Development and application of flexible a-Si:H detectors for advanced X-ray beam characterization

Keida Kanxheri on behalf of HASPIDE collaboration

HIGH PRECISION X-RAY MEASUREMENTS 2025

OUTLINE

- Introduction and Motivation
- Detector Fabrication
- Prototype Overview
- Experimental Characterization
  - – Clinical LINAC measurements
  - – Synchrotron radiation measurements
- Future Applications

HASPIDE PROJECT

INFN CSN5 call

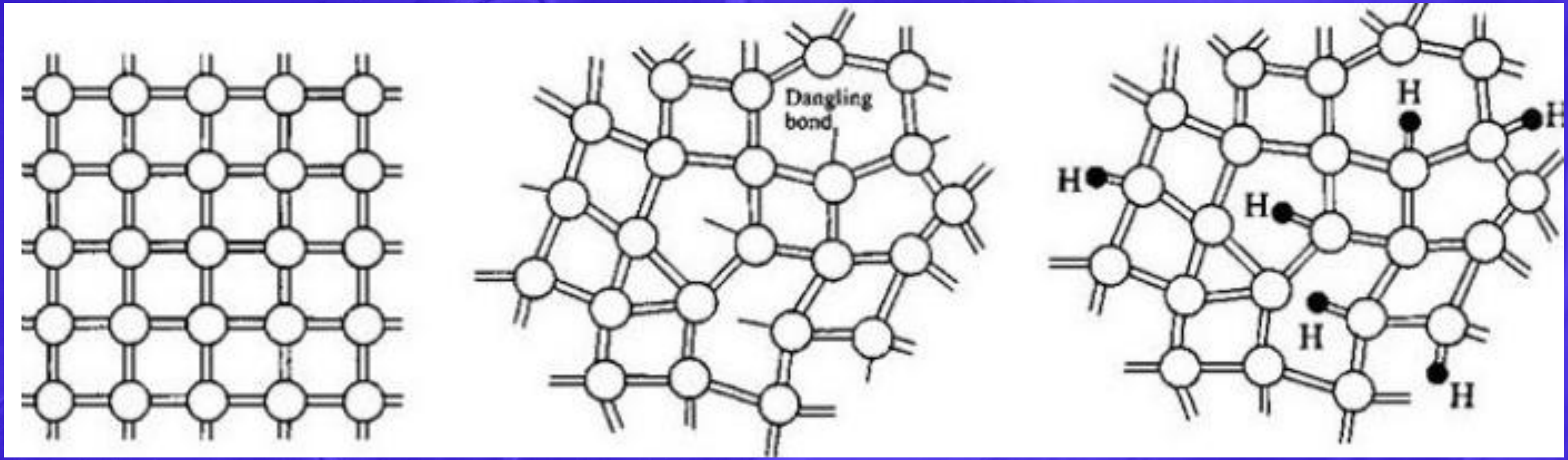
Started in 2022
3 years duration

8 institutions:
6 INFN Sections (FI, LE, LNS, MI, PG, TO)
University of Wollongong (Aus)
EPFL Neuchatel (Switzerland)

~ 50 researchers

→ **Sapienza Università di Roma**

HYDROGENATED AMORPHOUS SILICON



1969

- **Synthesized for the first time by Plasma Enhanced Vapor Deposition (PE-CVD) OF SiH_4**

1976

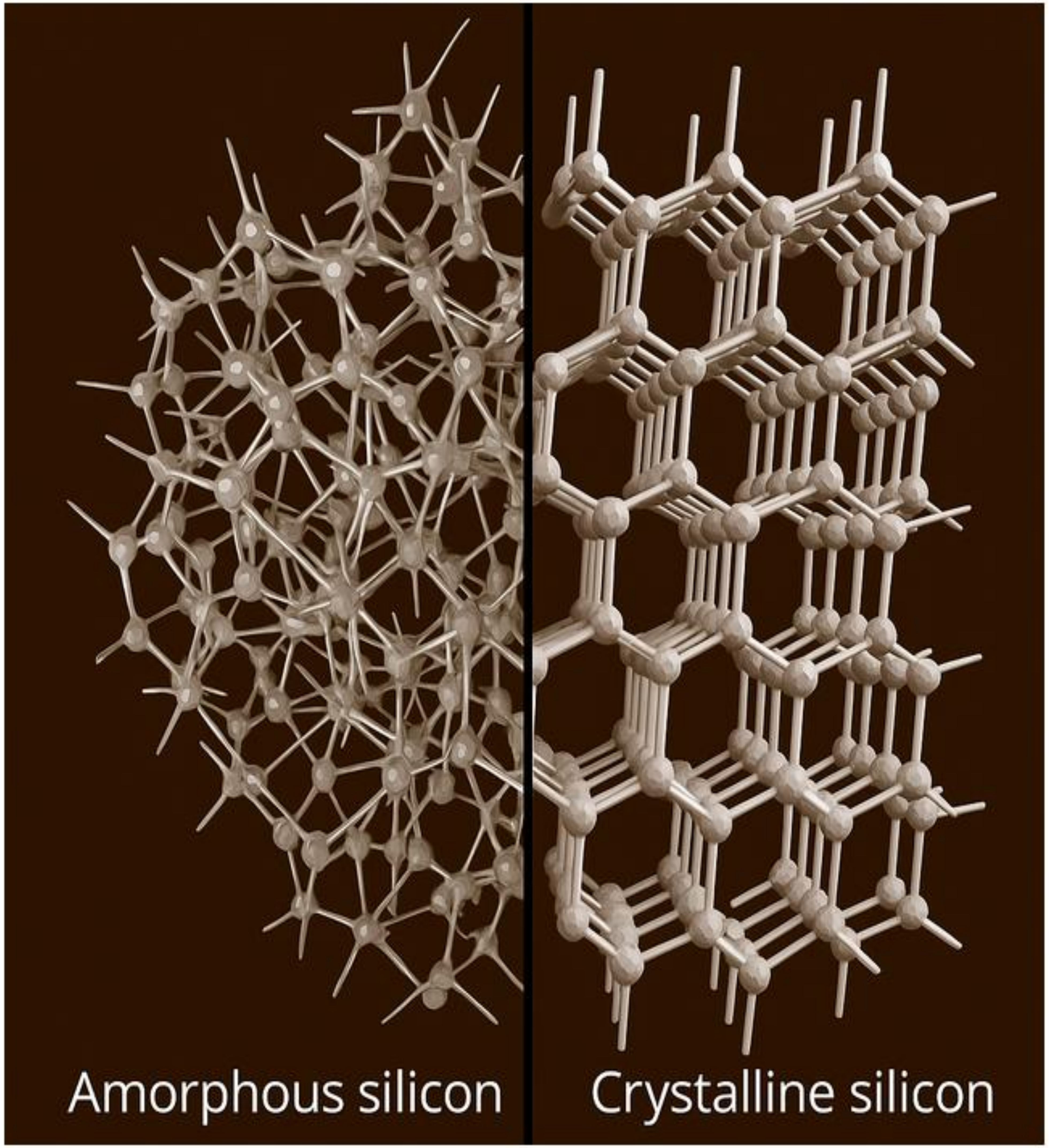
- **Development of transistors, solar cells and memories.**

FROM MID '80 ON

- **Direct detection of ionizing radiation based on diode structures**

WHY a-Si:H?

- It is intrinsically radiation resistant
- It can be deposited in thin layers (~ 0.4 - 100 um)
- It can be deposited on different substrates, even flexible ones like mylar and kapton
- It has a band gap value slightly higher than c-Si: 1.7-1.9 eV
- Material deposition process can be done on wide areas
- Hydrogen incorporation during deposition passivates structural defects



DEPOSITION TECHNIQUES

- **PECVD (Plasma Enhanced Chemical Vapor Deposition) [EPFL + ROMA]**
  In the process is used a mixture of silane (SiH4) and hydrogen, with working temperature between 160°C and 300°C

- **Radiofrequency PECVD (RF or VHF PECVD), at various frequencies.**

A NEW PROCEDURE IS UNDER DEVELOPMENT IN THE HASPIDE PROJECT:
→ REACTIVE SPUTTERING FOR THE SUBSTRATE [LECCE]
→ PULSED LASER DEPOSITION FOR CONTACTS [LECCE]

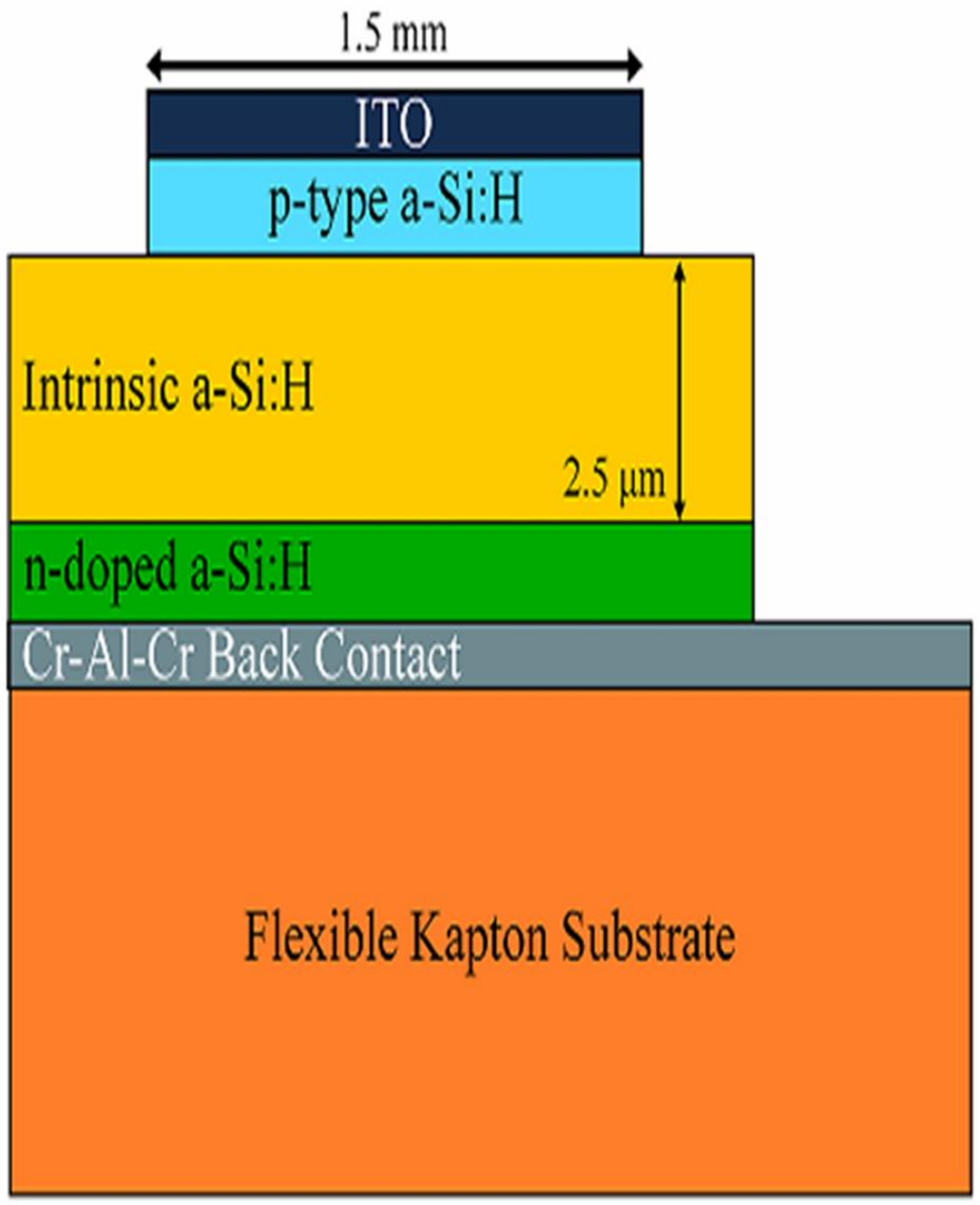
HASPIDE GOALS

FABRICATION OF THIN a-Si:H (0.4 - 10 um) IONIZING RADIATION DETECTORS DEPOSITED OVER THIN FLEXIBLE SUPPORTS TO BE USED FOR:

- **Beam monitoring of linacs and other types of accelerators**
- **Detection of radiation bursts in space, for example solar energetic particles events;**
- **Neutron detection via ^{10}B deposition over an a-Si:H layer to detect α produced by neutron conversion.**

PIN/NIP STRUCTURE

- 1.5 mm pixel with 28 nm ITO top contact
- PIN stack deposited via PECVD intrinsic layer: 2.5 µm SiH_4 + H_2
- Doping gases: PH_3/H_2 (n), TMB/H_2 (p)
- Cr–Al–Cr back contact
- Substrate: flexible kapton (25 um)
- SF_6/O_2 dry etch for pixel isolation



CSC STRUCTURE

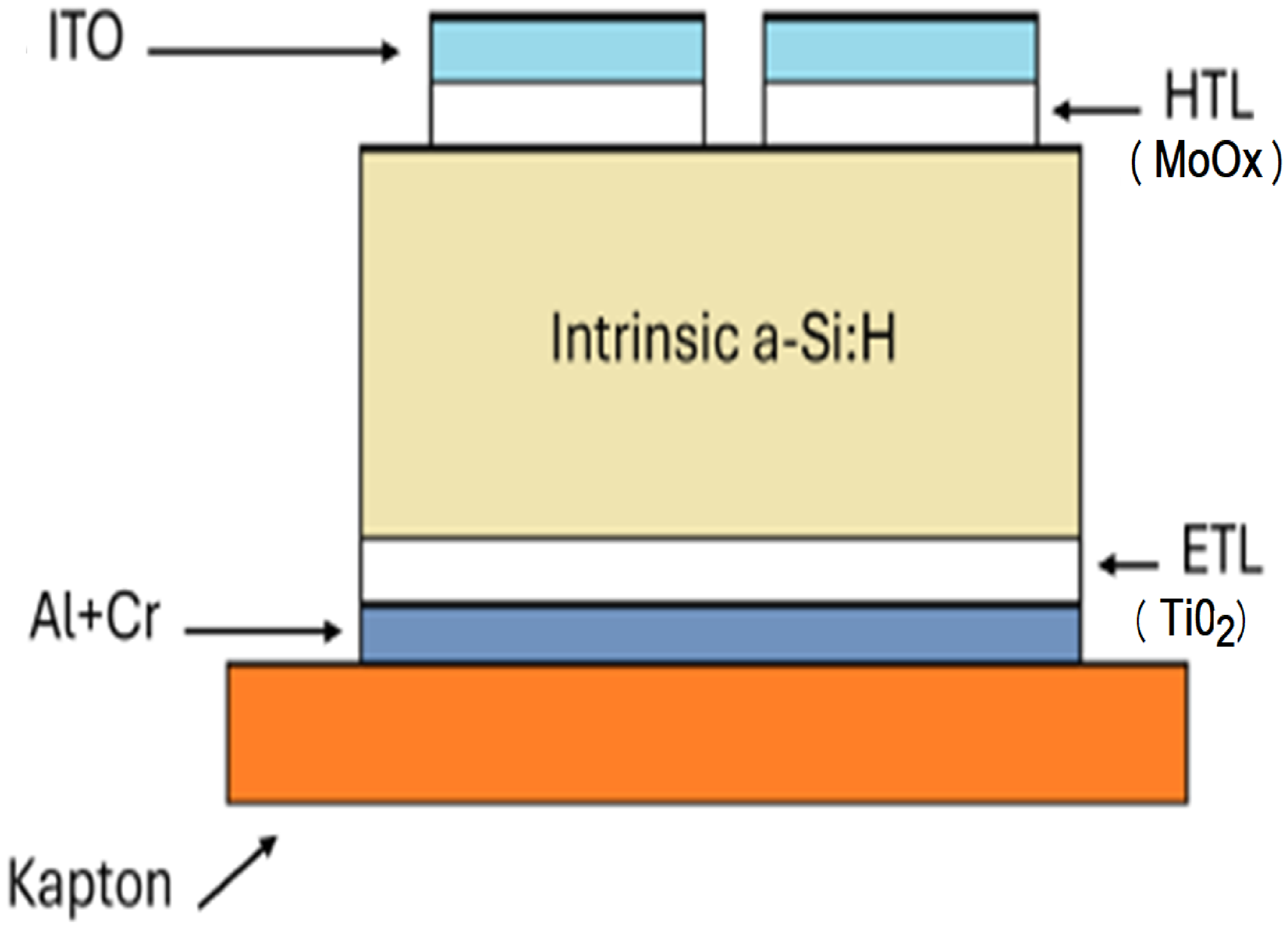
- CSC concept: two ultra-thin metal oxide layers isolate the intrinsic a-Si:H

- ETL (Electron Transport Layer): TiO_2 (or ZnO)

- HTL (Hole Transport Layer): MoOx Layer thickness: < 30 nm

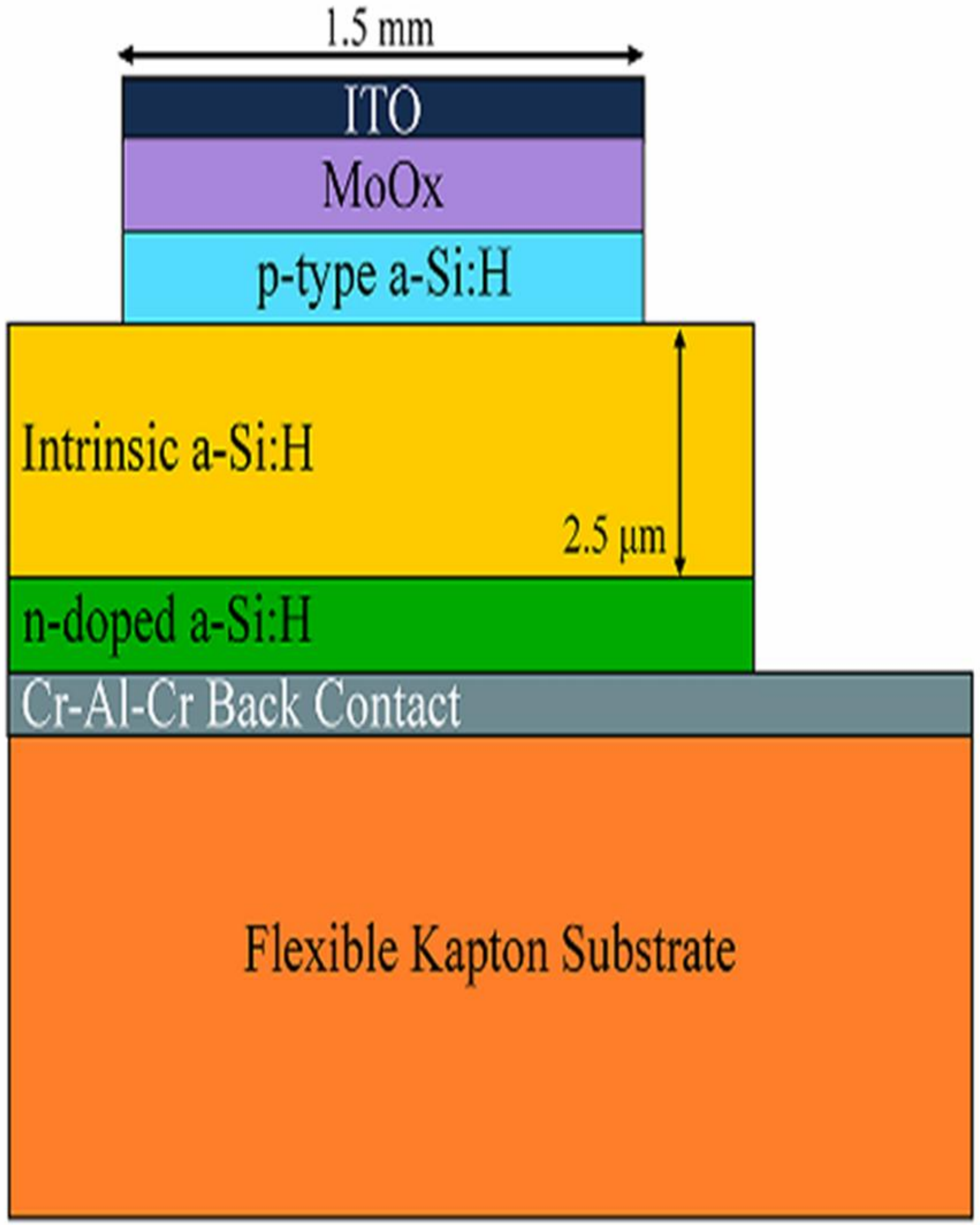
- Active layer: intrinsic a-Si:H (0.4 – 10 μm)

- Thanks to the presence of charge-selective contacts, these detectors can operate even without an external bias



NIP + CSC STRUCTURE

- Based on a standard n-i-p stack with added MoOx CSC
- 20 nm MoOx sputtered over the p-doped a-Si:H
- Final top contact: ITO (28 nm), followed by dry etching



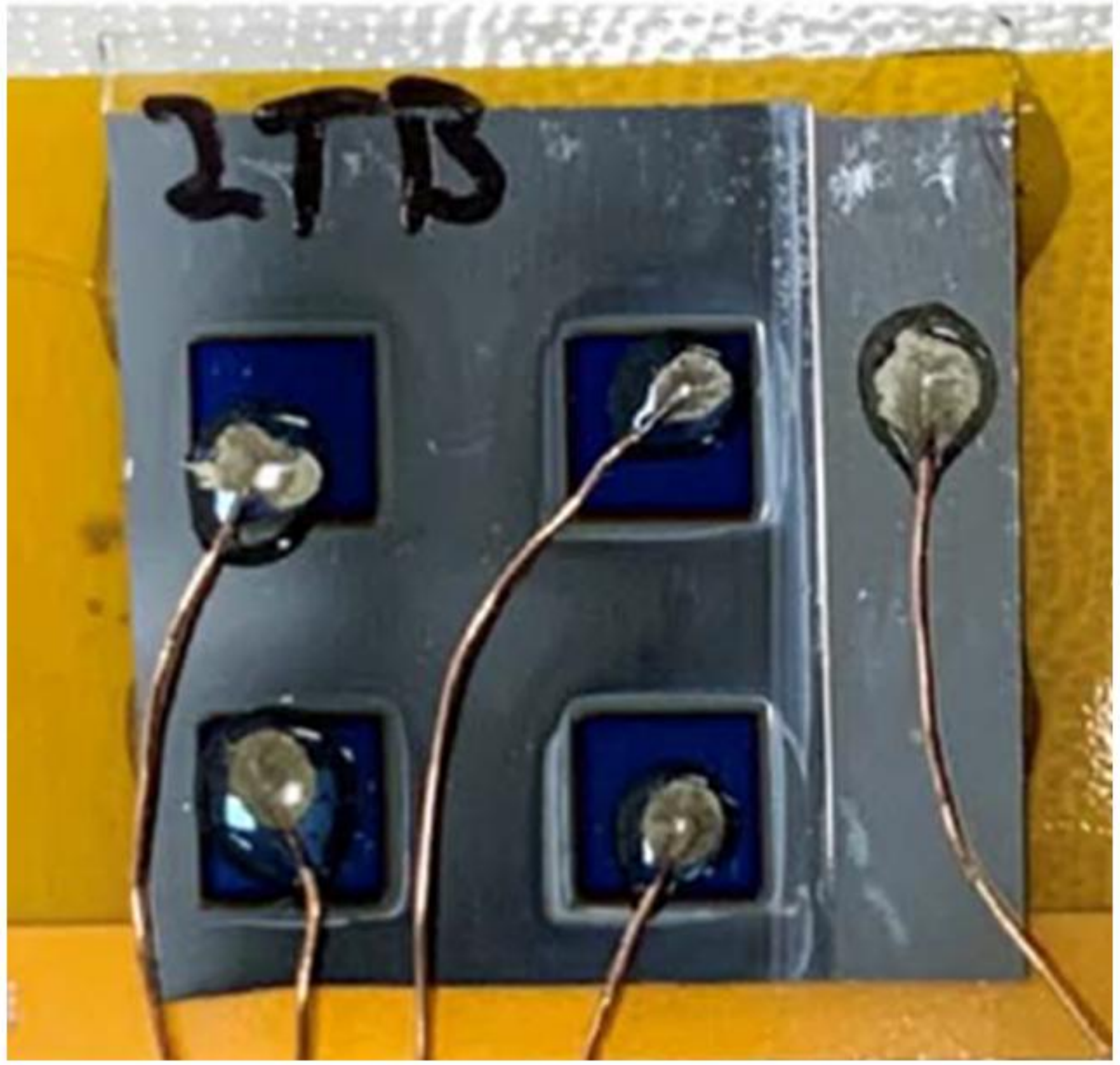
PROTOTYPES

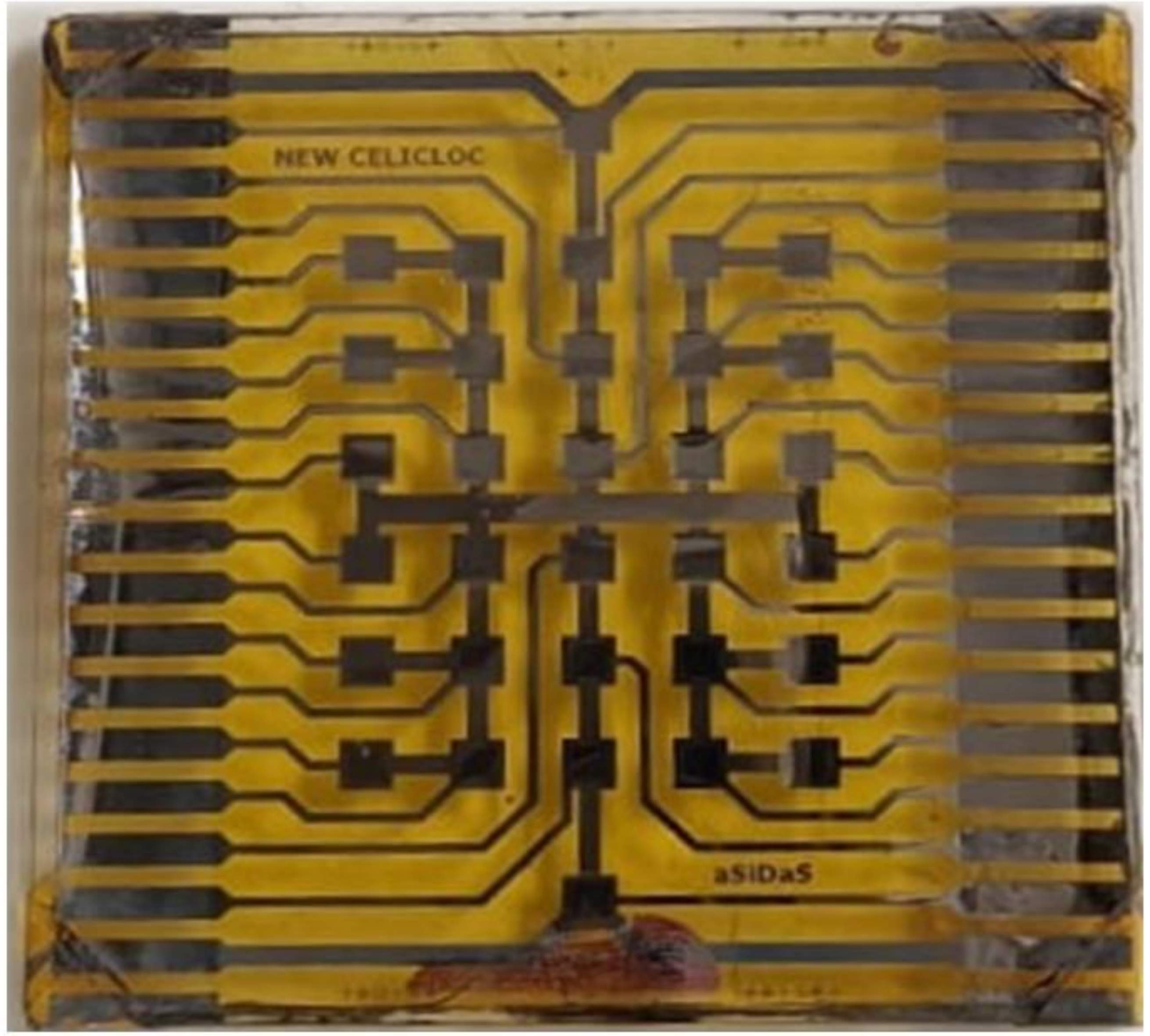
Previous Detectors

- Sensitive area: 4 × 4 mm²
- Intrinsic a-Si:H thickness: 1 μm
- Substrate: thick rigid silicon
- Back contact: silver-based conductive paint

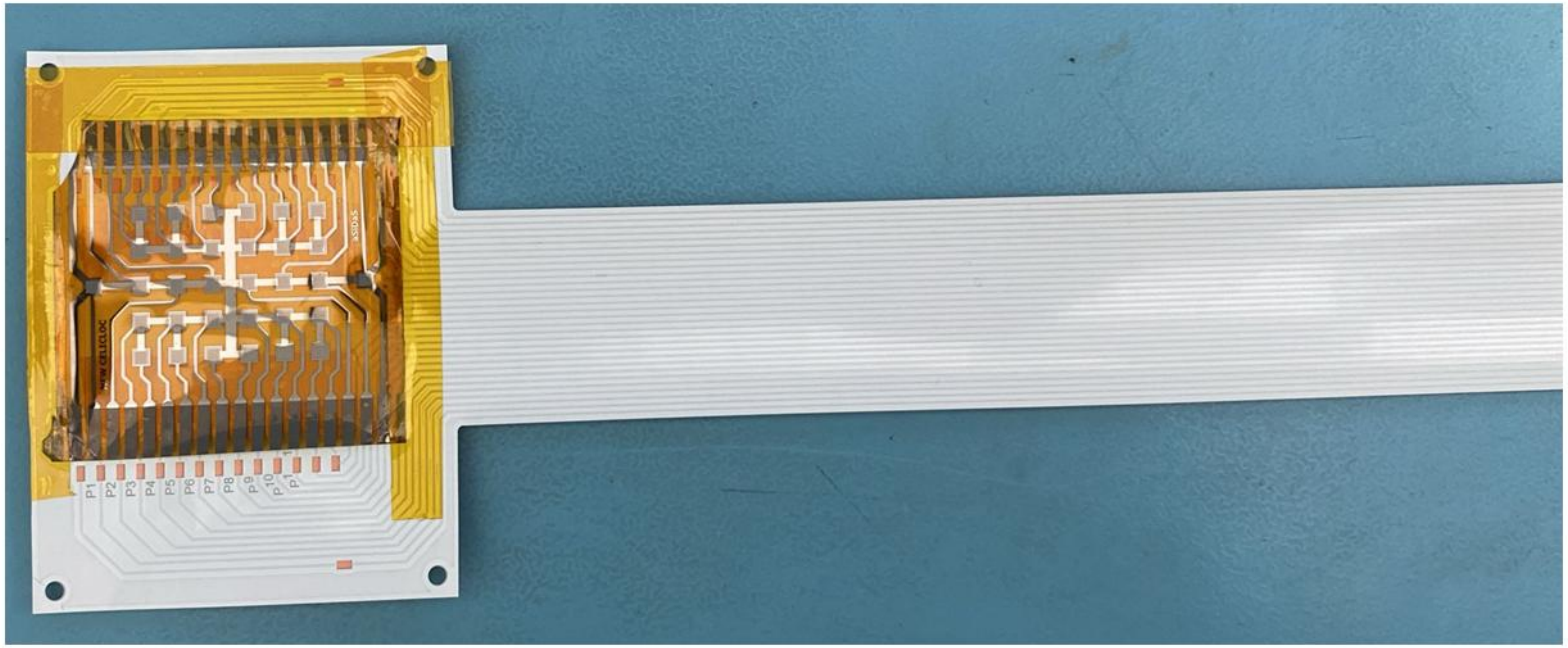
- Sensitive area: 2 × 2 mm² and 5 × 5 mm²
- Structure: p-i-n
- Intrinsic a-Si:H thickness: 2.5 μm
- Substrate: 25 μm polyimide

- Sensitive area: 2 × 2 mm²
- Structure: linear array of 5 × 6 p-i-n sensors
- Intrinsic a-Si:H thickness: 0.4 μm
- Substrate: 30 μm and 60 μm polyimide





CUSTOM-DESIGNED PRINTED CIRCUIT PIGTAILS



CLINICAL X-RAY BEAM SETUP (LINAC)

Reference conditions:

- **Varian LINAC @ Shoalhaven Cancer Care Centre (Australia)**
- **Beam: 6 MV X-rays**
- **Field size: 10 × 10 cm²**
- **SSD: 100 cm, depth: 1.5 cm (D_{max}) with 10 cm backscatter**

DOSE PER PULSE

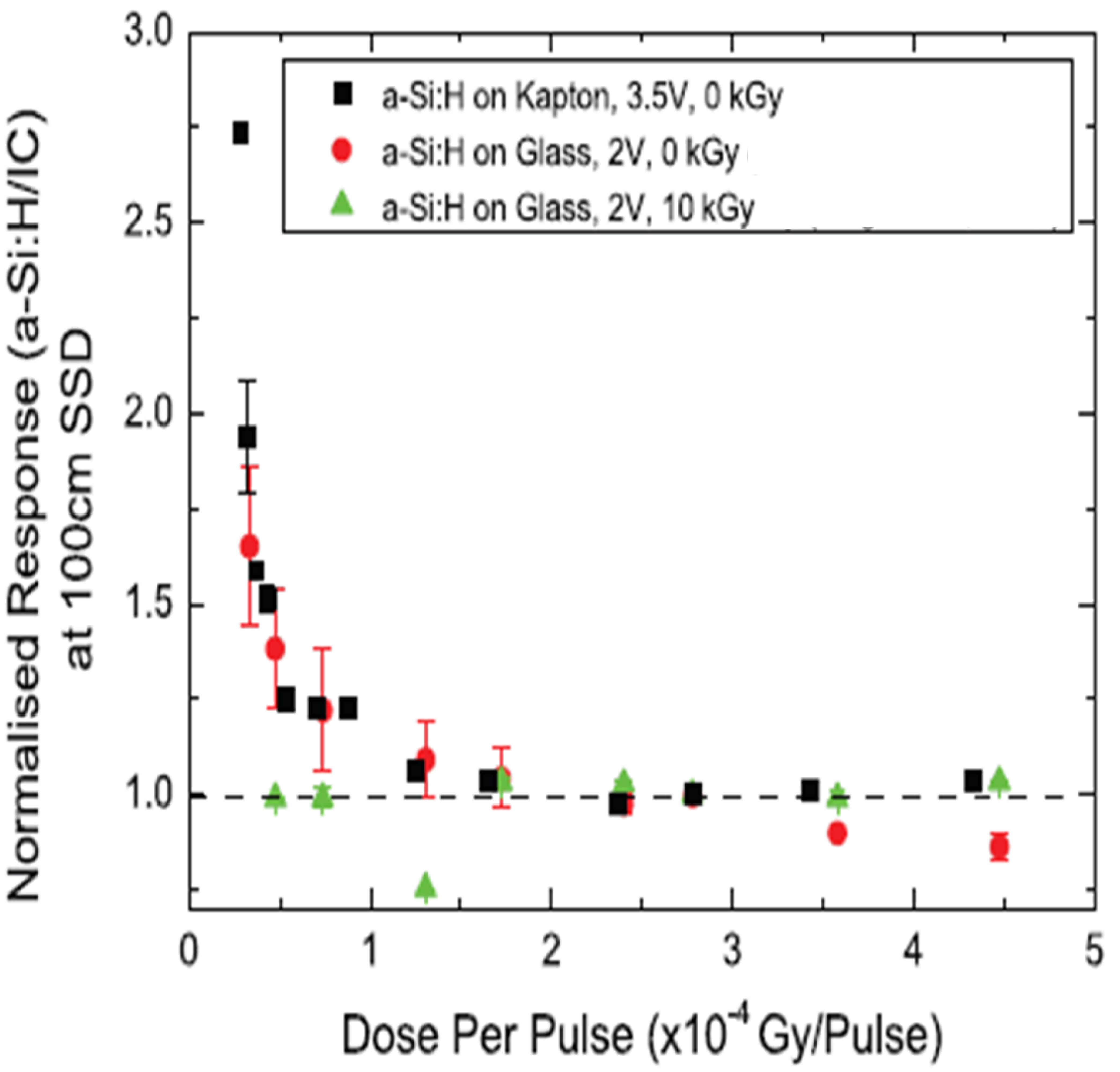
- At very low DPP (4.3×10^{-5} Gy/pulse), an over-response of +51% is observed

- The over-response is likely due to an unstable internal electric field, influenced by empty deep traps in the a-Si:H layer.

- Similar behaviour seen in previous rigid detectors on glass substrates

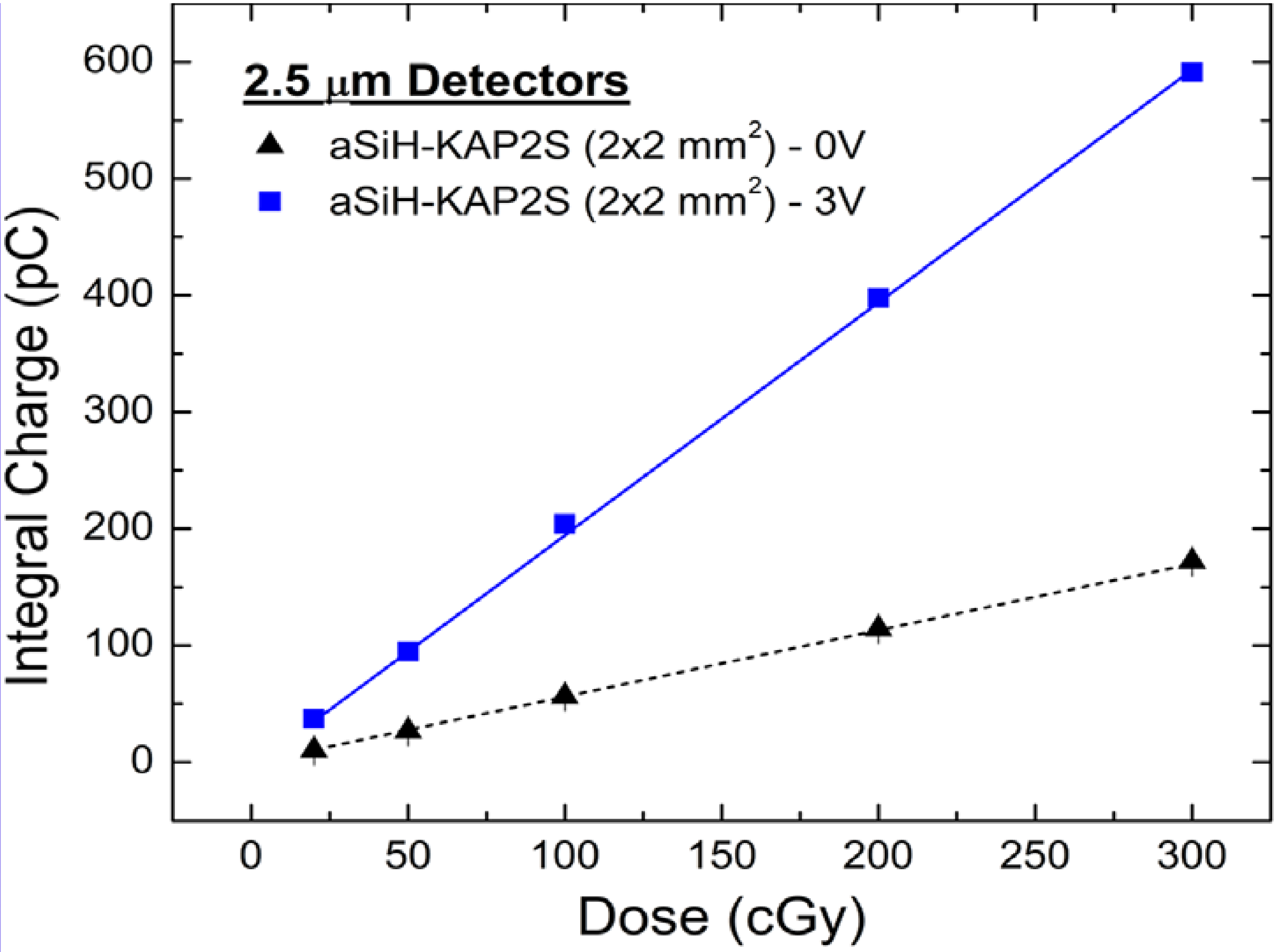
- Over-response is significantly mitigated after pre-irradiation (>10 kGy)

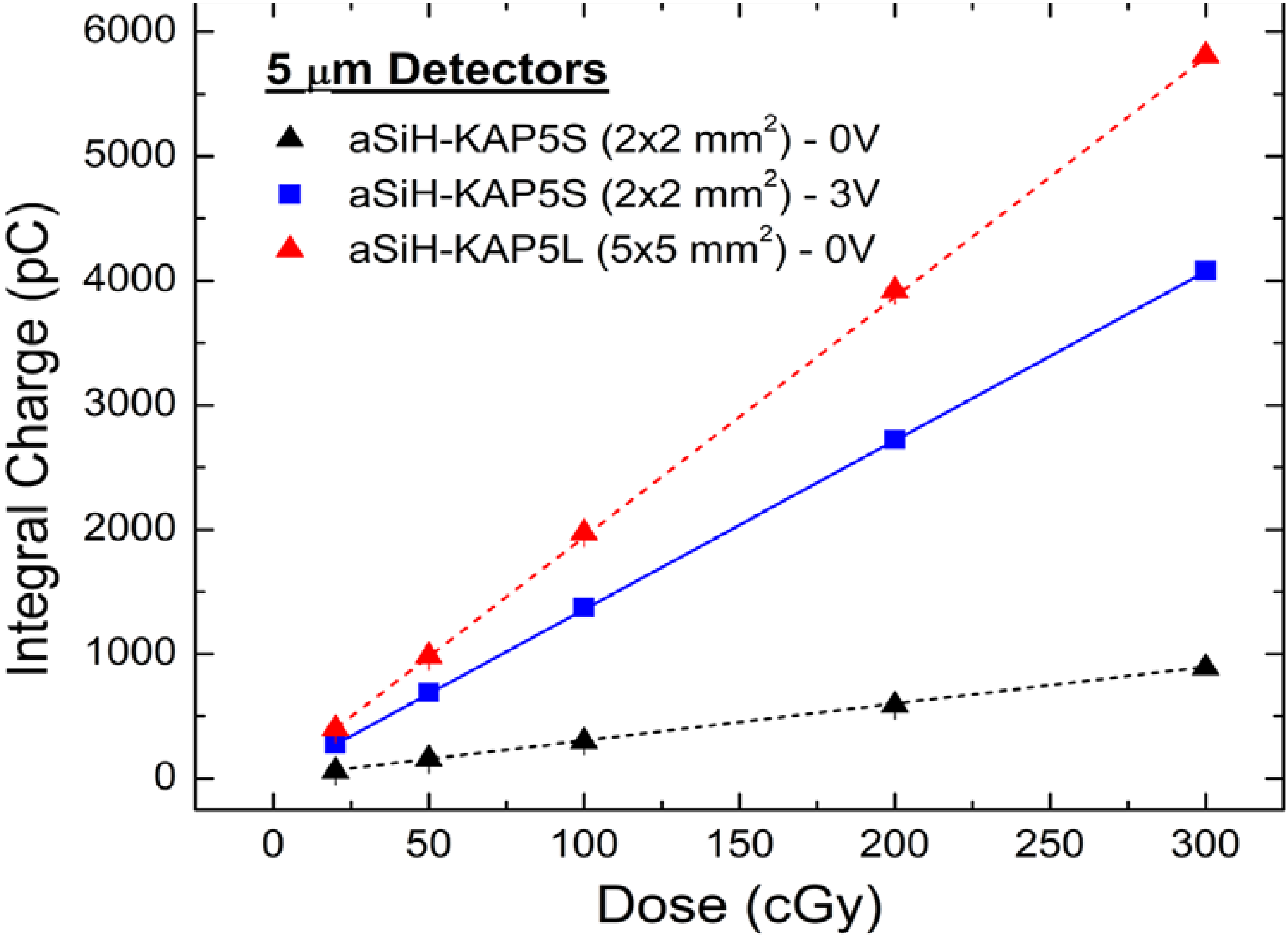
- The transfer of a-Si:H architecture to kapton preserves dosimetric response



DOSE LINEARITY

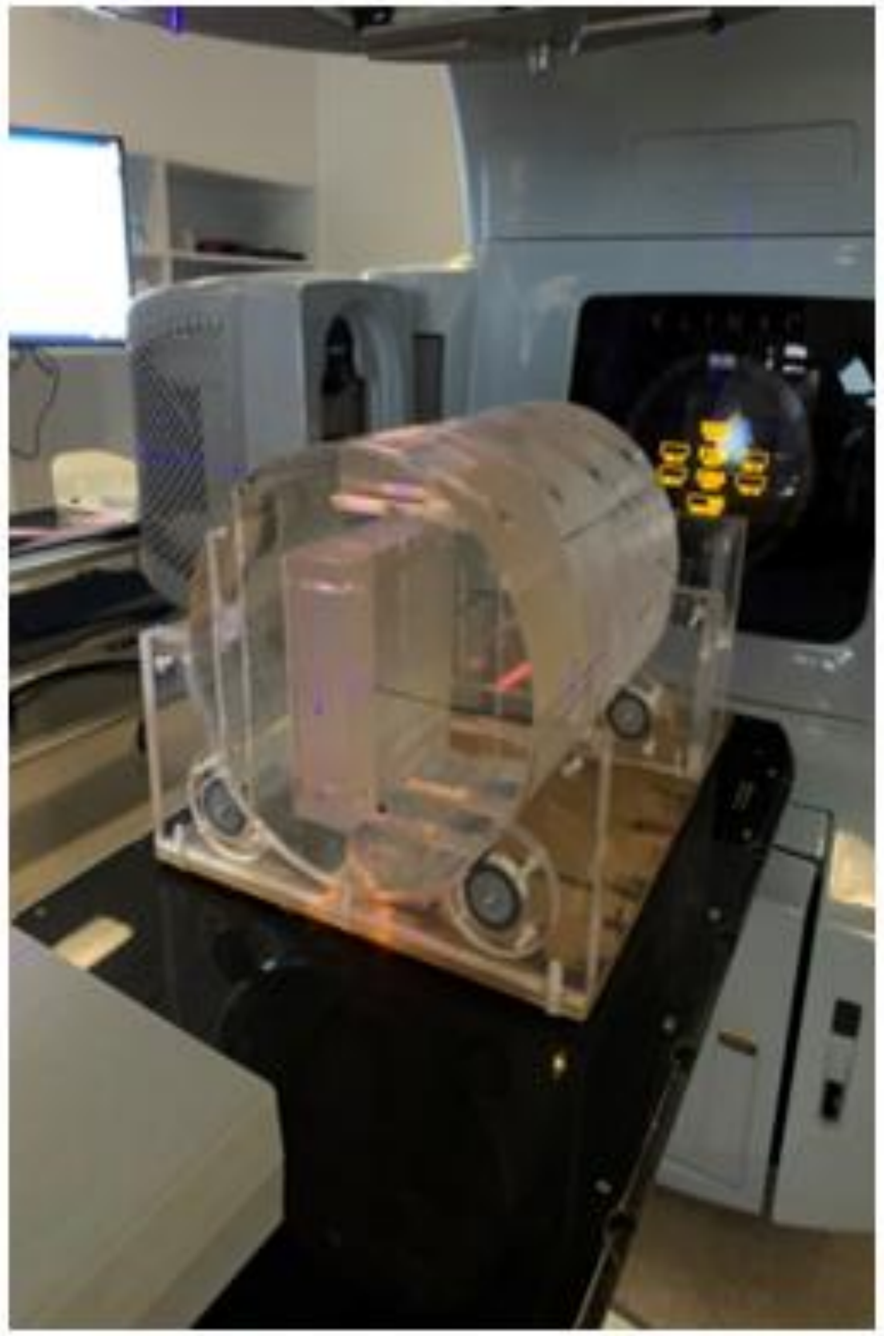
Detector ID	Thickness (μm)	Pixel area (mm^2)	Sensitivity at 0 V (pC/cGy)	Sensitivity at 3 V (pC/cGy)
aSiH-KAP2S	2.5	2×2	0.580 ± 0.002	1.981 ± 0.021
aSiH-KAP5S	5	2×2	2.943 ± 0.015	13.56 ± 0.02
aSiH-KAP5L	5	5×5	19.36 ± 0.10	–

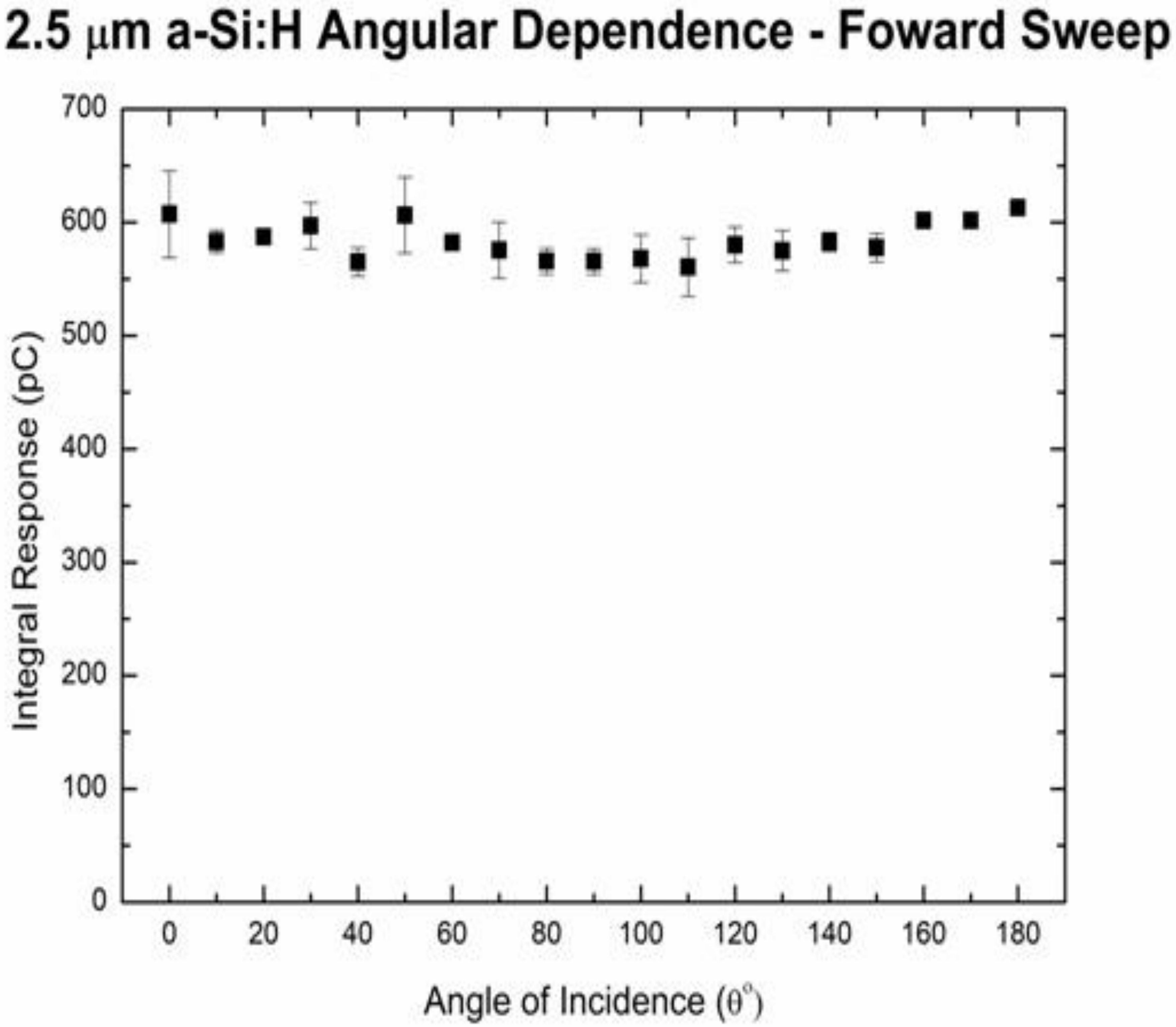




ANGULAR DEPENDENCE

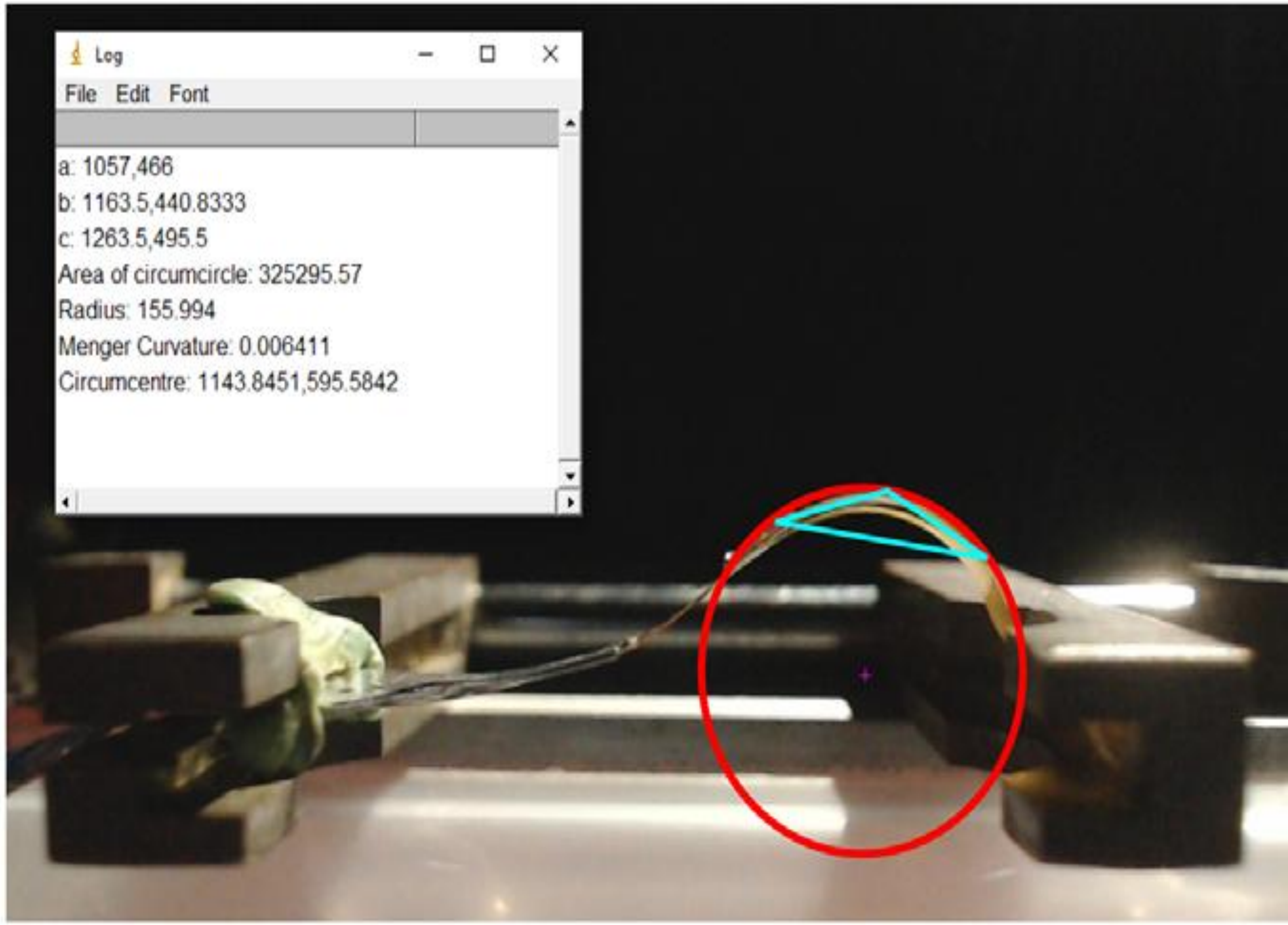
- Excellent angular stability: <5% variation across 0°–180°
- Ideal for applications with rotating beams or gantry motion





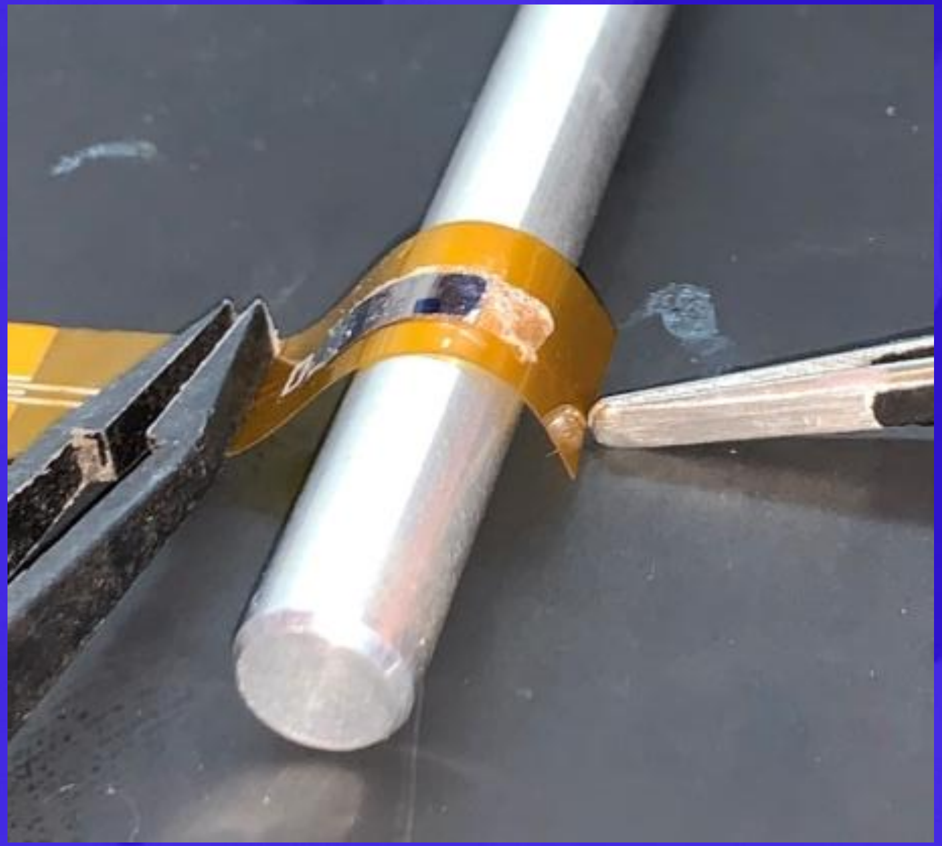
BENDING RADIUS TESTS FOR IN VIVO APPLICATIONS

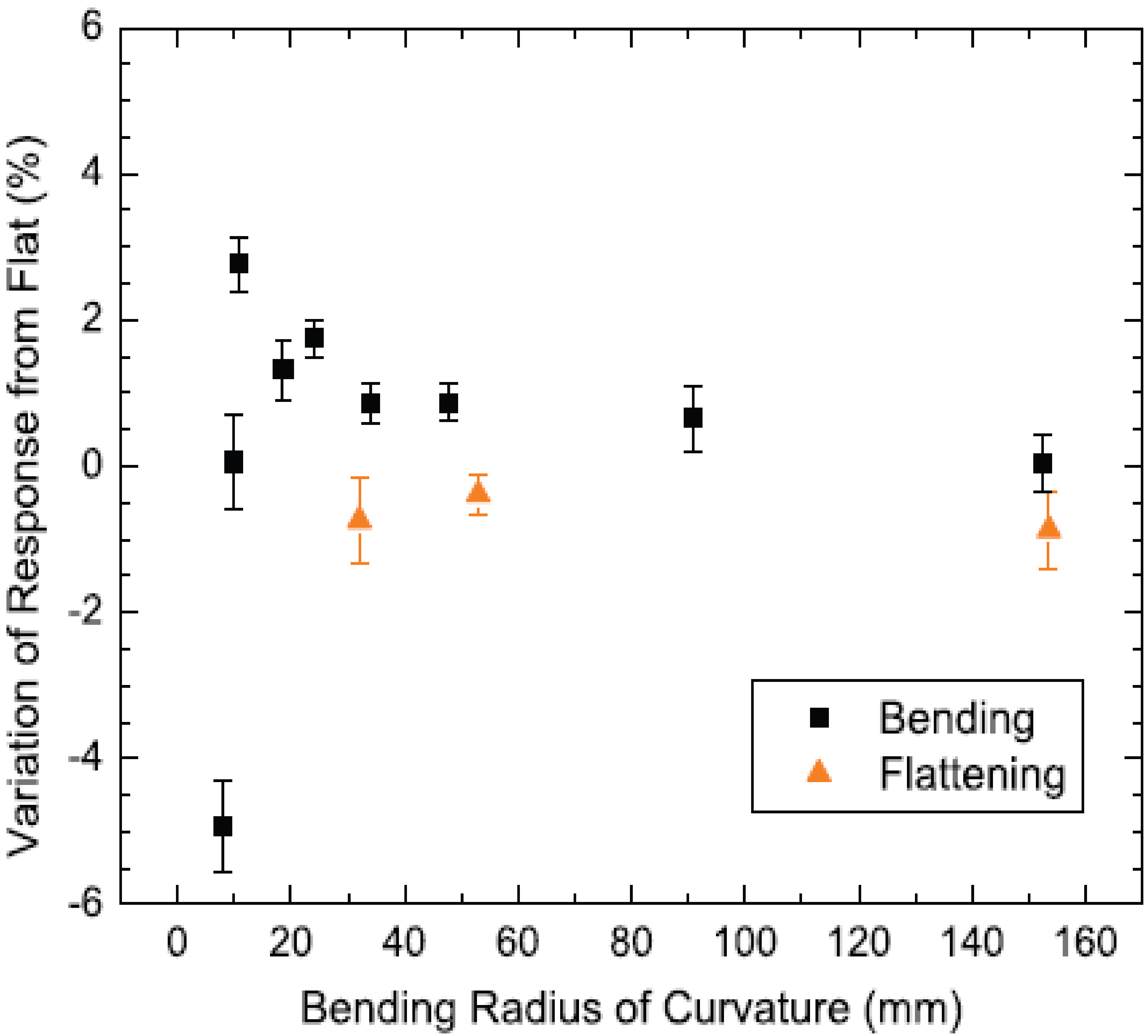
- **Bending radii from 152.38 mm – 7.98 mm**
- **A custom “push-to-flex” setup was used to bend the a-Si:H detectors in a controlled way**
- **The response was measured under 615 nm visible laser illumination during deformation**



BENDING RADIUS TESTS

- **Sensitivity degradation < 5% under maximum curvature**
- **Response returns to (99.1 ± 0.5)% after bending**
- **Enables conformal dosimetry for curved anatomy (e.G., Breast, head & neck).**





ANSTO AUSTRALIAN SYNCHROTRON

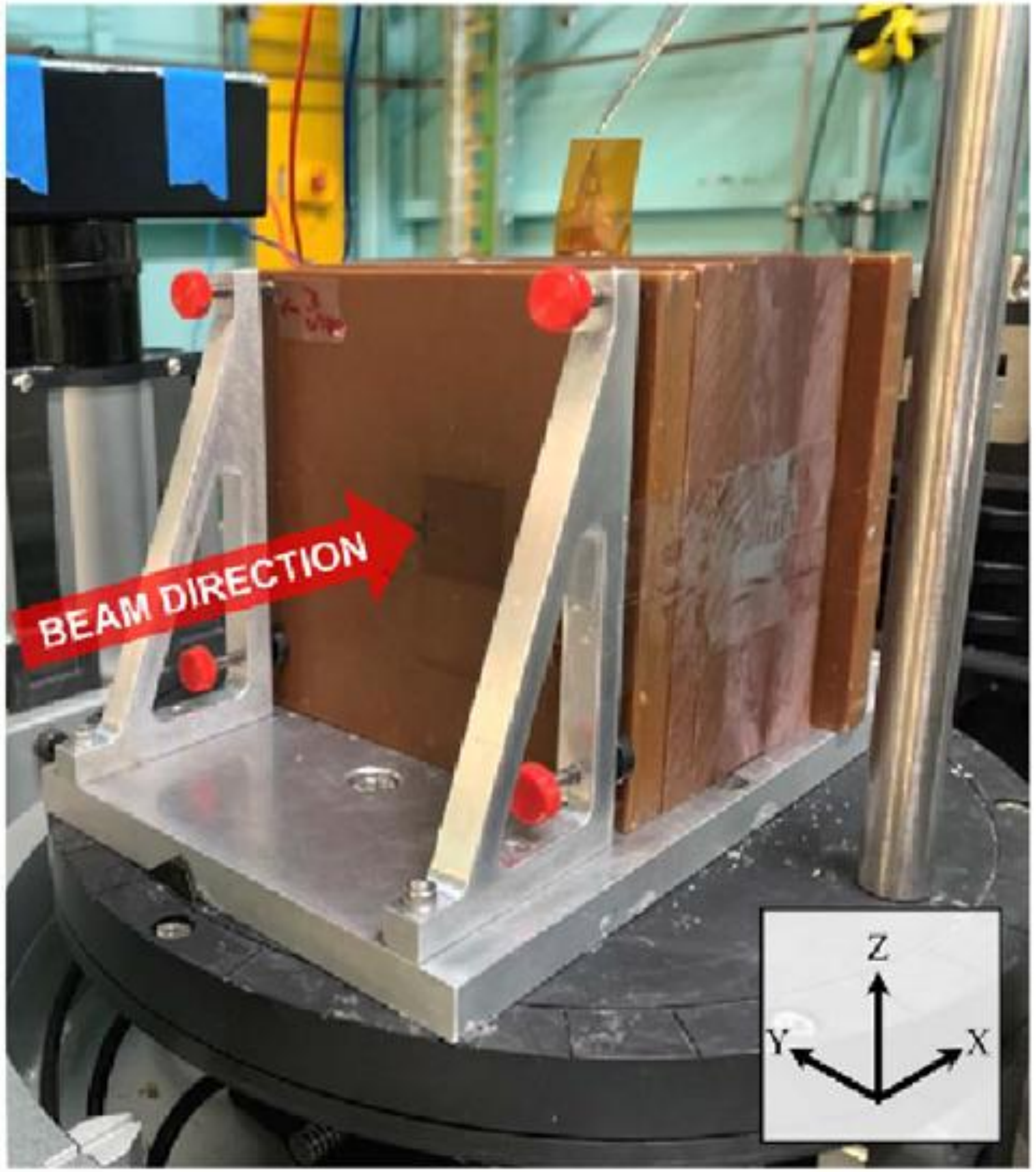
Beam filtration	Weighted average energy (keV)[a]	Delivered dose (Gy)[b]	Dose-rate (Gy s^{-1})
Mo–Mo	124	1.207 ± 0.045	22.12 ± 0.82
Cu–Cu	95.1	9.78 ± 0.36	179.1 ± 6.6
Cu–Al	82.9	25.08 ± 0.93	460 ± 17
Al–Al	55.0	219.8 ± 8.1	4027 ± 150

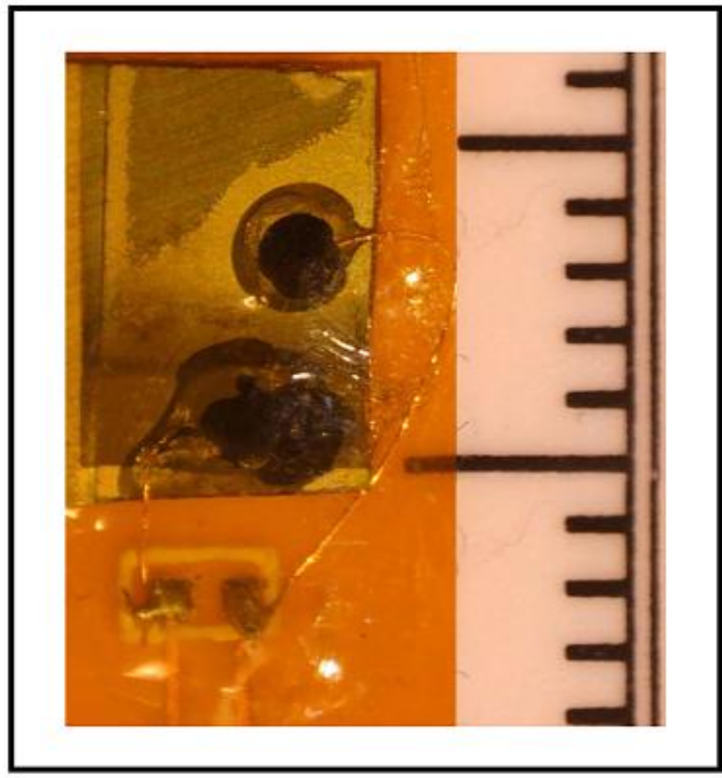
SYNCHROTRON

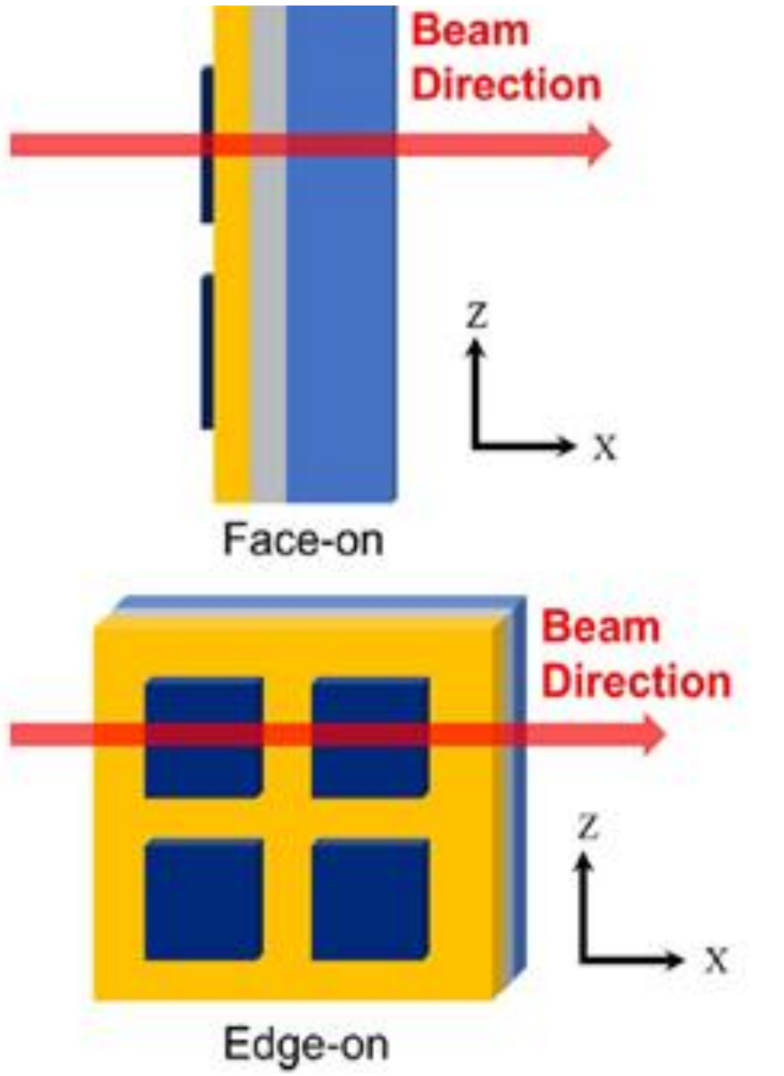
- ➢ **Beam modes:**
  – **broad beam (20 × 20 mm²)**
  – **microbeam (50 µm slits via collimator)**

- ➢ **Measurements performed in two detector configurations:**
  – ***face-on*** **for broad beam**
  – ***edge-on*** **for MRT microbeams**

- ➢ **Dose rates: 22–4027 Gy/s**

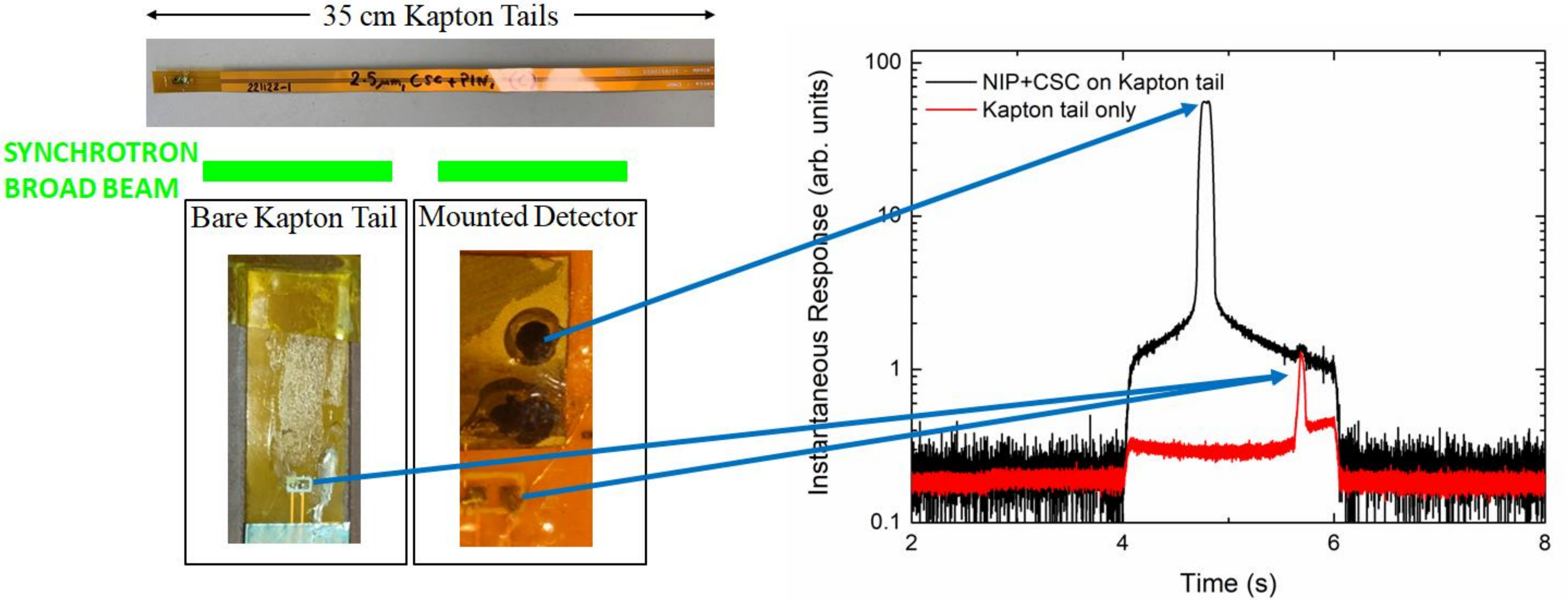






STEM EFFECT

- Signal induced in the kapton tail during beam exposure
- Comparison with bare tail shows a 3.6% contribution to the total detector response
- Main source: direct irradiation of the solder pads



SENSITIVITY MEASUREMENTS

- 2.5 µm intrinsic a-Si:H layer, pixels with a sensitive area of 1.5 × 1.5 mm^2

- Excellent linearity: R^2 between 0.9997 and 1.0000
- Highest sensitivity: 10.4 ± 0.03 pC/cGy with Cu–Al beam, 1 V bias, no pre-irradiation

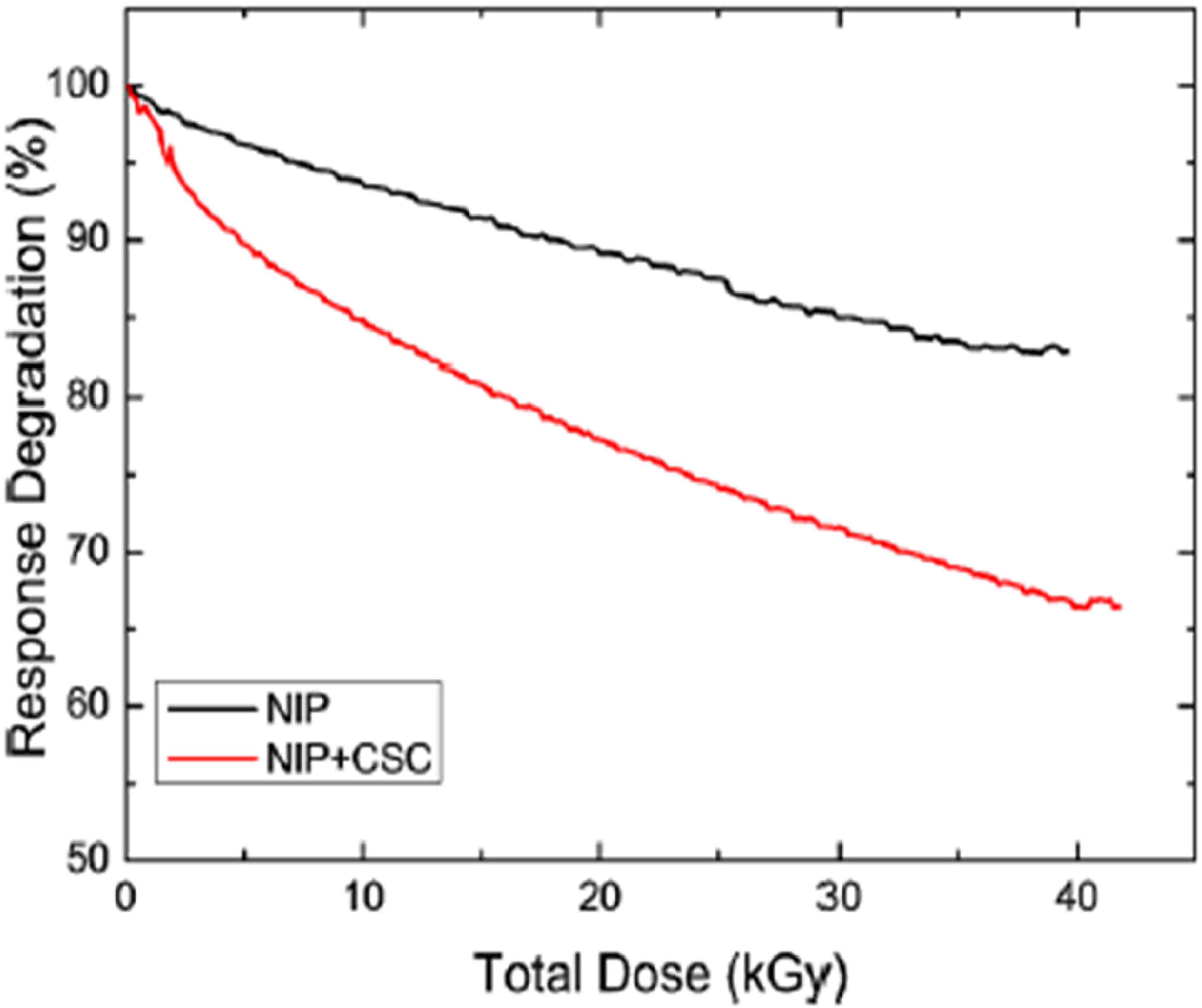
- At 0 kGy: +180% sensitivity gain with 1 V bias
- At 40 kGy: even larger gain, up to +234%

- Even after heavy irradiation, applying bias recovers much of the lost performance

		Sensitivity under 3T Beam Filtrations (pC/cGy)			
Pre-Irradiation	Detector Bias	Mo-Mo	Cu-Cu	Cu-Al	Al-Al
0 kGy	0 V	2.96 ± 0.01	4.57 ± 0.01	4.51 ± 0.02	8.64 ± 0.01
	1 V	5.50 ± 0.10	7.76 ± 0.01	10.4 ± 0.03	-
40 kGy	0 V	1.38 ± 0.01	2.33 ± 0.01	3.35 ± 0.01	5.92 ± 0.01
	1 V	3.71 ± 0.12	4.94 ± 0.01	7.39 ± 0.01	-

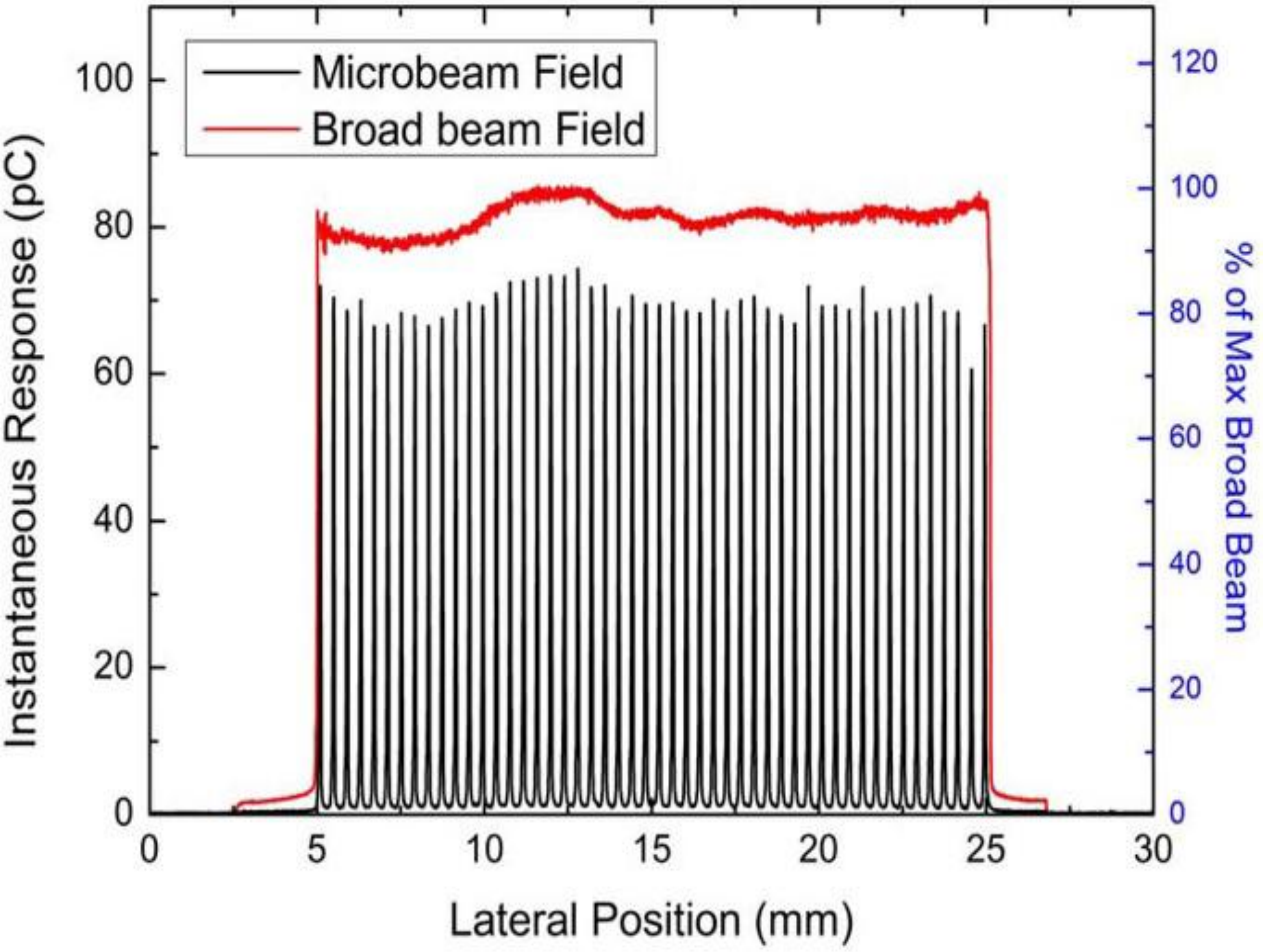
RADIATION TOLERANCE

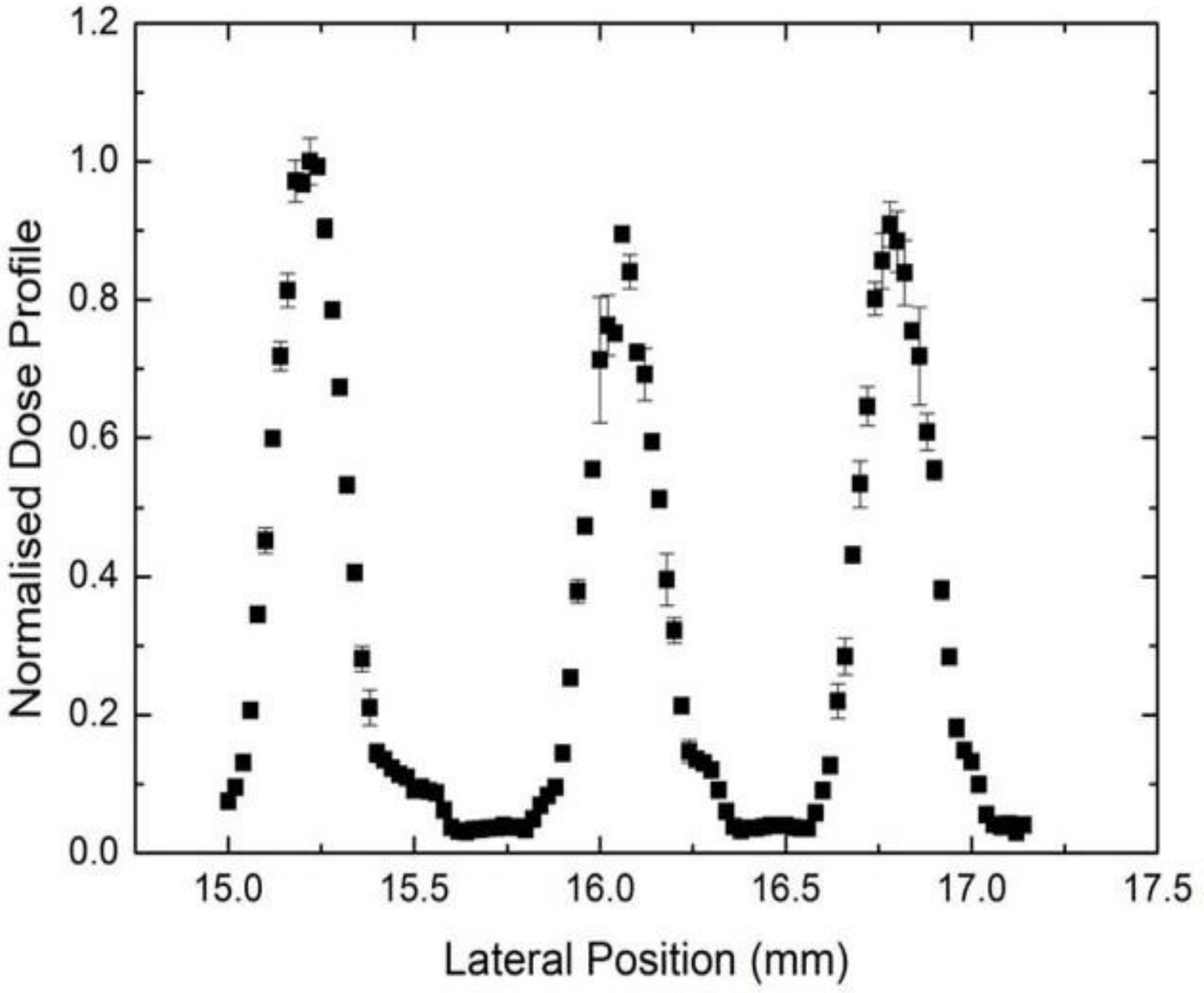
- Long-term exposure with Al–Al filtration
- NIP+CSC retains >66% of original response after 40 kGy
- NIP architecture shows better tolerance (only ~17% degradation) but lower sensitivity
- The difference is likely due to charge trapping at the additional CSC interface



MICROBEAM PROFILING

- Achieved spatial resolution: 2.5 μm (limited by the intrinsic layer thickness)
- FWHM of microbeam measured: 51 ± 1 μm
- Ideal for MRT field reconstruction and quality assurance

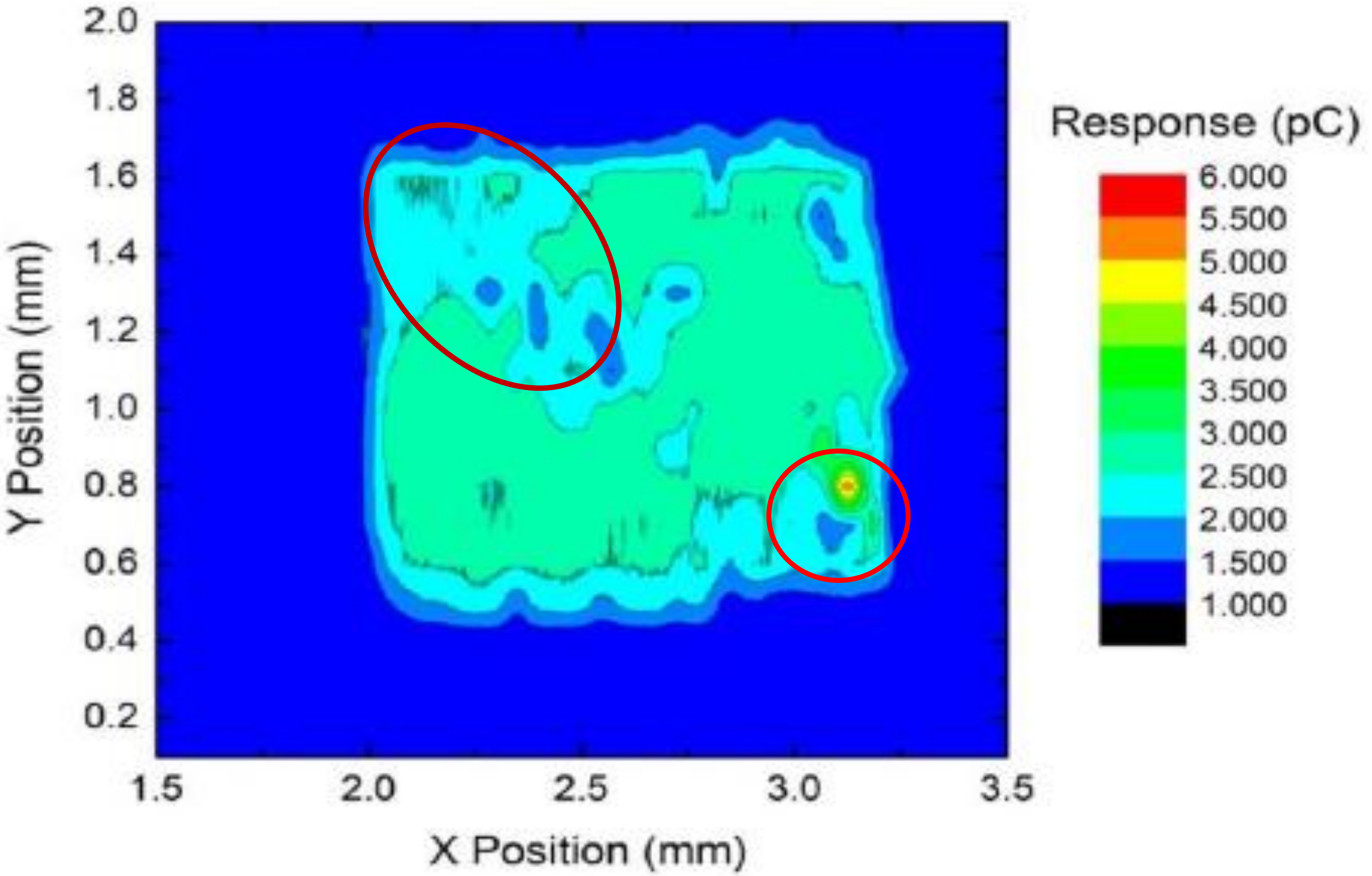


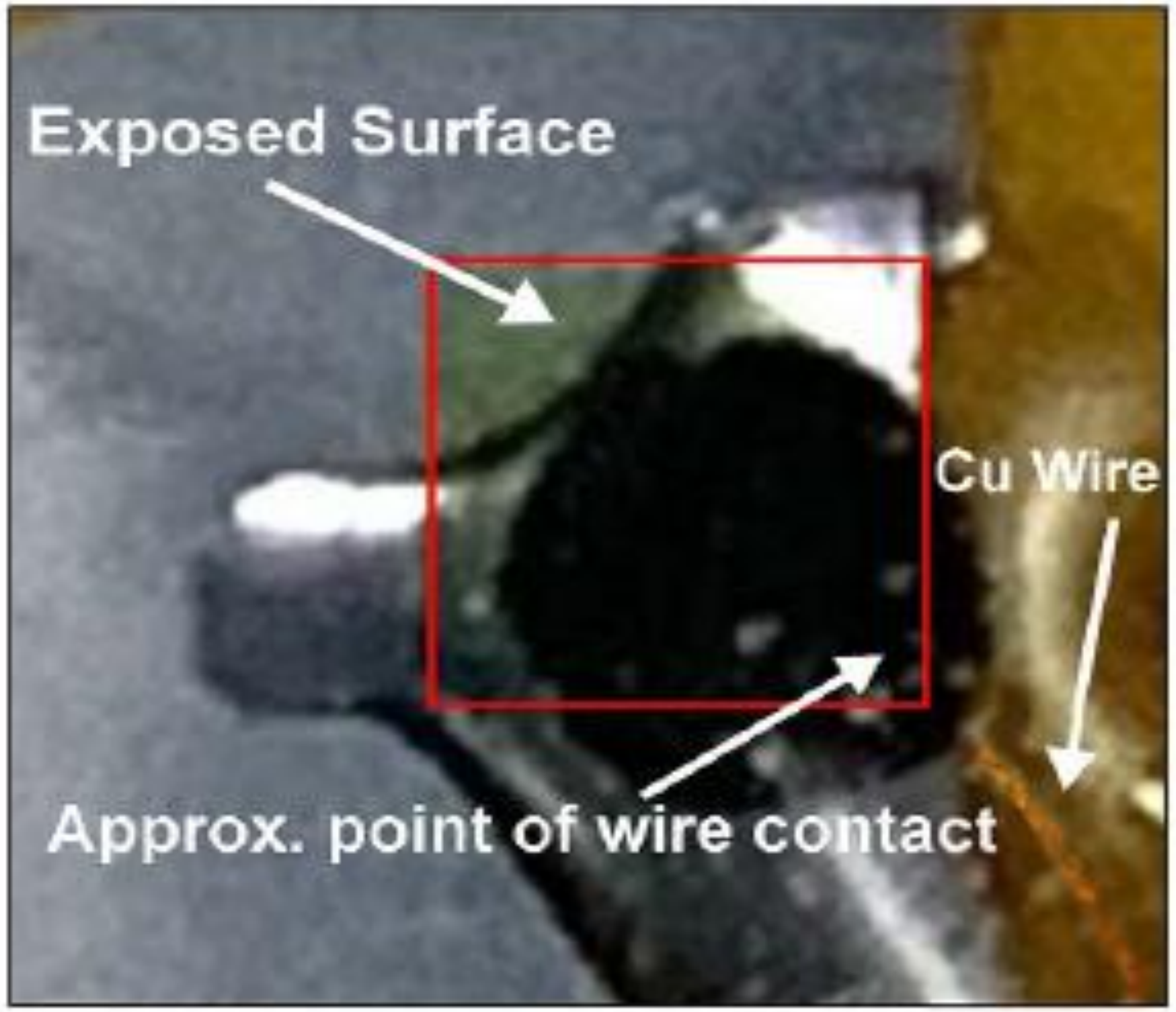


CHARGE COLLECTION MAP (XBIC)

- A single 50 × 50 µm microbeam was raster-scanned across the detector surface in 50 µm steps

- Bottom-right: stem effect from X-rays hitting Cu wire
- Top-left: Low-signal area, no epoxy → no signal enhancement from fluorescence
- No signal enhancement from carbon paint: confirms its low-Z composition avoids parasitic currents





FUTURE APPLICATIONS

POSSIBLE CLINICAL USE CASES:

SINGLE PIXEL DEVICES

– Skin surface dosimetry
– In-vivo monitoring during total body irradiation (TBI)

SMALL LINEAR ARRAYS (3-5 PIXELS):

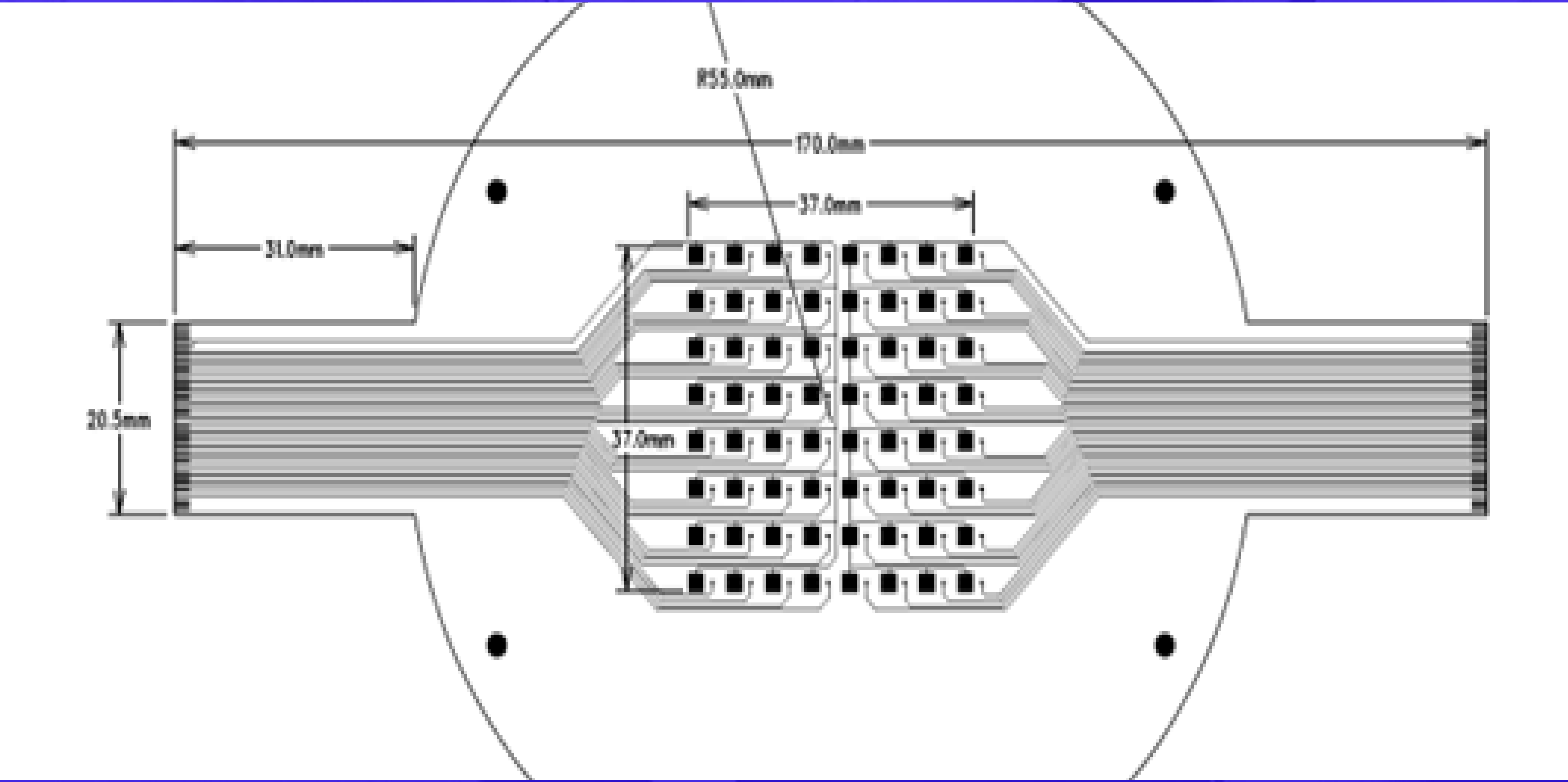
– Skin dose mapping in 3D-conformal breast treatments (e.g. steep dose gradients on the skin surface)
– Localized monitoring in soft tissue sarcoma treatments

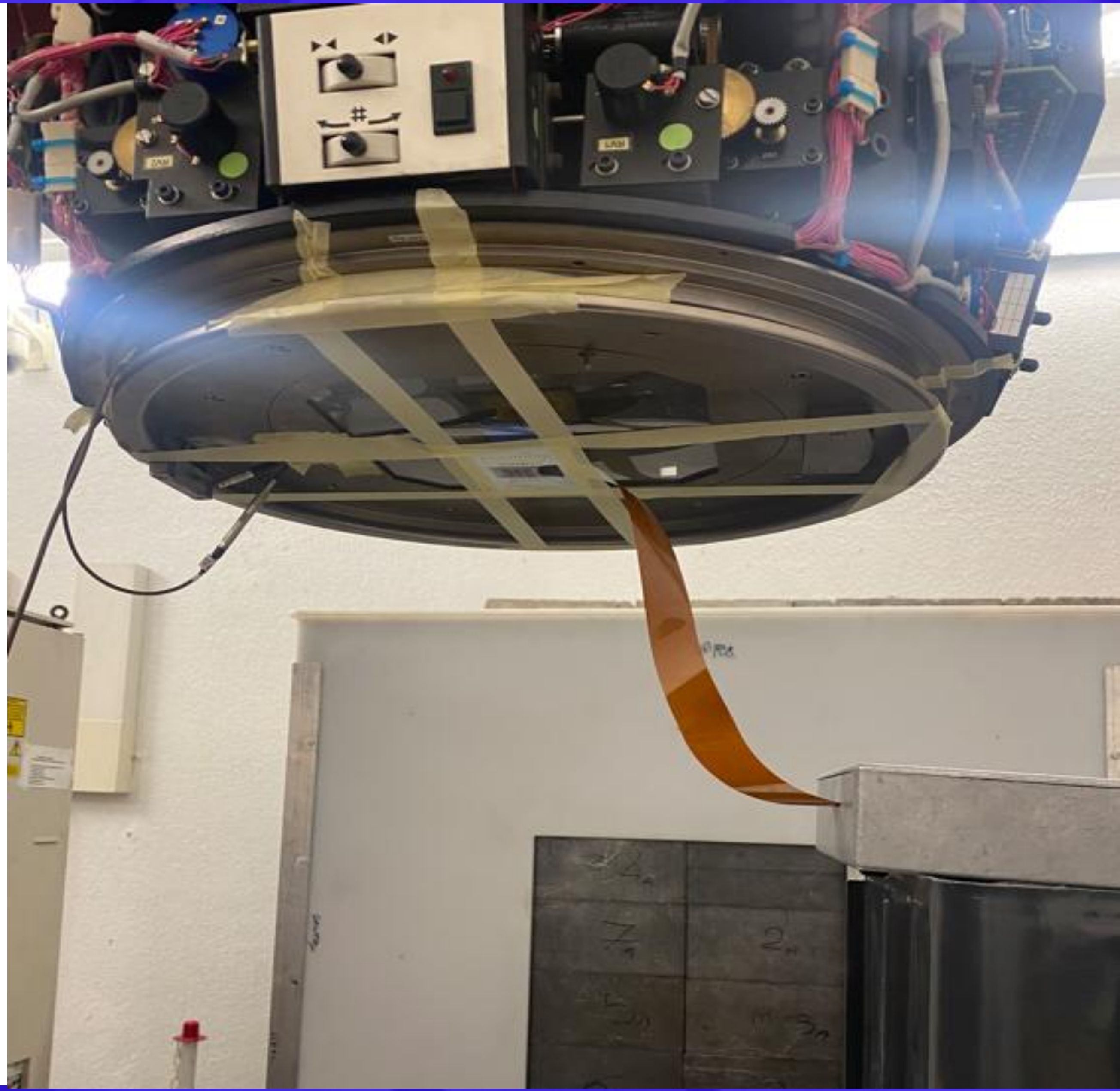
LARGE LINEAR ARRAYS (12+ PIXELS):

– Real-time beam profiling with 2 mm resolution
– Beam monitoring in ultra-high dose rate treatments, such as synchrotron microbeams and FLASH therapy

TRANSMISSION DEVICES

INSTRUMENTED ACCELERATOR'S EXIT WINDOW





Device with 2x2 mm^2 PIN diodes on flexible substrate,
2.5 um thick
total thickness ~ 100 um

Thank you

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