Design and characterization of a monolithic diamond ΔE-E telescope for particle identification

doctoral seminar

Alexandre PORTIER

PhD director: **Marie-Laure Gallin-Martel (LPSC)**

PhD co-director: **Julien Pernot (Institut Néel)**

The 15 / 03 / 2021

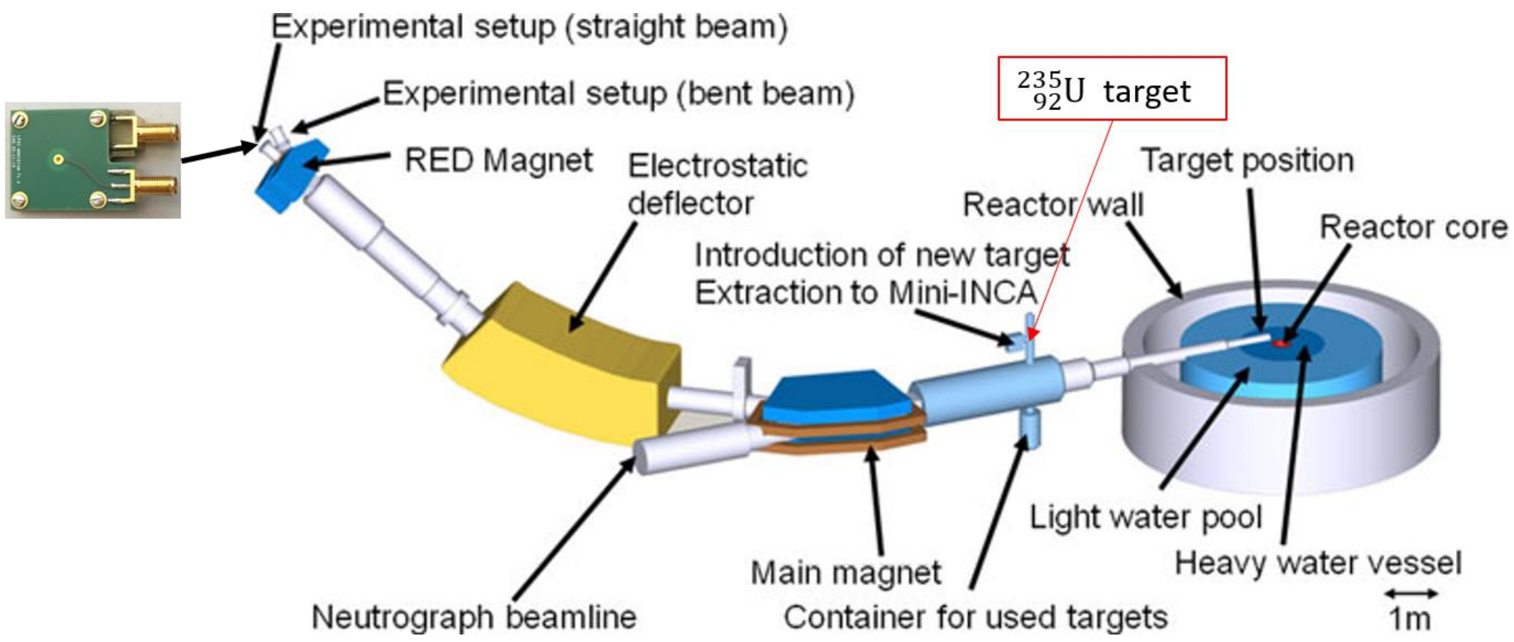
International collaboration: Japan-France collaboration (test of Japanese pn junction) ; experiments at ILL (Lohengrin and FIPPS)

Project DIATEL (IDEX UGA) hold by Denis Dauvergne + **Project DIAMTECH (IN2P3-CNRS)** hold by Marie-Laure Gallin-Martel

PRC JSPS – CNRS TYL IN2P3

PhD thesis motivations

LOHENGRIN experiment at ILL



LOHENGRIN spectrometer at the Laue-Langevin Institut Grenoble.

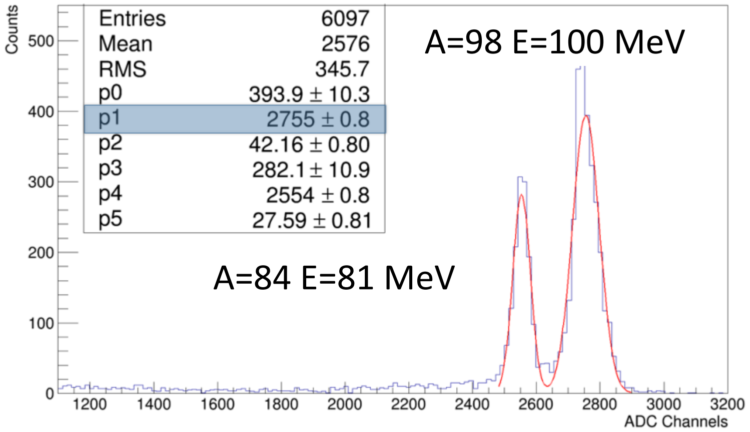
- **A magnetic field** deflects vertically the FF according to their $\frac{E}{q}$
- **An electric field** deflects horizontally the FF according to their $\frac{A}{q}$

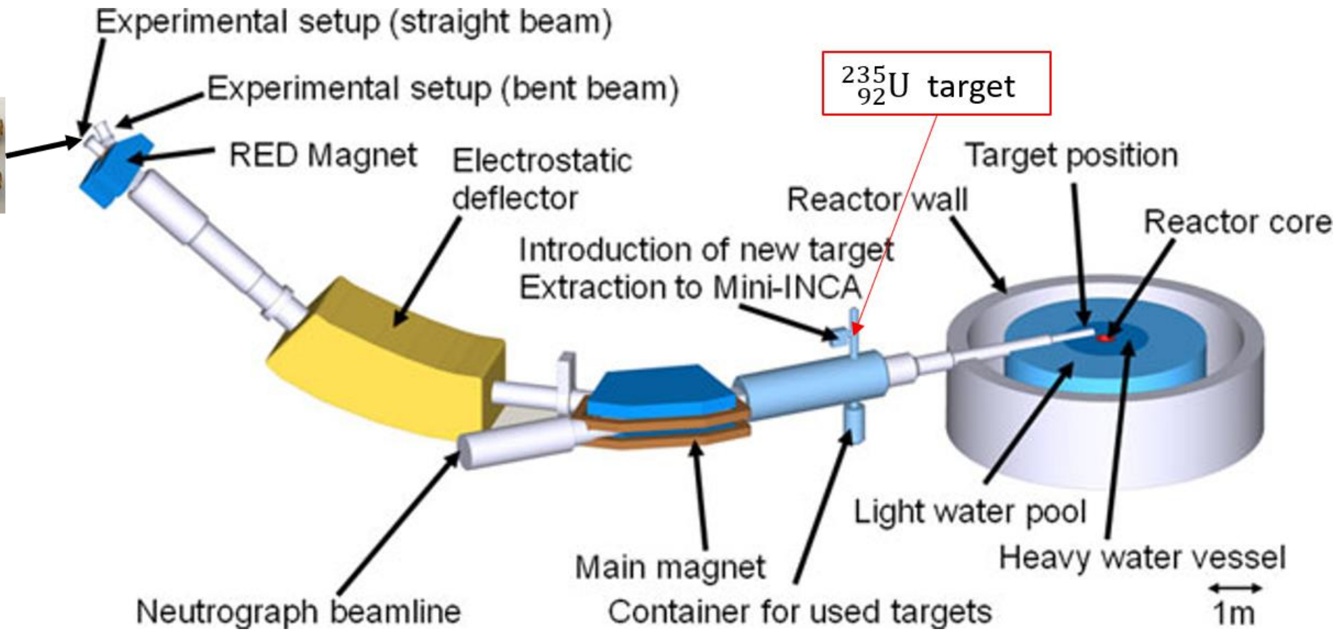
PhD thesis motivations

LOHENGRIN experiment at ILL

=> one should expect that the FF98 peak at the energy of 100 MeV is at ADC = 5527

BUT : observed at the channel 2755 !!!!





The Pulse Height Defect (PHD) :

$$\Delta E = E_k - E_{DD}.$$

E_k : The kinetic energy of an incident ion.

E_{DD} : The energy derived from the measured electric signal.

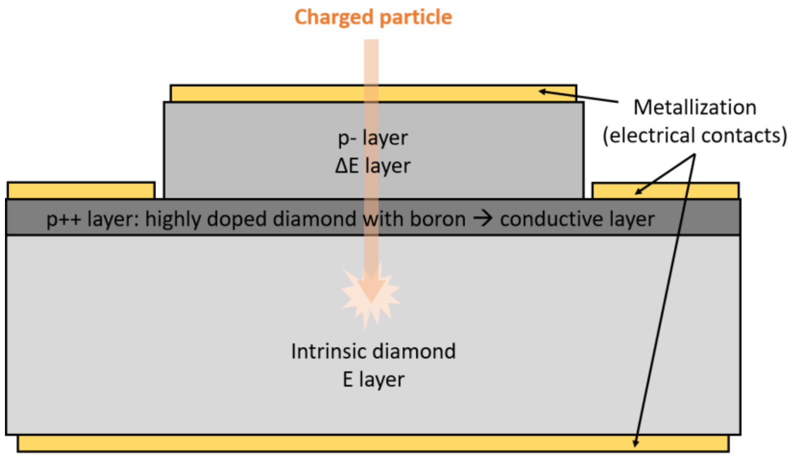
50 % of the deposited energy is not reconstructed: Pulse Height defect !

LOHENGRIN spectrometer at the Laue-Langevin Institut Grenoble.

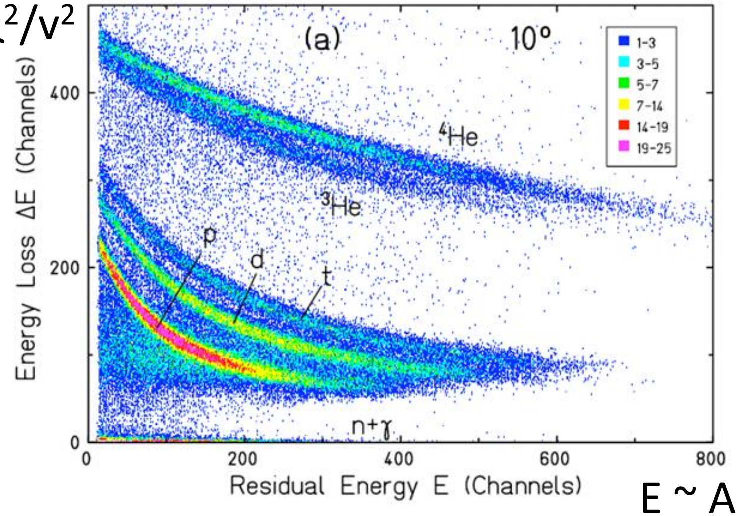
- **A magnetic field** deflects vertically the FF according to their $\frac{E}{q}$
- **An electric field** deflects horizontally the FF according to their $\frac{A}{q}$

PhD thesis main goals

ΔE-E detector



$\Delta E \sim Q^2/v^2$

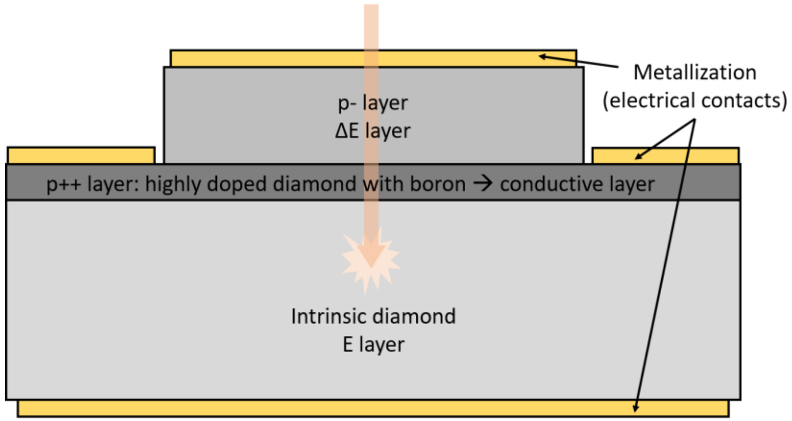


$E \sim A.v^2$

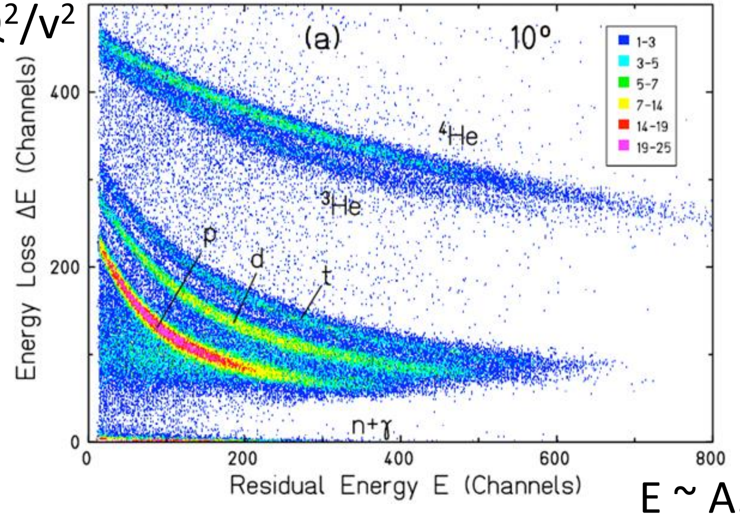
Gunzert-Marx *et al.*, *New Journal of Physics* **10** (2008)

PhD thesis main goals

ΔE-E detector



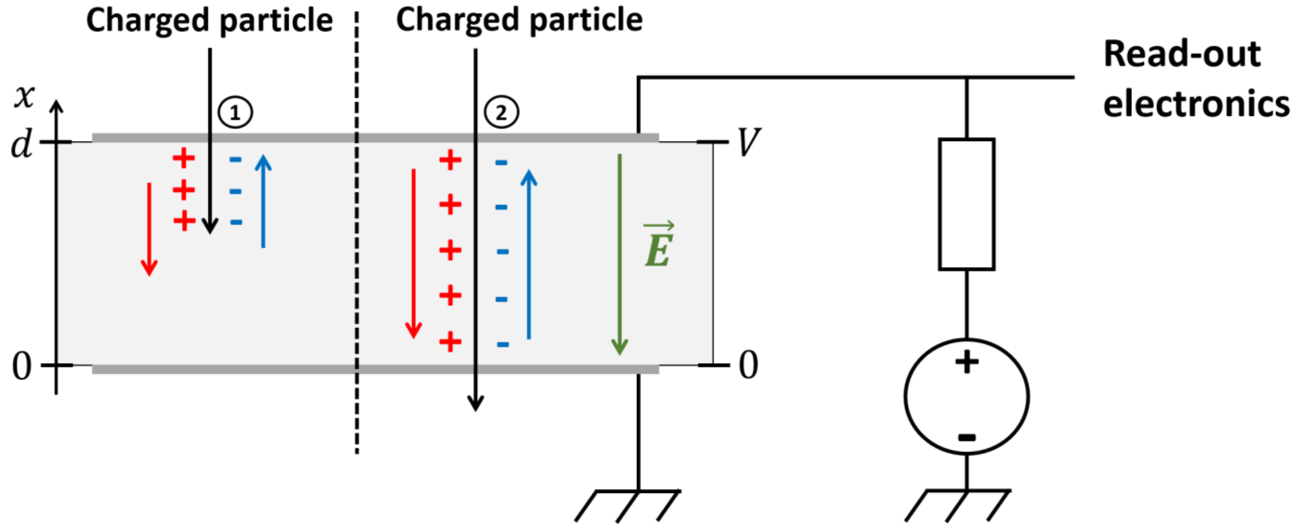
$\Delta E \sim Q^2/v^2$



$E \sim A.v^2$

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

Solid ionization chamber



Charge particle in the medium:

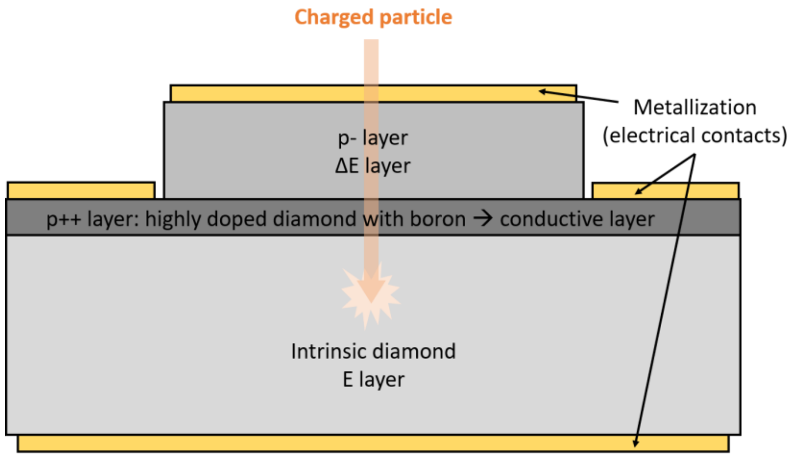
- Ionization: electron – hole pairs creation
- Electric field → charge carriers drift

Two different situations:

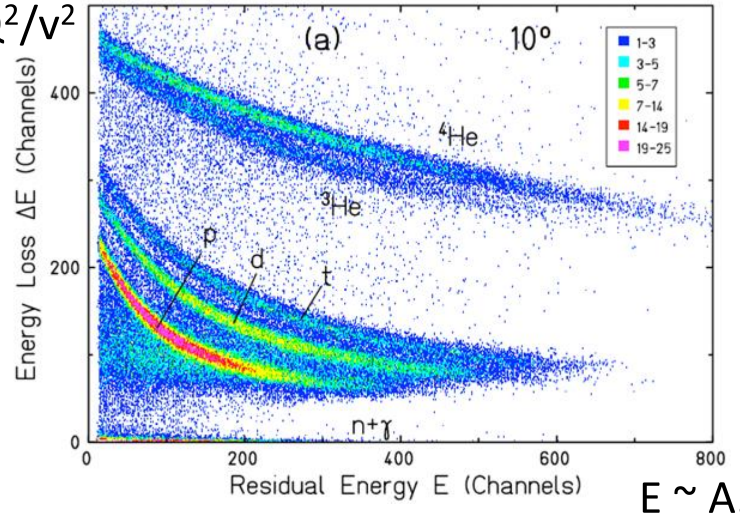
1. Particles that stop in the detector
2. Particles that pass through the detector

PhD thesis main goals

ΔE-E detector



$\Delta E \sim Q^2/v^2$

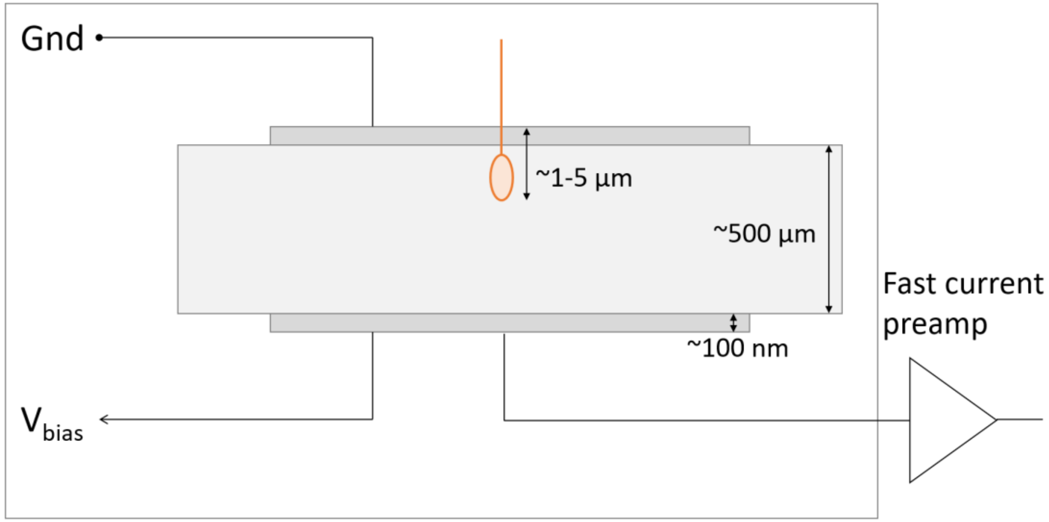


$E \sim A.v^2$

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

ToF – eBIC setup development

Time of Flight – electron Beam Induced Current



Study low range particles which stop in the detector

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

Diamond properties

Physical properties compared at 300 K

	Diamond	Silicon	SiC
Undoped material resistivity (Ω.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 ($cm^2.V^{-1}.s^{-1}$)	> 2000	800 – 1400	115 - 1000
Thermal conductivity ($W.cm^{-1}.K^{-1}$)	20	1.5	1.2

Diamond as a detector :

- ✓ **Very low leakage current**
- ✓ **Low noise**
- ✓ **Good radiation hardness**
- ✓ **Very fast**
- ✓ **Work at room temperature**

Diamond properties

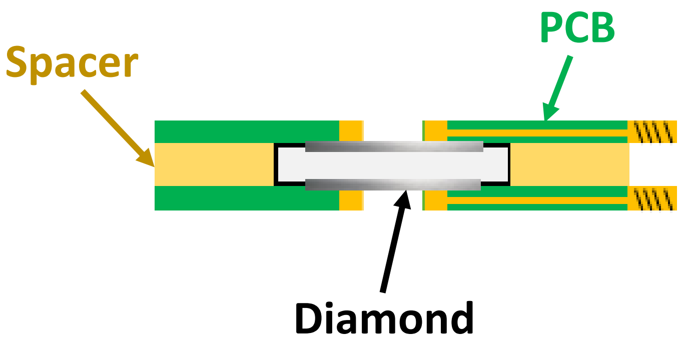
Physical properties compared at 300 K

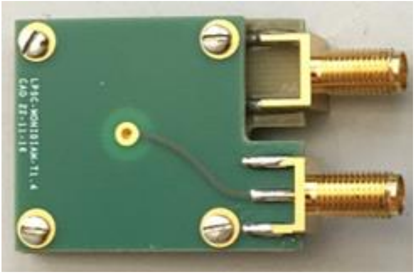
	Diamond	Silicon	SiC
Undoped material resistivity (Ω.cm)	> 10^{13}	$2.3 \cdot 10^5$	> 10^5
Bandgap (eV)	5.5	1.1	3.26
Pair creation energy e^-/h^+ (eV)	13.1	3.6	7.8
Displacement energy (eV)	43	25	20 - 35
Carrier mobility ($cm^2.V^{-1}.s^{-1}$)	> 2000	800 – 1400	115 - 1000
Thermal conductivity ($W.cm^{-1}.K^{-1}$)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

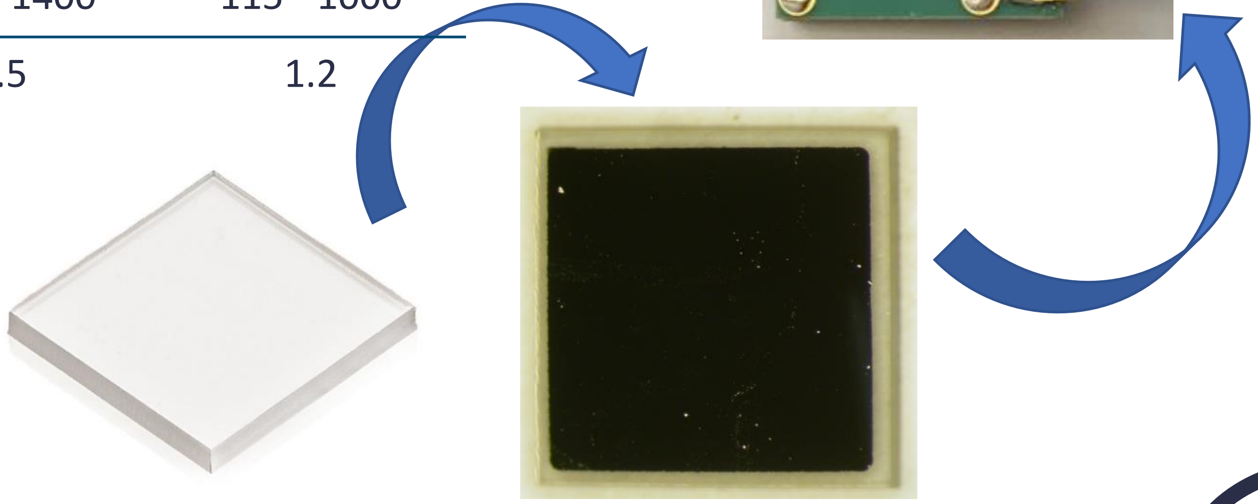
Diamond as a detector :

- ✓ **Very low leakage current**
- ✓ **Low noise**
- ✓ **Good radiation hardness**
- ✓ **Very fast**
- ✓ **Work at room temperature**

Diamond holder at LPSC







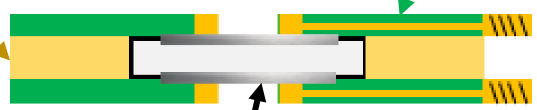
Diamond properties

Physical properties compared at 300 K

	Diamond	Silicon	SiC
Undoped material resistivity (Ω.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 ($cm^2.V^{-1}.s^{-1}$)	> 2000	800 – 1400	115 - 1000
Thermal conductivity ($W.cm^{-1}.K^{-1}$)	20	1.5	1.2

Diamond as a detector :
- ✓ Very low leakage current
- ✓ Low noise
- ✓ Good radiation hardness
- ✓ Very fast
- ✓ Work at room temperature

Diamond holder at LPSC



Read out electronic and acquisition

Large bandwidth current preamplifier
Gain > 40 dB
Bandwidth 2 GHz

Fast numerical oscilloscope

Outlines

1. ΔE-E detector : from simulation to first samples
    - SRIM Simulations & first design
    - First sample processing steps

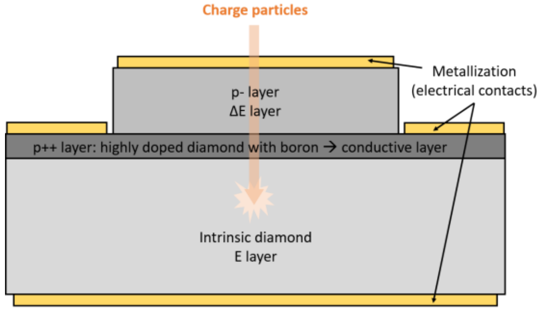
2. Electron Beam Induced Current (eBIC) experiments at Néel
    - Set up of the experiment
    - Time of flight studies
    - Diamond properties study at different temperatures
    - Detector mappings

Outlines

1. ΔE-E detector : from simulation to first samples
   - SRIM Simulations & first design
   - First sample processing steps

2. Electron Beam Induced Current (eBIC) experiments at Néel
   - Set up of the experiment
   - Time of flight studies
   - Diamond properties study at different temperatures
   - Detector mappings

SRIM simulations – requirements



The Stopping and Range of Ions in Matter

Goals:

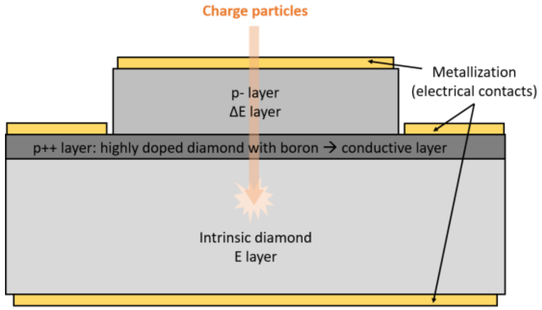
Simulate the energy deposition in the ΔE-E detector for different ions, ion energies and detector architectures.

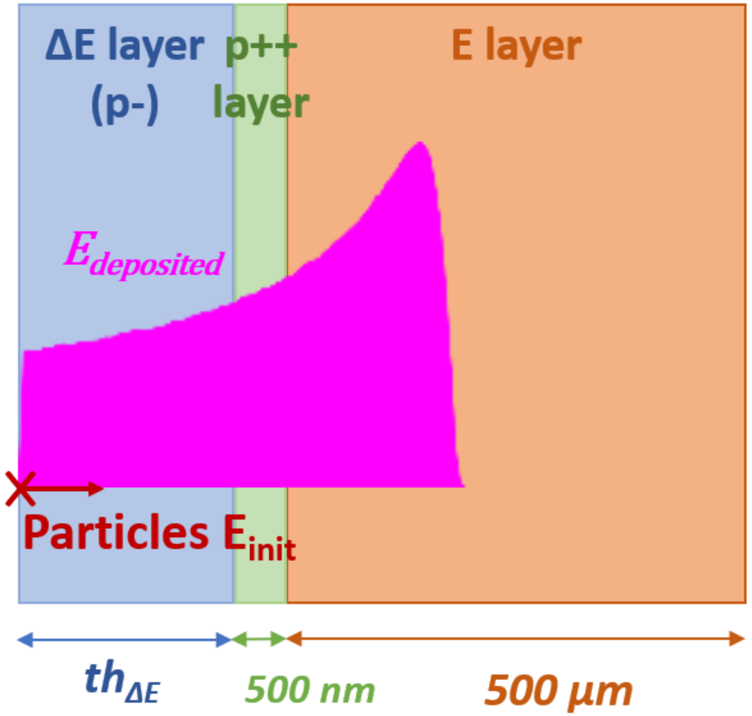
Determine the thickness of the ΔE (p-) layer of the first sample

Layers	Parameters	Consideration & criteria	Requirements	Growth method
p- layer	Thickness	• Energy deposition need to be measurable • Resistivity and leakage current	(1 MeV < ΔE < E_{init}/2) I_{leak} < 1 nA	MPCVD Microwave Plasma enhanced Chemical Vapor Deposition DiamFab
	Doping	• Non intentionally doped (Avoid defaults)	As low as possible	
	Contact	• Resistivity and leakage current	I_{leak} < 1 nA	
p++ layer	Thickness	• Dead area of detection • Growth layer feasibility	thinnest as possible > 200 nm ➔ 500 nm	
	Doping	• Could be considered as a conductor	[B] > 10^{20} cm^{-3}	
Substrate	Thickness	• Enough thick to stop the particle	~550 µm	E6 scCVD
	Doping	• Non intentionally doped (Avoid defaults)	As low as possible	

SRIM simulations – explanations

SRIM simulations explanation scheme





Goal : dimensioning the p- layer of the detector

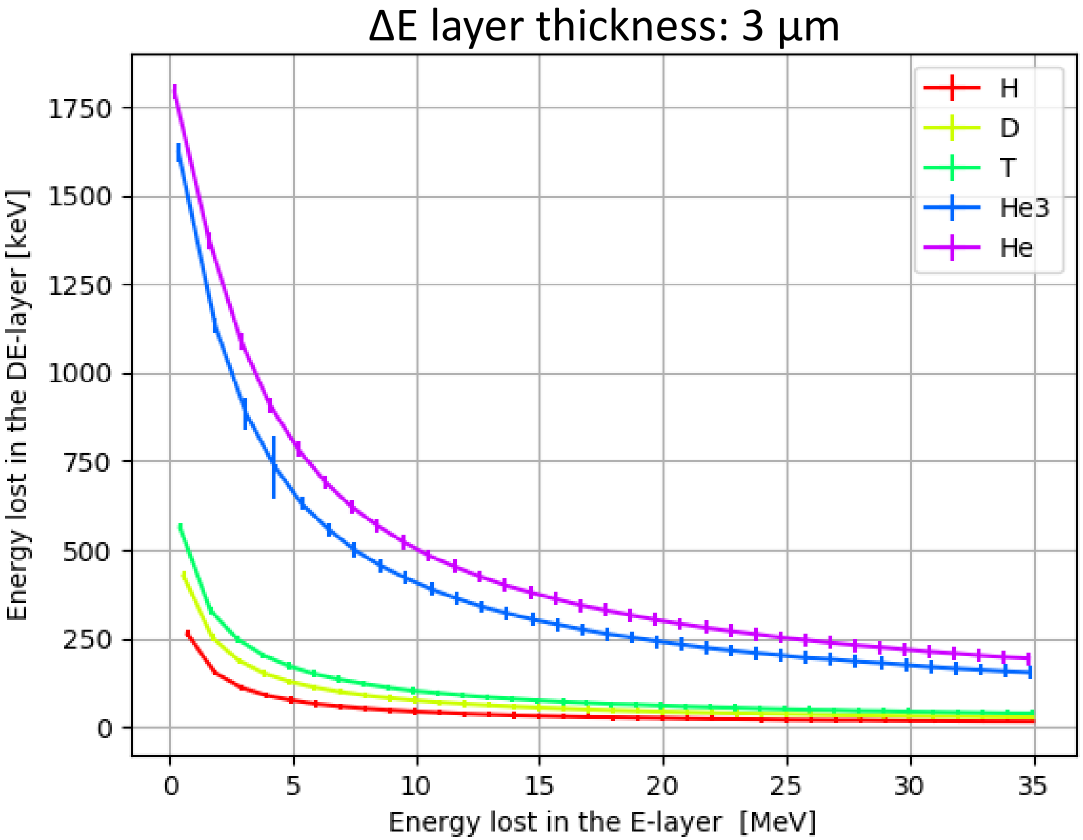
Simulation details :

- 1 ion (H, D, T, ^{3}He, **^{4}He,** FF)
- Different ion initial energies (for ^{4}He: [1; 10] MeV)
- Different ΔE stage thickness $th_{\Delta E}$ [0.1, 10] µm

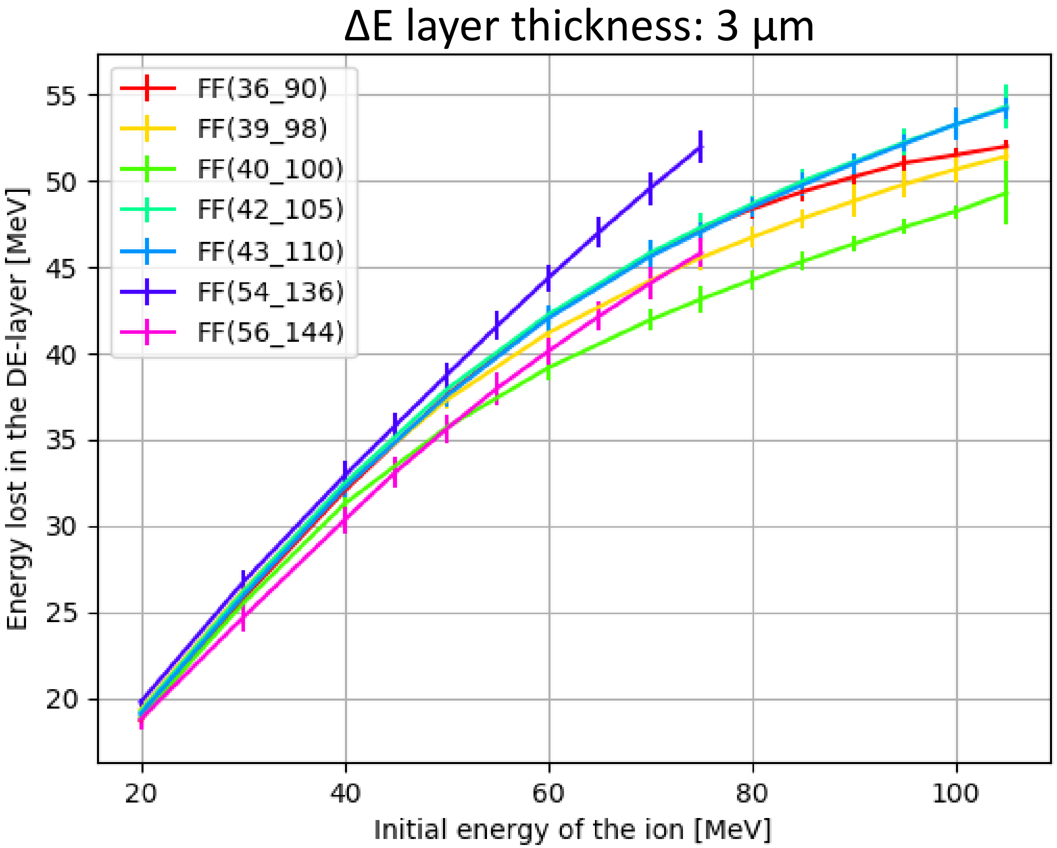
➔ Graph $\Delta E \pm \sigma_{\Delta E}$ vs E_{init}

SRIM simulations – Results

SRIM simulations for light ions



SRIM simulations for heavy ions

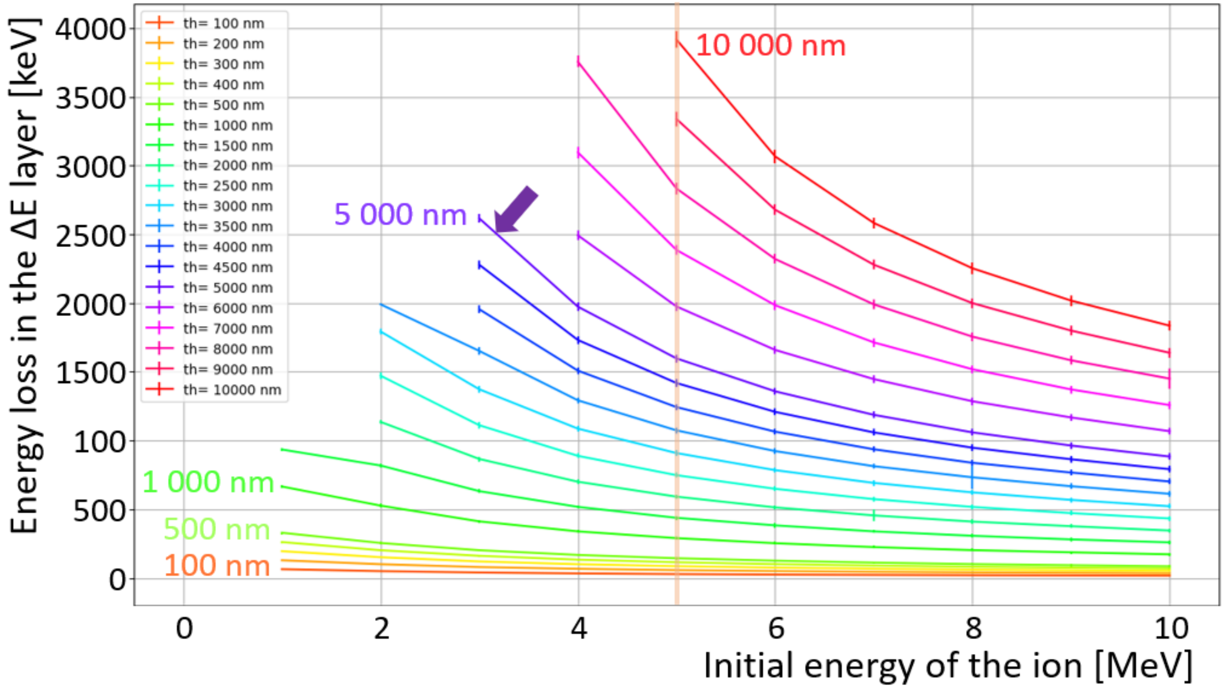


Observations : the mass ordering is respected for the light isotopes but not for the heaviest ones. **Discussion with Ulli Koester → difficult to do simulation using FF (Fission Fragments)**

1st design based on the light ion simulations → in particular: 5 MeV alpha particles

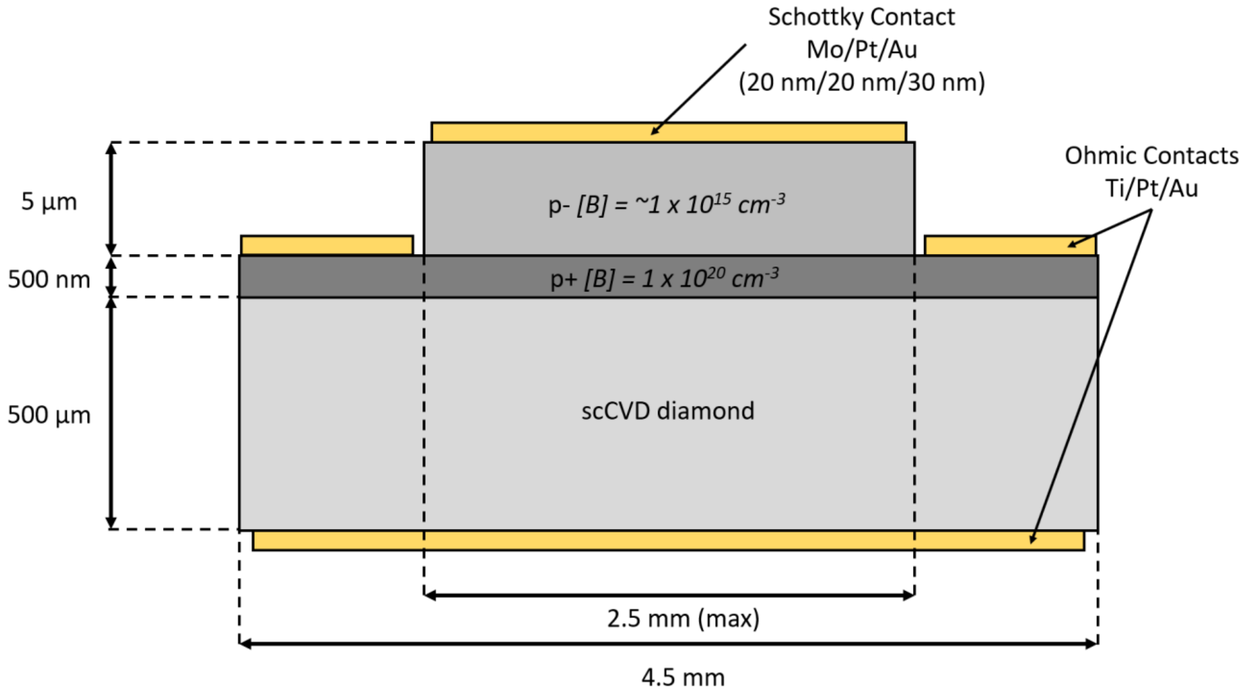
From simulations to first sample

SRIM simulations for α particles



Requirements: (For E_{init} = 5MeV)		**Solution chosen:**
Energy deposited: $E_{\Delta E} > 1$ MeV $E_{\Delta E} > E_{init}/2$	**Leakage current:** $I_{leak} < 1$ nA	Thickness: 5 µm Schottky Contact

First simple design scheme

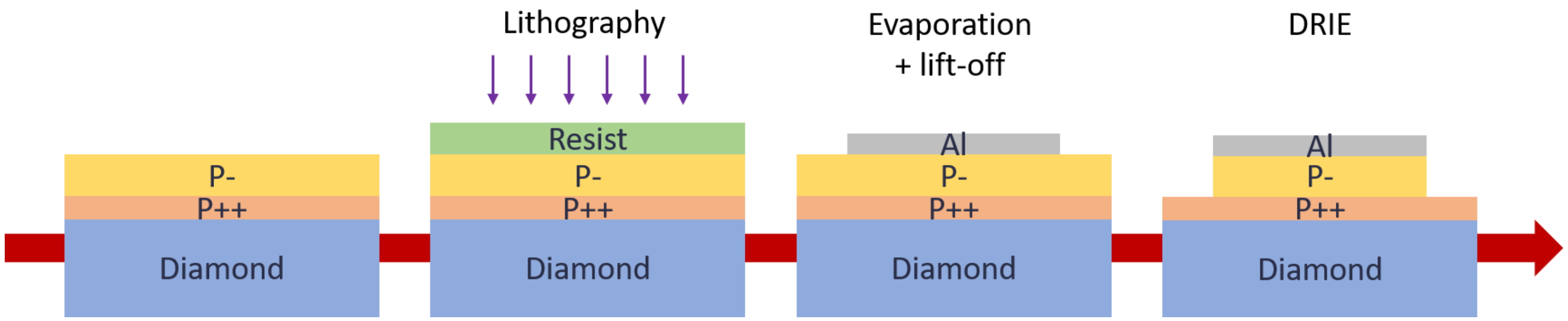


Alpha particle range
in diamond : 11.8 µm

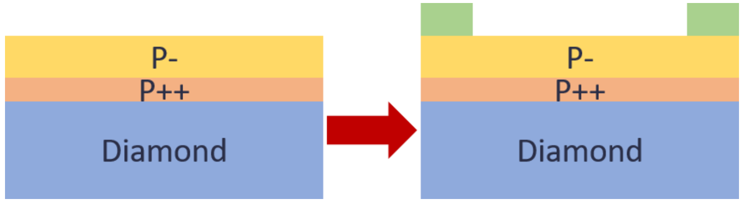
The start-up DiamFab is in charge of the epitaxial growth.

Etching process

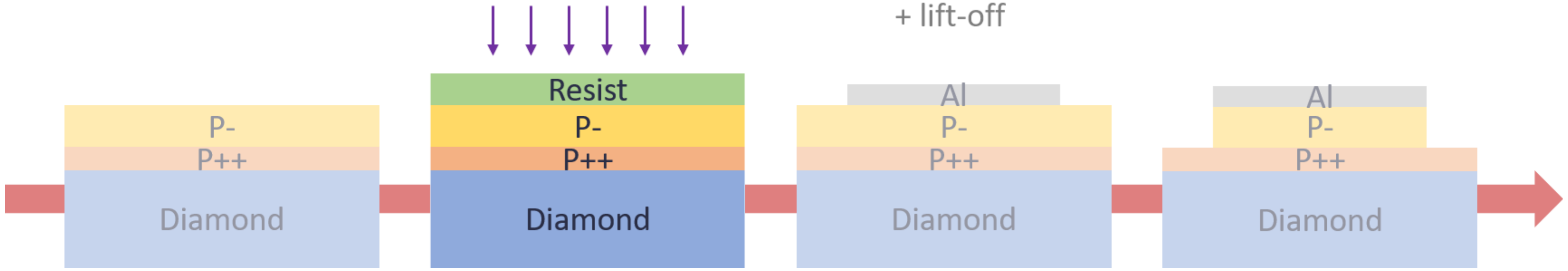
Etching process



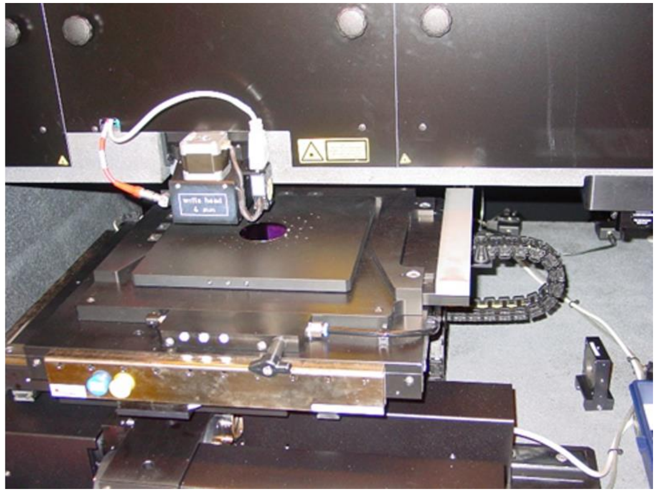
Etching process – lithography



Etching process

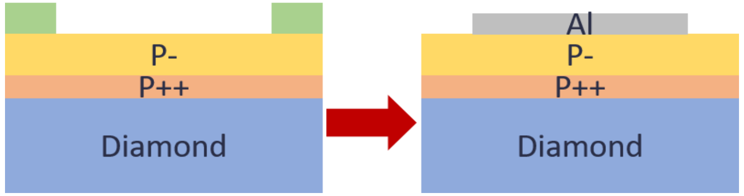


1
- Mask conception on Klayout
- Resist deposition
- Lithography
- Insulated resist lift-off

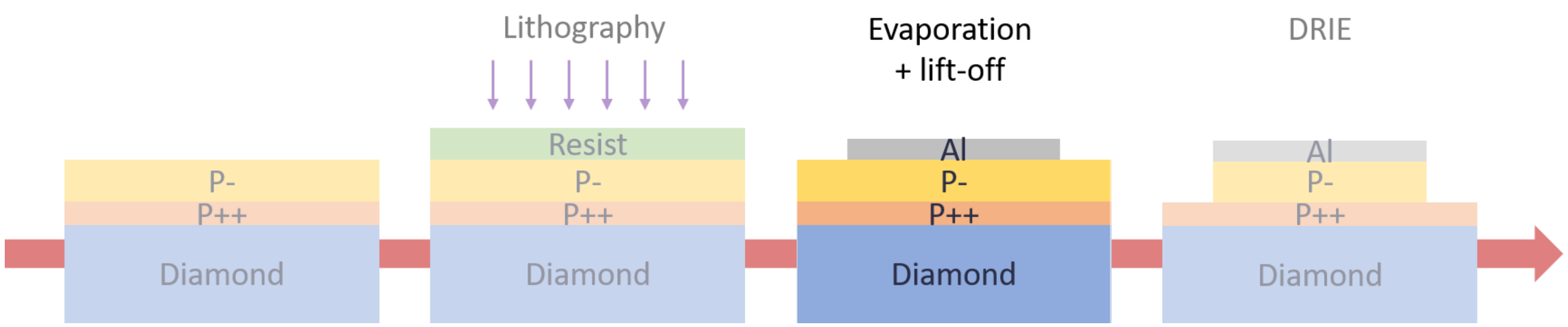


Lithography device at NanoFab clean room
NanoFab is a platform of Institut Néel

Etching process – Al evaporation



Etching process

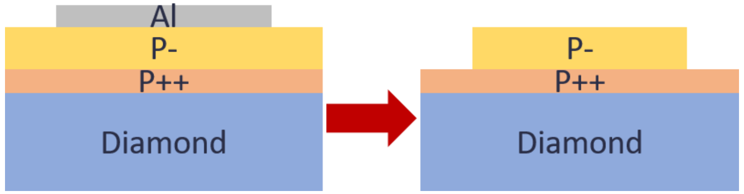


1
- Mask conception on Klayout
- Resist deposition
- Lithography
- Insulated resist lift-off

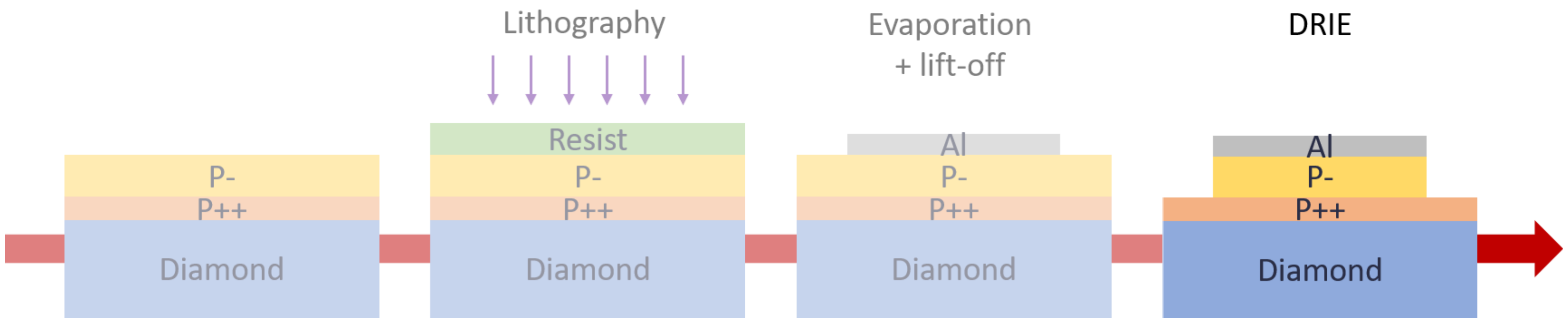
2
- Aluminium evaporation
- Lift-off

Plassys: metal deposition device at NanoFab
NanoFab is a platform of Institut Néel

Etching process – DRIE



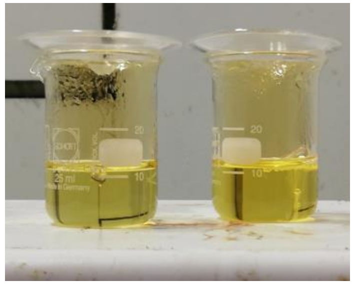
Etching process



1 Mask conception on Klayout
Resist deposition
Lithography
Insulated resist lift-off

2 Aluminium evaporation
Lift-off

3 Deep etching at PTA
Aluminium lift-off

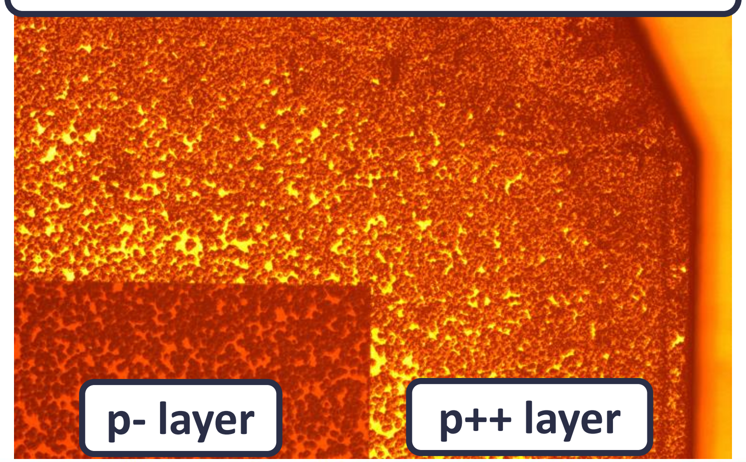


Aqua Regia for aluminium lift-off
($HCl + HNO_3$)

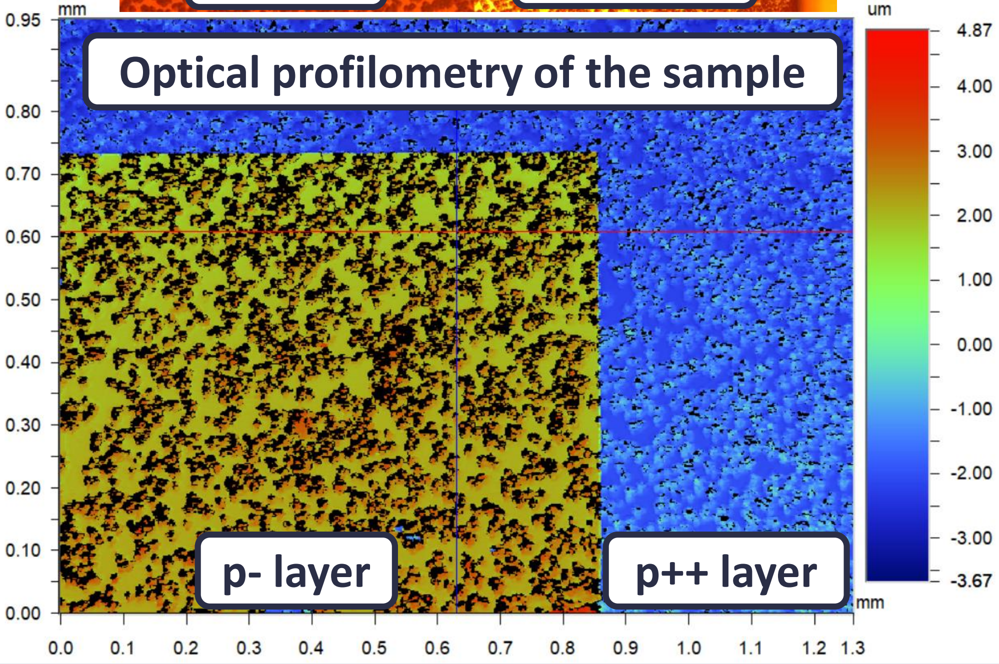
PTA: Plateforme Technologique Amont
DRIE: Deep Reactive-Ion Etching

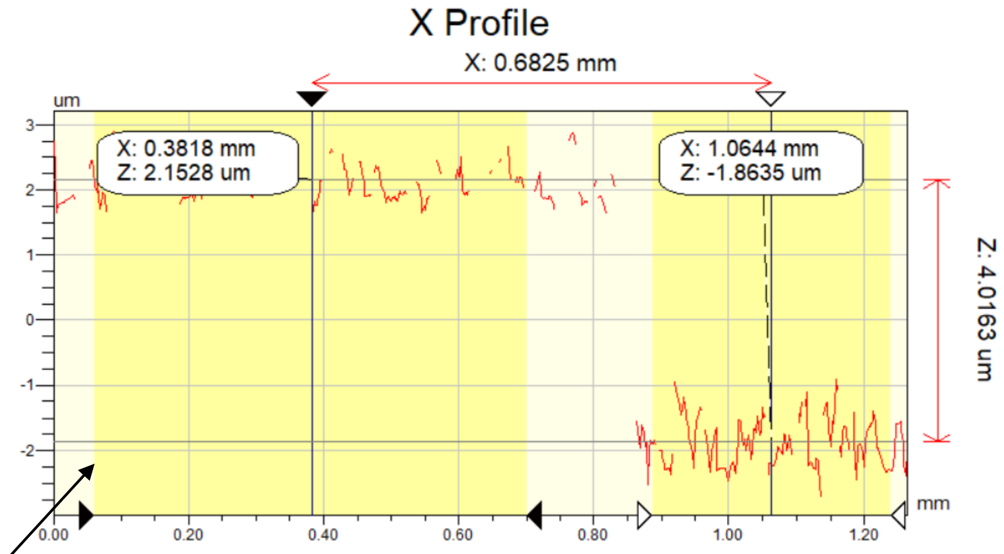
First sample – etching checking

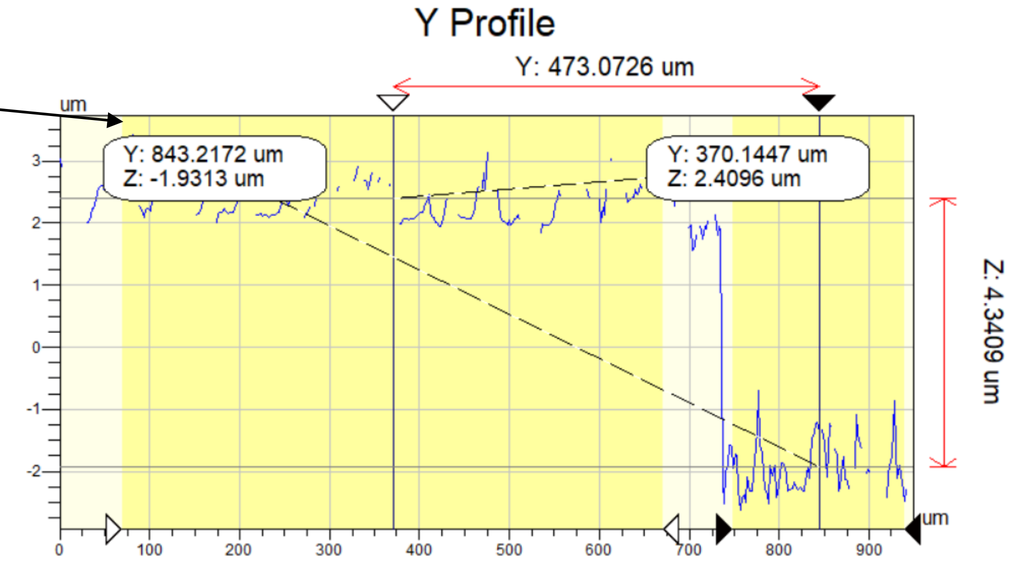
Microscope picture of the sample



Optical profilometry of the sample







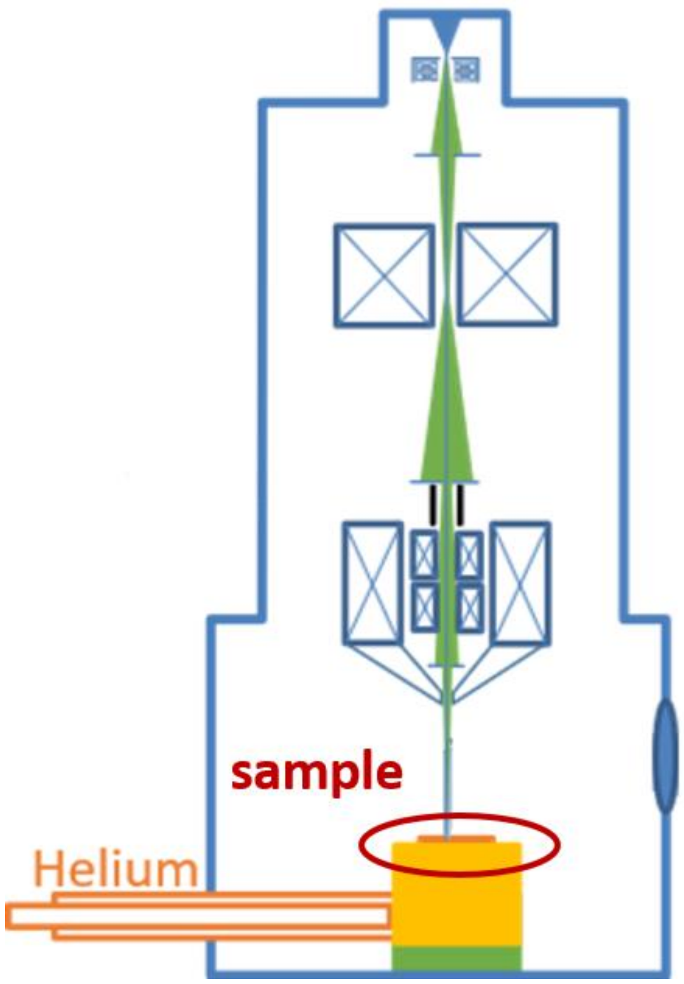
Outlines

1. ΔE-E detector : from simulation to first samples
   - SRIM Simulations & first design
   - First sample processing steps

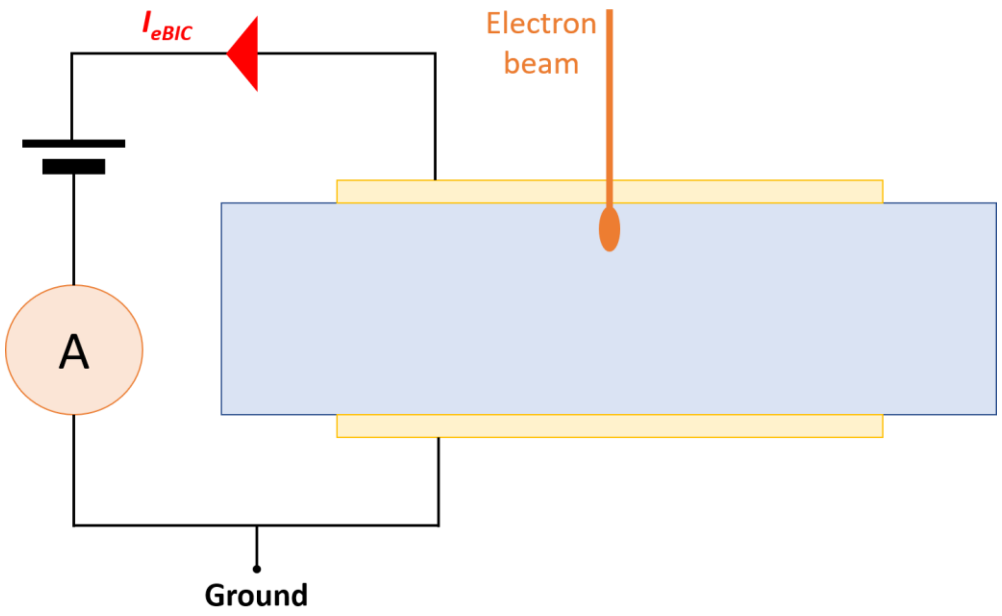
2. Electron Beam Induced Current (eBIC) experiments at Néel
   - Set up of the experiment
   - Time of flight studies
   - Diamond properties study at different temperatures
   - Detector mappings

eBIC setup

Scanning electron microscope (SEM) setup

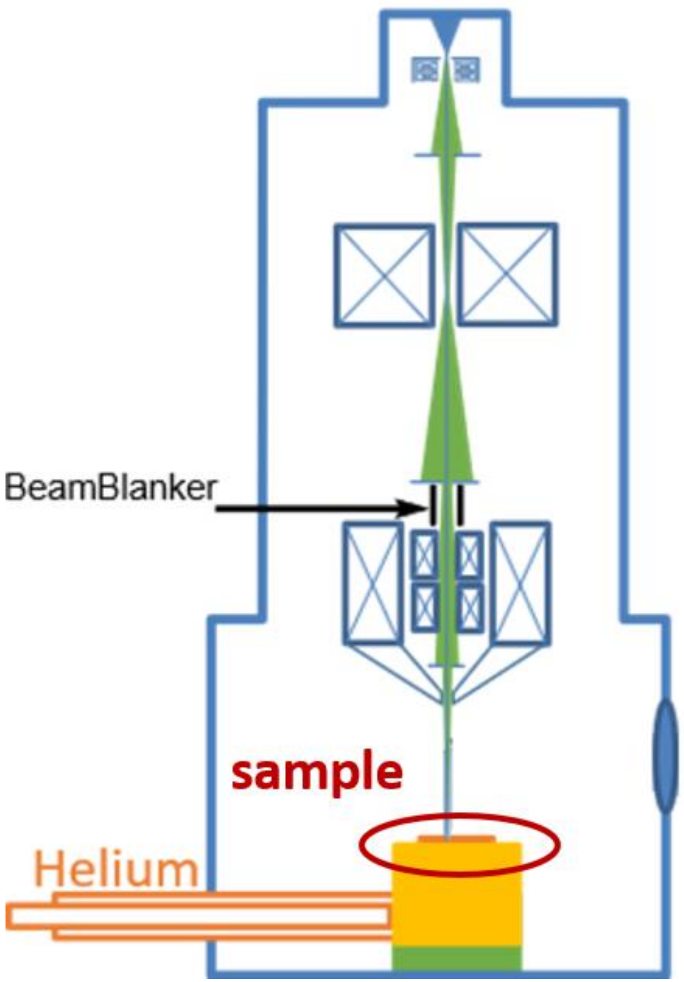


electron Beam Induced current (eBIC) setup

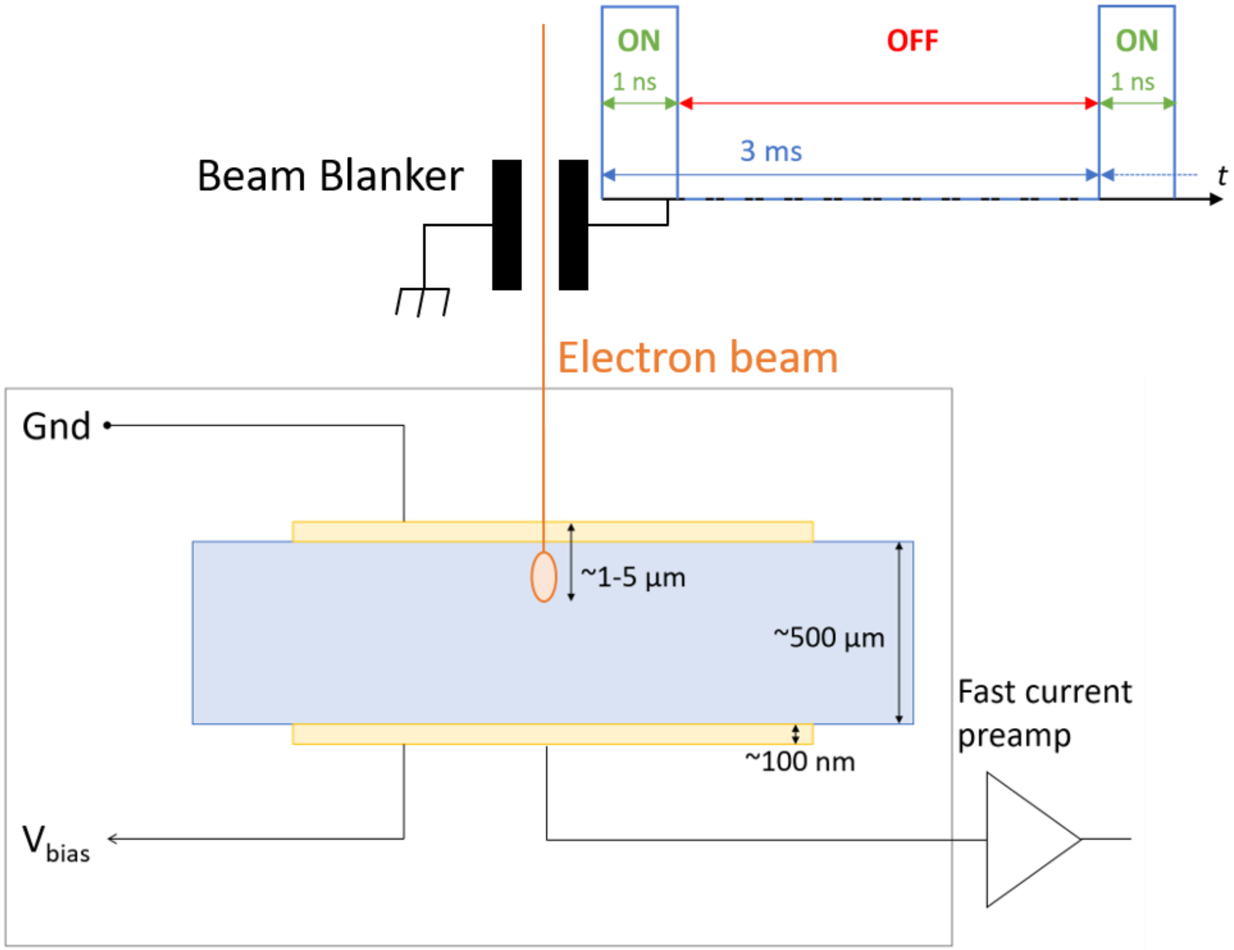


ToF – eBIC setup

Scanning electron microscope (SEM) setup

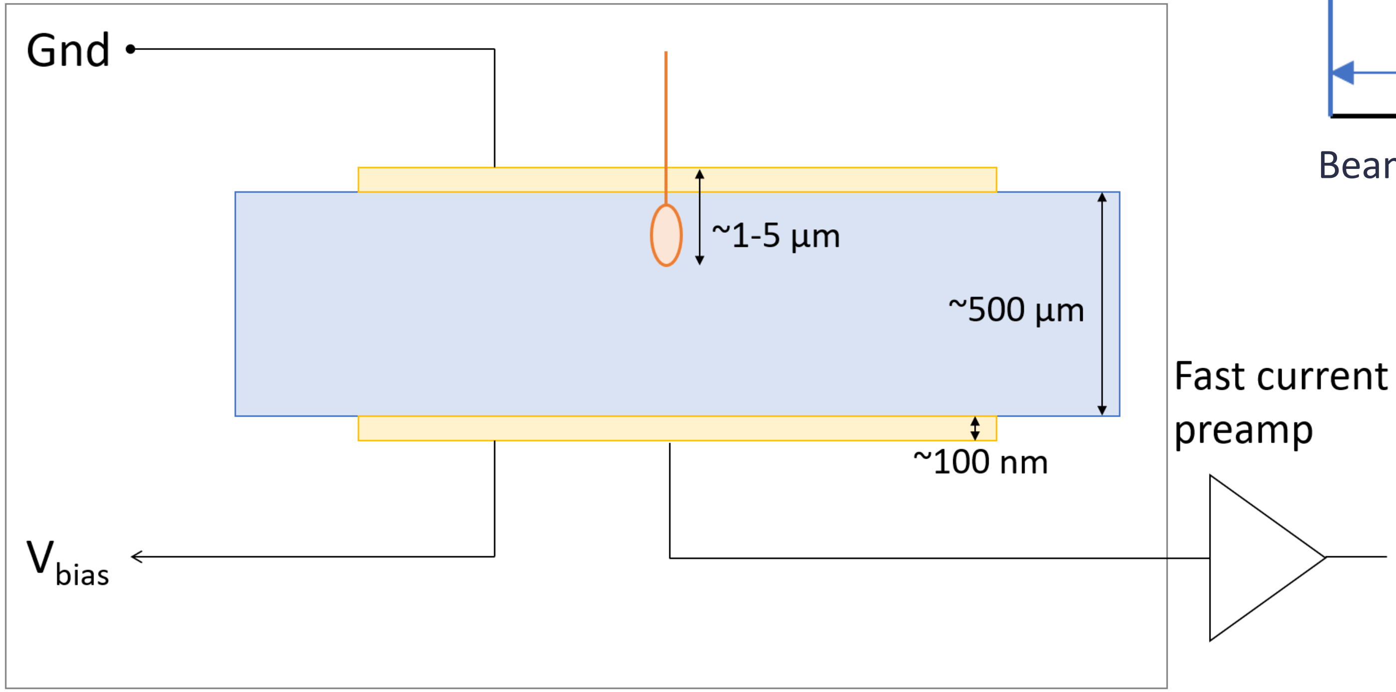


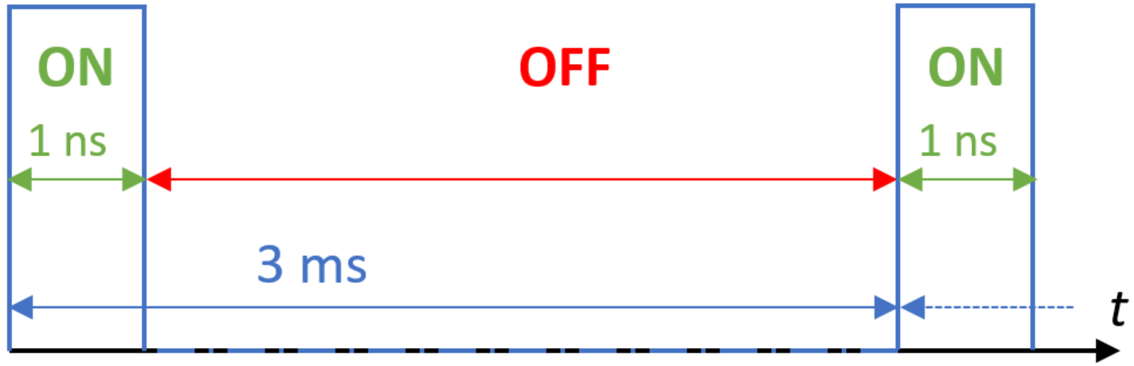
Time of Flight (ToF) – eBIC setup



ToF – eBIC – goals and advantages

ToF – eBIC setup





Beam goes through an air gap → Beam blanker → electron pulses

Development of a ToF – eBIC setup with F. Donatini (POM : Pôle Optique et Microscopie – Institut Néel)

ToF – eBIC : Time of Flight – electron Beam Induced Current

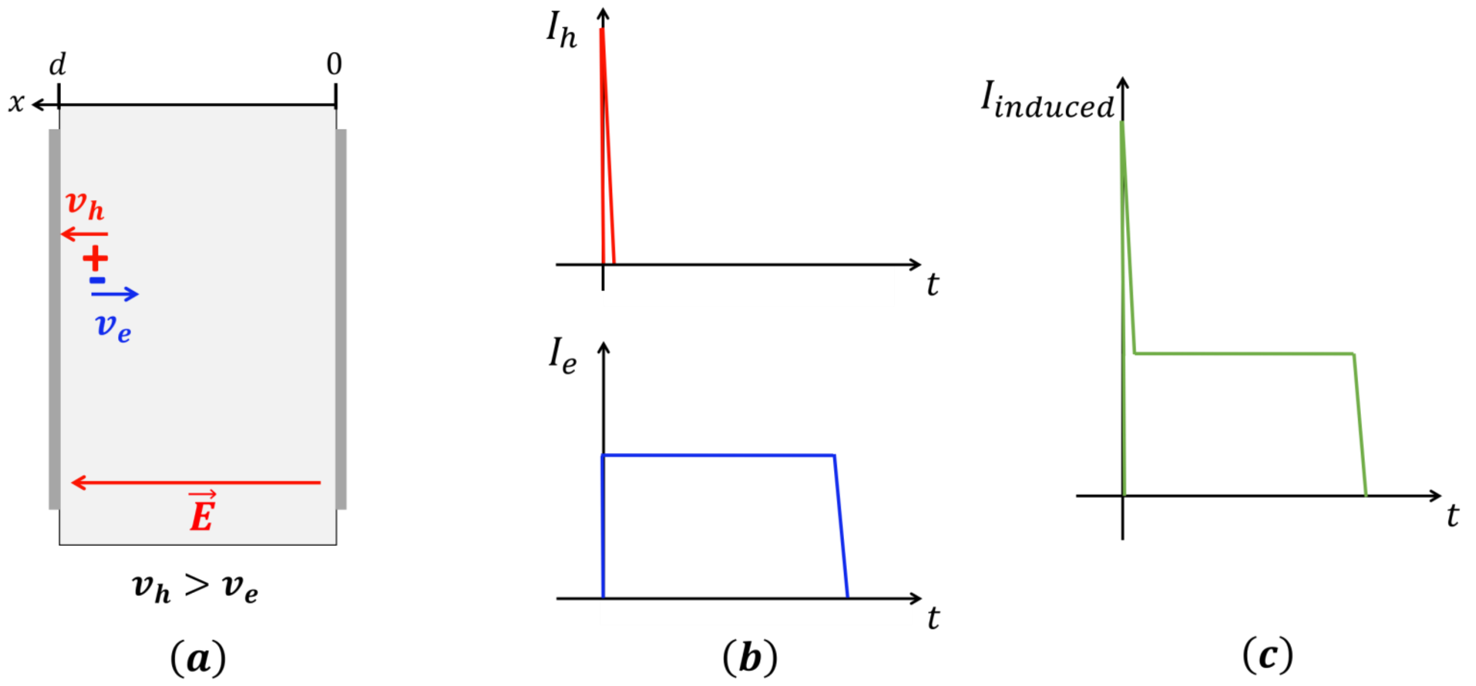
Goal: characterise the properties of the diamond using an electron beam (carrier mobilities)

Advantages:

- ✓ Setup **available** at Institut Néel
- ✓ Study one type of charge carrier (small penetration depth (< 5 µm))
- ✓ Electron → do **not damaged** the detector
- ✓ Allow **beam monitoring** (energy, intensity…)
  → Possible to do a **2D mapping**
- ✓ Have an **external trigger**
- ✓ **Monitor the temperature**

Shockley-Ramo Theorem

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



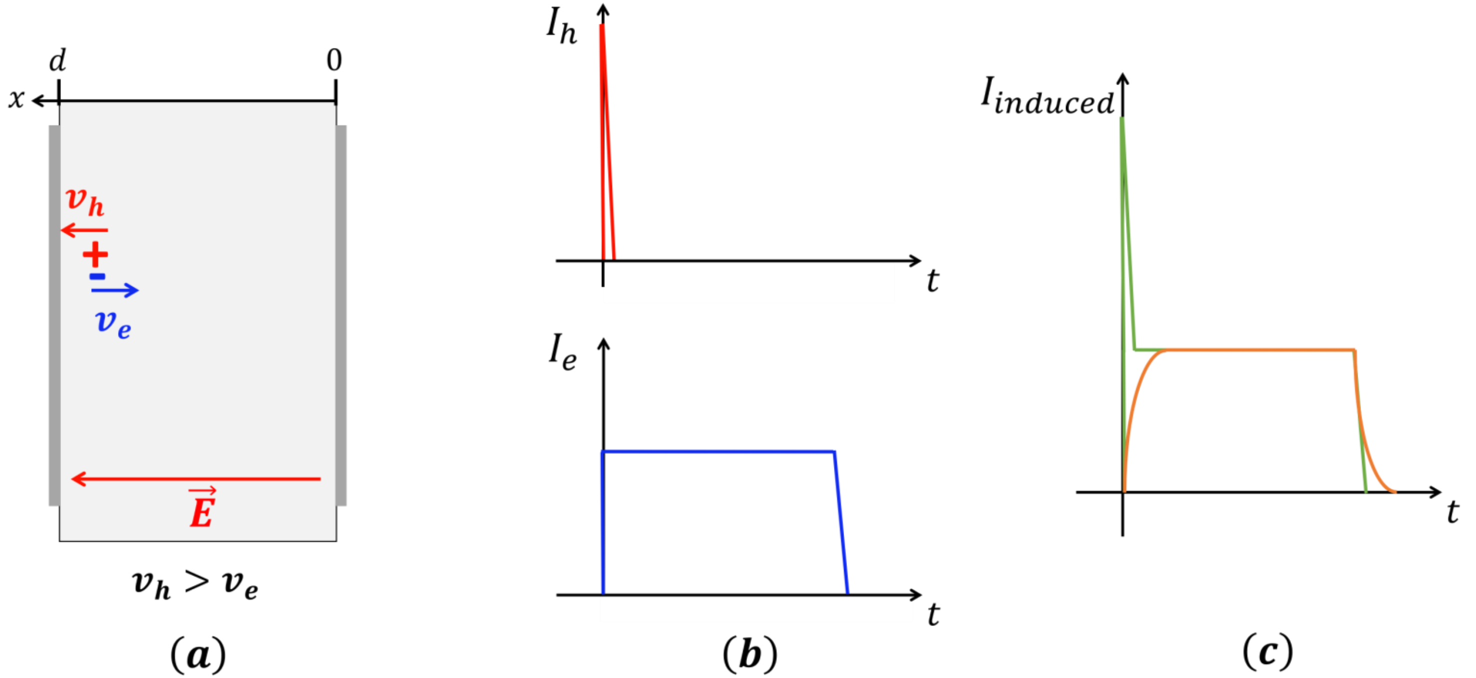
Shockley-Ramo theorem

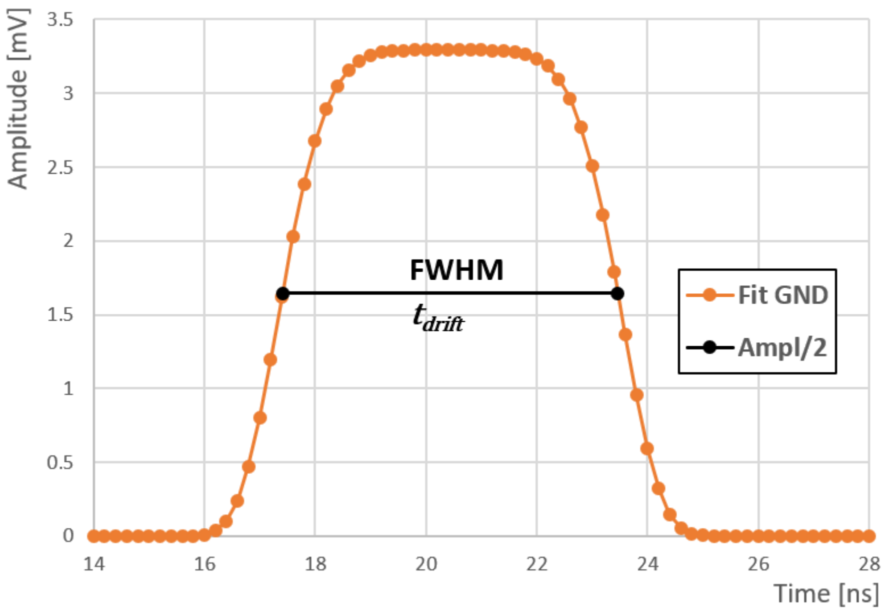
$$I_{induced} = q\, \vec{v_q} \cdot \vec{E_w}$$

Charge movement induces a current on detector electrodes

Shockley-Ramo Theorem

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





Shockley-Ramo theorem

$$I_{induced} = q\,\overrightarrow{v_q} \cdot \overrightarrow{E_w}$$

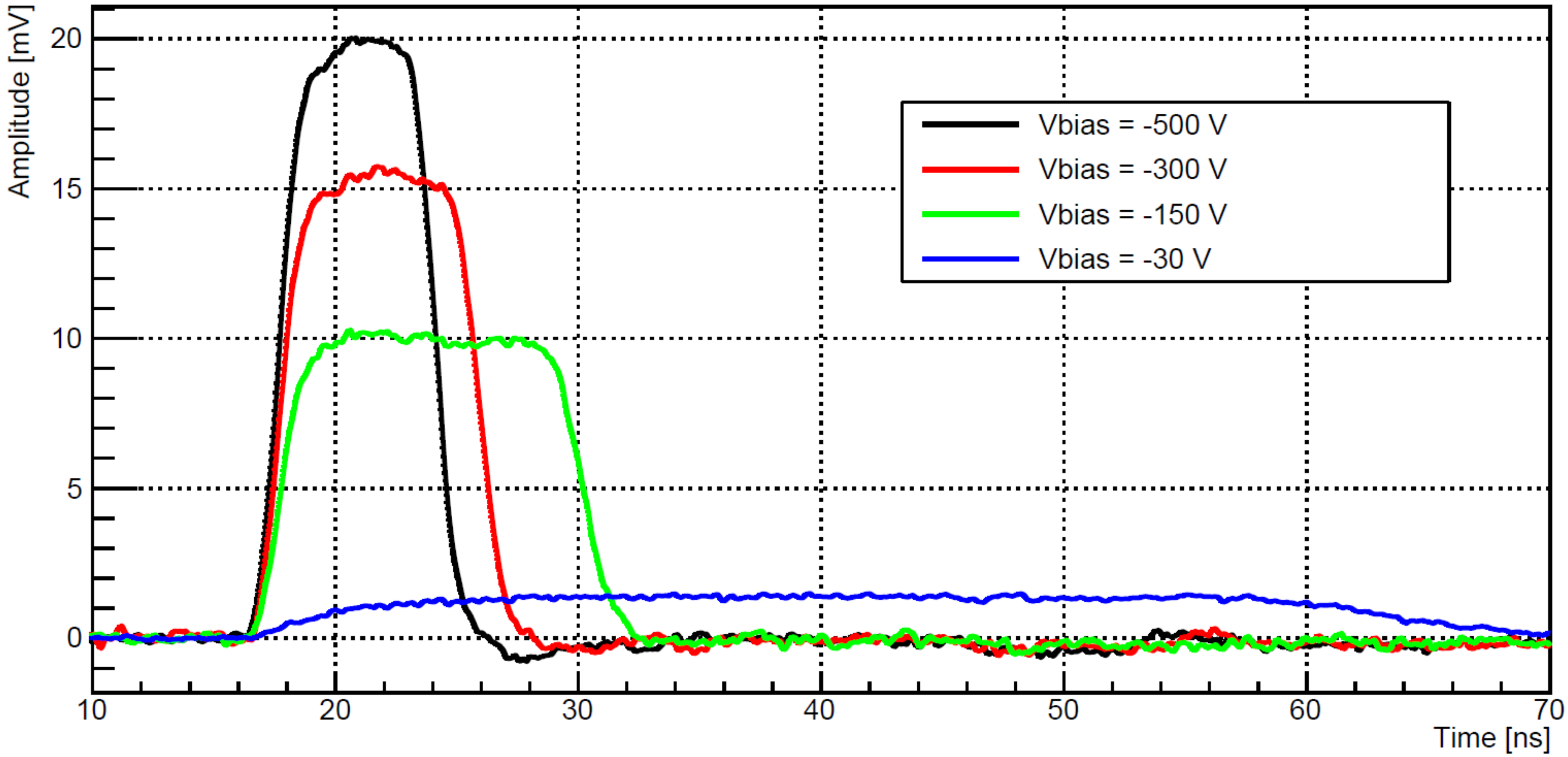
Charge movement induces a current on detector electrodes

Drift velocity calculation:

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

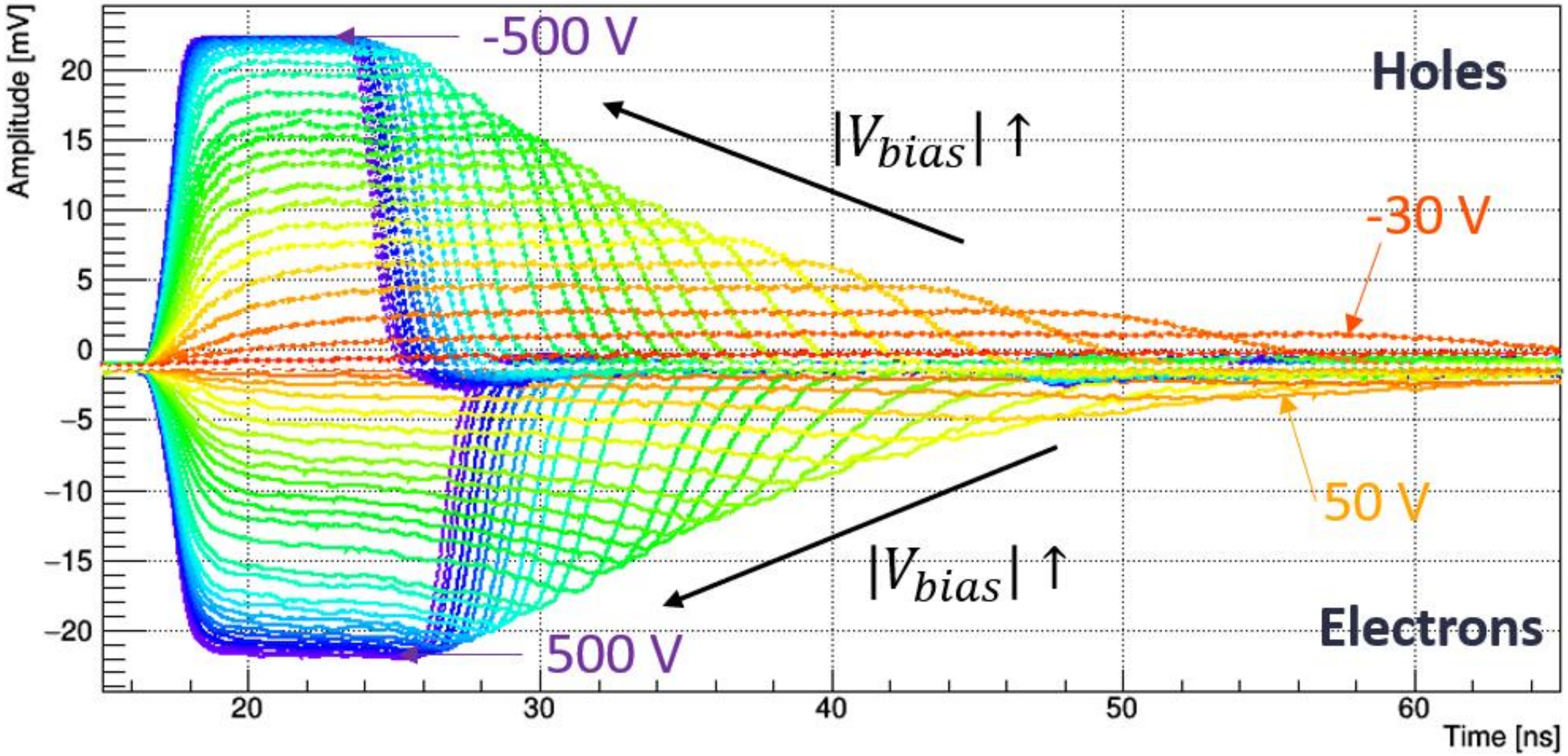
Traces for different polarizations

Signal observed on a scCVD diamond



Traces for different polarizations

Signal observed on a scCVD diamond



Drift velocity and mobility

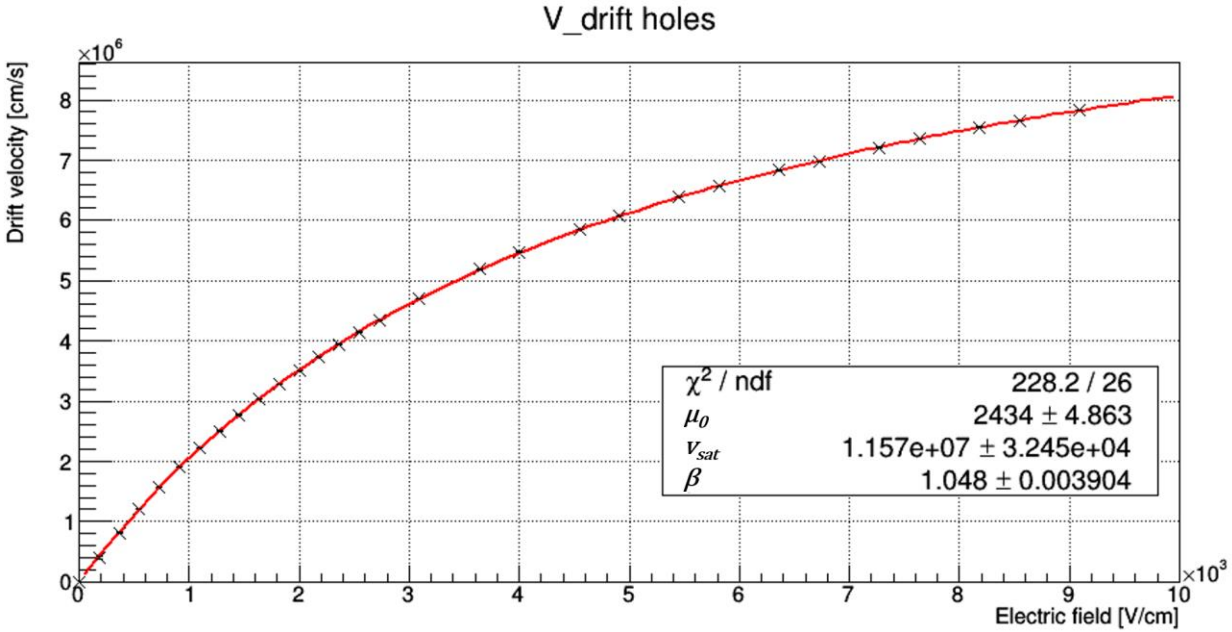
Signal observed on a scCVD diamond

Holes		
Measures	μ_0 [cm² / (V.s)]	v_{sat} [10^6 cm/s]
ToF – eBIC meas.	2334 ± 10	13.1 ± 0.1
LPSC α source meas.	2380 ± 20	12.1 ± 0.1
F. Marsolat *	2349 ± 28	14.1 ± 0.3

Electrons		
Measures	μ_0 [cm² / (V.s)]	v_{sat} [10^6 cm/s]
ToF – eBIC meas.	1853 ± 17	8.8 ± 0.1
LPSC α source meas.	2020 ± 20	8.2 ± 0.1
F. Marsolat *	2053 ± 87	9.2 ± 0.8

* F. marsolat, PhD Thesis, 2014 – measurement done with an α source

Drift velocity



Fit function:

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

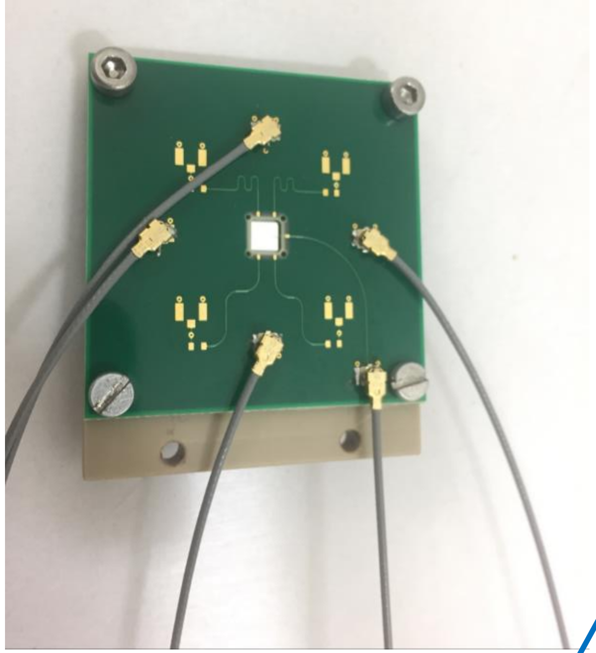
$$v_{drift}(E) = \frac{\mu_0 E}{\left[1 + \left(\frac{\mu_0 E}{v_{sat}}\right)^{\beta}\right]^{1/\beta}}$$

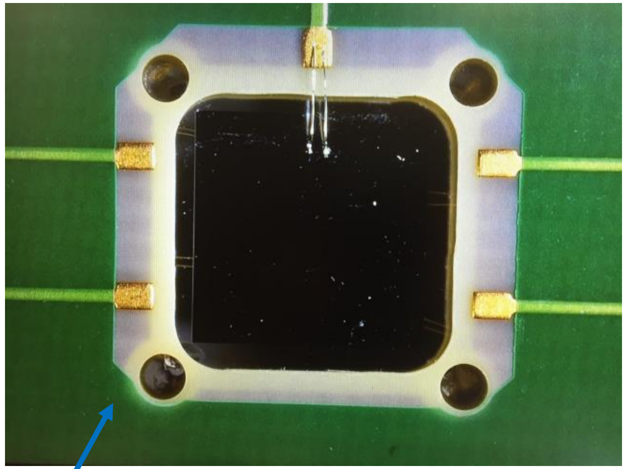
μ_0 Low field moblity

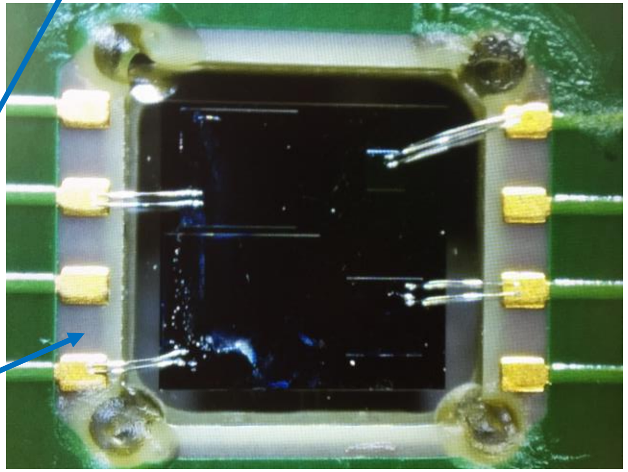
v_{sat} Saturation drift velocity

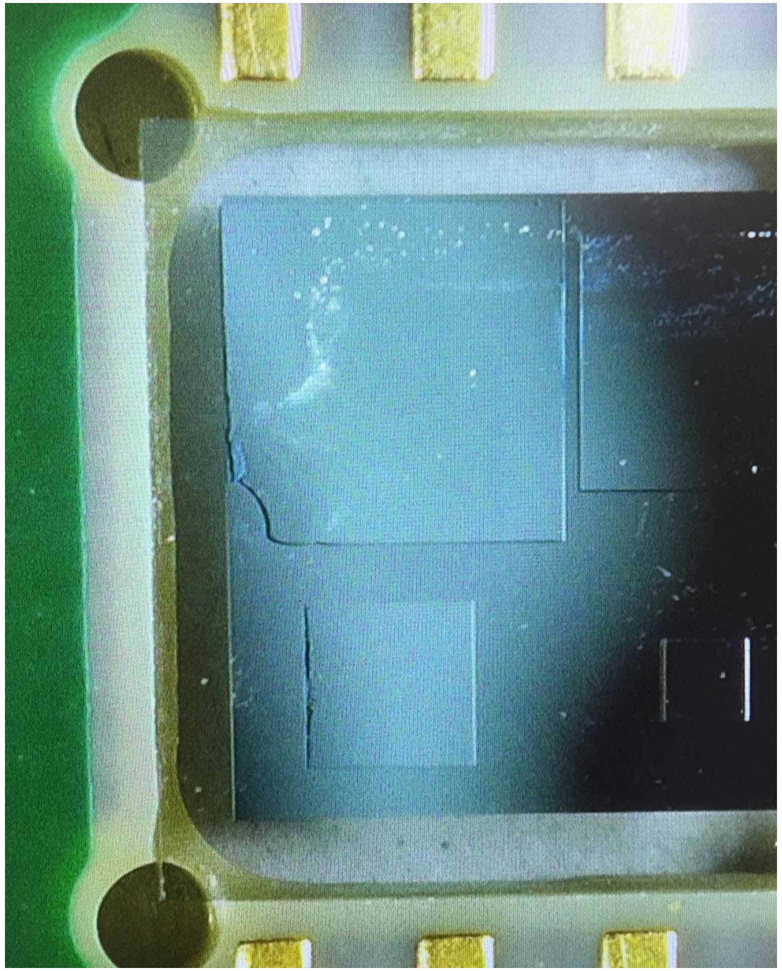
Mapping of the detector response

Picture of a pixelated diamond







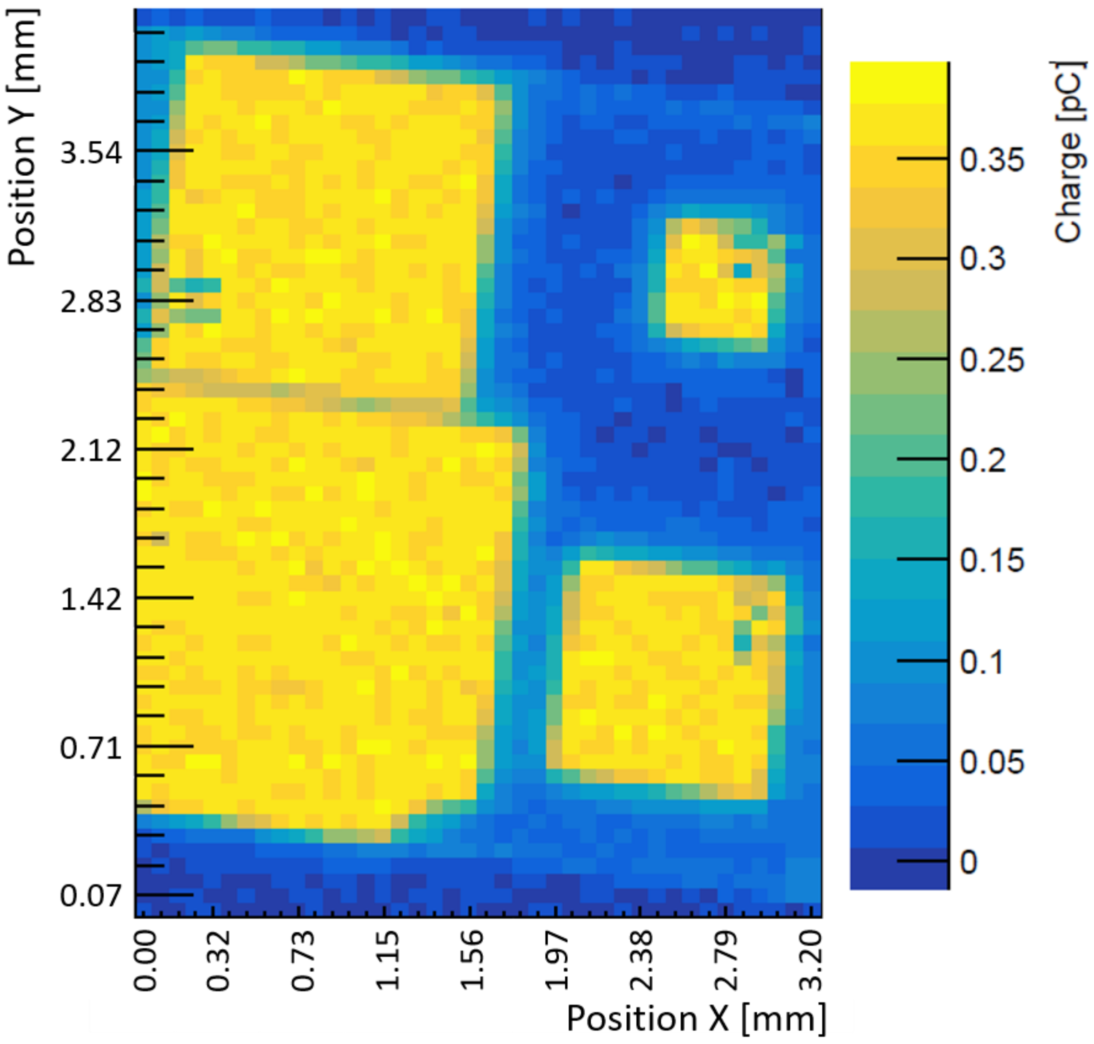


Metallization different on the two faces:

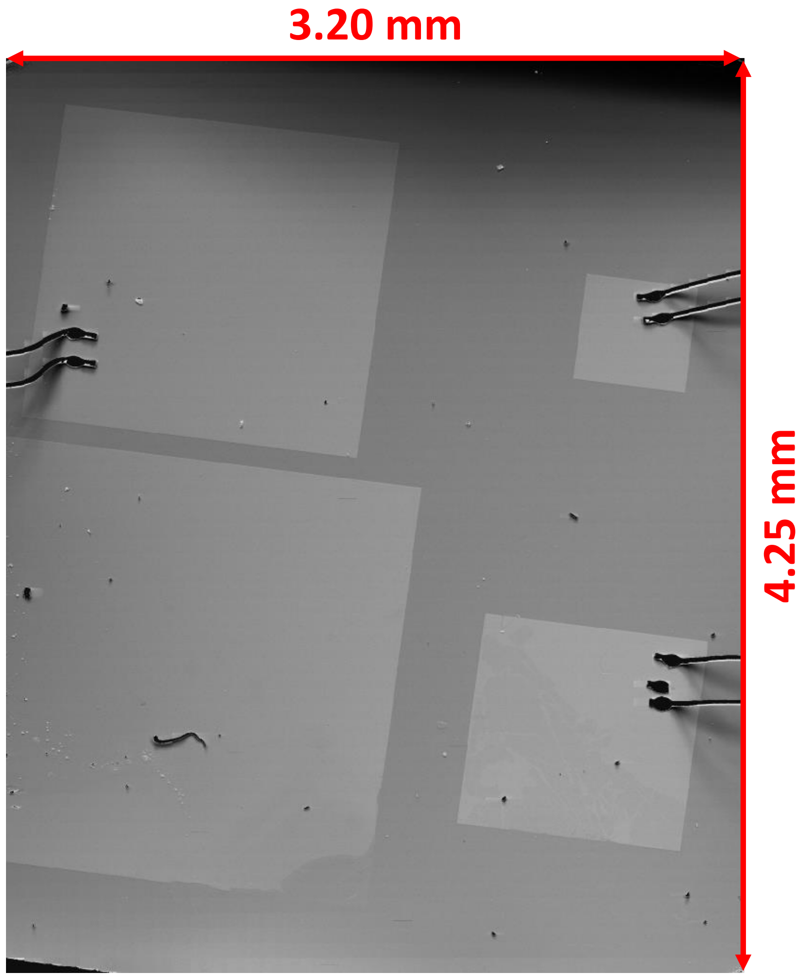
- Fully metallized face
- Pixelated face

Mapping of the detector response

Coarse mapping of detector charge response



SEM mapping picture



Conclusions and perspectives

Work done

ΔE-E detector

- SRIM simulations done ➔ **1st detector design based on light ions (^4He)**
- Manufacture of the 1st 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
- Charge mapping of the detector

Perspectives

ΔE-E detector

- p- stage tests of the 1st sample
- Manufacture of the 2nd sample + detector tests (LPSC setup, AIFIRA, eBIC…)
- Fission Fragment (FF) adapted design
- Experiments à ILL

ToF – eBIC experiments:

- **2 conferences (orals) 2021 MRS Spring Meeting** (April) and **NDNC** (June) and **write an article**
- Make the test bench technologically accessible (write technological instructions) ➔ experimental platform open to other experiments in diamond international community

Thank you for your attention!