



Development of a monolithic diamond ΔE -E telescope for particle identification and characterization of diamond detector using the ToF-eBIC technique

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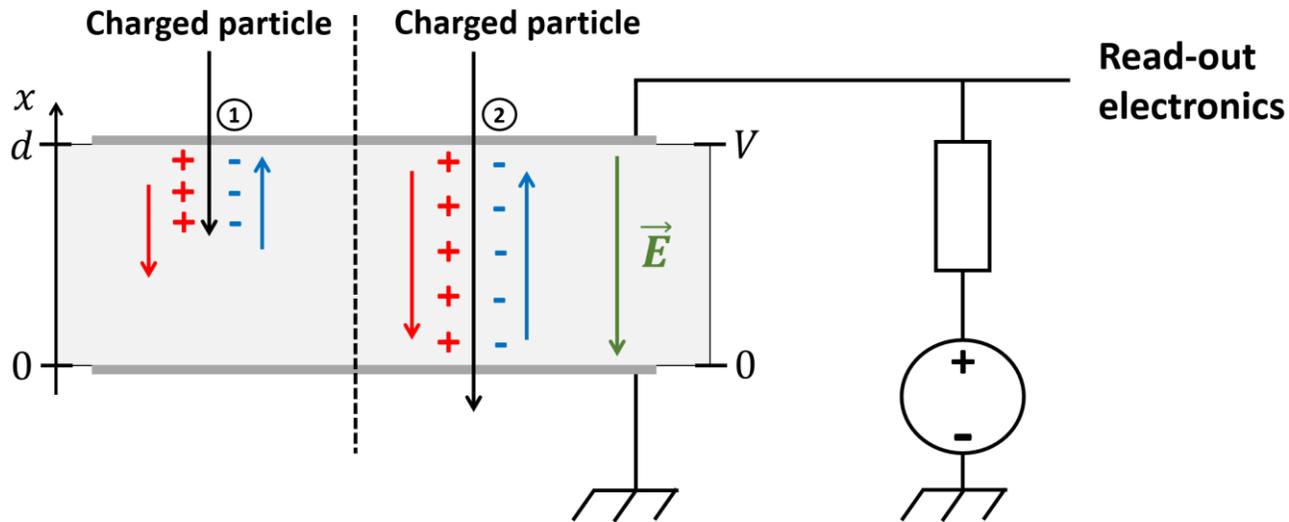
² Univ. Grenoble Alpes, CNRS, Institut Néel

This work is supported by DIAMTECH IN2P3 and by IDEX Université Grenoble Alpes.

+ Collaborations PRC CNRS – JSPS & TYL IN2P3 Japan – France

PhD thesis main goals

Solid state ionization chamber



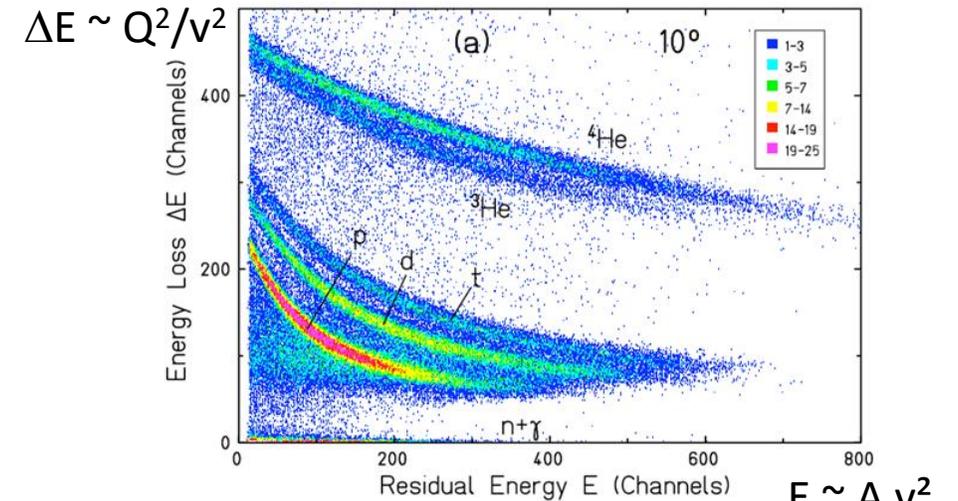
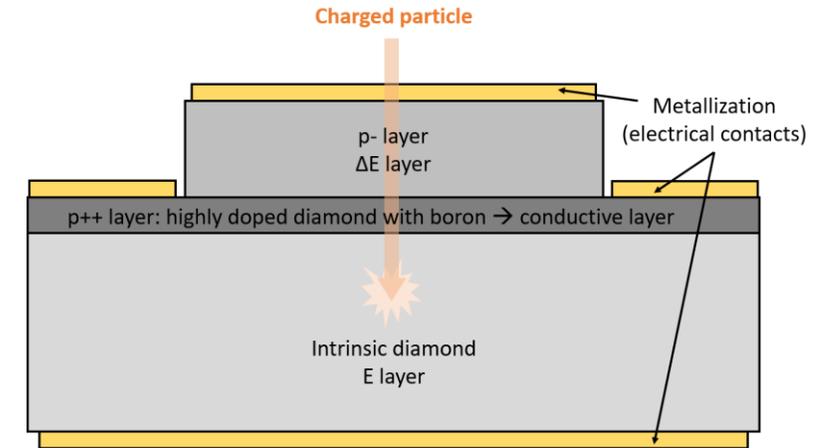
Charge particle in the medium:

- Ionization: electron – hole pairs creation
- Electric field \rightarrow charge carriers drift \rightarrow Induce a current

Two different situations:

1. Particles that stop in the detector
2. Particles that pass through the detector

Monolithic diamond ΔE -E telescope

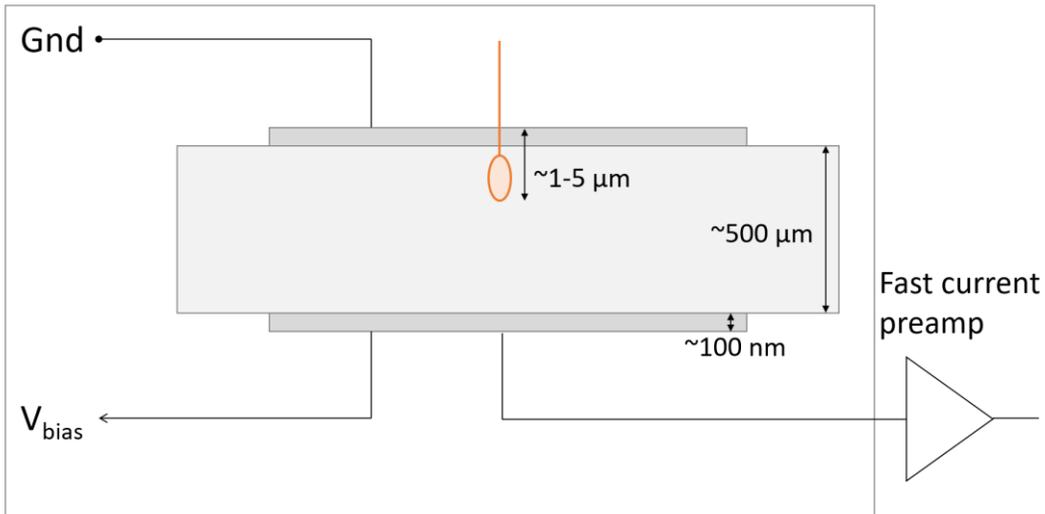


Gunzert-Marx et al., *New Journal of Physics* **10** (2008)

PhD thesis main goals

ToF – eBIC setup development

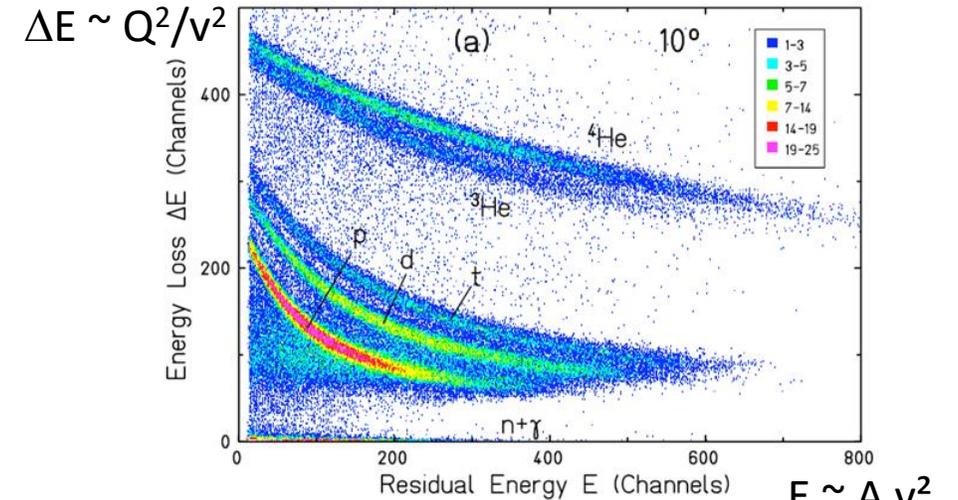
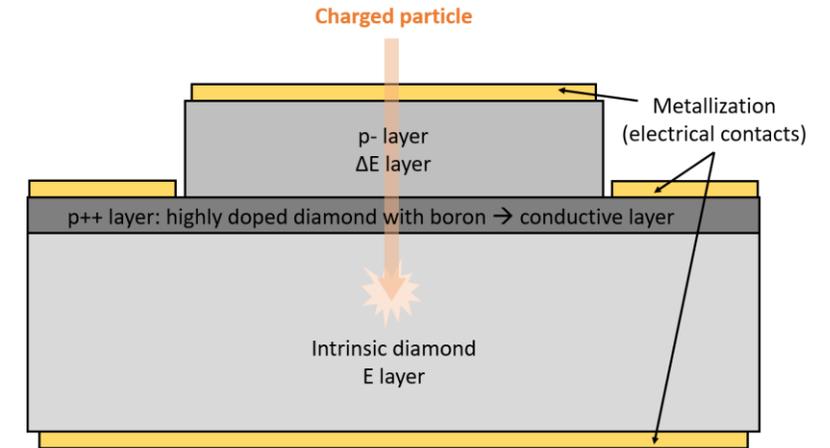
Time of Flight – electron Beam Induced Current



Study low range charged particles which stop in the detector

Beam \rightarrow allow to control the charge injection
Not the case for radioactive sources

Monolithic diamond ΔE -E telescope



Gunzert-Marx et al., *New Journal of Physics* 10 (2008)

$$E \sim A \cdot v^2$$

Diamond properties

Physical properties compared at 300 K

	Diamond	Silicon	SiC
Undoped material resistivity ($\Omega \cdot \text{cm}$)	$> 10^{13}$	$2.3 \cdot 10^5$	$> 10^5$
Bandgap (eV)	5.5	1.1	3.26
Pair creation energy e^-/h^+ (eV)	13.1	3.6	7.8
Displacement energy (eV)	43	25	20 - 35
Carrier mobility ($\text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$)	> 2000	800 – 1400	115 - 1000
Thermal conductivity ($\text{W} \cdot \text{cm}^{-1} \cdot \text{K}^{-1}$)	20	1.5	1.2

Diamond as a detector :

- ✓ **Very low leakage current**
- ✓ **Low noise**
- ✓ **Good radiation hardness**
- ✓ **Very fast**
- ✓ **No need of cryogenic**

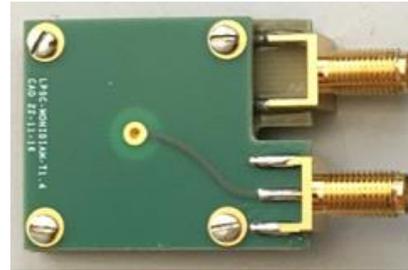
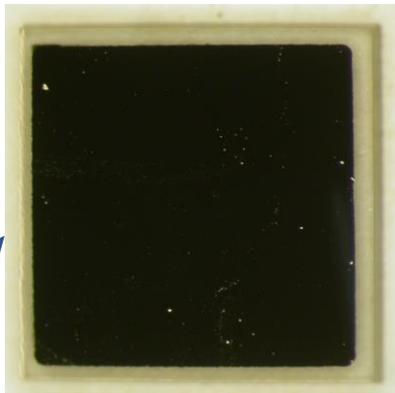


From synthetic diamond to diamond detector

single crystal Chemical Vapor Deposition (scCVD)
diamond – electronic grade from Element 6 (E6).

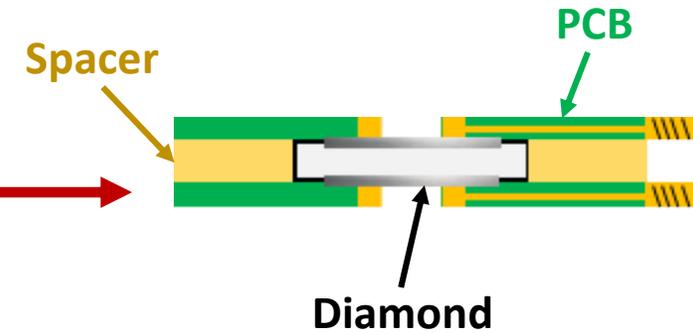
Impurities: [B] < 5 ppb (Measured by EPR)
[N] < 1 ppb (Measured by SIMS)

Metallization



Packaging with
connectors

Diamond holder at LPSC

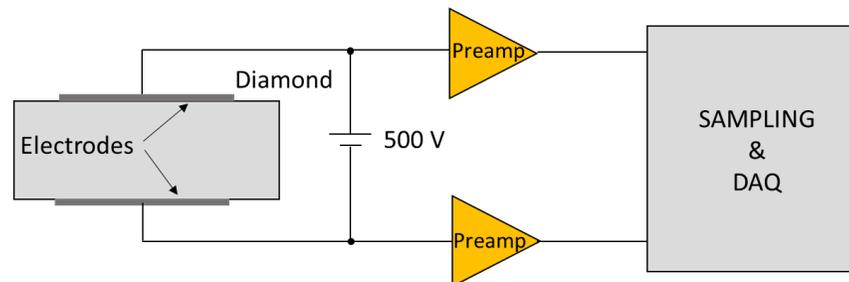


Read out electronic and acquisition



Large bandwidth
current preamplifier
Gain > 40 dB
Bandwidth 2 GHz

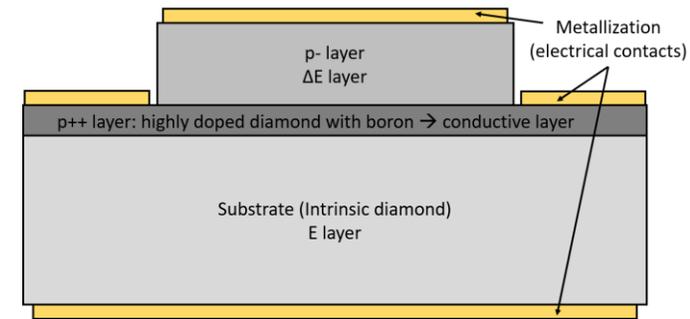
Fast numerical
oscilloscope



SRIM simulations – Requirement

Simulate the energy deposition in the ΔE -E detector for different ions, ion energies and detector architectures.

→ Determine the thickness of the ΔE (p-) layer of the first sample



Layers	Parameters	Consideration & criteria	Requirements	Growth method
p- layer	Thickness	Energy deposition needs to be measurable Resistivity and leakage current	$1 \text{ MeV} < \Delta E < E_{\text{init}}/2$ $I_{\text{leak}} < 1 \text{ nA}$	MPCVD Microwave Plasma enhanced Chemical Vapor Deposition 
	Doping	Non intentionally doped (Avoid defaults)	As low as possible	
p++ layer	Thickness	Dead area of detection Growth layer feasibility	As thin as possible > 200 nm → 500 nm	
	Doping	Could be considered as a conductor	$[B] > 10^{20} \text{ cm}^{-3}$	
Substrate	Thickness	Enough thick to stop the particle	~550 μm	single crystal MPCVD 
	Doping	Non intentionally doped (Avoid defaults)	As low as possible	

Simulation software → **SRIM**: The Stopping and Range of Ions in Matter

Adapted for light charged particles, trustworthy and user friendly

Many architectures, ions and energies tested → pysrim python package

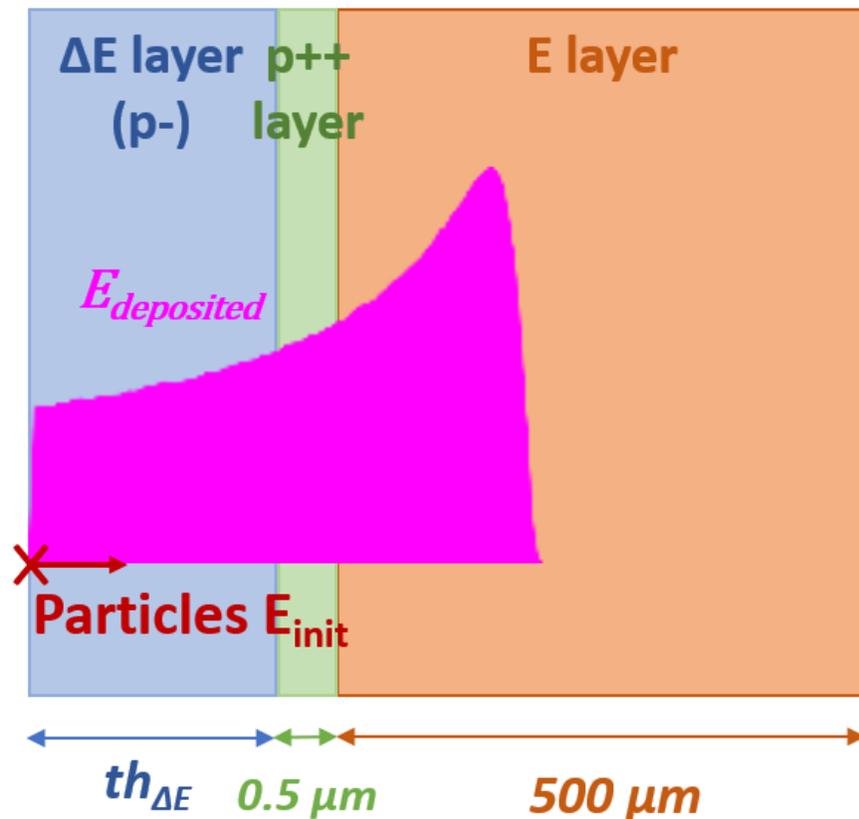


SRIM simulations

Simulate the energy deposition in the ΔE -E detector for different ions, ion energies and detector architectures.

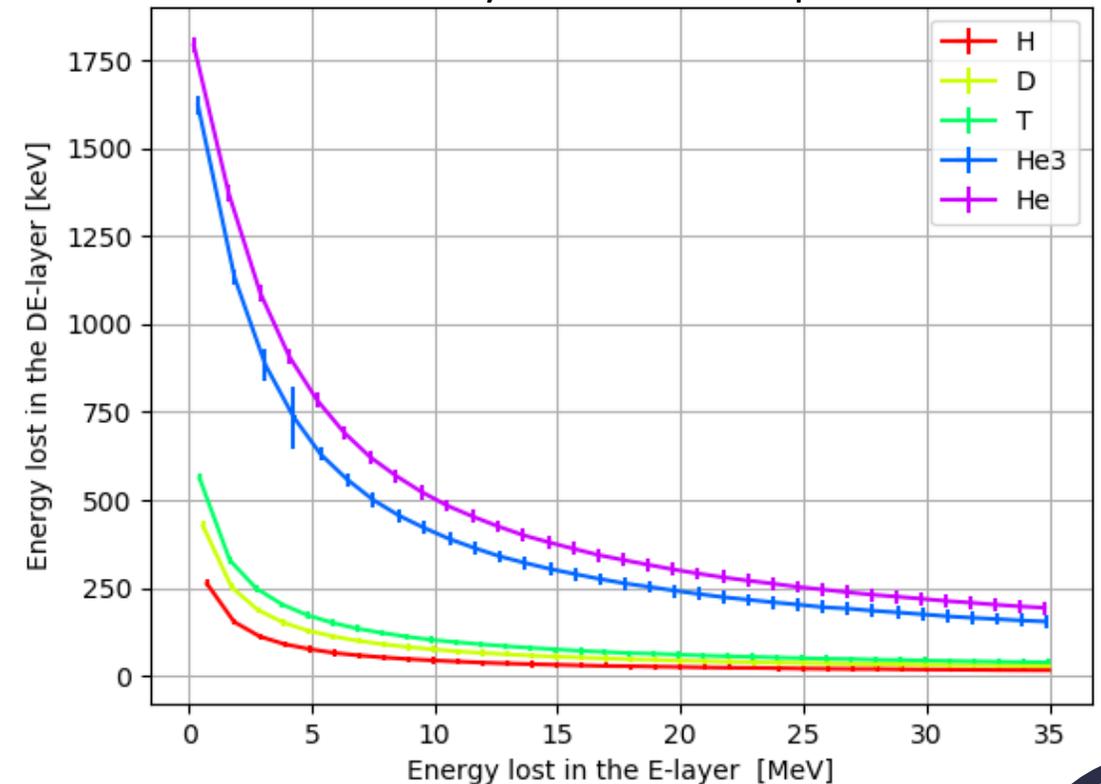
→ Determine the thickness of the ΔE (p-) layer of the first sample

SRIM Simulation scheme

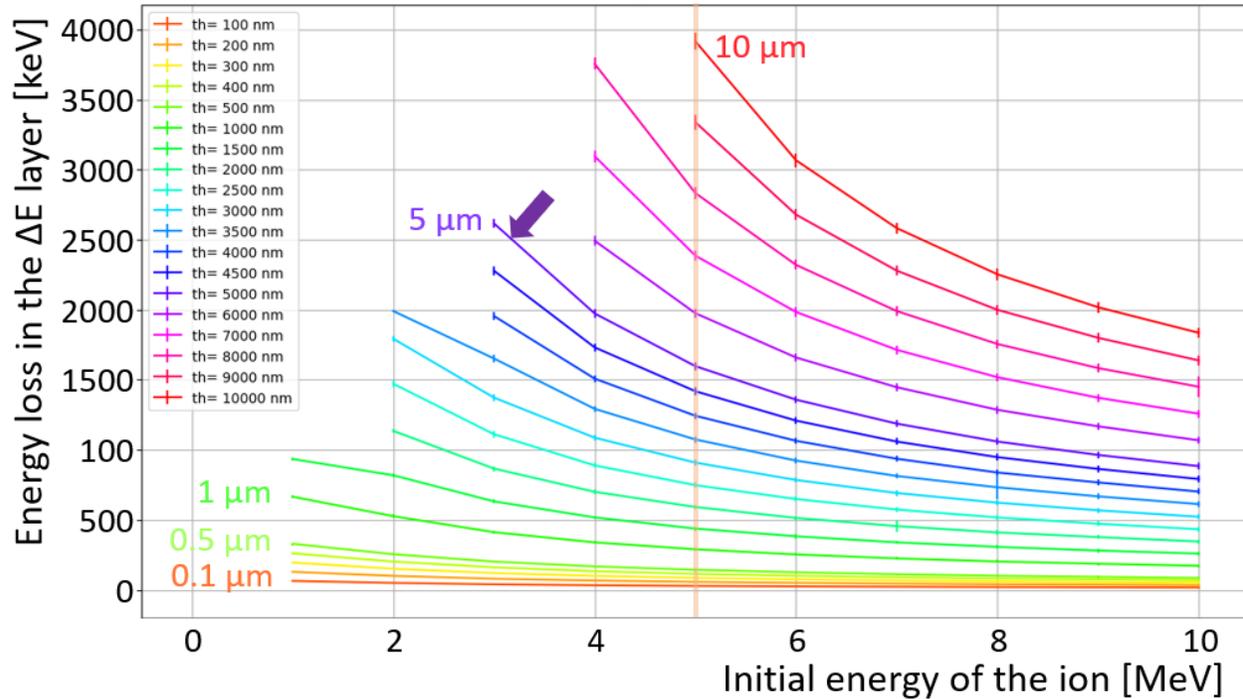


SRIM simulation results for light ions

ΔE layer thickness: $3 \mu m$



From simulations to first sample

SRIM simulations for α particles

Requirements: (For $E_{\text{init}} = 5\text{MeV}$)

Energy deposited:

$$E_{\Delta E} > 1 \text{ MeV}$$

$$E_{\Delta E} > E_{\text{init}}/2$$

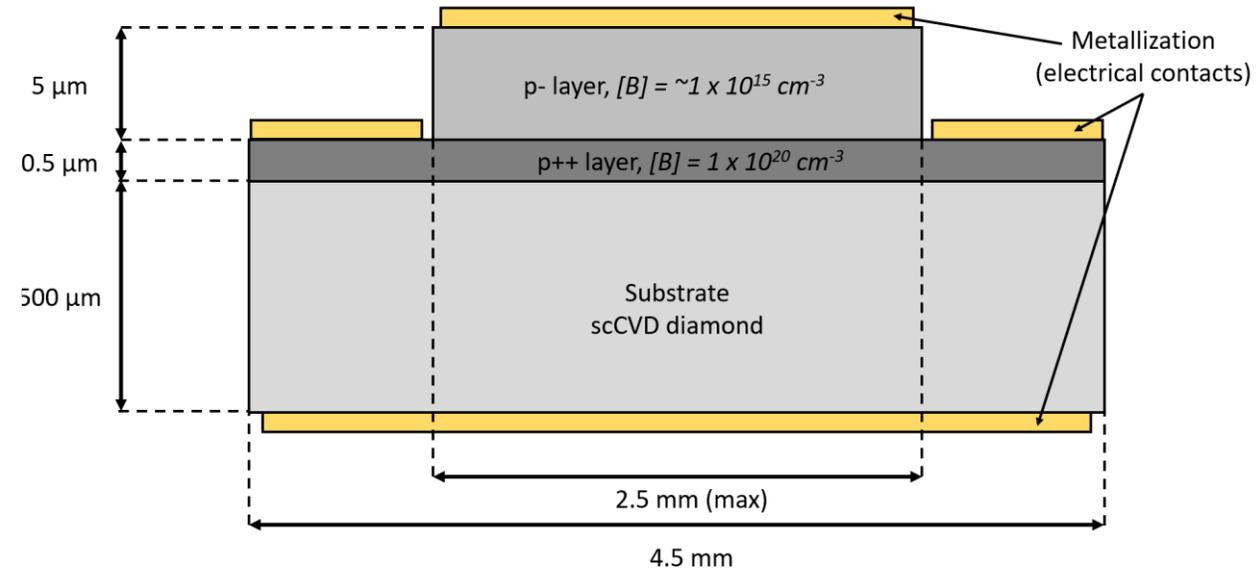
Leakage current:

$$I_{\text{leak}} < 1 \text{ nA}$$

Solution chosen:

Thickness: 5 μm
Schottky Contact

First simple design scheme

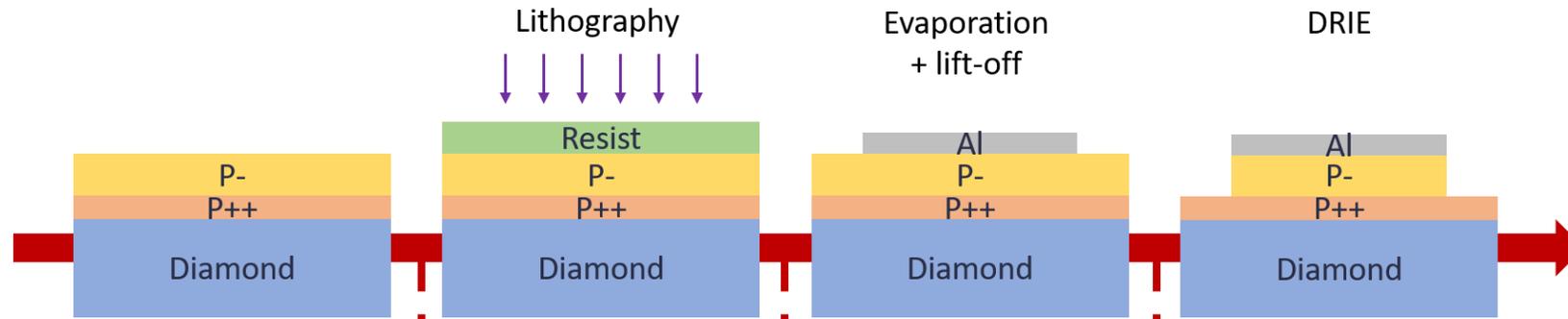


Alpha particle range
in diamond : 11.8 μm

The start-up DiamFab is in charge of
the epitaxial growth.



Etching process

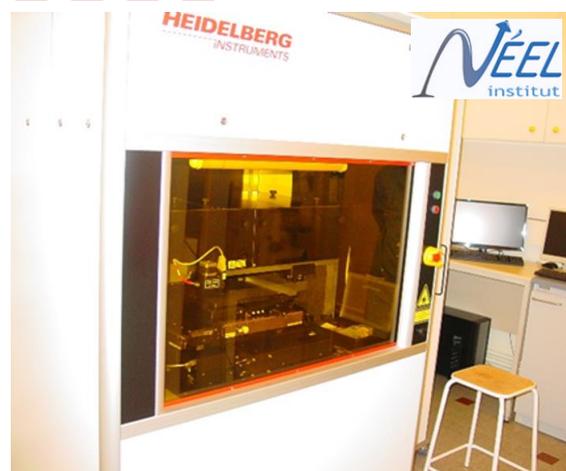


Diamond growths done by the start-up DiamFab
DiamFab reactor:

Laser lithography
at NanoFab:

Metal deposition
device at NanoFab:

PTA: Plateforme Technologique Amont
DRIE: Deep Reactive-Ion Etching



Diamond Growths

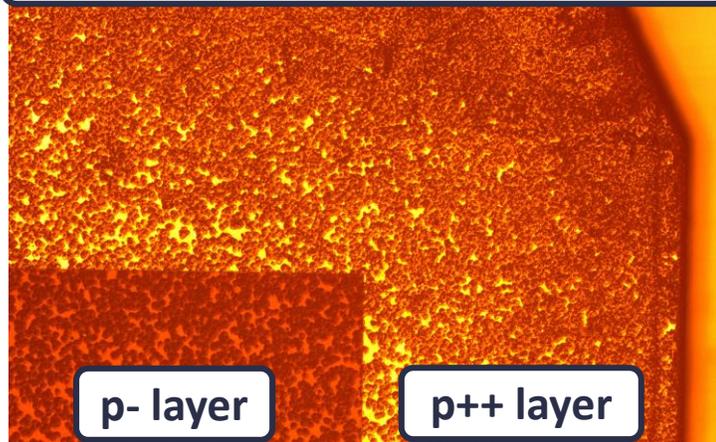
Lithography +
development

Al evaporation + Lift-off

Etching (DRIE) + Acid
treatment

First sample – etching checking

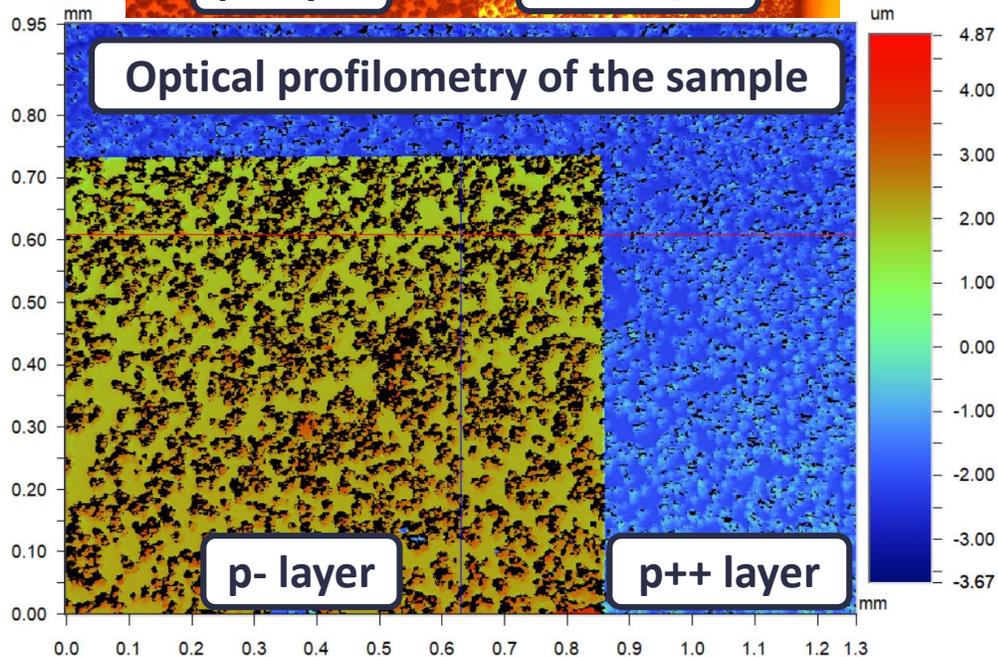
Microscope picture of the sample



p- layer

p++ layer

Optical profilometry of the sample

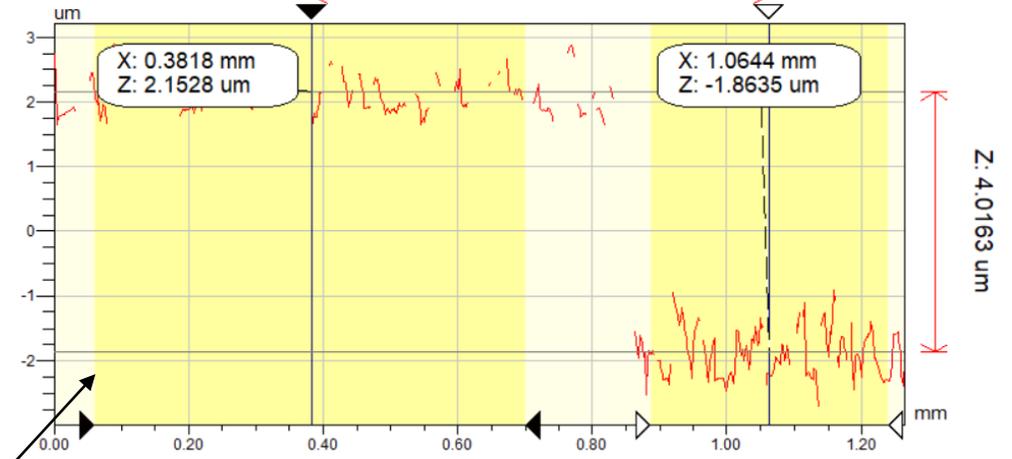


p- layer

p++ layer

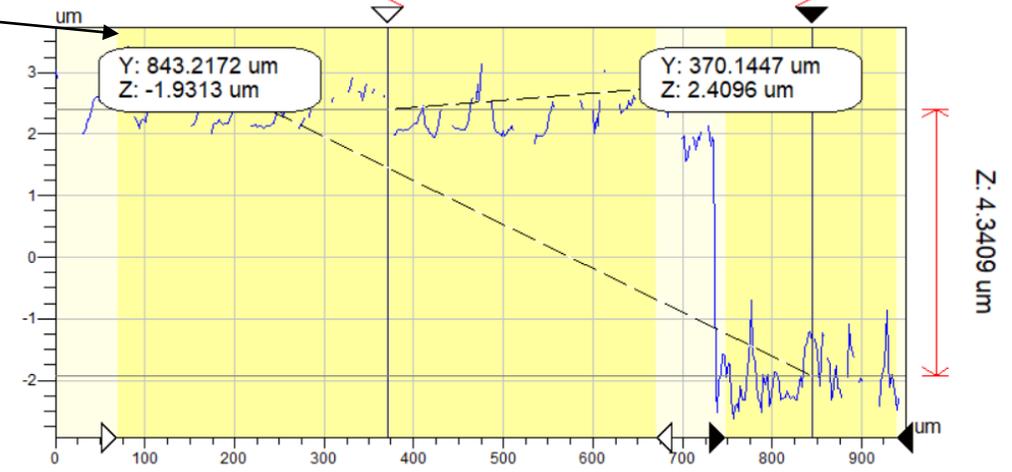
X Profile

X: 0.6825 mm



Y Profile

Y: 473.0726 um



Progress and future developments

 ΔE -E samples

Sample number	p++ growth	p- growth	Etching	Metallization	Test in lab.
1	✓	✓	✓	✗	✗
2	✓	Work in progress	Will be done soon		

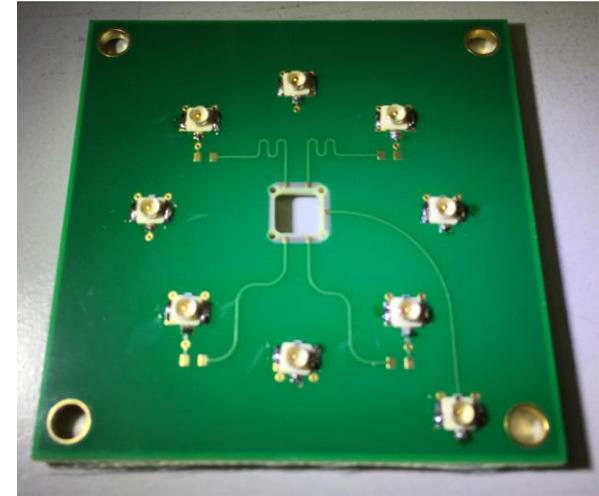
1st Sample: Not planned to be used as a detector

- ➔ Etching tests done at PTA
- ➔ Processing of 2nd sample can start

2nd Sample: 1st ΔE -E detector developed in this PhD

- ➔ Photocurrent experiments planned to study defaults
- ➔ Future experiments planned with radioactive sources (LPSC) and under α micro-beam (AIFIRA)

Electronic & instrumental developments



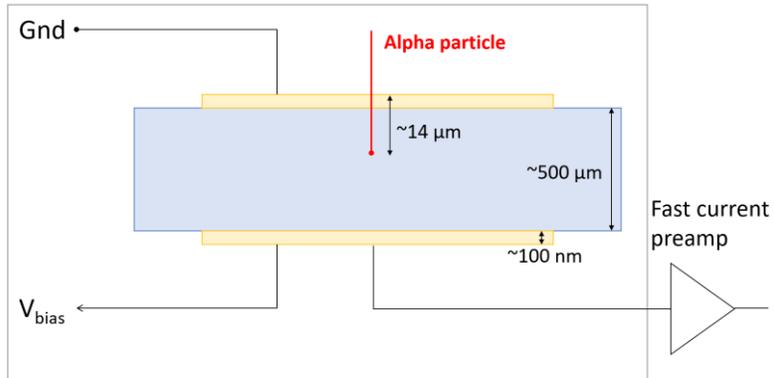
Sample electrical connection to the PCB will be done thanks to wire bonding.

The FE electronic will consist in charge preamplifiers.

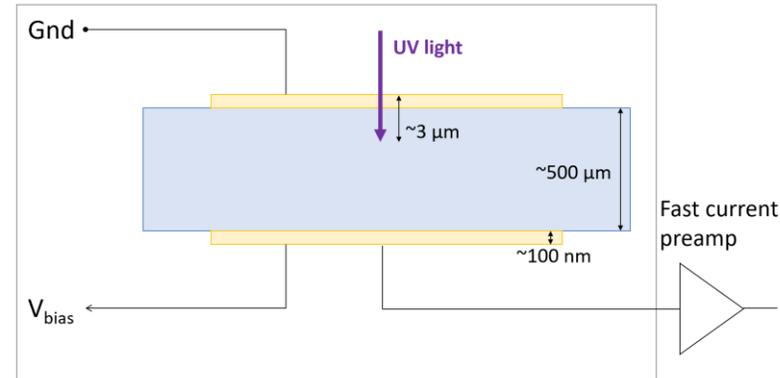


Electron Beam advantages

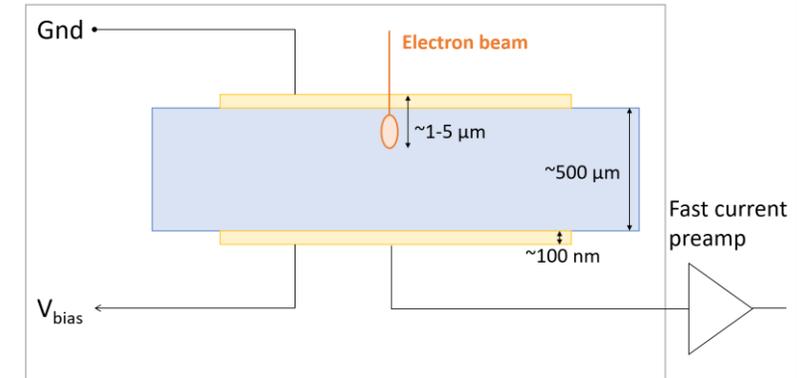
Radioactive alpha source



UV Light



Electron Beam



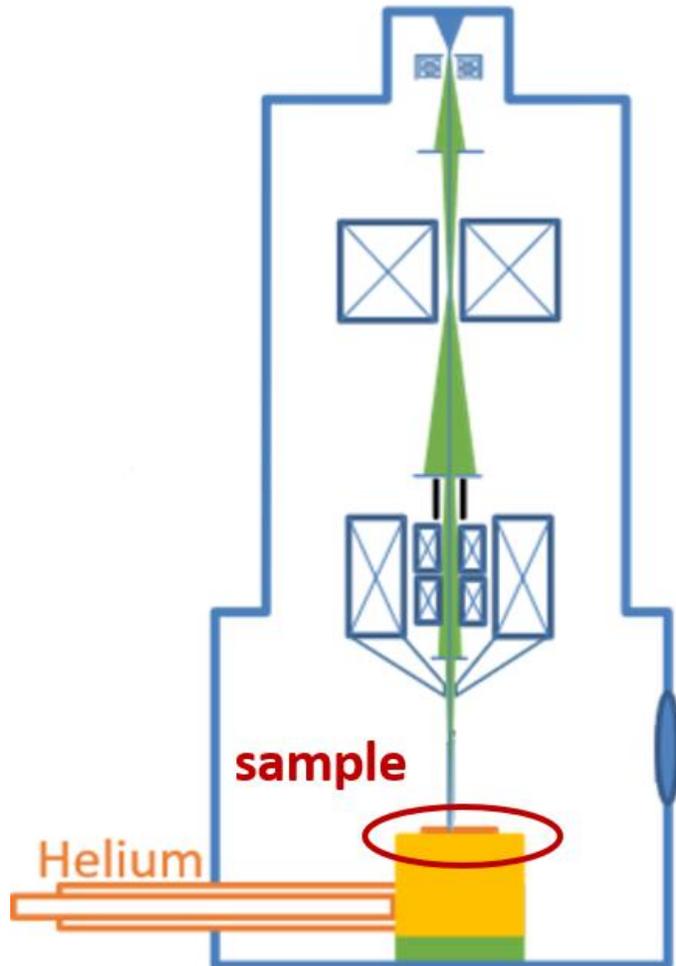
Properties	Tunable?
Energy of 1 particle	Difficult
Nb of particles / pulse	No
Injection rate \leftrightarrow Activity	Difficult
Lateral particle position	Limited [mm]

Properties	Tunable?
Laser wavelength	No
Nb of particles / pulse	Yes
Injection rate	Yes
Lateral beam position	Good [μm]

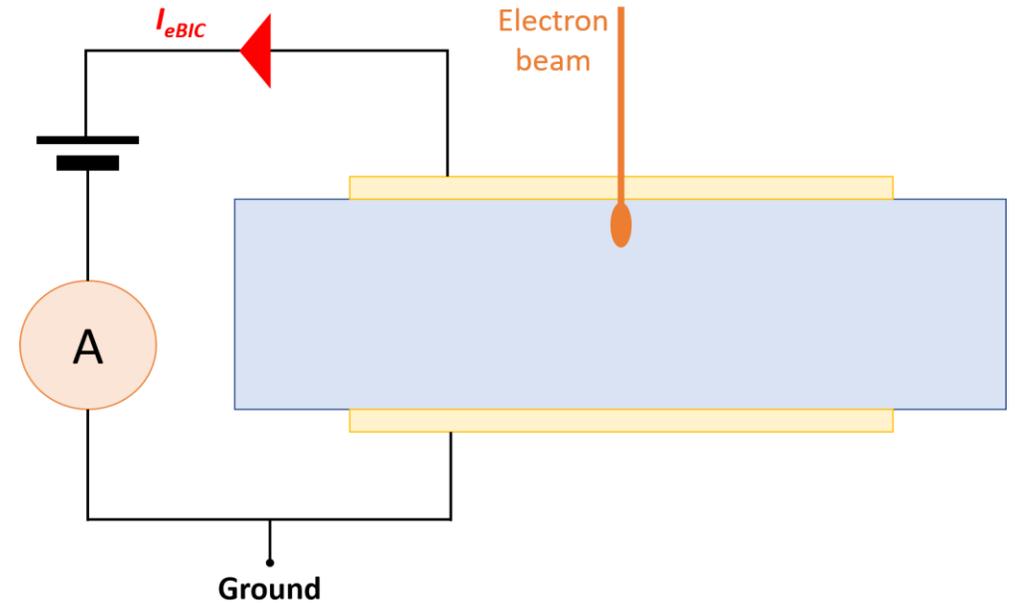
Properties	Tunable?
Energy of 1 particle	Yes
Nb of particles / pulse	Yes
Injection rate	Yes
Lateral beam position	Excellent [nm]

Standard eBIC setup

Scanning Electron Microscope (SEM) setup



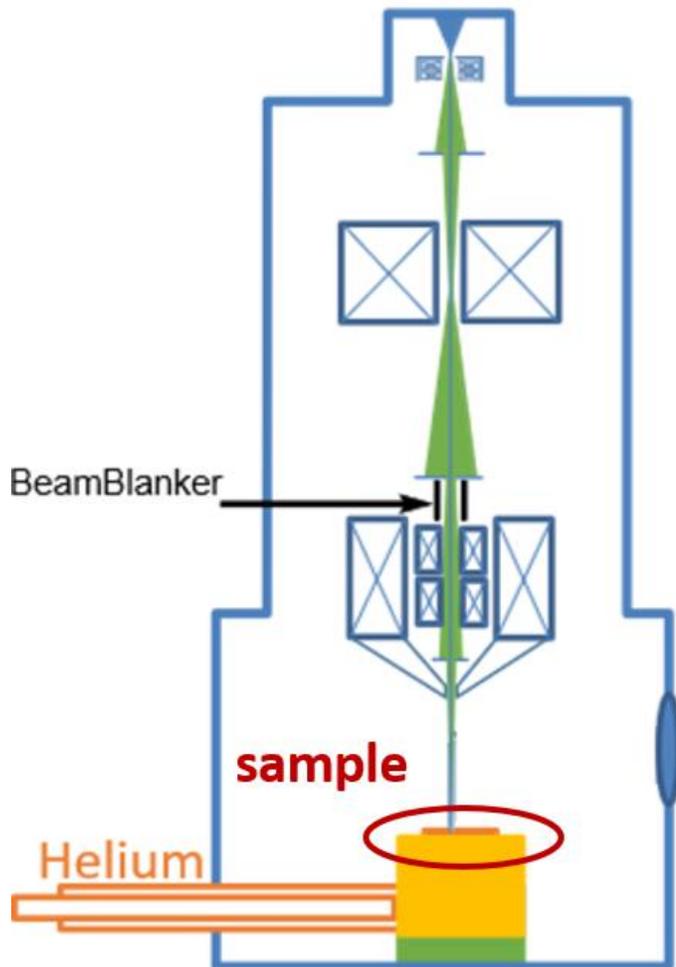
electron Beam Induced current (eBIC) setup



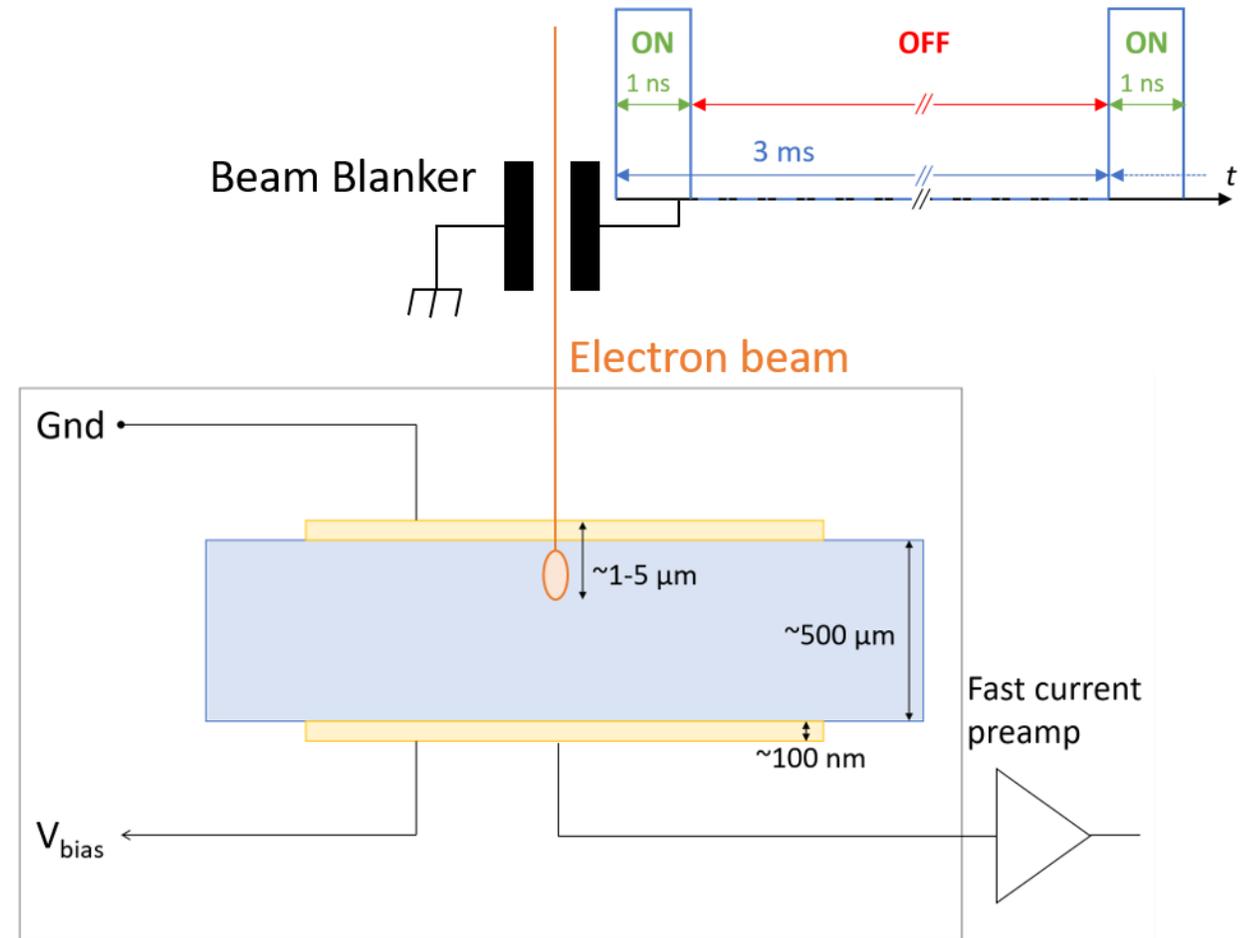
Goal: do time resolved eBIC measurements

Innovative ToF – eBIC setup

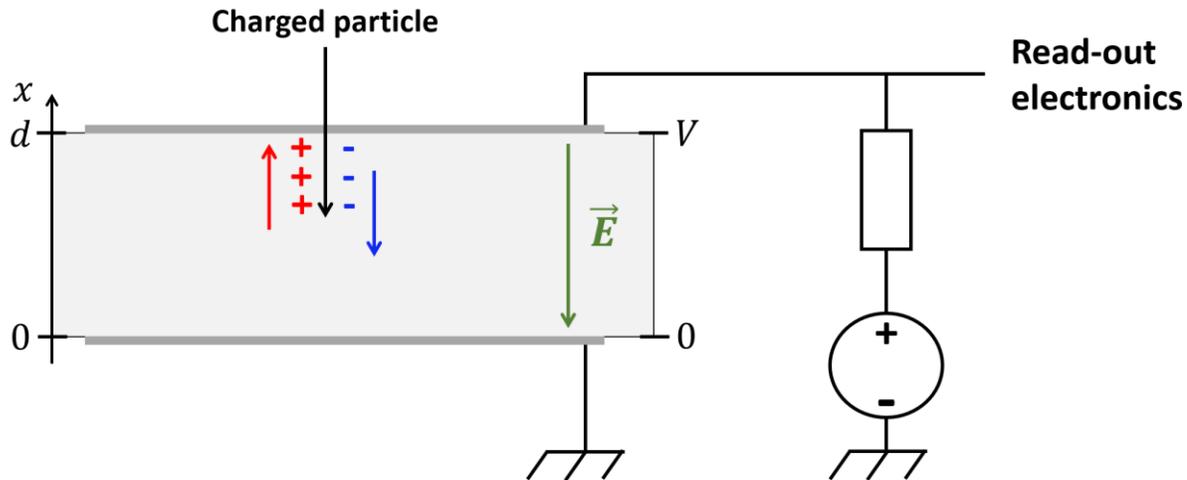
Scanning Electron Microscope (SEM) setup



Time of Flight (ToF) – eBIC setup



Solid state ionization chamber

**Charge particle in the medium:**

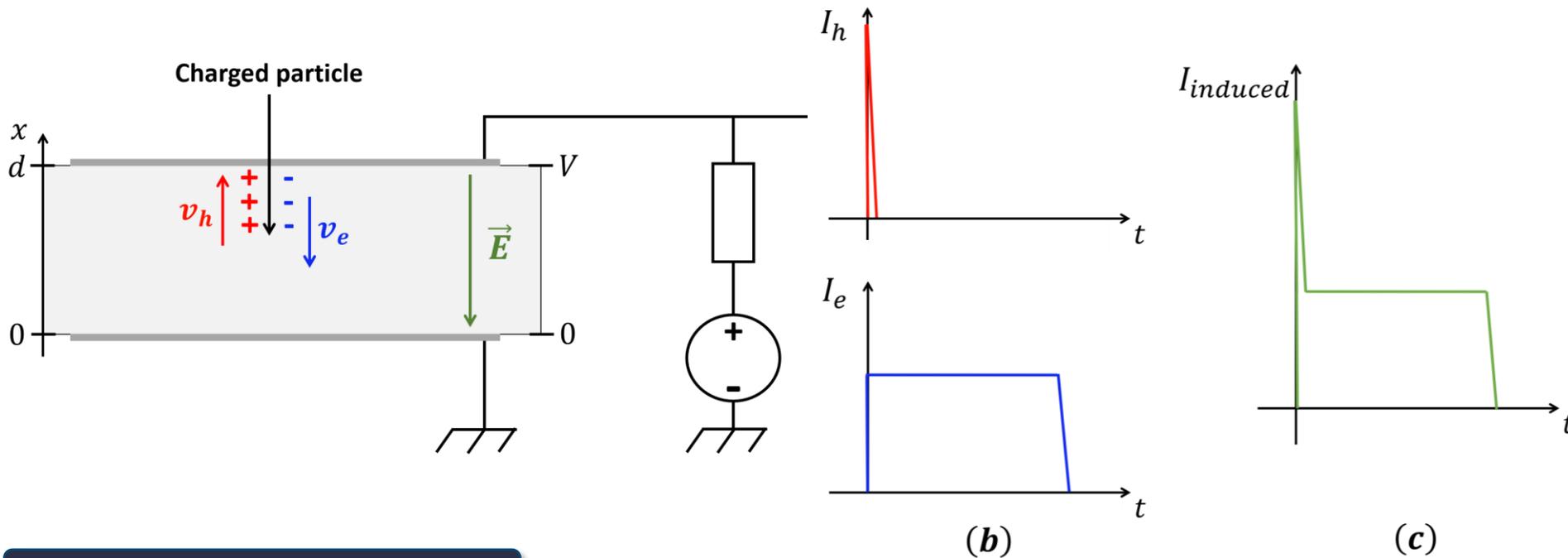
- Ionization: electron – hole pairs creation
- Electric field \rightarrow charge carriers drift

30 keV electrons \rightarrow penetration depth $\sim 5 \mu\text{m} \ll 500 \mu\text{m}$

Study low range particles which stop in the detector

Solid state ionization chamber

Signal shape for low penetration rate particles (like alpha ions or electrons)



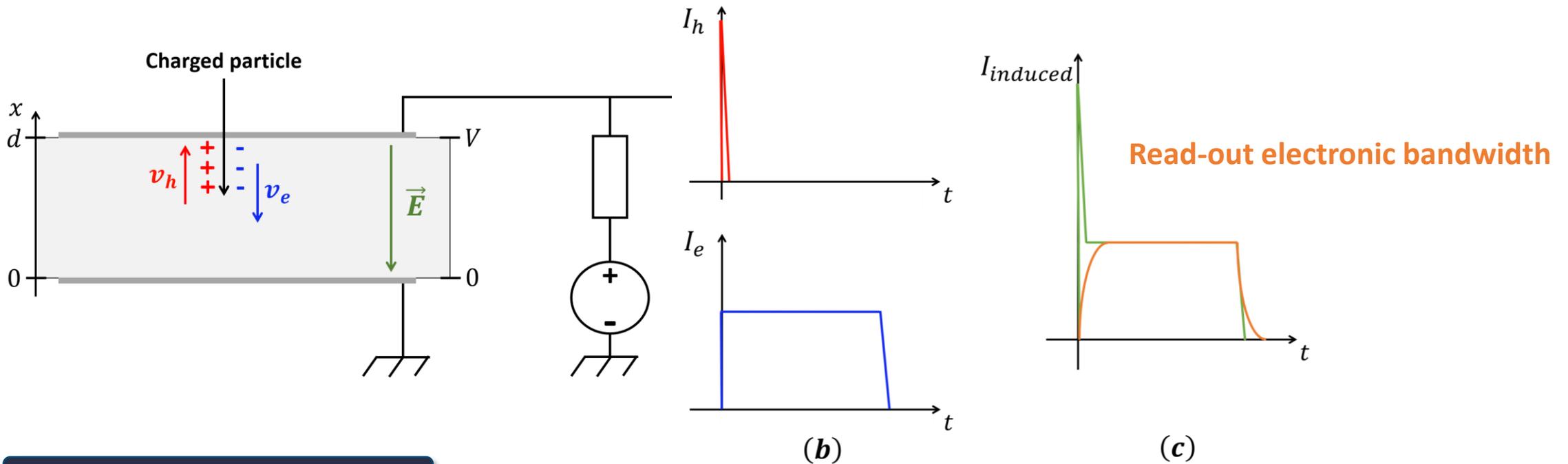
Shockley-Ramo Theorem

$$I_{induced} = q \vec{v}_q \cdot \vec{E}_w$$

Charge movement induces a current on detector electrodes

Solid state ionization chamber

Signal shape for low penetration rate particles (like alpha ions or electrons)



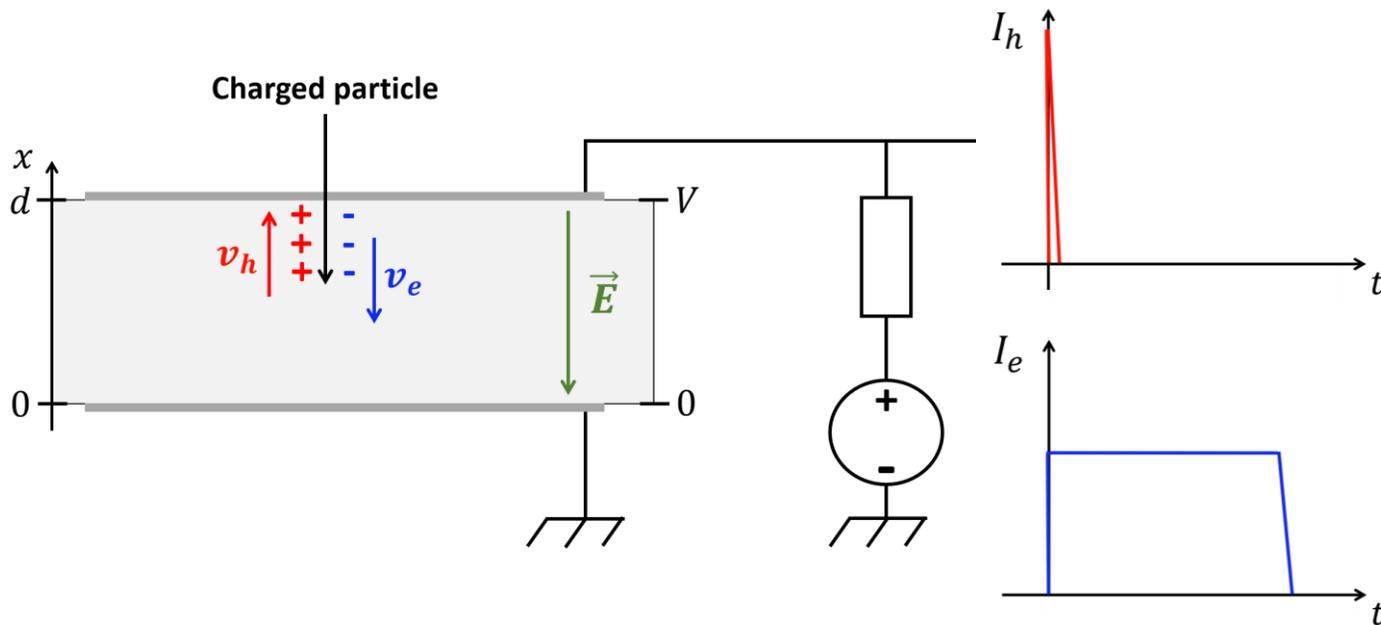
Shockley-Ramo Theorem

$$I_{induced} = q \vec{v}_q \cdot \vec{E}_w$$

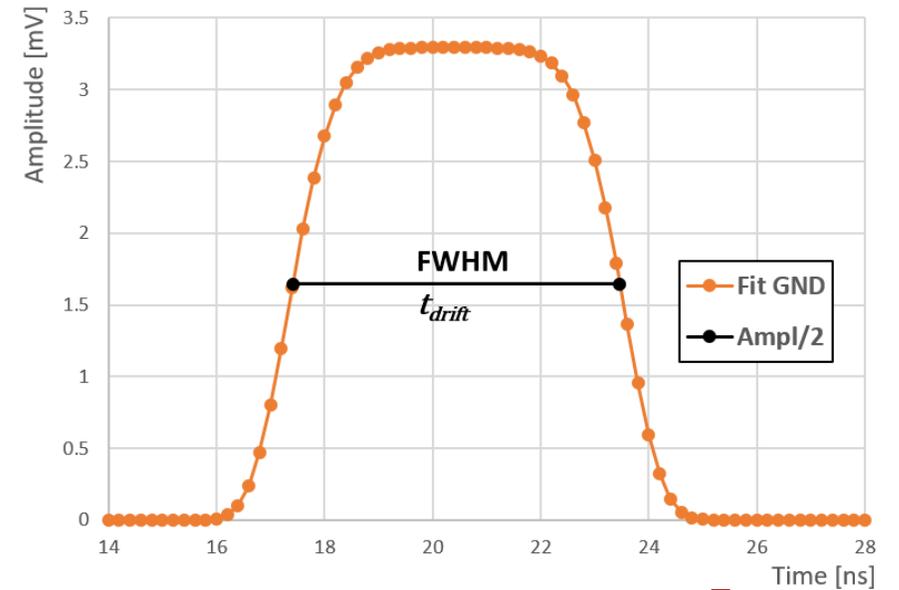
Charge movement induces a current on detector electrodes

Solid state ionization chamber

Signal shape for low penetration rate particles (like alpha ions or electrons)



(b)



(c)

Shockley-Ramo Theorem

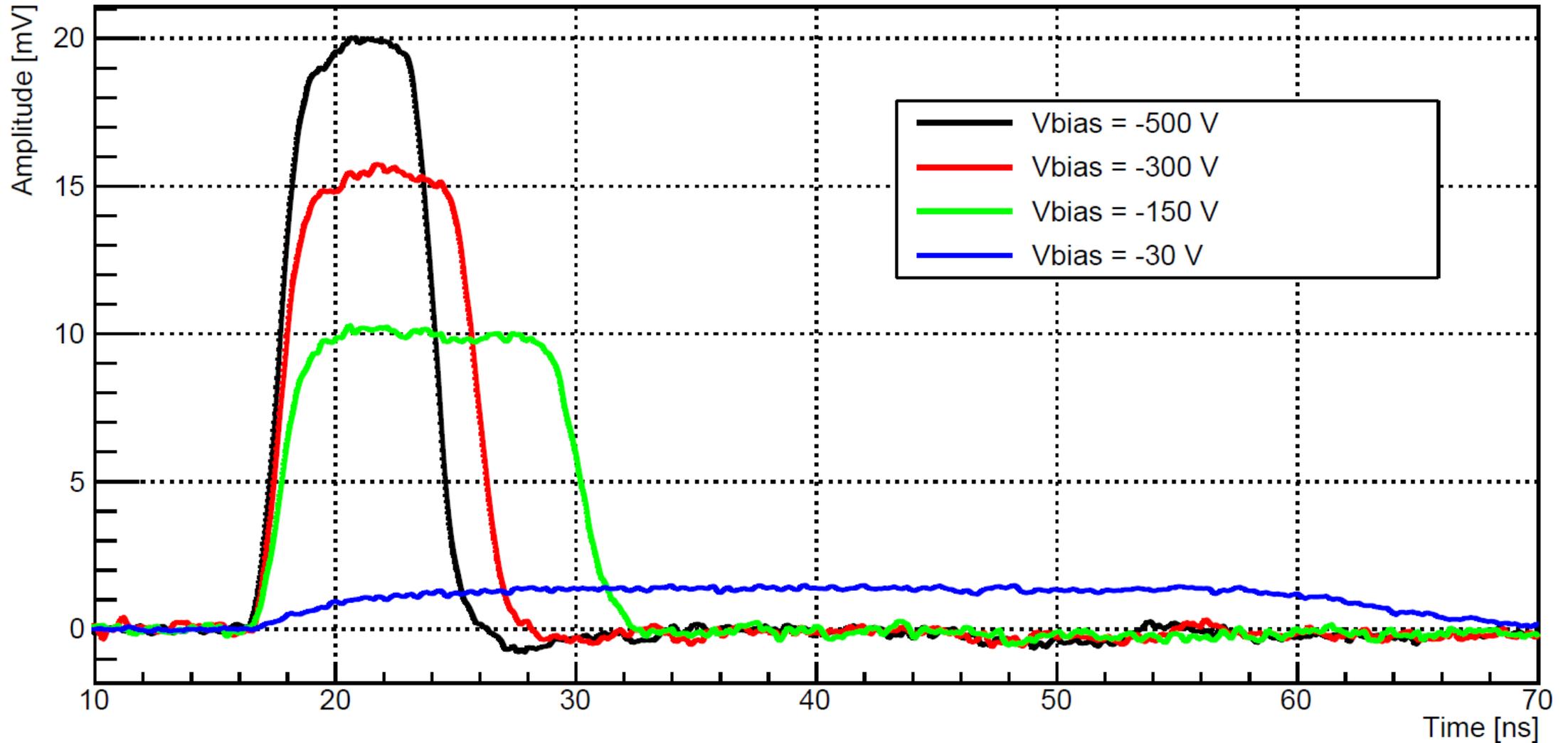
$$I_{induced} = q \vec{v}_q \cdot \vec{E}_w$$

Charge movement induces a current on detector electrodes

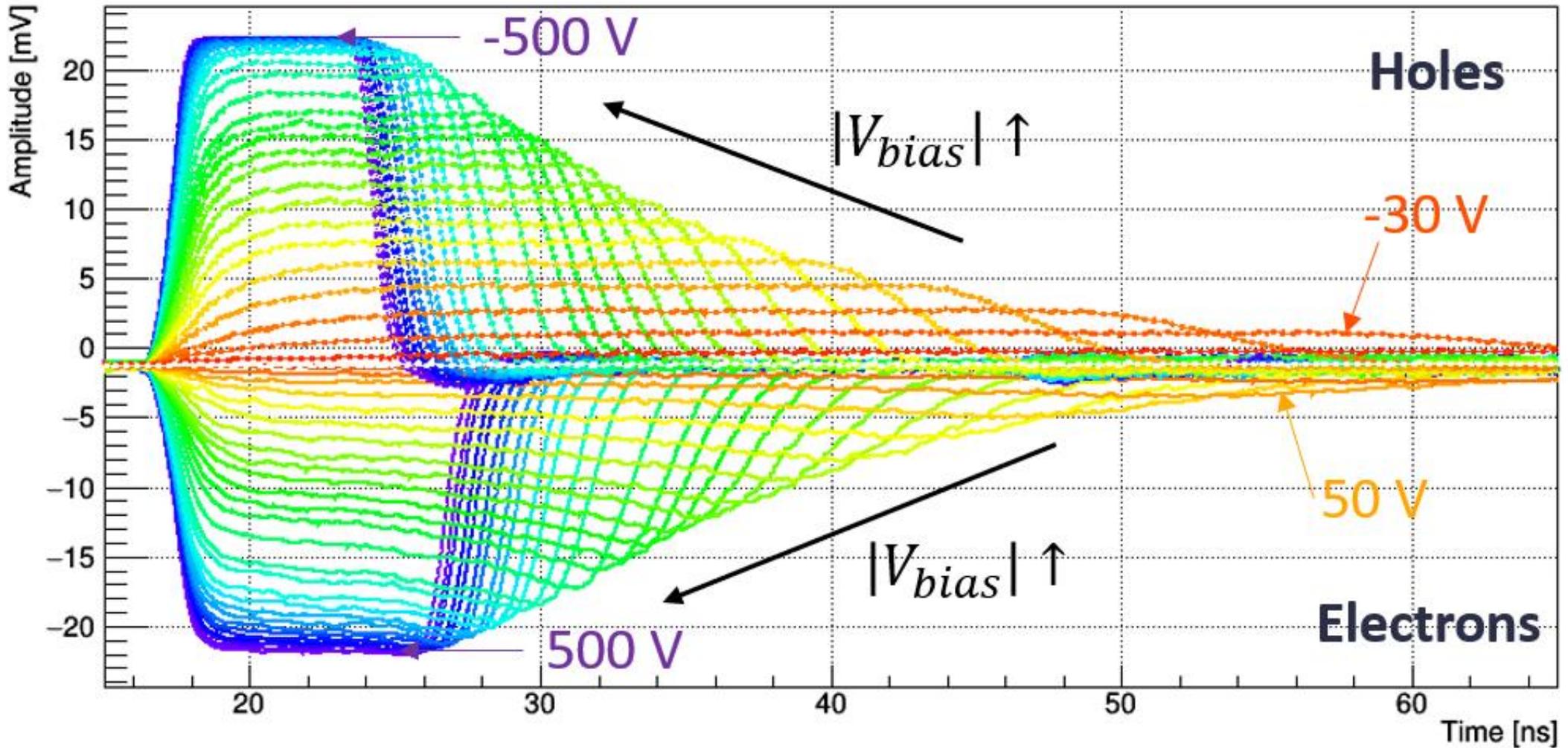
Drift velocity calculation:

$$v_{drift} = \frac{d}{t_{drift}} = \frac{d}{FWHM}$$

Traces on a scCVD diamond at 300 K for holes



Traces on a scCVD diamond at 300 K



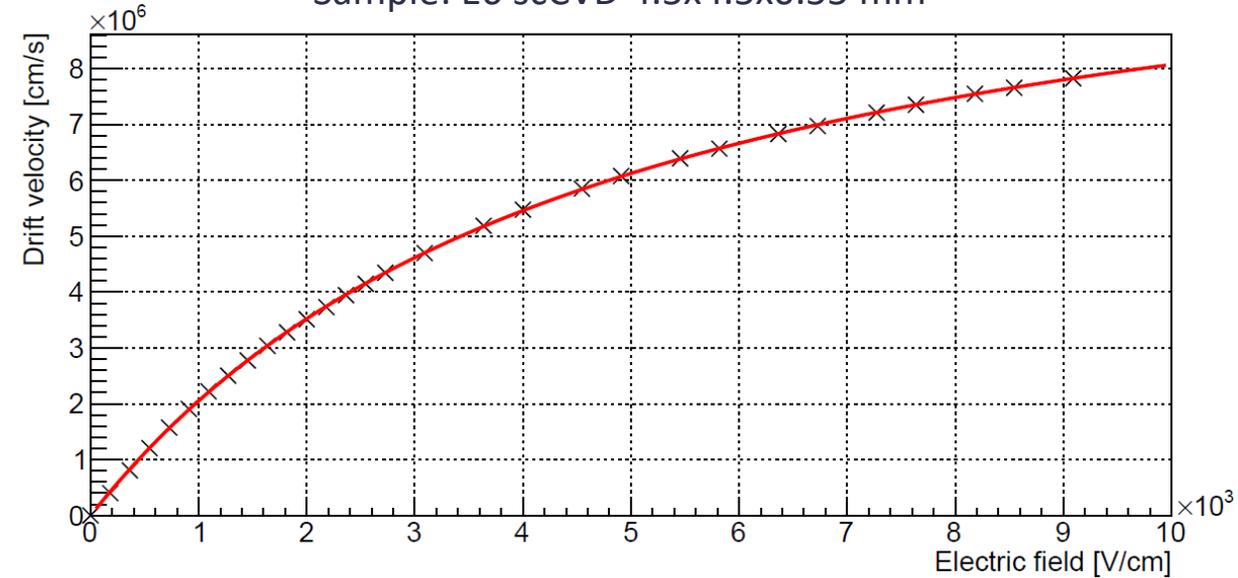
Drift velocity and mobility

Holes			
Sample	Technique	μ_0 [cm ² / (V.s)]	v_{sat} [10 ⁶ cm/s]
E6 scCVD (this work)	ToF – eBIC	2334 ± 10	13.1 ± 0.1
	α source	2380 ± 20	12.1 ± 0.1
E6 scCVD (CEA LIST) *	α source	2349 ± 28	14.1 ± 0.3

Electrons			
Sample	Technique	μ_0 [cm ² / (V.s)]	v_{sat} [10 ⁶ cm/s]
E6 scCVD (this work)	ToF – eBIC	1853 ± 17	8.8 ± 0.1
	α source	2020 ± 20	8.2 ± 0.1
E6 scCVD (CEA LIST) *	α source	2053 ± 87	9.2 ± 0.8

* F. Marsolat, PhD Thesis, 2014, Université Paris 6

Drift velocity for holes

Sample: E6 scCVD 4.5x4.5x0.55 mm³

Fit function:

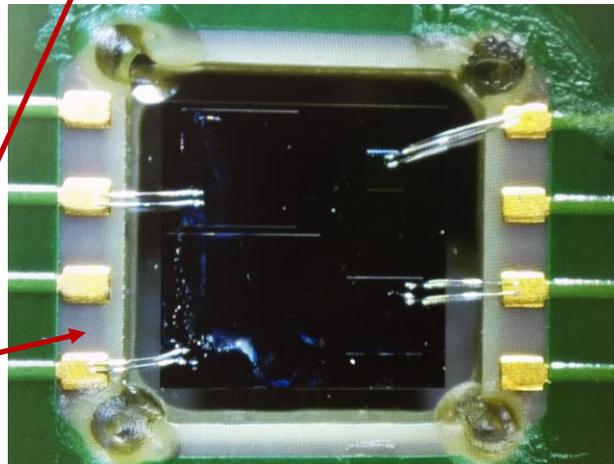
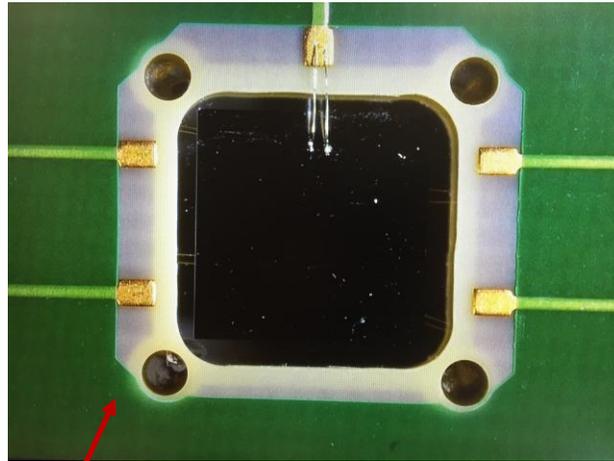
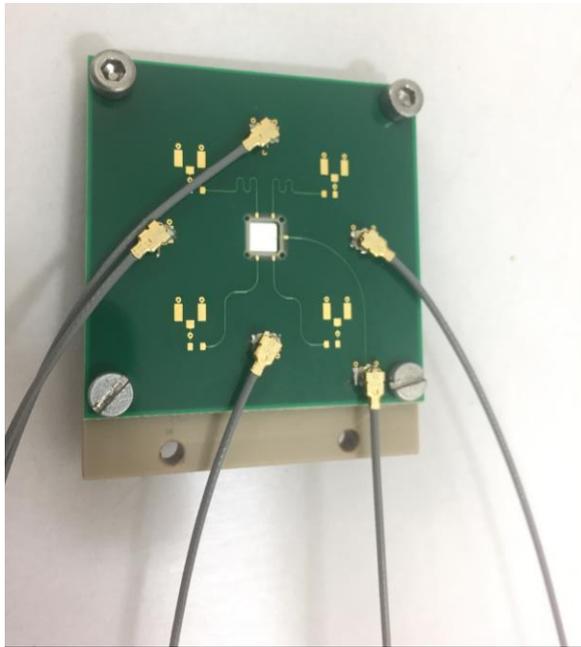
Caughey & Thomas, *Proc. IEEE*, **33**,
p. 1765-1766 (1965)

$$v_{drift}(E) = \frac{\mu_0 E}{1 + \frac{\mu_0 E}{v_{sat}}}$$

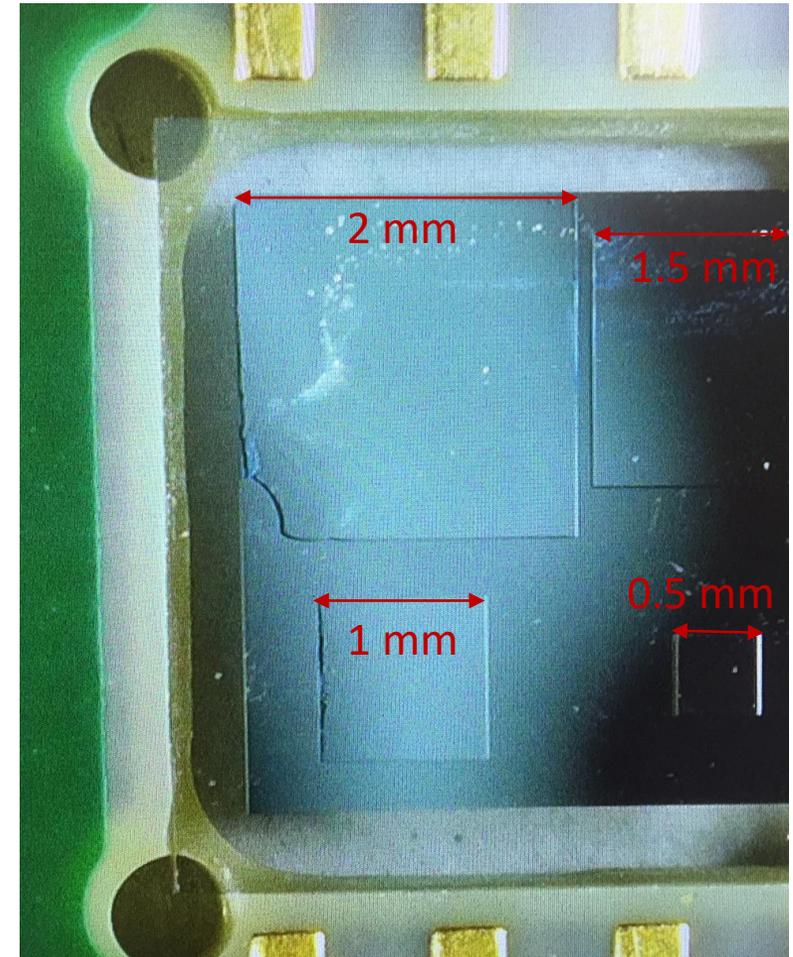
- μ_0 Low field mobility
- v_{sat} Saturation drift velocity
- E Electric field

2D charge mapping of the detector response

Picture of a pixelated diamond

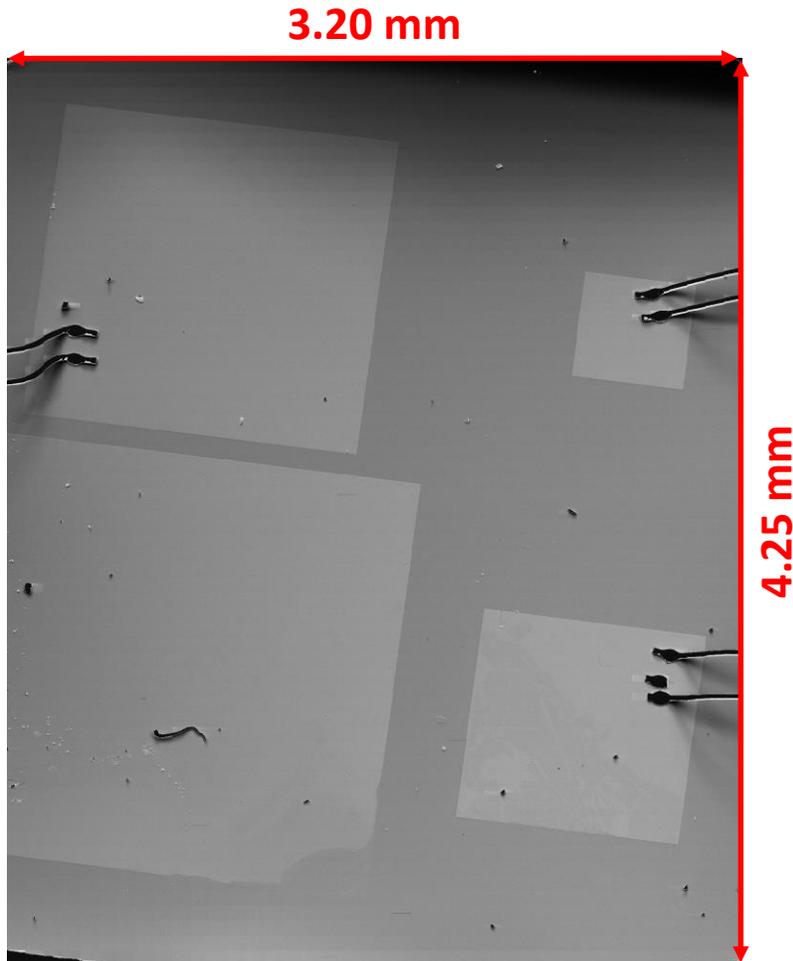
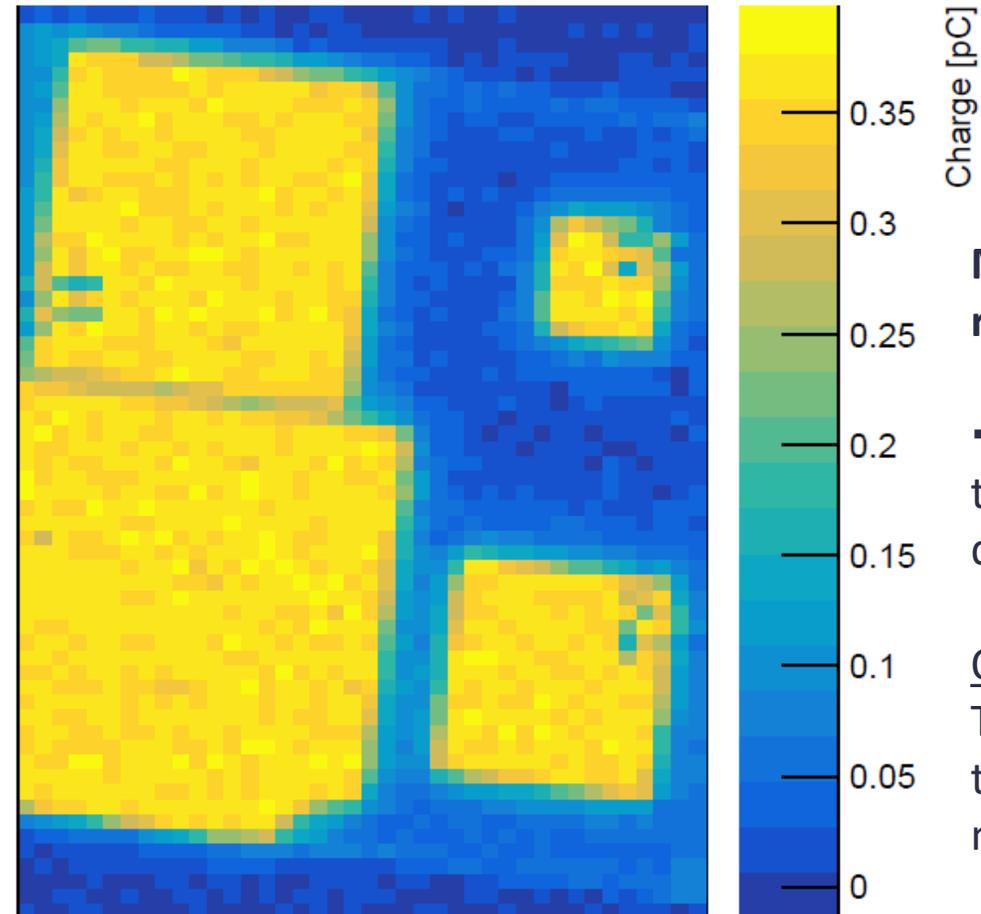


- Aluminium Metallization different on the two:
- Fully metallized side
 - Pixelated side



Mapping of the detector response

SEM mapping picture

Mapping of detector charge response (10 h acquisition – Pixels size: 70x80 μm)

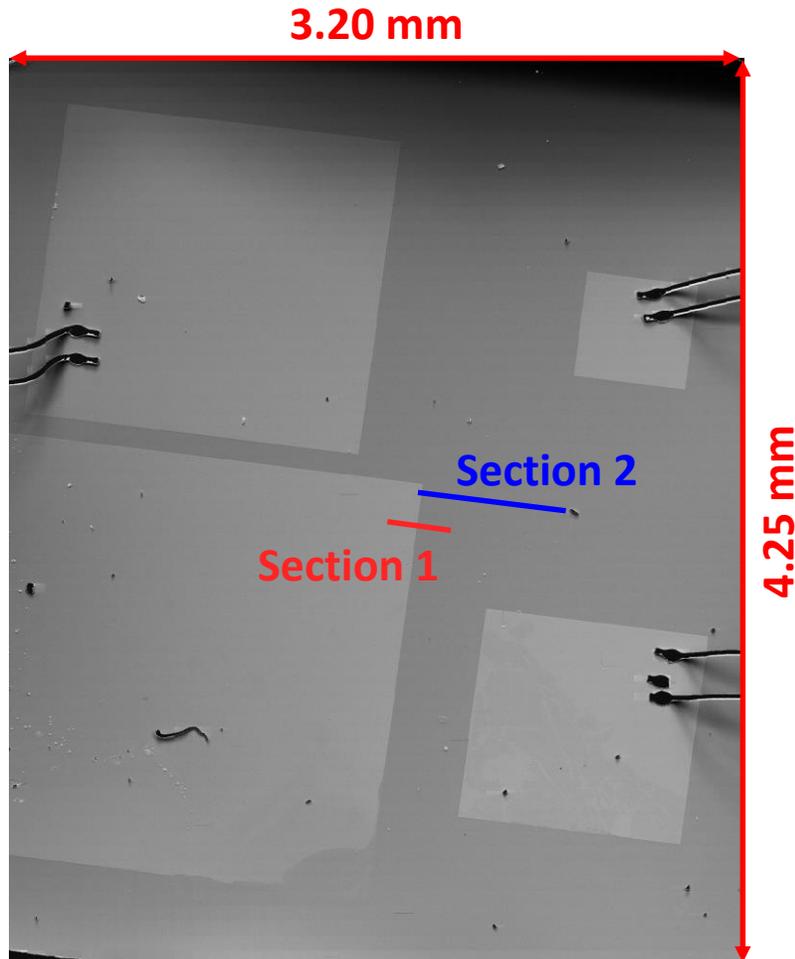
Micrometric spatial resolution

→ Powerful technique to study detector homogeneity

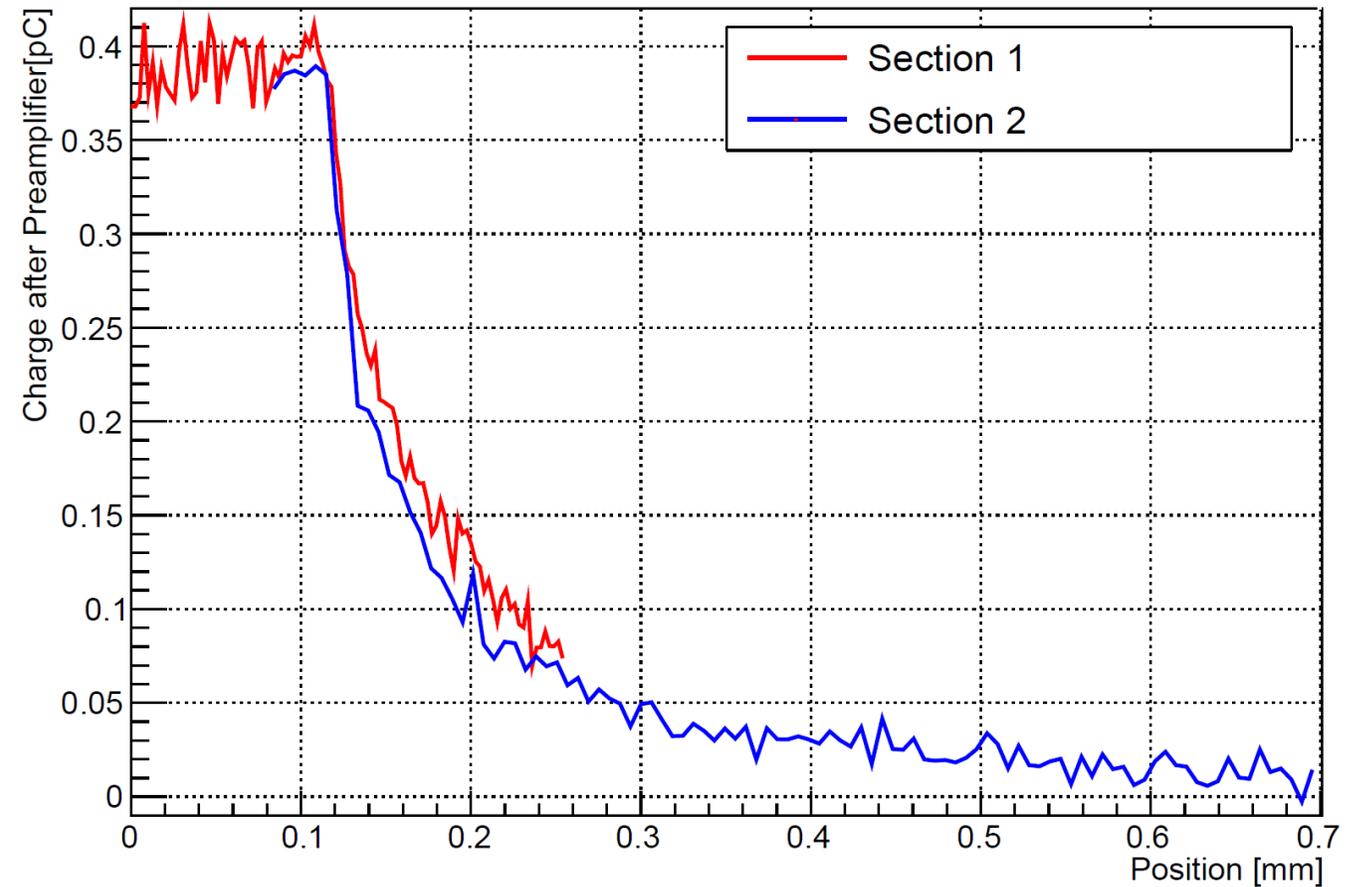
Ongoing:
Time resolved transient current measurement

Mapping of the detector response

SEM mapping picture



Decrease in charge collection when moving away from the edge of the pixel



Conclusions and perspectives

Work done ΔE -E detector

- SRIM simulations done → **1st detector design based on light ions (⁴He)**
- Growth of the p++ and p- layer: done for 1st and 2nd sample
- Etching tests : done (1st sample)
- Manufacture of the 2nd sample : work in progress

ToF – eBIC experiments:

- **First ToF – eBIC setup**
- Beam parameters optimization: work in progress
- Study the transport properties of charge carriers at different temperatures
 - Fundamental outcomes obtained
- Charge mapping of the detector

Perspectives ΔE -E detector

- Manufacture of the 2nd sample + detector tests (LPSC setup, AIFIRA, eBIC...)

ToF – eBIC experiments:

- Make the test bench technologically accessible (write technological instructions) → experimental platform open to other experiments in diamond international community

Scientific output

Oral Presentation in Conferences

- April 2021** A. Portier, J. Pernot, M.-L. Gallin-Martel, F. Donatini, D. Dauvergne, Time of Flight measurement using electron Beam Induced Current on a single crystal diamond detector, **2021 Virtual MRS Spring Meeting & Exhibit**
- June 2021** A. Portier, J. Pernot, M.-L. Gallin-Martel, F. Donatini, D. Dauvergne, Time of Flight measurement using electron Beam Induced Current on a single crystal diamond detector, **International Conference on New Diamond and Nano Carbons 2020-2021**
- Sept. 2021** A. Portier, F. Donatini, D. Dauvergne, M.-L. Gallin-Martel, J. Pernot, Transient time measurement using electron Beam Induced Current on a single crystal diamond, **31st International Conference on Diamond and Carbon Materials**

Awards in Conferences

- June 2021** **Silver Oral Award** received at the International Conference on New Diamond and Nano Carbons 2020-2021

Articles

- April 2021** C. Hoarau, G. Bosson, J.-L. Bouly, S. Curtoni, D. Dauvergne, P. Everaere, M.-L. Gallin-Martel, S. Marcatili, J.-F. Muraz, A. Portier, “RF pulse amplifier for CVD-diamond particle detectors”, [JINST](#) 16 T04005, 2021
- Sept. 2021** M.-L. Gallin-Martel, [...], A. Portier *et al.*, “Characterization of diamond and silicon carbide detectors with fission fragments”, [Front. Phys.](#) Vol. 9, p. 732 – 730
- Oct. 2021** A. Portier *et al.*, “Development of a time resolved electron Beam Induced Current setup and characterization of single crystal diamond using transient time technic”, will be submitted in APL



Thank you for your attention!

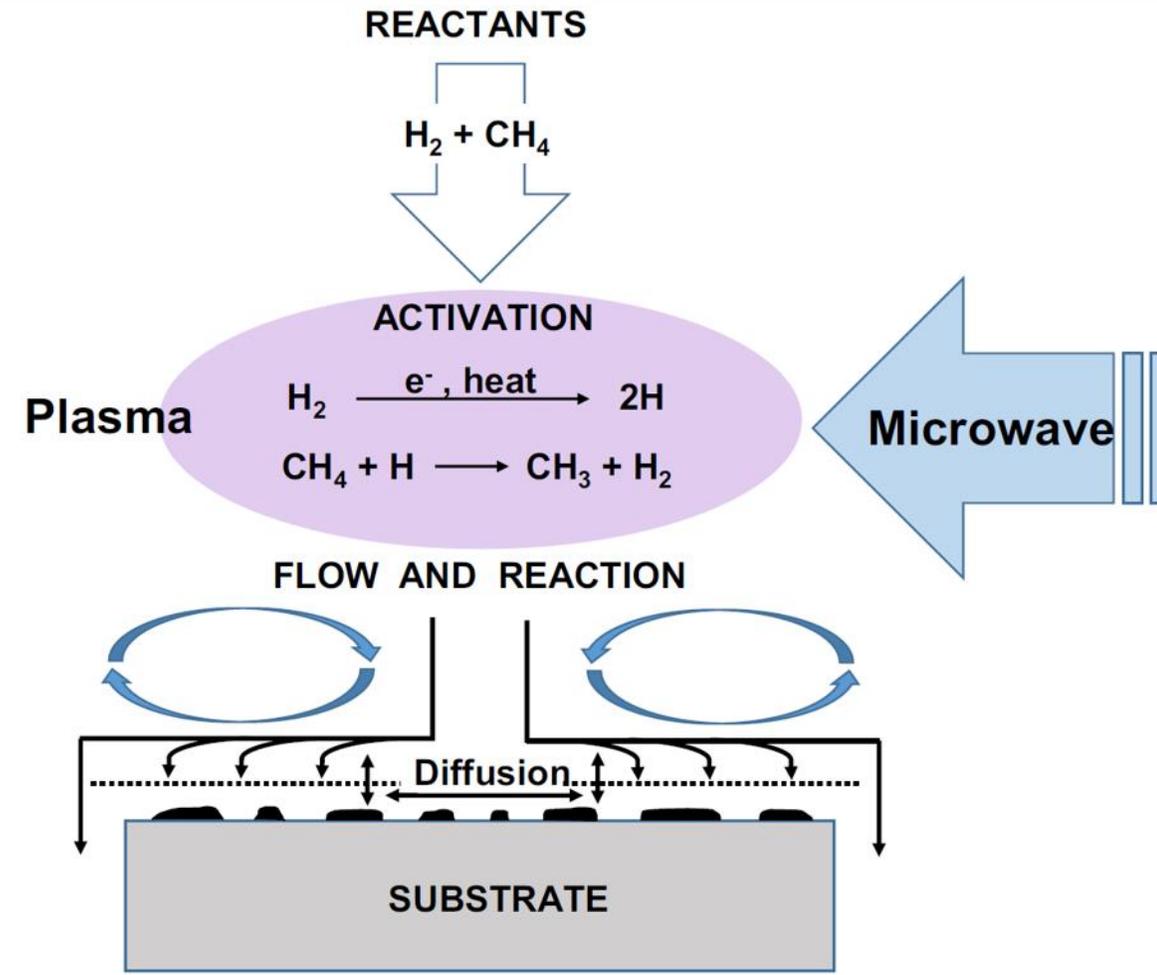
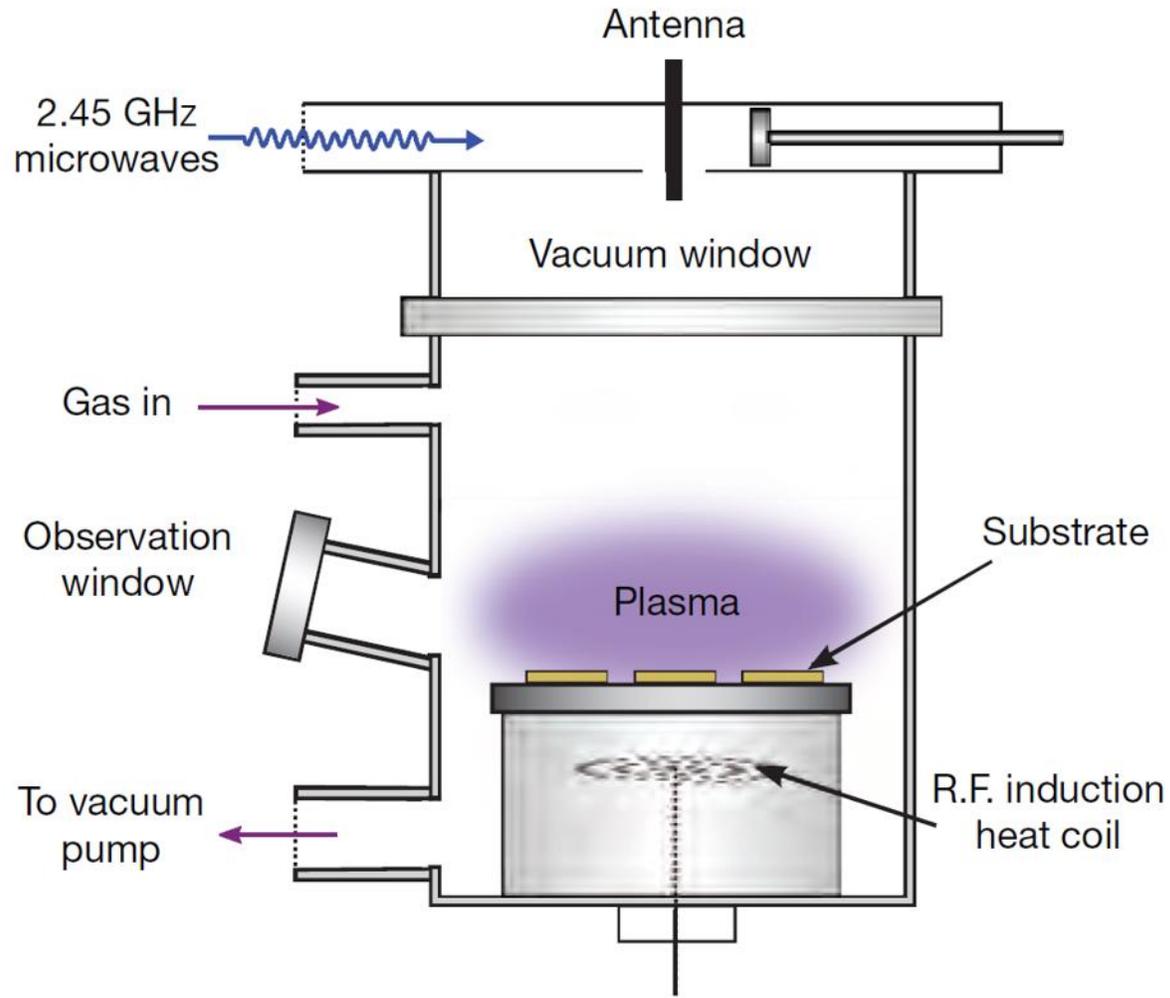




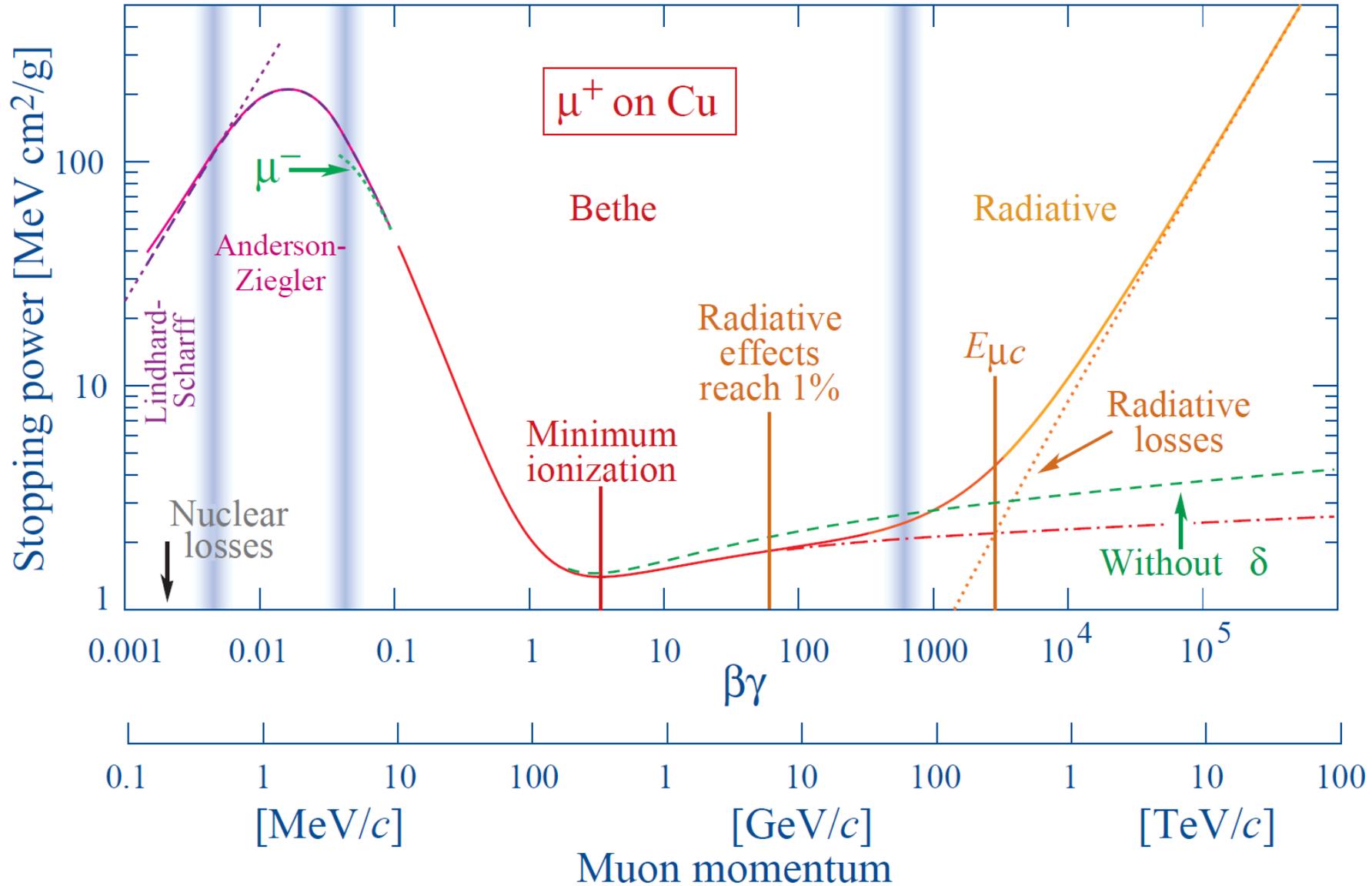
Backup slides



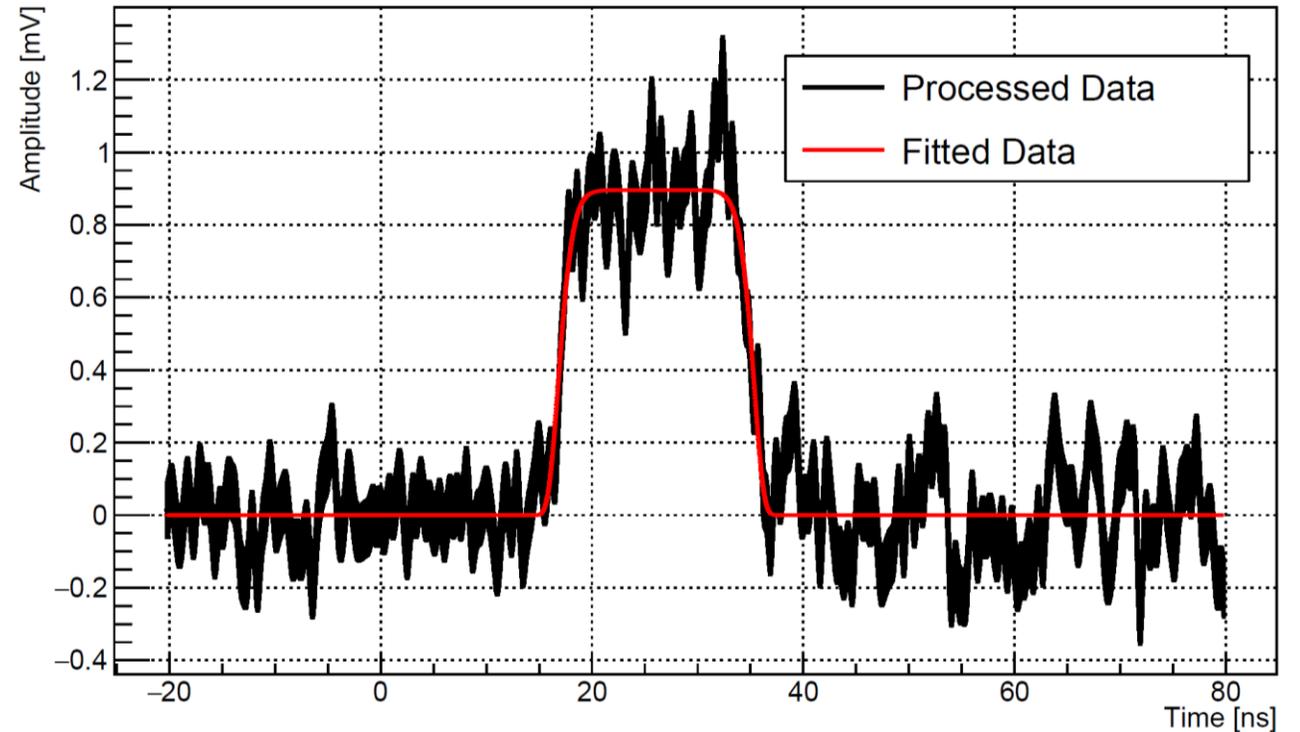
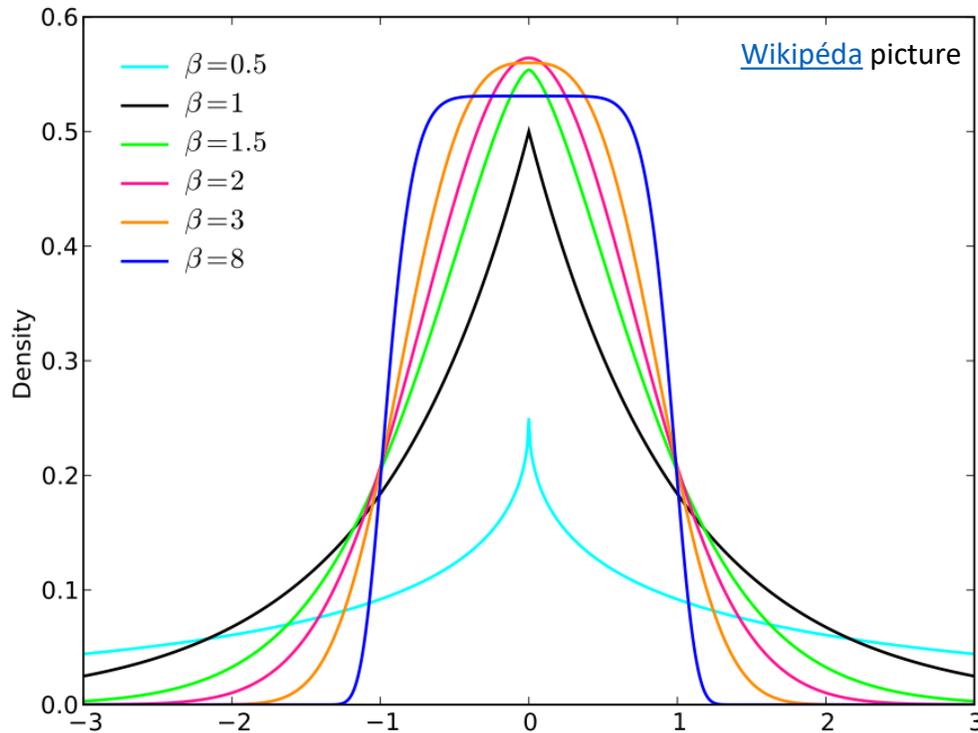
Diamond growth by Microwave Plasma enhanced Chemical Vapor Deposition (MPCVD)



Stopping power vs particle energy



Drift time calculation using Generalized Normal Distribution to fit the Waveforms



Variable:

t Time

Fit parameters:

$const$ Maximum amplitude

α Scale parameter

β Shape parameter

μ Position parameter

$$V(t) = const \cdot \exp \left\{ - \left(\frac{|t-\mu|}{\alpha} \right)^\beta \right\}$$



$$t_{drift} = 2\alpha \cdot \ln 2^{1/\beta}$$