Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Wearable, Lightweight and Flexible Ionizing Radiation Dosimeters for Real-Time Monitoring

Andrea Ciavatti

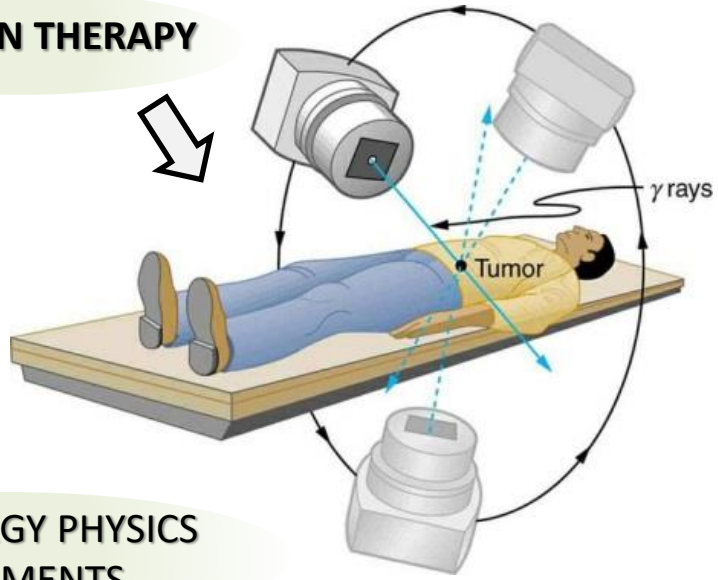
University of Bologna, Department of Physics and Astronomy, Bologna, Italy
National Institute for Nuclear Physics INFN, Section of Bologna, Bologna, Italy

andrea.ciavatti2@unibo.it

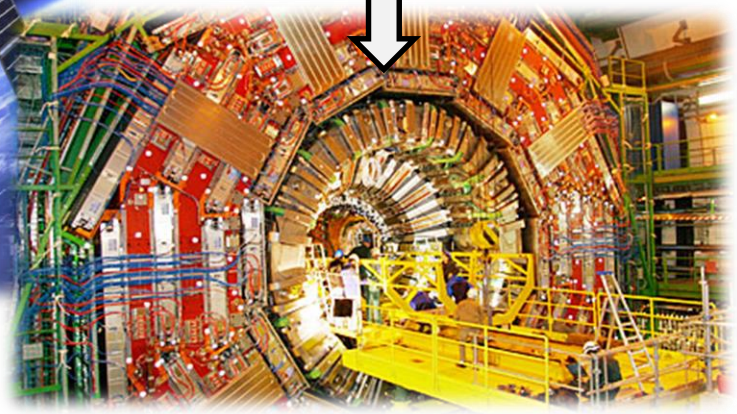
THIN FILM AND LARGE AREA: WHERE?

SPACE MISSIONS

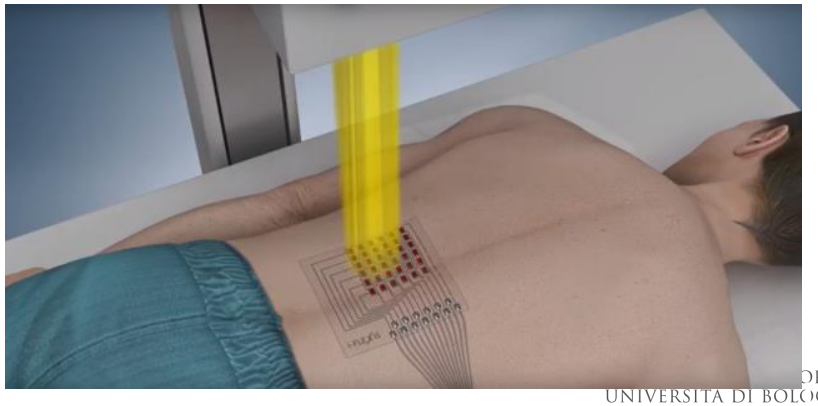
RADIATION THERAPY



HIGH ENERGY PHYSICS EXPERIMENTS



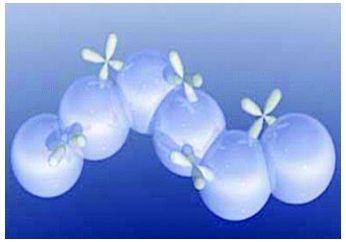
- **Light-weight** for limited amount of materials
- Possibility to **cover large surfaces** at low cost
- **Real-time** beam monitoring
- **Radiation hard** to strong fluxes due to weak radiation abortion
- **In-situ** dose evaluation thank to conformability to human tissues



FLEXIBLE LARGE AREA ELECTRONICS: MATERIAL PLATFORMS

High Mobility Oxide Semiconductors

e.g. $Ga_xIn_yZn_ZO$



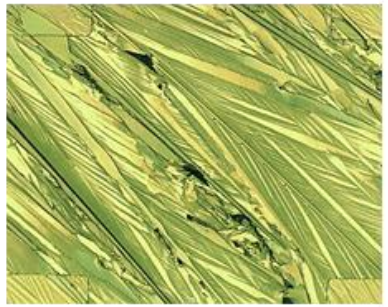
Physical/solution deposizion

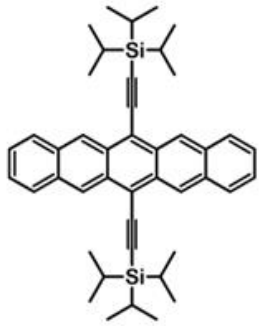
$\mu = 10 – 50\ cm^2/Vs$

*T. Cramer et al., Sc.Adv., **4**, 63 (2018)*
*C. Bordoni et al., APL Mater., **12**, 031106 (2024)*

Organic Semiconductors

e. g. TIPS pentacene





A. Tamayo et al., Adv. Electron. Mater. 2200293 (2022)

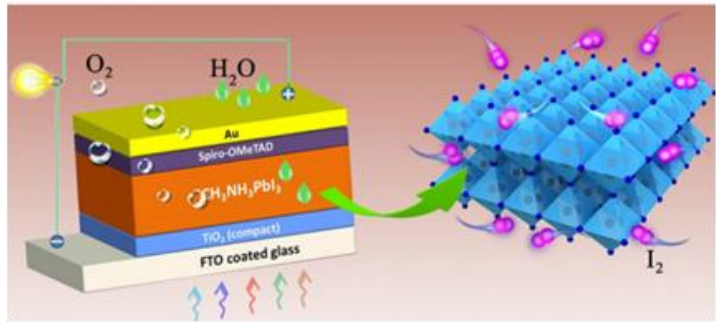
solution deposition

$\mu = 1\ cm^2/Vs$

*L. Basiricò et al. Nature Comm **7**, 13063 (**2016**)*
*I.Temino et al., Nature Comm. **11**, 235 (**2020**)*

Perovskites

e. g. $MAPbI_3$

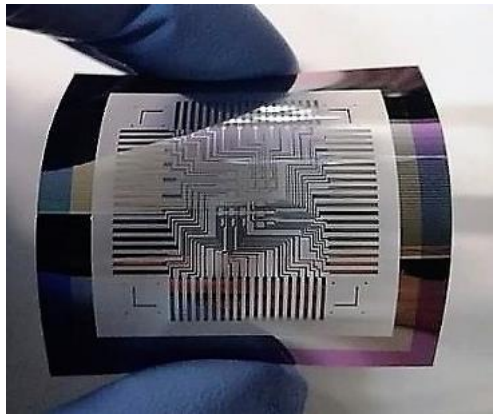


solution deposition

$\mu = 1\text{-}600\ cm^2/Vs$

*A.Ciavatti et al., Adv. Funct. Mater. **29**, 1902346 (**2019**)*

Radiation sensitive OXide Field Effect Transistors (ROXFETs)



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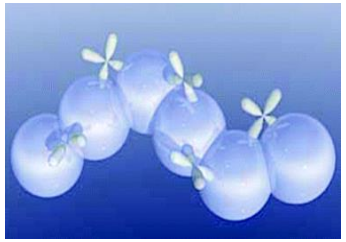
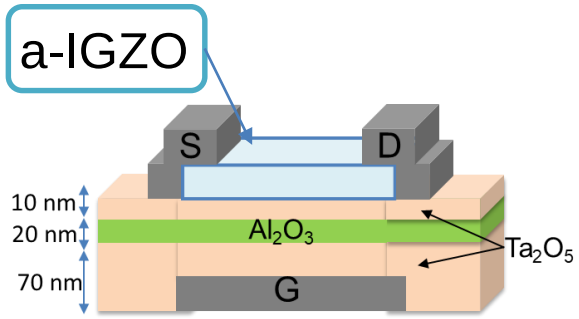
e.g. $Ga_xIn_yZn_ZO$



Physical/solution deposizion
$\mu = 10 - 50\ cm^2/Vs$

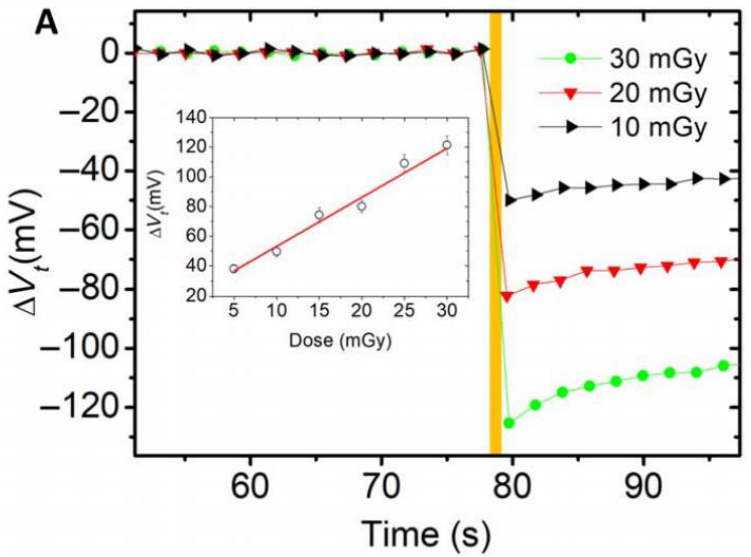
*T. Cramer et al., Sc.Adv., **4**, 63 (2018)*
*C. Bordoni et al., APL Mater., **12**, 031106 (2024)*

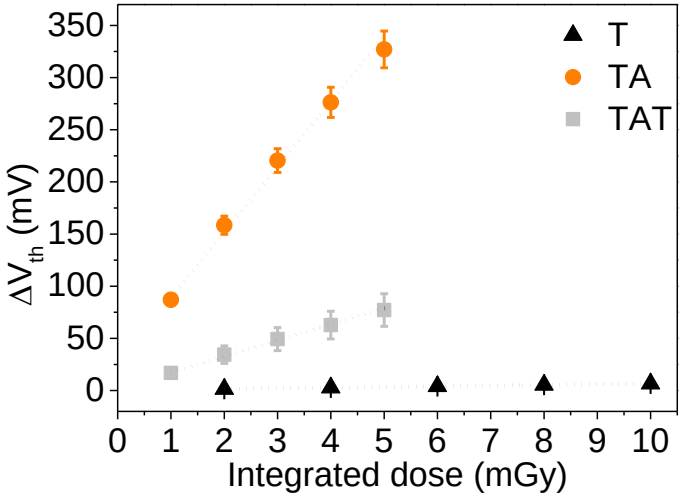


Ta_2O_5 (κ=26, Z=73)
Al_2O_3 (E_g>8 eV)

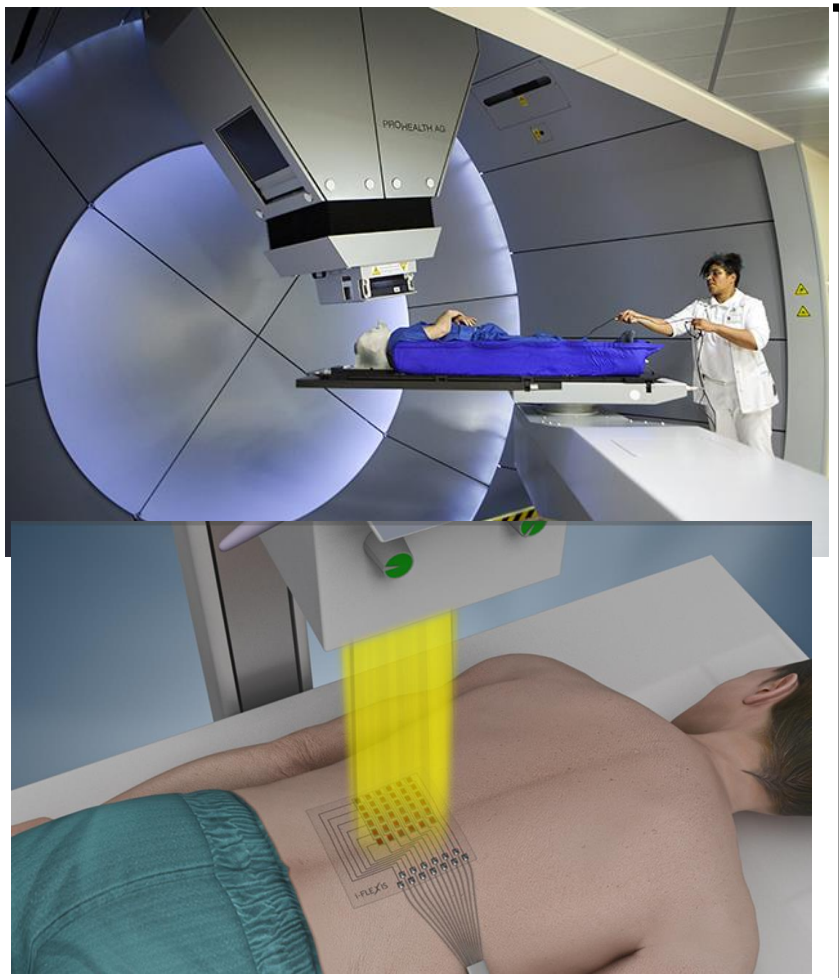
S_{ROXFET} = 63±2 V/Gy

(S_{RADFET} < 0.30 V/Gy)



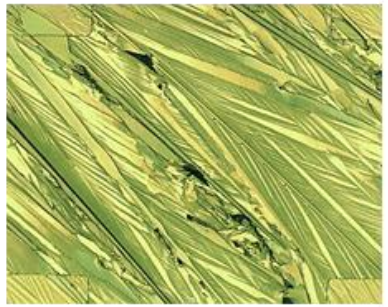


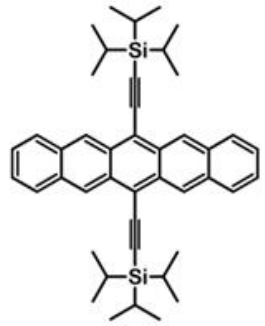
FLEXIBLE LARGE AREA ELECTRONICS: MATERIAL PLATFORMS



Organic Semiconductors

e. g. TIPS pentacene





A. Tamayo et al., Adv. Electron. Mater. 2200293 (2022)

solution deposition

μ = 1 cm^2/Vs

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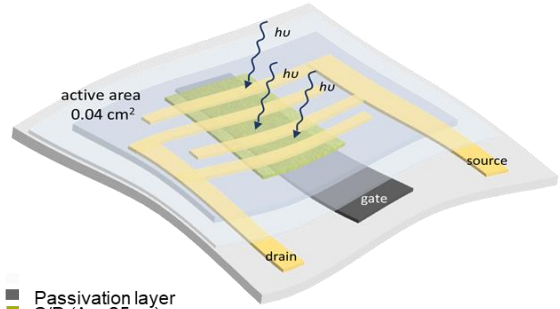
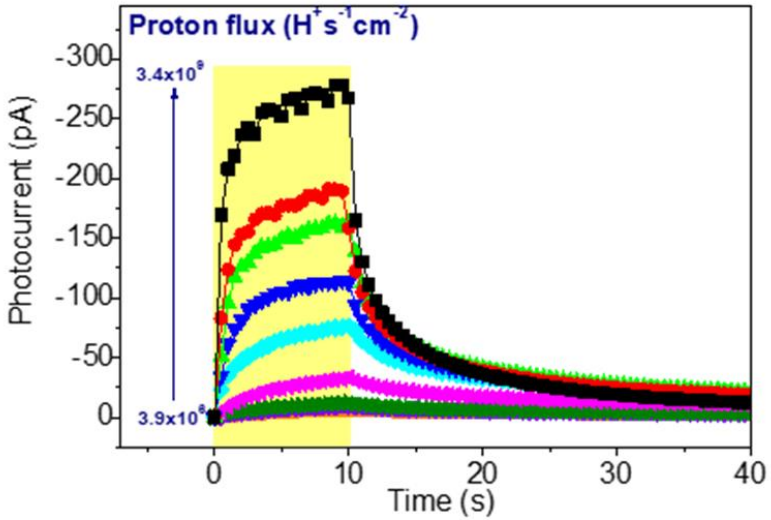
I.Temino et al., Nature Comm. ***11****, 235 (****2020****)*





Calvi, S., Basiricò, L., et al., Nature *Npj Flexible Electronics*, 1–11(2023)

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FLEXIBLE LARGE AREA ELECTRONICS: MATERIAL PLATFORMS

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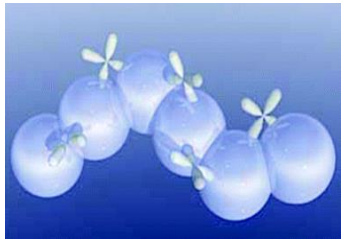

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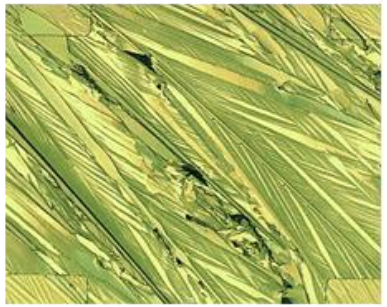

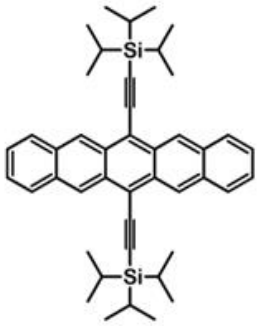

A. Tamayo et al., Adv. Electron. Mater. 2200293 (2022)

solution deposition

μ = 1 cm^2/Vs

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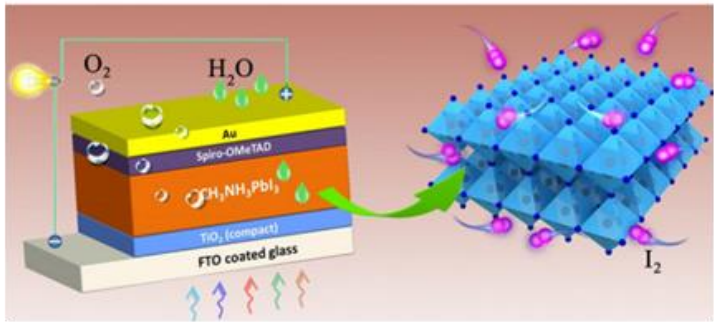
*I.Temino et al., Nature Comm. **11**, 235 (**2020**)*

Perovskites

e. g. $MAPbI_3$

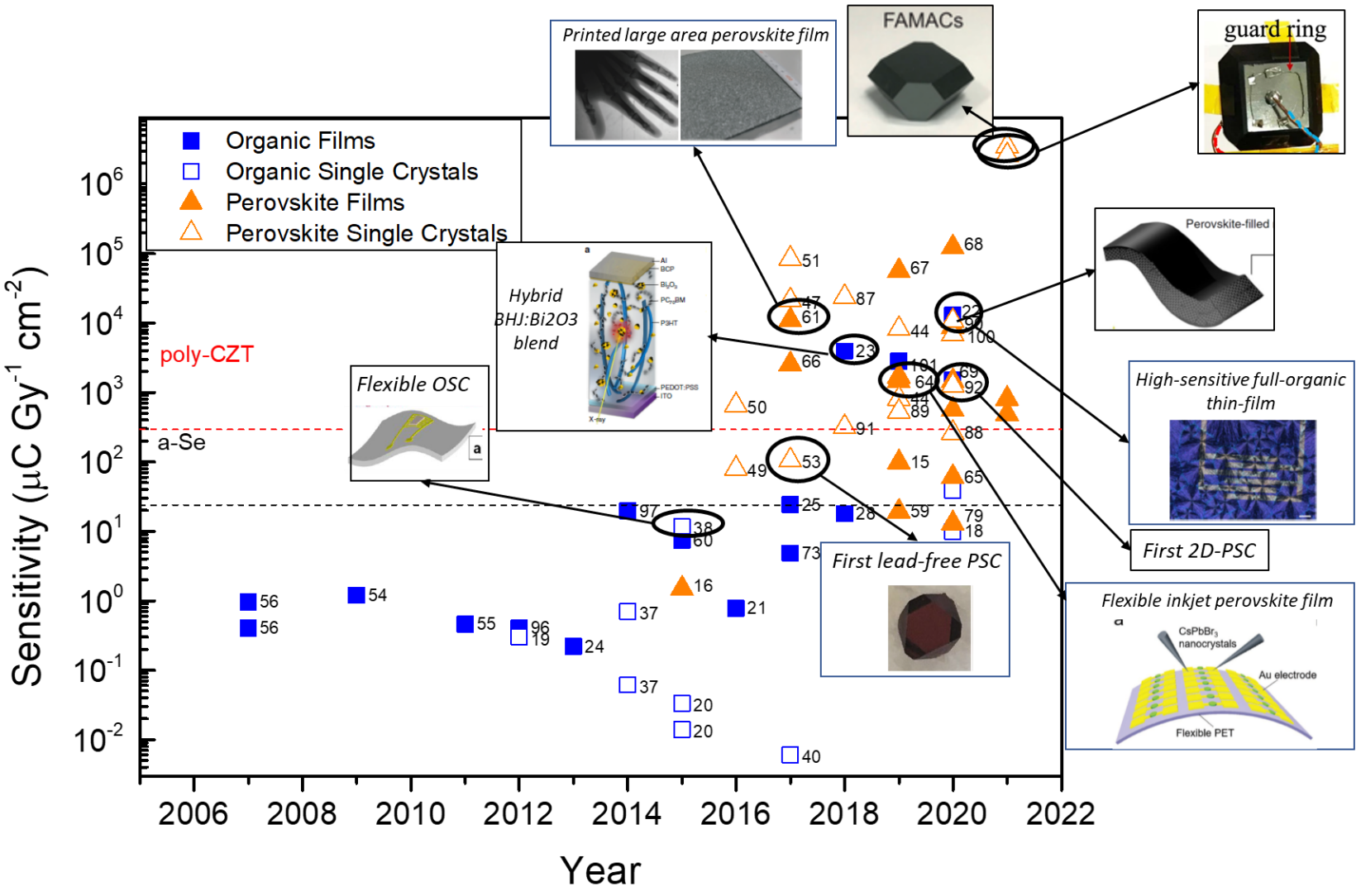


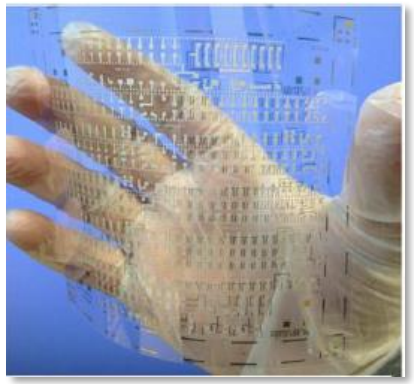
solution deposition

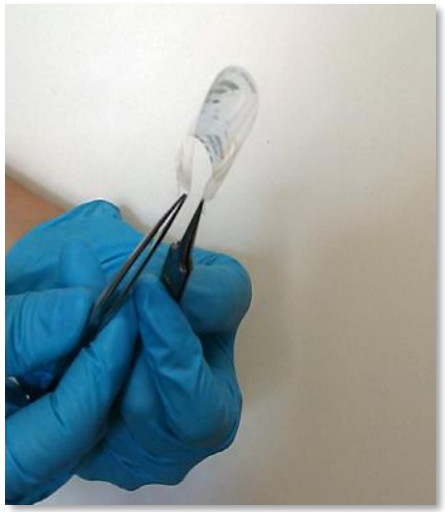
μ = 1-600 cm^2/Vs

*A.Ciavatti et al., Adv. Funct. Mater. **29**, 1902346 (**2019**)*

ORGANIC/HYBRID MATERIALS FOR X-RAY RADIATION DETECTION







L. Basiricò et al., Adv. Mater. Technol. ***2020,*** *2000475*

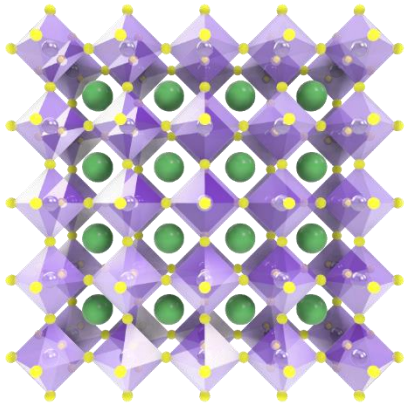
3D vs 2D Metal Halide Perovskites

3D

$APbX_3$

Organic cation (MA, FA)

Halogen anion (I, Br, Cl)



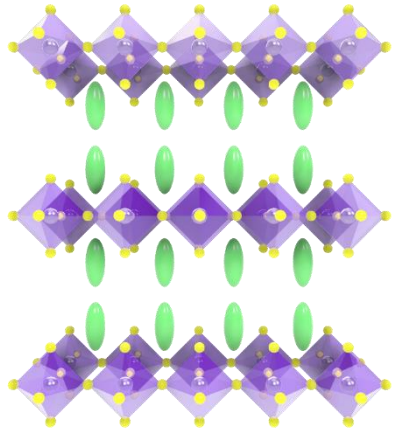
- High X-ray stopping power, comparable to CZT.
- Large carriers diffusion length
- Low cost, low temperature <150˚C deposition from solution.
- Optoelectronic properties tuning by controlling the relative amounts of the components

2D

A_2PbX_4

Organic cation (PEA, BA)

Halogen anion (I, Br, Cl)



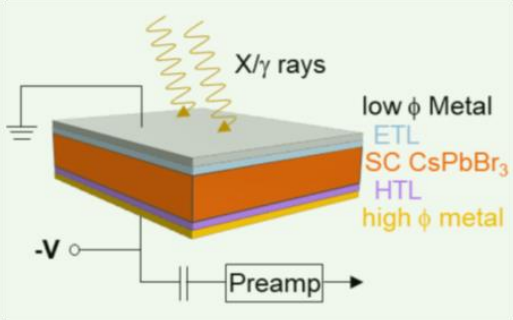
- High X-ray stopping power.
- **Lower mobility**
- **Lower Ion migration**
- **Better stability**
- Low cost, low temperature <150˚C deposition from solution.
- Optoelectronic properties tuning by controlling the relative amounts of the components

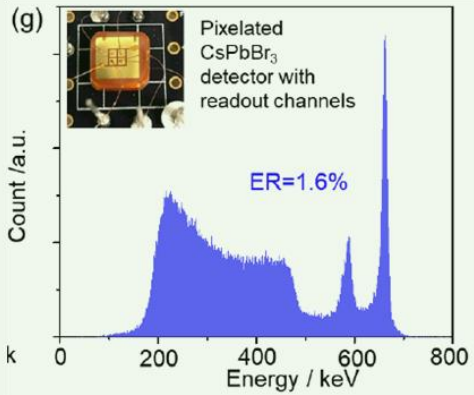
Perovskite Single Crystals

Bridgman crystals - CsPbBr3

Energy resolution = 1.4 % ^{137}Cs

RadHard up to 10 Mrad





He, Y. et al. Nat. Photonics 15, 36–42 (2021)

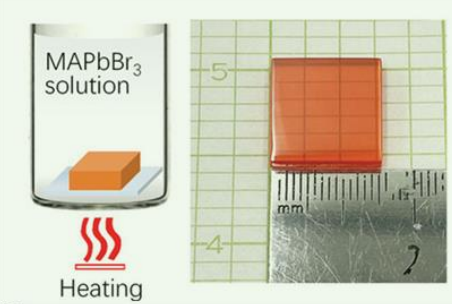
M. C. De Siena et al. *Adv. Mater.* 35, 2303244 (2023)

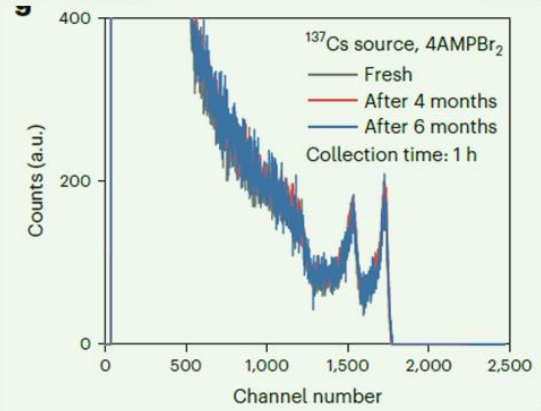
Solution-grown crystals

4AMPBr2 and FAPbBr3

ER up to 1.7 % ^{137}Cs

Stable over 6 months





Z. Ni et al. *Adv. Mater.* 36, 2406193 (2024)

L. Zhao et al. *Nat. Photon.* **18**, 250–257 (2024)

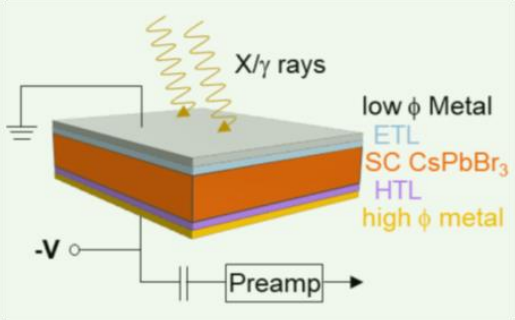
X/γ-rays

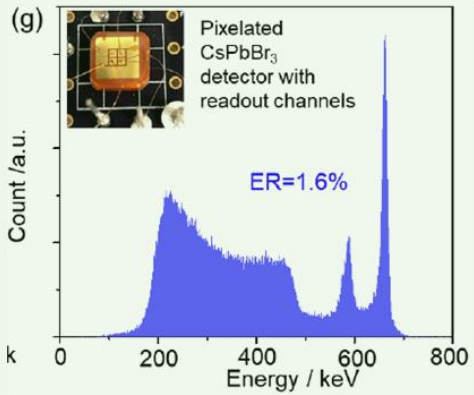
Perovskite Single Crystals

Bridgman crystals - CsPbBr3

Energy resolution = 1.4 % ^{137}Cs

RadHard up to 10 Mrad





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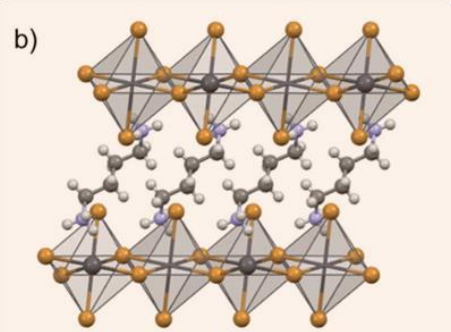
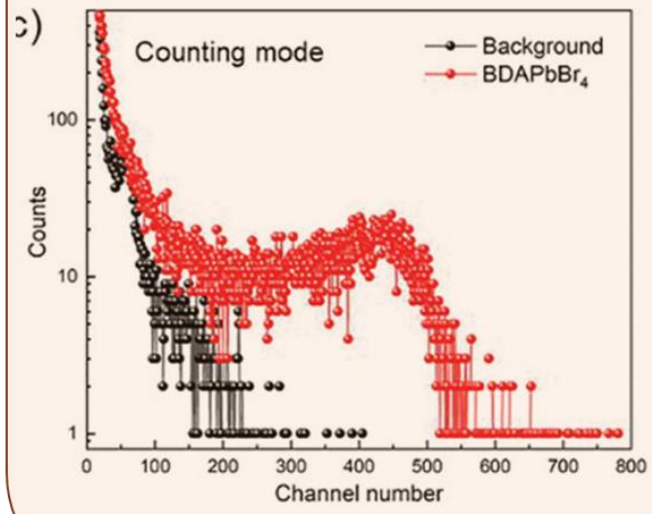
M. C. De Siena et al. *Adv. Mater.* 35, 2303244 (2023)

2D perovskite - (BDA)PbBr4



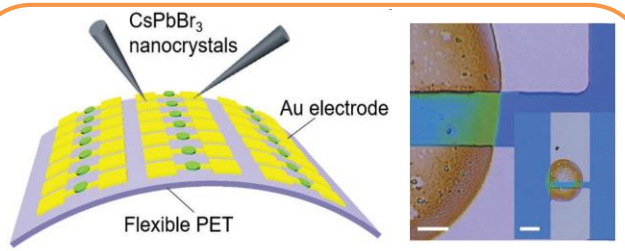


Y. Gao et al. Small, 19: 2301530 (2023)

X/γ-rays

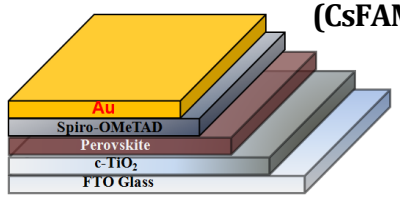
neutrons

Perovskite Thin Films

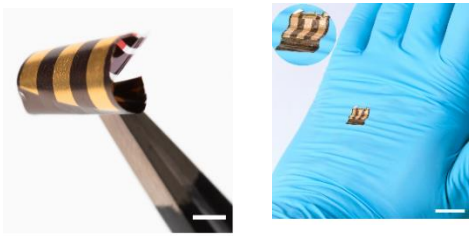


Liu et al. Adv. Mater. ***2019****, 31, 1901644*
Flexible, Printable Soft-X-Ray Detectors Based on All-Inorganic Perovskite Quantum Dots
Very thin film (20nm) – low absorption
Low energy <8keV
Sensitivity flex 17.7 µC Gy^{-1} cm^{-2}
Response time 30 ms

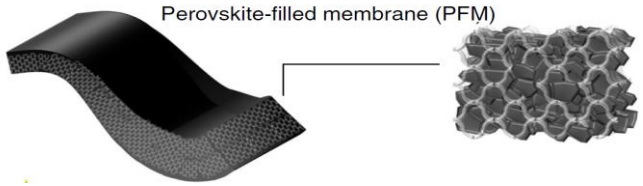
$Cs_{0.05}(MA_{0.17}FA_{0.78})Pb(I_{0.8}Br_{0.2})_3$
(CsFAMA)



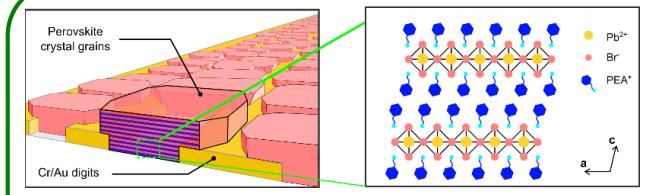
L. Basiricò, et. Al, Adv. Func. Mater. ***2019****, 1902346*
Detection of X-Rays by Solution-Processed Cesium-Containing Mixed Triple Cation Perovskite Thin Films
Sensitivity 40 µC Gy^{-1} cm^{-2} @ 80V



S. Demchyshyn et al.. Adv. Science ***2020***
Designing ultraflexible perovskite X-ray detectors through interface engineering
Ultraflexible substrate (1.4µm thick)
Sensitivity 9.3 µC Gy^{-1} cm^{-2} @ 0V



Zhao et al. Nat. Photonics ***14,*** *612(****2020****).*
Perovskite-filled membranes for flexible and large-area direct-conversion X-ray detector arrays
Sensitivity 8696 µC Gy^{-1} cm^{-2}
Bending radius 2 mm



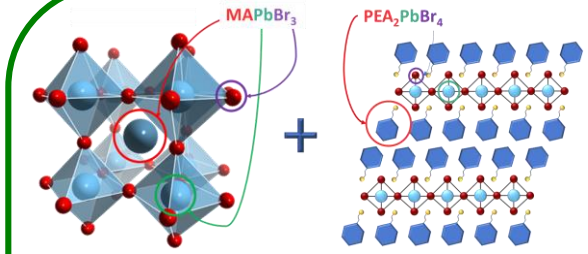
2D perovskite PEA_2PbBr_4

*F.Ledee et al. Advanced Optical Materials 10 (****2022****)*

Ultra-Stable and Robust Response to X-Rays in 2D Layered Perovskite Micro-Crystalline Films on Flexible Substrate
Solution deposited 1-3 micron thick films; dark current 10^{-13} A at 500 V mm-1 (no interlayers); Stable up to 80 days
Limit of Detection down to 42 nGy/s

X-rays
γ-rays

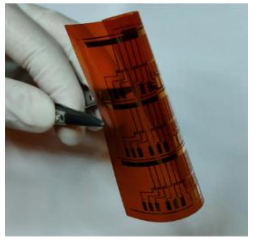
Perovskite Thin Films



2D/3D blends

Protons (5MeV -70MeV)

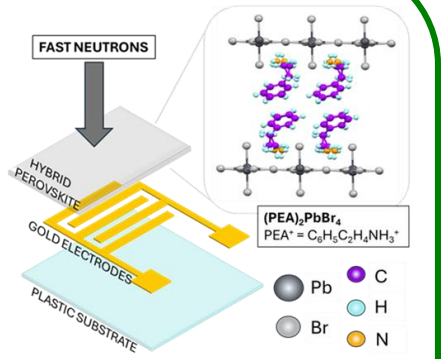
Basiricò L. et al., *Adv. Sci.* ***2023****,10, 2204815*
Mixed 3D-2D perovskite flexible films for the direct detection of 5 MeV protons



response scales with proton flux;
stable after 25Gy
$Sensitivity_V = (290 \pm 40)$ nC $Gy^{-1}mm^{-3}$
LoD at 1V as low as (1.06 ± 0.03) × 10^5 $H^+s^{-1}cm^{-2}$

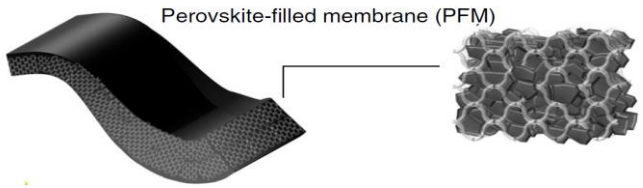
2D perovskite PEA_2PbBr_4

Fast neutrons (2.5MeV)



I.Fratelli. et al.,
submitted ***2024***

response scales with proton flux;
sensitivity $S = (2.6 \pm 0.2) \cdot 10^{-18}$ C n^{-1}
neutron flux range = $[0.4; 1; 2; 3] \cdot 10^5$ n s^{-1}
Bias=5 V



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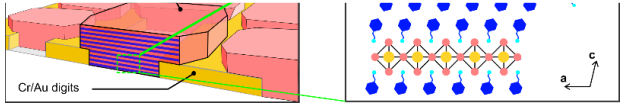
Sensitivity 8696 µC Gy^{-1} cm^{-2}
Bending radius 2 mm



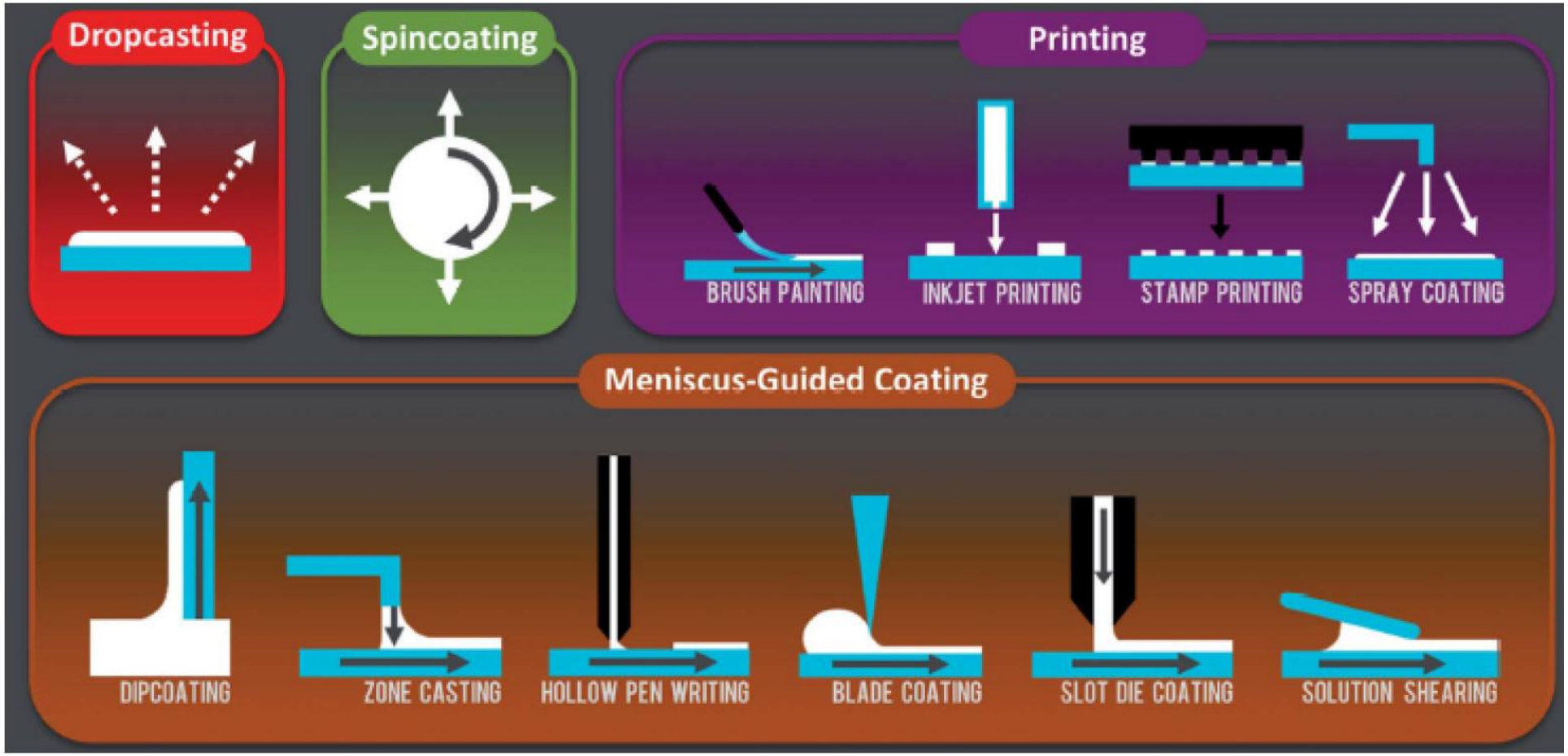
PEA_2PbBr_4

*F.Ledee et al. Advanced Optical Materials 10 (****2022****)*

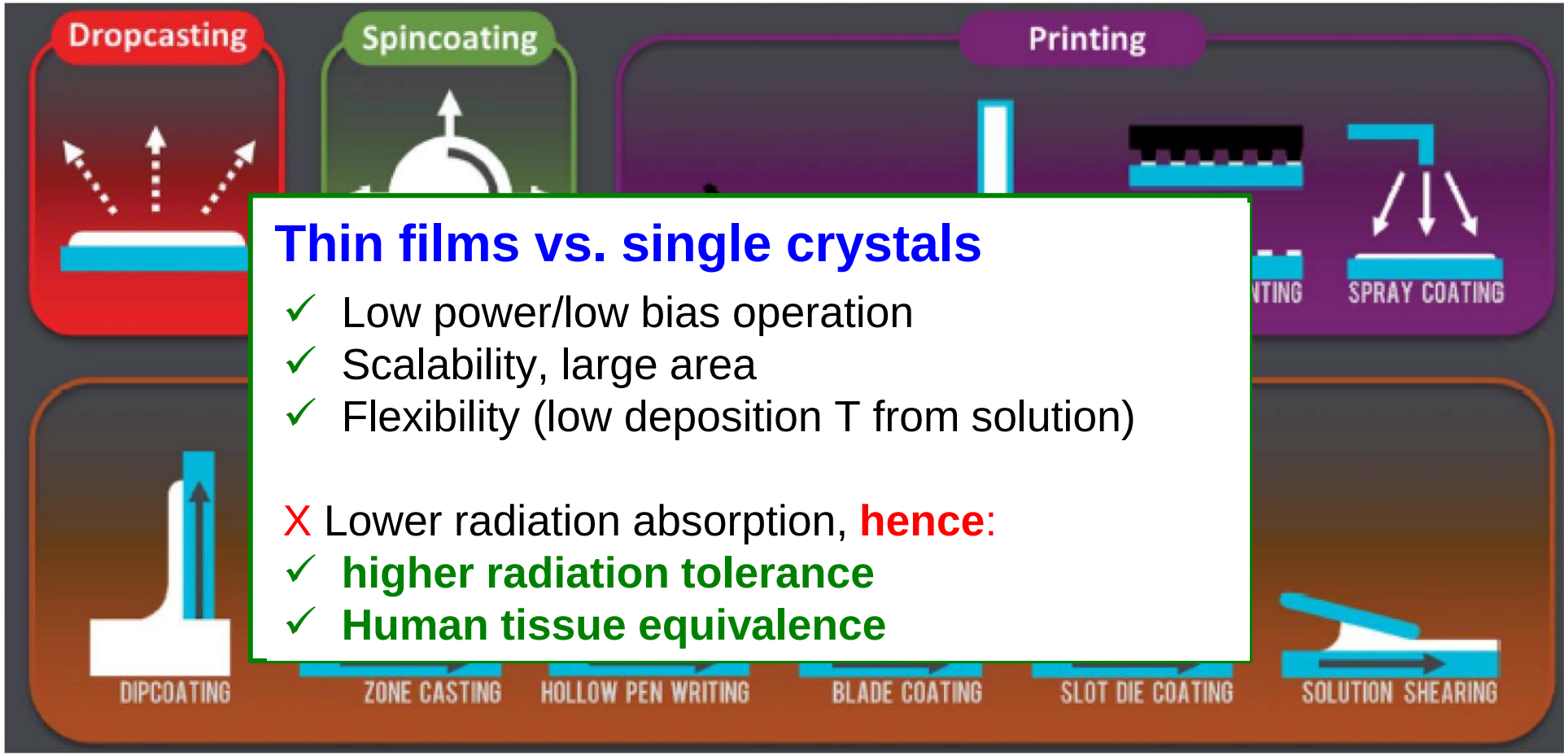
Ultra-Stable and Robust Response to X-Rays in 2D Layered Perovskite Micro-Crystalline Films on Flexible Substrate
Solution deposited 1-3 micron thick films; dark current 10^{-13} A at 500 V mm-1 (no interlayers); Stable up to 80 days
Limit of Detection down to 42 nGy/s

X-rays
γ-rays
protons
neutrons

PRINTED FLEXIBLE ELECTRONICS FOR A SUSTAINABLE FUTURE



PRINTED FLEXIBLE ELECTRONICS FOR A SUSTAINABLE FUTURE



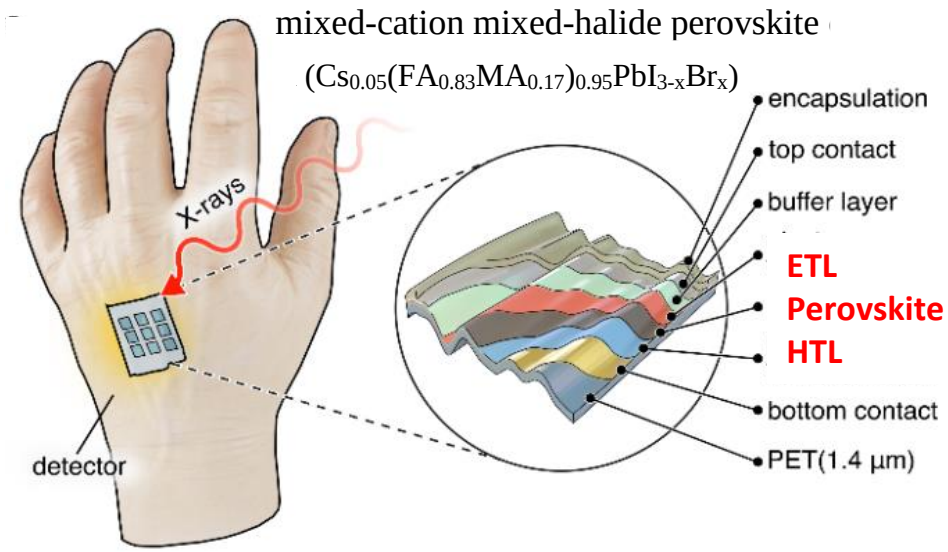
Thin films vs. single crystals

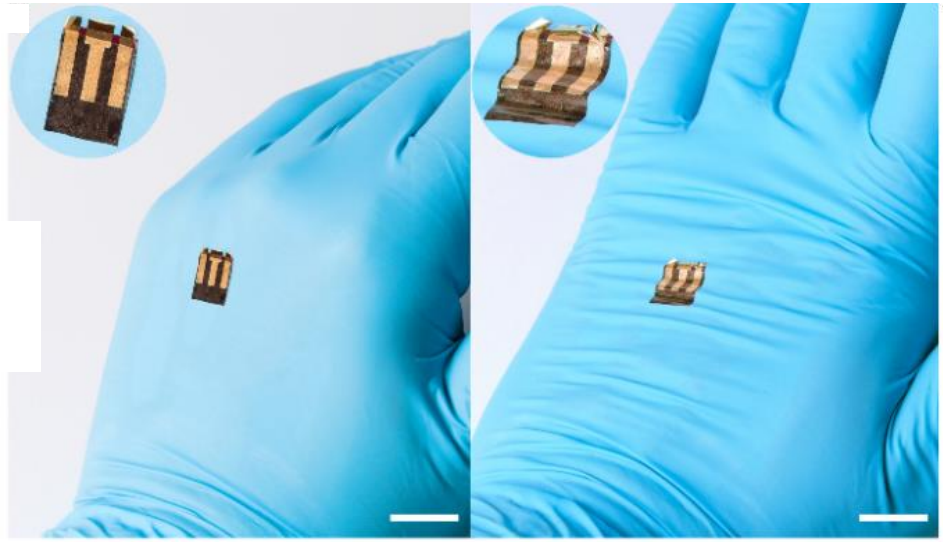
- ✓ Low power/low bias operation
- ✓ Scalability, large area
- ✓ Flexibility (low deposition T from solution)

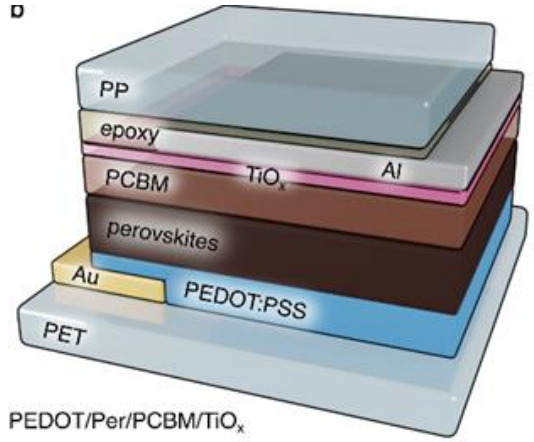
X Lower radiation absorption, **hence**:

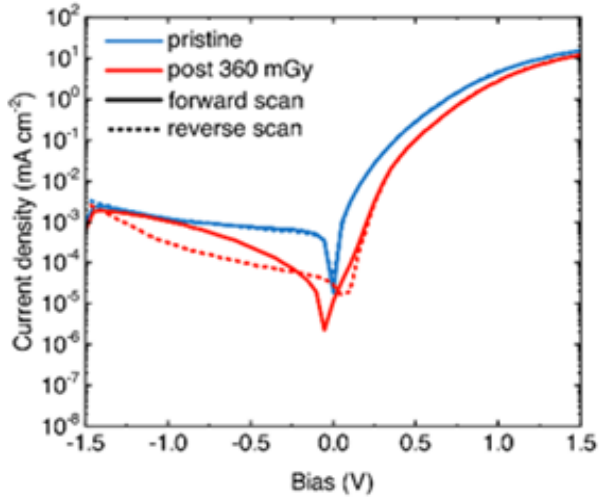
- ✓ **higher radiation tolerance**
- ✓ **Human tissue equivalence**

Direct X-ray detection by 3D perovskite thin films:
Ultraflexible and fully passive (bias=0V)



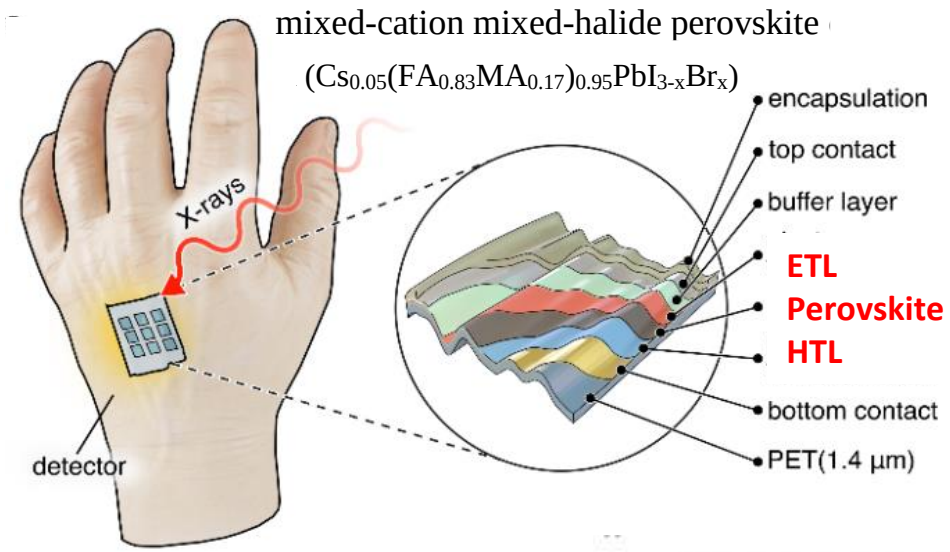


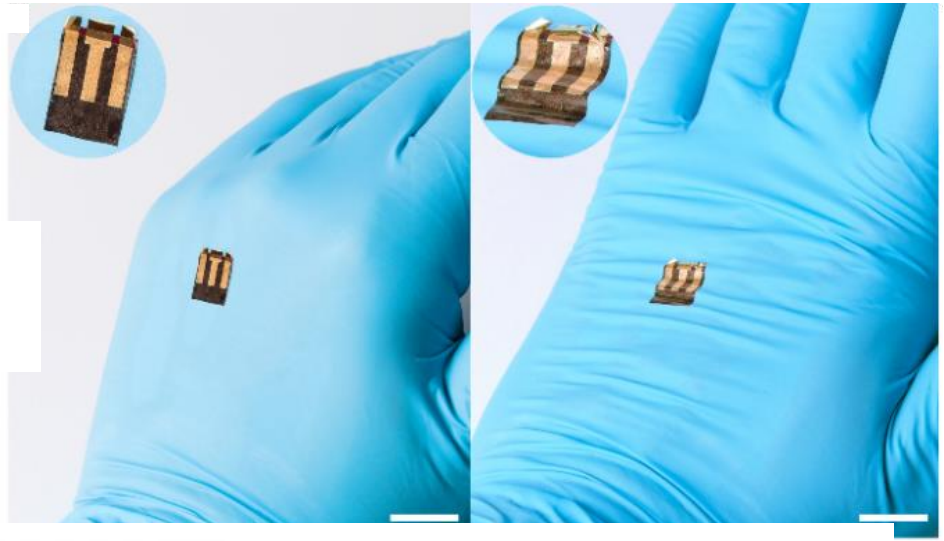


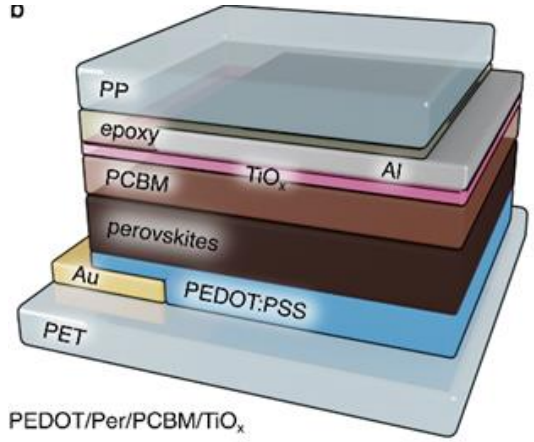


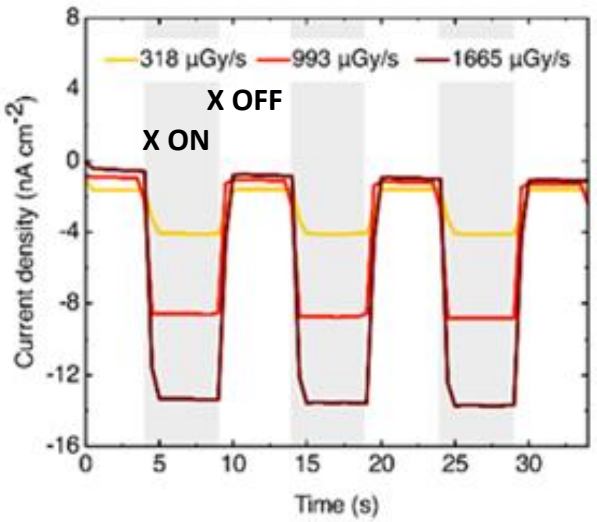
S.Denchyshyn et al *Advanced Science,* 24 2002586 ***(2020)***

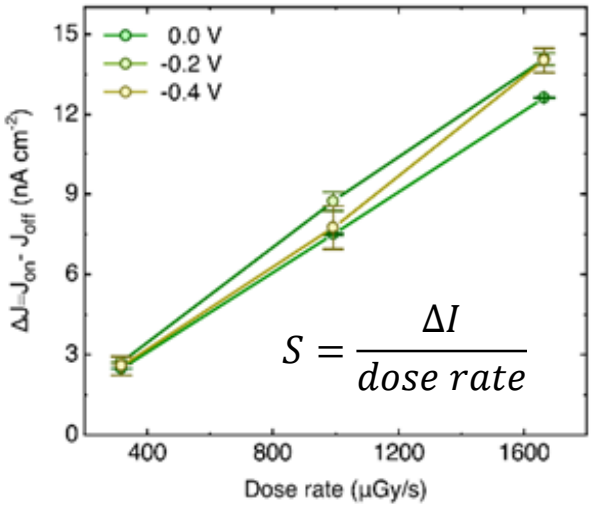
Direct X-ray detection by 3D perovskite thin films:
Ultraflexible and fully passive (bias=0V)











S.Denchyshyn et al *Advanced Science,* 24 2002586 ***(2020)***

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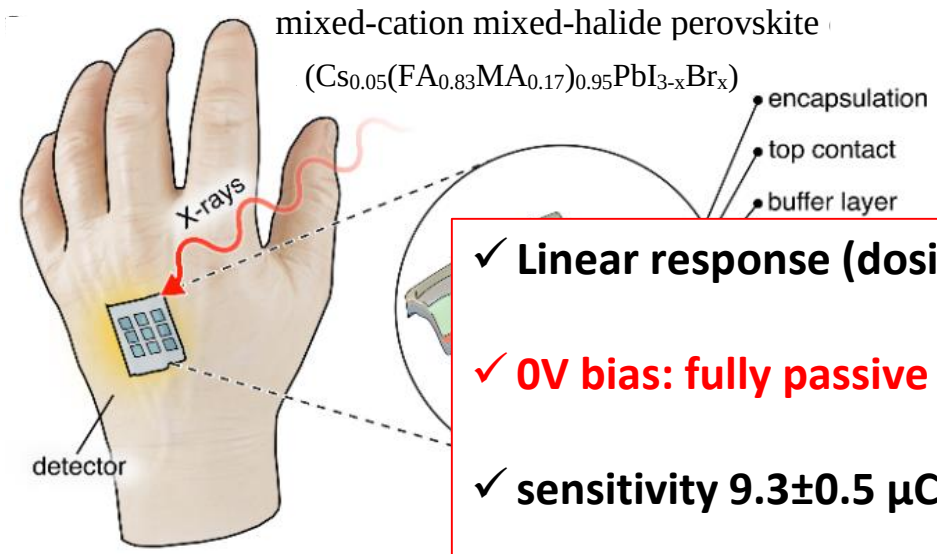
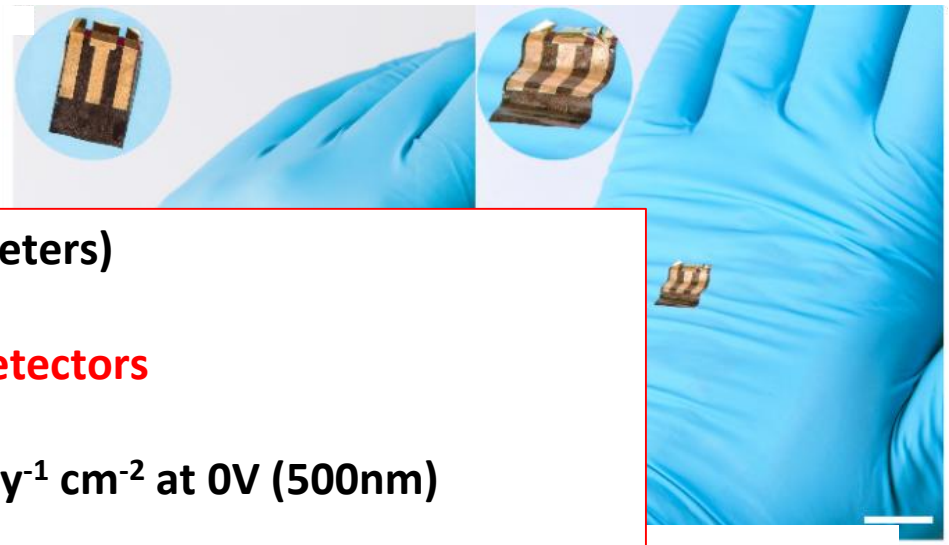
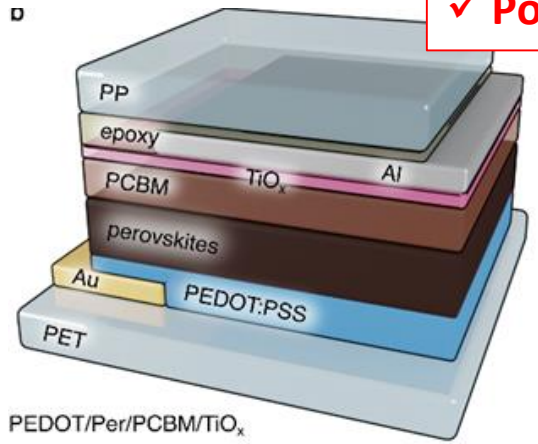
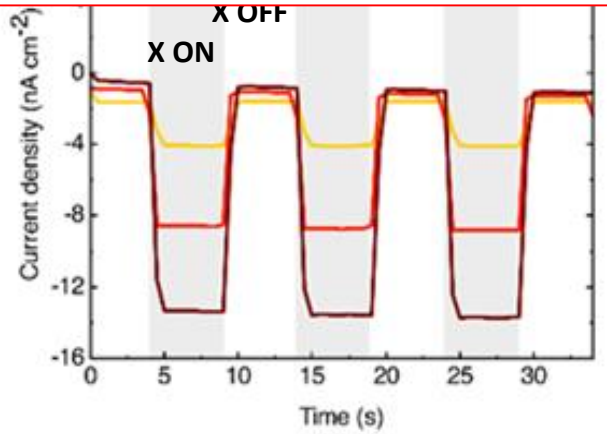
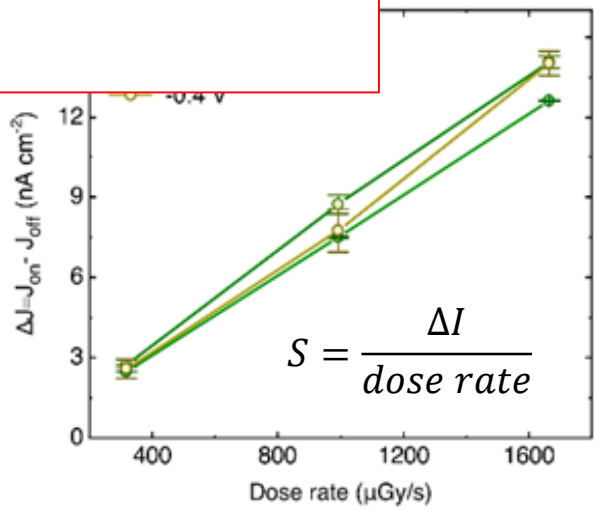




- ✓ **Linear response (dosimeters)**
- ✓ **0V bias: fully passive detectors**
- ✓ **sensitivity 9.3±0.5 µC Gy^{-1} cm^{-2} at 0V (500nm)**
- ✓ **Poor stability in time and in air**





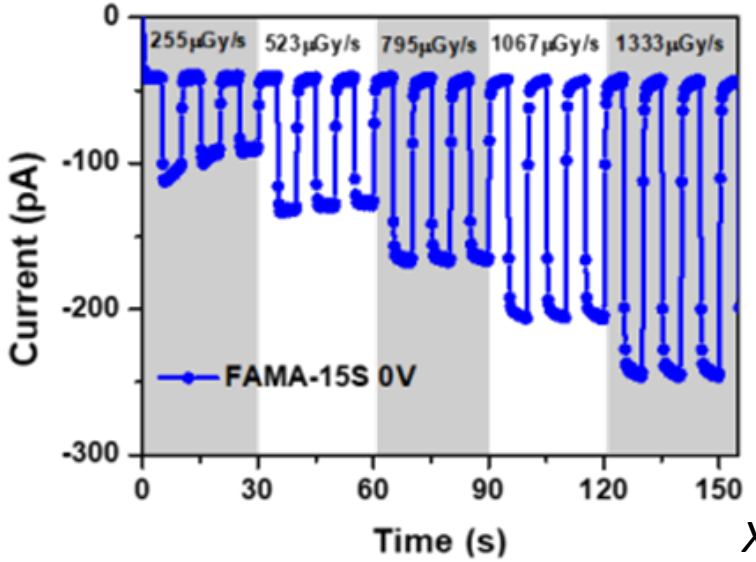


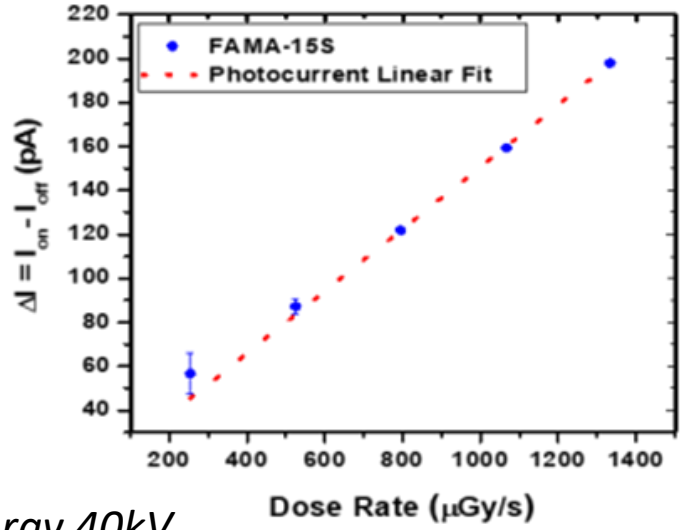
S.Denchyshyn et al *Advanced Science,* 24 2002586 ***(2020)***

X-ray detection with perovskite thin films
3D blends: MAPI+starch /FAMA+starch

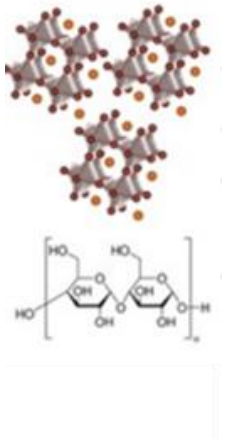
- methylammonium lead iodide **($MAPbI_3$) or** mixed formamidinium-methylammonium lead iodide **($FA_xMA_{1-x}PbI_3$) + up to 20% Starch**

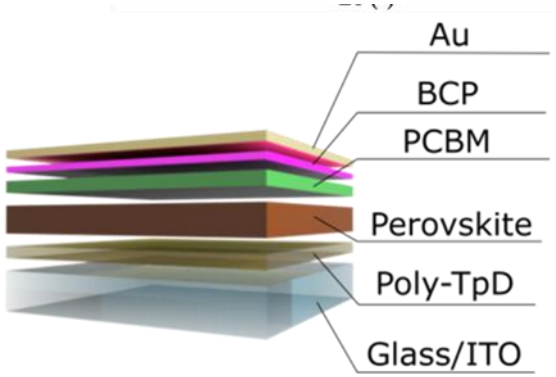
- Thickness > 1 micron

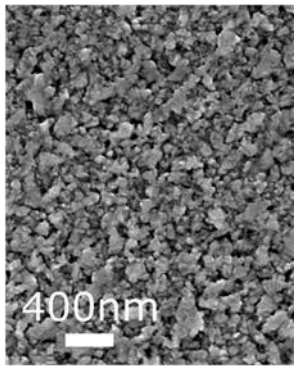


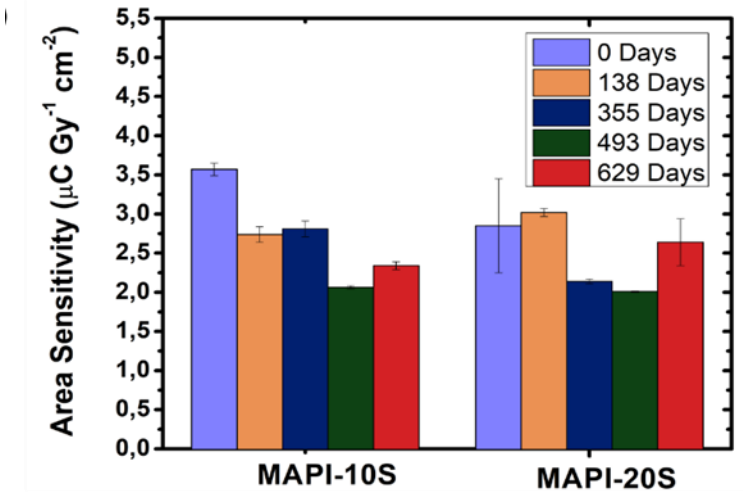


X-ray 40kV









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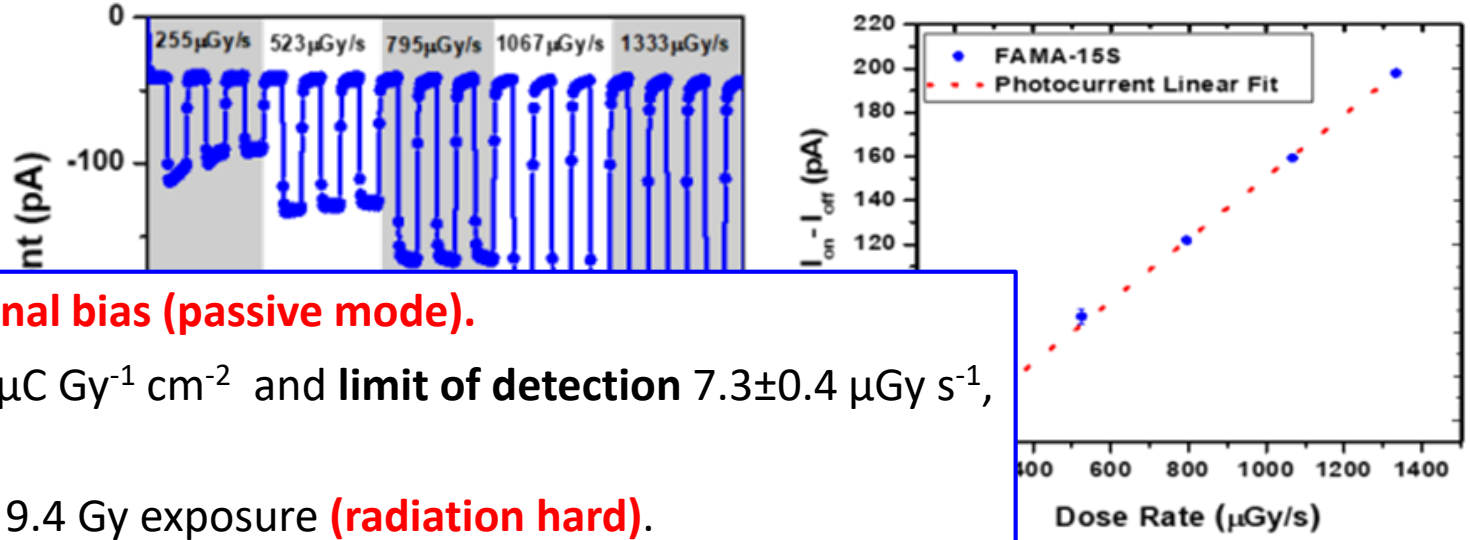
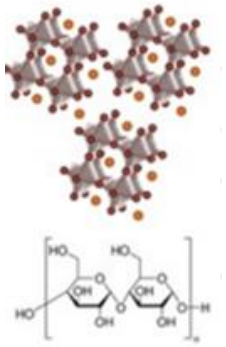
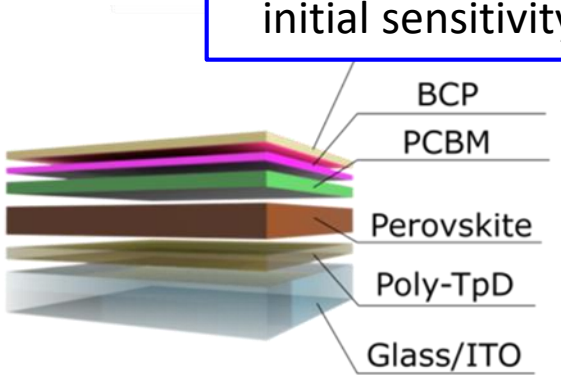
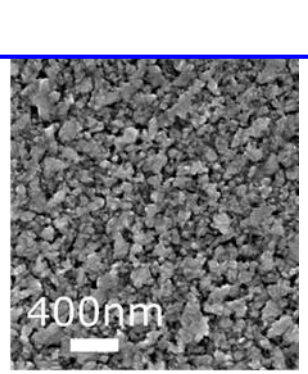
- methylammonium lead iodide **($MAPbI_3$) or** mixed formamidinium-methylammonium lead iodide **($FA_xMA_{1-x}PbI_3$) + up to 20%**
- Thickness > 1 micr

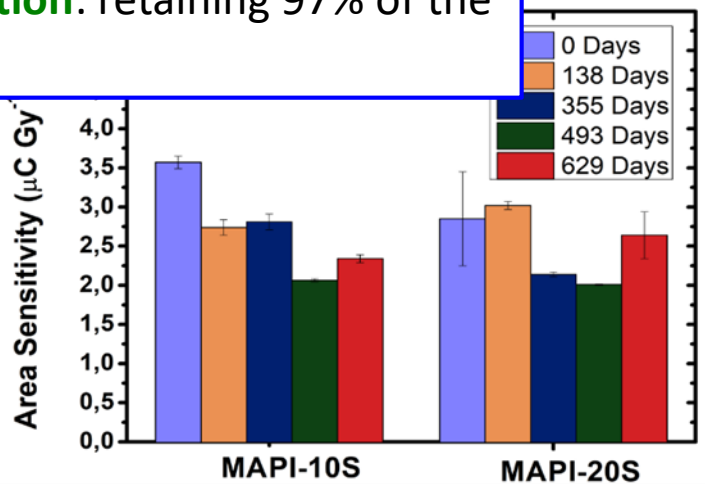


- ✓Operation at **0V external bias (passive mode).**
- ✓**sensitivity** of 5.5±0.2 μC Gy^{-1} cm^{-2} and **limit of detection** 7.3±0.4 μGy s^{-1}, for MAPI
- ✓ No degradation after 9.4 Gy exposure **(radiation hard)**.
- ✓**Stability for up to 1,7 years without encapsulation**: retaining 97% of the initial sensitivity

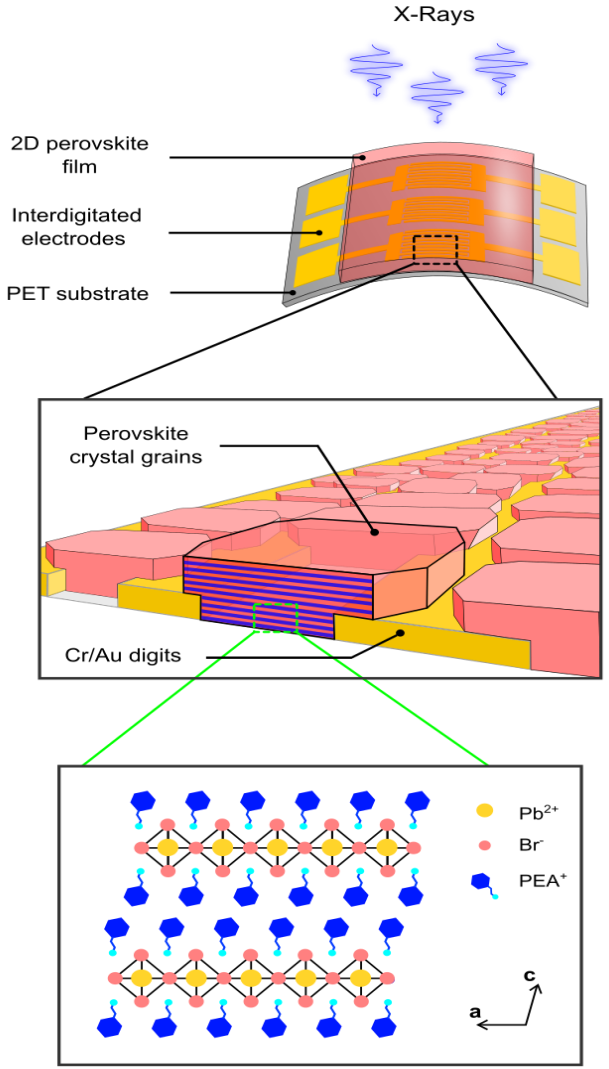




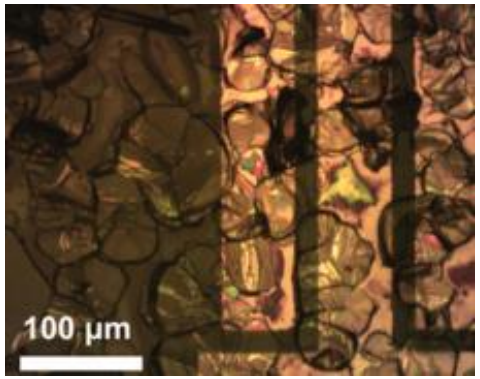




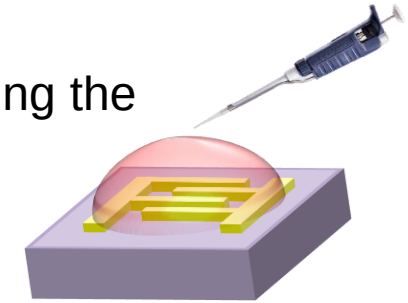
2D Perovskites thin film X-ray radiation detectors



- PEA_2PbBr_4
- Easy and scalable fabrication procedure (solution deposition)

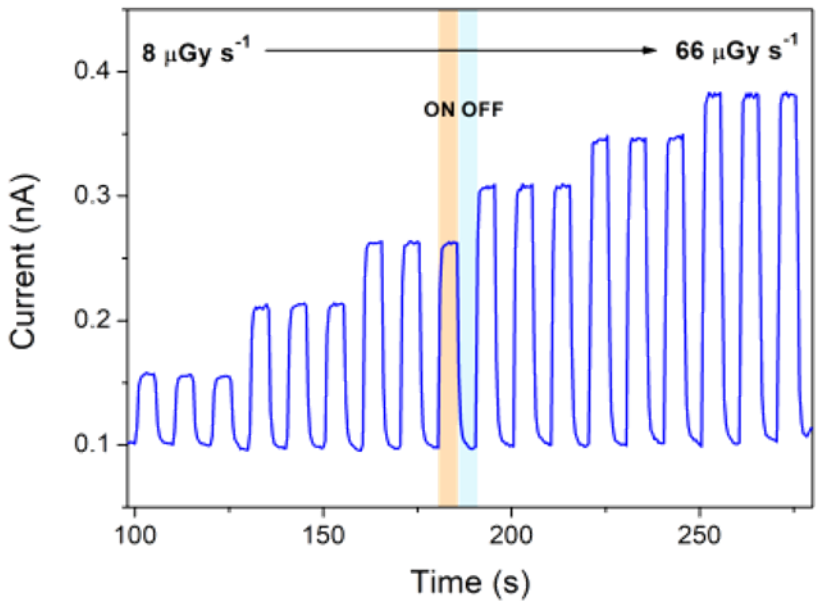


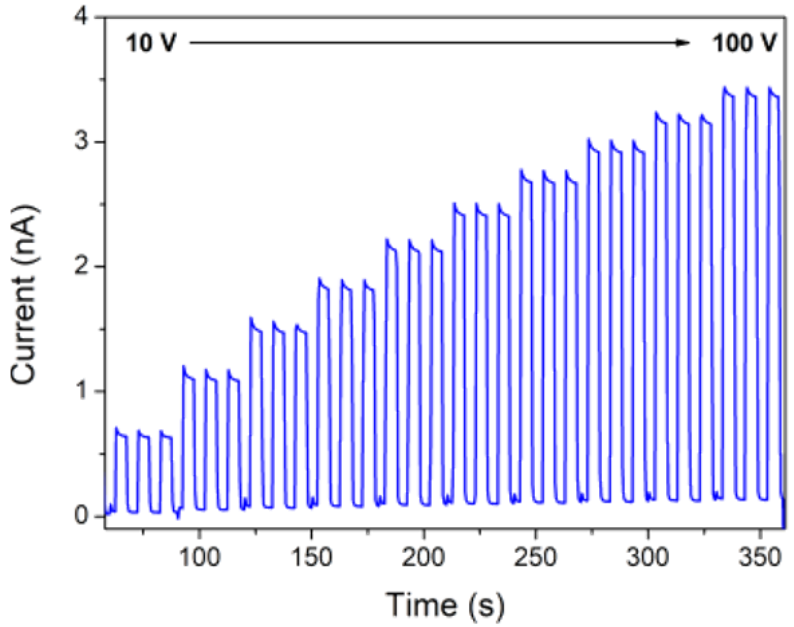
- 125 µm PET substrate
- large grains (33.5±8.3 µm) bridging the metal contacts



- Layer thickness < 1-2 µm
- **very low dark current for a non-diode structure** (10^{-13} A at 500 V mm-1 electric field), without the necessity of interlayers

2D Perovskites thin film X-ray radiation detectors



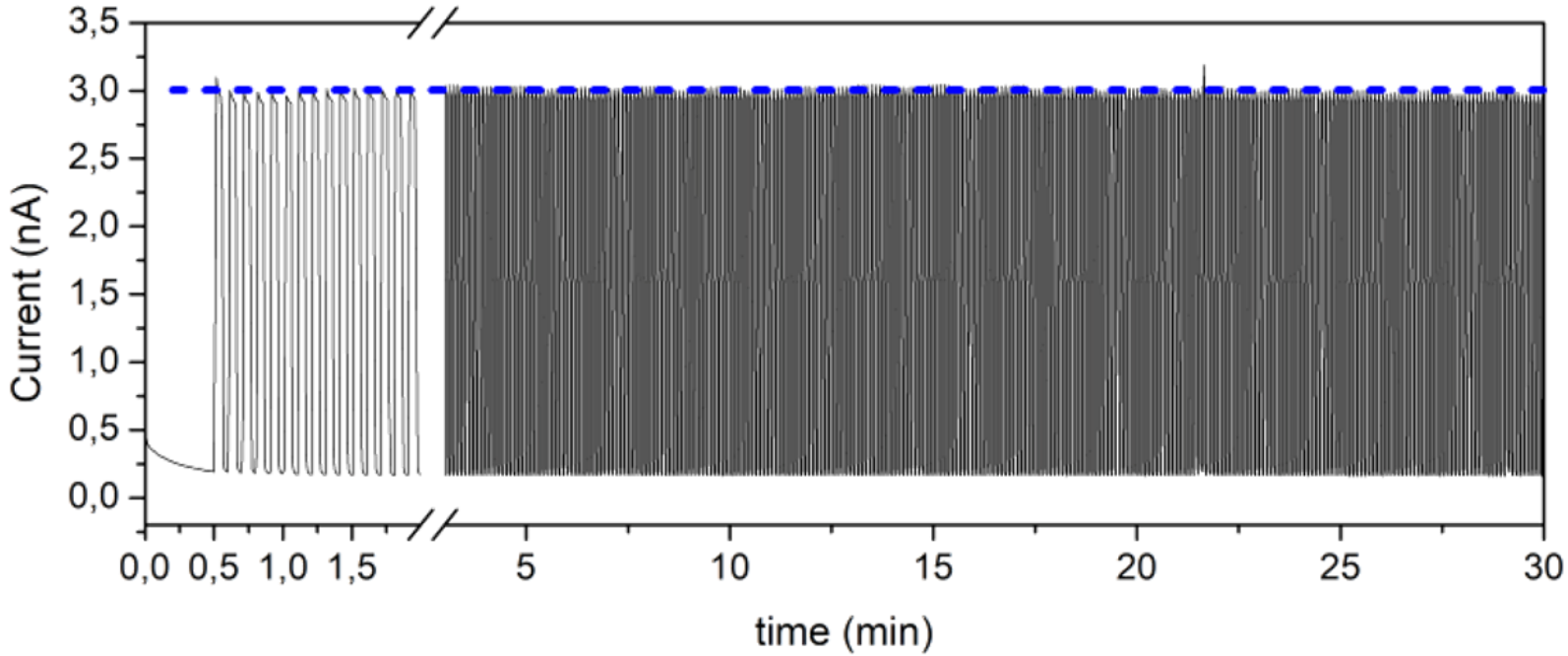


STABILITY & REPRODUCIBILITY

- Very stable to repeated pulses (300 consecutive pulses in a total of 30 minutes)
- Very stable under continuous irradiation of 10 minutes (4 Gy total dose at 80 V) Energies 40keV-150keV (mammography and CT scans).
- Same response after 80 days of storage in air not encapsulated

*F.Ledee et al. Advanced Optical Materials 10 (**2022**)*

2D Perovskites thin film X-ray radiation detectors



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*F.Ledee et al. Advanced Optical Materials 10 (**2022**)*

Perovskite for Radiotherapy

Wearable wireless X-ray sensor based on 2D perovskite thin films

Flexible, large-area patches for real-time detection of ionizing radiation

Fortress

UNIONE EUROPEA
Fondo europeo di sviluppo regionale

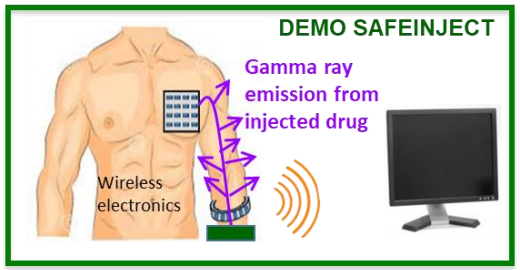
POR FESR EMILIA-ROMAGNA 2014/2020

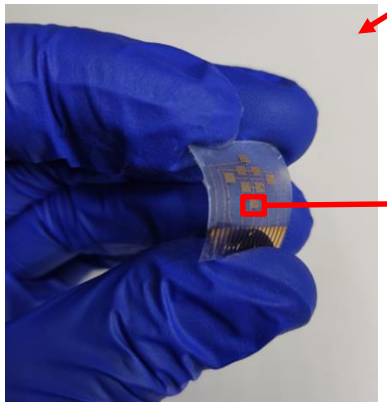
Istituto Nazionale di Fisica Nucleare
INFN TTLab

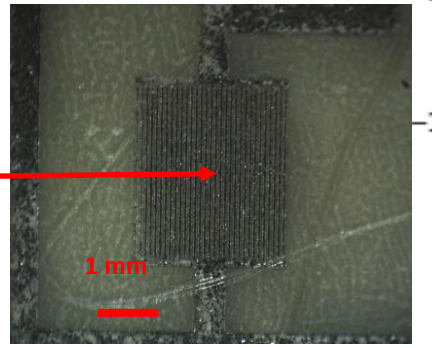
CENTRO INTERDIPARTIMENTALE MaM DI RICERCA INDUSTRIALE
MECCANICA AVANZATA E MATERIALI

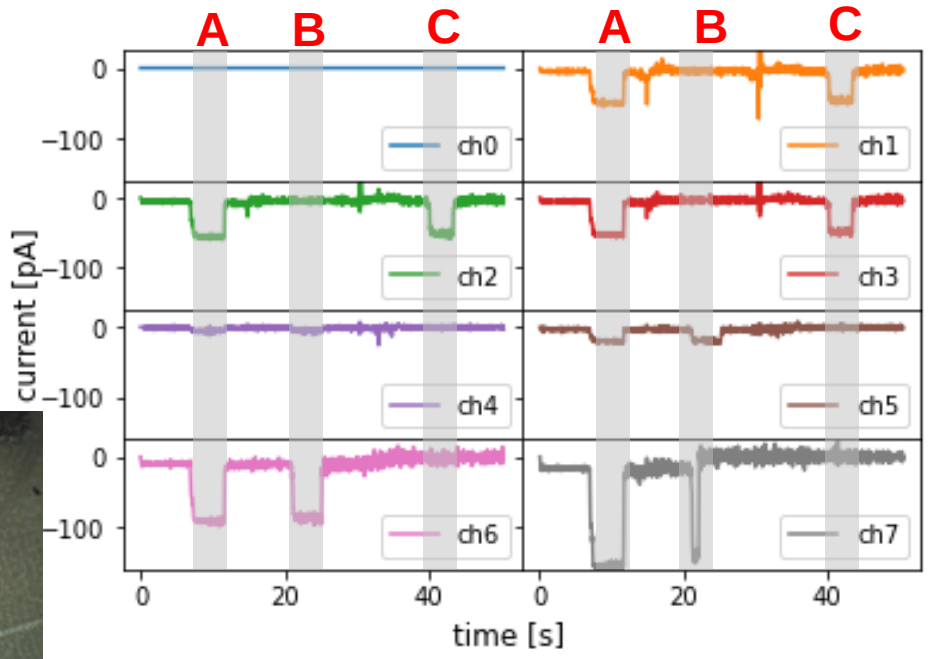
MISTER SMART TECHNOLOGIES

SERVIZIO SANITARIO REGIONALE EMILIA-ROMAGNA
Azienda Unità Sanitaria Locale di Reggio Emilia
IRCCS Istituto in tecnologie avanzate e modelli assistenziali in oncologia









A – all pixels exposed
B – pixels 0-3 shut
C – pixels 4-7 shut

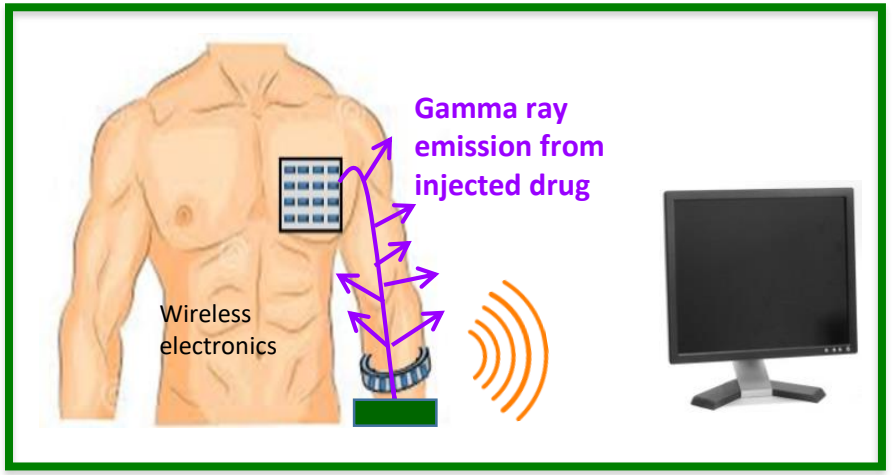
- **8 pixel matrix**
- **External V_{bias} =1V**
- Pixels ch 1,2,3 have same area → same response .
- Pixels ch 4-7 have different (larger) areas → signal scales with pixel area

*M. Natali, **A. Ciavatti** et al., Adv. Mater. Interf., 11(34), 2300968 (2024)*
*L. Basiricò, **A. Ciavatti** et al. Adv. Mater. Technol., 10, 2401111 (2025)*

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

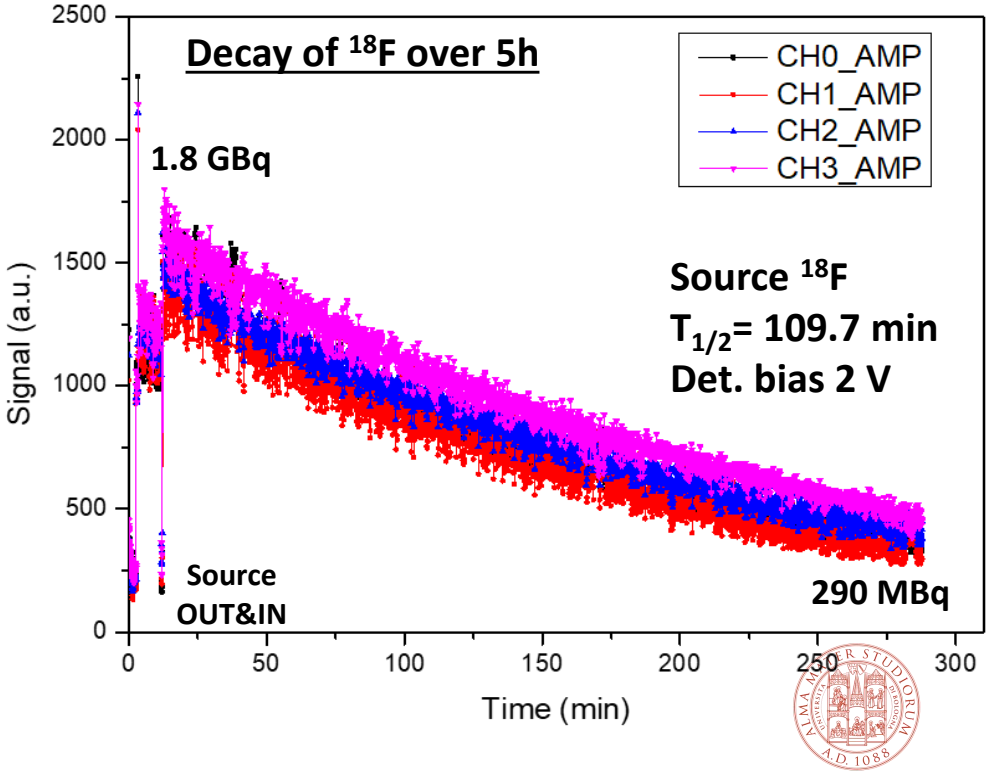
Real-time monitoring of radiopharmaceutical injection

Open issues **risks**



Automated injection system for radiopharmaceutical drugs require real-time alert to prevent extravasation

Conformable patches for in-situ monitoring of radioactive activity (writst, heart, etc…) and create a model for instant alert



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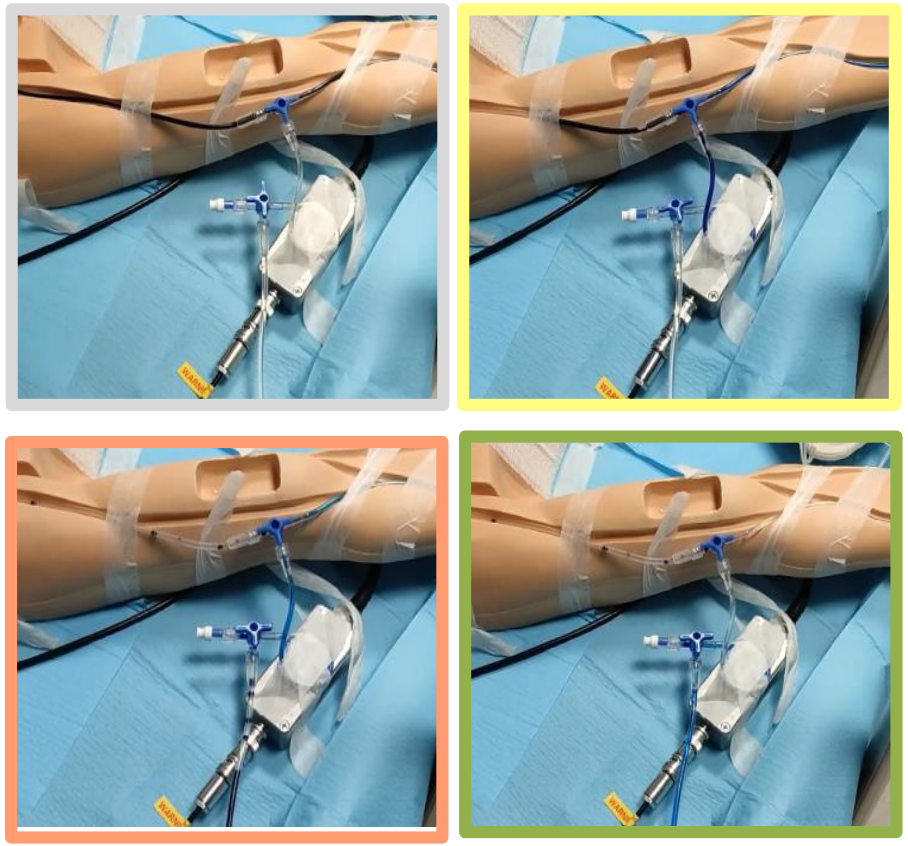
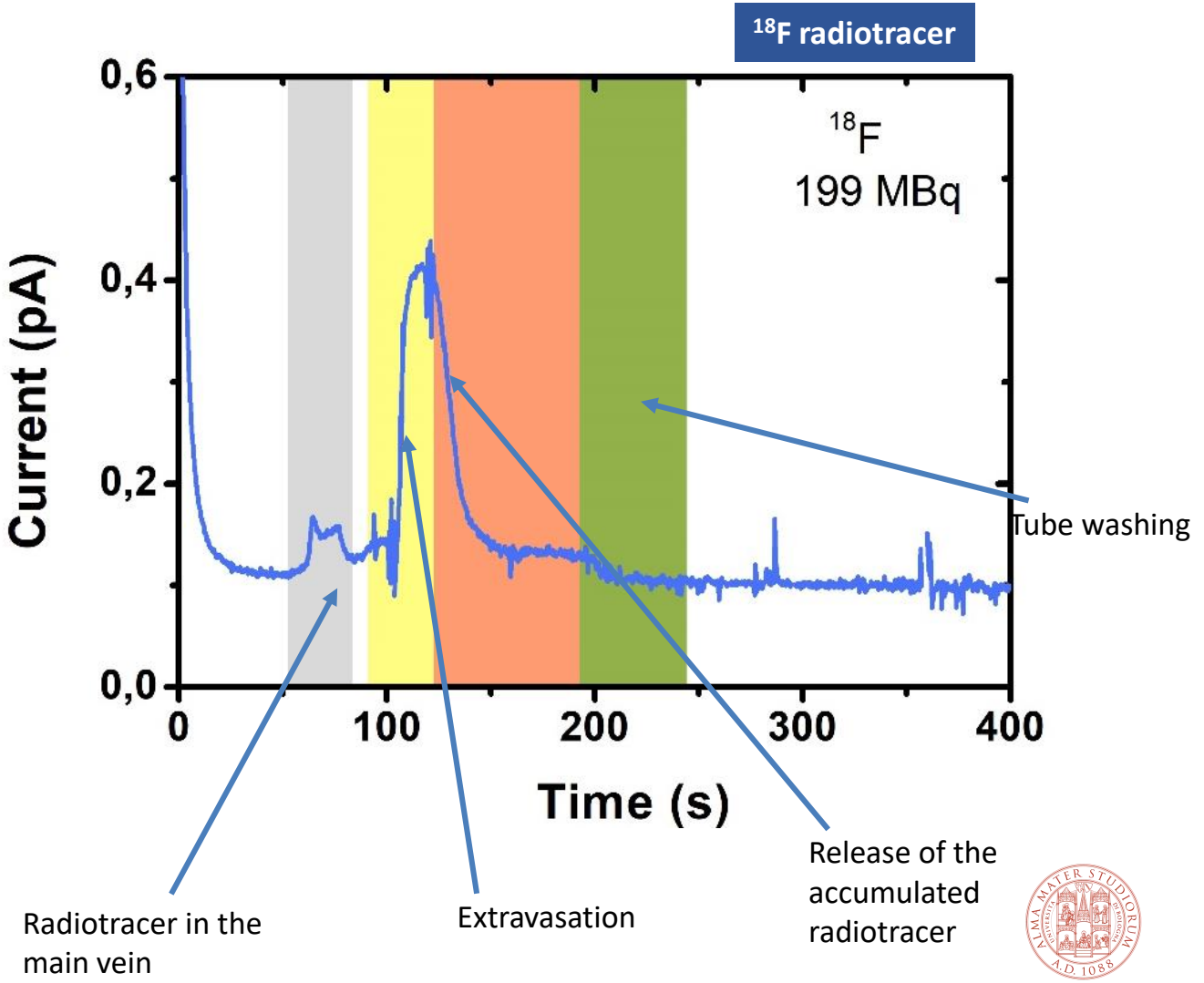


L. Basiricò, A. Ciavatti et al. Adv. Mater. Technol., 10, 2401111 (2025)

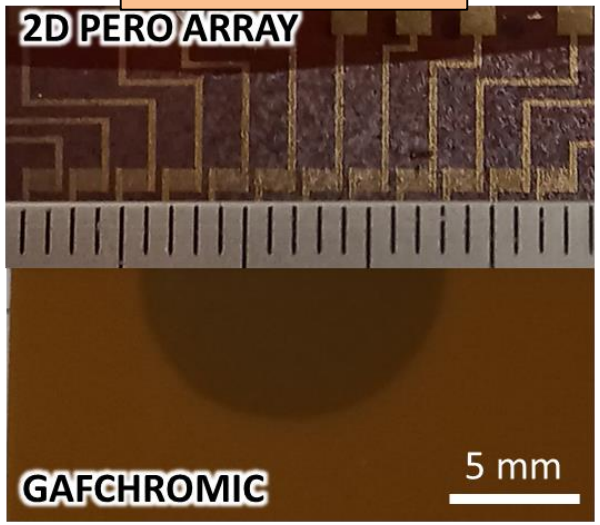


Perovskite for Beam Monitoring

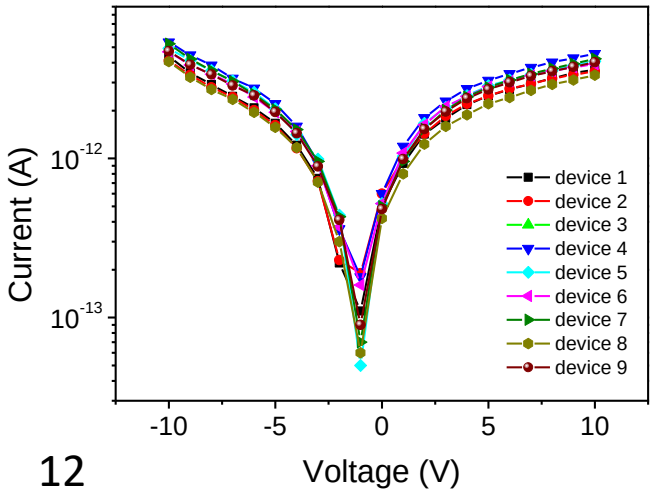
Flexible and large area beam monitor based on 2D perovskite thin film

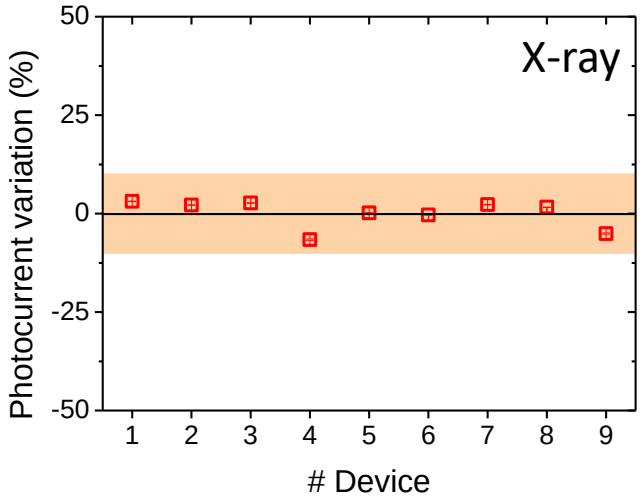
FLEXIBILITY and SCALABILITY

Pixel dimension down to 0.5 mm

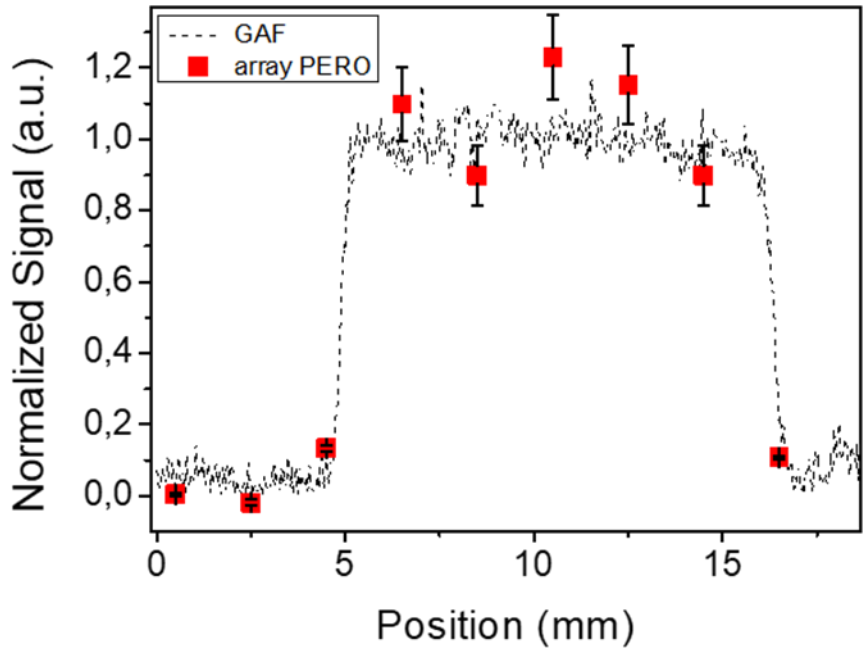


REPRODUCIBILITY





LARGE AREA and **FLEXIBLE** (> 10 x 10 cm^2) and good **SPATIAL RESOLUTION**



150 kVp, W-target X-ray tube

Fratelli et al., *Adv. Sci.* ***2024***, *101002/advs.202401124*

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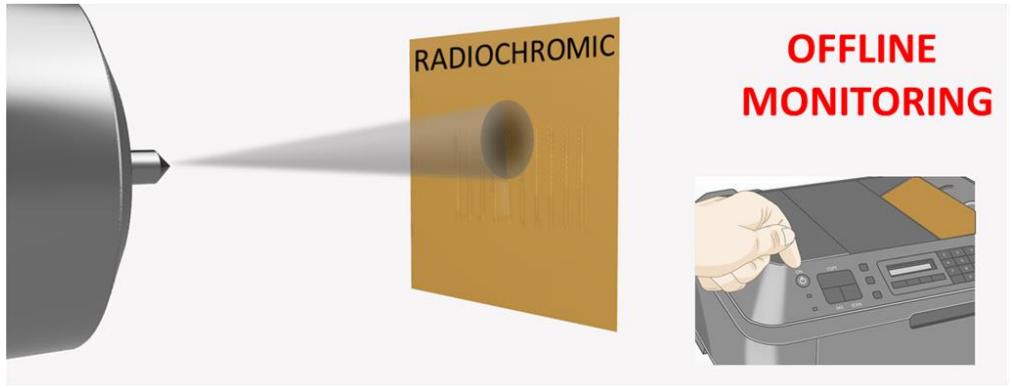
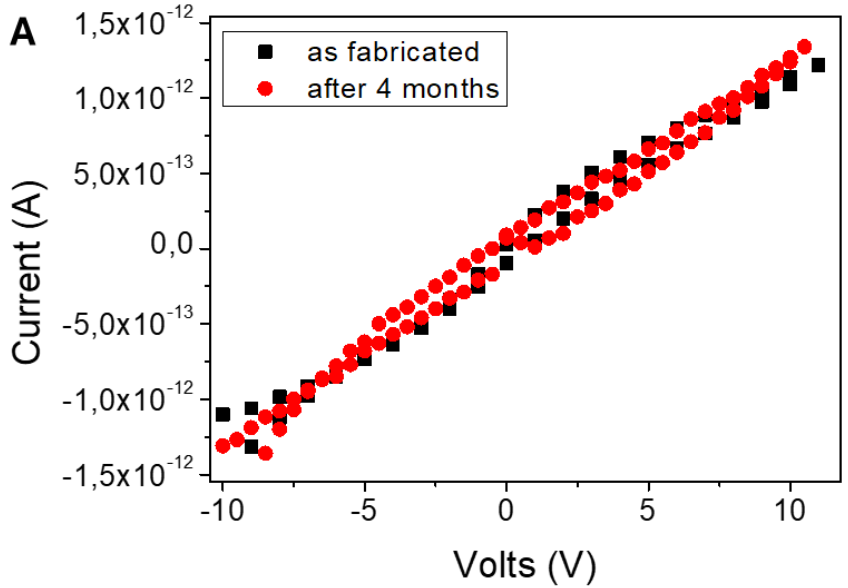
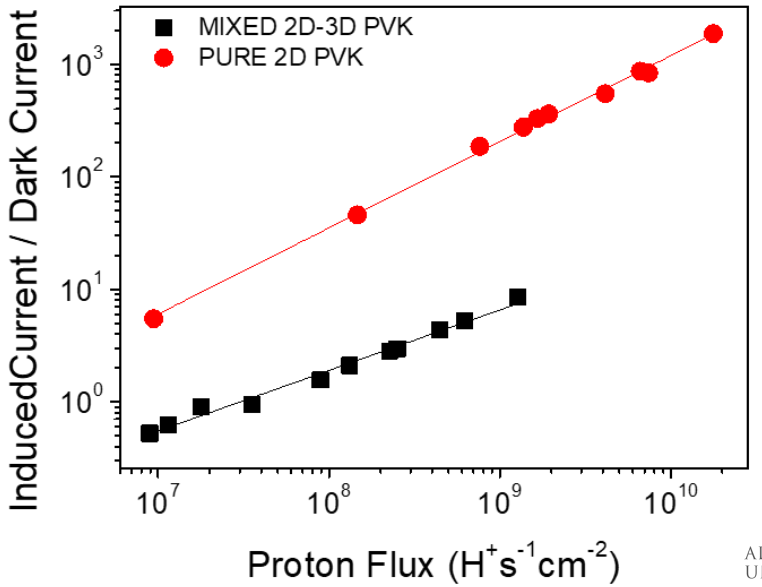
INFN
ANEMONE
hAdroN bEam MONitoring by pErovskite based detectors

Proton beam profiling – 2D perovskite film PEA_2PbBr_4







- ✓ Lower Ion migration
- ✓ Better stability
- ✓ Lower dark current
- ✓ Higher SNR

Fratelli et al., *Adv. Sci.* ***2024****, 101002/advs.202401124, in press*

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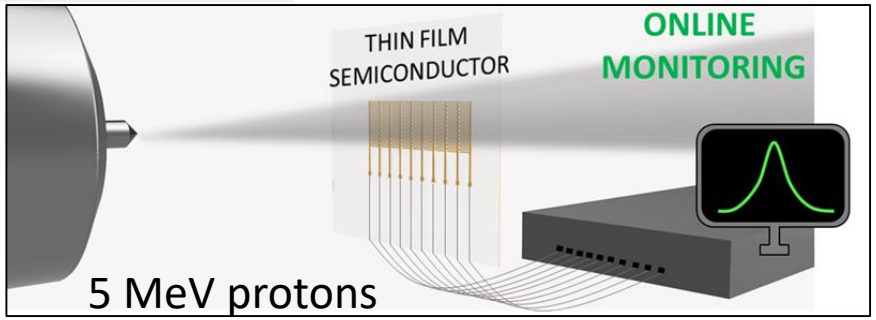
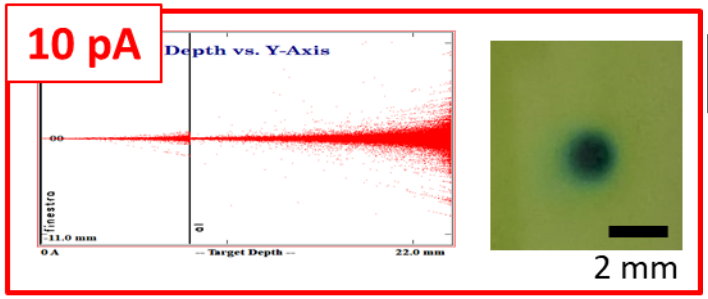
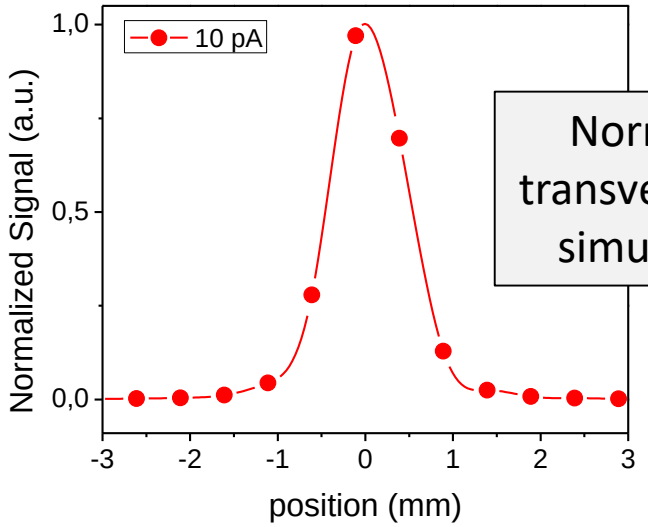
Proton beam transversal profiling – 2D perovskite film PEA_2PbBr_4





SIMULATED transversal trace (SRIM calculation)

beam spot on the RADIOCHROMIC FOILS



Normalization of the transversal trace from the simulation calculation

Fratelli et al., *Adv. Sci.* ***2024****, 101002/advs.202401124*

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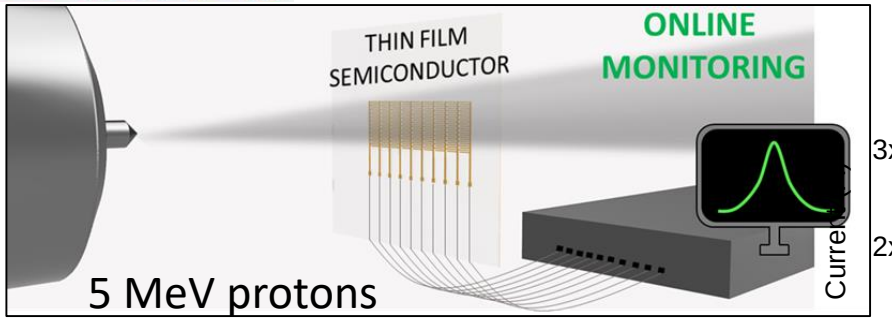
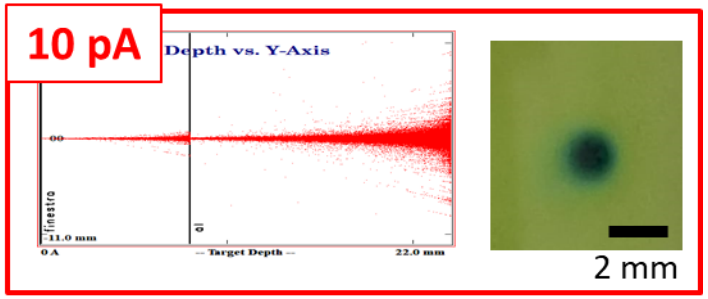
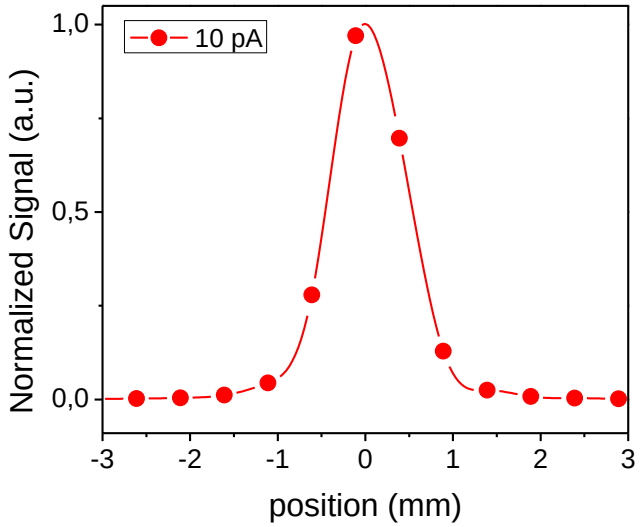
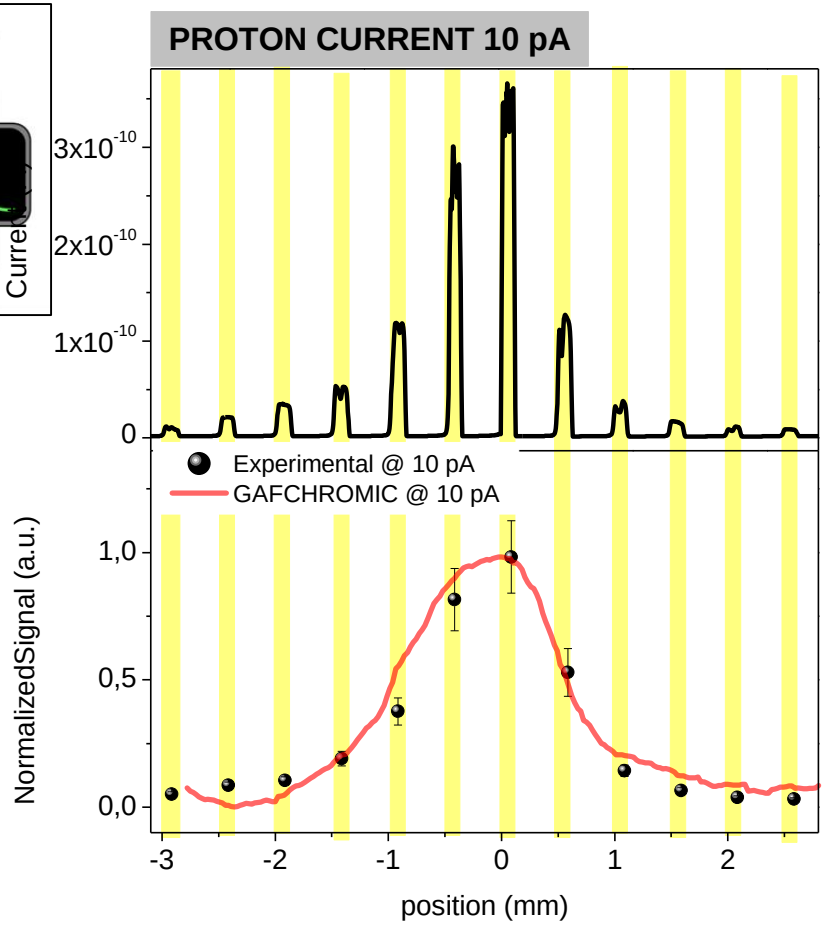
2D perovskite film PEA_2PbBr_4 VS RADIOCHROMIC FOILS









Good accordance between RADIOCHROMIC and 2D PVK based detector

Fratelli et al., *Adv. Sci.* ***2024****, 101002/advs.202401124*

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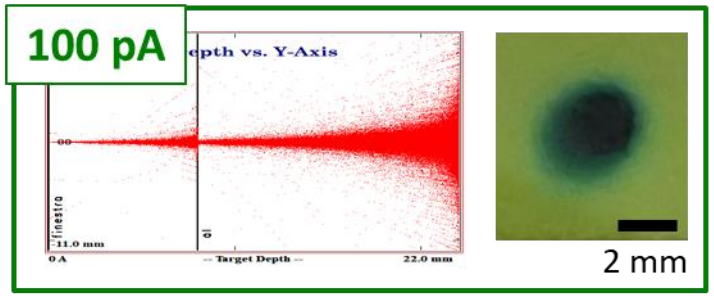
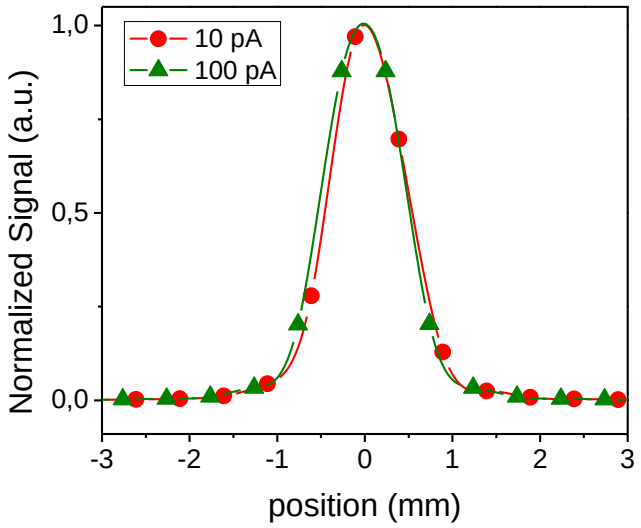
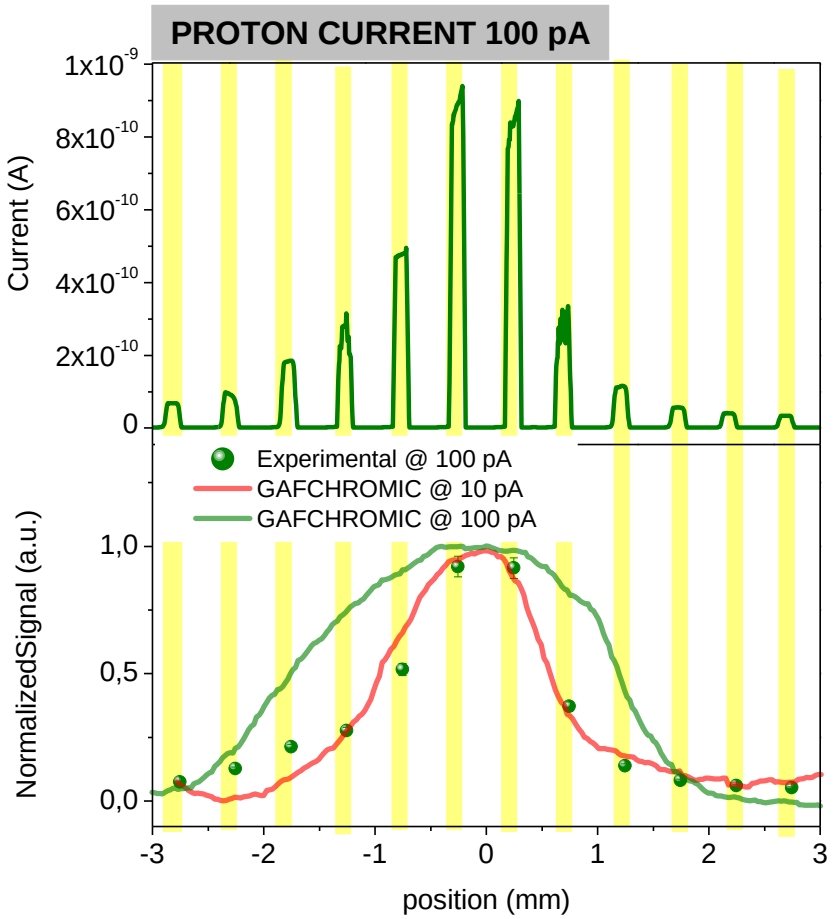
2D perovskite film PEA_2PbBr_4 VS RADIOCHROMIC FOILS



Higher proton fluxes **do not affect the proton beam shape**





After 10 seconds of exposure at high proton flux (10^{10} H^+ s^{-1} cm^{-2}):

→ the **radiochromic foil** shows a **saturation effect** leading to a **distortion of the beam shape**

→ the **2D perovskite** based-detector maintains its full detection properties and provides a **reliable performance**

Fratelli et al., *Adv. Sci.* ***2024****, 101002/advs.202401124*

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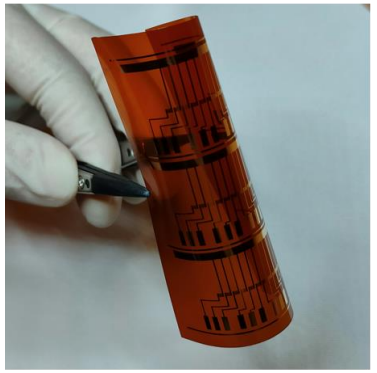
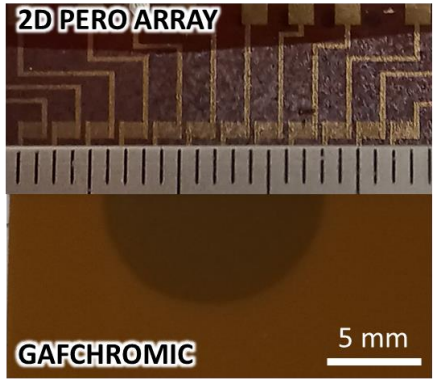
Tests under proton irradiation @ 70-228 MeV

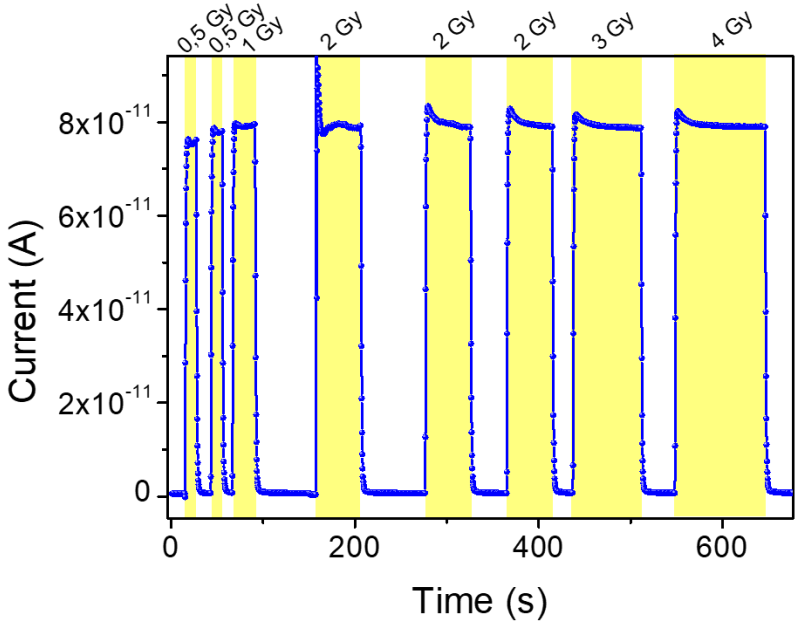
TIFPA

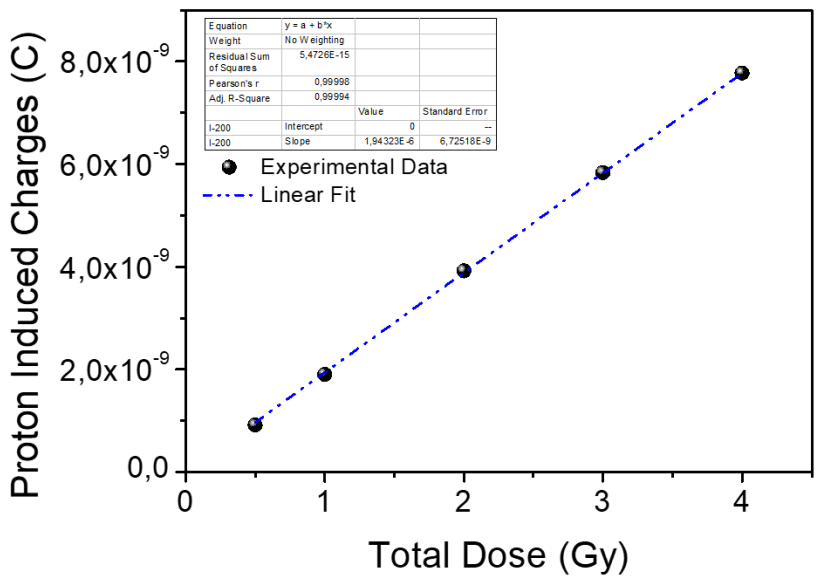
Trento Institute for Fundamental Physics and Applications





Data analysis still ongoing but… promising preliminary results:





- Sharp real time response to 70 MeV proton beam
- Linearity with dose

Still under analysis:

- Full dosimetric characterization
- Radiation hardness up to 2 kGy

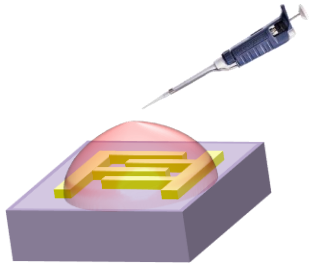
Perovskite for Space

IRIS on International Space Station

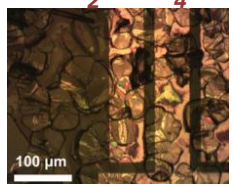
IRIS
Large area, wearable Ionizing Radiation dosimeters for real-tIme space crew perSonal monitoring

NASA · KAYSER ITALIA · INFN Istituto Nazionale di Fisica Nucleare, TTLab · ASI Agenzia Spaziale Italiana

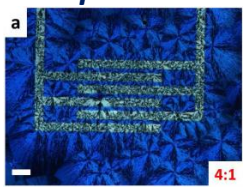
MAIN AIM:
Development and deployment in orbit on ISS of wearable, ultra-lightweight ionizing radiation detectors capable of real-time transmission of the radiation dose received by the crew members.

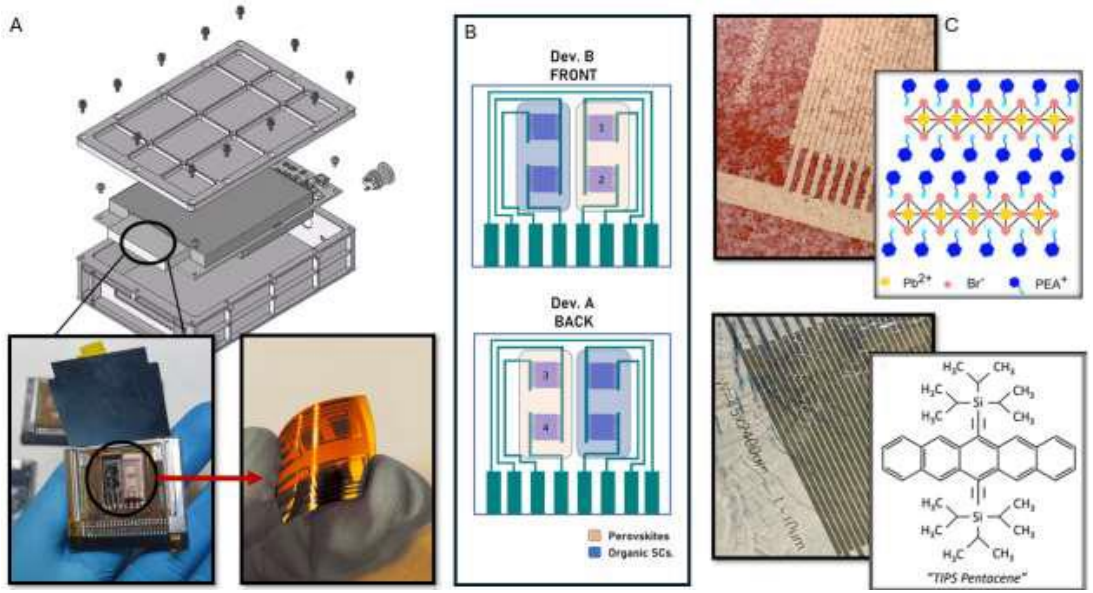


PEA_2PbBr_4

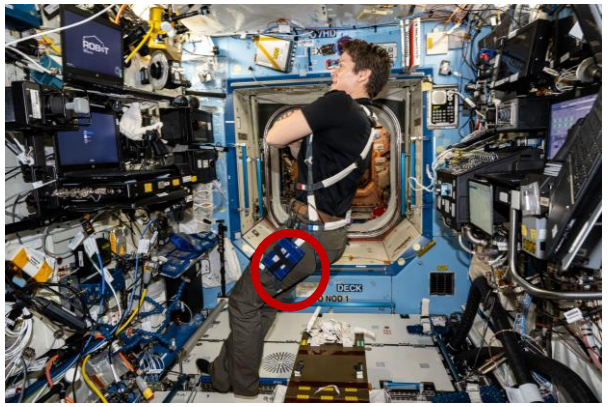


TIPS-pentacene





IRIS dosimeter on the kneeboard of Astronaut onboard of ISS (April 2025)



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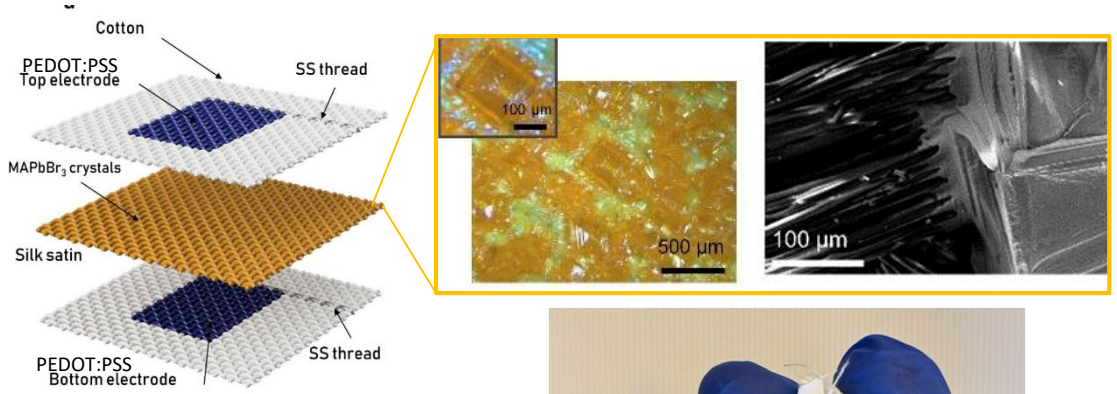
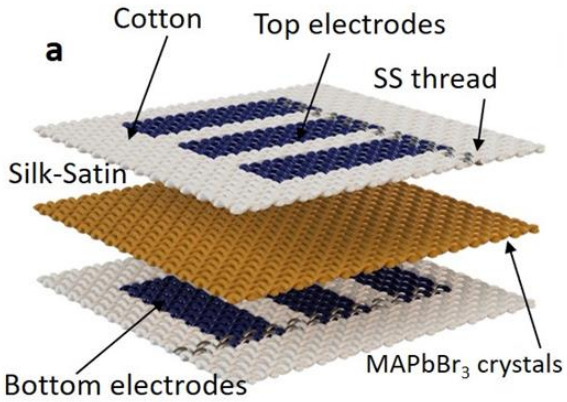
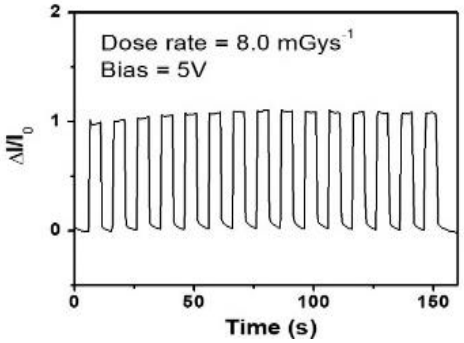
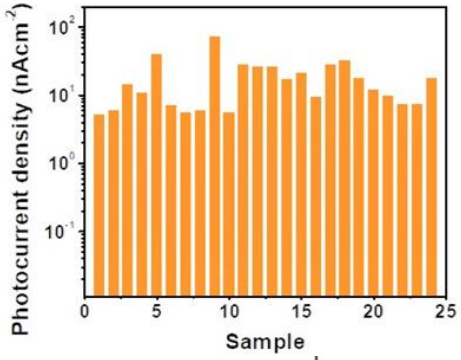
Direct detection by 3D perovskites on textiles

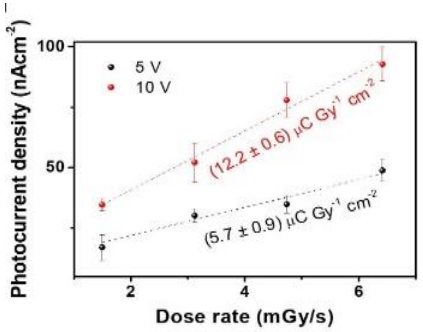




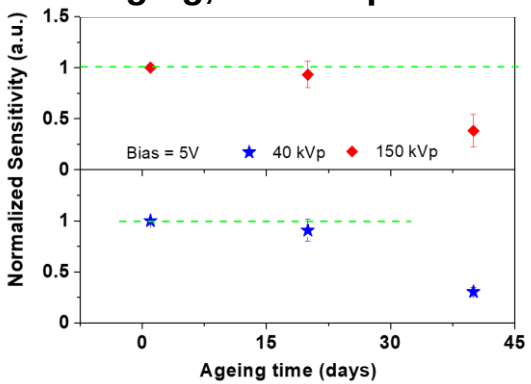


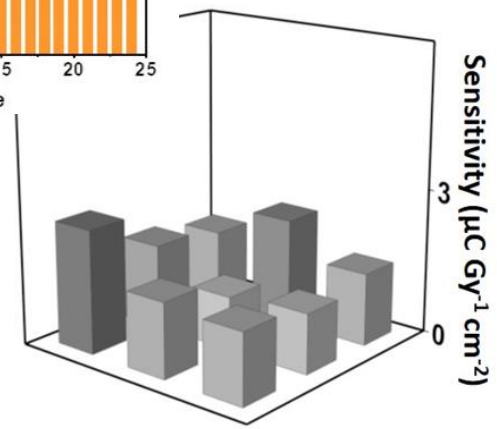


2D pixelated matrix



Aging, no encapsulation





L.Possanzini et al *Advanced Mat Interfaces, (***2021)**

Conclusions

Flexible, large-area, printed ionizing radiation dosimeters based on **thin films**, can effectively and quantitatively **detect high energy photon and proton beams** operating at **very low bias**

Further research is in progress:

- **to extend the operating range and functionalities**
- **to implement industrial prototypes**

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https://site.unibo.it/semiconductor-physics/en

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Dr. Mario Caironi

Dr. Marta Mas-Torrent

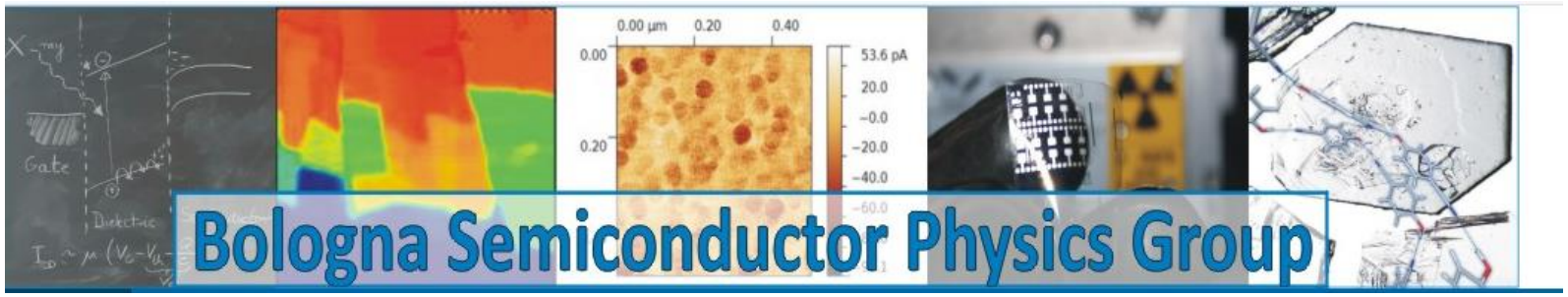
IRIS *Ionizing radiation detectors for wearable dosimetry of space crews (2022-2025)*

Flexible organic Ionizing Radiation dEtectors
(2019-2022)

(2019-2022)

RivELatOri innovativi per cure ADroterapiche
(2024-2025)

SEMICONDUCTOR PHYSICS GROUP @
DEPARTMENT OF PHYSICS AND ASTRONOMY-UNIVERSITY OF BOLOGNA



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Thank you for your attention

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