Study of 3D pixel sensors after non-uniform proton irradiation

Jordi Duarte-Campderrós
on behalf of CMS Collaboration

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CMS
Compact Muon Solenoid

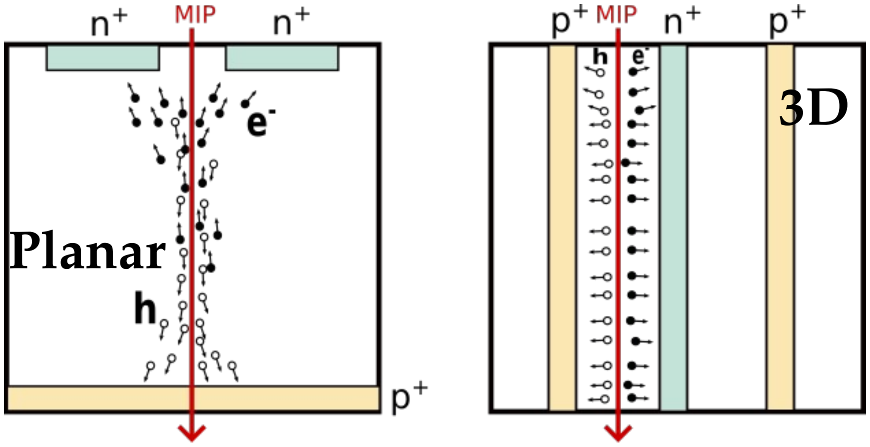
Outline

- 3D Pixel sensors for CMS
- Modules & Irradiation campaign
- Fluence estimation method
- Small study on non-uniform irradiated 3D FBK's sensors

3D pixels non-uniformly irradiated -- jordi.duarte@cern.ch

3D Pixels @ CMS

- Pixels 3D technology is being under consideration for the Innermost layer of TBPX and the innermost ring of TFPX for the Phase II
  - Charge collected after very short drift distance



  - Less trapping when irradiated (shorted drift distance)
  - Small bias voltage to deplete sensor: < 150 V after irradiation

  - Radiation tolerant → maintain spatial resolution, almost no degradation in hit efficiency

3D Pixels @ CMS

- "Radiation tolerant → maintain spatial resolution, almost no degradation in hit efficiency" → **demonstrated**[1] up to around 1E16 n_{eq}/cm^2
  - Plenty of work done to test and characterize available modules (FBK, CNM) during 2018-2019 → shown in conferences/workshop/papers

[1]
https://iopscience.iop.org/article/10.1088/1748-0221/14/06/C06018
https://www.sciencedirect.com/science/article/pii/S0168900219311246
https://indico.cern.ch/event/777112/contributions/3312274
https://indico.cern.ch/event/774201/contributions/3429263
https://indico.cern.ch/event/803258/contributions/3582883

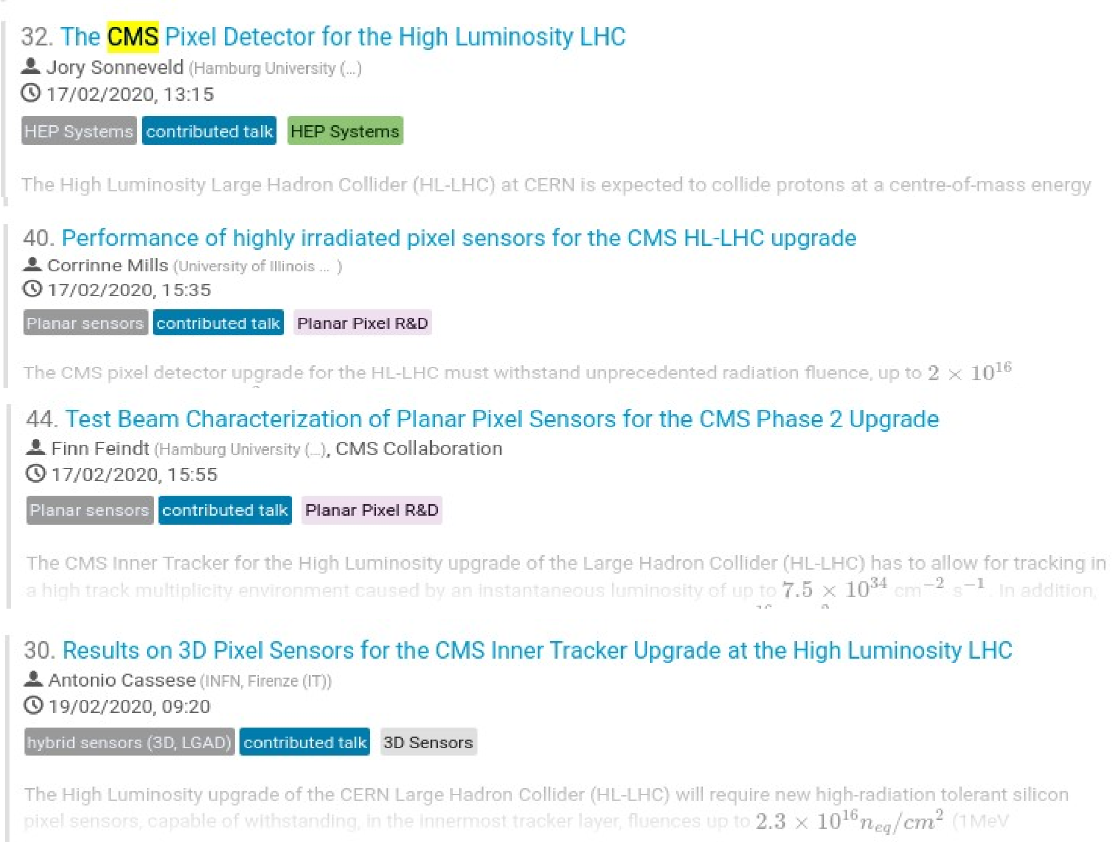
Biased selection
Not exhausted list!

- An introduction to the 3D R&D program in CMS, its motivation and many results can be found in these references.

- See other contributions at this workshop for the ongoing activities

3D Pixels @ CMS

- Related CMS Inner Tracker Phase II talks at TREDI2020 (planar and 3D)



32. The CMS Pixel Detector for the High Luminosity LHC
👤 Jory Sonneveld (Hamburg University (...)
🕓 17/02/2020, 13:15
HEP Systems | contributed talk | HEP Systems

The High Luminosity Large Hadron Collider (HL-LHC) at CERN is expected to collide protons at a centre-of-mass energy

40. Performance of highly irradiated pixel sensors for the CMS HL-LHC upgrade
👤 Corrinne Mills (University of Illinois ...)
🕓 17/02/2020, 15:35
Planar sensors | contributed talk | Planar Pixel R&D

The CMS pixel detector upgrade for the HL-LHC must withstand unprecedented radiation fluence, up to 2×10^{16}

44. Test Beam Characterization of Planar Pixel Sensors for the CMS Phase 2 Upgrade
👤 Finn Feindt (Hamburg University (...), CMS Collaboration
🕓 17/02/2020, 15:55
Planar sensors | contributed talk | Planar Pixel R&D

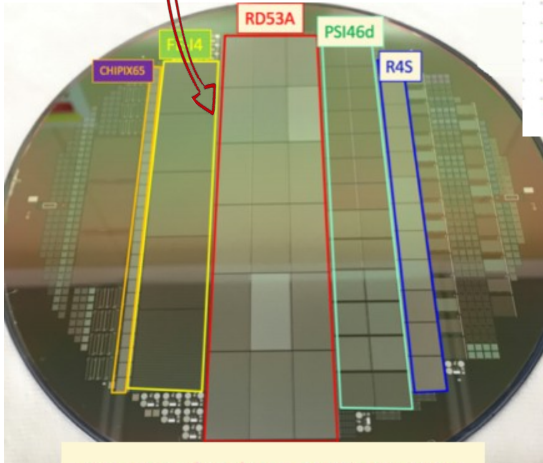
The CMS Inner Tracker for the High Luminosity upgrade of the Large Hadron Collider (HL-LHC) has to allow for tracking in a high track multiplicity environment caused by an instantaneous luminosity of up to 7.5×10^{34} cm^{-2} s^{-1}. In addition,

30. Results on 3D Pixel Sensors for the CMS Inner Tracker Upgrade at the High Luminosity LHC
👤 Antonio Cassese (INFN, Firenze (IT))
🕓 19/02/2020, 09:20
hybrid sensors (3D, LGAD) | contributed talk | 3D Sensors

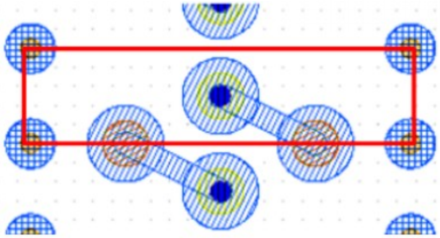
The High Luminosity upgrade of the CERN Large Hadron Collider (HL-LHC) will require new high-radiation tolerant silicon pixel sensors, capable of withstanding, in the innermost tracker layer, fluences up to $2.3 \times 10^{16} n_{eq}/cm^2$ (1MeV

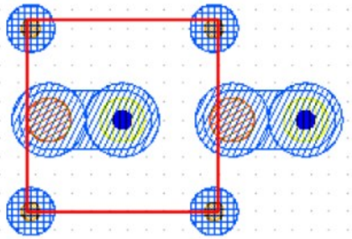
Sensor description

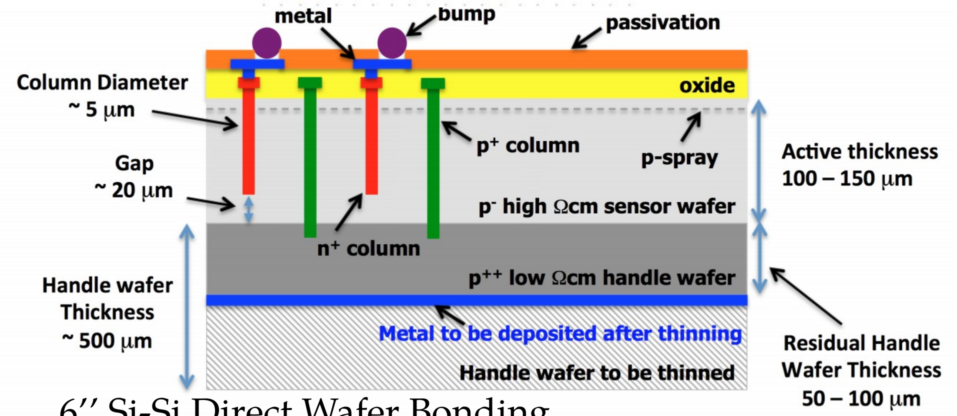
- Focus on FBK 3D sensors irradiated and tested during 2018
  - Sensors with 25x100 and 50x50 μm^2 unit pixel cell size bump-bonded to RD53A chip



3D Mask Aligner Oct 2017
18x RD53A sensors







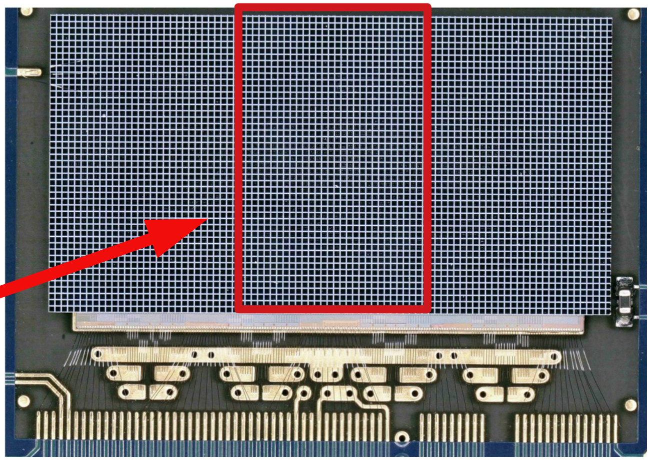
6″ Si-Si Direct Wafer Bonding
Single Side (Deep Reactive Ion Etching)

See details on https://indico.cern.ch/event/803258/contributions/3582883 or any ref. [1]

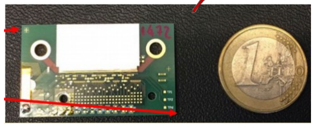
Single chip assemblies

[2] https://cds.cern.ch/record/2287593/files/%20RD53A_Manual_V3-42.pdf

- **RD53A**[2]: a demonstrator readout chip for HL-LHC upgrade of ATLAS and CMS
  - 65 um CMOS technology
  - Not a production chip
    - Chip divided in regions with 3 different analog front ends
    - Results shown for the **Linear AFE** only: CMS final choice



- Sensor+RD53A mounted over adapters cards for readout

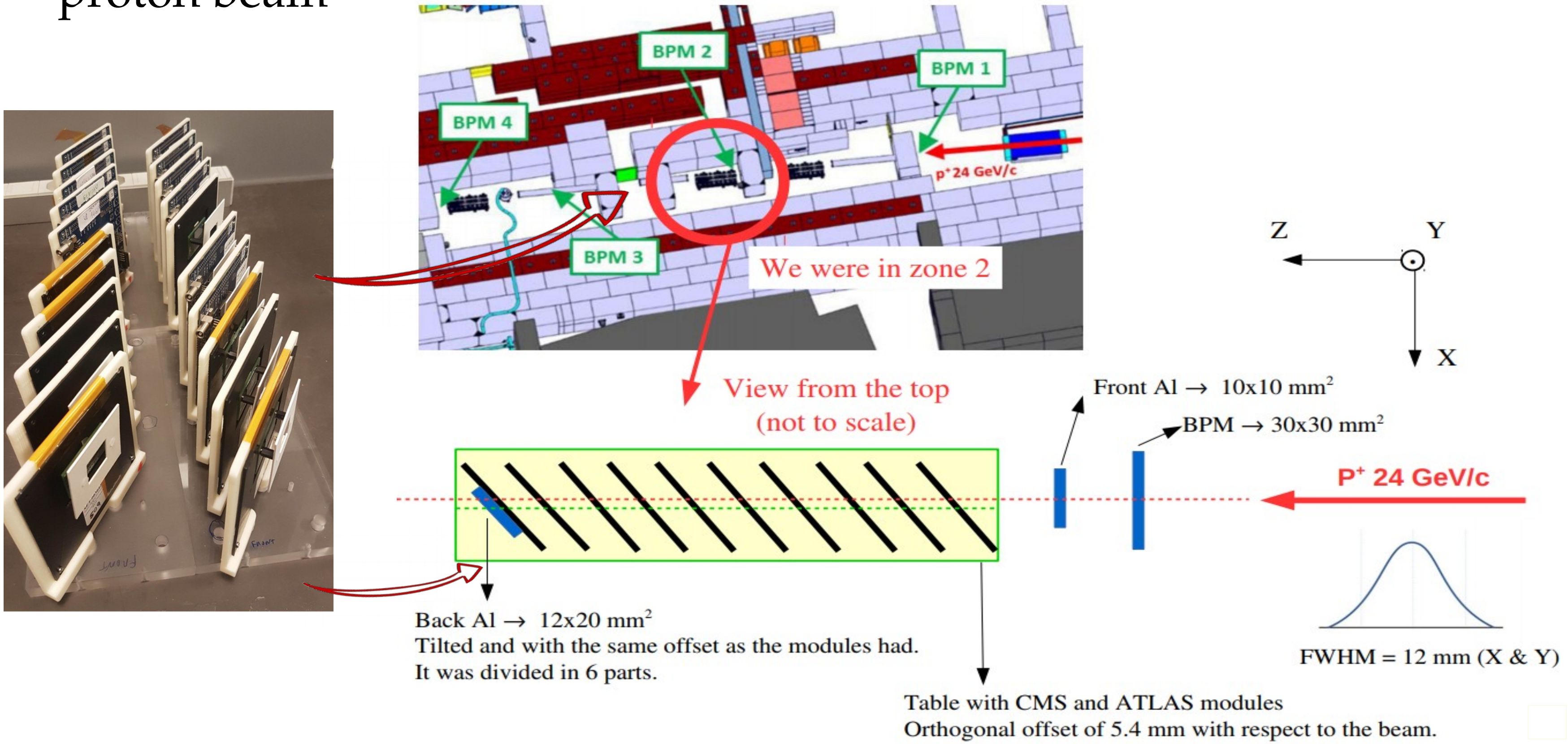


RICE card

Bonn SCC

Irradiation campaign

- Modules proton irradiated at IRRAD[3] facility during 2018
  - Mounted over supports and placed on tables in front of the 24 GeV/c proton beam



Front Al → 10x10 mm^2

BPM → 30x30 mm^2

FWHM = 12 mm (X & Y)

Back Al → 12x20 mm^2
Tilted and with the same offset as the modules had.
It was divided in 6 parts.

Table with CMS and ATLAS modules
Orthogonal offset of 5.4 mm with respect to the beam.

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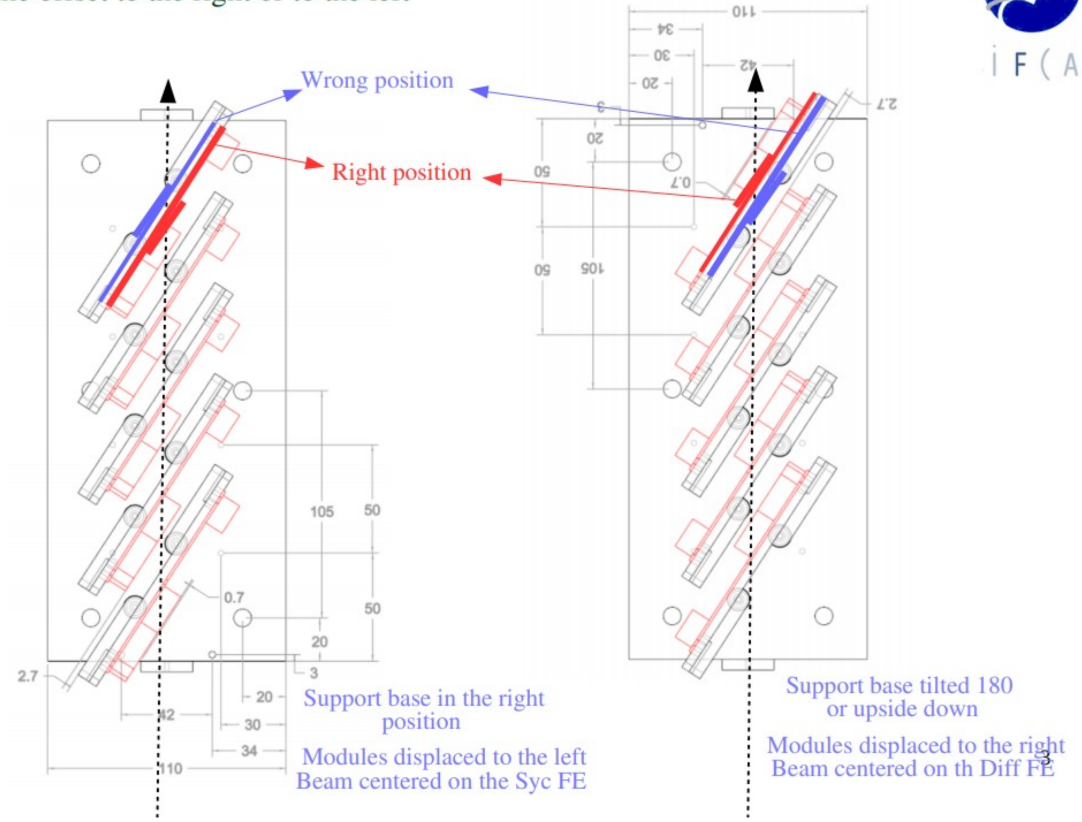
[3] https://cds.cern.ch/record/2237333?ln=es

Irradiation campaign

- Modules tilted 55º with respect to the beam to achieve uniform radiation

The base of the support was not symmetric, depending on the position we can have the offset to the right or to the left



Wrong position

Right position

Support base in the right position

Modules displaced to the left

Beam centered on the Syc FE

Support base tilted 180 or upside down

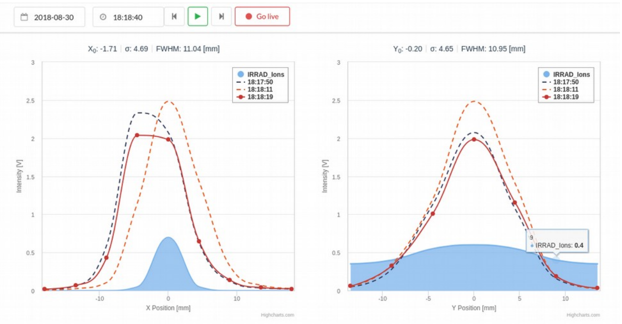
Modules displaced to the right

Beam centered on th Diff FE

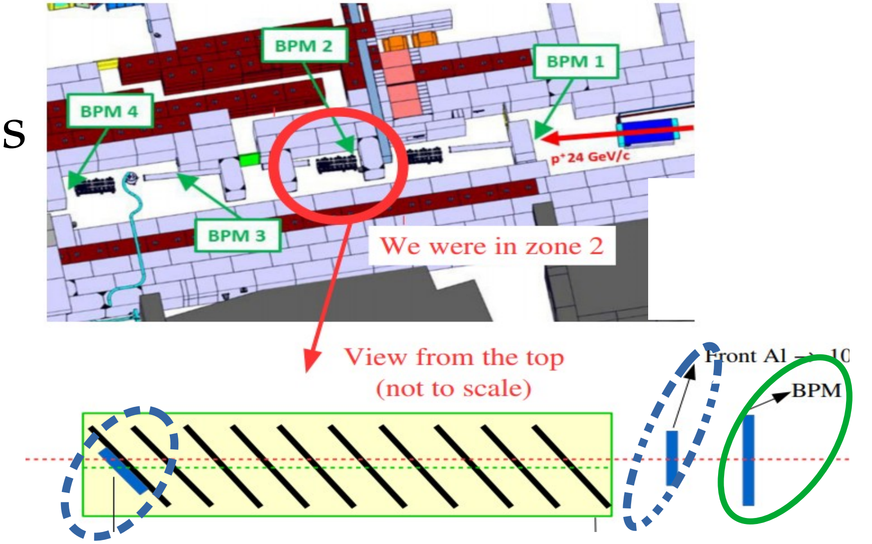
https://indico.cern.ch/event/814731/contributions/3402056/attachments/1833102/3024664/Dosimetry_measurements_update_13May19.pdf

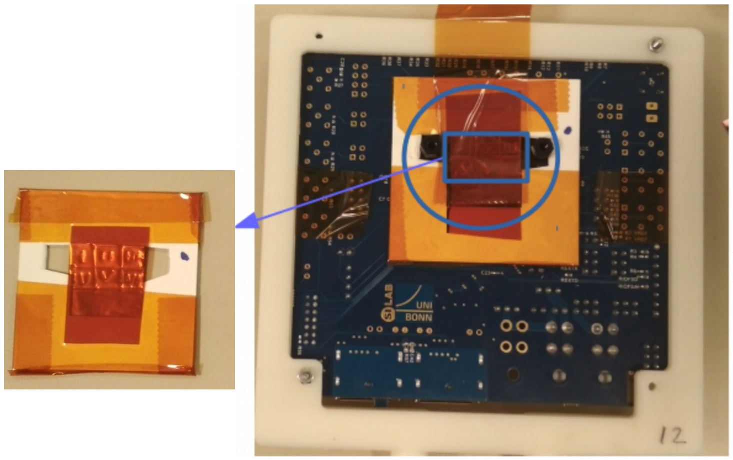
Irradiation campaign

- **Dosimetry assessment**
  - **BMP**: Beam monitoring profile: provides the instantaneous beam profile for X and Y just in front of the irradiation tables



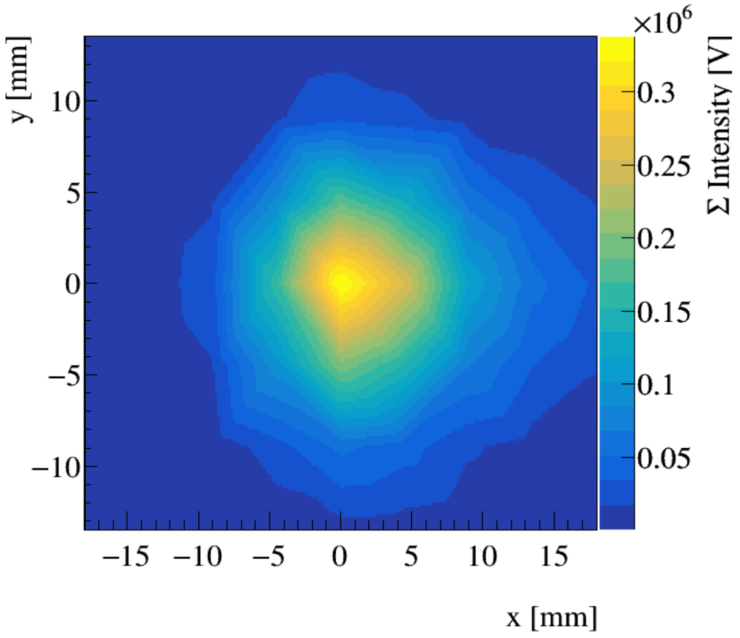
  - **Aluminum foils** placed in **front** of the irradiation tables and **behind** the sensors → determines the proton fluence by evaluating the ^{24}Na and ^{22}Na activity of the foils.

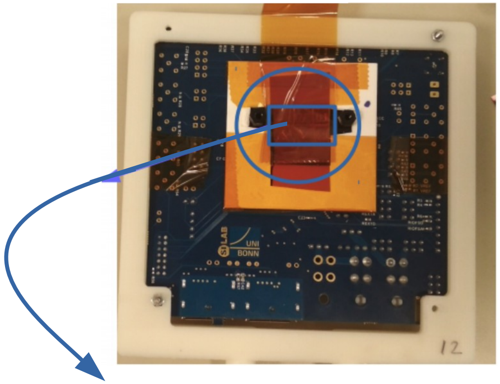




Sensor fluence estimation

- Finer granularity than the activation method with the foils (6 regions for the whole sensor) can be achieved by **cross-referencing** the BPMs data with the Al foils measurements

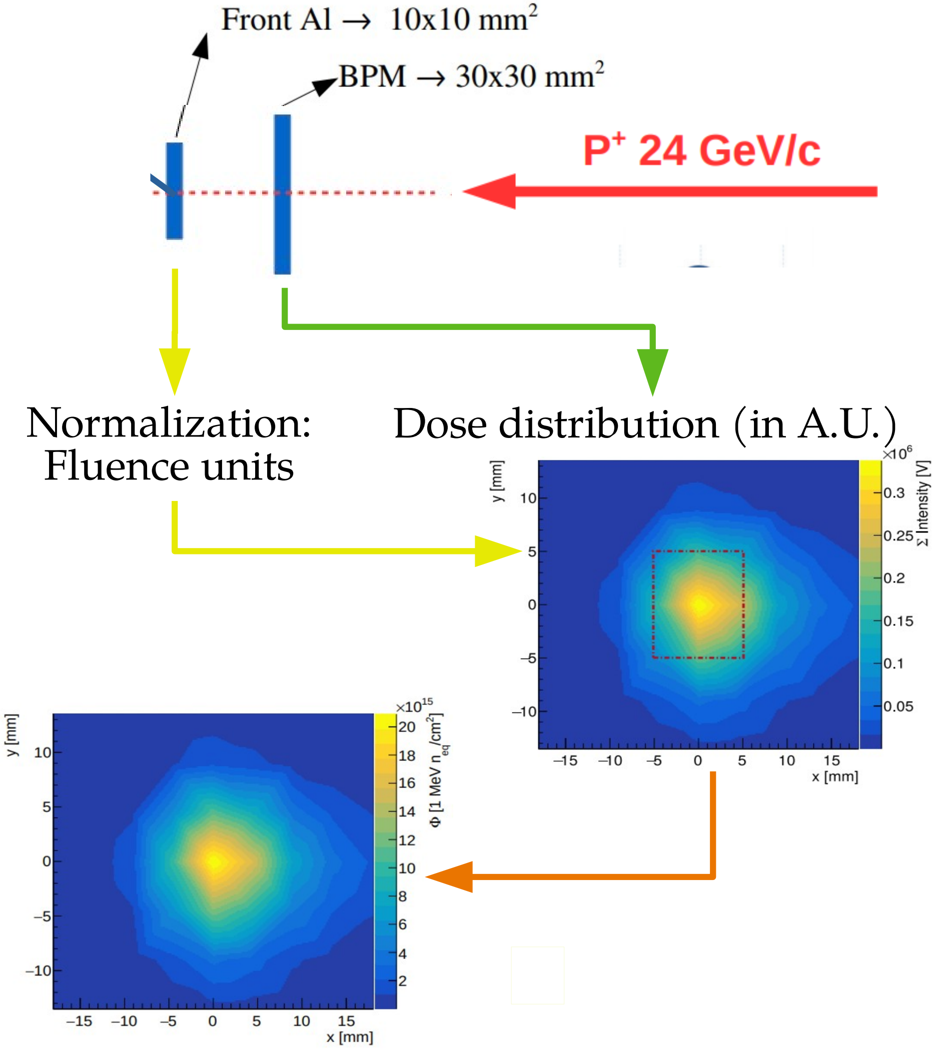




SYNC	LIN	DIFF
III (1.21±0.08)e15	I I (3.4±0.2)e15	I (1.05±0.07)e16
VI (0.83±0.06)e15	V (2.2±0.2)e15	IV (5.8±0.4)e15

Methodology

- Cross-reference **BPM** with **Front-Al** → The irradiation beam profile is normalized in fluence units



Front Al → 10x10 mm^2

BPM → 30x30 mm^2

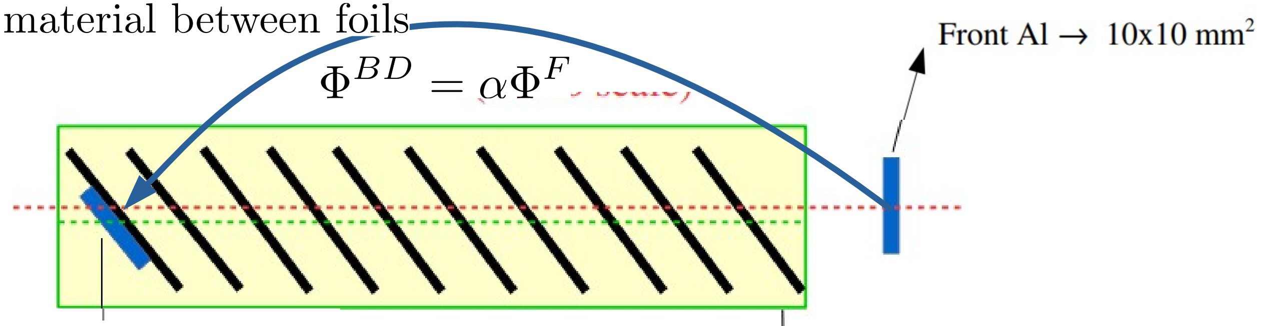
P$^+$ 24 GeV/c

Normalization: Fluence units

Dose distribution (in A.U.)

Methodology

α – effects due to material between foils

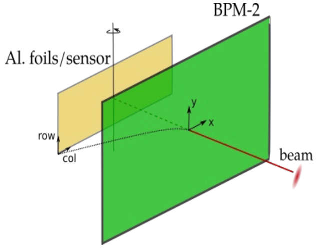


$$\Phi^{BD} = \alpha\Phi^{F}$$

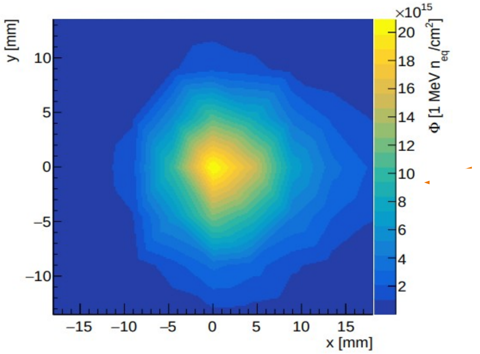
- Transform the beam profile in **Front-Al** into **Back-Al**
  - Scale
  - Rotation, translation

$$\Phi^{F}(x,y) \longmapsto \frac{1}{\alpha}\Phi^{B}(c,r)$$

$$\begin{aligned} f: \text{Front-Al} &\longmapsto \text{Back-Al} \\ x \quad & \quad c(x) = \frac{\Delta_x}{2} + \frac{\lambda_x}{\cos\omega}(x - x_0) \\ y \quad & \quad r(y) = \lambda_y y + r_0\,, \end{aligned}$$



Transformation to Back-Al frame

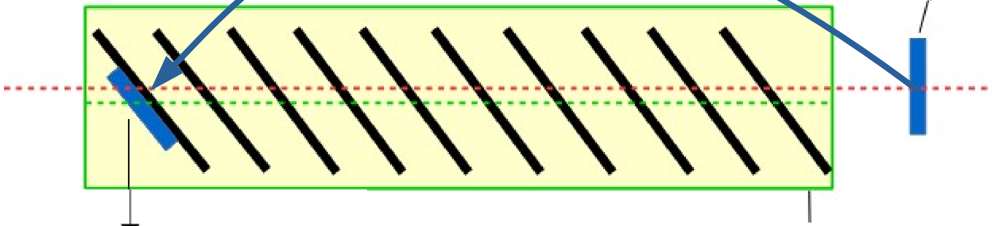


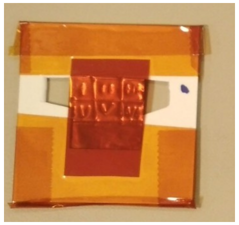
Methodology

α – effects due to material between foils

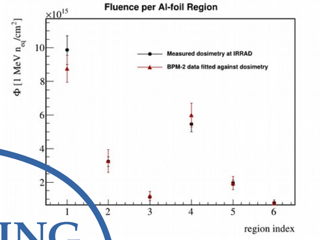
$$\Phi^{BD} = \alpha\Phi^{F}$$

Front Al → 10x10 mm²





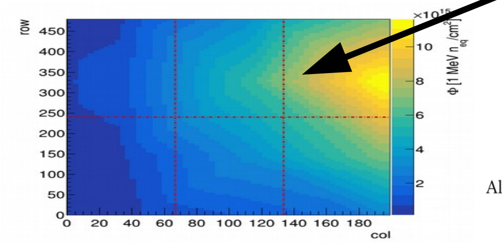
Back Al → 12x20 mm²
Divided in 6 regions
(6x6.7 mm²)



$$\int_{A_i^{Back-Al}} \frac{\lambda_x\lambda_y}{\cos\omega}\,\alpha\,\Phi^F\left(\frac{\Delta_x}{2}+\frac{\lambda_x}{\cos\omega}(x-x_0),\lambda_y y+r_0\right)\,dx\,dy = \Phi_{\Delta t}^{Back-Al,i}\,A_i^{Back-Al},\quad i=1,\dots,6$$

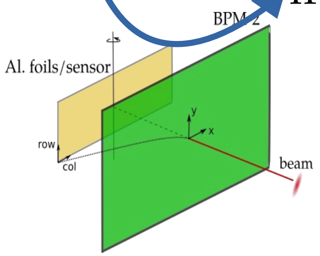
FITTING

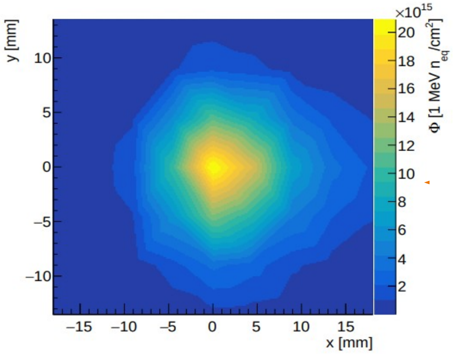
- Transformation parameters are **fitted simultaneously** in the 6 available dosimetry measurements at Back-Al



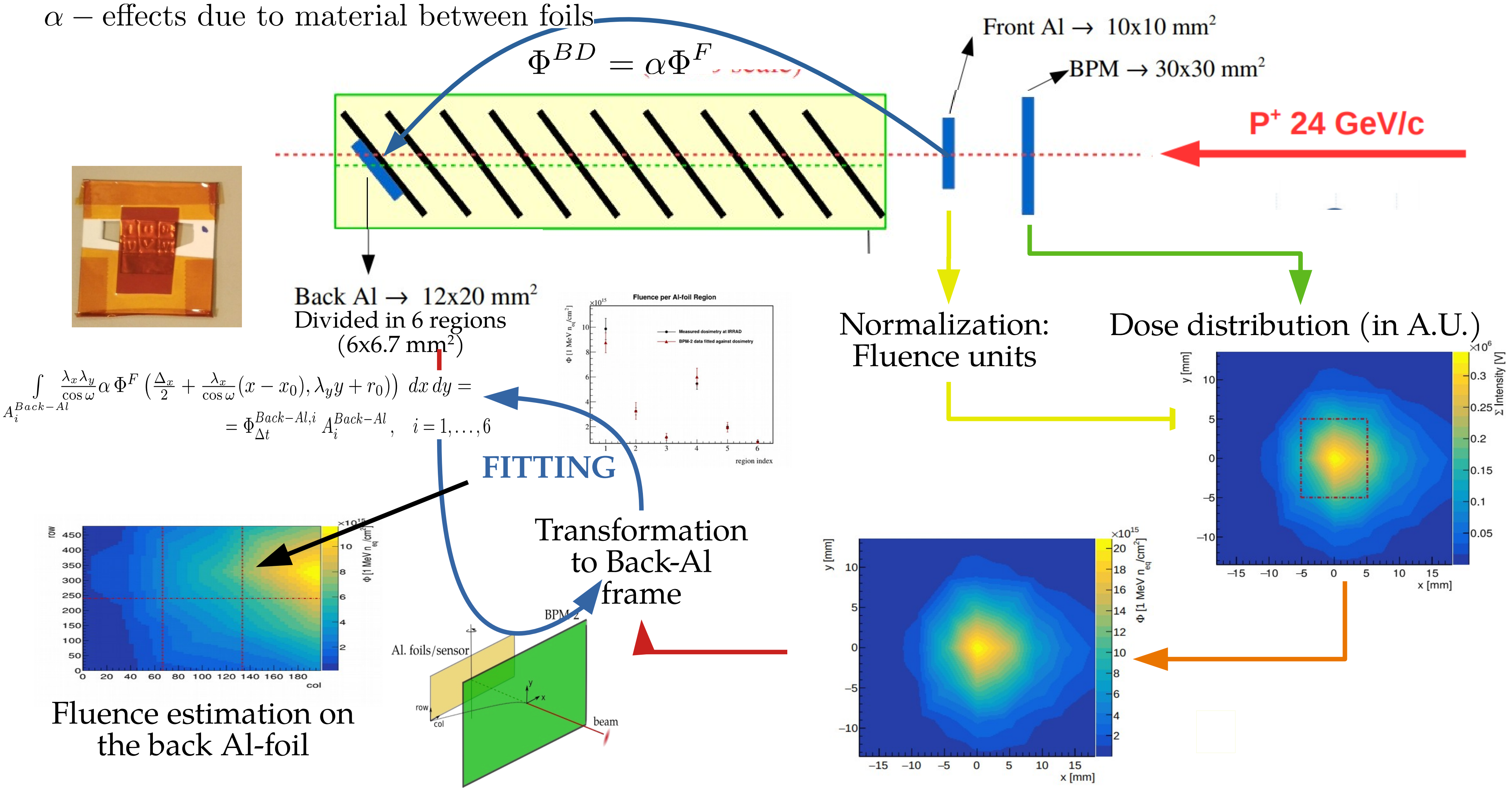
Fluence estimation on the back Al-foil

Transformation to Back-Al frame





Methodology



α – effects due to material between foils

$$\Phi^{BD} = \alpha \Phi^{F}$$

Front Al → 10x10 mm²

BPM → 30x30 mm²

P⁺ 24 GeV/c

Back Al → 12x20 mm²
Divided in 6 regions
(6x6.7 mm²)

$$\int_{A_i^{Back-Al}} \frac{\lambda_x \lambda_y}{\cos\omega} \alpha\, \Phi^F \left(\frac{\Delta_x}{2} + \frac{\lambda_x}{\cos\omega}(x - x_0), \lambda_y y + r_0\right)\ dx\, dy = \\ = \Phi_{\Delta t}^{Back-Al,i}\ A_i^{Back-Al}, \quad i = 1, \ldots, 6$$

FITTING

Normalization:
Fluence units

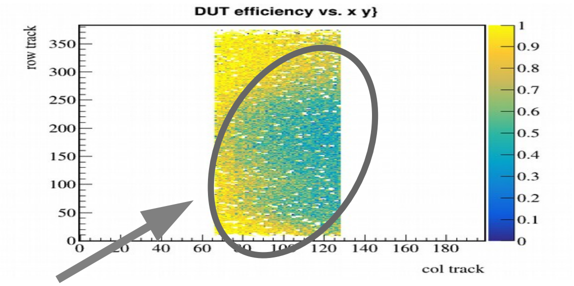
Dose distribution (in A.U.)

Transformation
to Back-Al
frame

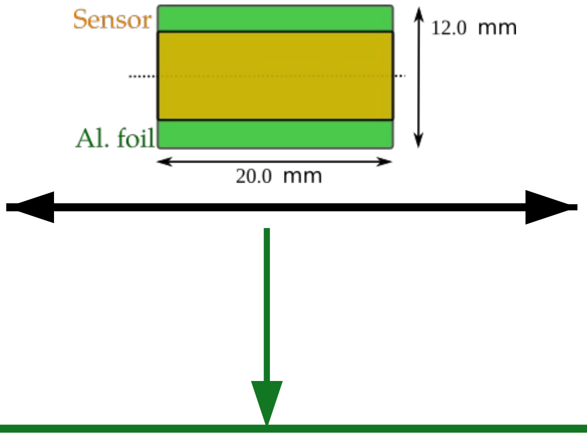
Fluence estimation on
the back Al-foil

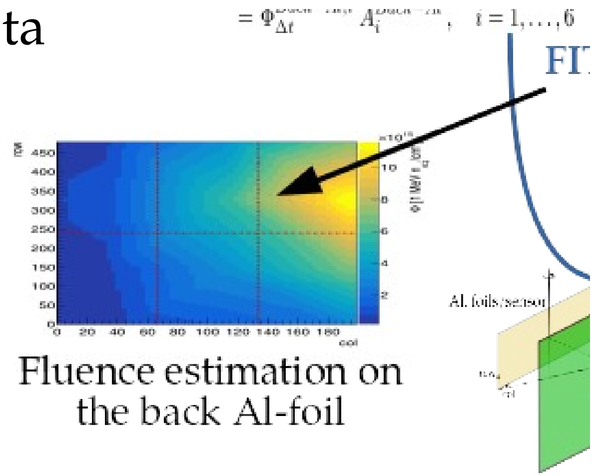
Fluence at sensor

Align sensor and Al-foil fluence estimation, compatible with observed data

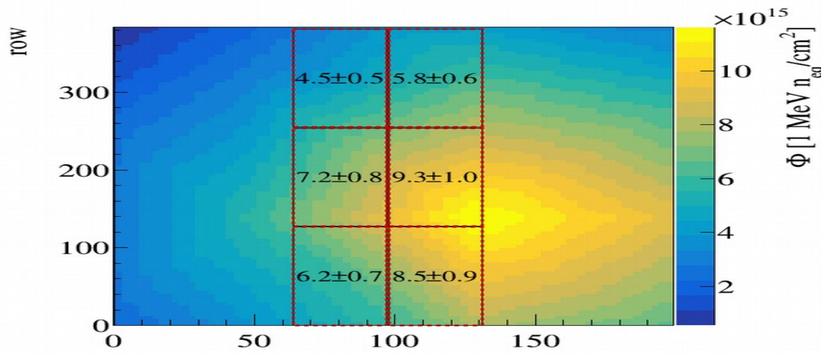


Under-depleted sensor shows irradiation spot





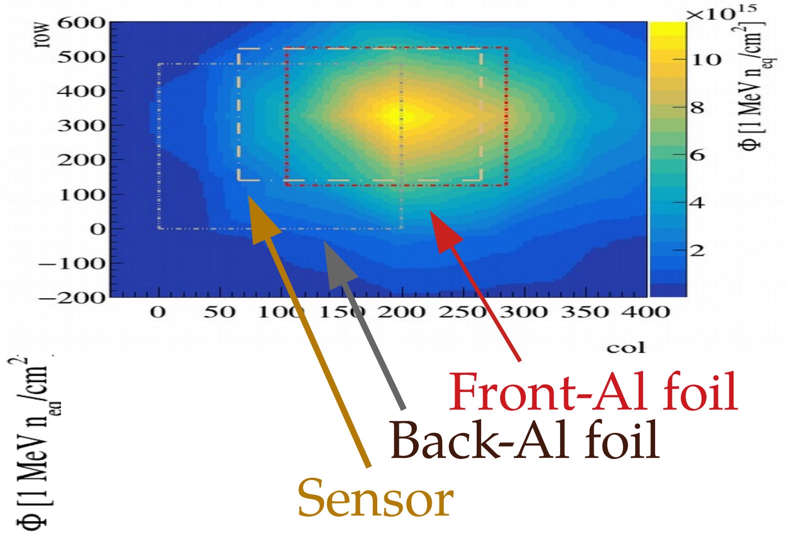
Fluence estimation on the back Al-foil

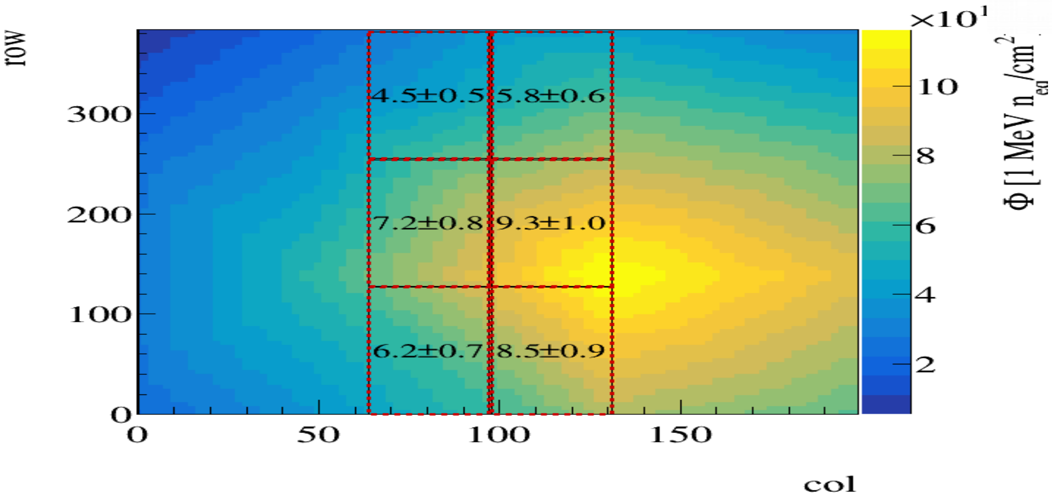


Fluence estimation on the sensor surface

Irradiation 2018: 1st campaign target 1E16 n_{eq}/cm^2 (1set)

- Estimated position of the sensor wrt. the beam
  - **IRRAD 1st campaign 2018 for a target fluence 1e16 n_{eq}/cm^2**

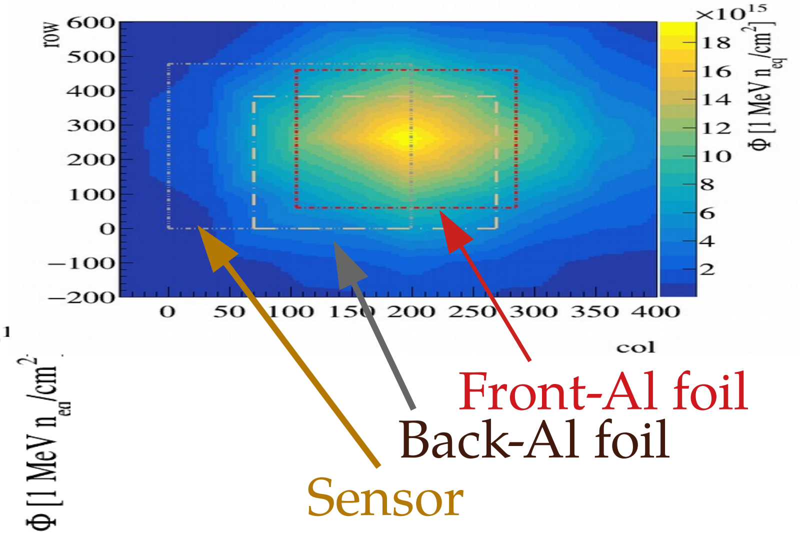




- **Estimated fluence at the sensor:** $\Phi = (6.1\pm^{1.2}_{1.2}) \cdot 10^{15}\ \mathrm{n_{eq}/cm^2}$
- **Estimated fluence at the LIN FE:** $\Phi_{\mathrm{LIN}} = (6.9\pm^{1.4}_{1.3}) \cdot 10^{15}\ \mathrm{n_{eq}/cm^2}$
- Several regions on the LIN FE **reached 1e16 n_{eq}/cm_2** fluence

Irradiation 2018: 2^{st} campaign target 1E16 n_{eq}/cm^2 (2set)

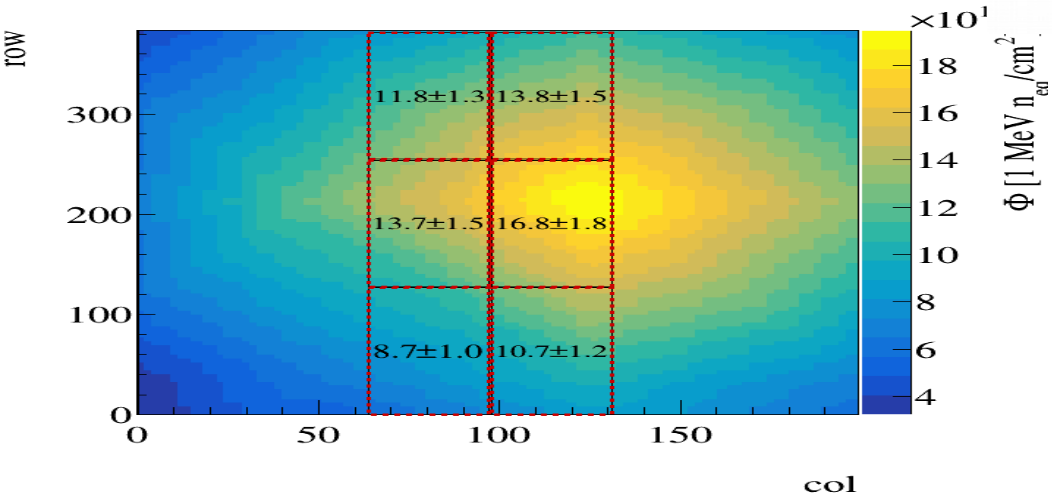
- Estimated position of the sensor wrt. the beam
  - **IRRAD 2^{nd} campaign 2018 for a target fluence 1e16 n_{eq}/cm^2**



Front-Al foil

Back-Al foil

Sensor

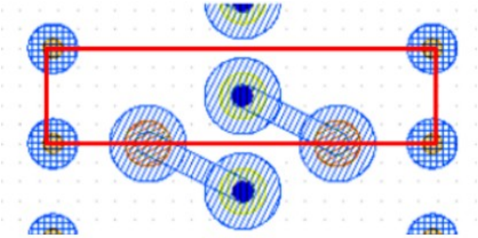


- **Estimated fluence at the sensor:** $\Phi = \left(11\pm^{2}_{2}\right) \cdot 10^{15}\ \mathrm{n_{eq}/cm^2}$
- **Estimated fluence at the LIN FE:** $\Phi_{\mathrm{LIN}} = \left(13\pm^{3}_{2}\right) \cdot 10^{15}\ \mathrm{n_{eq}/cm^2}$
- Most of the LIN FE **reached 1e16 n_{eq}/cm_2** fluence

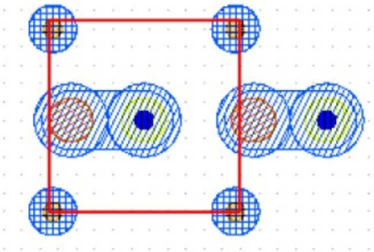
An application example: SPS CERN 2018 Test beams

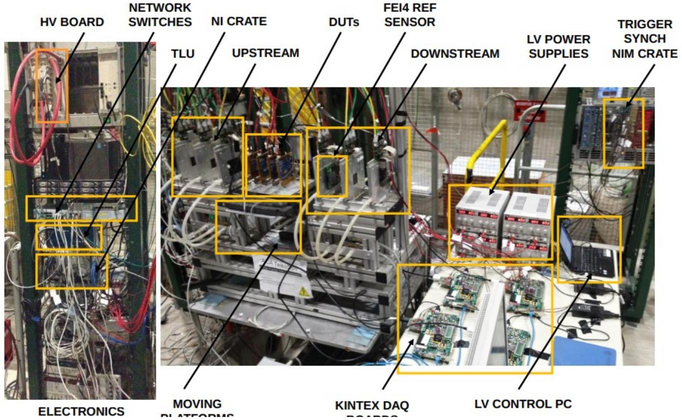
- Sensors from 1st irradiation campaign (target fluence 1E16 neq/cm2) tested at beam at CERN SPS (126 GeV/c p^+)

W3X3Y2:
FBK 3D 25x100 (1E)

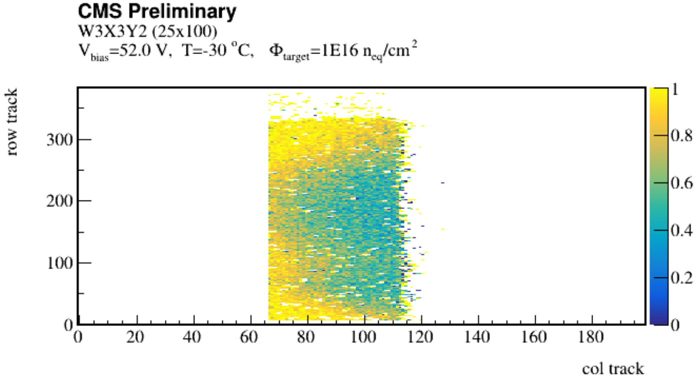


W91X1Y3
FBK 3D 50x50





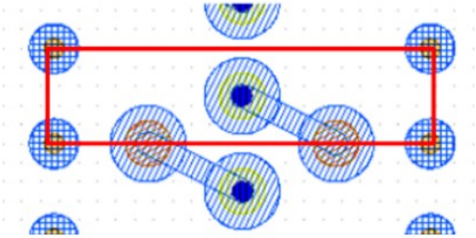
- Measured at cold temperature (~30°C), at different bias voltage applied, different particle incident angles. In particular, sensor under-depletion showed the irradiation spot (triggering the fluence estimation method)



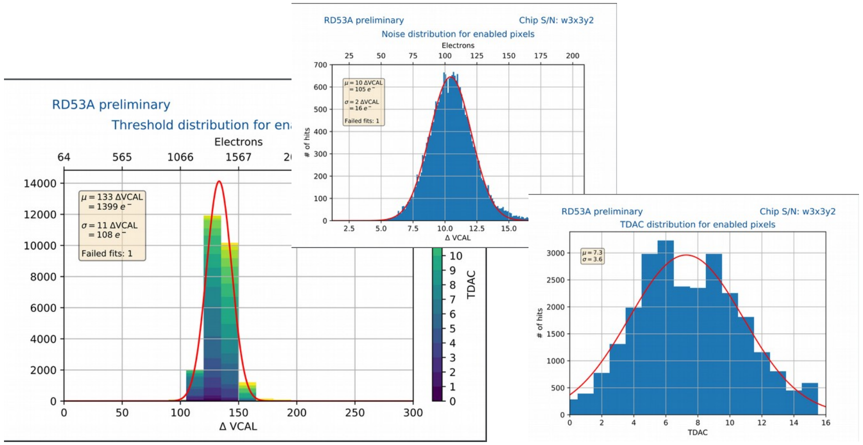
- Using **BDAQ53** readout system: https://gitlab.cern.ch/silab/bdaq53

Chip configuration and tunning

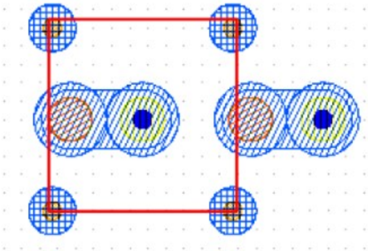
W3X3Y2:
FBK 3D 25x100 (1E)



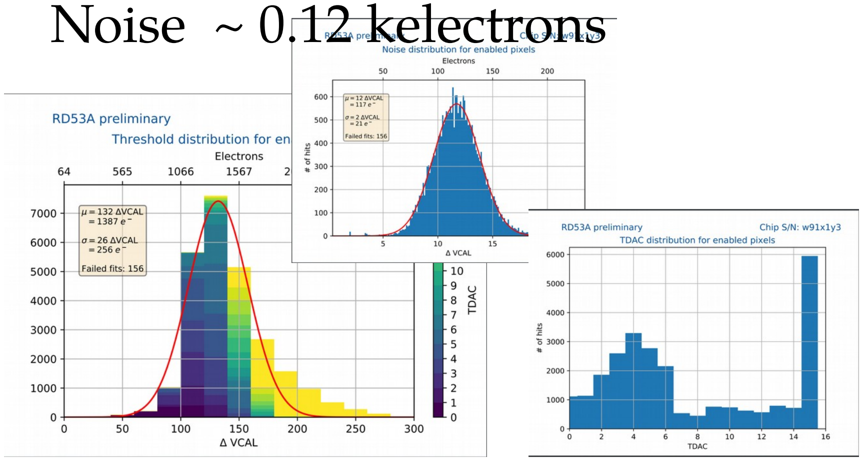
- Threshold ~ 1.4 kelectrons
- Noise ~ 0.11 kelectrons



W91X1Y3
FBK 3D 50x50



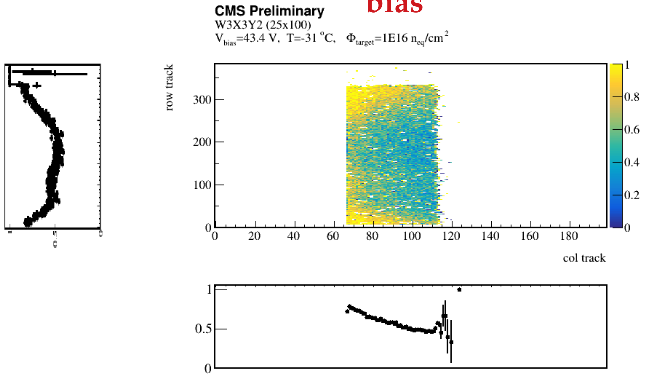
- Threshold ~ 1.4 kelectrons
  BUT wide thresholds amongst pixels → problems with tuning
- Noise ~ 0.12 kelectrons



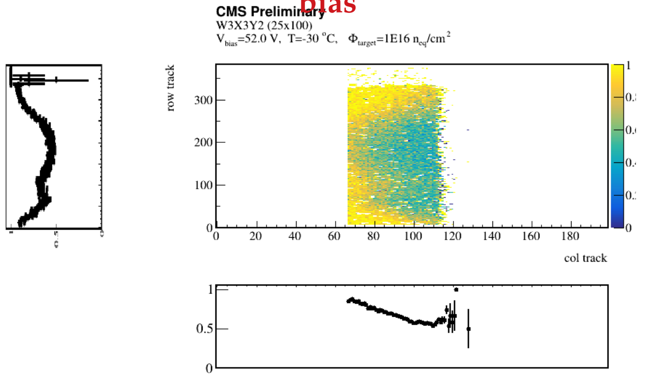
Hit efficiency FBK 3D 25x100 Perpendicular particles

W3X3Y2

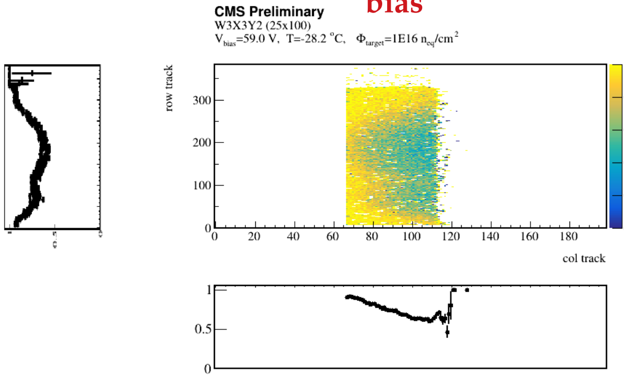
V_{bias} = 43 V



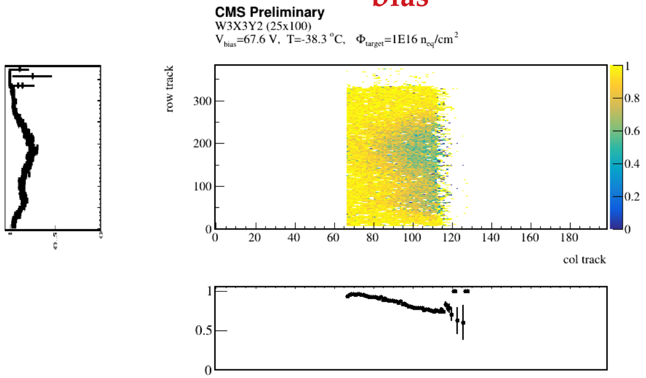
V_{bias} = 52 V



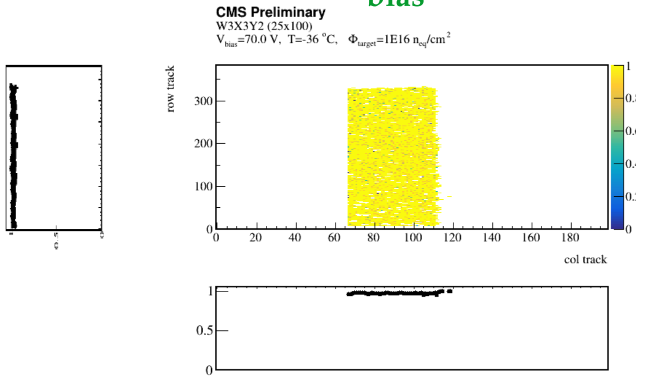
V_{bias} = 59 V



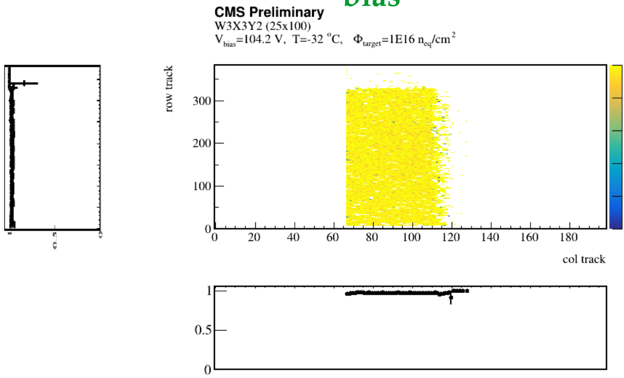
V_{bias} = 68 V



V_{bias} = 70 V



V_{bias} = 104 V

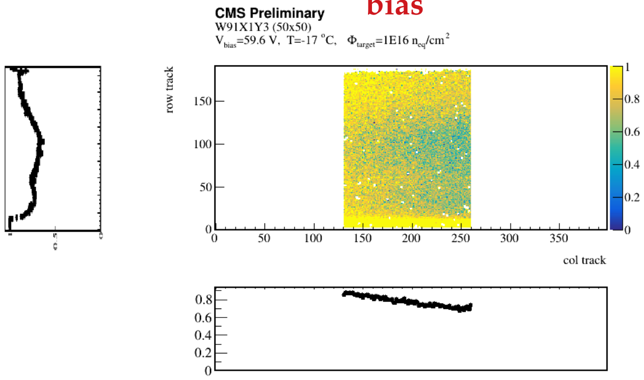


- Irradiation spot clearly visible under-depletion, **in-homogeneously disappearing** when increasing bias → in-homogeneous irradiation → **different fluences reached**

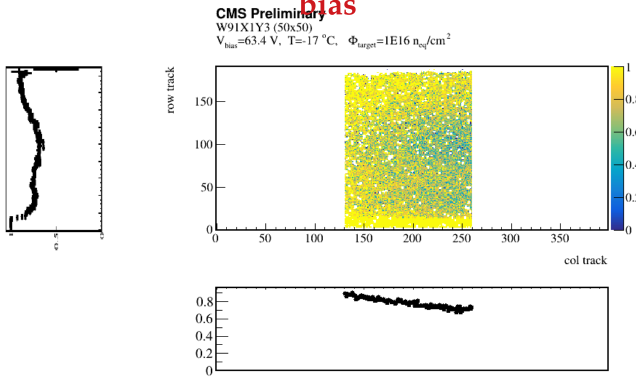
Hit efficiency FBK 3D 50x50 Perpendicular particles

W91X1Y3

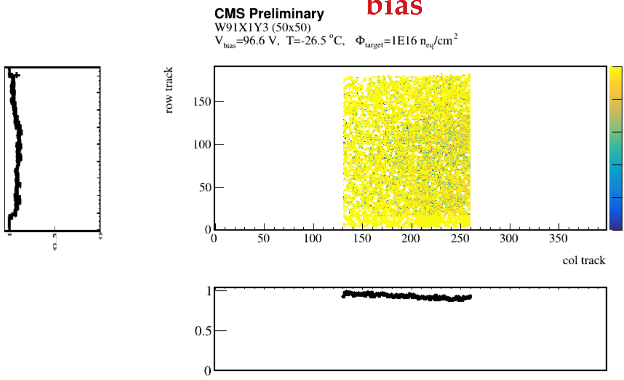
V_{bias}= 60 V



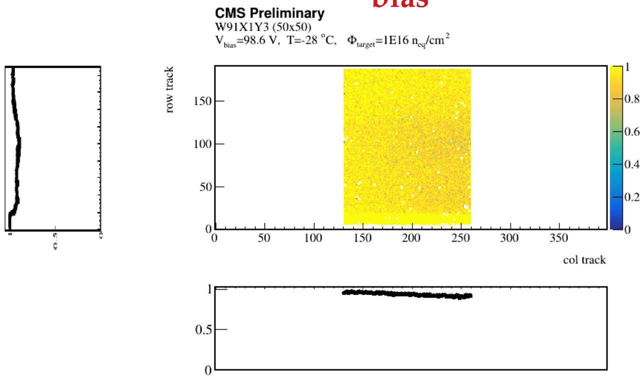
V_{bias}= 63 V



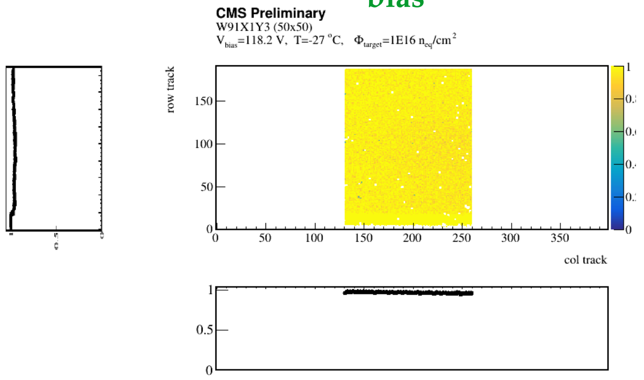
V_{bias}= 97 V



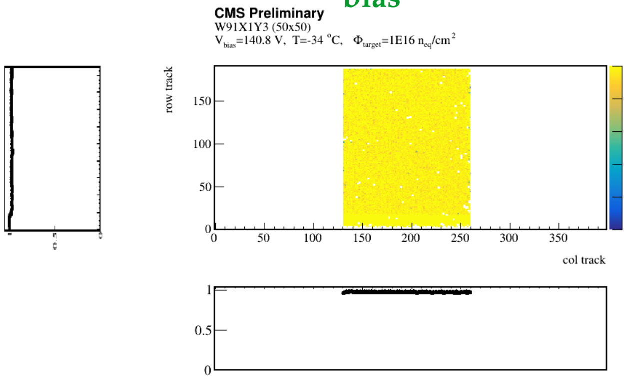
V_{bias}= 98 V



V_{bias}= 118 V



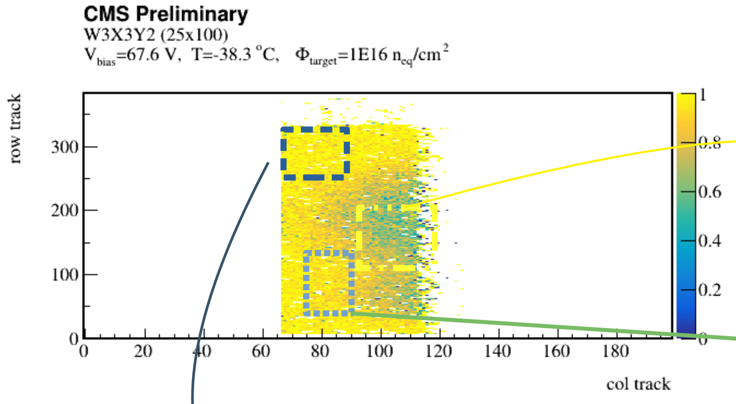
V_{bias}= 141 V

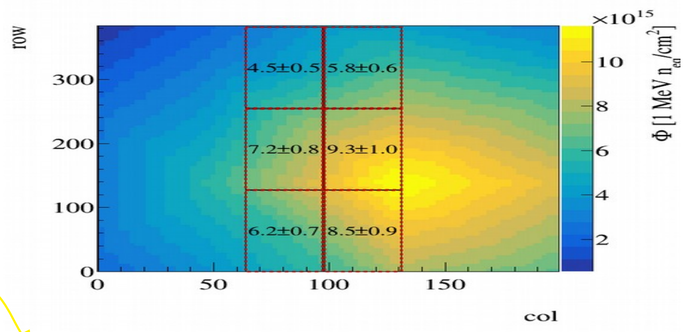


- Irradiation spot clearly visible under-depletion, however, **looks like** was more homogeneously irradiated (but missing important V_{bias} points to conclude)

Sensor behavior at different fluences (an example)

- Using previous info → study on the same module different fluences → fluence estimation from the presented method



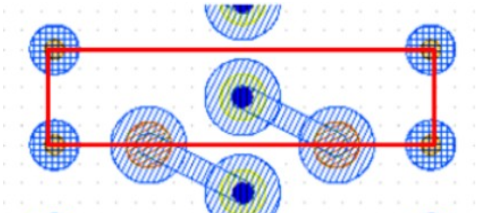


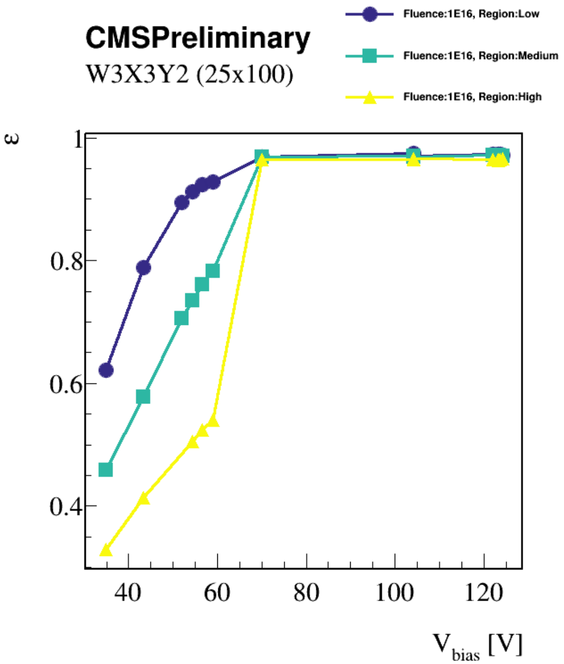
- High ~ 1E16 n_{eq}/cm^2
- Medium ~ 0.7E16 n_{eq}/cm^2
- Low ~ 0.5E16 n_{eq}/cm^2

Example for the 25x100

Sensor behavior at different fluences (an example)

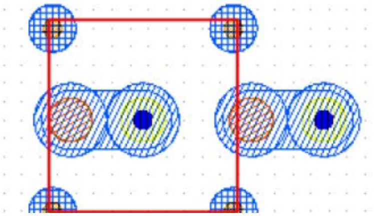
W3X3Y2:
FBK 3D 25x100 (1E)

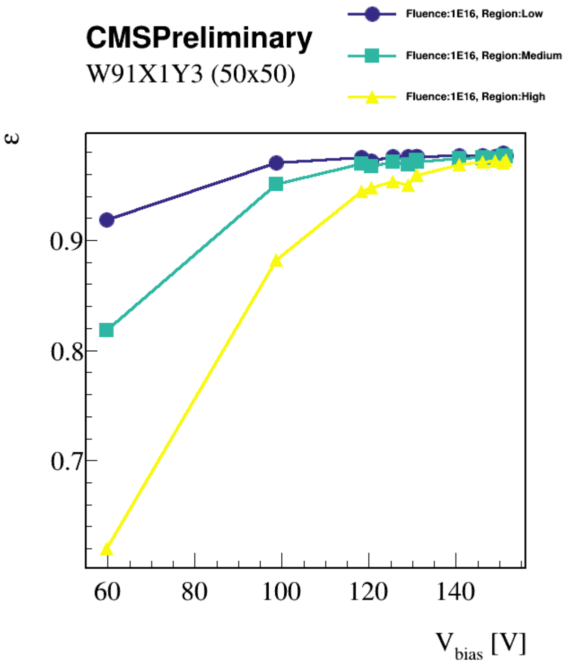




- High
- Medium
- Low

W91X1Y3
FBK 3D 50x50





- The different regions behave different as expected

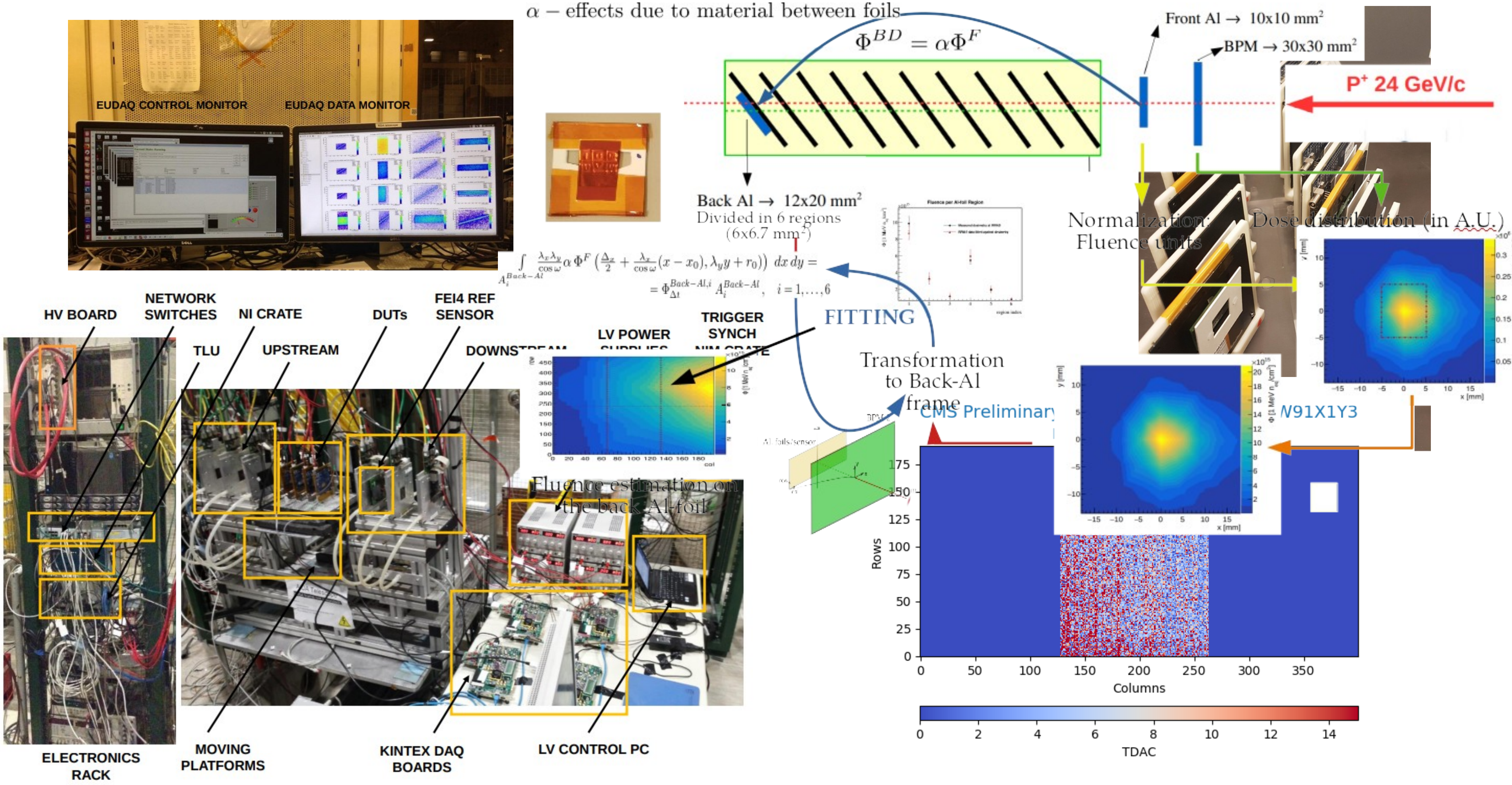
Conclusions

- A method to estimated the irradiation received by a sensor in the IRRAD facility with a finer granularity then the current activation method has been presented
  - The method cross-references data from the beam monitor instruments from IRRAD and dosimetry measurements

  - A paper is in preparation (details will be found there)

- The method has been used to estimate fluences regions in in-homogeneously irradiated sensors, allowing to study them in the same sensor
  - Several test beam data results from 2018 and 2019 already make use of the method

BACKUP SLIDES



α – effects due to material between foils

$$\Phi^{BD} = \alpha\Phi^{F}$$

Front Al → 10x10 mm²

BPM → 30x30 mm²

P⁺ 24 GeV/c

Back Al → 12x20 mm²
Divided in 6 regions
(6x6.7 mm²)

$$\int_{A_i^{Back-Al}} \frac{\lambda_x\lambda_y}{\cos\omega}\alpha\,\Phi^F\left(\frac{\Delta_x}{2}+\frac{\lambda_x}{\cos\omega}(x-x_0),\lambda_y y+r_0\right)\right)\,dx\,dy = \\ = \Phi_{\Delta t}^{Back-Al,i}\,A_i^{Back-Al},\quad i=1,\ldots,6$$

FITTING

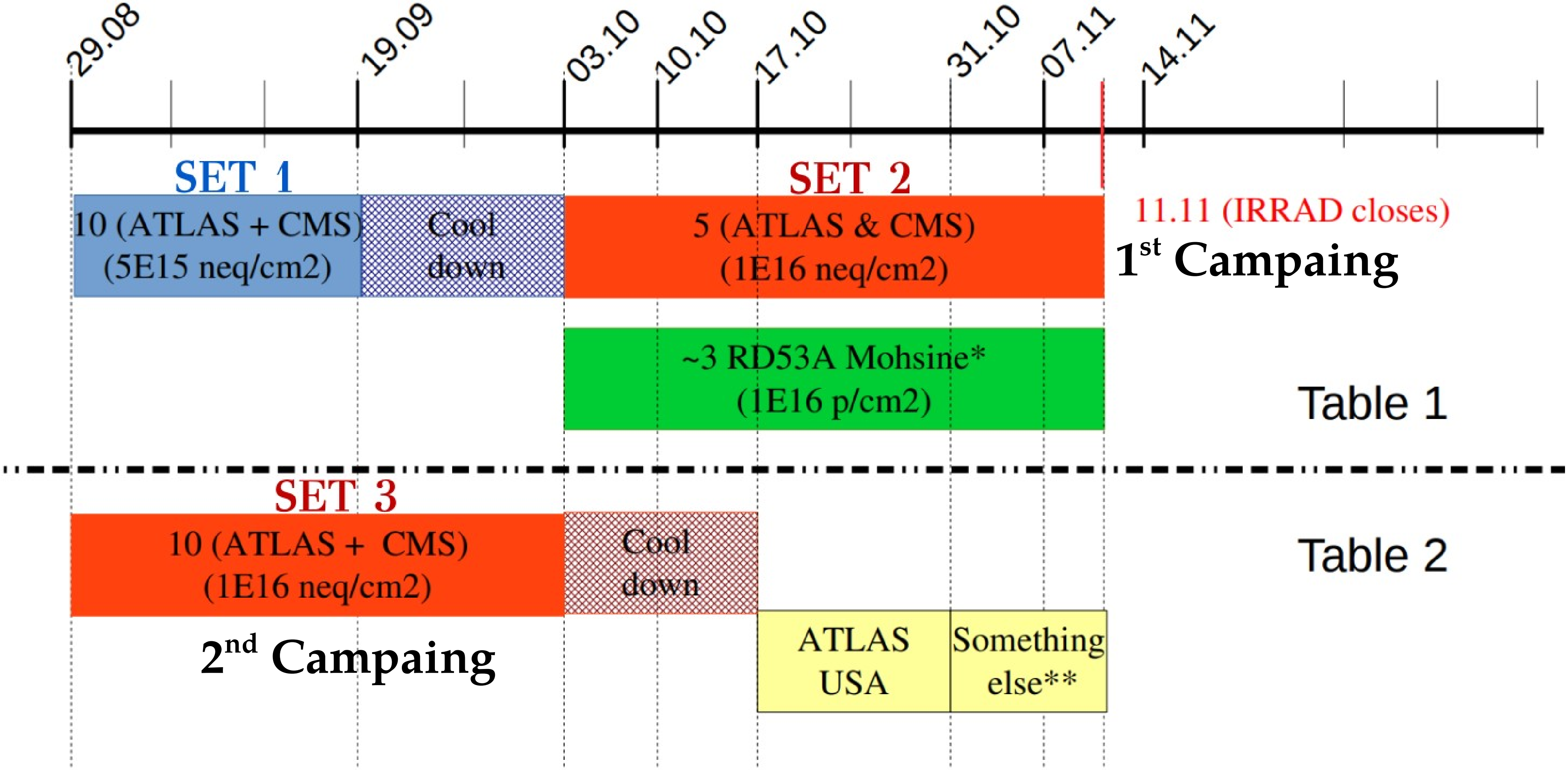
Transformation to Back-Al frame

Fluence estimation on the back Al-foil

Normalization: Fluence units

Dose distribution (in A.U.)

Irradiation tables



SET 1

10 (ATLAS + CMS)
(5E15 neq/cm2)

Cool
down

SET 2

5 (ATLAS & CMS)
(1E16 neq/cm2)

11.11 (IRRAD closes)

1st Campaing

~3 RD53A Mohsine*
(1E16 p/cm2)

Table 1

SET 3

10 (ATLAS + CMS)
(1E16 neq/cm2)

Cool
down

ATLAS
USA

Something
else**

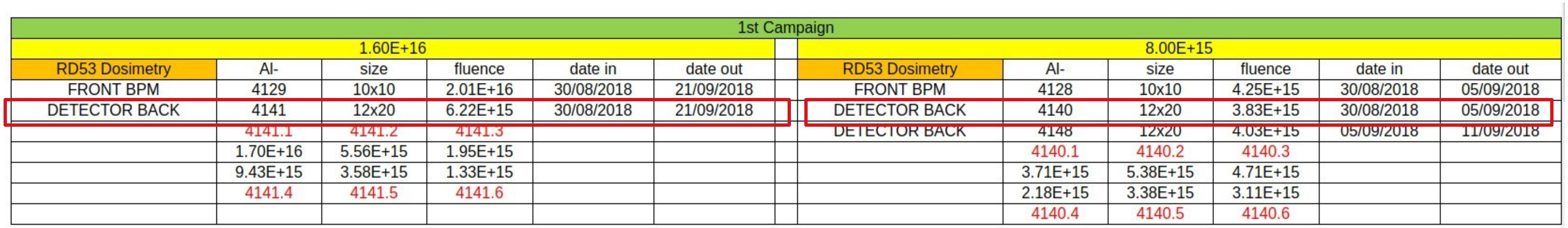
2nd Campaing

Table 2

Measured dosimetry

- Irradiation campaign

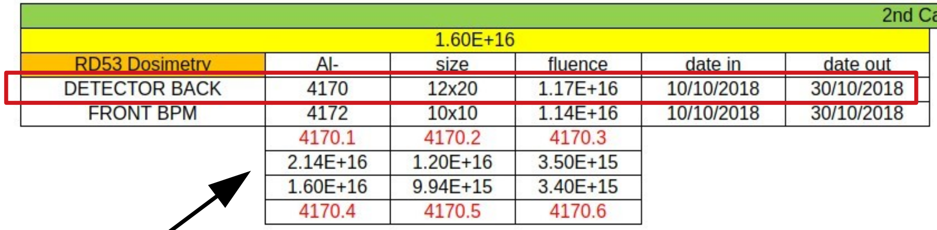
Values in protons!!



1st Campaign

1.60E+16					
RD53 Dosimetry	Al-	size	fluence	date in	date out
FRONT BPM	4129	10x10	2.01E+16	30/08/2018	21/09/2018
DETECTOR BACK	4141	12x20	6.22E+15	30/08/2018	21/09/2018
	4141.1	4141.2	4141.3		
	1.70E+16	5.56E+15	1.95E+15		
	9.43E+15	3.58E+15	1.33E+15		
	4141.4	4141.5	4141.6		

8.00E+15					
RD53 Dosimetry	Al-	size	fluence	date in	date out
FRONT BPM	4128	10x10	4.25E+15	30/08/2018	05/09/2018
DETECTOR BACK	4140	12x20	3.83E+15	30/08/2018	05/09/2018
DETECTOR BACK	4148	12x20	4.03E+15	05/09/2018	11/09/2018
	4140.1	4140.2	4140.3		
	3.71E+15	5.38E+15	4.71E+15		
	2.18E+15	3.38E+15	3.11E+15		
	4140.4	4140.5	4140.6		

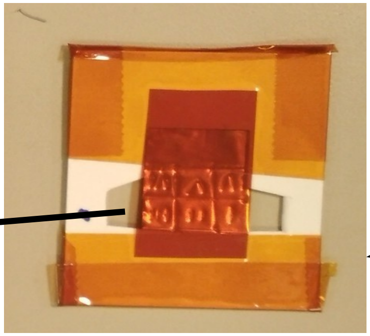


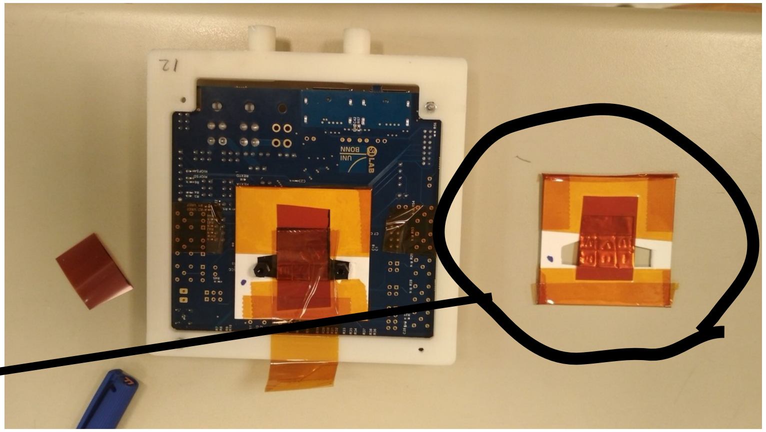
2nd Campaign

1.60E+16					
RD53 Dosimetry	Al-	size	fluence	date in	date out
DETECTOR BACK	4170	12x20	1.17E+16	10/10/2018	30/10/2018
FRONT BPM	4172	10x10	1.14E+16	10/10/2018	30/10/2018
	4170.1	4170.2	4170.3		
	2.14E+16	1.20E+16	3.50E+15		
	1.60E+16	9.94E+15	3.40E+15		
	4170.4	4170.5	4170.6		

I	II	III
IV	V	VI

IΛ	Λ	ΛI
III	II	I



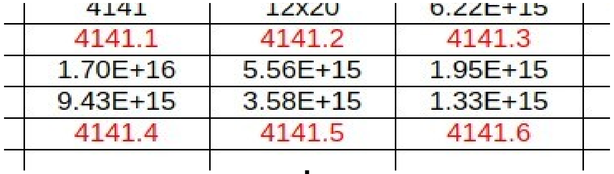


Measured dosimetry for 1^{st} set target fluence: 1E16 n_{eq}/cm^2

- Protons to neutron equivalent fluences hardness factor[1]:
  - **K=0.62±0.02**
- IRRAD measured fluence (in 1 MeV neutron equivalent)

Φ_p

$\frac{\delta\Phi_p}{\Phi_p} = 7\%$



4141	12x20	6.22E+15
4141.1	4141.2	4141.3
1.70E+16	5.56E+15	1.95E+15
9.43E+15	3.58E+15	1.33E+15
4141.4	4141.5	4141.6

k=0.62±0.02

Φ_{eq}

$\frac{\delta\Phi_{eq}}{\Phi_{eq}} = 7\%$

SYNC	**LIN**	**DIFF**
III **(1.21±0.08)e15**	**I I** **(3.4±0.2)e15**	**I** **(1.05±0.07)e16**
VI **(0.83±0.06)e15**	**V** **(2.2±0.2)e15**	**IV** **(5.8±0.4)e15**

---

[1] https://indico.cern.ch/event/754063/contributions/3222727/attachments/1758726/2852627/slidesHardness_4.pdf

Measured dosimetry for 2^{st} set target fluence: 1E16 n_{eq}/cm^2

- Protons to neutron equivalent fluences hardness factor[1]:
  - **K=0.62±0.02**
- IRRAD measured fluence (in 1 MeV neutron equivalent)

Φ_p

$$\frac{\delta\Phi_p}{\Phi_p} = 7\%$$

4172	10x10	1.14E+16
4170.1	4170.2	4170.3
2.14E+16	1.20E+16	3.50E+15
1.60E+16	9.94E+15	3.40E+15
4170.4	4170.5	4170.6

k=0.62±0.02

$\xrightarrow{\Phi_{eq}}$

$$\frac{\delta\Phi_{eq}}{\Phi_{eq}} = 7\%$$

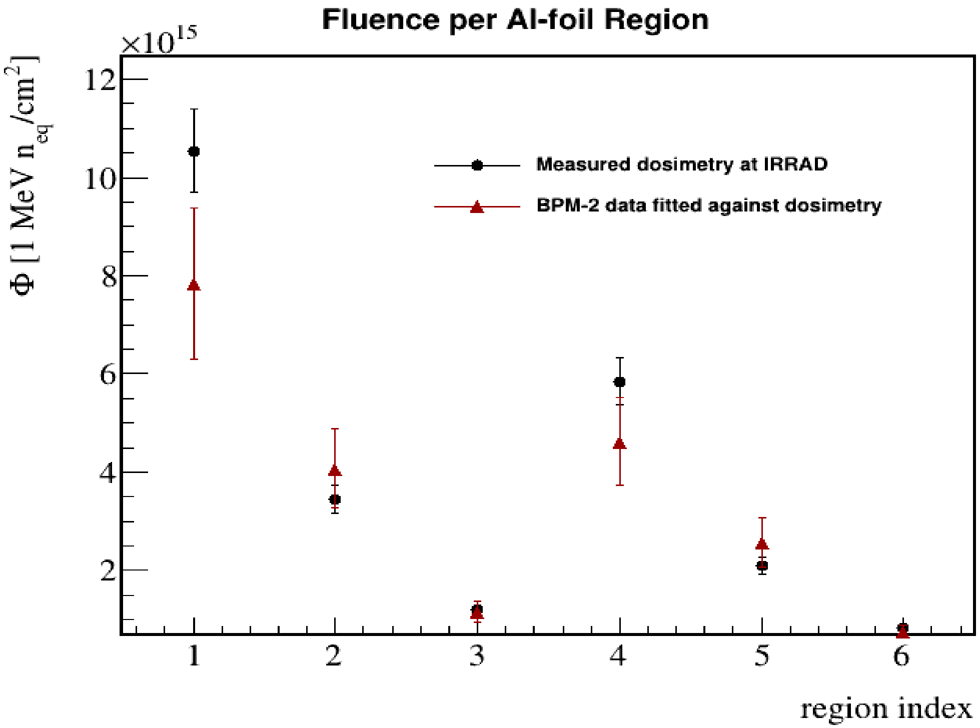
SYNC	**LIN**	**DIFF**
III **(2.2±0.2)e15**	**I I** **(7.4±0.5)e15**	**I** **(1.32±0.09)e16**
VI **(2.1±0.2)e15**	**V** **(6.2±0.4)e15**	**IV** **(9.9±0.7)e15**

---

[1] https://indico.cern.ch/event/754063/contributions/3222727/attachments/1758726/2852627/slidesHardness_4.pdf

Fit 1$^{\text{nd}}$ set

$$\int_{A_i^{Back-Al}} \frac{\lambda_x\lambda_y}{\cos\omega}\alpha\,\Phi^F\left(\frac{\Delta_x}{2}+\frac{\lambda_x}{\cos\omega}(x-x_0),\lambda_y y+r_0\right)\,dx\,dy = \Phi_{\Delta t}^{Back-Al,i}\;A_i^{Back-Al}\,, \qquad i=1,\ldots,6$$



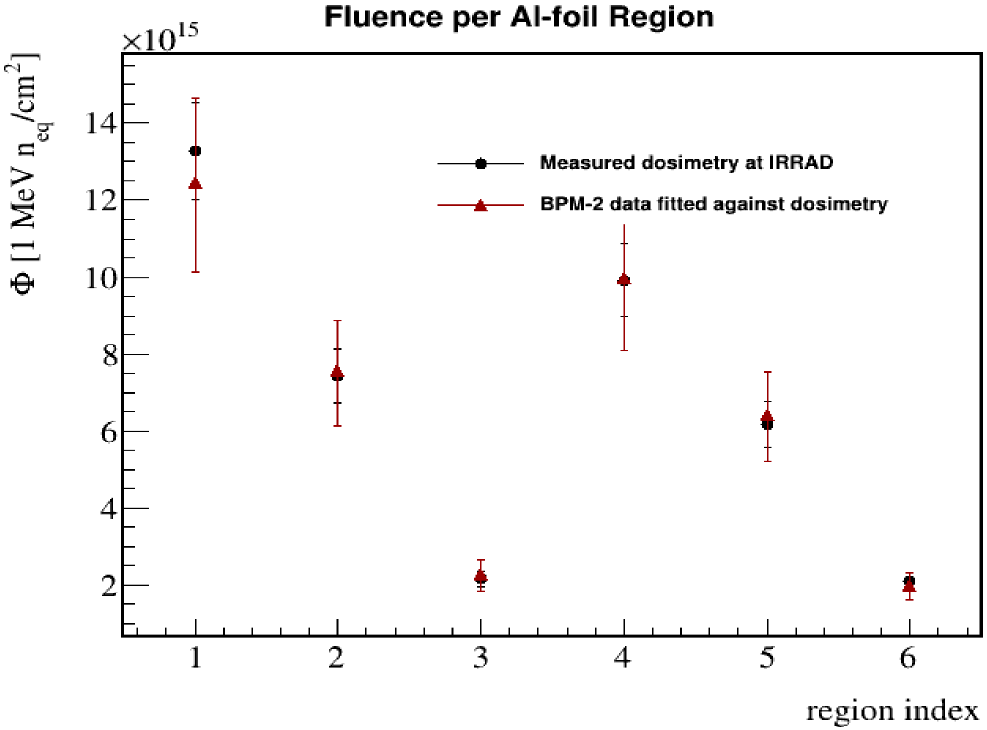
Best fit parameters

$$\begin{aligned} \alpha &= 0.55\,\pm^{0.05}_{0.05}\ \text{deg} \\ \omega &= 56\,\pm^{4}_{4}\ \text{deg} \\ \Delta x_0 &= 5.3\,\pm^{0.4}_{0.3}\ \text{mm} \\ \text{row}_0 &= 326\,\pm^{30}_{30}\ \text{row} \end{aligned}$$

- Angle and initial x-displacement perfectly consistent with visual inspection and previous campaign

Fit 2nd set

$$\int_{A_i^{Back-Al}} \frac{\lambda_x\lambda_y}{\cos\omega}\alpha\,\Phi^F\left(\frac{\Delta_x}{2}+\frac{\lambda_x}{\cos\omega}(x-x_0),\lambda_y y+r_0\right)\,dx\,dy = \Phi_{\Delta t}^{Back-Al,i}\,A_i^{Back-Al}, \qquad i=1,\dots,6$$



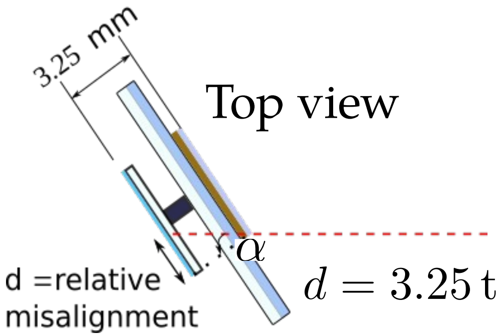
Best fit parameters

$$\begin{aligned} \alpha &= 1.6 \pm^{0.2}_{0.2}\ \text{deg} \\ \omega &= 56 \pm^{4}_{6}\ \text{deg} \\ \Delta x_0 &= 5.3 \pm^{0.4}_{0.4}\ \text{mm} \\ \text{row}_0 &= 260 \pm^{34}_{30}\ \text{row} \end{aligned}$$

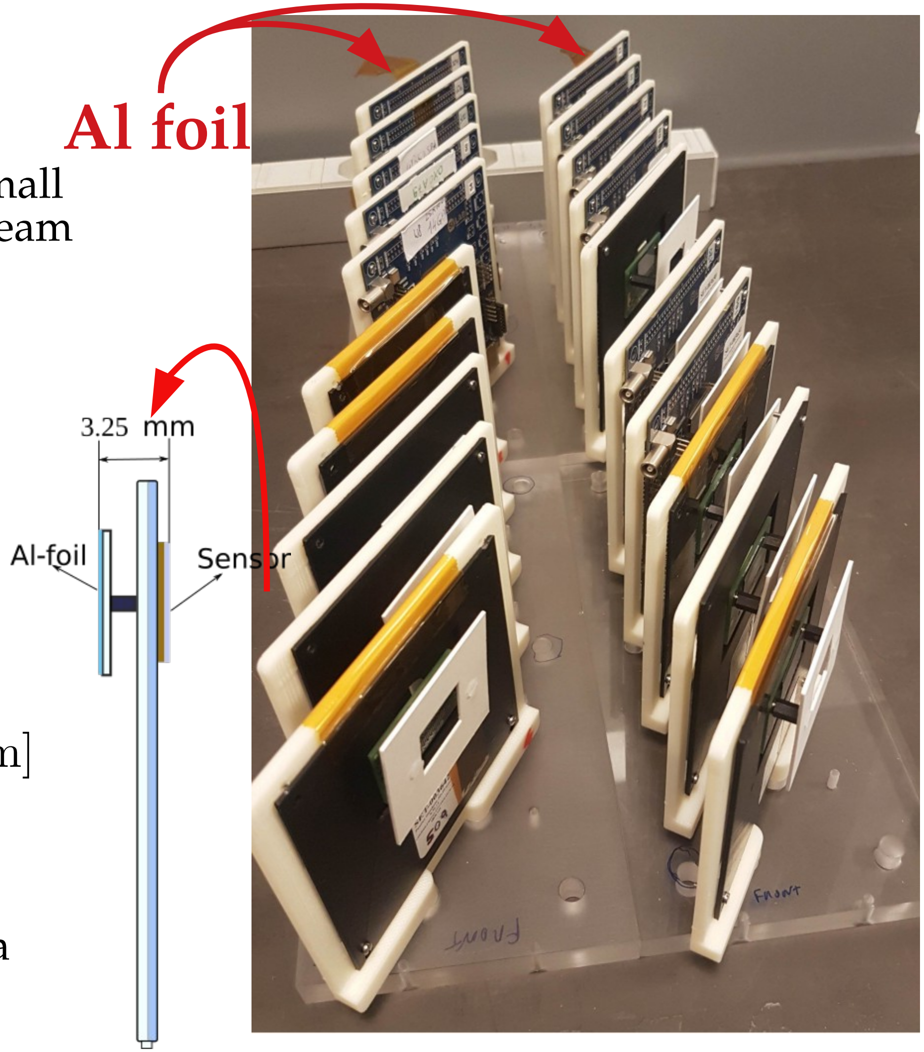
- Angle and initial x-displacement perfectly consistent with visual inspection and previous campaign

Sensor misalignment

- Al foil area: 12x20 mm^2 → Sensor area: 9.6x20 mm2
  - The farther the sensor is from the Al foil, the further the displacement could be, if exists a small misalignment of the table with respect to the beam
  - Distance between Al-foil and sensor estimated to be **3.25 mm**
    - With an angle w.r.t. the beam



$$d = 3.25\tan(\alpha)\ [\mathrm{mm}]$$

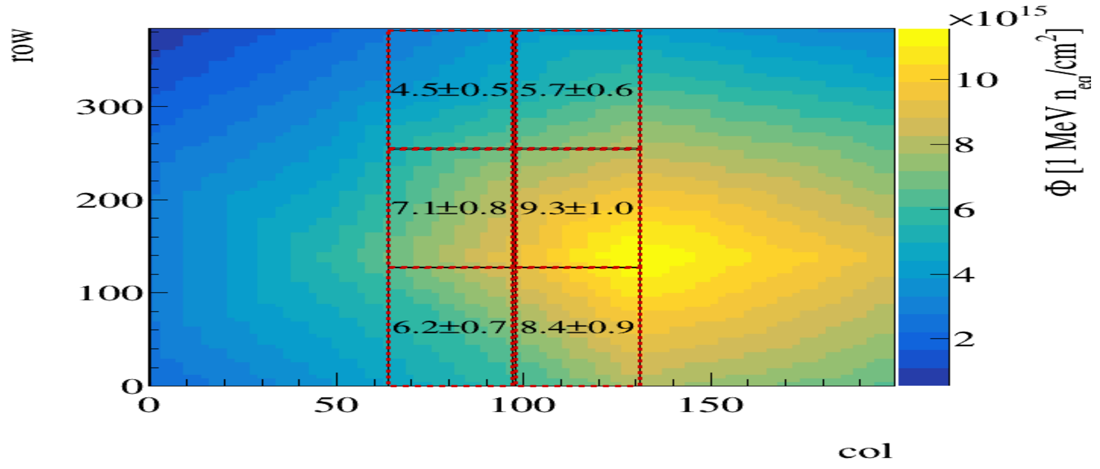


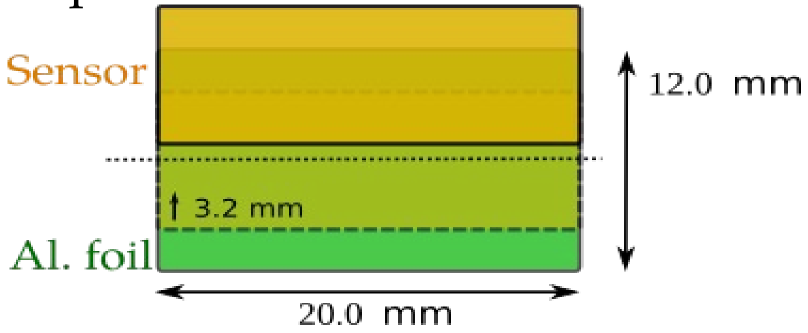
- Using the estimated angle: $56 \pm^{4}_{3}$ deg

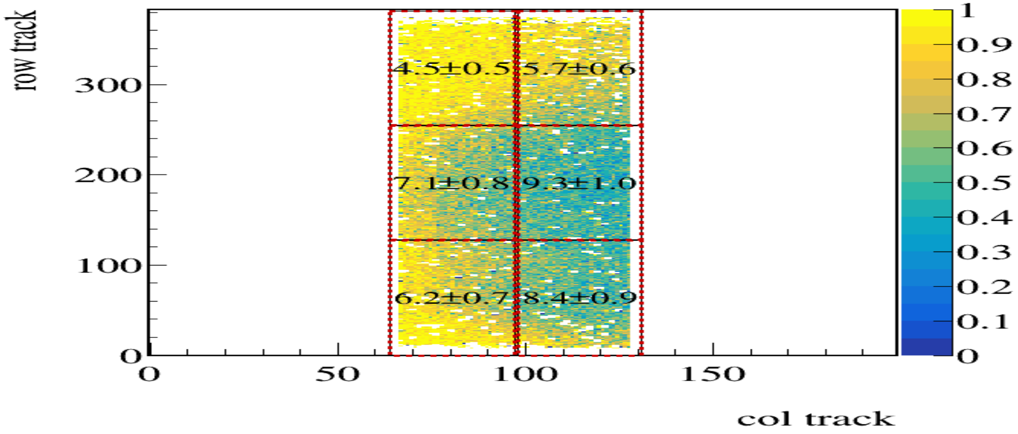
  → $\boxed{d = 4.8 \pm^{0.8}_{0.5}\ \mathrm{mm}}$
- This is "best case" scenario, where no extra misalignment (between supports and beam) has been considered

Sensor misalignment

- Fluence estimation: Take central value as 3.5 mm displacement



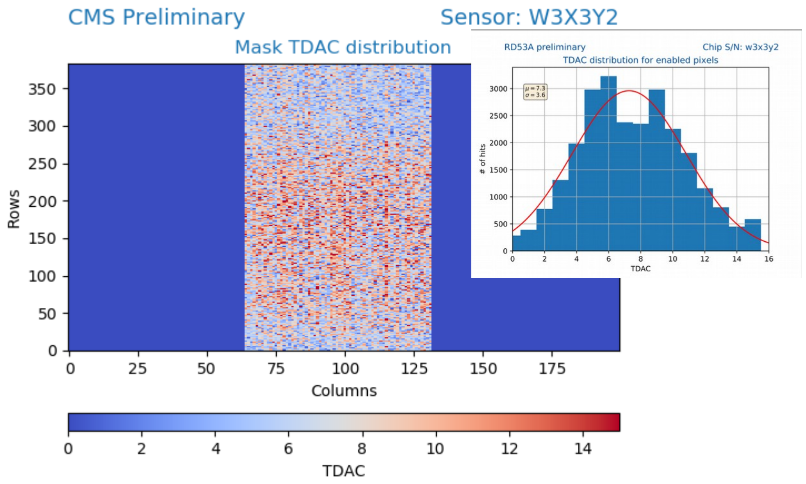




- Fluence estimation perfectly **consistent** with irradiation spot at sensor
- Relative fluences between left-right regions

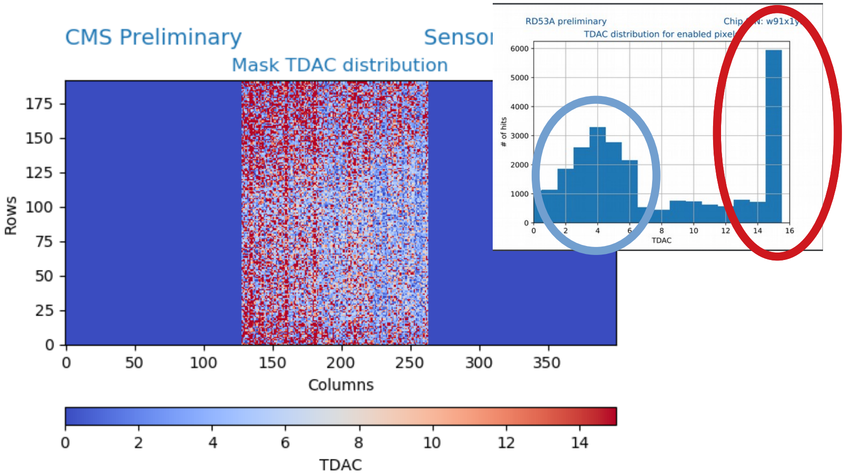
Chip configuration and tuning

W3X3Y2:
FBK 3D 25x100 (1E)



- Tuning worked fine, similar threshold amongst pixels

W91X1Y3
FBK 3D 50x50



- Peak at TDAC =15 (red) and distribution centered at TDAC = 4 (blue)
→ **large threshold dispersion**
→ systematically measuring different ToT, given same charge

$$ToT_{red} < ToT_{blue}$$

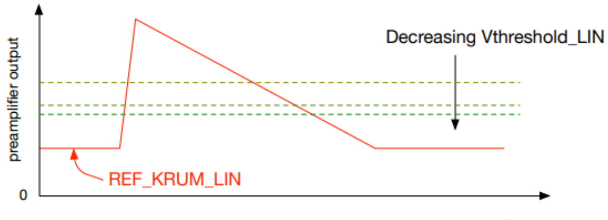


Fig. Extracted from https://twiki.cern.ch/twiki/pub/RD53/RD53ATesting/LIN_AFE_guidelines.pdf