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Screening effect and gain suppression using IBIC and Ion-TCT at RB

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Introduction - MOTIVATION

- Gain suppression in LGAD has been confirmed in previous studies. Charge density was seen as a key parameter. Further investigations are needed in order to better understand the charge density thresholds for such behaviour. This presentation present the most recent study performed at the Rudjer Boskovic Institute, using IBIC and Ion-TCT analysis.

- Since space charge screening effects depend on the spatial distribution and density of the injected charge, MeV energy ions of different masses could be a valuable probes to study consecutive anomalous behaviour of gain in LGAD.

- Investigating the role of screening in determining the charge collection dynamics is best performed by altering the density of electron-hole pairs along the ion track in a quantifiable manner. This can be best achieved by choosing different ions and their respective energies in a such way that either their Bragg peaks or their end-of-range correspond to the same depth in the active region of LGAD.

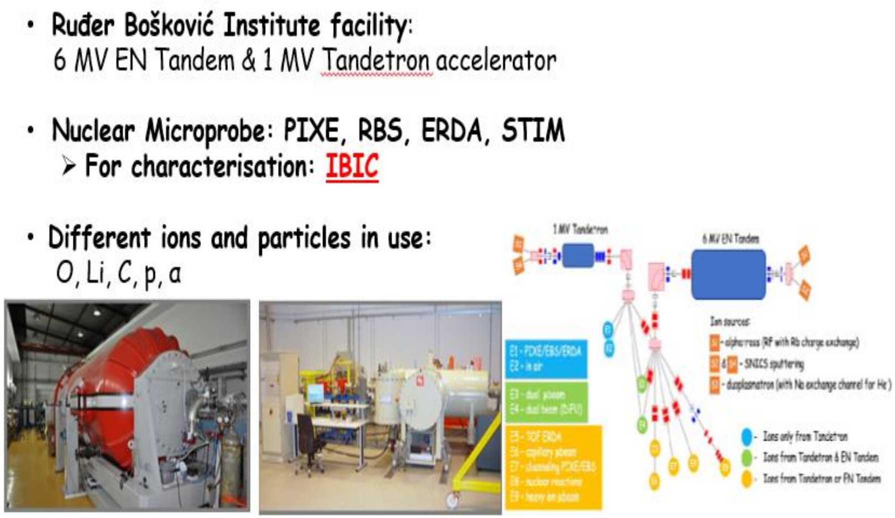
- It is also possible to chose energy of ion in a such way that, when irradiated from the back side, Bragg peak corresponds to the depth that is in the inactive-substrate layer of LGAD, but close enough to the active LGAD region. In such circumstances, by observing the time resolved structure of the signal (ionTCT), the charge transport through LGAD can be studied in more quantified way. Performing the same ion-TCT experiment, but from the front side of LGAD, comparison of collected data give deeper insight into charge transport through LGAD, including explanation for LGAD's gain anomalous behaviour

Materials

LGADs: 2x2 and single pad, WF36, unirradiated

Method:

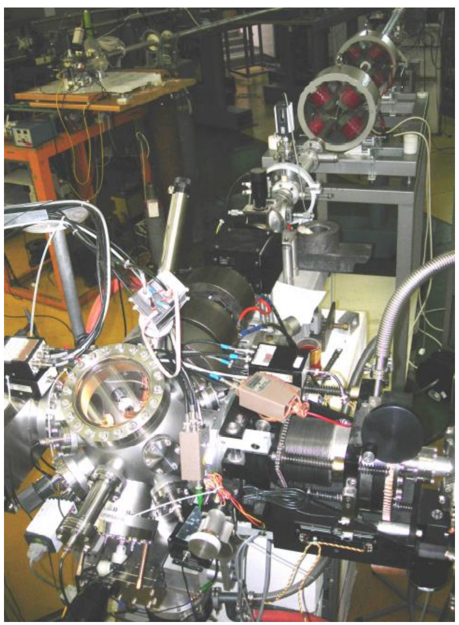
Charge collection, signal pulse measurements IBIC, ION-TCT at Rudjer Boskovic Institute



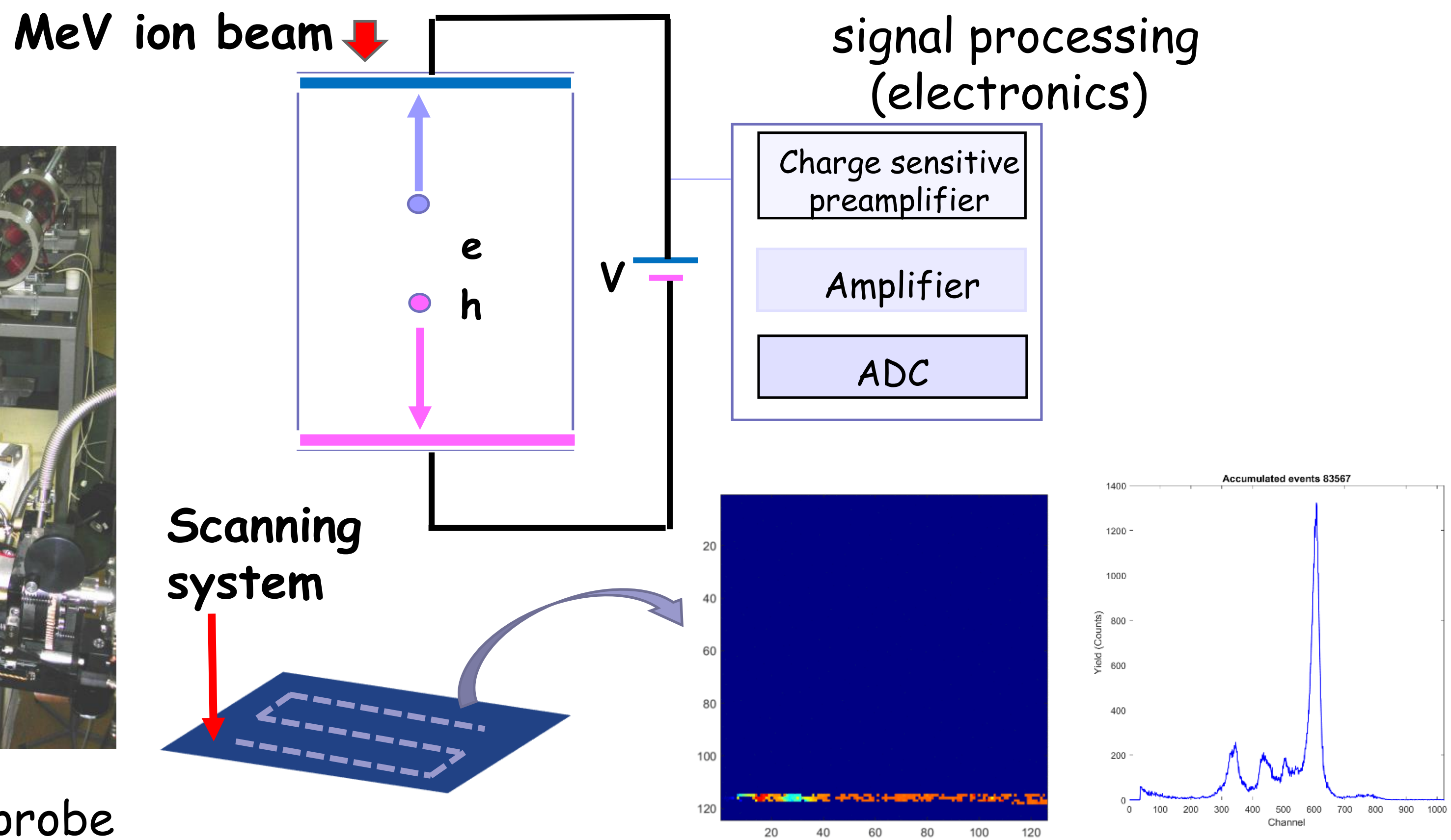
Three folded study/Work under progress:

- ❑ Mapping of Gain Suppression vs. Ion type/deposited energy
  - ❑ 2 experiments
- ❑ Time resolved measurement: Backside and frontside illumination with 4 MeV H+
- ❑ Interpad stuvs bias, exploiting different H+ energies

Ion Beam Induced Charge Technique



Nuclear Microprobe



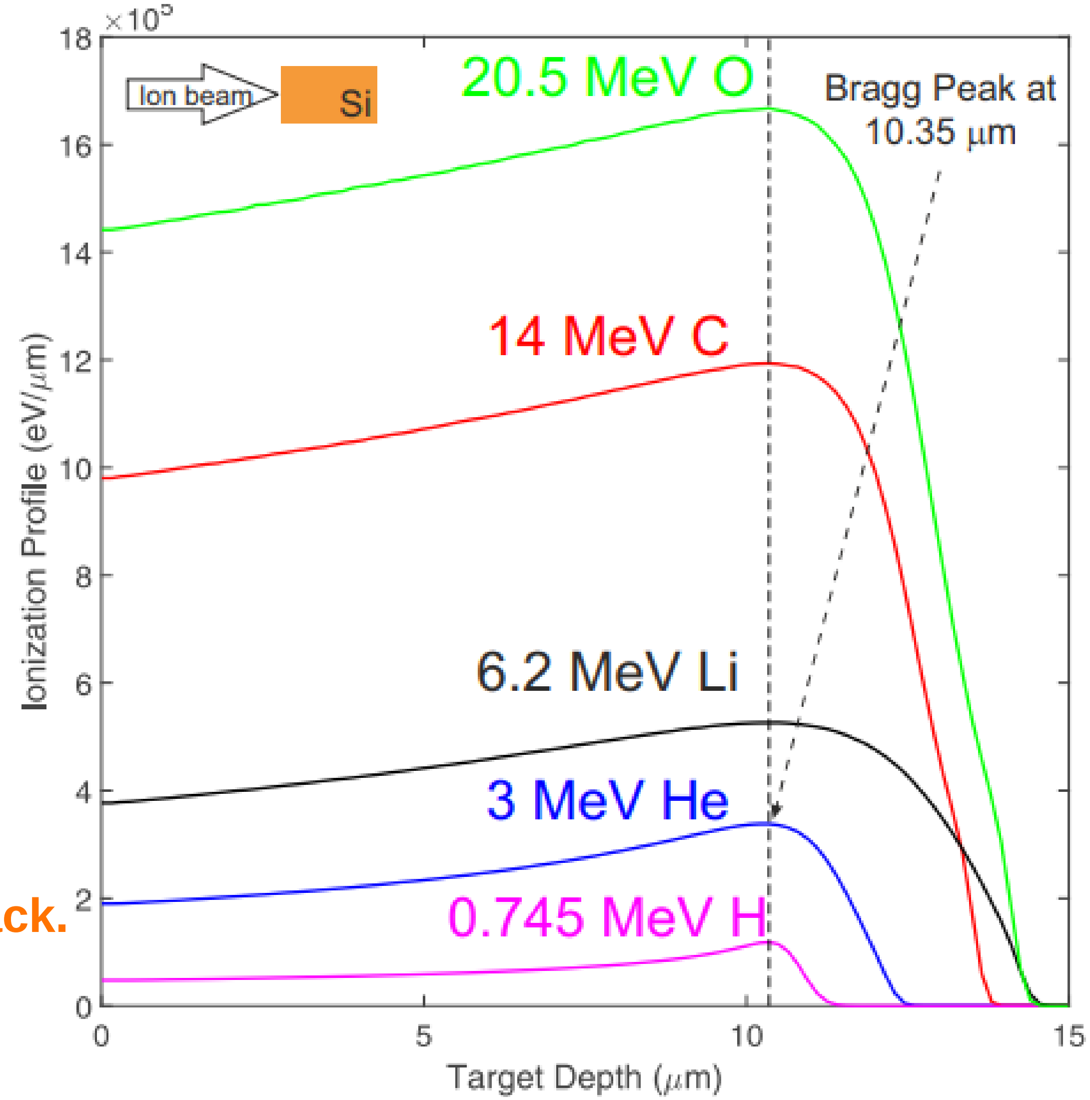
Gain Suppression vs. Ion Type.

1.Experiment

Different ions and their respective energies are selected in a such way that their Bragg peaks correspond to the same depth in the active region of LGAD.

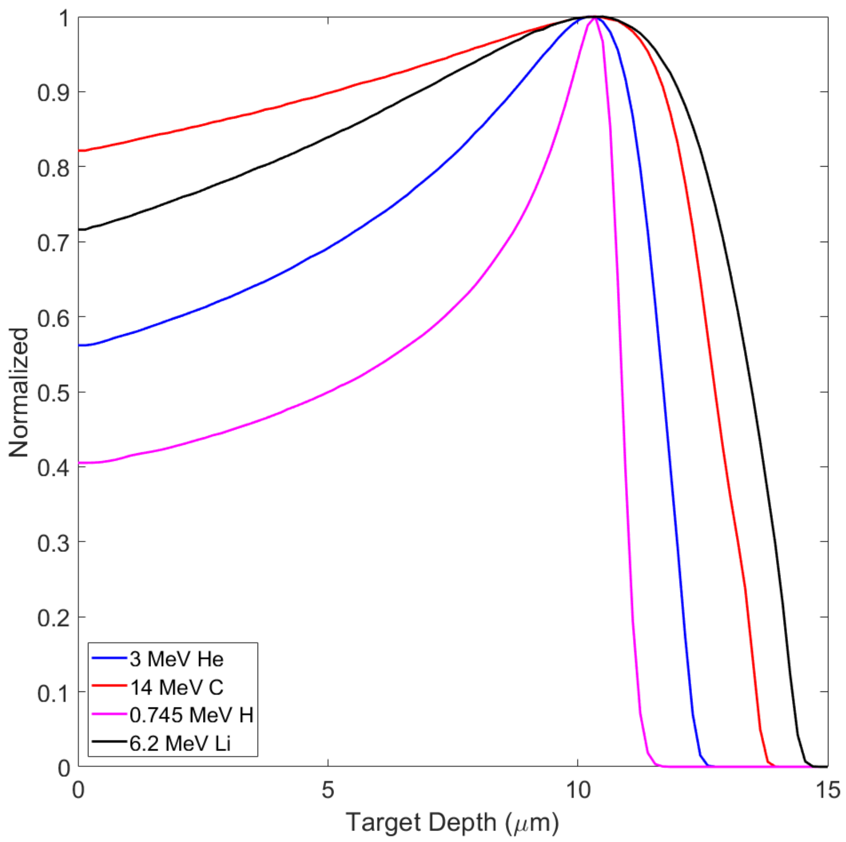
The ionization (**dE/dx)** profiles were evaluated through SRIM2008 simulations

Sensor: HPK-P2 W36 SE3-IP7
it was 2x2 with a hole from back.



* At this moment e managed only study with C, and He. We experienced some problems with Li. This work will continue.

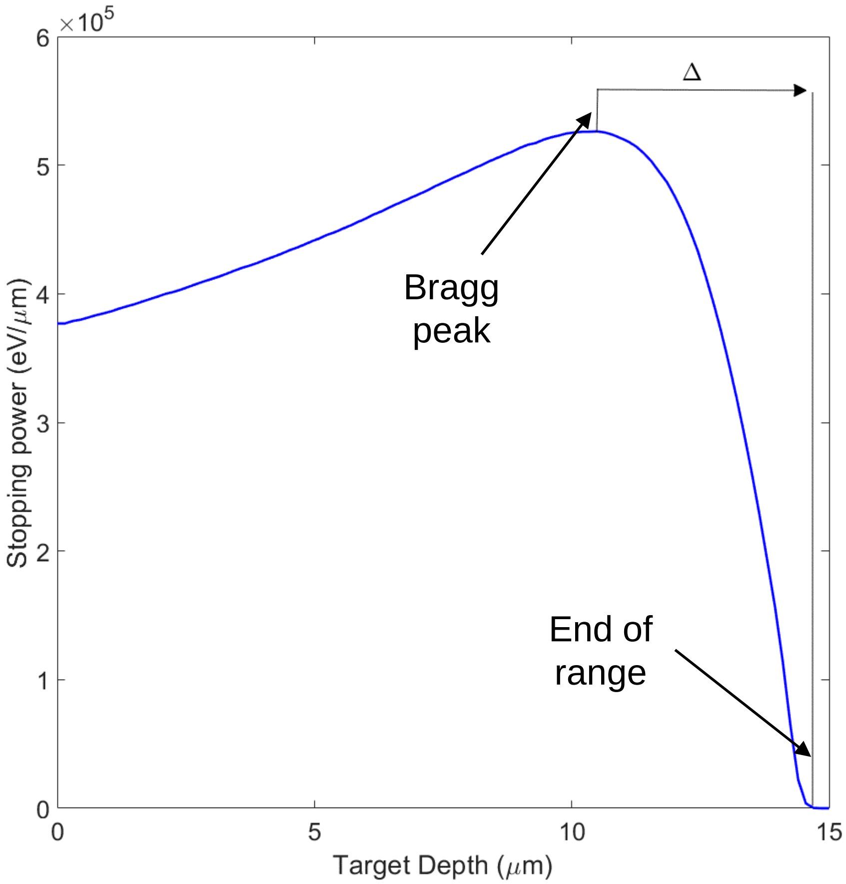
The "width" of Bragg peak is not the same for chosen ion species

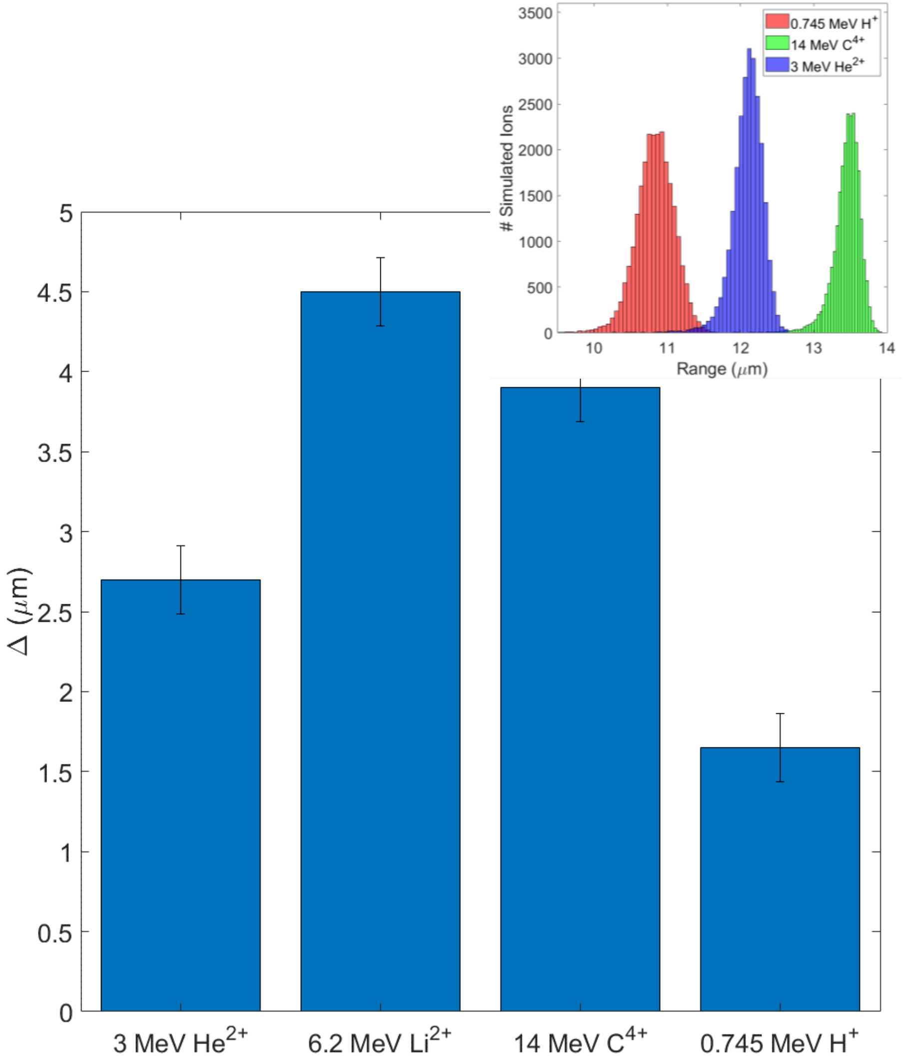


- the Bragg peaks were normalized to one for all the ion beams and species so one can observe the difference in the shape and width of the different Brag peaks.

Graph bellow shows the distance Δ between the Bragg peak position and the end of the particle range, plotting for each ion beam energy and specie.

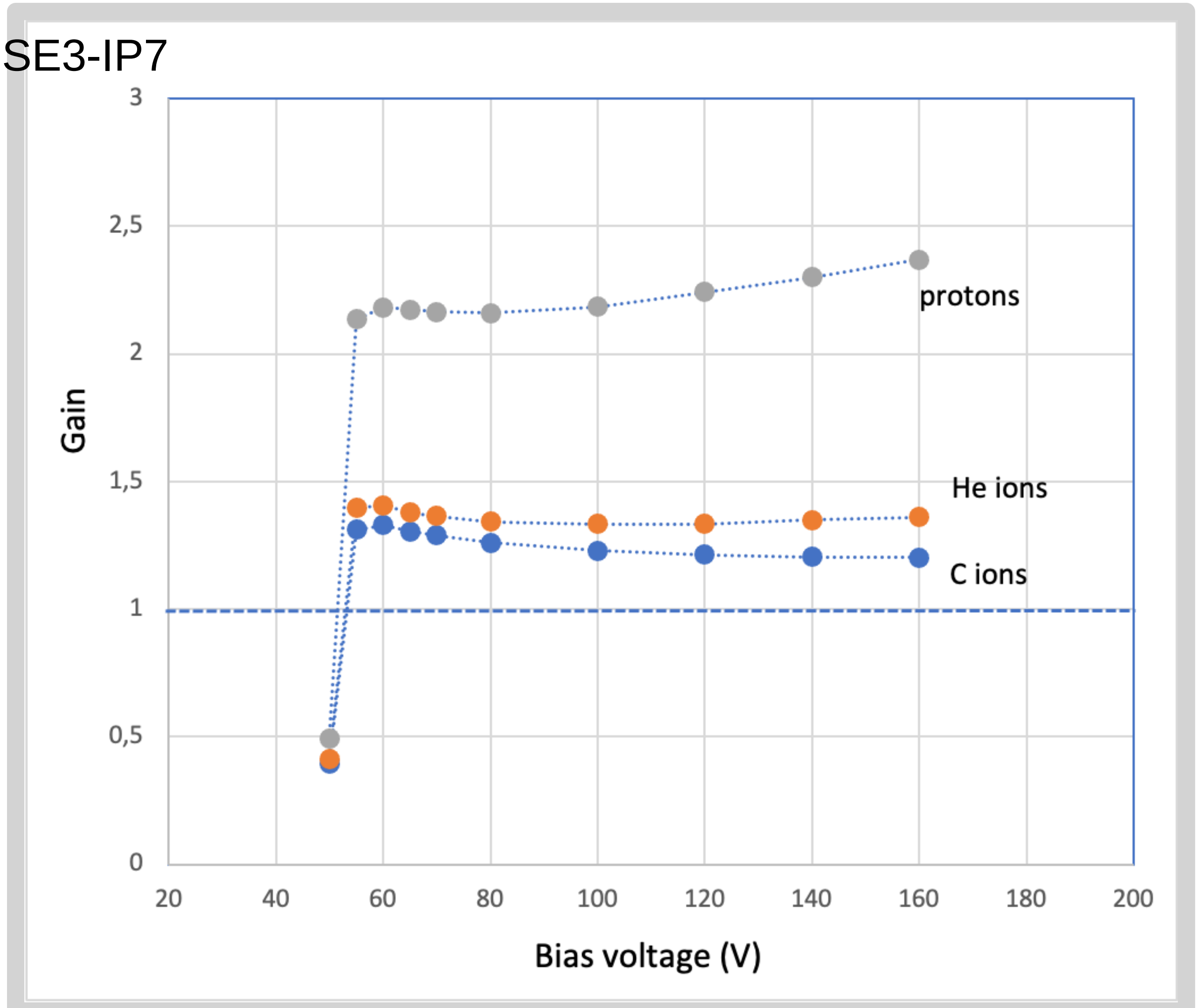
The error bars in the bar plot were obtained considering the target depth resolution given by SRIM.



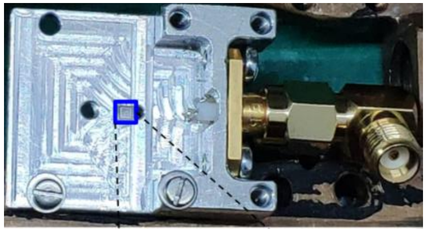


Gain Suppression Result

HPK-P2 W36 SE3-IP7



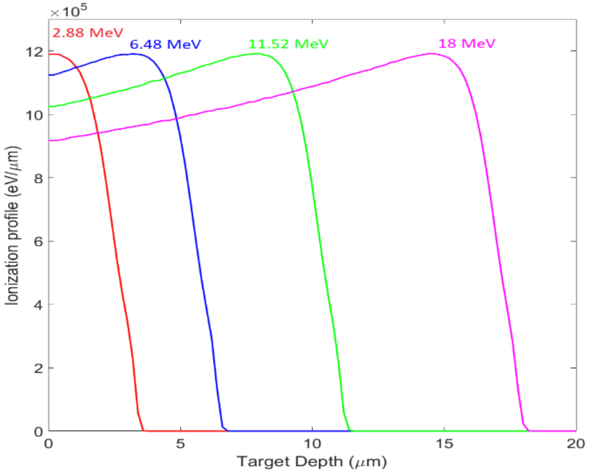
2. Experiment: The same ion specie(Carbon), but with different energies

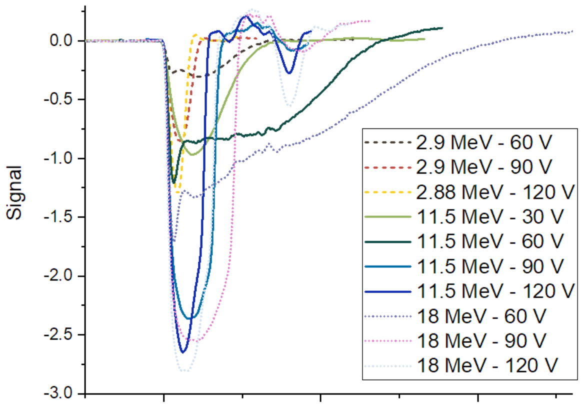


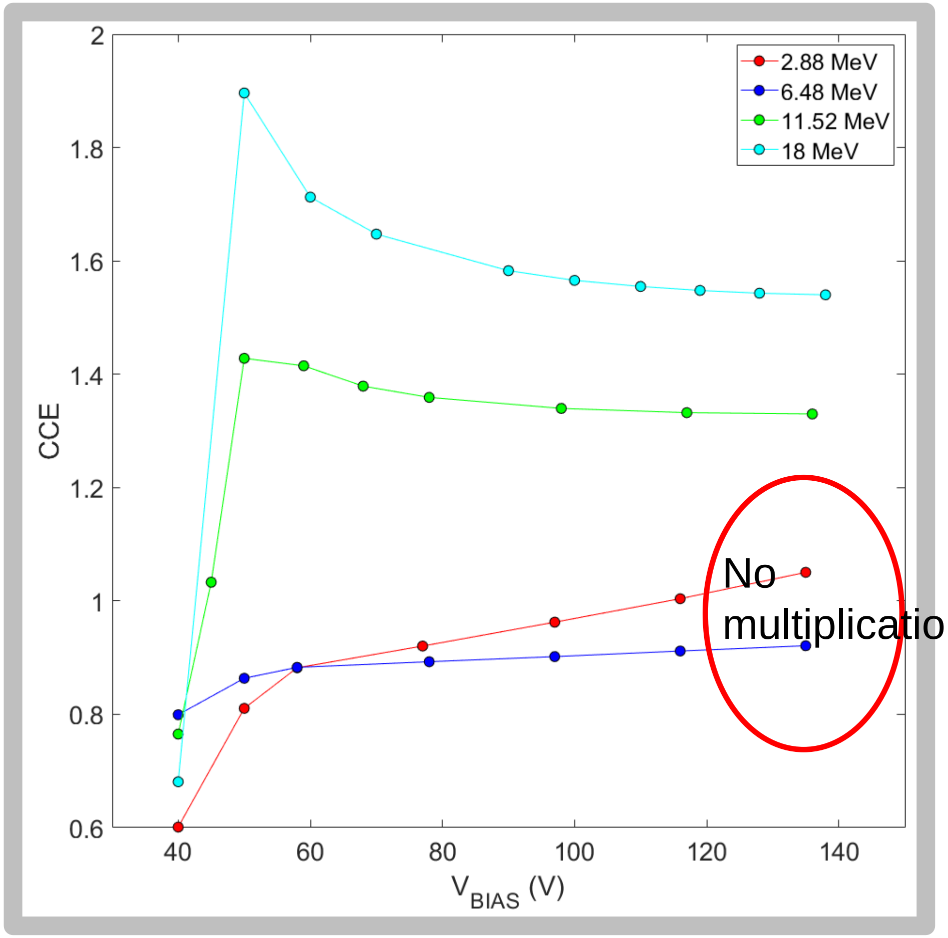
Single pad

HPK-P2 W28 L2P12 LGAD-SE3 Tray 1. (different doping pofile)

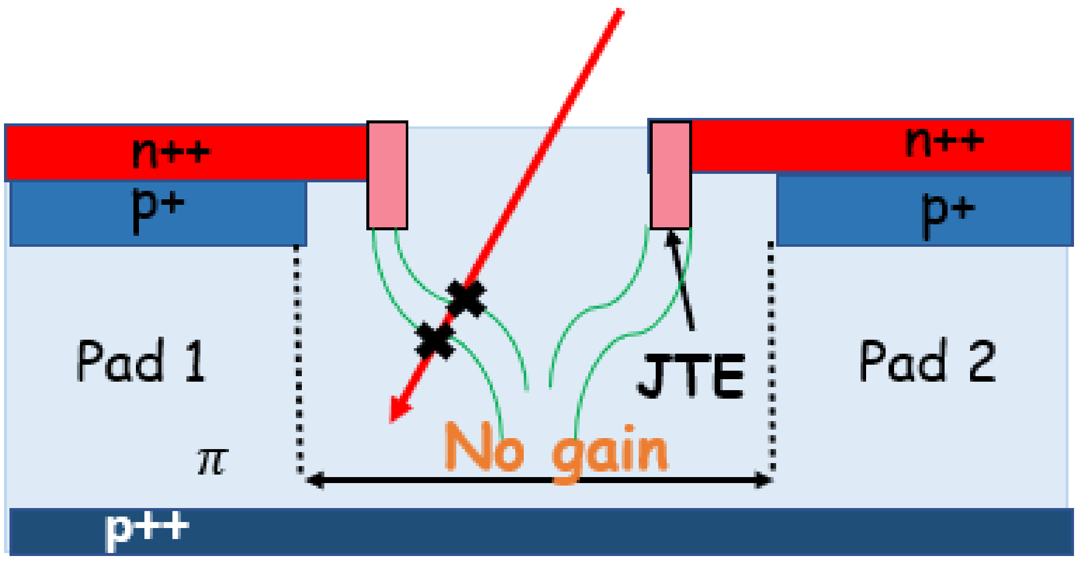
- Probing Ion Beams (**PIBs**): **18 MeV C^{5+}**, **11.52 MeV C^{4+}**, **6.48 MeV C^{3+}** and **2.88 MeV C^{2+}**





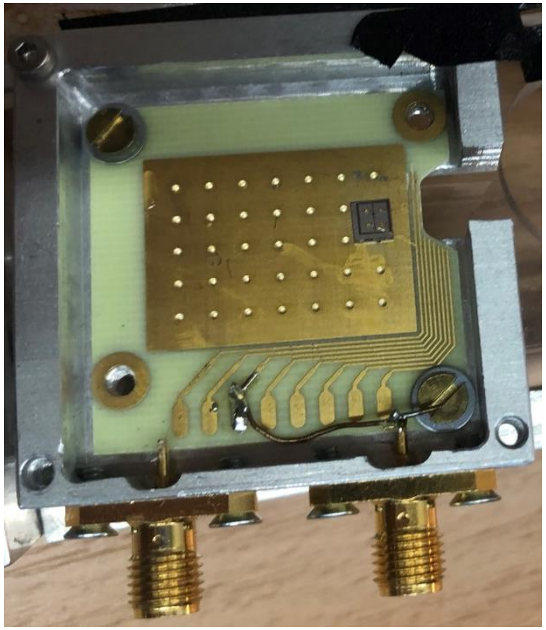


LGAD INTERPAD DISTANCE

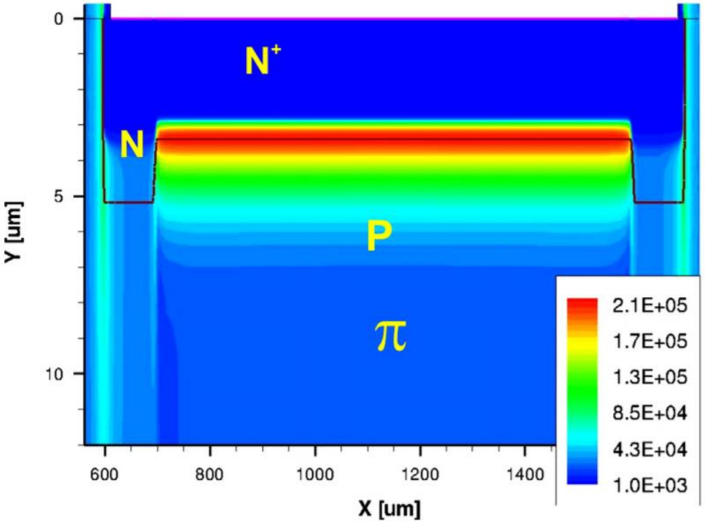


EXPERIMENTAL ANALYSIS

- Sample: Multipad LGAD detector (HPK-P2 W36 SE3-IP7)



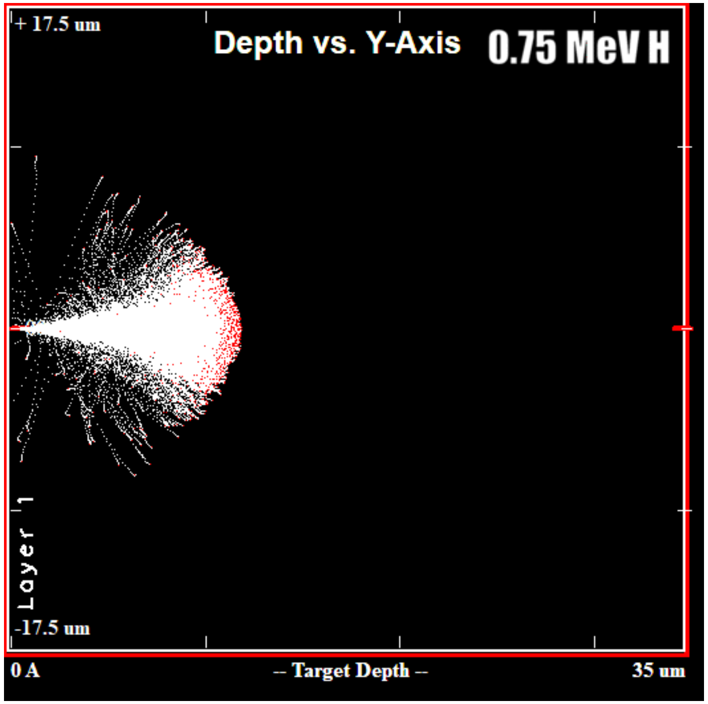
- 150 microns substrate + 50 microns of active area = total of 200 microns.
- Four sectors (2x2 PADs) LGAD fabricated by Hamamatsu
- Probing Ion Beams (PIBs): 0.75, 1.15 and 1.5 MeV H^+

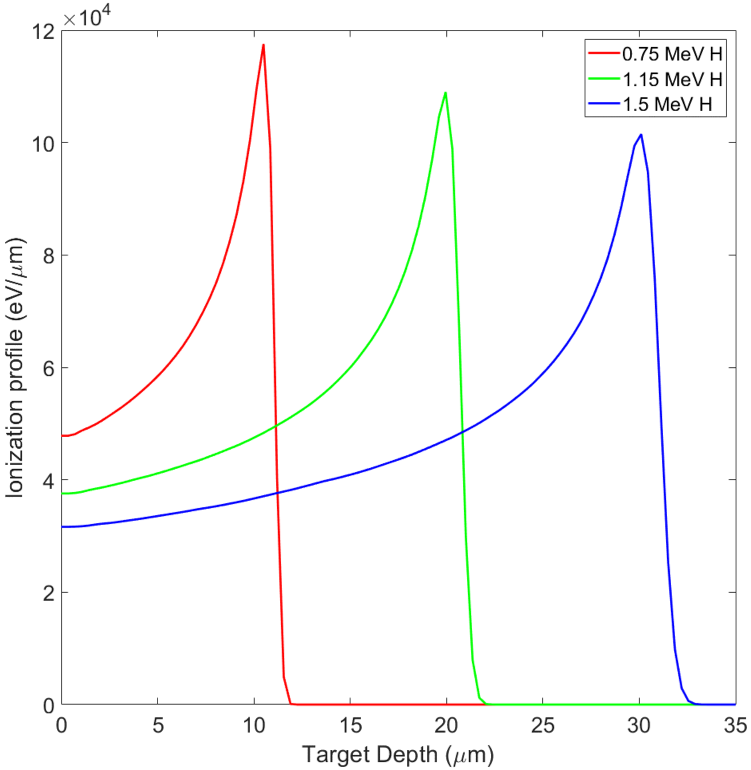


SRIM Simulations

The ionization **(dE/dx)** profiles were evaluated through SRIM2008 simulations, with the following input parameters:

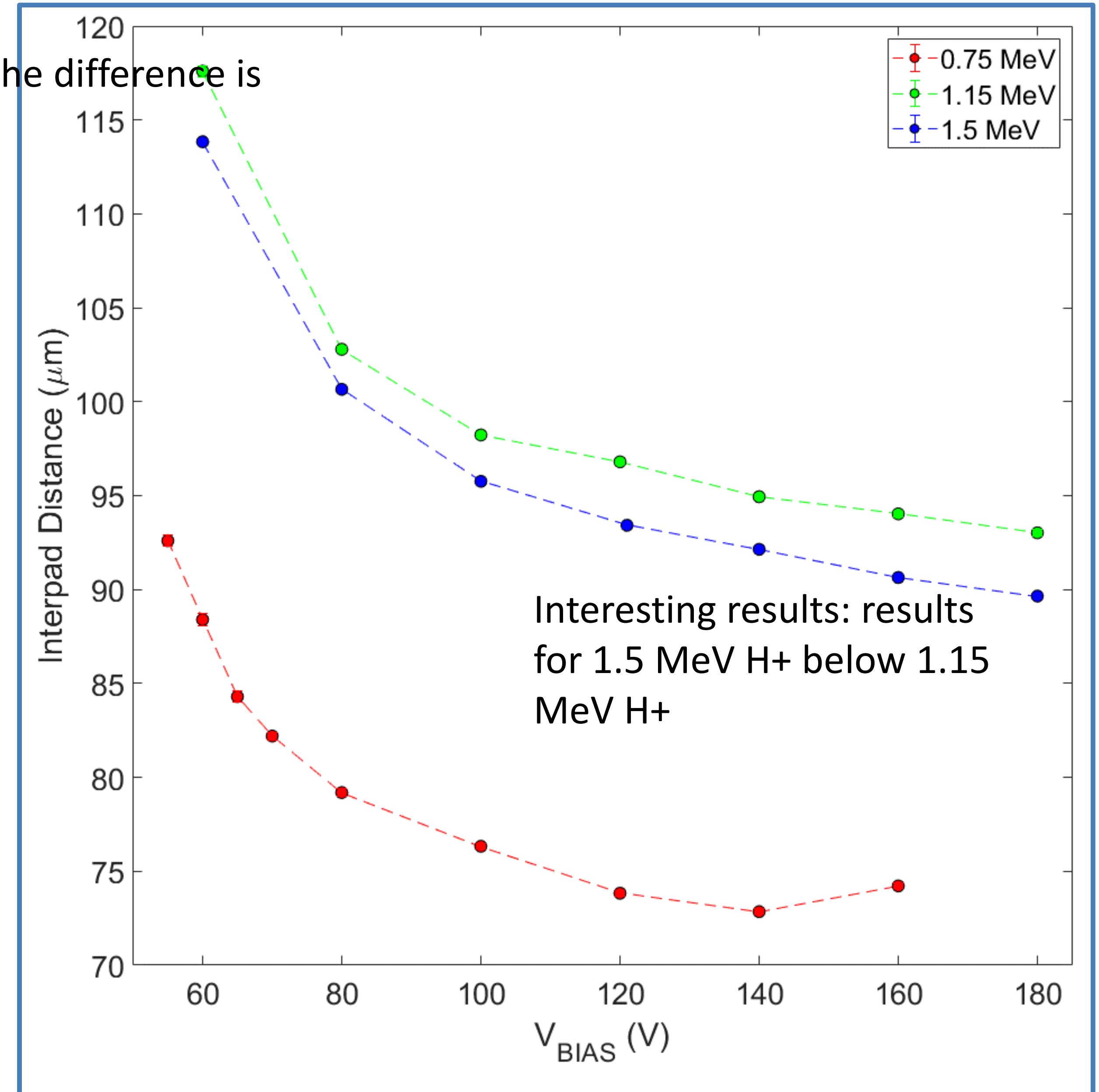
- Si target (without any oxide): density 2,3212 g/cm^3.
- Type of calculation: Ion distribution and quick calculation of damage





RESULTS: INTERPAD DISTANCES

- at lower voltages the difference is bigger

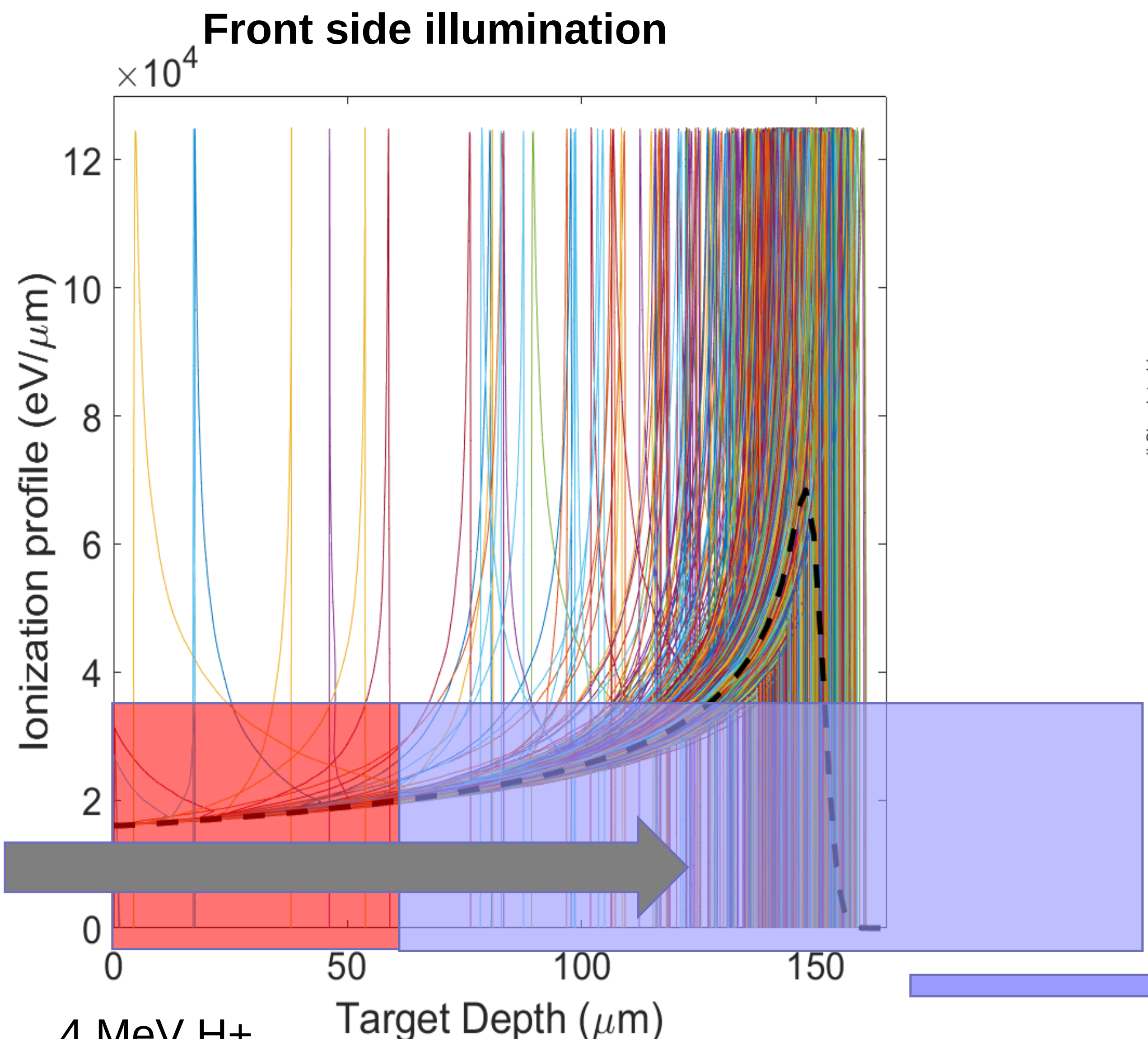


Intrpad gap measurements confirms electric line bending

More data needed for final conclusion

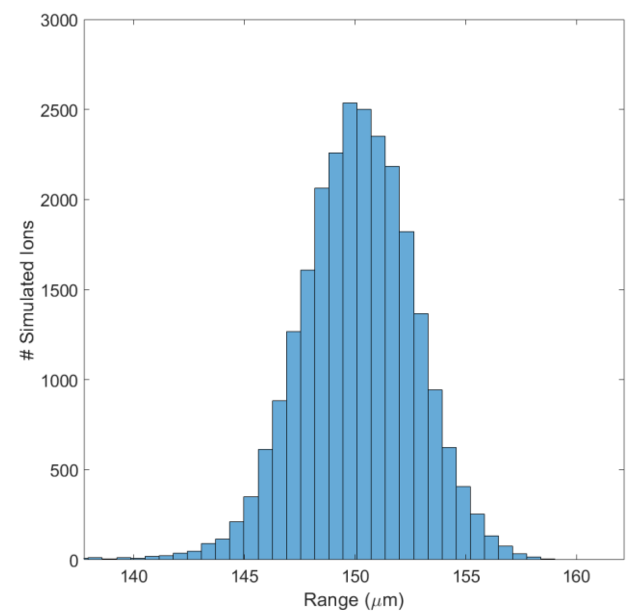
2 MeV, 3 MeV H+ proton will be added in the next campaign

4MeV H+
Back and Front side Ion-TCT with 4MeV H^+



4 MeV H+
front side

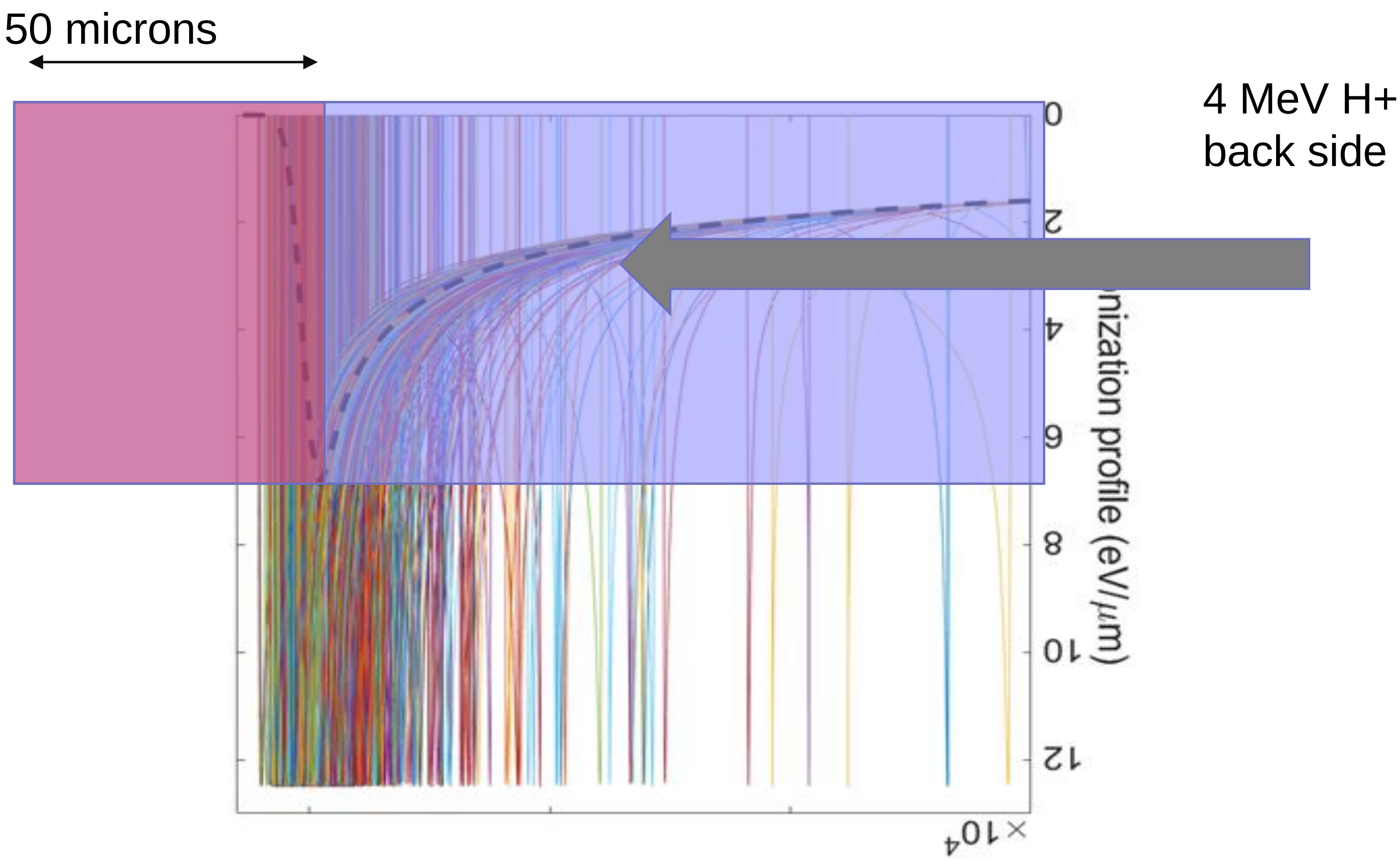
4.0 MeV H^+



Z-coordinate

4 MeV protons lose 900 KeV in 50 microns
when injected from the front-side of LGAD

Back side illumination



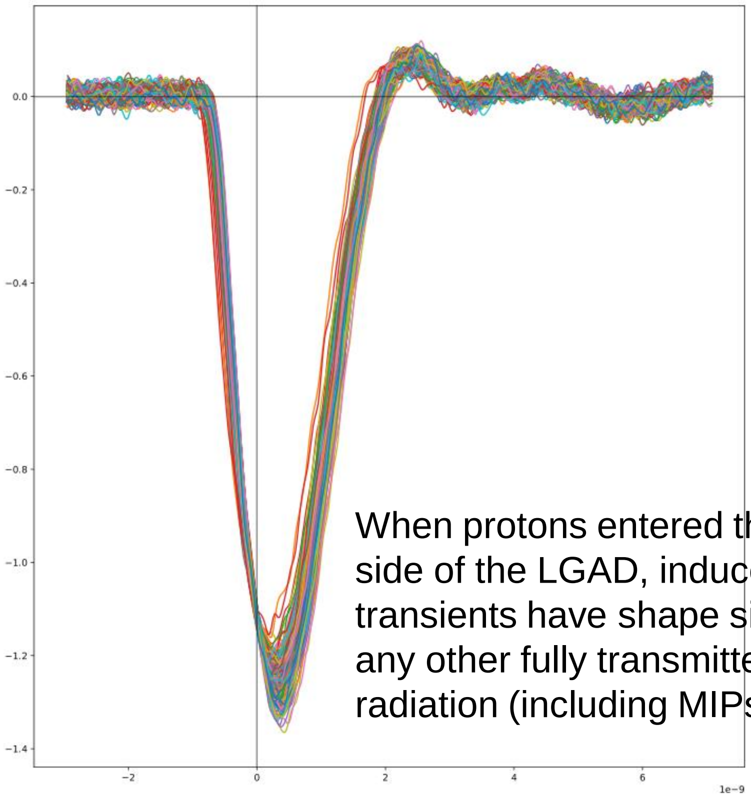
Some protons will not reach the active layer at all and we will not have a signal, and some will just enter the sensitive layer, so the distribution of pulse height will be very different, depending on the path along the active layer.

Raw data sets collected at 100 V bias

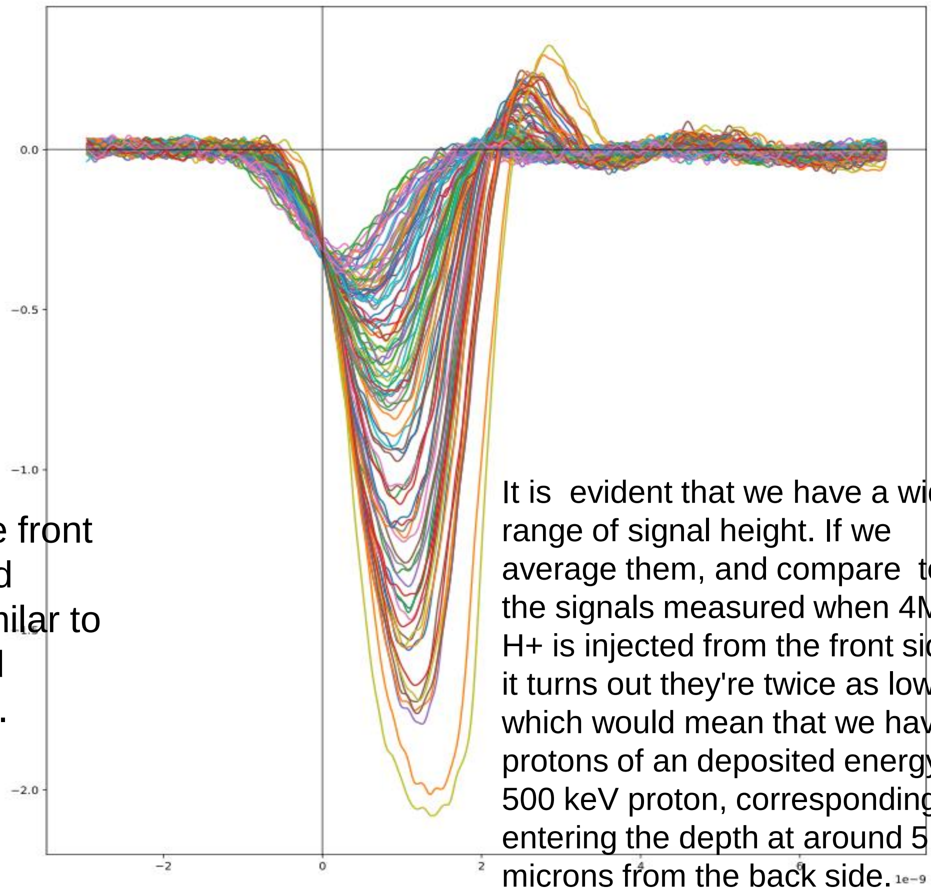
HPK-P2 W36 SE3-IP7

Injection from the **back**

Injection from the **front**



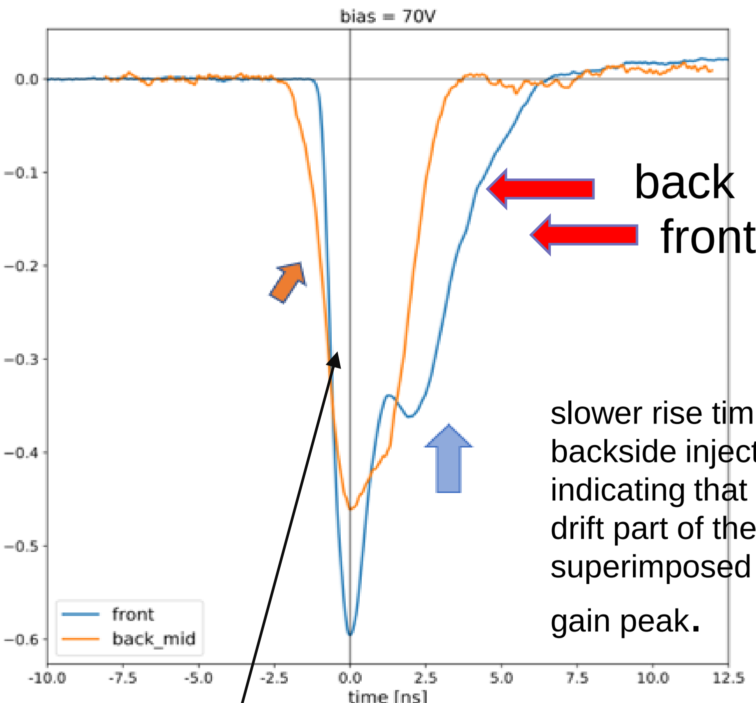
When protons entered the front side of the LGAD, induced transients have shape similar to any other fully transmitted radiation (including MIPs).



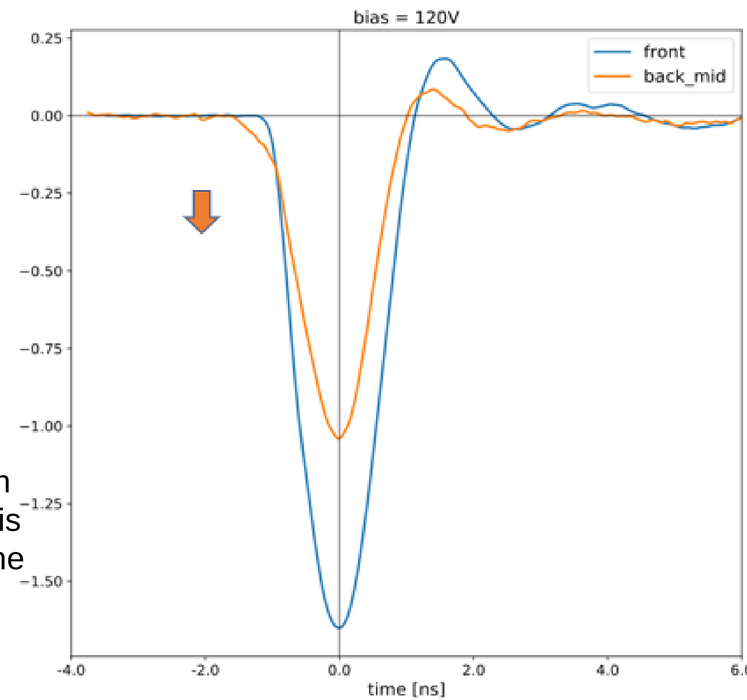
It is evident that we have a wide range of signal height. If we average them, and compare to the signals measured when 4MeV H+ is injected from the front side, it turns out they're twice as low, which would mean that we have protons of an deposited energy of 500 keV proton, corresponding to entering the depth at around 5 microns from the back side.

The very preliminary result:
Front and back (middle) injection traces,
time shifted so that zero mark is at max. amplitude

- **Without amplitude normalization!**



slower rise time for backside injected ion, indicating that electron drift part of the signal is superimposed onto the gain peak.



More to come in future.

Drift of electrons before gain peak is reached:
effect visible at both biases 70 V and 120 V

- ✓ Slower rise of back signal (contribution of the drift of the electrons before onset of multiplication)
- ✓ Slower fall of signal for front signals (contribution of secondary holes)

At low bias (70 V) signal from secondary holes is longer at the front illumination, although intuitively this should not be the case.

The working hypothesis is that this is due to the **electric field screening** at the front illumination. It seems that electrons that travel towards the gain part are not screened in the case of the back illumination as they are in the case of front illumination

Overview & Conclusion

- Gain suppression and screening effect has been exploited using two techniques: IBIC and Ion-TCT.
  - In the first experiment we used Carbon ion with energy of 14 MeV, He ion with energy of 3 MeV and H + ion with an energy of 0.745 MeV. The aim was to set Bragg peak at the same LGADs depth of around 10 microns, but with significantly different stopping power (dE/dx).
  - In the second experiment the same type of ion was used but chosen energies differ allowing us to probe LGAD at the different LGAD's depth (within bulk LGAD). Carbon with energies 2.88, 6.47, 11.52, 18 MeV and proton with energies 0.8,1.5 and 2.0 MeV have been exploited for this purpose.
    - **Significant gain suppression is observed in study with heavy ions**
    - **Decrease of gain with increase of bias not yet understood: Open question**
    - **possible explanation that with higher ionisation there is higher recombination of holes and electrons**
      - **Additional experiment involving angle ion study**

- In the Ion-TCT method, protons of **4 MeV** energy were used to irradiate LGAD from two sides (**back and front).** This measurement was used to observe contribution of impact ionization and multiplication of holes and electrons in more distinguishable way, knowing at the same time the exact depth where induced charge is mostly generate. The idea is to study in more systematic way the gain suppression and screening effects following charge transport from its original deposit..

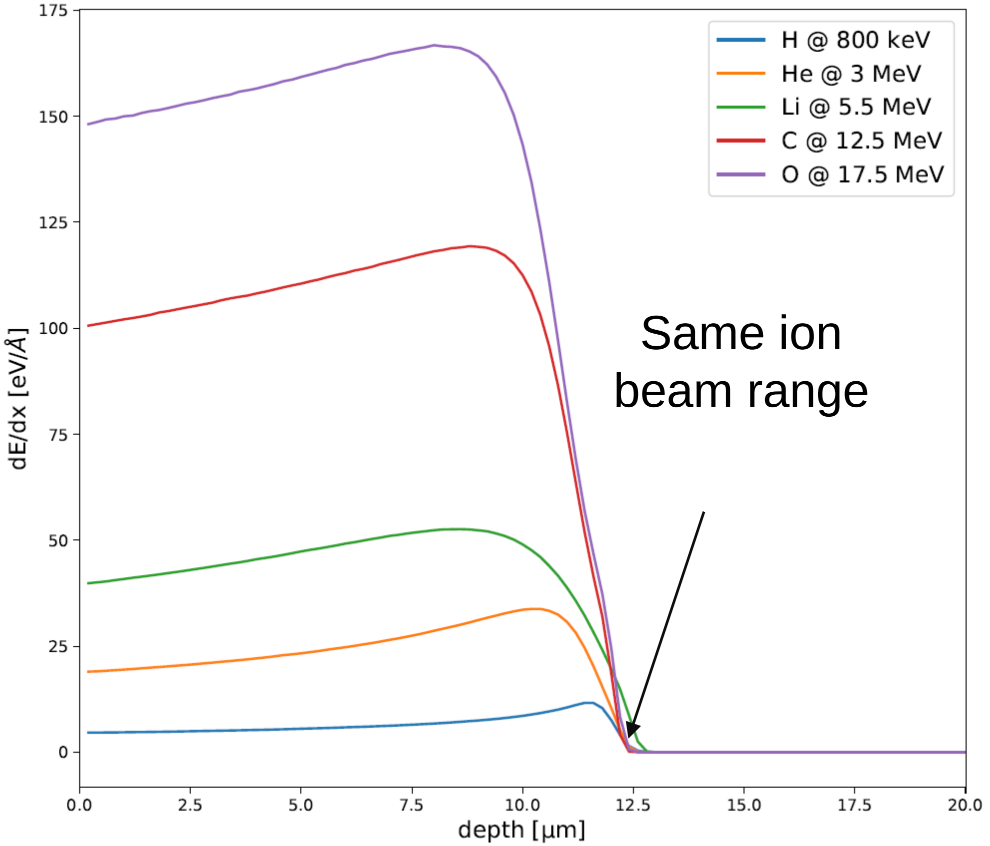
  - ✓ **However, the study shows that actually it is not an straightforward way;**
  - ✓ **It is more complexed analysis than we originally thought due to stochastic distribution of signals with different heights;**
  - ✓ **Thus, our aim is to focus further on development more advanced technique to deal with data '**
  - ✓ **Such analysis might be very useful for LGAD's use in medica reserarch (hadrin accelerators for hadron therapy), so more control one can gainover experiment.**

- Intrepad distance is studied too.

Backslides

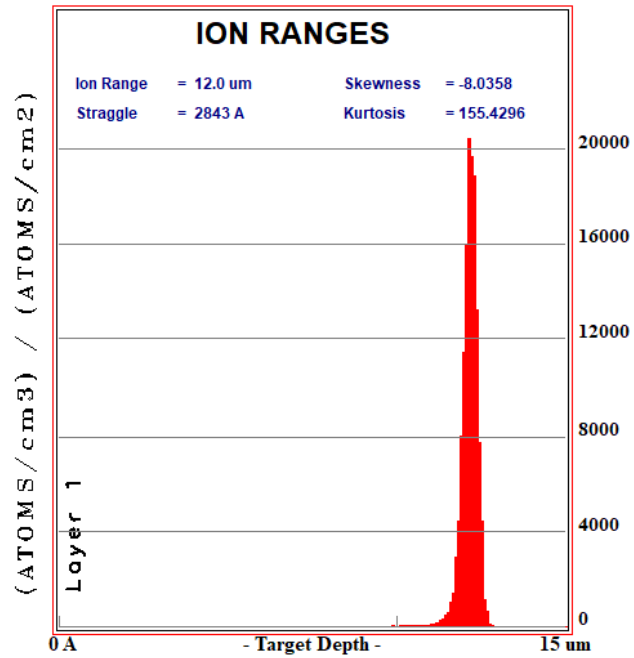
Different ions (heavy, light) with the same end-of-range

- different ions and their respective energies selected in a such way that either their end-of-range correspond to the same depth in the active region of LGAD.



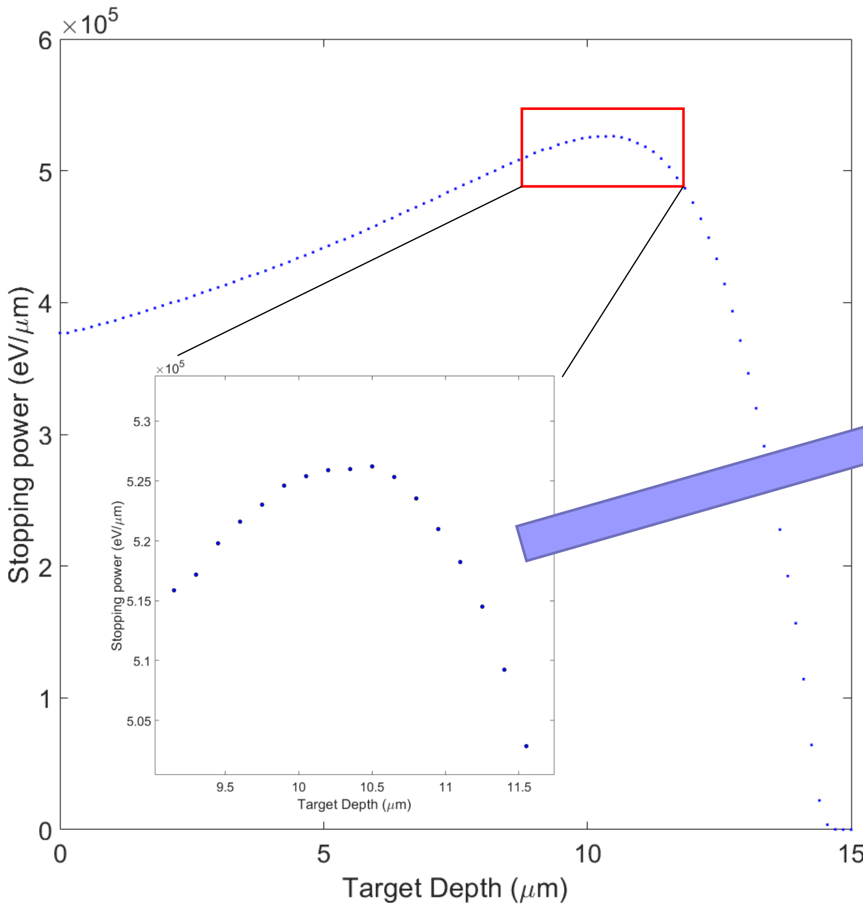
ION BEAM RANGE

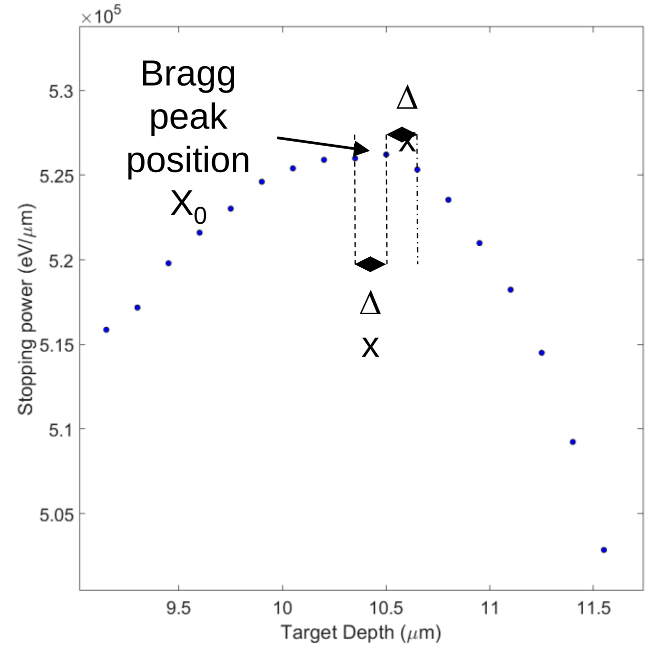
- the ion beam range (and uncertainty) for the different ion beam species and energies used in your work. These simulations were performed with SRIM assuming a pure Si sample (without any electrode or layer in the surface).



Energy (MeV)	Range (mm)
0.745 H^{+}	10.8 ± 0.3
0.75 H^{+}	10.9 ± 0.4
1 H^{+}	16.6 ± 0.5
1.15 H^{+}	20.5 ± 0.6
1.5 H^{+}	30.8 ± 0.9
3 He^{2+}	12.0 ± 0.3
6.2 Li^{2+}	14.1 ± 0.3
14 C^{4+}	13.4 ± 0.3

Uncertainty in Bragg peak for those chosen ions and their energies.





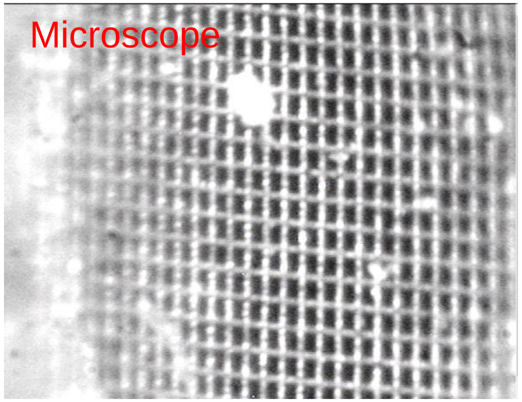
The Bragg peak corresponds to the maximum of the ionization profile curve (dE/dx) so the uncertainty in the Bragg peak position is given by the resolution in the target depth (ΔX) given by SRIM.

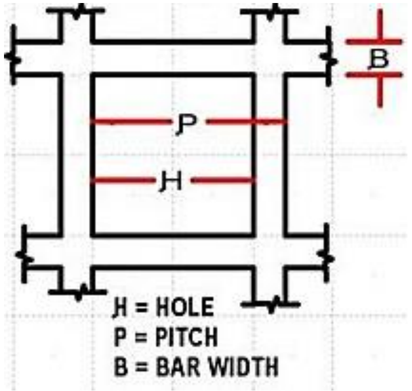
So we can say that the Bragg position is: $X_0 \pm \Delta X$. In our simulations, $\Delta X = 0.15$ μm but this number we believe can change according to the set parameters in the SRIM software.

Interpad distance/
Method explained

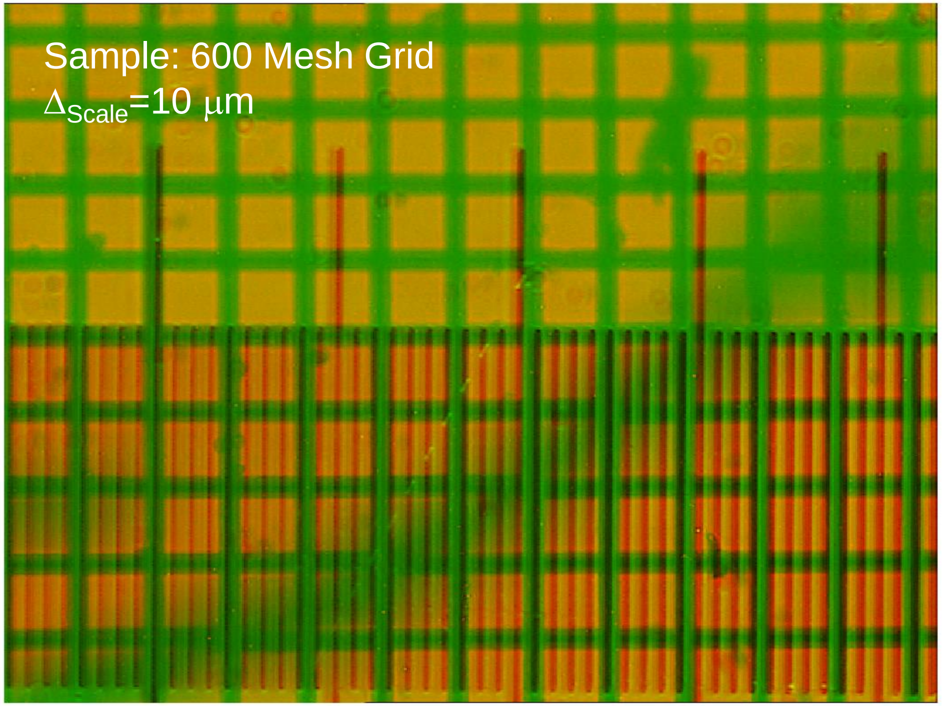
Scan areas are estimated from the STIM images of the copper fine mesh.

- Scanning transmission ion microscopy (**STIM**) is a technique in which transmitted ions are detected





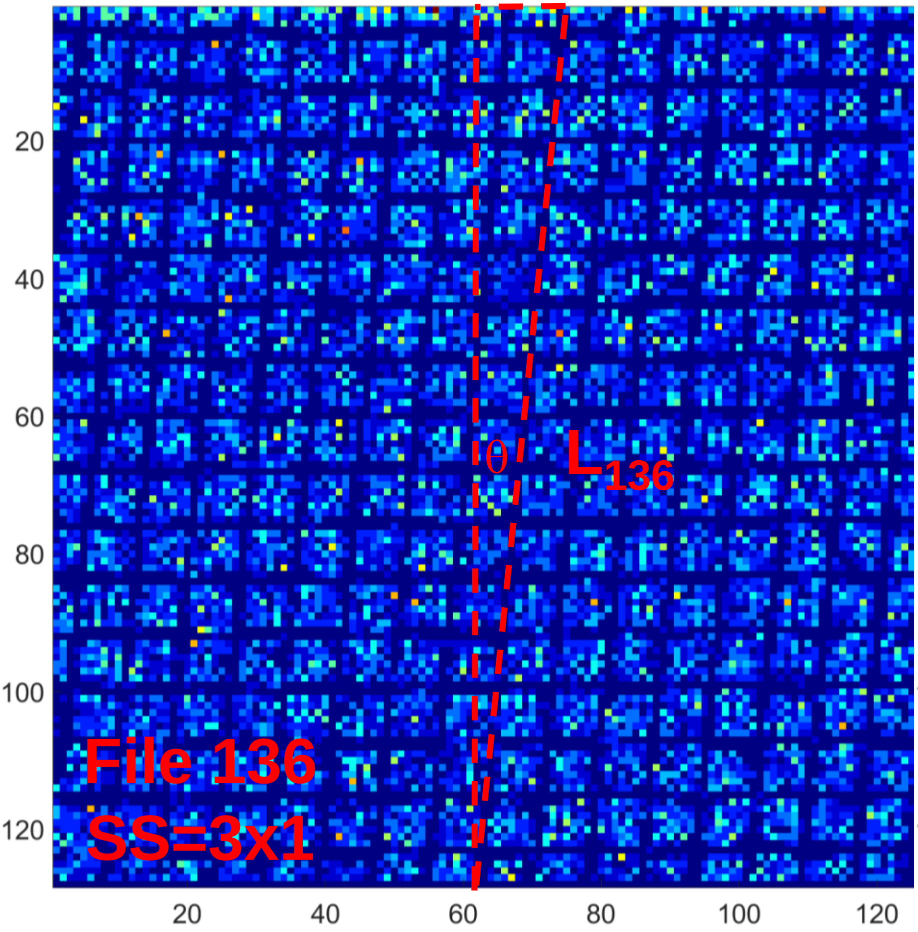
- According to Milko, the **600 mesh grid** was used during this experiment.

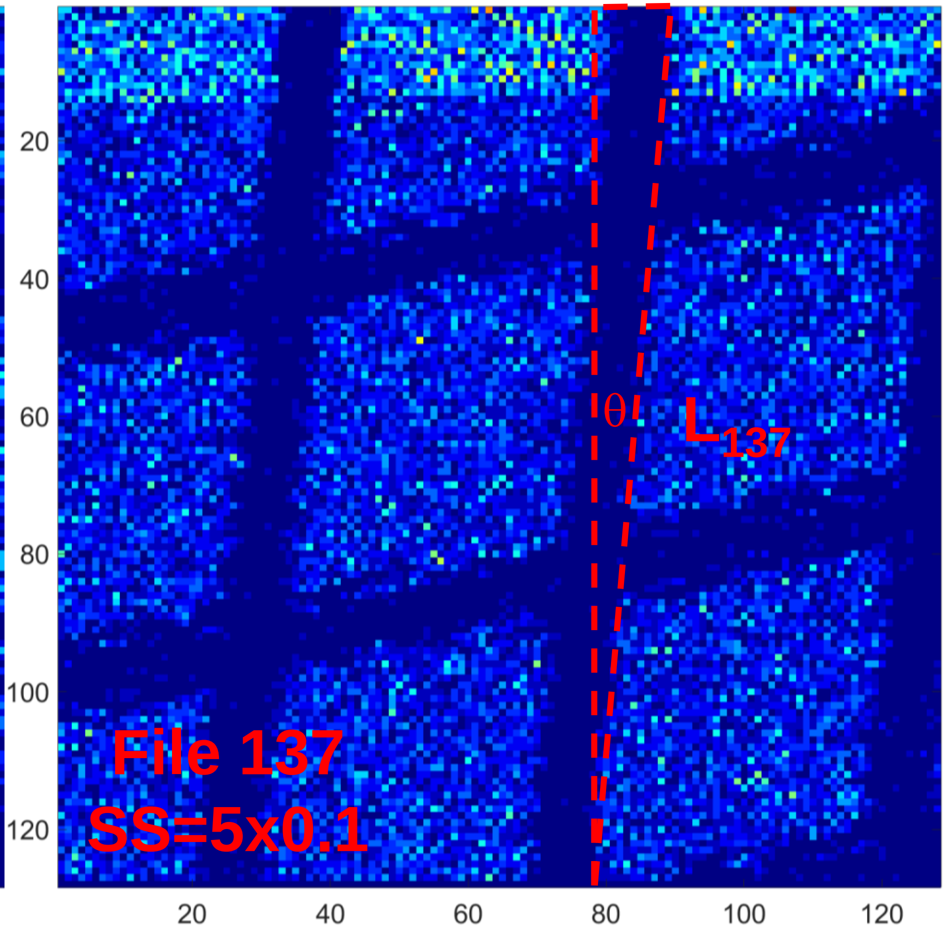


Bar width B= 5 μm

Hole width H= 37 μm

STIM MAPS 0.75 MeV H^+.





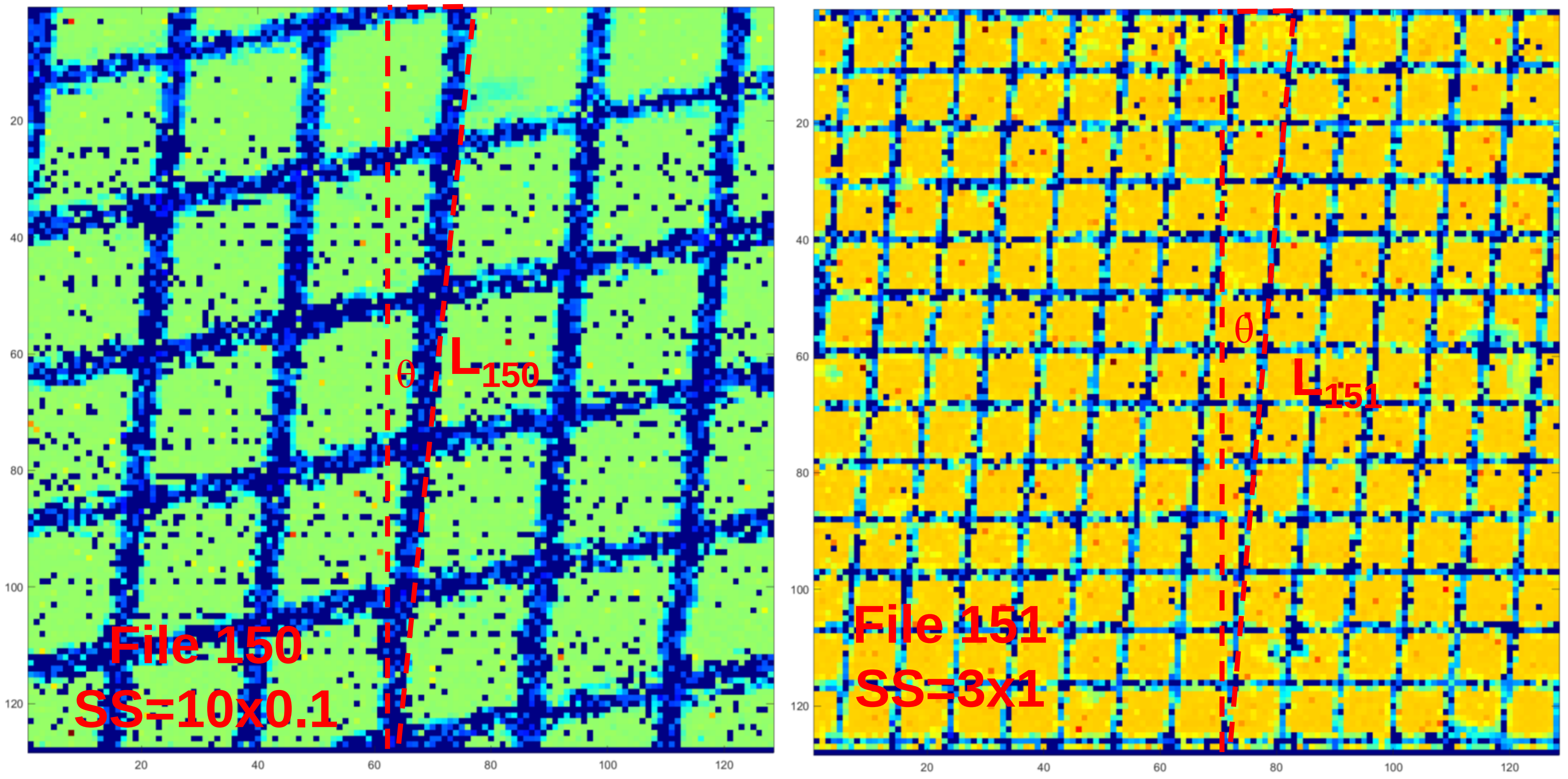
L_{136}=16x37+16x5=672 μm->Δ_{136}=672*cos(5.69)/128= 5.224 μm/px

L_{137}=2.6x37+2x5=106.2 μm->Δ_{137}=106.2*cos(5.69)/128=0.826 μm/px

θ=5.69°

Δ≈1.70 μm/px for SS=1

STIM MAPS 1.15 MeV H^+.



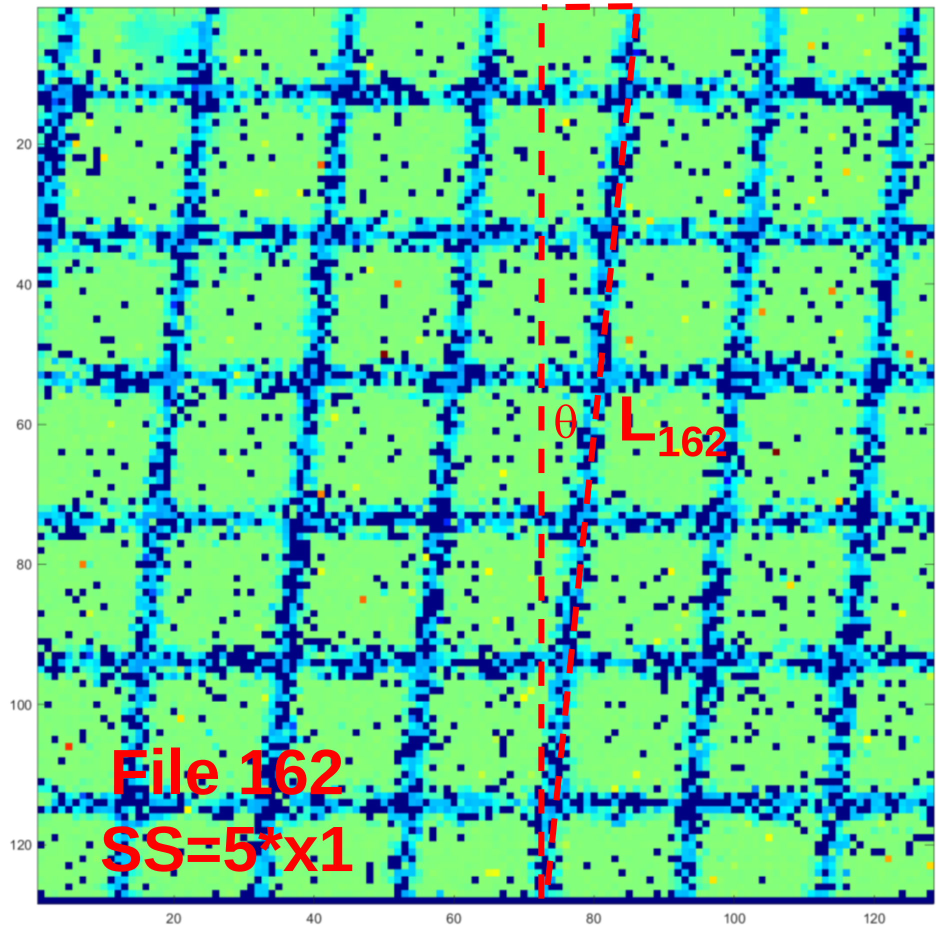
L_{150}=5x37+5x5=210 μm->Δ_{150}=210*cos(5.69)/128= 1.633 μm/px

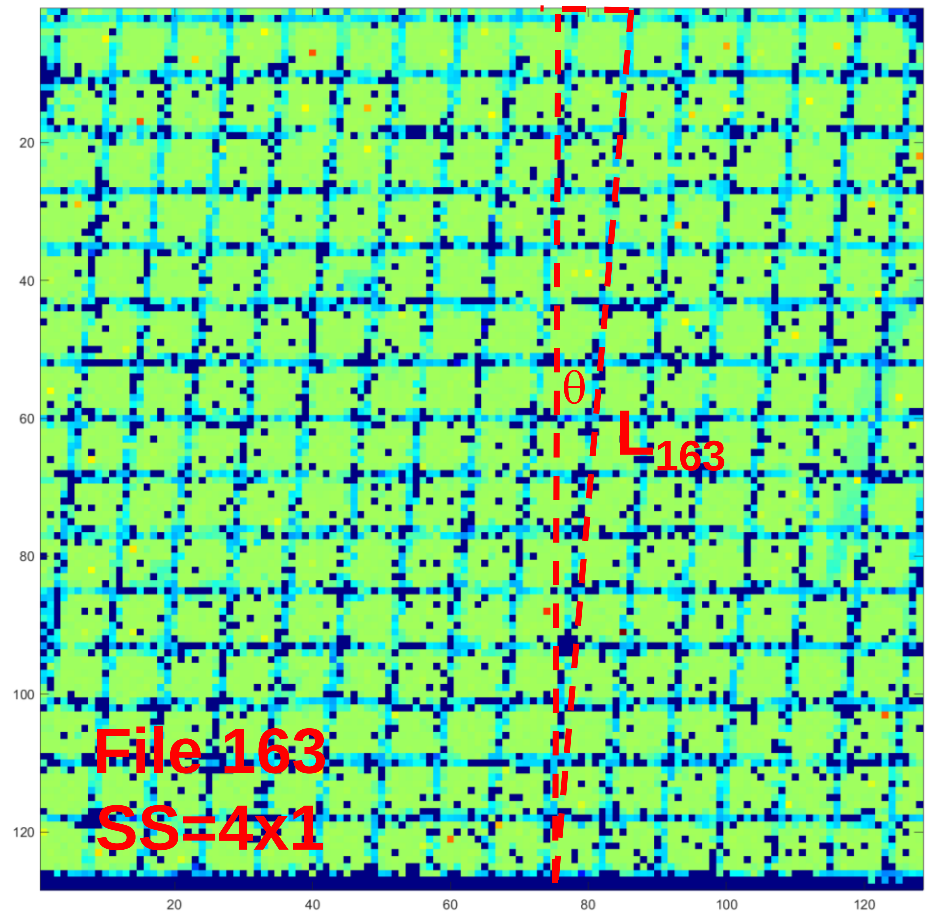
L_{151}=13x37+14x5=551 μm->Δ_{151}=551*cos(5.69)/128= 4.283 μm/px

θ=5.69°

Δ≈1.53 μm/px
for SS=1

STIM MAPS 1.5 MeV H^+.





L_{162}=6x37+6x5=252 μm->Δ_{162}=252*cos(6.24)/128= 1.957 μm/px

L_{163}=15x37+16x5=635 μm->Δ_{163}=635*cos(6.24)/128= 4.932 μm/px

θ=6.24°

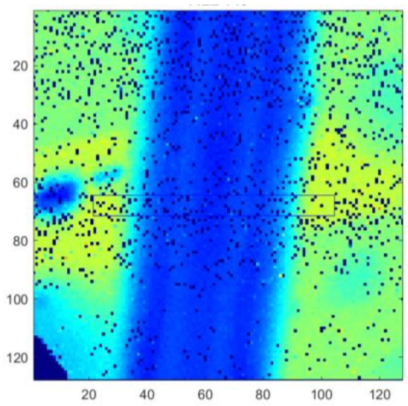
Δ≈1.27 μm/px for SS=1

* Mistake in the logbook. I believe is SS=1.5x1

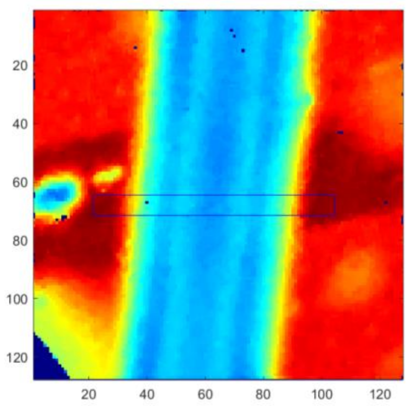
Interpad distance calculation/METHOD I:

Estimation of the interpad distance using projection profiles and the **Sigmoidal-Boltzmann** equation

A rectangular ROI is defined in boths maps

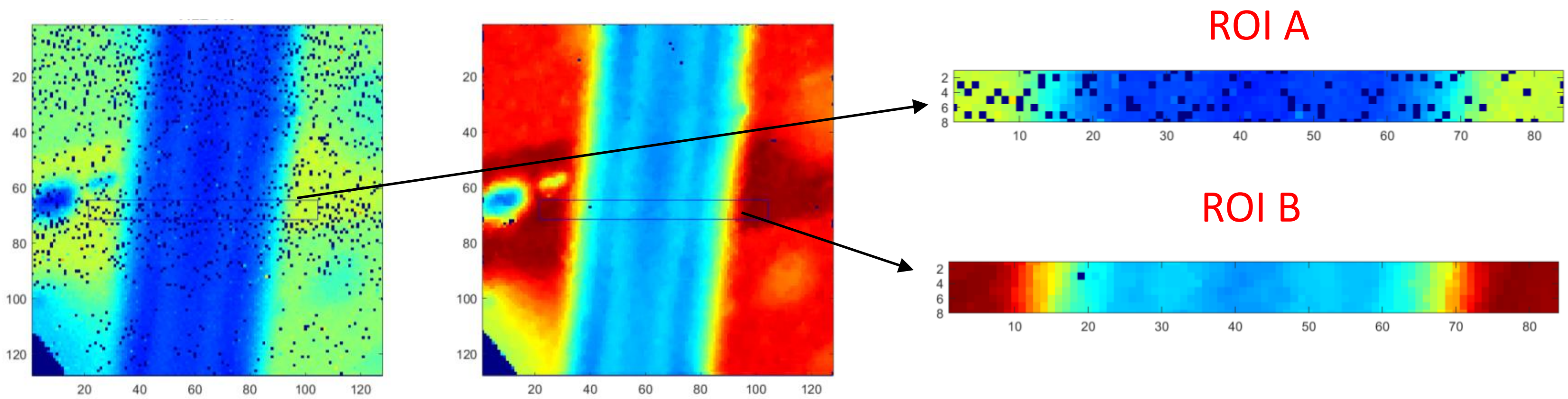


Original Map



Original Map with
3x3 median filter

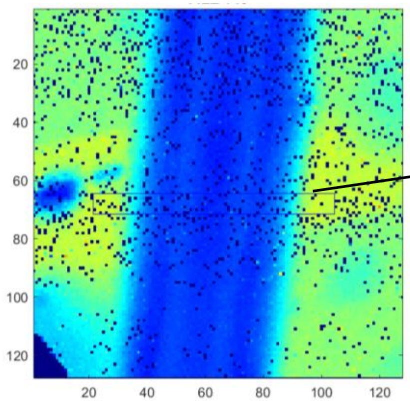
The intensity maps from the ROIs are extracted



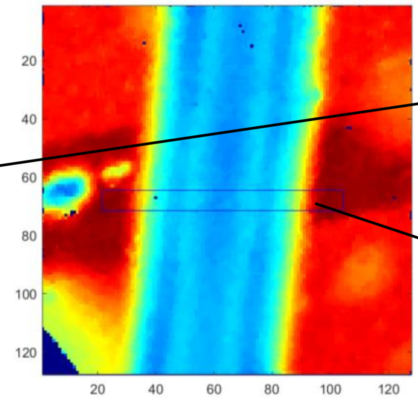
Original Map

Original Map with 3x3 median filter

Mean pofiles of the selected ROIs

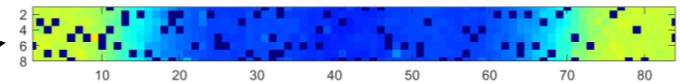


Original Map

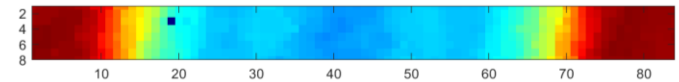


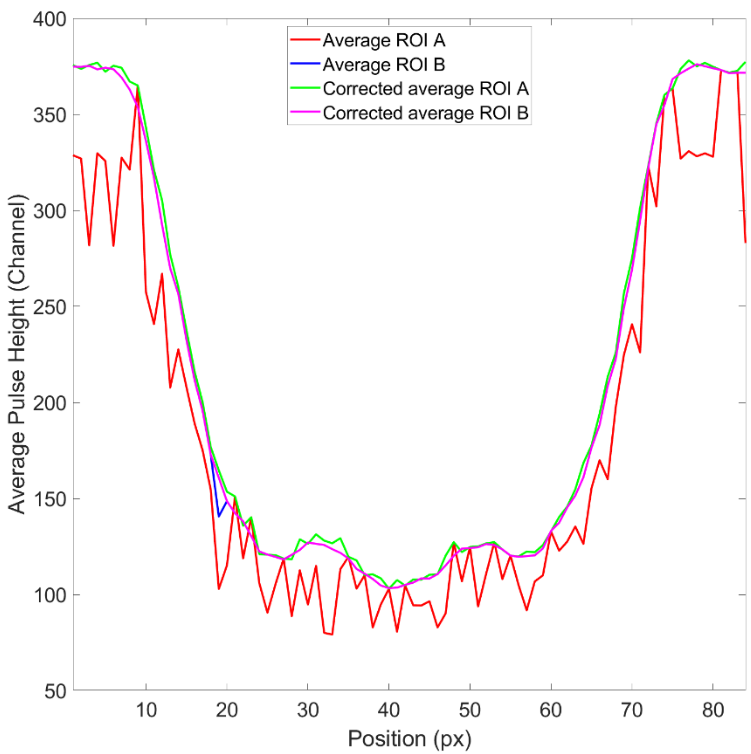
Original Map with 3x3 median filter

ROI A



ROI B

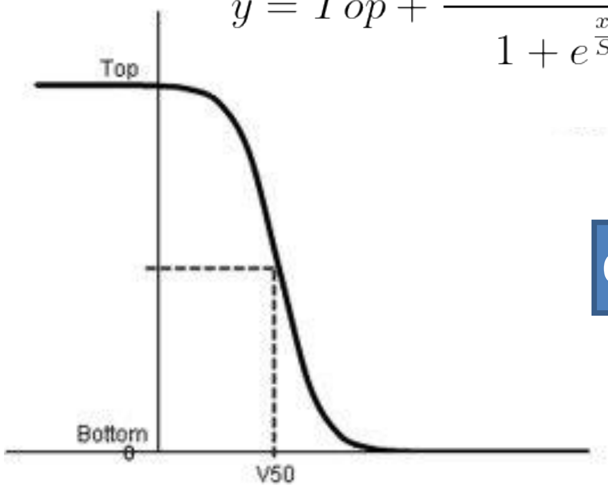




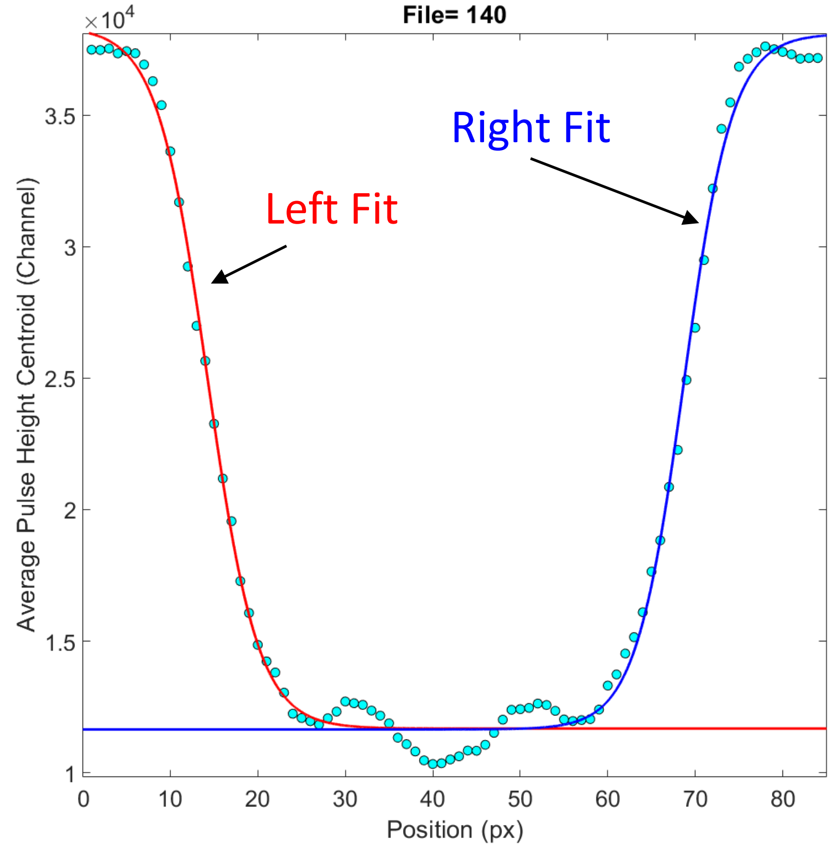
For both ROIs, two intensity profiles were extracted. In the corrected profiles, the pixels without counts weren't taken into account for the calculation of the mean.

The left and right part of the profile were fitted to the Sigmoidal Boltzman equation

$$y = Top + \frac{Bottom - Top}{1 + e^{\frac{x - x_0}{Slope}}}$$



Origin Fitting tool

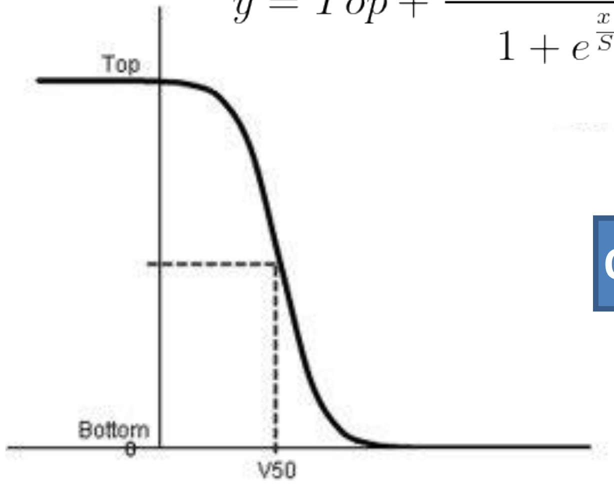


Sigmoidal-Boltzmann equation

The function is characterized by a plateau top and bottom with a characteristic x_0 value describing the point where the x-value is exactly between the top and bottom value and slope indicating the range in which the transition between top and bottom occurs.

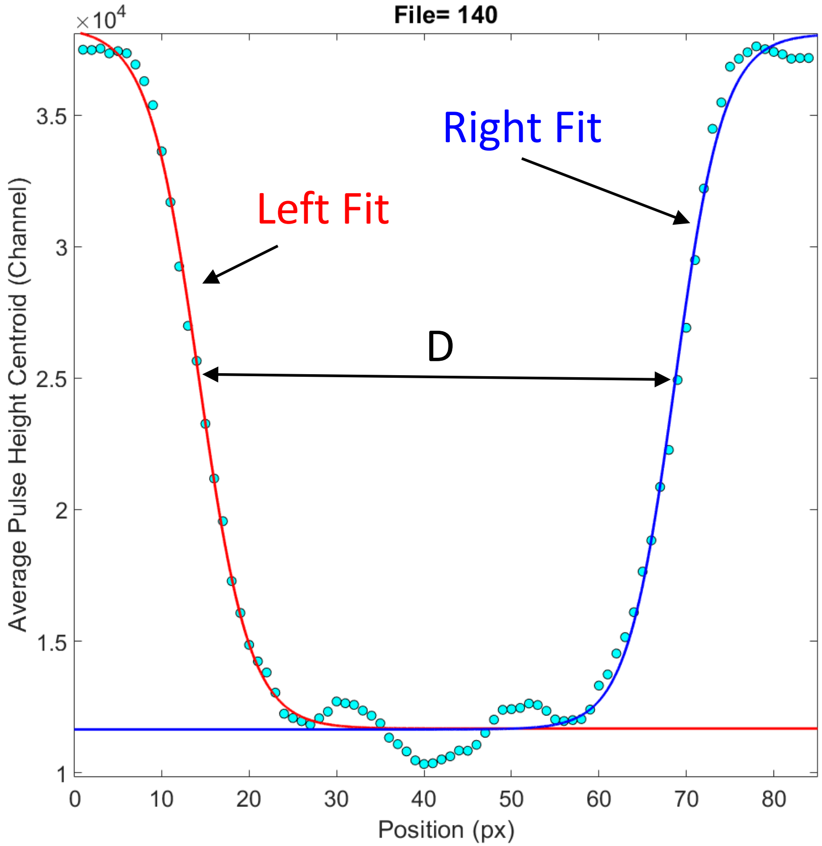
The distance (in pixels) can be calculated from the fitting parameters

$$y = Top + \frac{Bottom - Top}{1 + e^{\frac{x - x_0}{Slope}}}$$



Sigmoidal-Boltzmann equation

Origin Fitting tool



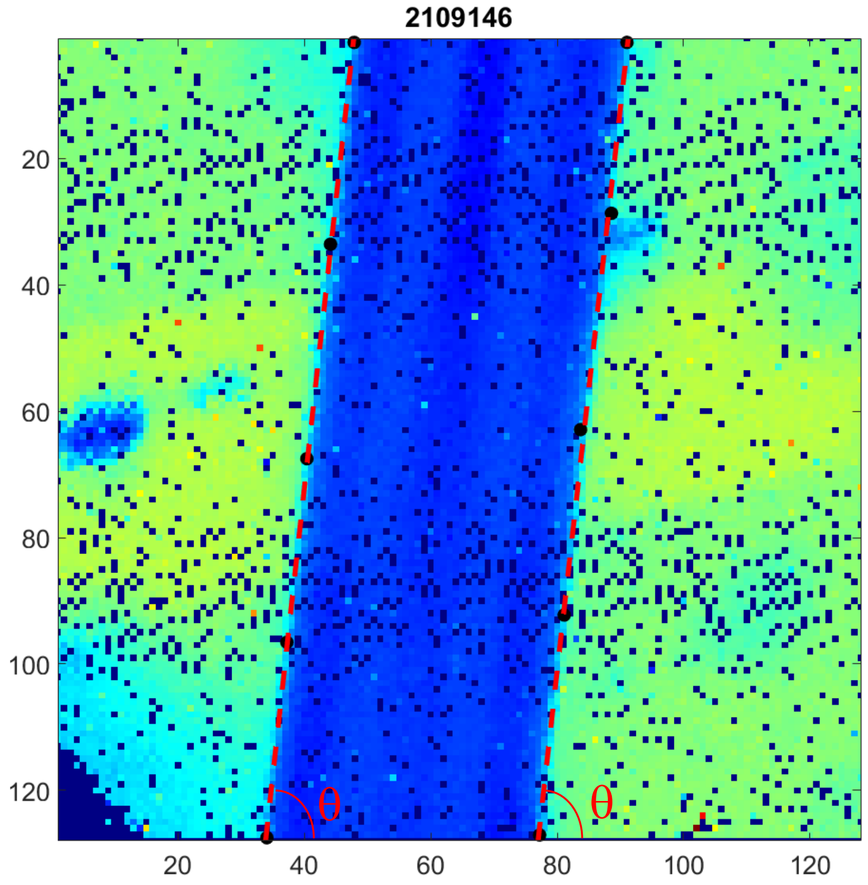
Fitting coefficients

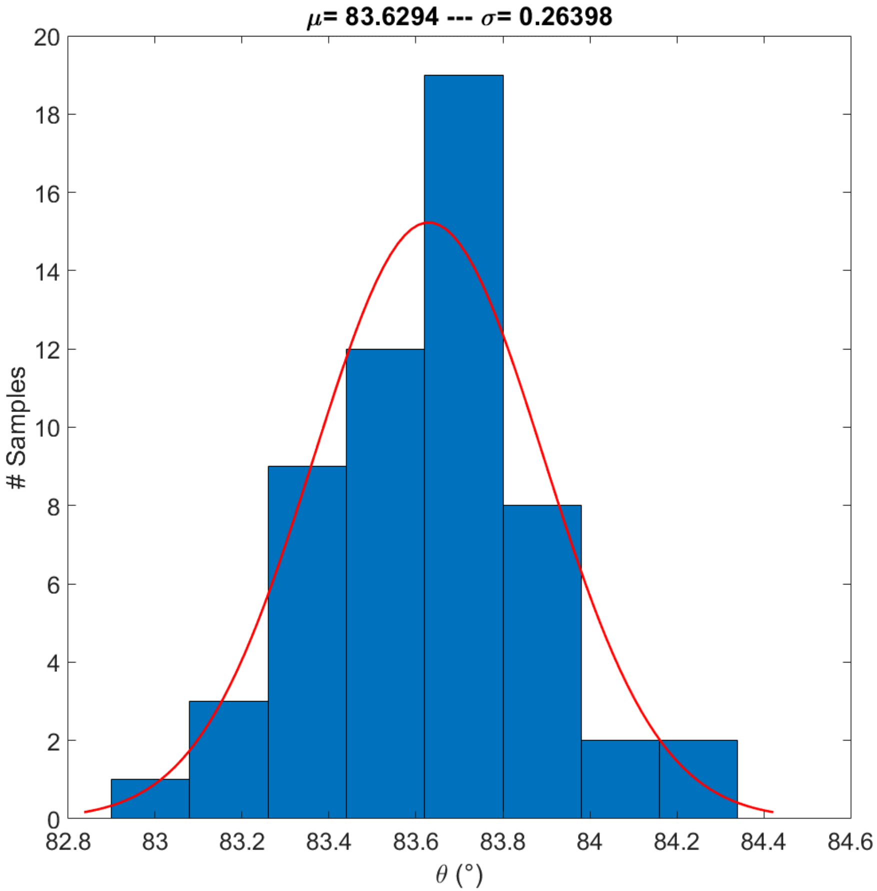
File	x_0	Δx_0	x'_0	$\Delta x'_0$
140	14.25	0.13	68.71	0.15

$$D = x_0' - x_0 = 54.46\ px$$

$$\Delta D = \sqrt{(\Delta x_0)^2 + (\Delta x_0')^2} = 0.20\ px$$

An angular correction should be applied to obtain the real distance between pads: Angular distribution of the interpads



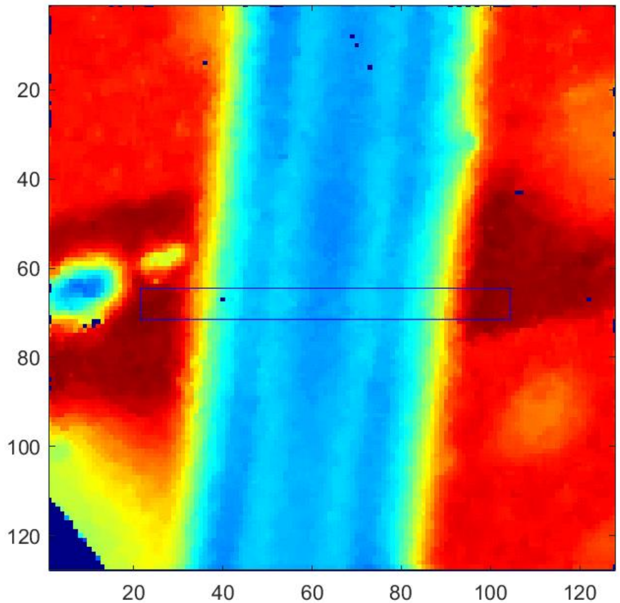


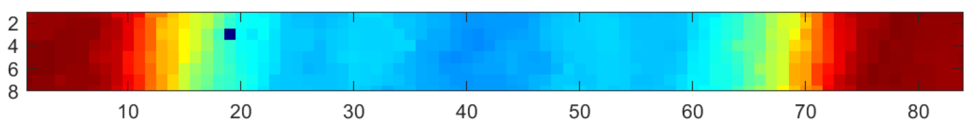
For each file, the interpad inclinations were measured

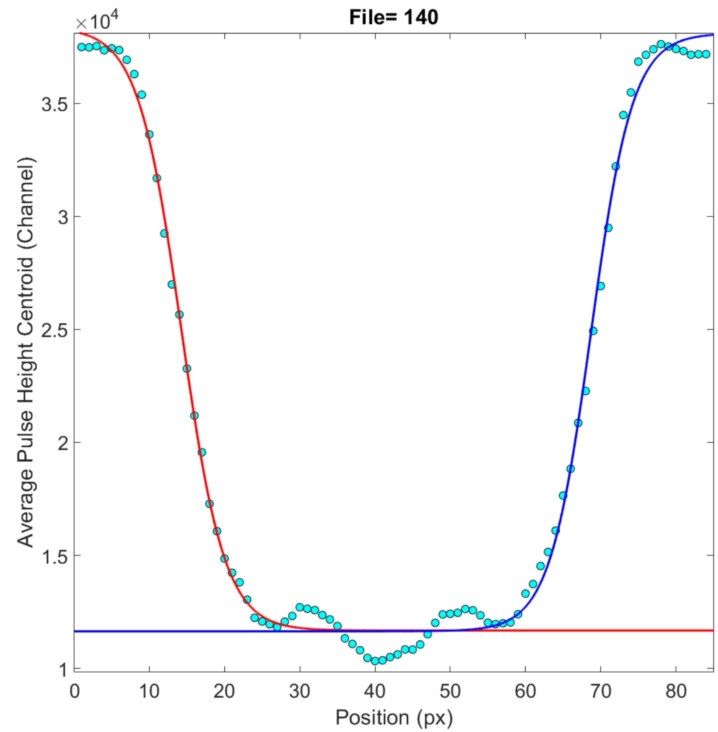
Histogram of all measured angles.

$\theta_{Interpads}=(83.6\pm0.8)°$

RESULTS 0.75 MeV H^+

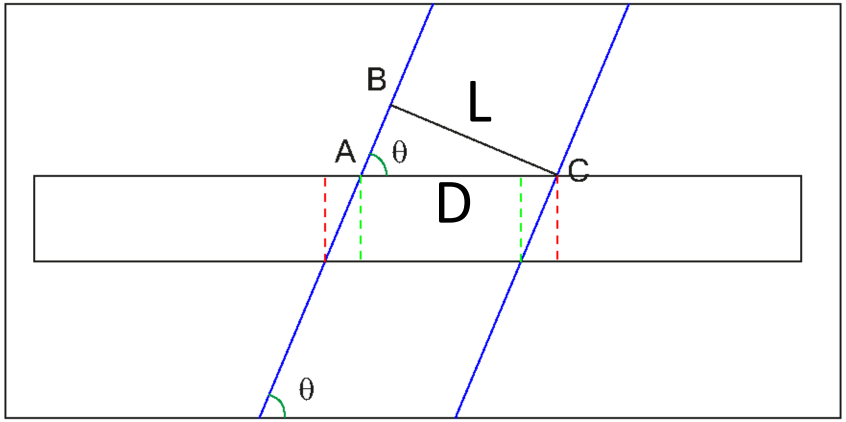






File	BIAS (V)	x_0 (px)	Δx_0 (px)	x_0 (px)	Δx_0 (px)	D (px)	ΔD (px)
140	55	14.25	0.13	68.71	0.15	54.46	0.20
141	60	15.57	0.13	67.58	0.15	52.01	0.20
142	65	16.80	0.11	66.38	0.13	49.58	0.17
143	70	17.33	0.08	65.68	0.10	48.35	0.13
144	80	18.18	0.06	64.76	0.09	46.58	0.11
145	100	18.74	0.07	63.64	0.07	44.90	0.10
146	120	19.30	0.07	62.73	0.06	43.43	0.09
147	140	19.38	0.06	62.23	0.06	42.85	0.08
148	160	18.78	0.05	62.44	0.08	43.66	0.09

The interpad distance can be obtained using the conversion factor (mm/px) measured from STIM maps



$$L = D \times sin(\theta) \approx D$$

Sin(83.6)=0.994≈1

* The angular correction is negligible

$$L_{REAL} = \alpha \times D = 1.7 \times 54.46 = 92.6\ \mu m$$

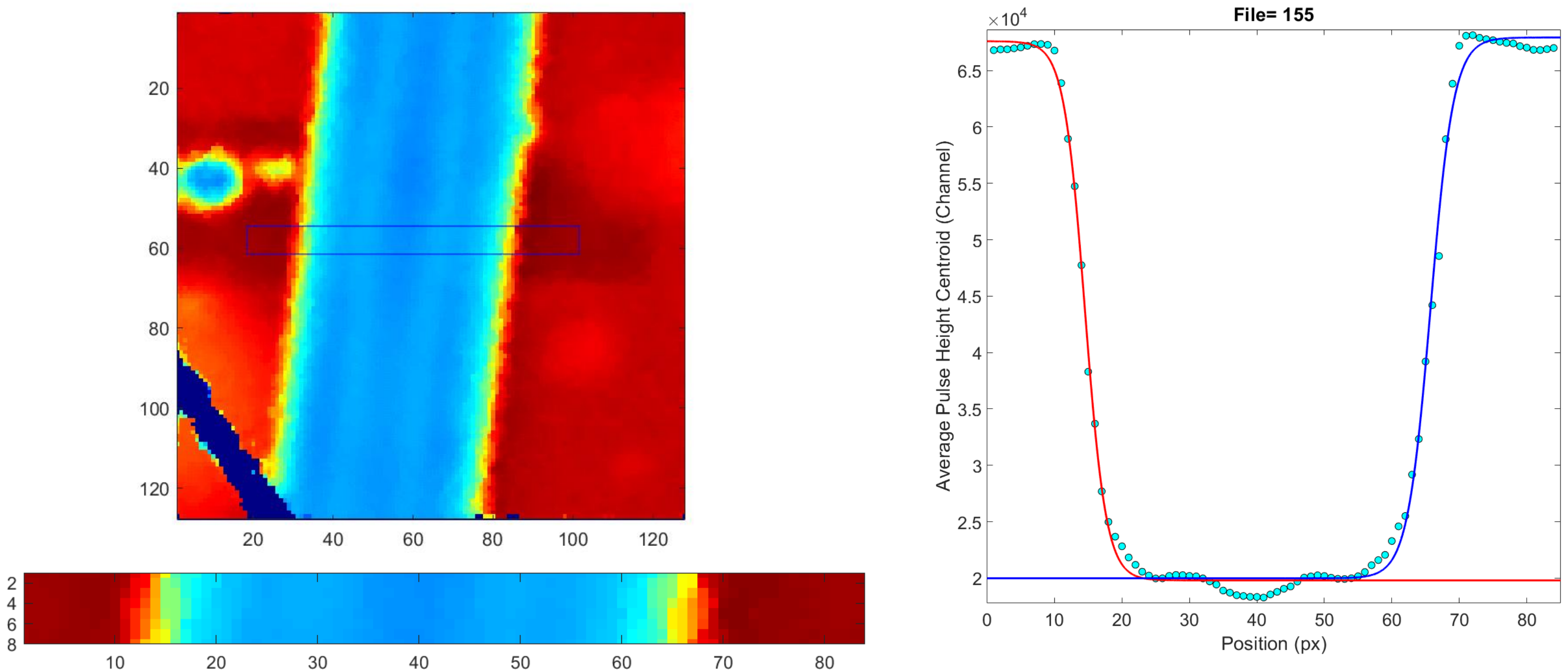
α≈1.7 μm/px
for SS=1

Δα=0?->Grid uncertainty?

$$\Delta L_{Real} = \sqrt{\alpha^2 \times \Delta D^2 + D^2 \times \Delta\alpha^2} \approx \alpha \times \Delta D = 0.3$$

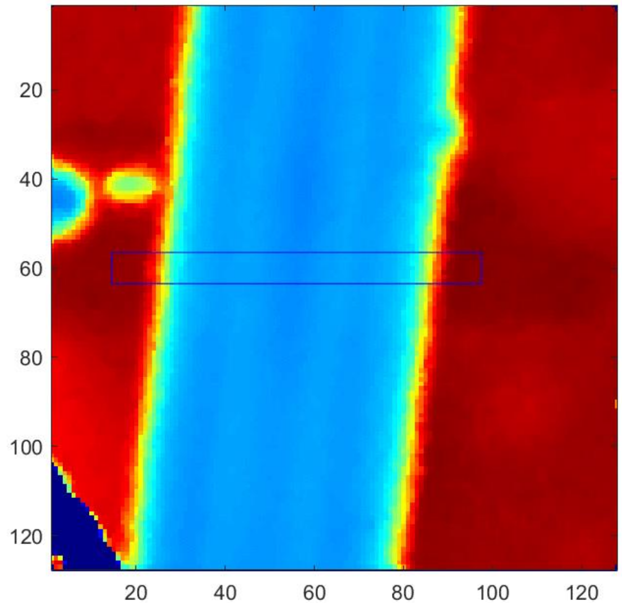
$$L_{REAL} = (92.6 \pm 0.3)\ \mu m$$

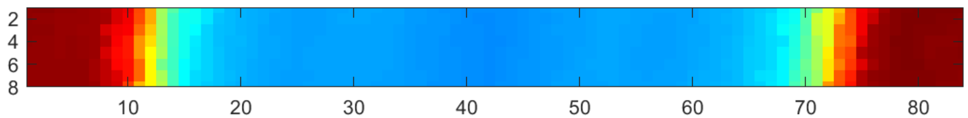
RESULTS 1.15 MeV H^+

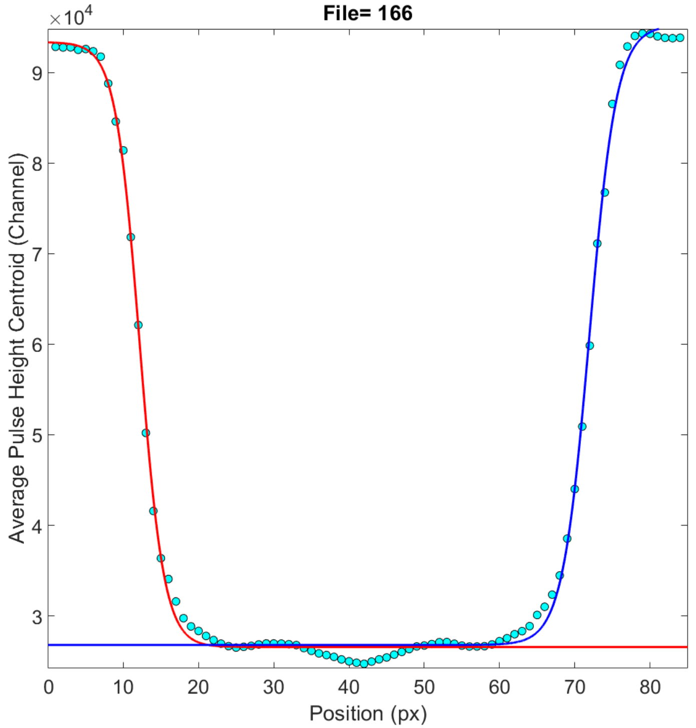


File	BIAS (V)	x_0 (px)	Δx_0 (px)	x_0 (px)	Δx_0 (px)	D (px)	ΔD (px)
155	60	14.52	0.07	65.75	0.10	51.23	0.12
156	80	17.38	0.04	62.17	0.04	44.79	0.06
157	100	18.14	0.04	60.94	0.04	42.80	0.06
158	120	18.44	0.04	60.62	0.04	42.18	0.06
159	140	18.56	0.05	59.93	0.04	41.37	0.06
160	160	18.15	0.06	59.12	0.04	40.97	0.07
161	180	18.26	0.05	58.79	0.05	40.53	0.07

RESULTS 1.5 MeV H^+







File	BIAS (V)	x_0 (px)	Δx_0 (px)	x_0 (px)	Δx_0 (px)	D (px)	ΔD (px)
166	60	12.19	0.06	71.95	0.07	59.76	0.09
167	80	15.29	0.04	68.13	0.04	52.84	0.06
165	100	13.09	0.04	63.36	0.05	50.27	0.06
169	121	16.93	0.06	65.97	0.05	49.04	0.08
170	140	16.87	0.05	65.24	0.05	48.37	0.07
171	160	17.21	0.07	64.79	0.04	47.58	0.08
172	180	17.21	0.07	64.27	0.04	47.06	0.08