BEYOND

– flexiBlE hYbrid neutrON Detectors –

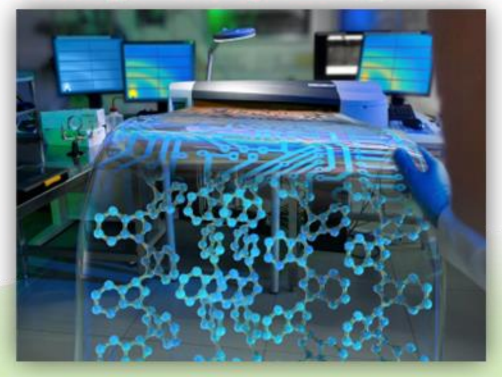
INFN - Grant Giovani Ricercatori e Ricercatrici
2023-2024

Ilaria Fratelli – associata INFN Bologna, RTT UNIBO DIFA

16 Dicembre 2024

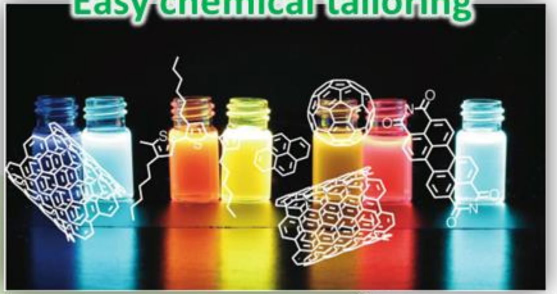
Semiconduttori Innovativi per Rivelazione di Radiazione

Low-cost large-area printing techniques

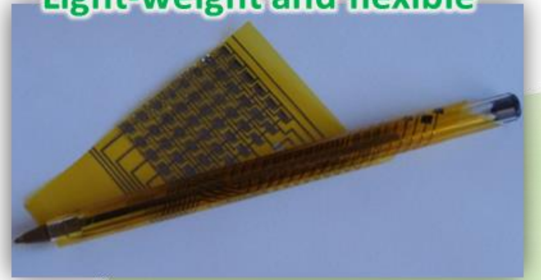


Wearable

Easy chemical tailoring



Light-weight and flexible



New generation of
low cost, low power supply and **mechanical flexible**
Thin and **comformable** sensor panels and patches

Cultural Heritage

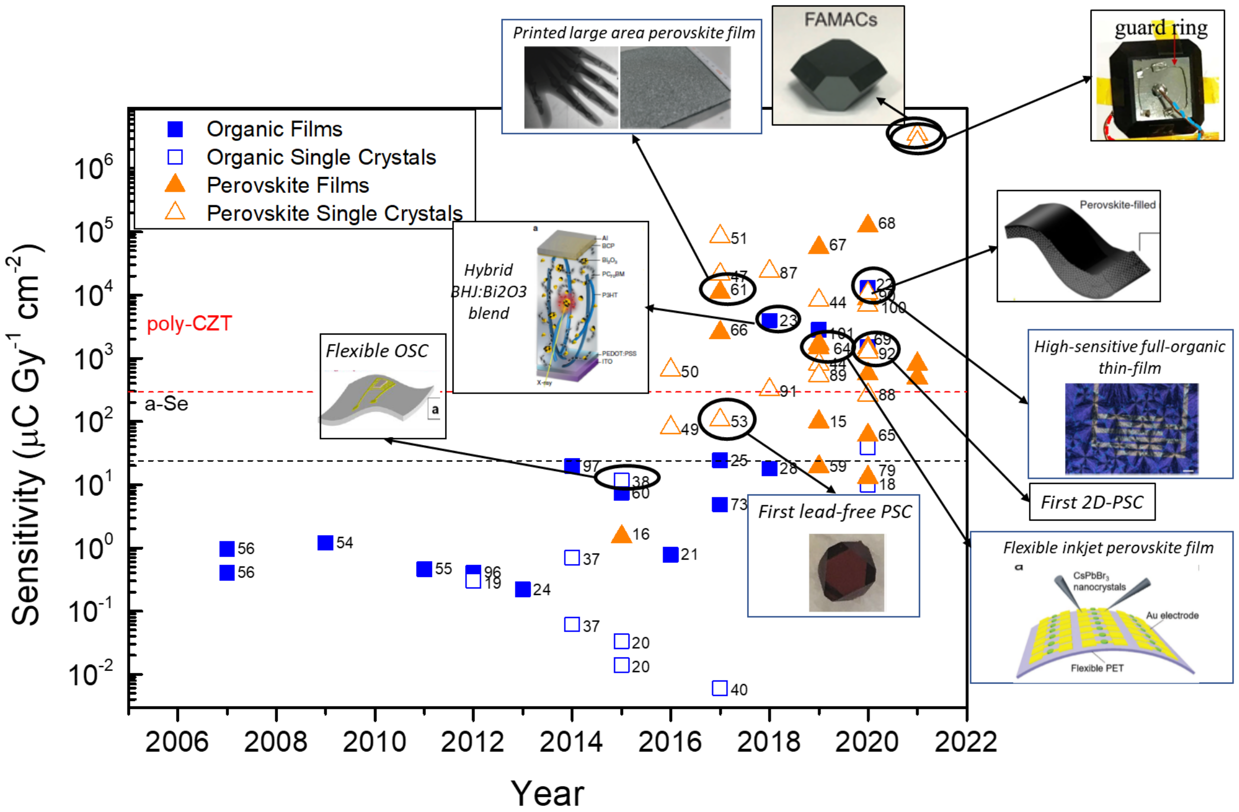
Space Missions

Airport Security

Medical Applications

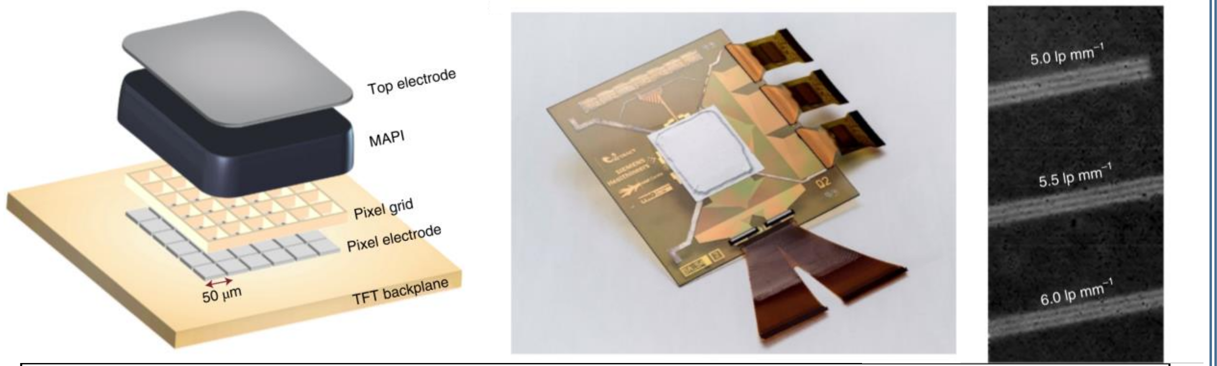
Nuclear wastes management

Semiconduttori Innovativi per Rivelazione di Radiazione



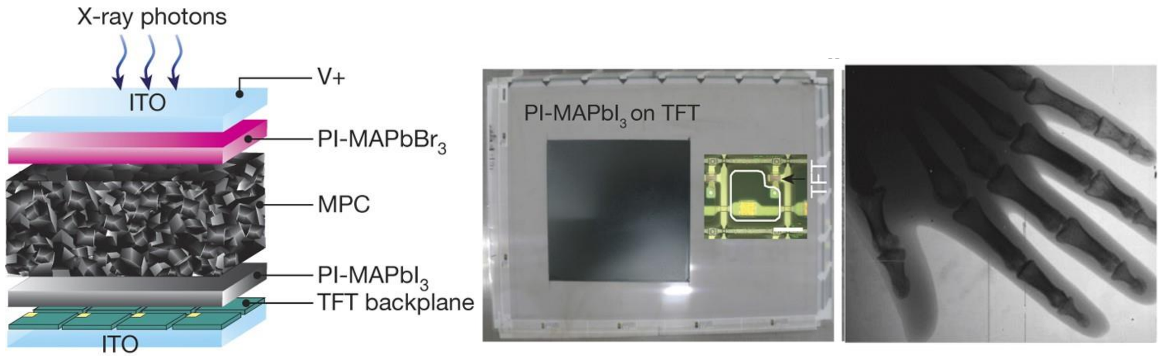
Basiricò L, Ciavatti A, Fraboni B., Adv Mater Technol. 2020 Aug; 2000475

SIEMENS – X-ray detectors – PEROVSKITES



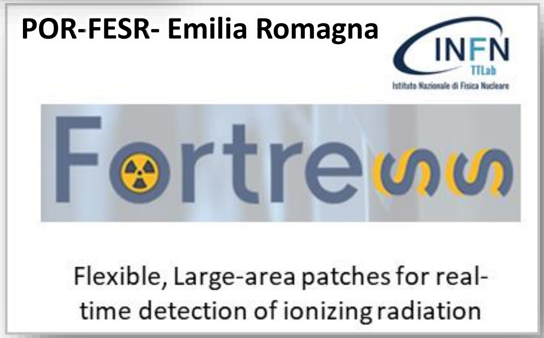
Tedde S. *et al.* High-sensitivity high-resolution X-ray imaging with soft-sintered metal halide perovskites. *Nat Electron* **4**, 681–688 (2021). https://doi.org/10.1038/s41928-021-00644-3

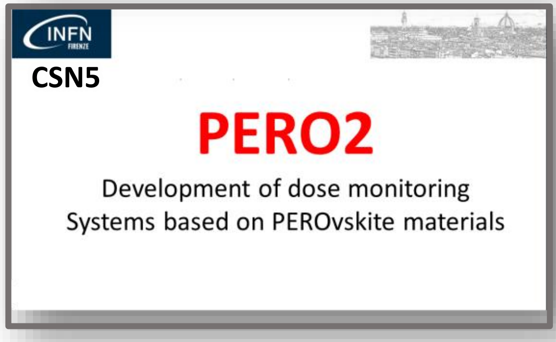
SAMSUNG – X-ray detectors – PEROVSKITES



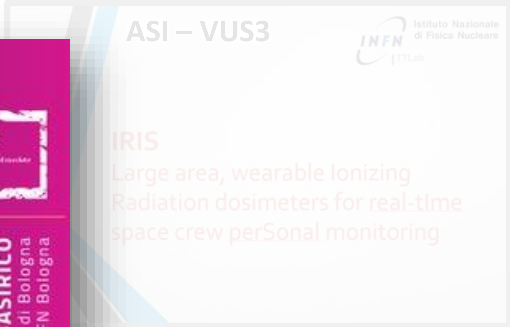
Kim, Y., Kim, K., Son, DY. *et al.* Printable organometallic perovskite enables large-area, low-dose X-ray imaging. *Nature* **550**, 87–91 (2017). https://doi.org/10.1038/nature24032

Sinergie e Background





Sinergie e Background



Sinergie e Background

INFN
CSN5
ANEMONE
hAdroN bEam MONitoring by pErovskite based detectors

INFN
CSN5
FIRE
Flexible organic Ionizing Radiation dEtectors

ASI – VUS3
INFN Istituto Nazionale di Fisica Nucleare TTLab
IRIS
Large area, wearable Ionizing Radiation dosimeters for real-tIme space crew perSonal monitoring

Università del Salento – Dipartimento di Matematica e Fisica "Ennio De Giorgi" – INFN Istituto Nazionale di Fisica Nucleare Sezione di Lecce – CEDAD
CSN5
BoLAS-NEXT
Flexible ^{10}*B-based converter*
deposited by the *laser ablation technique*

POR-FESR- Emilia Romagna
INFN TTLab Istituto Nazionale di Fisica Nucleare
Fortress
Flexible, Large-area patches for real-time detection of ionizing radiation

INFN
CSN5
Progetto Gr. V TN
HYDE - 2014
New hybrid detectors for neutrons
Gian-Franco Dalla Betta
Dipartimento di Ingegneria Industriale, Università di Trento
INFN Padova, Gruppo Collegato di Trento

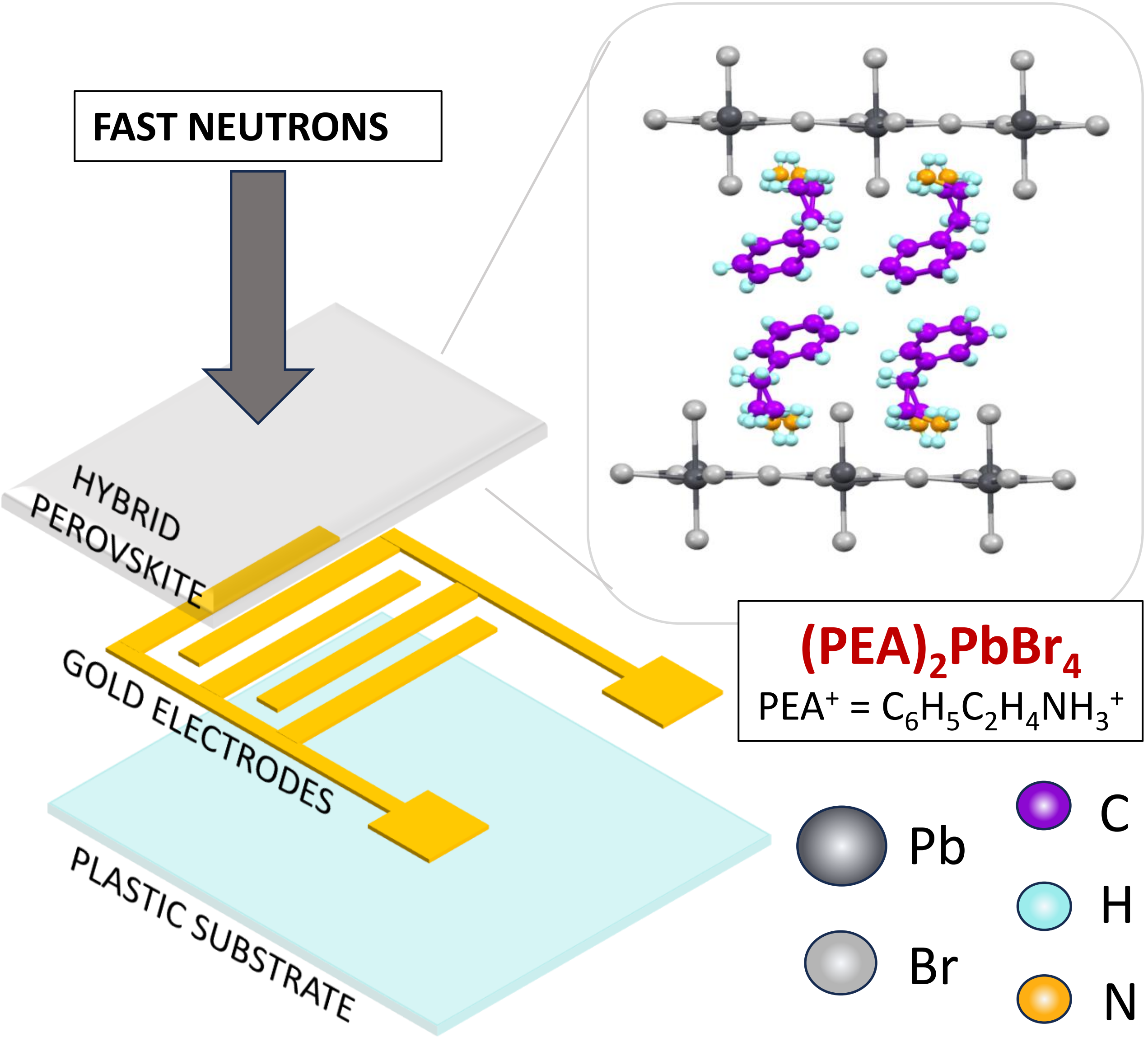
INFN Firenze
CSN5
PERO2
Development of dose monitoring Systems based on PEROvskite materials

BEYOND

Dispositivi **FLESSIBILI**, scalabili su **LARGHE AREE**, a **BASSO COSTO** per la **RIVELAZIONE DIRETTA** di neutroni termici e veloci in applicazioni mediche (**BNCT**) e **monitoring ambientale**

NEUTRONI VELOCI
– perovskiti a film sottile –

2D hybrid perovskite thin films

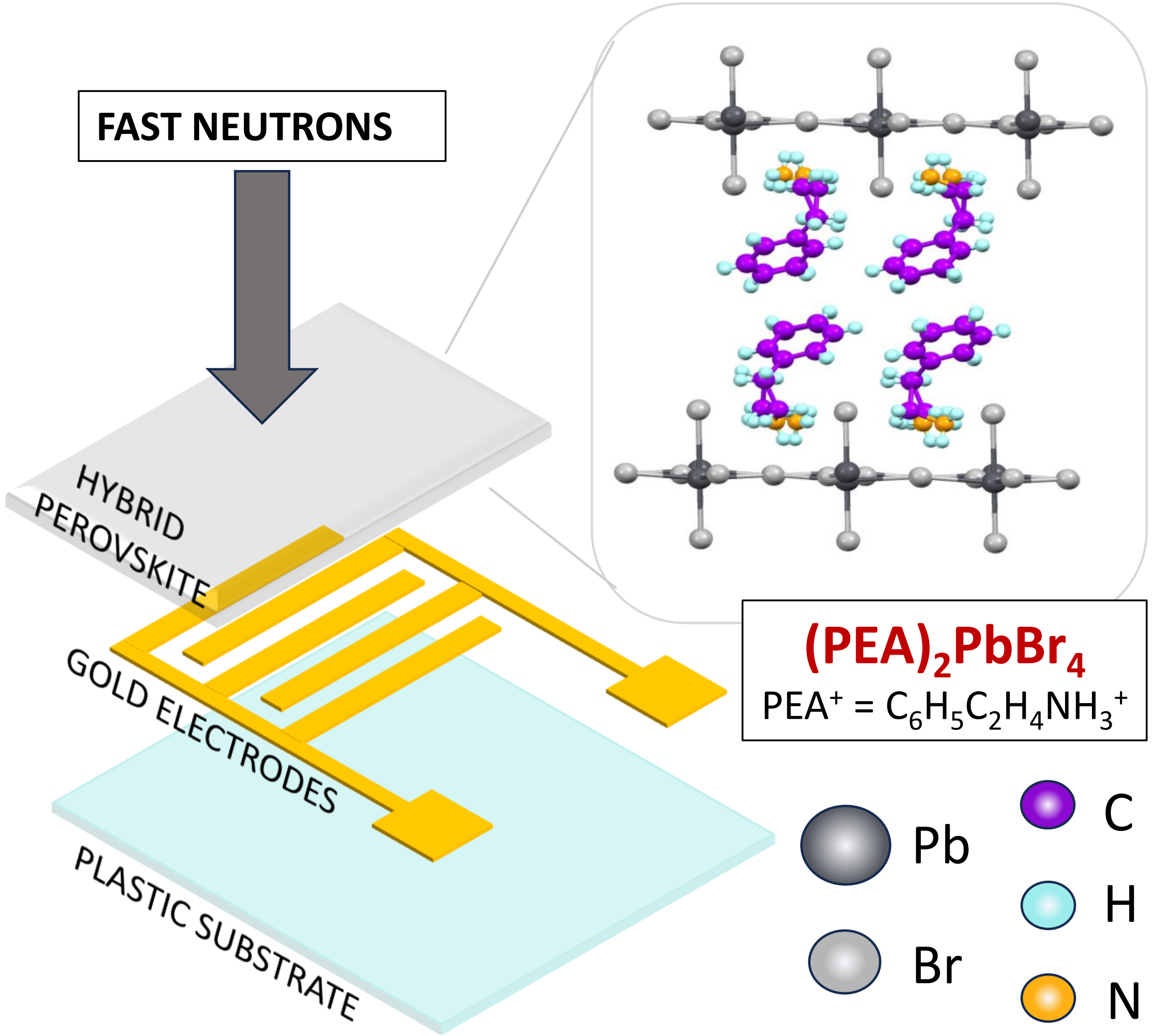


$(PEA)_2PbBr_4$

$PEA^+ = C_6H_5C_2H_4NH_3^+$

Lédée, F., Ciavatti, A., Verdi, M., Basiricò, L., Fraboni, B., (2022). *Advanced Optical Materials*, *10*(1), 2101145.
Fratelli, I., Basiricò, L., Ciavatti, A., Margotti, L., Cepić, S., Chiari, M., & Fraboni, B. (2024) *Advanced Science*, *2401124*.
Ciavatti A., Foderà V., Armaroli G., Maserati L., Colantoni E., Fraboni B., Cavalcoli D., Adv. Funct. Mater. 2024, 34, 2405291

2D hybrid perovskite thin films



$(PEA)_2PbBr_4$

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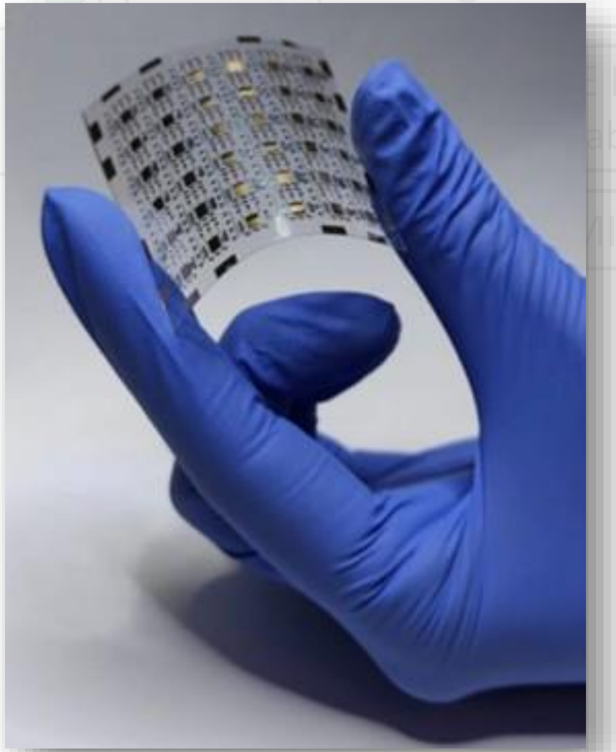
DEPOSIZIONE DA SOLUZIONE → DISPOSITIVI FLESSIBILI e LARGE-AREA

BASSA CORRENTE DI BUIO (10^{-13} A @ 500 V mm^{-1})

PEROVSKITI IBRIDE 2D



Lédée, F., Ciavatti, A., Verdi, M., Basiricò, L., Fraboni, B., (2022). *Advanced Optical Materials*, *10*(1), 2101145.
Fratelli, I., Basiricò, L., Ciavatti, A., Margotti, L., Cepić, S., Chiari, M., & Fraboni, B. (2024) *Advanced Science*, *2401124*.
Ciavatti A., Foderà V., Armaroli G., Maserati L., Colantoni E., Fraboni B., Cavalcoli D., Adv. Funct. Mater. 2024, 34, 2405291

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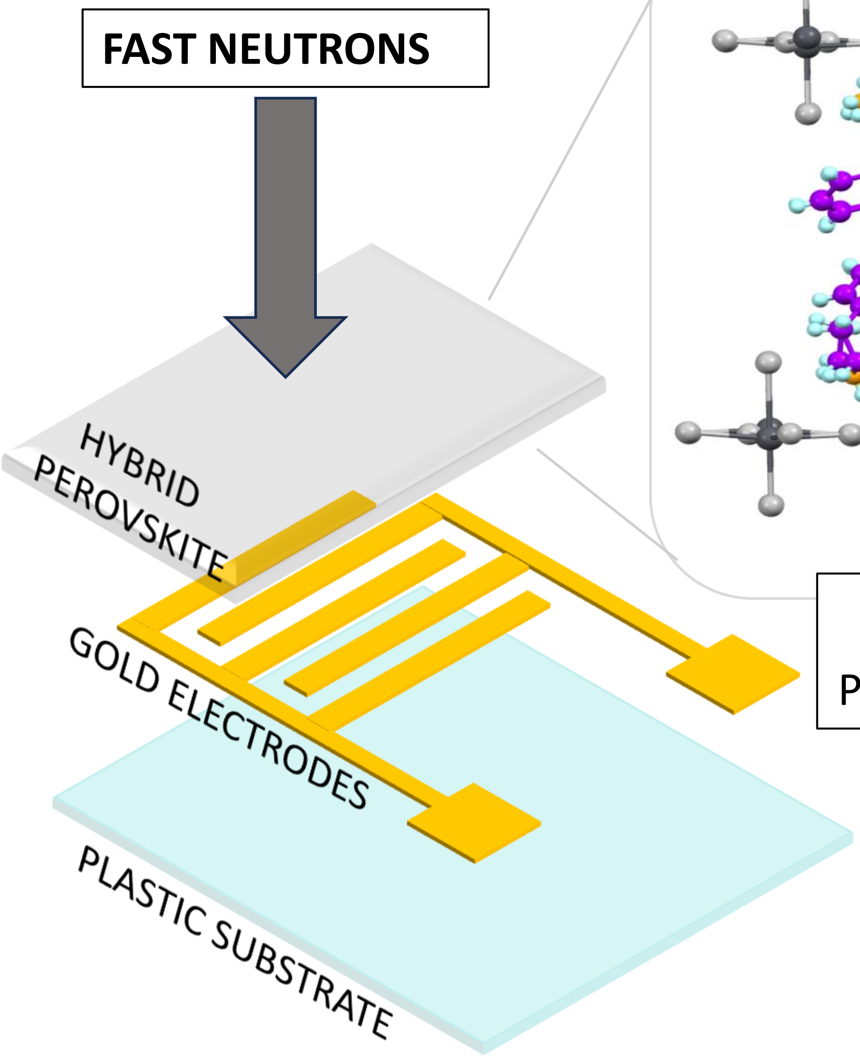

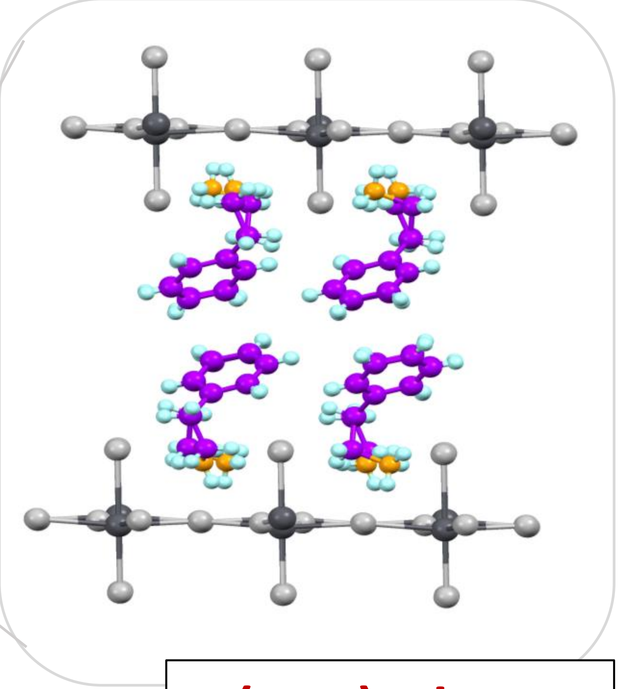

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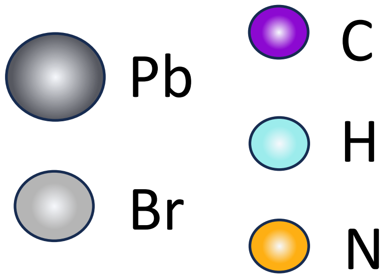
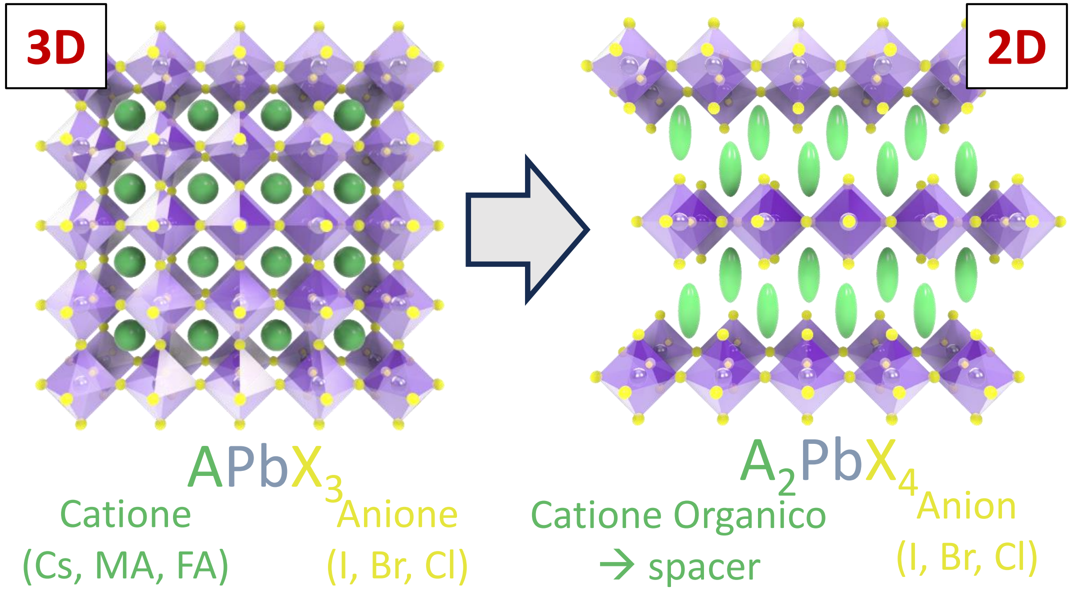
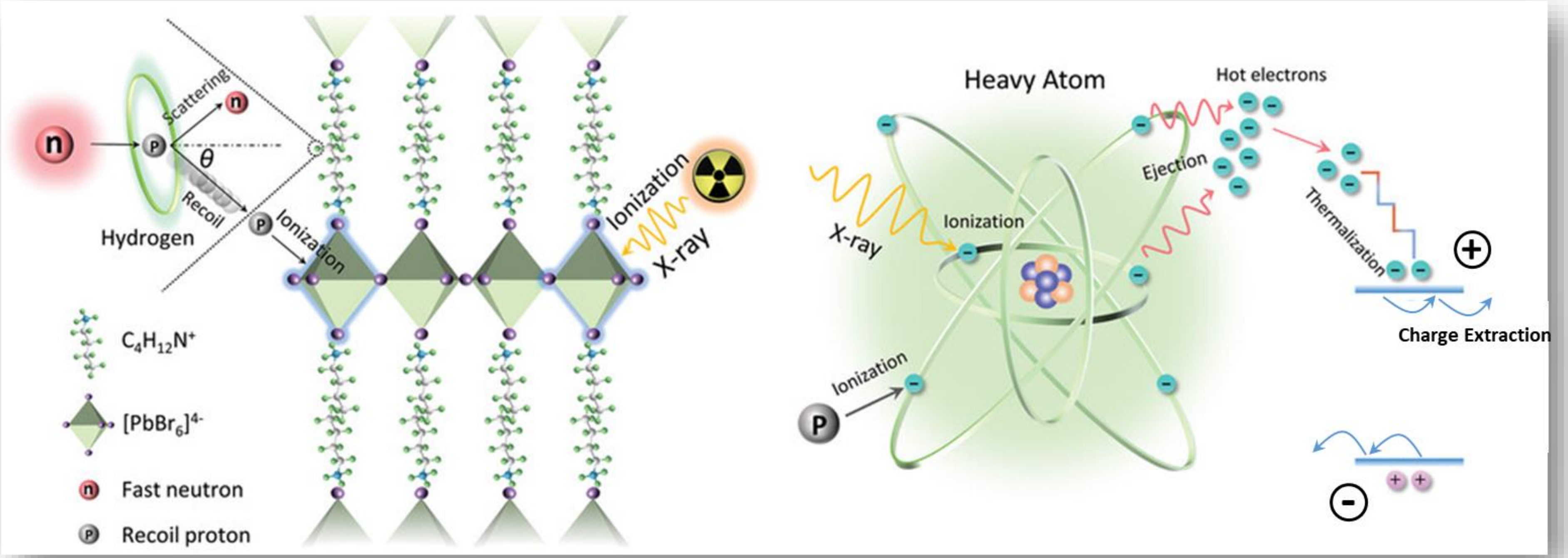


DEPOSIZIONE DA SOLUZIONE → DISPOSITIVI FLESSIBILI e LARGE-AREA

PEROVSKITI IBRIDE 2D →
- BASSA CORRENTE DI BUIO (10^{-13} A @ 500 V mm^{-1})
- NO MIGRAZIONE IONICA → Maggiore Stabilità
- ALTA DENSITÀ di ATOMI a BASSO Z

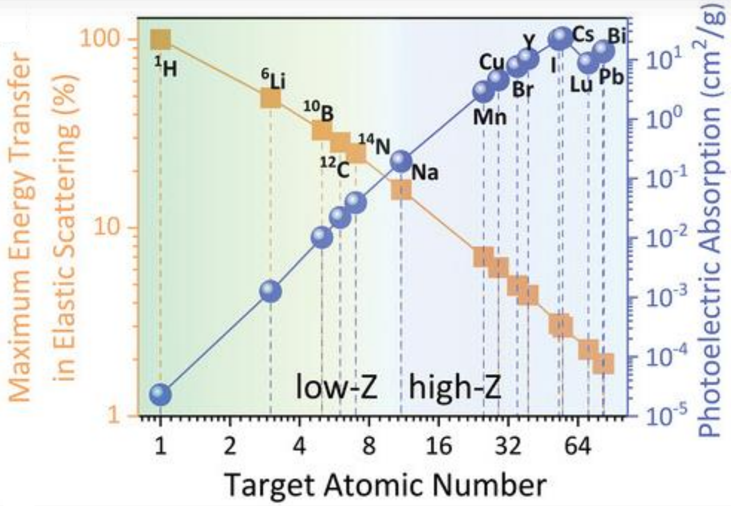


Meccanismo di Interazione



Frazione di Energia Trasferita al nucleo di Recoil a seguito dell'**URTO ELASTICO**

$$\frac{E_R}{E_N} = \frac{4A}{(1+A)^2}\,cos^2\theta$$



Shao, W., Liang, H. et al. (2023). *Advanced Functional Materials*, *33*(40)

Simulazioni – Toolkit Geant4

Fratelli I., in preparation

PPEROVSKITE IBRIDA 2D
→ ALTA DENSITÀ DI ELEMENTI A BASSO Z
→ MAX TRASFERIMENTO DI ENERGIA A SEGUITO DELL'URTO ELASTICO

CLASS	ACTIVE MATERIAL	DENSITY g cm^{-3}	HYDROGEN DENSITY $\times 10^{22}$ cm^{-3}	CARBON DENSITY $\times 10^{22}$ cm^{-3}
SOLID STATE	MHyPbCl3	3.242	3.79	--
	Rubrene	1.26	3.99	--
	4MHB	1.46	4.62	--
LIQUID SCINTILLATOR	EJ301	--	4.82	3.98
	EJ309	--	5.43	4.35
	Stilbene	1.15	4.61	--
PLASTIC SCINTILLATOR	EJ276D	1.099	4.65	4.94
	EJ200	1.023	5.17	4.69
THIS WORK	PEA_2PbBr_4	2.27	4.25	2.84

Simulazioni – Toolkit Geant4

Fratelli I., in preparation

Neutron Energy = 2.5 MeV
PVK thickness = 5 μm

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→ ALTA DENSITÀ DI ELEMENTI A BASSO Z
→ MAX TRASFERIMENTO DI ENERGIA A SEGUITO DELL'URTO ELASTICO

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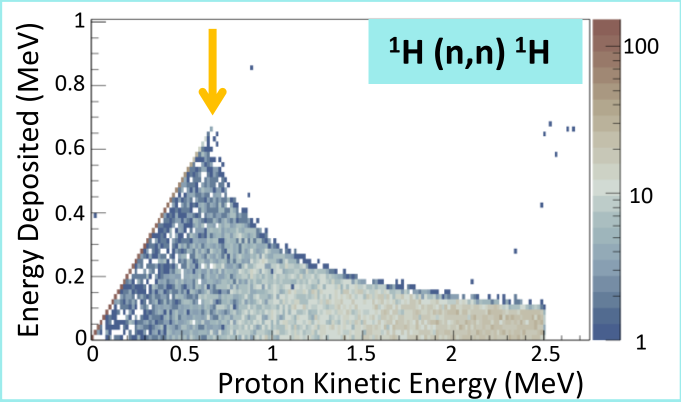

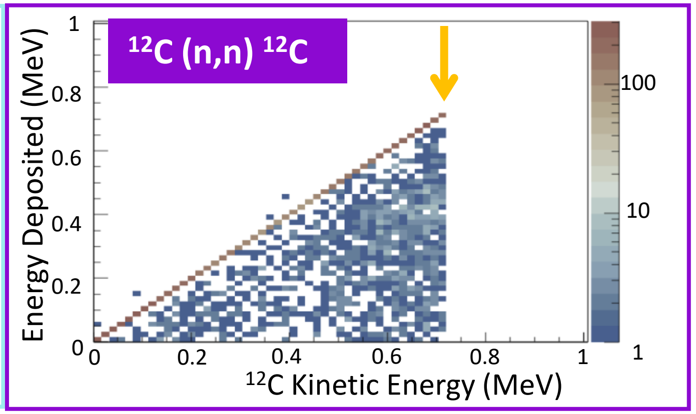

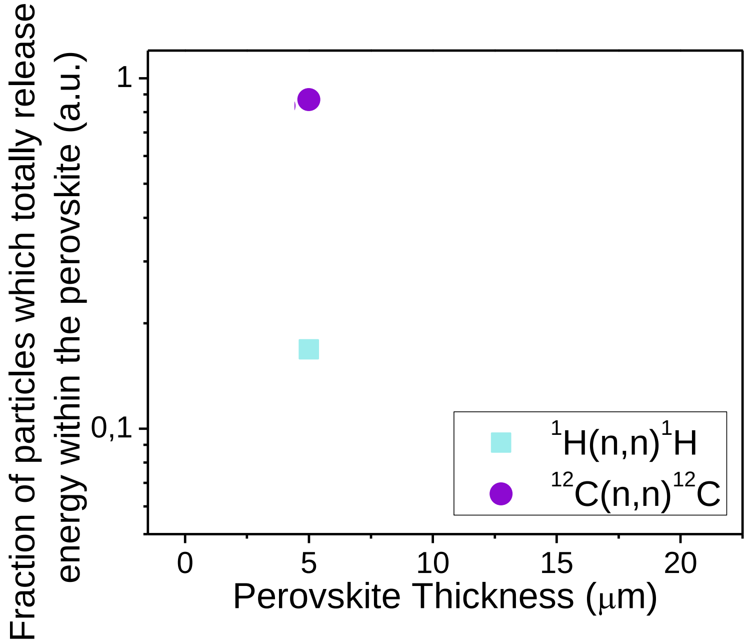

Simulazioni – Toolkit Geant4

BEYOND

Fratelli I., in preparation

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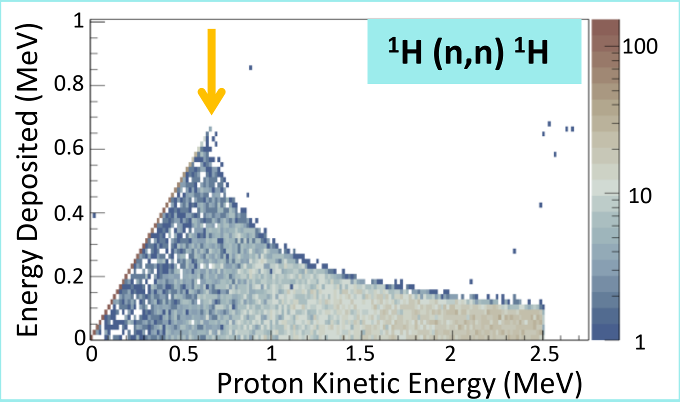
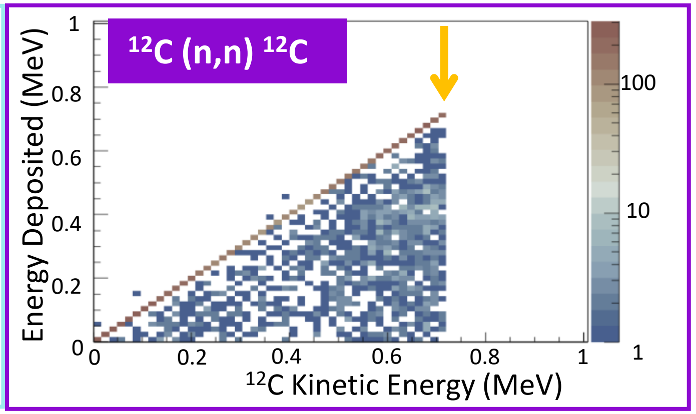
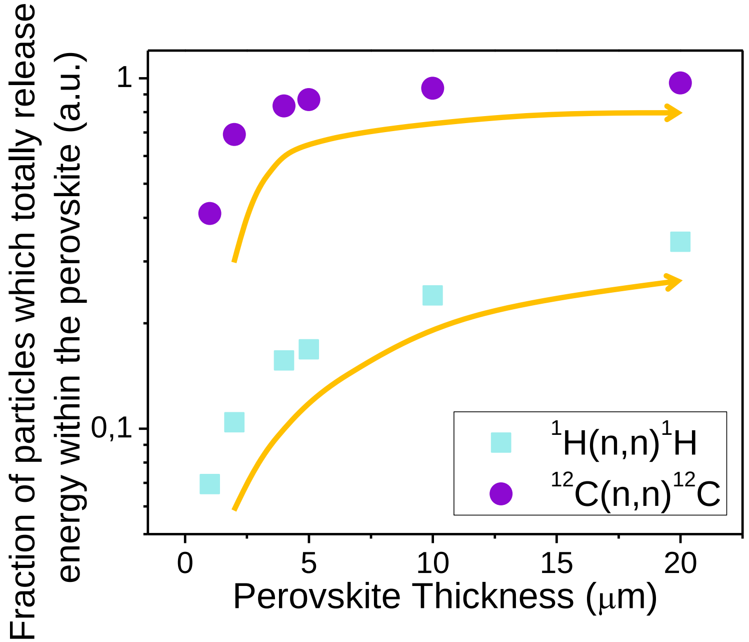


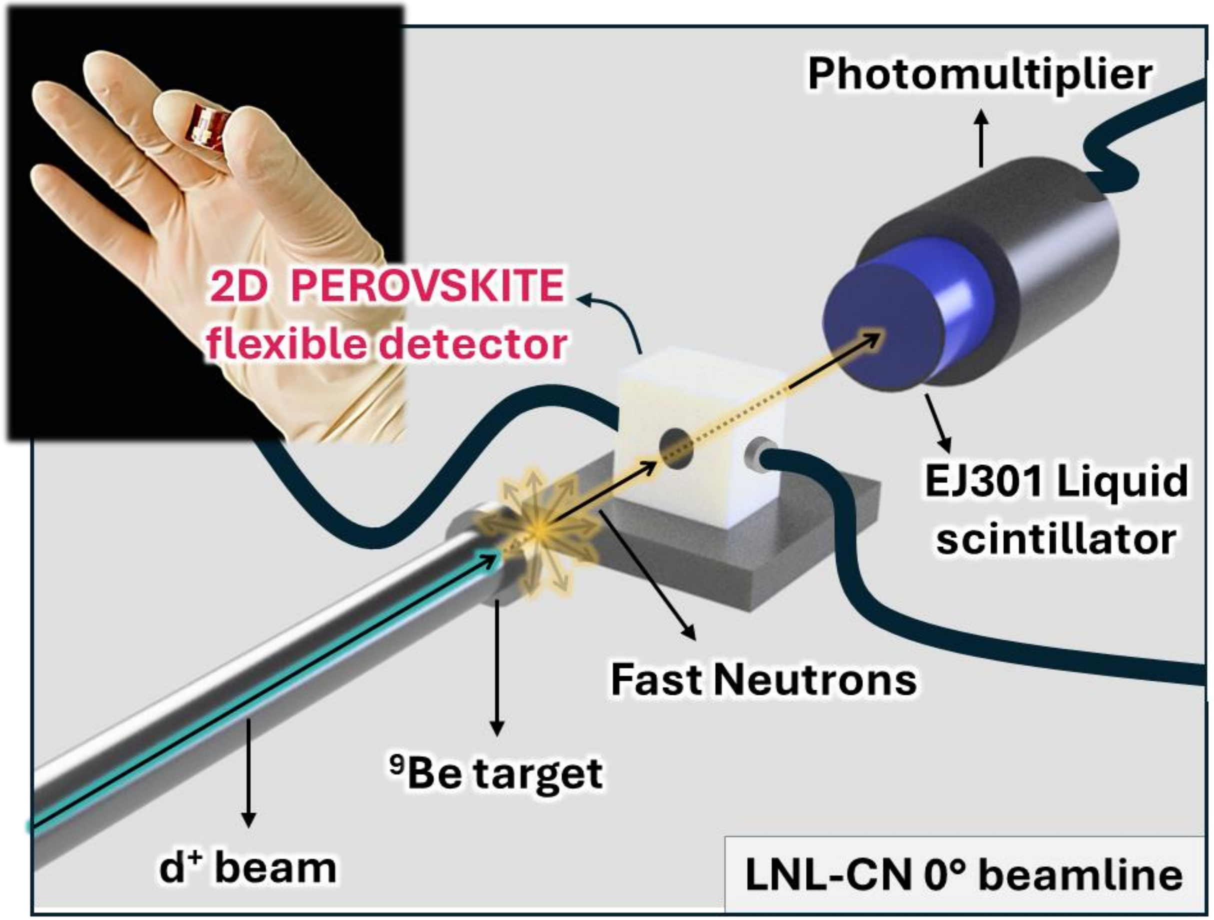




Irraggiamento @ INFN-LNL

Fratelli I., in preparation

Acceleratore Van der Graaff (INFN-LNL, CN, 0° beamline)
Fascio 5 MeV di Deuterio, target ^{9}Be
Fast Neutrons $^{9}Be(d,n)^{10}B$
(**Energia = [1 – 4] MeV Flusso = [0.4 - 3] · 10^{5} n s^{-1} cm^{-2}**)



Meadows, J. W. (1993). In *Nuclear Instruments and Methods in Physics Research* (Vol. 324).

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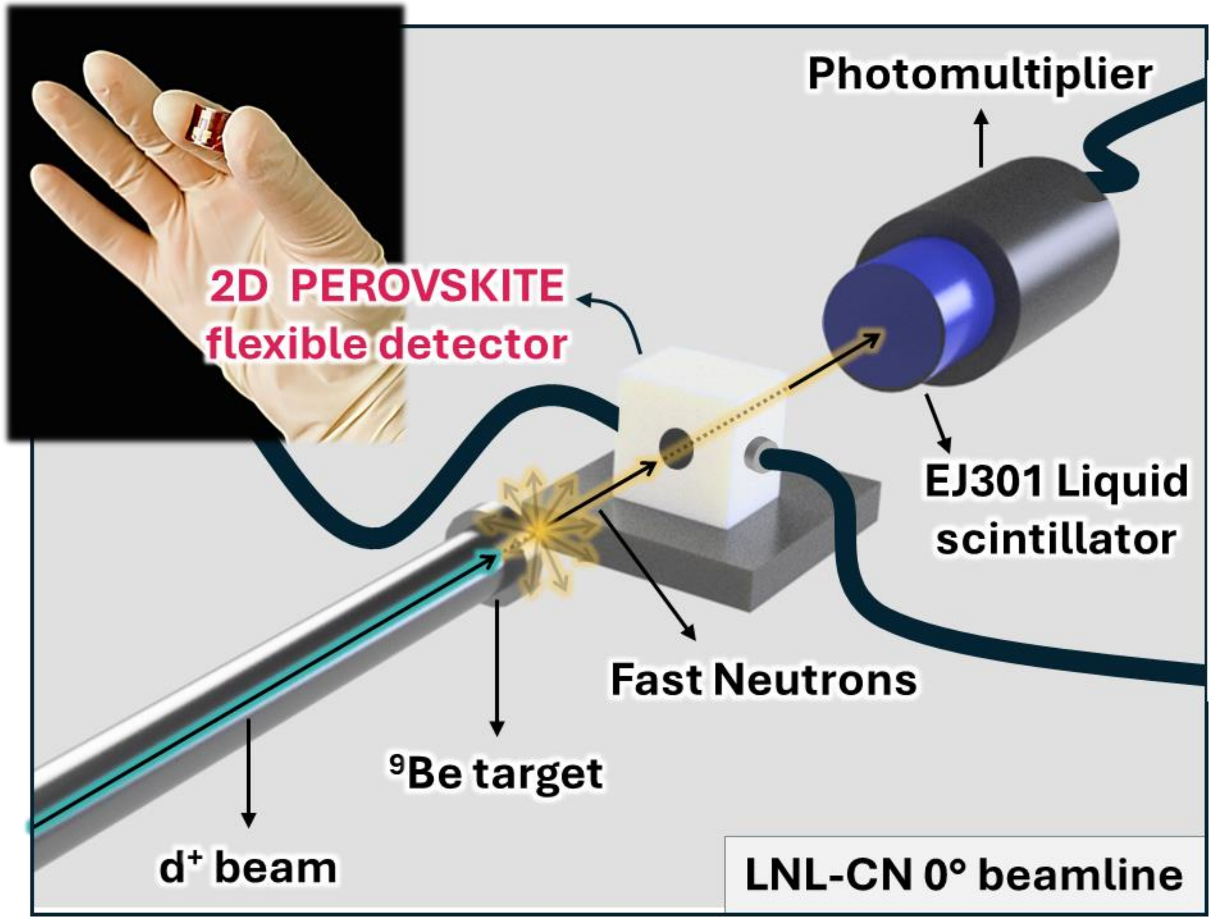
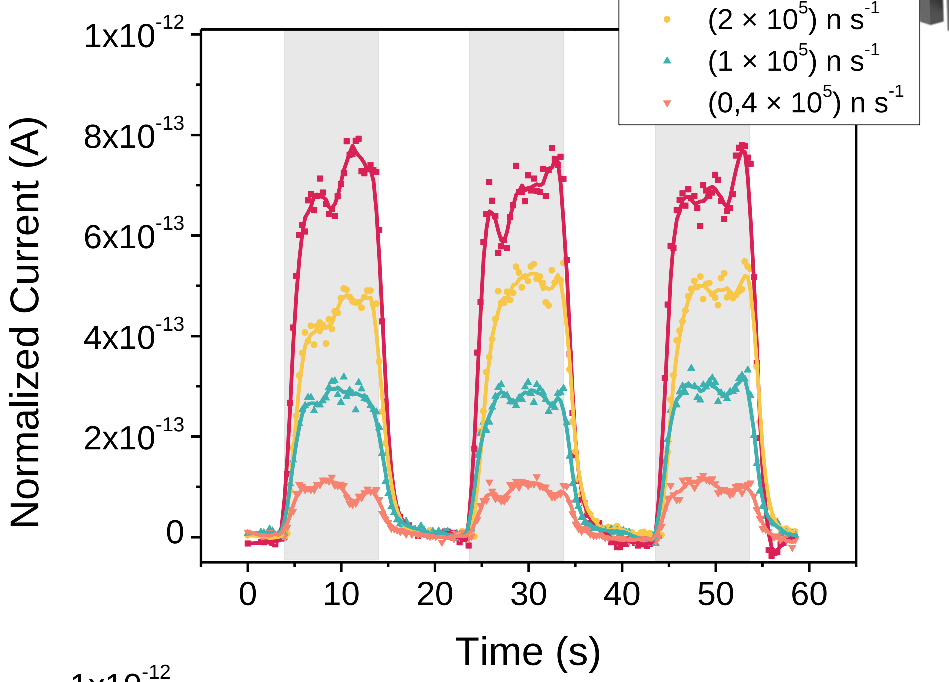
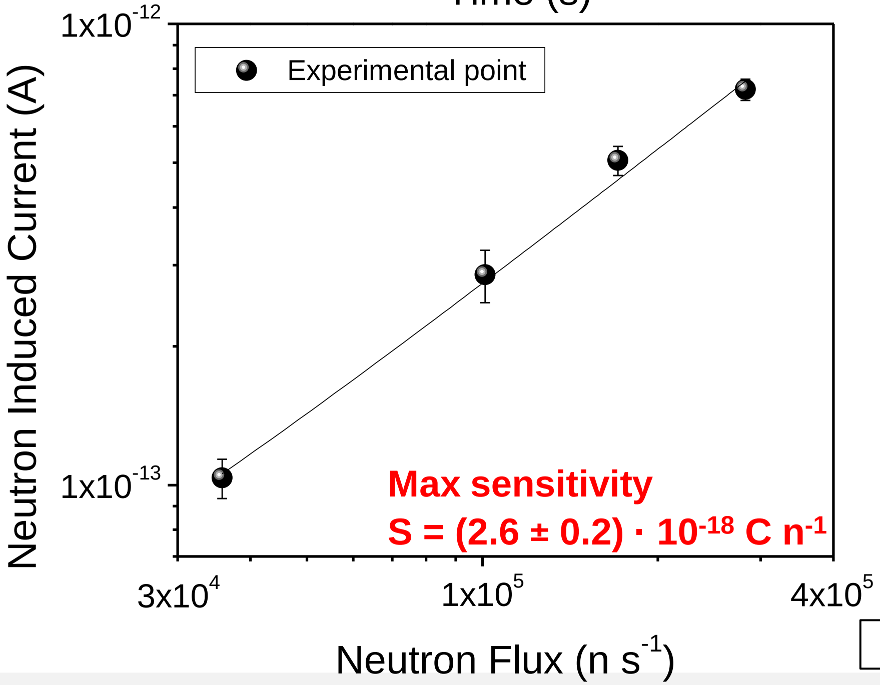






Fratelli I., in preparation

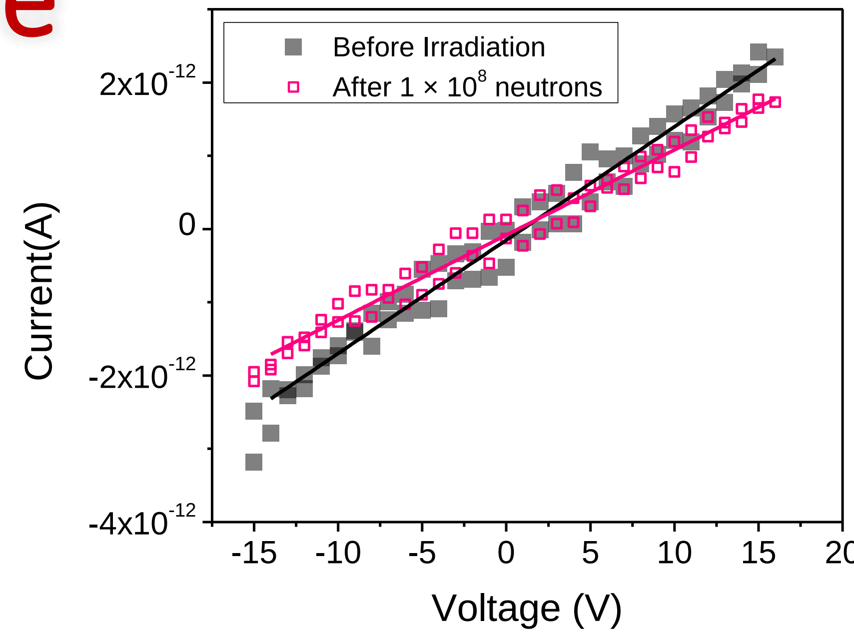
Caratterizzazione del Rivelatore

✓ **Radiation Tolerance** up to 10^8 neutrons

✓ **Tempo di risposta** (τ_{rise} = 1,6 s; τ_{fall} = 4,2 s)

✓ **Ripetibilità e Stabilità**

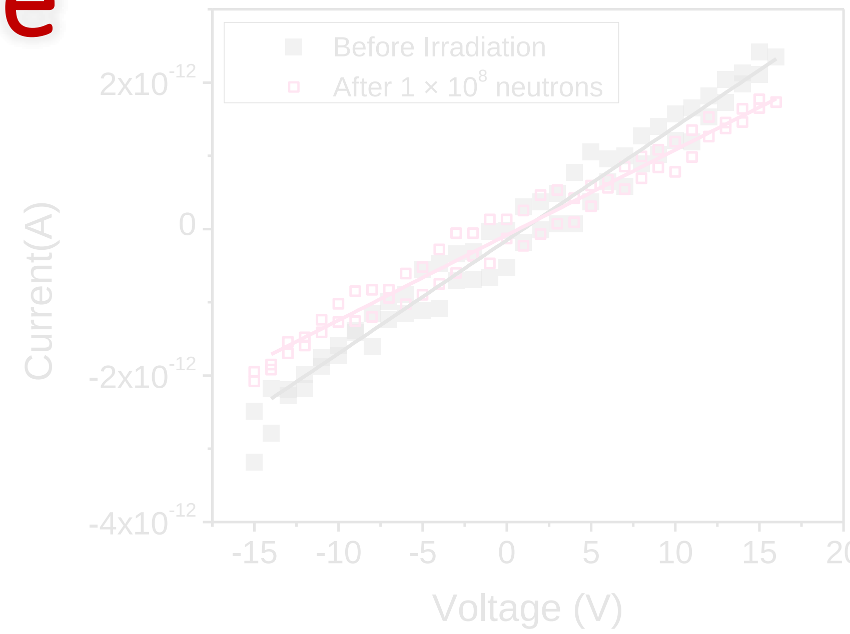
✓ **SELETTIVITÀ** (= trasparenza al campo gamma)



Fratelli I., in preparation

Caratterizzazione del Rivelatore

Fratelli I., in preparation



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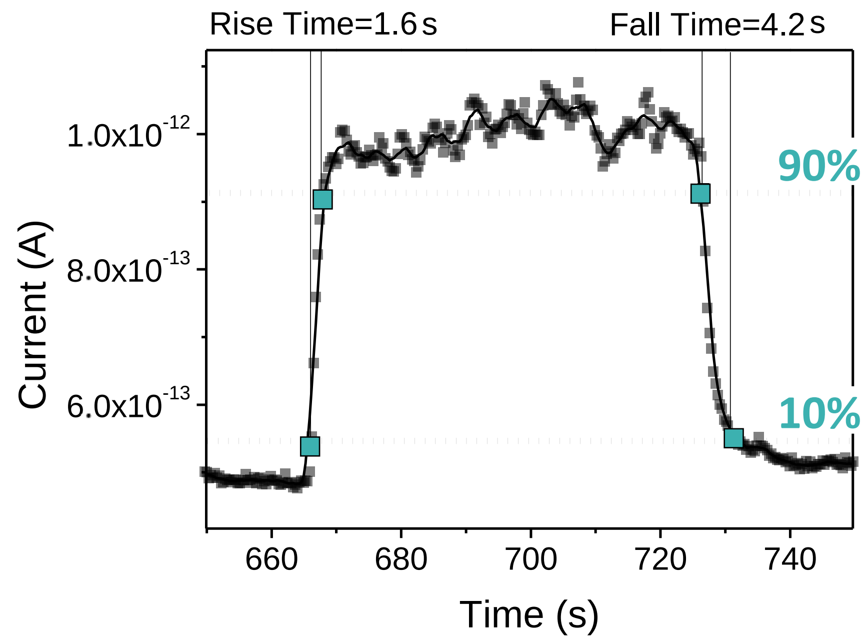

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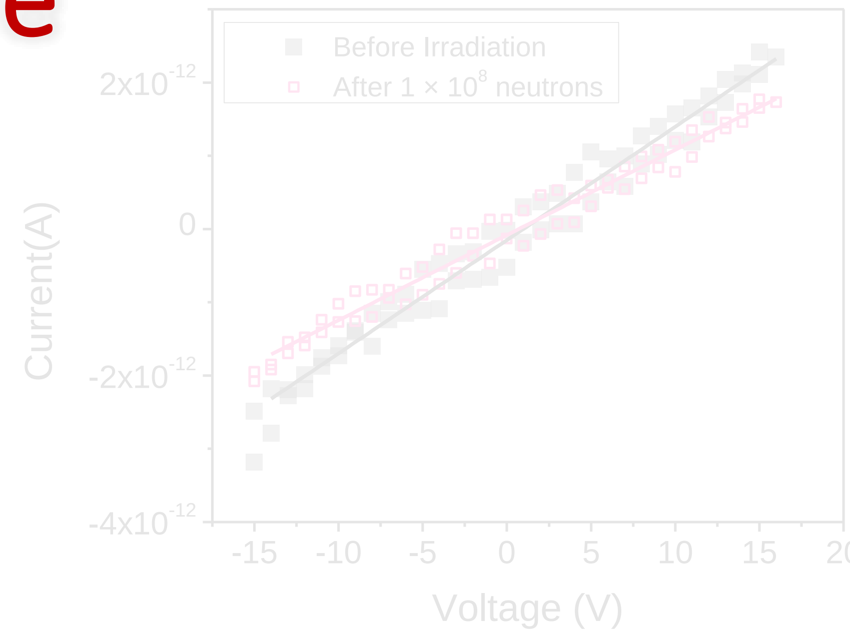

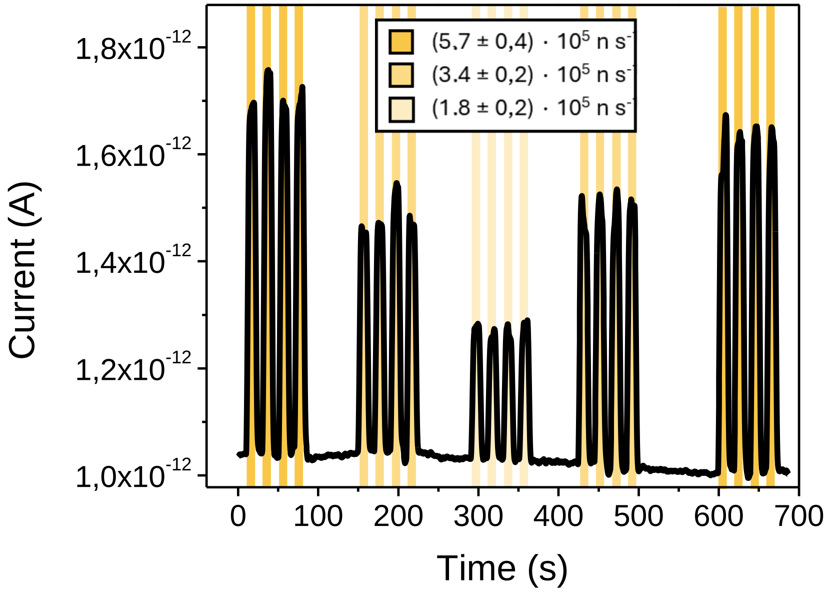

Caratterizzazione del Rivelatore

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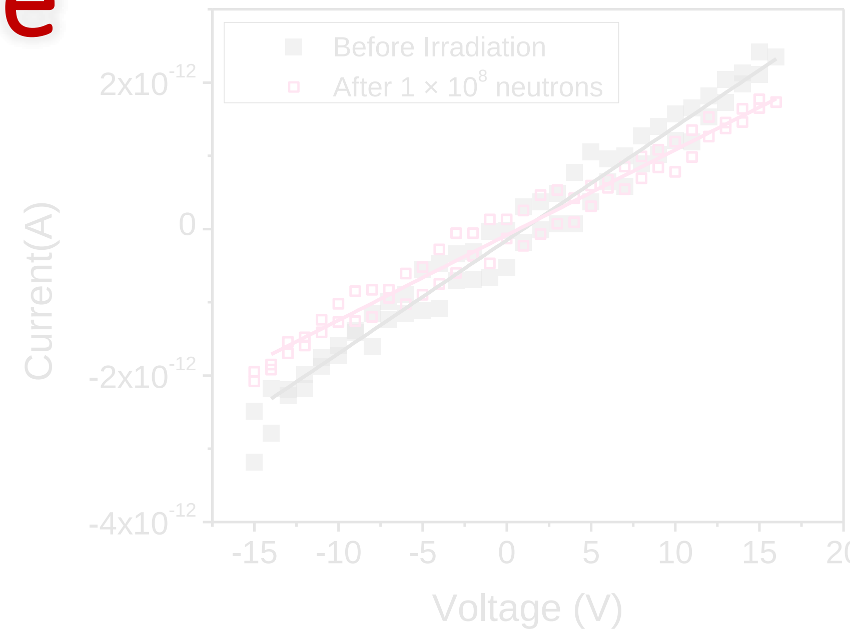
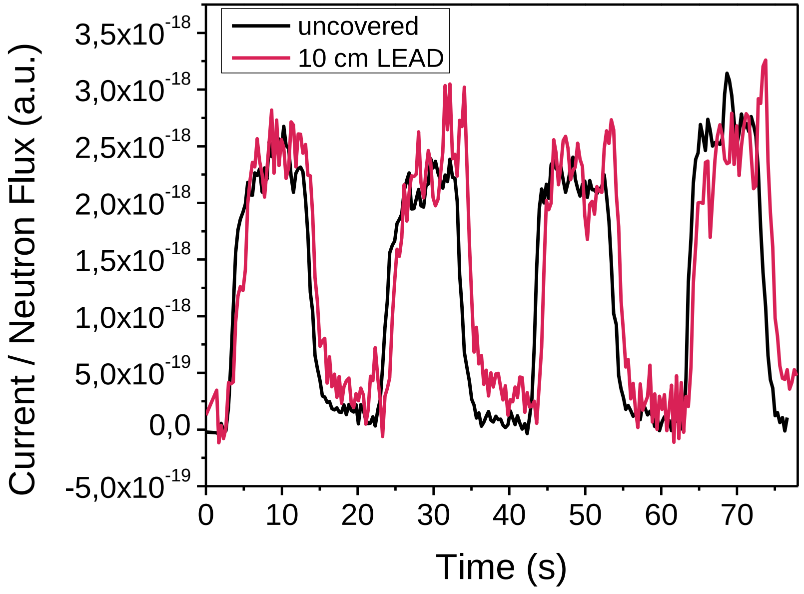
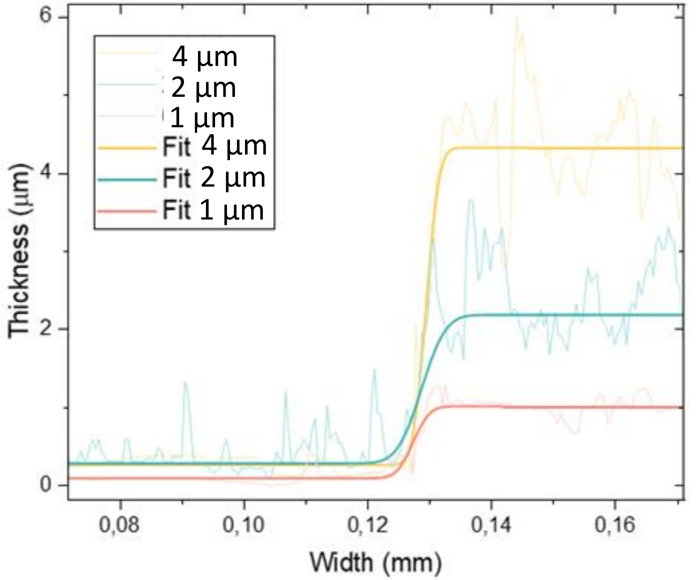
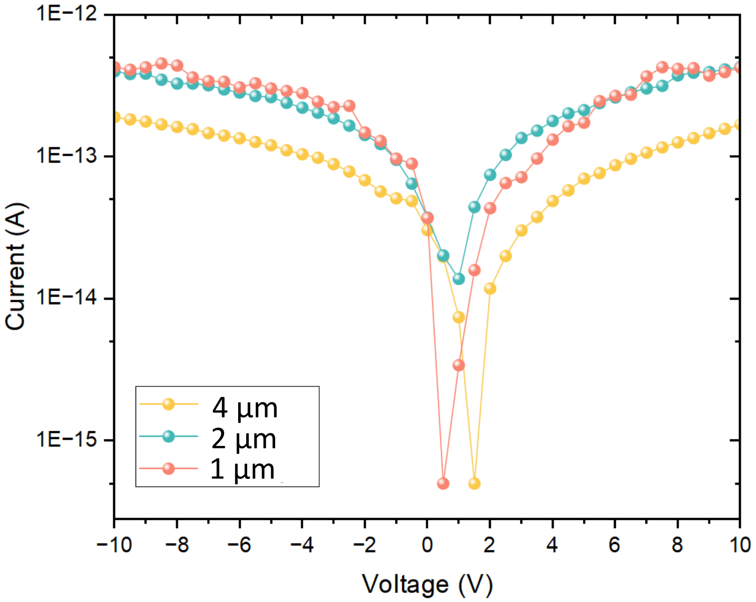




Efficienza a diversi spessori di perovskite



Variando la velocità di deposizione (spin coating)
→ **AUMENTO dello spessore della PEROVSKITE (thickness = [1-4] µm)**

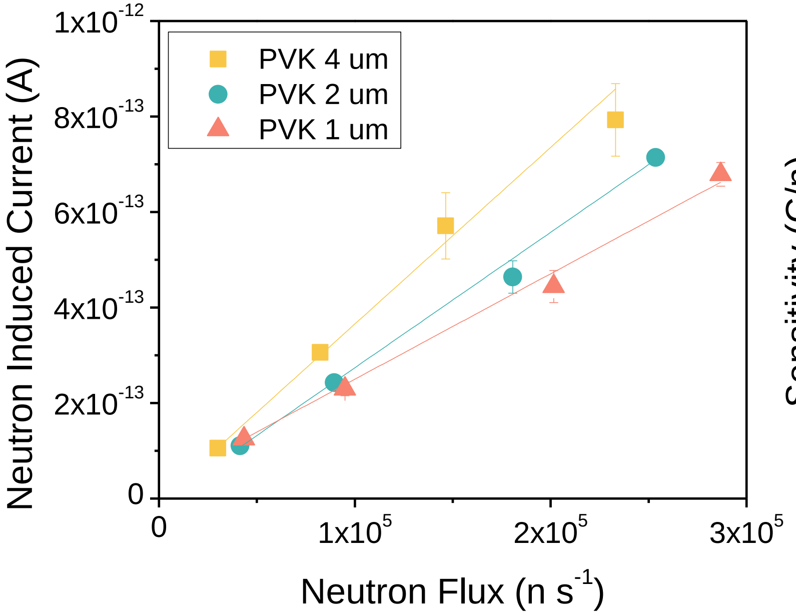


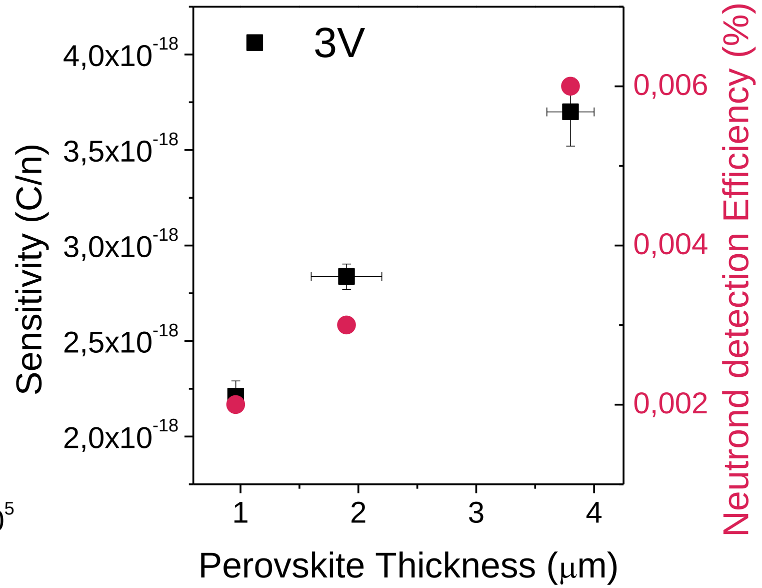
PROPRIETÀ di TRASPORTO CONFRONTABILI

Fratelli I., in preparation

Efficienza a diversi spessori di perovskite

Fratelli I., in preparation





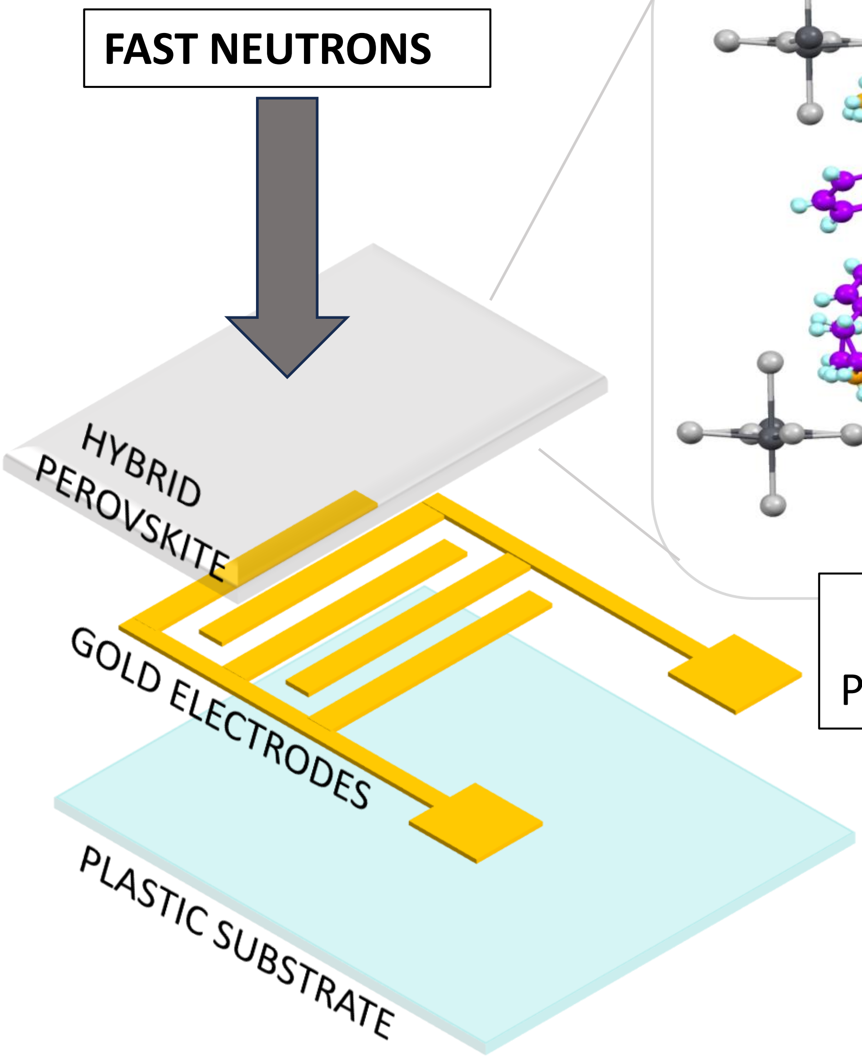
→ **AUMENTO della SENSITIVITY e dell'EFFICIENZA del RIVELATORE**
all'aumentare dello **SPESSORE della PEROVSKITE**

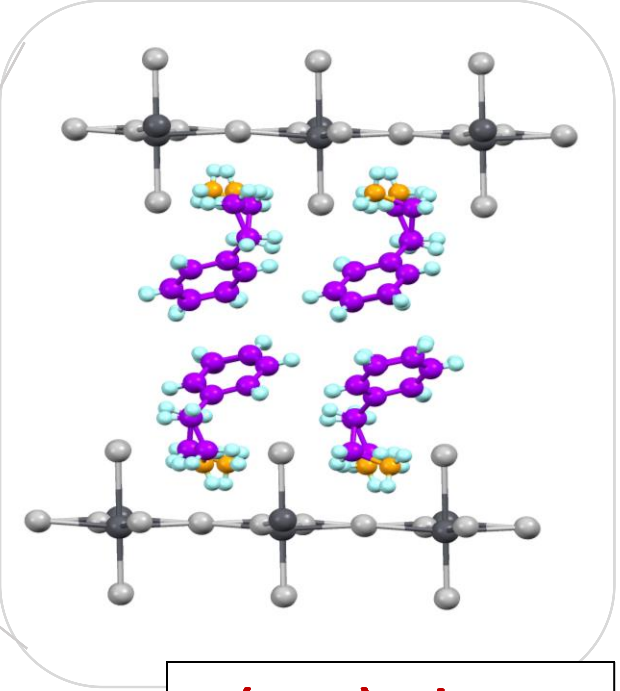
MA ATTENZIONE!

1) Aumento del numero di elementi ad alto Z
→ **calo della SELETTIVITÀ**
2) FILM SPESSI offrono spesso PROPRIETÀ di TRASPORTO peggiori
→ **calo dell'EFFICIENZA di COLLEZIONAMENTO**

E I NEUTRONI TERMICI??

Fabbricazione del rivelatore





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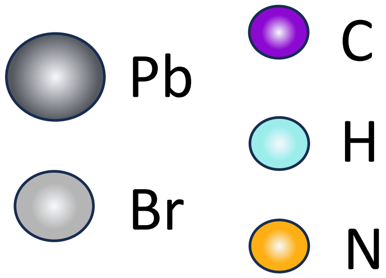

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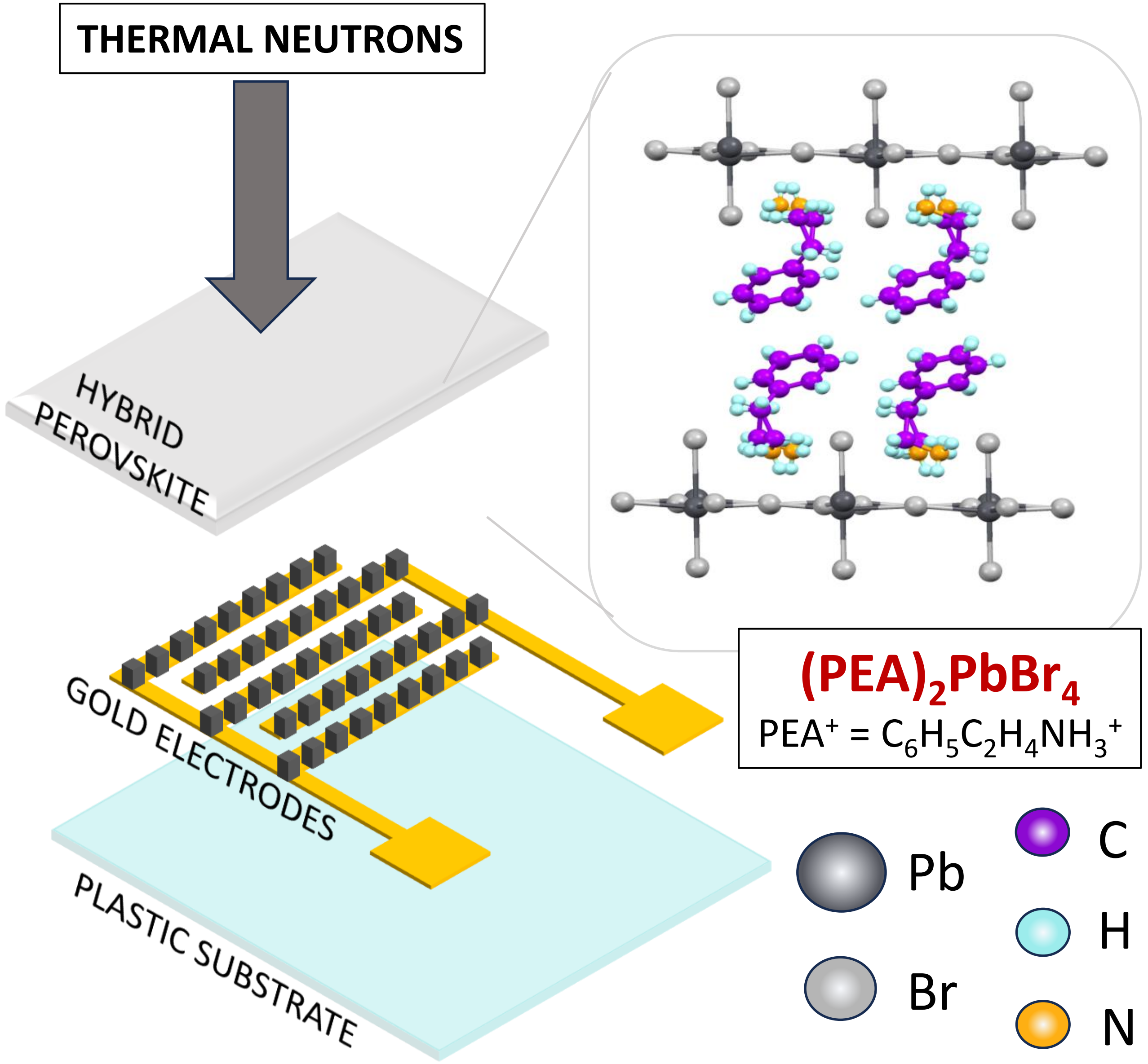
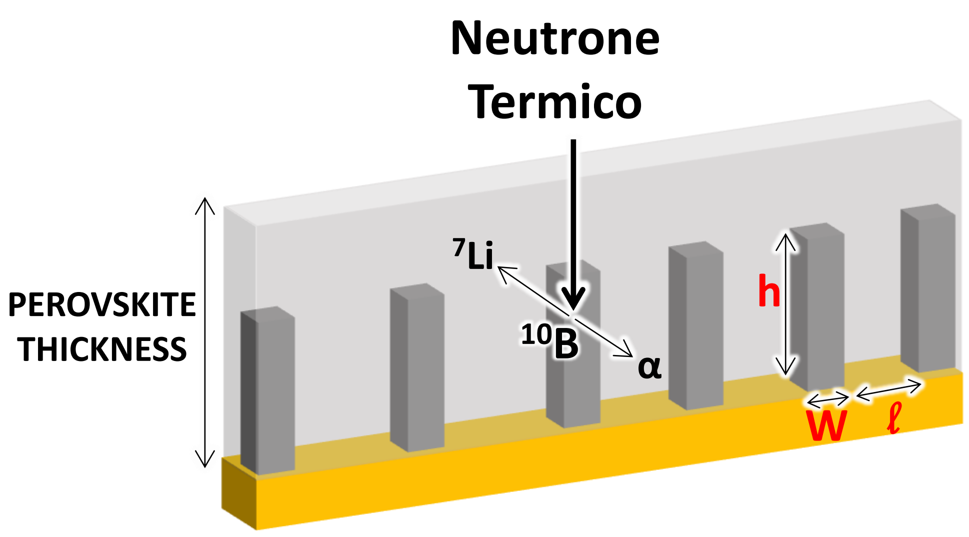
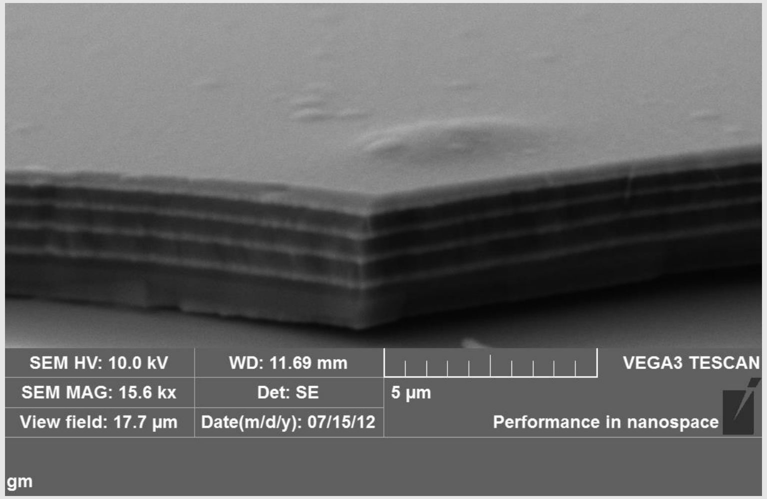


MECCANISMO DI INTERAZIONE



$$^{10}B + n \begin{cases} \xrightarrow{94\%} \alpha(1.47MeV +^7 Li(0.84MeV) + \gamma(0.48MeV) \\ \xrightarrow{6\%} \alpha(1.78MeV +^7 Li(1.01MeV) \end{cases}$$

Fabbricazione del rivelatore



①

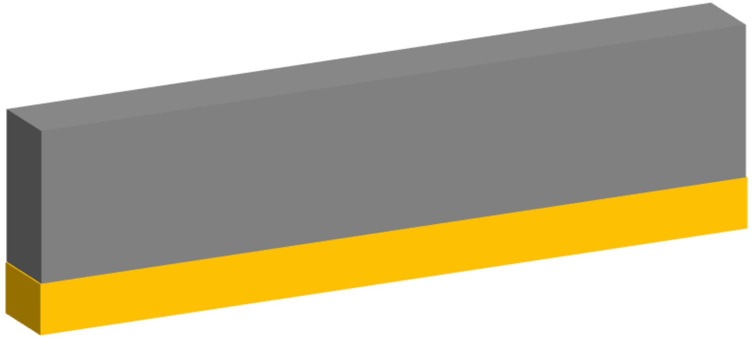
DEPOSIZIONE DEL LAYER CONVERTITORE

RF magnetron sputtering

$^{10}B/Ti$ multilayer

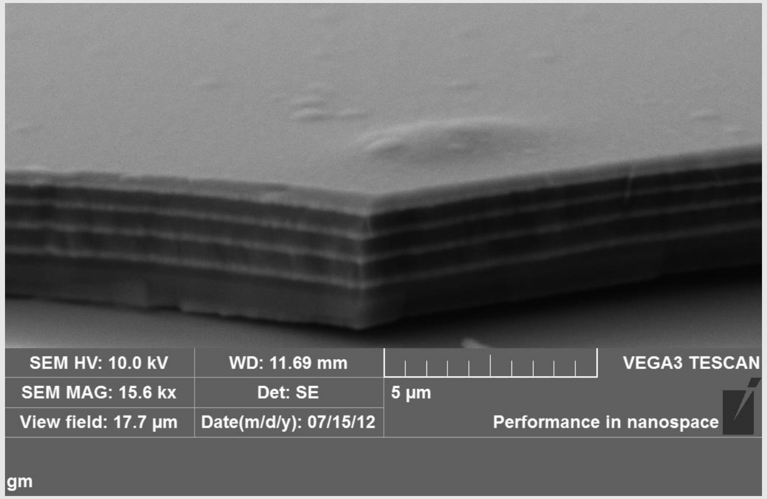
$h \approx 1\ \mu m$

MECCANISMO DI INTERAZIONE



$$^{10}B + n \begin{cases} \xrightarrow{94\%} \alpha(1.47MeV +^{7} Li(0.84MeV) + \gamma(0.48MeV) \\ \xrightarrow{6\%} \alpha(1.78MeV +^{7} Li(1.01MeV) \end{cases}$$

Fabbricazione del rivelatore



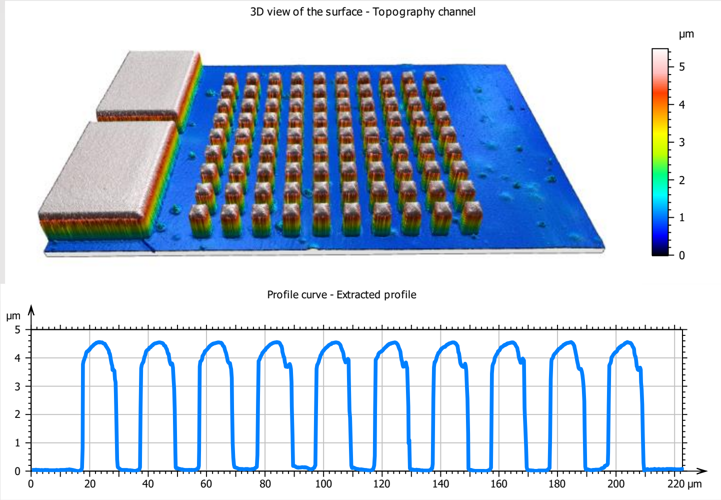
①
DEPOSIZIONE DEL LAYER CONVERTITORE

RF magnetron sputtering

^{10}B/Ti multilayer

h ≈ 1 μm

INFN LNL



②
PATTERNING DEL LAYER CONVERTITORE

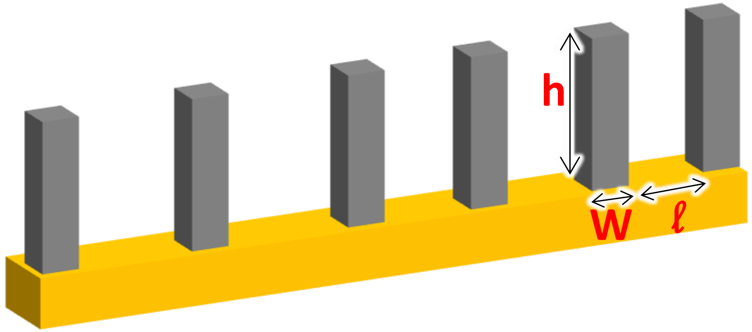
Microstrutture 3D attraverso tecniche di photolitografia

W ≈ 15 μm

ℓ ≈ 20 μm

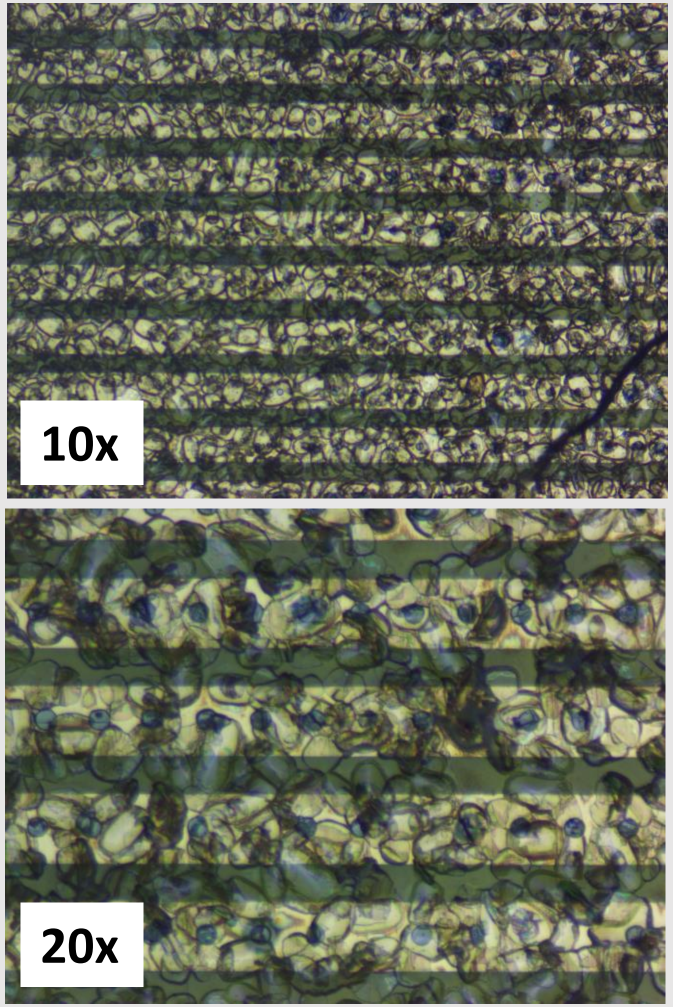
INFN BOLOGNA

MECCANISMO DI INTERAZIONE



$$^{10}B + n \begin{cases} \xrightarrow{94\%} \alpha(1.47MeV +^{7} Li(0.84MeV) + \gamma(0.48MeV) \\ \xrightarrow{6\%} \alpha(1.78MeV +^{7} Li(1.01MeV) \end{cases}$$

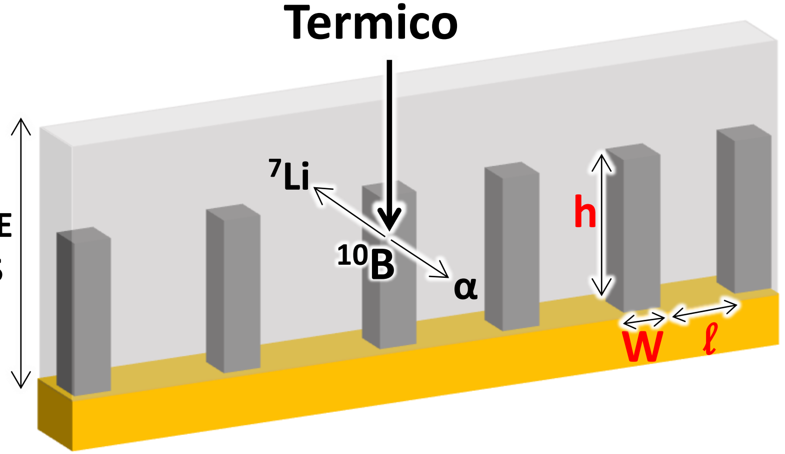
Fabbricazione del rivelatore



③
DEPOSIZIONE della PEROVSKITE IBRIDA 2D

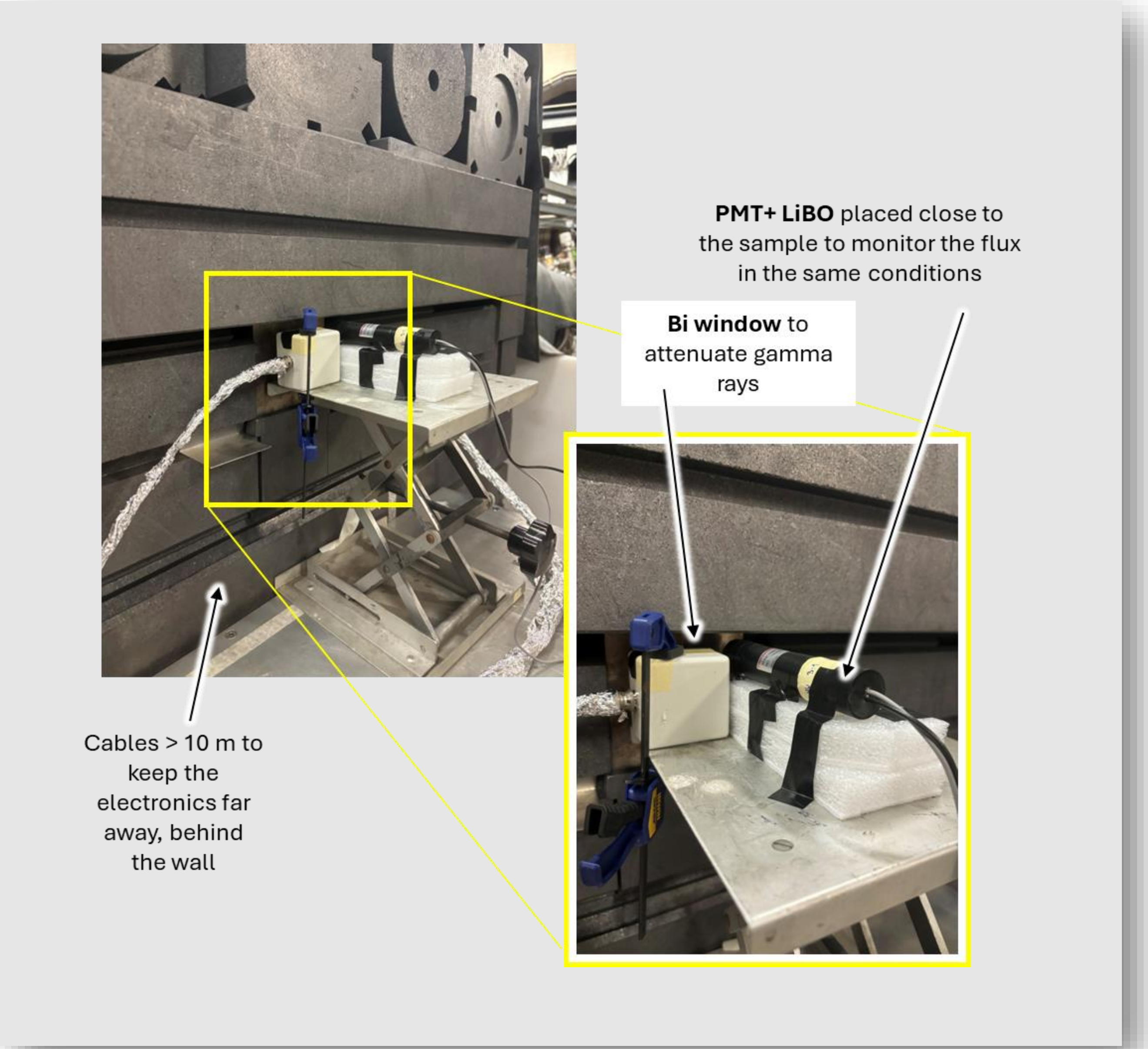
SPIN COATING
Thickness ≈ 2 µm

MECCANISMO DI INTERAZIONE

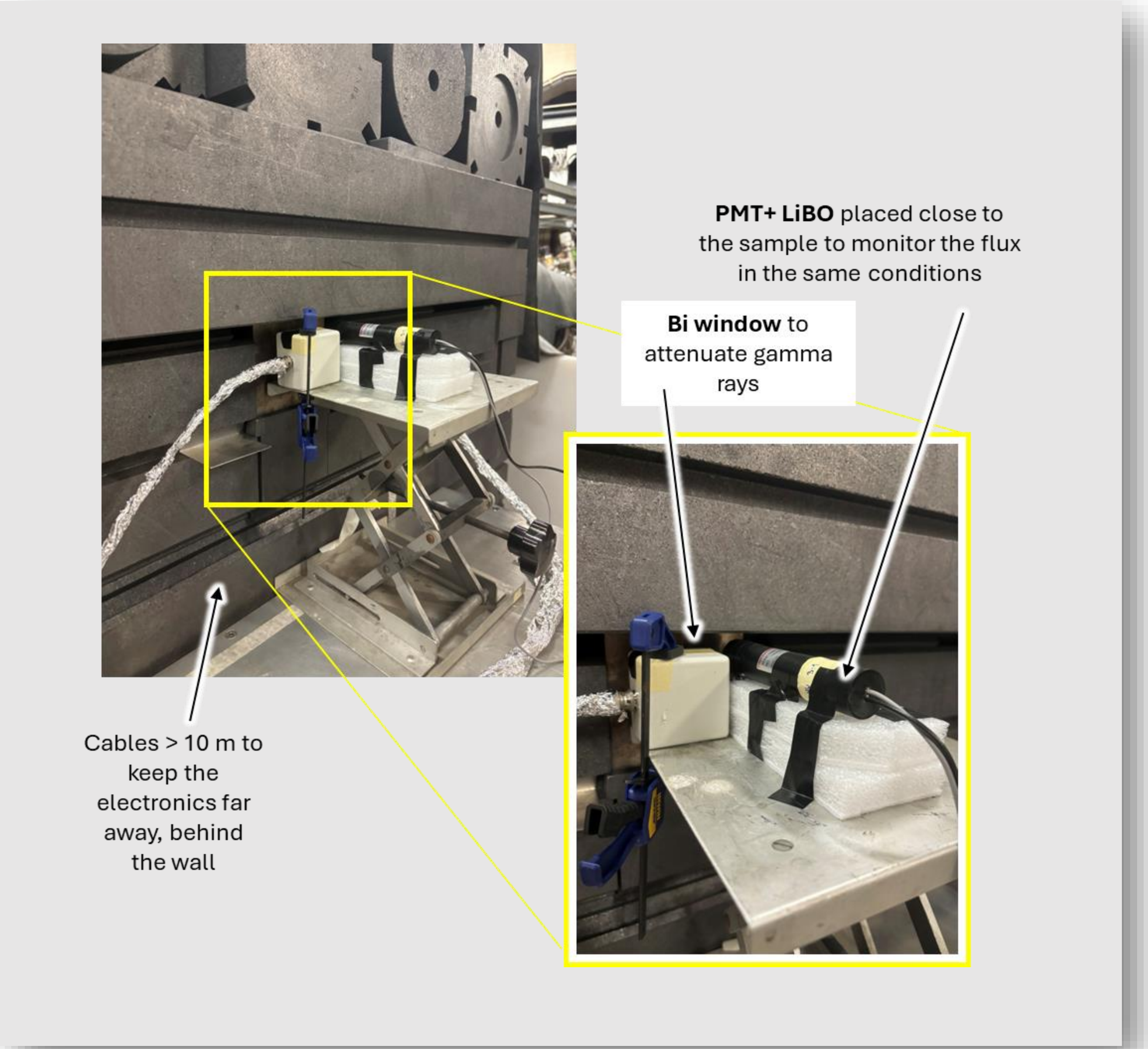


$$^{10}B + n \begin{cases} \xrightarrow{94\%} \alpha(1.47MeV +^{7} Li(0.84MeV) + \gamma(0.48MeV) \\ \xrightarrow{6\%} \alpha(1.78MeV +^{7} Li(1.01MeV) \end{cases}$$

Irraggiamento @ INFN-LNL (linea MUNES)



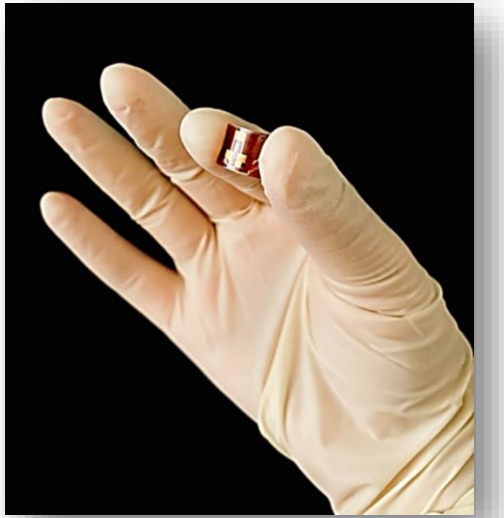
Irraggiamento @ INFN-LNL (linea MUNES)



Turno 10 giorni fa…

Stay tuned…

Conclusioni



RIVELAZIONE NEUTRONI VELOCI

PEROVSKITE IBRIDA 2D

- → Alta densità intrinseca di atomi a basso Z (H e C)
- → Migliori proprietà di trasporto rispetto ai materiali organici
- → Maggior stabilità ambientale, soppressione della migrazione ionica, bassa dark current

Configurazione a **FILM SOTTILE**

- → Stampa da soluzione scalabile su larghe aree e substrati flessibili
- → Trasparenza ai raggi gamma = selettività

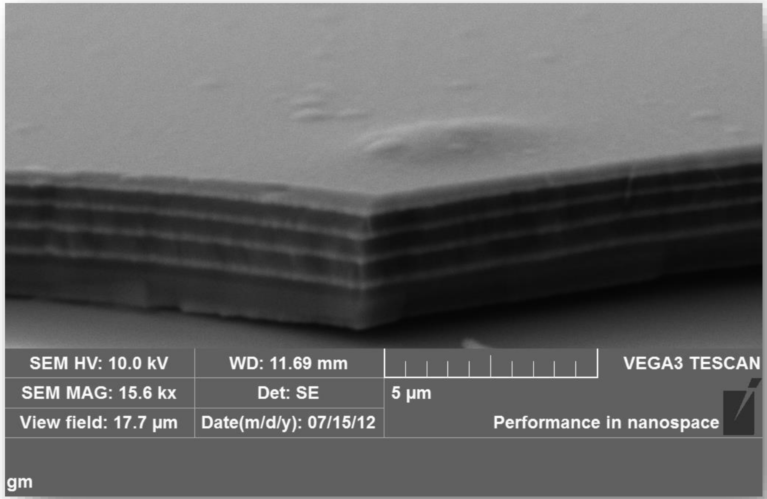
RIVELAZIONE NEUTRONI TERMICI

PEROVSKITE IBRIDA 2D

- → Stampa da soluzione scalabile su larghe aree e substrati flessibili + possibilità di avere un miglior ricoprimento delle microstrutture 3D

MICROSTRUTTURE 3D ^{10}B

- → Trasferimento di carica al semiconduttore più efficiente



INFN-Bologna and UNIBO Department of Physics and Astronomy - DIFA


Prof. B. Fraboni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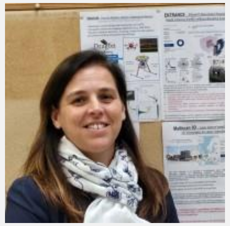
Prof. S. Moretto


Dr. J. Delgado


Dr. M. Cinausero


Dr. A. Selva


Dr. L. Bellan

BEYOND: *flexiBlE hYbrid neutrON Detectors*
INFN (Italian Institute for Nuclear Physics)
(2023-2024)

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

IRIS *Large area, wearable Ionizing Radiation dosimeters for real-tIme crew perSonal monitoring*
Italian Space Agency
(2022-2025)

ANEMONE
hAdroN bEam MONitoring by pErovskite based detectors

ANEMONE
INFN (Italian Institute for Nuclear Physics)
(2022-2024)

Co-funded by the European Union

Hybrid detectors for medical radiation therapies
MSCA Global PF
(2024-2027)

FIRE: *Flexible organic Ionizing Radiation dEtectors*
INFN (Italian Institute for Nuclear Physics)
(2019-2022)

RELOAD: *RivELatOri innovativi per cure Adroterapiche*
CARIPLO-CDP grant
(2023-2025)

INFN-Bologna and UNIBO Department of Physics and Astronomy - DIFA


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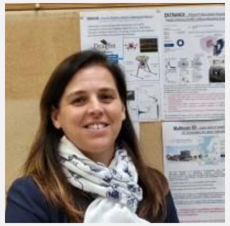
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Grazie per il supporto e… per la pazienza ;)

Eugenio Scapparone
Carla Sbarra e Gruppo V
Anselmo Margotti e l'officina meccanica
Riccardo Travaglini e Ignazio Lax
Elisa Zini e Antonella Aiello
Elena Amedei
Martina Allegro
Alberta Raimondi e Susan Bondi
Sara Haghshenas
Cecilia Pancaldi e Carlo Crescentini

GRAZIE a tutte e tutti voi per l'attenzione!

Starting Point – Neutroni Veloci

Moderatori + contatori neutroni termici

Contatori proporzionali a gas ^{3}He

RIVELAZIONE INDIRETTA

Scintillatori Plastici e Liquidi

PEROVSKITE SINGLE CRYSTALS

- J. Zheng et al., J. Am. Chem. Soc. 2021, 143, 50, 21302–21311

ORGANIC SINGLE CRYSTALS – RIVELAZIONE DIRETTA

- Kargar, A., Loef, E. V. van, Cirignano, L., Shah, K. S., & Member, S. (2011). *1*, 4545–4549.
- Carman, L., Paul Martinez, H., Voss, L., Hunter, S., Beck, P., Zaitseva, N., Payne, S. A., Irkhin, P., Choi, H. H., & Podzorov, V. (2017). *IEEE Transactions on Nuclear Science*, *64*(2), 781–788.
- Zhao, D., Cai, P., Cheng, W., Jia, W., Zhang, B., Zhu, M., Liu, L., Ouyang, X., Sellin, P., Jie, W., & Xu, Y. (2022). *Advanced Functional Materials*, *32*(7), 1–9.

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- Panaccione, W., Shi, Z., Kandlakunta, P., Nichols, T., White, S., Huang, J., & Cao, L. R. (2024). Testing of an Organic Metal Halide Perovskite for Fast Neutron Detection. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *1064*(September 2023)

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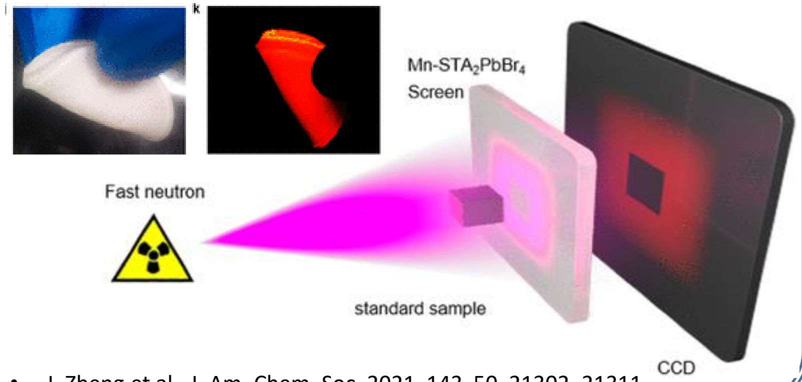
Contatori proporzionali a gas ^{3}He

RIVELAZIONE INDIRETTA

Scintillatori Plastici e Liquidi

PEROVSKITE SINGLE CRYSTALS



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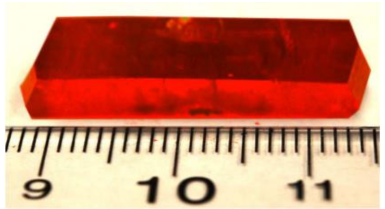

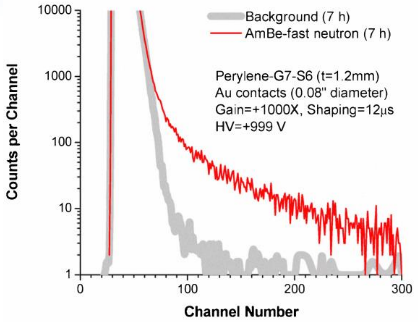

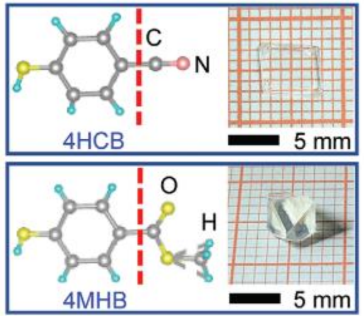

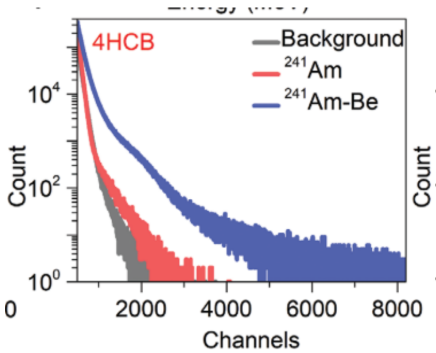

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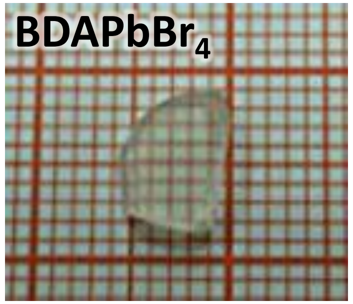
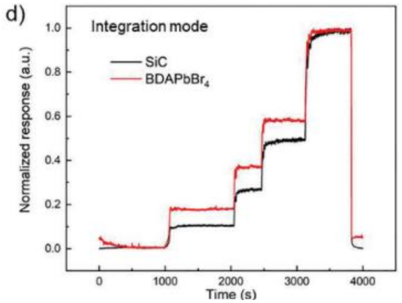
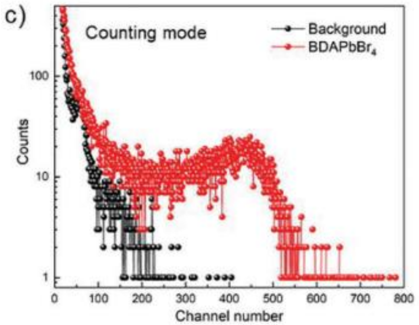
PEROVSKITE SINGLE CRYSTALS RIVELAZIONE DIRETTA







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Starting Point – Neutroni Termici

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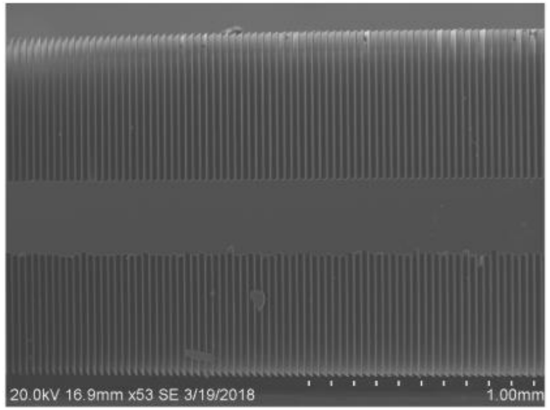
ORGANIC SINGLE CRYSTALS – RIVELAZIONE DIRETTA

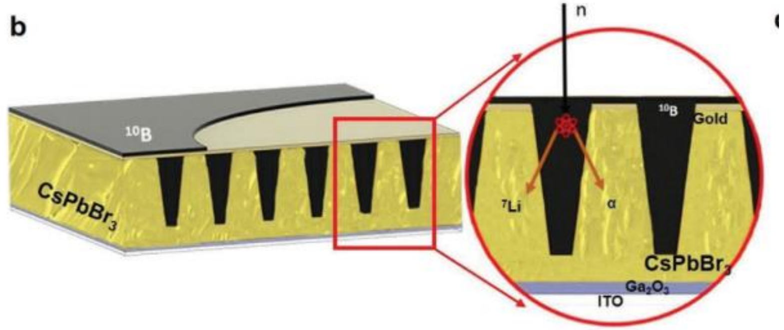
PEROVSKITE SINGLE CRYSTALS RIVELAZIONE DIRETTA

RIVELATORI al SILICIO con MICROSTRUTTURE 3D COVERTITRICI



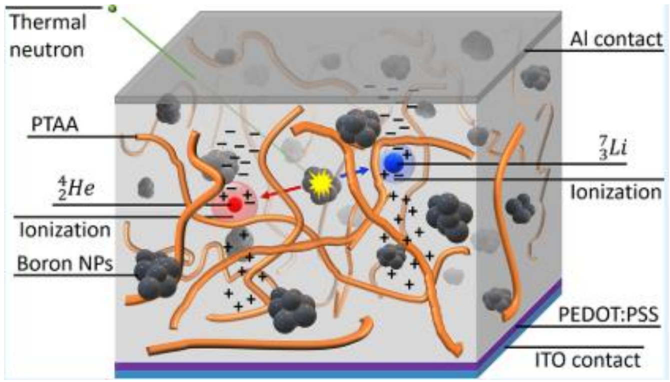
- McGregor DS.. Nucl Instruments Methods Phys Res Sect A Accel Spectrometers, 2020;954(November 2018):161696

RIVELATORI basati su PEROVSKITE INORGANICA + MICROSTRUTTURE 3D COVERTITRICI



- Quevedo-Lopez M., et al. Adv Mater Technol. 2020;5(12):3–9.
- Quevedo-Lopez M., et al. ACS Appl Mater Interfaces. 2021;13(24):28049–56.
- Quevedo-Lopez M., et al. Adv Mater Technol. 2022;2100956:1–7.

POLIMERO + NANOPARTICELLE ^{10}B convertitrici



- Sellin P., et alACS Appl Mater Interfaces. 2020;12(29):33050–7.

- J. Zheng et al., J. Am. Chem. Soc. 2021, 143, 50, 21302–21311

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2D layered Perovskites

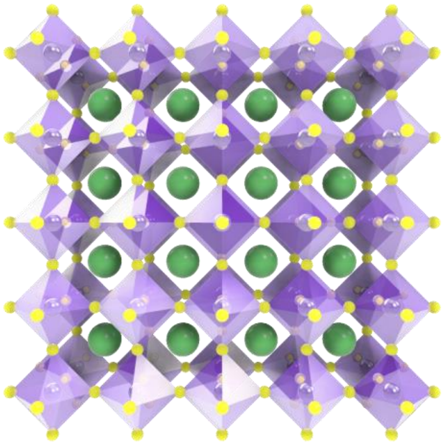
PEA_2PbBr_4 (PEA = $C_6H_5C_2H_4NH_3^+$)

3D vs. 2D

$APbX_3$

Organic cation (MA, FA)

Halogen anion (I, Br, Cl)

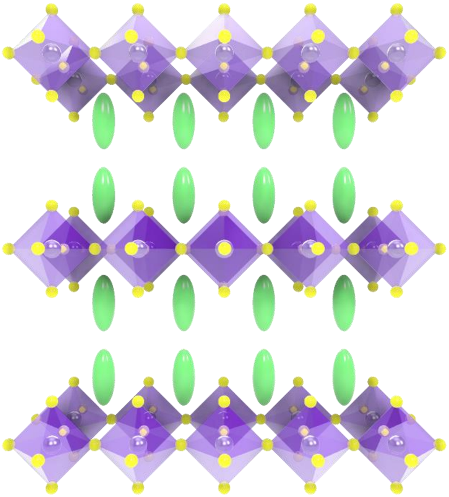


- High X-ray stopping power 10 cm^{-1}, comparable to CZT.
- High carriers diffusion length >1µm in polycrystalline films.
- Low cost, low temperature <150 ̊C deposition from solution.
- Optoelectronic properties tuning by controlling the relative amounts of the components

A_2PbX_4

Organic cation (PEA, BA)

Halogen anion (I, Br, Cl)

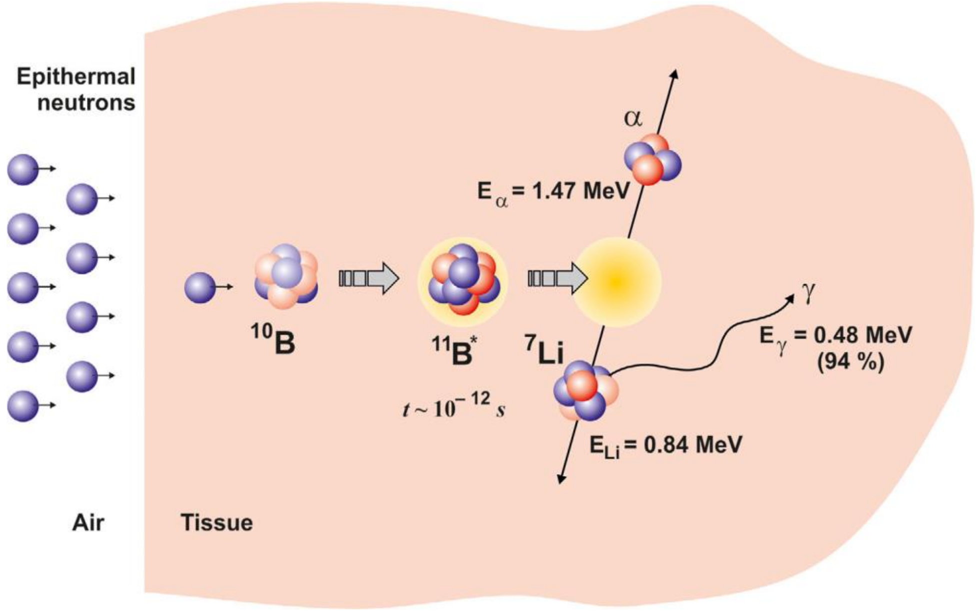


- High X-ray stopping power.
- **Lower mobility**
- **Lower Ion migration**
- **Better stability**
- Low cost, low temperature <150 ̊C deposition from solution.
- Optoelectronic properties tuning by controlling the relative amounts of the components

Boron Neutron Capture Therapy e dosimetria

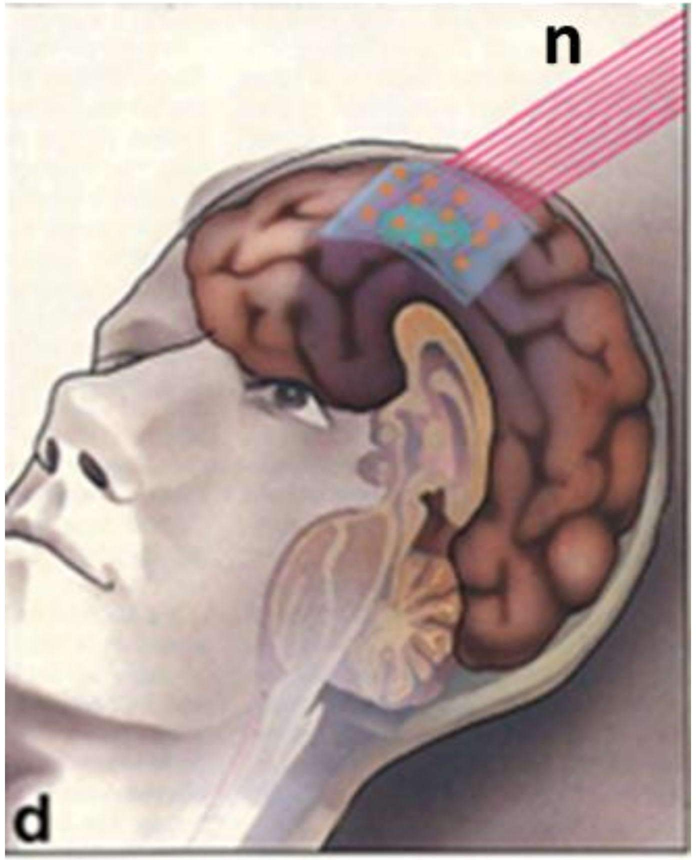
Incident Beam Quality

1) Epithermal neutron flux > $\mathbf{10^{9}\ n\ cm^{-2}\ s^{-1}}$
2) Neutron energy range [**0,5 eV – 10 keV**]
3) Fast neutrons and gamma rays as low as possible



$$^{10}B + n \begin{cases} \xrightarrow{94\%} \alpha(1.47MeV + ^{7}Li(0.84MeV) + \gamma(0.48MeV) \\ \xrightarrow{6\%} \alpha(1.78MeV + ^{7}Li(1.01MeV) \end{cases}$$
(Q = 2,31 MeV) (Q = 2,792 MeV)

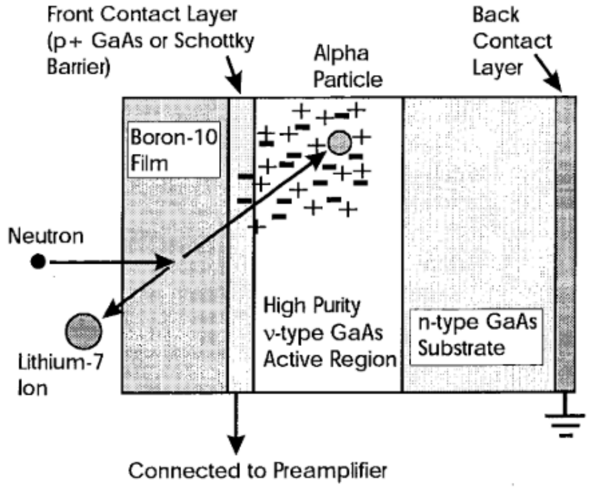
$$^{6}Li + n \longrightarrow ^{3}H(2.72MeV + \alpha(2.05MeV)$$
(Q = 4,78 MeV)



✓ **WEARABLE DOSIMETER**
✓ **LOW-COST** ✓ **RAD-HARD**
✓ **LOW POWER CONSUMPTION**

Dymova MA, et al. Boron neutron capture therapy: Current status and future perspectives. Cancer Commun 2020;40(9):406–21.

Stato dell'Arte per la rivelazione di neutroni

Contatori Proporzionali a Gas	Scintillatori	Rivelatori allo Stato Solido
		
❌ Carenza di ^{3}He ❌ Alti costi di produzione ❌ Impatto ambientale ❌ Alto consumo energetico	❌ Bassa emissione di luce ❌ Tempi di risposta ❌ Accoppiamento → < SNR	❌ Trasferimento alpha inefficiente
• Fares M, et al. 3He proportional counter development for thermal neutron detection. Radiat Detect Technol Methods, 2021;5(2):264–72. • Amaro FD, et al. Novel concept for neutron detection: Proportional counter filled with 10 B nanoparticle aerosol. Sci Rep. 2017;7(1):1–7.	• Carturan SM, et al. Flexible scintillation sensors for the detection of thermal neutrons based on siloxane 6 LiF containing composites: Role of 6 LiF crystals size and dispersion. Nucl Instruments Methods Phys Res Sect A Accel Spectrometers, Detect Assoc Equip. 2019 May 1;925:109–15. • Xie A, et al. Lithium-doped two-dimensional perovskite scintillator for wide-range radiation detection. Commun Mater 2020 11; 1(1):1–10.	• McGregor DS et al. Self-biased boron-10 coated high-purity epitaxial GaAs thermal neutron detectors. IEEE Trans Nucl Sci. 2000;47(4 PART 1):1364–70. • Lai CC, Boyd R, et al. Effect of substrate roughness and material selection on the microstructure of sputtering deposited boron carbide thin films. Surf Coatings Technol. 2022;433

Interazione neutrone termico-materia

$$^{10}B + n \begin{cases} \xmapsto{94\%} \alpha(1.47MeV +^7 Li(0.84MeV) + \gamma(0.48MeV) \\ \xmapsto{6\%} \alpha(1.78MeV +^7 Li(1.01MeV) \end{cases}$$

(Q = 2,31 MeV)

(Q = 2,792 MeV)

$$^6Li + n \longmapsto ^3H(2.72MeV + \alpha(2.05MeV)$$

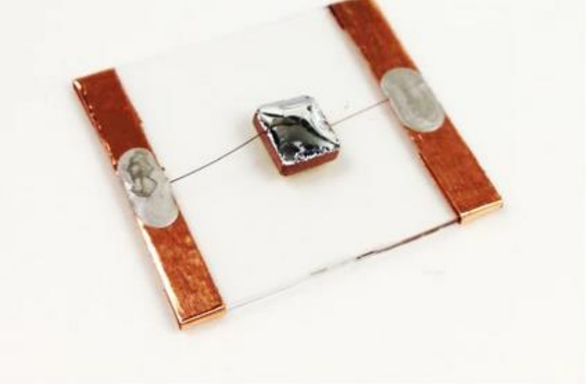
(Q = 4,78 MeV)

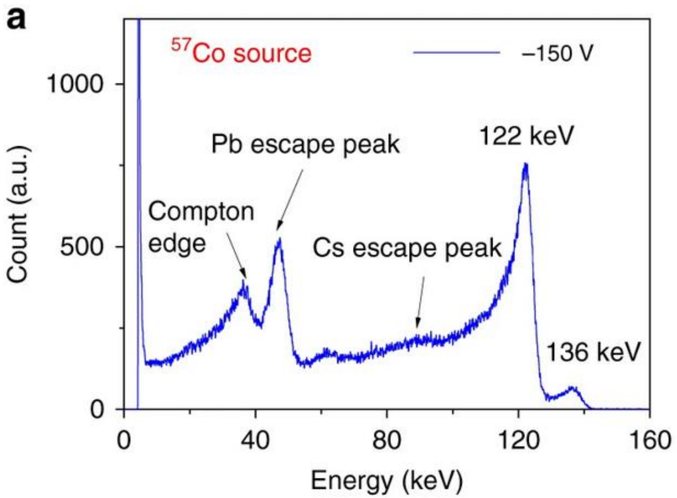
	Cross Section (barn) @ 0.025 eV	Natural Abundance (%)
^{6}Li	942	7,6%
^{10}B	3842	19,9%

Spettrometria con PVK - letteratura

Gamma

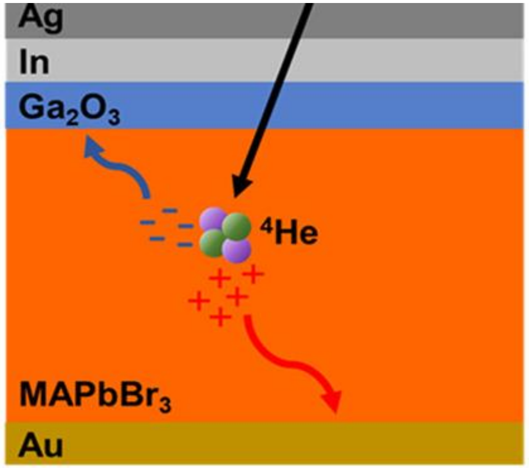
CsPbBr3

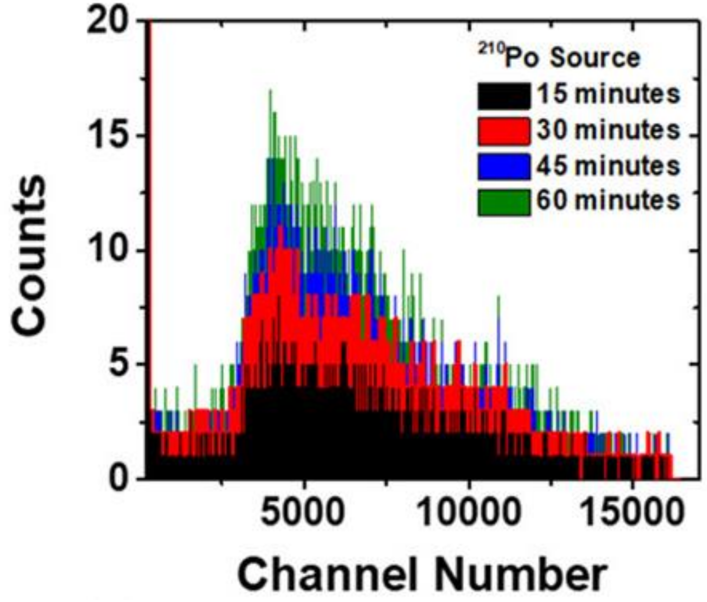




He, Y., Matei, L., Jung, H.J. *et al. Nat Commun* **9**, 1609 (2018).

Alpha





Quevedo-Lopez M., et al. Adv Mater Technol. 2020;5(12):3–9.

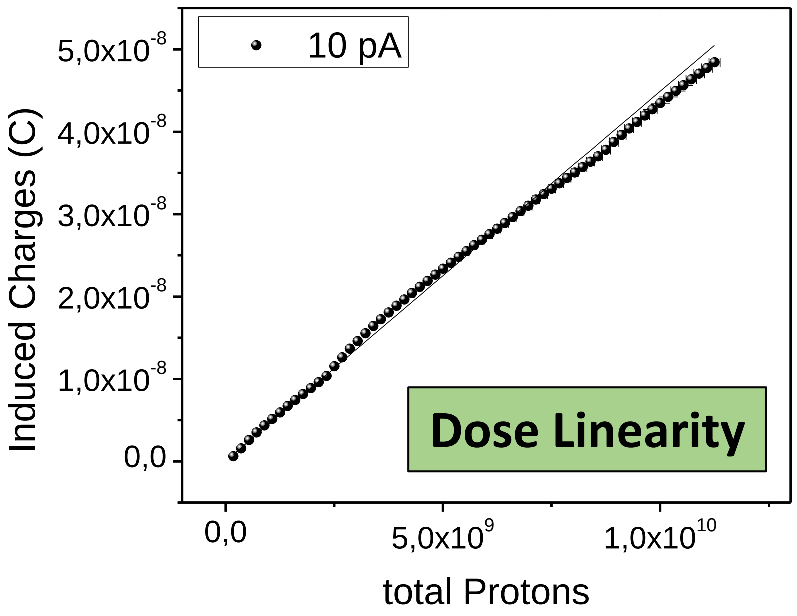
Electron/hole pair creation mean energy

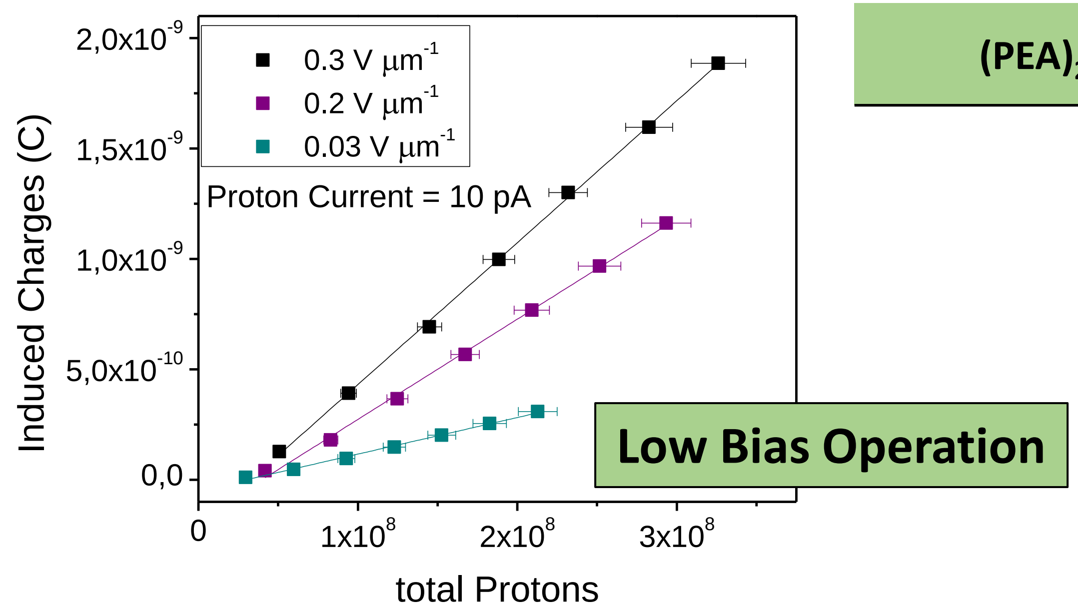
empirical model of Devanathan

$W = 2E_G + 1.43$ eV

The energy gap value of $(PEA)_2PbBr_4$ of $E_G = (3.00 \pm 0.03)$ → $W_{(PEA)2PbBr4} = (7.43 \pm 0.06)$ eV.

5 MeV proton Detection @ LABEC





REQUIRED PROPERTIES

- **HIGH SENSITIVITY**

MATERIAL	ELECTRIC FIELD ($V\ \mu m^{-1}$)	PROTON ENERGY (MeV)	SENSITIVITY	REF.
$MAPbBr_3$ + $(PEA)_2PbBr_4$	0.2	5	$(1.12 \pm 0.01)\cdot10^{-18}$ C $H^{+\ -1}$	[1]
TIPGe-pentacene	0.03	5	$(6.4 \pm 0.2)\cdot10^{-20}$ C $H^{+\ -1}$	[2]
$MAPbBr_3$	0.01	3	$(2.19 \pm 0.03)\cdot10^{-18}$ C $H^{+\ -1}$	[3]
$CsPbCl_3$	2	100-228	$4\cdot10^{-20}$ C $H^{+\ -1}$	[4]
$(PEA)_2PbBr_4$	0.2	5	$(4.25 \pm 0.02)\cdot10^{-18}$ C $H^{+\ -1}$	This work

Basiricò, Fraboni et al., *Adv. Sci.* **2022**, *2204815*, 1.

I. Fratelli, Fraboni et al., *Sci Adv* **2021**, *7*, eabf4462.

H. Huang, et al., *ACS Appl Electron Mater* **2022**, DOI 10.1021/acsaelm.2c01406.

M. Bruzzi, et al., *Front Phys* **2023**, *11*, 1.

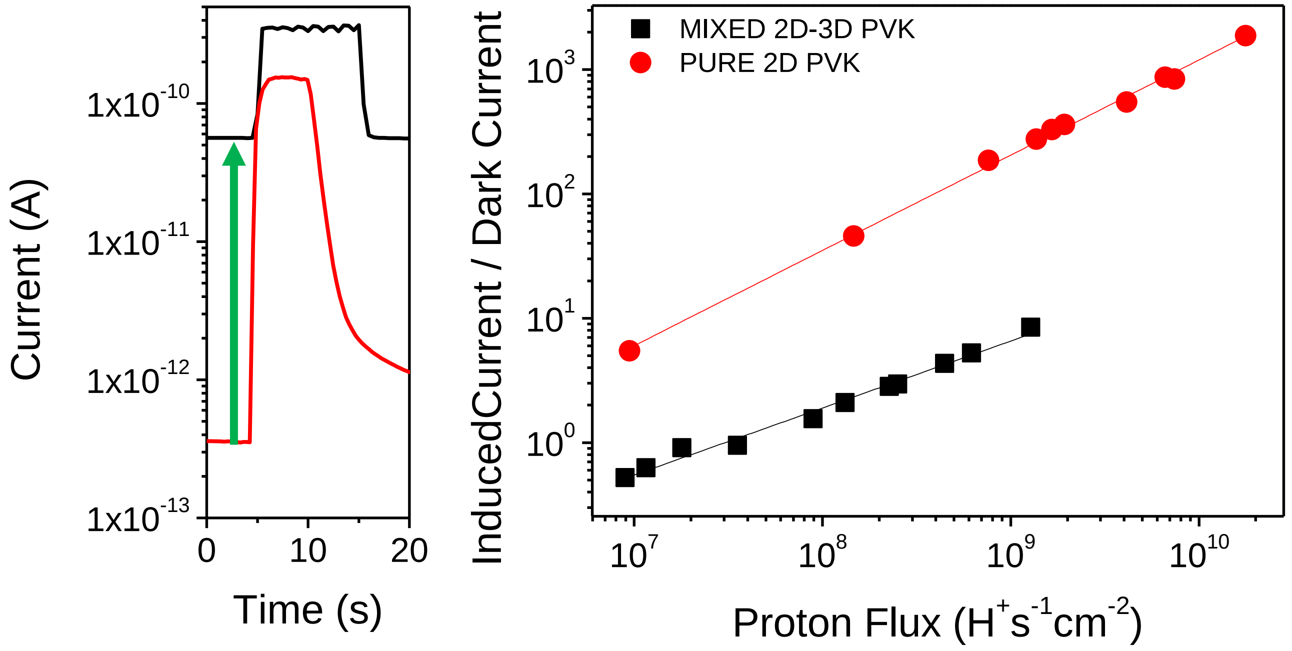
5 MeV proton Detection @ LABEC

INFN LABEC

REQUIRED PROPERTIES

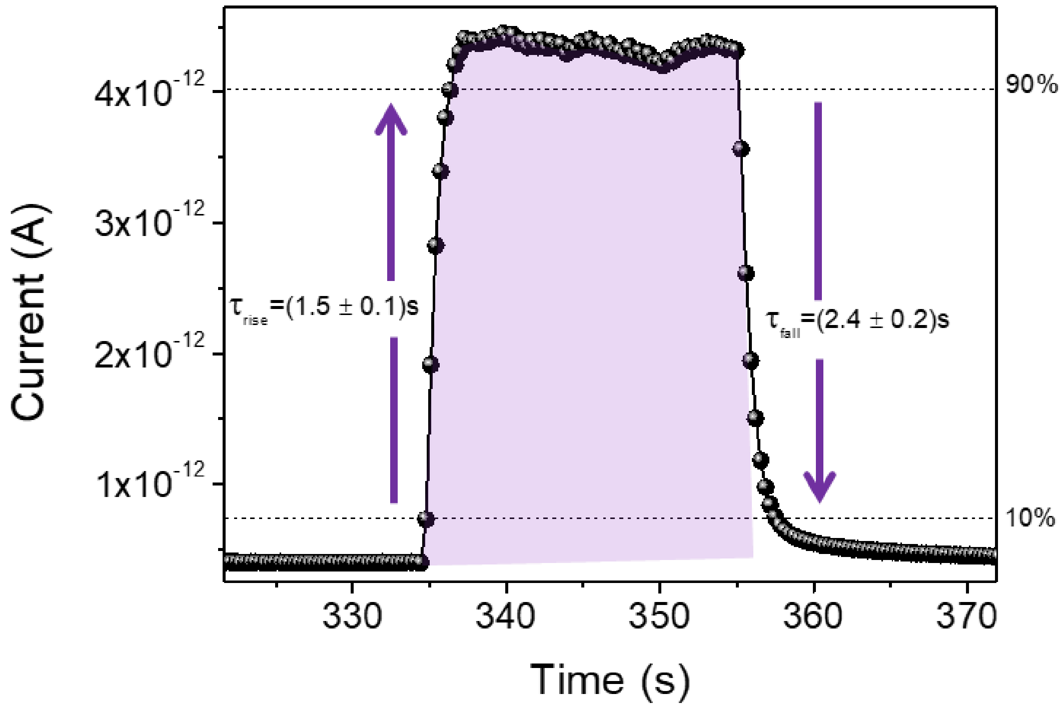
- HIGH SENSITIVITY
- HIGH Signal to Noise Ratio → dark current has to be lower than 1% of the signal current
- FAST RESPONSE for Real-Time monitoring
- TRANSPARENT to be placed in-line avoiding perturbation of the primary beam
- RADIATION TOLERANT for reliable and stable response (> 2 Gy)
- LARGE AREA and FLEXIBLE (> 10 x 10 cm^2) and good SPATIAL RESOLUTION

Very Low Dark Current and High SNR



Basiricò, Fraboni et al., *Adv. Sci.* 2022, *2204815*, 1.

5 MeV proton Detection @ LABEC



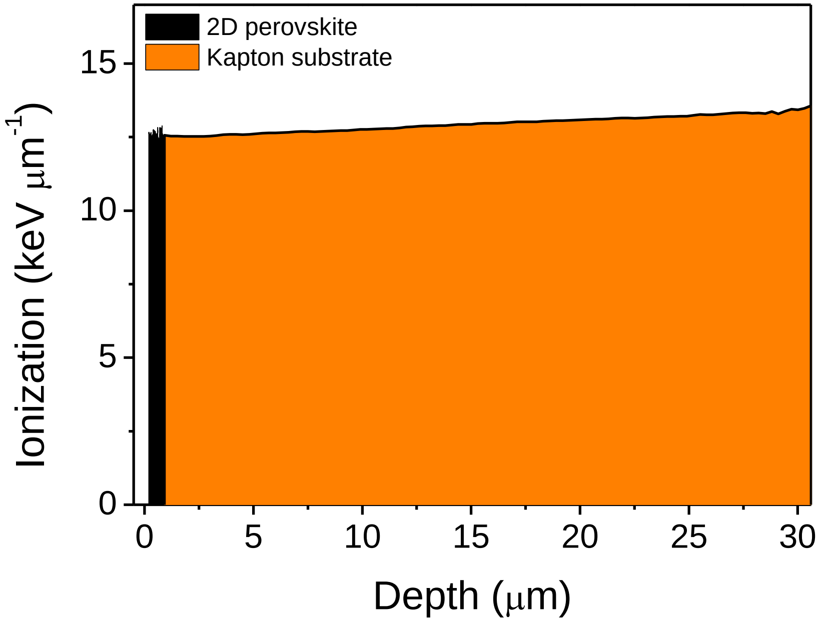
REQUIRED PROPERTIES

- HIGH SENSITIVITY
- HIGH Signal to Noise Ratio → dark current has to be lower than 1% of the signal current
- **FAST RESPONSE** for Real-Time monitoring
- TRANSPARENT to be placed in-line avoiding perturbation of the primary beam
- RADIATION TOLERANT for reliable and stable response (> 2 Gy)
- LARGE AREA and FLEXIBLE (> 10 x 10 cm^2) and good SPATIAL RESOLUTION

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

5 MeV proton Detection @ LABEC

Each 5 MeV proton passes through the 2D perovskite layer releasing 12 keV μm^{-1}



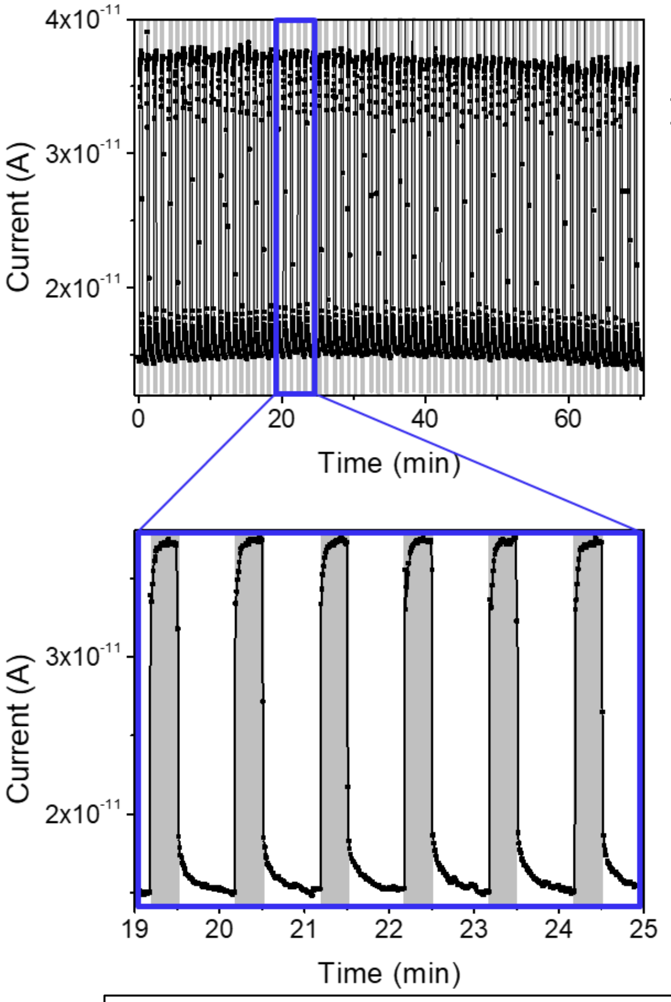
REQUIRED PROPERTIES

- HIGH SENSITIVITY
- HIGH Signal to Noise Ratio → dark current has to be lower than 1% of the signal current
- FAST RESPONSE for Real-Time monitoring
- **TRANSPARENT** to be placed in-line avoiding perturbation of the primary beam
- RADIATION TOLERANT for reliable and stable response (> 2 Gy)
- LARGE AREA and FLEXIBLE (> 10 x 10 cm^2) and good SPATIAL RESOLUTION

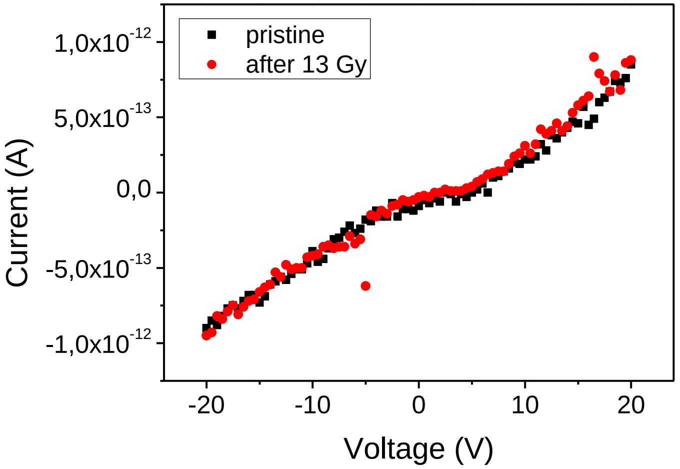
Fratelli et al., *Adv. Sci.* ***2024***, *101002/advs.202401124*

5 MeV proton Detection @ LABEC

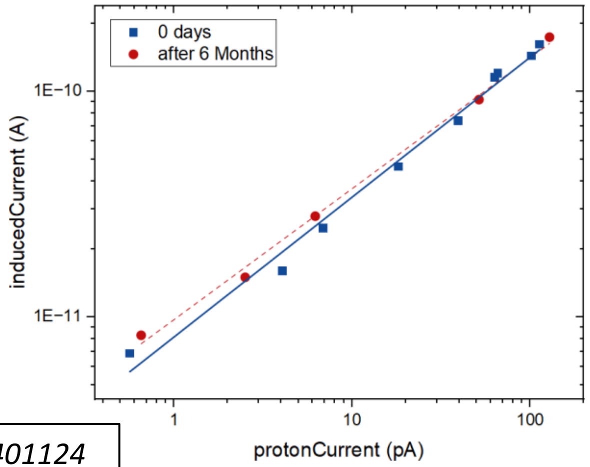
RADIATION HARDNESS
X-ray (20 s; 8 mGy s^{-1}; 11.2 Gy total) → 4% degradation



RADIATION HARDNESS
5 MeV protons (13 Gy)



AGEING
5 MeV protons (6 months)



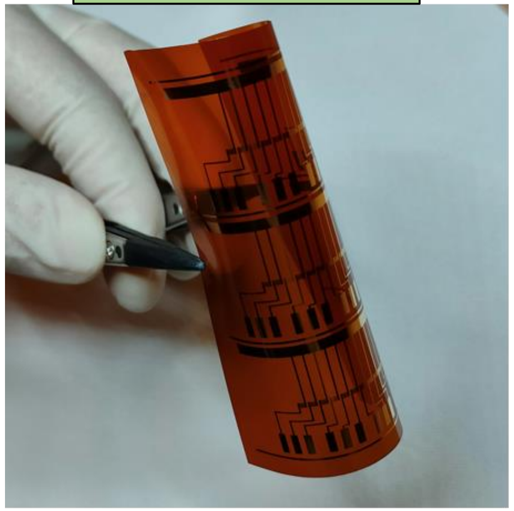
REQUIRED PROPERTIES

- HIGH SENSITIVITY
- HIGH Signal to Noise Ratio → dark current has to be lower than 1% of the signal current
- FAST RESPONSE for Real-Time monitoring
- TRANSPARENT to be placed in-line avoiding perturbation of the primary beam
- **RADIATION TOLERANT** for reliable and stable response (> 2 Gy)
- LARGE AREA and FLEXIBLE (> 10 x 10 cm^2) and good SPATIAL RESOLUTION

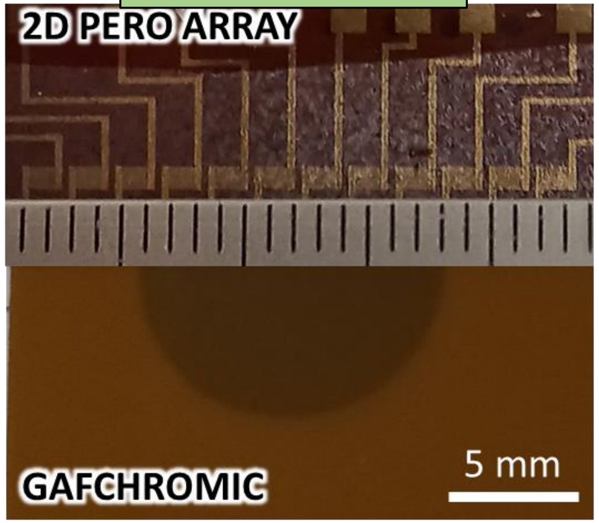
Fratelli et al., *Adv. Sci.* **2024**, *101002/advs.202401124*

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

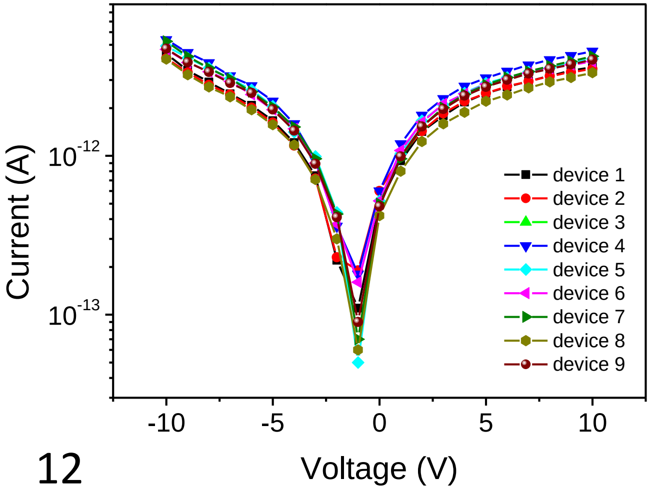
FLEXIBILITY and SCALABILITY

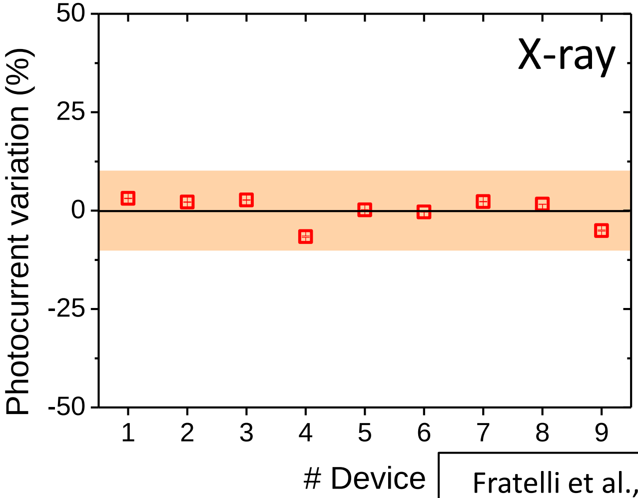


Pixel dimension down to 0.5 mm



REPRODUCIBILITY



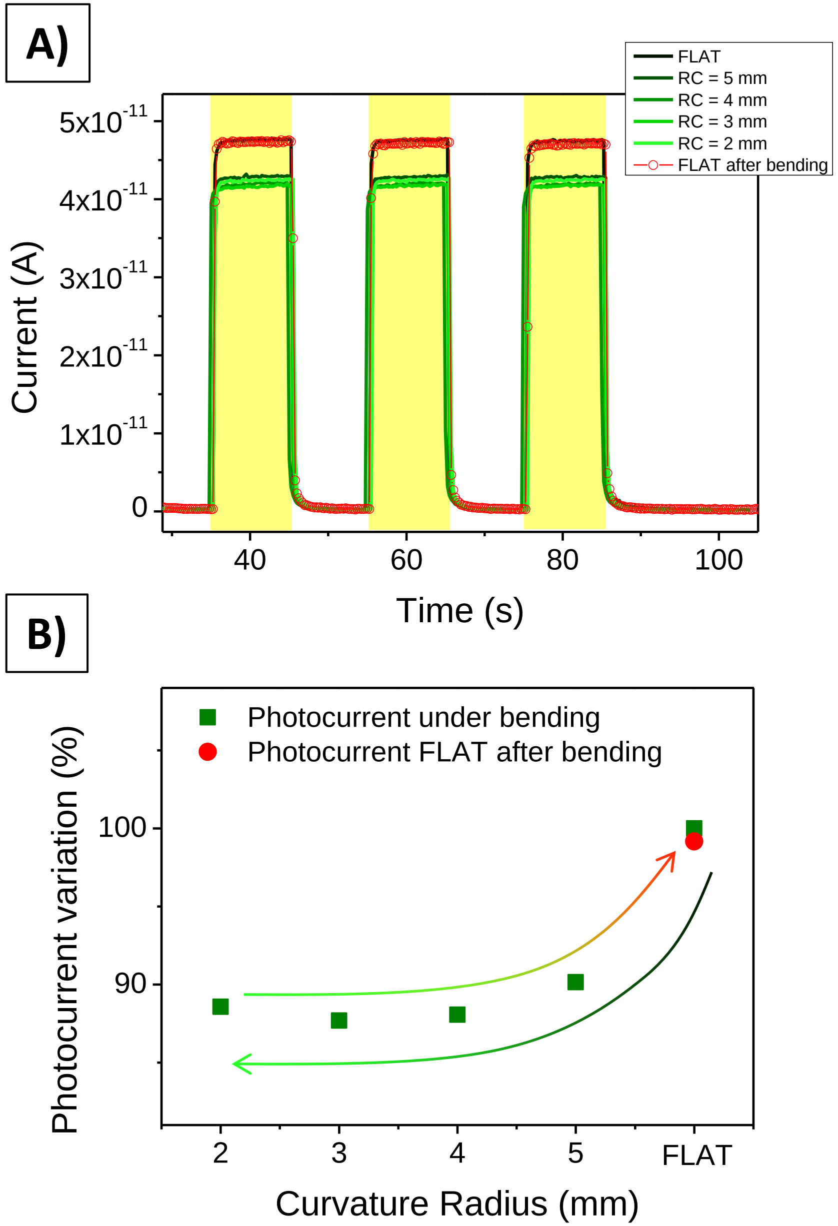


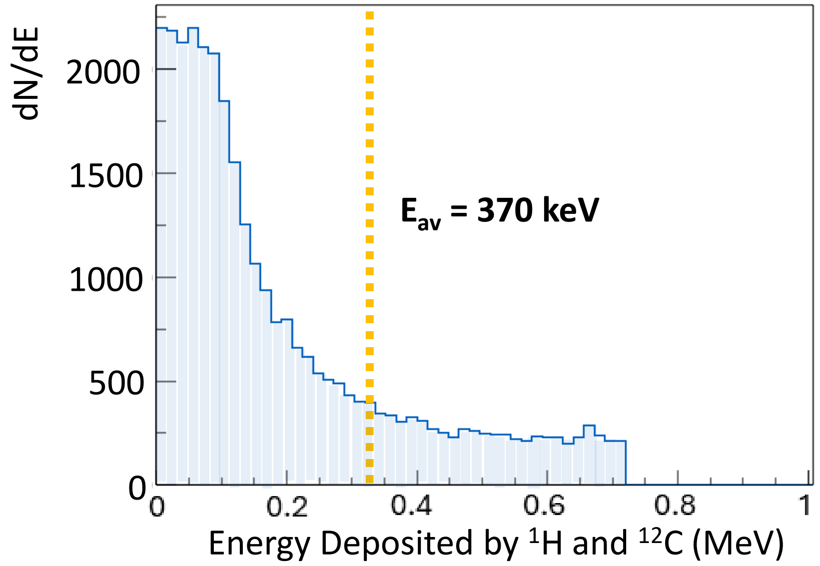
REQUIRED PROPERTIES

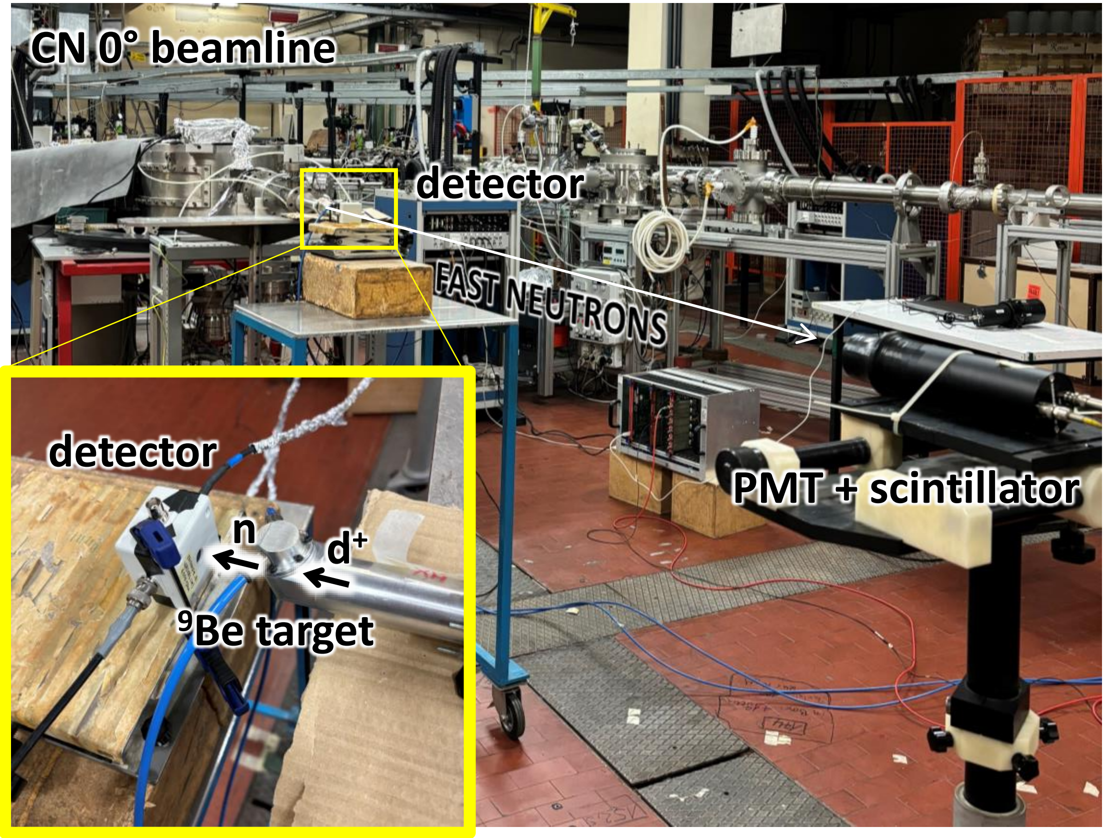
- HIGH SENSITIVITY
- HIGH Signal to Noise Ratio → dark current has to be lower than 1% of the signal current
- FAST RESPONSE for Real-Time monitoring
- TRANSPARENT to be placed in-line avoiding perturbation of the primary beam
- RADIATION TOLERANT for reliable and stable response (> 2 Gy)
- **LARGE AREA** and **FLEXIBLE** (> 10 x 10 cm^2) and good **SPATIAL RESOLUTION**

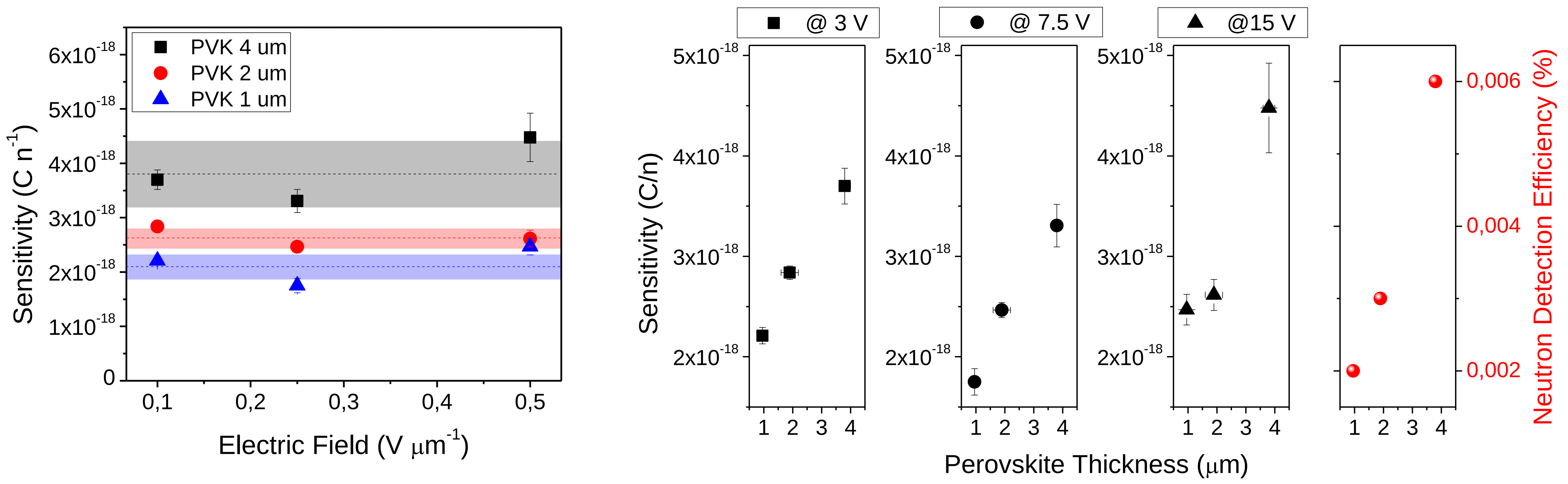
Fratelli et al., *Adv. Sci.* ***2024***, *101002/advs.202401124*

Flexibility




dN/dE
2000
1500
1000
500
0
0
0.2
0.4
0.6
0.8
1
E_av = 370 keV
Energy Deposited by 1H and 12C (MeV)

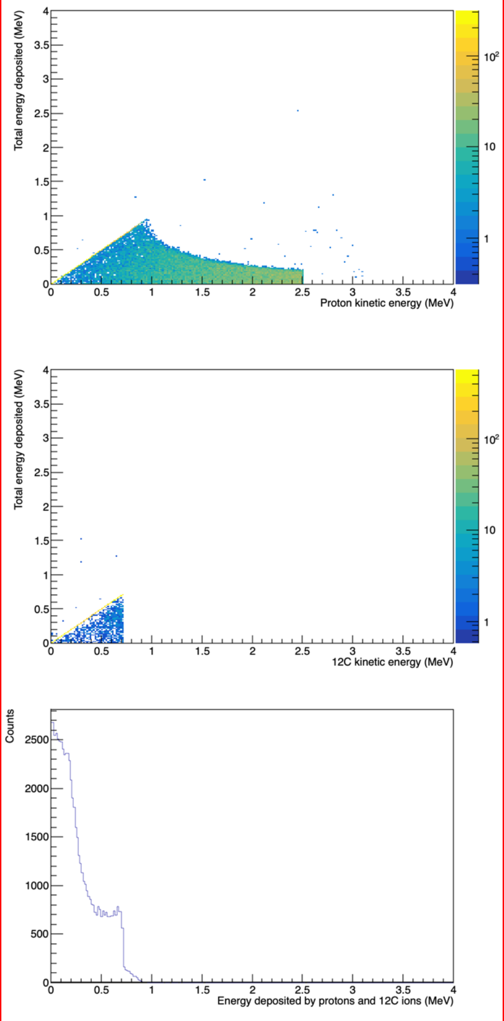

CN 0° beamline
detector
FAST NEUTRONS
PMT + scintillator
detector
n
d+
9Be target



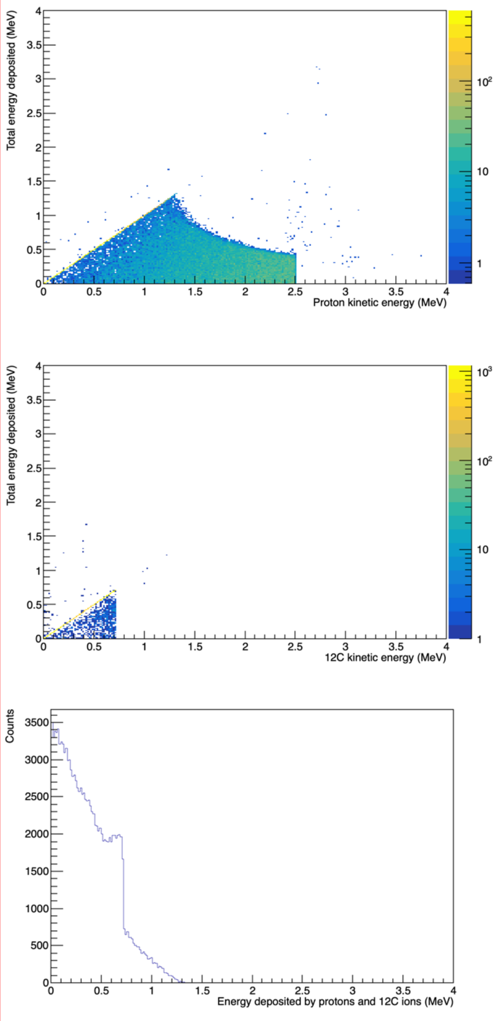
PVK 4 um
PVK 2 um
PVK 1 um
Sensitivity (C n^{-1})
Electric Field (V μm^{-1})
0
$1x10^{-18}$
$2x10^{-18}$
$3x10^{-18}$
$4x10^{-18}$
$5x10^{-18}$
$6x10^{-18}$
0,1
0,2
0,3
0,4
0,5
@ 3 V
@ 7.5 V
@15 V
Sensitivity (C/n)
Perovskite Thickness (μm)
Neutron Detection Efficiency (%)
0,002
0,004
0,006
1
2
3
4

Studio di diversi spessori per aumentare l'efficienza

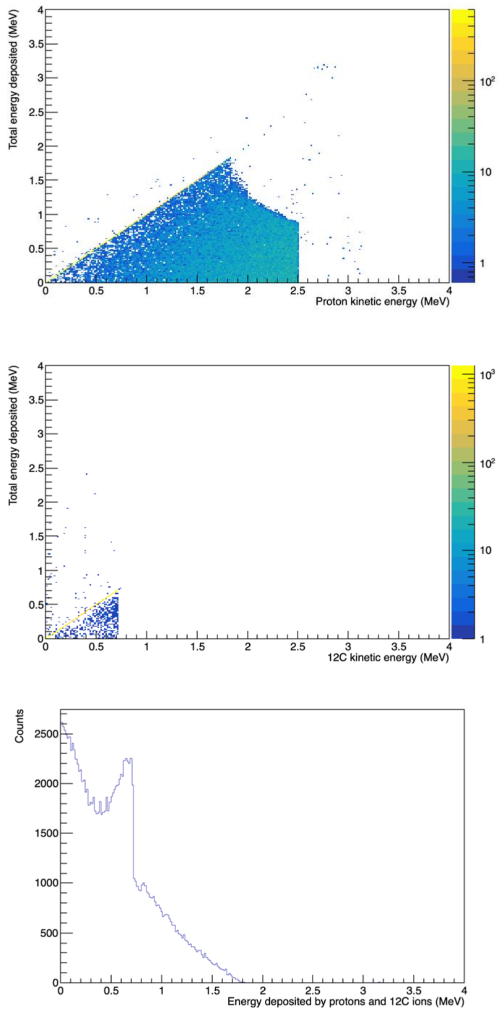
10 µm



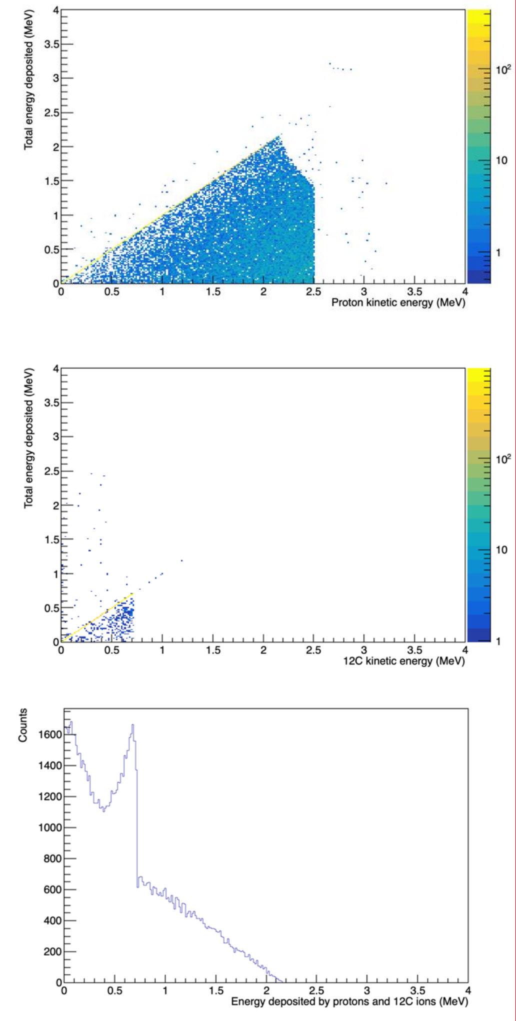
20 µm



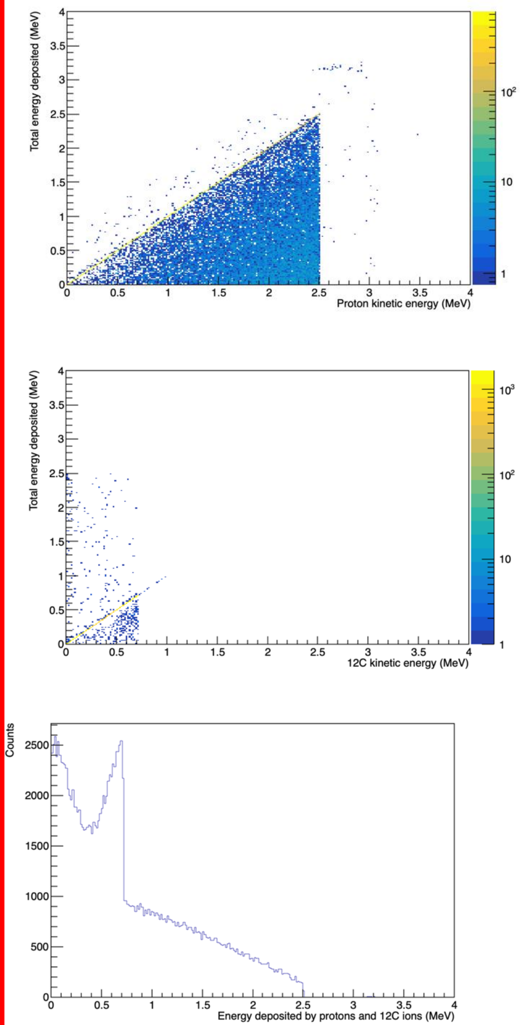
40 µm

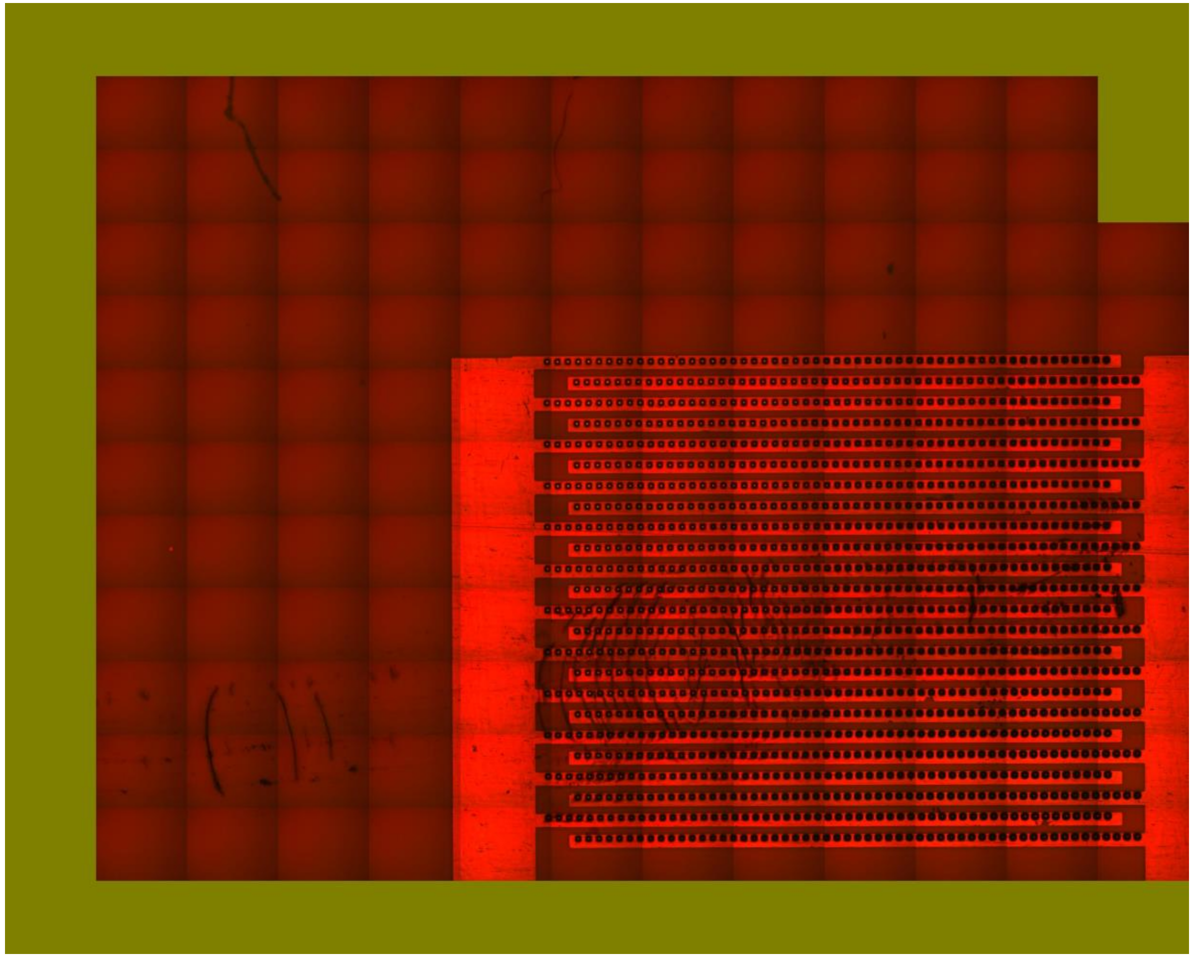


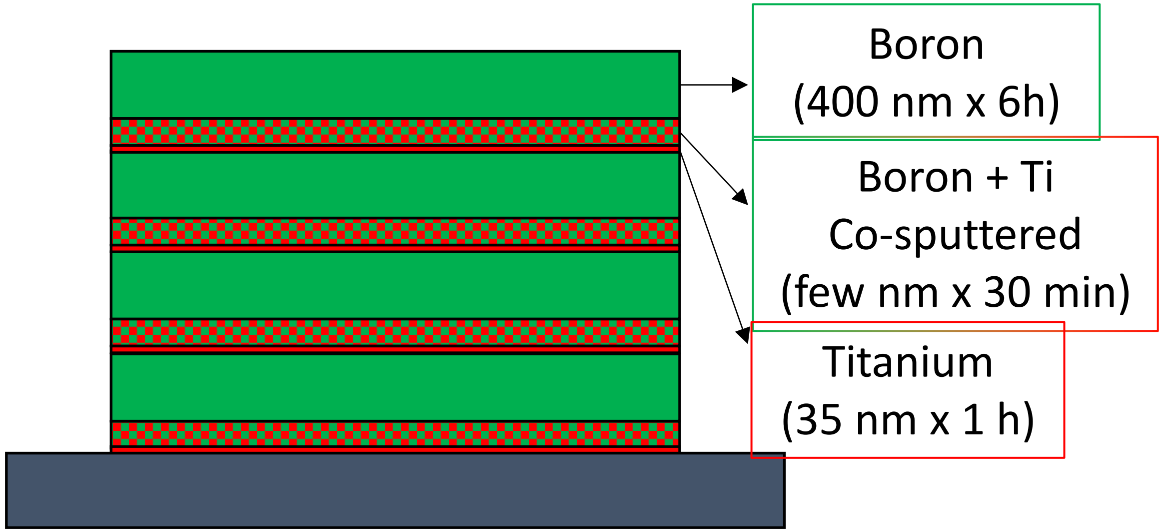
60 µm



100 µm






Boron
(400 nm x 6h)
Boron + Ti
Co-sputtered
(few nm x 30 min)
Titanium
(35 nm x 1 h)

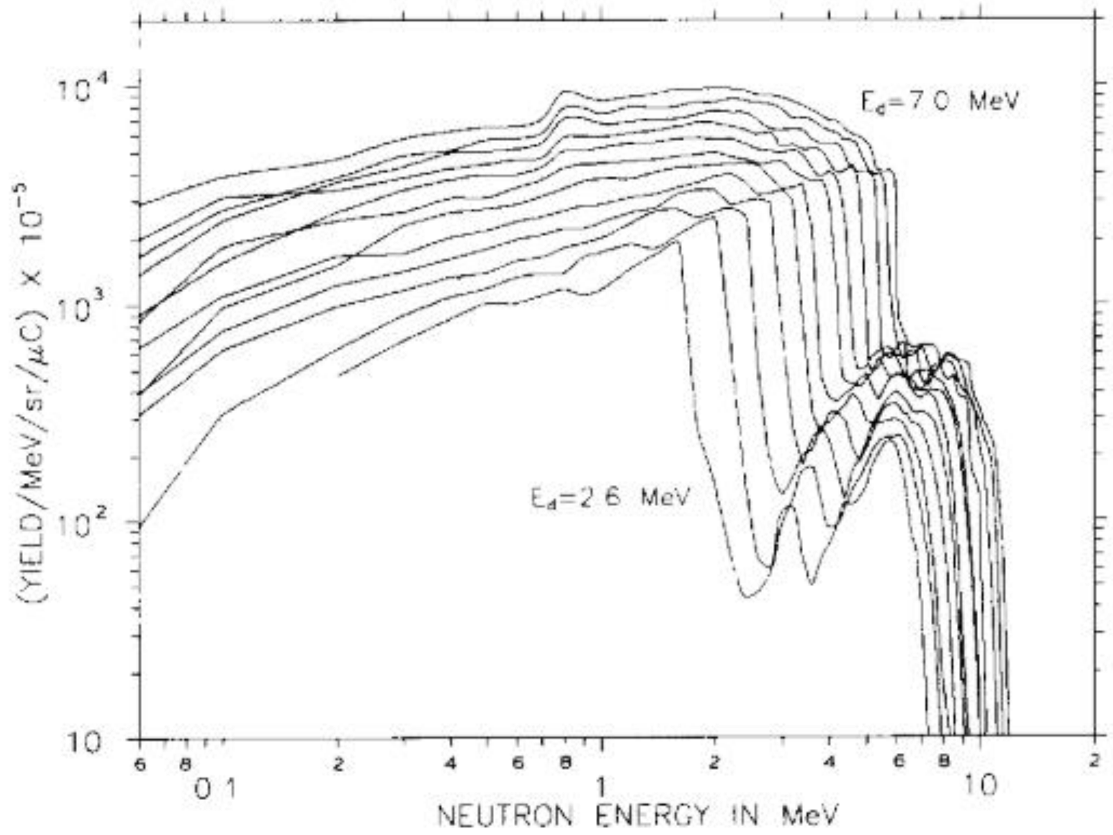


Fig. 4. A summary of the ^{9}Be(d, n) thick-target spectra for deuteron energies of 2.6 to 7 MeV in steps of 0.4 MeV.

Meadows, J. W. (1993). The 9 Be(d, n) thick-target neutron spectra for deuteron energies between 2.6 and 7.0 MeV. In *Nuclear Instruments and Methods in Physics Research* (Vol. 324).