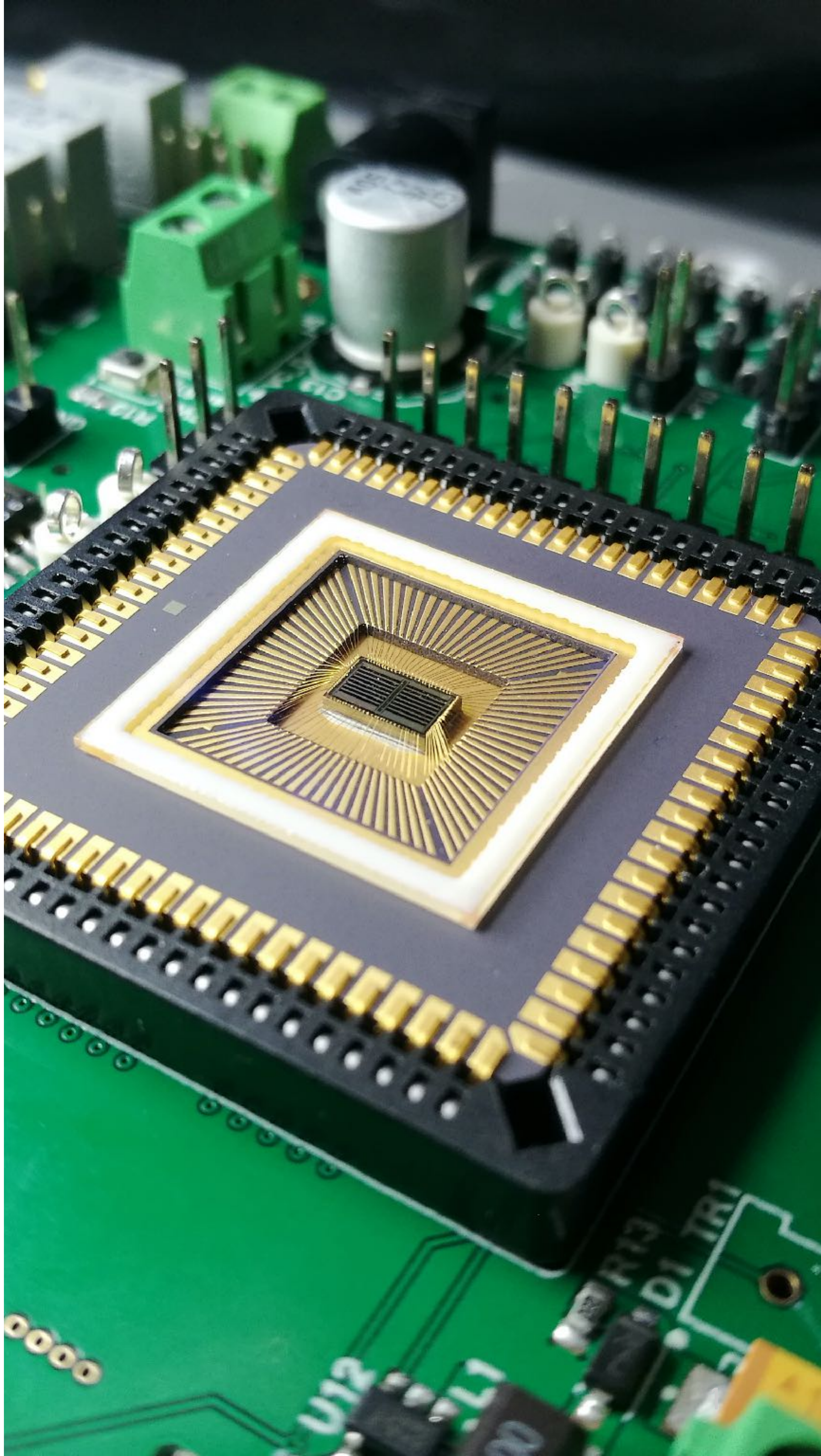
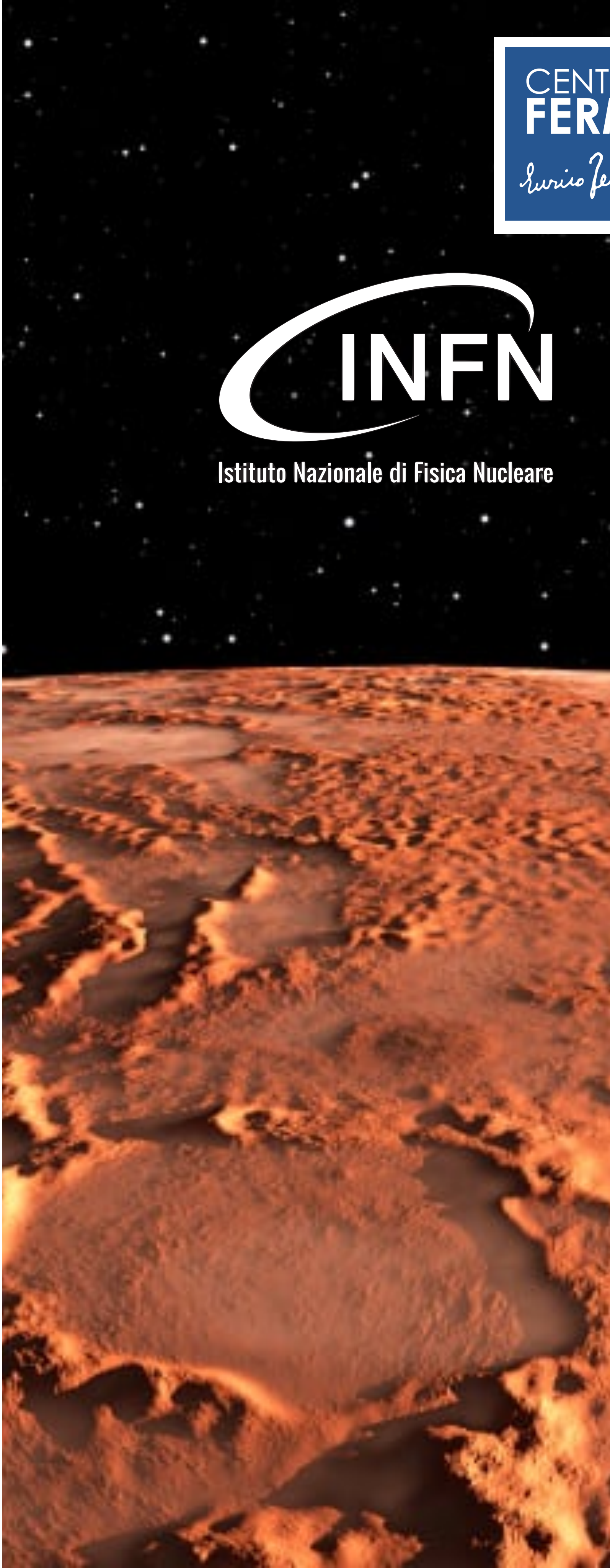
DEVELOPMENT OF A NEW TRACKING DEVICE FOR CHARACTERISATION AND MONITORING OF ULTRA FAST NEUTRON BEAMS

Riccardo Mirabelli
12/11/2018
Supervisor: Prof. Vincenzo Patera
Co-supervisor: Dott.ssa Michela Marafini





CENTRO FERMI
MUSEO STORICO DELLA FISICA E CENTRO STUDI E RICERCHE ENRICO FERMI

agenzia spaziale italiana

SPARE PROJECT

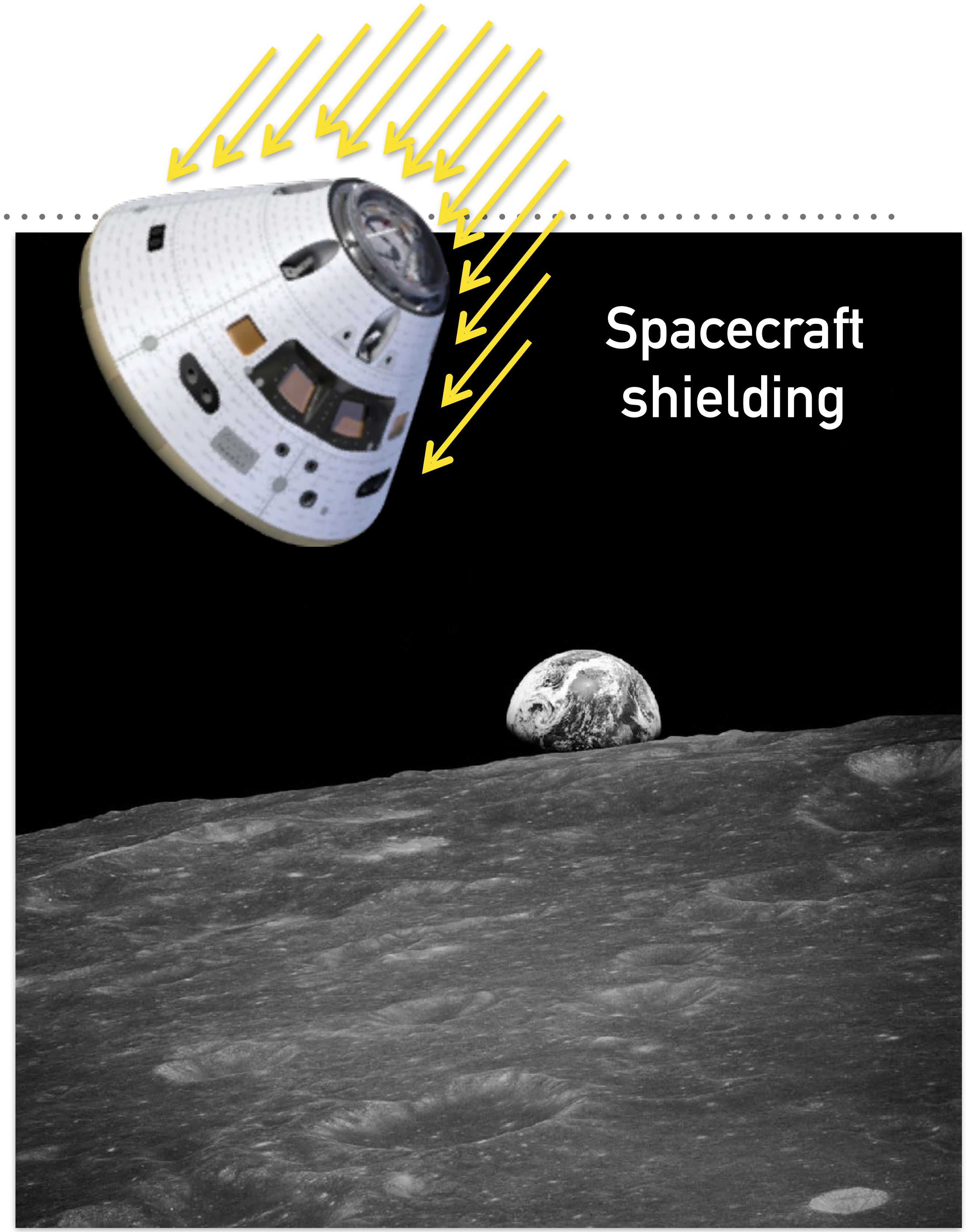
Space Radiation Shielding

- Spare is a project* involving INFN, Centro Fermi, ASI and other institutions, consisting of a test campaign of **active and passive shielding materials for the human activity on Mars**, using a proton cyclotron facility;
- One of the principal tasks of the project is **the development, test and calibration of an ultra-fast neutron beam facility.**

* progetto premiale 2016 MIUR

NEUTRONS IN SPACE

- The main radiation sources in space are Solar Particle Events (SPEs) and Galactic Cosmic Rays (GCRs). SPEs are mainly composed by protons (85 %) and their energy ranges from MeV/n to TeV/n).



NEUTRONS IN SPACE

Köhler, J. *et al*. **Measurements of the neutron spectrum in transit to Mars on the Mars**. Science Laboratory. *Life Sci. Space Res.* **5,** 6–12 (2015).

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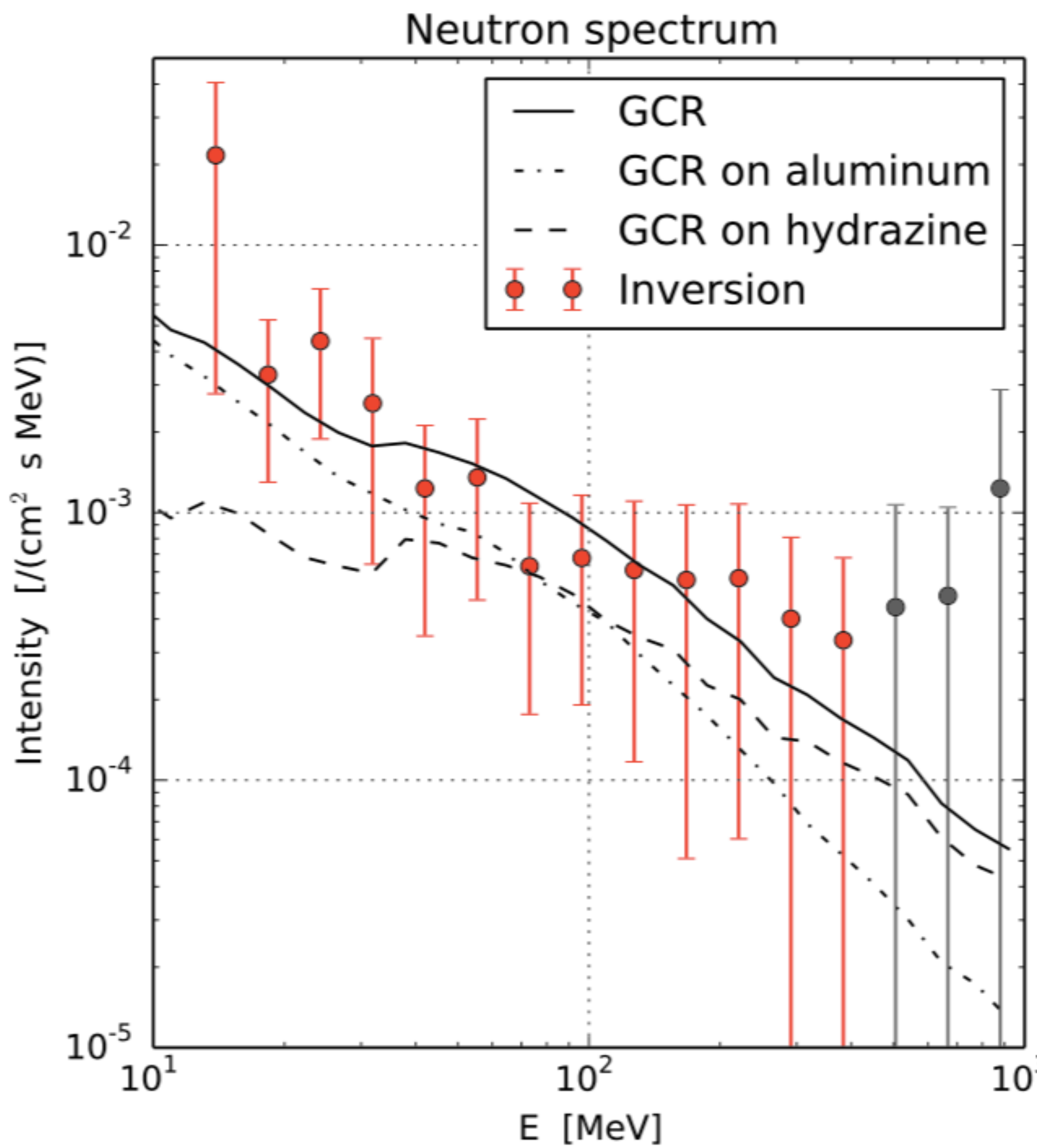
- Neutrons are mostly produced from the nuclear interaction between GCRs and SPEs with spacecraft walls, astronauts human body and atoms of Earth's atmosphere.
- The energies of the produced secondary neutrons span a range from thermal neutrons to several GeV.

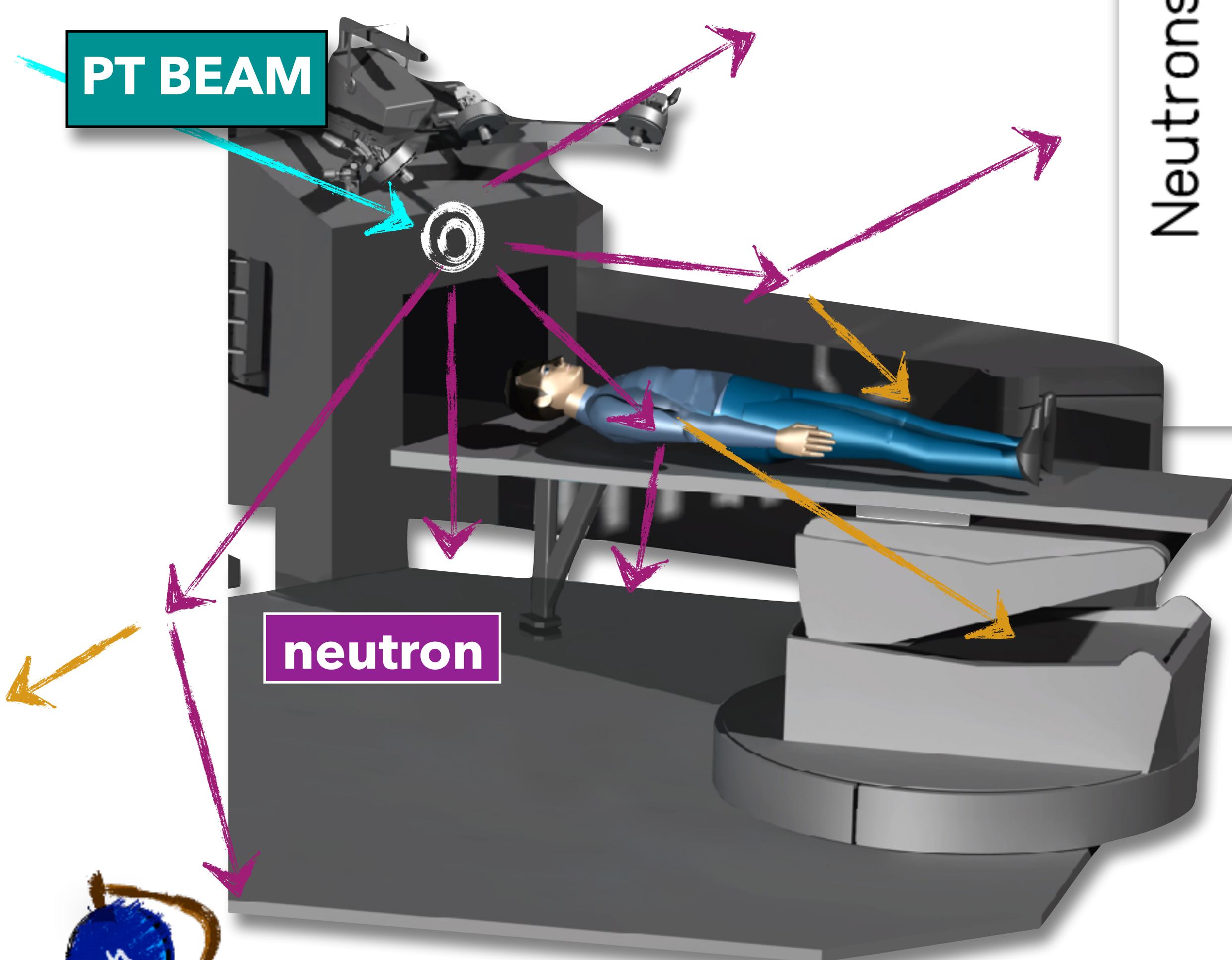


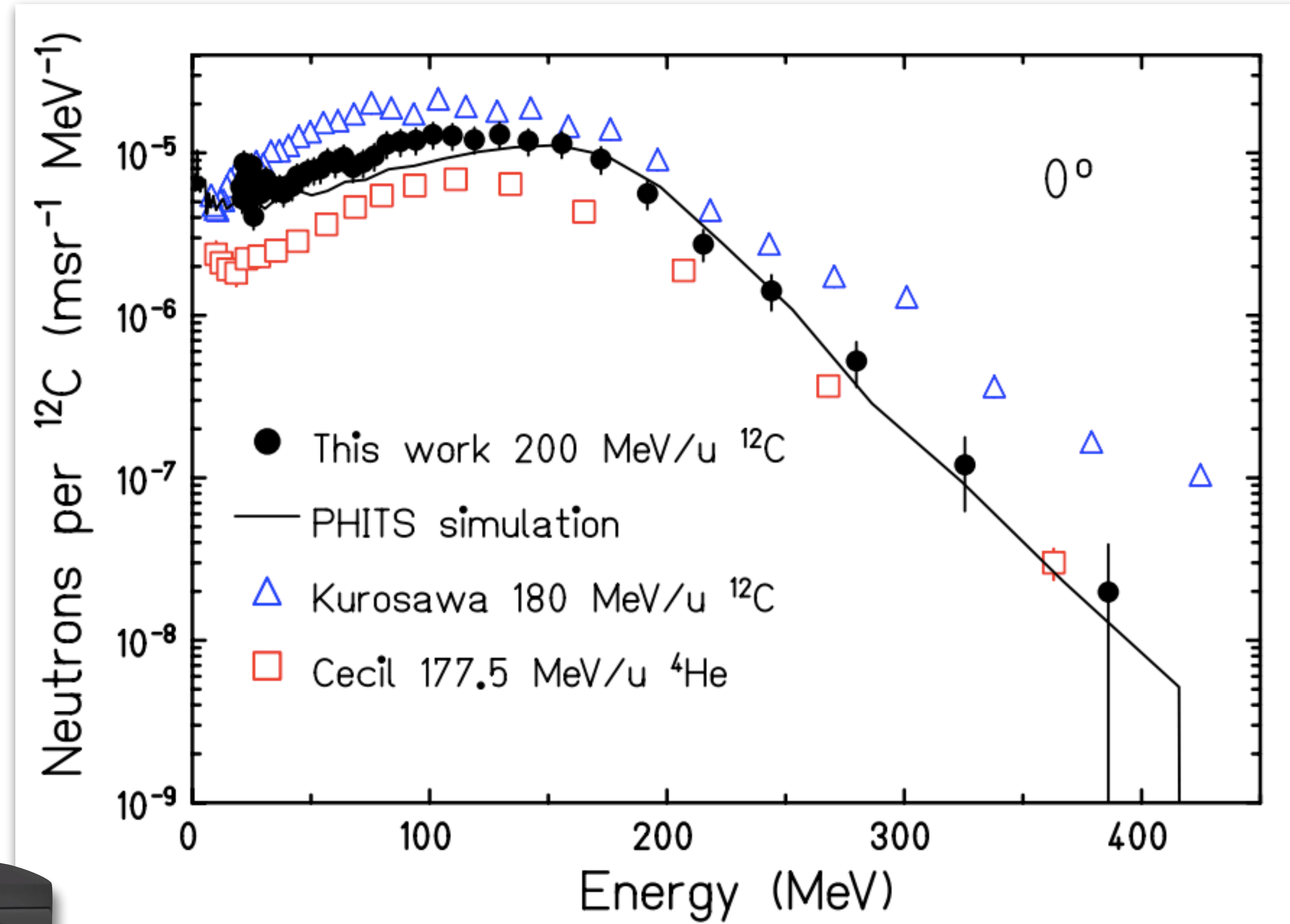
- In order to study the effect of these particles on humans and electronics, facilities that provided neutrons with controlled energy have to be used.

NEUTRONS IN PARTICLE THERAPY

Gunzert-Marx et al. **Secondary beam fragments produced by 200 MeV/u ^{12}C ions in water and their dose contributions in carbon ion radiotherapy**, doi:10.1088/1367-2630/10/7/075003

Neutrons are produced (as protons) in the beam nuclear interactions with matter, in particular with the patient tissues. Secondary neutrons interact also with the treatment room (and with the patient!) degrading their energy - **moderation process.**

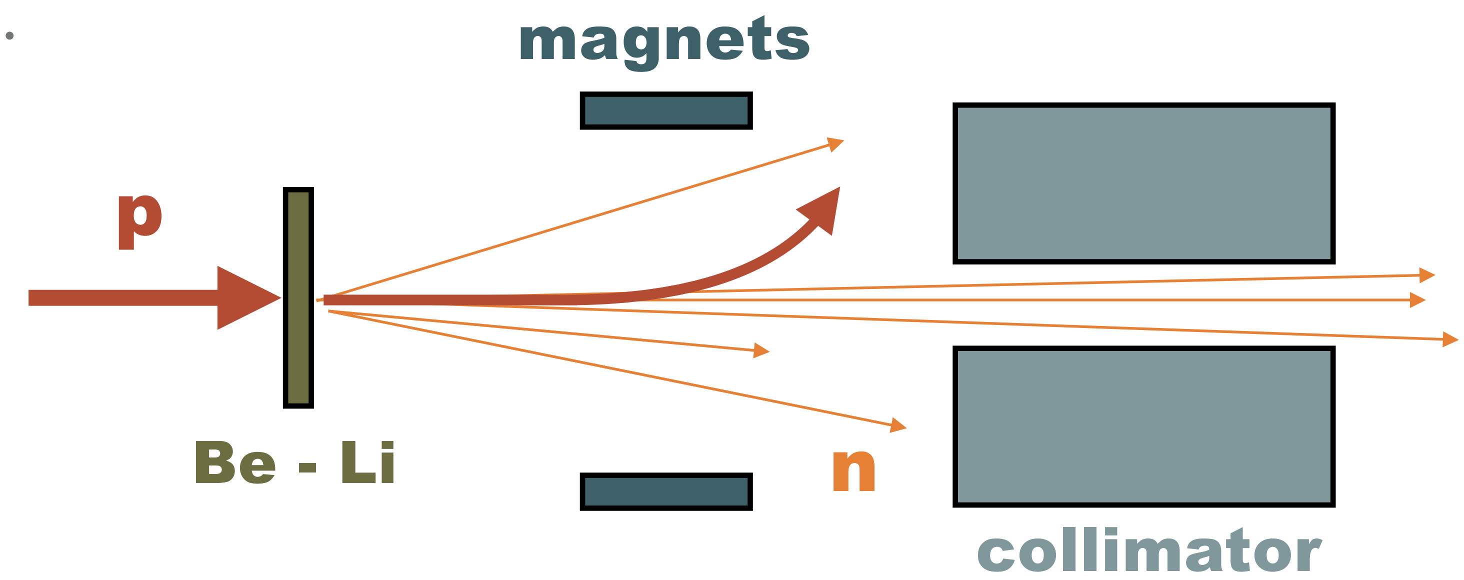


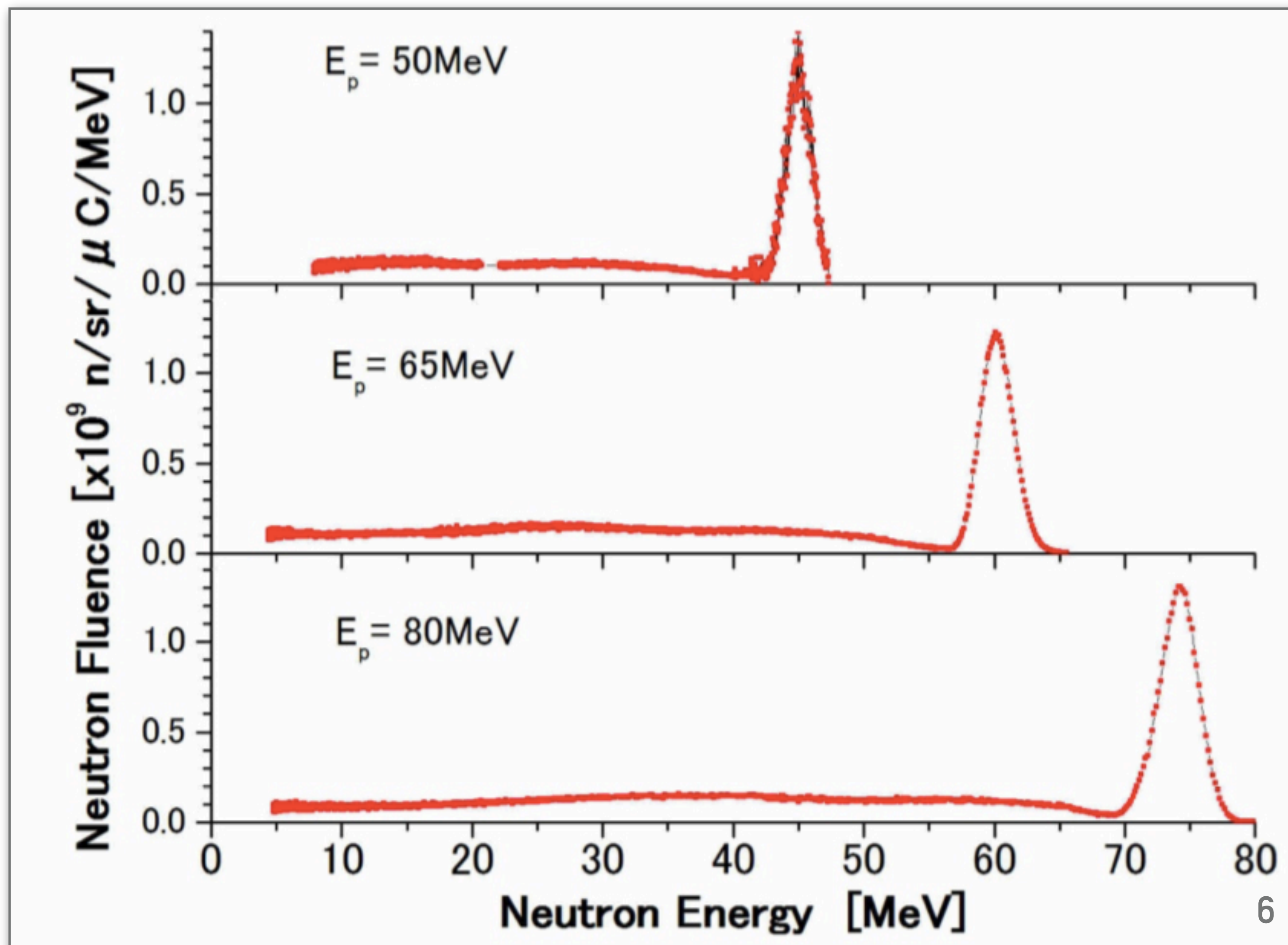


Neutron energy spectra (treatment-like carbon beam) measured at different energies and laboratory angles.

HIGH ENERGY NEUTRON FACILITY

- Quasi Mono-energetic Neutron fields (QMN) are produced using thin **Li or Be targets**, according to the reactions $^{7}Li(p,xn)$ and $^{9}Be(p,xn)$. The protons that pass through the thin targets without causing nuclear reactions are magnetically deflected towards a beam dump;
- The resulting neutron energy spectrum in the forward direction **is not purely mono-energetic:** it does present a **high energy peak** close to the energy of the incoming proton, but also a **broad distribution at lower energies**.
- The ratio of neutrons contained in each of these two components is 50:50.

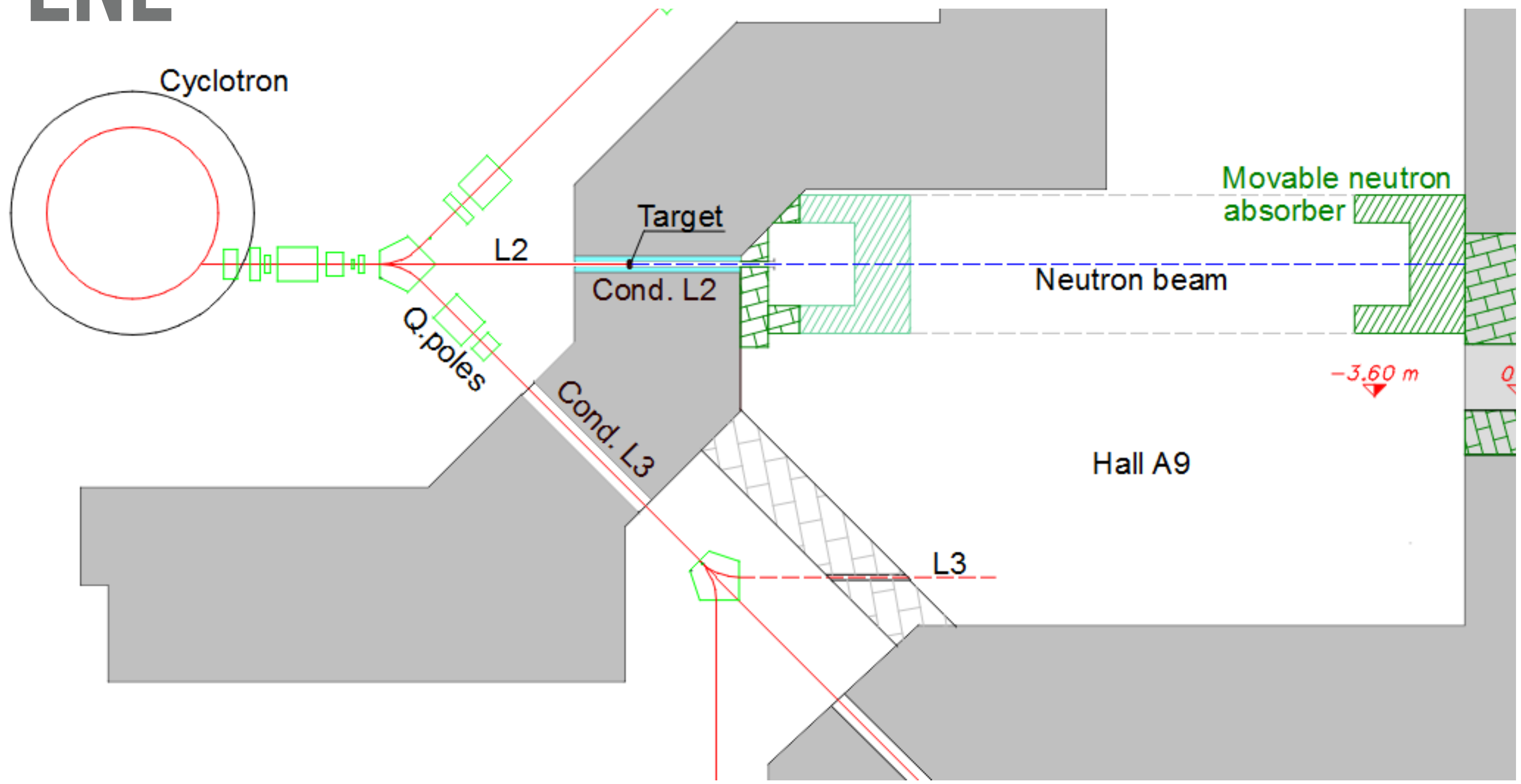




EURADOS Report 2013-02
"High-energy QMN fields: existing facilities and future needs"

NEPIR@SPES-LNL

- The **SPES** cyclotron can provide high current (max 750 μA) proton beams in the **energy range [30 – 70] MeV**;
- Presently within the **NEPIR project** a Quasi Mono-energetic Neutrons (QMN) beams facility has been proposed.



- Neutron peak energies below 30 MeV could be obtained using a *Carbon energy degrader*.

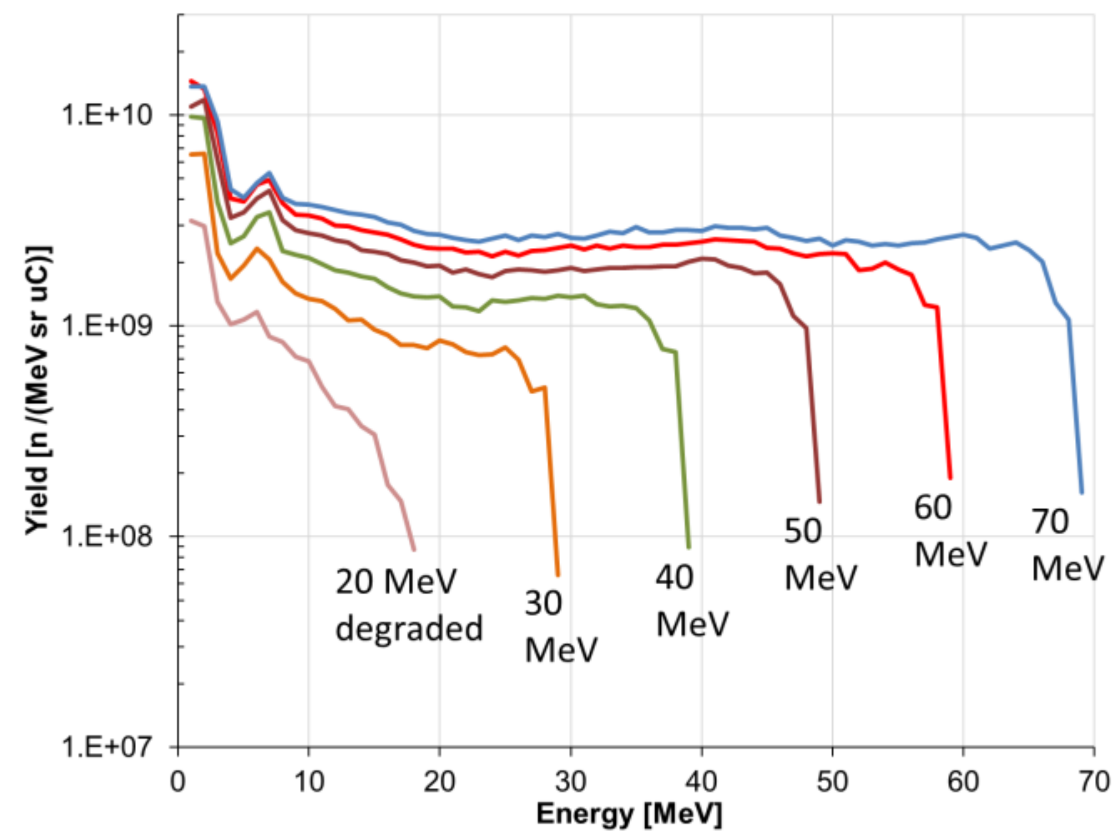
	LNL NEPIR
Energy of Protons	30 - 70 MeV
Distance of Li target from test point	3 m
Mono-energetic neutron (peak) flux at the test point	~2.7x10^5 n cm^{-2}s^{-1} for max 10 μA

The development of the QMN neutron facility in the framework of NEPIR has been scheduled in two different phases: **in the phase-0 a pseudo-QMN will be realized**. After its completion, the pseudo-QMN facility will be upgraded with the implementation of a true QMN source.

NEPIR@SPES-LNL

- The pseudo-QMN source will exploit the shielding of the cyclotron hall and required a small set of additional changes **limiting the need of additional shielding** with a direct impact to the production cost.

- In phase-0 neutrons will be produced with a continuous energy spectrum from a **30 mm thick Be target**.



- The spectrum generated has a relatively **flat distribution** with a sharp cutoff depending on the proton beam energy.

NEPIR@SPES-LNL

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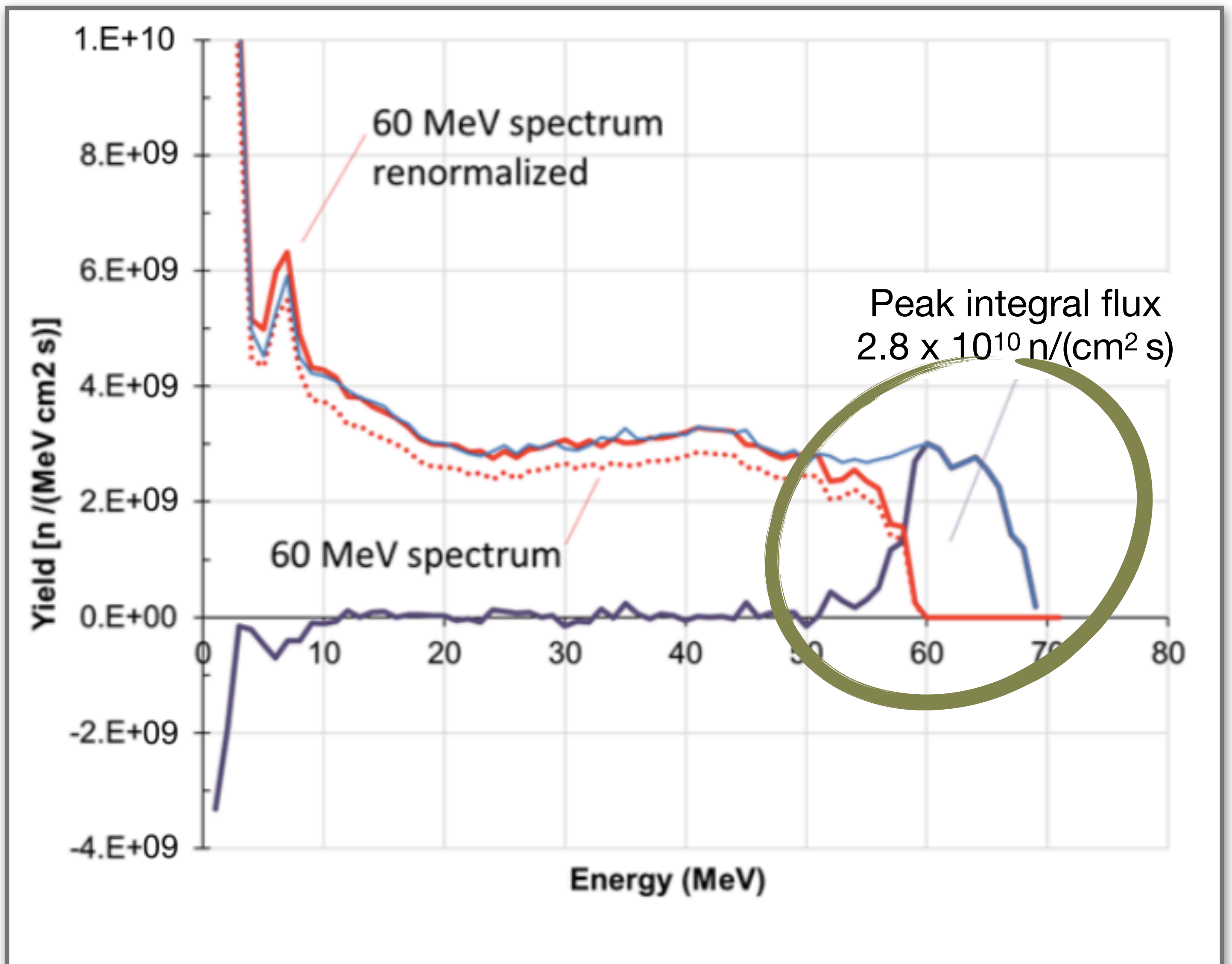

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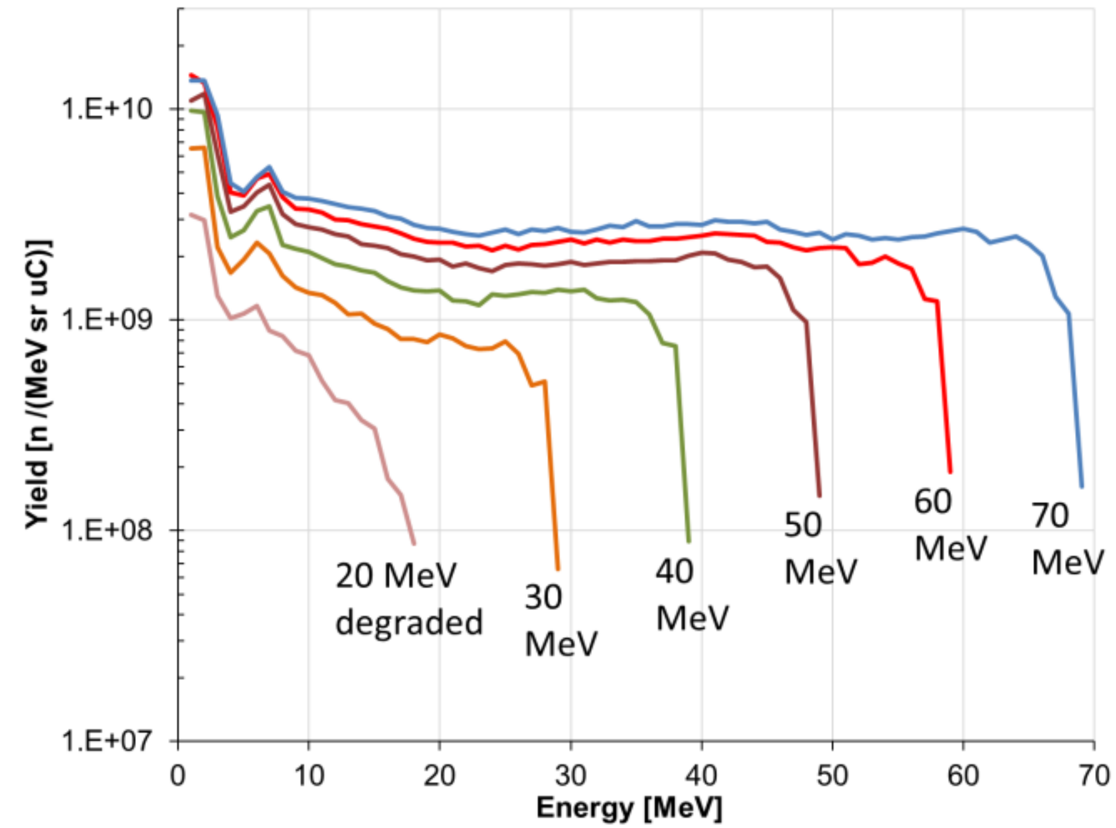


- The spectrum generated has a relatively **flat distribution** with a sharp cutoff depending on the proton beam energy.
- The effect of a QMN beam could be obtained **by difference** irradiating a sample with the neutron spectrum produced from two different proton beam energies.

MONDO FOR SPARE PROJECT

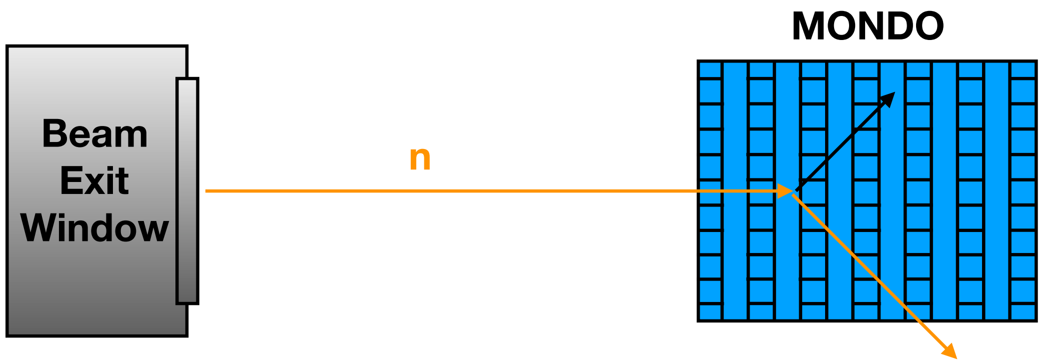
MONDO was originally designed for the detection of ultrafast neutrons emitted in Particle Therapy.

MOnitor for **N**eutron **D**ose for hadr**O**ntherapy

SIR 2014 (Centro Fermi)
RBSI140VL4
GRANT YOUNG RESEARCHER
INFN GROUP V 2015

Principal applications of the MONDO detector in the framework of the SPARE project are linked with the characterisation of the QMN beam in Legnaro.

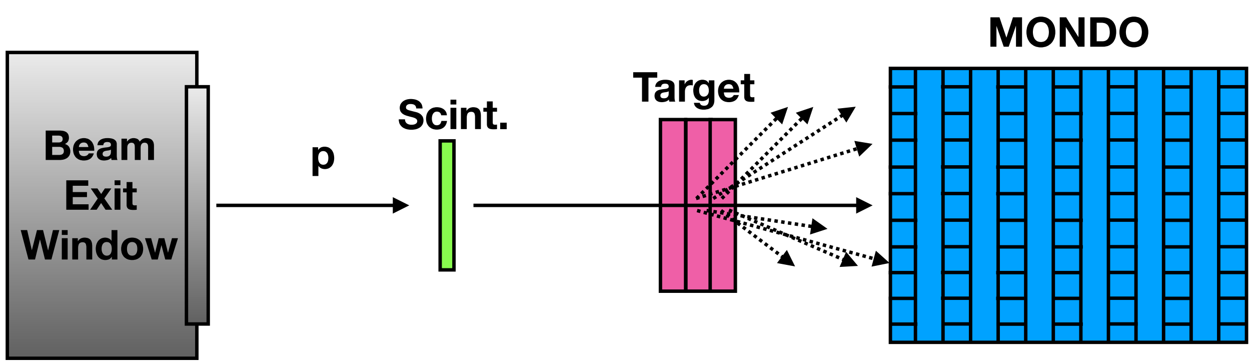
- Measure the flux and the energy spectrum of the QMN neutron beam at Legnaro (<70 MeV)



Beam monitor: MONDO placed directly on the neutron beam line

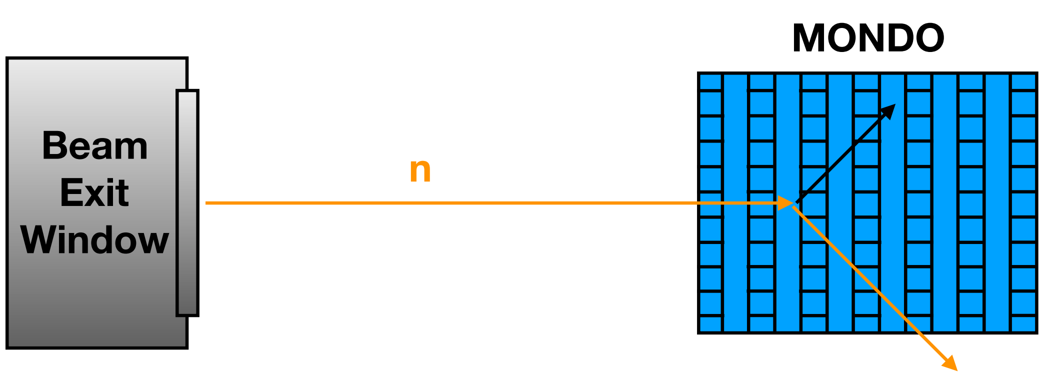
MONDO FOR SPARE PROJECT

- **Measure the yields and the energy spectrum of the neutrons produced in the interaction of the beam with the selected target** ([50-200] MeV).
- Measure the yields and the energy spectrum of the light ions (mainly Z=1,2) produced in the interaction of the beam with the selected target ([50-200] MeV/u)



Secondary particles detector: MONDO positioned after the Target

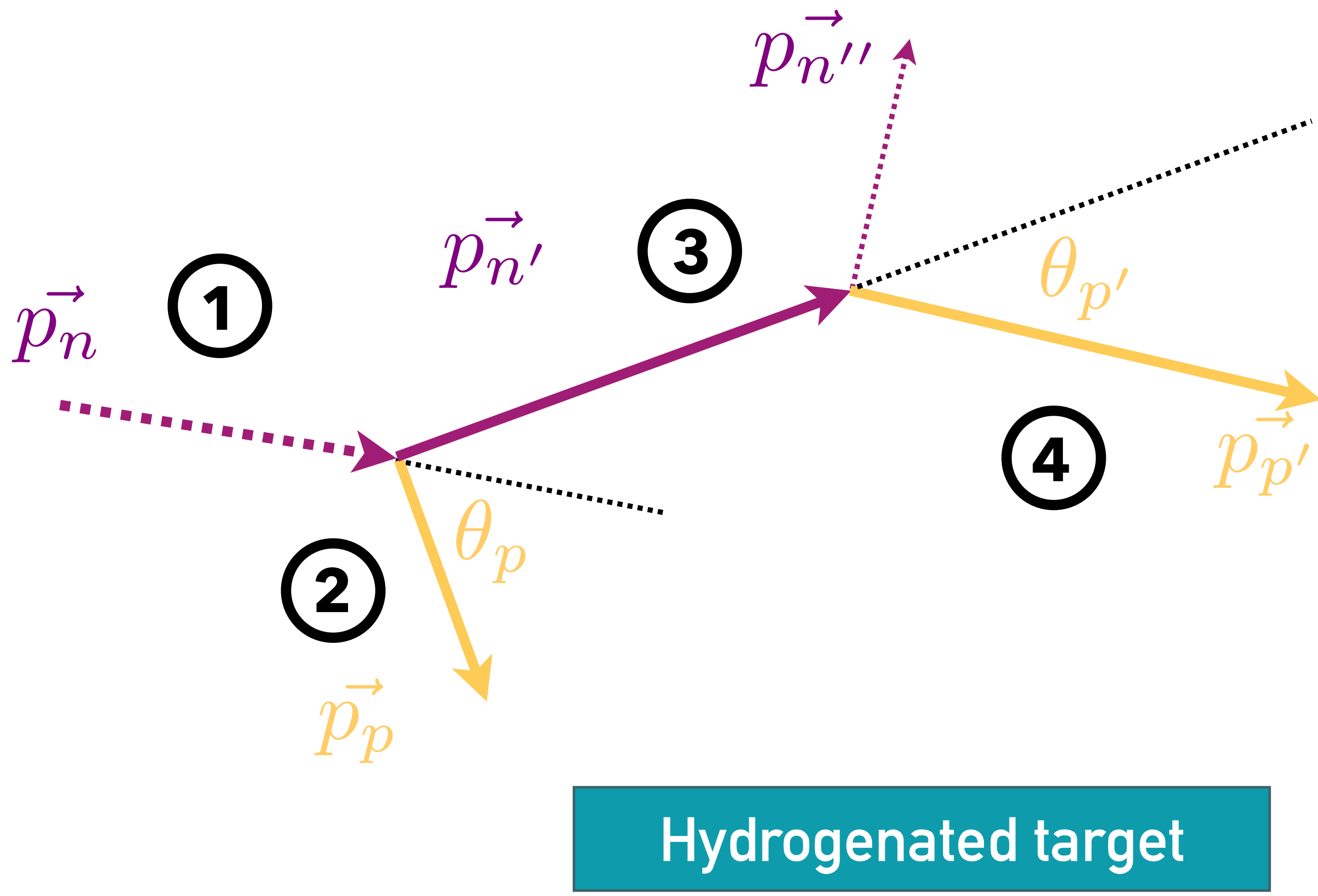
- **Measure the flux and the energy spectrum of the QMN neutron beam** at Legnaro (<70 MeV)



Beam monitor: MONDO placed directly on the neutron beam line

THE DETECTION MECHANISM

➤ Double elastic scattering



1. First neutron interaction: elastic scattering (ES). The incoming direction is known.
2. Proton recoil (E_{kin} from range)

$$E_n = \frac{E_p}{\cos^2 \theta_p}$$

3. The diffused neutron interacts again via ES
4. Second proton recoil

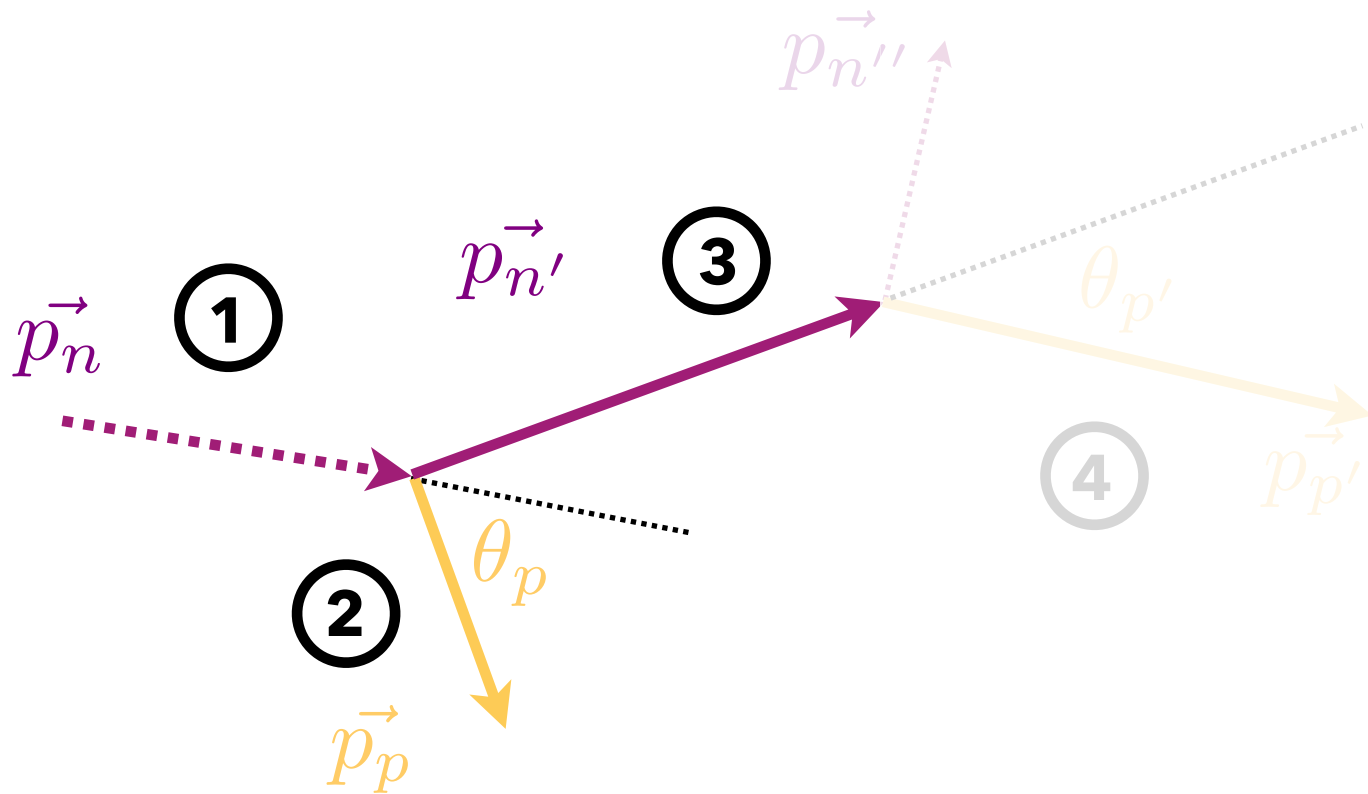
$$E_{n'} = \frac{E_{p'}}{\cos^2 \theta_{p'}} \hat{n}$$

- Tracking neutrons with *high efficiency*
- Proton Energy is reconstructed via range measurement

THE DETECTION MECHANISM

Only ES if neutrons direction is known!

Double elastic scattering



Hydrogenated target

1 First neutron interaction: elastic scattering (ES). The incoming direction is known.

2 Proton recoil (E_{kin} from range)

$$E_n = \frac{E_p}{\cos^2\theta_p}$$

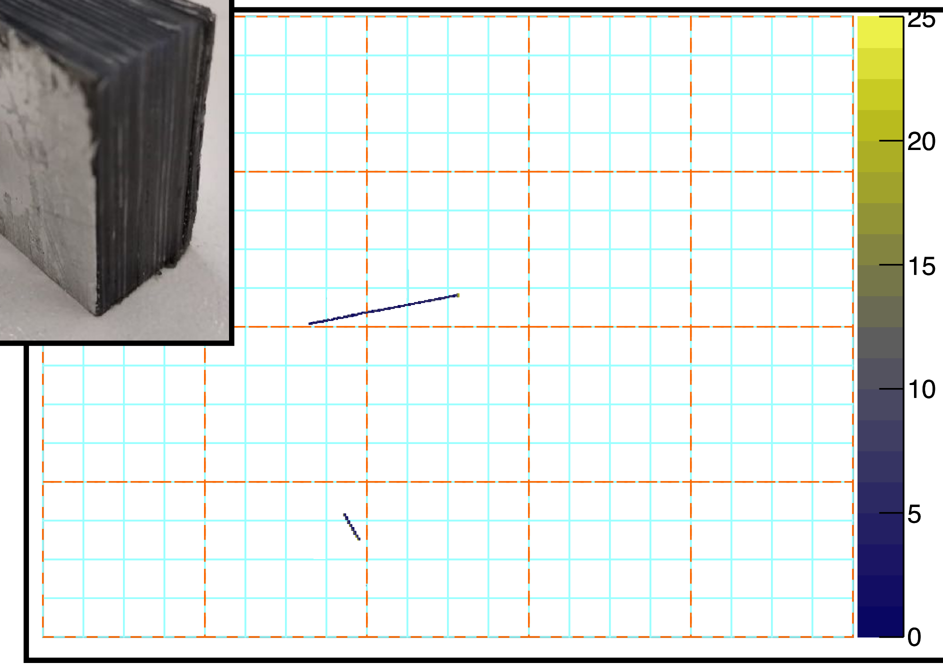
3 The diffused neutron interacts again via ES

4 Second proton recoil

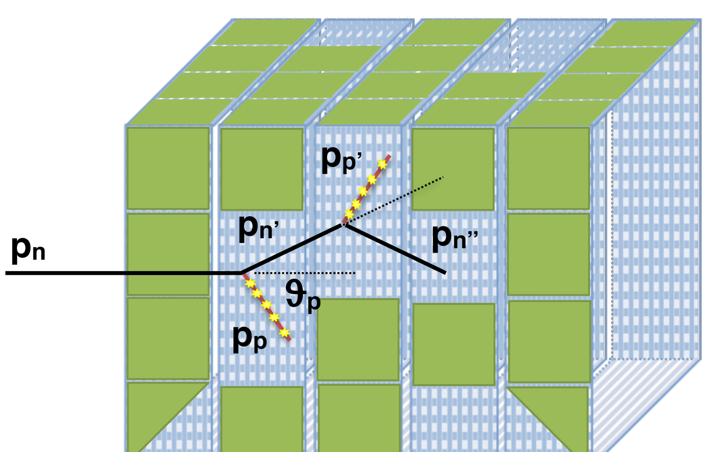
$$E_{n'} = \frac{E_{p'}}{\cos^2\theta_{p'}}\hat{n}$$

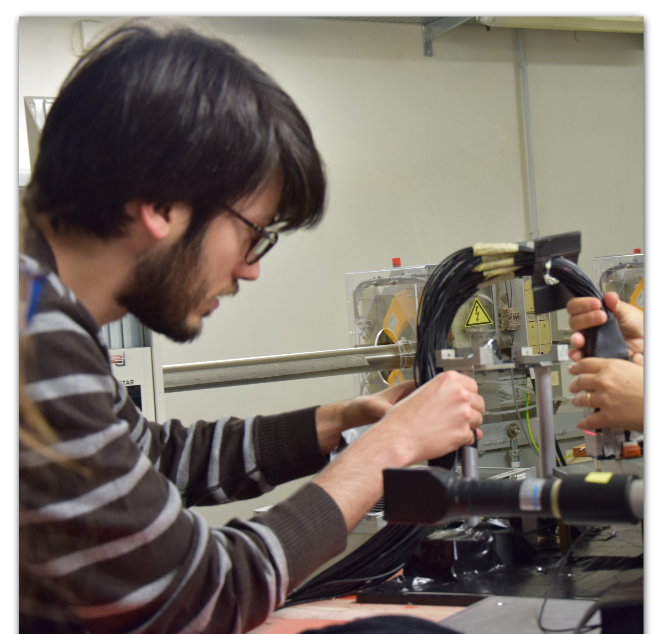
- Low energy protons are emitted with larger angles w.r.t. protons with higher energy;
- In order to track low energy protons, a high granularity in sampling the proton tracks is needed.

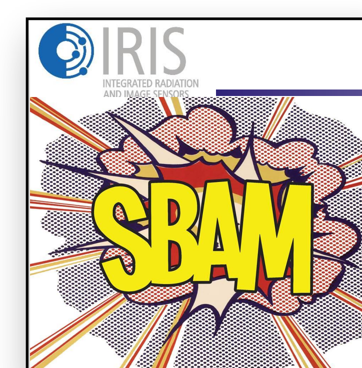
WHAT DID I DO DURING MY PHD?



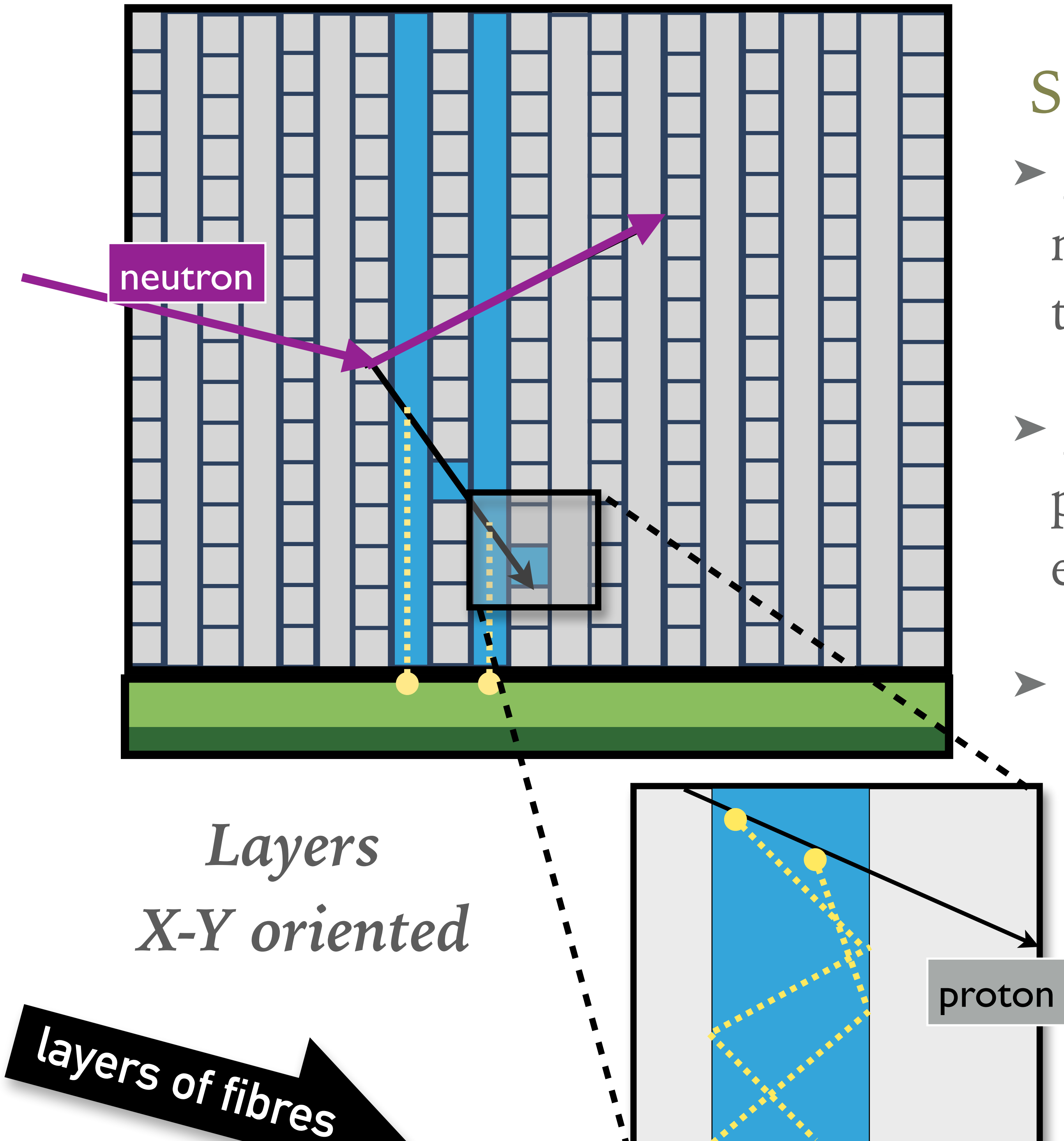
- Prototype construction;
- Montecarlo simulation (FLUKA):
  - Detector geometry optimisation;
  - Performances evaluation;
- Design and development of the readout sensor;
- Preliminary measurement on prototype and characterization measurement on first sensor chip.







THE MONDO CHALLENGE



Layers
X-Y oriented

layers of fibres

target and tracker

SCINTILLATING PLASTIC FIBRES

- squared 250 μm: minimal size in order to maximise the granularity on the proton tracks (proton energy is measured by range);
- plastic: increase the neutron interaction probability on light nucleus (H) to increase elastic scattering events;
- "easy" to manipulate and "cheap" 1.2€/1m

More than 6x10^5 channels
~ 50 km of fibers

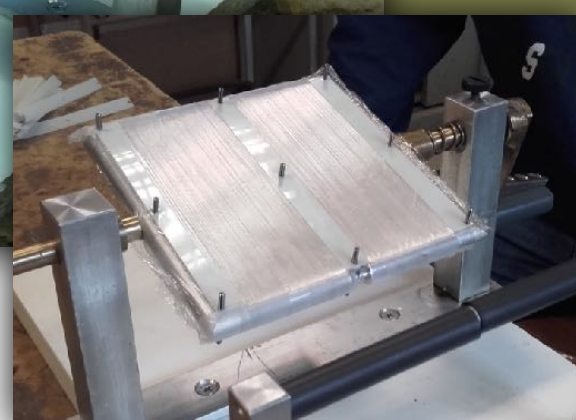
→ silicon readout **system**

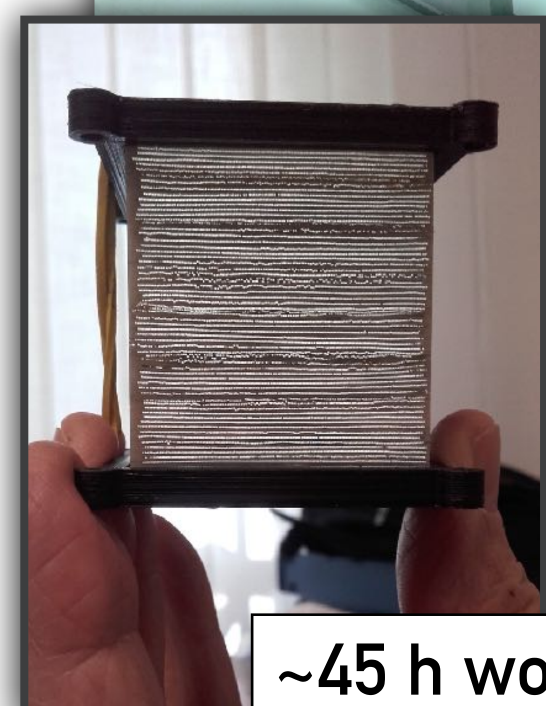
NEUTRONS TRACKER PROTOTYPE

The construction of the fibers matrix is a crucial point in the detector development: mechanics has a direct impact on space resolution and detector dimensions.

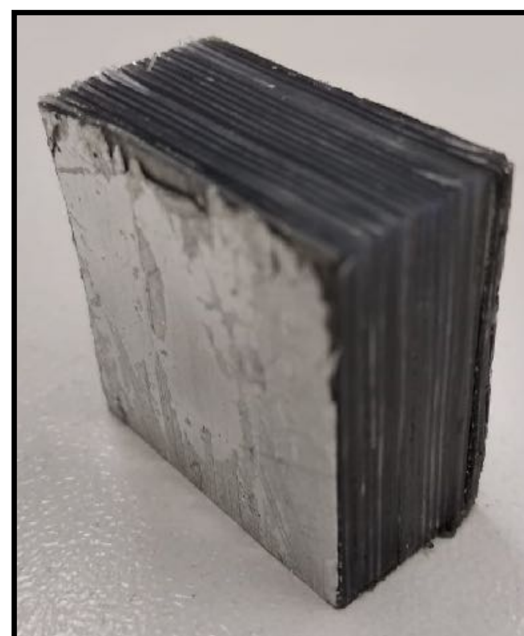
PENELOPE

A tracker prototipe (4 x 4 x 4.8 cm^3) has been realised as a proof of principle for proton tracking and in order to test the assembling procedure.





~45 h work



ARGO: 2x2x1 cm^3

New weaving methods (with a motorized part)

Dipartimento di Scienze di Base e Applicate per l' Ingegneria

NEUTRONS TRACKER PROTOTYPE

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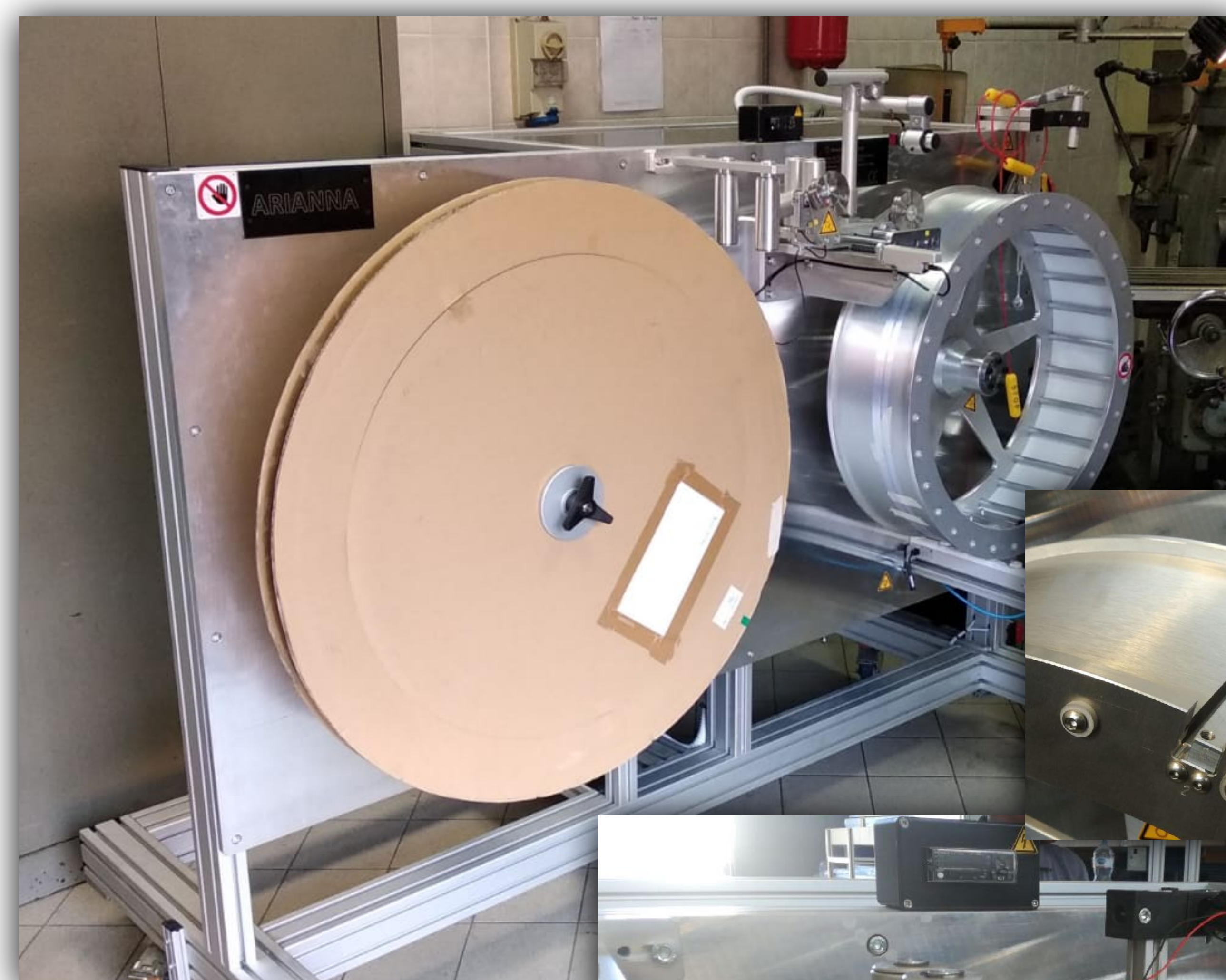
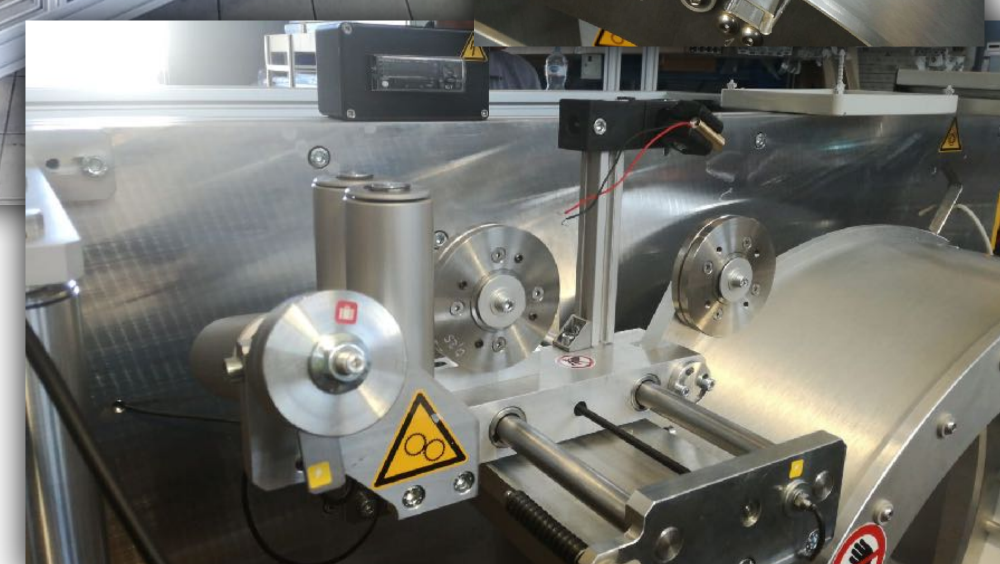
~ 1 km





~ 80 km

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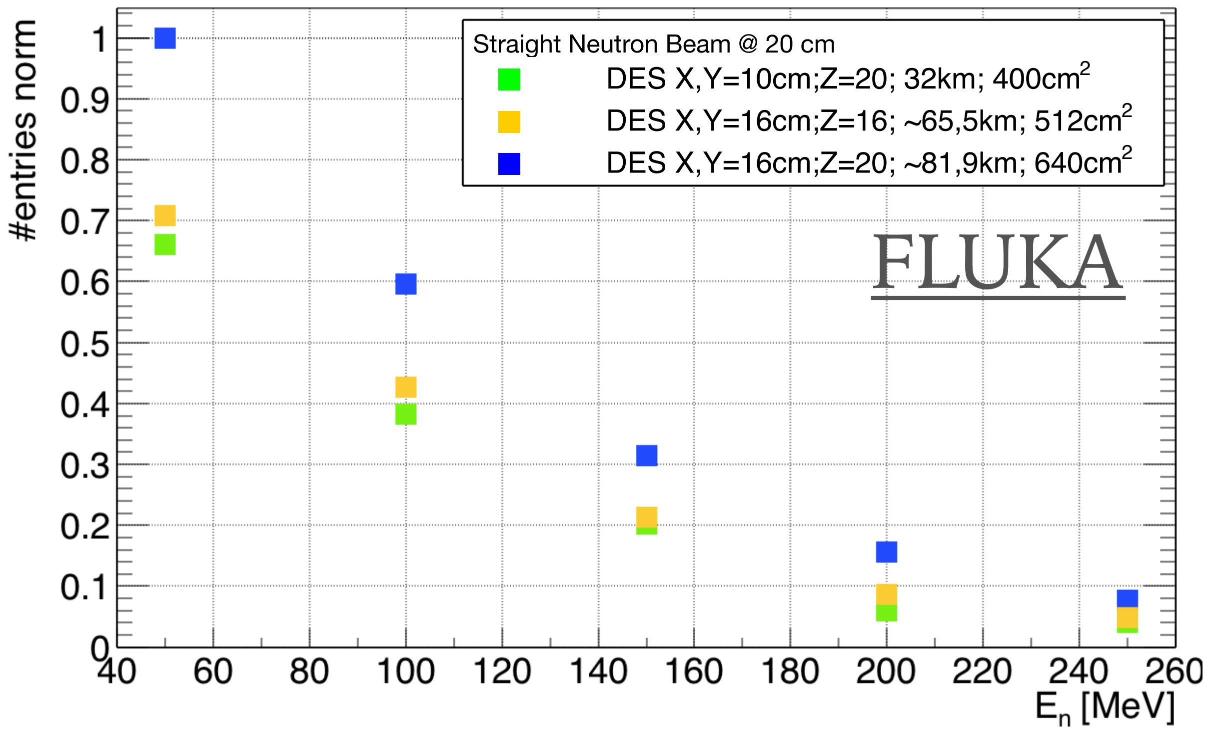
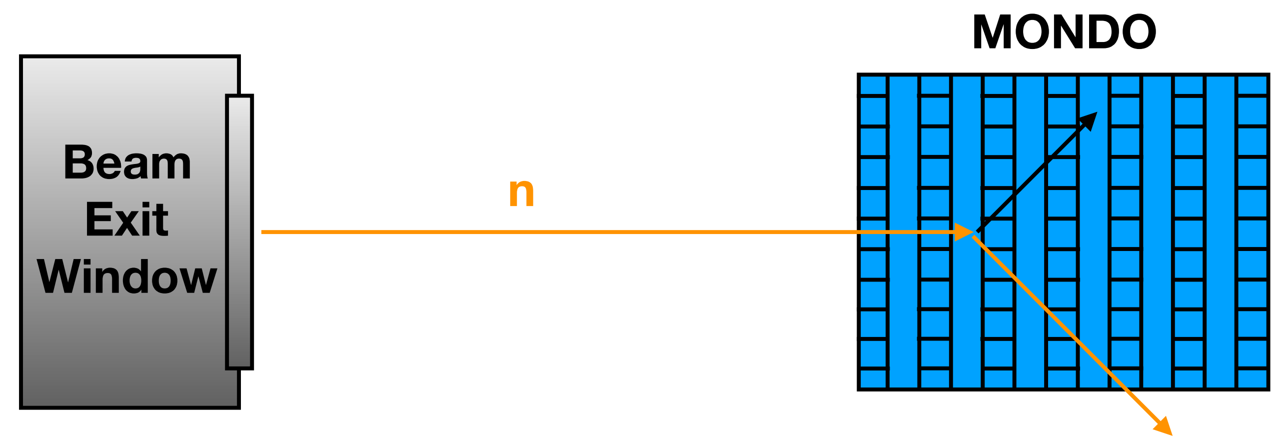
e Applicate per l' Ingegneria

DIMENSIONS OPTIMISATION



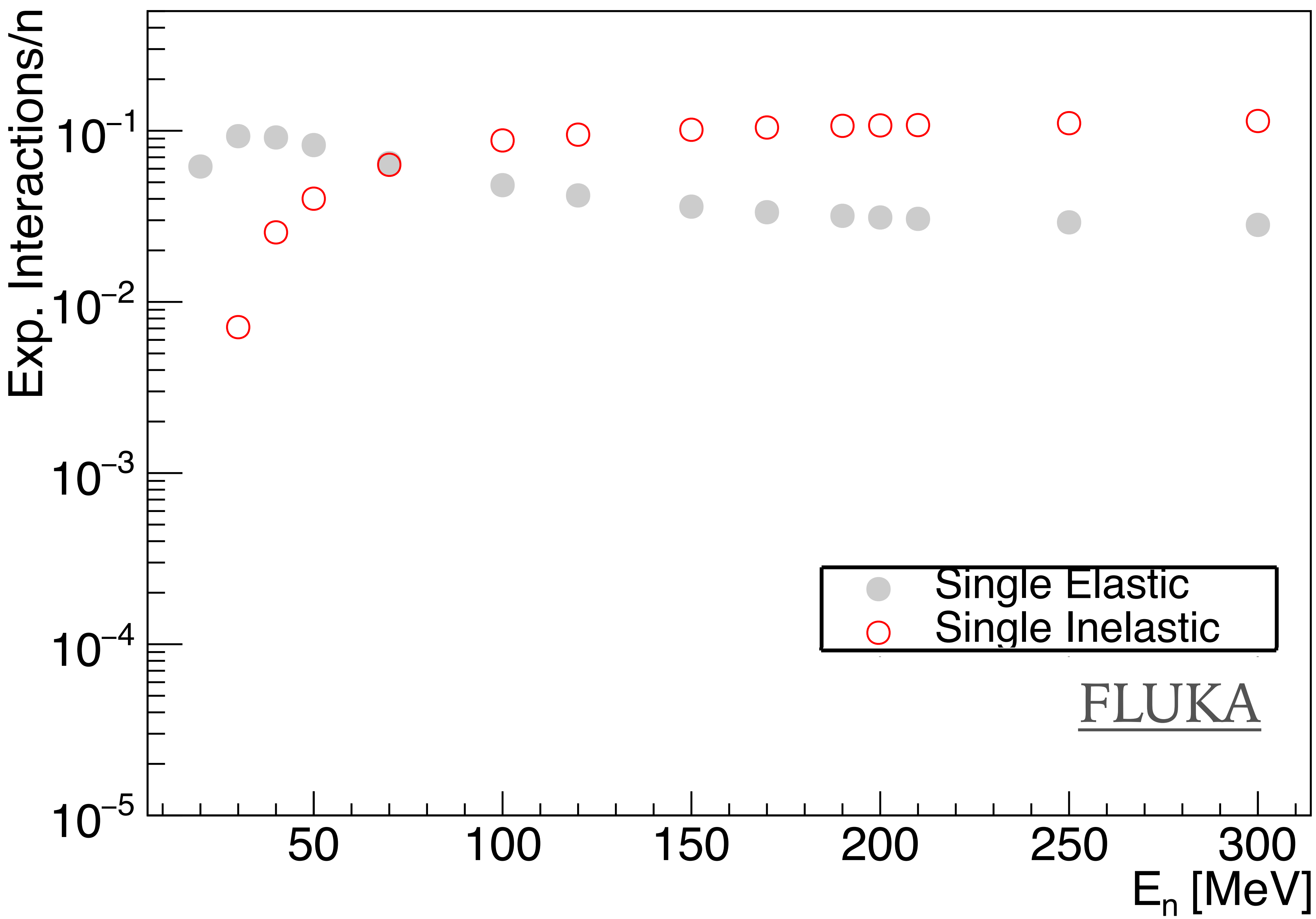


- A full-MC FLUKA simulation has been implemented **to study the probability for neutrons** of undergoing a double elastic scattering **as a function of the detector dimensions**.
- The study has been repeated both for a straight neutron beam generated at 20 cm from MONDO and for a neutron source at 1 mm from the detector with an isotropic emission.
- The chosen configuration provided an efficiency up to **1.5 times higher** with respect to the other geometries under study.

The final simulated detector has **800 layers** of 16 cm × 16 cm × 250 μm fibres made of plastic scintillating material, x-y oriented, for a total size of **16 × 16 × 20 cm^3.**

SIMULATION: BACKGROUND STUDY

Inelastic interactions (IS) are the main intrinsic background for the elastic events (ES). ES are dominant below 100 MeV, while IS are not negligible for higher energies.



Background:

- The probability of inelastic interactions could have a non-negligible impact on the detector performances and it has to be taken into account when calculating the intrinsic background.

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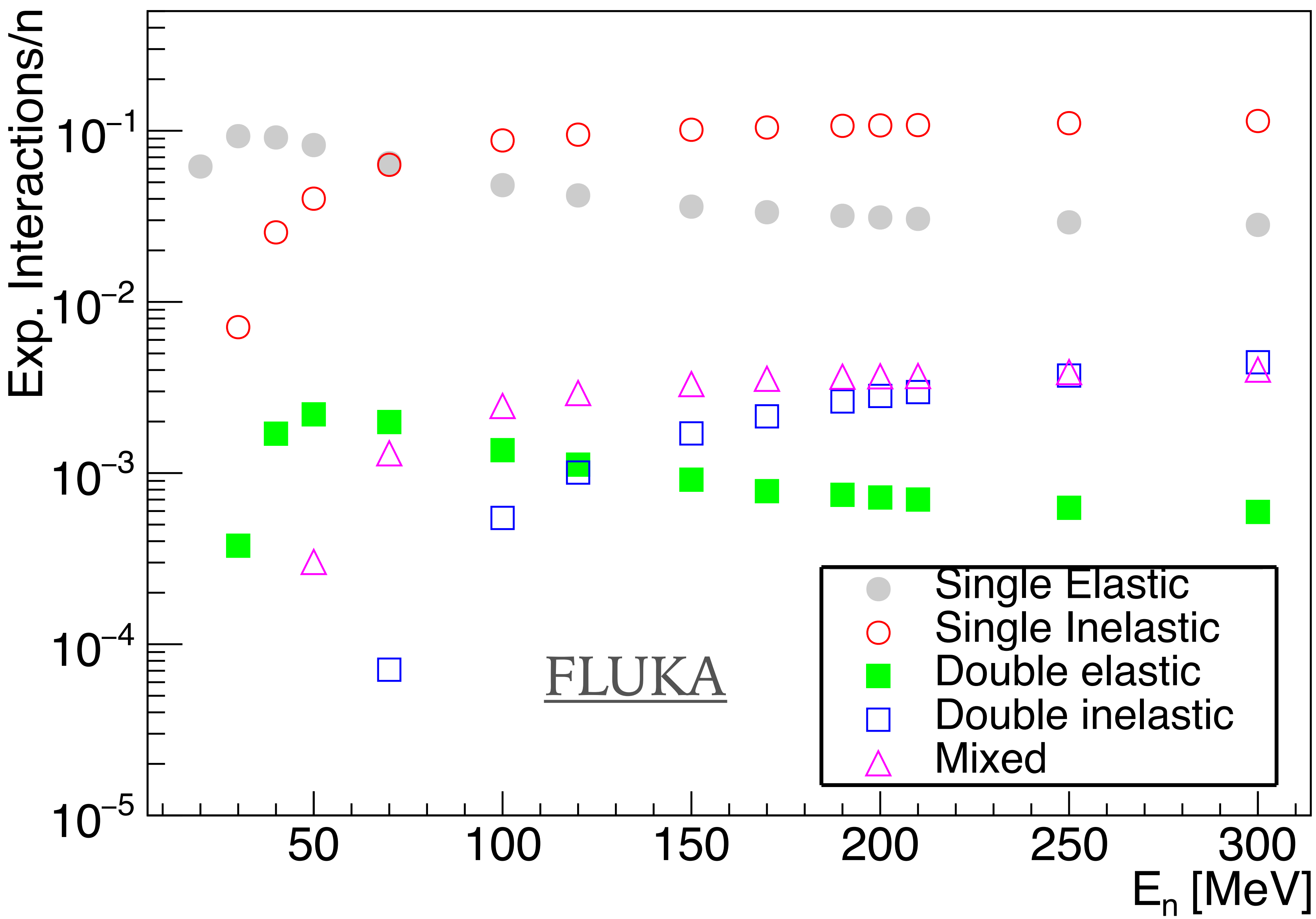

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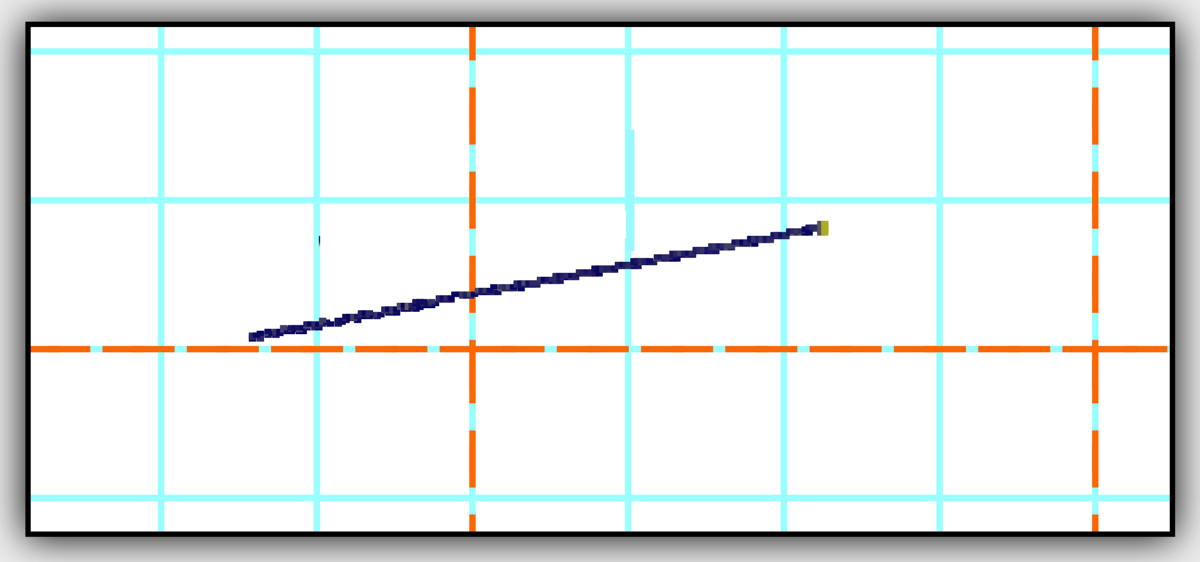
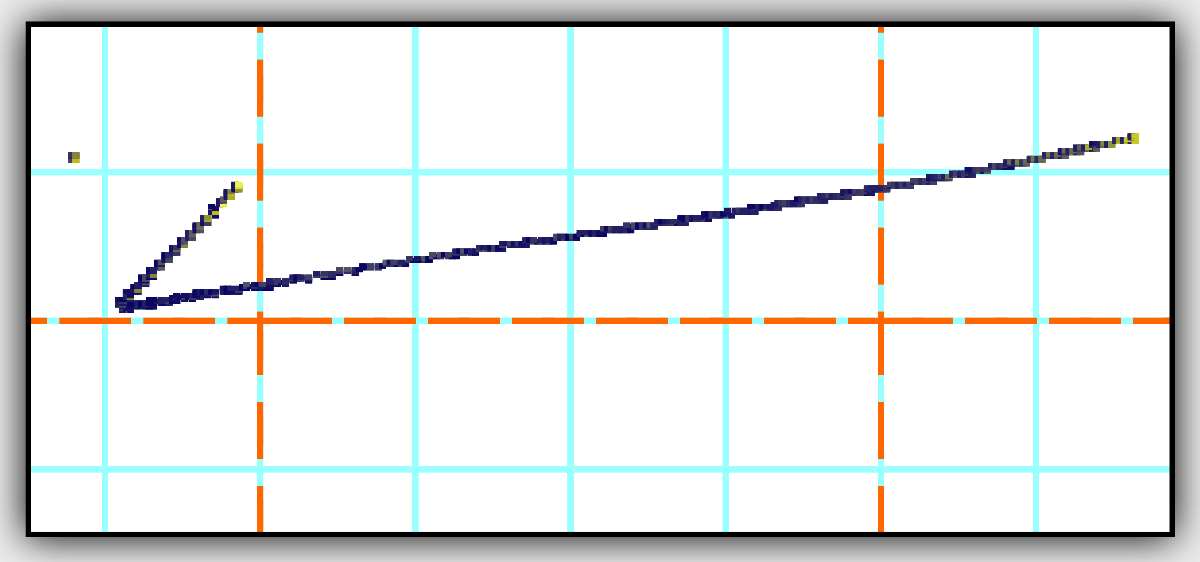
Track multiplicity and dE/dx measurement at the interaction vertex will be used to reduce the background contamination and reject inelastic events.

Rejection through track multiplicity is possible thanks to high granularity.



Elastic Scattering Event

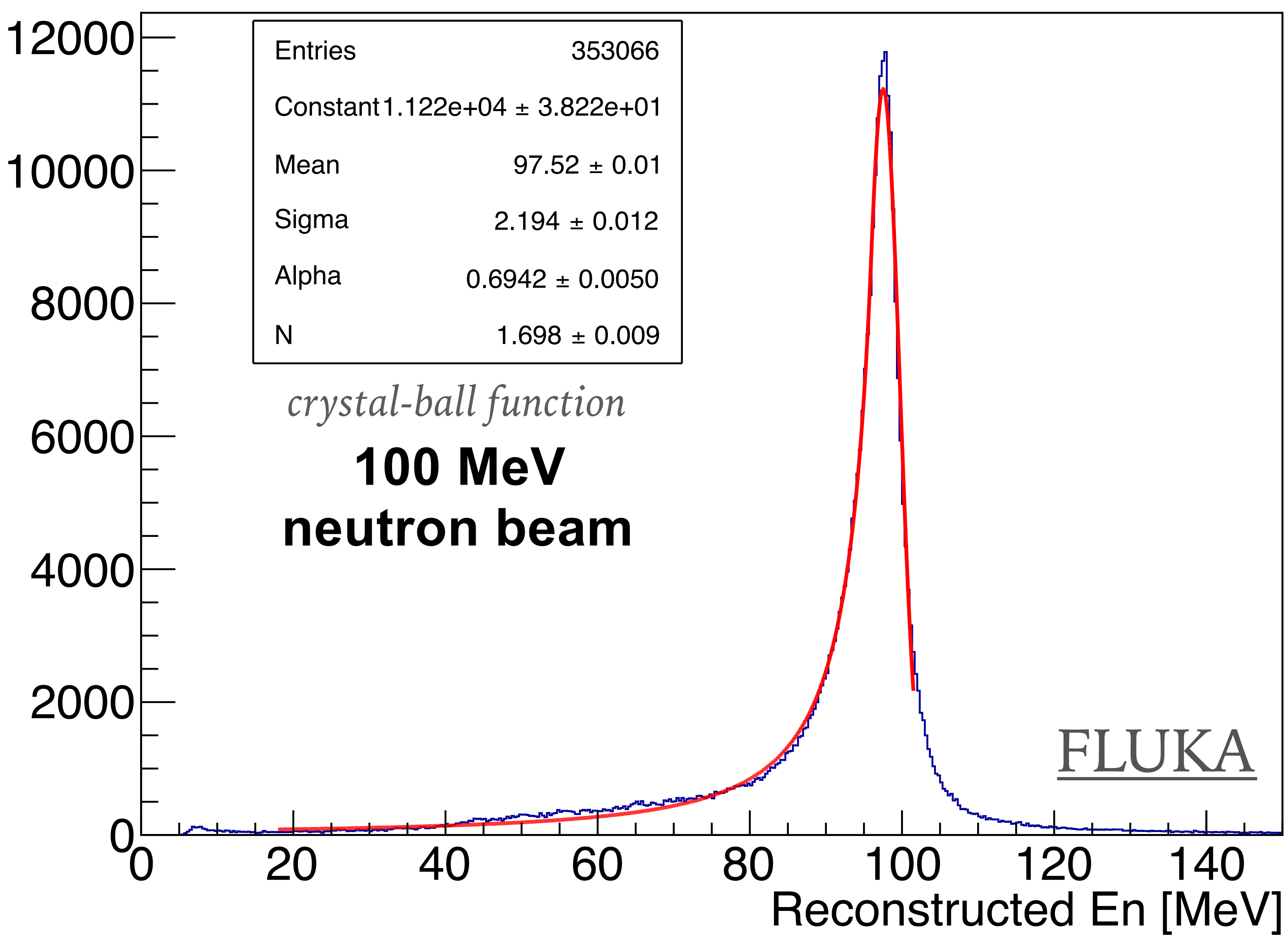


Inlastic Scattering Event

➤ The readout response has been simulated in an external dedicated code that uses as input the energy release in the fibers and process this information **following the measured performances of the SBAM sensor that will be described hereafter.**

SIMULATION: ENERGY RESOLUTION

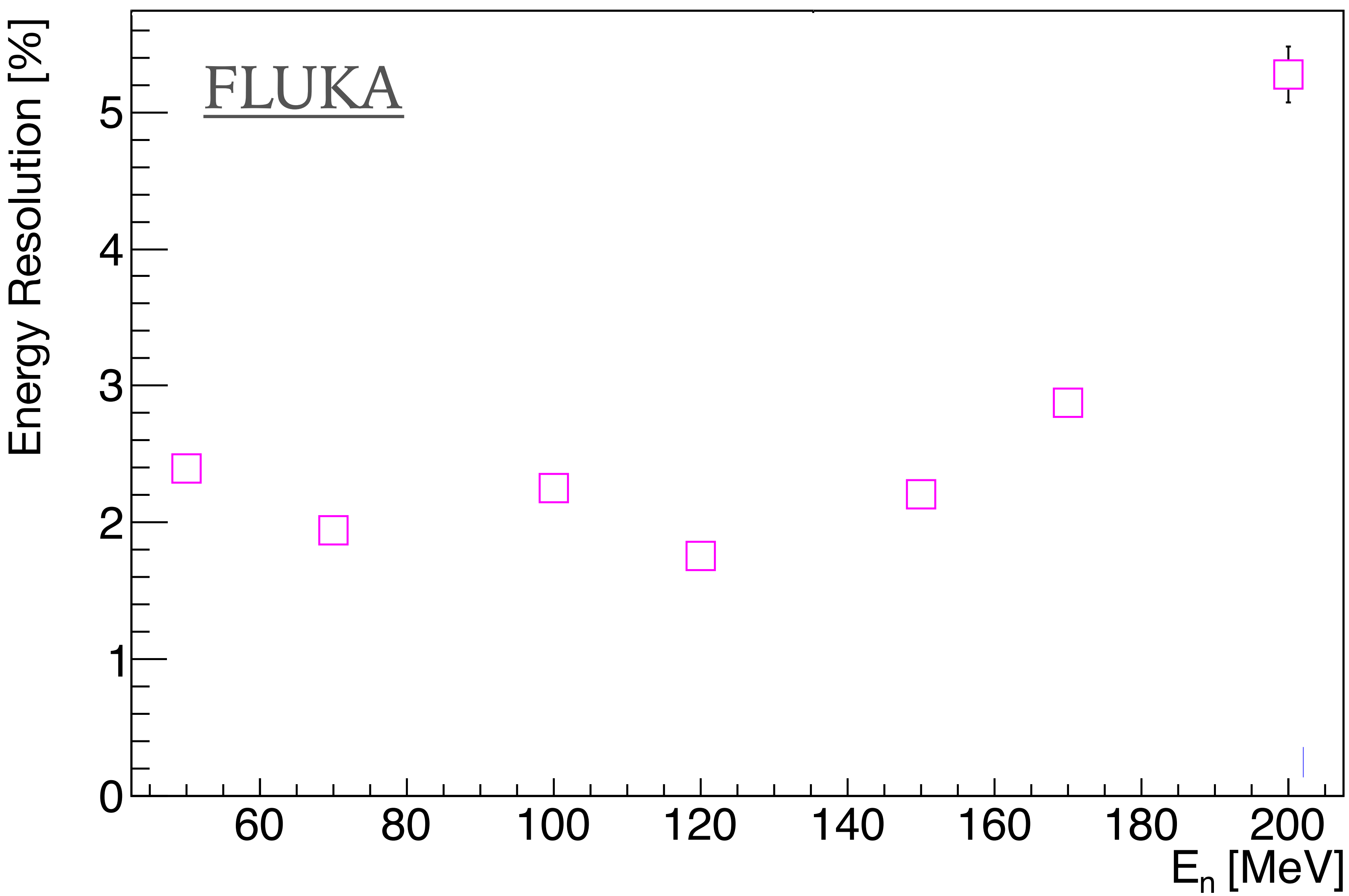
- Primary neutrons **are generated with straight directions at 20 cm**, simulating **an ideal collimated neutron beam with $\sigma_{beam} = 0$;**
- Constraints: full containment request of the protons;
  at least 6 pixels crossed (about 10 MeV);



The primary neutrons kinetic energy has been reconstructed **from the detection of the secondary proton**. The proton kinetic energy has been calculated using the **length of the particle track** with NIST range-energy values. The proton angle is computed by means of a **linear fit to the proton track**.

SIMULATION: ENERGY RESOLUTION

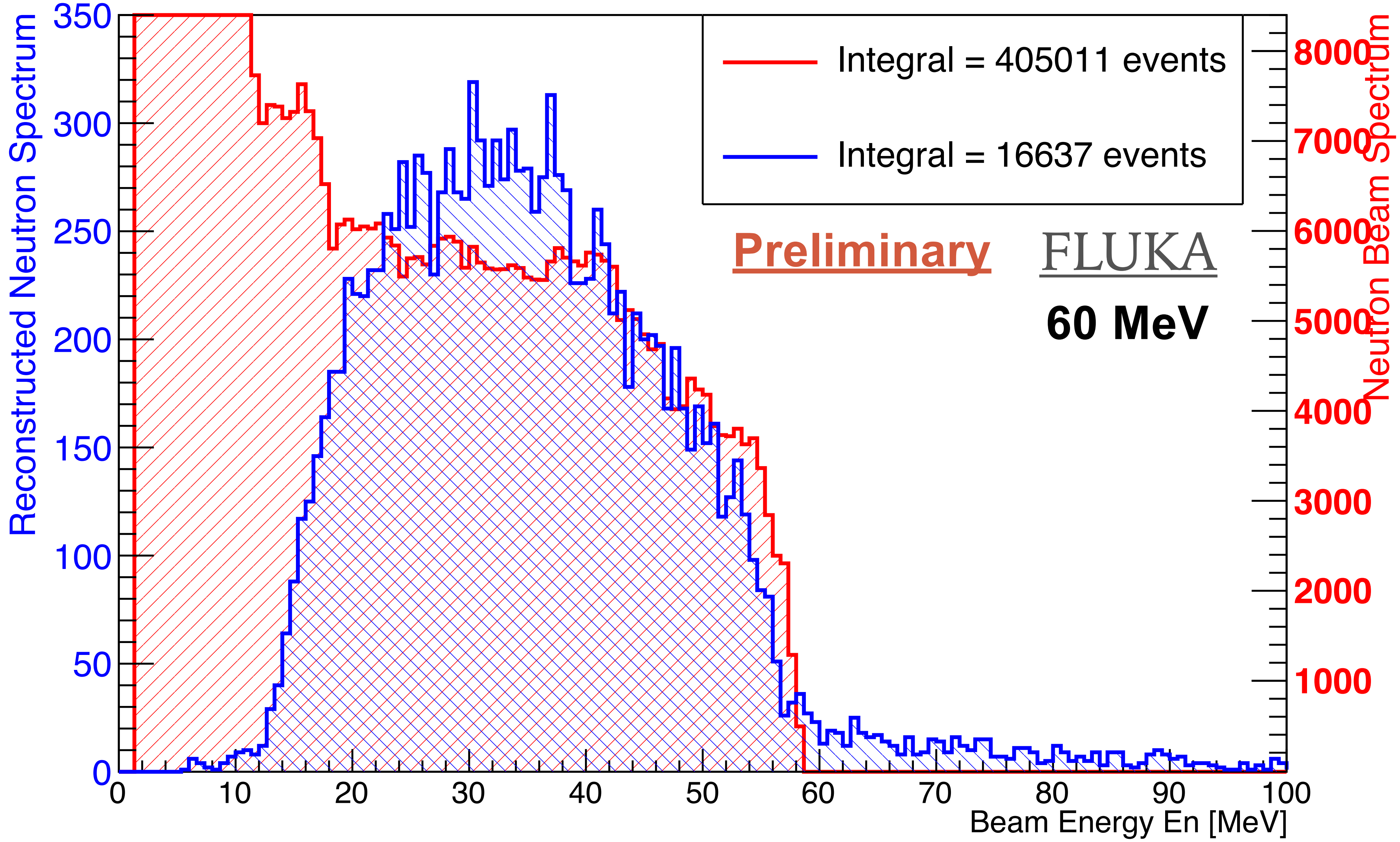
The kinetic energy of primary neutrons has been reconstructed **from the detection of the secondary proton**. The proton kinetic energy has been calculated using the **length of the particle track** with NIST range-energy values. The proton angle is computed by means of a **linear fit to the proton track**.



The resolution is reported as a function of the neutron kinetic energy.

Neutron **energy uncertainty is dominated by the uncertainty affecting the proton angles reconstruction**. This uncertainty decreases with the proton emission angle and, **for lower energies, the resolution improves.**

SIMULATION: NEUTRONS PRODUCTION SPECTRUM

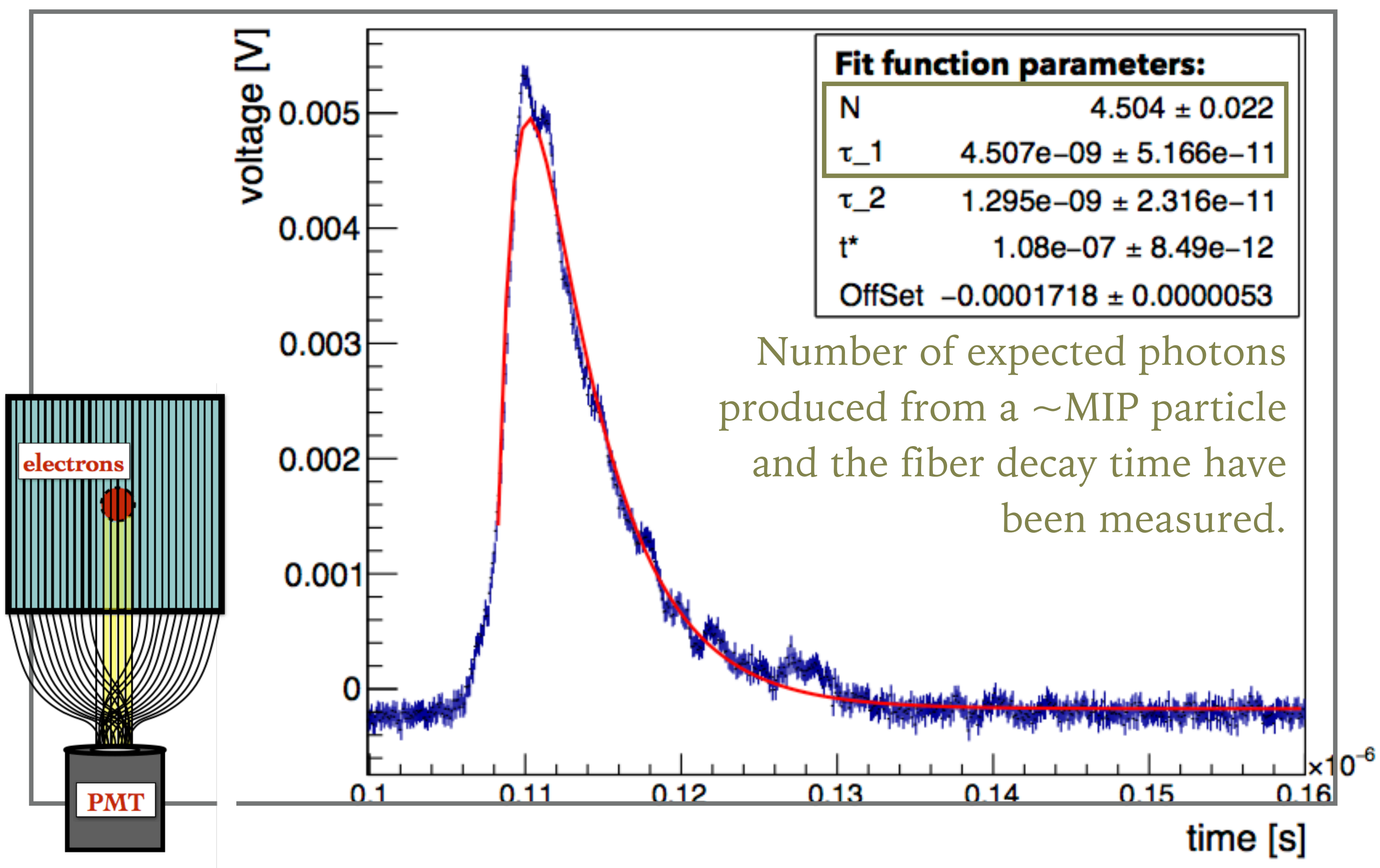


- Reconstruction of the neutrons spectrum produced from a **27 mm Be** target with **60 MeV** protons.
- The sharp edge in the distribution due to the energy of the proton beam from which the neutron spectrum is generated appears to be **well reproduced**.

STEPS TOWARD THE READOUT SENSOR...

- MONDO tracker scintillating fibers are readout with a customized sensor based on Single Photon Avalanche Diode (SPAD), solid state device in CMOS technology.
- In order to address the specific MONDO features and needs, preliminary measurements with **conventional PMT** and **SPAD-based prototype, *spad-net**** have been performed.

BTF - Beam Test Facility@LNF
Electron Beam Energy[100 - 450] MeV



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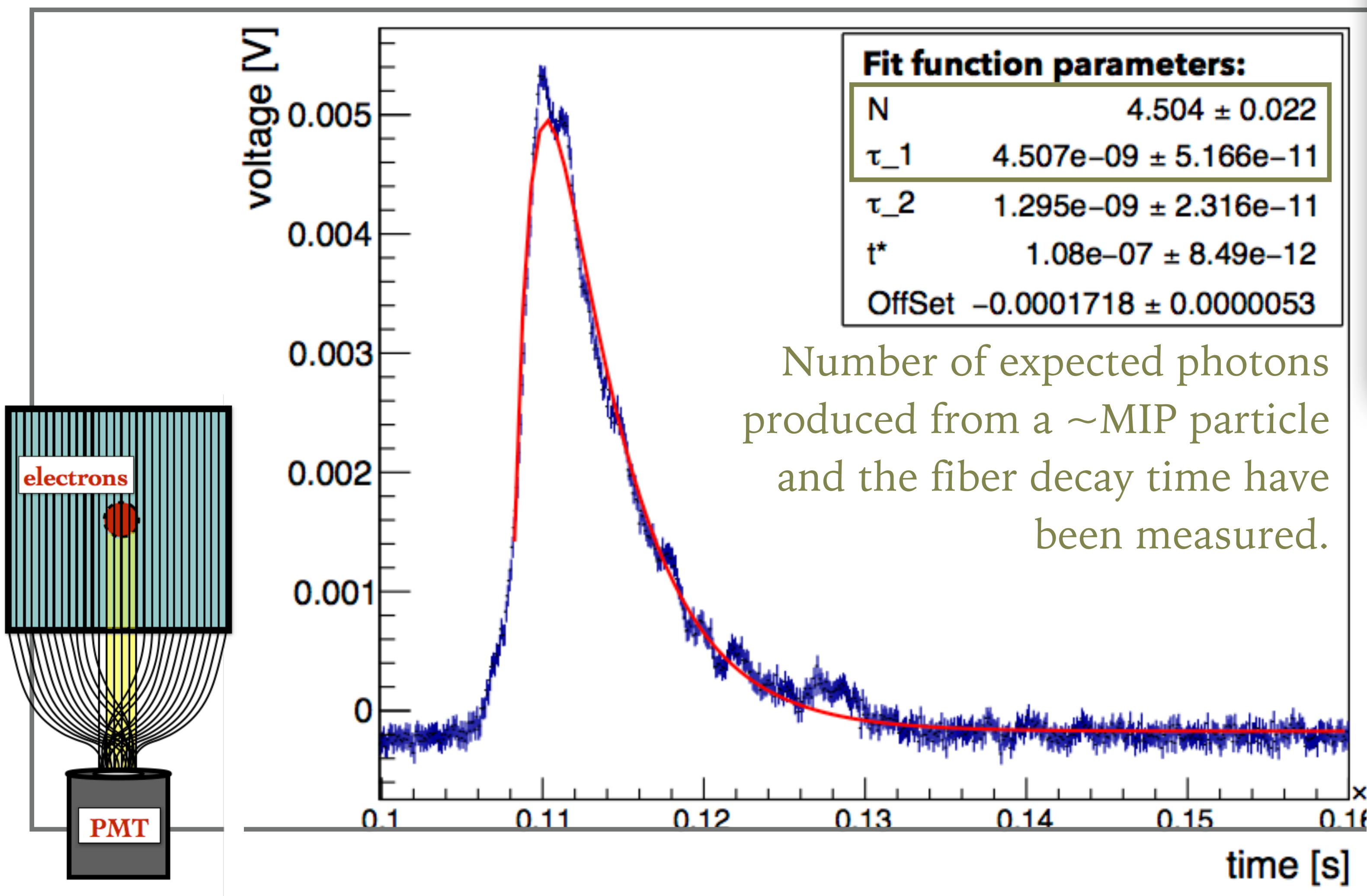
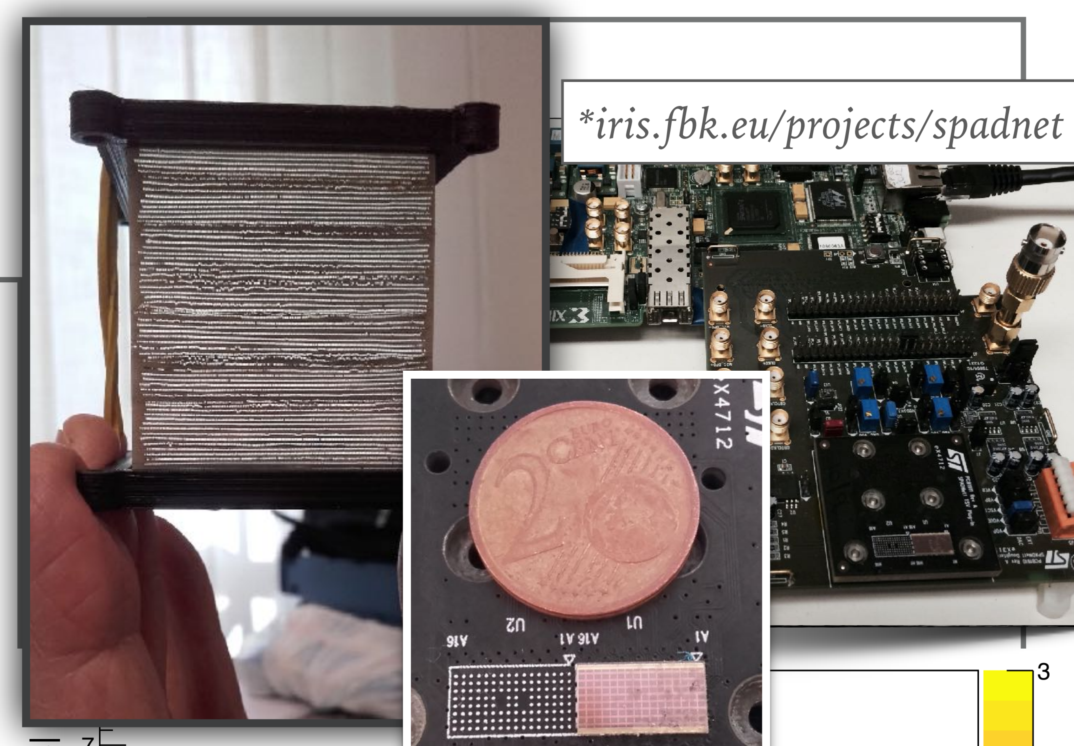
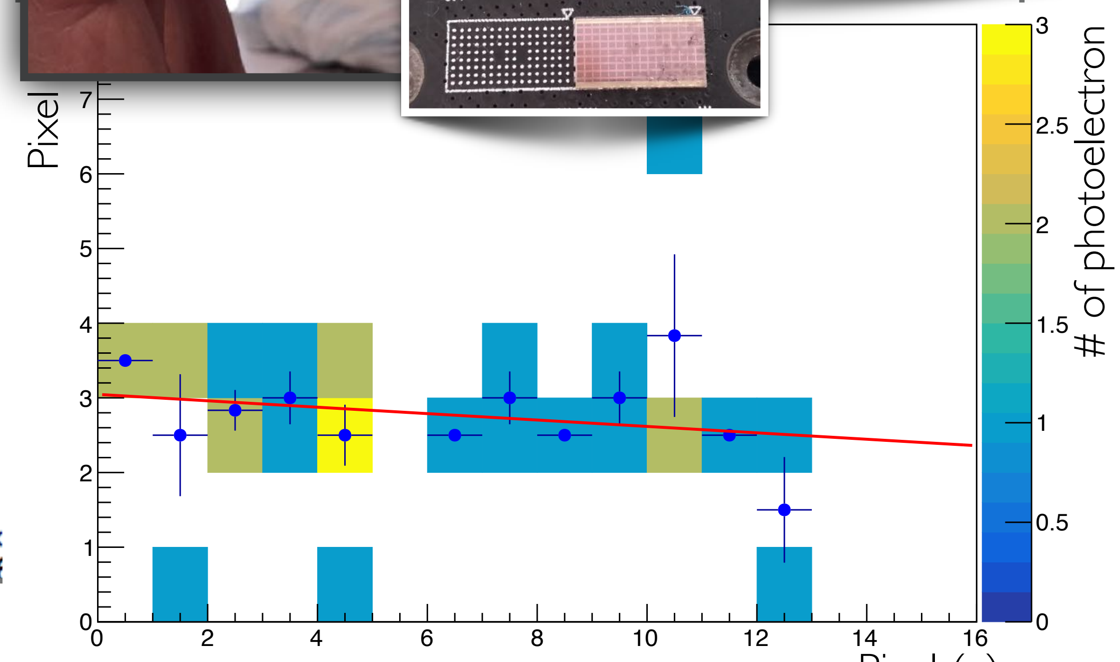


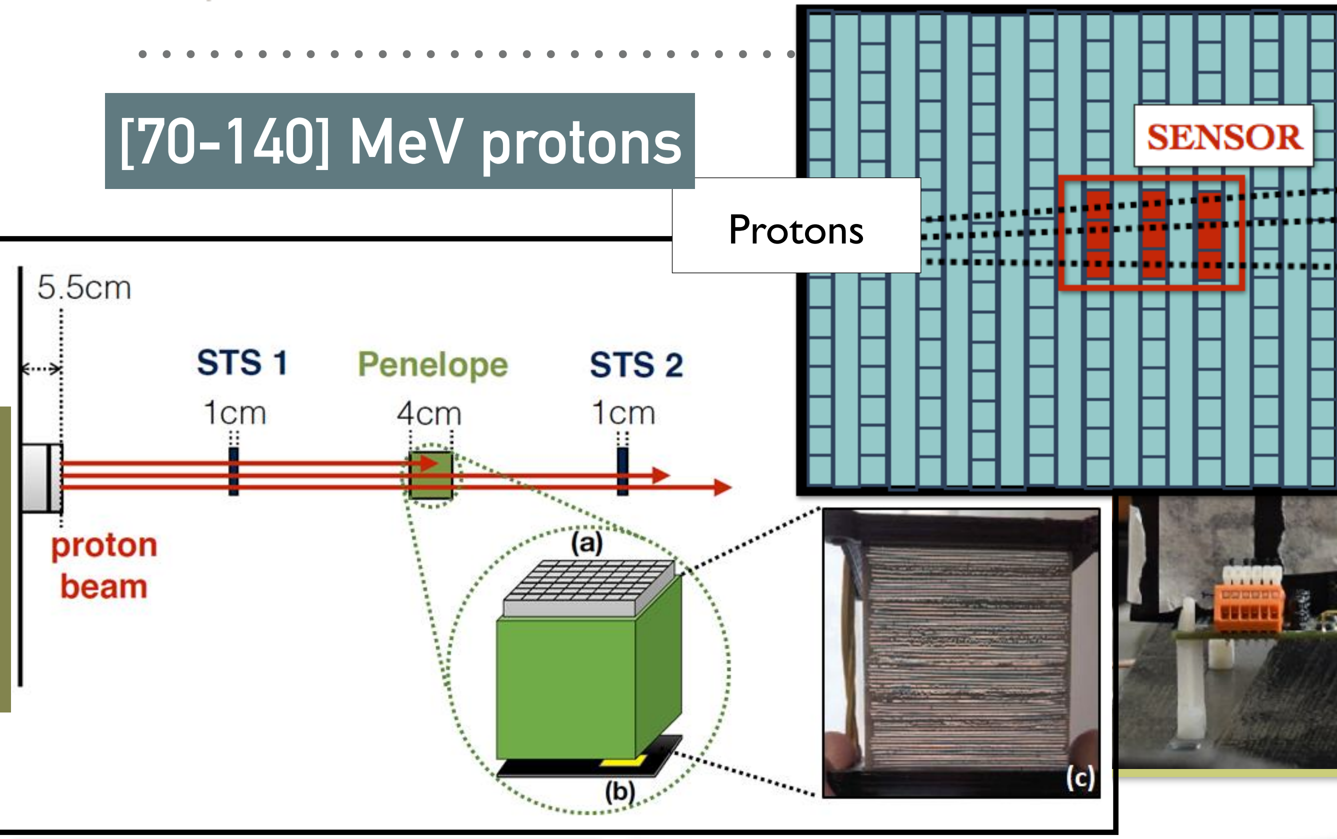


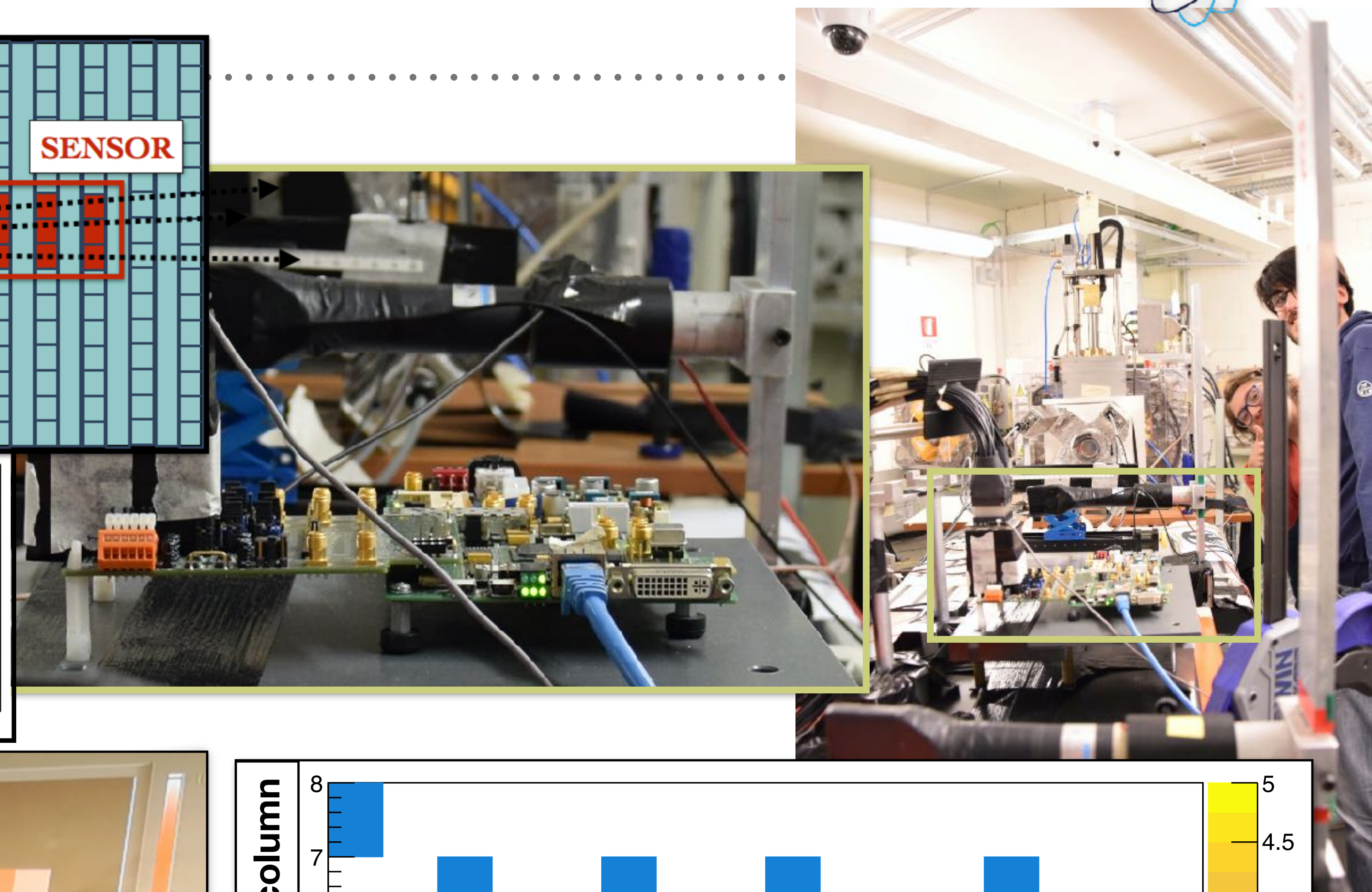
*iris.fbk.eu/projects/spadnet



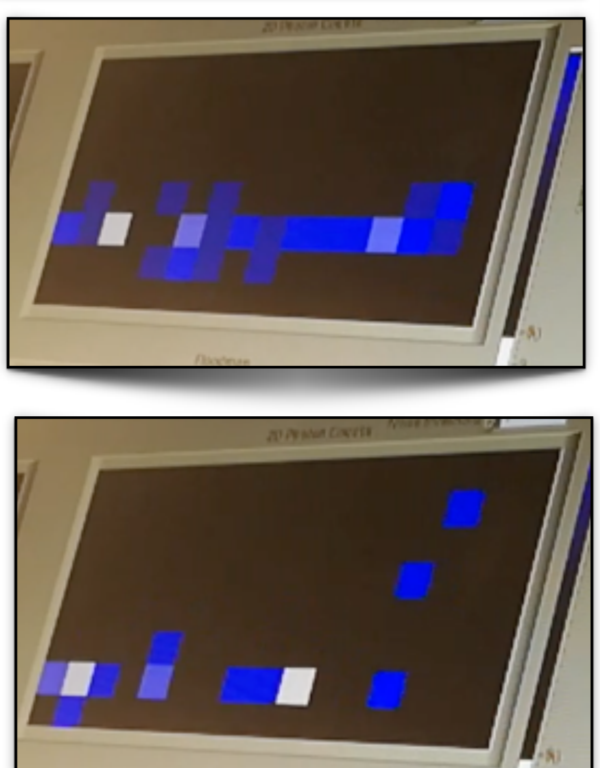
STEPS TOWARD THE READOUT SENSOR...

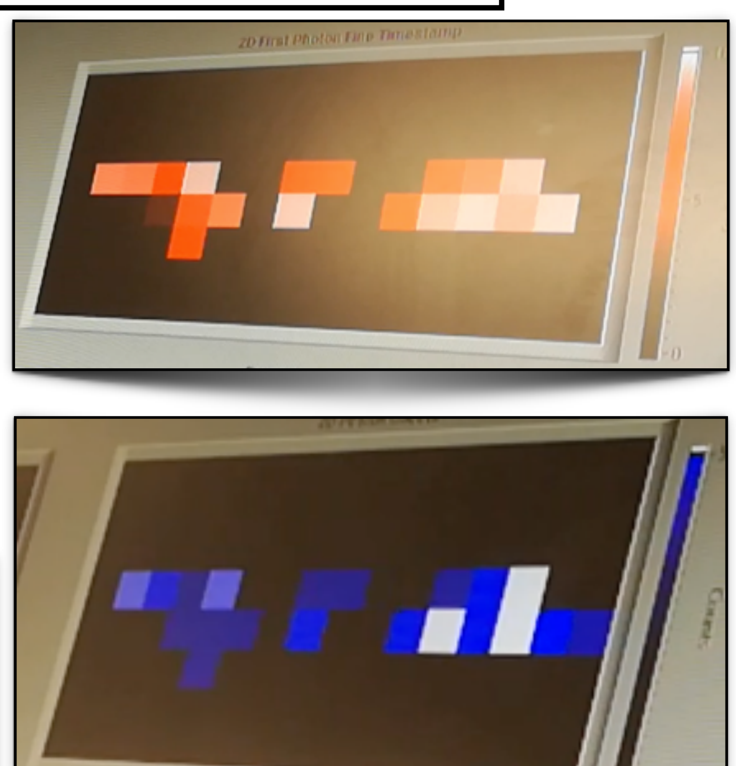
[70-140] MeV protons



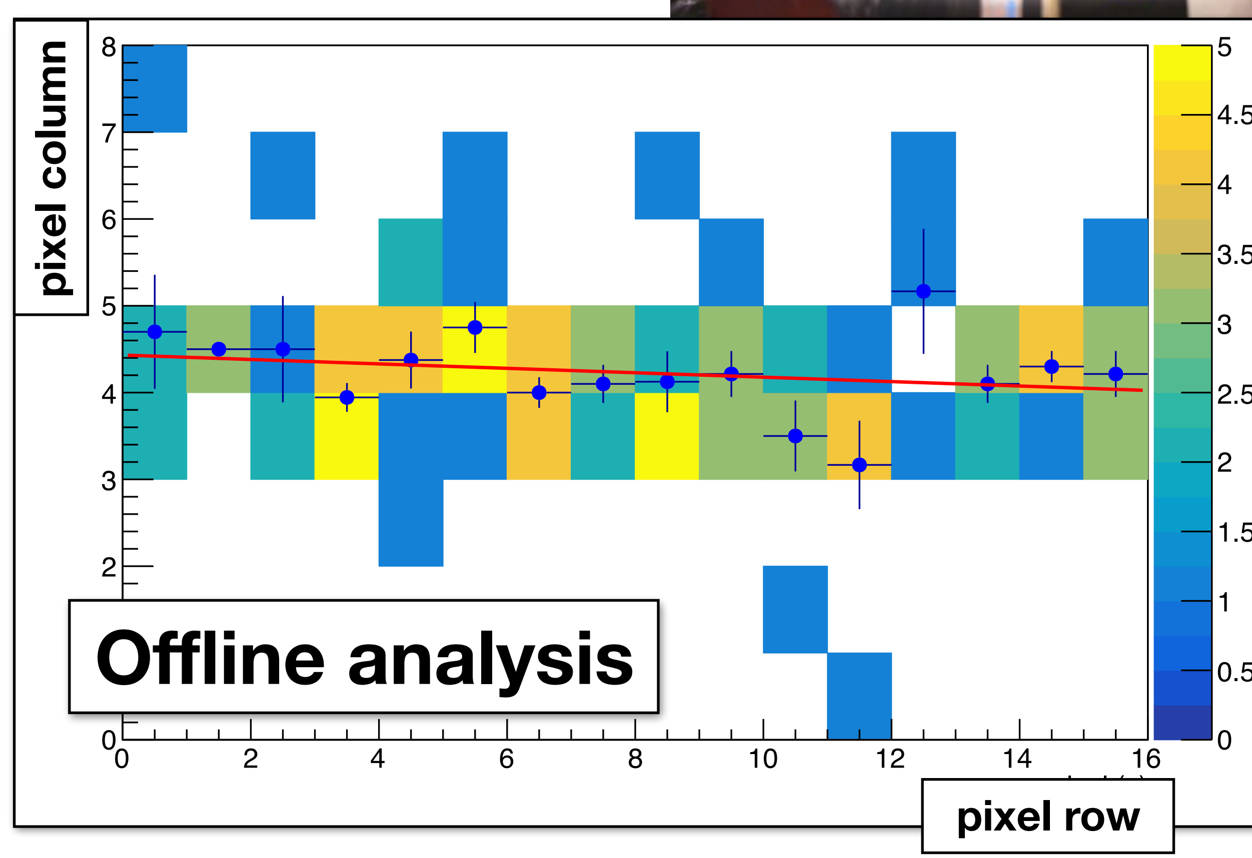


Online readout





time and charge info



Offline analysis

...SBAM-I

Main request for the sensor:

- Need to keep the **space granularity of the fibres;**
- **Few photons** (few ph. electrons);
- System capable of **ToF measurement**
- Fast signals: typically **~5ns**
- **Proton Track** identification
- **Trigger** for electronic background rejection;

...SBAM-I

Main characteristics of the sensor

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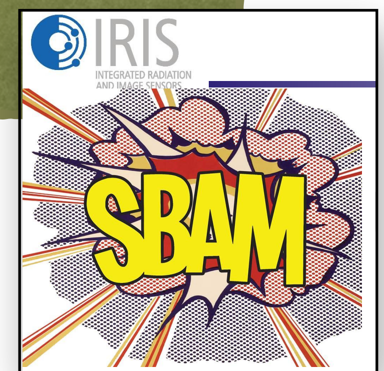

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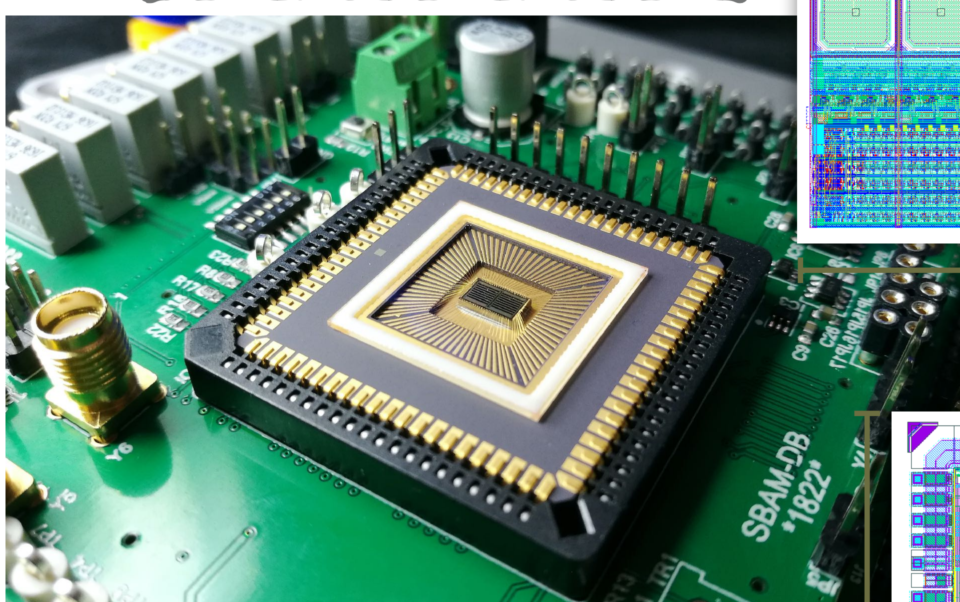
- **Pixel** 125x250 μm
- **Photon dynamic range** per pixel [0-30]
- **TDC** on Pixels (100ps resolution)
- **Two level Trigger logic** tuned for fast scintillation signals
- Quantum efficiency ~40%
- Possibility to turn-off noisy SPAD (Dark Current reduction)
- Sensors designed to be implemented in Tiles ("large" area, final detector ~400cm^2)
- Fill Factor ~30%
- Side-by-side sensors

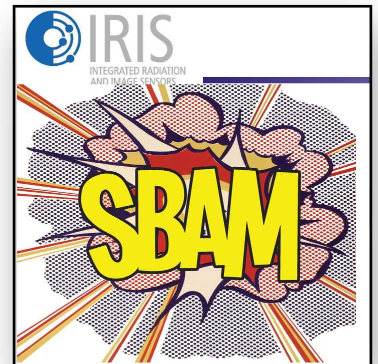
...SBAM-I

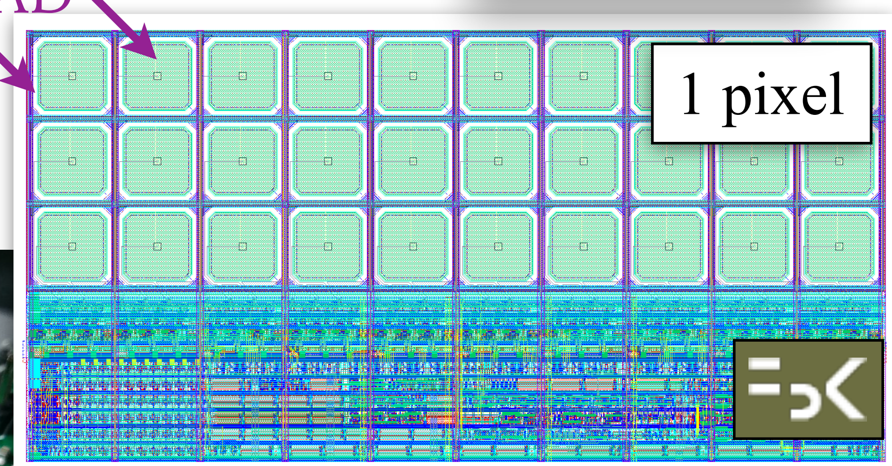
The FBK and CF developed in collaboration the SBAM sensor: **the first chip** - SBAM_1 - **has been produced at LFundry and tested at FBK for the preliminary checks.**

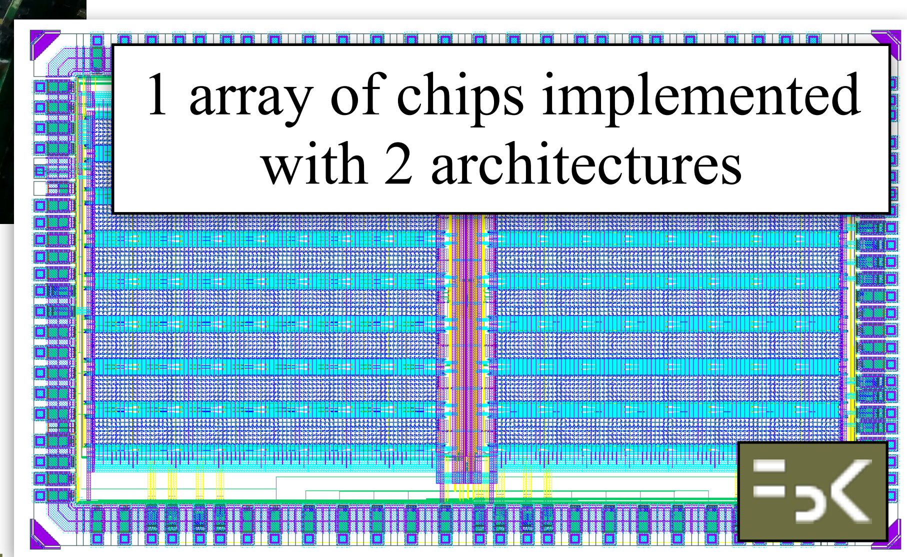
First SBAM chip design: 8x16 pixel



SBAM: Spad Based Acquisition for the Mondo Experiment







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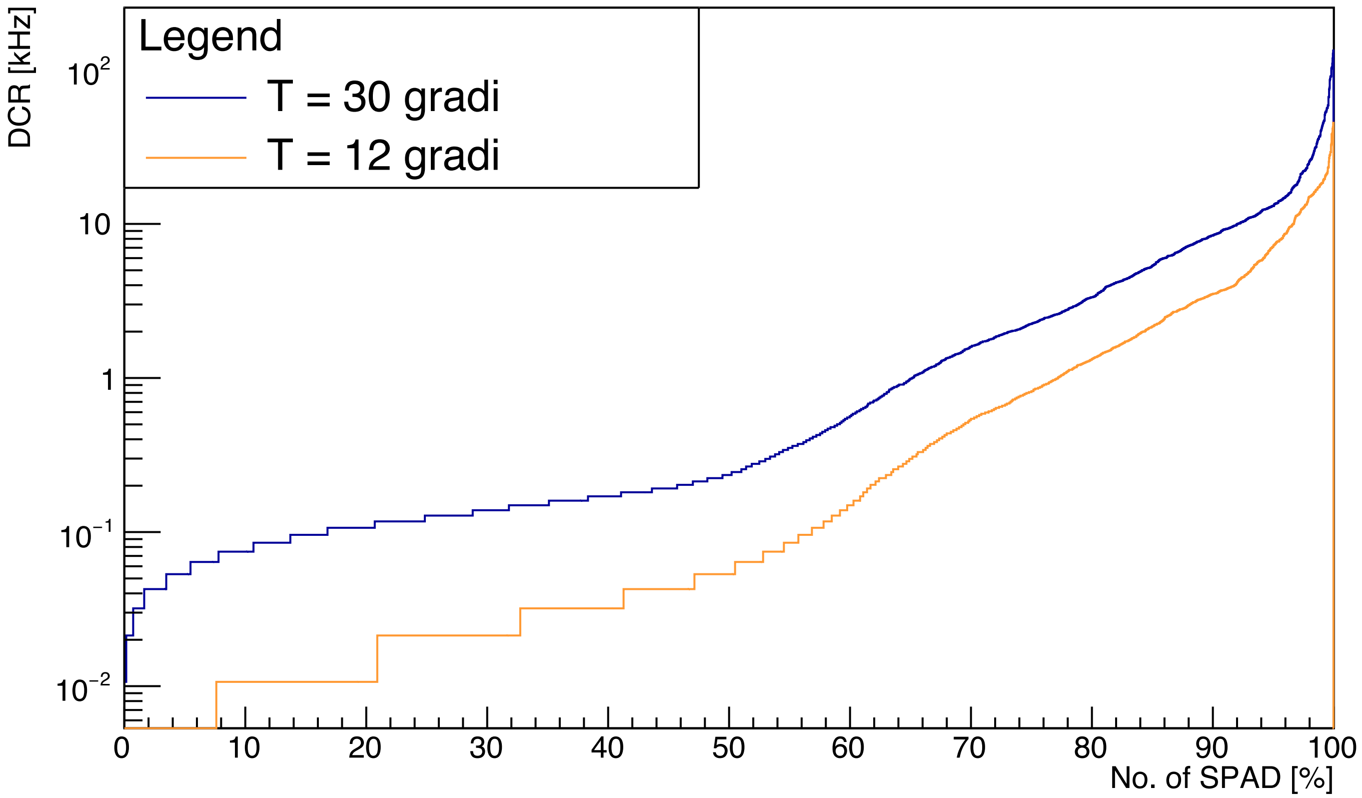
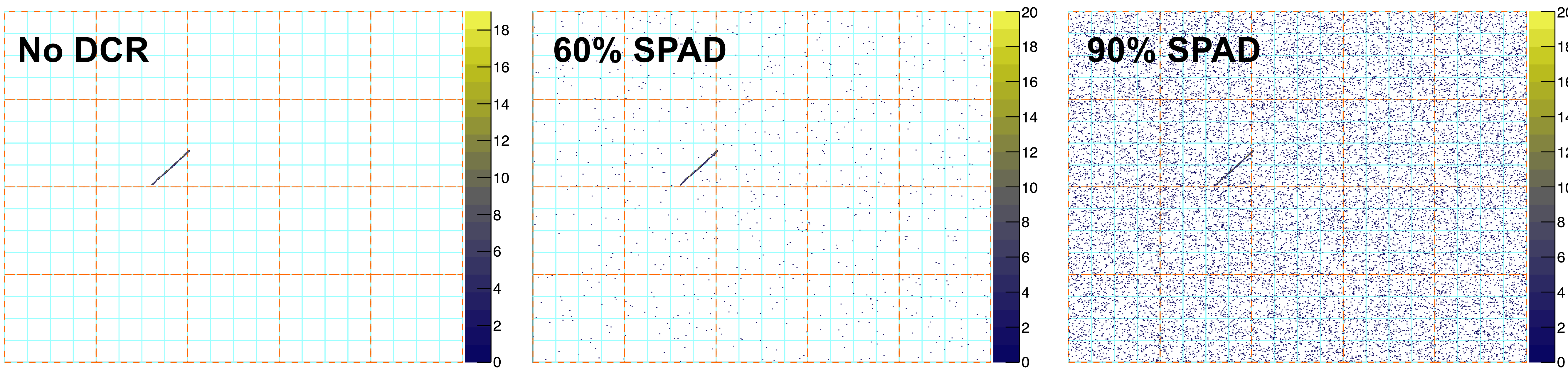
SBAM-I TEST: DCR STUDIES



The first part of the SBAM-I characterisation has been carried out in Trento exploiting my know-how in scintillating material and detector development

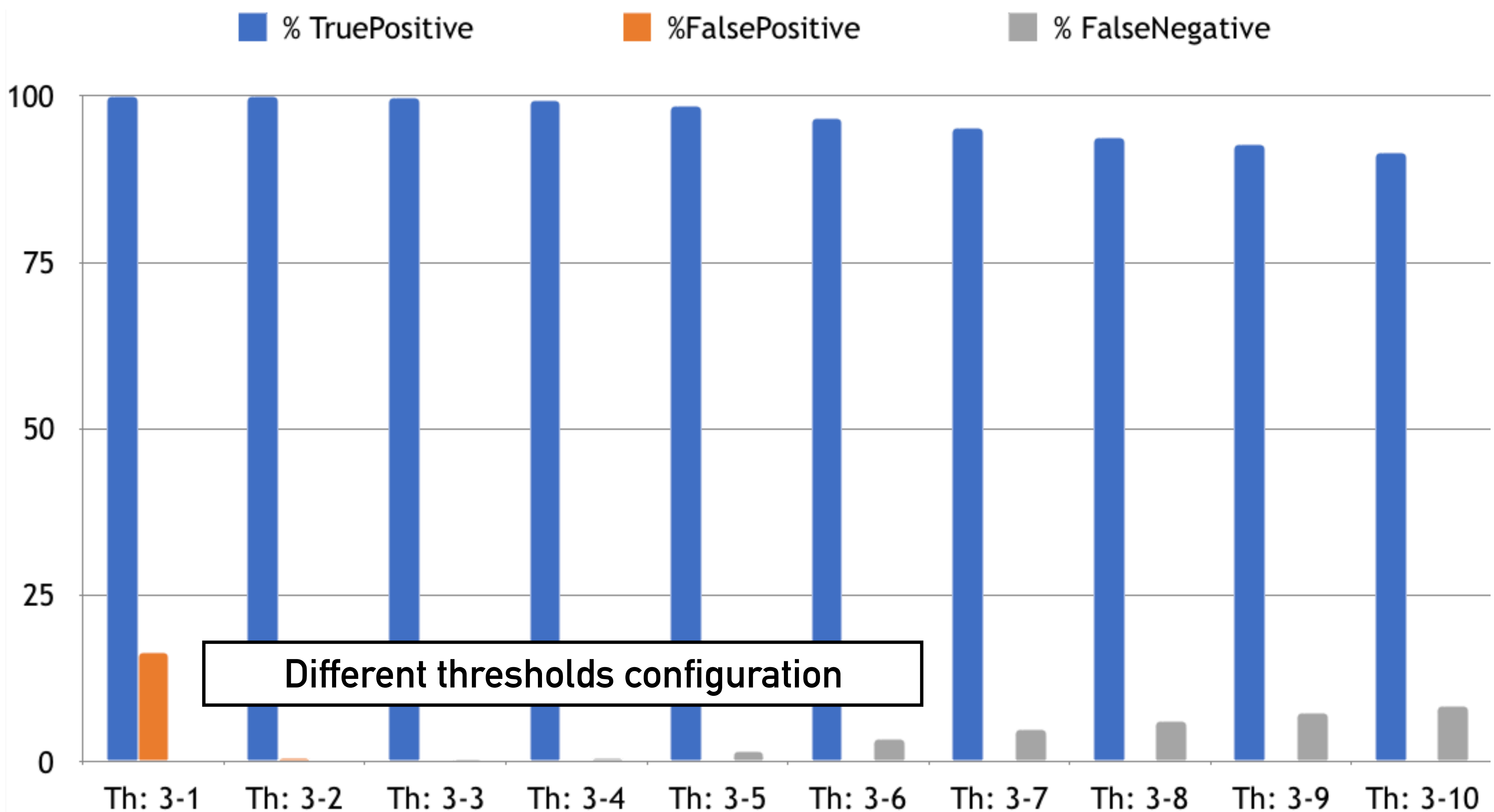
DCR distribution for Single SPAD for two temperatures

After the acquisition of the DCR value for each SPAD, it is possible to switch-off the most noisy SPAD in order to decrease the dark counts effect.

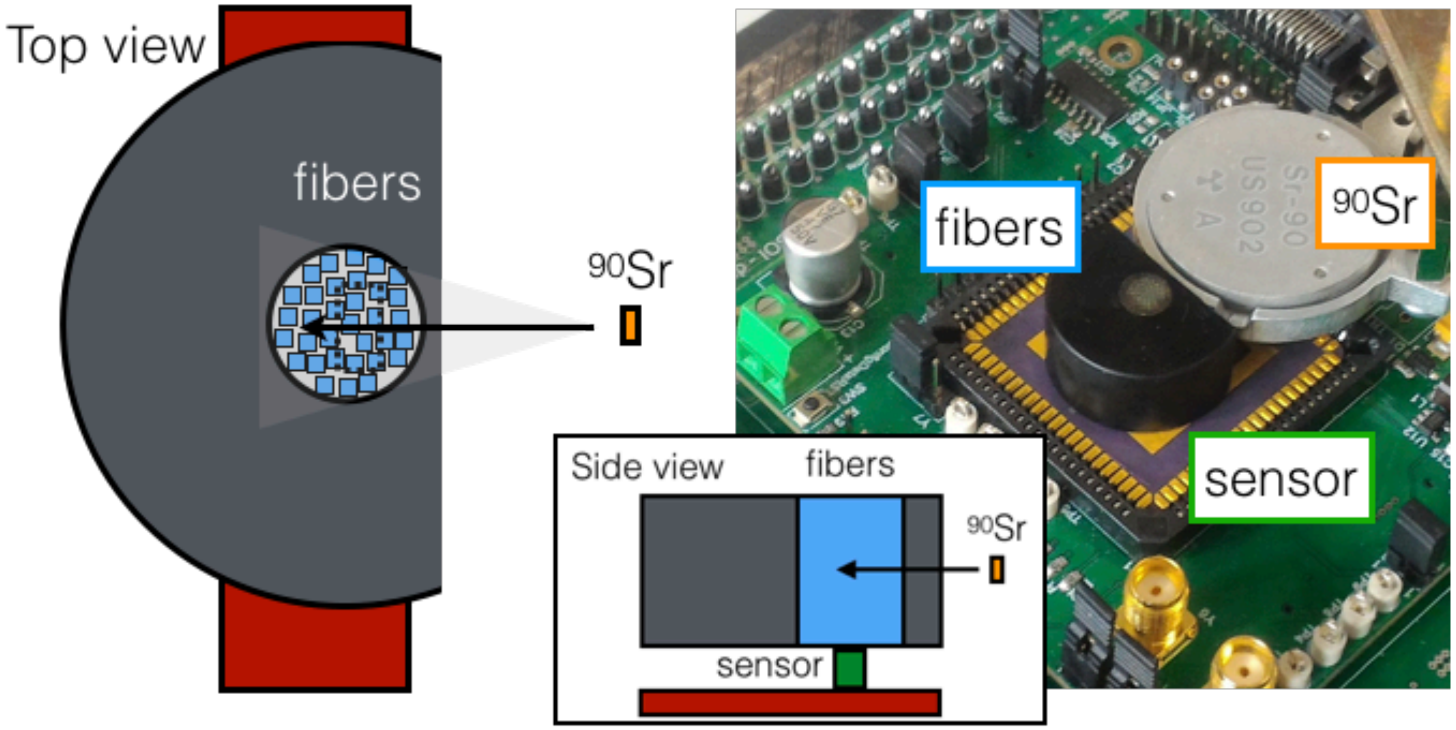


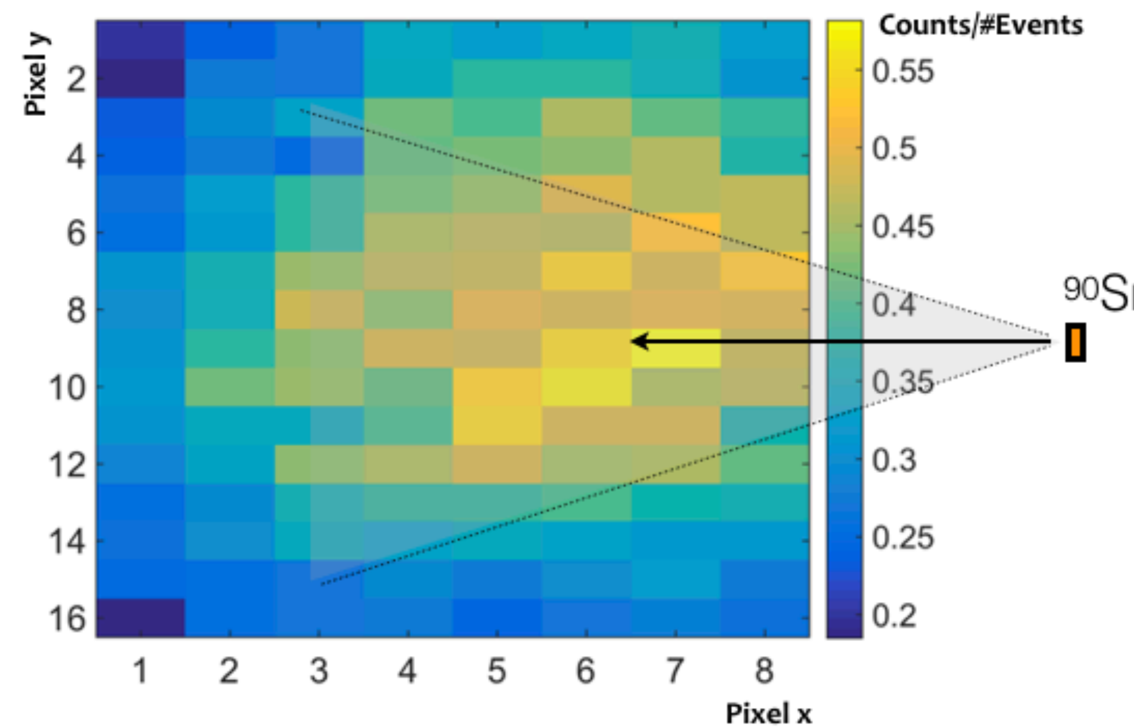
SBAM-I TEST: DCR STUDIES

Double threshold trigger logic ensures both excellent efficiency and rejection even when 90% of the SPADs are activated. Here are reported the results obtained using protons that have an energy spectrum in the [0-100] MeV range



SBAM-I TEST: CHARACTERISATION WITH ^{90}SR

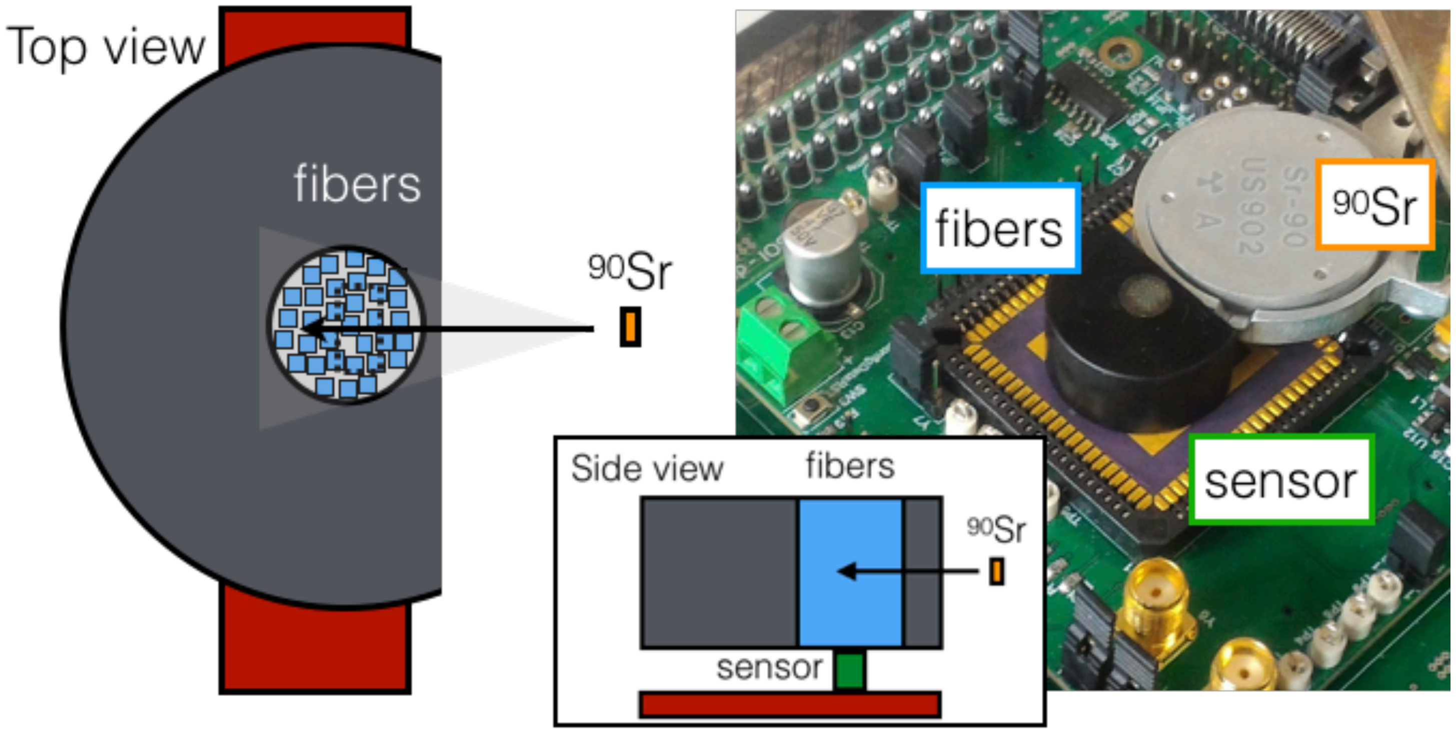




Normalized cumulative distribution of the counts for each single pixel (TH1=2 photons TH2=3 pixels).

- The sensor has been optically coupled to a PVC cylinder filled with square scintillating fibers. A source of ionizing electrons ^{90}Sr is placed next to the tracker (LOW SNR).

SBAM-I TEST: CHARACTERISATION WITH ^{90}SR



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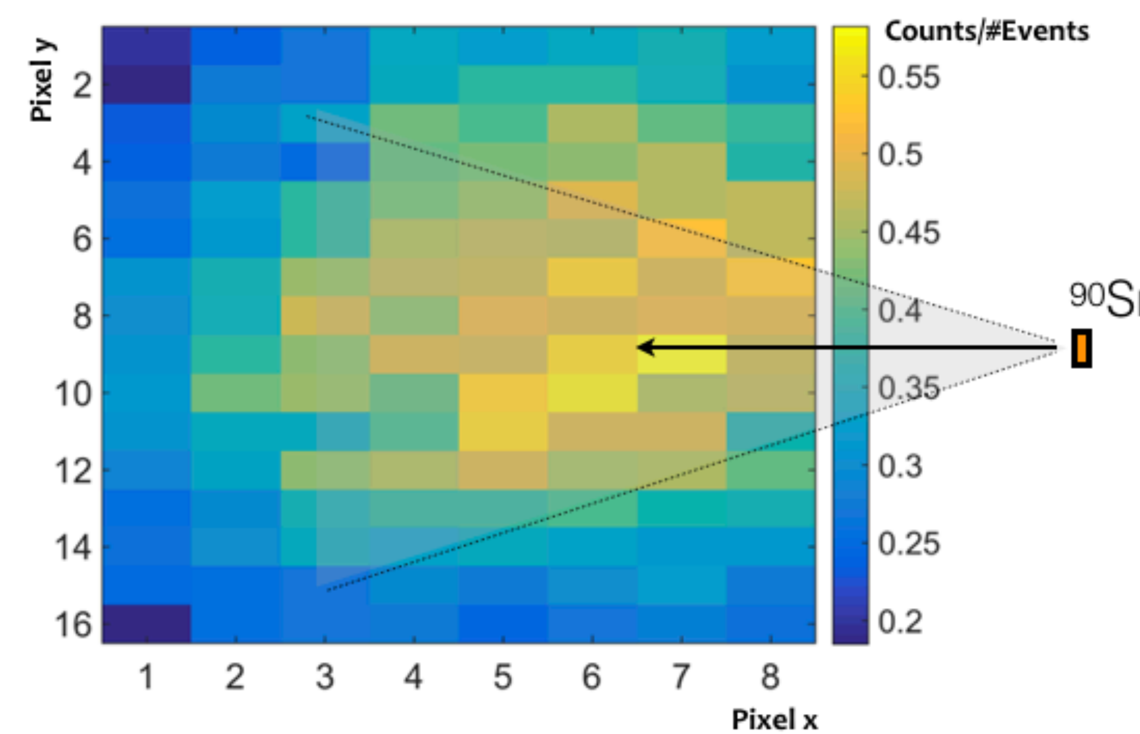

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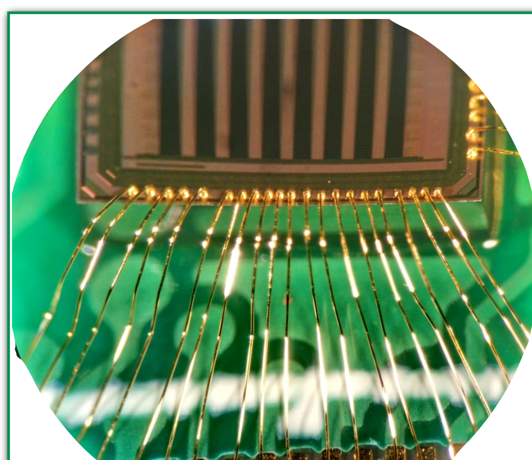
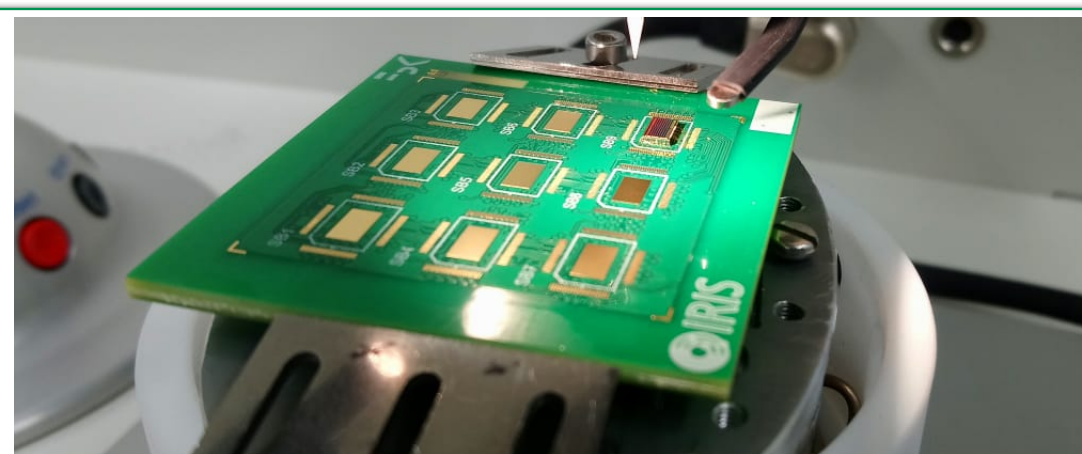




Bonding and Tile Studies

CONCLUSION

	I year PhD	II year PhD	III year PhD
Sensor		SBAM design & development	Electronic Test FBK and Rome
Tracker	Construction of *Penelope* prototype	Development of the final construction technique	Development of the machine for tracker realisation
Simulation and Software		Event reconstruction software and detector resolution with ES	Final readout implementation
Measurements		Calibration of prototypes with Protons	Final Sensor test with different particle sources

- During my PhD I developed the strategy for the fibers matrix construction;
- I implemented the algorithms in the full MonteCarlo framework to evaluate the MONDO detector performances for the application as a Beam Monitor exploiting the Single Elastic Scattering (SES) events. I have also implemented the sensor readout in the simulation.
- I developed the readout system and, after the first SBAM-I production (December 2018), I tested and characterised the chip.

TALKS AND PRESENTATIONS

- September 2019: *"MONDO tracker for secondary ultra-fast neutron characterisation in particle therapy."*
  105° Italian Physical Society Congress (SIF) - L'Aquila (Italy)

- September 2017: *"Study and design of a Drift Chamber for the FOOT experiment"*
  103° Italian Physical Society Congress (SIF) - Trento (Italy)

- September 2017: *"MONDO neutron tracker characterisation by means of proton therapeutical beams and Monte Carlo simulation studies"*
  103° Italian Physical Society Congress (SIF) - Trento (Italy)

- May 2017: *"MONDO: A tracker for the characterization of secondary fast and ultrafast neutrons emitted in Particle Therapy"*
  8° Young Researcher Meeting - Cagliari (Italy)

- September 2016: *"MONDO: A neutron tracker for particle therapy secondary emission fluxes measurements"*
  102° Italian Physical Society Congress (SIF) - Padova (Italy)

POSTER CONTRIBUTIONS

- July 2018: *"Secondary neutrons characterization in Particle Therapy with the MONDO tracker"*
  NDRA 2018 - Summer School on Neutron Detectors

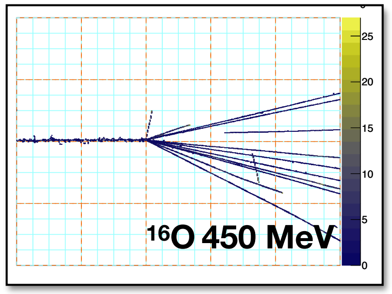
- October 2017: *"The SBAM sensor for the MONDO experiment"*
  SQUAD 2017 - Advanced School in Quantum Detector - Trento (Italy)

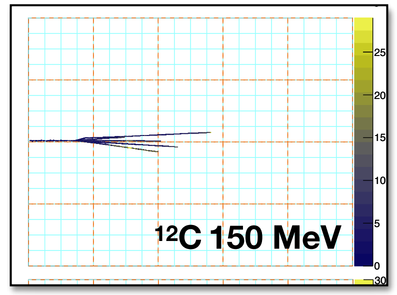
- June 2018: *"Particle Therapy secondary neutrons characterisation with the MONDO project"*
  World Congress on Medical Physics and Biomedical Engineering - Prague (Czech Republic)

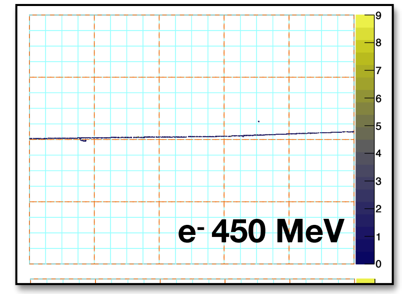
- *September 2019: "TOPS Project: Development of New Fast Timing Plastic Scintillators"*
  FATA2019: FAst Timing Applications for nuclear physics and medical imaging workshop - Catania (Italy)

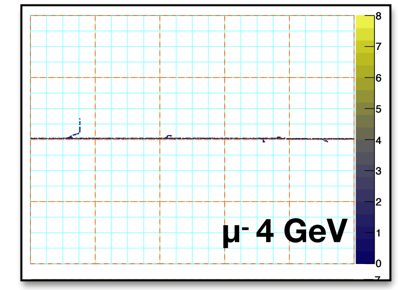
- November 2018: *"In-room performance evaluation of a novel charged particles monitor of light ions PT treatments"*
  IEEE Nuclear Science Symposium and Medical Imaging Conference - Sydney (Australia)

PAPERS









- Traini, G. et al, *Review and performance of the Dose Profiler, a particle therapy treatments online monitor (2019)* Physica Medica, 65, pp. 84-93. DOI: 10.1016/j.ejmp.2019.07.010
- Rucinski, A. et al, *Secondary radiation measurements for particle therapy applications: Charged secondaries produced by ^{16}O ion beams in a PMMA target at large angles* (2019) Physica Medica, 64, pp. 45-53. DOI: 10.1016/j.ejmp.2019.06.001
- Russomando A. et al, *The β - radio-guided surgery: Method to estimate the minimum injectable activity from ex-vivo test* (2019) Physica Medica, 58, pp. 114-120. DOI: 10.1016/j.ejmp.2019.02.004
- Morrocchi M. et al, *Development and characterization of a ΔE-TOF detector prototype for the FOOT experiment* (2019) Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 916, pp. 116-124. DOI: 10.1016/j.nima.2018.09.086
- **Gioscio, E. et al. *Development of a novel neutron tracker for the characterisation of secondary neutrons emitted in Particle Therapy* (2019) Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, art. no. 162862, . DOI: 10.1016/j.nima.2019.1628625 (Correspondig author)**
- Montesi M.C. et al, *Ion charge separation with new generation of nuclear emulsion films* (2019) Open Physics, 17 (1), pp. 233-240. DOI: 10.1515/phys-2019-0024
- Collamati F. et al, *Radioguided surgery with β radiation: a novel application with Ga68* (2018) Scientific Reports, 8 (1), art. no. 16171 . DOI: 10.1038/s41598-018-34626-x
- Mirabelli, R., *In-room performance evaluation of a novel online charged secondary particles monitor of light ions PT treatments* (2018) 2018 IEEE Nuclear Science Symposium and Medical Imaging Conference, NSS/MIC 2018 - Proceedings, art. no. 8824552, . DOI: 10.1109/NSSMIC.2018.8824552*r*
- **Fischetti M. et al, *Characterisation of the secondary-neutron production in particle therapy treatments with the MONDO tracking detector* (2018) Nuovo Cimento della Società Italiana di Fisica C, 41 (6), art. no. 206, . DOI: 10.1393/ncc/i2018-18206-5 © (*Correspondig author*)**
- De Simoni M. et al., *In-room test results at CNAO of an innovative PT treatments online monitor (Dose Profiler)* (2018) Nuovo Cimento della Società Italiana di Fisica C, 41 (6), art. no. 209, . DOI: 10.1393/ncc/i2018-18209-2
- Valle S.M. et al, *The FOOT (FragmentatiOn Of Target) experiment* (2018) Nuovo Cimento della Societa Italiana di Fisica C, 41 (5), art. no. 169. DOI: 10.1393/ncc/i2018-18169-5
- **Giacometti V. et al, "*Characterisation of the MONDO detector response to neutrons by means of a FLUKA Monte Carlo simulation*" Radiation Measurement (in press)**
- Mattei I. et al, "*Scintillating fiber devices for particle therapy applications*" (2018) IEEE Transactions on Nuclear Science, 65 (8), art. no. 8370744, pp. 2054-2060. DOI: 10.1109/TNS.2018.2843179
- Morganti S. et al, "*Position sensitive β- Detector based on p-terphenyl scintillator for medical applications*" (2018) Journal of Instrumentation, 13 (7), art. no. P07001. DOI: 10.1088/1748-0221/13/07/P07001
- Solestizi L.A. et al, "*Use of a CMOS image sensor for beta-emitting radionuclide measurements*" (2018) Journal of Instrumentation, 13 (7), art. no. P07003. DOI: 10.1088/1748-0221/13/07/P07003
- **Traini G. et al, "*Preliminary test of the MONDO project secondary fast and ultrafast neutrons tracker response using protons and MIP particles*" (2018) Journal of Instrumentation, 13 (4), art. no. C04014. DOI: 10.1088/1748-0221/13/04/C04014**
- **Mirabelli R. et al, "*The MONDO Detector Prototype Development and Test: Steps Toward an SPAD-CMOS- Based Integrated Readout (SBAM Sensor)*", (2018) IEEE Transactions on Nuclear Science, 65 (2), pp. 744-751. DOI: 10.1109/TNS.2017.2785768**
- **Mirabelli R. et al, "*MONDO: A tracker for the characterization of secondary fast and ultrafast neutrons emitted in particle therapy*", (2018) Journal of Physics: Conference Series, 956 (1), art. no. 012013, . DOI: 10.1088/1742-6596/956/1/012013**
- Carlotti D. et al, "*Use of bremsstrahlung radiation to identify hidden weak β- Sources: Feasibility and possible use in radio-guided surgery*" (2017) Journal of Instrumentation, 12 (11), art. no. P11006, . DOI: 10.1088/1748-0221/12/11/P11006
- Mancini-Terracciano C. et al, "*Feasibility of beta-particle radioguided surgery for a variety of "nuclear medicine" radionuclides*" (2017) Physica Medica, 43, pp. 127-133. DOI: 10.1016/j.ejmp.2017.10.012
- **Mirabelli R. "*MONDO: A neutron tracker for particle therapy secondary emission fluxes measurements*" (2017) IL NUOVO CIMENTO 40 C 99 DOI: 10.1393/ncc/i2017-17099-0**
- **Marafini M. et al, "*MONDO: A neutron tracker for particle therapy secondary emission characterisation*" (2017) Physics in Medicine and Biology, 62 (8), pp. 3299-3312. DOI: 10.1088/1361-6560/aa623a**

22 paper in referred journals

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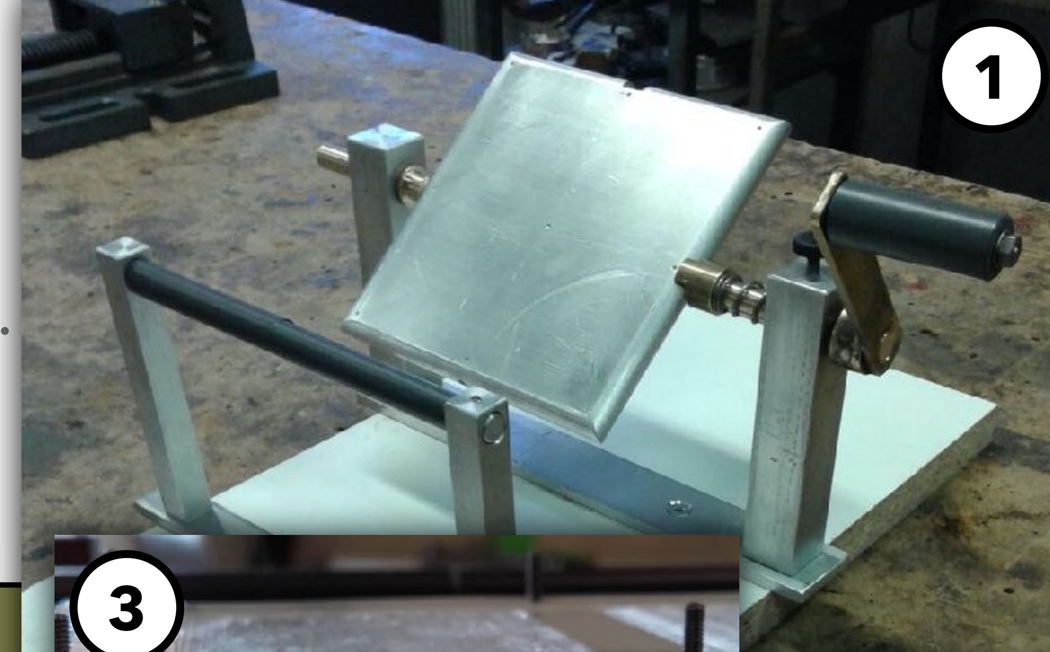
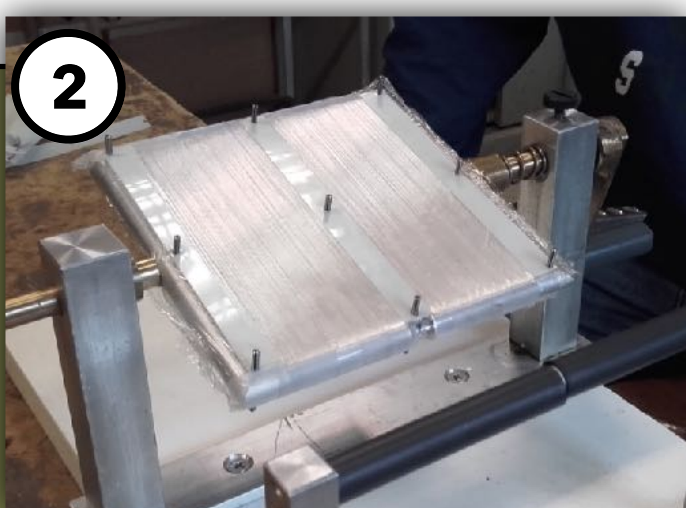
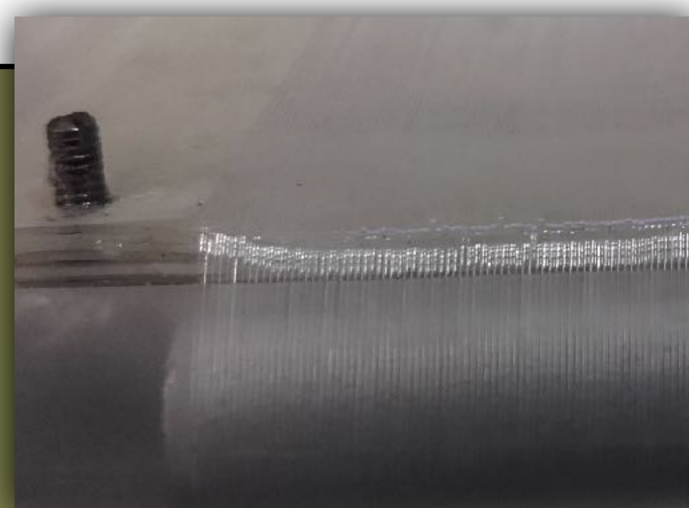
BACKUP SLIDE

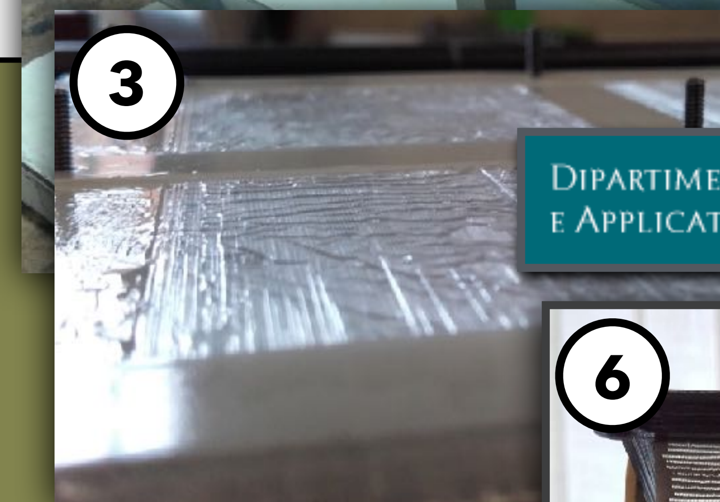
NEUTRONS TRACKER: PROTOTYPE

dimensions: 4 x 4 x 4.8 cm³

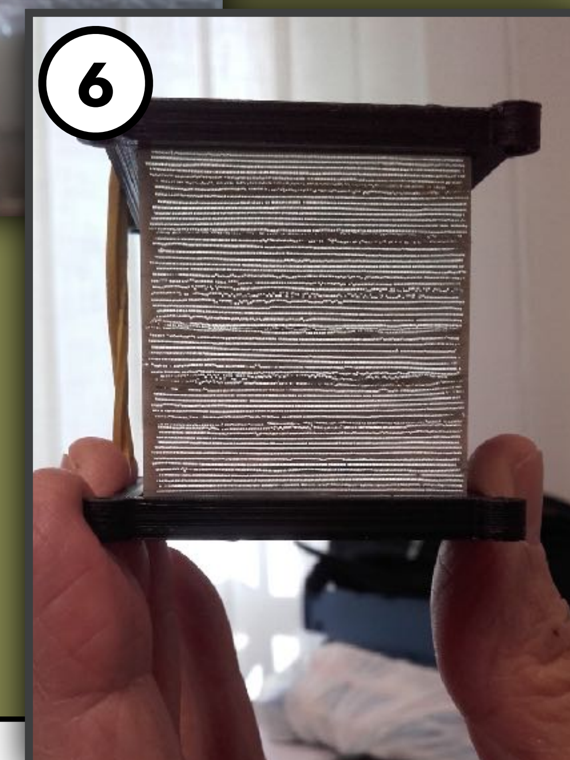




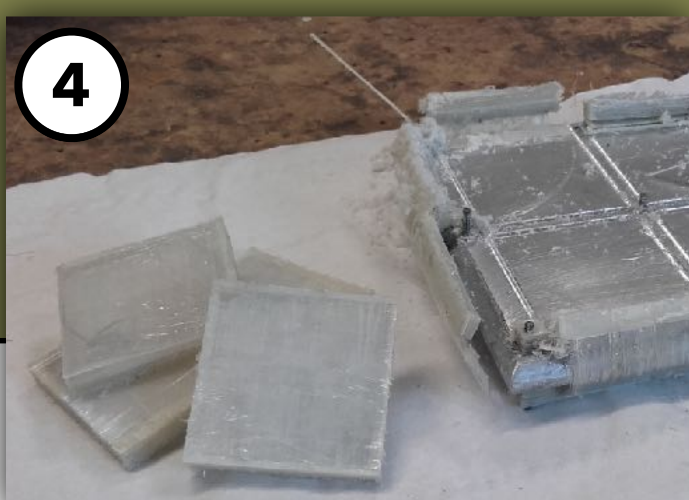


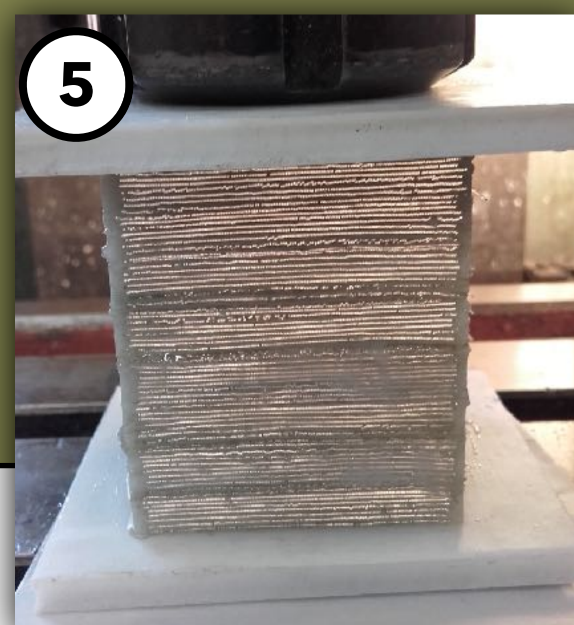


DIPARTIMENTO DI SCIENZE DI BASE E APPLICATE PER L' INGEGNERIA



~ 45 h of work





A tracker prototipe (4 x 4 x 4.8 cm³) has been realised as a proof of principle for proton tracking and in order to test the assembling procedure: **final matrix will be realized in early 2019**

PROTOTYPE: PENELOPE

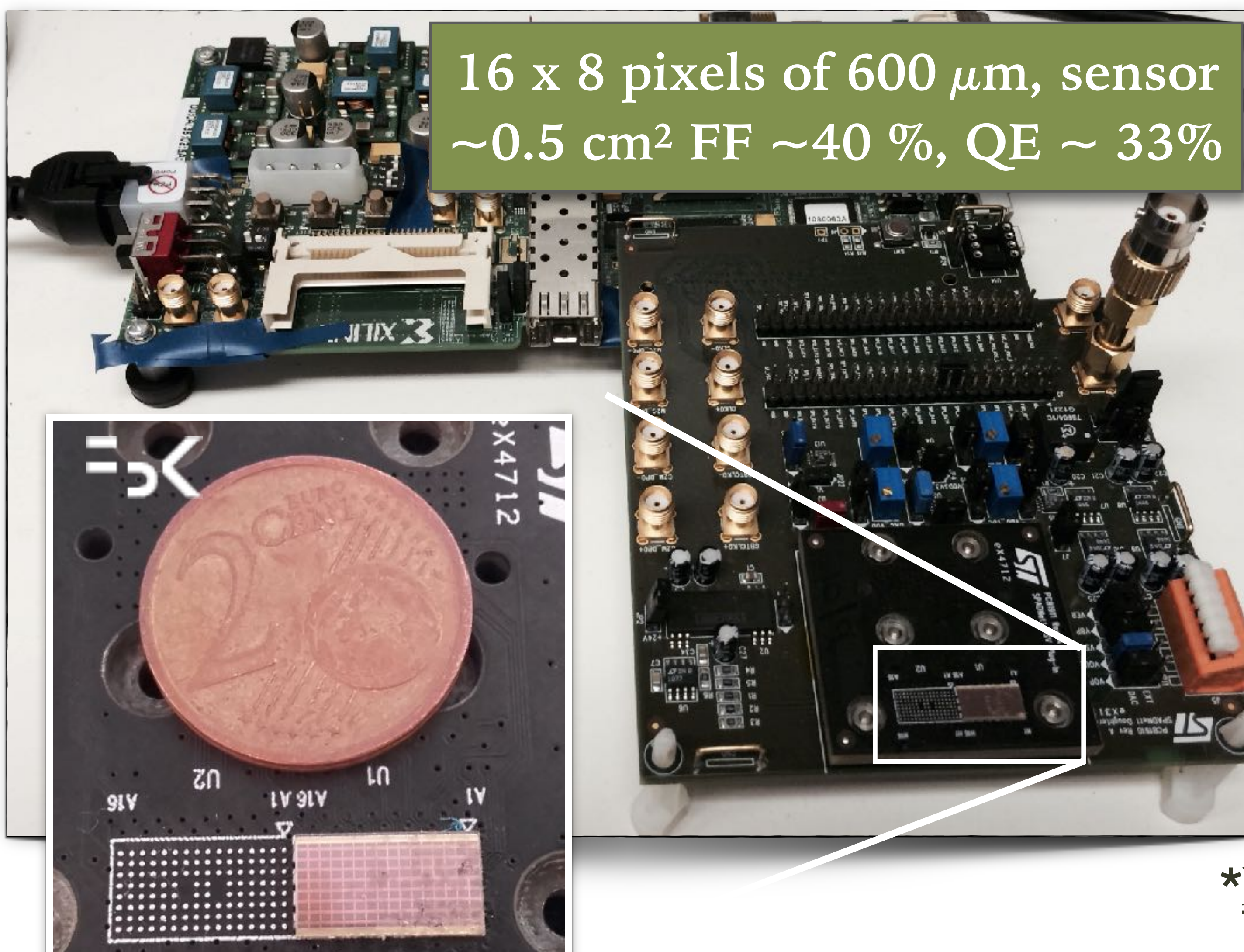
The new sensor SBAM has been developed (FBK-CF) starting from the experience gained using an other sensor prototype: *spad-net**. Practicing with *spad-net* allowed us to point out the critical issues to be addressed in the SBAM development phase.

The 40% of the most noisy SPADs has been turned off (DCR > 10kHz). We want to evaluate the critical issues of this technology with protons:

- ➤ Discriminate the signal from the noise floor
- ➤ Extract particle direction from recorded data

** S.M. Vallle et al., The MONDO project: A secondary neutron tracker detector for particle therapy, doi:10.1016/j.nima.2016.05.001

*** R. Mirabelli et al, The MONDO detector prototype development and test: steps towards a SPAD-CMOS based integrated readout (SBAM sensor) doi:10.1109/TNS.2017.2785768



16 x 8 pixels of 600 μm, sensor ~0.5 cm² FF ~40 %, QE ~ 33%

<u>Test PENELOPE prototype</u>:

- ^{90}Sr (electrons ~2 MeV)**;

- cosmic rays

=> electron beam ~ 400 MeV***

=> protons (60-230 MeV)

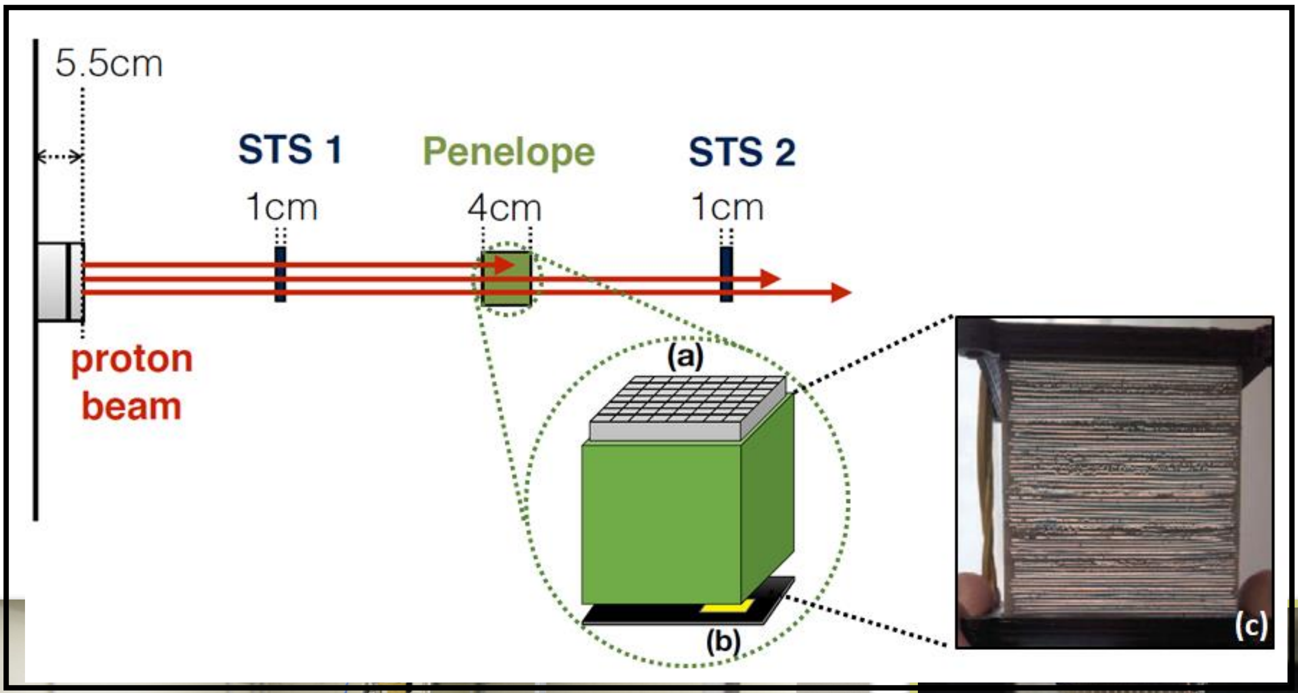
*<u>http://iris.fbk.eu/projects/spadnet</u>

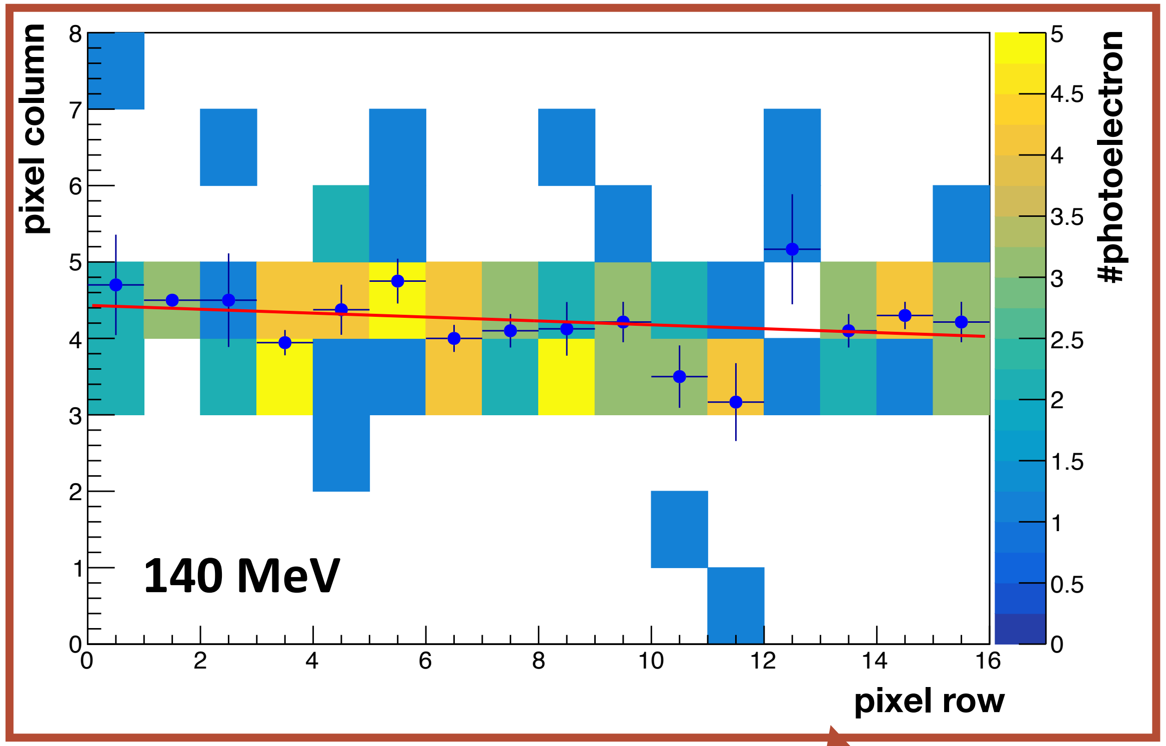
PROTONS @ TRENTO PROTON THERAPY CENTER

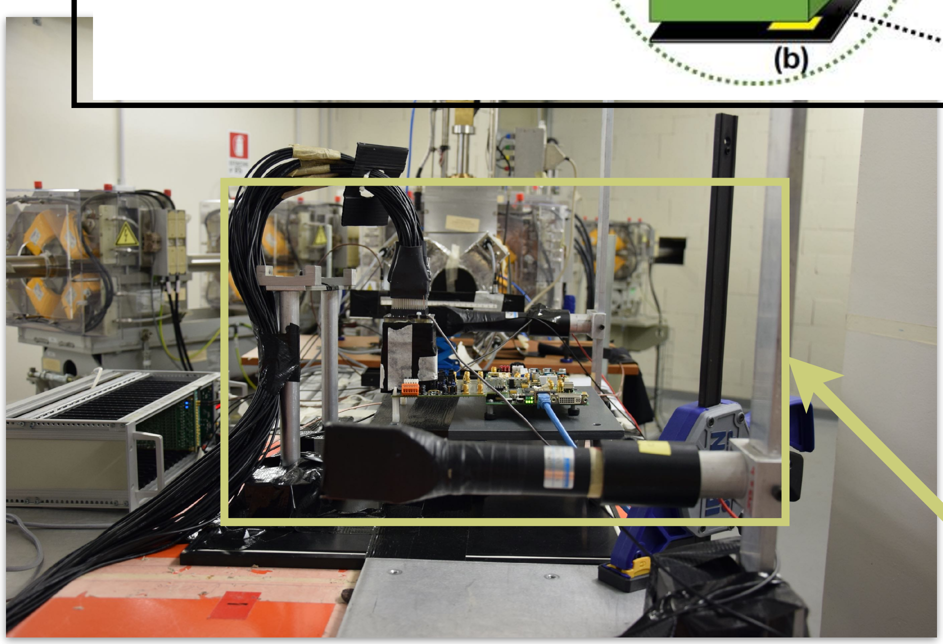
PROTONTERAPIA TRENTO

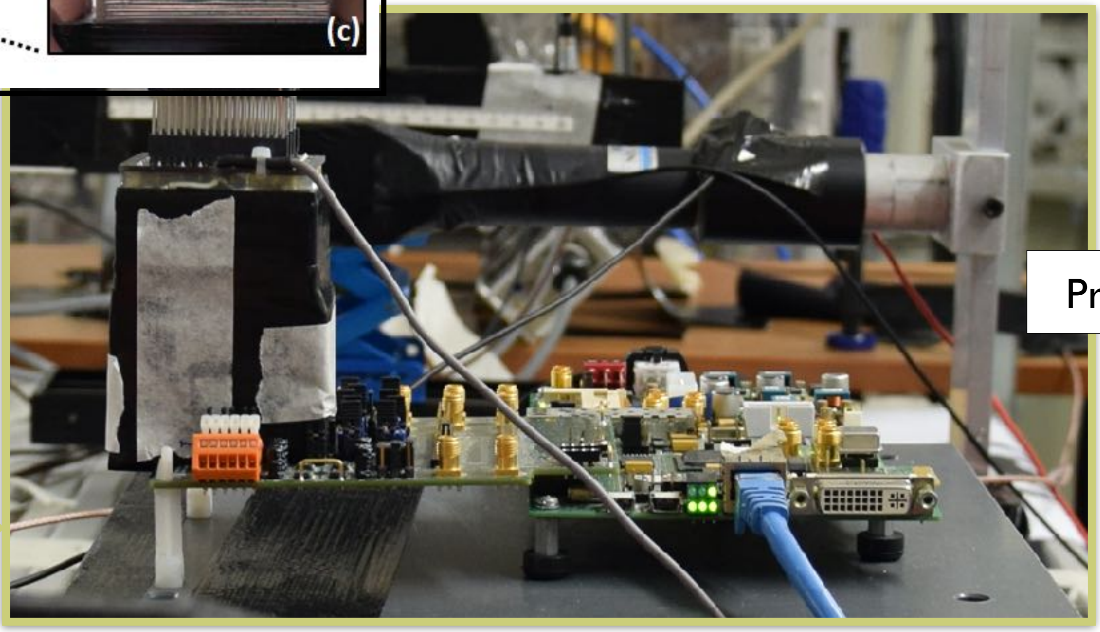
Beam energy: [70-140] MeV protons

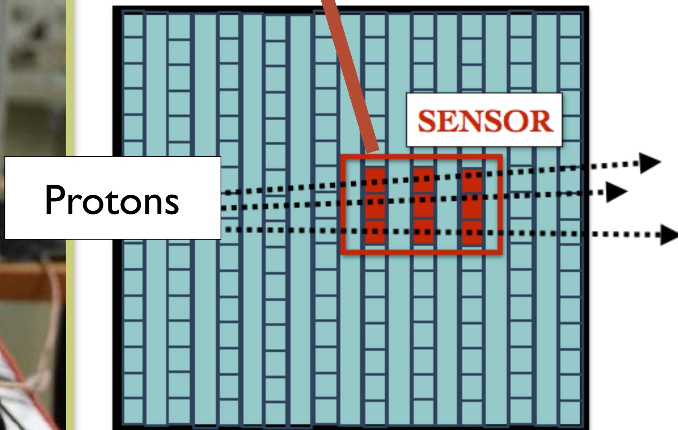
Beam size (σ): [3-7] mm



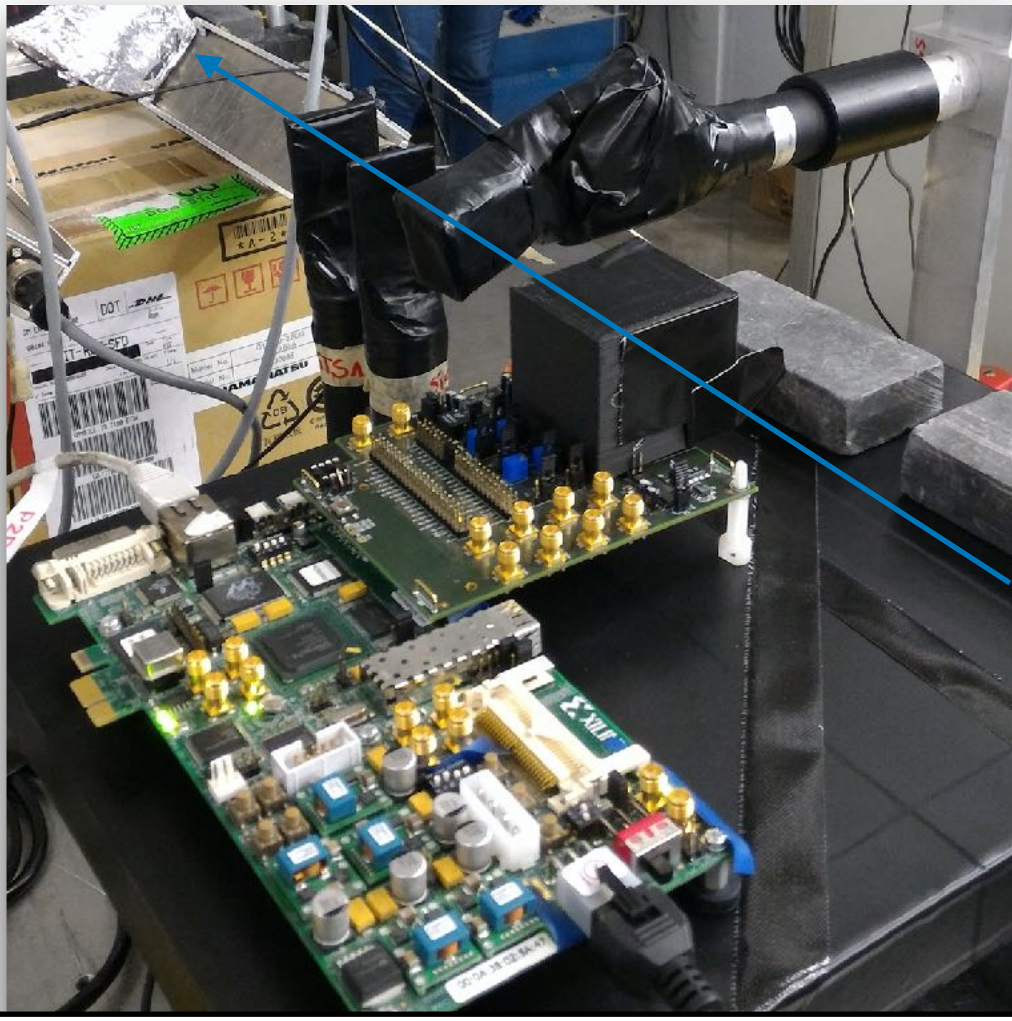


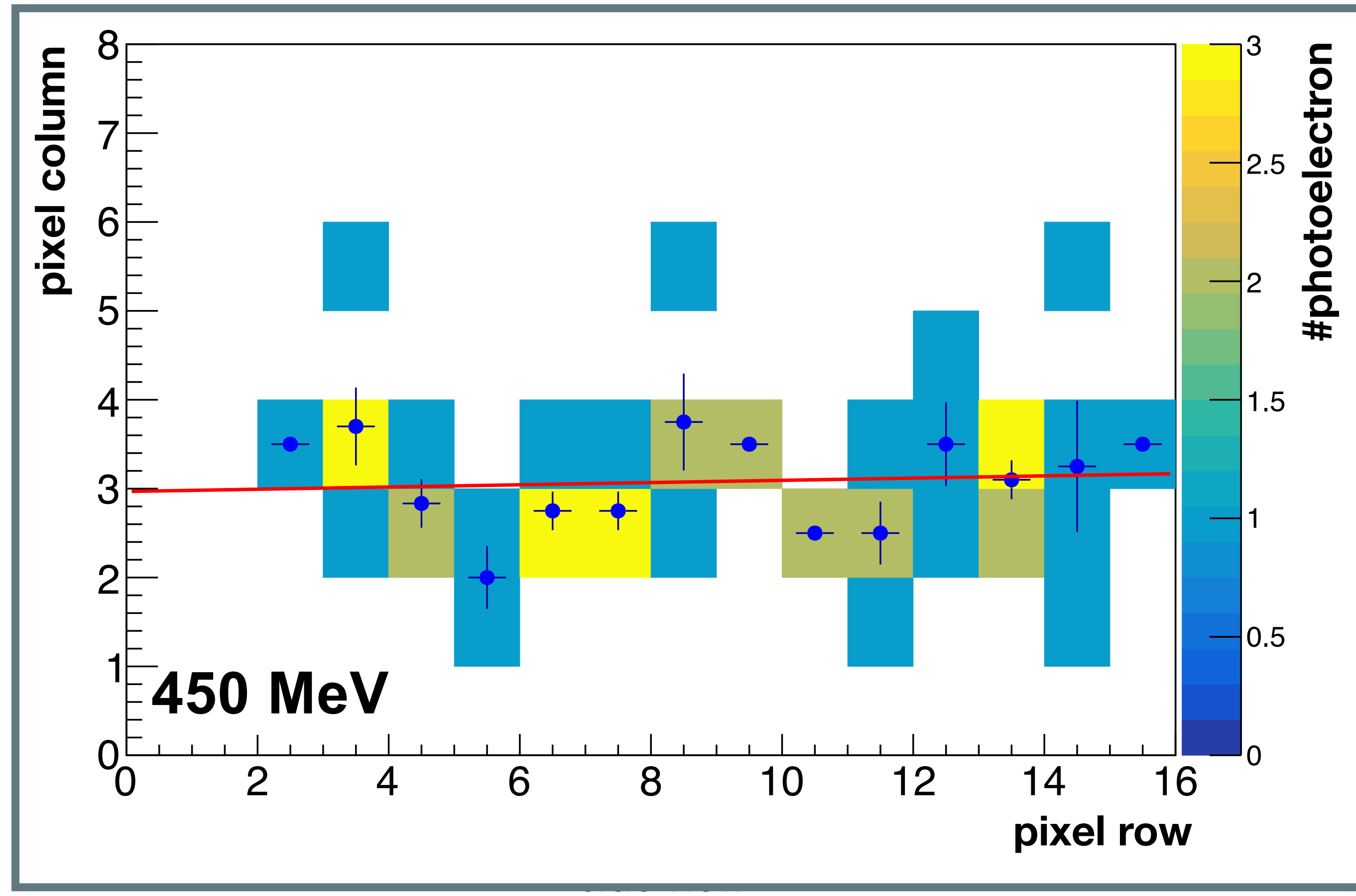


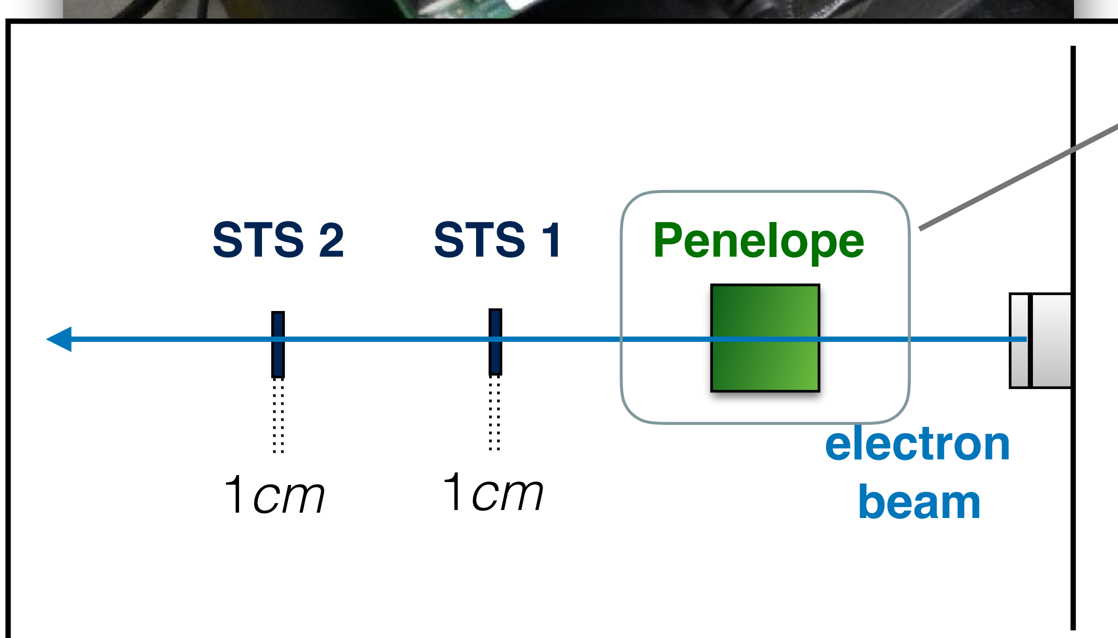


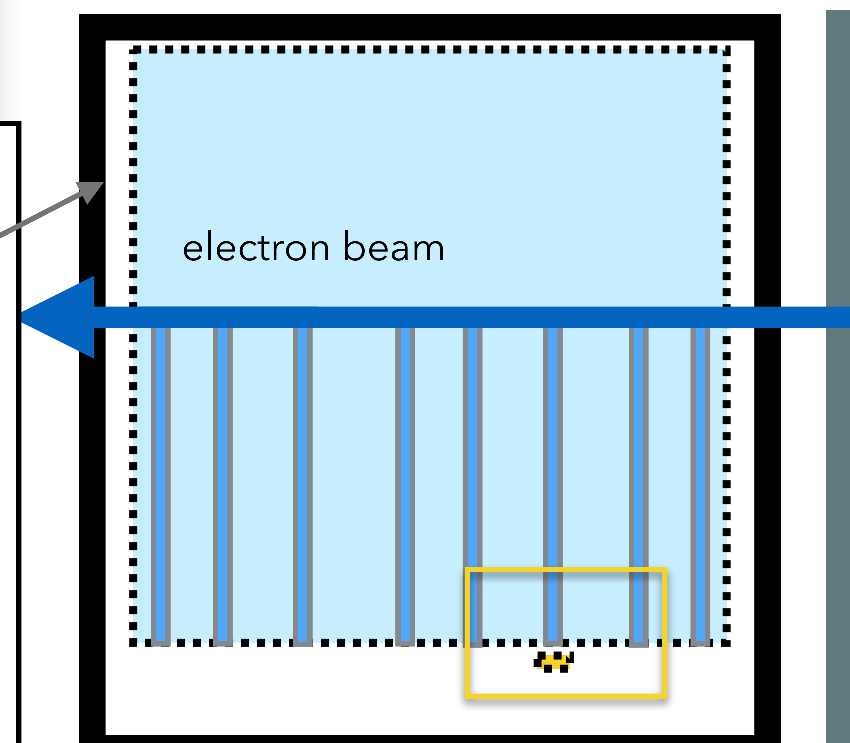


ELECTRONS @ BTF - LABORATORI NAZIONALI FRASCATI









Characteristics:

-Beam Energy:

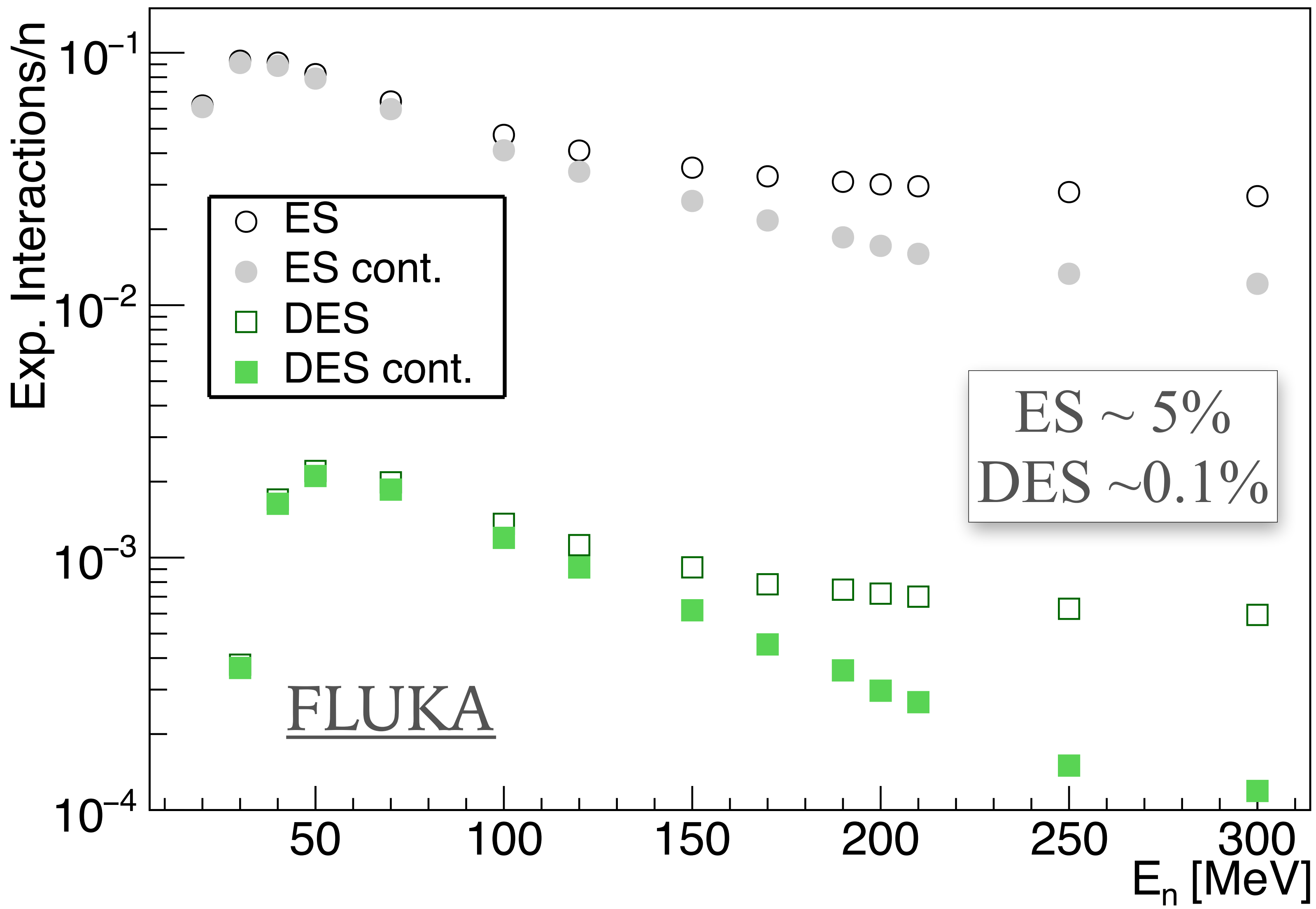
[100 - 450] MeV electrons

-Beam Size(σ) ~ 1 mm

-External Trigger

SIMULATION: INTERACTION PROBABILITY STUDY

Comparison of the expected number of interactions per incident neutron for single and double elastic scattering as a function of the neutrons initial kinetic energy.



Constraints:

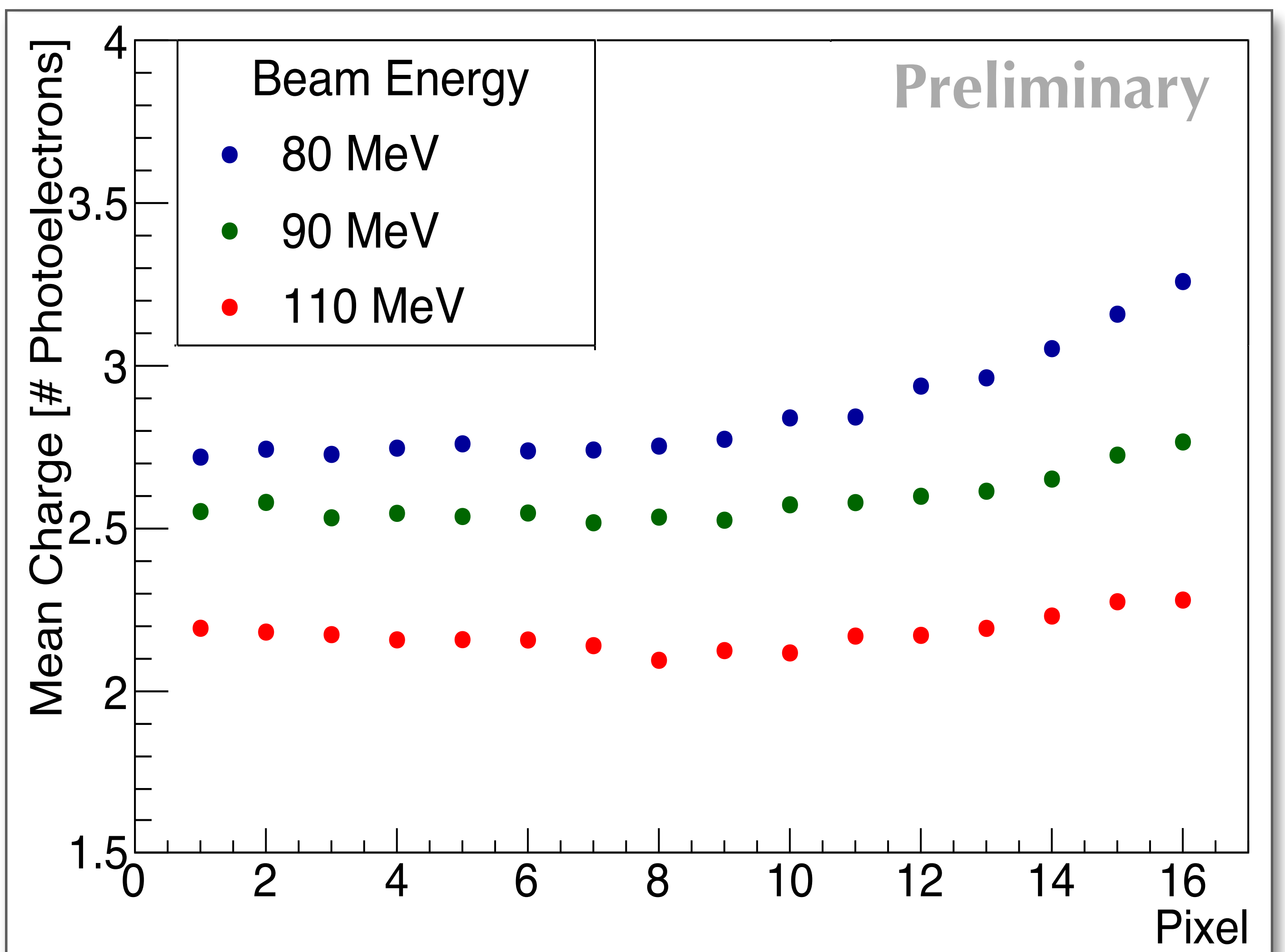
- full containment request of the protons;
- at least 6 pixels crossed (about 10 MeV)

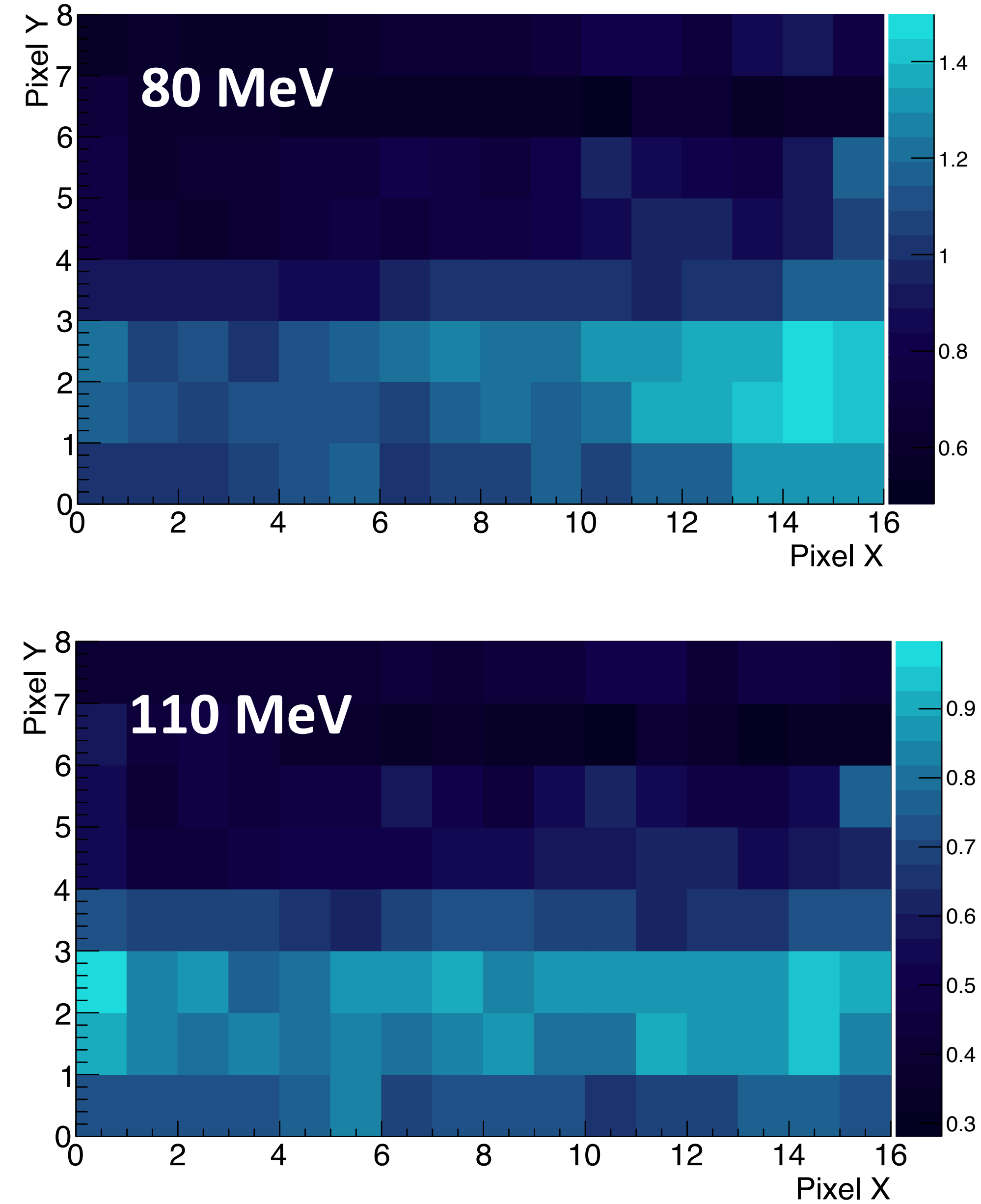
containment decreases of one order of magnitude the detection efficiency

Other proton kinetic energy measurement strategies are under evaluation (e.g. energy loss along the track)

ENERGY LOSS DE/DX INSIDE SPADNET-I

Measurement of the proton range through the energy loss in the fibres (dE) readout by one pixel column (dx). Test with different energies (Bragg Peak @ 83 MeV) in order to reconstruct the protons not totally contained in the detector.

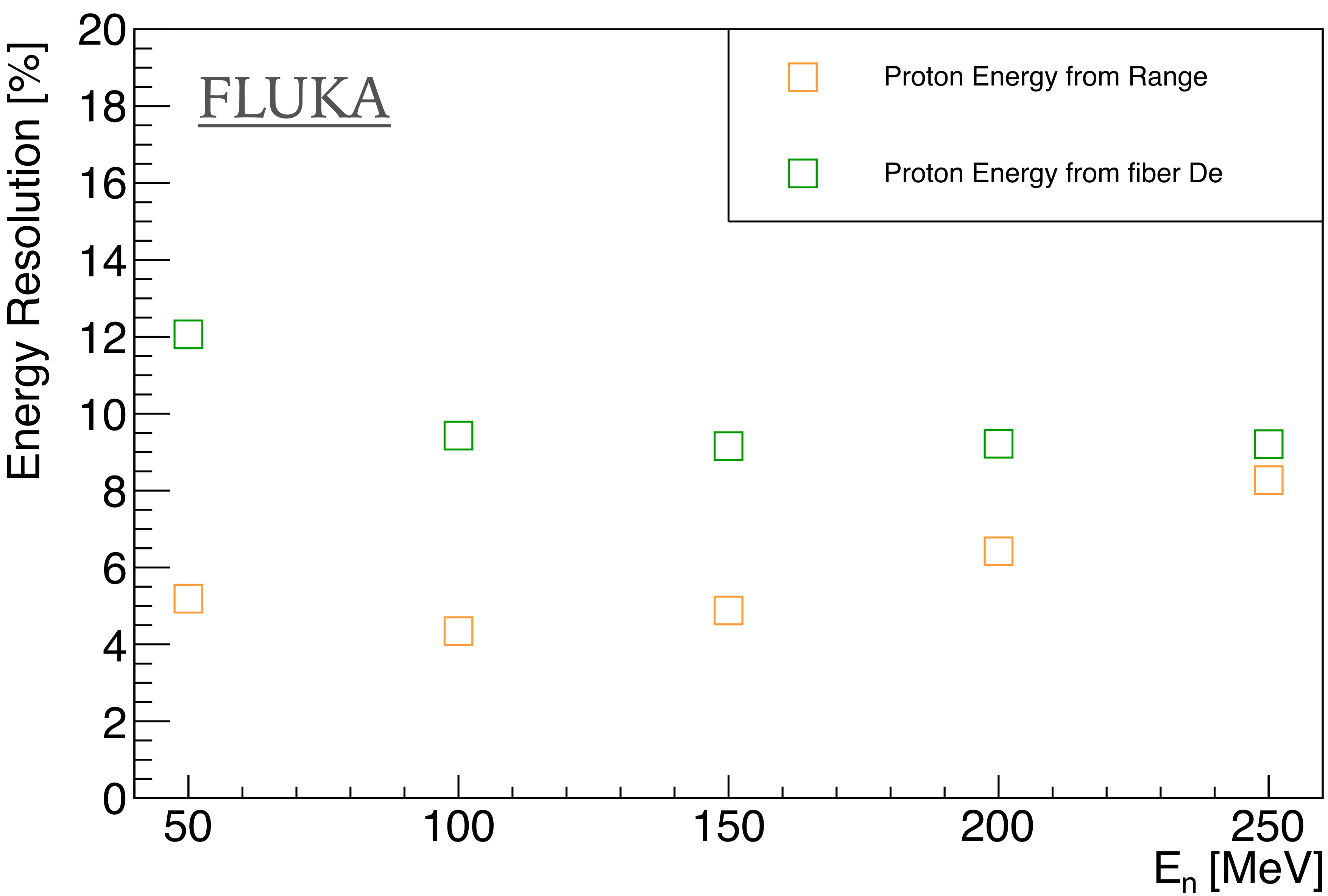




G. Traini et al, Preliminary test of the MONDO project secondary fast and ultrafast neutrons tracker response using protons and MIP particles doi: 10.1088/1748-0221/13/04/C04014

SIMULATION: ENERGY RESOLUTION

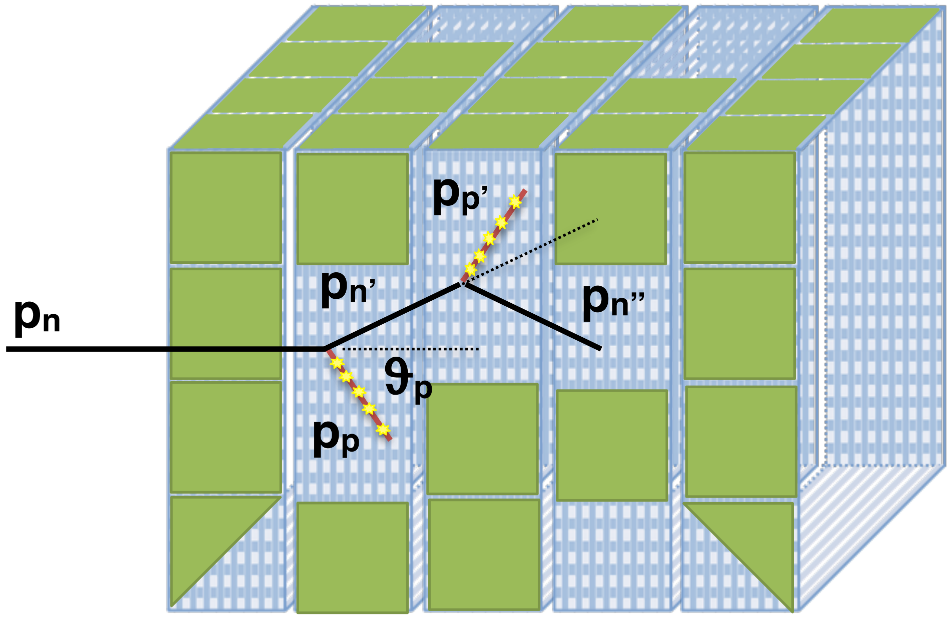
An alternative methods for the proton energy evaluation based on the **energy loss reconstruction in MONDO fibers** and **not considering the proton tracks containment** constraint has been also studied.



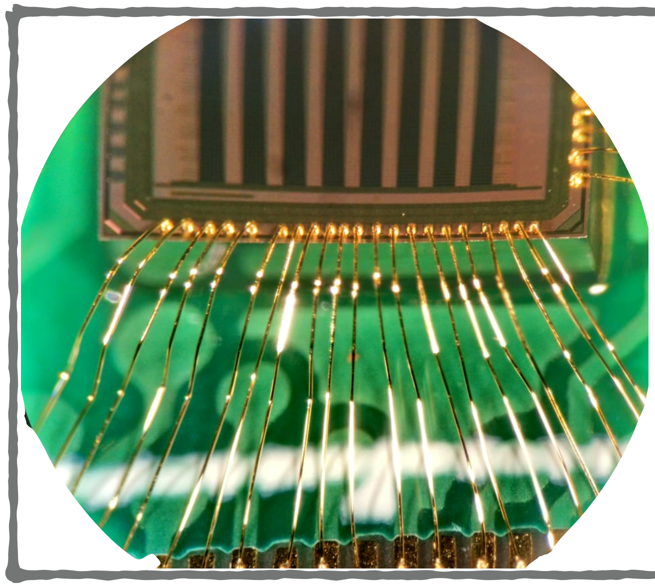
The **resolution**, compared with the one obtained from proton range is reported as a function of the neutron kinetic energy.

Neutron energy resolution obtained from energy loss **are higher** than the ones evaluated via proton range measurements. However, **it is possible to study energy that are not approachable with range measurement**

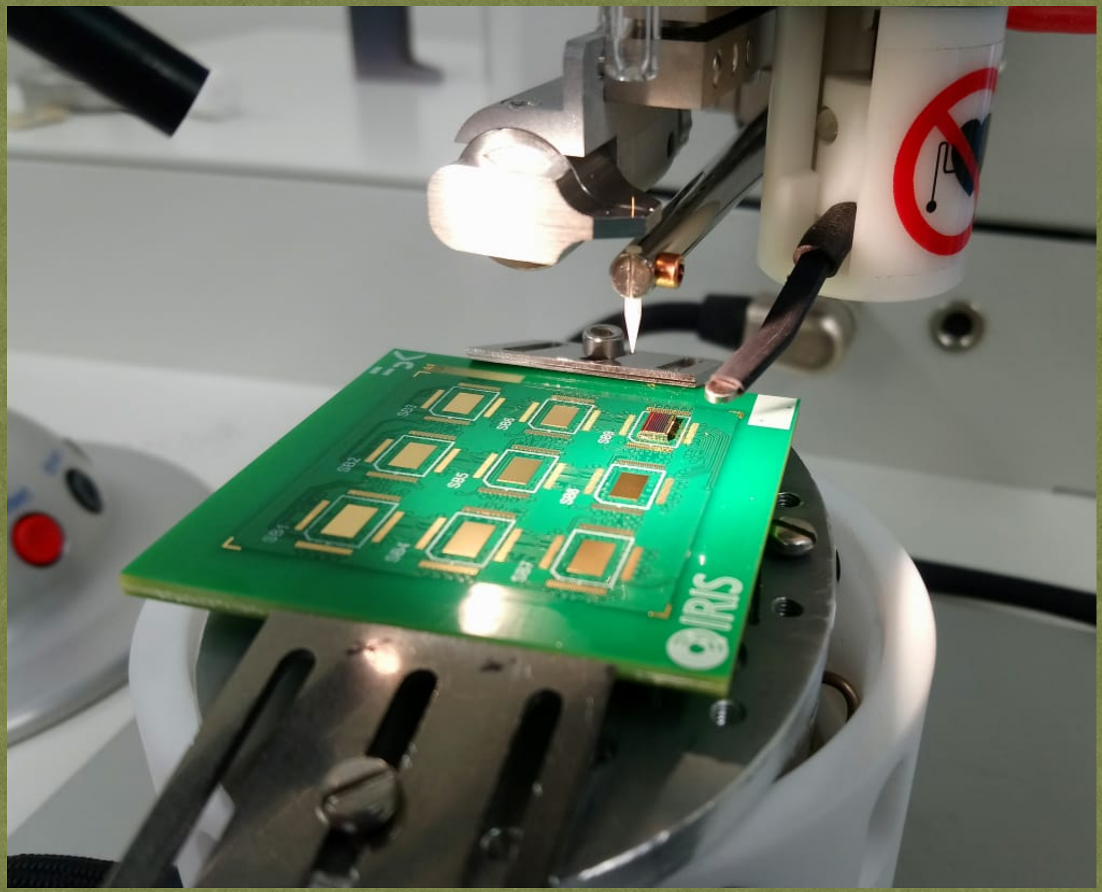
SBAM-I TEST: TILE DEVELOPMENT



- In the final MONDO setup both 16 × 20 cm^2 x-y faces will be covered with chip tiles of ~ 4 × 4 cm^2.



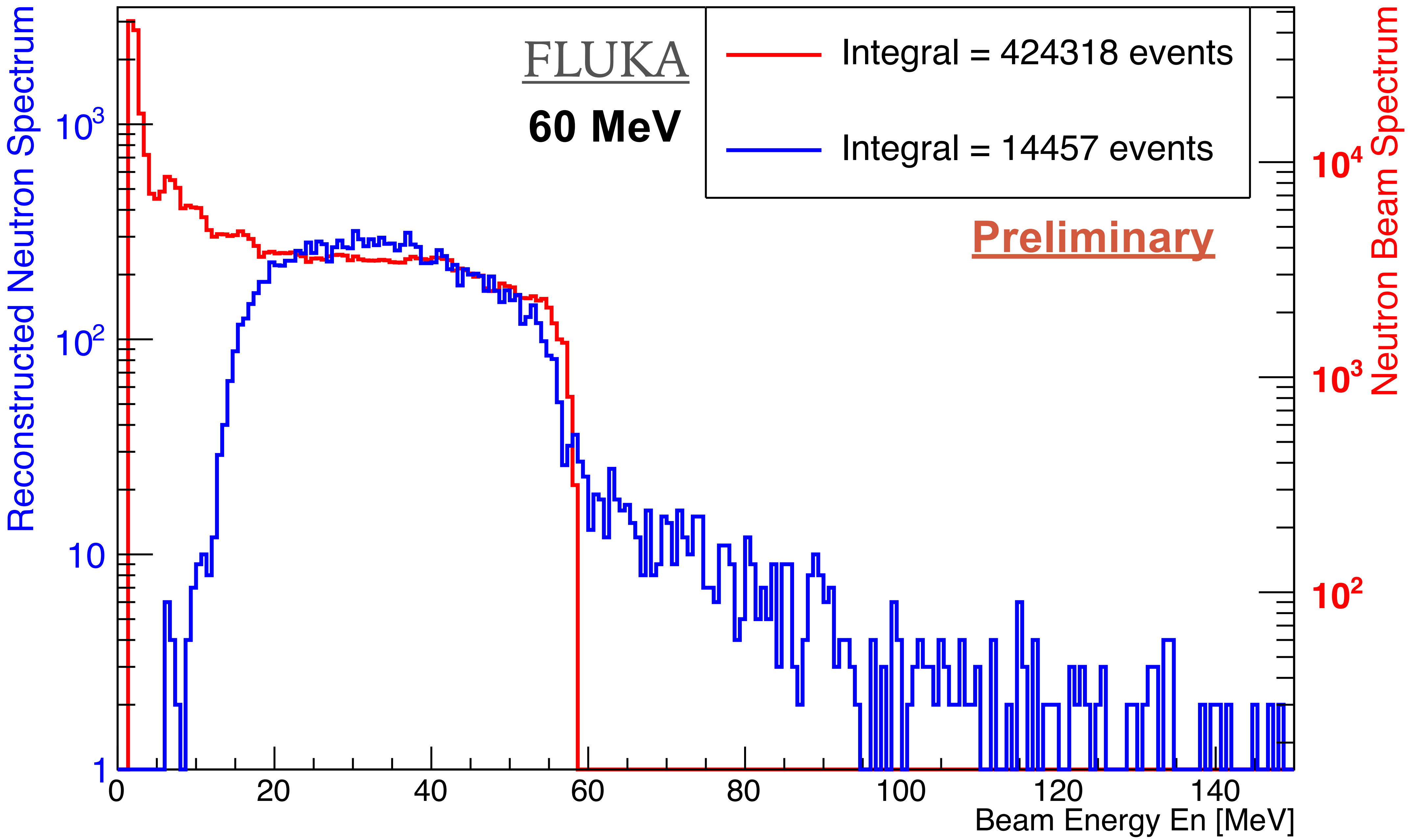
- Bonding wires have been placed all around each chip.



A first sensors tile (3 × 3 sensor), has been realised in order to test the bonding procedure and to idenify possible problems in the tile construction and in the communication capacity .

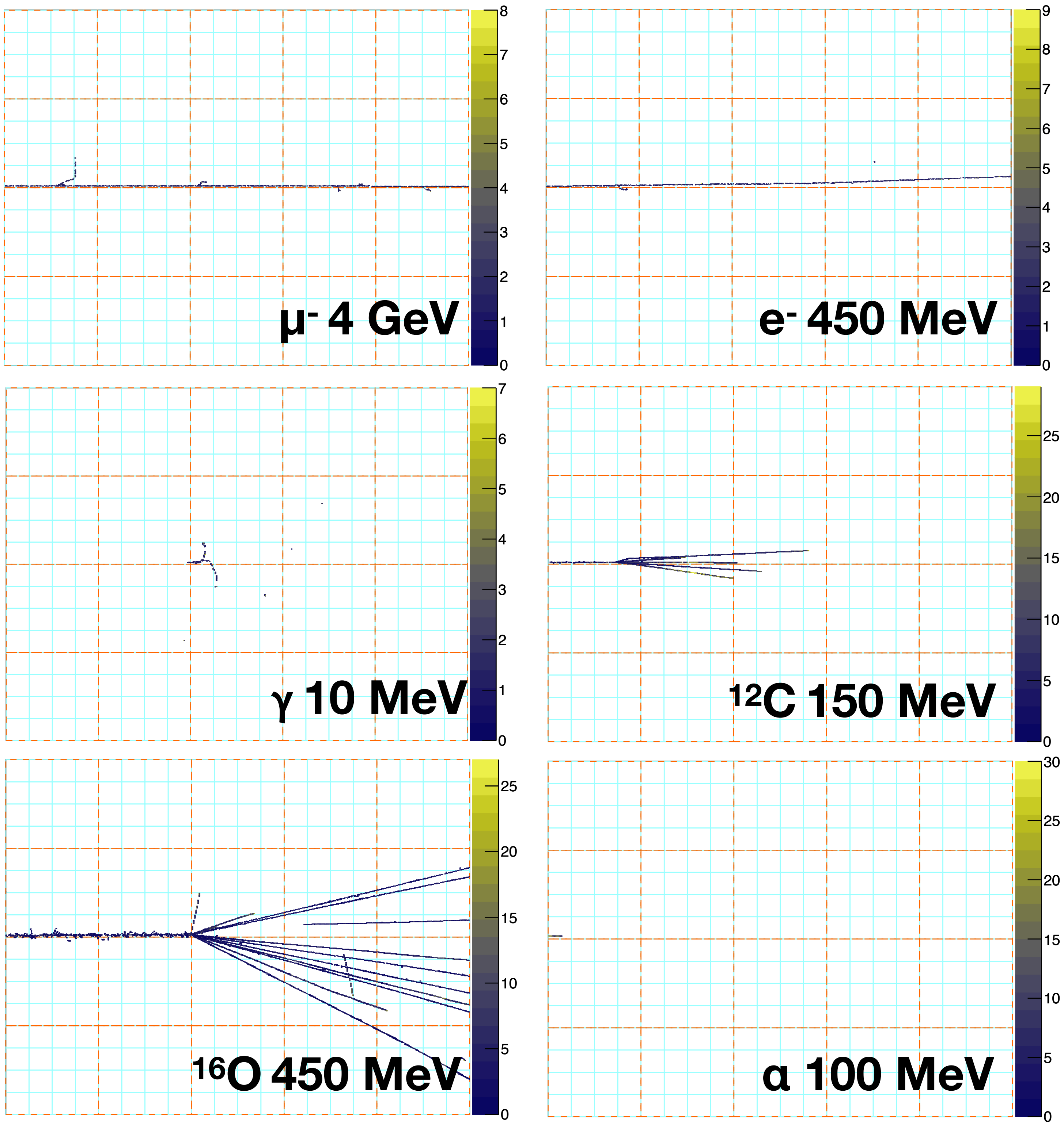
- In the next future, **tests and characterisation measurements will be extent to the chip tile**, in order to address all the possible hardware defects.

SIMULATION: NEUTRONS PRODUCTION SPECTRUM



- Reconstruction of the neutrons spectrum produced from a **27 mm Be** target with **60 MeV** protons.
- The sharp edge in the distribution due to the energy of the proton beam from which the neutron spectrum is generated appears to be **well reproduced**.

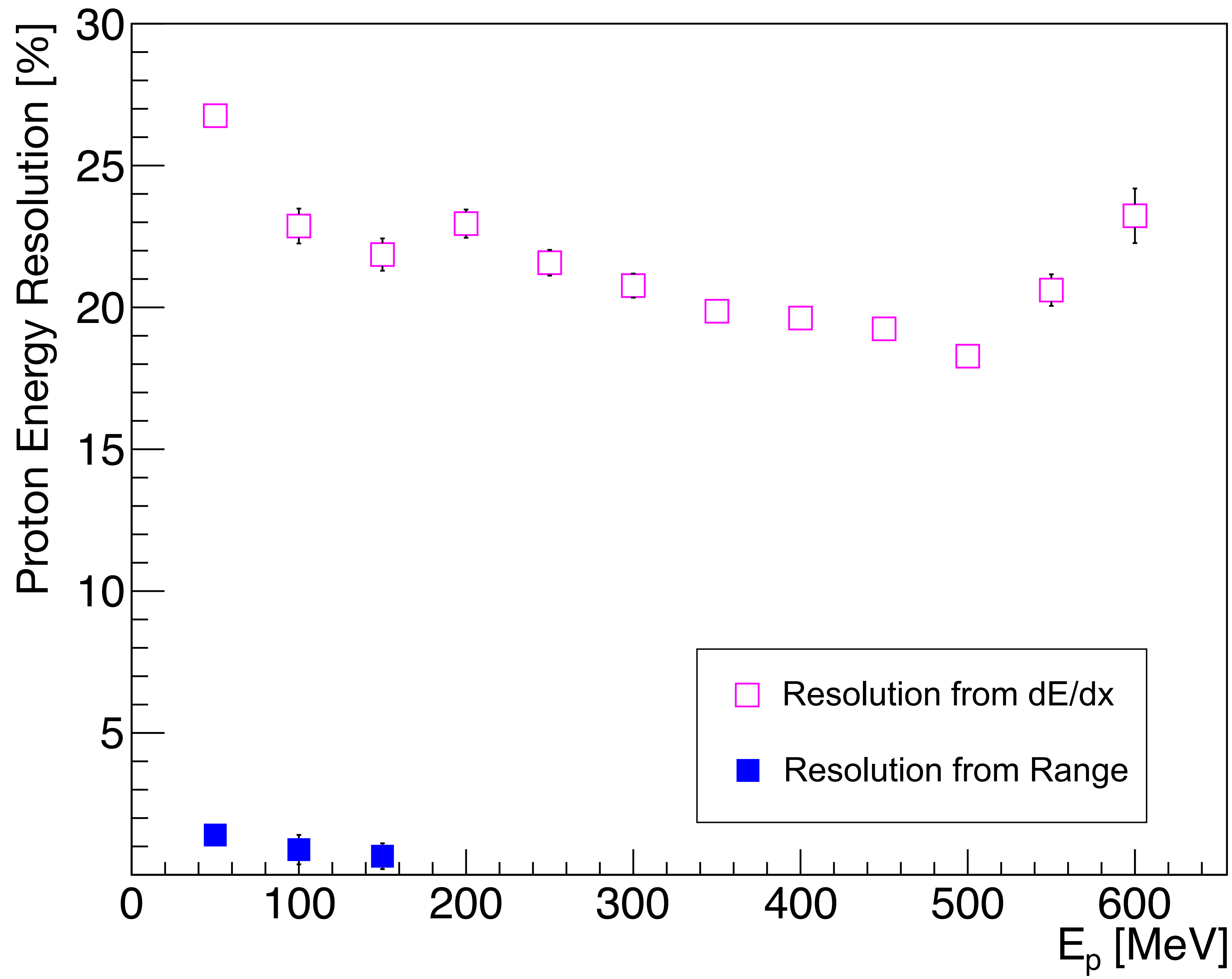
NEUTRAL AND CHARGED PARTICLE TRACKER



- MONDO can be used to detect and to measure energy and direction of several particle in a large energy range.
- Type and energy of different particle can be reconstructed considering **the products of their interaction** in the fibers, the **length of the particle tracks** or the energy deposition in fibers that can be measured exploiting the photons counter readout capability.
- Information provided from readout can be exploited for the rejection of background events where particles other than protons are produced.

NEUTRAL AND CHARGED PARTICLE TRACKER

- An alternative methods for the proton energy evaluation based on the **energy loss reconstruction in MONDO fibers** and **not considering the proton tracks containment** constraint has been also studied.
- With the dE/dx techniques is possible to reconstruct the kinetic energy for protons up to 600 MeV.



- The information provided from SBAM-I readout can be exploited also for high energy particle reconstruction for MONDO as secondary fragments detector configuration.