2nd DRD3 Workshop
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Fluence Profiling at JSI TRIGA Reactor Irradiation Facility

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Introduction

- significant differences of gain degradation between LGADS irradiated together in the Ljubljana reactor were observed
- check if differences were caused by non-uniform neutron flux within the irradiation container

  ➔ measurements presented in this talk were made in year 2000

  ➔ preliminary results were shown at the 36th RD50 workshop (online) in June 2020 by V. Sola:
  https://indico.cern.ch/event/918298/contributions/3880586/attachments/2049824/3435546/vs-JSIprofile-36thRD50.pdf

- here we present new data analysis and new simulations
- work was published in **V. Sola et al., NIMA 1063 (2024) 169258** (https://doi.org/10.1016/j.nima.2024.169258)
- information about neutron flux uniformity important for DRD3 community because many samples were (and hopefully will be) irradiated in the reactor in Ljubljana

The Idea

- Use 5x5 pad array LGAD sensor to map fluence dispersion
  [pad size 1.3x1.3 mm^2 - W1 FBK UFSD3 production]

- Measure V_{GL} of each pad when the sensor is NEW and AFTER Irradiation

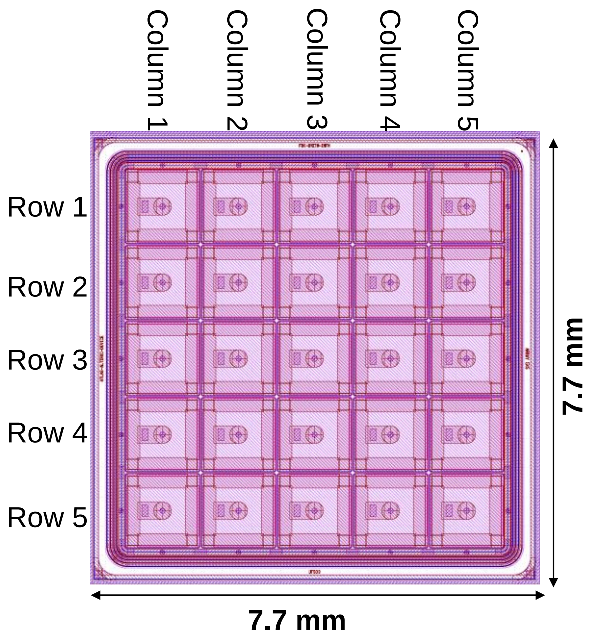
- V_{GL} proportional to acceptor concentration in the gain layer: $V_{GL} \propto N_A$

- $N_A(\Phi) = N_A(0) \cdot e^{-c \cdot \Phi}$ ➔ V_{GL} exponential dependence on fluence

- Measure Ratio = $\frac{V_{GL}(\Phi)}{V_{GL}(0)} = e^{-c\Phi_{eq}}$, to eliminate variations of $V_{GL}(0)$

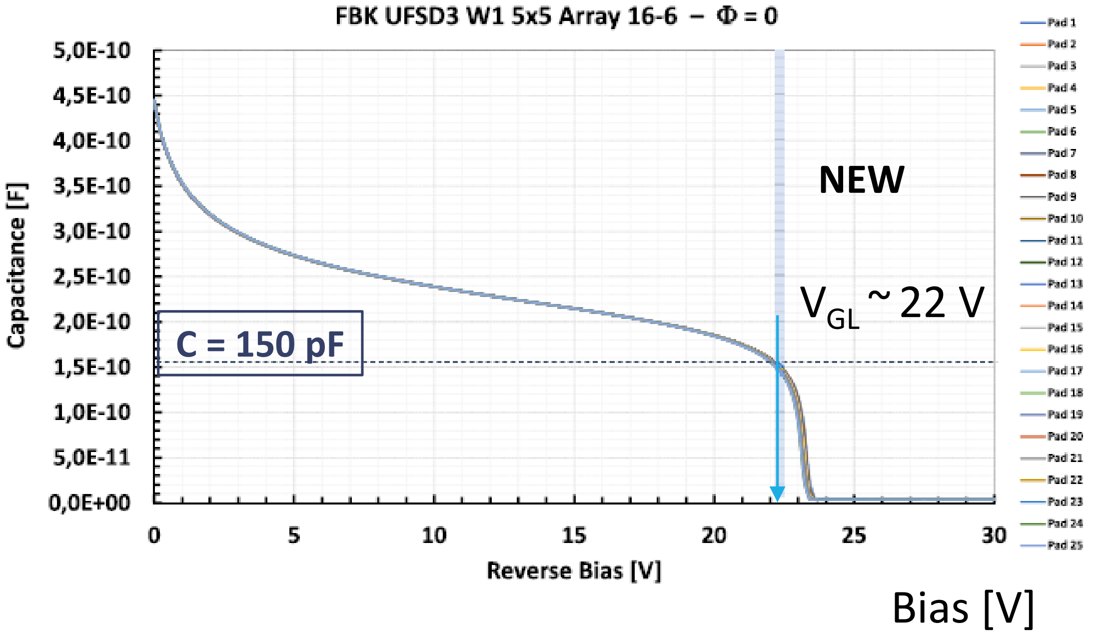
- Parameter ***c* = 3.85 × 10^{-16} cm^2** known for these devices
  - See: M. Ferrero, R. Arcidiacono, M. Mandurrino, V. Sola, N. Cartiglia, *An Introduction to Ultra-Fast Silicon Detectors*, CRC Press, 2021, http://dx.doi.org/10.1201/9781003131946

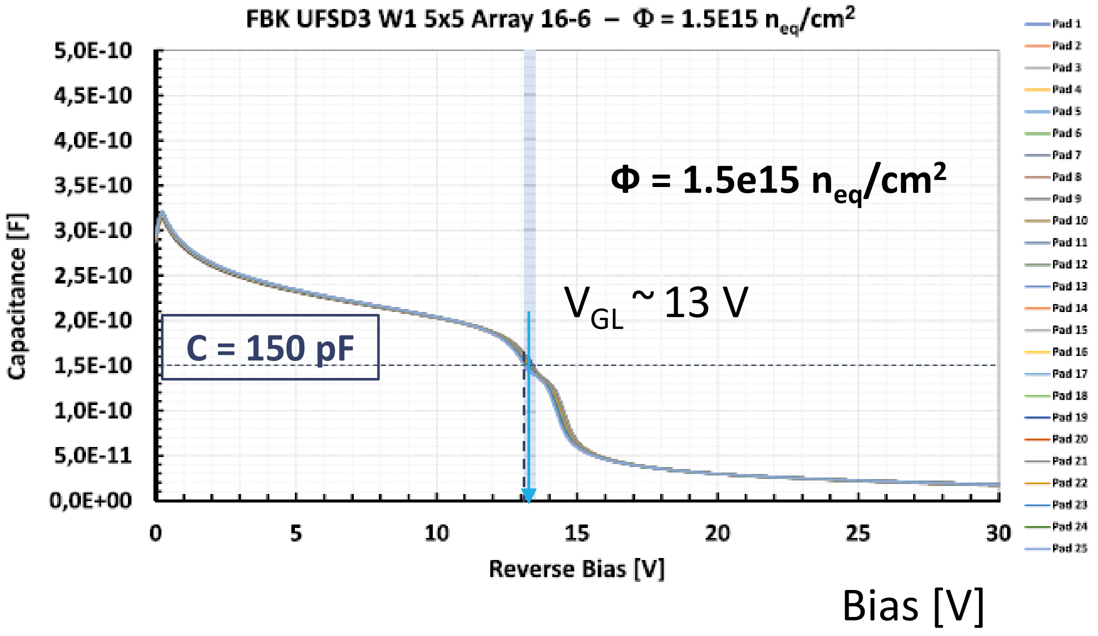
- $\boldsymbol{\Phi_{eq}}$ can be estimated from the change of $\mathbf{V_{GL}}$
- pad size 1.3x1.3 mm^2 → good spatial resolution



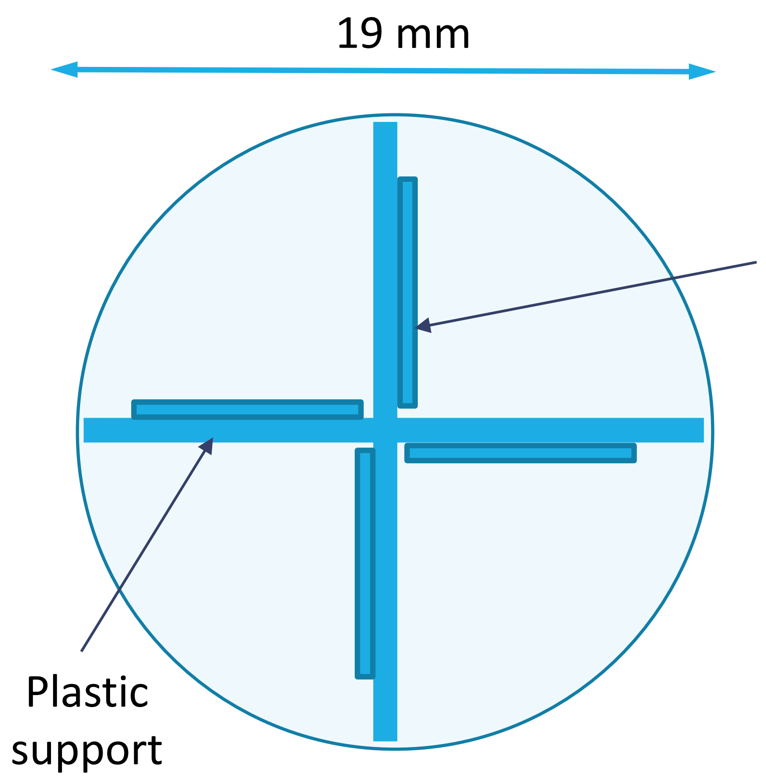
The Idea

- V_{GL} defined as voltage at C = 150 pF
- V_{GL} can be measured with a precision of ± 0.1V

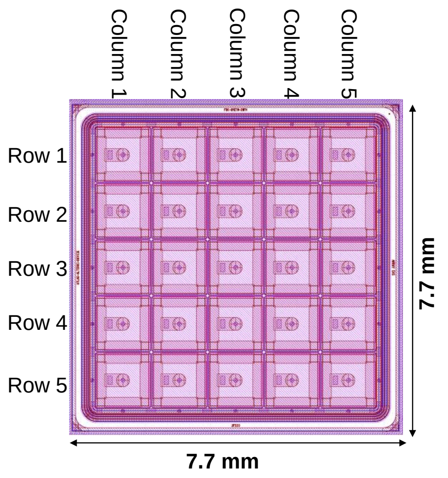




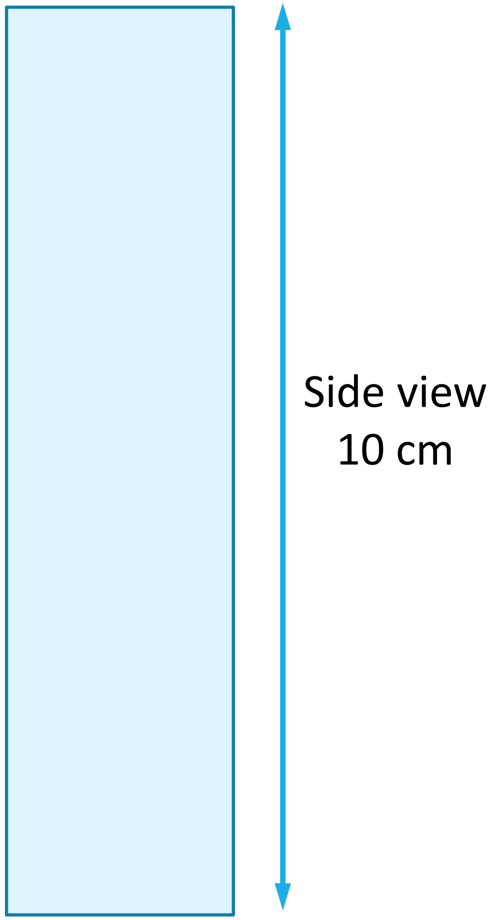
Irradiation Strategy - The Assembly

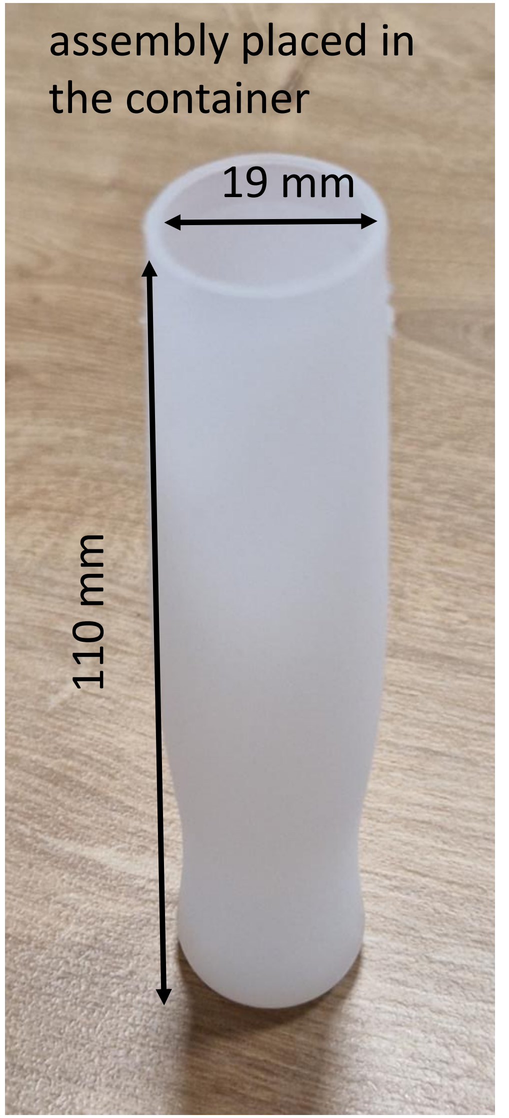


Irradiation container, top view



Sensor

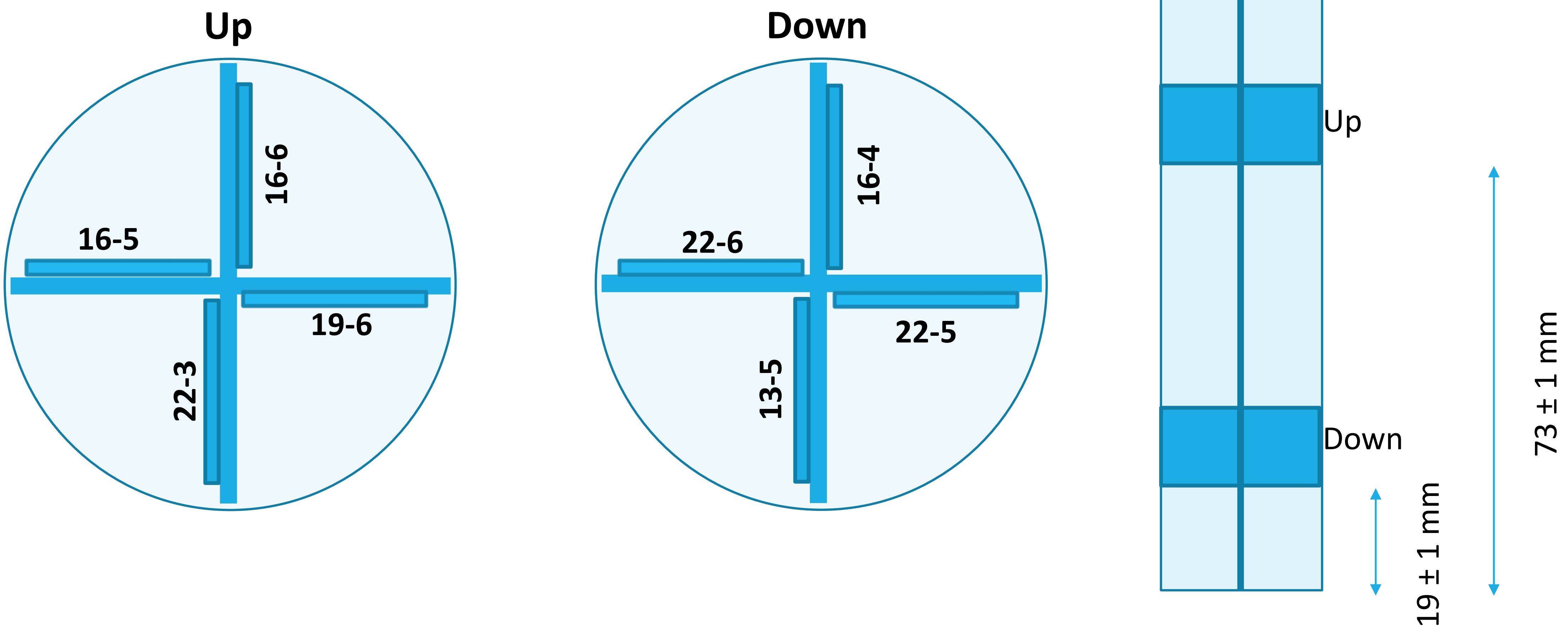




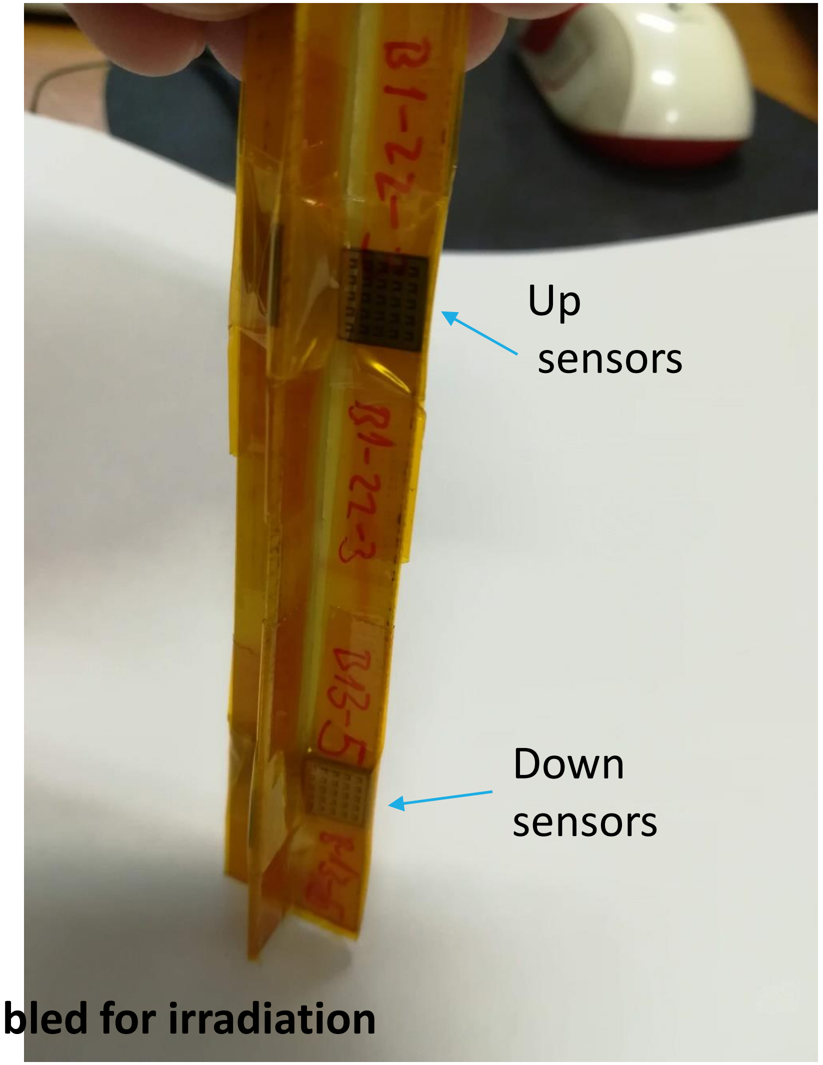
Container is in vertical position during irradiation, parallel to fuel rods

Irradiation Strategy - Sensor Placement

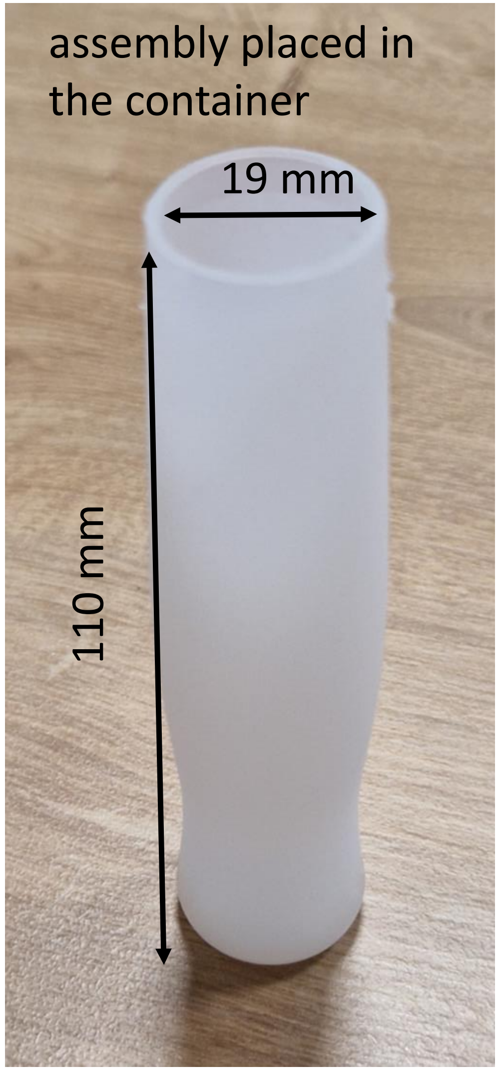
- 8 devices irradiated: 4 at Up position and 4 at Down



Irradiation Strategy - Support Structure



Samples assembled for irradiation



Container gets into the core through a tube and it is in vertical position during irradiation, parallel with fuel rods

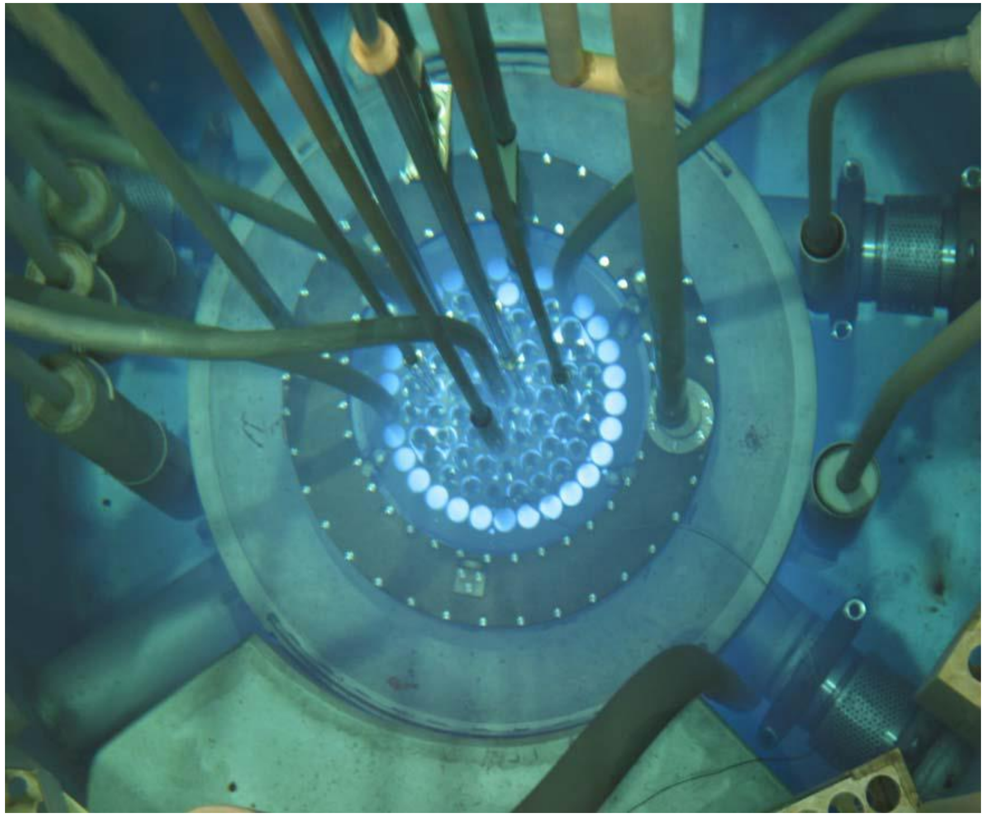
Our samples were irradiated in channel F19 at full reactor power for 926 seconds, target fluence: Φ_{eq} = 1.5e15 n_{eq}/cm^2

Rotation of the irradiation container around the axis of the cylinder is **not controlled**

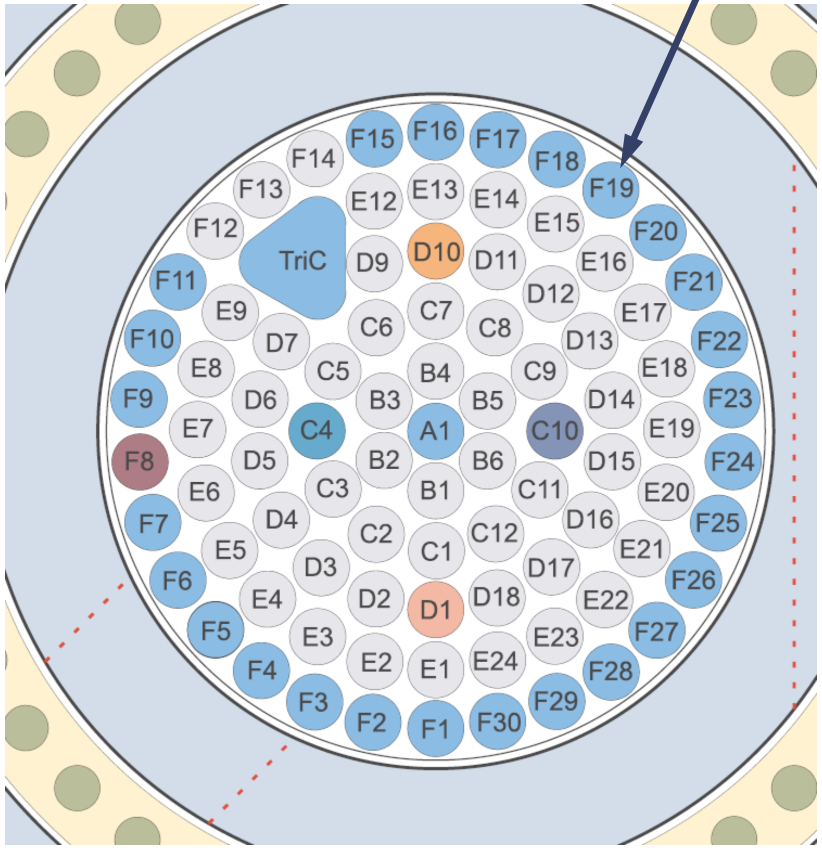
→ We don't know the rotation angle during irradiation

More detail of the reactor in e.g.: [L. Snoj et al.,doi: 10.1016/j.apradiso.2011.11.042]

Photo of reactor core when reactor is on power (photo taken through 5 m of water from the platform)

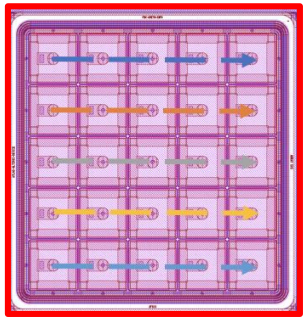


Location of irradiation channel



V_{FD} ratio on W1 16-6 at Φ= 1.5E15 n_{eq}/cm^2

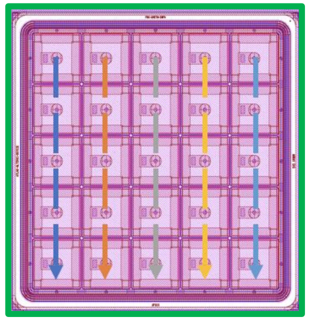
Horizontal uniformity

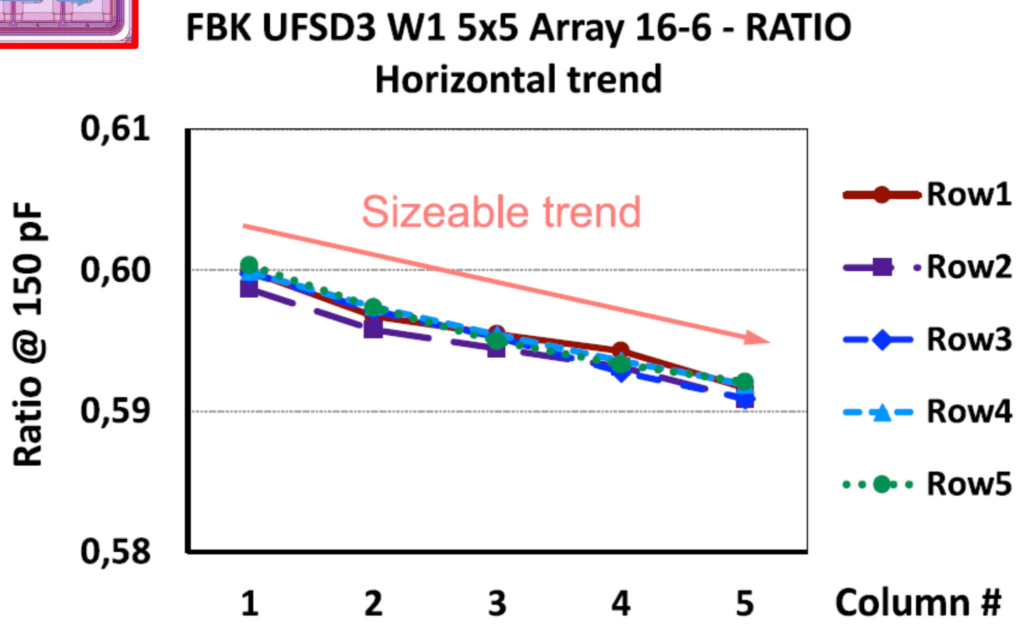


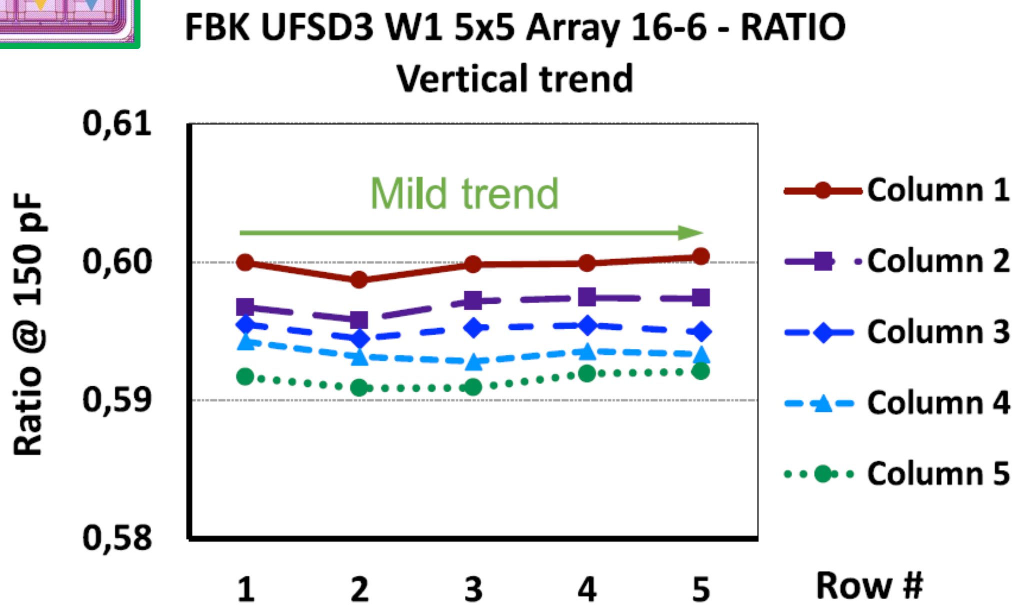
$$\text{Ratio} = \frac{V_{GL}(\Phi = 1.5E15)}{V_{GL}\ (\Phi = 0)}$$

Error on each data point = 0.9%

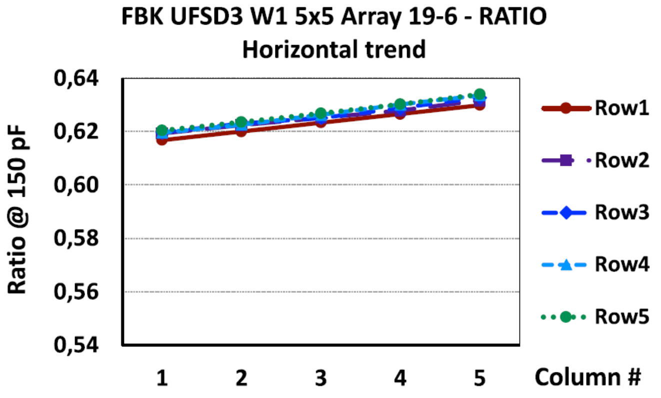
Vertical uniformity



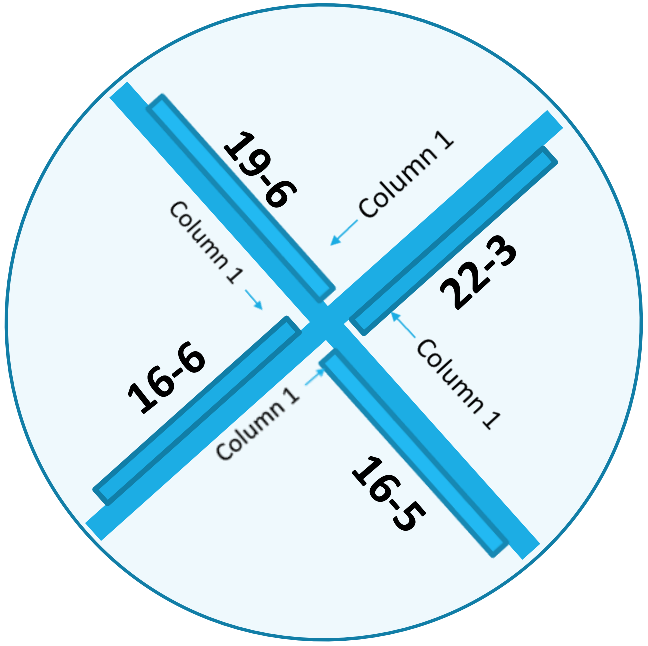


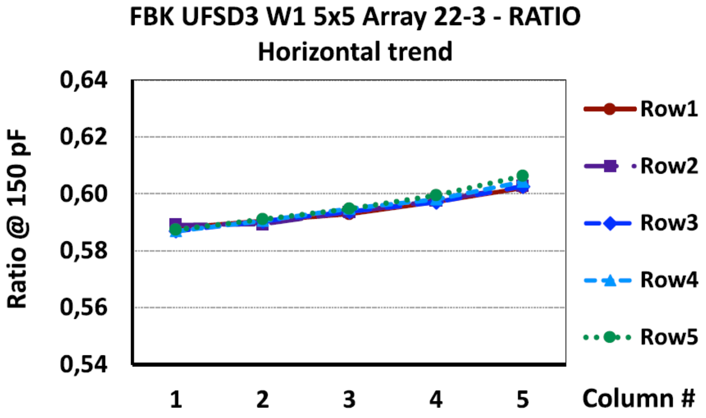


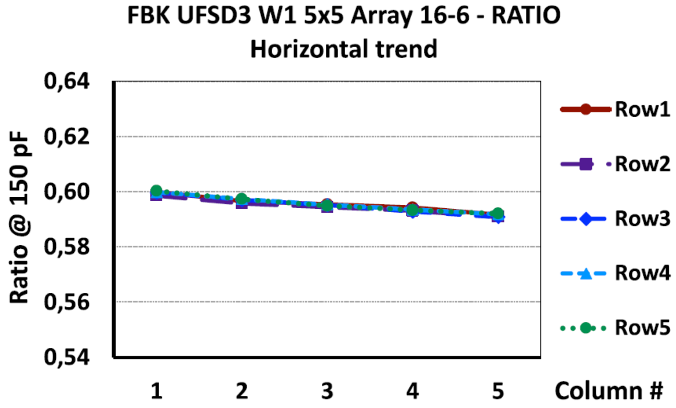
Horizontal Trend – Up sensors

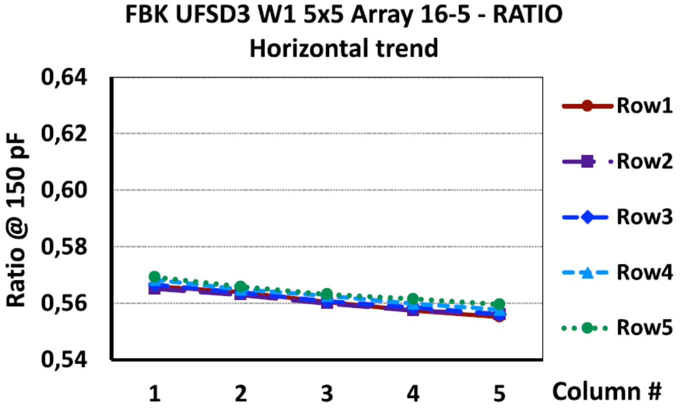


$$\text{Ratio} = \frac{V_{GL}(\Phi = 1.5E15)}{V_{GL}\ (\Phi = 0)}$$



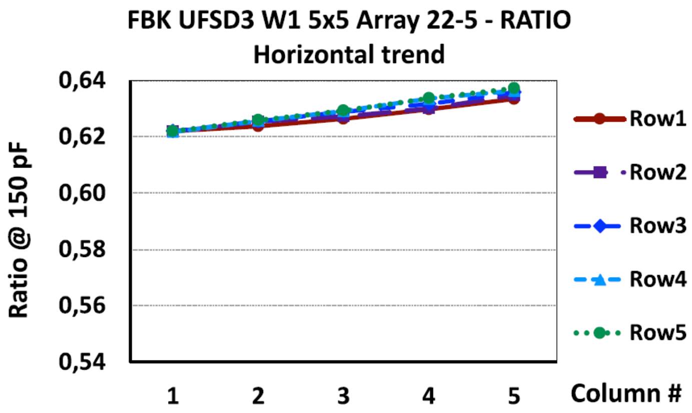






Error on each data point = 0.9%

Horizontal Trend – Down sensors



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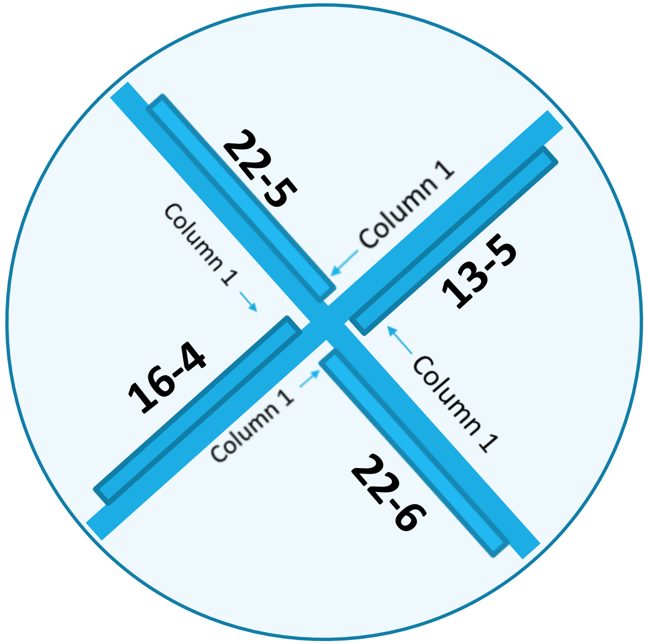
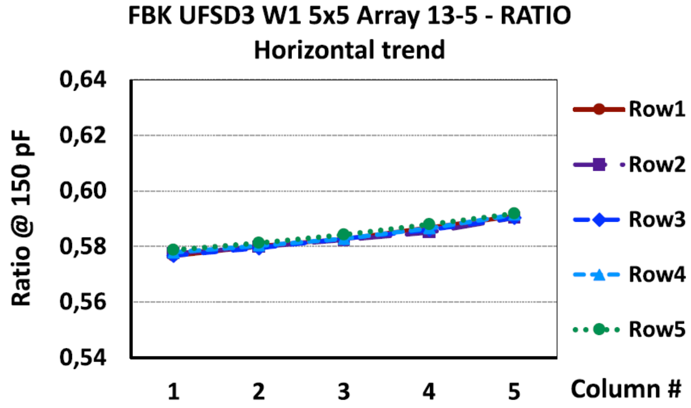
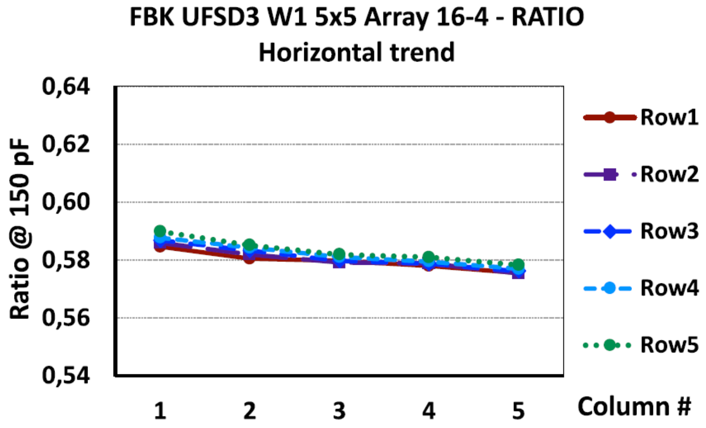
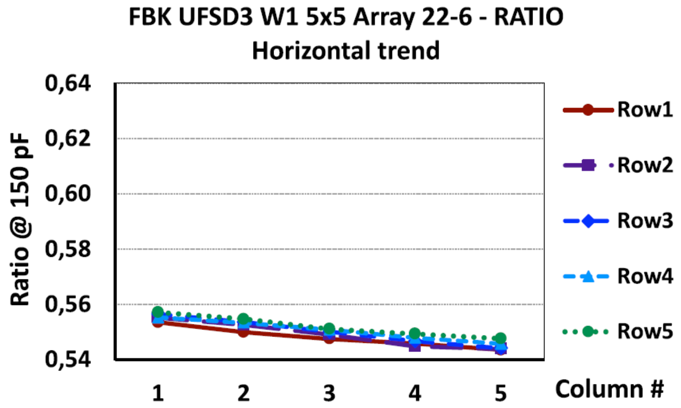




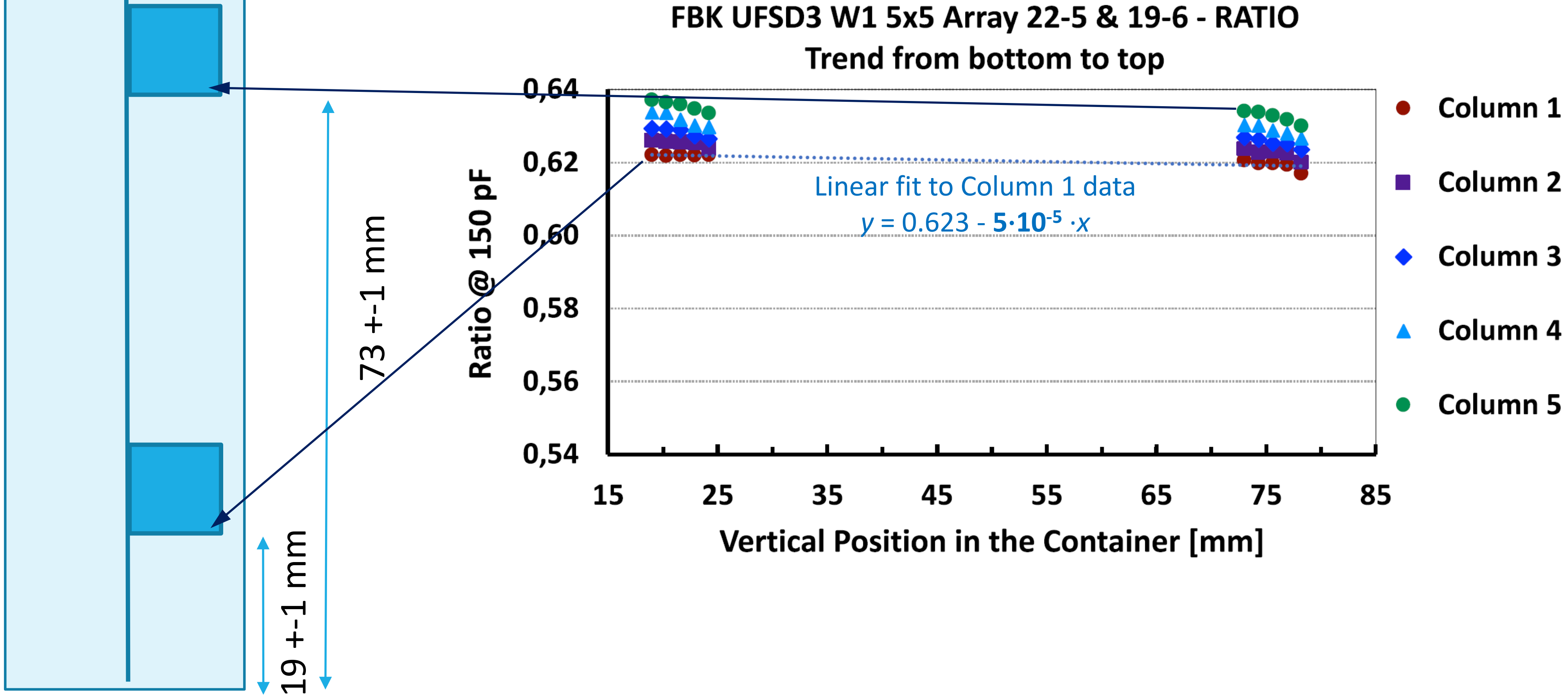




Error on each data point = 0.9%

Vertical Trend

Minor vertical trend observed

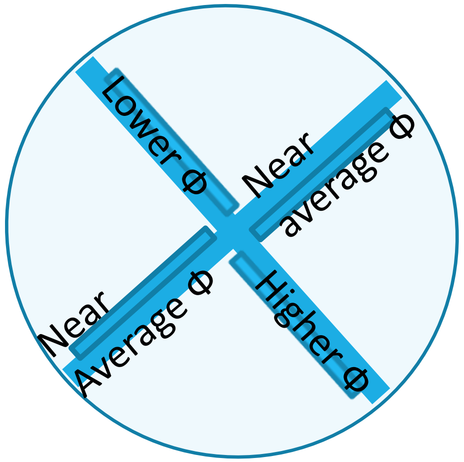


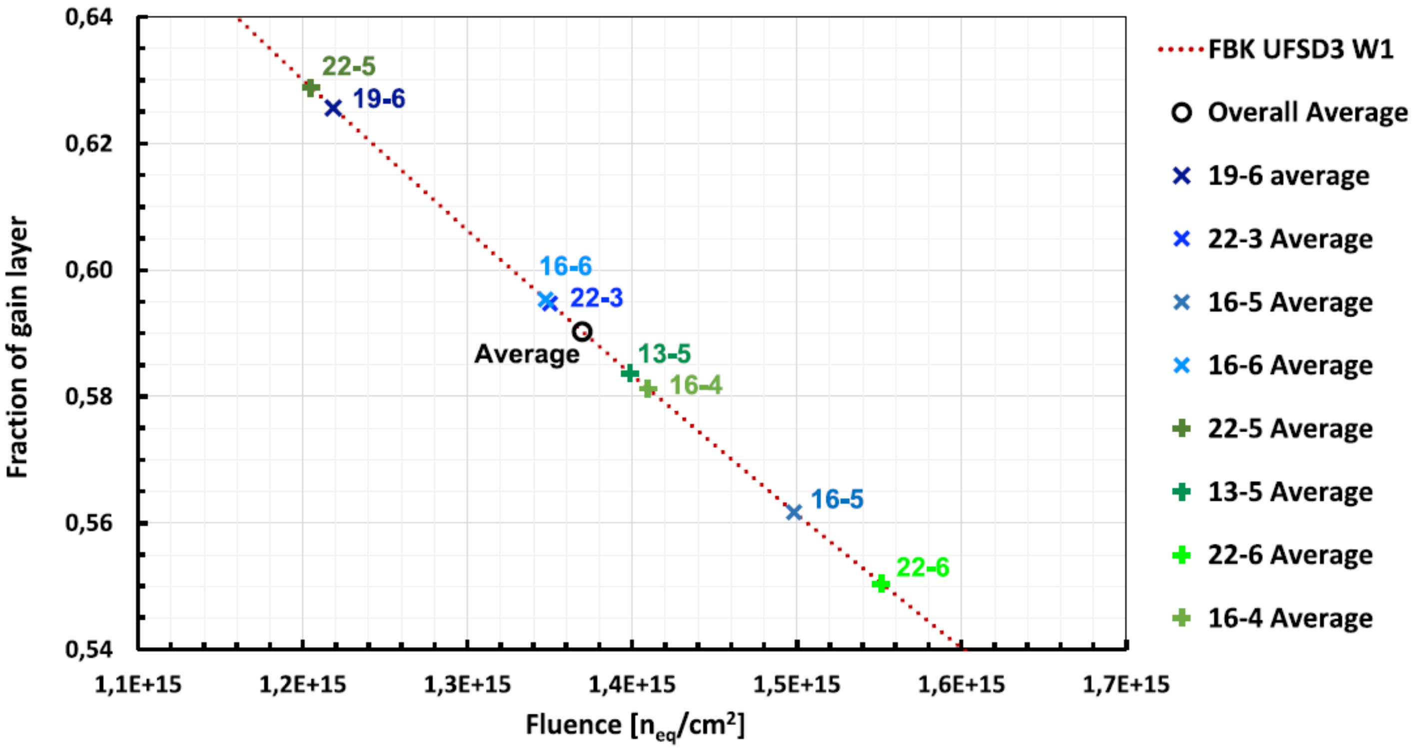
Average V_{GL} per Sensor Converted into Fluence

$$\frac{N(\Phi)}{N(0)} = e^{-3{,}85E-16\cdot\Phi}$$

Using parametrisation from [M.Ferrero et al, doi:10.1016/j.nima.2018.11.121]

- Average V_{GL} ratio over 25 pixels of each sensor
- Fluences within -11% to +13% from the average value
- Consistent with **ΔΦ ~ ± 10%** usually quoted for reactor fluence accuracy





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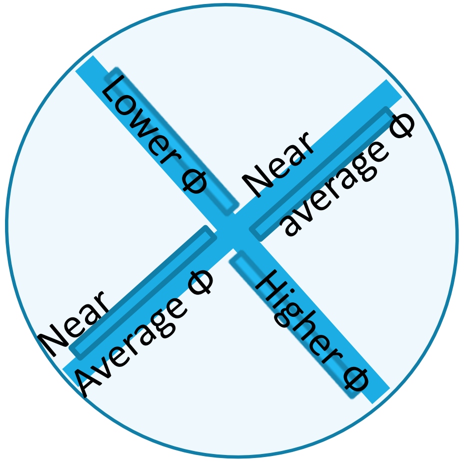
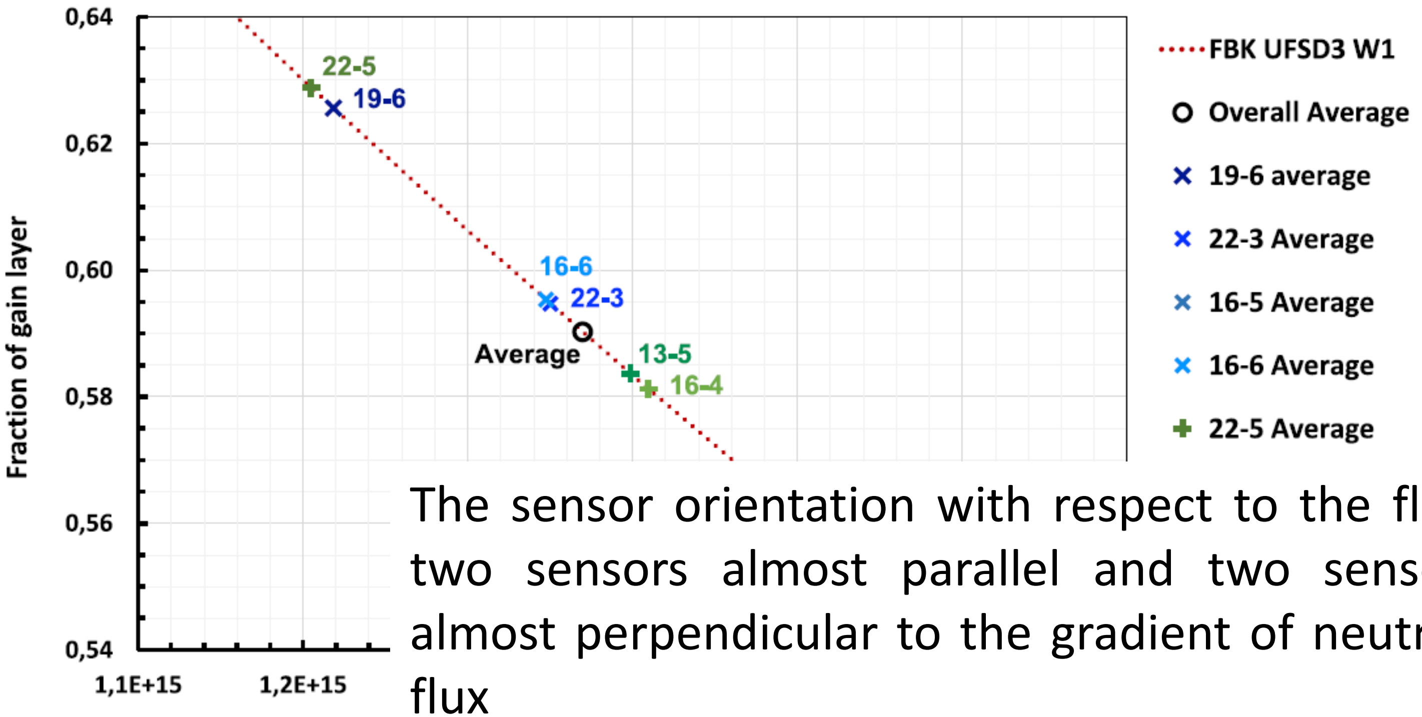




The sensor orientation with respect to the flux: two sensors almost parallel and two sensors almost perpendicular to the gradient of neutron flux

→ **We were lucky to probe the maximal fluence variation within the container volume**

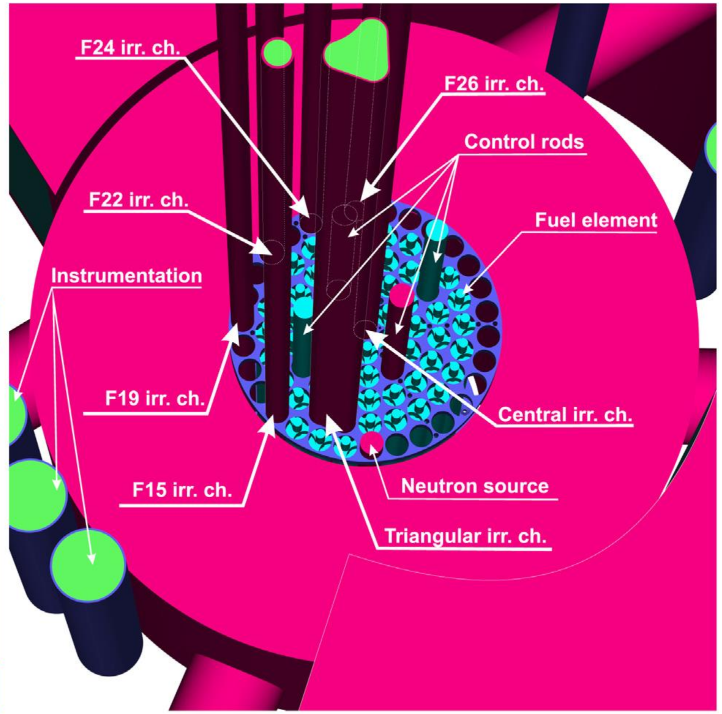
Neutron Flux Simulation in F19 Volume

- Calculations are made using Monte Carlo MCNP v 6.1 software and ENDF/B-VII.0 nuclear data libraries

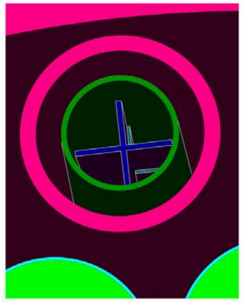
  For more details see [K. Ambrožič et al., doi: 10.1016/j.apradiso.2017.09.022]

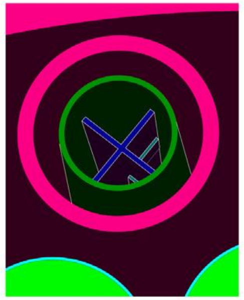
- Calculated flux of fast neutrons (E_n > 100 keV) in the F19 irradiation channel
- Irradiation assembly (sensors, support structure, container) included in the simulation
- Calculations made on a mesh of 2x2x2 mm³
- Two orientations of sensors in the channel simulated
- Flux calculated with and without sample in the tube
  → insertion of the sample changes the flux by ~ 10%

Reactor model in the simulation



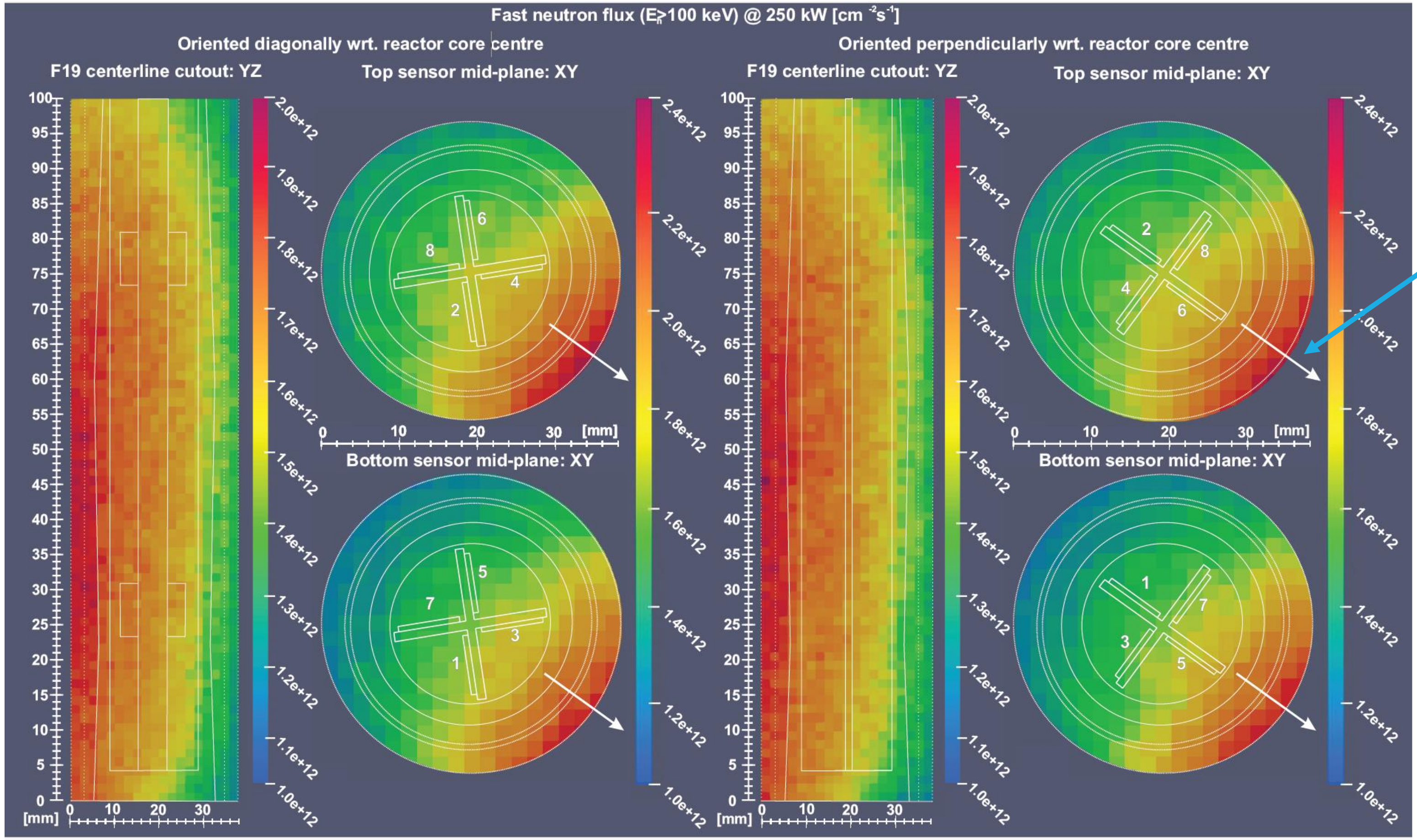
Assemblies in the irradiation tube F19 → two orientations





Flux Simulation in F19 Volume

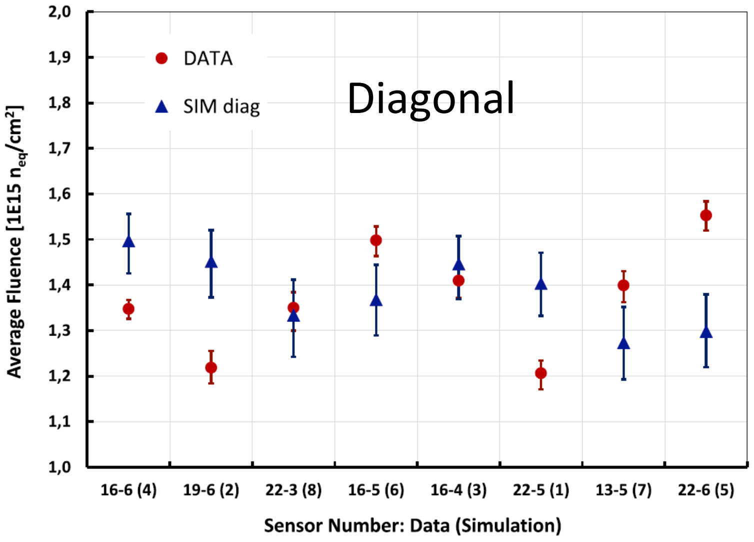
- flux of fast neutrons in F19 calculated for two orientations of irradiation container
- flux increases towards the centre of the reactor core (because of the proximity of fuel element)
- variation of flux in z (height) direction within the container smaller

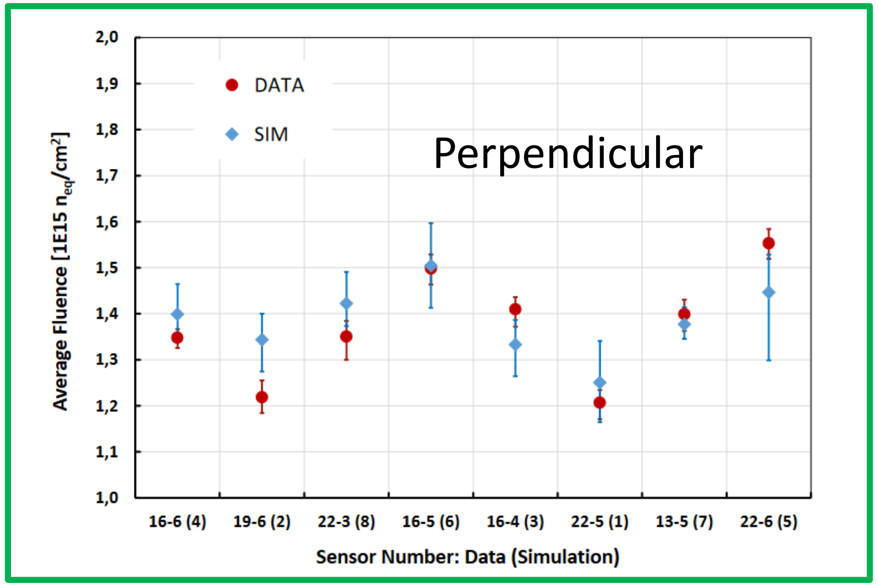


The arrow points to the centre of the reactor core

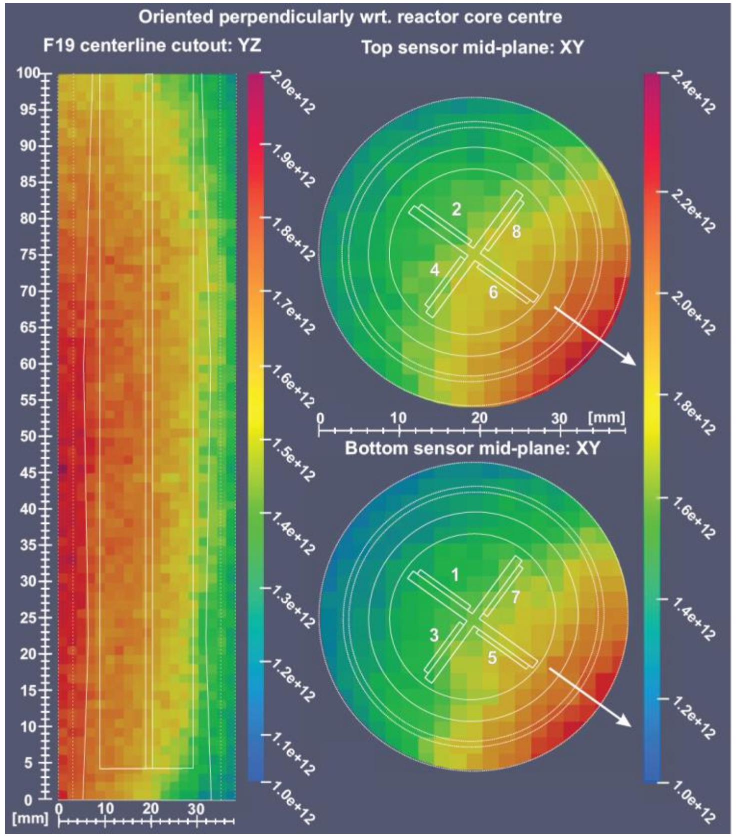
Compare measurements with simulation

- better agreement of measured values with simulation in perpendicular orientation
- confirms that samples were close to perpendicular orientation during irradiation





Better agreement!

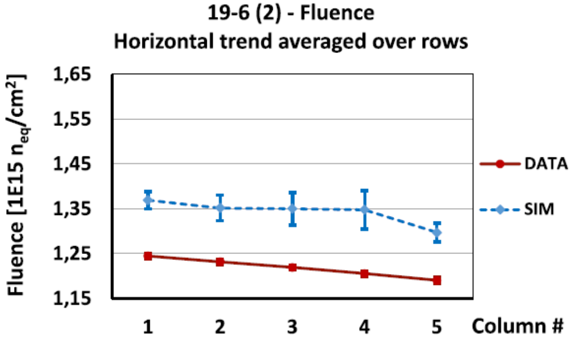


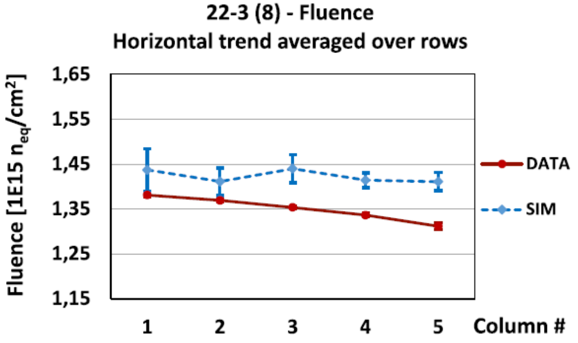
Simulation in perpendicular orientation

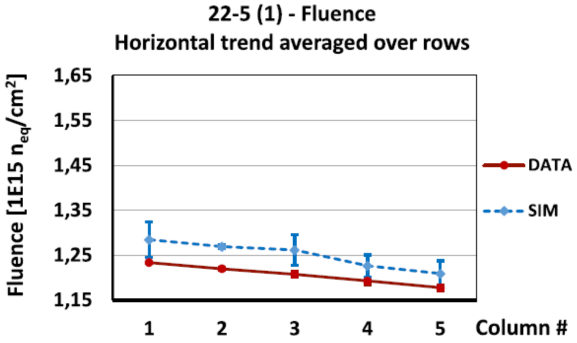
Comparison within sensor

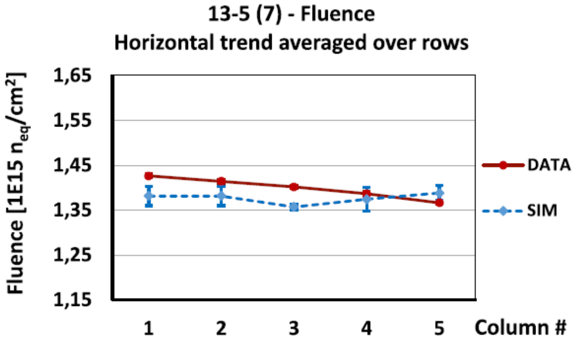
- agreement with simulation also for individual pixels within sensor
- distance between points only 1.3 mm!
- maximal fluence deviation from the average measured by individual pixels −14.7% to +15.4%

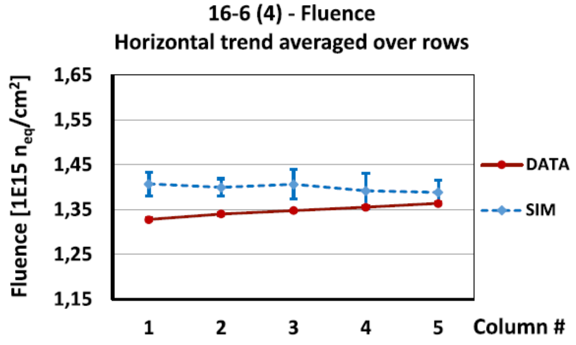
- LGAD arrays are excellent tool for monitoring of neutron flux with high spatial resolution!

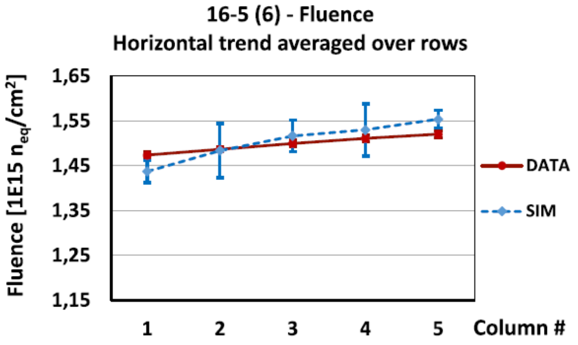


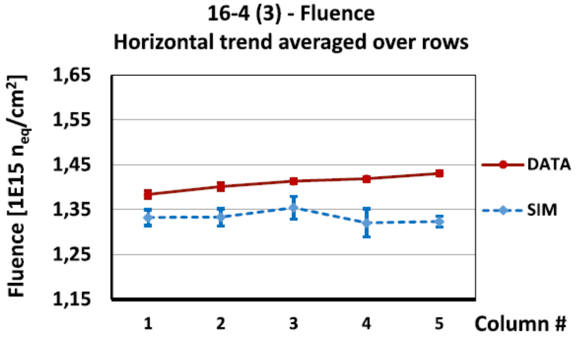


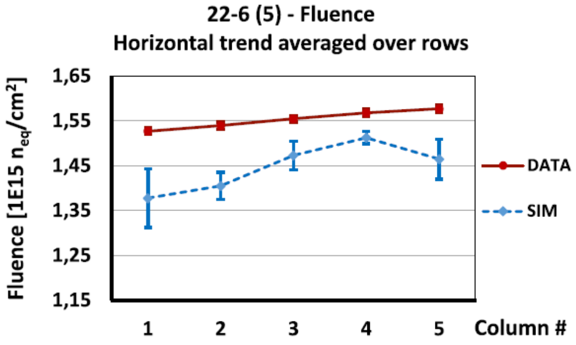












Summary

- LGAD arrays demonstrated to be very a precise tool to map fluence profile at the JSI TRIGA neutron reactor irradiation facility
- The variation of the fluence delivered to the sample is larger in radial than in azimuthal or vertical directions within the irradiation channel F19
- Fluences per sensor inside irradiation container within **$\Delta\Phi \sim \pm 10\%$**
- The maximal difference between individual pixels $^{+15.4\%}_{-14.7\%}$
- Monte Carlo based flux calculation confirms data observation
- For more detail please read:
  V. Sola et al. *Fluence profiling at JSI TRIGA reactor irradiation facility* ,
  NIMA 1063 (2024) 169258 (https://doi.org/10.1016/j.nima.2024.169258)

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- Gian Franco Dalla Betta, Lucio Pancheri, Maurizio Boscardin, Giovanni Paternoster and the FBK SD group for designing and producing the tested sensors
- Nicolò Cartiglia, Roberta Arcidiacono and the whole UFSD Torino group for providing the LGAD sensors and for the continuous and fruitful discussion and support
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- the JSI TRIGA reactor group for irradiation