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CMOS-Sensor Calibration for the Measurement of Field Emission Electron Currents

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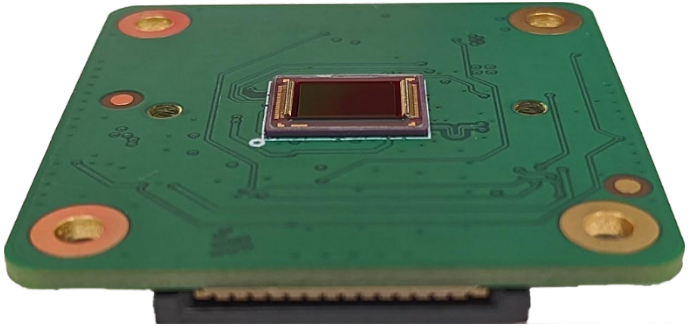
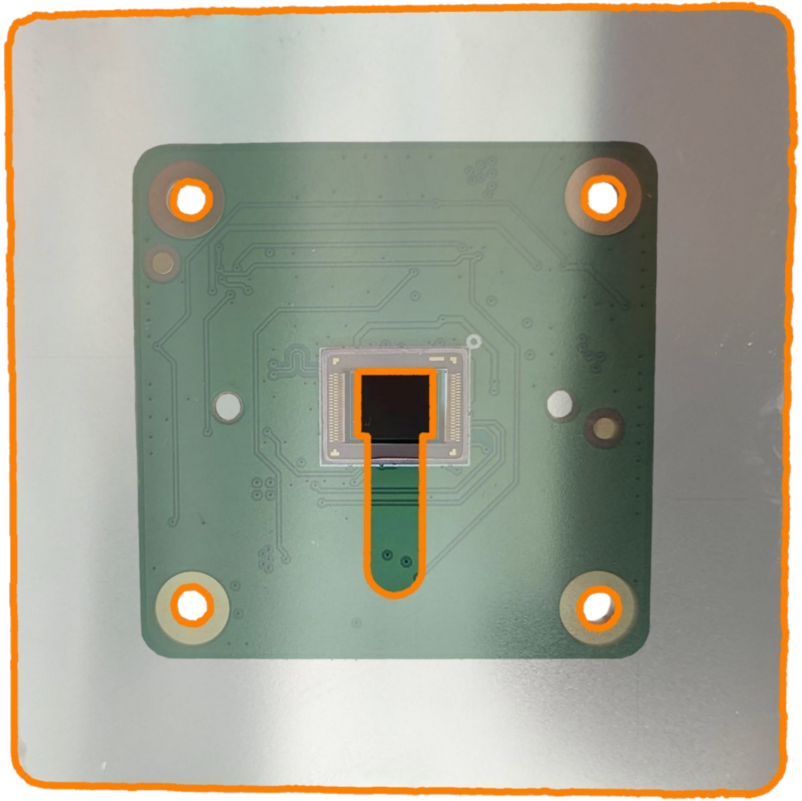
10th IVEW and 16th IVeSC

29. August 2026

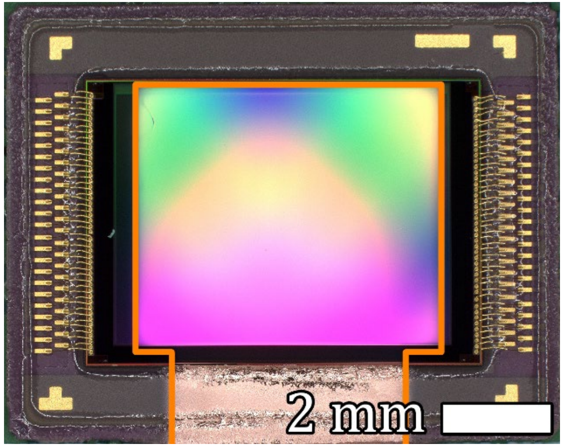
Overview

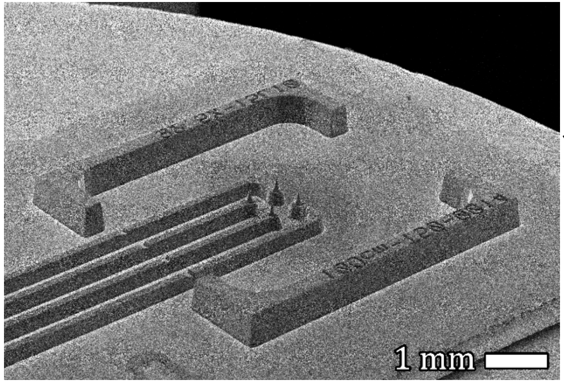
Basics of the Detection Method - Hardware + Modifications

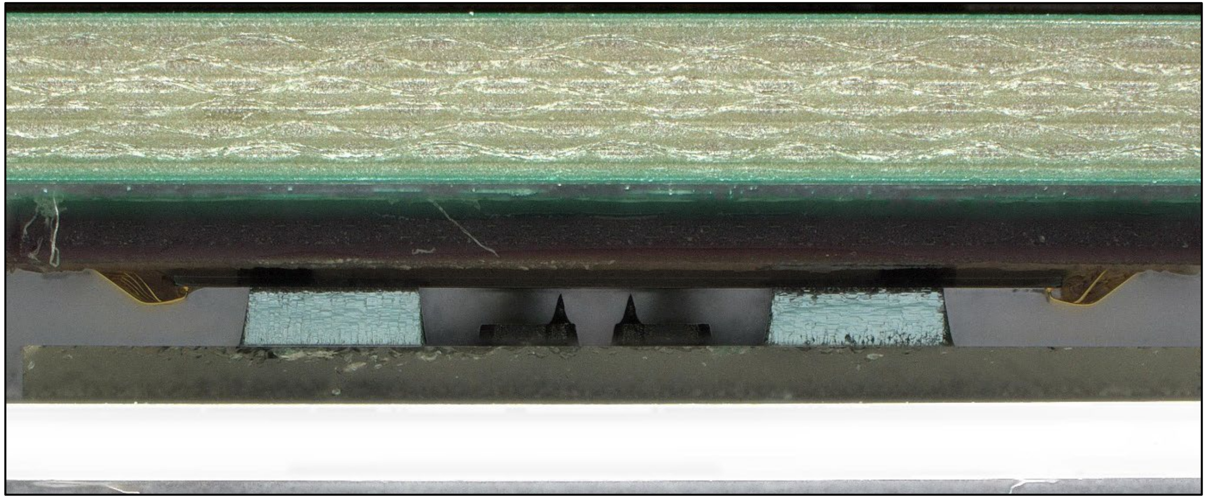




Basics of the Detection Method - Hardware + Modifications





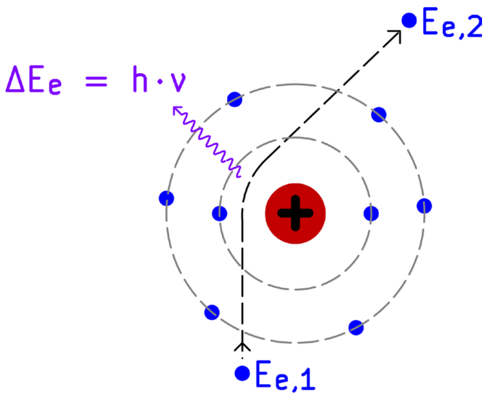


All FE-samples
- made from nSi (Ph, 5-10 Ωcm, <100>)
- anodically bonded on BF33
- fabricated via Laserablation and wet-chemical after-treatment

M. Hausladen *et al.*, “Measurement of field emission array current distributions by metal-coated CMOS image sensors,” *JVST B*, doi: 10.1116/6.0004074.

Basics of the Detection Method - Signal Origin and Description

Concept of Bremsstrahlung

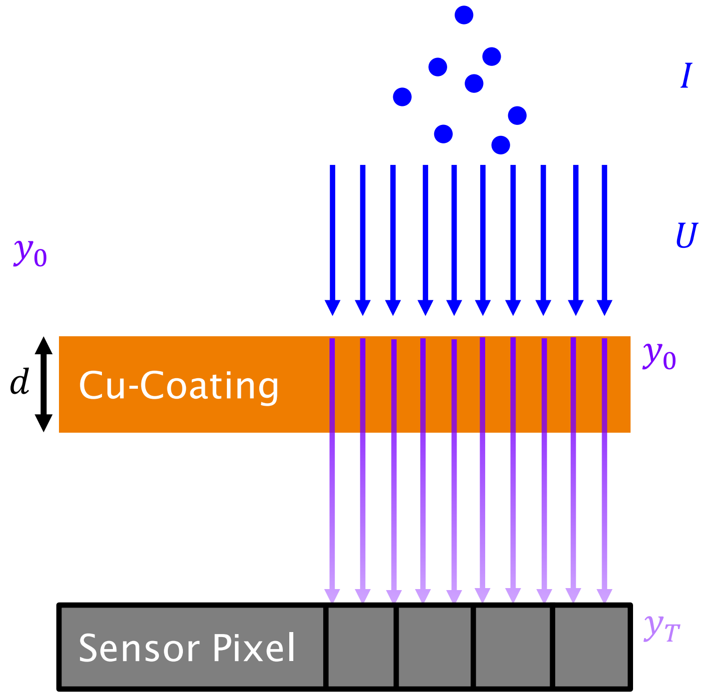


$$\lambda_{min} = \frac{h \cdot c}{e \cdot U_B}$$

$$\frac{dY}{d\lambda} = const \cdot I \cdot \left(\frac{1}{\lambda_{min}} - \frac{1}{\lambda}\right) \cdot \frac{1}{\lambda^b} = y_0$$

$$y_T = y_0 \cdot e^{-\mu(\lambda)\cdot(d - R_e(U_B))}$$

$$\frac{dY_T}{d\lambda} = \frac{dY}{d\lambda} \cdot e^{-\mu(\lambda)\cdot(d - R_e(U_B))} = y_T$$



Basics of the Detection Method - Signal Origin and Description

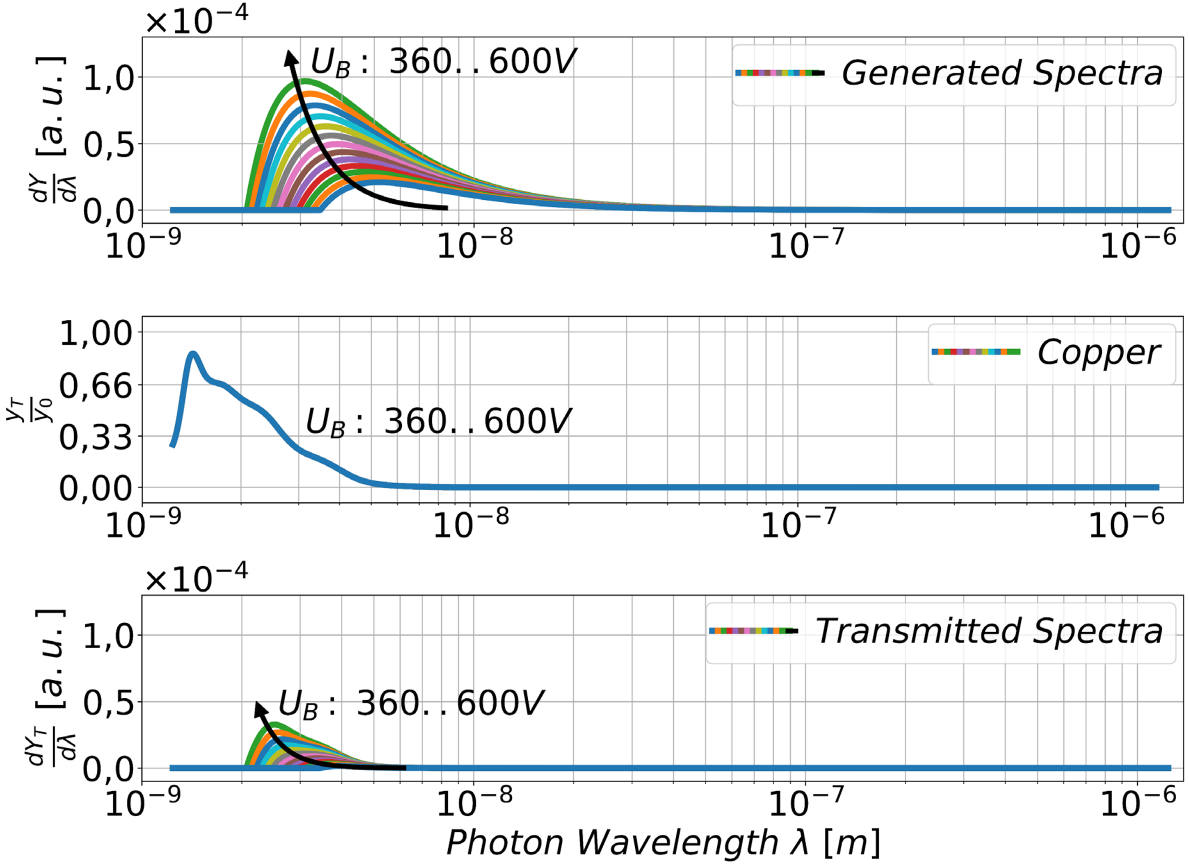
$$\frac{dY}{d\lambda} = const.\cdot I \cdot \left(\frac{1}{\lambda_{min}} - \frac{1}{\lambda}\right) \cdot \frac{1}{\lambda^b}$$

Assumption: $I = 1\,\mu A$, b = 2

$$T = \frac{y}{y_0} = e^{-\mu(\lambda)\cdot(d - R_e(U_B))}$$

$d = 150nm$

$$\frac{dY_T}{d\lambda} = \frac{dY}{d\lambda} \cdot e^{-\mu(\lambda)\cdot(d - R_e(U_B)}$$



Basics of the Detection Method - Signal Origin and Description

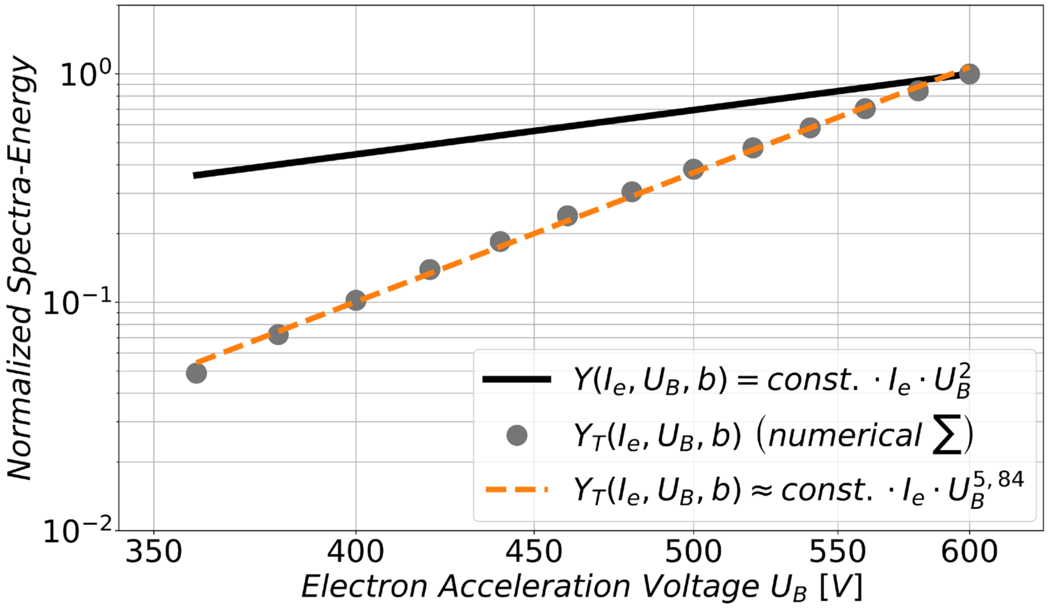
$$Y_T = \underbrace{\int_{\lambda_{min}}^{\infty} \frac{dY_T}{d\lambda}}_{\mu(\lambda)\text{ analytically unknown!}} d\lambda = \, ? \quad \longrightarrow \quad Y_T \approx \sum_{\lambda} \frac{dY_T}{d\lambda}$$

vs.

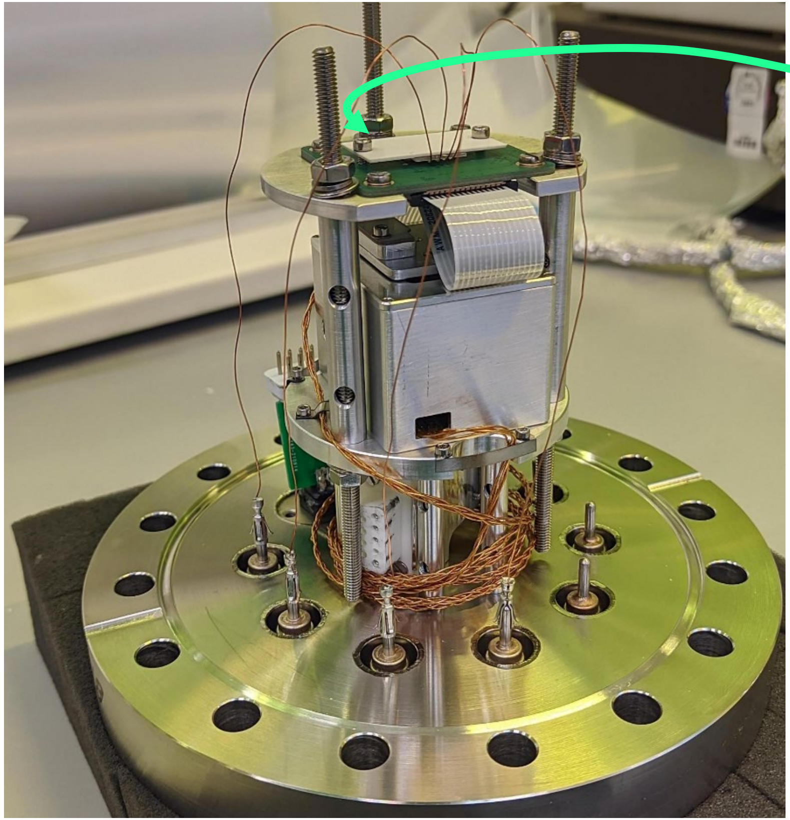
$$Y = \int_{\lambda_{min}}^{\infty} \underbrace{\frac{dY}{d\lambda}}_{\propto \frac{1}{\lambda^b}} d\lambda = \frac{const}{b \cdot (b-1)} \cdot \frac{I}{\lambda_{min}^b(U_B)}$$

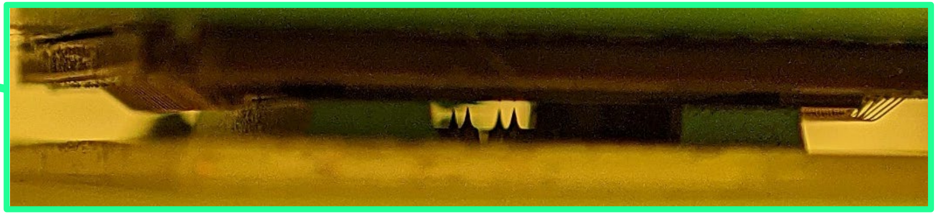
$$\Big\downarrow \; \lambda_{min} = \frac{h \cdot c}{e \cdot U_B}$$

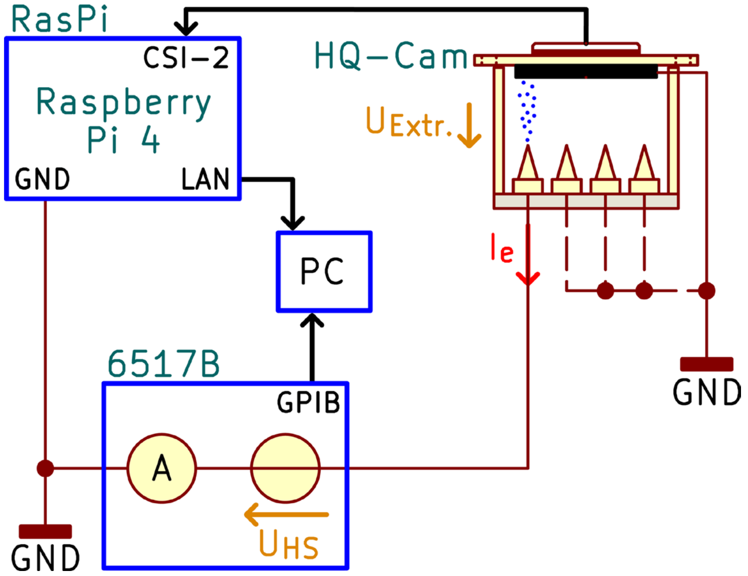
$$Y = const \cdot I \cdot U_B^b \quad \Rightarrow \quad Y_T$$



Basics of the Detection Method - Hardware + Modifications







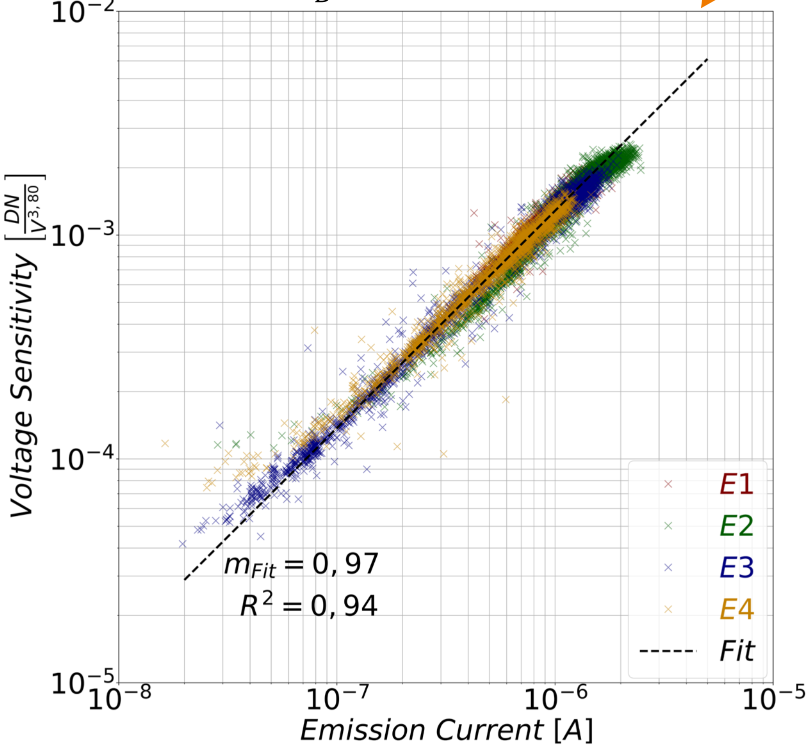
$U_{HS} = 360V \dots 560V$ in $\Delta U = 10V$ steps

150 Datapoints for each voltage (held for 5 min)

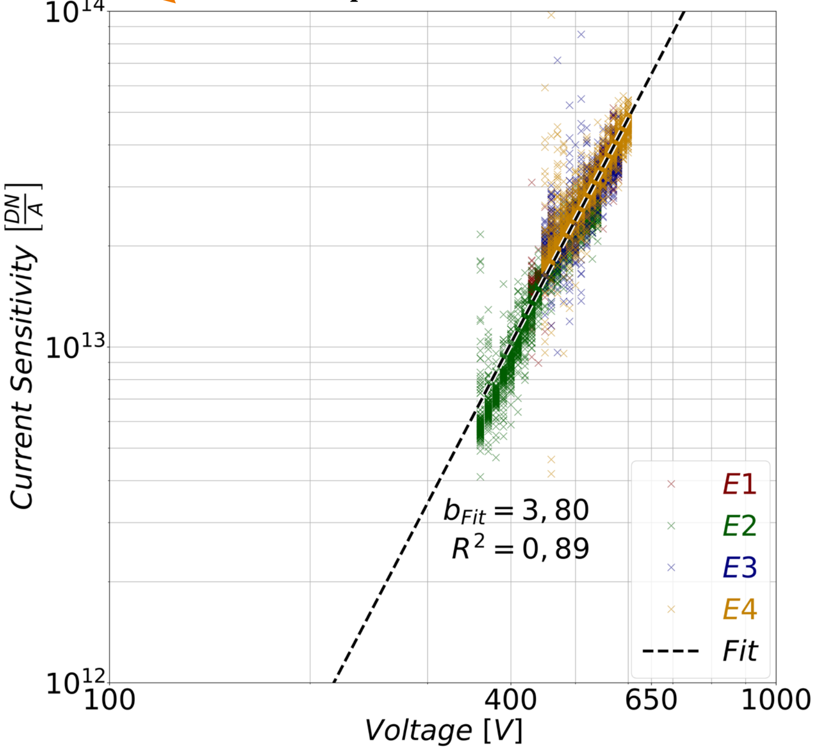
Basics of the Detection Method - Signal Origin and Description

$$Y = const \cdot I \cdot U_B^b$$

$$\frac{Y}{U_B^b} = const \cdot I$$



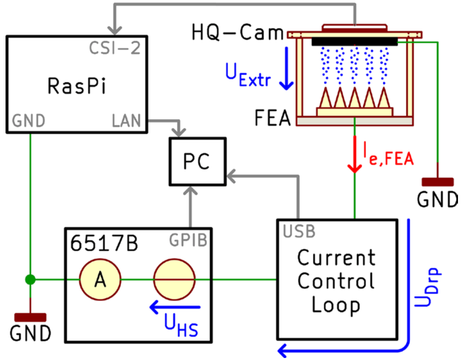
$$\frac{Y}{I} = const \cdot U_B^b$$

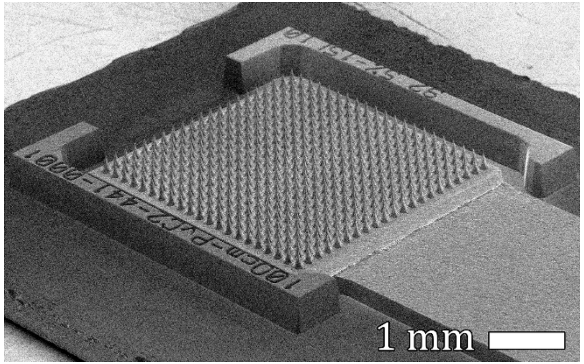


M. Hausladen *u. a.*, „Investigation of Influencing Factors on the Measurement Signal of a CMOS Image Sensor for Measuring Field Emission Currents“, *Sensors*, doi: 10.3390/s25051529.

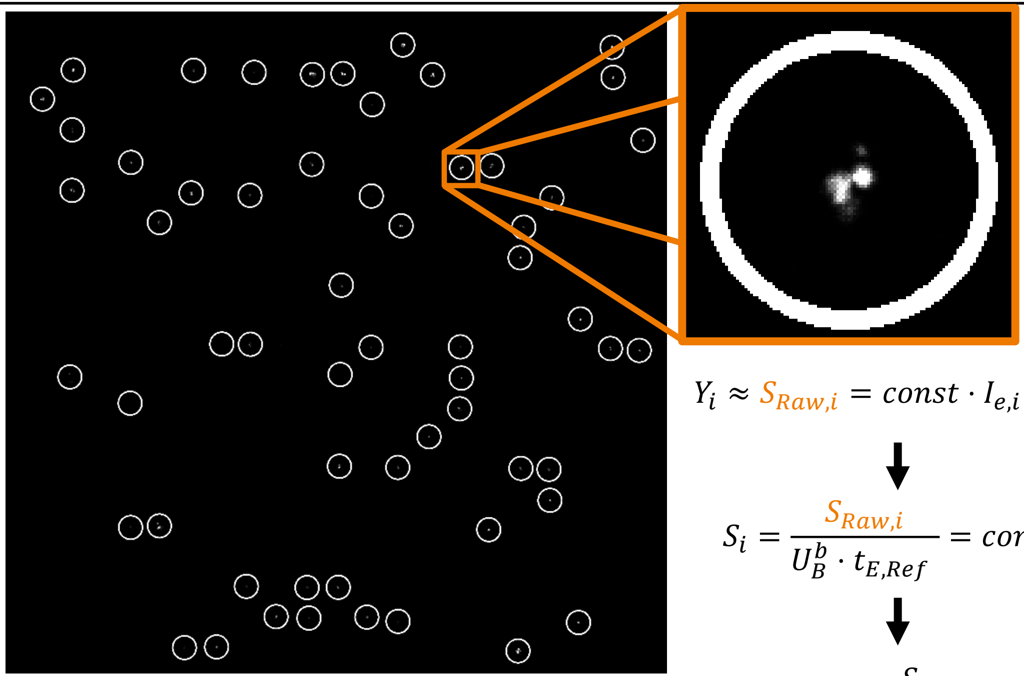
Overview

Gain and Use the Image Data
Spot Sensor Signal and Momentary Current Determination





FEA with
- 21x21 Emitters
- squared arrangement
- pitch: 200µm



$$Y_i \approx S_{Raw,i} = const \cdot I_{e,i} \cdot U_B^b \cdot \overbrace{t_{E,Ref}}^{f(t_E)}$$

$$\Downarrow$$

$$S_i = \frac{S_{Raw,i}}{U_B^b \cdot t_{E,Ref}} = const \cdot I_{e,i}$$

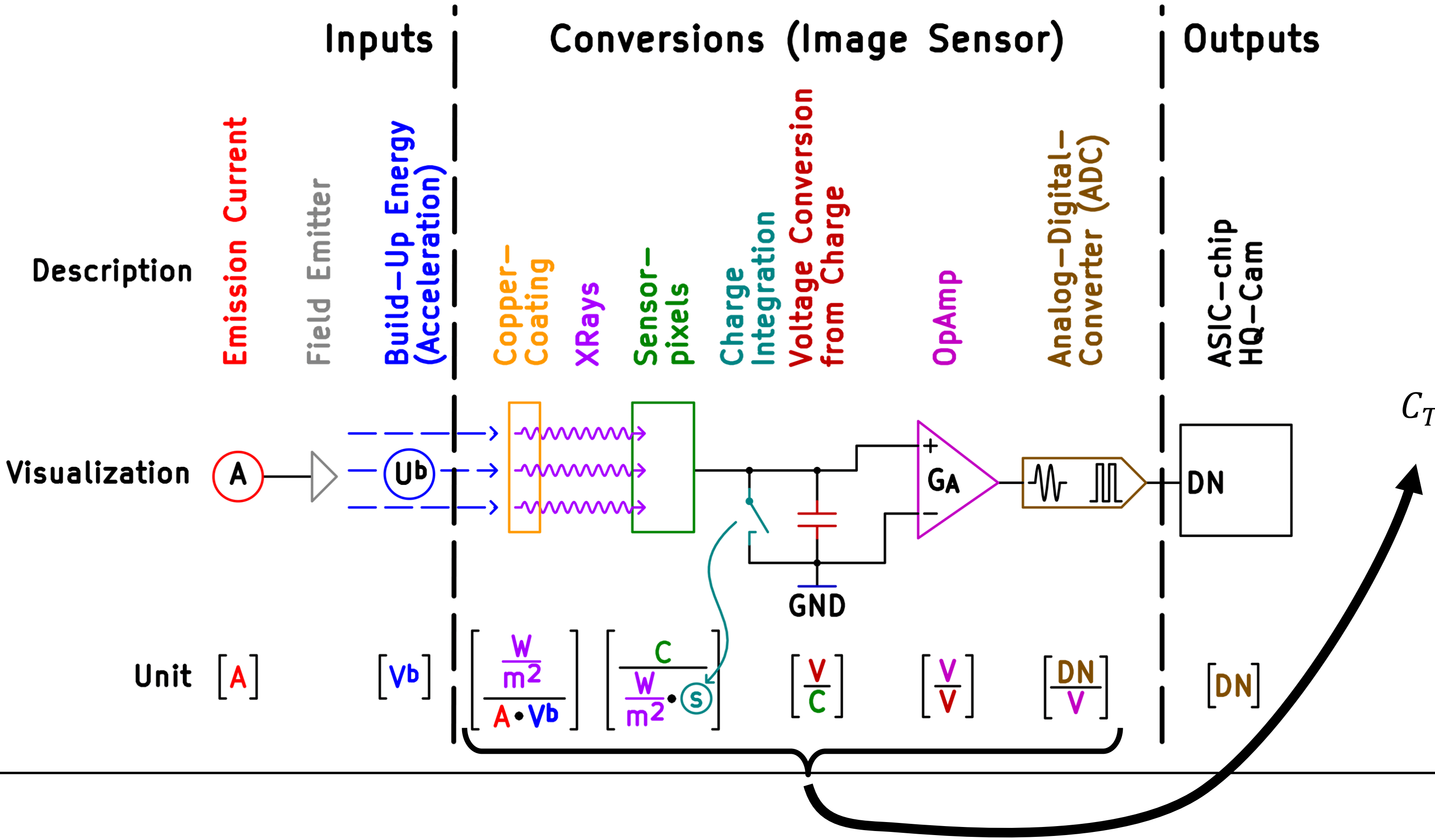
$$\Downarrow$$

$$F_i = \frac{S_i}{\sum_j S_j}$$

$$I_{Opt,i} = I_e \cdot F_i$$

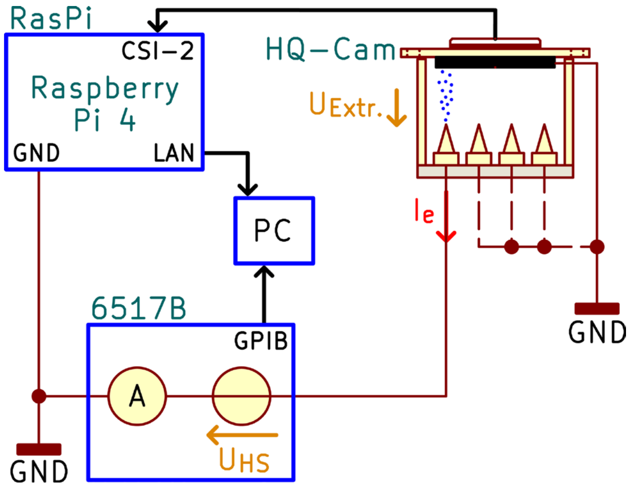
Overview

Sensor Calibration - Transfer Constant

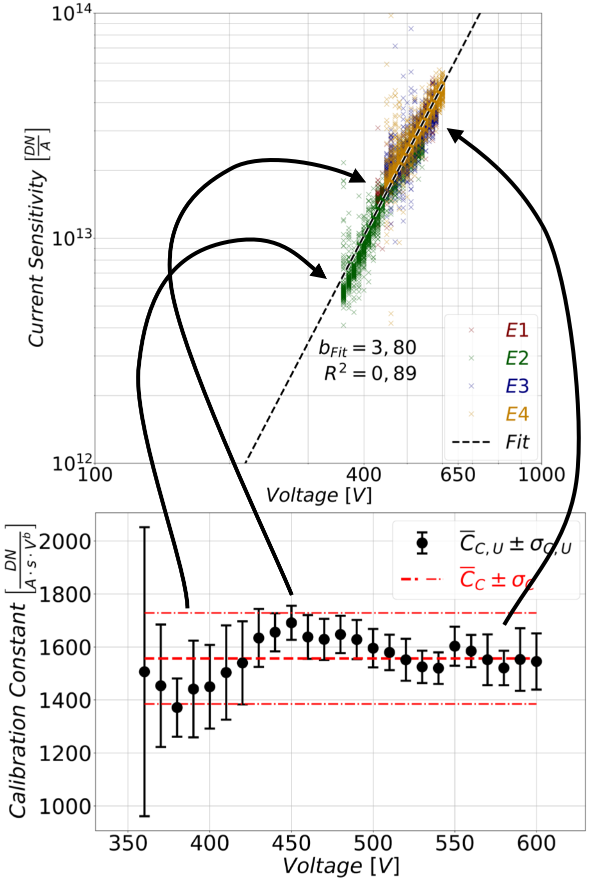


$$C_T = \left[\frac{DN}{A \cdot s \cdot V^b}\right]$$

Sensor Calibration - Calibration Constant and Experiments

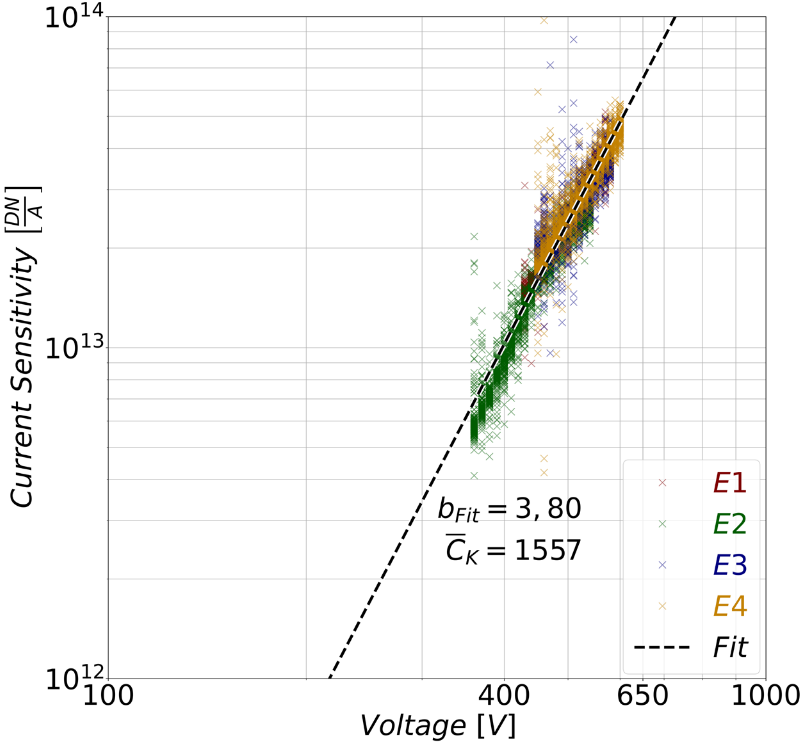


$$S_i = \frac{S_{Raw}}{U_B^b \cdot t_{E,Ref}} = \underbrace{const}_{C_C} \cdot I_{e,i} \;\Rightarrow\; \frac{S_i}{I_{e,i}} = C_C$$

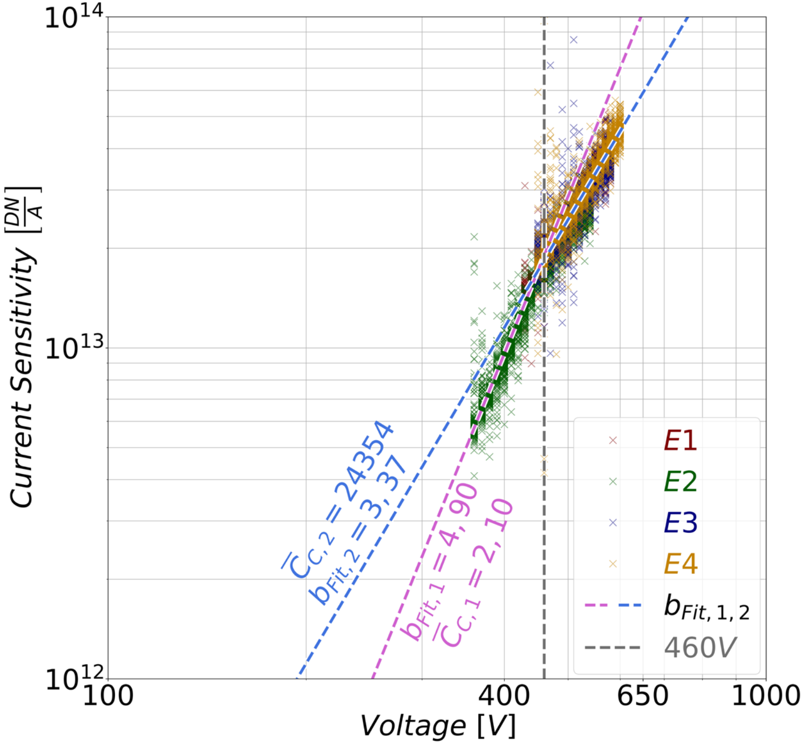


$$\frac{S_{Raw}}{I_{e,i}} \propto U_B^b$$

Sensor Calibration - Calibration Constant and Experiments

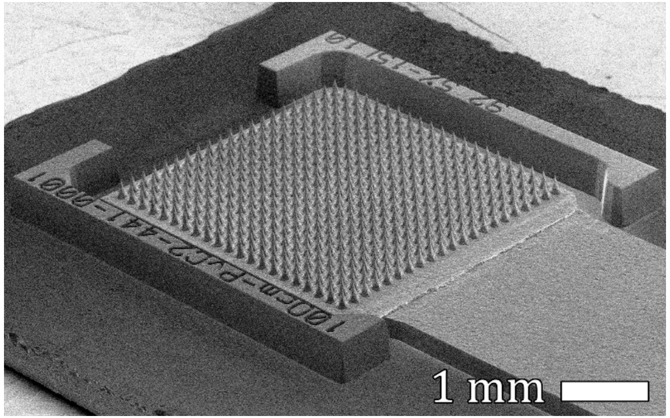


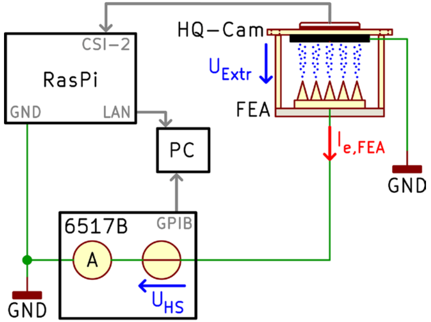
Full-Range-Fit



Splitted Lo-Hi Range

Sensor Calibration - Calibration Constant and Experiments

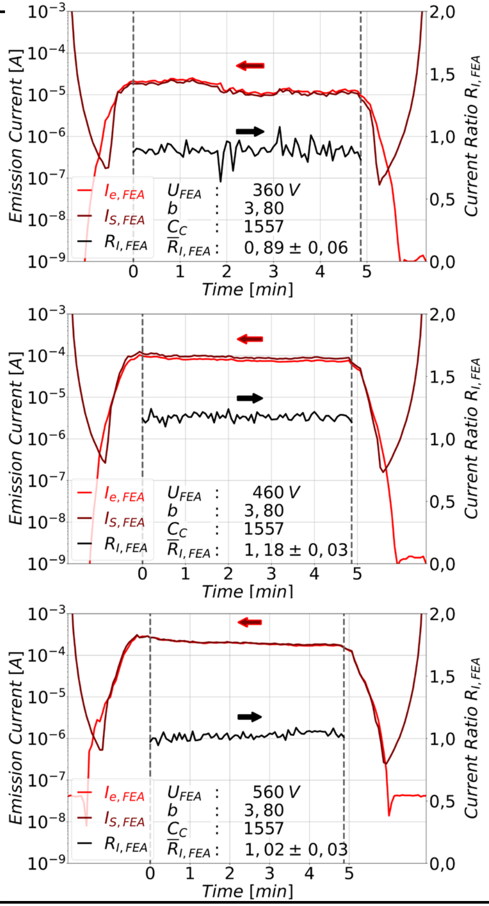




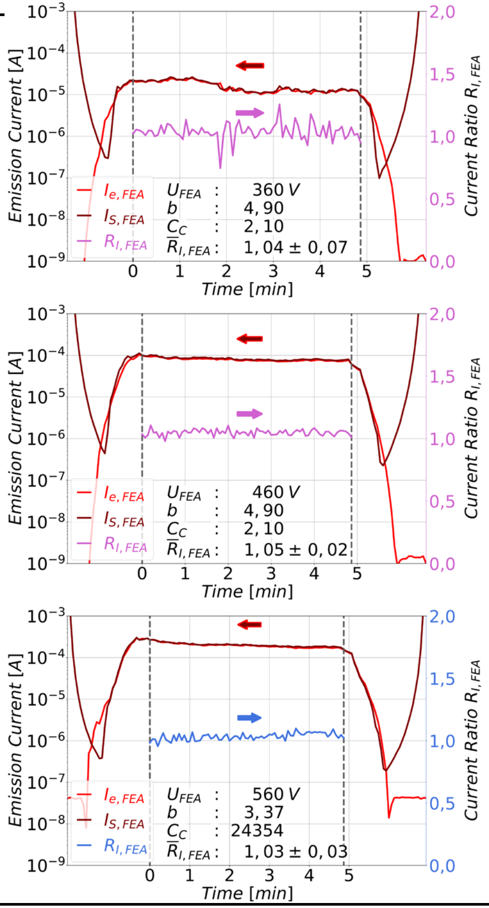
$$S_{FEA} = C_C \cdot I_{e,FEA}$$

$$\frac{S_{FEA}}{C_C} = I_{S,FEA} \stackrel{!}{=} I_{e,FEA}$$

$$R_{I,FEA} = \frac{I_{S,FEA}}{I_{e,FEA}}$$



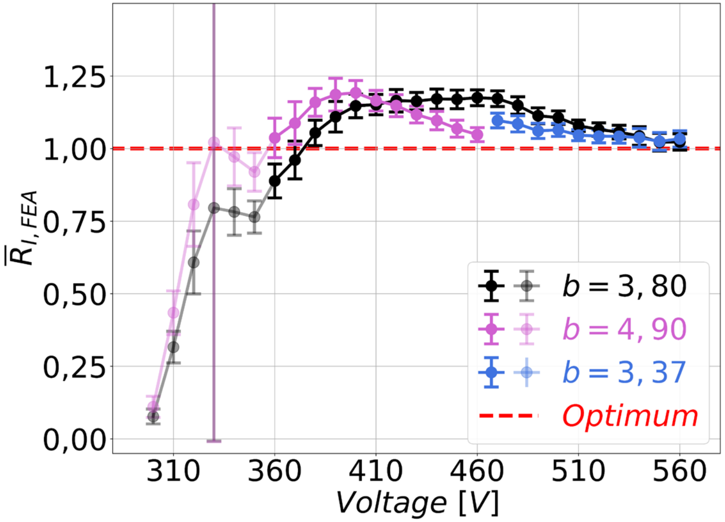
Full-Range Fit

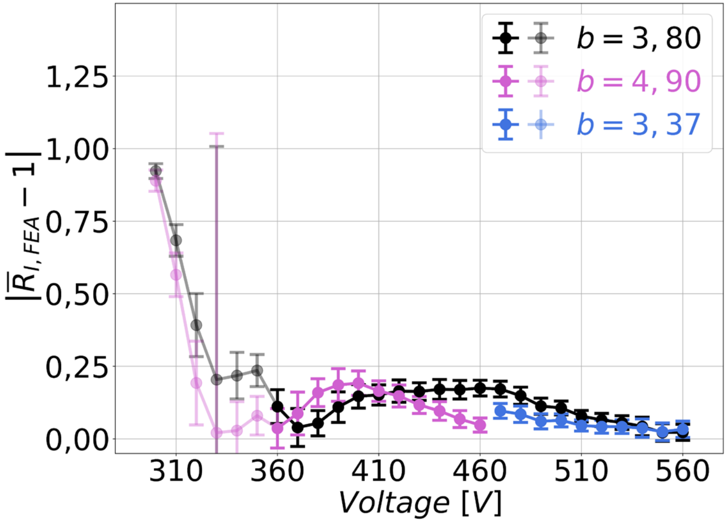


Splitted Lo-Hi Range Fits

Voltages: 300-560V (10V spacing)
Duration: 5 min each Voltage

Sensor Calibration - Calibration Constant and Experiments





➔ Partly, but overall better accuracy by splitted fits (Lo-Hi).

➔ More accurate description of U^b allows reduces linearization error (e.g. $U^{b(U)}$)

➔ For a perfect Y_T (analytical solution) so that C_C becomes a constant

Overview

Summary

- Overview on the method
  - Sensor modifications (optical sensor → electron-detector)
    - Image sensor: IMX477 (Raspberry Pi HQ-Camera)
  - How it works (signal description, how to determine current)
- Method has potential for
  - Gaining high detailed observations of dynamic emission process and its changes over time (in-situ)
- For now, method only allows analysis of cathodes with low/no internal voltage drops (causing different U_B values per emitter)
  - $S_{Raw} \approx Y \propto I \cdot U^b$ → appropriate conductivity allowing assumption $U_1 \approx U_2 \ldots \approx U$
- Calibration can be done:
  - Determined C_C values (Full-/Lo-Hi Range) with „image sensor 1“ and „FE-Cathode 1“ (4 individual tips)
  - Applied them on data of „image sensor 2“ (same type) and „FE-Cathode 2“ (FEA)
  - Results showed calibration works in principle, but deviates (depending on voltage) as
    - $S_{Raw} \approx Y$ due to U_B^b; b assumed as const → multi-calibration for different voltage ranges (Lo-Hi)
    - Deviations especially for Full-Range-Fit and at (very) low voltages!
  - With more accurate Y_T descriptions → less linearization error → C_C approaches a real constant:
    - better approximations treating b as $f(U)$ to describe the curvature of the S_{Raw} signal
    - or analytical primitives Y_T (demands availability of absorption coefficients $\mu(\lambda)$ and their integrability)

More info and details on this method:

Signal description and System analyzation

Sensor modifications and method applied

GitHub-Project

Thank you for your attention