Joint ICTP-IAEA Advanced Workshop on Single Ion Technologies for Bio-medical and Materials Sciences

30 June – 4 July 2025

Single Ion Detection II: where

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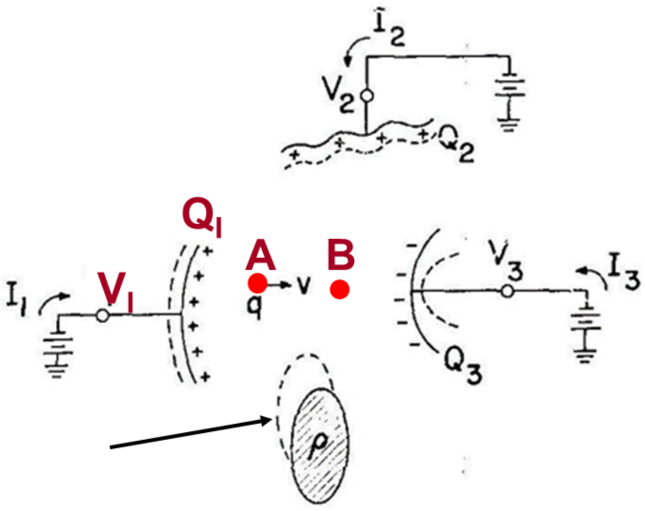
Summary

- Induced charge in multielectrode semiconductor devices
- A “simple” linear position sensitive detector
- Examples of a two dimensional position sensitive detectors
- Sensitivity, spectral and spatial resolution

Gunn's Theorem

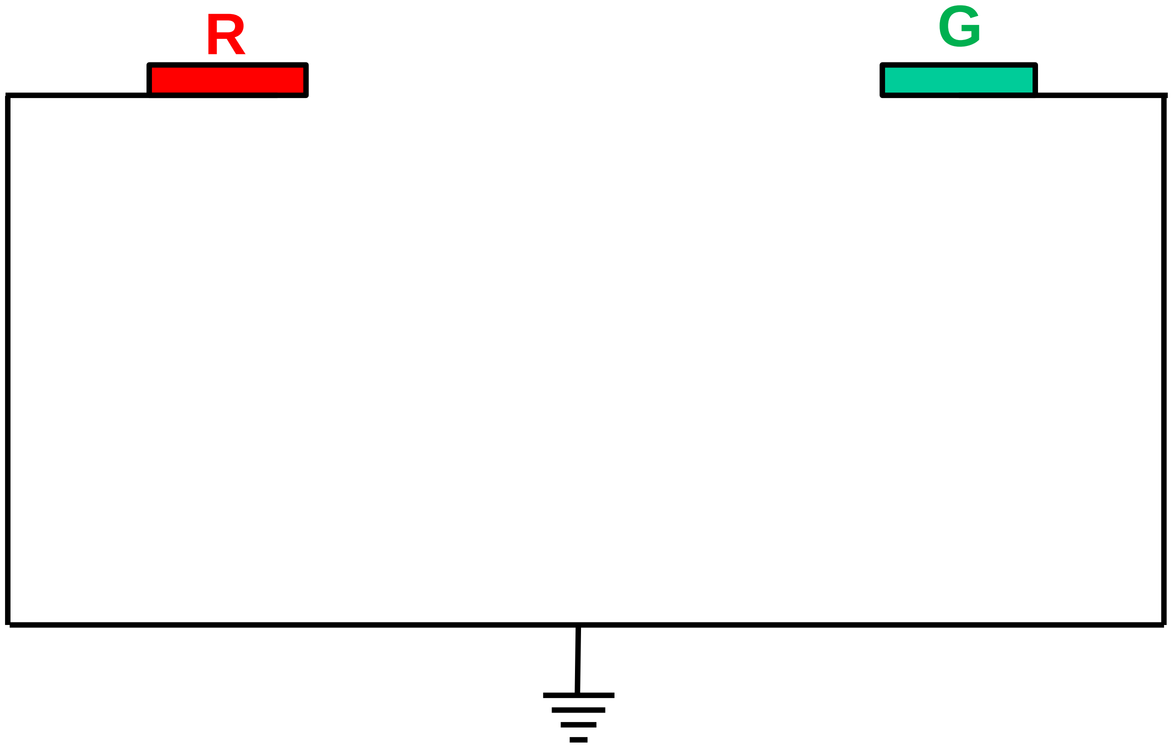
$$\boxed{\nabla_{\mathbf{r}} Q_i = -q \cdot \frac{\partial \mathbf{E}}{\partial V_i} = -\boldsymbol{q} \cdot \mathbf{E}_{\boldsymbol{w}}}$$

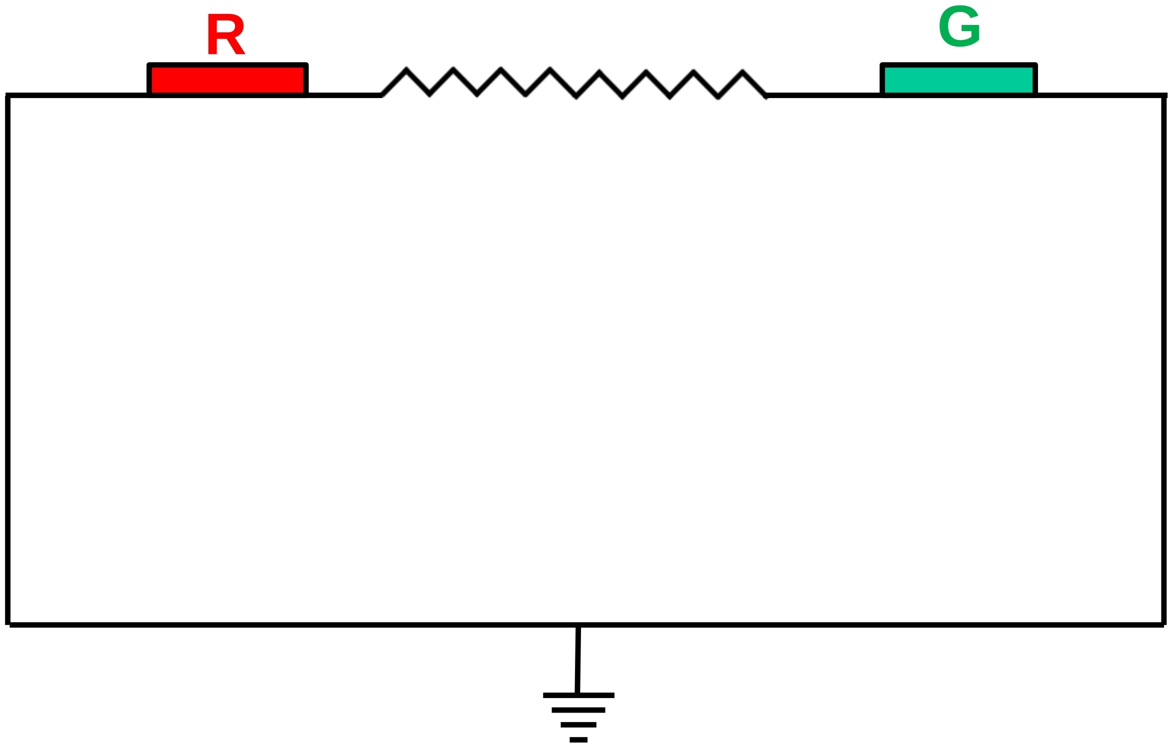
$$\mathbf{Q} = \mathbf{q} \cdot [\boldsymbol{\psi}_{\mathbf{w}}(\mathbf{B}) - \boldsymbol{\psi}_{\mathbf{w}}(\mathbf{A})]$$



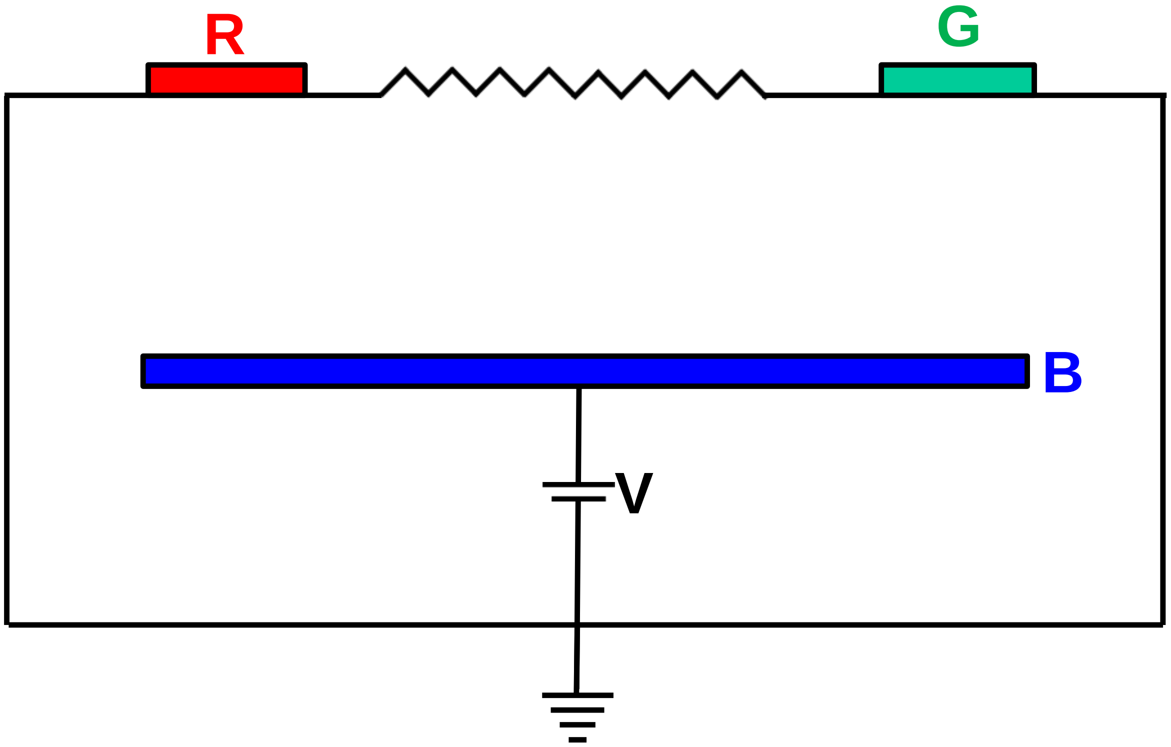
The induced charge Q at the sensing electrode is given by the difference in the weighting potentials between any two positions (A and B) of the moving charge

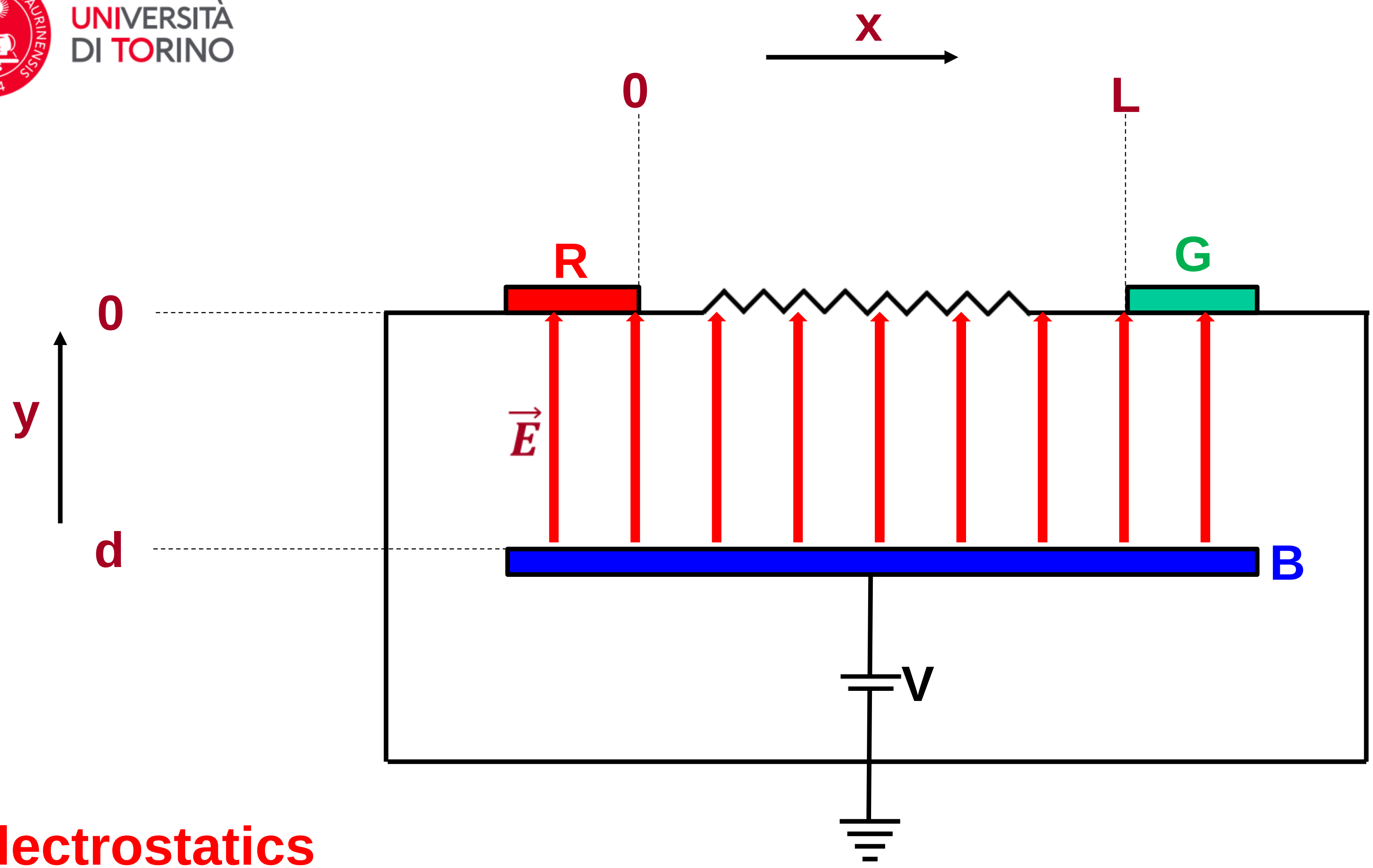
CHARGE SHARING IN MULTIELECTRODE DEVICES


R
G


R
G

Three electrodes R, G, B



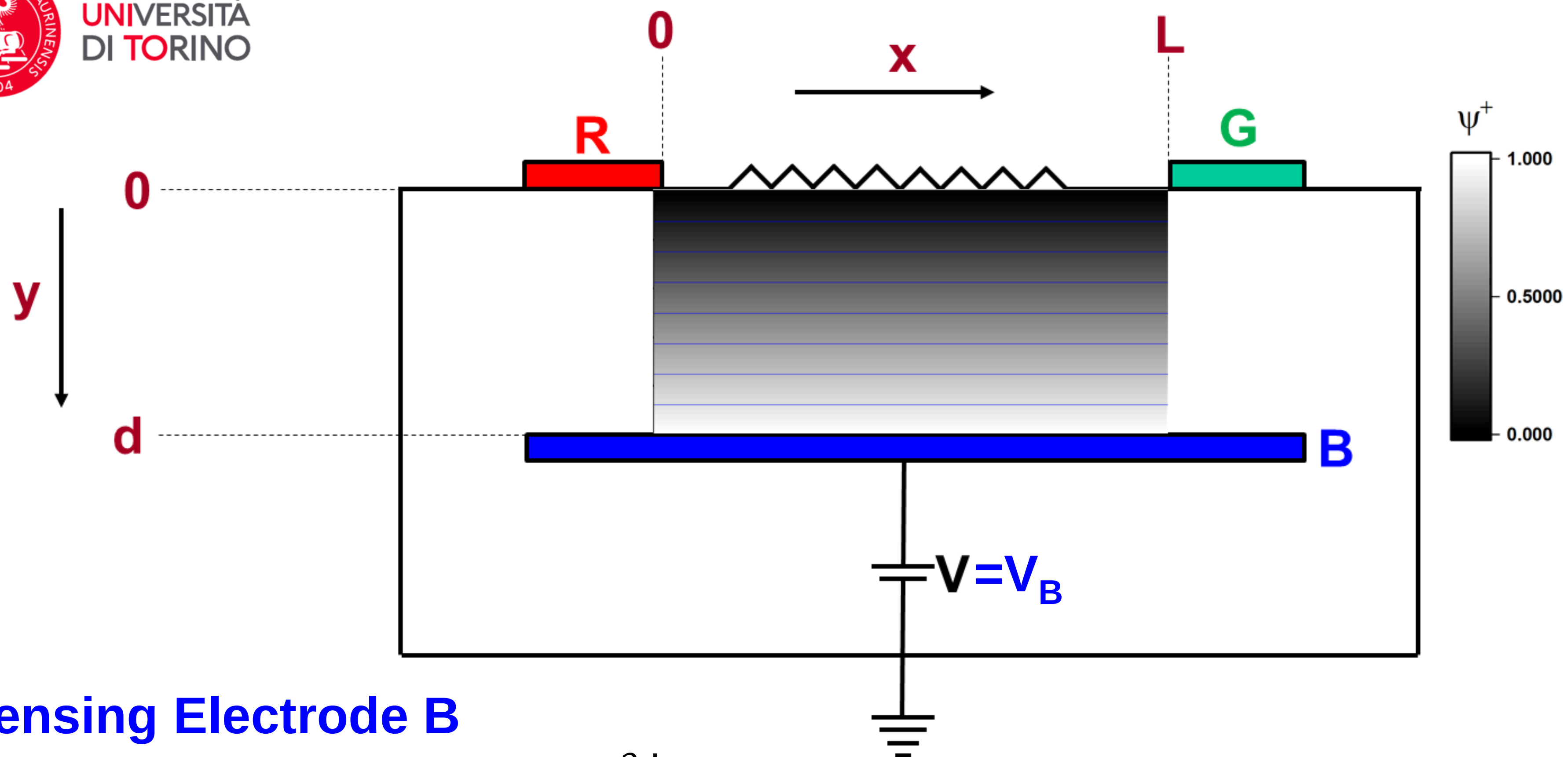


Electrostatics

Electric potential: $\psi = V \cdot \frac{x}{d}$

Electric Field: $E = -\frac{V}{d}$

Vertical trajectories



Sensing Electrode B

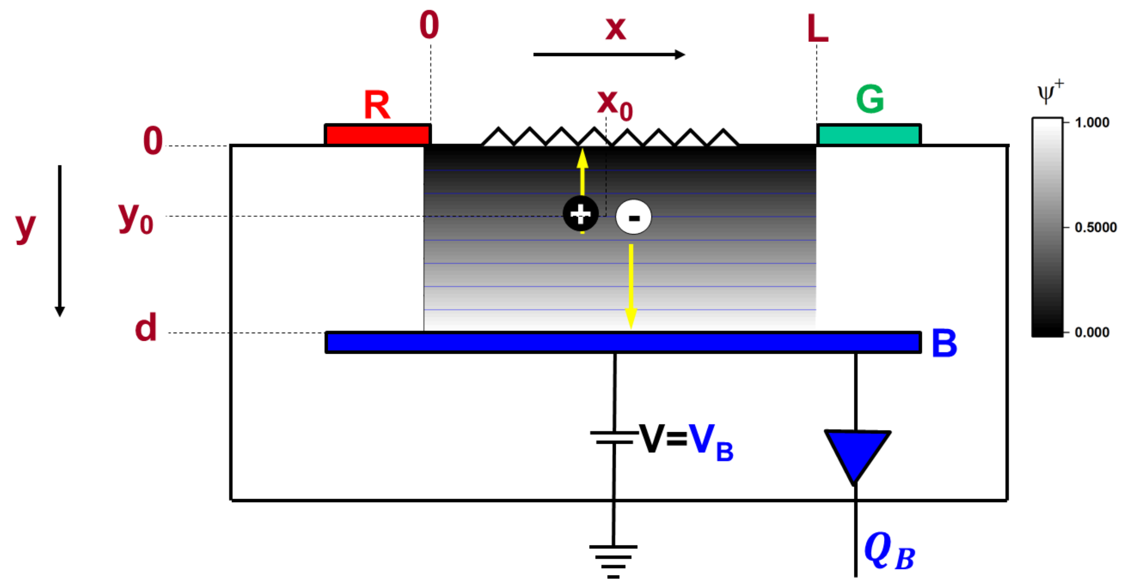
Weighting Potential $\psi_{wB} = \frac{\partial\psi}{\partial V} = \frac{y}{d}$

Weighting Field $E_{wB} = \frac{\partial E}{\partial V} = -\frac{1}{d}$

R and G are grounded

Sensing Electrode B

The induced charge Q_B at the sensing electrode B is given by the difference in the weighting potential ψ_{wB} between any two positions of the moving charges



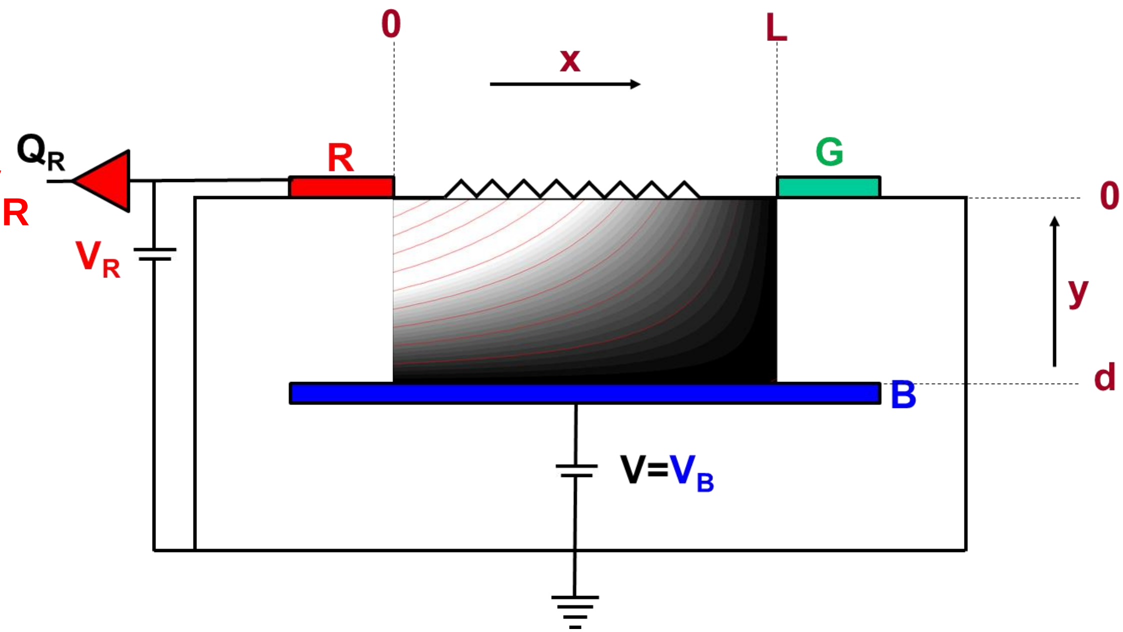
$$Q_B = -q[\psi_{wB}(y=d) - \psi_{wB}(y=y_0)] + q[\psi_{wB}(y=0) - \psi_{wB}(y=y_0)] = q$$

electron		hole
y=y_0; $\psi_{wB} = \frac{y_0}{d}$	Initial position	y=y_0; $\psi_{wB} = \frac{y_0}{d}$
y=d; $\psi_{wB} = 1$	Final position	y=0; $\psi_{wB} = 0$

Sensing Electrode R at $V=V_R$

Electrode B at $V_B=V$

Electrode G at $V_G=0$

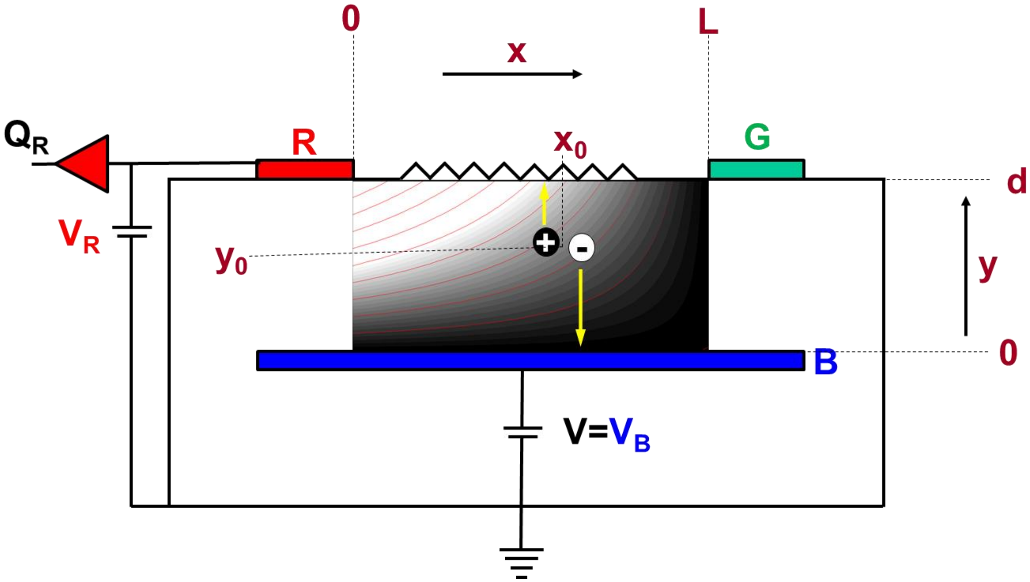


Electric potential: $\psi_R = V_R - \frac{V_R}{L} \cdot x + \frac{V_B - V_R}{d} \cdot y + \frac{V_R}{L \cdot d} x \cdot y$

Weighting Potential $\psi_{wR} = \frac{\partial \psi_R}{\partial V_R} = 1 - \frac{x}{L} - \frac{y}{d} + \frac{x \cdot y}{L \cdot d}$

Sensing Electrode R

The induced charge Q_R at the sensing electrode R is given by the difference in the weighting potential ψ_{wR} between any two positions of the moving charges



Weighting Potential $\psi_{wR} = \frac{\partial \psi_R}{\partial V_R} = 1 - \frac{x}{L} - \frac{y}{d} + \frac{x \cdot y}{L \cdot d}$

Electron **Hole**

$$Q_R = -q[\psi_{wR}(x_0, d) - \psi_{wR}(x_0, y_0)] + q[\psi_{wR}(x_0, 0) - \psi_{wR}(x_0, y_0)] = 1 - \frac{x_0}{L}$$

Initial position $\psi_{wR}(x_0, y_0) = 1 - \frac{x_0}{L} - \frac{y_0}{d} + \frac{x_0 \cdot y_0}{L \cdot d}$

Final position:

Electron $\psi_{wR}(x_0, d) = 0$

Hole $\psi_{wR}(x_0, 0) = 1 - \frac{x_0}{L}$

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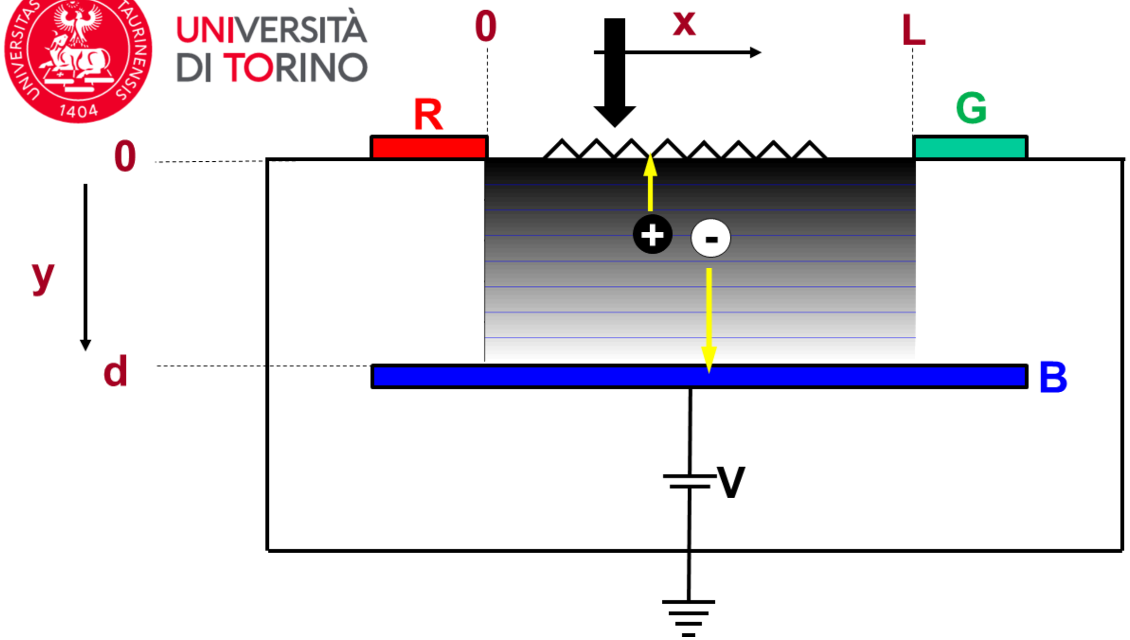
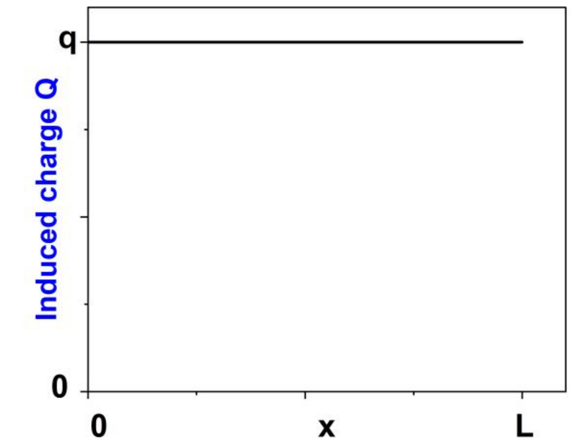
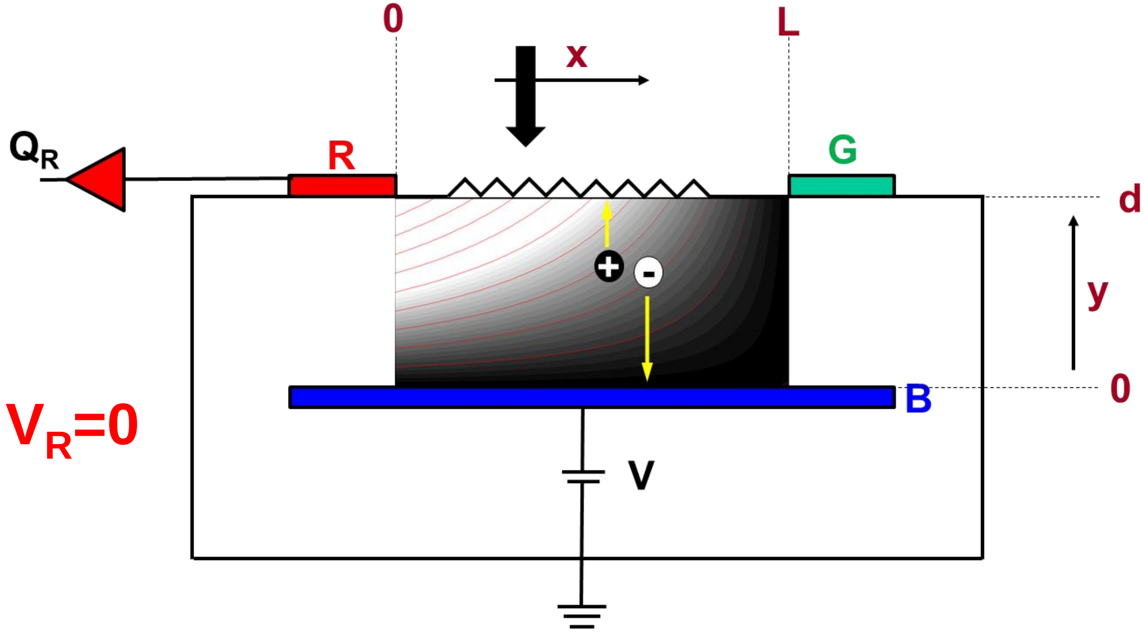
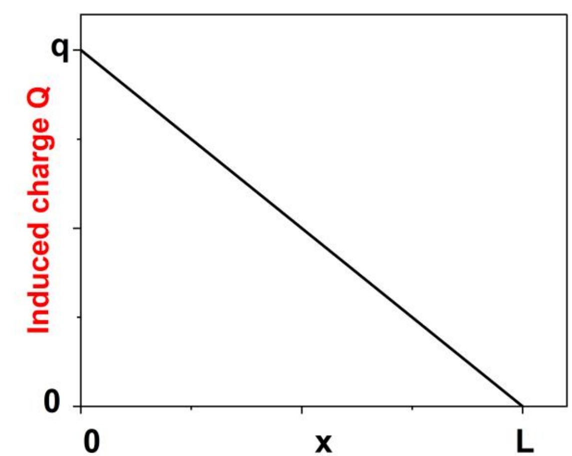






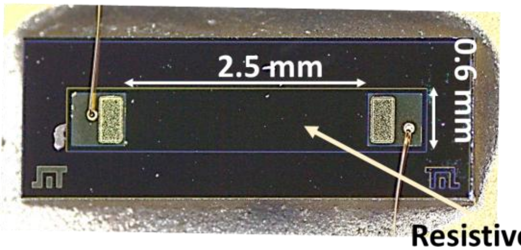


IBIC ANALYSIS OF A LINEAR POSITION SENSITIVE DETECTOR: MODEL AND EXPERIMENT

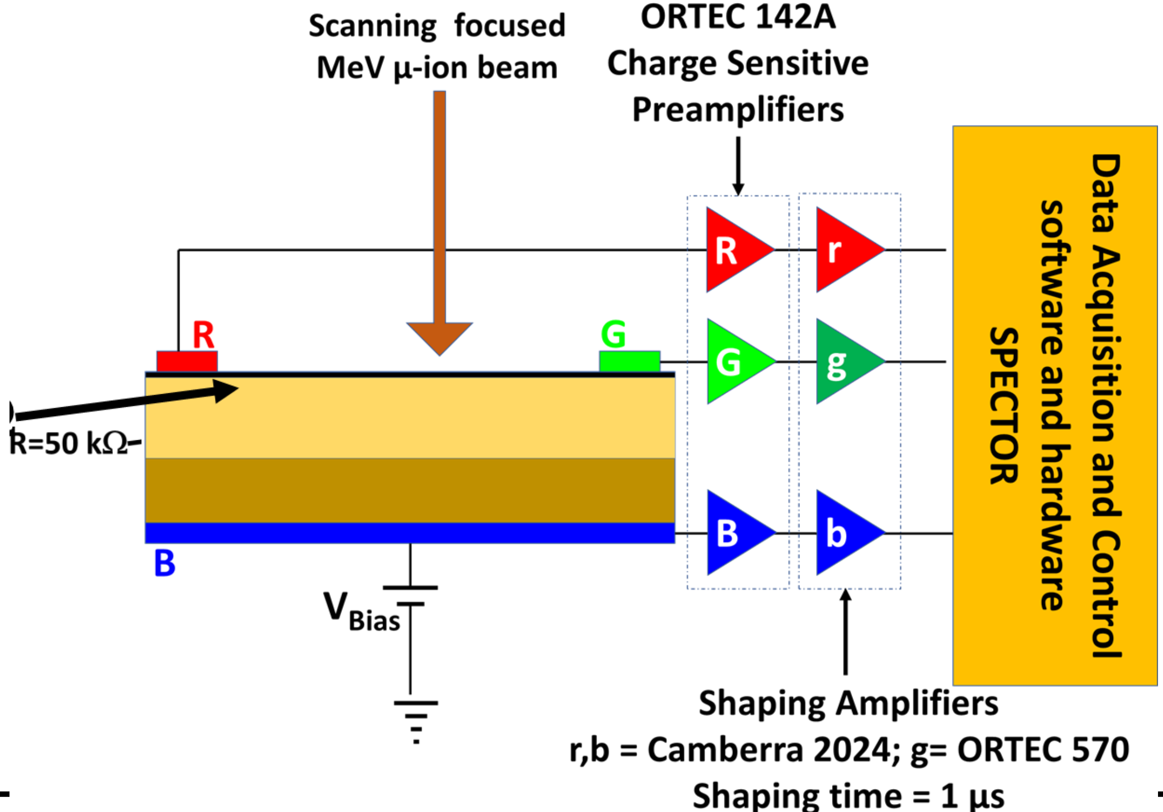
SiTeK Position Sensing Detector 1L2.5 UV

European Physical Journal 2025, 140 (5), 369

The device consists of
- A uniform resistive p-type layer formed on an n-type semiconductor substrate,
- Two electrodes (R and G) on both ends of the resistive layer
- A common electrode (B) located on the backside of the substrate.



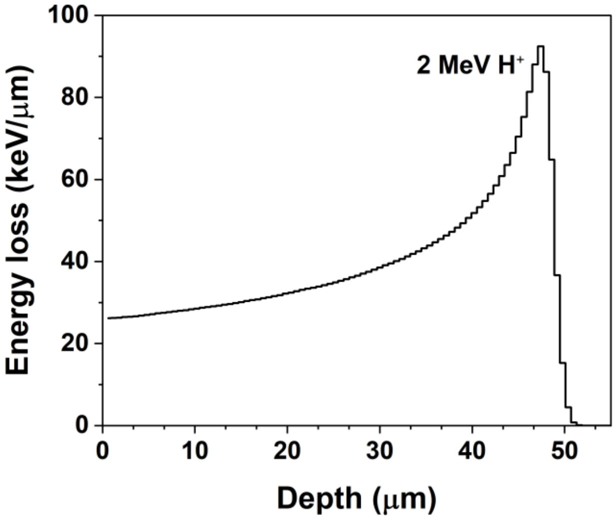
Capacitance < 2 pF
Dark current < 12 nA @ 20V

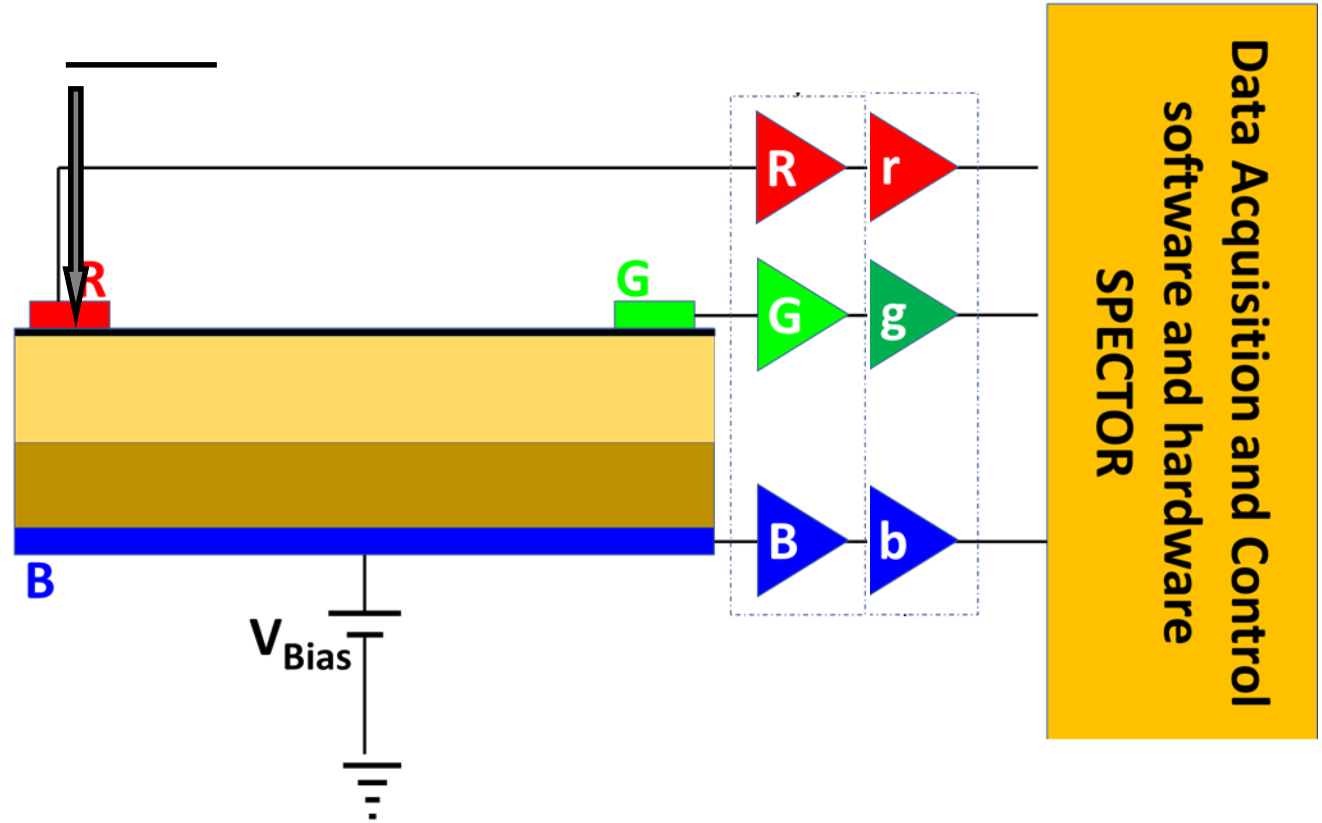


The IBIC experiment was carried out at the Laboratory for Ion Beam Interaction (LIBI) of the Ruder Boskovic Institute in Zagreb (HR).

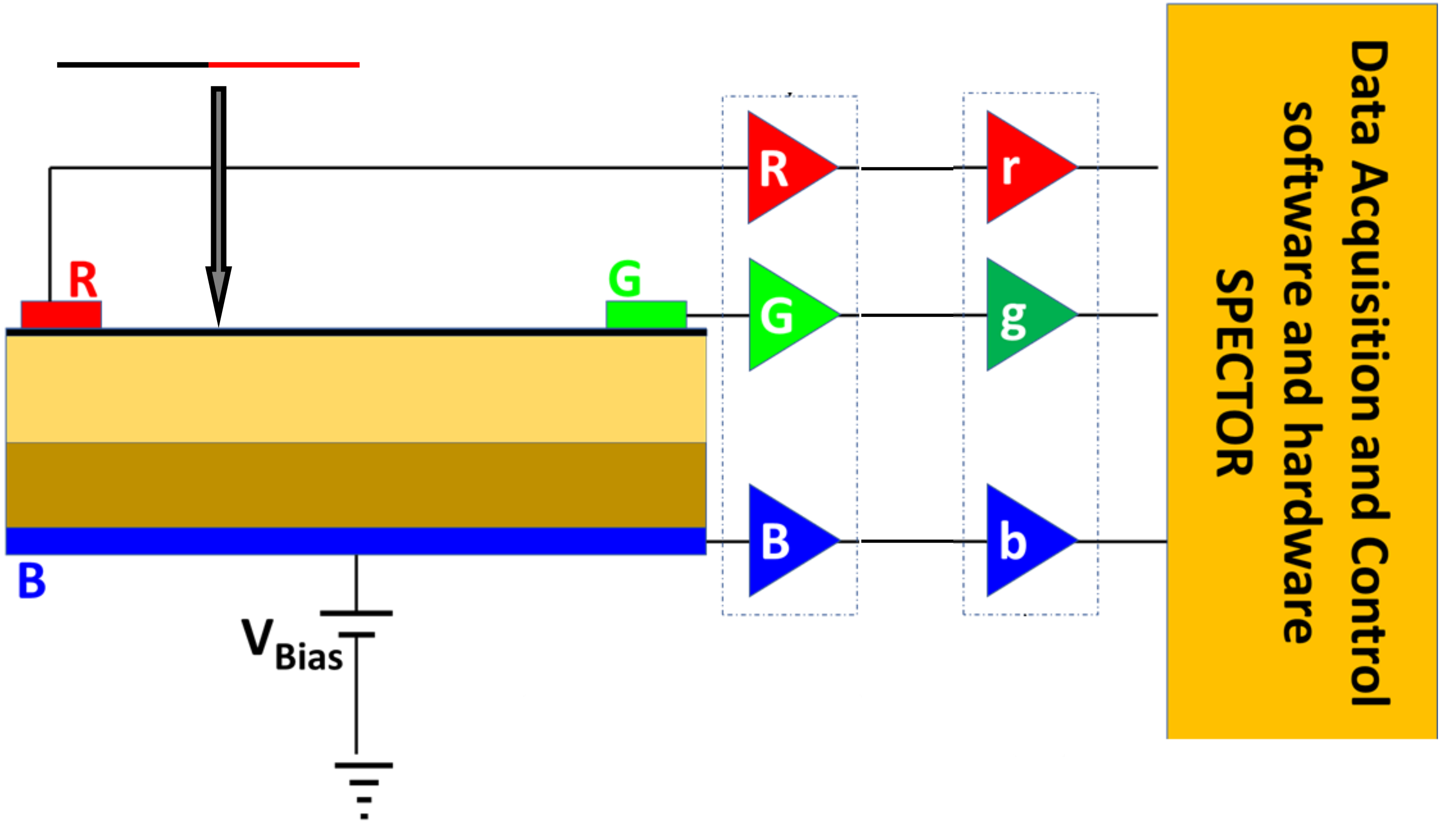
Spectral resolution: 32 keV (ORTEC PIPS detector)
Beam spot size: 2 μm – from on-axis STIM
Pixel size: 23 μm^2
Scan area: (128x128)x(Pixel Size)=(0.62x0.62) mm^2

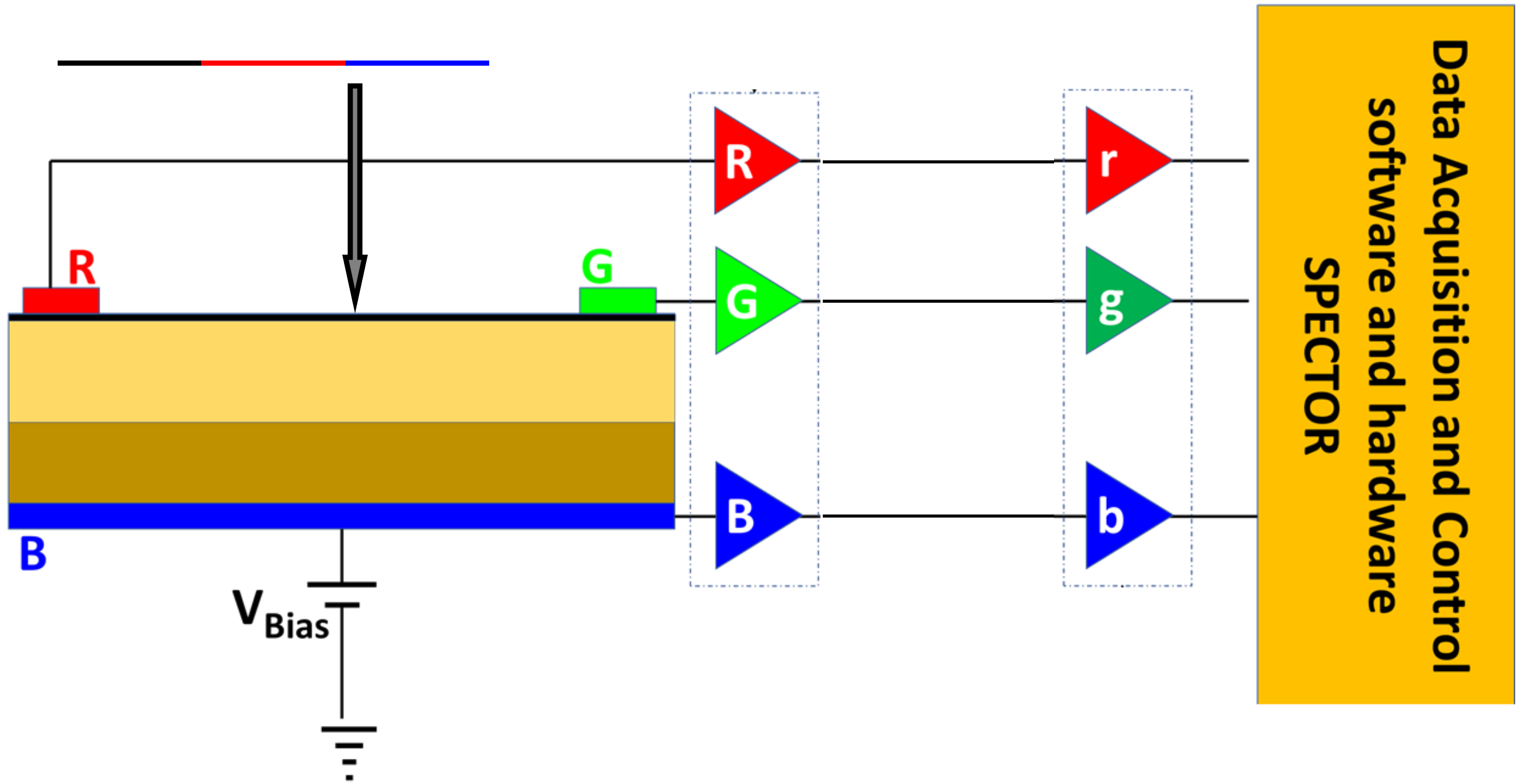
Ion microprobe: 2 MeV protons





R
G
B
V_{Bias}
R
r
G
g
B
b
Data Acquisition and Control software and hardware SPECTOR


R
G
B
V_Bias
R
G
B
r
g
b
Data Acquisition and Control software and hardware
SPECTOR


R
G
B
VBias
R
G
B
r
g
b
Data Acquisition and Control
software and hardware
SPECTOR

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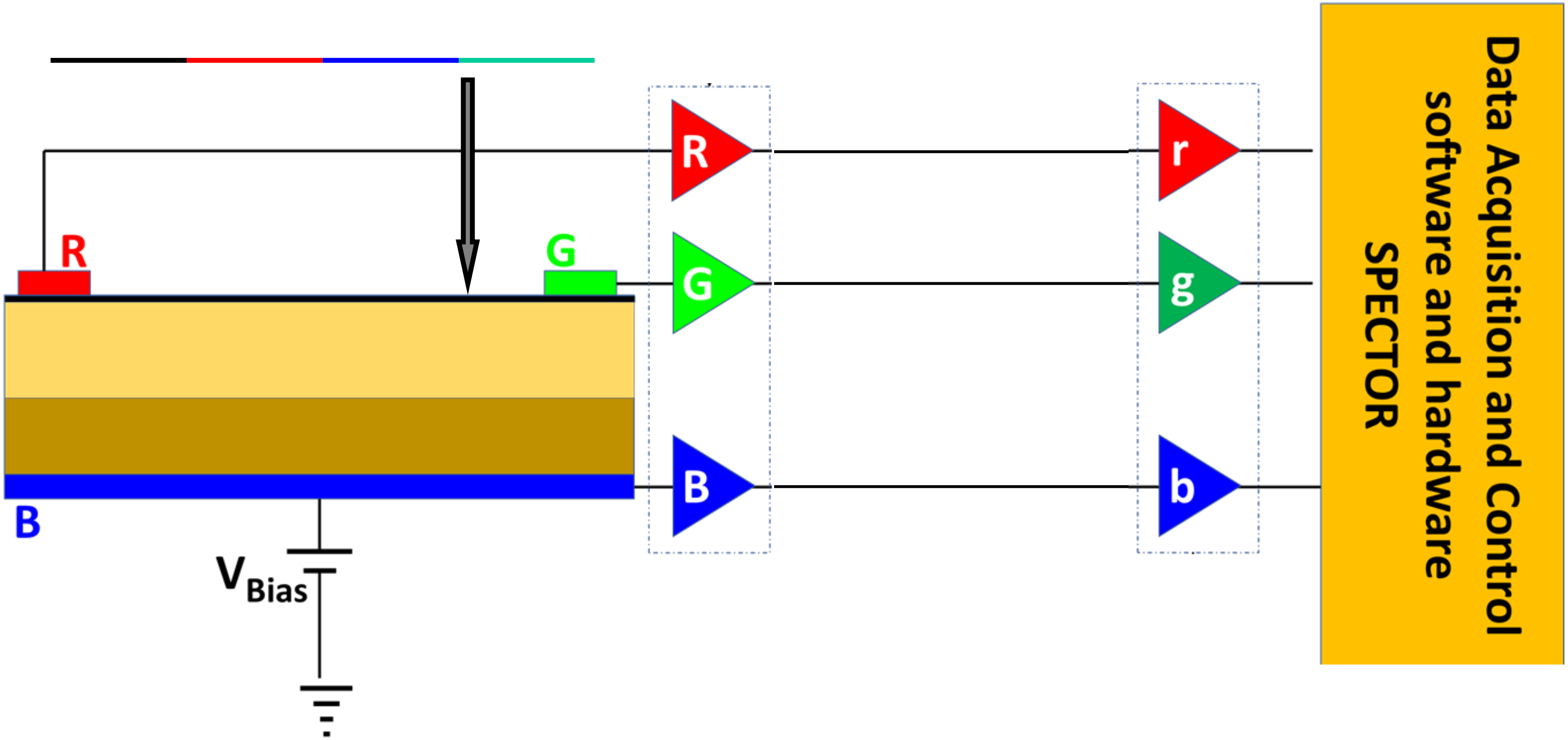
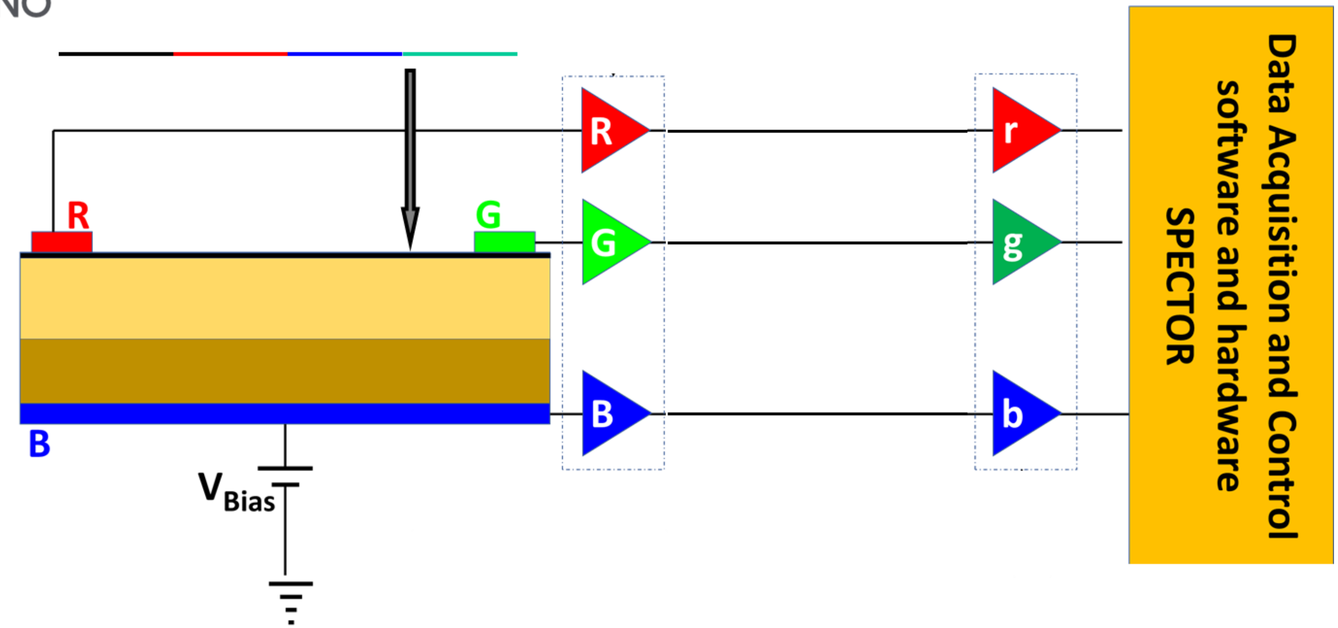
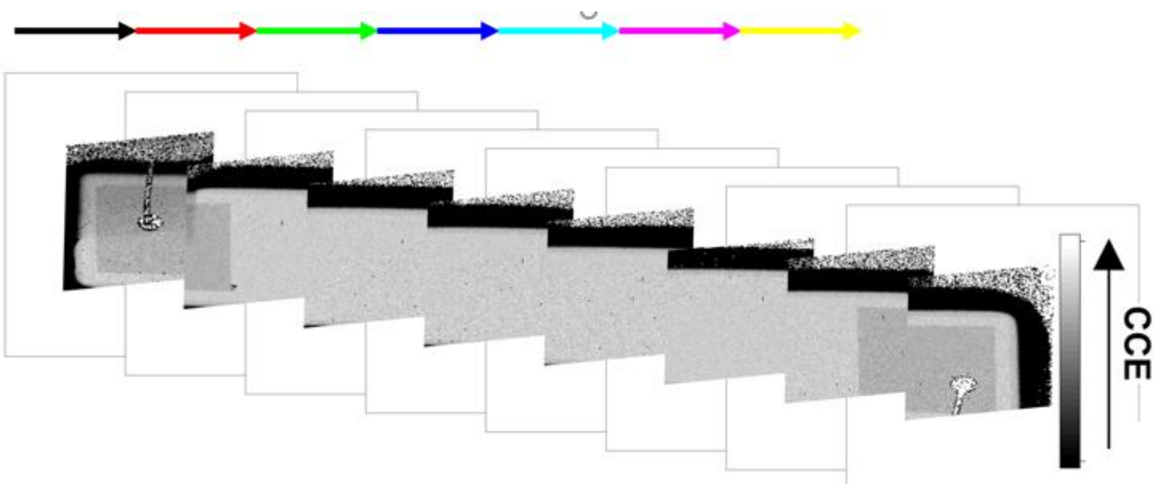
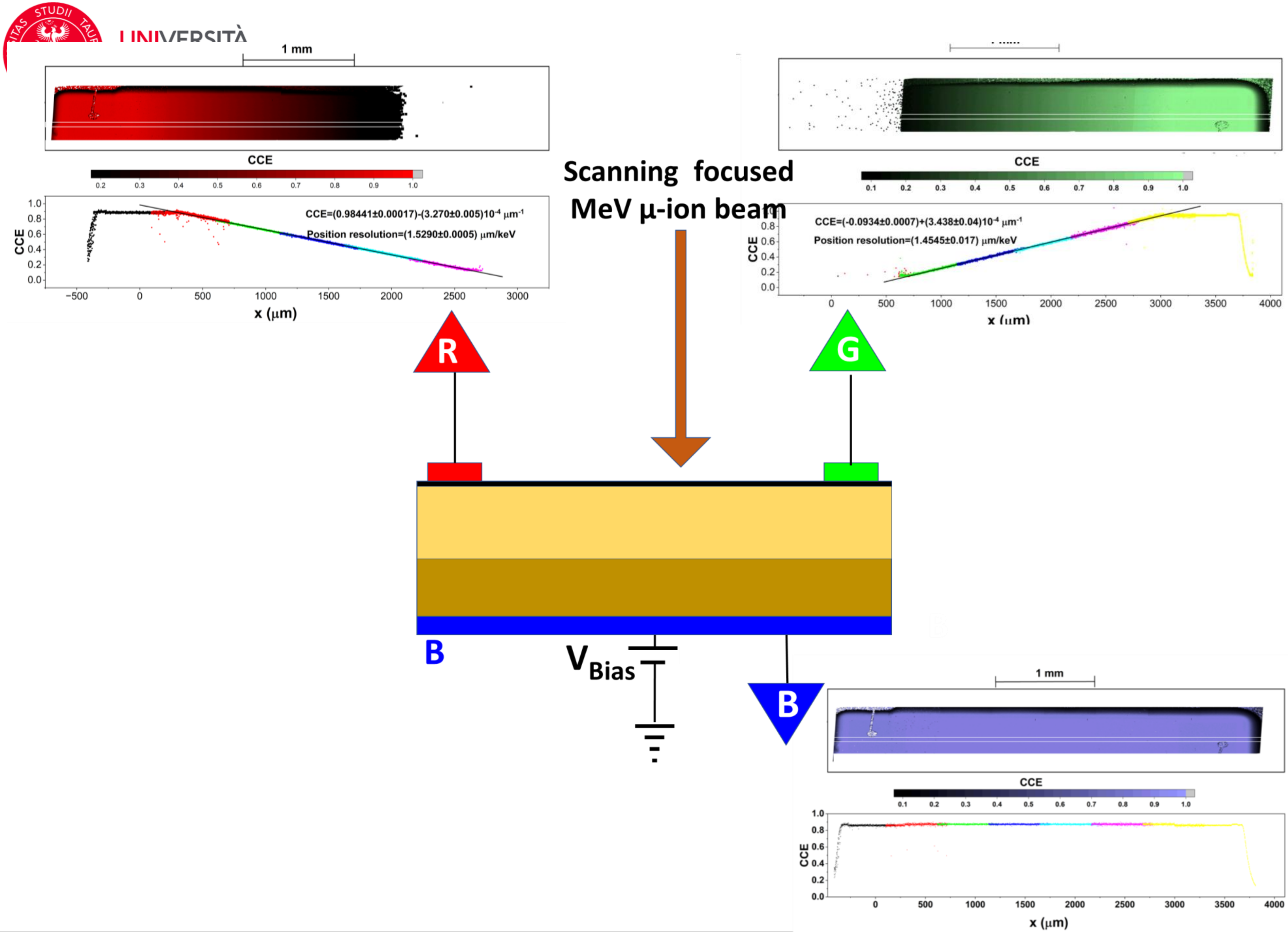




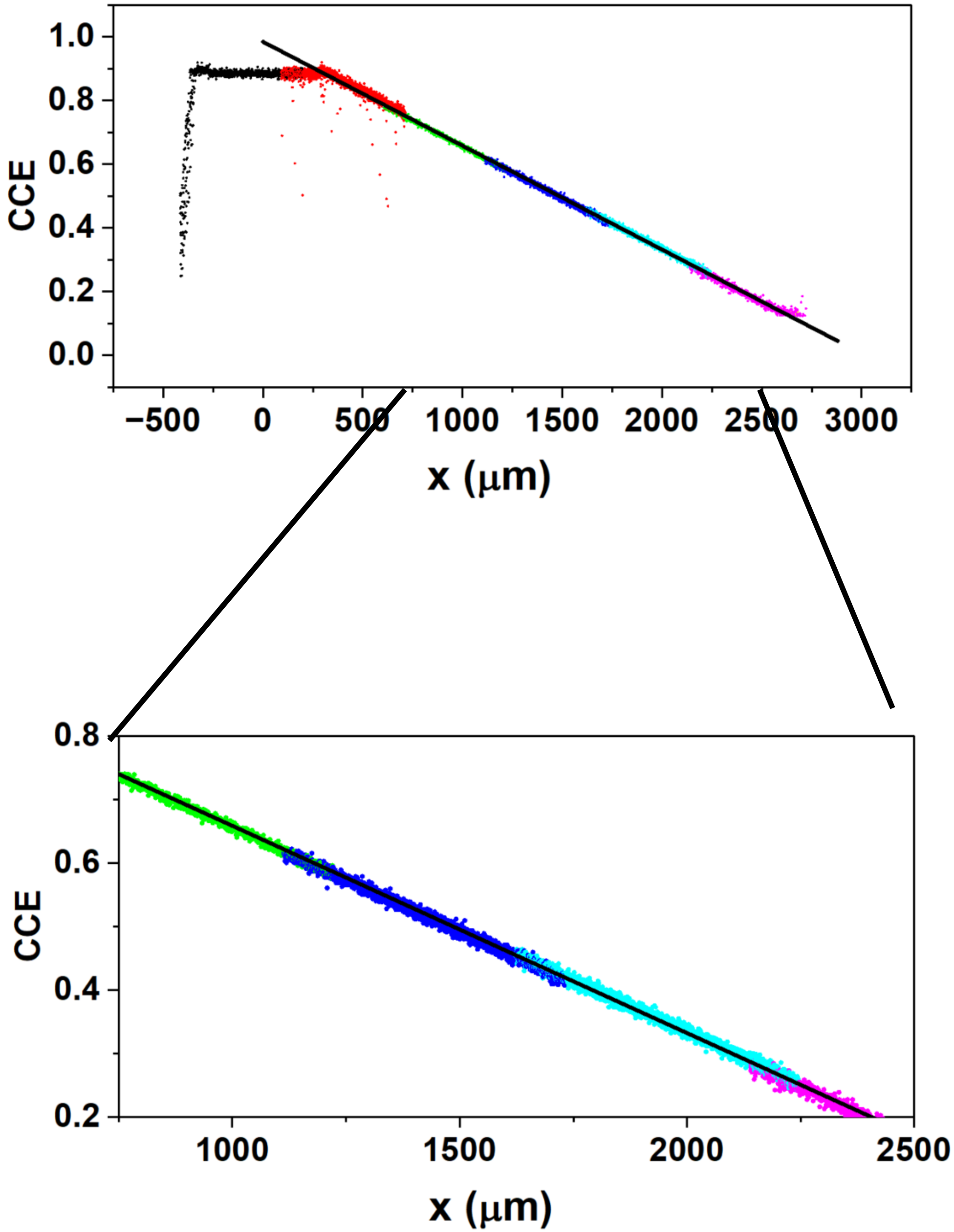


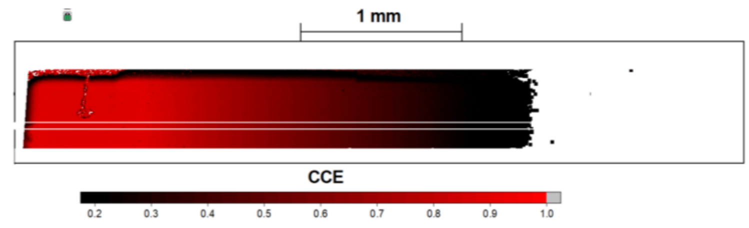
8 scanning regions (128x128 pixels) (500x500) μm^2 Shift: 500 μm

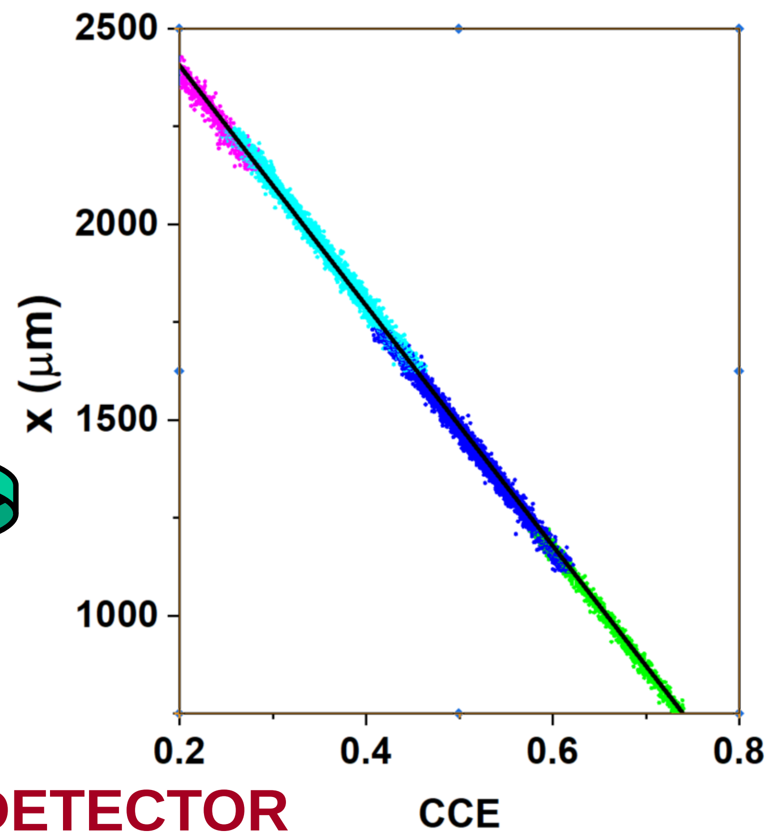


1 mm
CCE
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
CCE=(0.98441±0.00017)-(3.270±0.005)10⁻⁴ μm⁻¹
Position resolution=(1.5290±0.0005) μm/keV
x (μm)
Scanning focused
MeV μ-ion beam
CCE
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
CCE=(-0.0934±0.0007)+(3.438±0.04)10⁻⁴ μm⁻¹
Position resolution=(1.4545±0.017) μm/keV
R
G
B
V
Bias
B
1 mm
CCE
x (μm)

Red Electrode

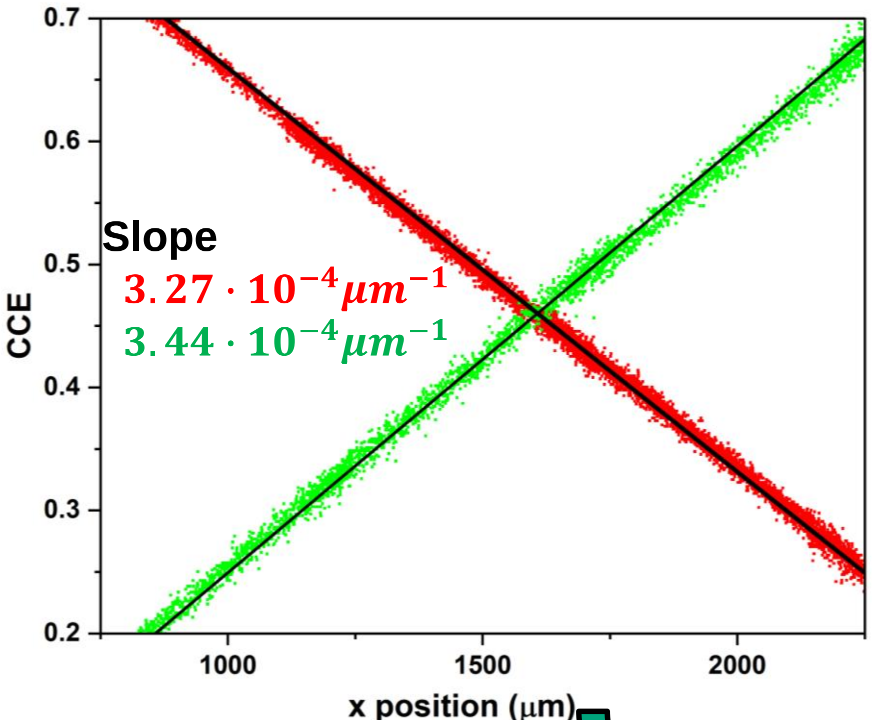




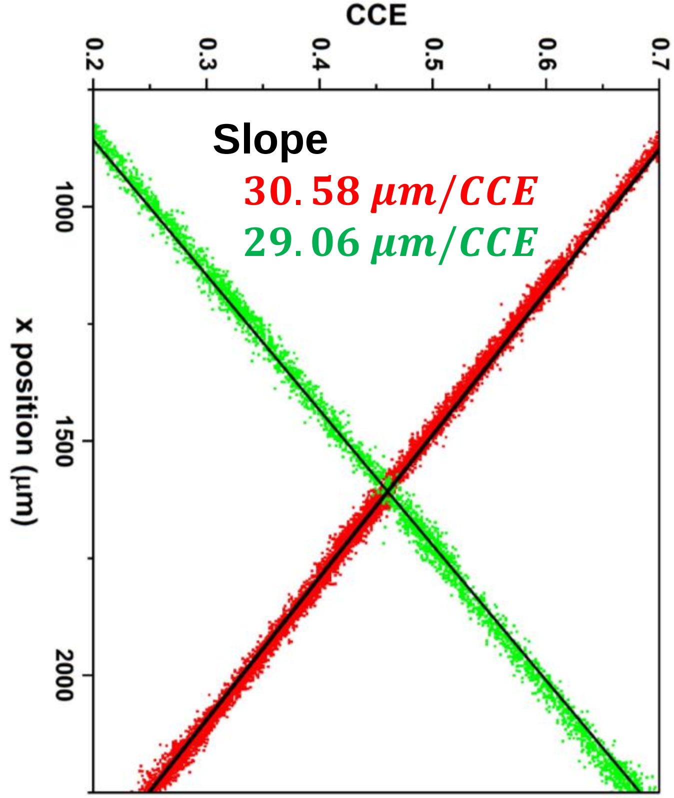


LINEAR POSITION SENSITIVE DETECTOR

CCE(x)



x(CCE)



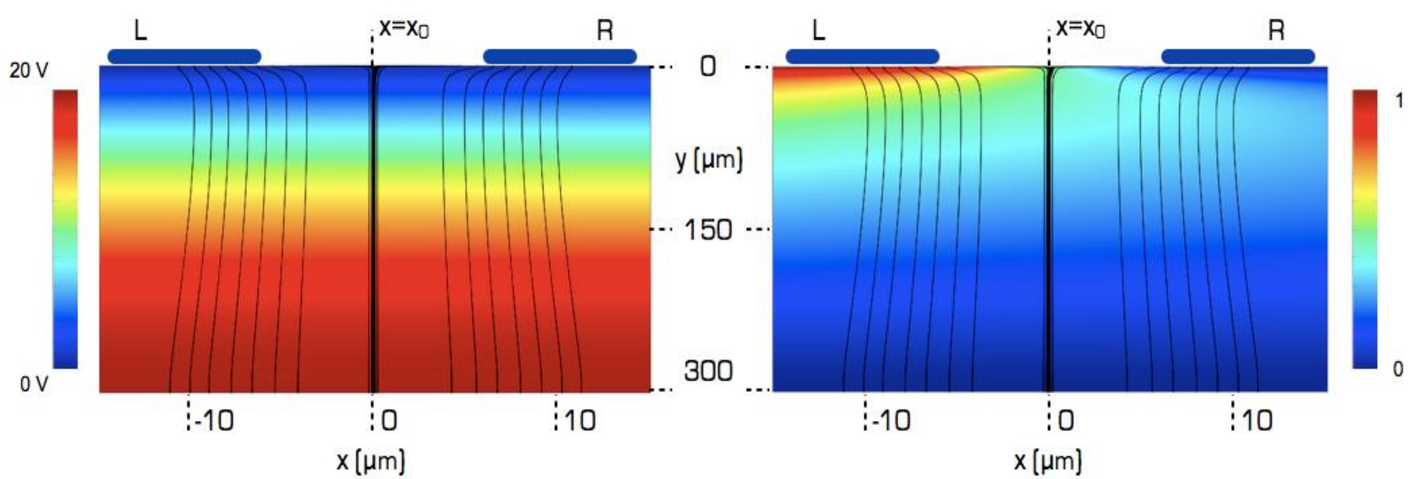
LINEAR POSITION SENSITIVE DETECTOR

Spectral resolution: 34 keV → 0.017 CCE → 49 μm

The induced charge Q at the sensing electrode is given by the difference in the weighting potentials between any two positions (r_A and r_B) of the moving charge

$$Q = q \cdot \left(\left.\frac{\partial \psi}{\partial V}\right|_{\substack{\text{final}\\\text{position}}} - \left.\frac{\partial \psi}{\partial V}\right|_{\substack{\text{initial}\\\text{position}}} \right)$$

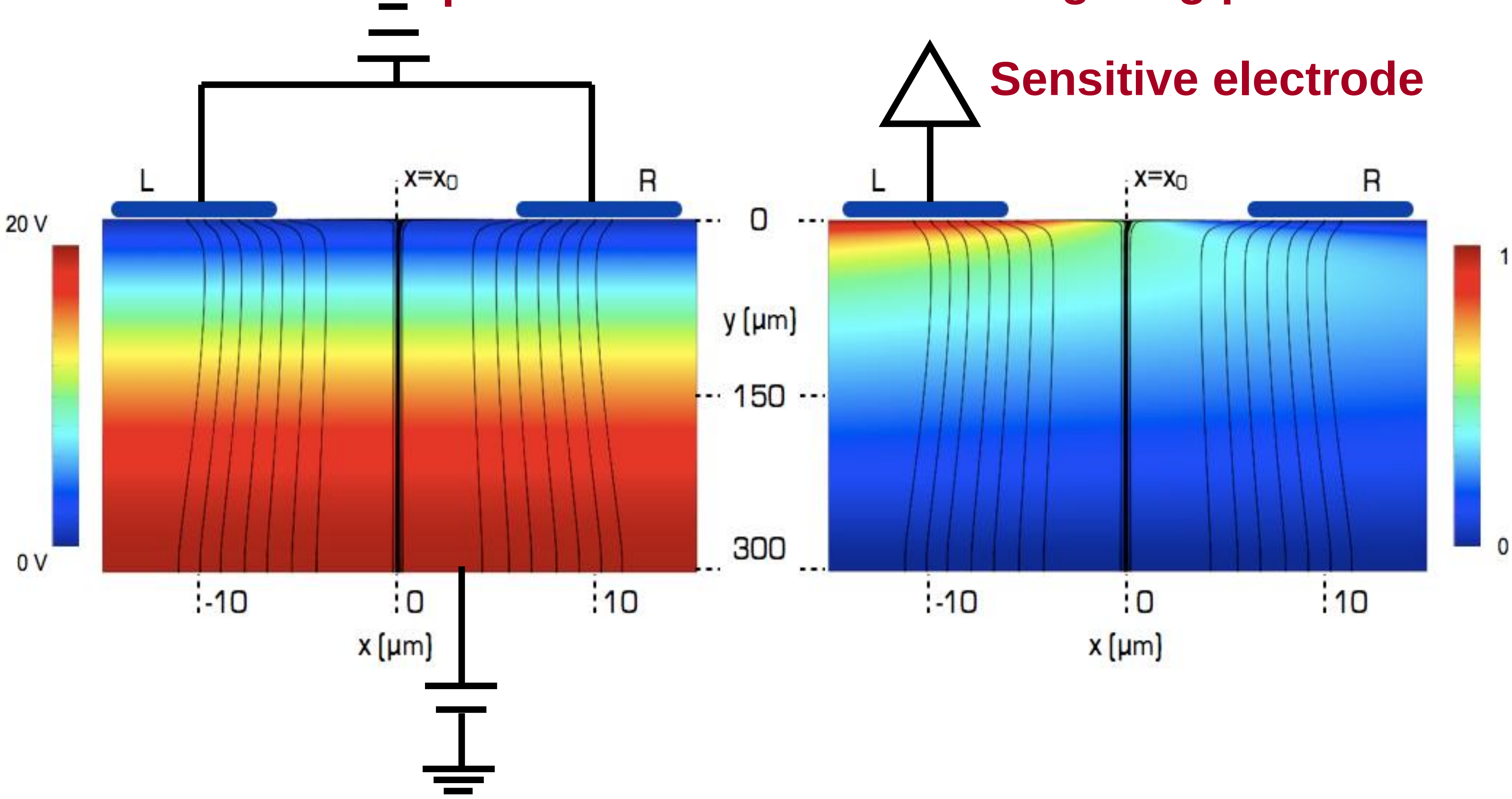
CHARGE SHARING IN MULTIELECTRODE DEVICES



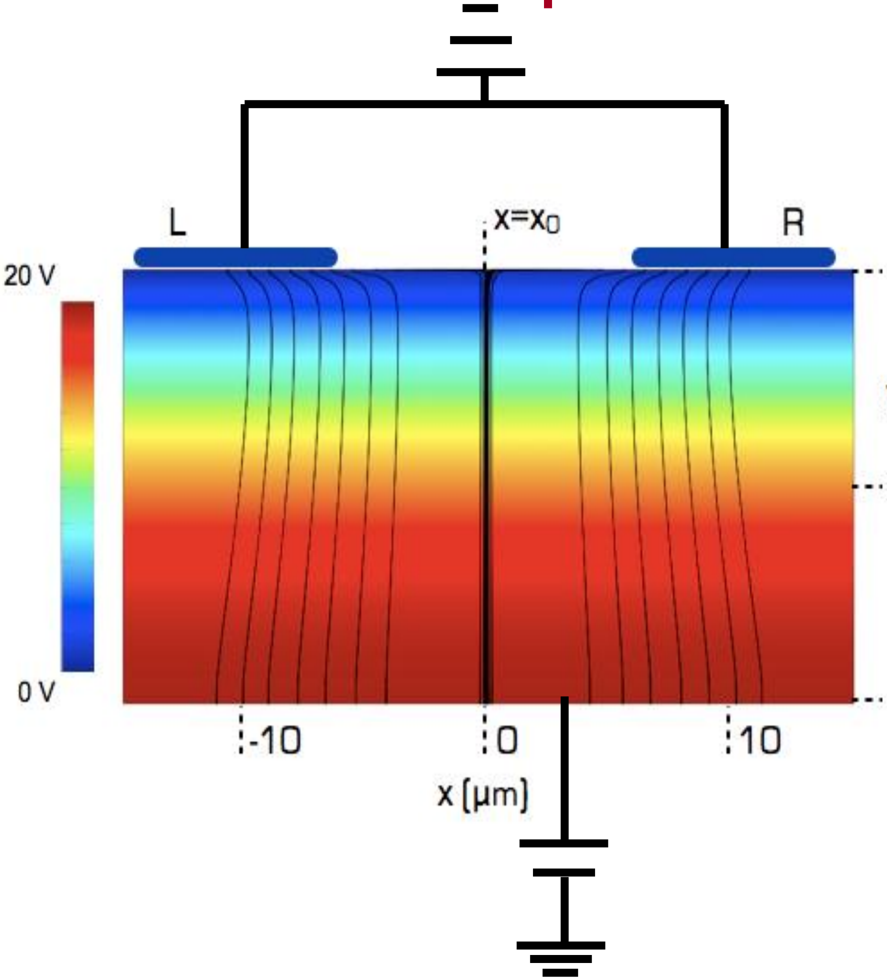
Actual potential

Weighting potential

Sensitive electrode

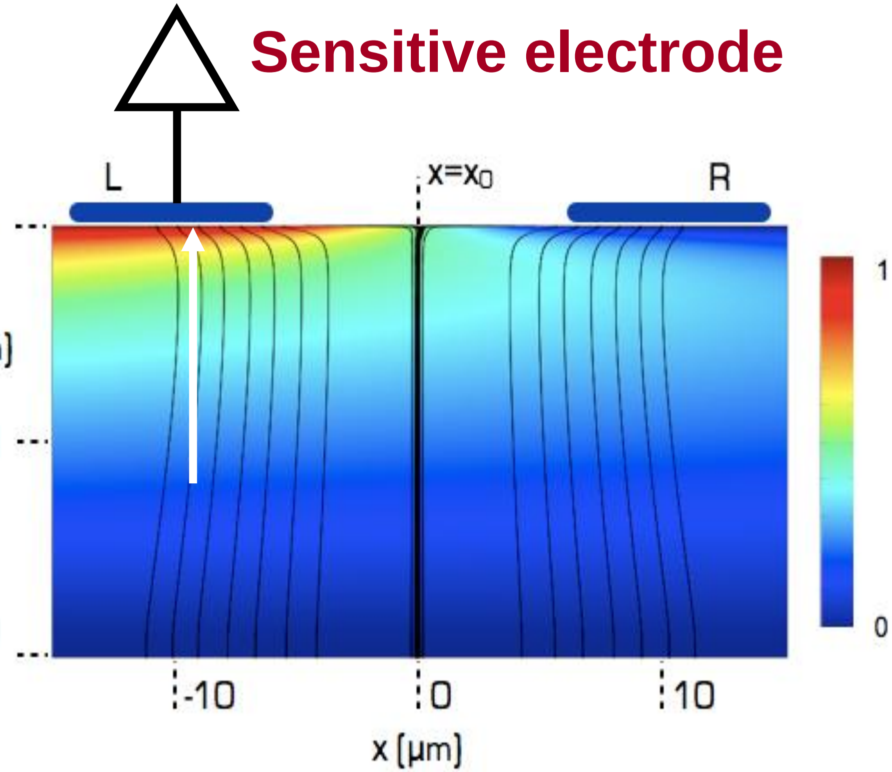


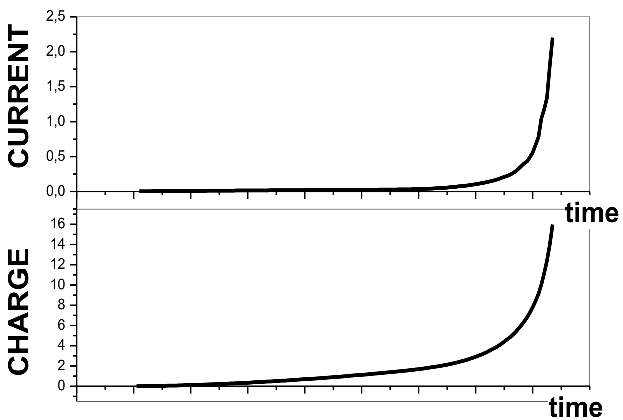
Actual potential



Weighting potential

Sensitive electrode

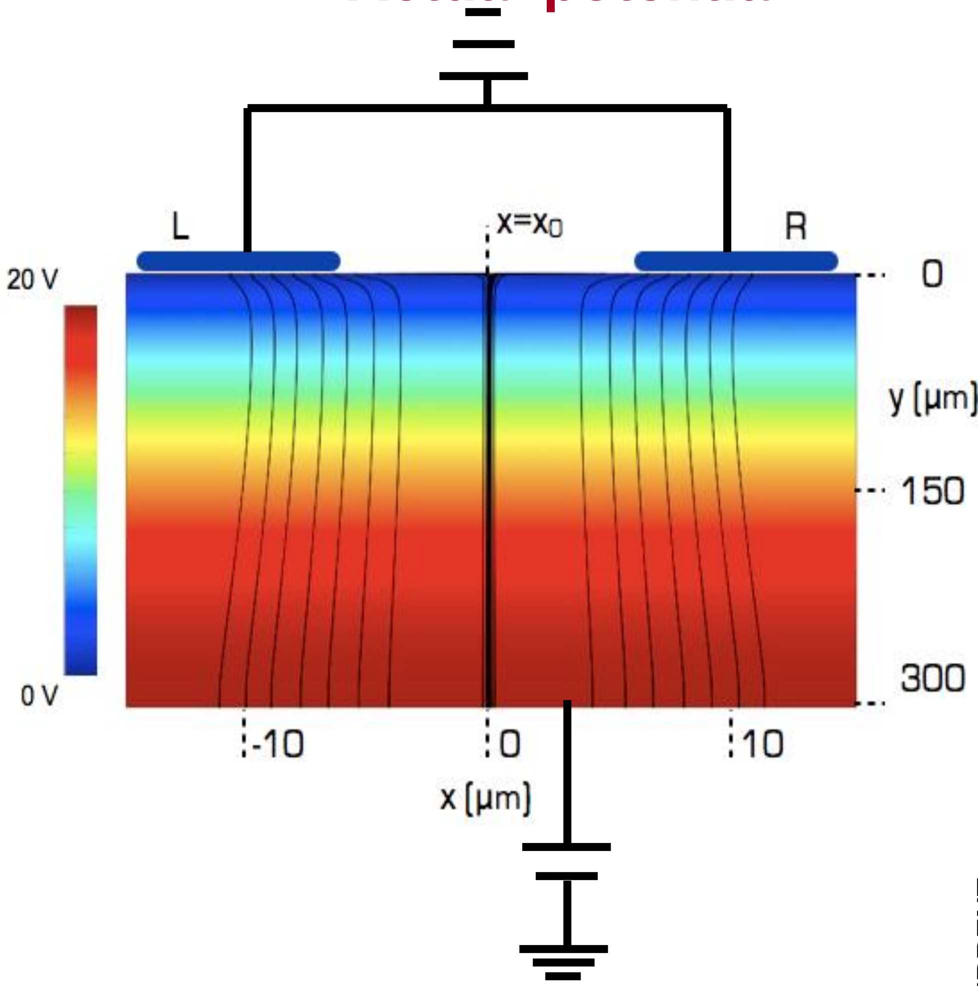




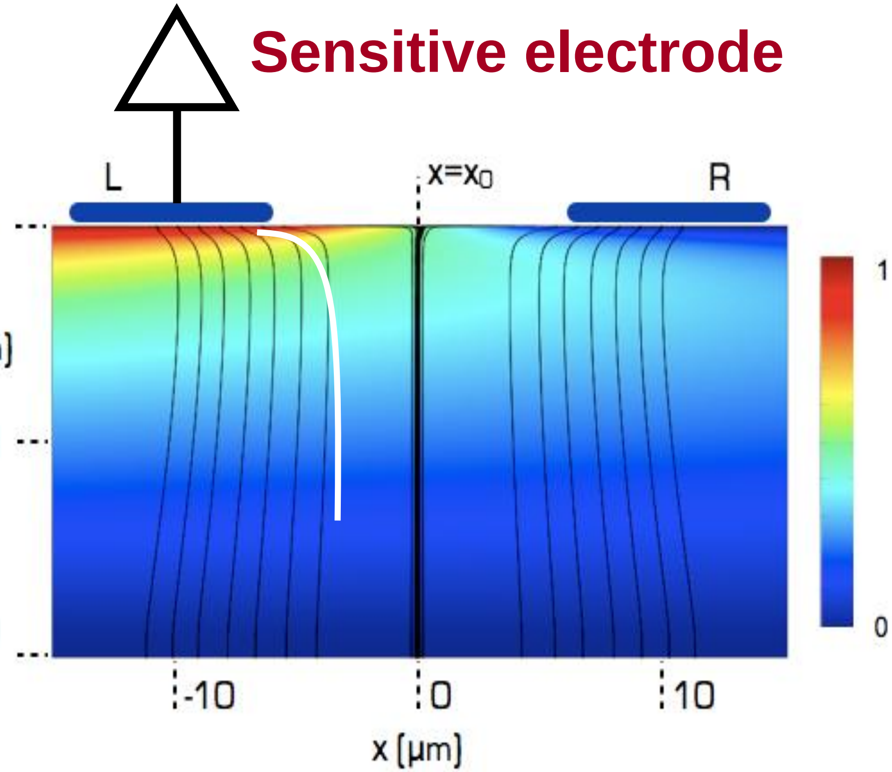
$$Q = q \cdot \left(\left.\frac{\partial \psi}{\partial V}\right|_{\text{final position}} - \left.\frac{\partial \psi}{\partial V}\right|_{\text{initial position}} \right)$$

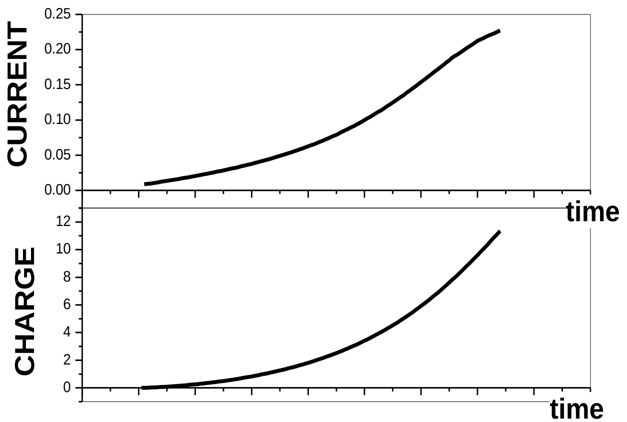
Actual potential

Weighting potential



Sensitive electrode

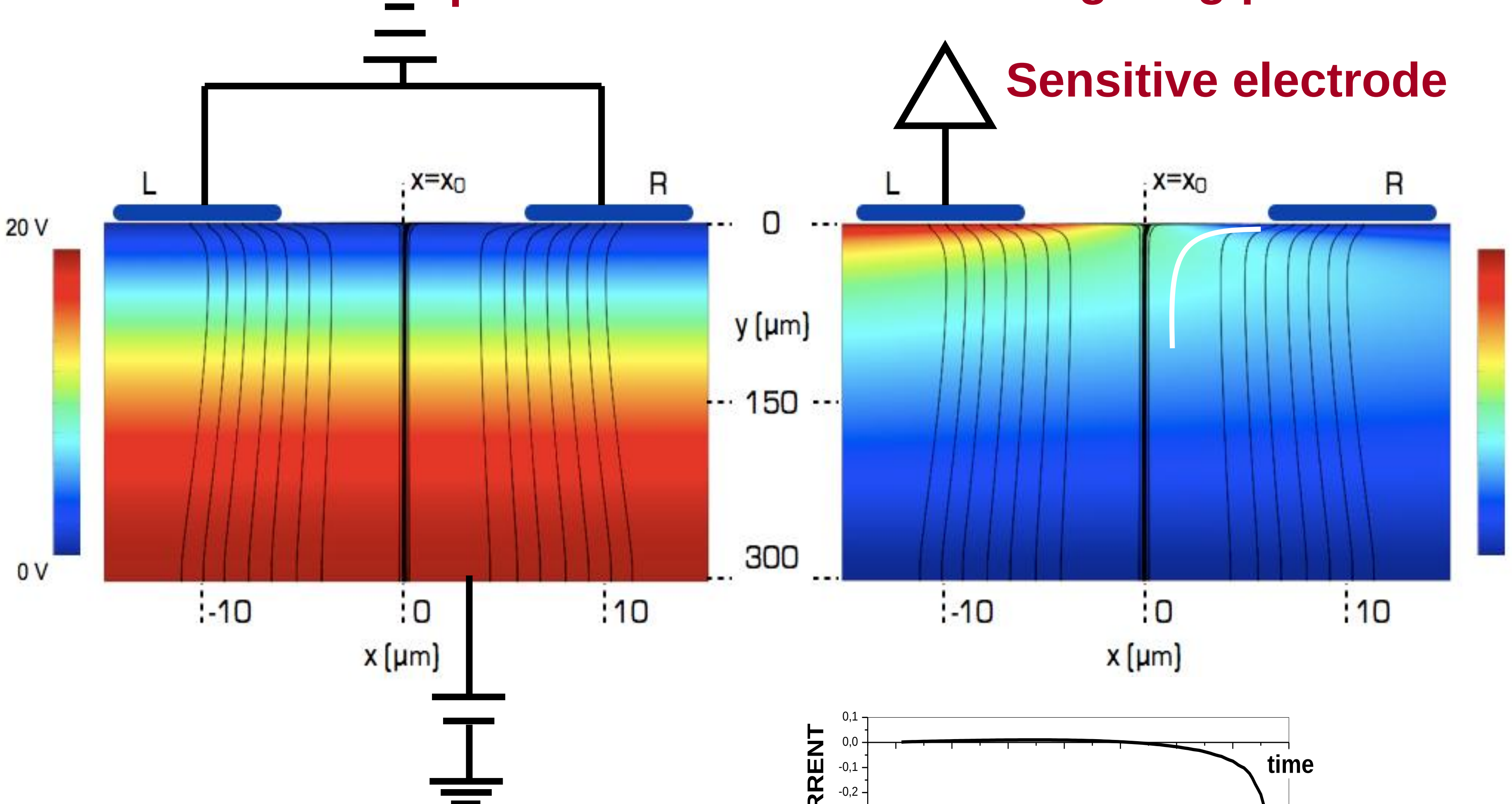


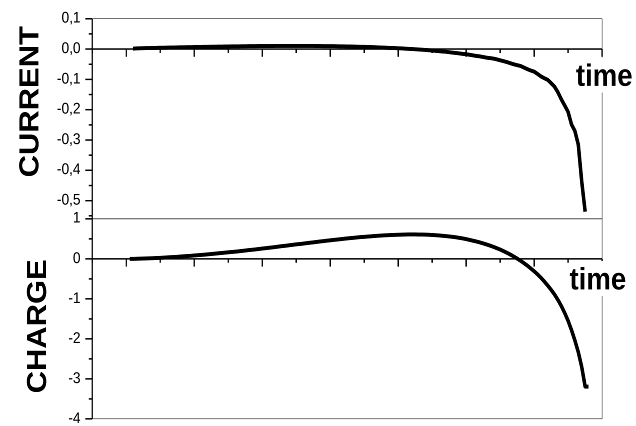


$$Q = q \cdot \left(\left.\frac{\partial \psi}{\partial V}\right|_{\substack{\text{final}\\ \text{position}}} - \left.\frac{\partial \psi}{\partial V}\right|_{\substack{\text{initial}\\ \text{position}}} \right)$$

Actual potential

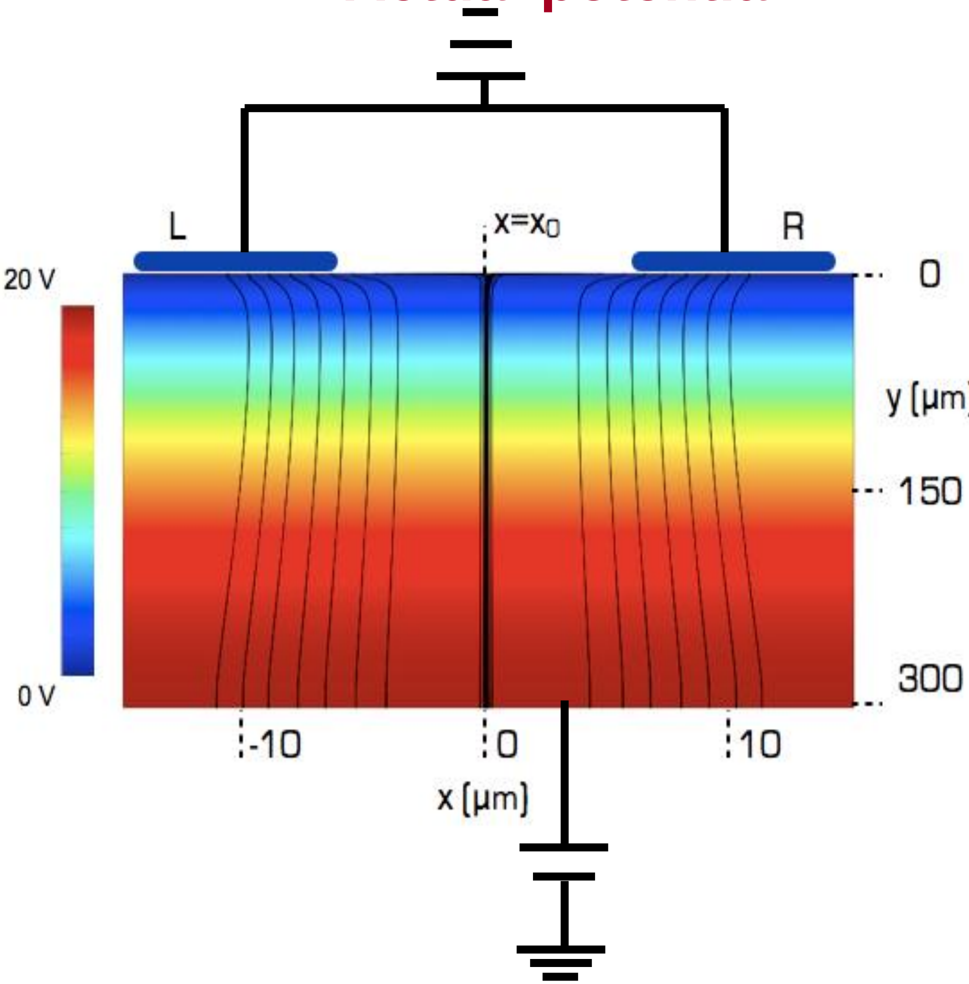
Weighting potential





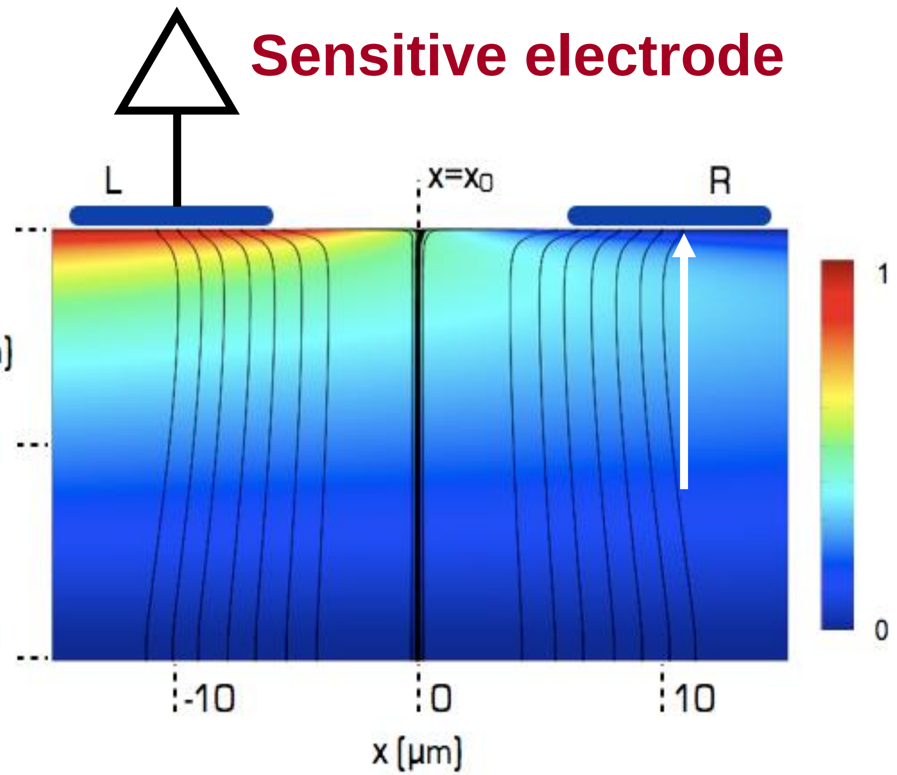
$$Q = q \cdot \left(\left.\frac{\partial \psi}{\partial V}\right|_{\substack{\text{final}\\ \text{position}}} - \left.\frac{\partial \psi}{\partial V}\right|_{\substack{\text{initial}\\ \text{position}}} \right)$$

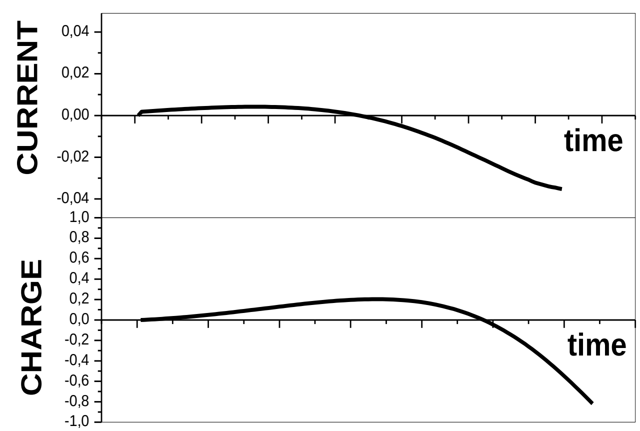
Actual potential



Weighting potential

Sensitive electrode





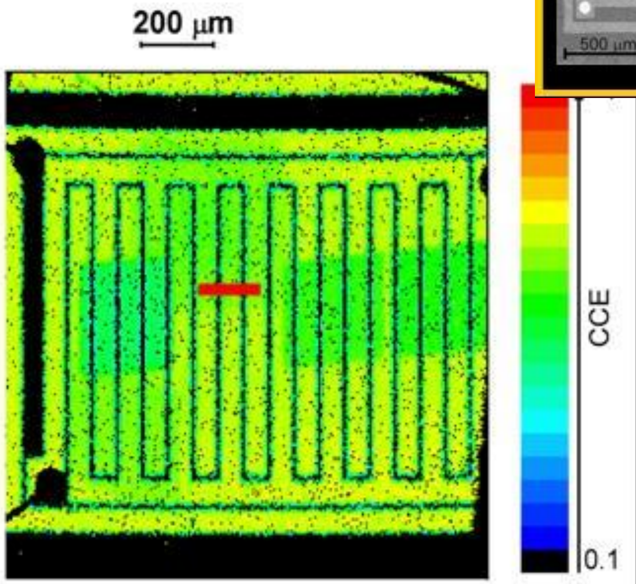
$$Q = q \cdot \left(\frac{\partial \psi}{\partial V}\bigg|_{\substack{\text{final}\\\text{position}}} - \frac{\partial \psi}{\partial V}\bigg|_{\substack{\text{initial}\\\text{position}}} \right)$$

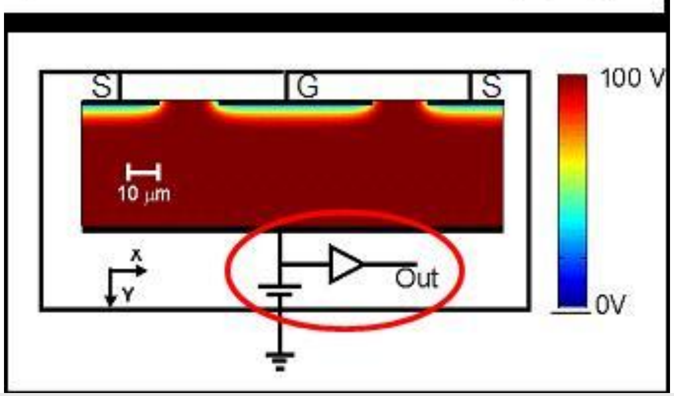
SEM image

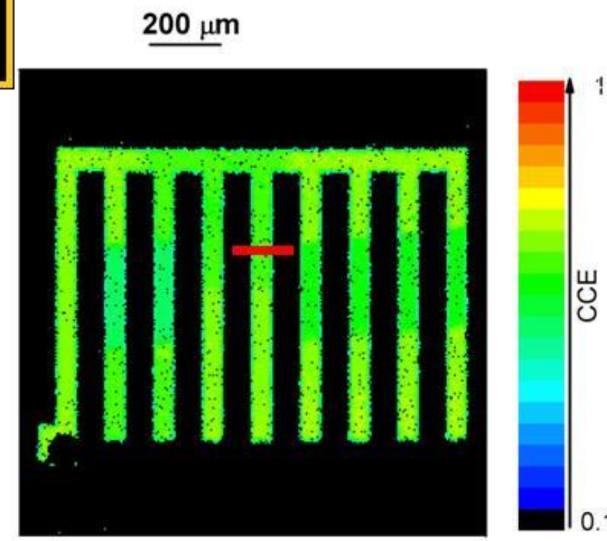
4H-SiC Schottky diode

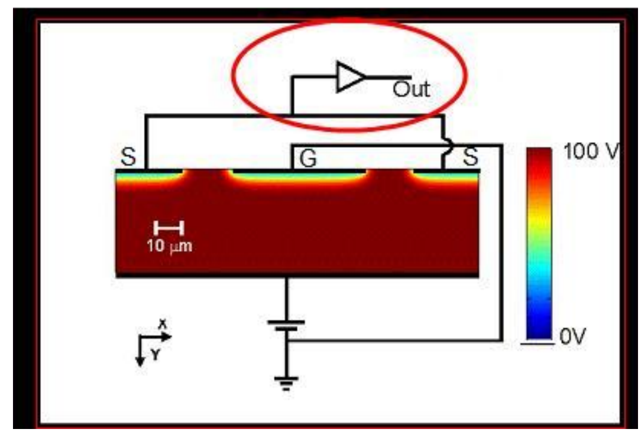
Inter-digitated frontal electrodes

- Finger width: 50 µm
- Finger length: 700 µm
- Finger-finger gap = 20 µm;
- Finger-guard ring = 70 µm.









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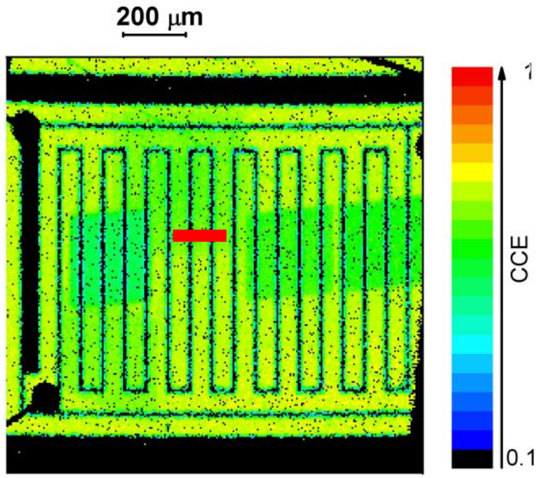
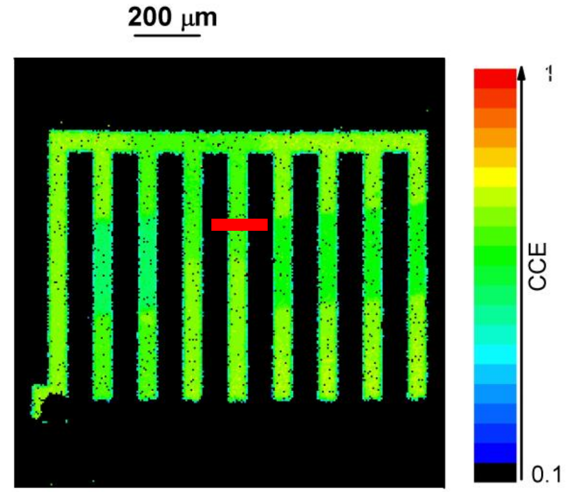
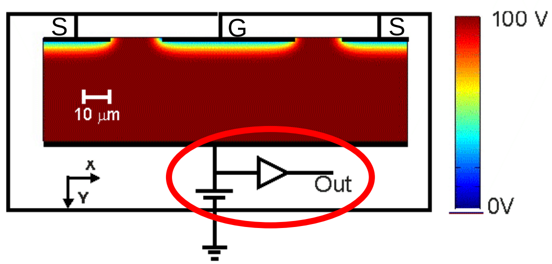
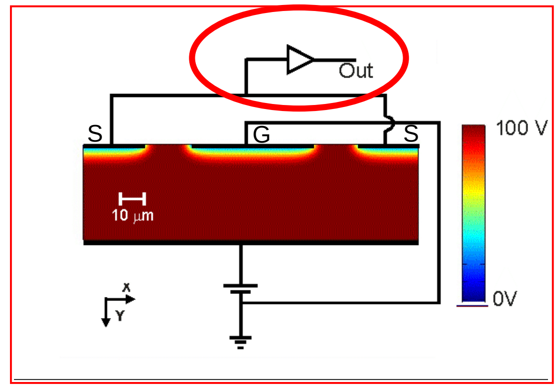
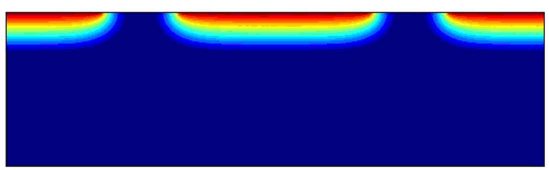
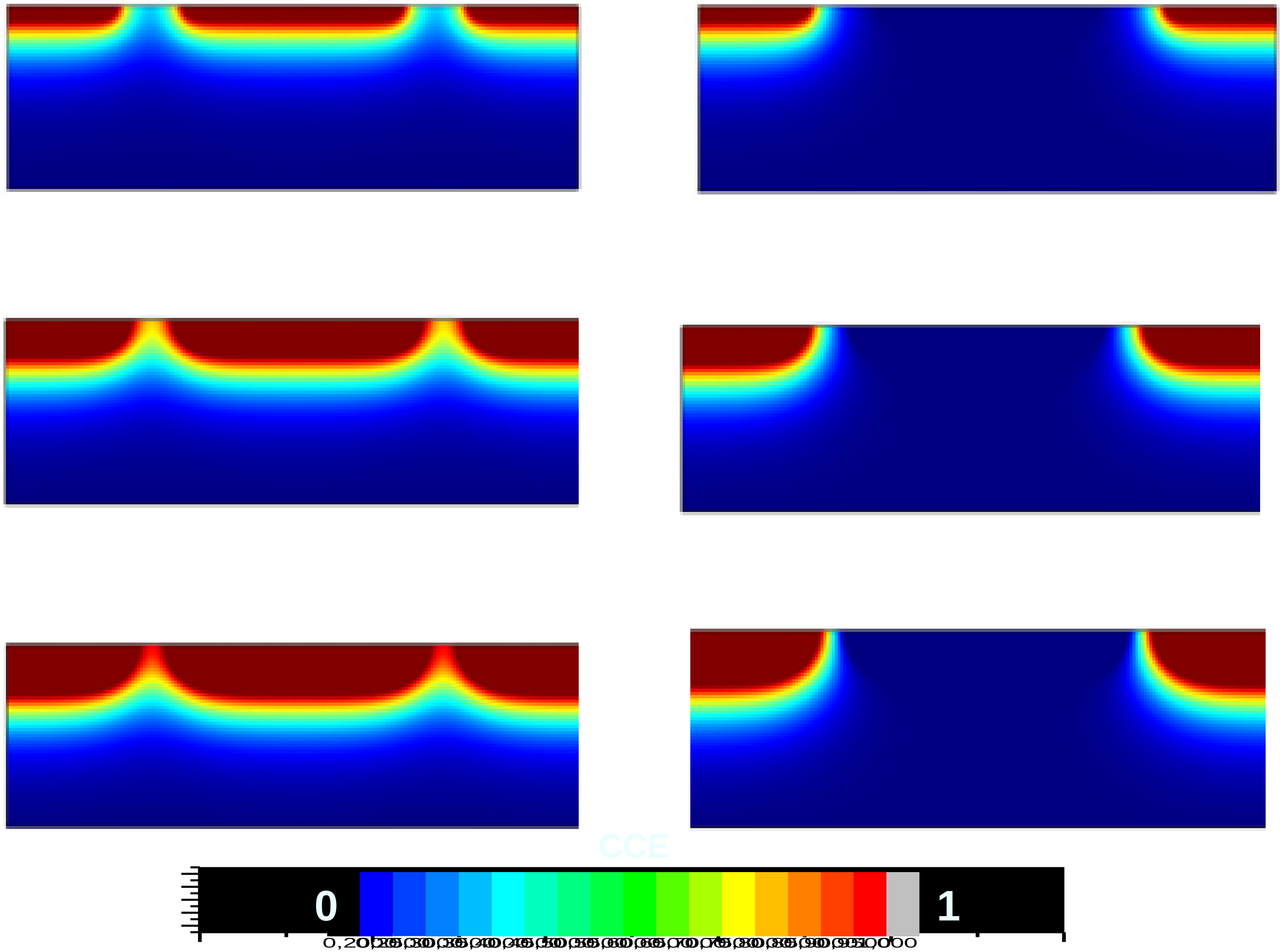

200 μm
CCE
1
0.1


200 μm
CCE
1
0.1

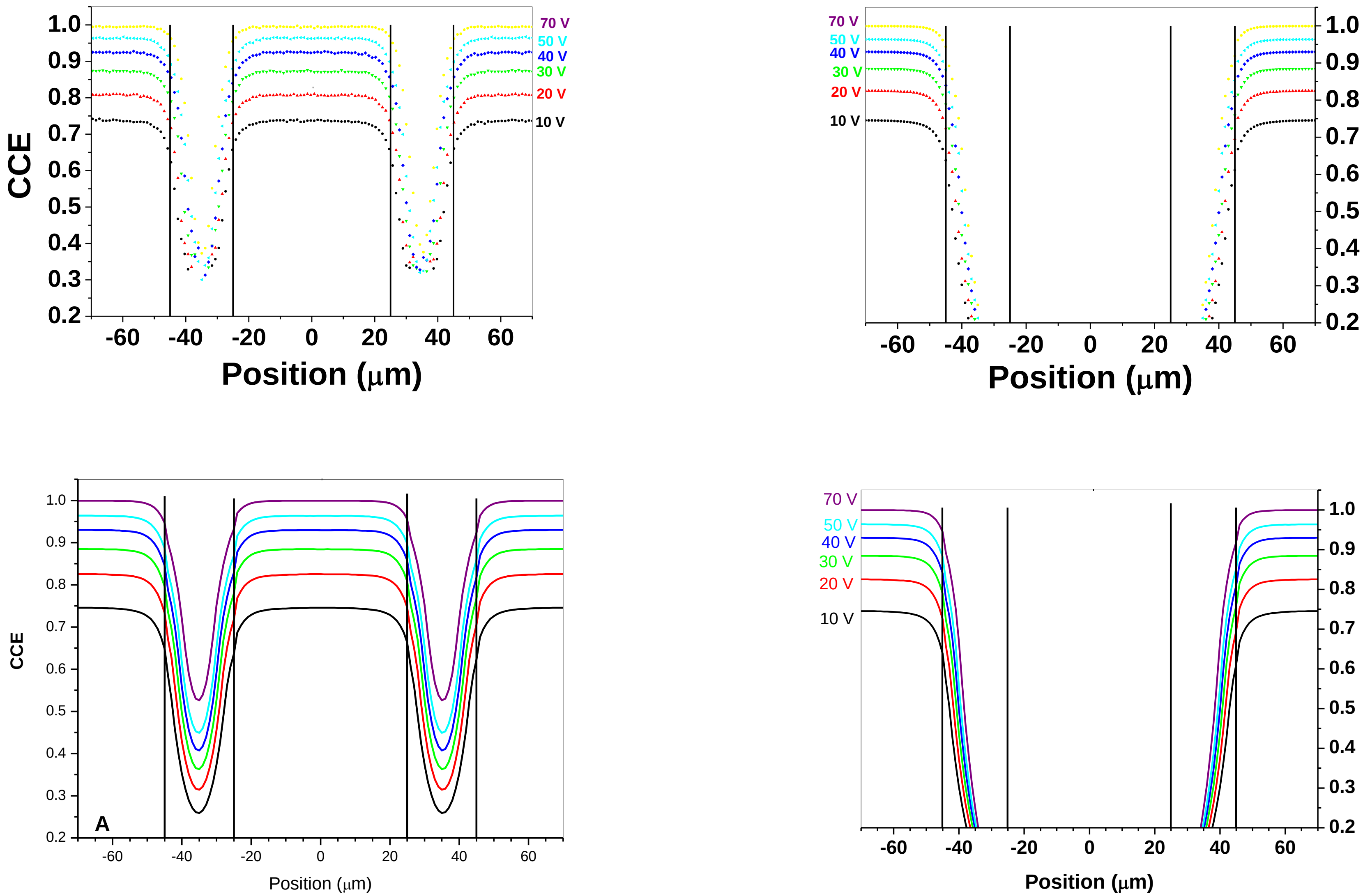

S
G
S
10 μm
Out
x
Y
100 V
0V


Out
S
G
S
10 μm
x
Y
100 V
0V

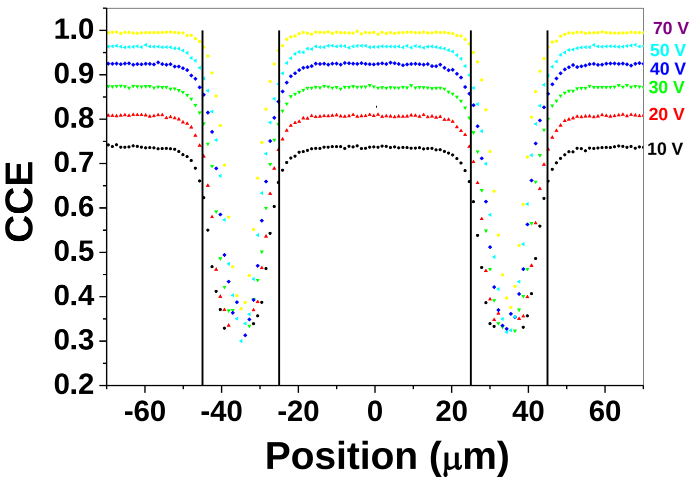


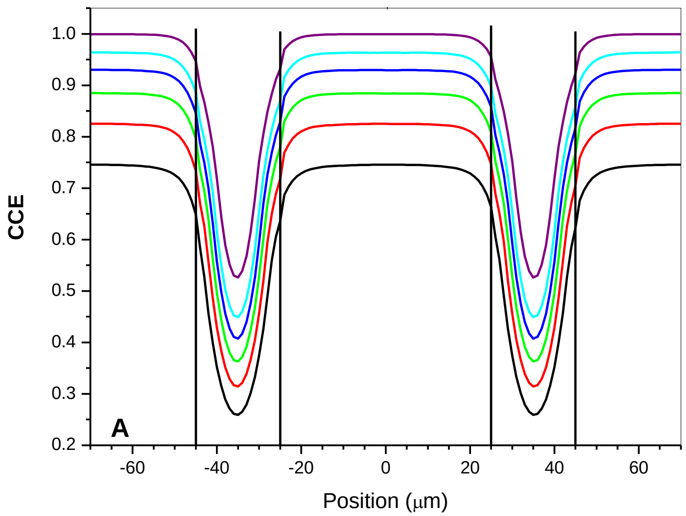

CCE
0
1

0.9 MeV protons

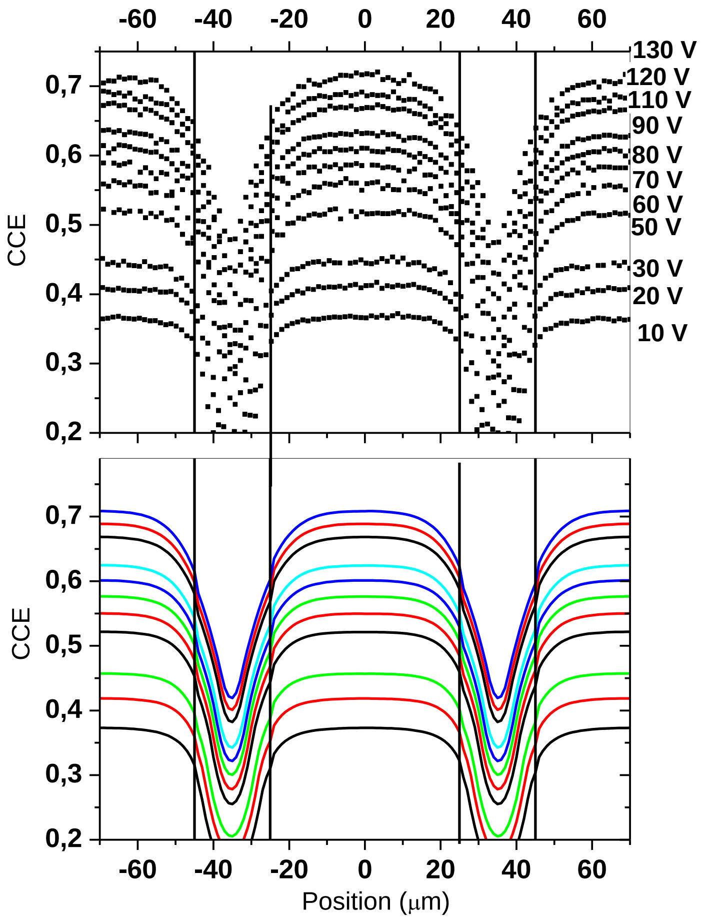


0.9 MeV protons



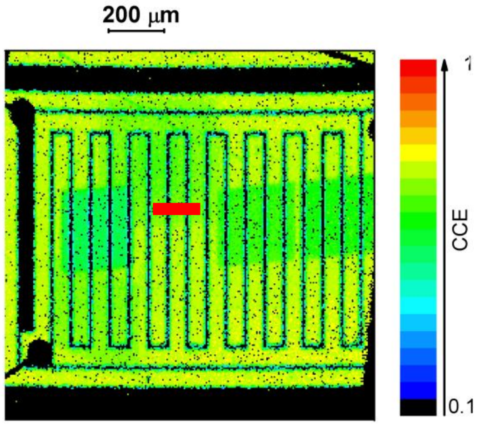


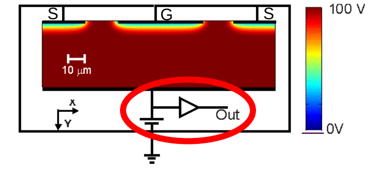
1.5 MeV protons

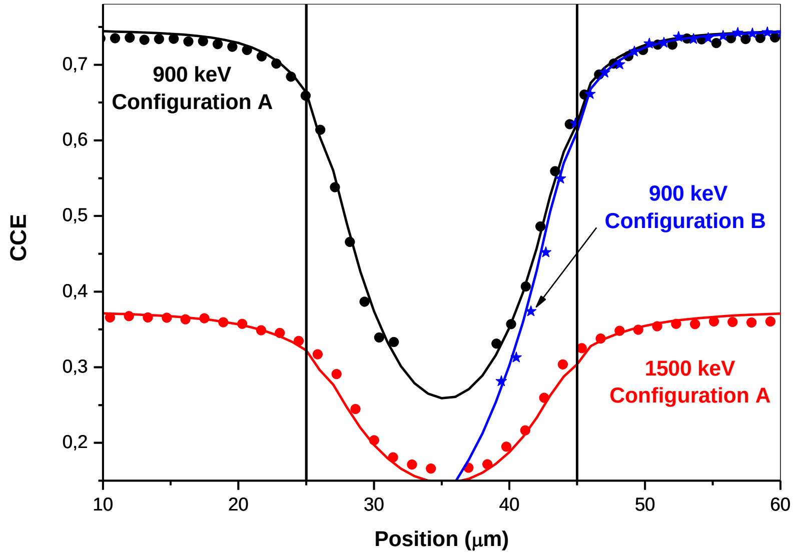


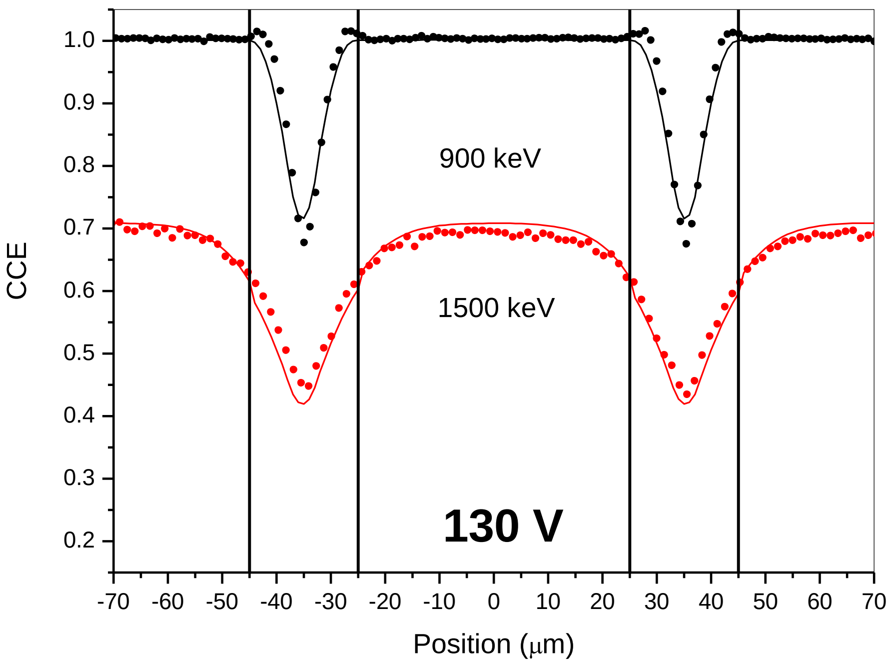
CCE profile details

hole diffusion length = 8.7 μm.
hole lifetime = τp = 250 ns



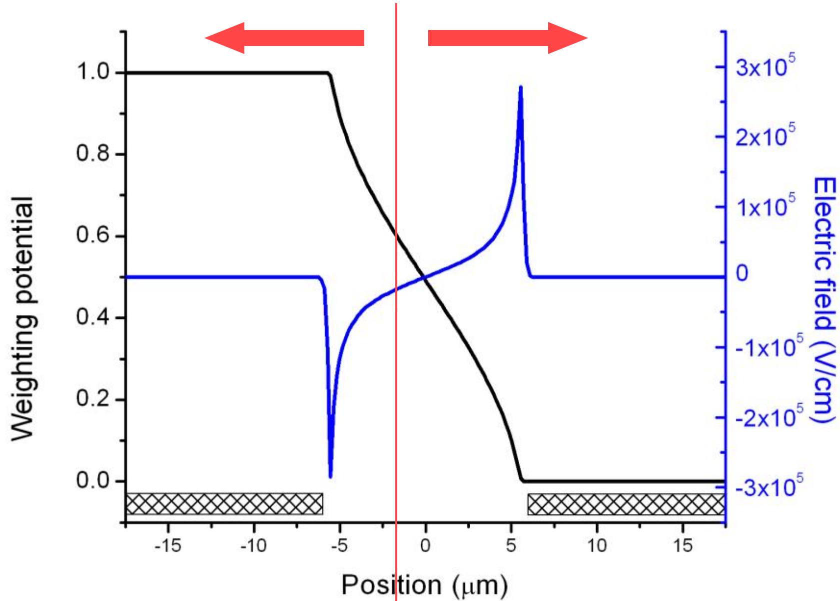




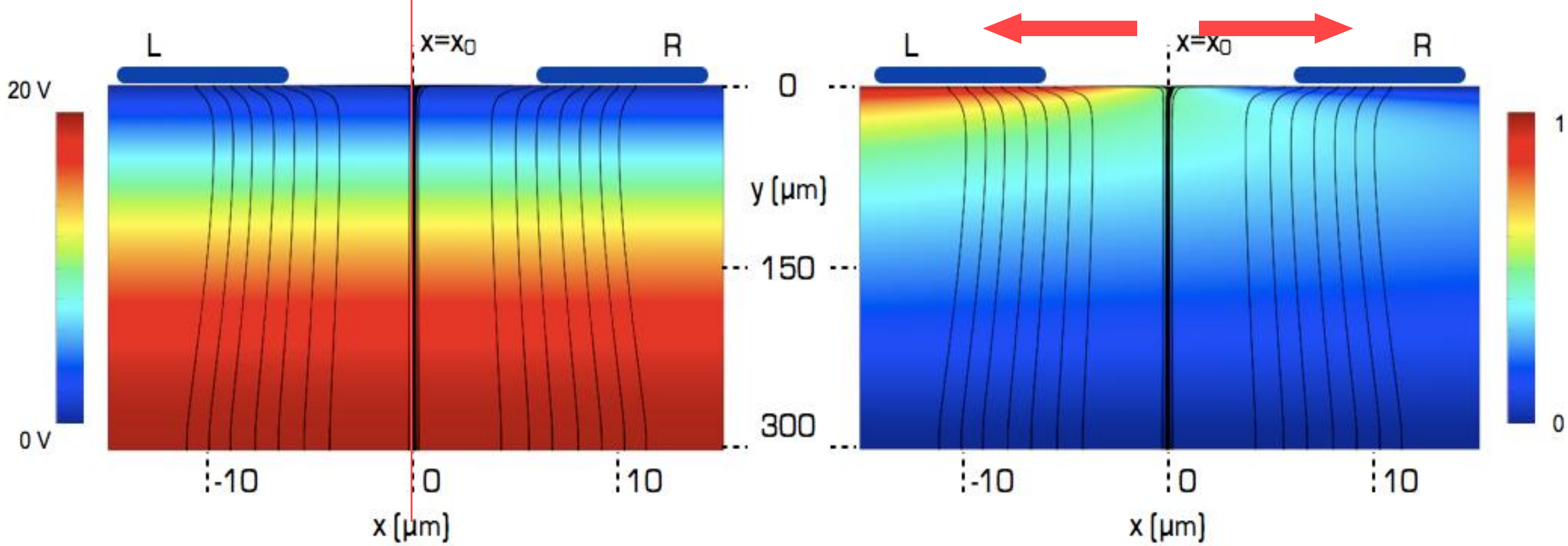


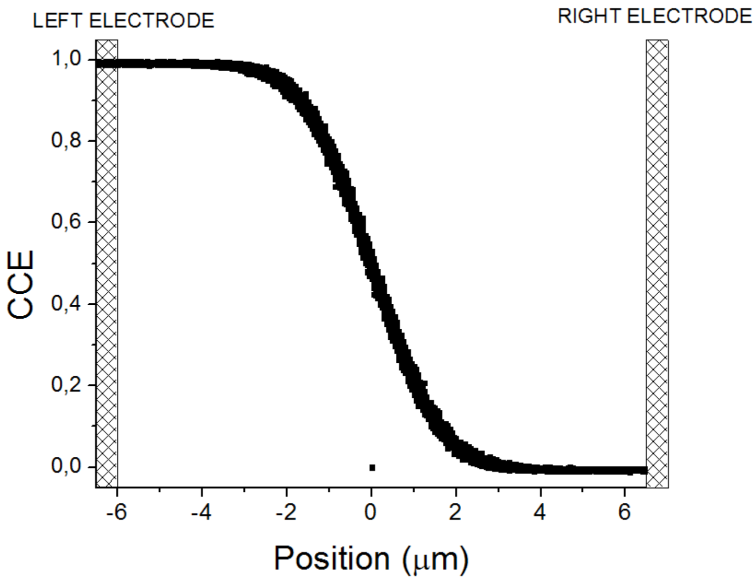
The electrode edges are highlighted by the vertical black line.

Horizontal electric field

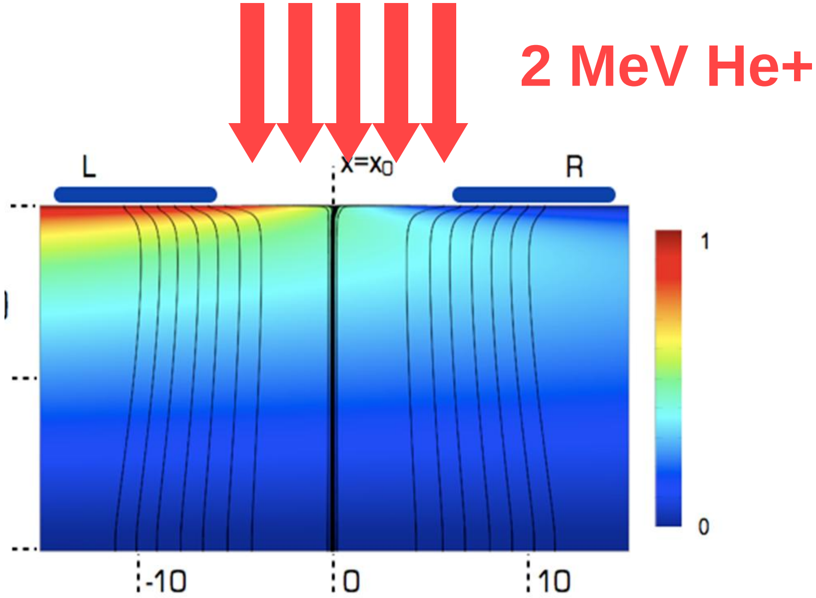


$$Q = q \cdot \left(\left.\frac{\partial \psi}{\partial V}\right|_{\substack{\text{final}\\\text{position}}} - \left.\frac{\partial \psi}{\partial V}\right|_{\substack{\text{initial}\\\text{position}}} \right)$$

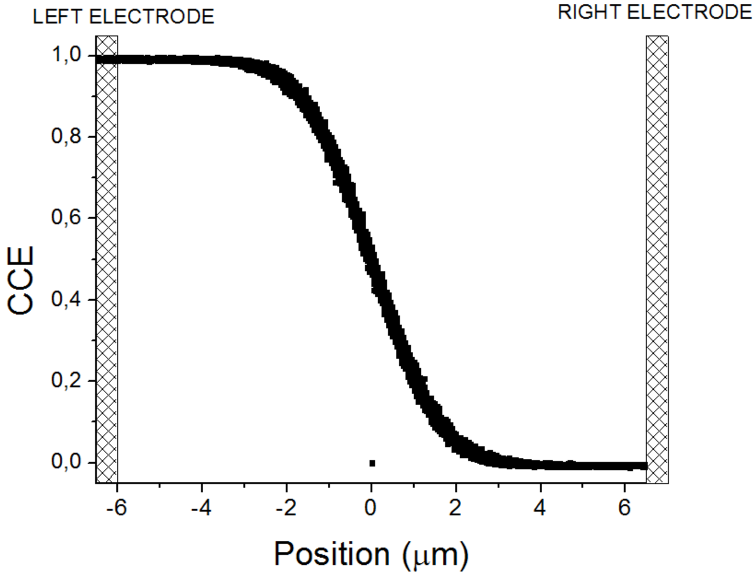


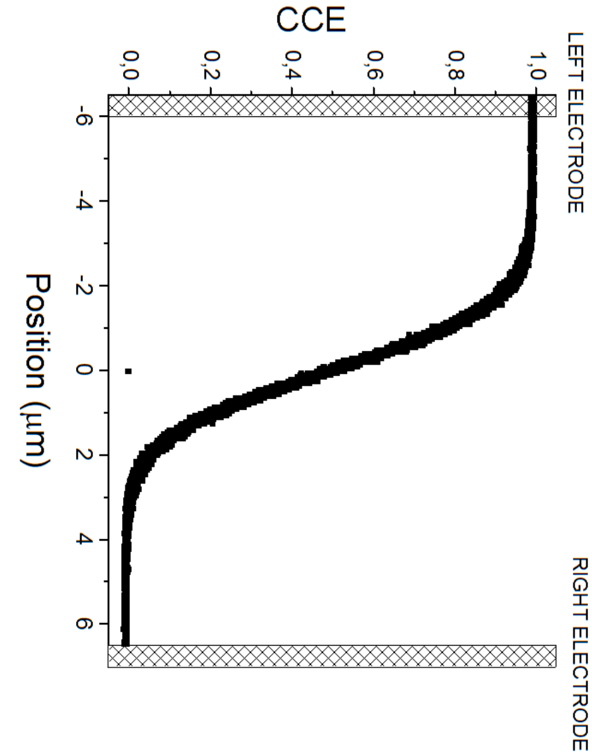


LEFT ELECTRODE
RIGHT ELECTRODE
1,0
0,8
0,6
0,4
0,2
0,0
CCE
-6
-4
-2
0
2
4
6
Position (μm)

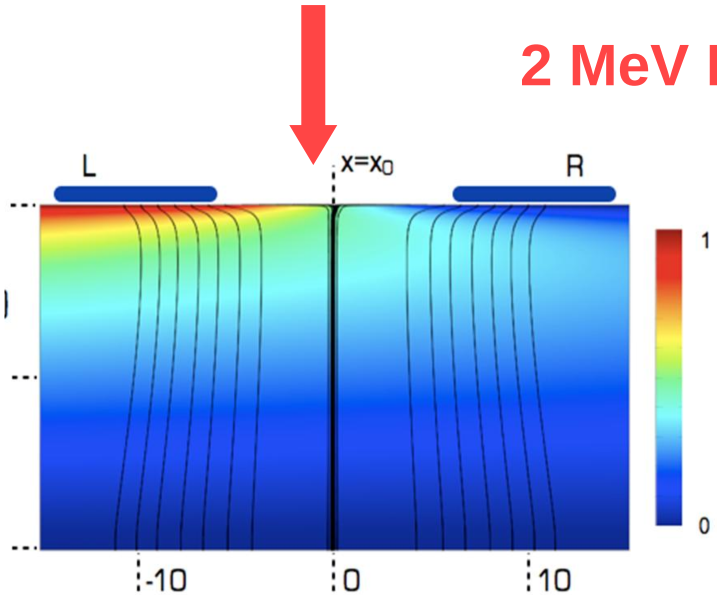


2 MeV He+
L
R
x=x0
1
0
-10
0
10


LEFT ELECTRODE
RIGHT ELECTRODE
CCE
1,0
0,8
0,6
0,4
0,2
0,0
-6
-4
-2
0
2
4
6
Position (μm)

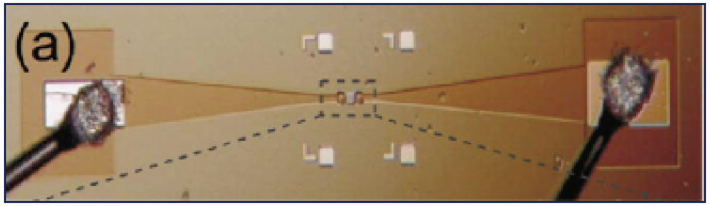

CCE
0,0
0,2
0,4
0,6
0,8
1,0
LEFT ELECTRODE
RIGHT ELECTRODE
Position (μm)
-6
-4
-2
0
2
4
6

2 MeV He+


L
R
x=x0
1
0
-10
0
10

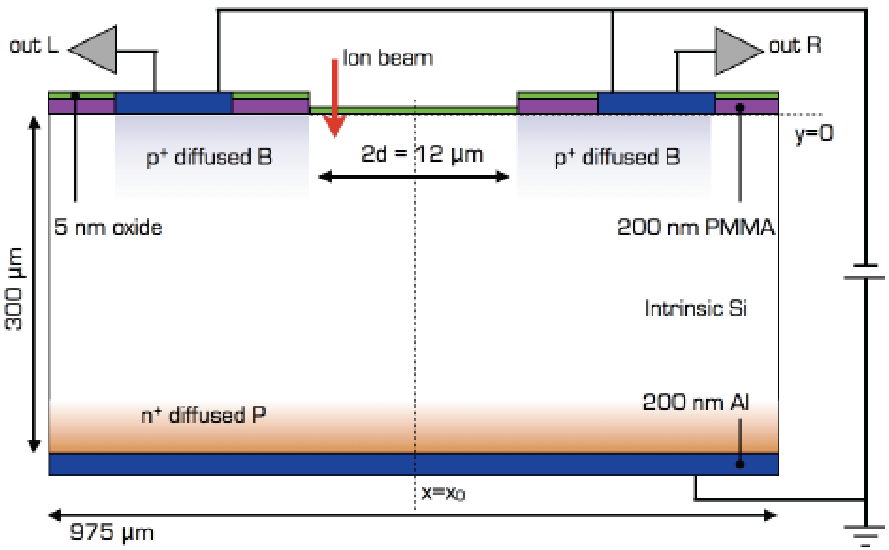
Position sensitivity - proof of concept: three-electrodes test device

L.M. Jong et al., Nuclear Instr. Meth. B 269 (2011) 2336

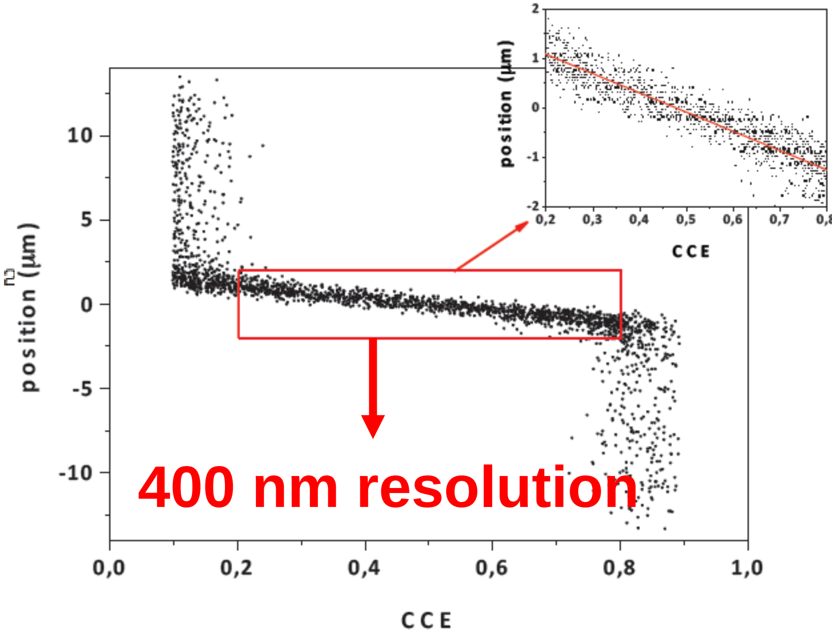


Top view

2 MeV He beam @ NEC 5U Pelletron, Melbourne
1 μm spot size



Cross sectional scheme



A SUB-MICROMETER POSITION SENSITIVE DETECTOR

A multi-electrode two-dimensional position-sensitive diamond detector

Ditalia Tchernij et al. Applied Physics Letters 2024, 124(22), 223502

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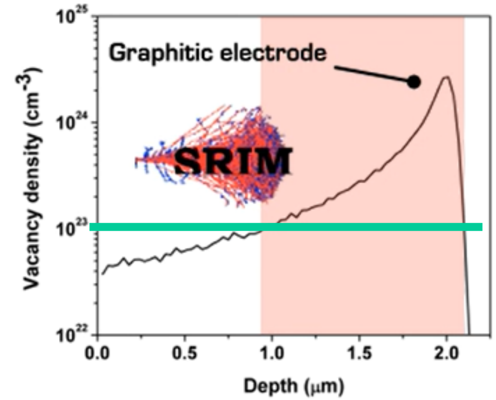
Graphite-diamond-graphite device fabrication

4 MeV C^{3+} ion

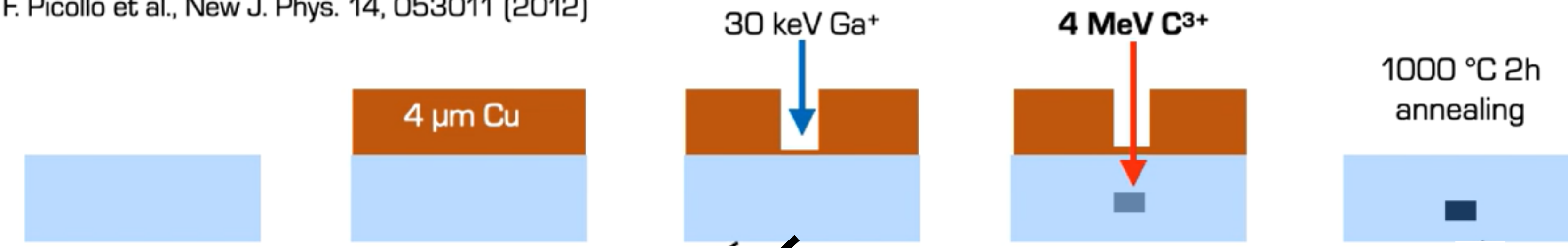


Deep Ion Beam Lithography

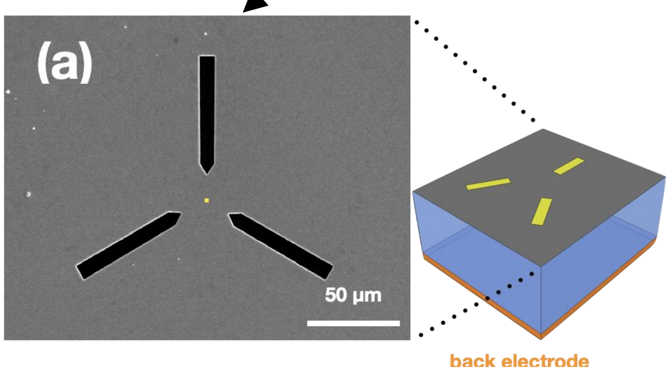
Exploitation of **MeV** ion nuclear energy loss
Cumulation of **damage** at the **end of ion range**
Amorphization of buried diamond layer

Thermal treatment: **Conductive channels** embedded in **insulating diamond**, high dielectric strenght

F. Picollo et al., New J. Phys. 14, 053011 (2012)



3×3×0.3 mm^3 synthetic "electronic grade" <100> single-crystal diamond substrate

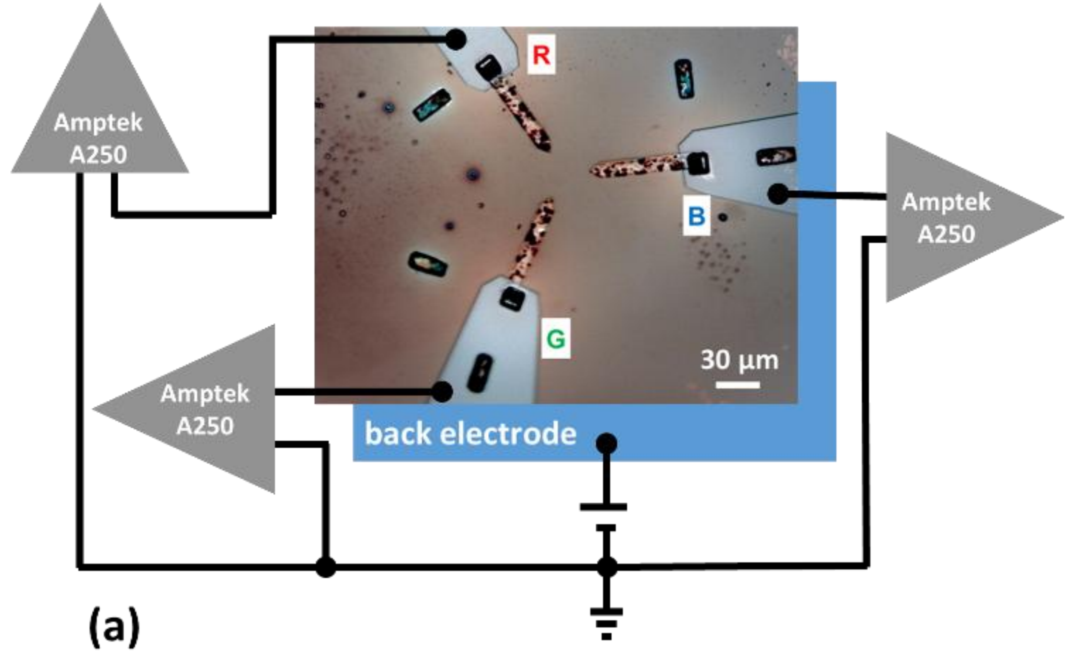


~1 µm thick graphitic electrodes at 1.5 µm depth from the diamond surface

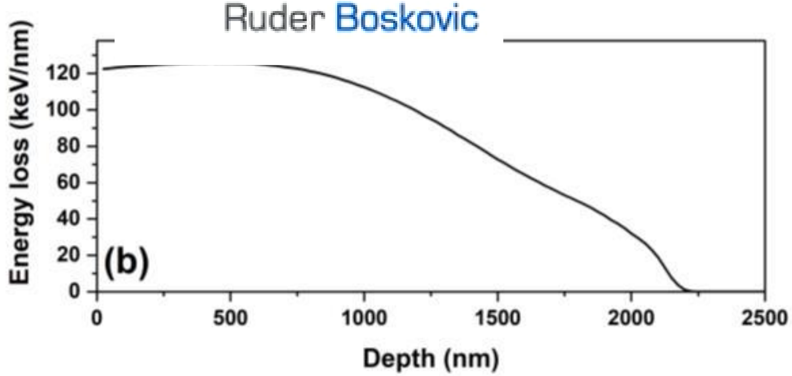
The IBIC experiment

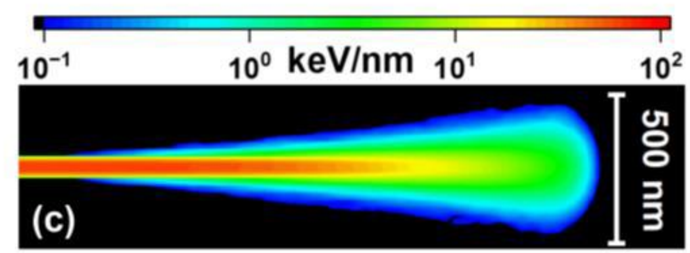
3 independent sensing electrodes
5 µm wide, 75 µm long
26 µm equilateral triangle
1 common back electrode

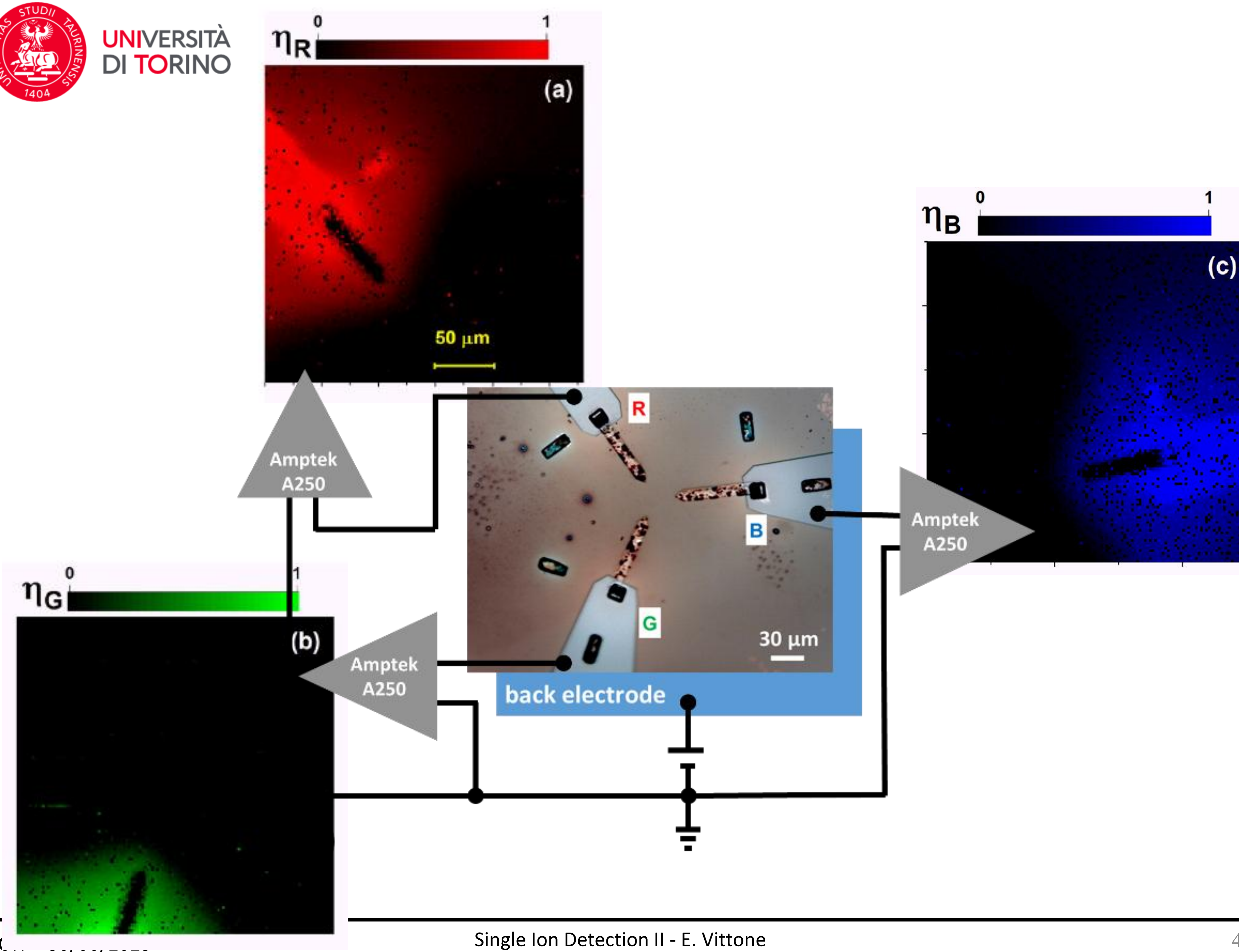
Amptek A250 preamplifier
Ortec 570 shaping amplifier
MCA interfaced with SPECTOR
Bias voltage= 60 V



2 MeV Li microbeam
2 µm spot size
3 individual 128x128 IBIC maps



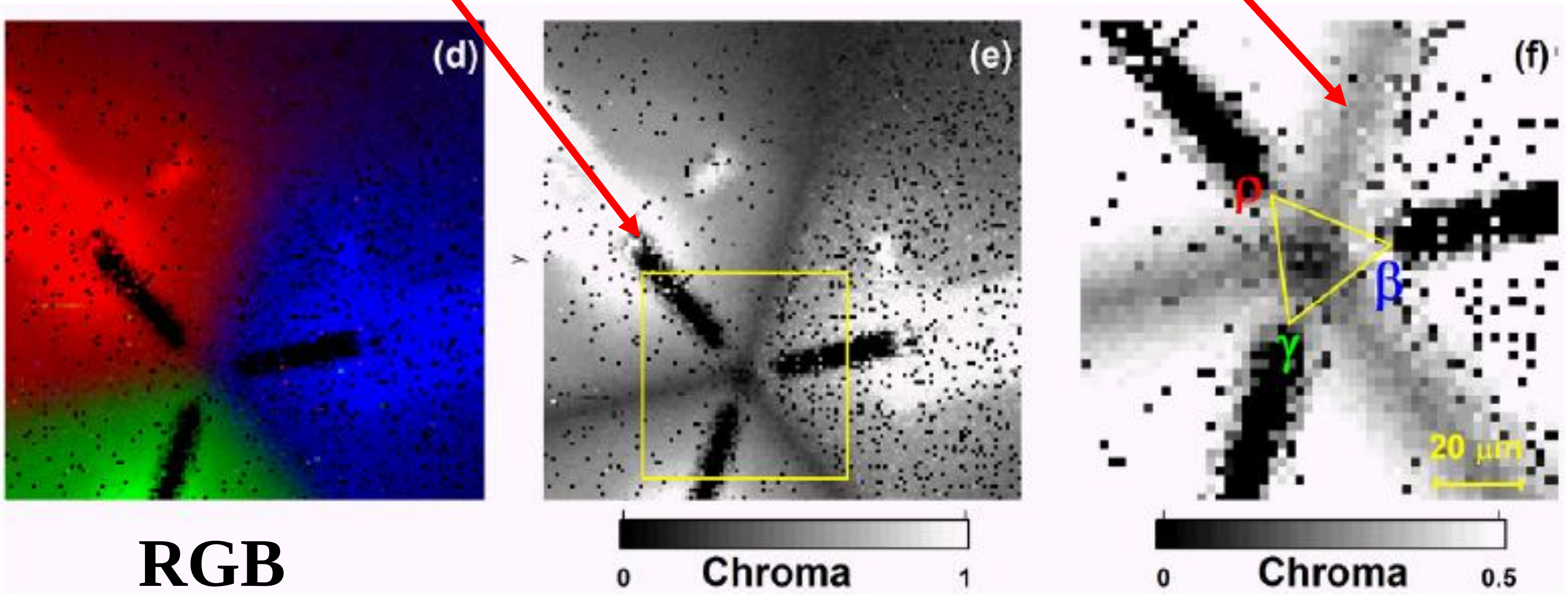



η_R
0
1
(a)
50 µm
Amptek
A250
R
B
G
30 µm
back electrode
Amptek
A250
η_B
0
1
(c)
Amptek
A250
η_G
0
1
(b)

Snowflake's sixfold symmetry

Three main arms are the graphitic channels

three main arms correspond to the regions where charge sharing occurs between two adjacent electrodes.

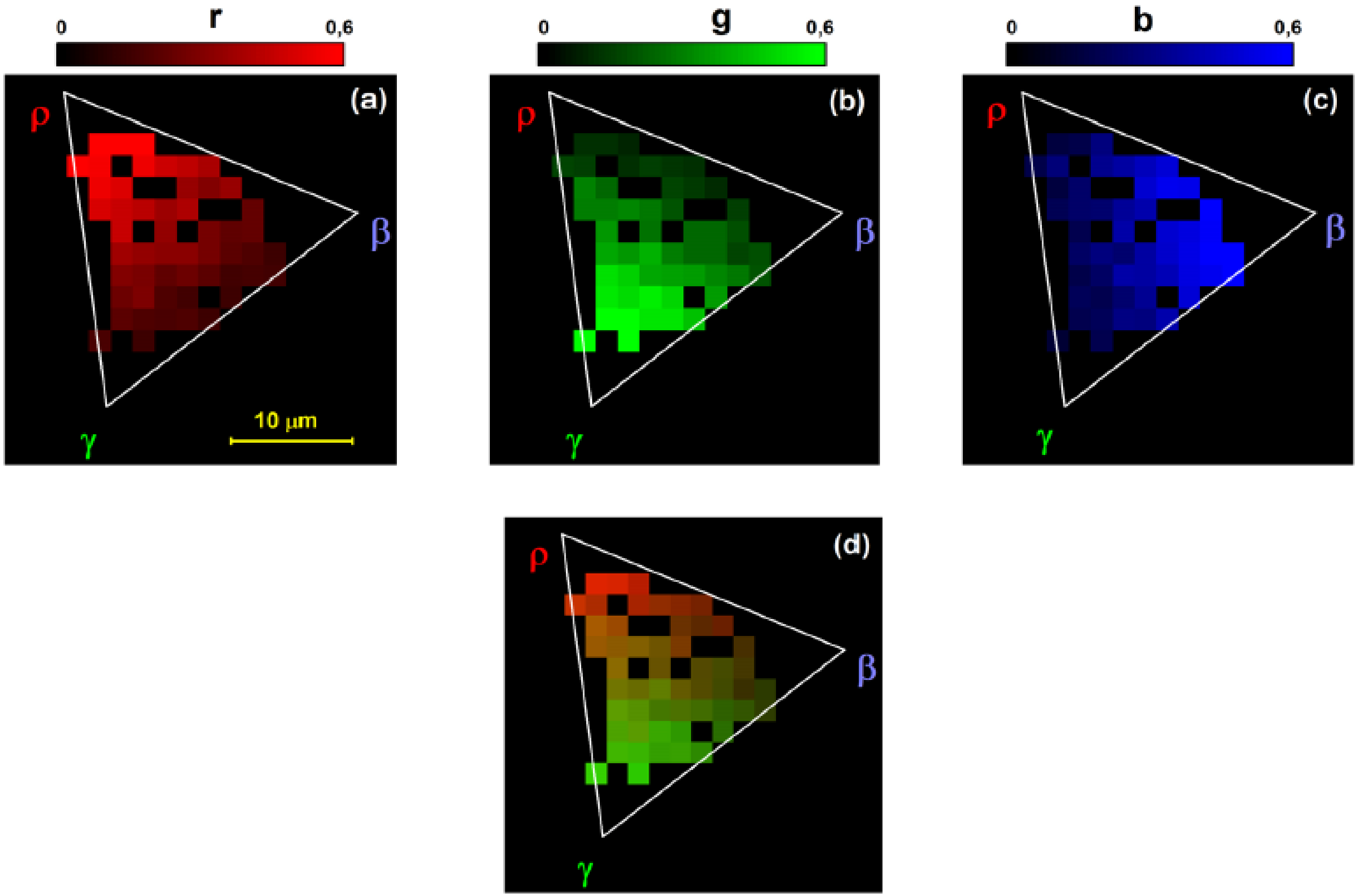


RGB

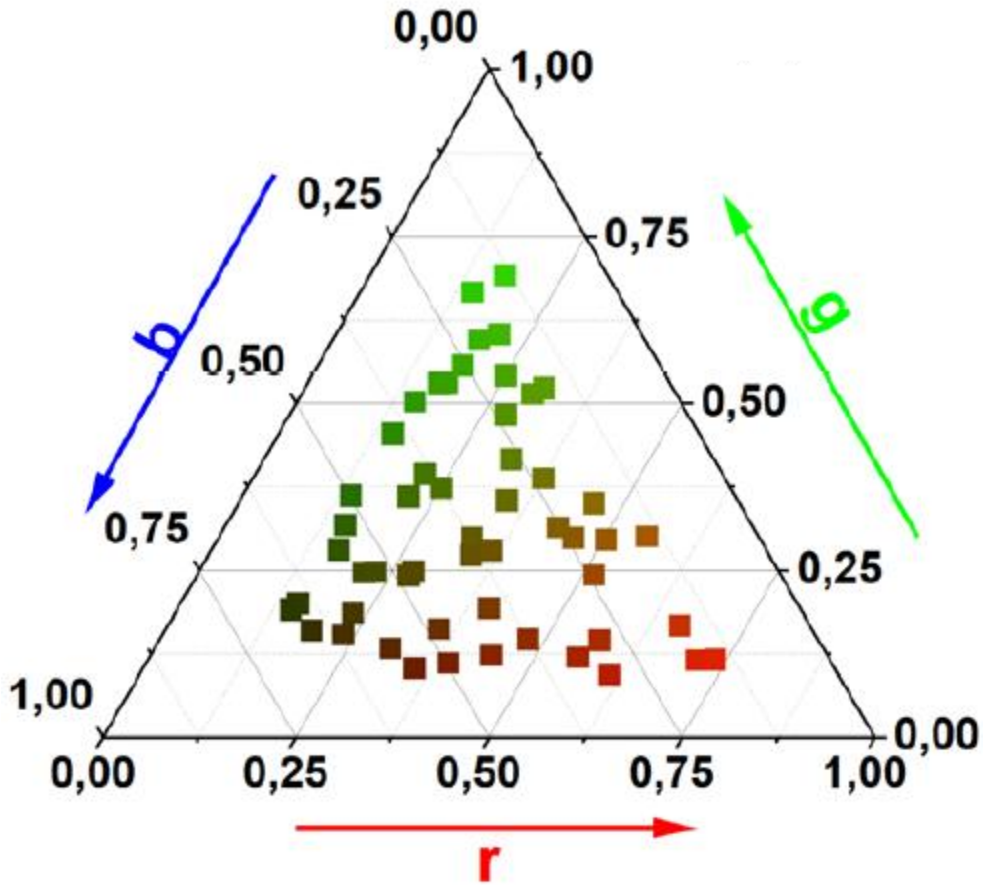
Chroma (absolute color purity)

$$Max(\eta_{R,G,B}) - min(\eta_{R,G,B})$$

$$r = \frac{\eta_R}{(\eta_R+\eta_G+\eta_B)}\,;\; g = \frac{\eta_G}{(\eta_R+\eta_G+\eta_B)}\,;\; b = \frac{\eta_B}{(\eta_R+\eta_G+\eta_B)}$$



The charge space



Ternary diagram -> Maxwell triangle

Search for the one-to-one correspondence (bijective function), which correlates

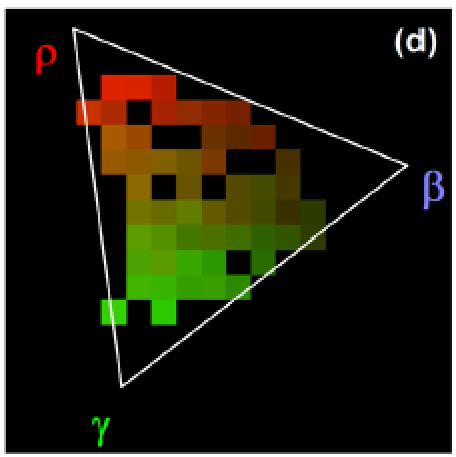
one point identified by (x,y) within the triangular region of interest

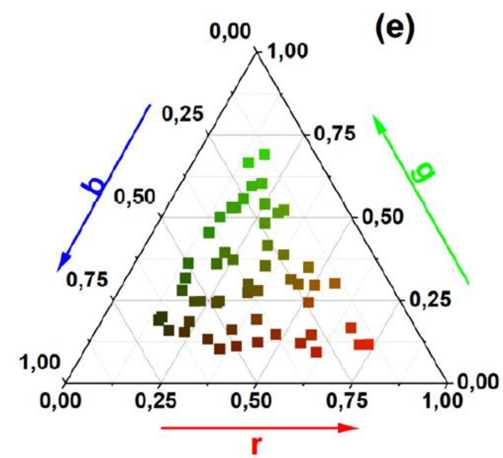
to

one point identified by (r,g,b) in the charge space

Coordinate space $\begin{pmatrix} x \\ y \end{pmatrix}$

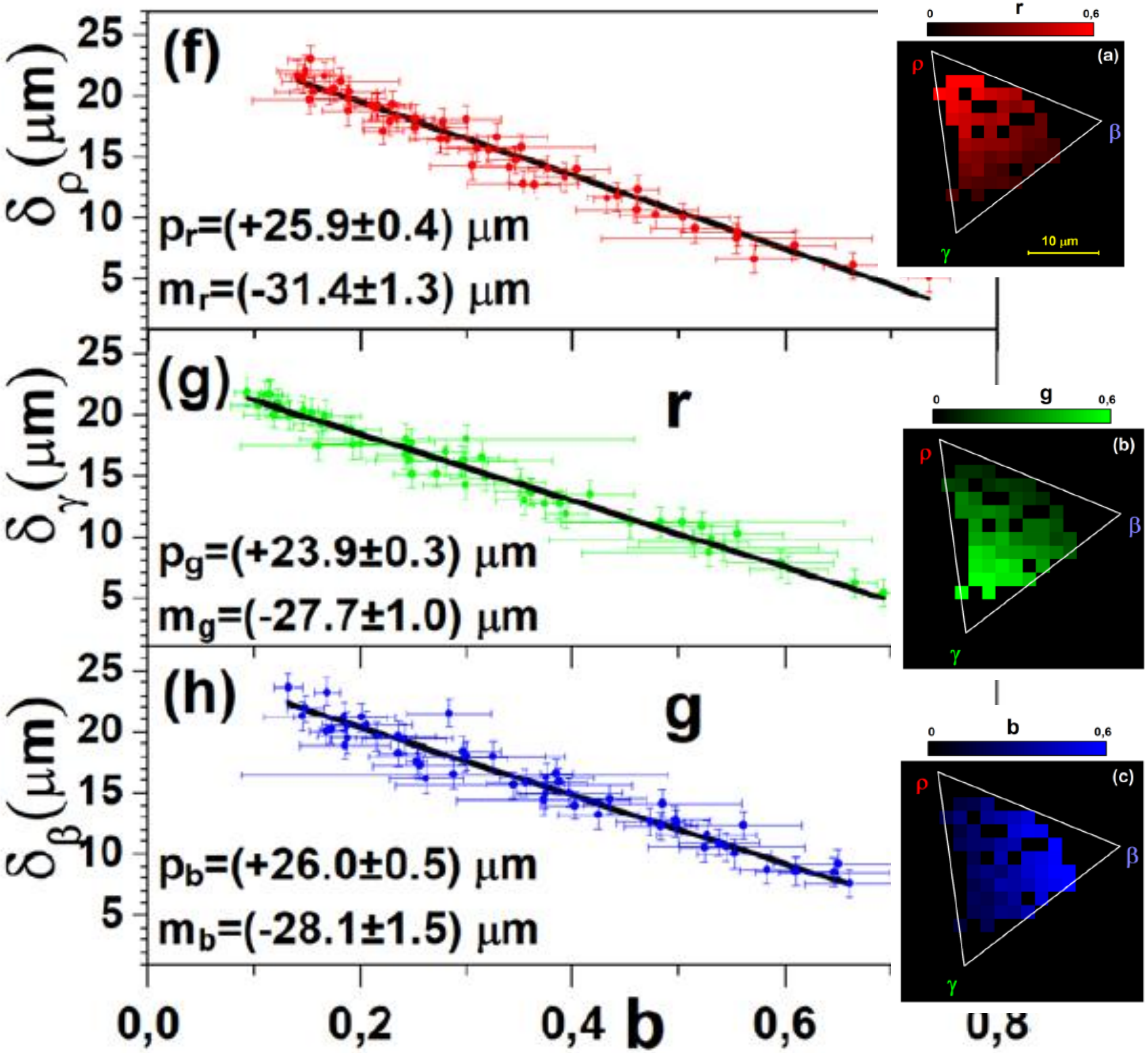
Charge space $\begin{pmatrix} r \\ g \\ b \end{pmatrix}$

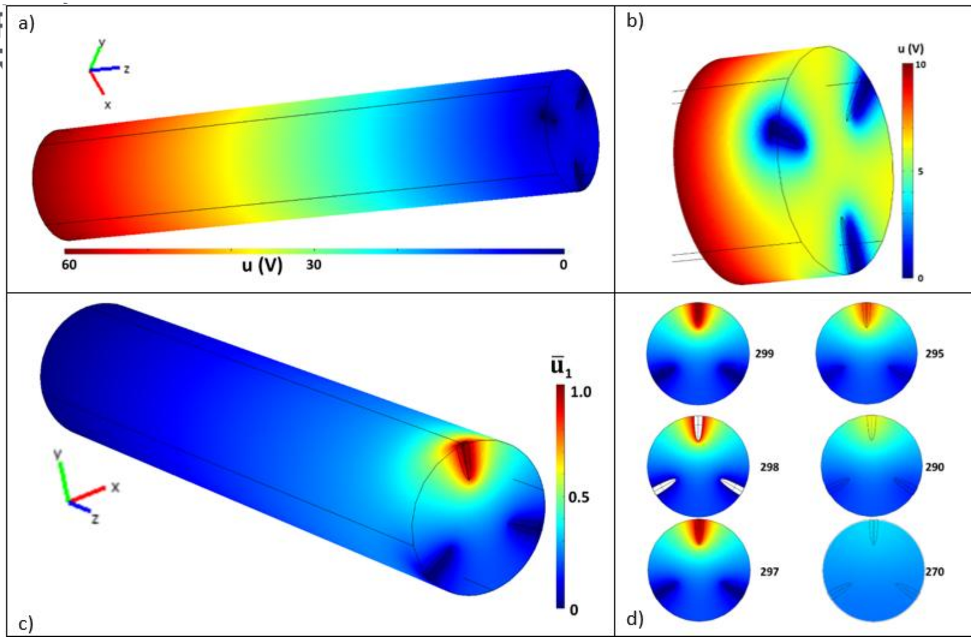




$\delta_{\rho\gamma\beta}$ = distance from the vertex

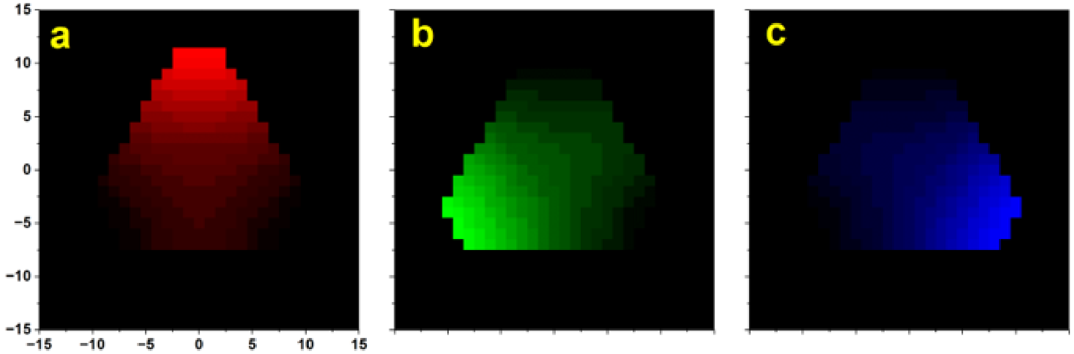
$$\begin{cases} \delta_\rho = p_r + m_r \cdot r, \\ \delta_\gamma = p_g + m_g \cdot g, \\ \delta_\beta = p_b + m_b \cdot b, \end{cases}$$

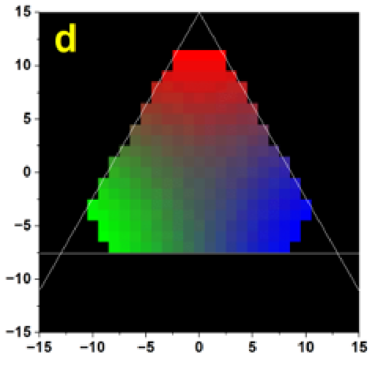


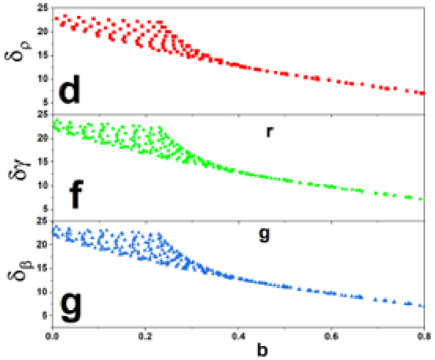


Electrostatic potential

Gunn weighting potential







Simulated r,g,b maps

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Coordinate space $\begin{pmatrix} x \\ y \end{pmatrix}$ $\rightleftarrows$ Charge space $\begin{pmatrix} r \\ g \\ b \end{pmatrix}$

$$
\begin{cases}
\delta_\rho = p_r + m_r \cdot r, \\
\delta_\gamma = p_g + m_g \cdot g, \\
\delta_\beta = p_b + m_b \cdot b,
\end{cases}
$$

Coordinates of the vertex

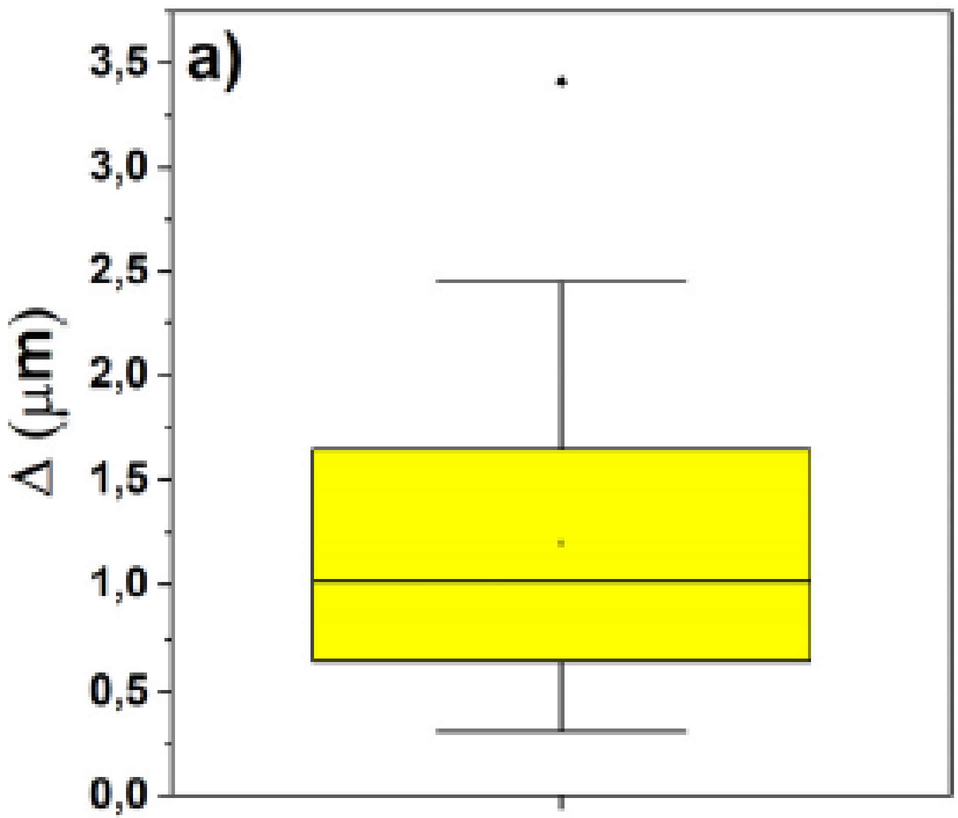
$$\rho \Longrightarrow (x_\rho, y_\rho)$$
$$\gamma \Longrightarrow (x_\gamma, y_\gamma)$$
$$\beta \Longrightarrow (x_\beta, y_\beta)$$

$$x_{pred} = +\frac{1}{2}\frac{y_\beta\left(\delta_\rho^2 - x_\rho^2 - y_\rho^2 - \delta_\gamma^2 + x_\gamma^2 + y_\gamma^2\right) + y_\gamma\left(\delta_\beta^2 - x_\beta^2 - y_\beta^2 - \delta_\rho^2 + x_\rho^2 + y_\rho^2\right) + y_\rho\left(\delta_\gamma^2 - x_\gamma^2 - y_\gamma^2 - \delta_\beta^2 + x_\beta^2 + y_\beta^2\right)}{(y_\beta - y_\rho)(x_\gamma - x_\rho) - (x_\beta - x_\rho)(y_\gamma - y_\rho)},$$

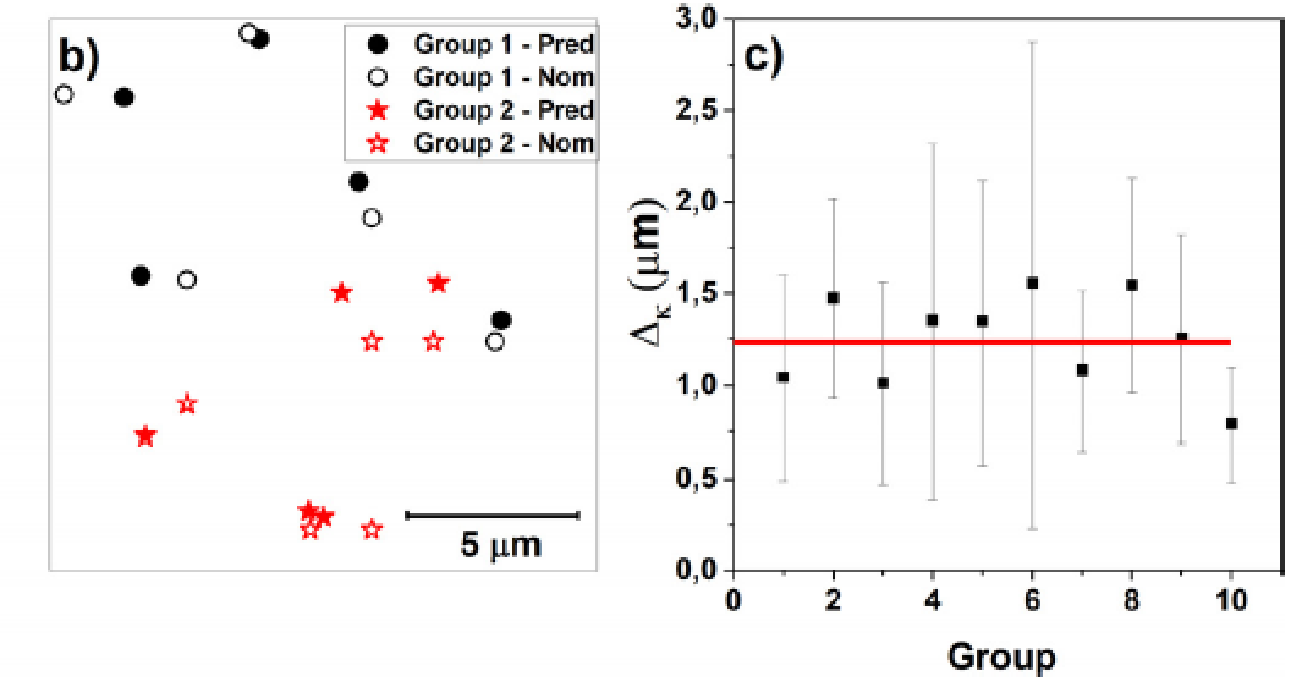
$$y_{pred} = -\frac{1}{2}\frac{x_\beta\left(\delta_\rho^2 - x_\rho^2 - y_\rho^2 - \delta_\gamma^2 + x_\gamma^2 + y_\gamma^2\right) + x_\gamma\left(\delta_\beta^2 - x_\beta^2 - y_\beta^2 - \delta_\rho^2 + x_\rho^2 + y_\rho^2\right) + x_\rho\left(\delta_\gamma^2 - x_\gamma^2 - y_\gamma^2 - \delta_\beta^2 + x_\beta^2 + y_\beta^2\right)}{(y_\beta - y_\rho)(x_\gamma - x_\rho) - (x_\beta - x_\rho)(y_\gamma - y_\rho)}.$$

Boxplot of the distribution distances Dᵢ of the nominal impact point position from the predicted impact point,

$$\Delta_i = \sqrt{(x_{pred,i} - x_{nom,i})^2 + (y_{pred,i} - y_{nom,i})^2}.$$



Predictive accuracy of the model through the tenfold cross validation test.



The 52 data points were randomly assigned to ten groups, containing five points identified by the three "charge" coordinates (r, g, b) relevant to the nominal point of coordinates (x_{nom}, y_{nom}).

In turns, the remaining 47 points were used to build the above described model to evaluate the predicted impact point (x_{pred}, y_{pred}).

In this 2nd lecture

- **The Gunn's theorem provides the theoretical background to compute the induced charge signal in multielectrode devices**
- **The formalism correlates the charge generation position with the charge signals induced in the sensing electrodes**
- **Bi- or Tri-lateration approaches to retrieve the two-dimensional position of impact of each ion**
- **The spatial resolution depends on the extension of the active area and on the electronic noise**

Limitations
Intrinsic: straggling
Instrumental: Electronics: spectral resolution

1D position sensitive detector
Extension of the active region; 2.5 mm
Ion Probe: 2 MeV H;Spectral resolution: 34 keV
Spatial resolution: 49 μm
E.Vittone et al., "IBIC analysis of a linear position sensitive detector: model and experiment", Eur. Phys. J. Plus (2025) 140:369

1D position sensitive detector
Extension of the active region; 12 μm
Ion Probe: 2 MeV He;Spectral resolution: 200 keV
Spatial resolution: 0.4 μm
J. Forneris et al., "Modeling of ion beam induced charge sharing experiments for the design of high resolution position sensitive detectors" Nuclear Instruments and Methods in Physics Research B 306 (2013) 169Â–175.

2D position sensitive detector
Extension of the triangular active region: 26 μm side
Ion Probe: 2 MeV Li; Spectral resolution: 20 keV
Spatial resolution: 3 μm
S. Ditalia Tchernj et al. , A multi-electrode two-dimensional position-sensitive diamond detector
Appl. Phys. Lett. 124, 223502 (2024);