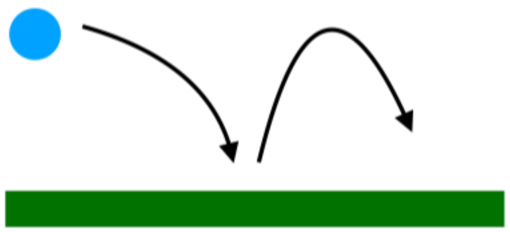
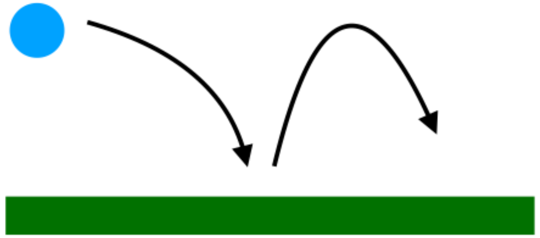
UCN Detection using CLICPix2/Timepix3

Ultra-Cold Neutron experiments

- Ultra-Cold Neutron (UCN) are neutron with a kinetic energy reduced to ~ peV-neV range. Their speed is therefore in the classical range.
- Cold Neutrons can be channeled using mechanical collimator and slits made with special material that reflect the neutrons.
- System where the UCN couple to gravity can be build using such apparatus i.e. : Bouncing neutrons
- Bouncing neutrons can be an interesting way to study coupling with gravity in a quantum system



G. Ichikawa, S. Komamiya, YK *et al.*,
PRL 112, 071101 (2014)



Schrodinger equation for UCNs under the gravity

$$\{-\frac{\hbar^2}{2m}\frac{\mathrm{d}^2}{\mathrm{d}z^2} + V(z)\}\psi_n(z) = E_n\psi_n(z)$$

neutron mass

where $V(z) = \begin{cases} mgz, & z \geq 0 \\ \infty, & z \leq 0 \end{cases}$

Dimensionless equation is written as a function of $\xi_n \equiv z/z_0 - E_n/E_0$

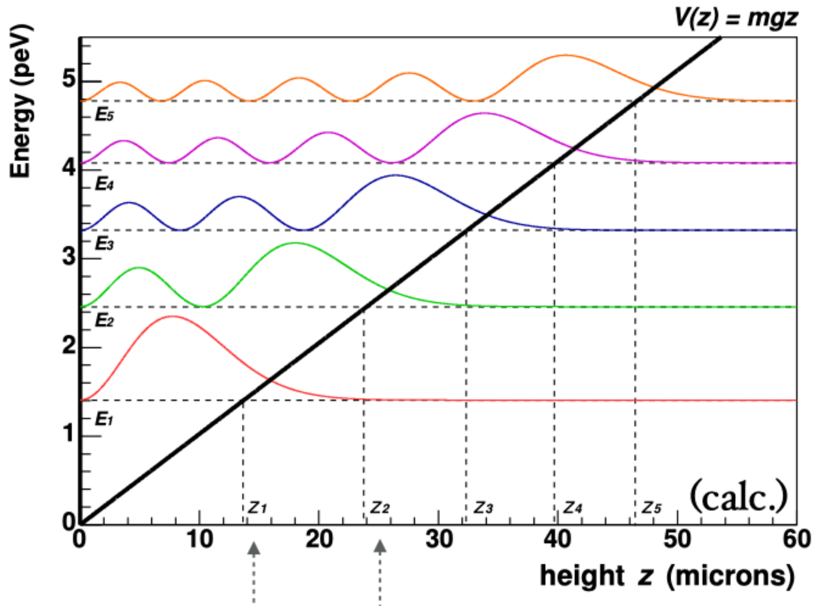
$$(\frac{\mathrm{d}^2}{\mathrm{d}\xi_n^2} - \xi_n)\psi_n(\xi_n) = 0$$

where the system's scales,

$$z_0 = (\frac{\hbar^2}{2m^2 g})^{1/3} \sim 6\ \mu\mathrm{m}$$

$$E_0 = (\frac{mg^2\hbar^2}{2})^{1/3} \sim 0.6\ \mathrm{peV}$$

Classical turning points
$z_n \equiv z_0 E_n/E_0 \quad (\xi_n = 0)$



The measured quantum modulations

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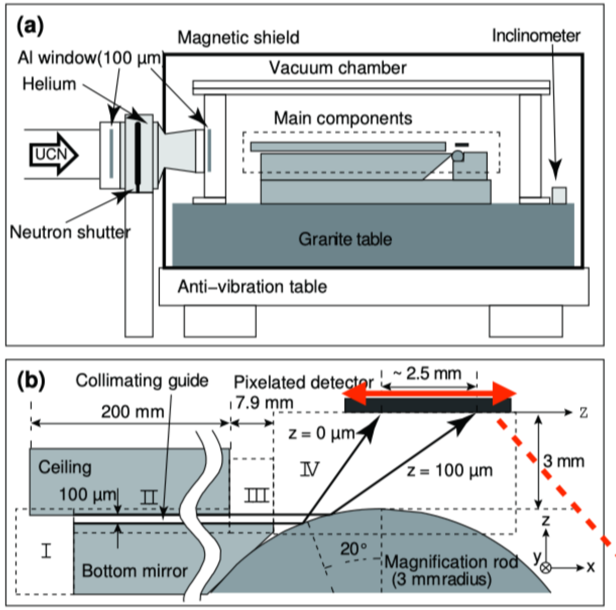


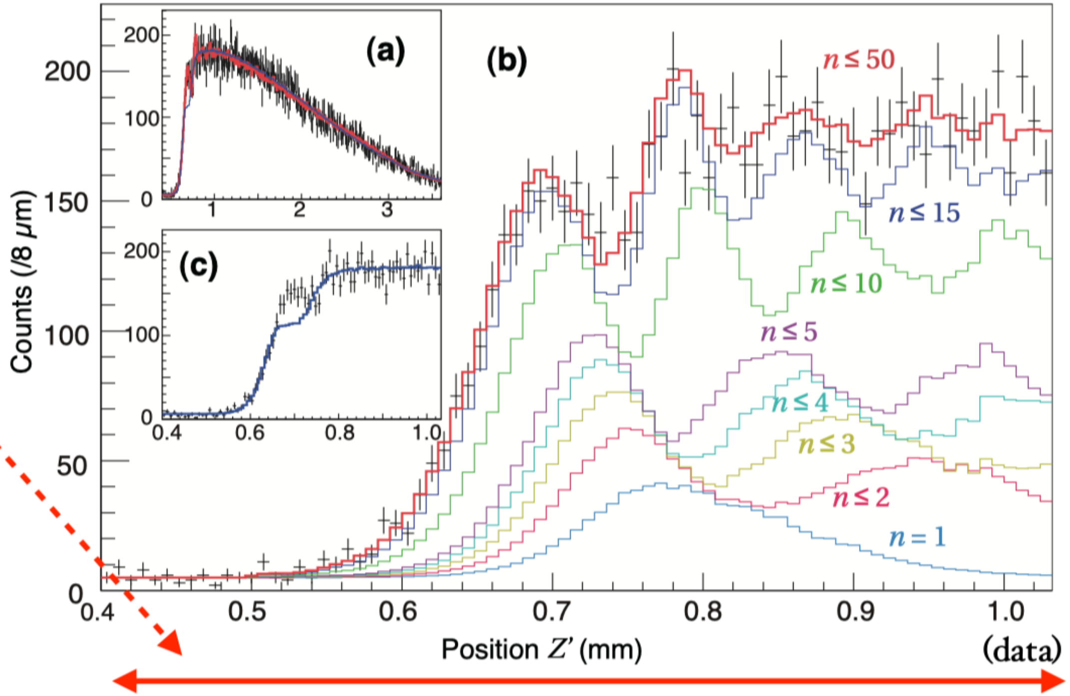
(a) expectations from quantum mechanics

(b) expectations from quantum mechanics (zoomed in)

(c) expectations from classical mechanics

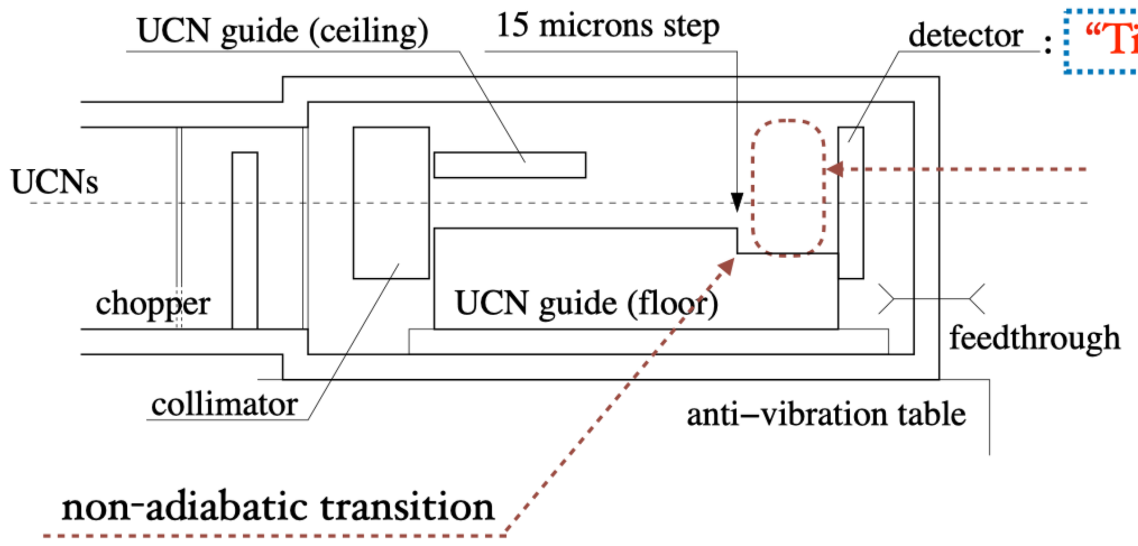
consistent with quantum mechanics $\chi^2/\mathrm{NDF} = 0.96$

Crosses : data / Histograms : model fittings



Now we have got a quantum system which couples to gravity!!

Proposed experiment



== Key Technology ==

detector : "Time-resolving imaging detector"

- length scale is measured by seeing spacial distribution of neutrons directly.
- energy scale is evaluated by measuring oscillation frequencies between the states

The step rotate the basis of the Hilbert space in this quantum system.

$$\psi_{(z,t=0)} = a_1\phi_{1(z)} + a_2\phi_{2(z)}$$

energy scale

$$|\psi_{(z,t)}|^2 = |\psi_{(z,t=0)}|^2 - 4a_1a_2\phi_{1(z)}\phi_{2(z)}\sin^2\frac{(\varepsilon_2-\varepsilon_1)}{2}t$$

oscillating term

G. Ichakawa

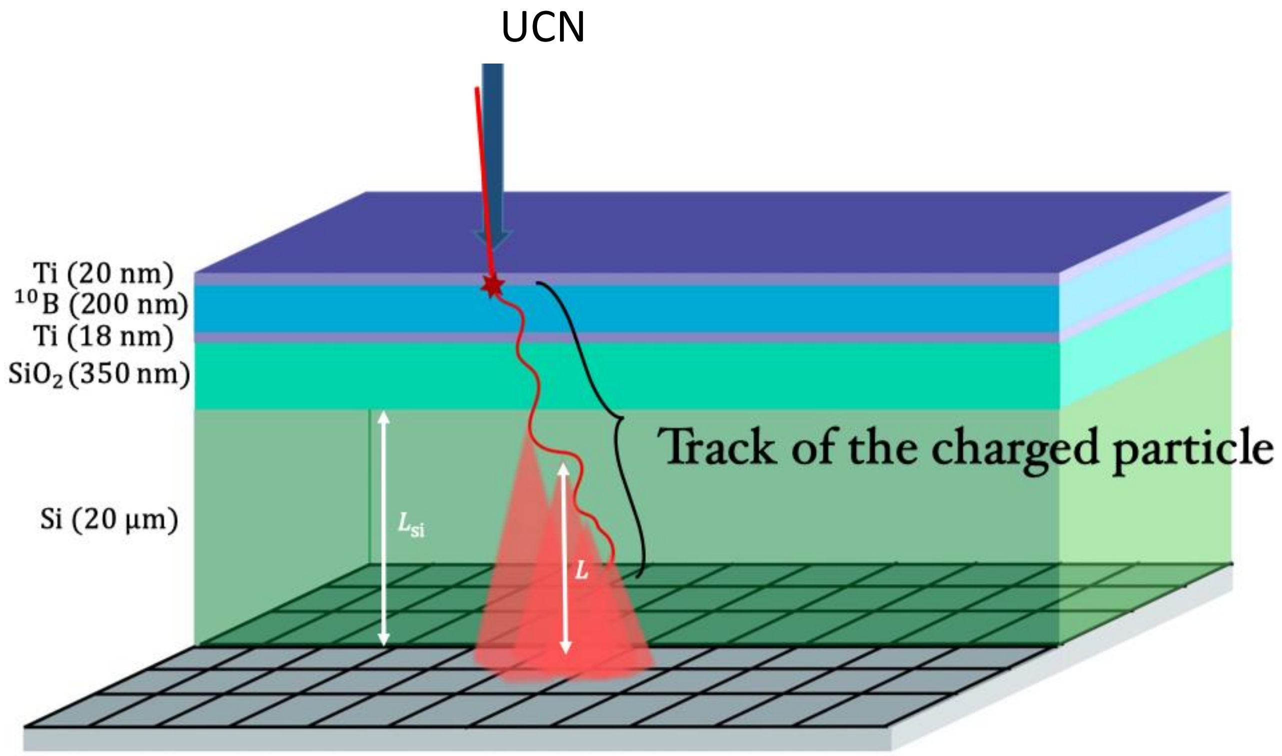
Detector system

- Neutrons are detected using a pixelated detector coated with a conversion materials , Boron10
- Neutron position is determined from the decay product detected position

Gamma background

$$n + {}^{10}\mathrm{B} \rightarrow \begin{cases} \alpha(1.47\,\mathrm{MeV}) + {}^{7}\mathrm{Li}^{*}(0.84\,\mathrm{MeV}) & (93.9\,\%) \\ \quad \hookrightarrow {}^{7}\mathrm{Li}(0.84\,\mathrm{MeV}) + \gamma(0.48\,\mathrm{MeV}) & \\ \alpha(1.78\,\mathrm{MeV}) + {}^{7}\mathrm{Li}(1.01\,\mathrm{MeV}) & (6.1\,\%) \end{cases}$$

Double-sided sensor would detect both decay products!

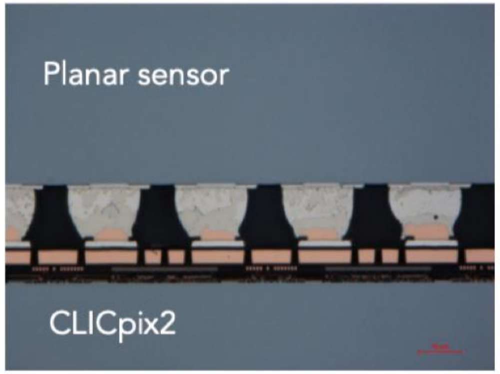


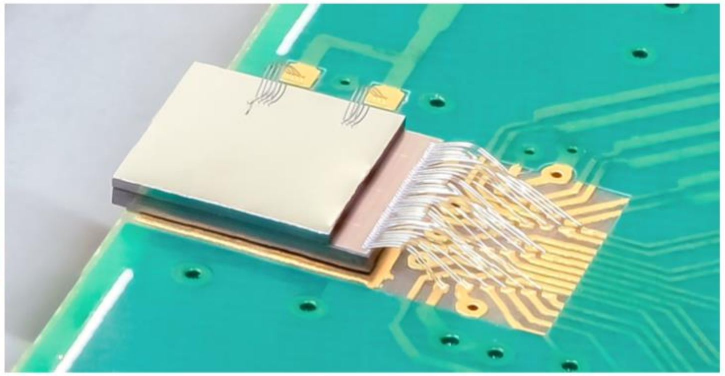
Detector requirement

- Provide excellent spatial resolution of the order of 3 µm.
- Resolve neutron capture events with a granularity of 5 ms.
- Allow to reduce γ background by energy measurement or coincidence with α or Li.
- Can be assembled in a double sided topology to improve spatial resolution

Table 2.1: CLICpix2 design features [2]

	CLICpix2
ASIC size	3.35 mm × 4.06 mm
Active area	3.2 mm × 3.2 mm
Matrix size	128 pixels × 128 pixels
CMOS technology	65 nm
Pixel pitch	25 µm × 25 µm
ToT counter depth	5 bit
ToA counter depth	8 bit
TOT dynamic range	270 ke (h^+)
ToA minimum bin size	10 ns
ENC (w/o) sensor	67 e
Minimum threshold (6 σ)	440 e
Acquisition mode	frame-based
Readout mode	1/2/4/8 parallel column readout
Data encoding	8 bit / 10 bit
Readout system	CaRiBOu
Voltage reference	bandgap
Testpulse	internal
Analogue power diss./pixel	6.6 µW
Amplifier gain	33 mVk^{-1}
Slow control	SPI
Clock speed	up to 100 MHz (acquisition) and 320 MHz (readout)
Data type	Zero compression





CLICpix2 could be a candidate to improve the current performance

- 25x25µm2 pixels
- TOT + ToA measurements (5/8bits)
- Frame-Based
- Low energy resolution when operating on large dynamic range
- Complexity of assembly

Timepix3

Timepix3 is another possible candidate for a first prototype :

- Continuous readout
- 1.2ns time resolution, 14bit TOT (good energy resolution)
- 55x55µm pixels
- Available commercially

Main Features:

- Readout chip type.................................. Timepix3
- Pixel size ....55 x 55 µm
- Sensor resolution....................................256 x 256 pixels
- Time resolution.................. ....1,6 ns
- Power.. External or via second USB 3.0
- Interface..USB 3.0 (Super-Speed)
- Maximum readout speed.........................40 million pixels / s
- Dimensions ....125 x 79 x 25.5 mm
- Weight .... 503 g

imaging, multilayer Compton camera and many other. The sensors can be adapted for neutron imaging by deposition of converter layers[1]. Recording

Symbol	Parameter	Si				CdTe	Units	Comment
	Thickness	100	300	500	675	1000	µm	
σ	Energy resolution of energy discrimination threshold (σ @ 23 keV)	0.5				1.1	keV	
σ	Energy resolution of energy discrimination threshold (σ @ 60 keV)	0.6				1.5	keV	
σ	Energy resolution in full spectral mode (σ @ 23 keV)	0.7				3.0	keV	
σ	Energy resolution in full spectral mode (σ @ 60 keV)	1.0				3.6	keV	
	Typical detectable energy range for X-rays[2]	1.0				3 to 600	keV	See chart below
	Pixel size	55				55	µm	

Possible assembly for double sided sensors

- Using CLICpix2, multiple detector must be assembled on PCB to cover the interesting area of detection. The final assembly is narrow in X and wide in Y (1x5 assemblies)
- To obtain good precision in a double-sided assembly, the sensors must be aligned accurately between each other on a PCB, and between PCBs
- Two possible methods :
  - Jig alignment based
  - Flip-Chip alignment based

Jig assembly methods

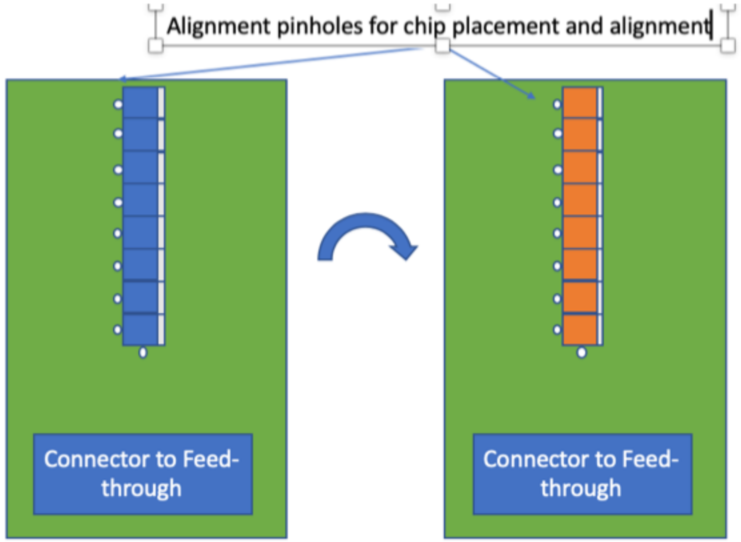
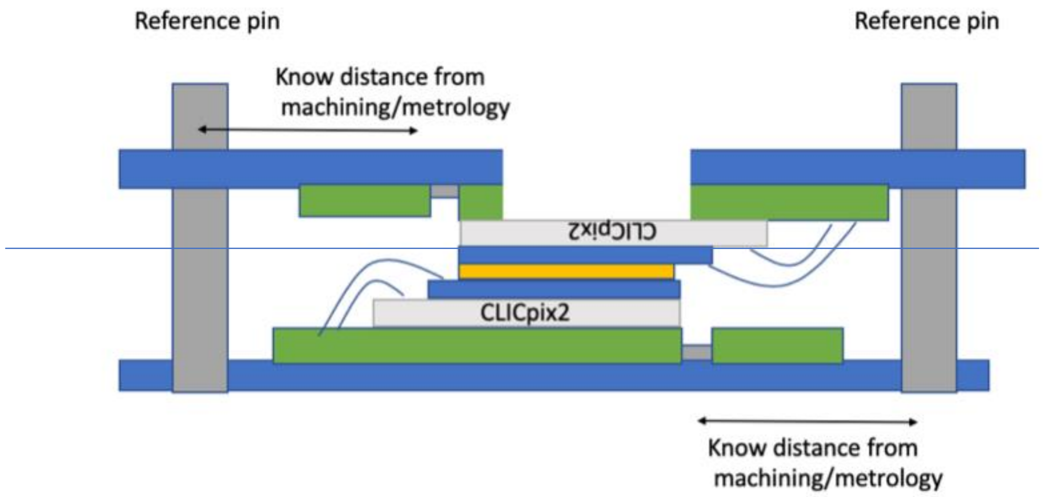


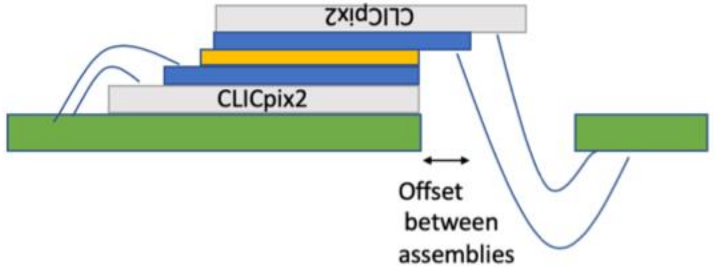
Figure 3.1: Schematics of the PCBs for integration of the double-sided detector



Two high-precision Jig aligned to each other

- Each jig has pins to refer to the position of the chip on PCB
- These pins are precisely placed wrt the master alignment pins

Flip-Chip assembly method



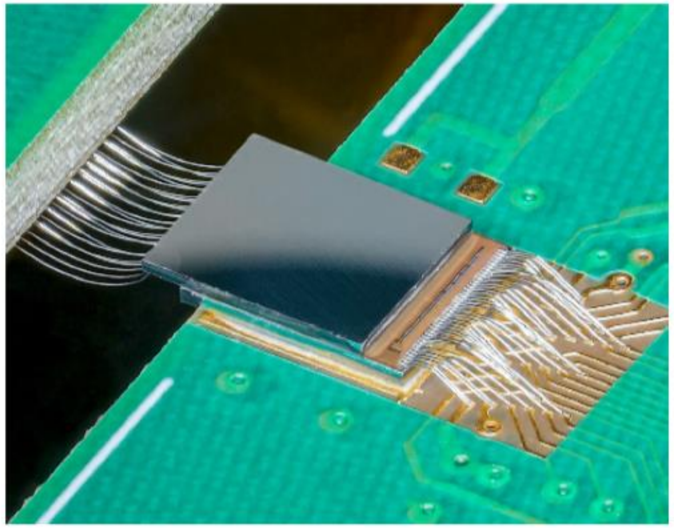
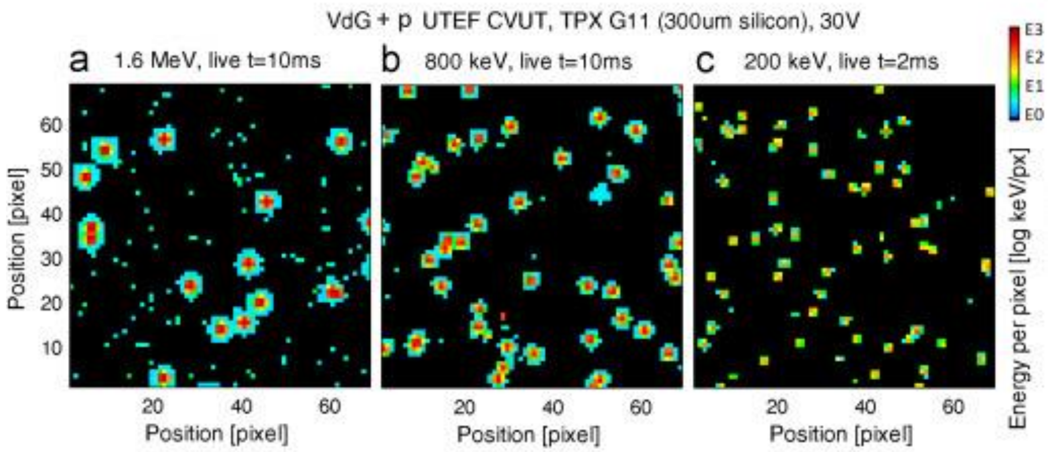


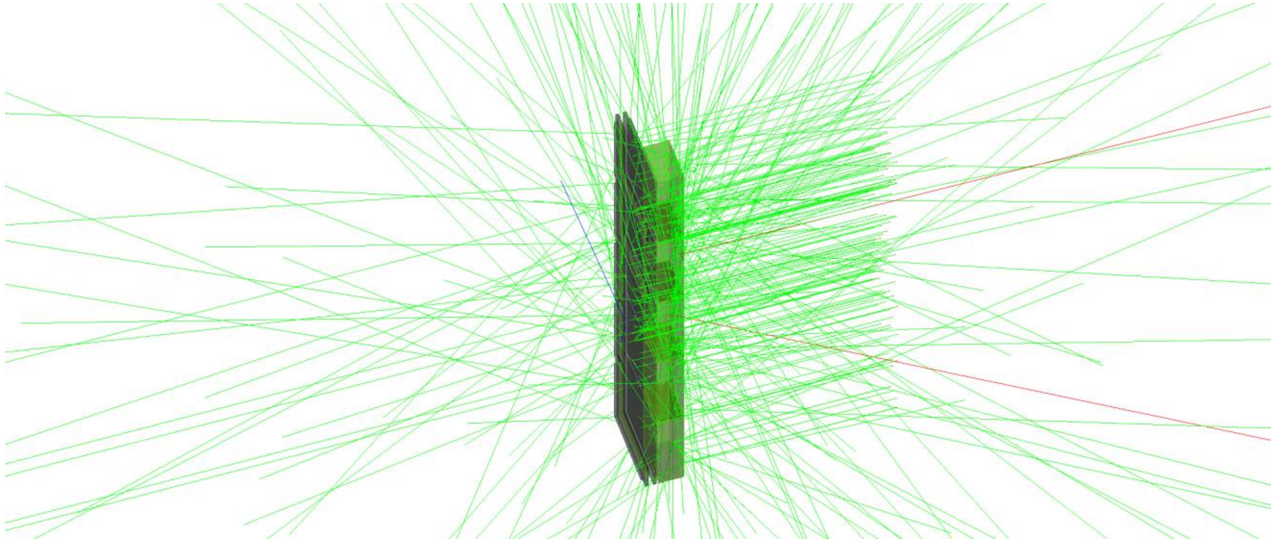
Figure 3.3: Proposed assembly method for alignment and positioning of the double-sided UCN detector using flip-chip placement (left). Example of double-sided wire-bonding with CLICPix2 [2] (right)

- Top and bottom sensors are assembled with 1.5µm precision in the Flip-chip machine
- Assembly stack is glued to PCB using flip-chip or jig method
- Wire-bonding is performed on both side of the PCB

Data analysis

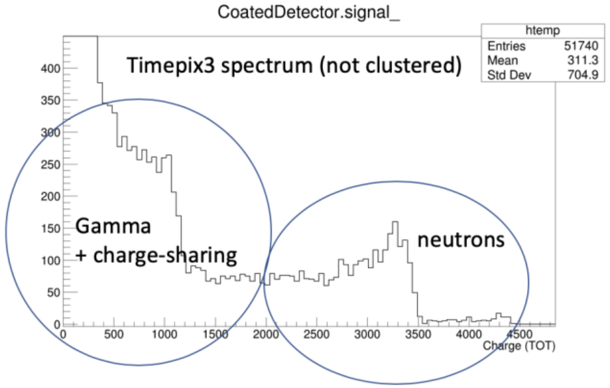


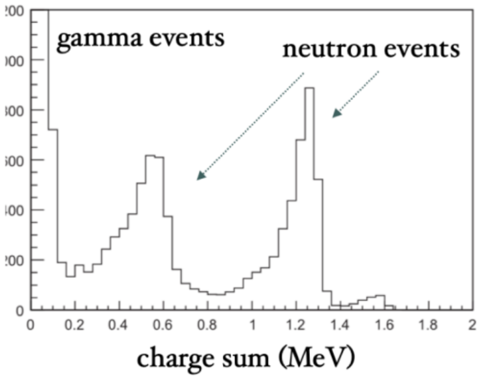
- Cluster produced by ions in Silicon tend to be quite large due to electro-static repulsion at the beginning of the event
  - It might be that we are dominated by this for resolution, not pitch
  - Will 55µm pitch with 14bit TOT do better than 25µm pitch with 5bit TOT ?
- Regarding gamma rejection, both CLICpix and Timepix3 can easily reject non-ion event by shape recognition + energy discrimination
- Thickness of the sensor will play a role on final cluster size
  - Thin sensor provide better single point resolution (?)
  - Thick sensor favor charge sharing
- Simulation required to sort the benefits from both approach



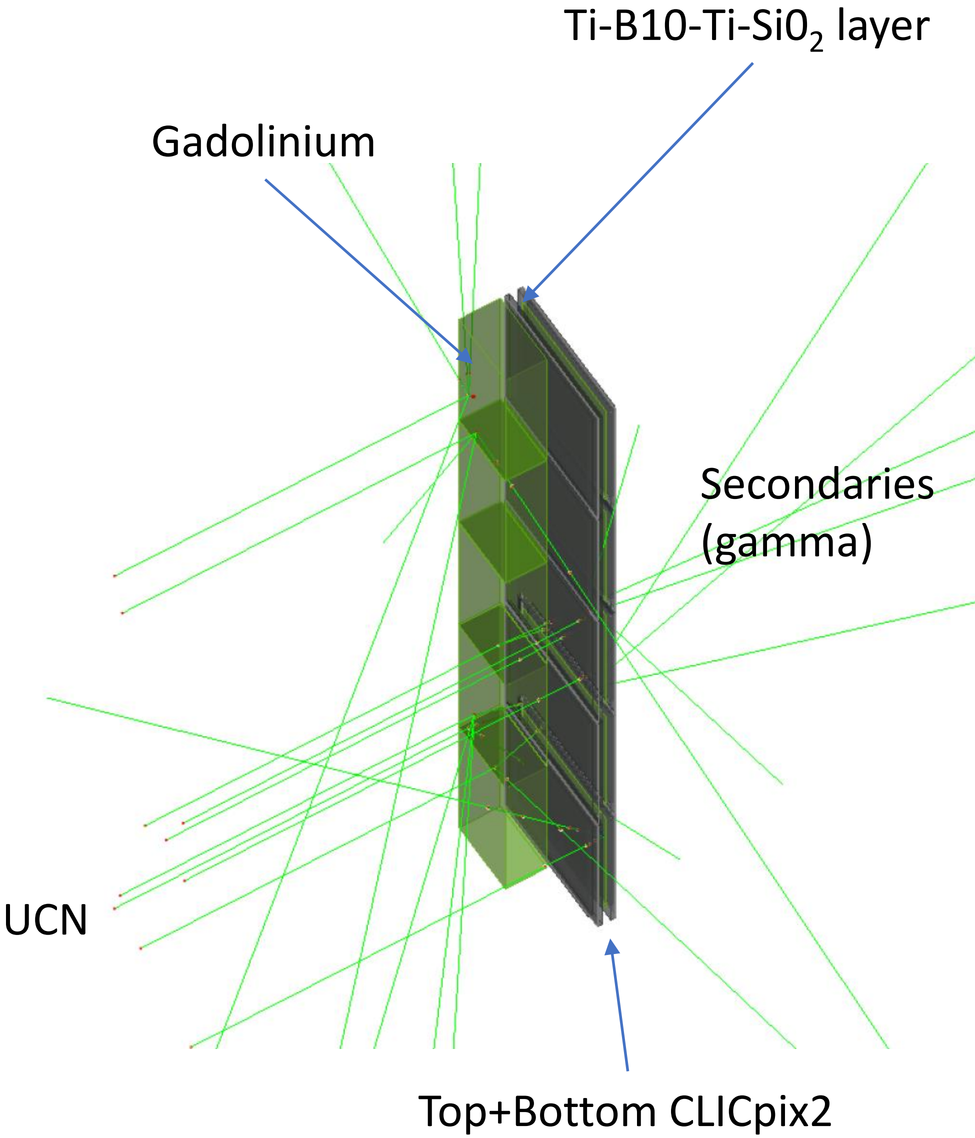
Simulation

- Simplified geometry of the experiment
- Sensor simulation by charge transport
- Electric field extracted from TCAD
- 20nm Ti- 200nm B10- 20nm Ti- 350nm SiO_2 layer on top of the bottom assembly
- UCN physics implemented in allpix2
- Neutron capture simulated by GEANT4
- Charge deposition is transported in the field (+ diffusion) and signal digitized to mimic CLICpix2/Timepix3
- Can vary thickness, bias, distances, pitch etc.





So far so good



Schedule

- https://cernbox.cern.ch/index.php/s/Bopm1kgyUlf1A8P

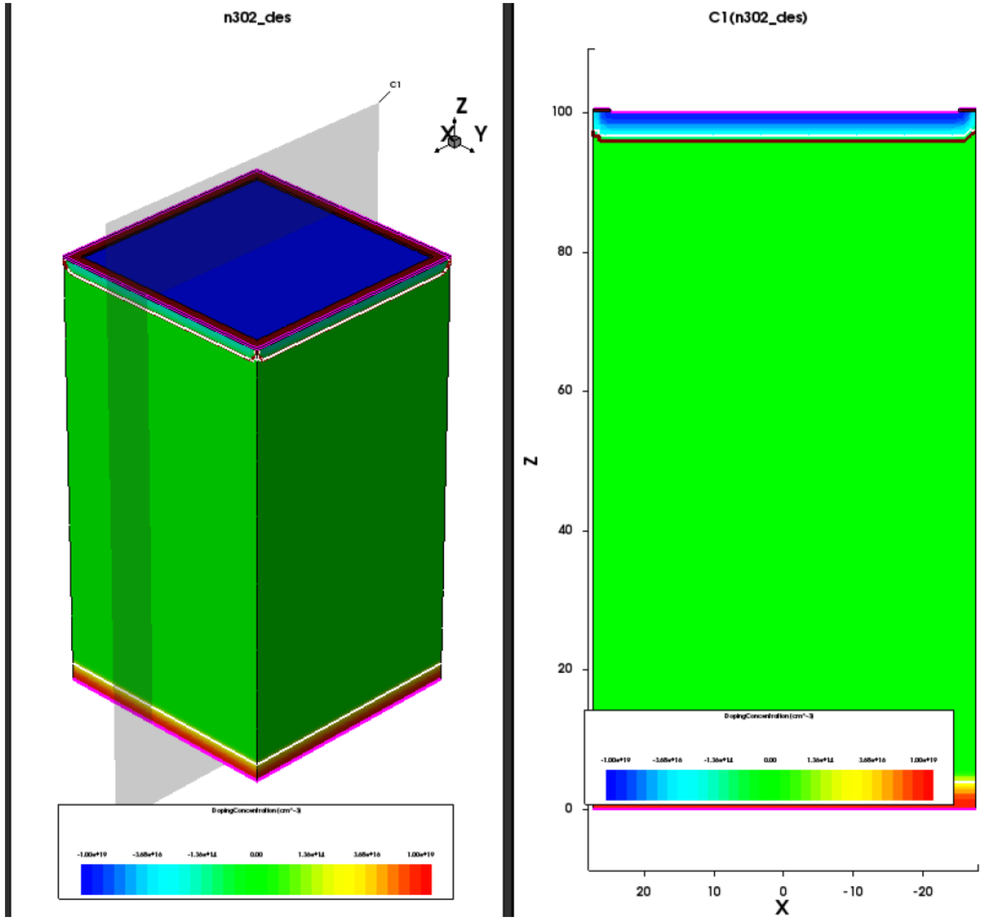
Open questions

- What is the influence of dead material in front of the detector. This can affect the assembly method required.
- Is there any material to be avoided ?
- With the jig Assembly method, can the sensor be aligned sufficiently accurately ?
- What accuracy is required ?
- Can wire-bonding be done with the assembly method using the fine placer ?
- Can a gap exist between the top and bottom layer ?
- Literature demonstrate a resolution of using a standard Timepix assembly coated with Lithium or Boron. Can the CLICPix, with a thinner sensor , a smaller pixel pitch but a worse TOT resolution do better ? Using a Timepix3 would have the advantage of a single 1.4 cm×1.4 cm active area, of continuous readout, of a 1.2 ns timing accuracy and 14 bits TOT accuracy. The Fine placer assembly method could then be used easily to assemble a double-sided detector. An Allpix 2 simulation of both geometry and ASIC should be performed to evaluate the possible achievable performance for both.
- If CLICpix2 is better suited for this application, what mode of operation is the most appropriate?
- Can alignement be performed in-situ with Gadolinum mask?

From Didier

- - A double side layer is something new to me but if I understand correctly on one side we will detect the emitted Alpha and on the other side the Li coming from the neutron capture with Boron 10 layer. How will we manage to get 1 micron resolution with 25 microns pitch? This is not clear to me... BTW with TOA and TOT is it not enough to have one layer?
- - The intrinsic alignment of the assembly has to be specified and it is not clear to me that we need to make a front to back assembly super precise. However if needed we can make something like few microns up to 10 microns to the cost of some development effort using a combination of the flip chip (for each chip to PCB assembly refs) and of assembly jigs in between the two layers wrt refs. (To be discussed between us)
- - You mentioned that CLICPix2 is known to be sensitive to temperature change. Is there any requirement about operating temperature and uniformity across the all assembly? Should we consider cooling? May be decoupled cooling is possible from the mechanics with thermal grease of PGS foil connected to a cold surface
- - The all assembly stackup even with the sketch you made does not look very clear yet at least to me. The two back to back sensors are separated by some material. Is this the B10 and if so it is very thin... I am a bit lost of where to get the sensor back-plane biasing with wire bonds without clashes.

TCAD



n302_des
C1
Z
X
Y
DopingConcentration (cm^-3)
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-3.68e+16
-1.36e+14
0.00
1.36e+14
3.68e+16
1.00e+19
C1(n302_des)
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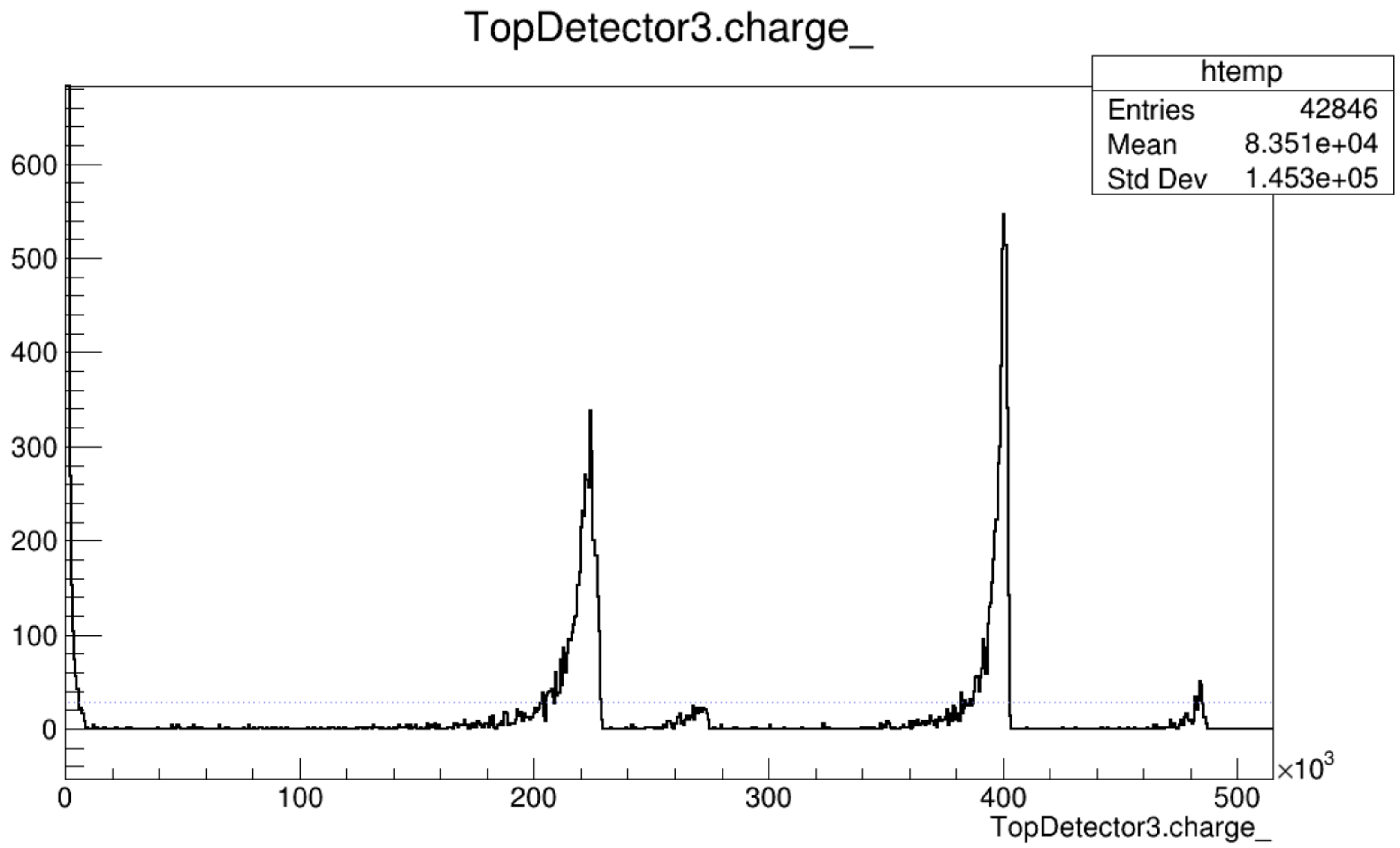
80
60
40
20
0
Z
20
10
0
-10
-20
X

MC Truth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Std Dev 1.453e+05
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TopDetector3.charge_