Characterization of the proton beam at Cyrcé cyclotron using MIMOSIS-1 sensor

M2 PSA internship

Tabatha DUFOUR

supervised by Marc ROUSSEAU (DRHIM) and Ziad EL BITAR (PICSEL)

Content

Context of the internship

IPHC	
Hadrontherapy (DRHIM)	**PICSEL**
Hadrontherapy Radiobiology - Improvement and control of treatment plans in hadrontherapy - Cyrcé Platform	Physics with Integrated Cmos Sensors and ELectron machines Development and optimization of monolithic active pixel sensors - vertexing - tracking

Problematic : Characterization of the proton beam at Cyrcé cyclotron using MIMOSIS-1 sensor

Hadrontherapy and DRHIM

$$D = \frac{\mathrm{dE}}{dm}$$

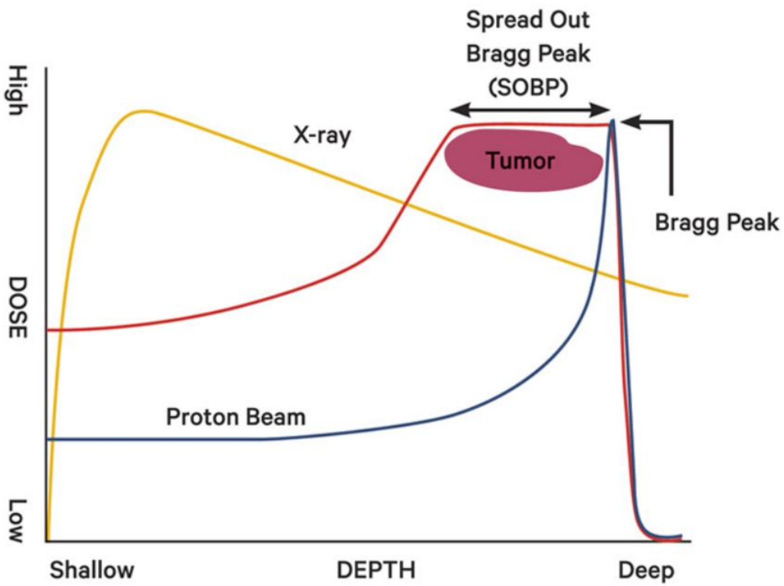
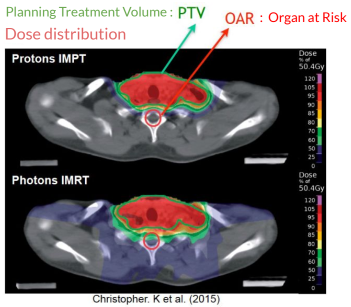


Figure from ref. [1]

- Radiotherapy
- X-ray: common source, deposited dose is spread out
- Protons: stop at their target *(200 MeV proton in water → Bragg peak≈ 25 cm deep)*
- Effects of radiation protons need further investigation to ensure control of the dose deposit



Christopher. K et al. (2015)

Hadrontherapy and DRHIM

- ***Dose :*** amount of energy deposited by unit mass
- ***LET :*** energy transferred locally by the particle to the material per unit length
- ***Fluence :*** Number of particle per unit surface

Dose:

$$D = \frac{\mathrm{dE}}{dm}$$

$$D = \Phi \times \frac{\mathrm{LET}}{\rho}$$

Linear Energy Transfer = dE/dx

25 MeV protons in water : LET = 2.38 ± 0.02 keV / µm

Fluence: $\Phi = \frac{N}{dS}$

CBM and PICSEL

MIMOSIS-1

Monolithic Active Pixel Sensors (MAPS) in Complementary Metal–Oxide–Semiconductor (CMOS) technology

Designed and tested by the laboratory's microelectronics platform:
C4PI (Centre de Compétence de Capteurs CMOS à Pixels Intégrés)

Carried by **PICSEL**

Physics parameter	Requirements
Spatial resolution	~ 5 um
Time resolution	~ 5 us
Material budget	0.05% X_0
Power consumption	< 100 – 200 mW/cm^2
Operation temperature	- 40 °C to 30 °C
Temp gradient on sensor	5K
Radiation (non-ion)	~ 7 x 10^{13} n_{eq}/cm^2
Radiation (ionizing)	~ 5 MRad
Data flow (peak hit rate)	@ 7 x 105 / (mm^{2}s) > 2 Gbit/s

CBM and PICSEL

- Compressed Baryonic Matter at future Facility for Antiproton and Ion Research *in Darmstadt Germany*
- High density region of QCD phase diagram

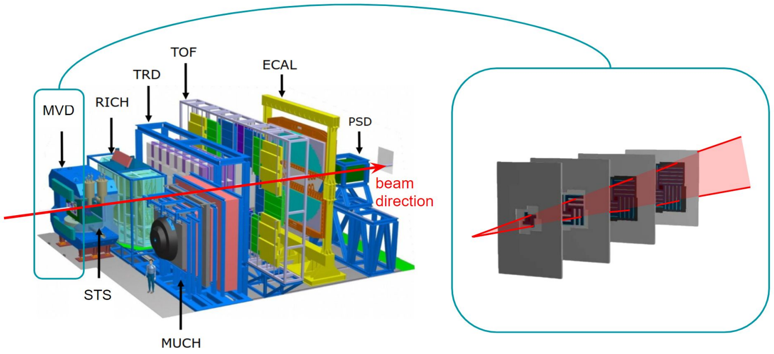


Figure from ref. [3]

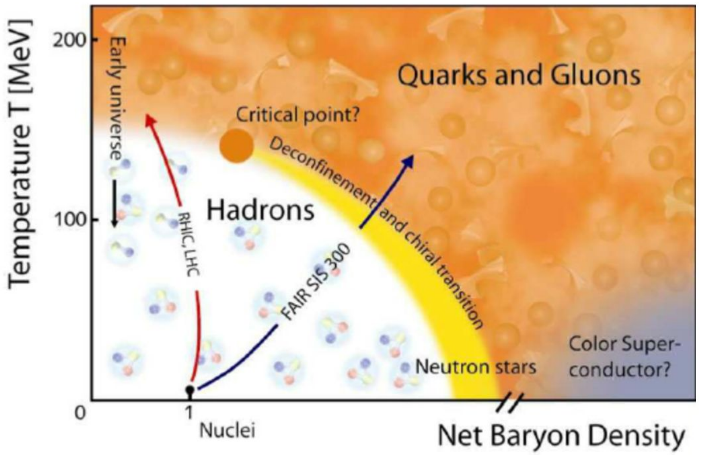


Figure from ref. [2]

Requirements :

① Vertex detector
⇒ Spatial resolution

② First to encounter the beam
→ high intensity
⇒ Radiation resistant

Motivation of the internship

Characterization of the proton beam at Cyrcé cyclotron using MIMOSIS-1 sensor

Fluence: $\Phi = \frac{N}{dS}$

Dose: $D = \frac{\mathrm{dE}}{dm}$

$D = \Phi \times \frac{\mathrm{LET}}{\rho}$

Precy beam characterization : Homogeneity of the beam

Hadrontherapy and radiobiology

MIMOSIS-1 sensor characterization

Localized and controlled irradiation
Bandwidth saturation effect

CBM experiment

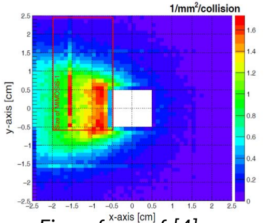
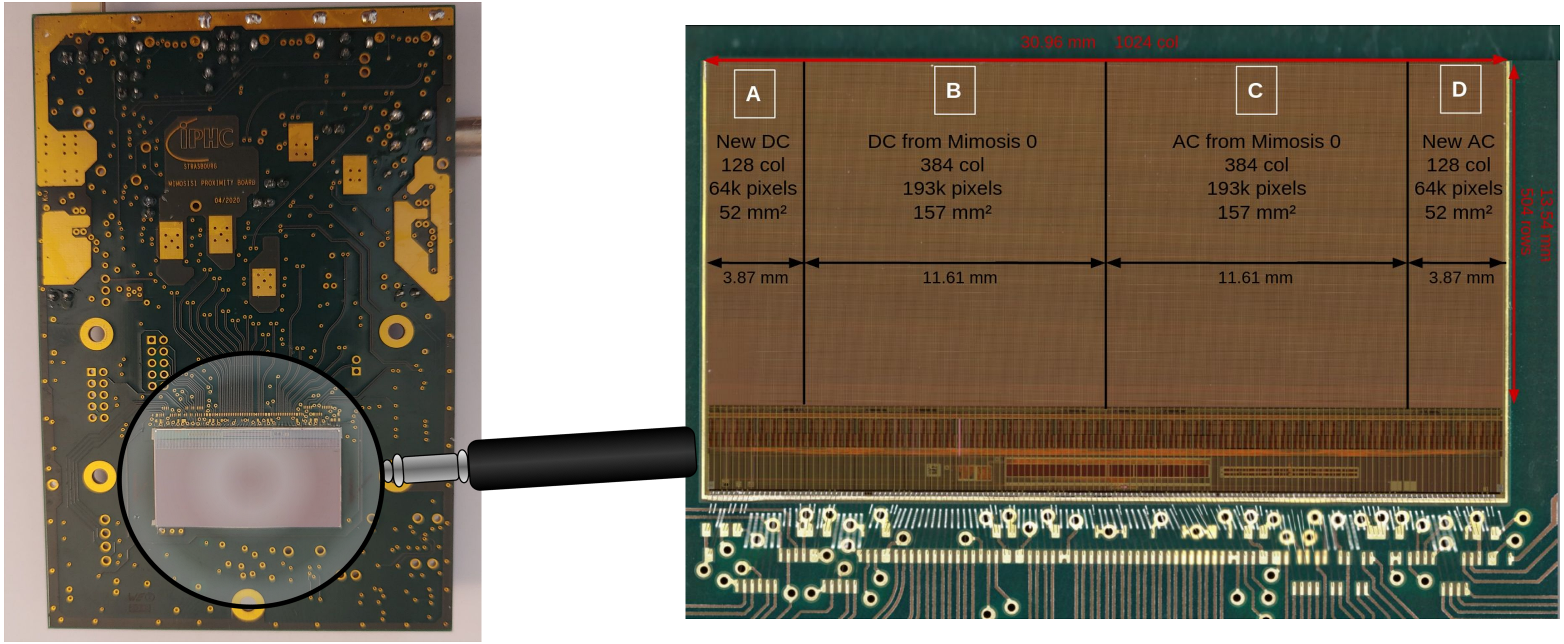
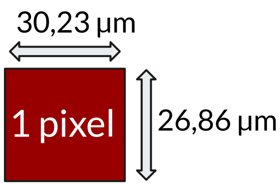


Figure from ref. [4]

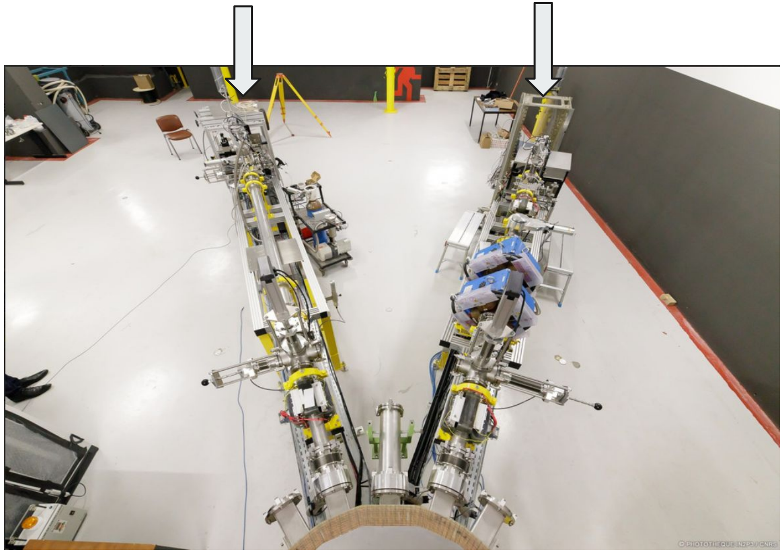
Description of the MIMOSIS-1 sensor





Description of cyclotron of Cyrcé platform and its beamlines

Figure from ref. [5]



Precy beamline

- 25 MeV protons
- Precise control of the current

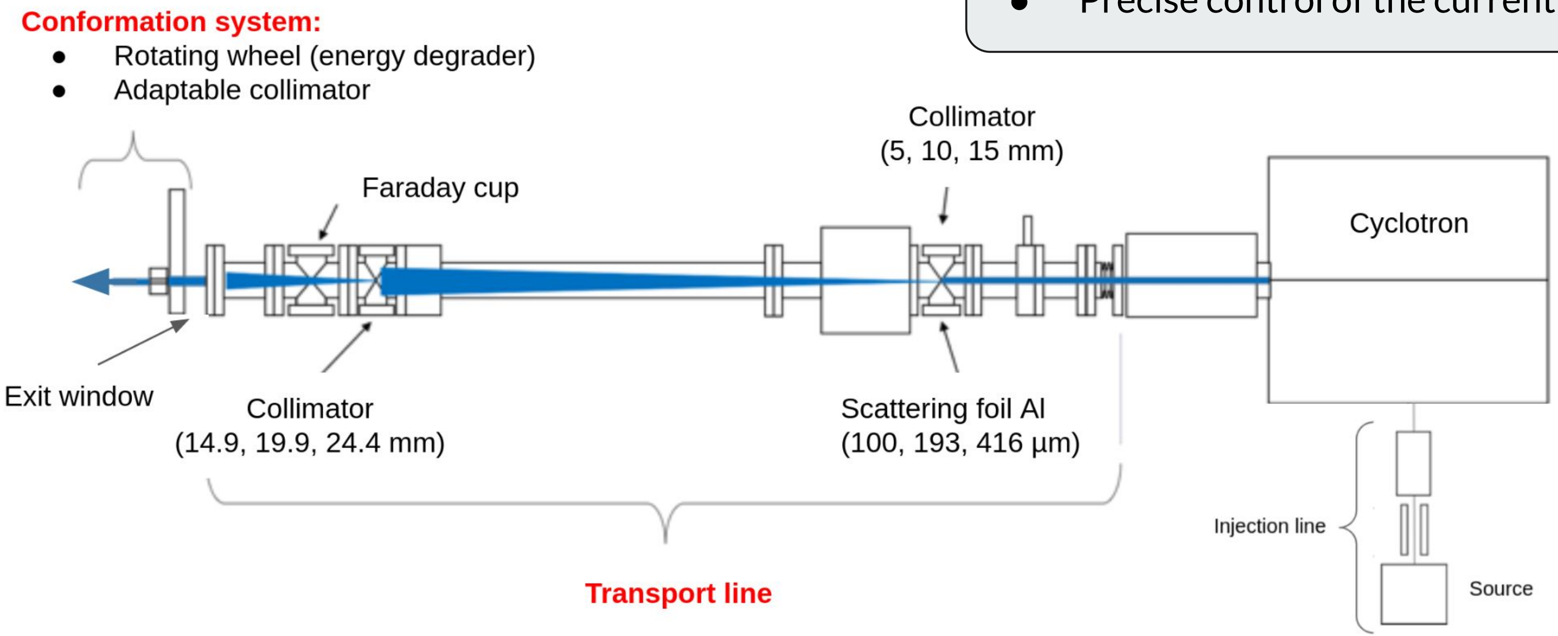
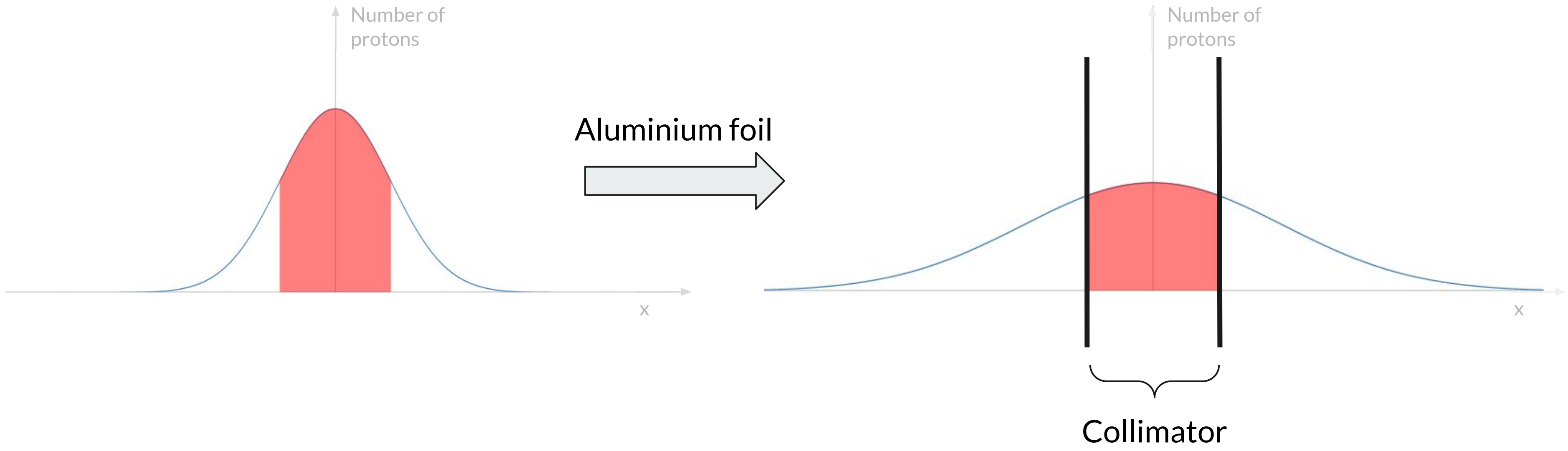


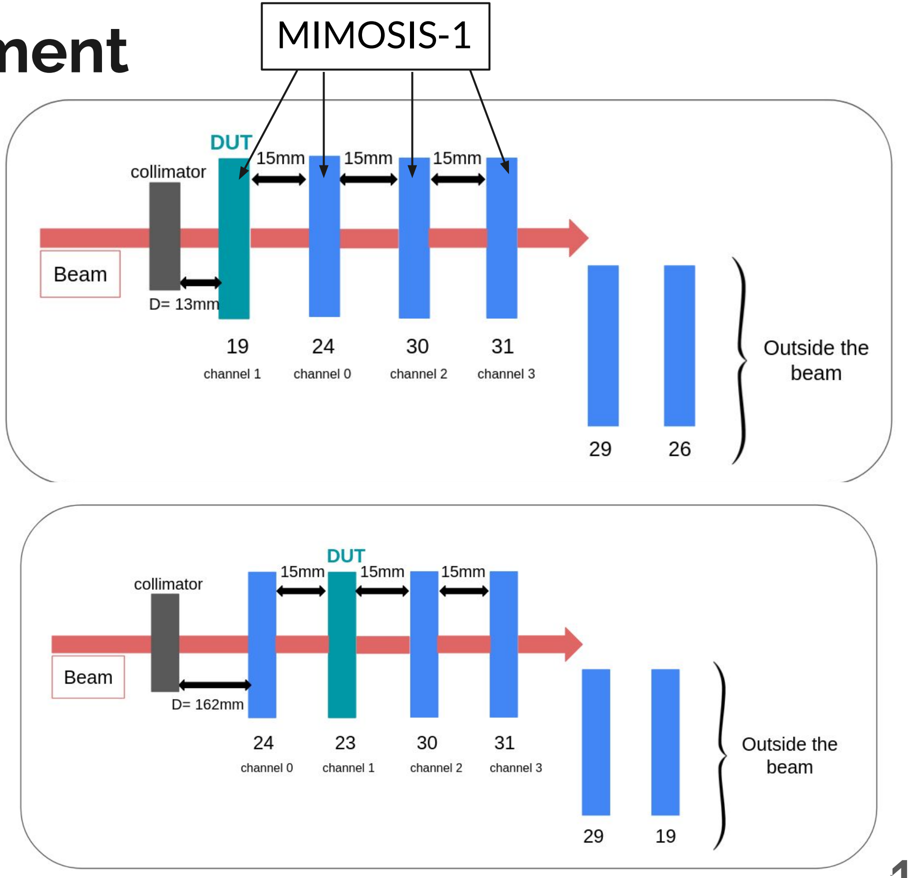
Figure from ref. [6]

Precy beamline : Transverse beam profile



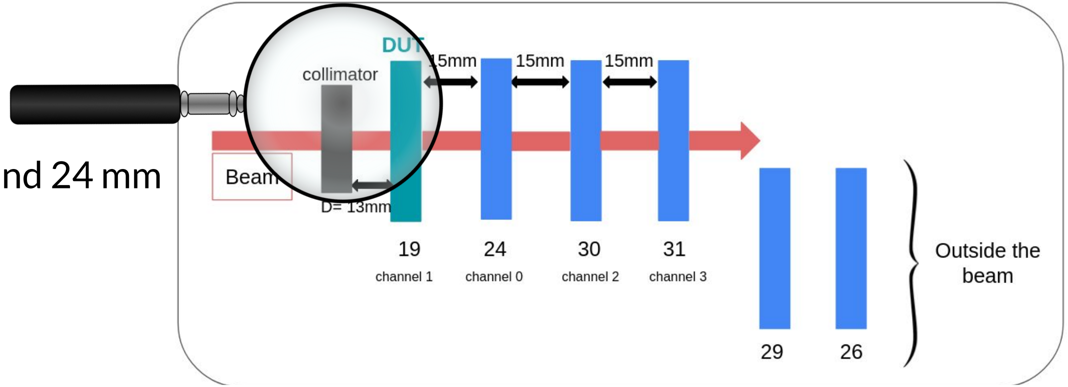
Description of the experiment

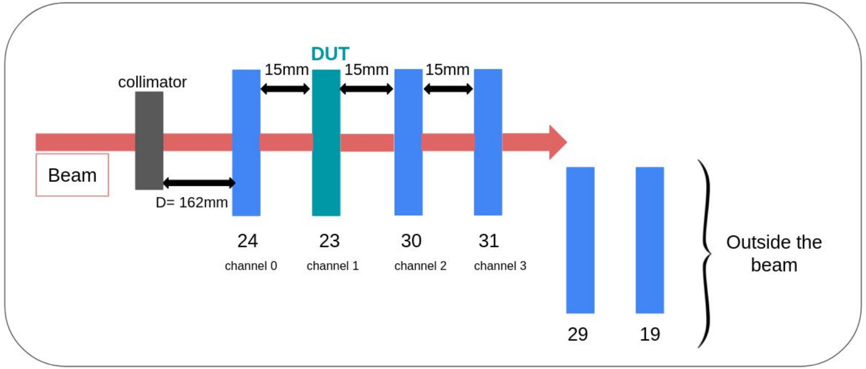
Telescope: several planes of sensor to follow the trajectory of particles.
DUT: Device Under Test



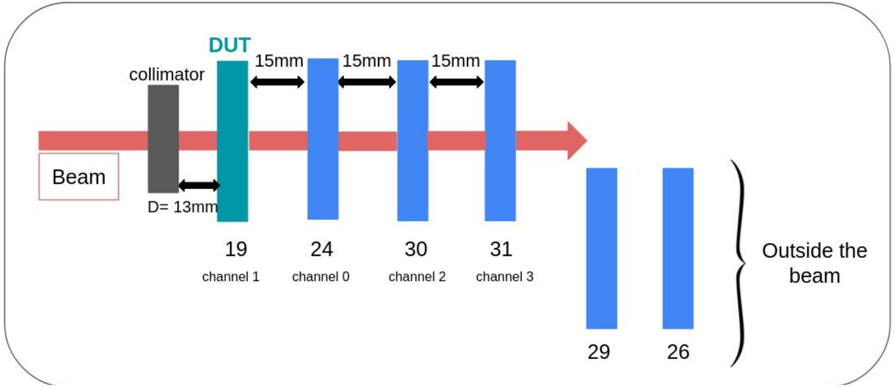
Description of the experiment

Collimator scan
→ Fluence characterization
Diameter : 2, 3, 5, 8, 10, 12, 15, 16.5 and 24 mm

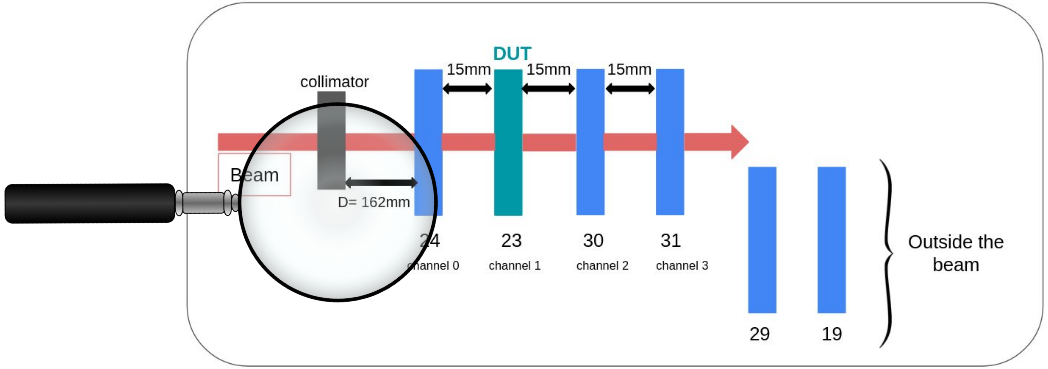




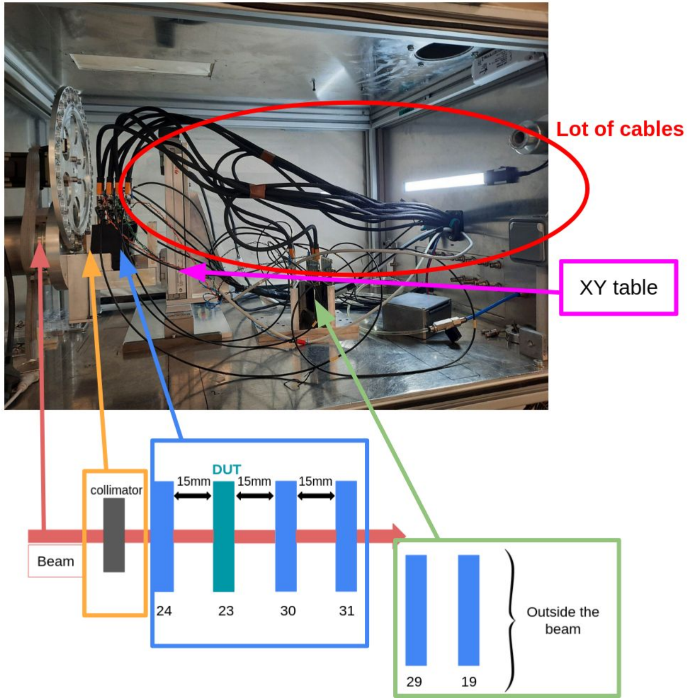
Description of the experiment



Distance scan
→ Dispersion characterization
Distance: 14, 60, 110 and 162 mm

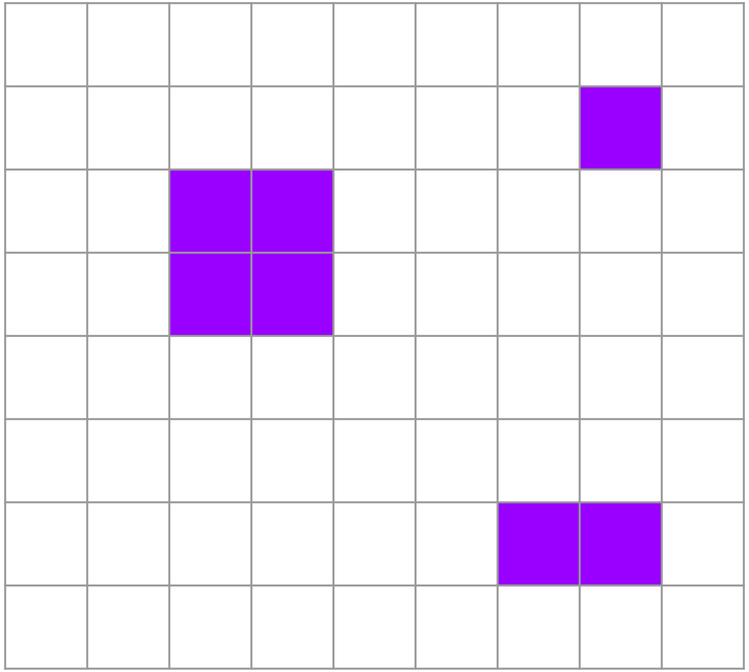


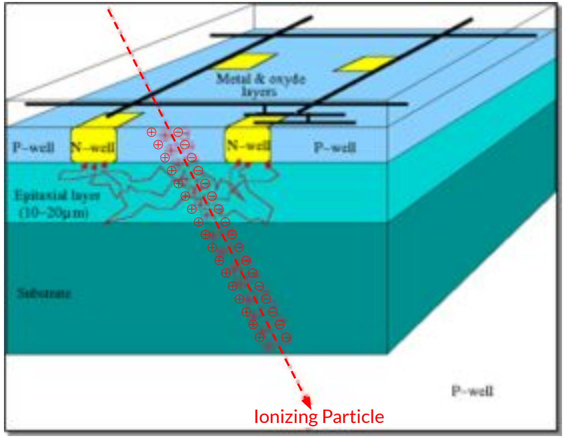
Description of the experiment



Clusterisation

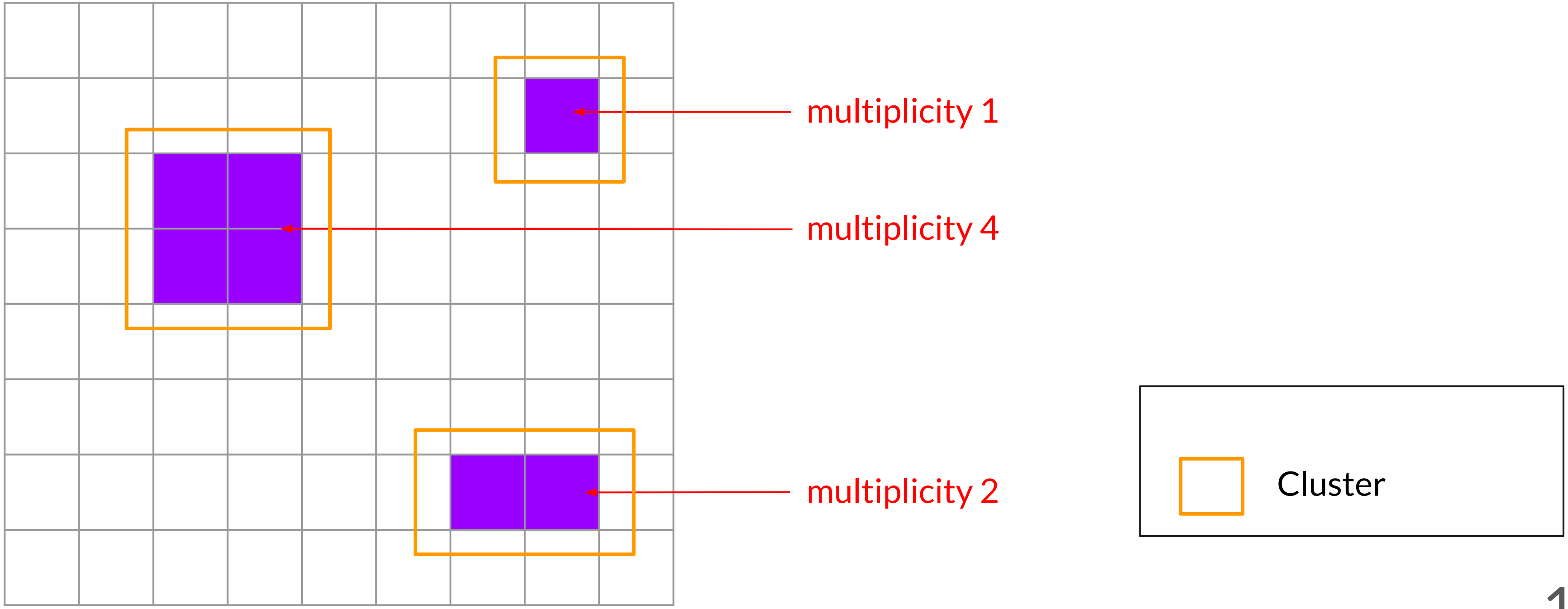
Map of pixels (Binary output) for 1 frame ⇨ 5 µs





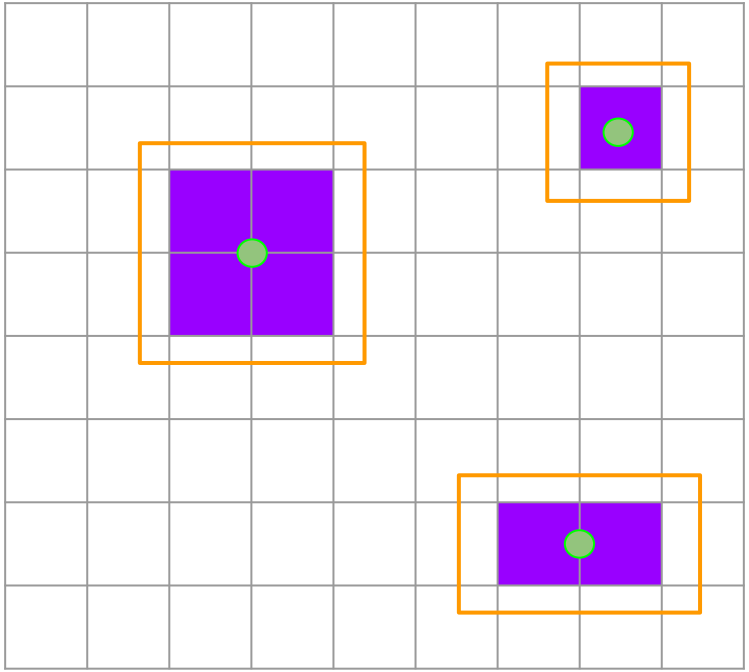
Clusterisation

Map of pixels (Binary output)



Clusterisation

Map of pixels (Binary output)

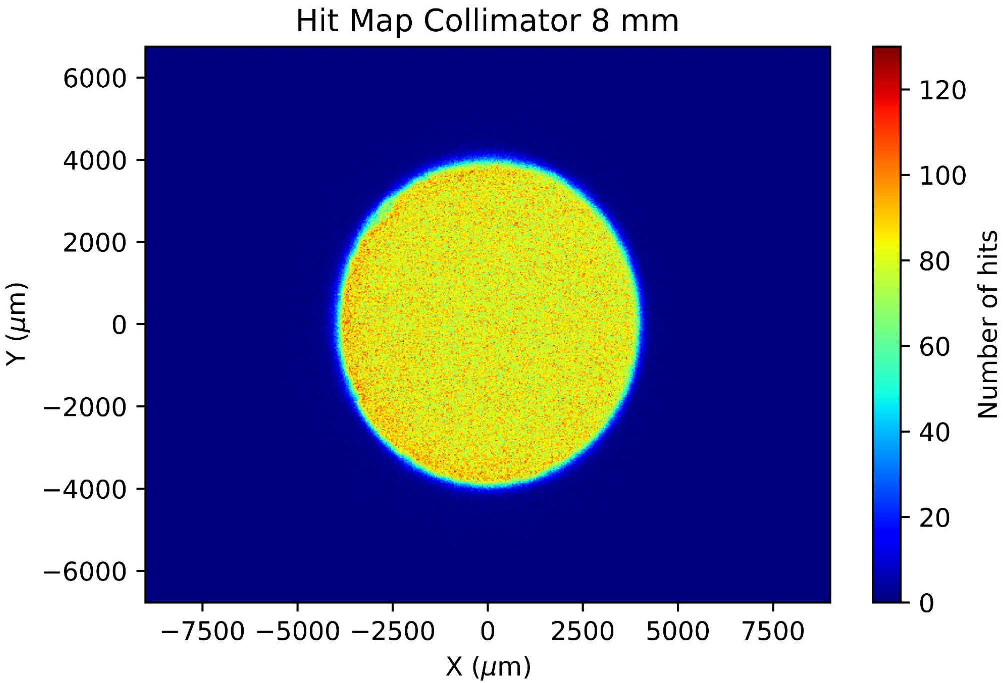


TAF : Telescope Framework Analysis (*Ref. [7]*)

→ *created and managed by IPHC to characterize CMOS pixel and strip sensors*

Hit Maps

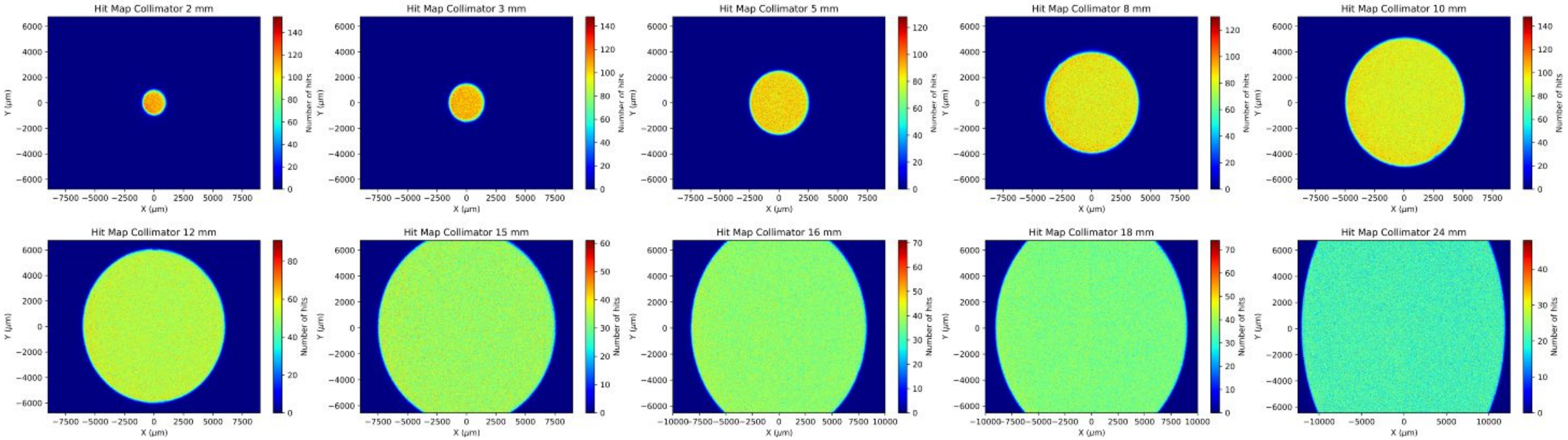
Motivation: Localized and controlled irradiation



Cumulated data over 5 000 000 frames

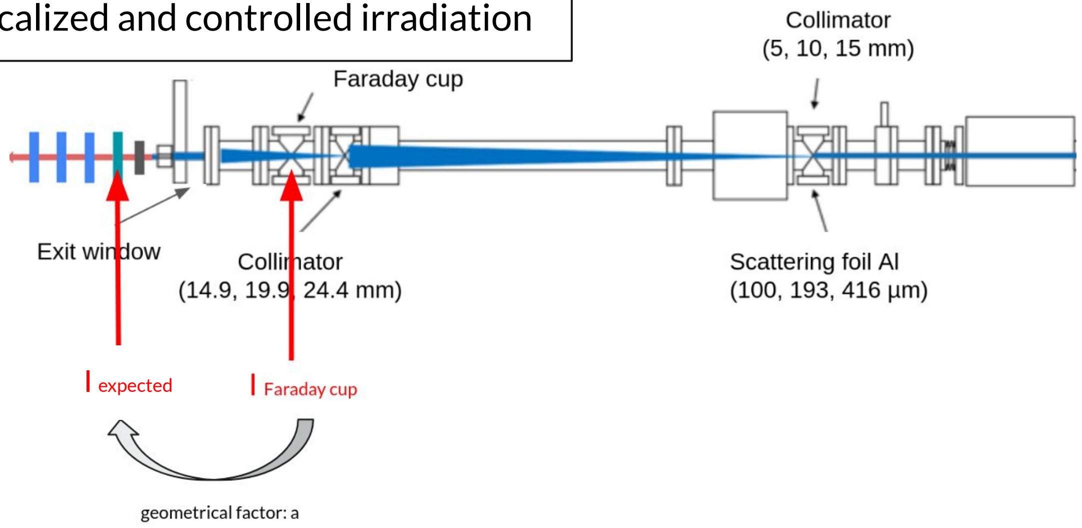
Hit Maps for different collimators diameter

Motivation: Localized and controlled irradiation



Comparison of 2 measurements of intensity

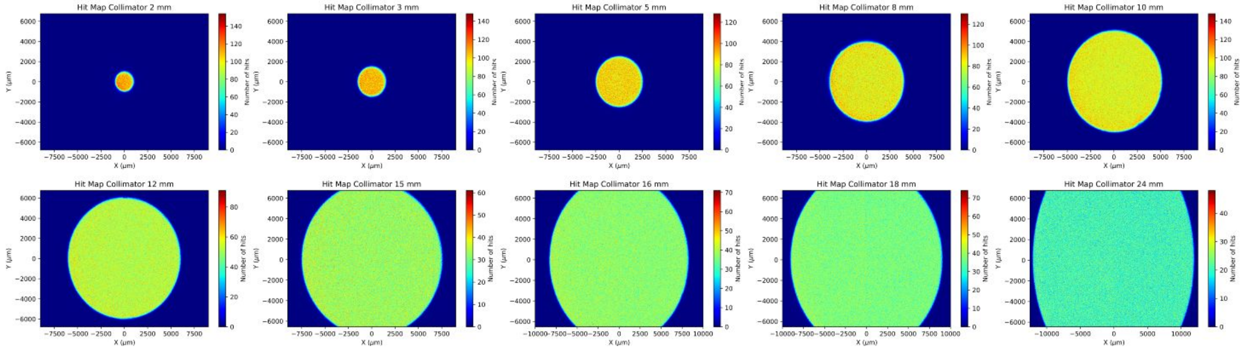
Motivation: Localized and controlled irradiation



Collimator diameter [mm]	2	3	5	8	10	12	15	16,5	18	24
I measured in Faraday cup [fA]	250	253	252	253	251	253	254	250	250	251
a (geometrical factor)	0,0116	0,0258	0,0705	0,1778	0,2814	0,3977	0,2249	0,2709	0,3222	0,5693
I expected [fA]	**2,90**	**6,53**	**17,77**	**44,98**	**70,63**	**100,62**	**57,12**	**67,73**	**80,55**	**142,89**

Hit Maps and intensity comparison

Motivation: Localized and controlled irradiation



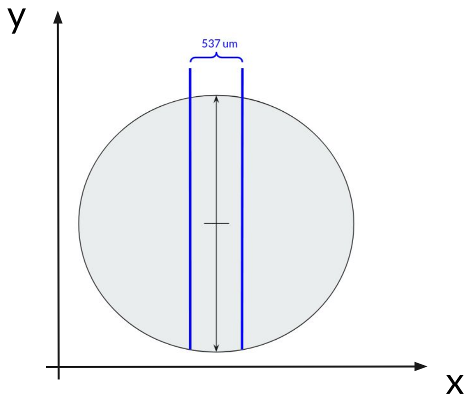
$$I = \frac{N \times q}{t}$$

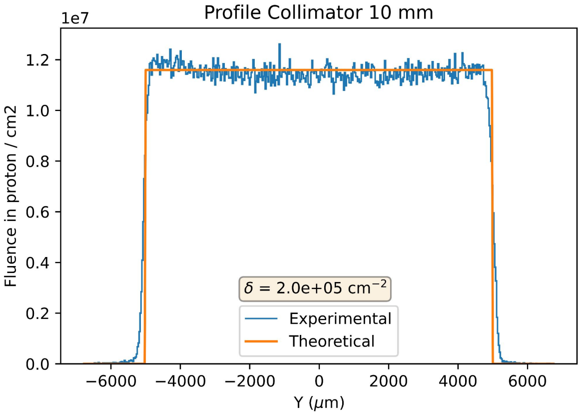
1 frame = 5 µs

Collimator diameter [mm]	2	3	5	8	10	12	15	16,5	18	24
I measured in Faraday cup [fA]	250	253	252	253	251	253	254	250	250	251
a (geometrical factor)	0,0116	0,0258	0,0705	0,1778	0,2814	0,3977	0,2249	0,2709	0,3222	0,5693
I expected [fA]	**2,90**	**6,53**	**17,77**	**44,98**	**70,63**	**100,62**	**57,12**	**67,73**	**80,55**	**142,89**
Number of hits	441897	923633	2095225	5181738	9208285	7374390	3187467	3585974	3575492	1988380
Number of read frames	4659001	4637003	3597003	3472001	4125003	2199896	3839003	4339001	4358002	2411679
I measured from Hit Map [fA]	**3,04**	**6,37**	**18,64**	**47,76**	**71,43**	**107,27**	**59,78**	**72,00**	**85,06**	**151,97**
Error between measured and expected	**4,66%**	**-2,35%**	**4,92%**	**6,17%**	**1,14%**	**6,61%**	**4,65%**	**6,31%**	**5,60%**	**6,35%**

Profiles in fluence (Y)

Motivation: Characterization of the beam





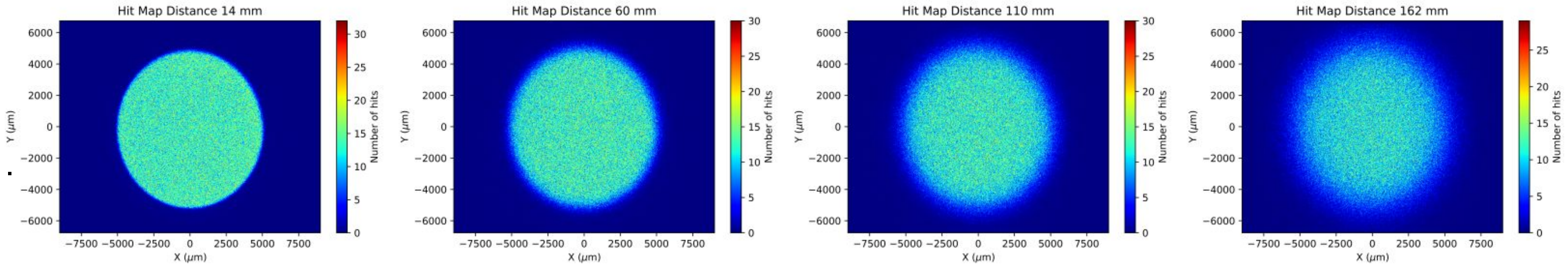
$$\Phi = \frac{N}{S}$$

$$N = \frac{I \times t}{q}$$

Collimator diameter [mm]	2	3	5	8	10	12
Theoretical fluency [cm^{-2}]	1,34E+07	1,34E+07	1,02E+07	9,71E+06	1,16E+07	6,12E+06
Experimental mean of fluency [cm^{-2}]	1,39E+07	1,30E+07	1,06E+07	1,02E+07	1,14E+07	6,39E+06
δ (theoretical - experimental mean) [cm^{-2}]	-4,92E+05	3,61E+05	-4,45E+05	-5,38E+05	2,02E+05	-2,71E+05
Standard deviation [cm^{-2}]	3,02E+05	3,29E+05	2,80E+05	2,62E+05	2,89E+05	6,04E+10

Dispersion as function of distance

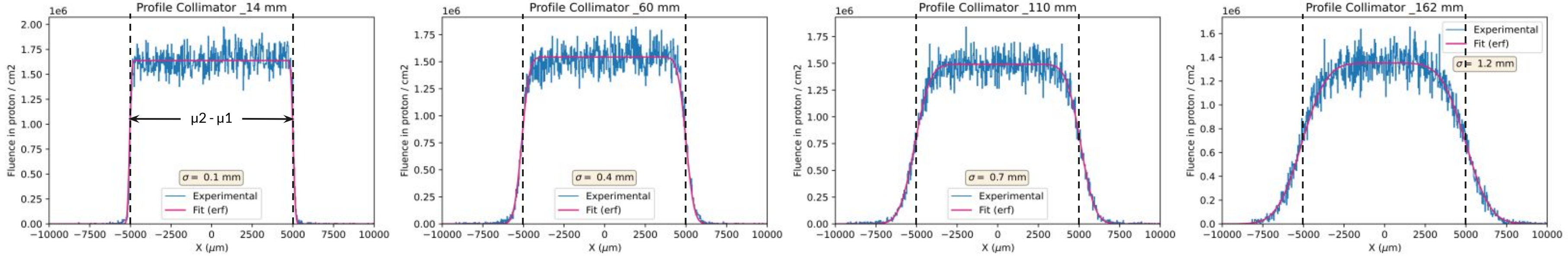
Motivation: Characterization of the beam



(a) 14 mm (b) 60 mm (c) 110 mm (d) 162 mm

Dispersion as function of distance

Motivation: Characterization of the beam



(a) 14 mm (b) 60 mm (c) 110 mm (d) 162 mm

$$erf(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^x e^{-\left(\frac{1}{2}\frac{x'-\mu}{\sigma}\right)^2} dx'$$

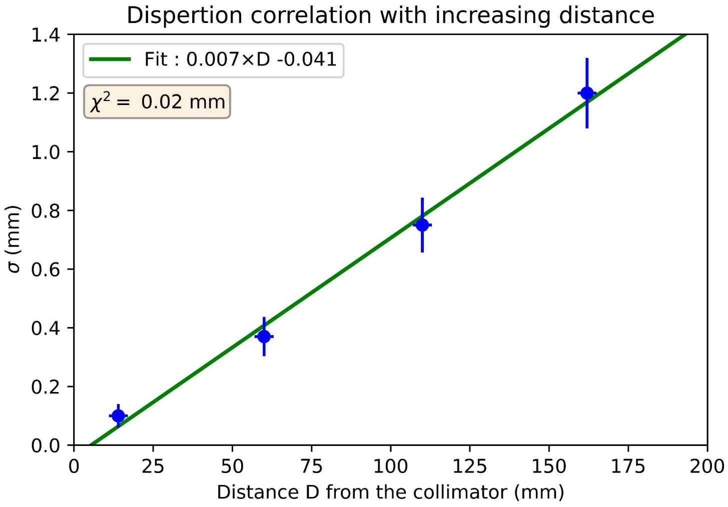
Distance (mm)	14	60	110	164
σ (mm)	0,10	0,37	0,75	1,20
Reconstructed diameter µ2-µ1 (mm)	10,07	10,10	10,20	10,10
Uncertainty on diameter (mm)	0,11	0,17	0,22	0,28

Mean fluence (cm^{-2})	1,64E+06	1,54E+06	1,49E+06	1,35E+06
Standard deviation (cm^{-2})	1,16E+05	1,10E+05	1,06E+05	1,14E+05

Dispersion as function of distance

Motivation: Characterization of the beam

Distance (mm)	14	60	110	164
σ (mm)	0,10	0,37	0,75	1,20
μ1 (mm)	-5,05	-5,10	-5,10	-5,10
μ2 (mm)	5,02	5,00	5,10	5,00
Reconstructed diameter (mm)	10,07	10,10	10,20	10,10
Uncertainty on diameter (mm)	0,11	0,17	0,22	0,28



$$\chi^2 = \sum_i \frac{(O_i - E_i)^2}{E_i}$$

Comparison between dose and fluence

Motivation: Characterization of the beam

Dose:

$$D = \frac{\mathrm{dE}}{dm}$$

$$D = \Phi \times \frac{\mathrm{LET}}{\rho}$$

Linear Energy Transfer = dE/dx

25 MeV protons in water :
LET = 2.38 ± 0.02 keV / µm

Comparison between dose and fluence

Motivation: Characterization of the beam

- Self-developing radiochromic films for radiotherapy dosimetry
- Dose is received → color of the film changes proportionally to the gradient of dose
- Scan the film → dose distribution

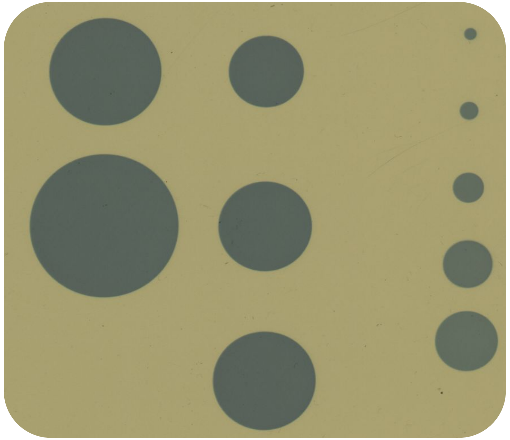
Dose:

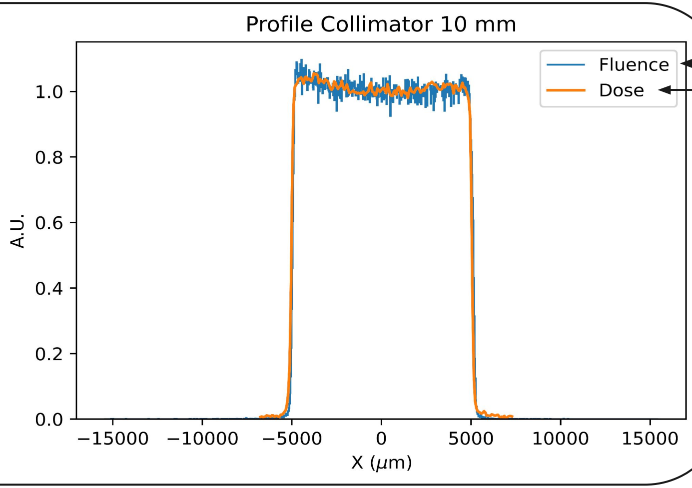
$$D = \frac{\mathrm{dE}}{dm}$$

$$D = \Phi \times \frac{\mathrm{LET}}{\rho}$$

Linear Energy Transfer = dE/dx

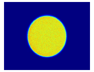
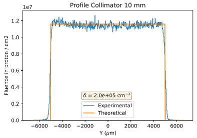
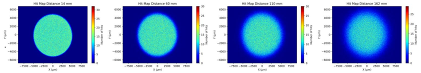
25 MeV protons in water : LET = 2.38 ± 0.02 keV / μm





with MIMOSIS-1
with Gafchromic

<u>Problematic :</u> Characterization of the proton beam at Cyrcé cyclotron using MIMOSIS-1 sensor.

What have been done ?	***What is left to be done ?***
Hit Maps → localised and controlled irradiation 	More sensor characterisation (bandwidth saturation effect, efficiency as function of threshold…)
Profiles in fluence →homogeneous beam in fluence 	Difference theoretical and experimental fluence ⇩ Secondary electrons (tracking) Instability of the beam Frame management
Dispersion quantification 	Further analysis
Dose and fluence comparison 	LET x ϕ = dose dose / ϕ = LET

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Bethe-Bloch

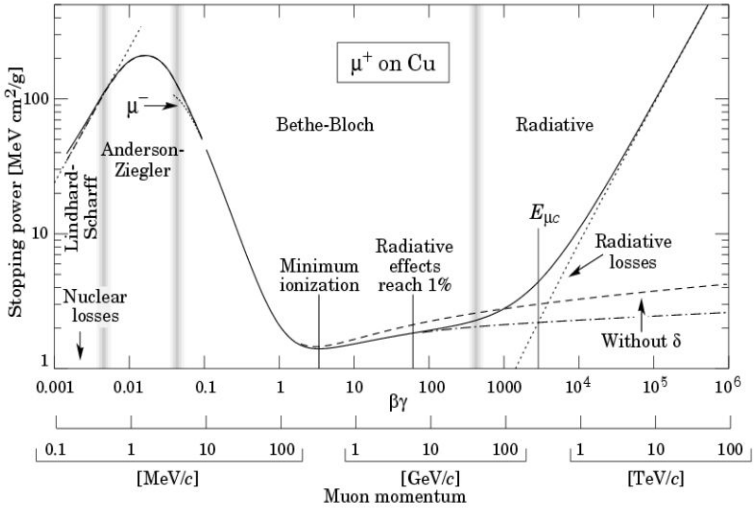


Figure from ref. [9]

$$E_{kin} = (\gamma - 1).m_{proton} \Leftrightarrow \gamma = \frac{E_{kin}}{m_{proton}} + 1$$

$$\gamma = \frac{1}{\sqrt{1-\beta}} \Leftrightarrow \beta = \sqrt{1 - \frac{1}{\gamma^2}}$$

$$E_{kin} = 25 \text{ MeV},$$
$$m_{proton} = 938.272 \text{ MeV.cm}^{-2},$$

$$\gamma = 1.03.$$
$$\beta = 0.17.$$
$$\beta\gamma = 0.1751.$$

$$\frac{1}{\rho}(\mathrm{dE/dx}) = 16.95 \text{ MeV.cm}^2.\text{g}^{-1}.$$
$$\frac{1}{\rho}(\mathrm{dE/dx}) = 2.71.10^{-9} \text{ Gy.cm}^2.$$

Values from ref. [10]

Difference LET and stopping power

- Stopping power: energy loss by the particle (in the matter),
- LET : energy transferred locally by the particle to the material per unit length.

$$\mathrm{LET} = \left(\frac{\mathrm{dE}}{\mathrm{dx}}\right) - \sum E_c(e_\delta).$$

kinetic energies of the δ electrons having an energy higher than a threshold

For protons:

$$\sum E_c(e_\delta) \approx 0 \Rightarrow \mathrm{LET} \approx \left(\frac{\mathrm{dE}}{\mathrm{dx}}\right)$$

NIEL factor

- Non-ionizing doses calculated by means of the NIEL (Non-Ionizing Energy Loss) factor,
- Normalizes the radiation damage caused by 1 MeV neutrons.
- Goal: Inter-facility comparison and collaboration.
- Derived by evaluating the leakage current in the bulk of a silicon sensor.
- For 25 MeV protons in Silicon: the NIEL factor is 2.558.

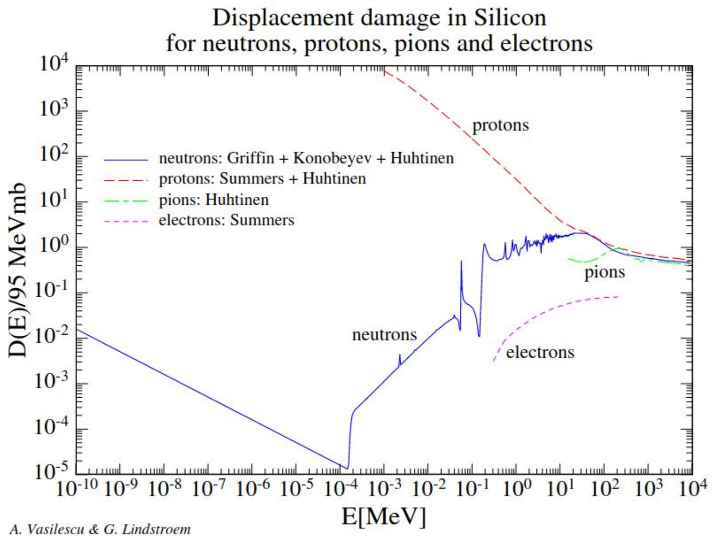


Figure from ref. [11]

CBM and PICSEL

- STS : Silicon Tracking System
- RICH : Ring Imaging Cherenkov detector
- TRD : Transition Radiation Detectors
- MUCH : MUon tracking CHamber
- TOF : Time-Of-Flight detector
- ECAL : Electromagnetic Calorimeter
- PSD : Projectile Spectator Detector

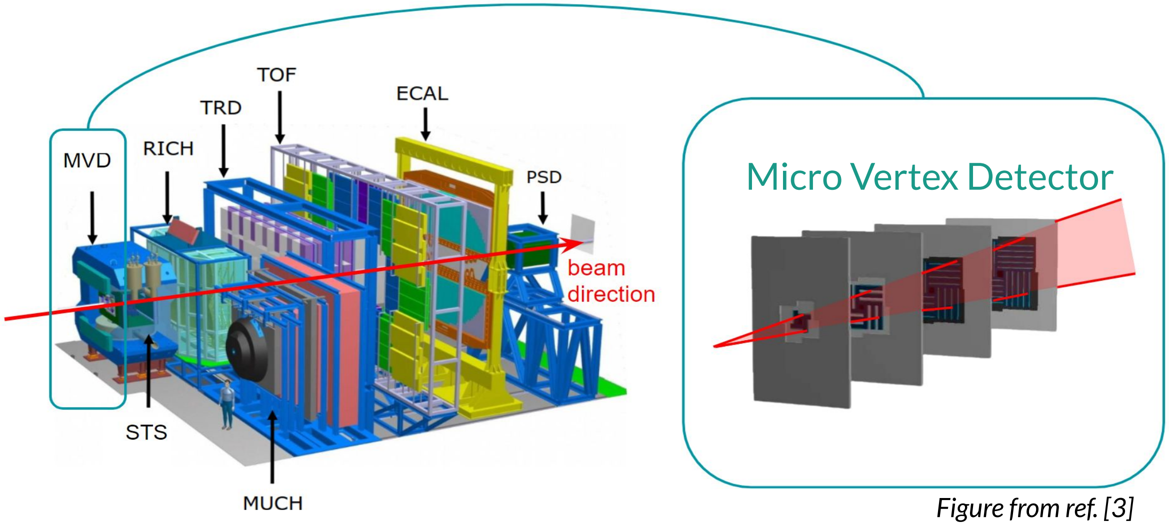


Figure from ref. [3]

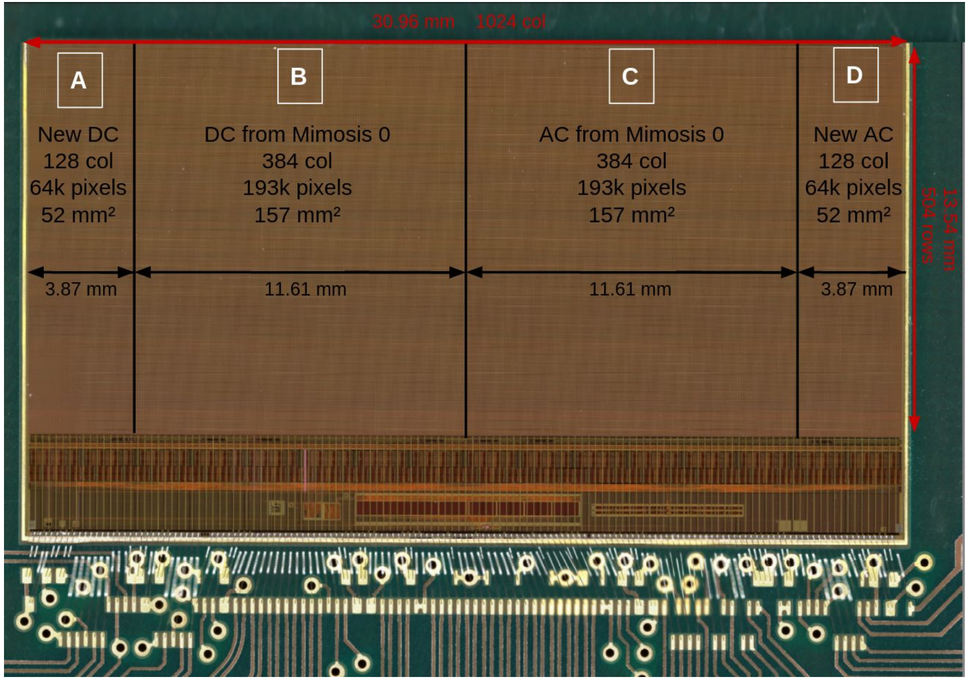
Requirements :

Charm meson can't reach detector ($c\tau(D^0)$ = 123 µm)
⇒ Spatial resolution

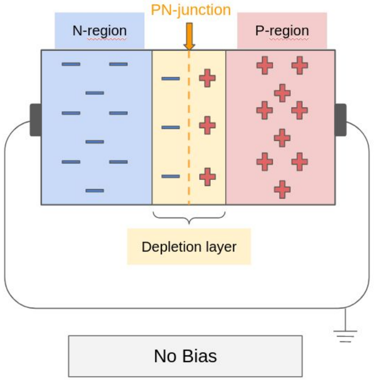
Rare probe → high intensity
⇒ Radiation resistant

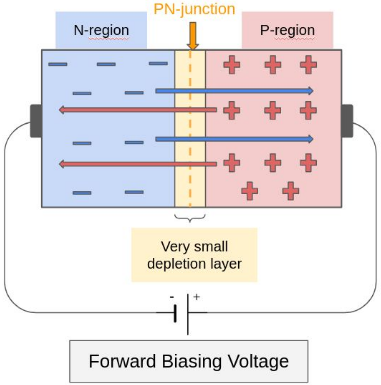
Description of the MIMOSIS-1 sensor

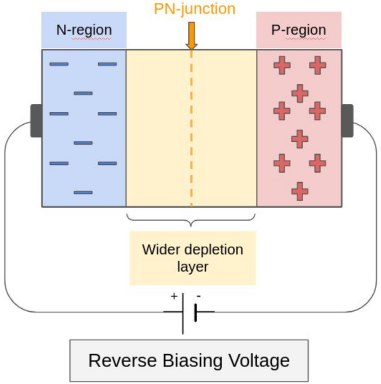
DC matrices:	AC matrices:
power supply of 1.8 V particle creates a potential difference that can be measured → better spatial resolution	additional 10 V voltage (high voltage) increases the depletion layer → faster collection of the charges → better resistance to radiations



Description of the sensor







N region : excess of electrons (on the valence band)
P region : lack of electrons, or holes
PN junction: electrons and holes recombine -> no free charges (depletion zone) -> barrier for charge carriers

Electrons flow from the n-type side to the p-type side,
Reduce the depletion region increase the flow of current

Increases the depletion region
Restrict the flow of current

PN junction create a depletion zone (and therefore an electric field) to limit recombination when a charged particle passes through.
Electron-hole pairs are collected easily by the detector's electrodes when the material is ionized.

Description of the sensor

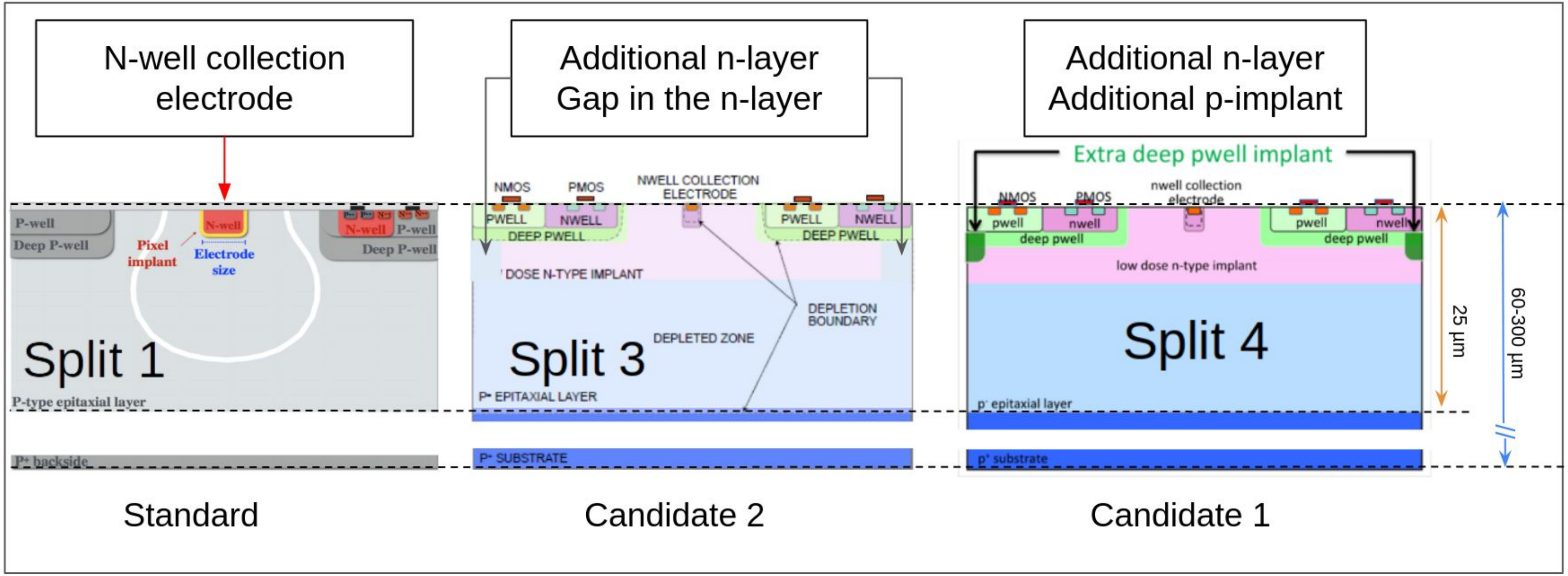


Figure from ref. [4]

MIMOSIS timeline

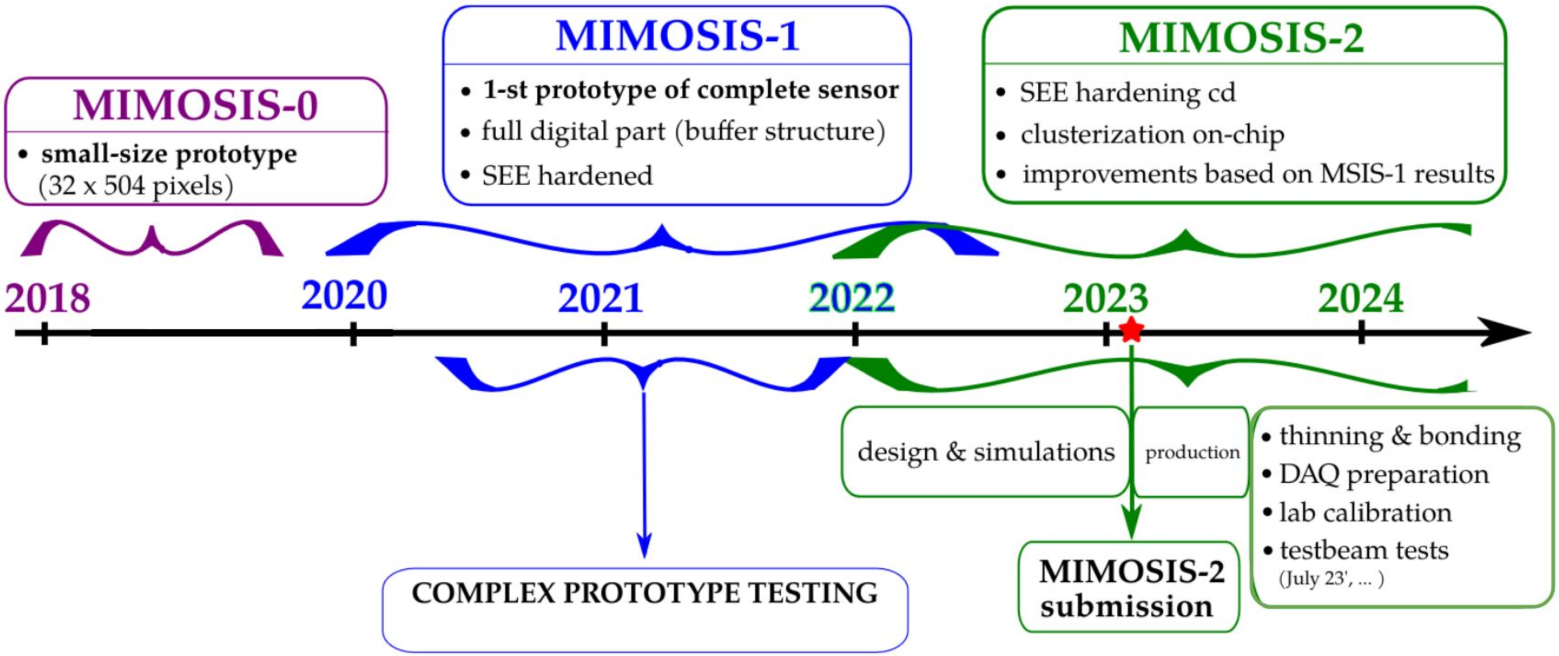


Figure from ref. [10]

MIMOSIS requirements

Physics parameter	Requirements
Spatial resolution	~ 5 um
Time resolution	~ 5 us
Material budget	0.05% X_0
Power consumption	< 100 – 200 mW/cm^2
Operation temperature	- 40 ^{o}C to 30 ^{o}C
Temp gradient on sensor	5K
Radiation* (non-ion)	~ 7 x 10^{13} n_{eq}/cm^2
Radiation* (ionizing)	~ 5 MRad
Data flow (peak hit rate)	@ 7 x 105 / (mm^{2}s) > 2 Gbit/s

* without safety factor

Goals of the experiment

Efficiency as a function of the threshold

→ different matrices

→ different back-bias

Bandwidth saturation (number of events the sensor is able to process) as a function of the beam intensity.

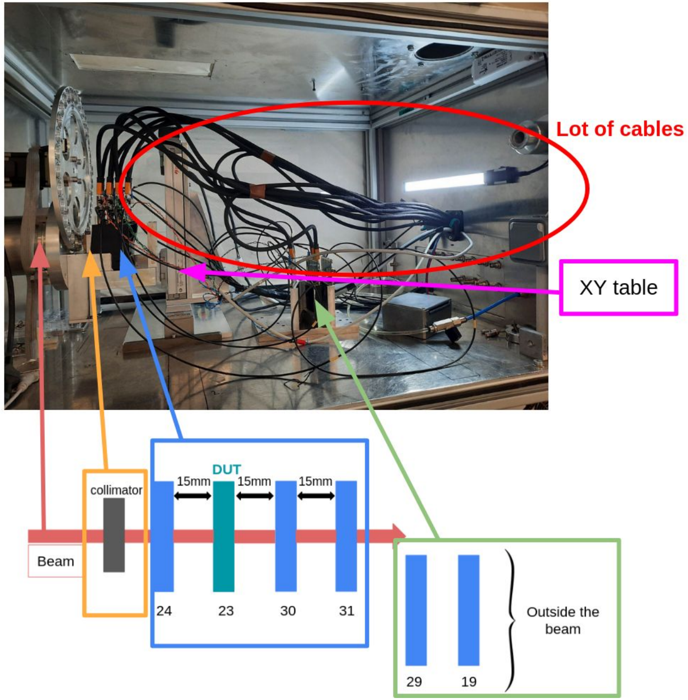
Check the performances of the sensors under non uniform high rate radiation which is expected in the CBM experiment.

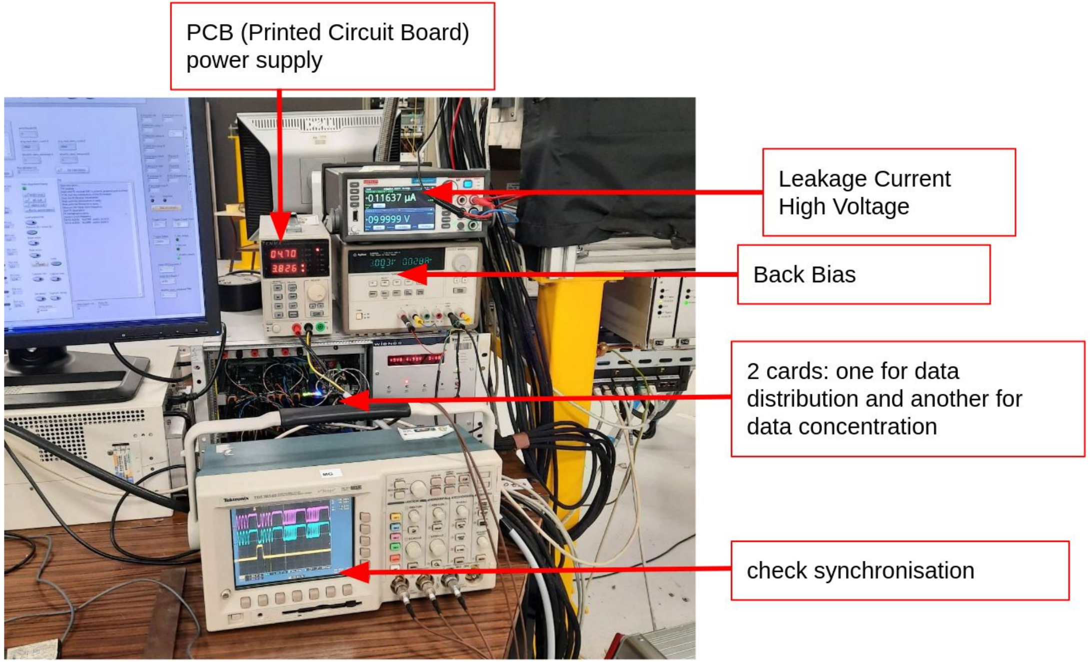
- better qualify the sensors
- choose the best parameters for the final version of the MIMOSIS

Determine the profile in fluence of the beam

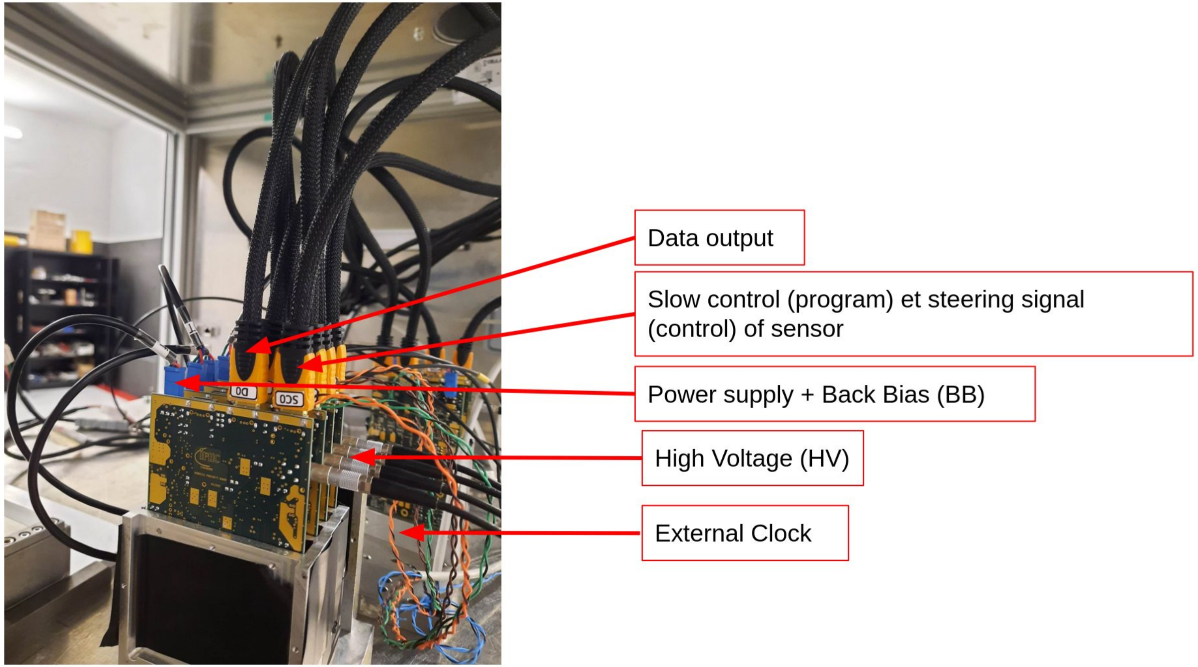
- better understand the deposited dose for radiobiology applications

Description of the experiment





Description of the experiment



Description of the other experiments

Change of threshold

Threshold : minimum number of electrons detected to interpret it as a signal

high threshold → some events can be missed.
low threshold → noise can be interpreted as signal.

Goal: analyse the efficiency as a function of this threshold.

Reference planes: threshold is 120 electrons (e-)
DUT: measurements at 90 e-, 120 e-, 150 e-, 200 e-, 240 e-

Scan:

for each split (1, 3 and 4).
for back bias on the DUT at -1 V and -3 V
for matrix B and matrix C.

VCASN values for threshold

	Chip 23 split 1			
	-1V (Vclip = 55)		-3V (Vclip = 75)	
	B	C	B	C
70e	163	165	220	230
80e	153	155	210	220
90e	143	145	200	210
120e	128	131	179	187
150e	113	114	152	160
200e	104	104	145	146
240e	102	100	141	142

	Chip 19 split 3			
	-1V (Vclip = 55)		-3V (Vclip = 75)	
	B	C	B	C
60e		140	197	203
70e		130	190	194
80e		120	183	185
90e	124	110	176	176
120e	113	100	157	153
150e	101	94	136	136
200e	87	88	132	130
240e	85	86	128	126

	Chip 26 split 4			
	-1V (Vclip = 55)		-3V (Vclip = 75)	
	B	C	B	C
90e	131	113	172	161
120e	116	98	150	141
150e	104	93	132	126
200e	91	88	120	118
240e	88	86	117	115

Chip 34 Back Bias -1V	
A	98 (187e)
B	123 (192e)
C	127 (185e)
D	107 (183e)

Plan references	Chip 24 (Vcasn2 = 110)	Chip 29 (Vcasn2 = 110)	Chip 30 (Vcasn2 = 110)	Chip 31 (Vcasn2 = 120)
120e	115 / 120 / 113 / 105	90 / 115 / 120 / 90	100 / 113 / 108 / 95	120 / 130 / 135 / 130
-1V Back Bias				
10V High Voltage				

Description of the other experiments

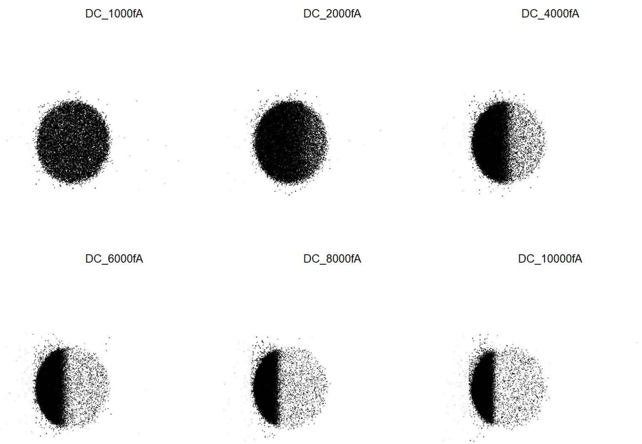
Intensity scan

Goal: observe bandwidth saturation effect.

DUT: measurements from 18 to 2876 fA, (0.1 to 20 MHz/cm2).

Scan:

for split 1 and 3
for back bias on the DUT at -3 V
for matrix B and matrix C.

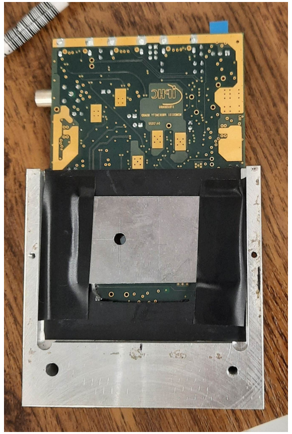


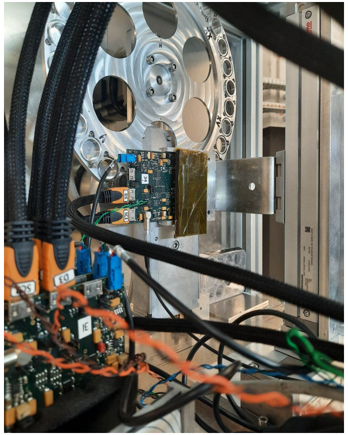
Description of the other experiments

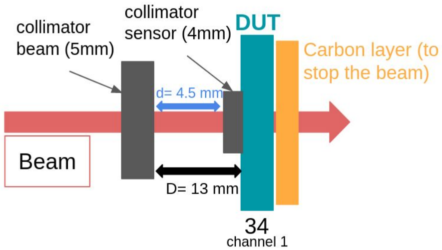
Irradiation resistivity

Goal: reproduce non-uniformity of MVD irradiations → localized irradiations at high rate (fluence of 10^{13} and 10^{14} neq / cm^2)

Long irradiation time (1h20) → profile of the beam can vary







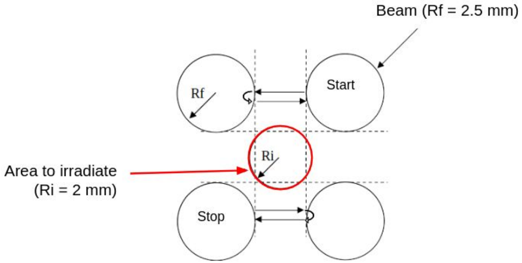
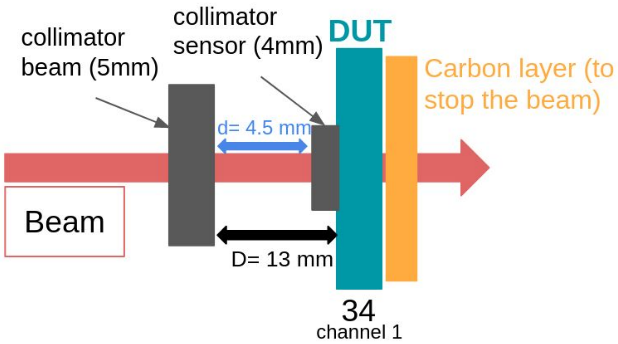
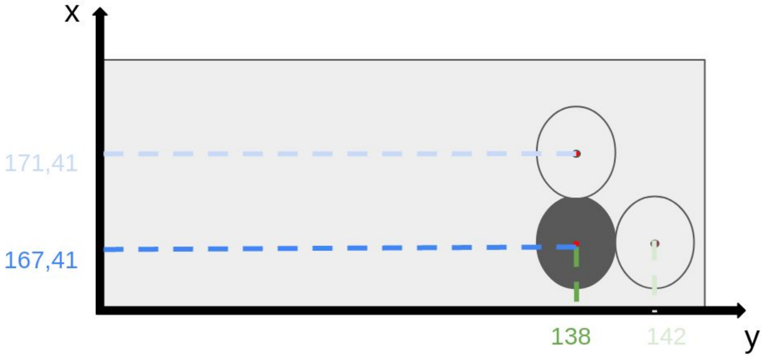


Figure from ref. [12]

Irradiation configuration

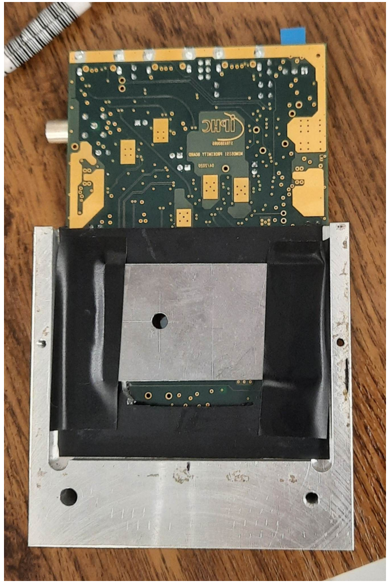
Configuration ⑤

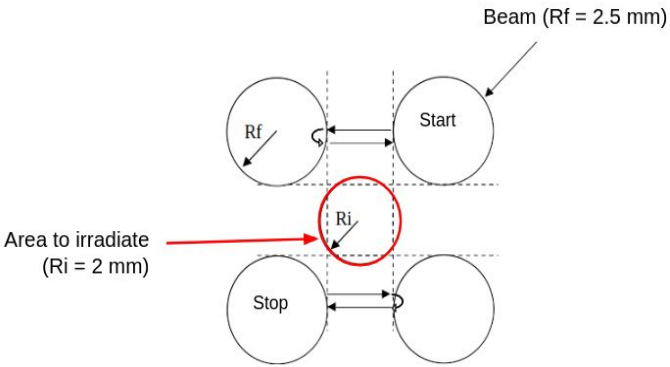


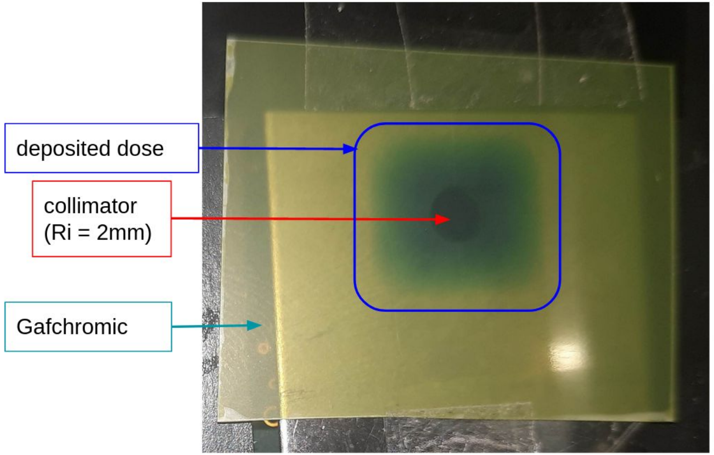


/!\ sensor is turned by 90°
(x↔y compared to other configurations)

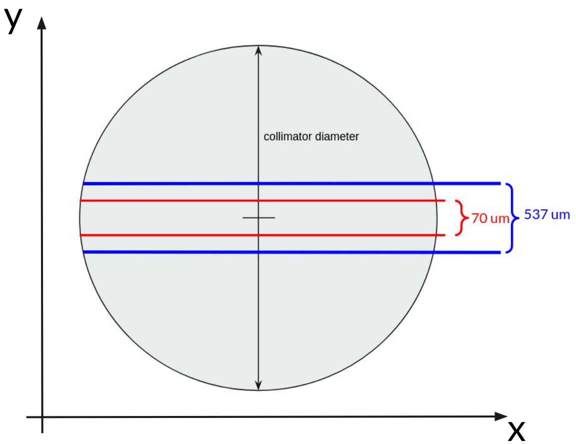
Irradiation configuration



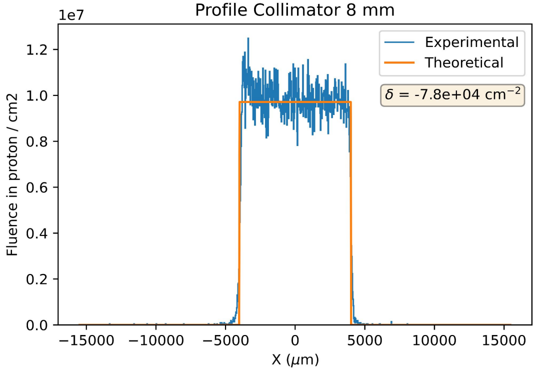




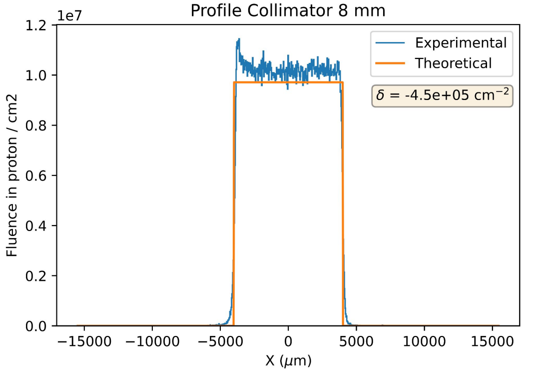
Profiles in fluence (X)



70 µm
less statistics: more uncertainty on plateau
less effect from beam geometry



537 µm
more statistics: less uncertainty on plateau
more effect from beam geometry



537 µm

Run Number	23334	23335	23336	23337	23338	23339	23340	23341	23342	23343
Collimator diameter [mm]	2	3	5	8	10	12	15	16,5	18	24
Theoretical fluency [cm^{-2}]	1,34E+07	1,34E+07	1,02E+07	9,71E+06	1,16E+07	6,12E+06	3,94E+06	4,38E+06	4,39E+06	2,40E+06
Experimental mean of fluency [cm^{-2}]	1,38E+07	1,29E+07	1,05E+07	1,02E+07	1,13E+07	6,41E+06	4,06E+06	4,57E+06	4,56E+06	2,54E+06
δ (theoretical - experimental mean) [cm^{-2}]	-3,46E+05	4,62E+05	-3,66E+05	-4,48E+05	2,82E+05	-2,89E+05	-1,20E+05	-1,95E+05	-1,72E+05	-1,45E+05
Standard deviation [cm^{-2}]	2,26E+05	2,17E+05	2,58E+05	2,60E+05	2,73E+05	1,88E+05	1,54E+05	1,69E+05	1,67E+05	1,30E+05

X profiles for different collimators

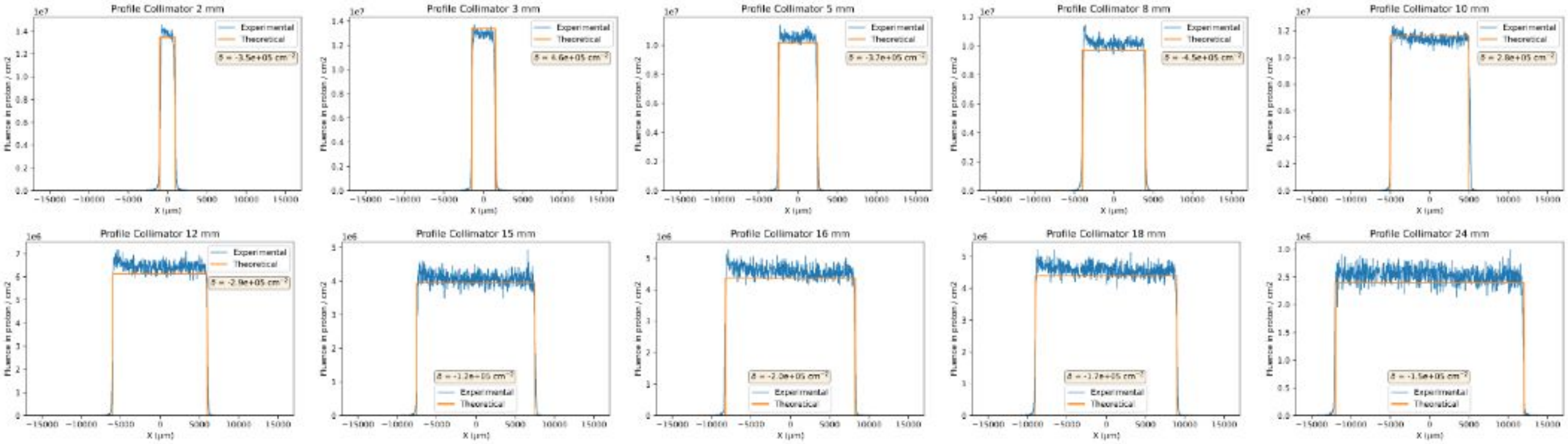


Figure F.2: X profile for different collimator diameters for bandlenght of 537 μm.

X profiles for different collimators

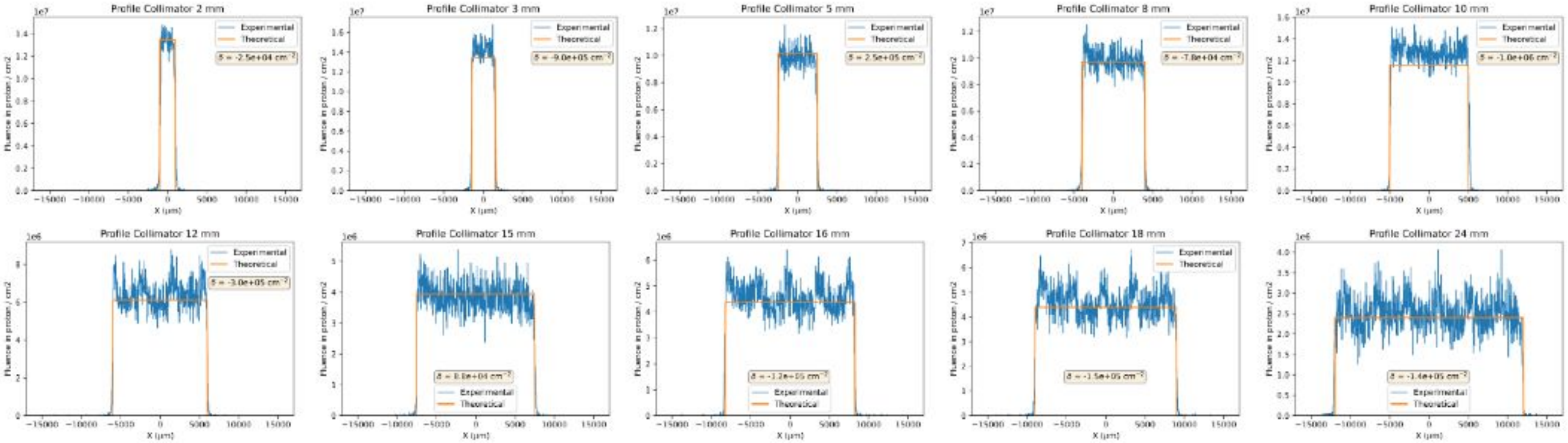


Figure F.1: X profile for different collimator diameters for bandlenght of 71 μm.

Y profiles for different collimators

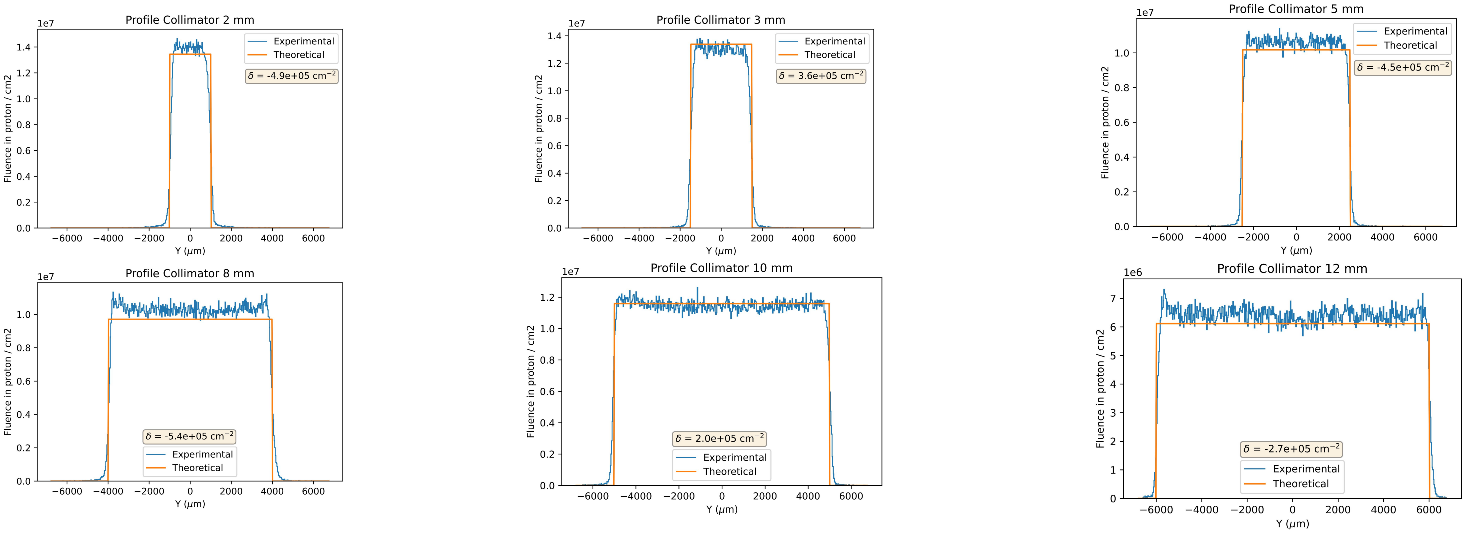


Figure F.3: Y profile for different collimator diameters for bandlenght of 537 μm.

Profiles in fluence: X and Y comparison

Run Number Collimator diameter [mm]	23334 2	23335 3	23336 5	23337 8	23338 10	23339 12	23340 15	23341 16,5	23342 18	23343 24
Theoretical fluency [cm⁻²]	1,34E+07	1,34E+07	1,02E+07	9,71E+06	1,16E+07	6,12E+06	3,94E+06	4,38E+06	4,39E+06	2,40E+06
Experimental mean of fluency [cm⁻²]	1,38E+07	1,29E+07	1,05E+07	1,02E+07	1,13E+07	6,41E+06	4,06E+06	4,57E+06	4,56E+06	2,54E+06
δ (theoretical - experimental mean) [cm⁻²]	-3,46E+05	4,62E+05	-3,66E+05	-4,48E+05	2,82E+05	-2,89E+05	-1,20E+05	-1,95E+05	-1,72E+05	-1,45E+05
Standard deviation [cm⁻²]	2,26E+05	2,17E+05	2,58E+05	2,60E+05	2,73E+05	1,88E+05	1,54E+05	1,69E+05	1,67E+05	1,30E+05

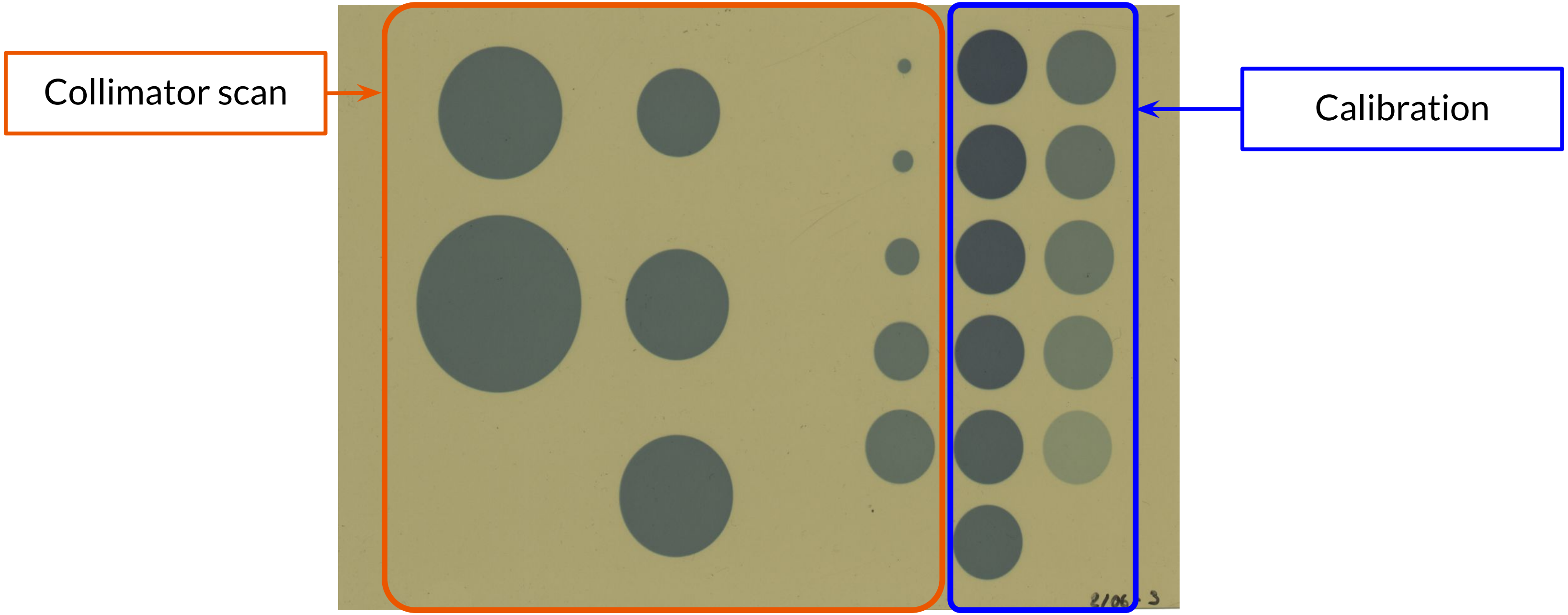
Run Number Collimator diameter [mm]	23334 2	23335 3	23336 5	23337 8	23338 10	23339 12
Theoretical fluency [cm⁻²]	1,34E+07	1,34E+07	1,02E+07	9,71E+06	1,16E+07	6,12E+06
Experimental mean of fluency [cm⁻²]	1,39E+07	1,30E+07	1,06E+07	1,02E+07	1,14E+07	6,39E+06
δ (theoretical - experimental mean) [cm⁻²]	-4,92E+05	3,61E+05	-4,45E+05	-5,38E+05	2,02E+05	-2,71E+05
Standard deviation [cm⁻²]	3,02E+05	3,29E+05	2,80E+05	2,62E+05	2,89E+05	6,04E+10

Error between X and Y	**1,05%**	**0,78%**	**0,74%**	**0,88%**	**0,70%**	**-0,28%**

Profiles in fluence: distance scan intensity

Distance (mm)	14	60	110	162
Run Number	23210	23159	23157	23155
Collimator diameter [mm]	10	10	10	10
I measured in Faraday cup [fA]	63	60	60	60
a (geometrical factor)	0,2879	0,2879	0,2879	0,2879
I theoric [fA]	**18,14**	**17,27**	**17,27**	**17,27**
Number of hits	1311678	1242447	1240637	1149329
Number of read frames	2229622	2188187	2185496	2175707
I measured from Hit Map [fA]	**18,83**	**18,17**	**18,17**	**16,90**
Error between measured and theoric	**3,79%**	**5,18%**	**5,16%**	**-2,14%**

Gafchromic calibration



F.2 Dose and fluence comparison

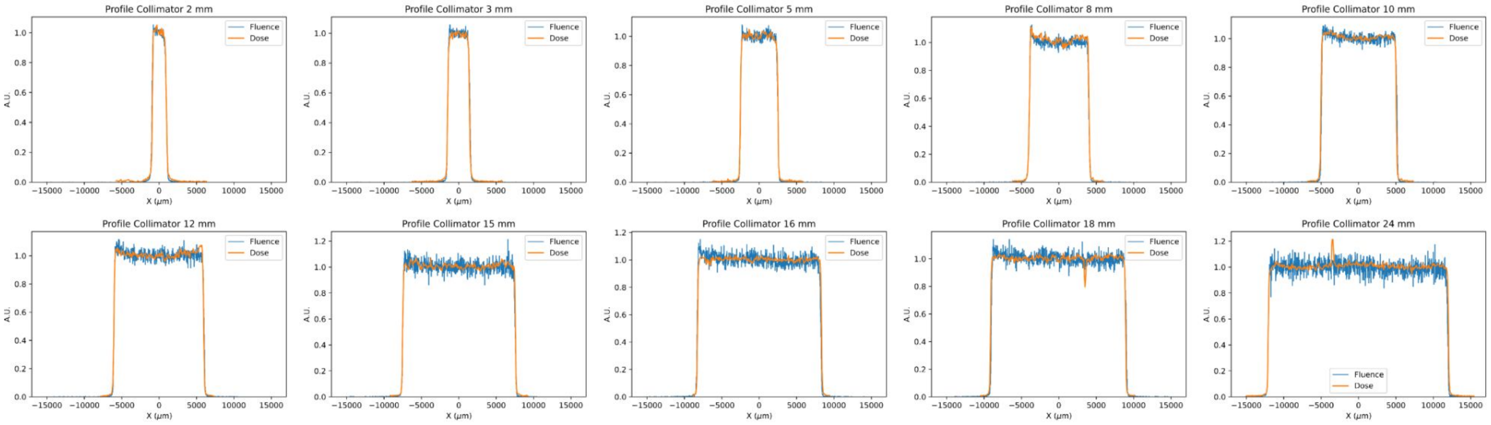


Figure F.4: Comparison of x profile of the beam in fluence and in dose for all collimators. The dose and fluence have been normalized.