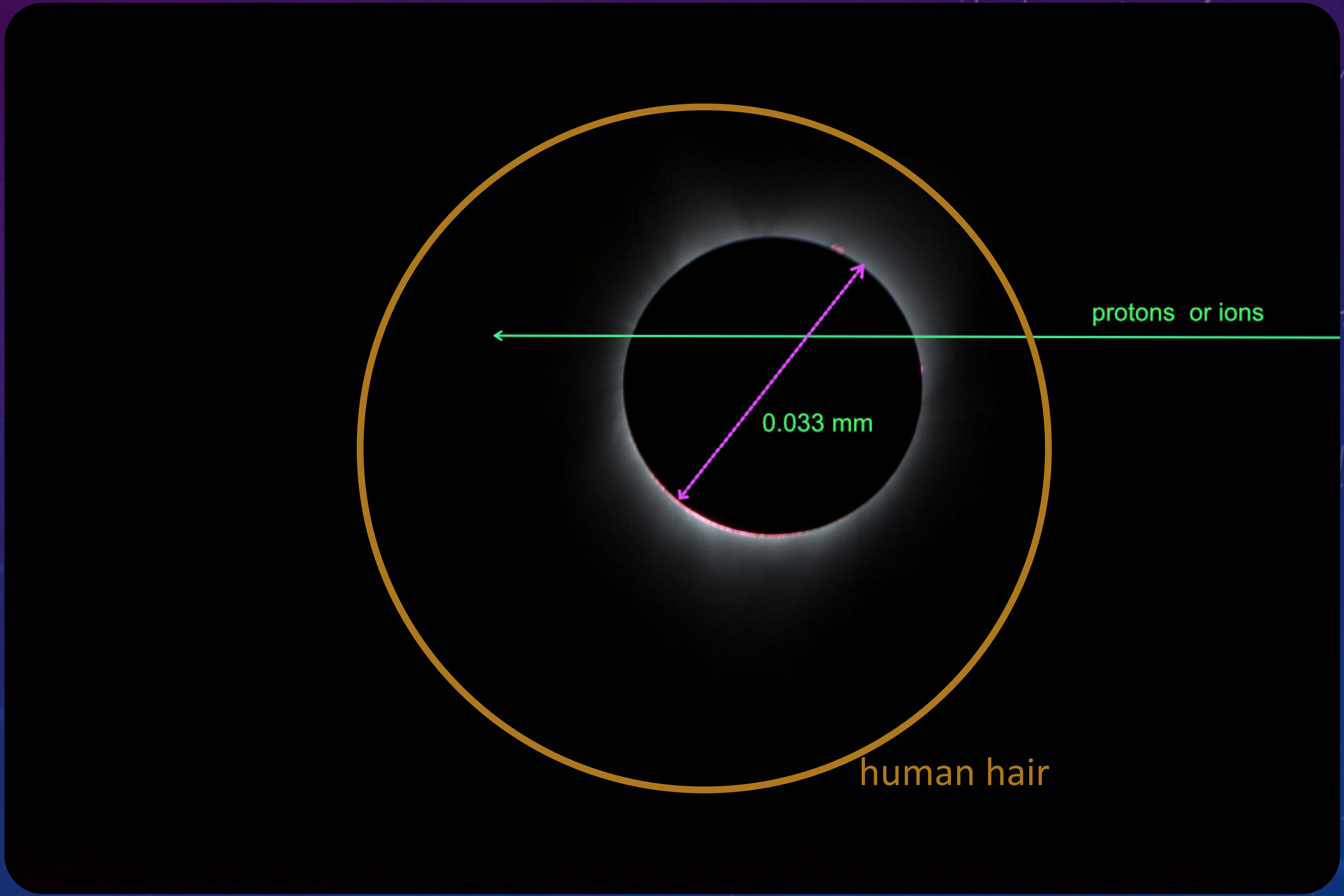
Mariusz Sapinski

Beijing, September 13, 2024

INTRODUCTION

I will talk about protons (or ions) interacting with thin targets.

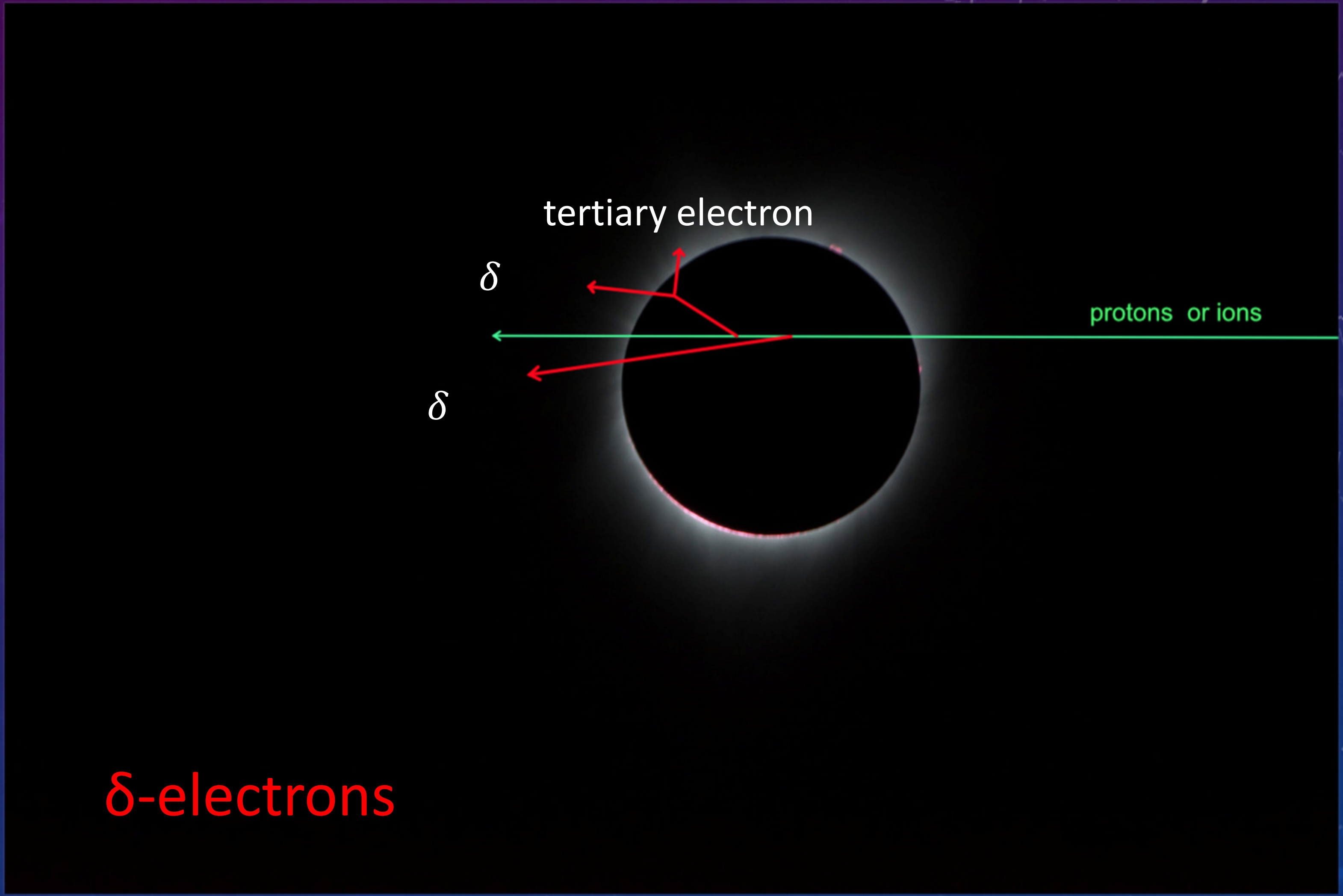
- Small perturbation to the beam.
- Favourable thermal properties:
    - Large cooling surface.
    - Small energy deposit.



INTRODUCTION

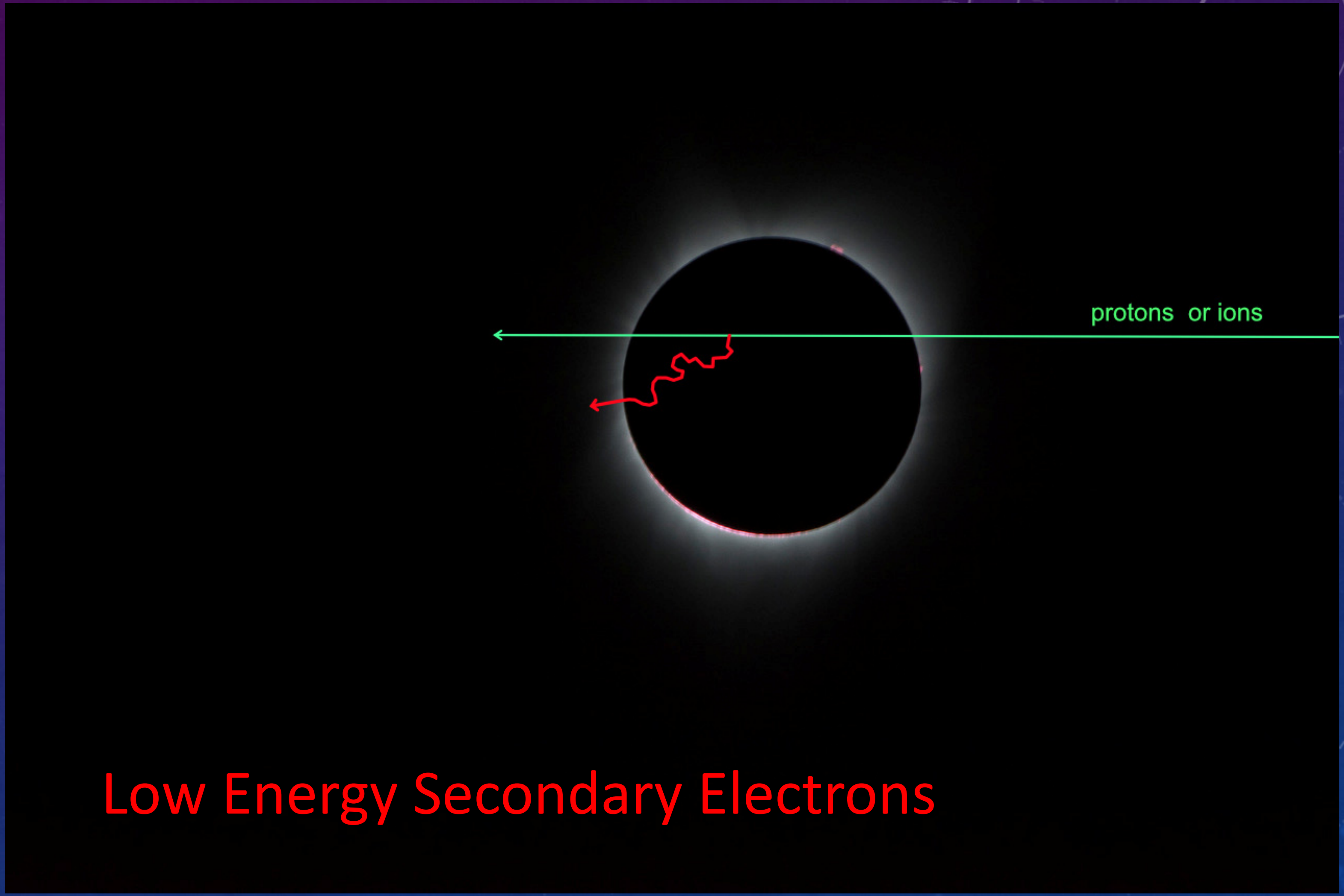
Protons interactions produce secondary particles.

- Energy and number of secondary particles increase with energy of the primary proton.
- Most secondary particles (from thin target) are electrons.
- When they have large energy (head-on collision) they can even produce further ionization.
- We call them δ-electrons - this term was first used by Joseph Thomson, who discovered electrons.



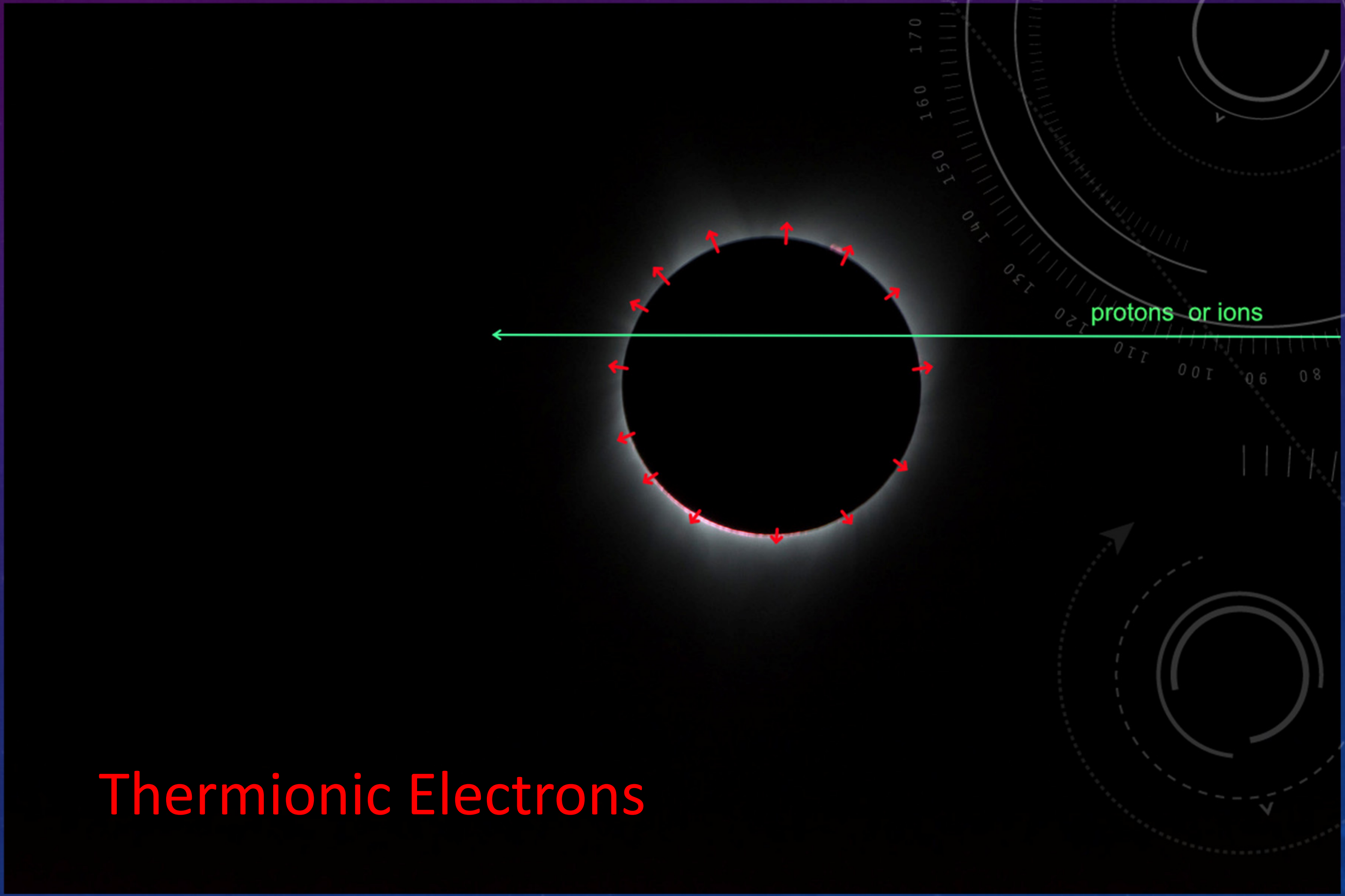
INTRODUCTION

- Some secondary electrons have energies < 100 eV.
- They come from excitation/ionization by primary proton, but:
  - The initial energy transfer is small – it is more energy transfer to electron plasma.
  - Their creation is more a collective effect than binary collision.
  - They can undergo multiple collisions in the target material.
- I will call them Low Energy Secondary Electrons (LESE).



INTRODUCTION

- When beam is:
  - High power,
  - High brightness.
- Target becomes very hot and emmits thermionic electrons.
- They have sub-eV energies, but the current can be very strong.



OUTLOOK

- Motivation.
- Thin targets and devices employing thin targets.
- Delta electrons: yield, spectrum, effect on energy deposit in the target.
- Other particles emitted.
- Secondary electrons: yield.
- Comparison of secondary electron and δ-electron current.
- Thermionic current and spectrum of thermionic electrons.
- Thermionic electron interaction with bunch field.
- Space-charge limit of thermionic emission?
- Thermionic cooling.

MOTIVATION

When those three types of electrons are important?

Mainly:

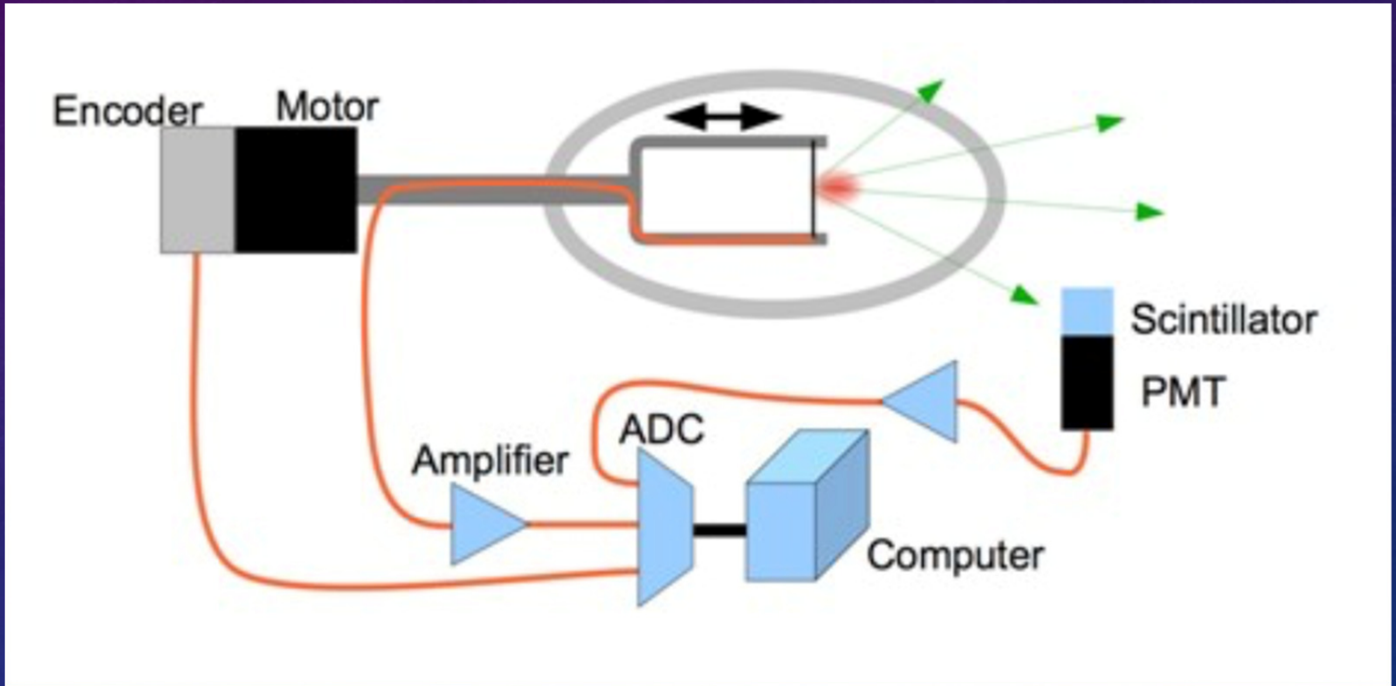
- High brightness beams - targets at very high temperatures.
- SEM grids or wire scanners based on measurement of secondary electron current.

But:

- Some of this information can be useful for other cases of thin targets and other types of beams.

WIRE SCANNER: PRINCIPLE OF OPERATION

- Thin wire is moved transversely to the beam.
- Wire current or/and signal of the scintillator are measured synchronously with wire position from the motor encoder.
- Beam profile is obtained by plotting wire current or scintillator signal against wire position.
- Usually wire current is measured for low energy (<500 MeV) beams.



Plot Benjami Cheymol

THIN TARGETS – STUDY CASES

- Golden standard: 33 µm carbon fibre (graphitized), density ρ = 2 g/cm^3 (*)
- Proton beams, typical cases of high-brightness beams:
  - 590 MeV: PSI, Main Ring Cyclotron, Long Radial Probe (RRL), last orbit.
  - 3 GeV: J-PARC Main Ring flying wire at injection.
  - 450 GeV: CERN – SPS, flat top.

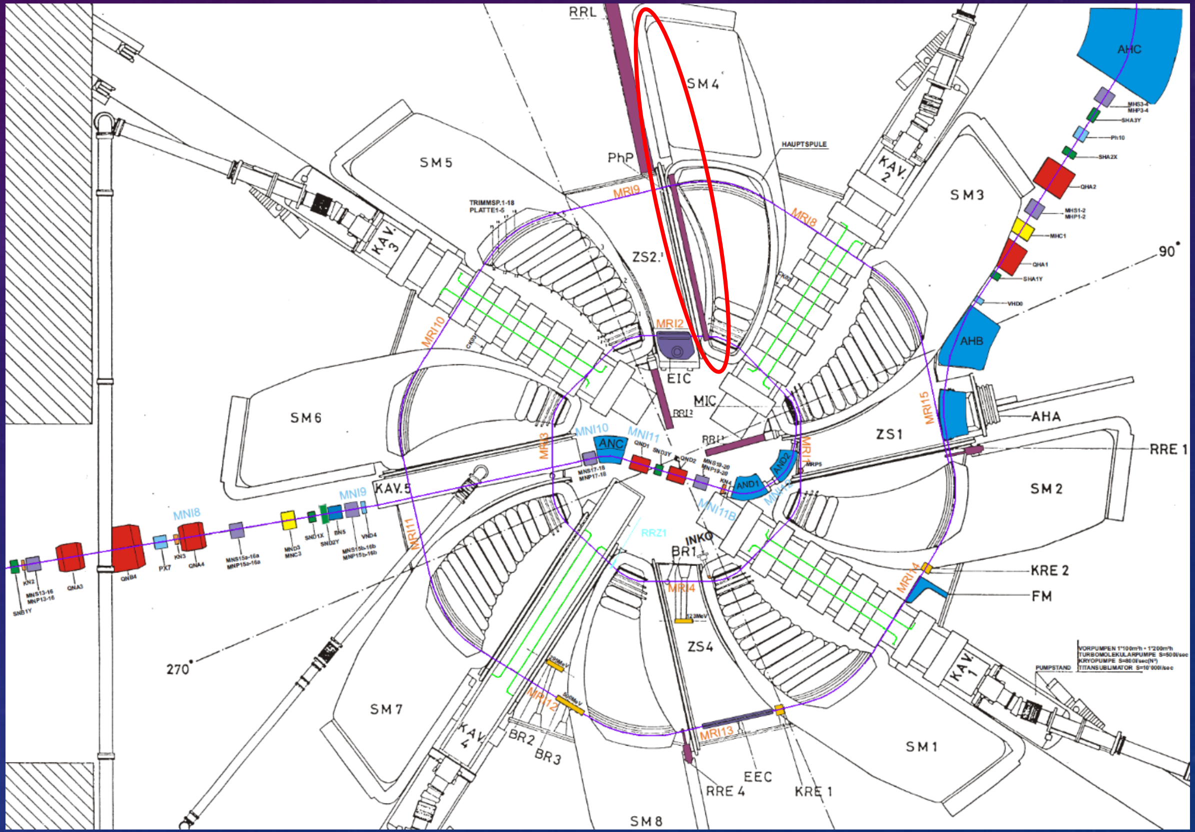
$$N_w = N_p \cdot f_{LHC} \cdot d_w / v_w$$

	I_{beam} [mA]	I_{beam} [p/s]	Wire speed [m/s]	Wire diameter [µm]	Number of particles crossing wire during scan
PSI-RRL @ 590 MeV	2	$1.25*10^{16}$	0.03	33	$1.375*10^{13}$
J-PARC-MR @ 3 GeV	1120	$7.0*10^{18}$	5 (- 10)	7 (33)**	$1.0*10^{13}$
CERN-SPS @ 450 GeV	150	$1.25*10^{17}$	9.0 (1-20)	33	$3.44*10^{12}$

* Typical carbon fiber densities are 1.7-2.1 g/cm^3
** 33 µm assumed for clear comparison with other cases

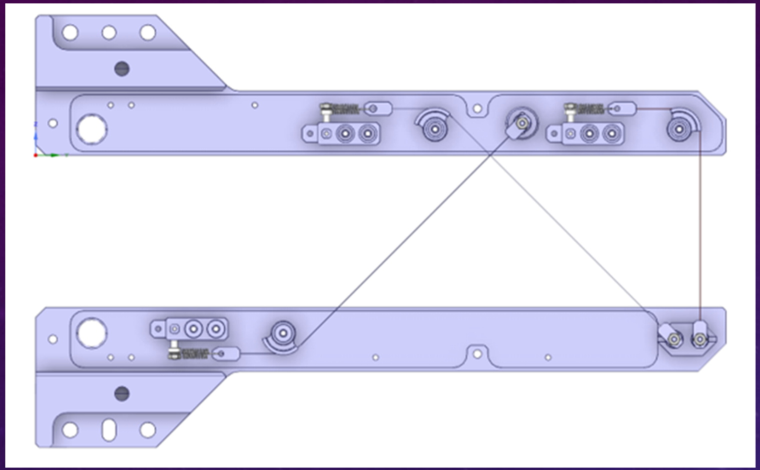
EXAMPLE 1: PSI MAIN RING LONG RADIAL PROBE

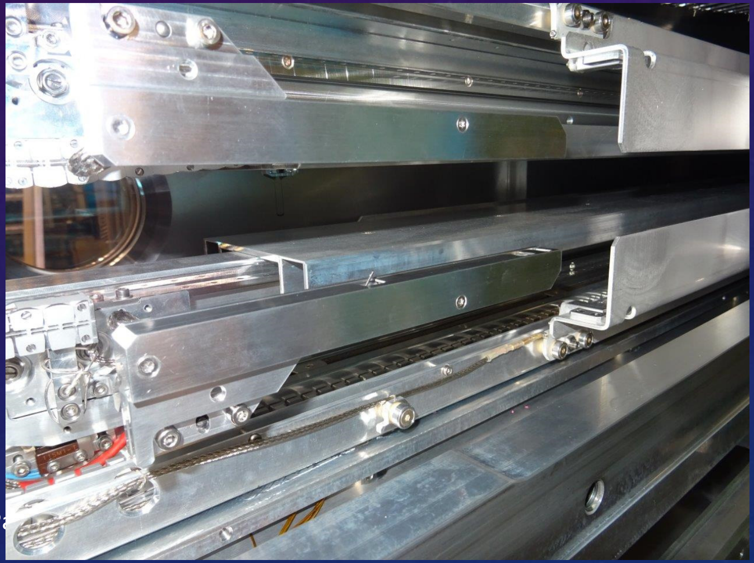
- Radial probes measure multiple turns of the cyclotron beam.
- The most sophisticated: Main Ring Long Radial Probe (RRL).
- Moves over 2.5 meters, at speed 3 cm/s.



M. Sapinski, R. Doelling, M. Rohrer, *Commissioning of the renewed radial probe in PSI's Ring Cyclotron*, Proc. of IBIC22, Cracow, MOP019.

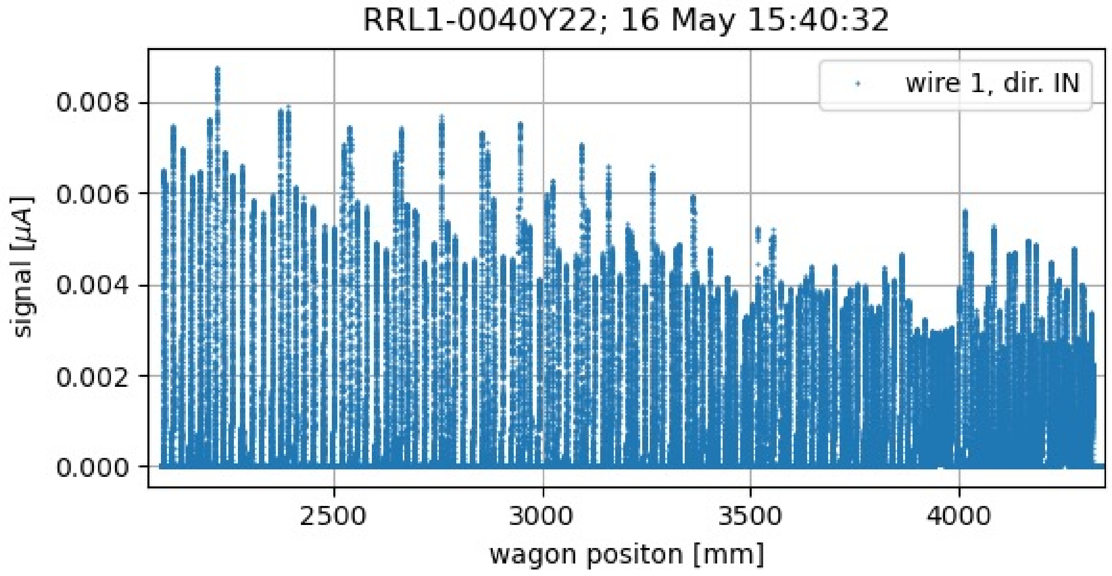
EXAMPLE 1: PSI MAIN RING LONG RADIAL PROBE





Typical measurement:

- 186 orbits.
- 160.000 steps (one way).
- Tilted wires allow to reconstruct vertical beam size and position.



DELTA ELECTRONS: YIELD AND SPECTRUM

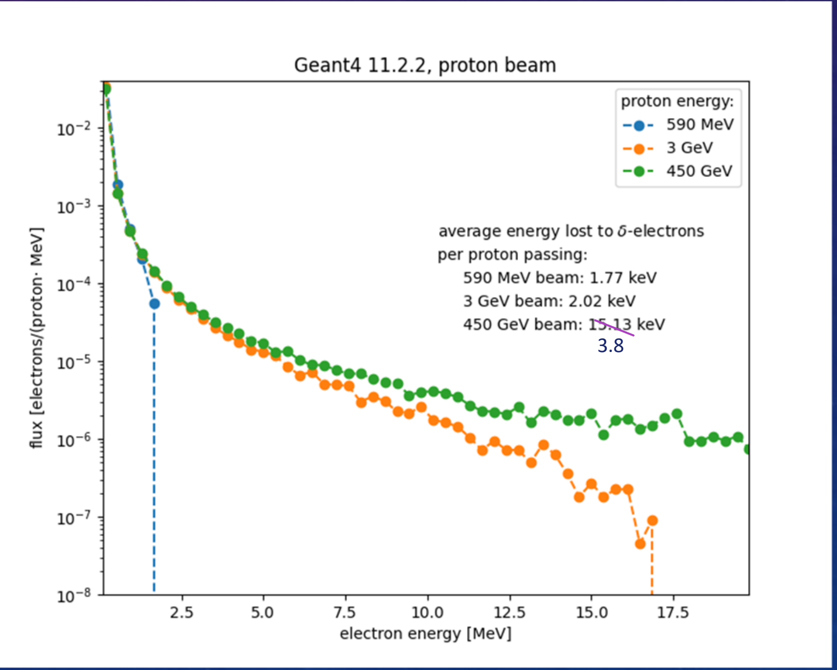
PSI

- Maximum energy transfer.
- Emission probability (yield).
- Average energy increases with projectile energy.

$$T_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + \frac{2\gamma m_e}{M} + \left(\frac{m_e}{M}\right)^2}$$

Proton energy	Proton β	T_{max} [MeV]	δ-electron Emission probability	Average δ-electron energy [MeV]
590 MeV	0.79	1.69	1.93 %	0.092
3 GeV	0.971	17	1.34 %	0.150
450 GeV	0. 999998	155 000	1.29 %	0.297

G4EmStandardPhysics_option4 used following discussion on Geant4 forum.



OTHER TARGET MATERIALS

- Probability of δ-electron emission increases with material density because they contain more electrons.

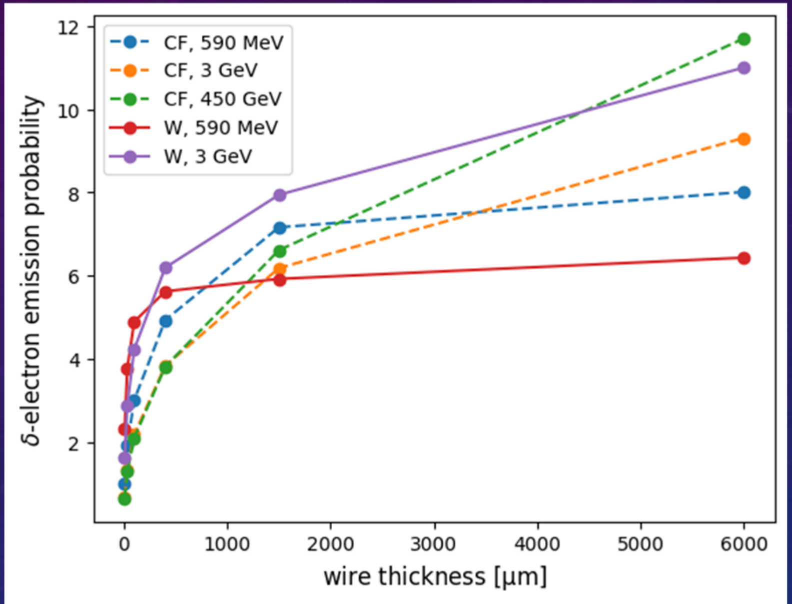
	δ-electron emission probability [%] (33 µm wire)			
Proton energy	Carbon (CF)	Molybdenum	Tungsten	Molybdenum (24 µm wire)
590 MeV	1.93	3.31	3.78	2.92
3 GeV	1.34	2.44	2.87	-
450 GeV	1.29	2.38	2.86	-

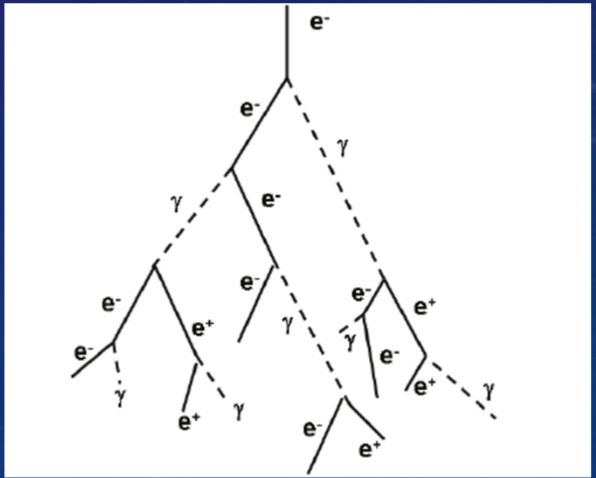
TARGET THICKNESS

- Number of electrons is proportional to target volume.
- But thicker targets means more delta electrons are stopped!
- Not-anymore thin targets: electromagnetic cascade!

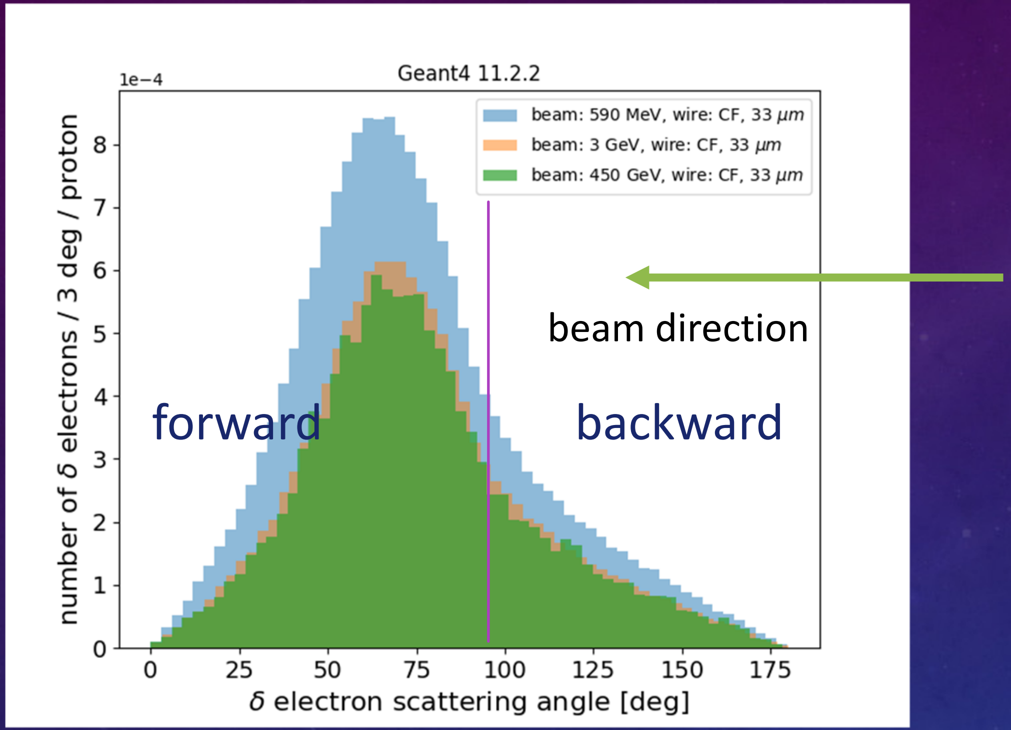
	δ-electron emission probability [%] CF wire					
Proton energy	7 µm	33 µm	100 µm	400 µm	1.5 mm	6 mm
590 MeV	1.00	1.93	3.01	4.93	7.16	8.01
3 GeV	0.67	1.34	2.18	3.83	6.18	9.31
450 GeV	0.64	1.29	2.10	3.81	6.61	11.7
	Tungsten wire					
590 MeV	2.30	3.78	4.89	5.62	5.92	6.43
3 GeV	1.64	2.87	4.23	6.19	7.94	11.0
450 GeV	1.59	2.86	4.37	7.39	15.6	100

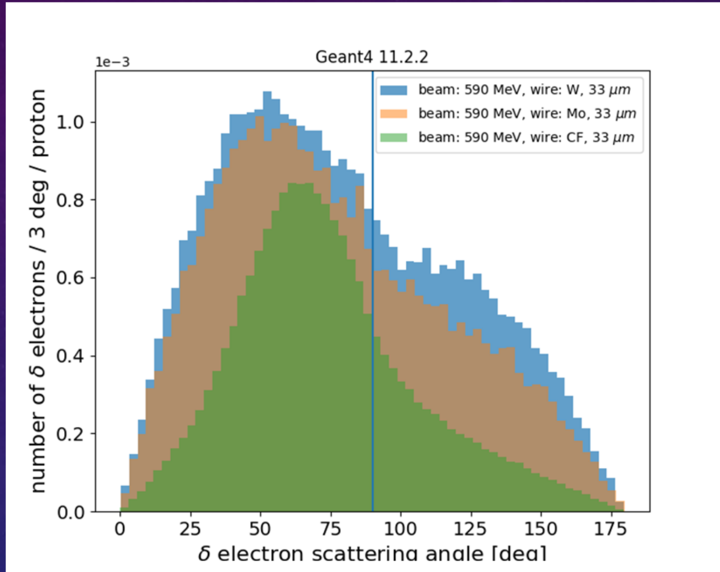
Radiation length graphite: 19 cm, tungsten: 3.5 mm.

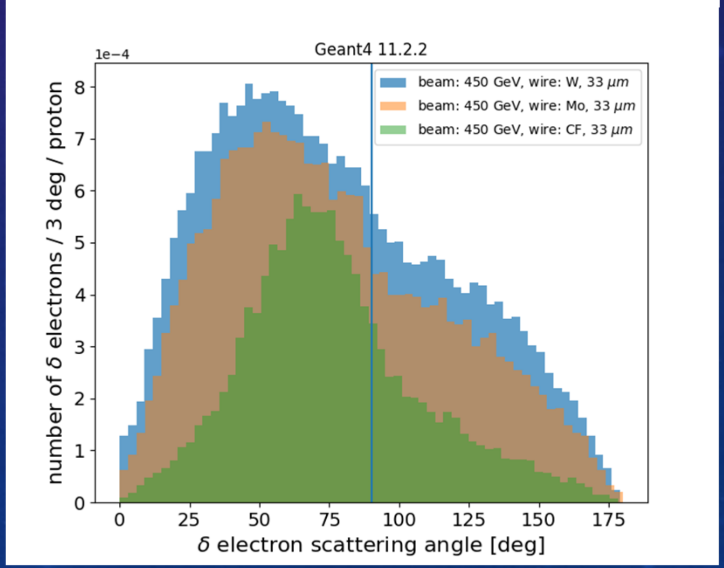




DELTA ELECTRONS: ANGLE OF EMISSION

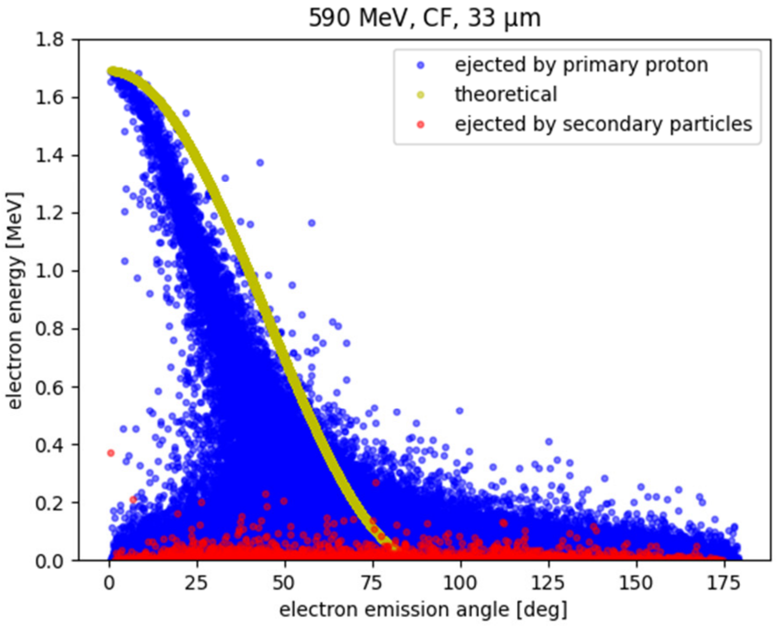


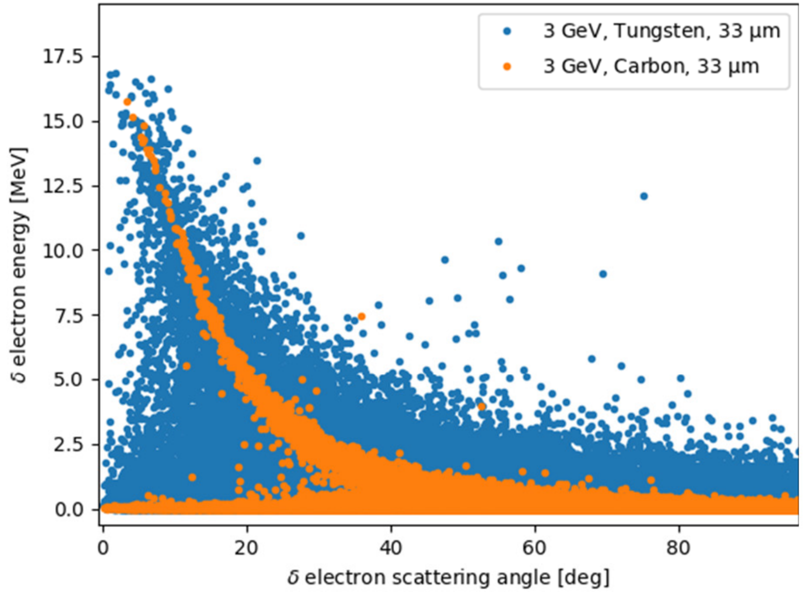


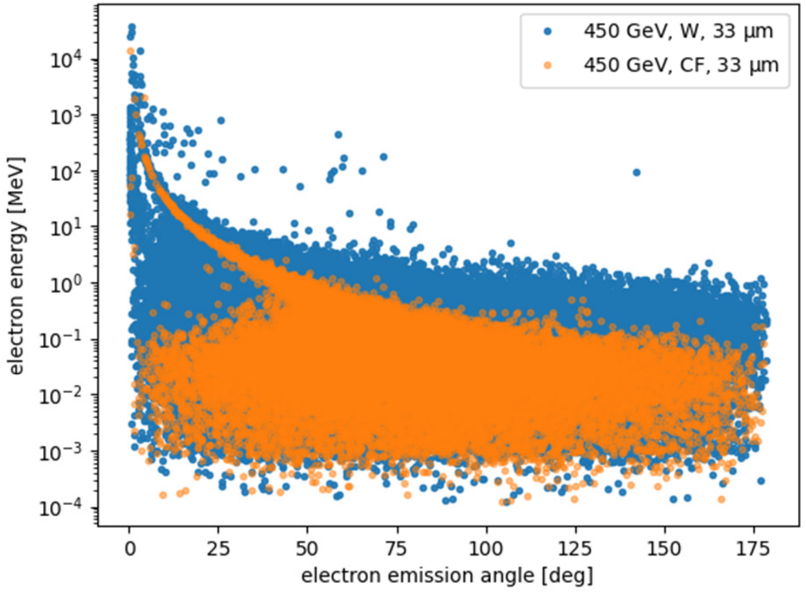


- Weak dependence on beam energy.
- Strong dependence on material density.
- More electrons emitted backwards for denser materials

DELTA ELECTRONS: ANGLE OF EMISSION VERSUS ENERGY

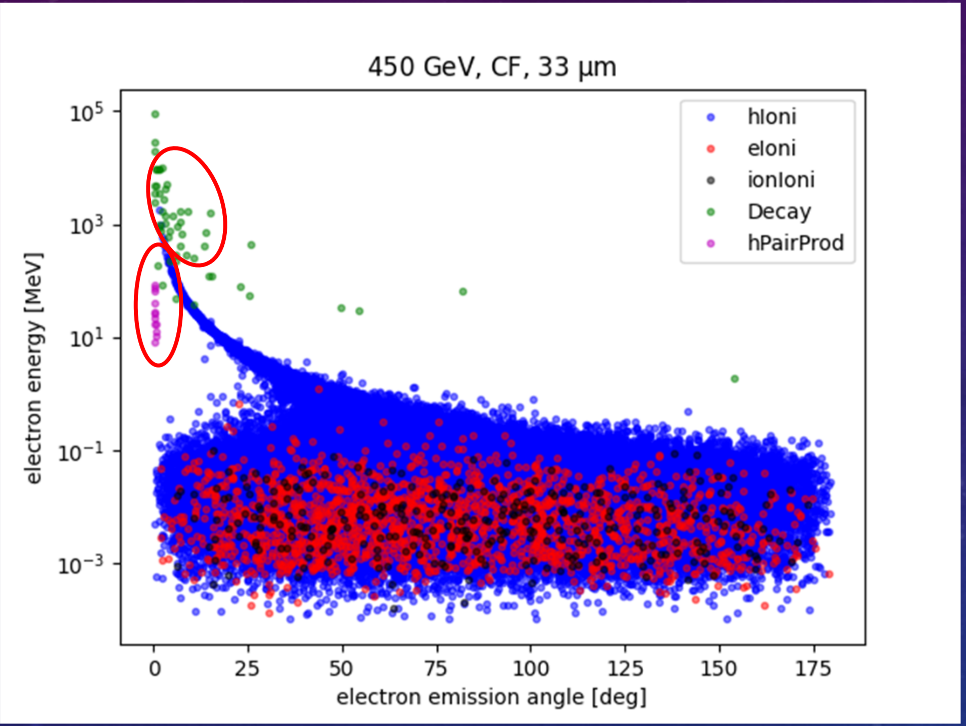






ARE ALL HIGH-ENERGY ELECTRONS DELTA ELECTRONS?

- In simulation we can check how they are produced:



process	Probability per incident proton	Energy per incident proton
hIoni	1.26%	3.83 keV
eIoni	0.02%	2.4 eV
Decay	0.00052%	23.6 keV
Pair production	0.00012%	40 eV
total	1.29%	27.5 keV

- Most energy in electrons from nuclear interactions – no impact on energy deposit in the target.
- Onset of electromagnetic cascade.

OTHER PARTICLES PRODUCED

	590 MeV	3 GeV	450 GeV
		CF, 33 µm, 2 g/cm^3	
e-	0.0193	0.0135	0.0128
n	9.0e-5	1.25e-4	2.38e-4
γ	7.2e-5	1.24e-4	8.83e-4
π+	9.0e-6	4.13e-5	3.76e-4
π-	2.1e-6	2.36e-5	3.52e-4
π^0	-	-	3.31e-5
KL(0)/KS(0)	-	-	2.57e-5/2.35e-5
K-	-	-	1.92e-5
K+	-	-	3.05e-5

Other strange particles, like Lambda0, Lambda0bar, Sigma+, Sigma-, e+, nbar, etc

DELTA ELECTRONS AND ENERGY DEPOSIT IN THE TARGET

- Delta electrons "remove" some of the energy which otherwise would stay in the target
- This creates a "correction" to standard Bethe-Bloch
- e.g. for d=33 µm Carbon fibre:

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

Proton energy	dE/dx from Bethe-Bloch [MeV*cm²/g]	E_{dep} from dE/dx [keV]	Energy removed by δ electron, Geant4 [keV]	E_{dep}-$E_{kin}(\delta)$	Geant4 E_{dep} simulation [keV]
590 MeV	2.27	11.76	1.77	9.99	10.28
3 GeV	1.75	9.05	2.02	7.03	7.32
450 GeV	2.44	12.67	3.83	8.84	7.30

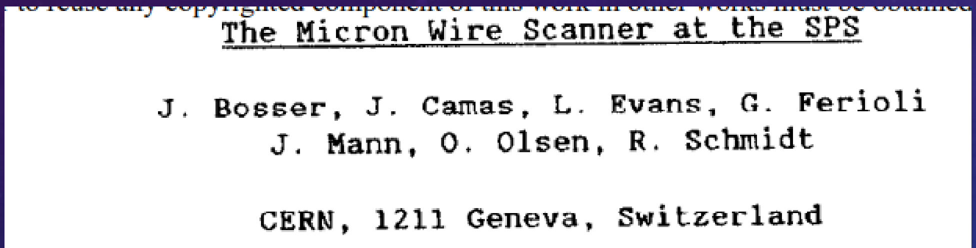
E_{dep}=dE/dx · d · ρ · $\pi/4$

Discrepancy at high beam energies – use Monte Carlo code to calculate real energy deposit in the target.

ENERGY DEPOSIT CORRECTION WRT. BETHE-BLOCH

$E_{dep,Geant4}/E_{dep,Bethe\text{-}Bloch}$ = δ-electron correction coeff.

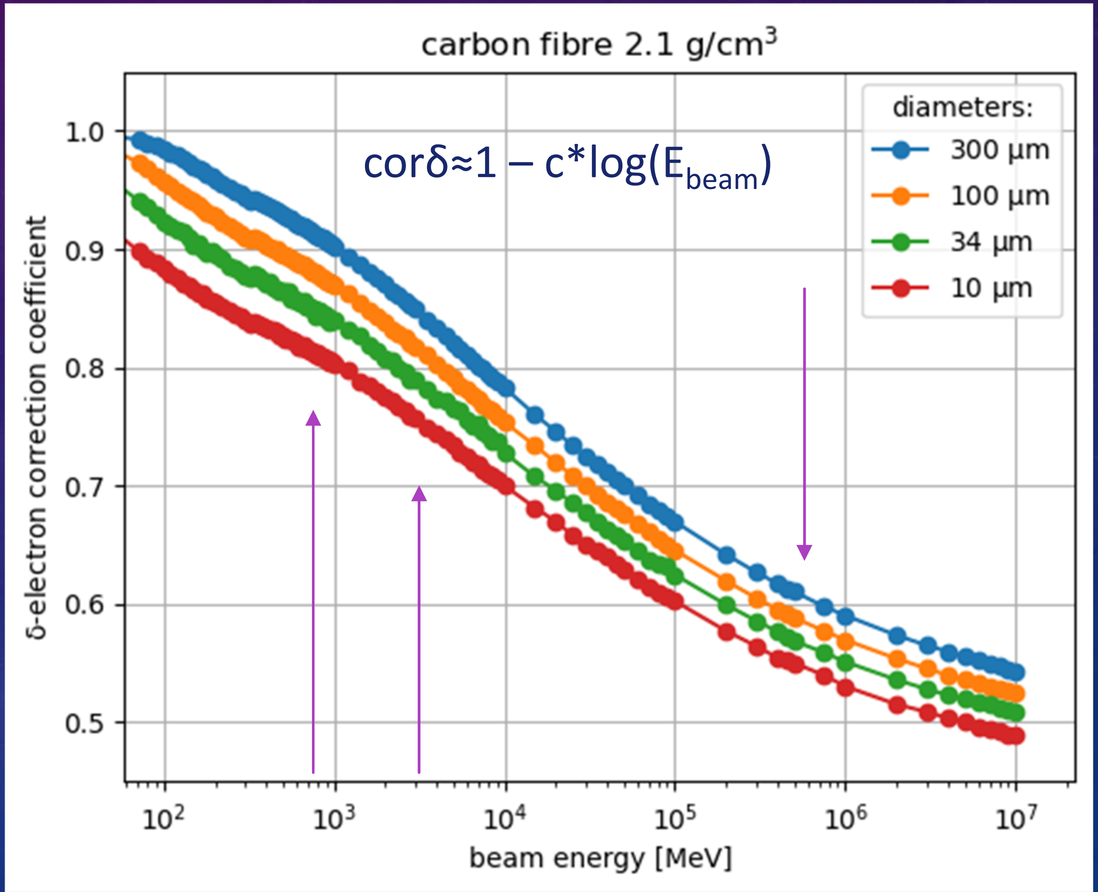
- For low beam energies it is almost 1.
- For high beam energies – good news, it decreases down to 0.5.
- This effect was already discussed in note CERN SPS/86-26


The Micron Wire Scanner at the SPS

J. Bosser, J. Camas, L. Evans, G. Ferioli
J. Mann, O. Olsen, R. Schmidt

CERN, 1211 Geneva, Switzerland

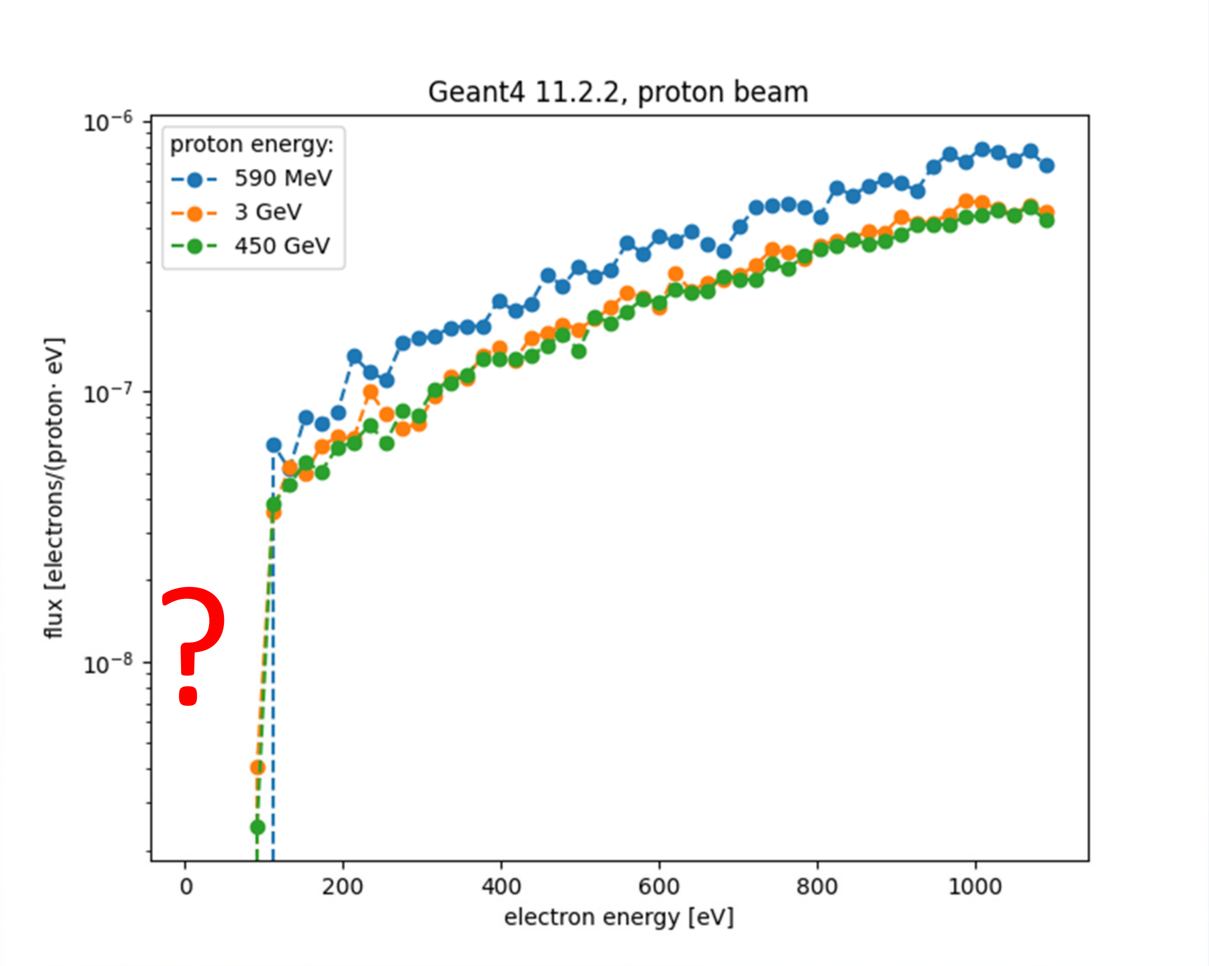
Electrons with sufficient energy will escape, so will not contribute to the heating. Rough calculations 41 have shown that up to 70% of the incident proton energy loss can be accounted for in this way.



Geant 4.10.4. Close to linear dependence of thickness, exponential in energy

DELTA ELECTRONS – LOW ENERGY SPECTRUM

- What happens below Geant 4 electron transport cut of 100 eV?
- Delta electrons – close, head-on collisions.
- Distant resonance collisions – excitation of electron plasma - low energy electrons.
- Equipartition rule between plasma excitations and direct collisions – similar amount of proton energy goes into δ-electrons and low energy secondary electrons.
- See J.Lindhard and A. Winther "Stopping power of electron gas and equipartition rule", Mat. Fys. Medd. Dan. Vid. Selsk. 34, no. 4 (1964)
- P. Koschar et al., Secondary-electron yield as a probe of preequilibrium stopping power of heavy ions colliding with solids, Phys. Rev. A 40, 3632 - 3636, 1989



(LOW ENERGY) SECONDARY ELECTRONS

- Historically the term *secondary electrons* originates from electron microscopy.
  - Transmission Electron Microscopy (TEM).
  - Scannining Electron Microscopy (SEM) – actually using secondary electrons.
- Therefore, the first semi-empirical model of secondary electron production was proposed by Stenglass in 1957. It was valid for backscattered secondary electrons.
- Electron interactions are very different than protons, but Sternglass model has been modified to include protons.
- Final properties of secondary electrons depend on material, surface quality and even its history (e.g. conditioning effect).

SECONDARY ELECTRONS – STERNGLASS MODEL

- Electron yield described by a 3-step process:
  - Generation (ionization)
  - Diffusion
  - Emission process – surface barrier.
- Sternglass theory (1957):

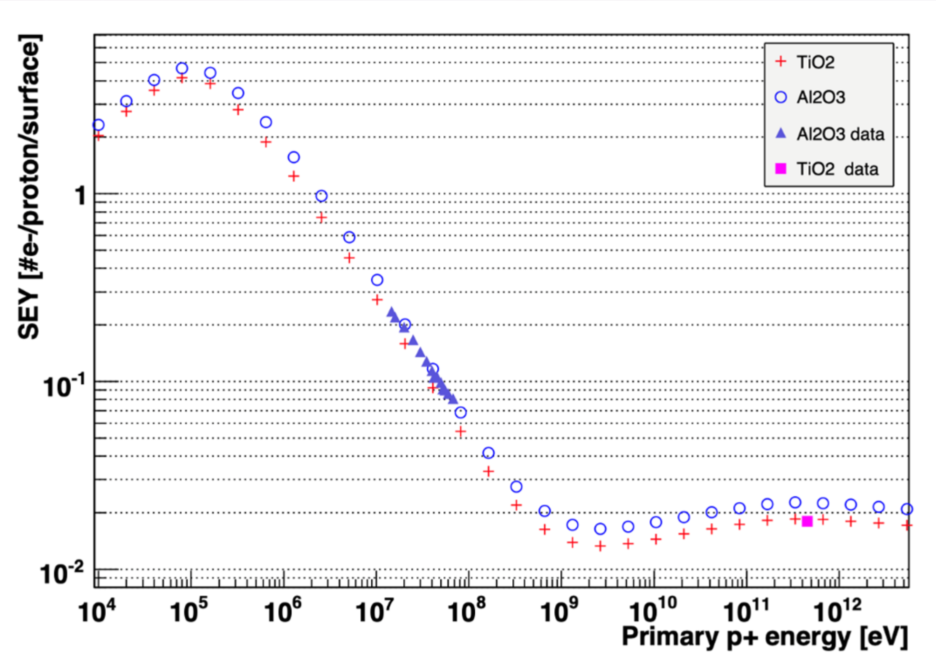
$$SEY = 0.01 L_S \left.\frac{dE}{dx}\right|_{el} \left[1 + \frac{1}{1 + 5.4 \cdot 10^{-6} E/A_p}\right]$$

$$L_S = \left(3.68 \cdot 10^{-17} N_v Z^{1/3}\right)^{-1}$$

material	L_S [nm]
Carbon fibre 2g/cm^3	1.4
Molybdenum	1.1
Tungsten	0.93

electron diffusion - distance between inelastic collisions

SECONDARY EMISSION YIELD (SEY)



D. Kramer "Design and Implementation of a Detector for High Flux Mixed Radiation Fields", CERN-THESIS-2008-090

$$SEY = 0.01 L_S \left.\frac{dE}{dx}\right|_{el} \left[1 + \frac{1}{1 + 5.4 \cdot 10^{-6} E/A_p}\right]$$

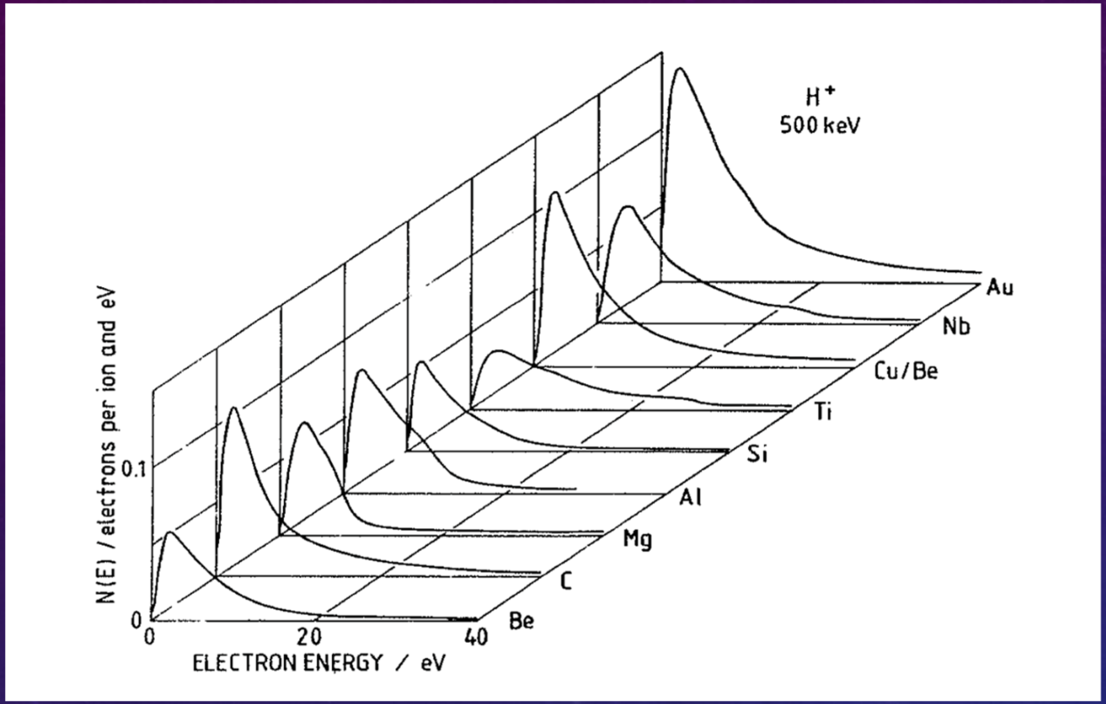
E – projectile energy [eV]

A_p- projectile mass

dE/dx – in [eV/cm]

SEY function of energy follows dE/dx shape with damping term at high energy.

LOW ENERGY SECONDARY ELECTRONS SPECTRUM



D. Hasselkamp, S. Hippler and A. Scharmann, Ion-induced secondary electron spectra from clean metal surfaces, Nucl. Instrum. and Methods Phys. Res. B 18 (1987) 561

- Spectrum is material-dependent and surface-dependent.
- Several parametrizations and experimental results are available in the literature.
- It peaks at 2-5 eV, then decreases.
- It extends to several tenths of eV (100 eV).

SECONDARY ELECTRONS YIELD - EXAMPLES

- SEY is calculated for every time particle crosses surface of target.
- If particles go **through** the target, they cross the surface twice (et entrance and at exit).
- However, δ electrons also produce low energy secondary electrons. This is partly taken into account in Sternglass model:

	SEY*2 surfaces [%]		
Proton energy	Carbon	Molybdenum	Tungsten
590 MeV	1.14	4.19	6.10
3 GeV	0.93	3.42	5.00
450 GeV	1.66	6.06	8.79

- Dense materials produce more secondary electrons.
- The SEY is similar to δ electron emission probability.

SECONDARY ELECTRON AND δ-ELECTRON CURRENTS

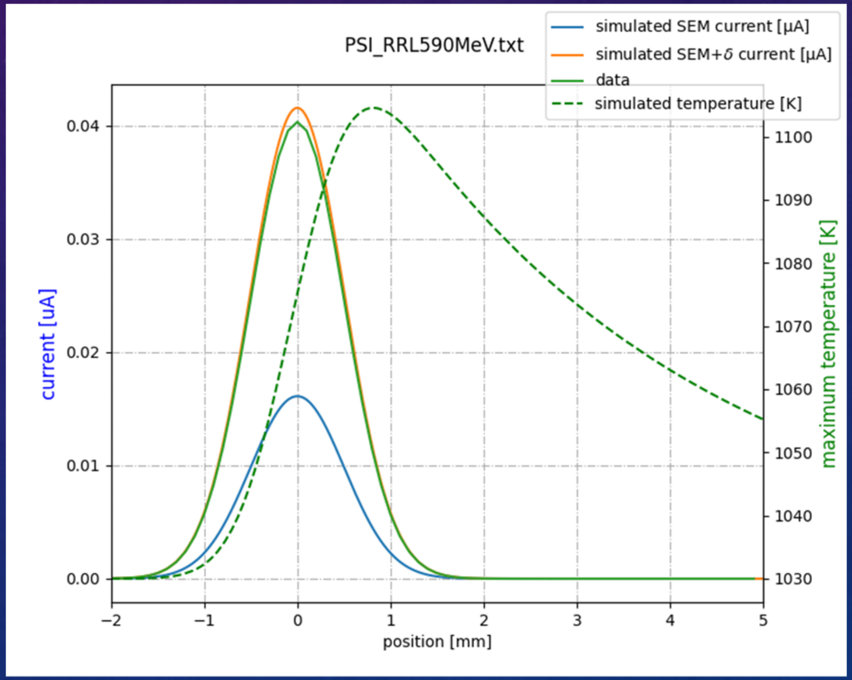
	SE current/(SEY+δ current)			
	33 µm wire			24 µm
Proton energy	Carbon	Molybdenum	Tungsten	Molybdenum
590 MeV	0.37	0.56	0.62	0.59
3 GeV	0.41	0.57	0.64	-
450 GeV	0.57	0.72	0.76	-

The signal in wire scanners and SEM grids has significant contribution from high-energy (>100 eV) δ-electrons!

Especially for low density targets and low beam energies.

EVIDENCE FOR δ-ELECTRON CONTRIBUTION TO WIRE SCANNER SIGNAL

- The amplitude of signal registered in a Wire Scanner can be explained by adding contributions from low energy Secondary Electrons and δ-electrons.
- The plot generated with PyTT – python package for Thin Target simulations, see:
  - https://github.com/ClaudePP/PyTT
  - Araceli Navarro Fernandez, *Understanding Secondary Emission Process and Beam Matter Interactions for Optimization of Diagnostic Wire Grid System in Particle Accelerators*, PhD thesis, Universita Politecnica de Catalunya, March 2023



EXPERIMENTAL INVESTIGATION OF ELECTRON SPECTRUM

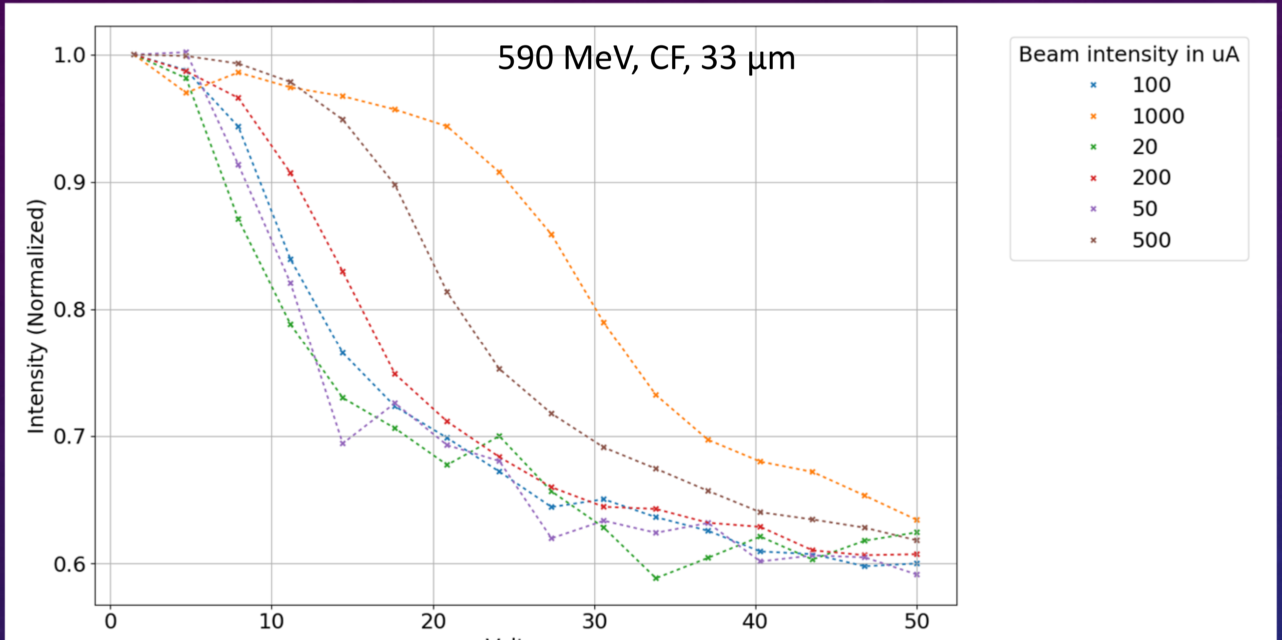
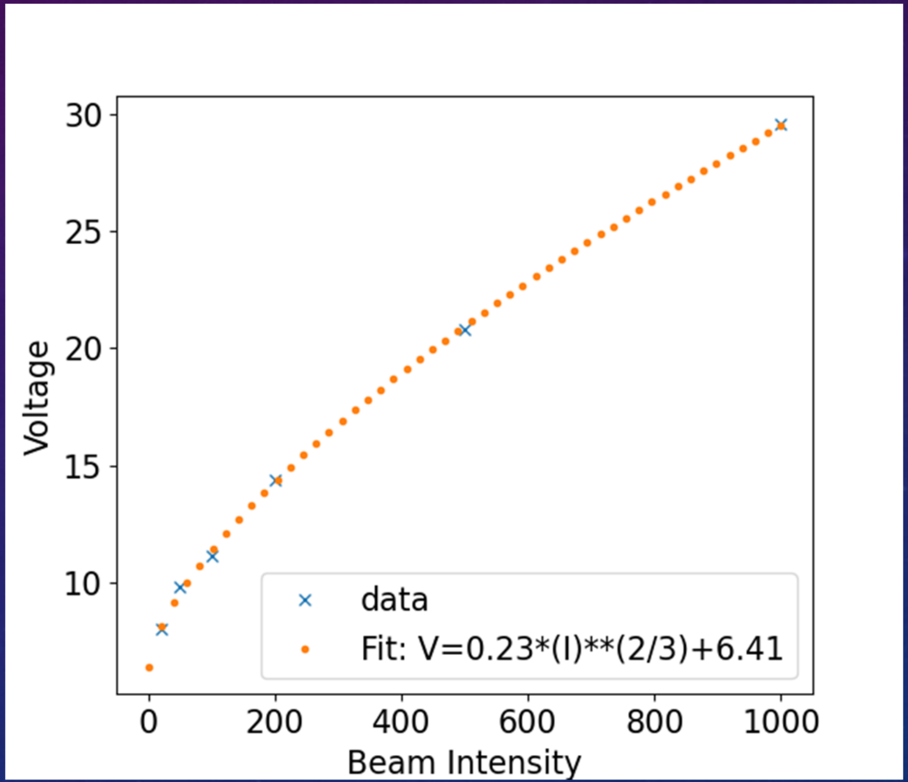


Fig. courtesy of J. Touguet



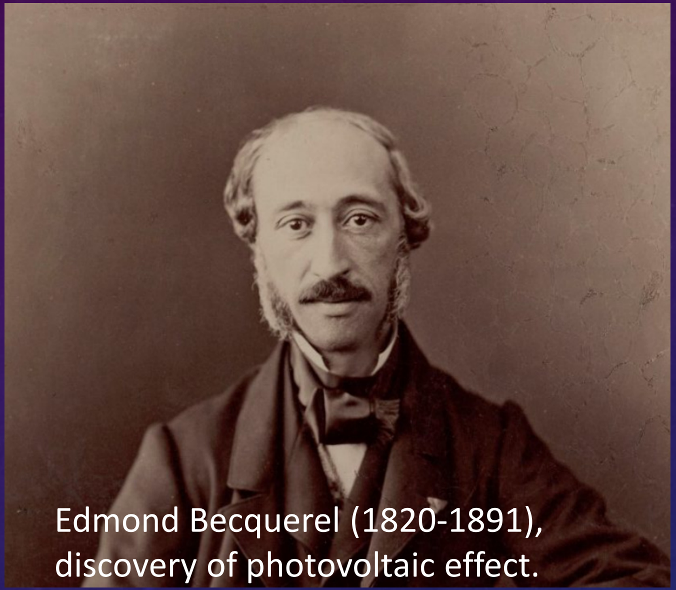
- Signal amplitude as a function of bias voltage and beam intensity.
- Bias voltage reduces part of the signal, corresponding to Secvondary Electrons, δ-electrons have too high energies to be affected.
- Presence of strong bunch field delays effect of signal reduction due to bias voltage – bunch field helps electrons to escape biased wire.

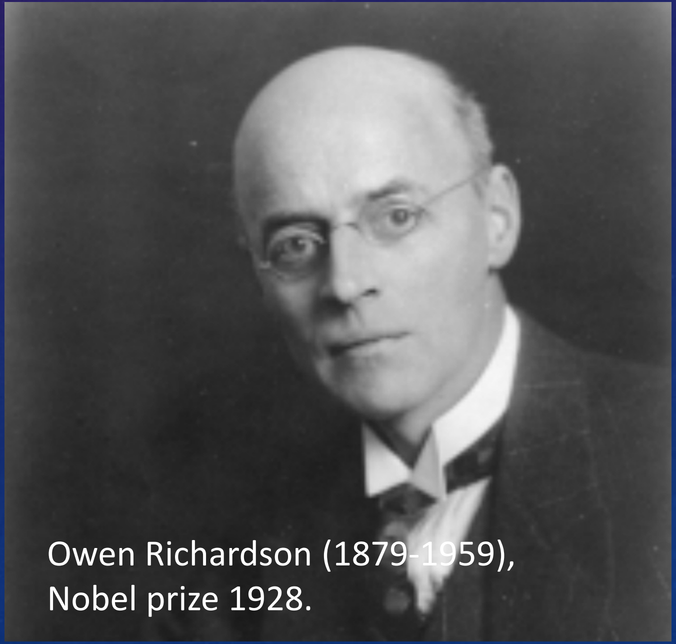
THERMIONIC ELECTRONS

- Thermionic current: reported already in 1853 by Edmond Becquerel (father of Henri); BTW electron was discovered 1897 (Thomson).
- 1911 – Owen Richardson published thermionic emission theory, with current density:

$$J = A_G T^2 e^{\frac{-W}{kT}}$$

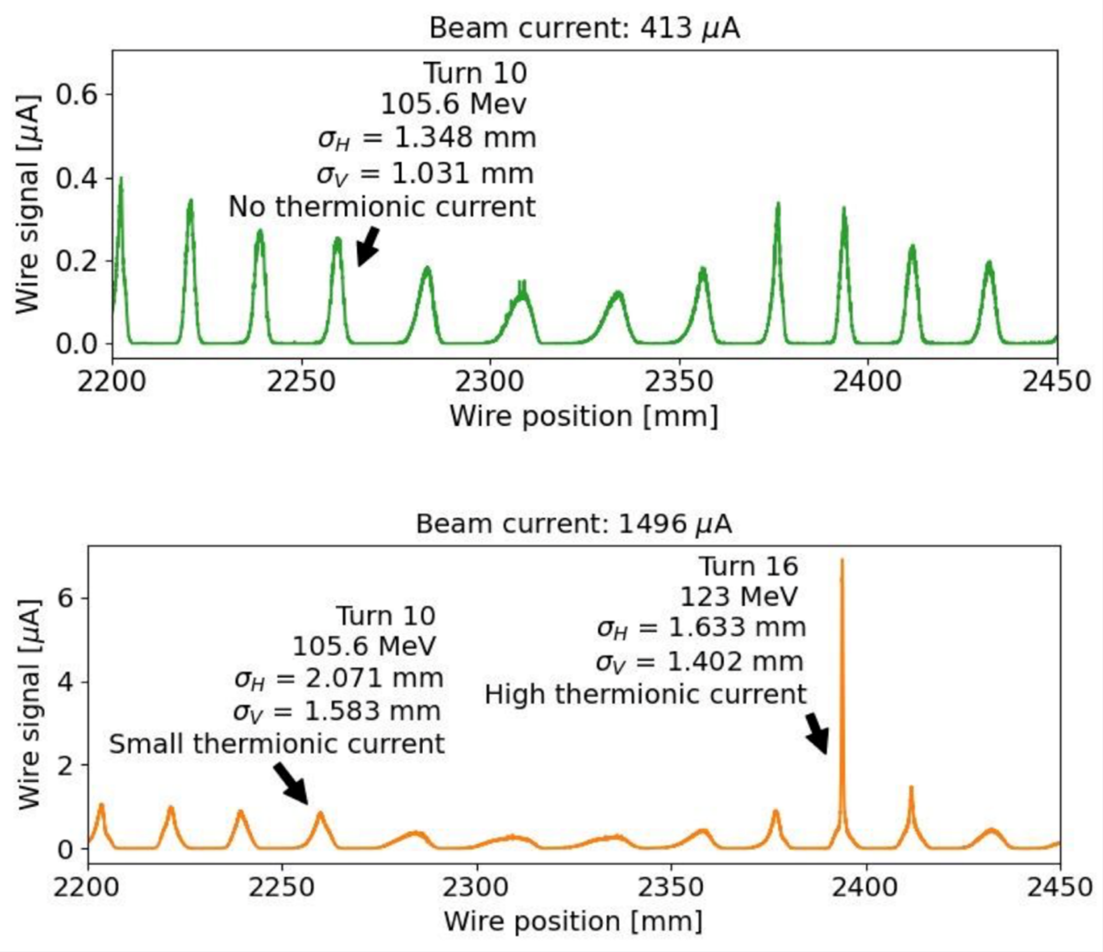
- W – work function, depends on material (graphite 4.5-5.0 eV).
- A_G – Richardson constant 120.2 A/(cm^2 K^2), usually additional parameter is used because thermionic emission also depends on surface properties.
- Thermionic emission depends on wire temperature, not transverse density of the particles on the beam.
- Thermionic current is disturbing the beam profile measurement!


Edmond Becquerel (1820-1891), discovery of photovoltaic effect.

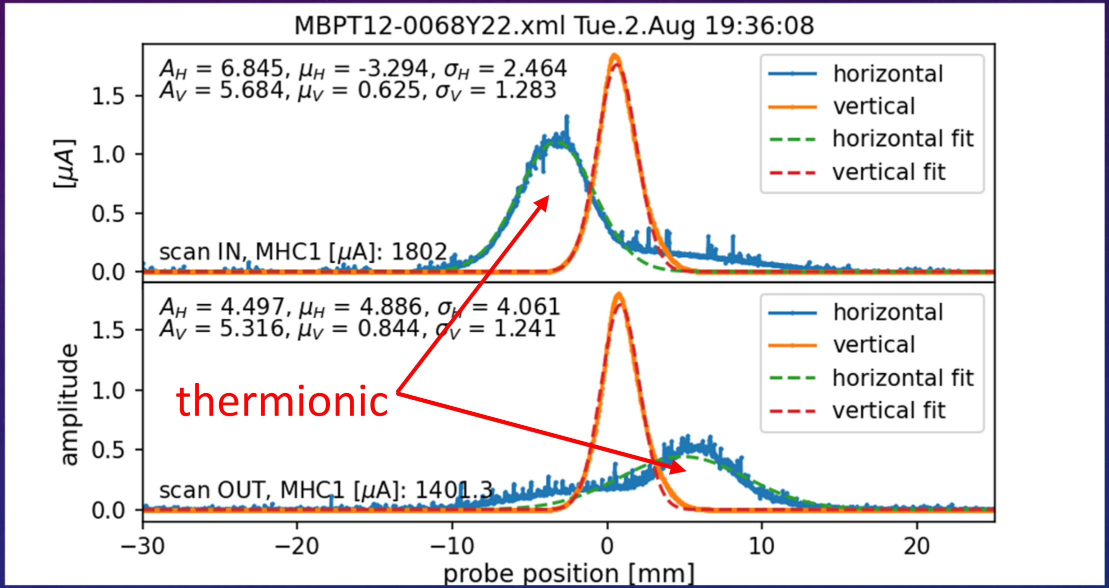

Owen Richardson (1879-1959), Nobel prize 1928.

THERMIONIC ELECTRONS – OBSERVATIONS

RRL – carbon fibre, 33 µm



MBPT – pair of 24 µm Molybdenum wires

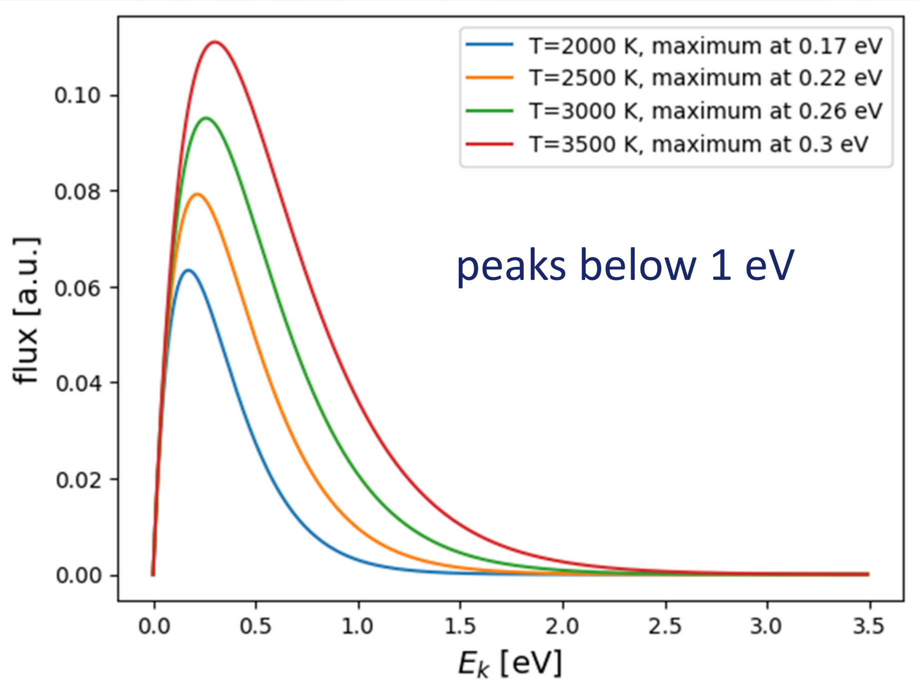


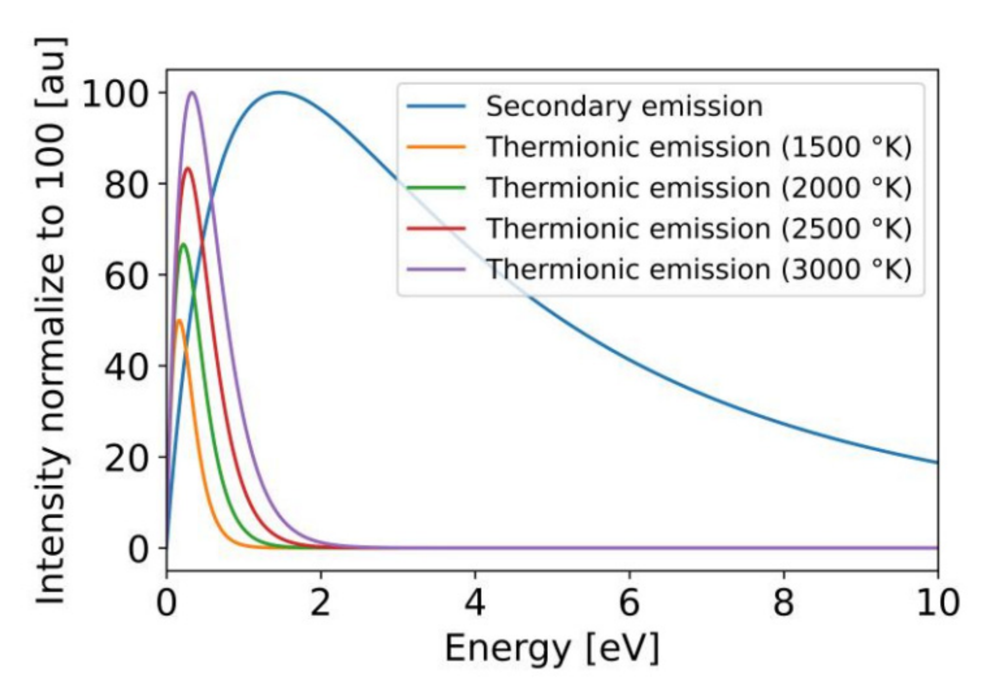
- R. Doelling, M. Sapinski, F. Marcellini, *Test of a prototype for modular profile and position monitors in the shielding of the 590 MeV beam line at HIPA*, in Proc. of IBIC22, Cracow, Poland, MOP24.
- M. Sapinski, *About the Damage Mechanisms of Thin Targets Exposed to High-Power Particle Beams*, in Proc. of IPAC23, Venice, Italy, THPL151.

THERMIONIC ELECTRONS - SPECTRUM

Spectrum of thermionic electrons: $N(E) \propto E \exp\left(-\frac{E-\phi}{k_B T}\right)$

Φ – work function





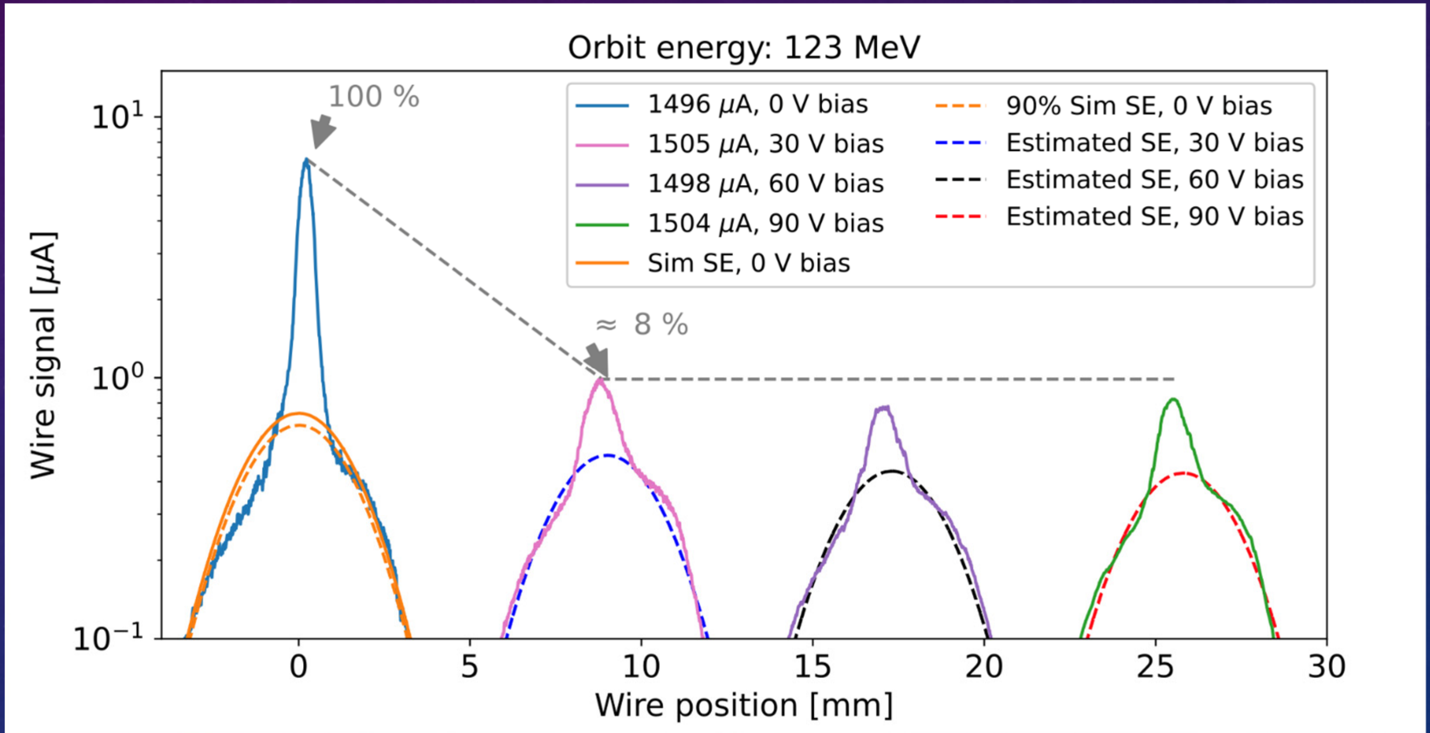
Bias voltage of 30 V should affect both.

THERMIONIC ELECTRONS – OBSERVATIONS

- Thermionic emission renders profile measurement impossible in current-based wire scanners.
- Usual method of dealing with thermionic emission: positive bias of the wire but:
- “It is remarkable that the positive bias of the wire catches thermionically emitted electrons much better than secondary electrons from the wire, although both are mostly slow. This is probably due to the fact that all the secondary electrons created by the bunch are born in the bunch potential which pulls them away, while most of thime (i.e. between the bunches) the bias potential retards the termionically emitted electrons.”
  R. Doelling, “Bunch-shape measurements at PSI’s High-Power Cyclotrons and Proton Beam Lines”, in Proc. Of Cyclotrons 2013, Vancouver, Canada.

REMNANT THERMIONIC CURRENT OF BIASED WIRES

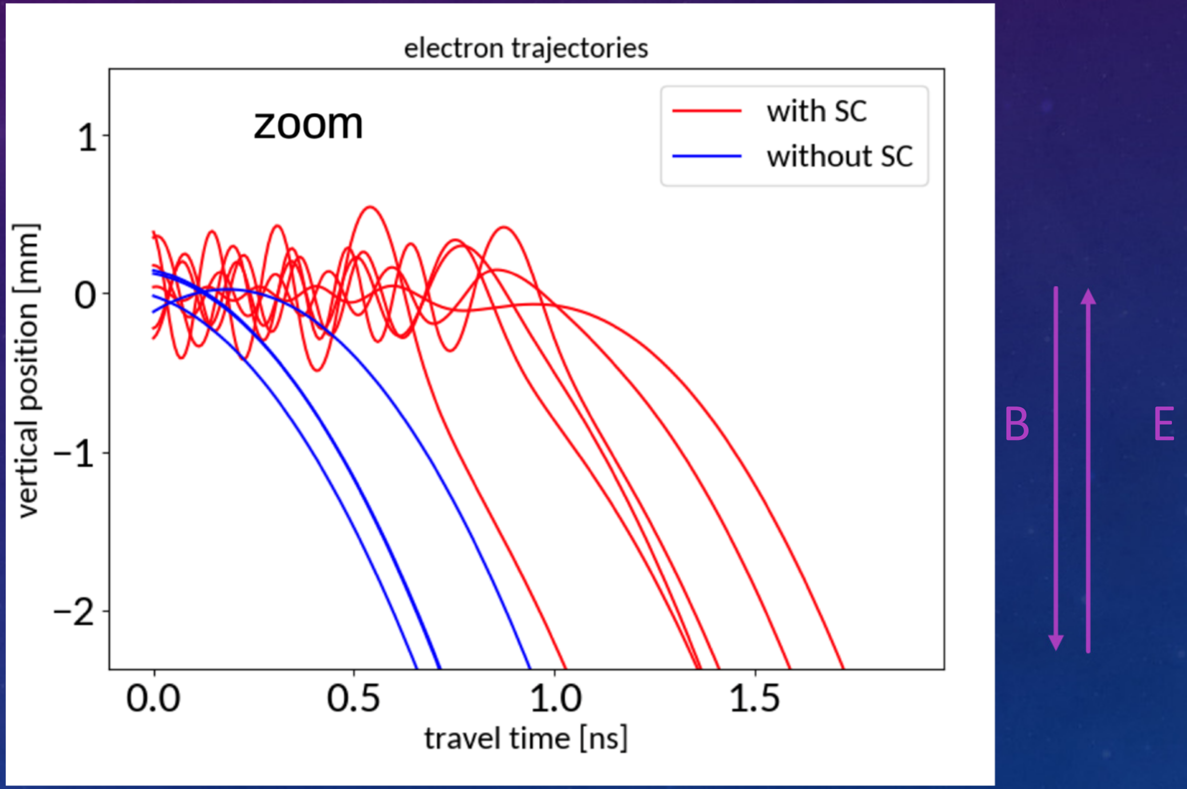
- After initial reduction to about 8% of the initial amplitude, the thermal peak does not decrease anymore despite increase of bias voltage.
- 8% is ratio of bunch length to distance between bunches.
- Is bunch potential really carrying away thermal (and secondary!) electrons against bias voltage?



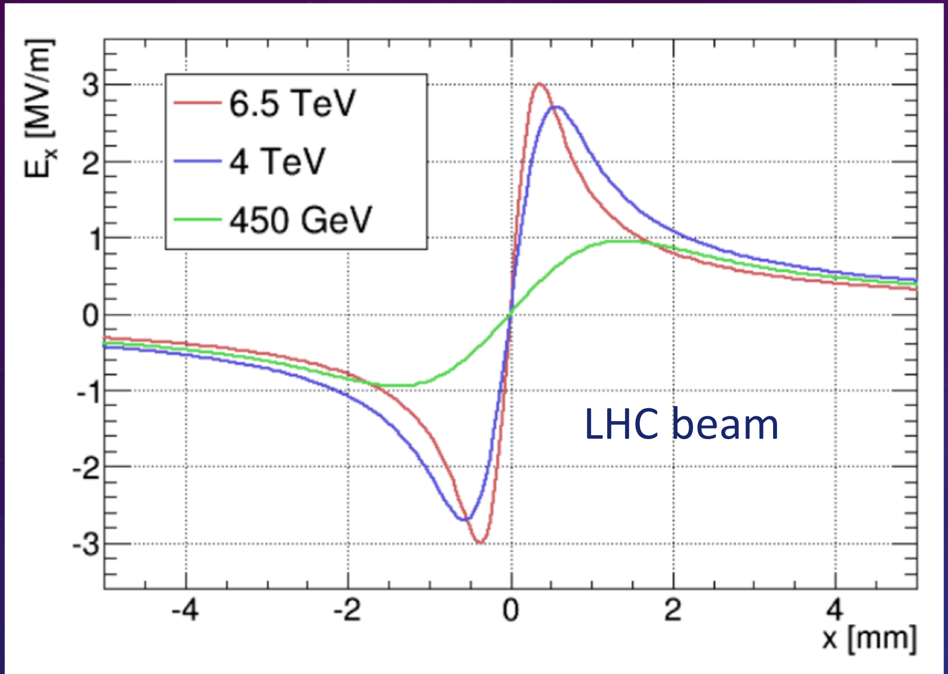
M. Boucard, M.Sapinski, *Dealing with Thermionic Emission in Wire Scanners Based on Secondary Electron Emission*, in Proc. of IPAC23, Venice, Italy, THPL150

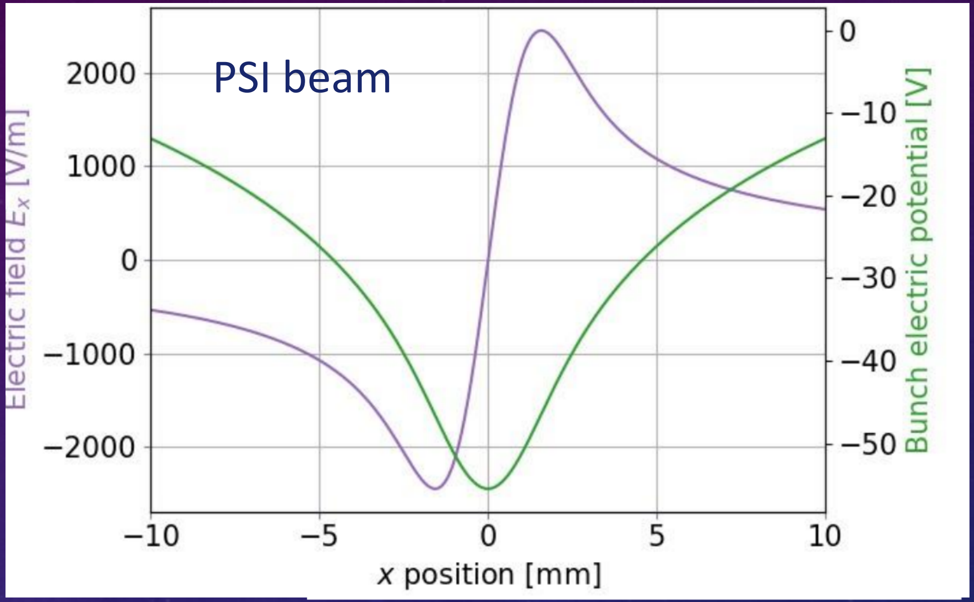
ELECTRON INTERACTION WITH BUNCH FIELD IN IPM

- Extensive study done to understand how bunch field affects electrons from gas ionization.
- For example, for 4 TeV LHC proton beam:
    - Beam space charge (SC) is trapping electrons.
    - Electrons also get additional transverse “kick”.
    - Those effects heavily distort the beam profile reconstucted from electrons registered at the bottom of profile monitor.
- Dedicated software have been prepared for this study called Virtual-IPM:
    - D. Vilsmeier. “Virtual-IPM Python Package Index .”, Available: https://pypi.org/project/virtual- ipm/
    - Includes analytical formulas for bunch field.
    - Various particle tracking algorithms (e.g. 4-th order Runge-Kutta)

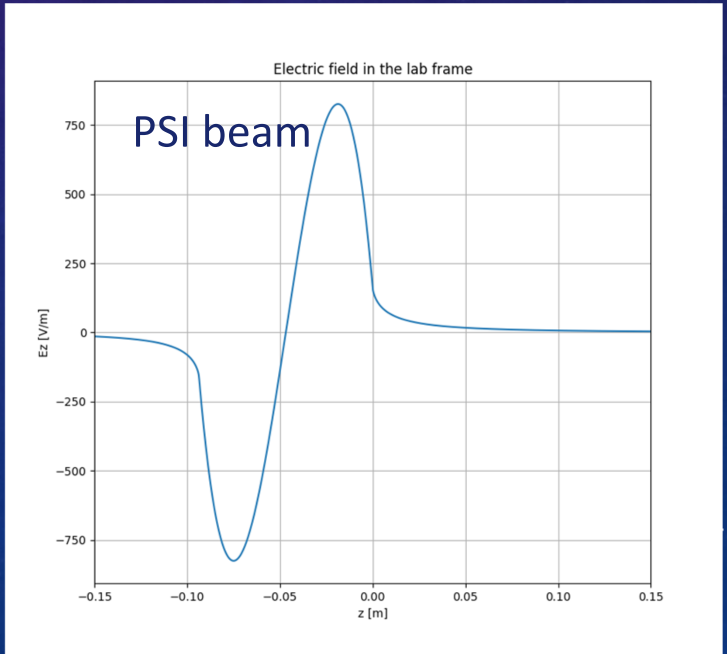


ELECTRON INTERACTION WITH BUNCH FIELD



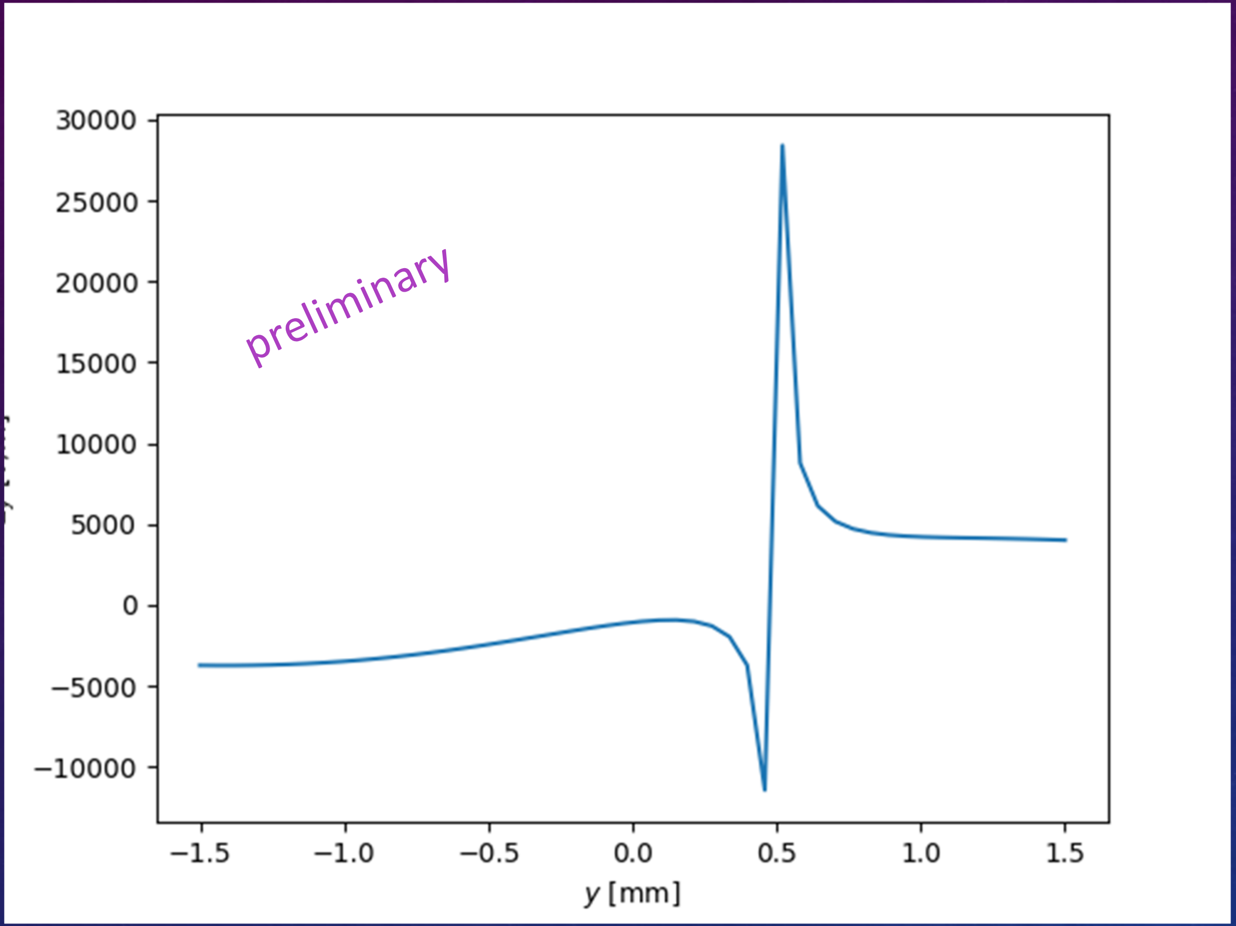


590 MeV protons,
σ_x = 0.5 mm
σ_y = 1.0 mm
σ_l = 0.2 ns
N_p = 2.5*10^8



Bunch fields of highly relativistic proton beams. Field in beam direction (E_z) is very small. At low energies E_z is very important to understand electron movement.

ELECTRON INTERACTION WITH BUNCH AND WIRE FIELDS



590 MeV protons,
+ wire at y=0.5 mm biased to +30V

Observations:

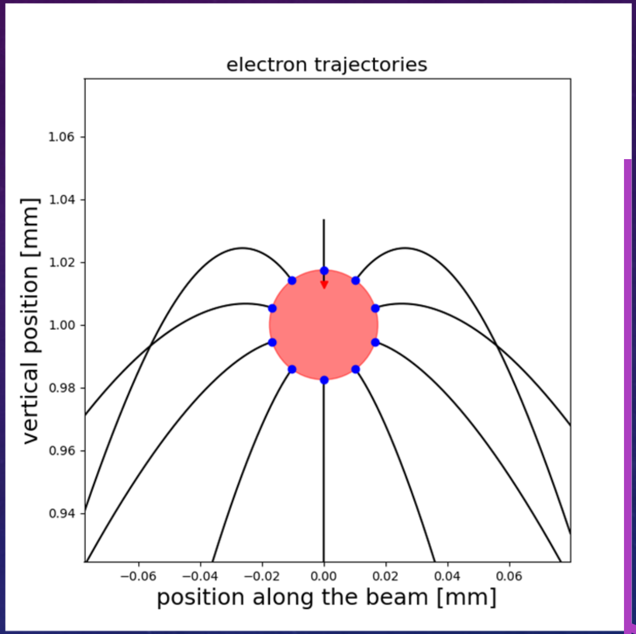
- Wire field dominates in vicinity of the wire (radius of about 0.2 mm).
- If electrons manage to scape wire potential, they "see" mainly bunch potential.

However:

- Wire potential reacts to bunch potential within finite time.
- This reaction is quite slow - electron mobility in graphite is 3000 cm^2/Vs, v_e=1000 m/s.
- Because of this, the bunch potential can dominate electron movement at the bunch head.

ELECTRON INTERACTION WITH BUNCH FIELD

- Example trajectories, using development version of Virtual-IPM
- Parameters:
  - bunch 590 MeV, 2 mA, σ_x=1mm, σ_y=0.5mm, σ_z=0.5 ns (lab frame).
  - Wire bias: 30 V, wire position dx=1 mm, dy=0.5 mm, electron temperature 3000 K.
  - Electrons generated at the head of the bunch.
  - In this simulation most thermal electrons escape the wire in the presence of the bunch field!
- Interesting problem:
  - Electron trapping efficiency as a function of wire position – potential profile deformation.

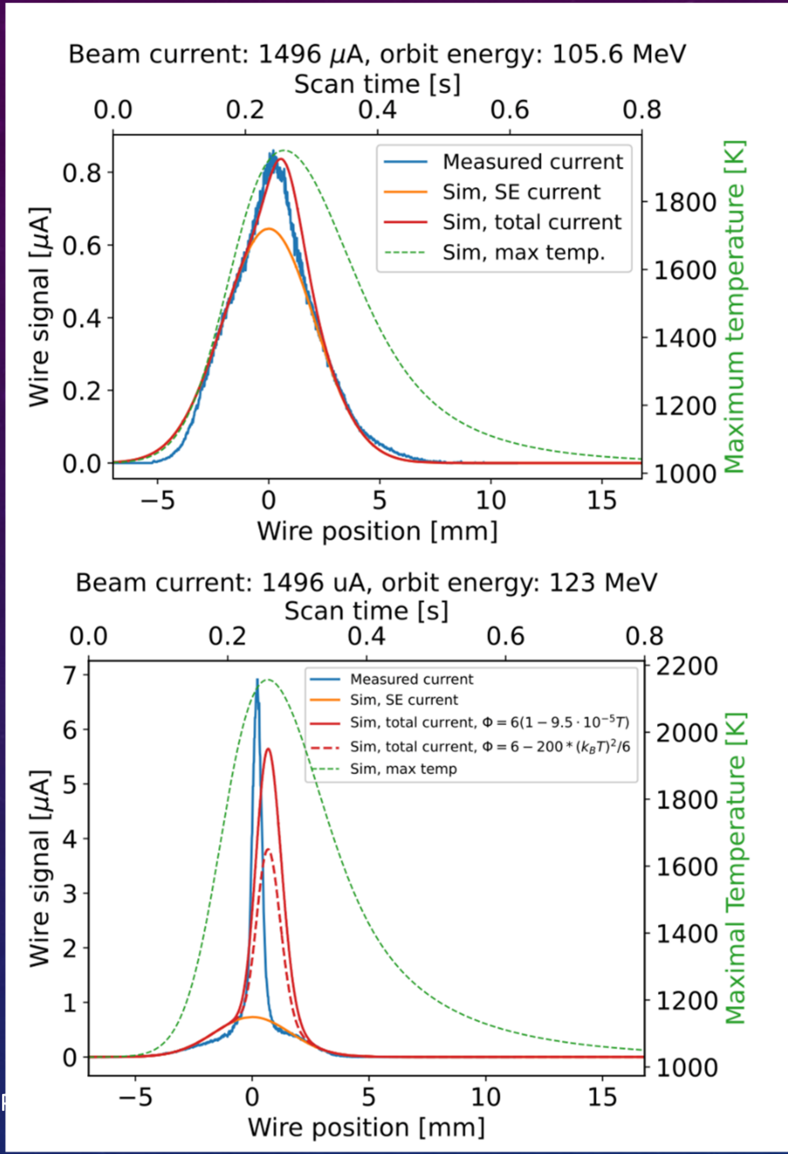


Preliminary results

Is it the only phenomena behind the observed profile deformation?

SPACE-CHARGE OF HIGH THERMIONIC CURRENTS

zero bias



- PyTT code generally reproduces well the beam profile based on secondary and thermionic electron currents.
- Above certain thermionic current the PyTT simulation does not agree with data anymore. Investigation of parameter variation did not help.
- Hypothesis to test: the effect is due to electron “cloud” build up around the wire (nC charge).
- Observed current density ~50 A/m^2.
- Child-Langmuir law gives space-charge limit of about 300 A/m^2.
- The space charge of build up electron cloud may play important role in screening of wire field.

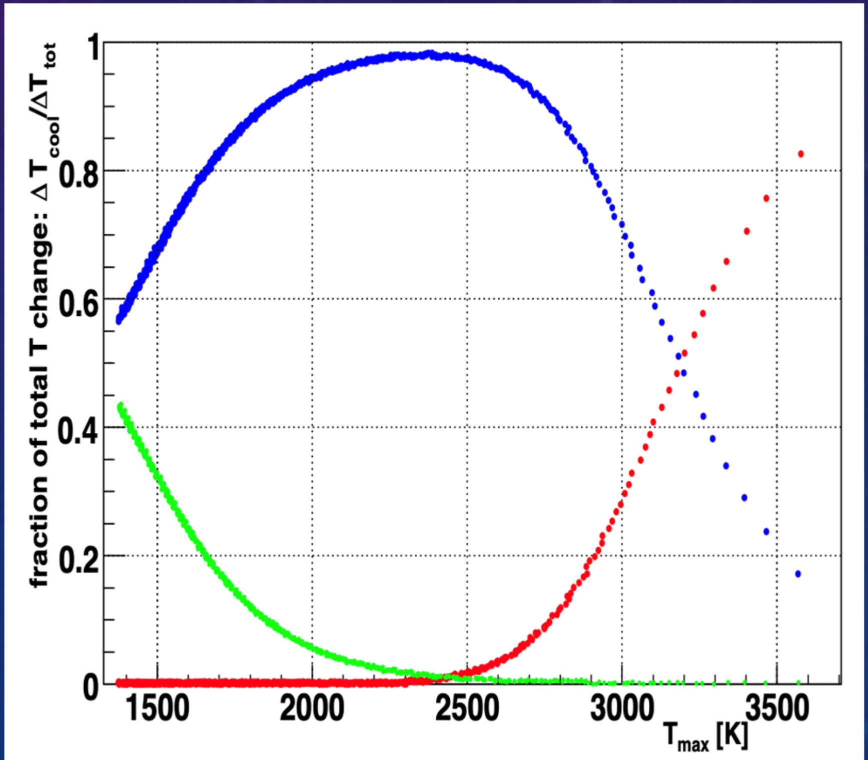
THERMIONIC EMISSION AS COOLING PROCESS

$$\left(\frac{\partial T}{\partial t}\right)_{Tot} = \frac{\Phi(x,y,t)}{Cp(T)} \cdot \frac{dE}{dx} - \frac{S \cdot \sigma_{SB} \cdot \epsilon(T) \cdot (T^4 - T_0^4)}{V \cdot Cp(T) \cdot \rho} - \frac{k(T)}{Cp(T) \cdot \rho} \cdot \frac{\partial^2 T}{\partial^2 y} - S \cdot \left(\phi + \frac{2 k_B T}{Q_e}\right) \cdot \frac{J_{Th}(T)}{V \cdot Cp(T) \cdot \rho}$$

dE/dx - δ-electron contribution – more corrections for high energies

Radiative cooling

Heat conduction along the wire - negligible



- Thermionic electrons, carry away the thermal energy from a target.

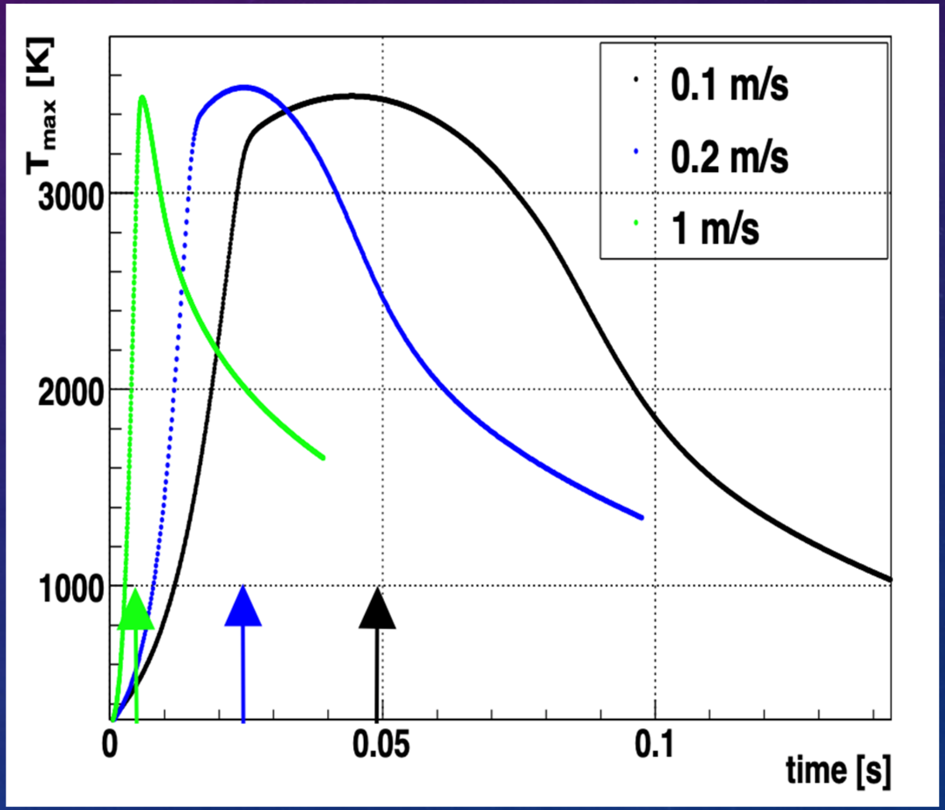
Thermionic cooling is dominating cooling process at extremly high temperatures.

(M. Sapinski, Model of Carbon Wire heating in accelerator beam, CERN AB-2008-030-BI report 2008)

THERMIONIC EMISSION AS COOLING PROCESS

Power of thermionic cooling:

- It flattens the temperature evolution curve!
- Wire sublimation rate at thermionic emission temperature is high.
- Thinning of the wire is a negative feedback.



Simulations of CERN SPS wire scanner experiment, details see: M. Sapinski, Model of Carbon Wire Heating in Accelerator Beam, CERN-AB-2008-030)

PLANS

- Systematic study of effects of bias voltage on secondary and thermionic electron trajectories in presence of strong bunch fields.
    - Establish electron trajectory simulation, compare CST-studio and Virtual-IPM.
- Propose countermeasure to the persistant thermionic contribution to the signal:
    - Magnetic field
    - Very high electric field
    - Numerical method based on machine learning (successful for IPM)
    - …
- Investigate space charge effect on electron trajectories.

SUMMARY

Thin targets: low impact on particle beam trajectories, low energy deposit in the material – useful tool in beam diagnostics. They limits are due to heating. For low-energy beams thermionic emission affects the signal.

electrons	δ	low energy secondary	thermionic
energy	100 eV-100 keV	<100 eV	< 10 eV
proportional to beam density	yes	yes	no
affected by bias voltage	no	yes	yes
“cooling” effect	yes, decrease Bethe-Bloch	no	yes, efficient cooling process

Acknowledgements: Rudolf Doelling, Dominik Vilsmeier, Manon Boucard, Jerome Touguet, Aracelli Navarro, Hui Zhang, Richard Kan, Peter Forck, Plamen Boutachkov, Jan Koopman, Kenichiro Satou and others

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