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

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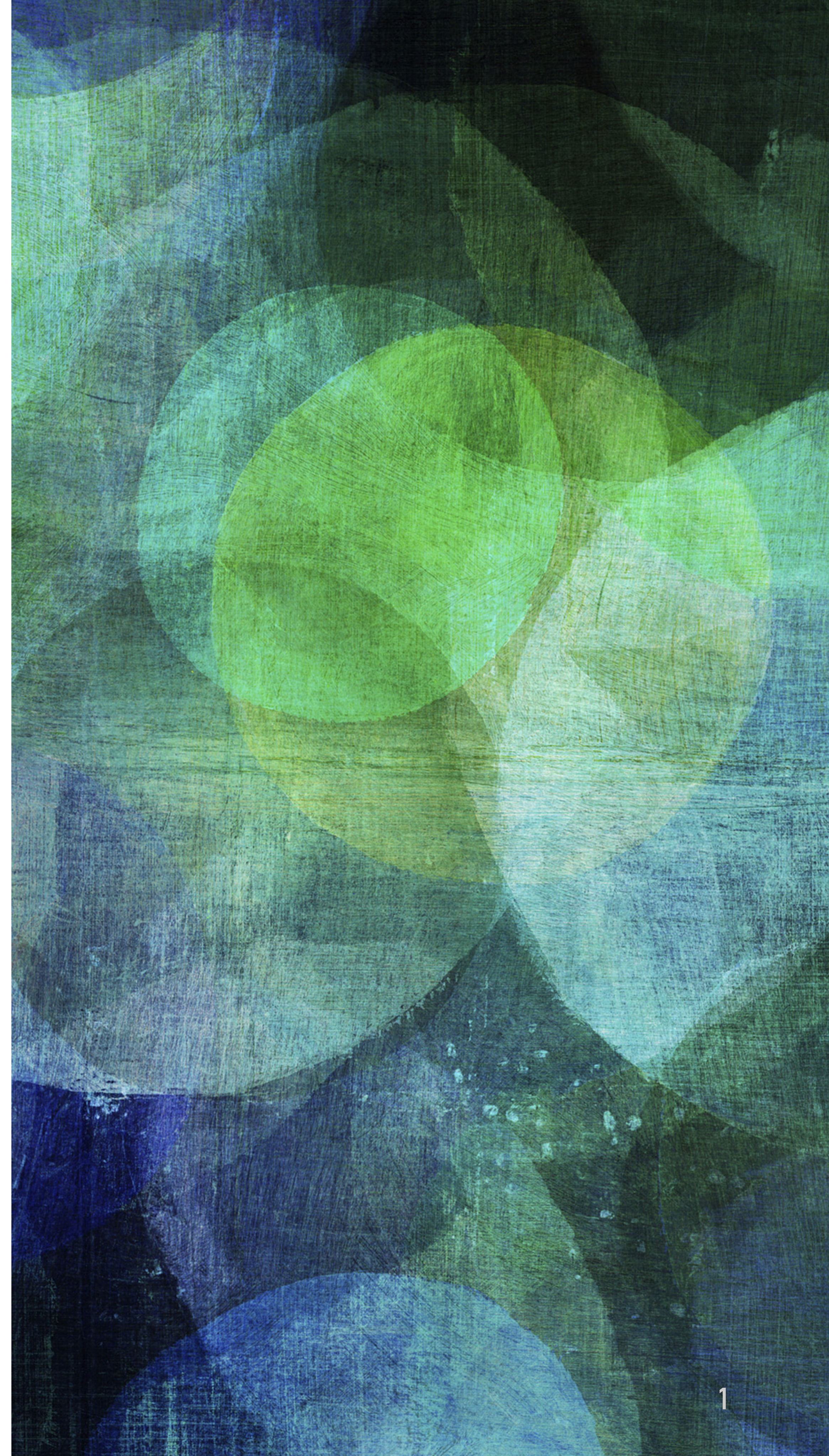
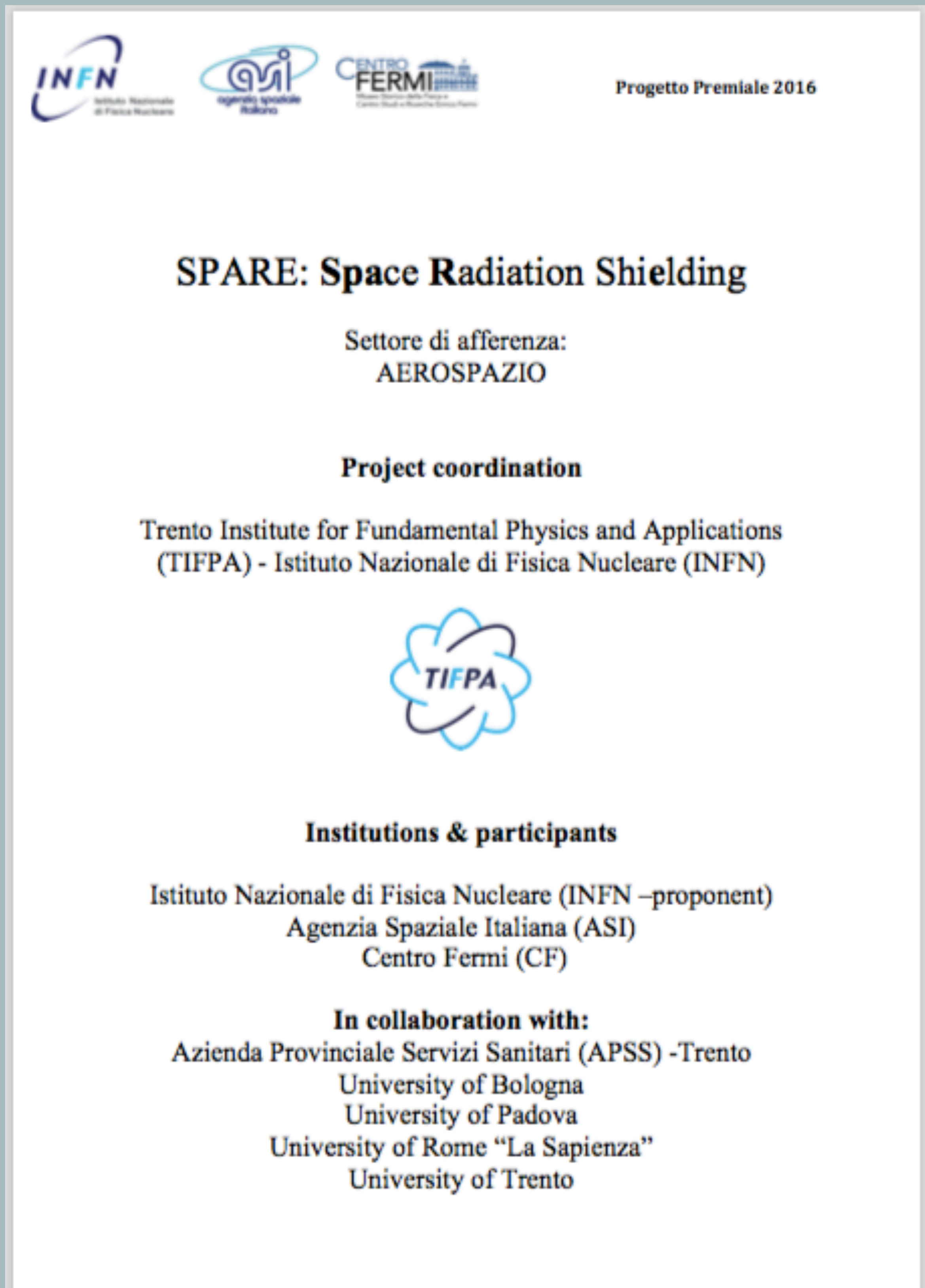


SPARE PROJECT

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 proton cyclotron facility;
- One of the principals tasks of the project is **the development, test and calibration of two ultra-fast neutron beam facilities.**

* progetto premiale 2016 MIUR


Progetto Premiale 2016

SPARE: Space Radiation Shielding

Settore di afferenza:
AEROSPAZIO

Project coordination

Trento Institute for Fundamental Physics and Applications (TIFPA) - Istituto Nazionale di Fisica Nucleare (INFN)

Institutions & participants

Istituto Nazionale di Fisica Nucleare (INFN –proponent)
Agenzia Spaziale Italiana (ASI)
Centro Fermi (CF)

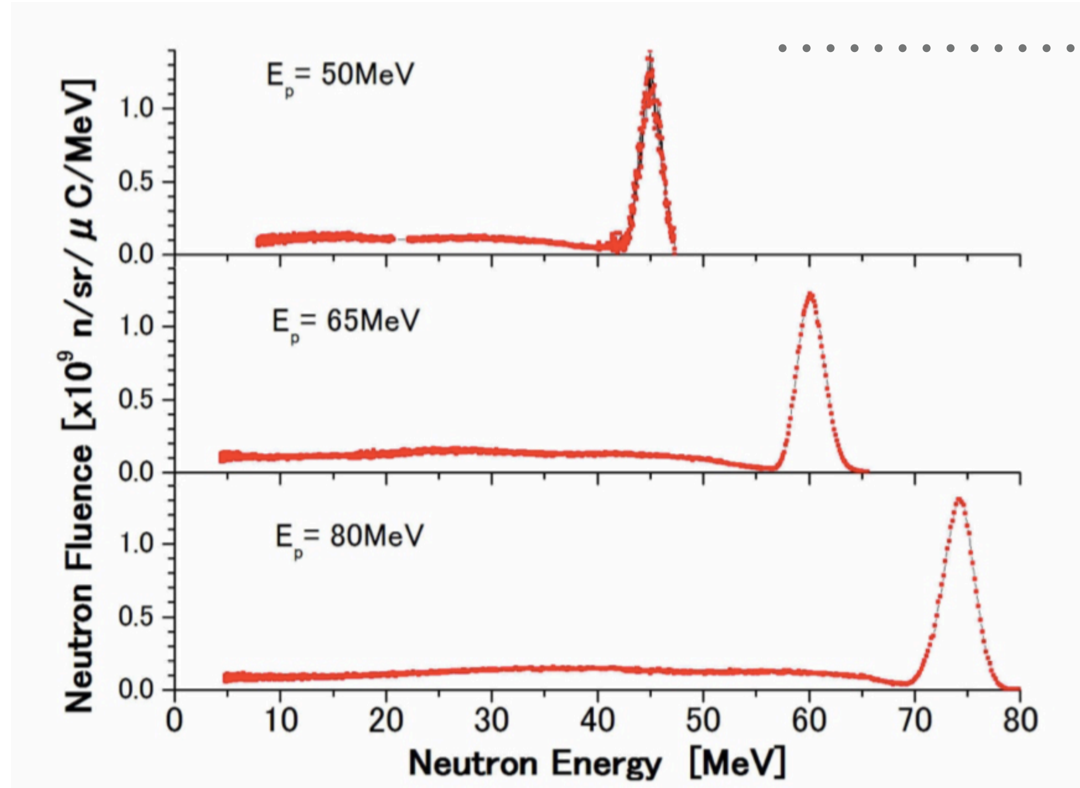
In collaboration with:
Azienda Provinciale Servizi Sanitari (APSS) -Trento
University of Bologna
University of Padova
University of Rome "La Sapienza"
University of Trento

"Quasi Mono-energetic Neutron (QMN) reference fields allow one to study energy dependent neutron interaction mechanisms with matter, be it electronic, detector, dosimeter material, or living tissue. Many research fields can take advantage of a quality QMN facility:

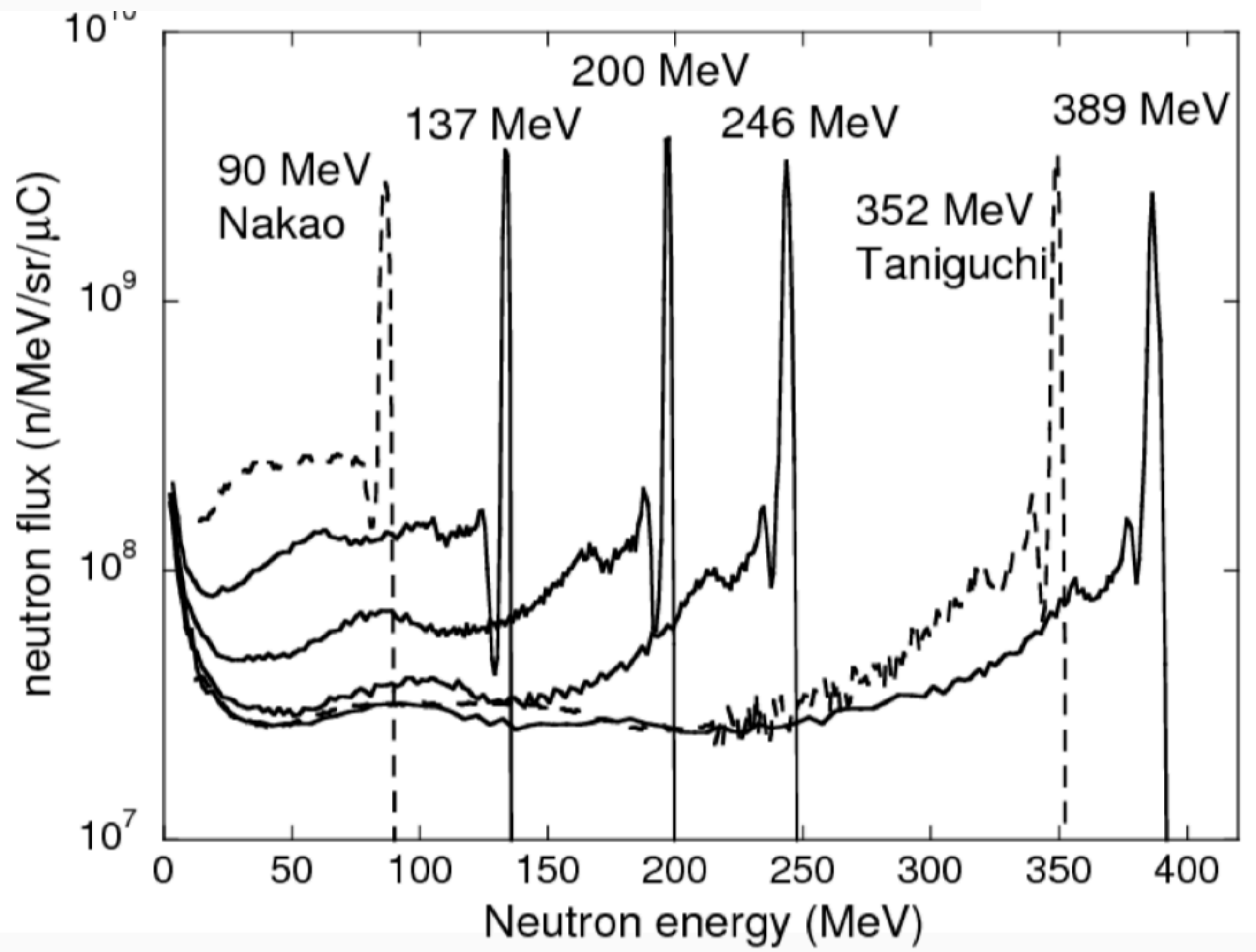
- *nuclear physics (cross-section data for basic science, MC code development and nuclear applications such as accelerator-driven subcritical fission reactors and the transmutation of radioactive waste);*
- *measurement of neutron sensitivity of detectors, for instance those usable in dark matter experiment (WIMP searching);*
- *manufacturers and users of radiation instrumentation and dosimeters important in high- energy neutron work places (energy response and calibration);*
- *radiation protection of workplaces (shielding-benchmark experiments);*
- *neutron radiation effects: with growing numbers of high energy accelerators in research and medicine, there is an increased concern about the high-energy neutron fields (exposure to secondary neutrons: patients/personnel and ancillary electronics);*
- *neutron effects in electronics (space-craft, avionics and state-of-the-art systems at sea-level)."*

HIGH ENERGY NEUTRONS FACILITY

- Energetic 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 an high energy peak close to the energy of the incoming proton, but also a broad distribution at lower energy.
- The ratio of neutrons contained in each of these two components is 50:50.



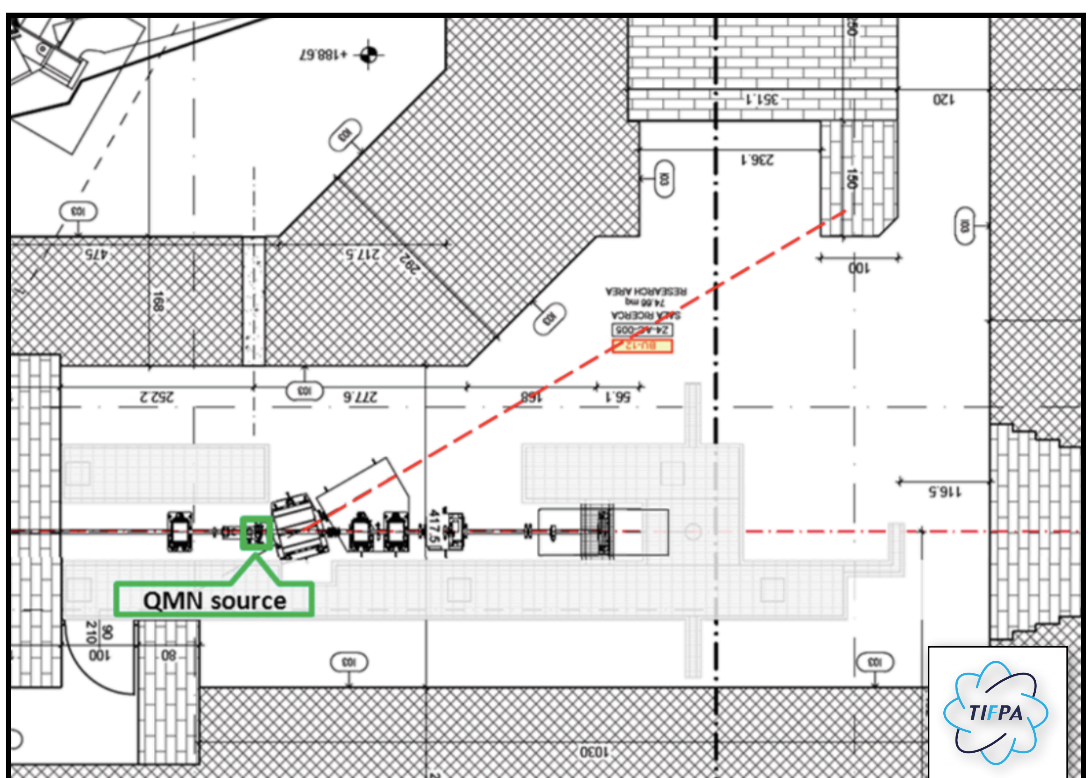
EURADOS Report 2013-02
"High-energy QMN fields: existing facilities and future needs"

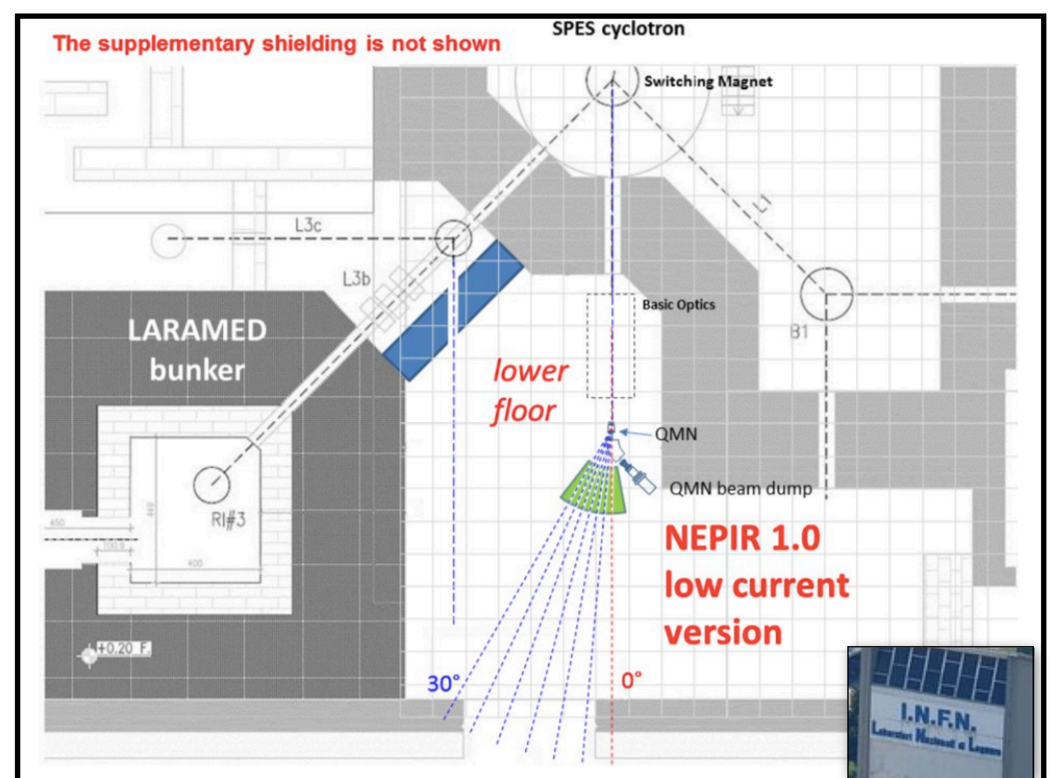


HIGH ENERGY NEUTRONS FACILITY

- The two ultrafast neutron beam facilities expected to be constructed with SPARES;
- In order to **characterize** the energy spectra of the incoming neutrons and **monitor** the beam during operations the MONDO detector has been proposed.

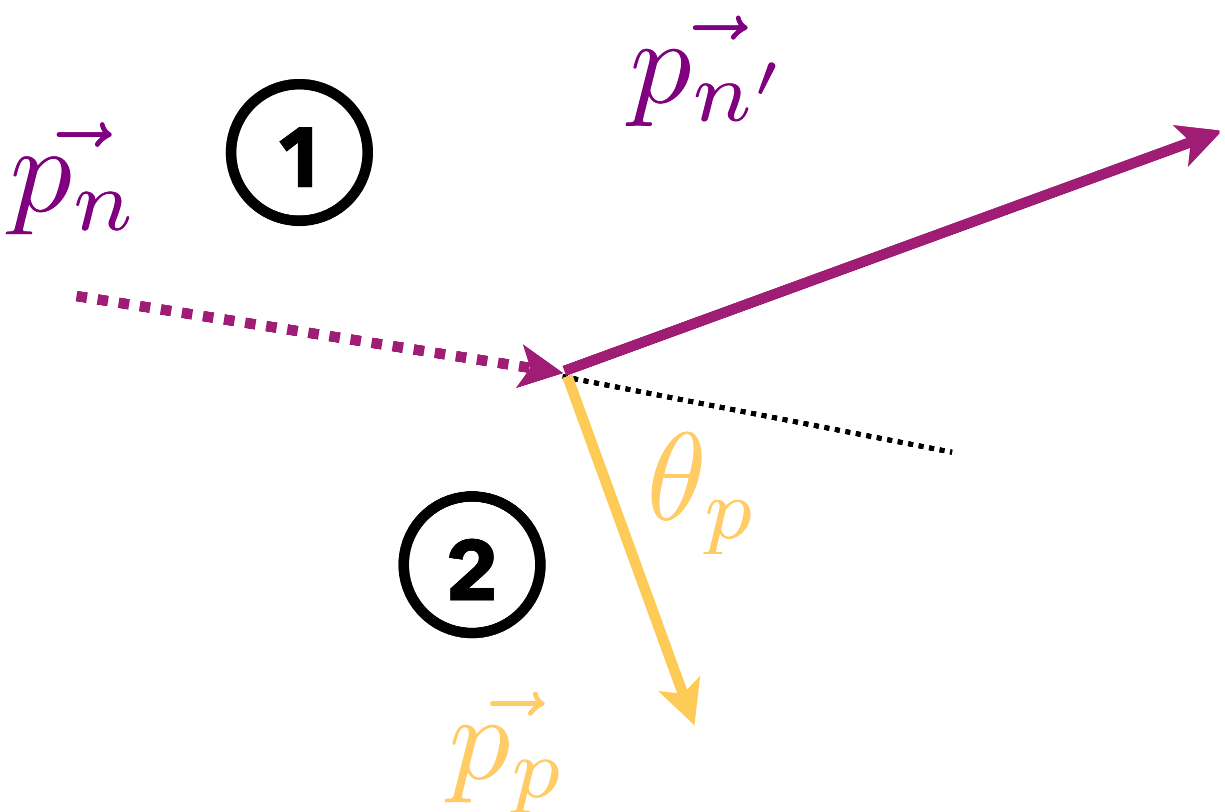
	TIFPA QMN	LNL NEPIR
Energy of Protons	70 - 230 MeV	30 - 70 MeV
Distance of Li target from test point	5 m	3 m
Mono-energetic neutron (peak) flux at the test point	$4x10^{3}$ n $cm^{-2}s^{-1}$ for 0.1μA	~$5x10^{5}$ n $cm^{-2}s^{-1}$ for max 10 μA





THE DETECTION MECHANISM

Hydrogenated target



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

2. Proton recoil (E_{kin} from range)

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

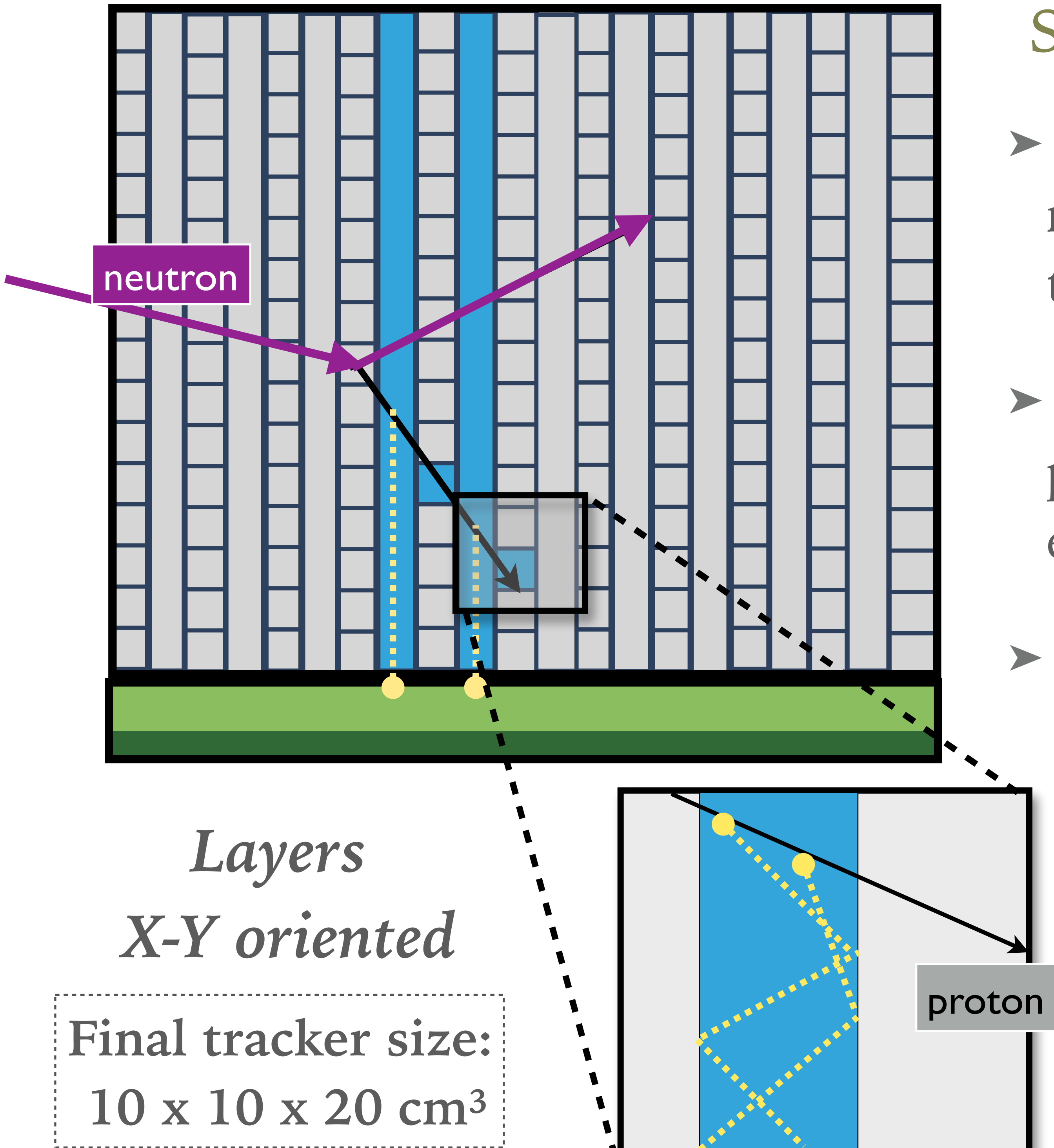
Why a pixelated detector based on proton recoil?

- Neutrons at NEPIR and TIFPA QMN are produced from a continuous beam (not pulsed) → There is not START signal for performing Time Of Flight measurement!!

THE MONDO CHALLENGE

The device has been initially design for secondary neutrons chracterisation (both energy and direction unknown): the dimensions have been chosen for the DES containment

Elastic scattering



Layers X-Y oriented

Final tracker size: 10 x 10 x 20 cm^3

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€/1m

layers of fibres → **target and tracker**

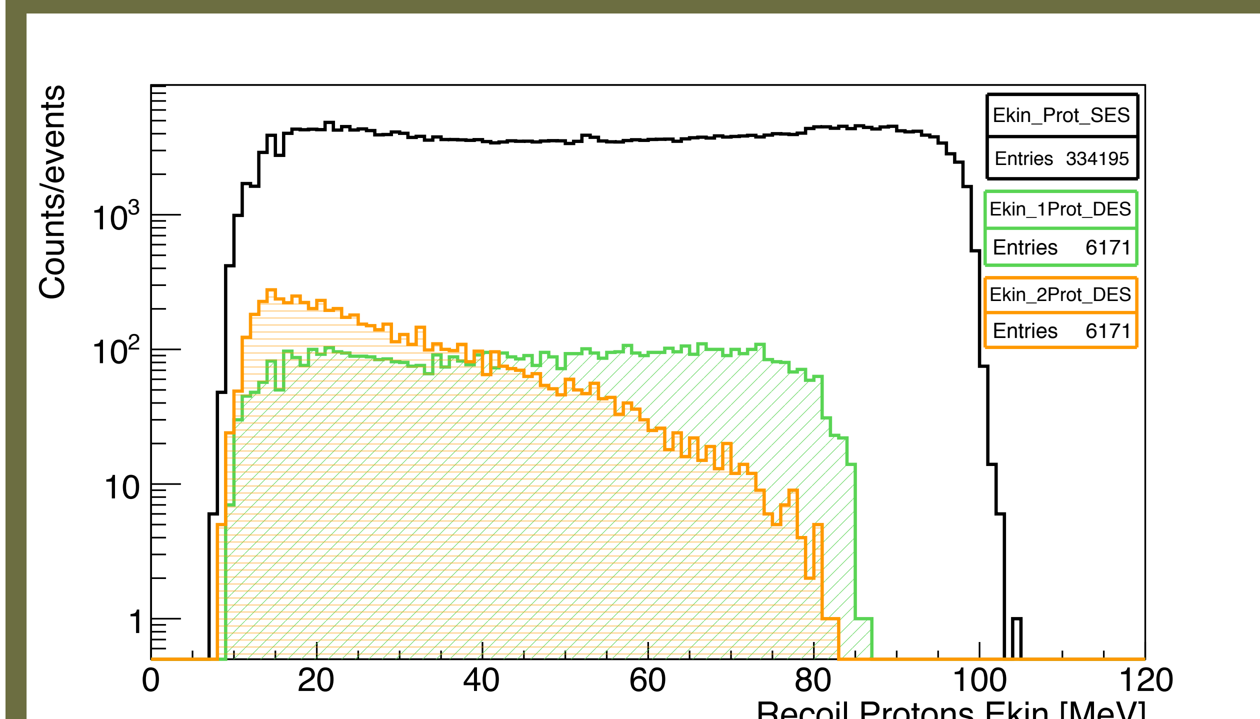
More than 6x10^5 channels

=> silicon readout **system**

SIGNAL EVALUATION

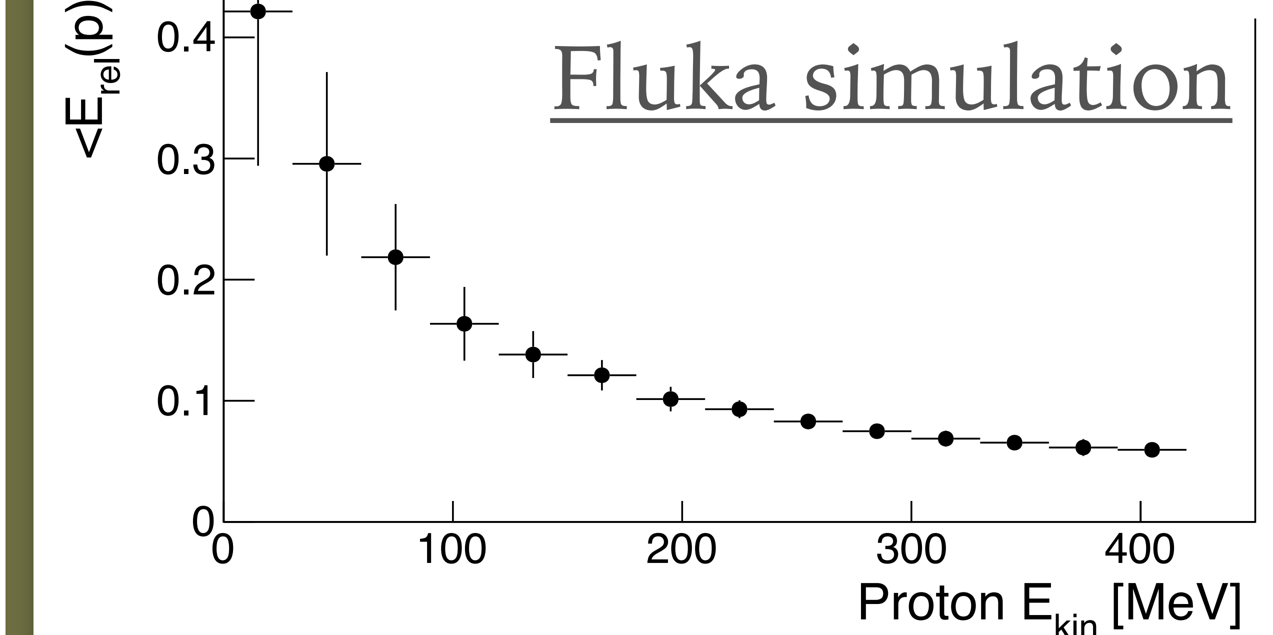
A Monte Carlo simulation has been developed using FLUKA code to optimise the detector layout. The energy release of the protons in the fibres as a function of the neutron (and proton) energy has been evaluated.

Ex. of the proton spectrum for 100MeV neutrons



V. Giacometti et al. Characterisation of the MONDO detector response to neutrons by means of a FLUKA Monte Carlo simulation (in press).

Deposited energy per fibre	100 keV in 250 μm
Light yield (BCF-12)	8000 ph. MeV^{-1}
Trapping eff. (double clad.)	7%
$N^{prod}_{Ph.}$	60 ph.



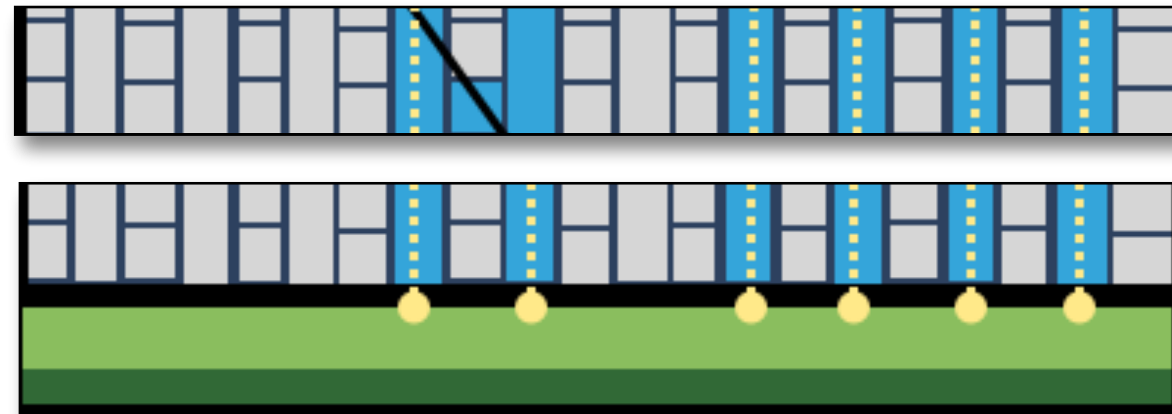
M. Marafini et al., PMB (2017) doi: 10.1088/1361-6560/aa623a

READOUT SYSTEM

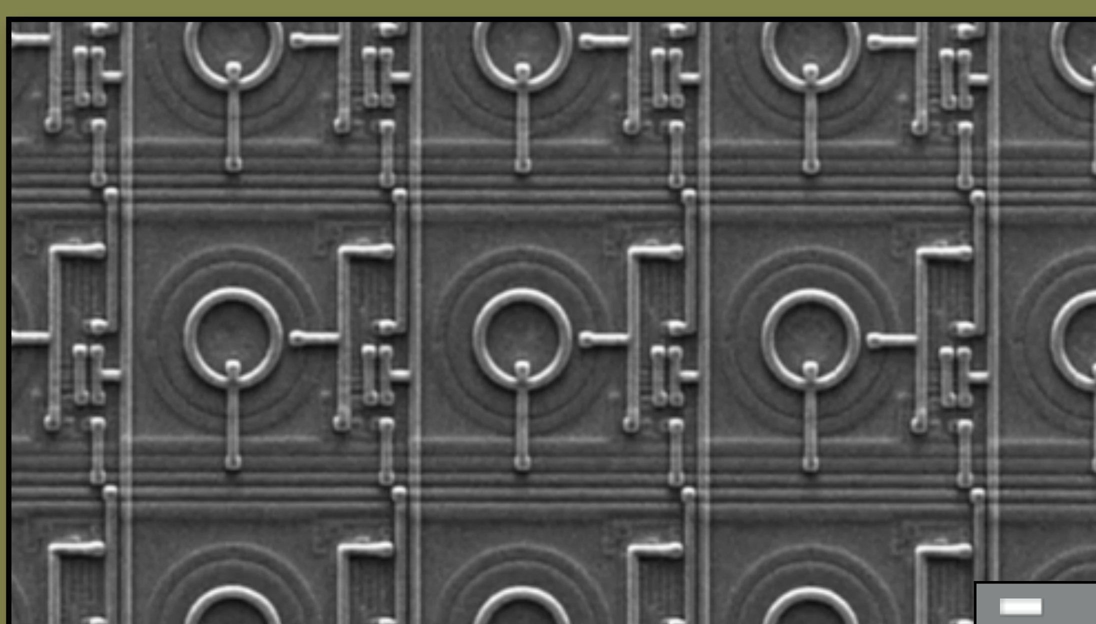
SPAD: Single Photon Avalanche **Diode**

- Space granularity of few 100μm => fibres of 250-200 μm

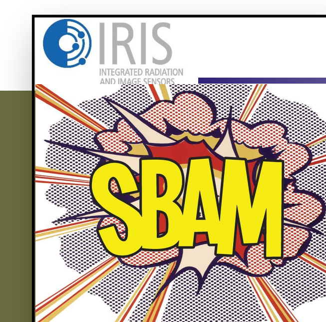
- Few photons (few ph.ele)
- Fast signals: typically ~5ns



Digital silicon diode allows to build a sensor with customised pixel size. An internal **smart trigger logic** allows to discriminate the scintillation light signals from the background due to the dark count rate.



We choose to develop a new SPAD array sensor - in collaboration FBK (SBAM sensor) - tailored for the MONDO needs.



R. Mirabelli et al, *The MONDO detector prototype development and test: steps towards a SPAD-CMOS based integrated readout (SBAM sensor)* IEEE TNS VOL. 65, NO. 2, FEBRUARY 2018

IRIS INTEGRATED RADIATION AND IMAGE SENSORS

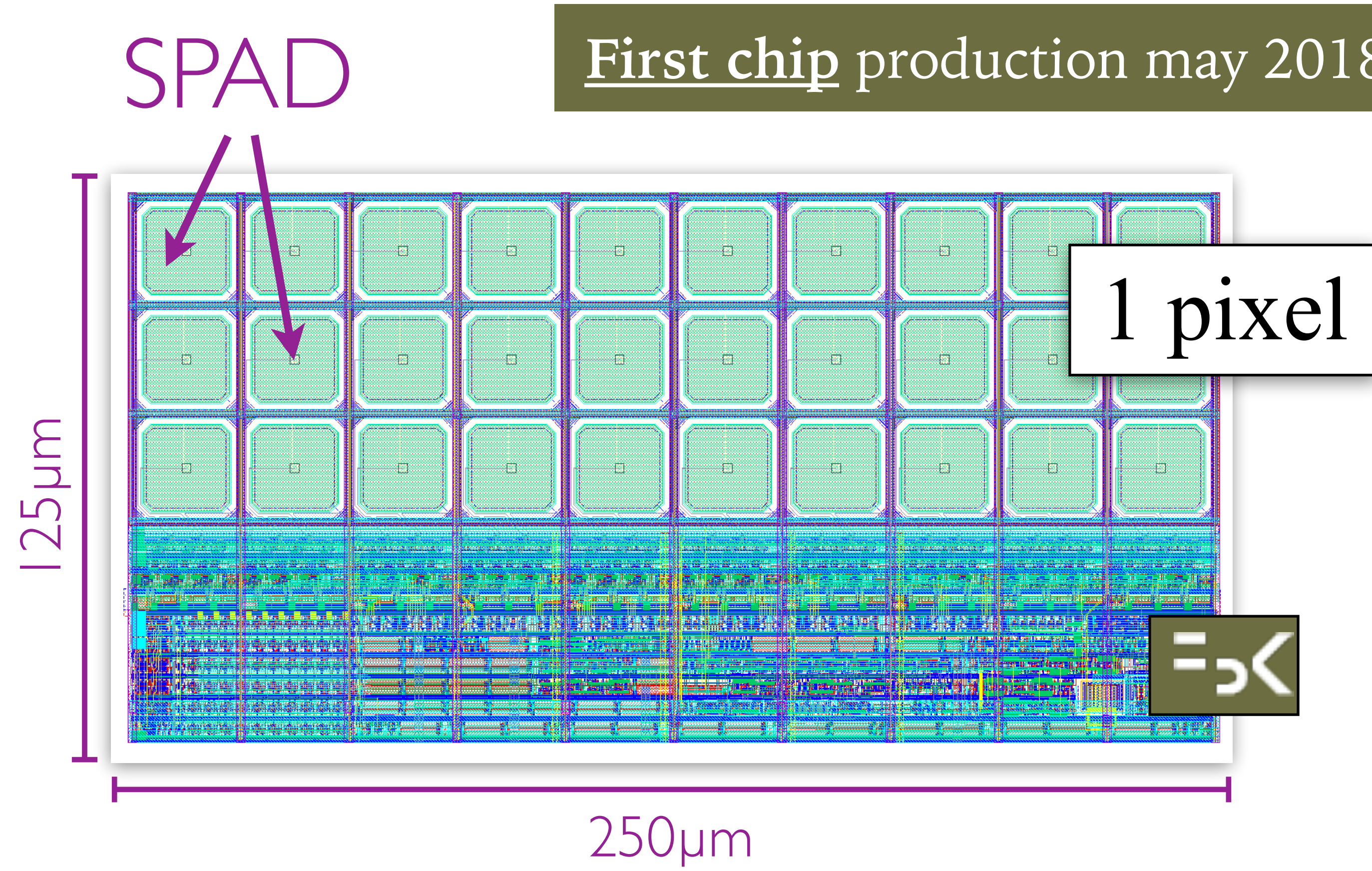
READOUT SYSTEM

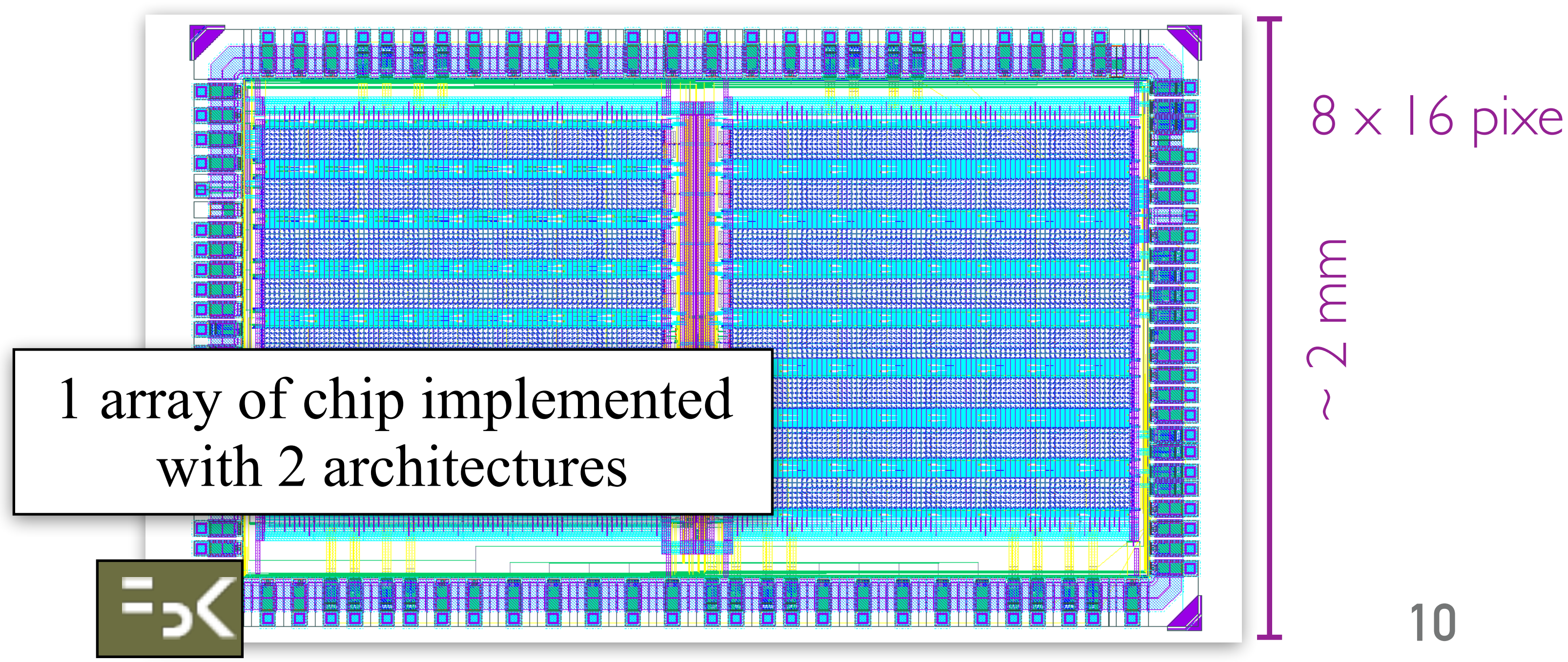
SBAM:Spad Based Acquisition for the Mondo Experiment

Main characteristics of the new sensor

- **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 ~400cm²)
- Fill Factor ~30%
- Side-by-side sensors

First chip production may 2018

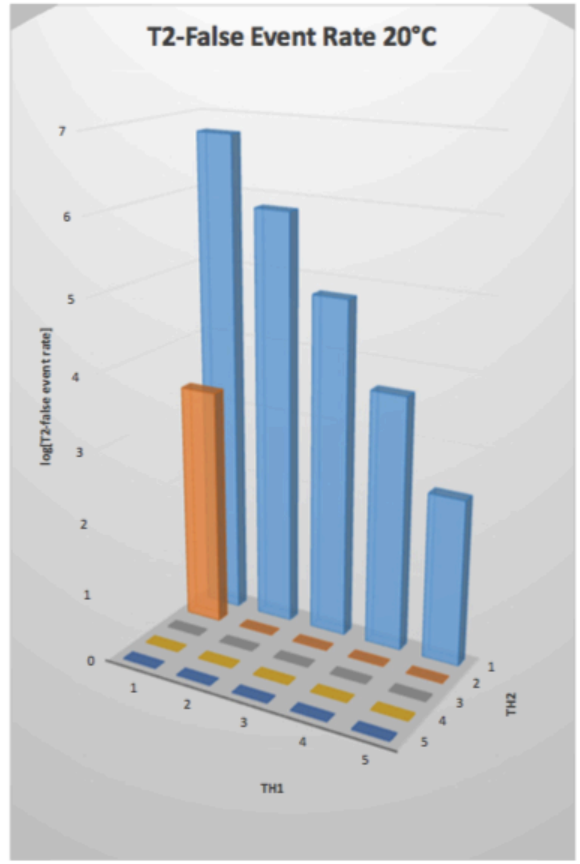


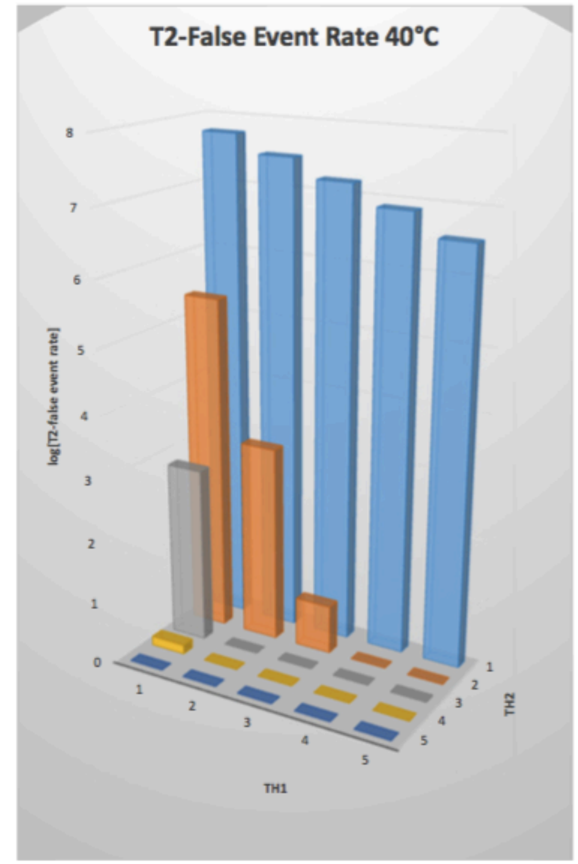


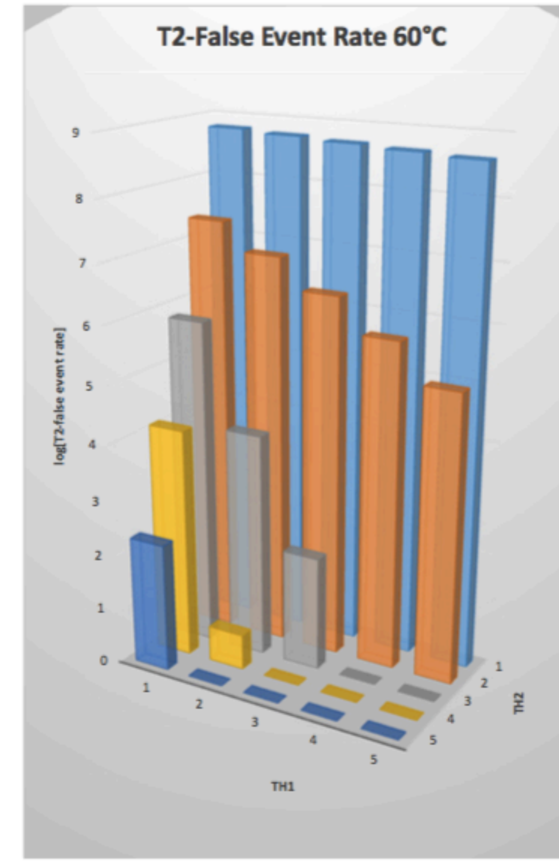
SIMULATION: READOUT SYSTEM

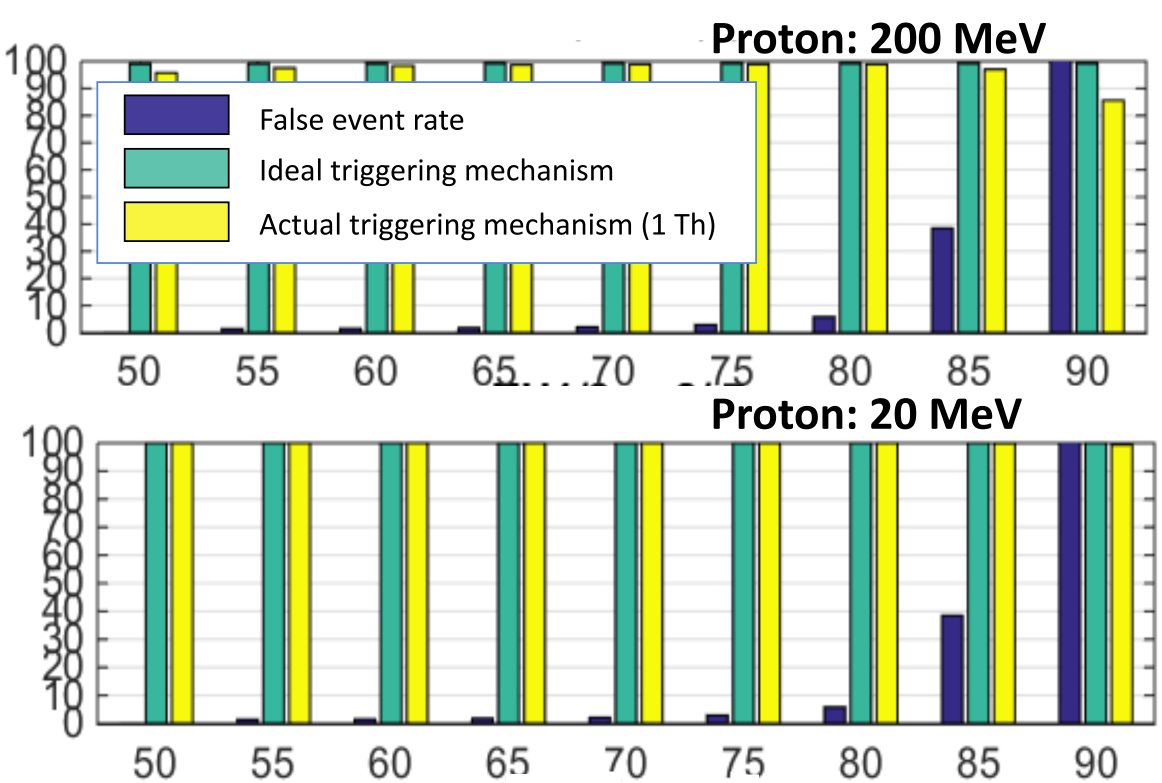
FBK feasibility study

Trigger logic based on double threshold: Th1 is the number of activated SPAD, Th2 is the number of activated pixel.
Simulator investigates the process of detection of protons from [10-250] MeV with a pixelated sensor.







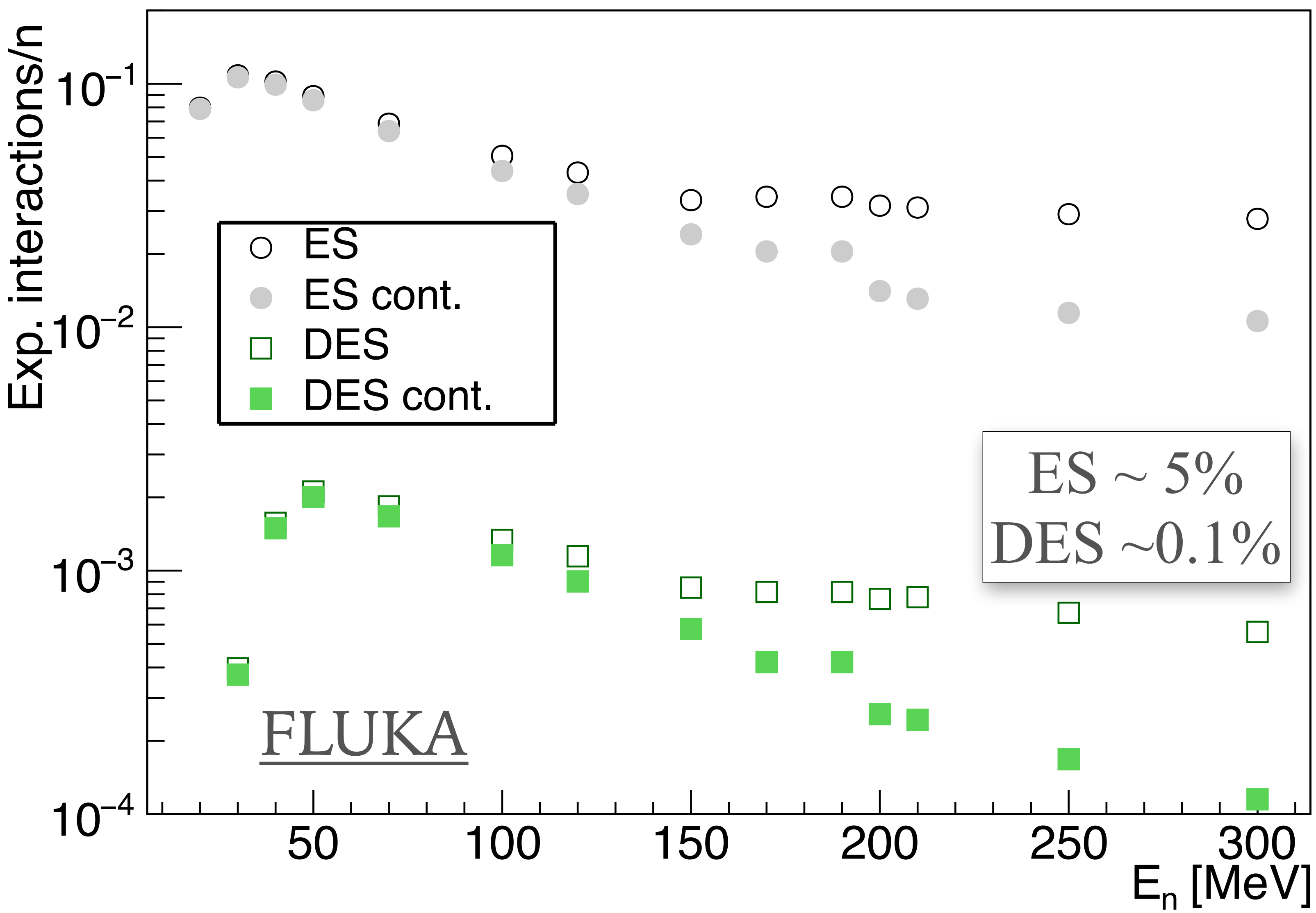


Evaluation of the best working point: estimate the efficiency in detecting protons vs false event rate due to the detector dark counts.
The study has been performed for different proton kinetic energies and different temperatures

Next Step: Evaluation of the best working point with simulated events in FLUKA!

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.



<u>Constraints:</u>

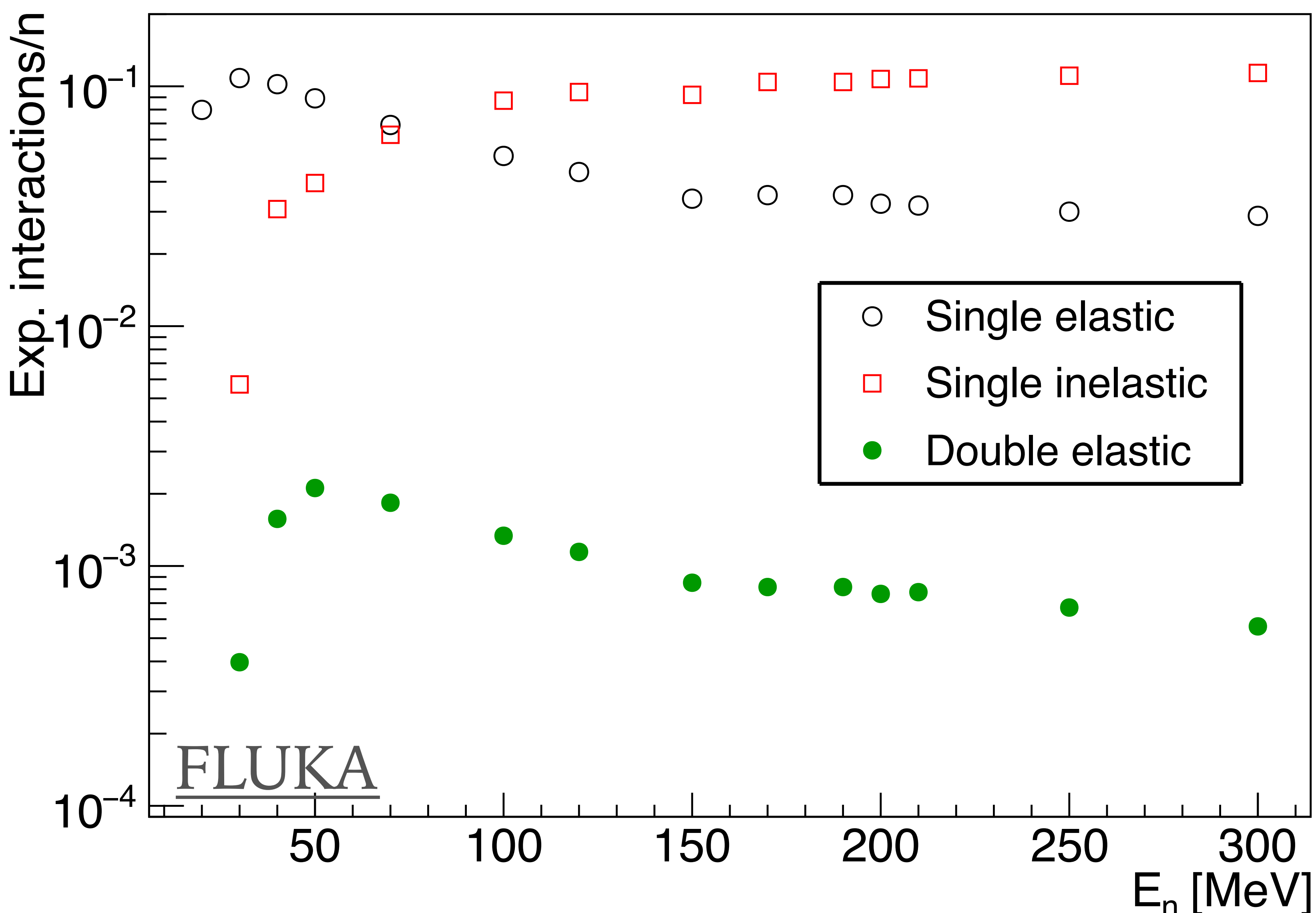
- ➤ full containment request of the protons;
- ➤ at least 6 fibers crossed (about 12 MeV)

containment decreases of one order of magnitude the detection efficiency => under evaluation other proton kinetic energy measurements strategies (i.e. energy loss along the track, ToF, etc, ..)

V. Giacometti et al. *Characterisation of the MONDO detector response to neutrons by means of a FLUKA Monte Carlo simulation (in press)*

SIMULATION: BACKGROUND STUDY

Inelastic interactions (IS) are the main intrinsic background for the elastic events (ES). ES are dominant below100 MeV, while IS are not negligible for higher energies.



V. Giacometti et al. *Characterisation of the MONDO detector response to neutrons by means of a FLUKA Monte Carlo simulation (in press)*

Background:

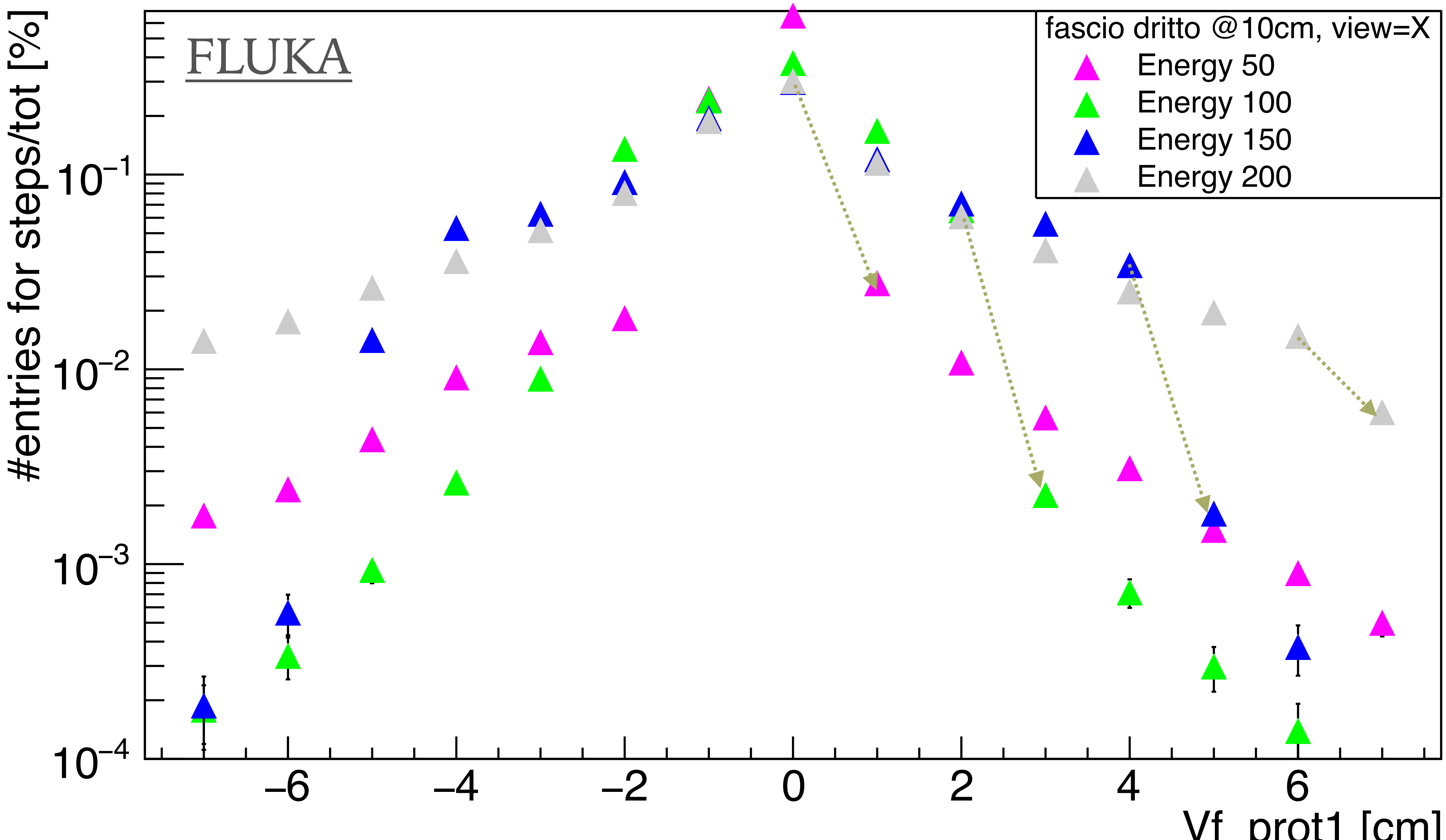
- The probability of mixed elastic and inelastic interactions could have a non-negligible impact on the detector performances and it has to be taken into account when calculating the intrinsic background.

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

SIMULATION: CONTAINMENT STUDY

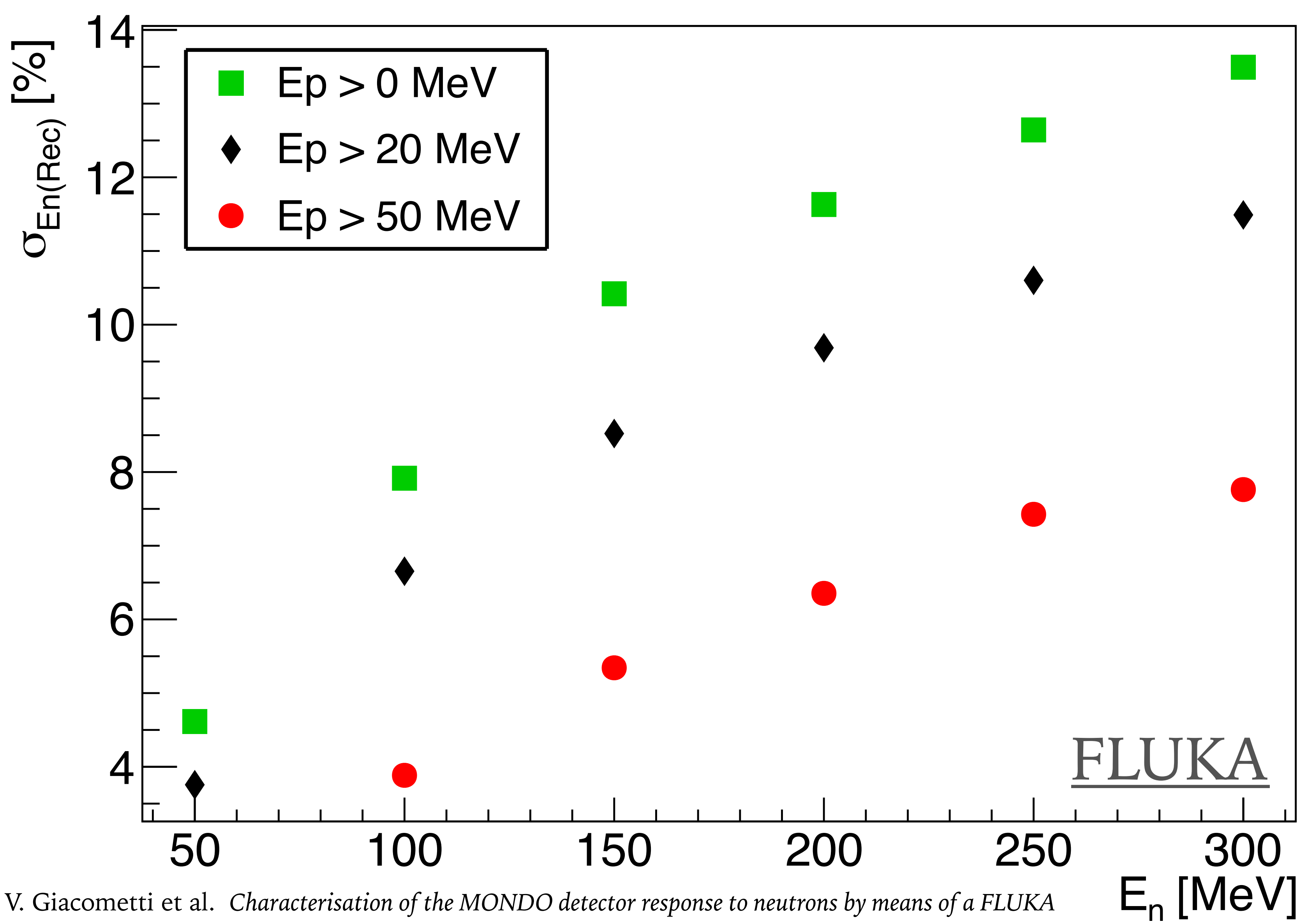
The protons containment has been studied in order to finalize the detector dimensions. We are in search of a value in traverse dimensions for which the most part of protons are contained

Drop in the distribution!



SIMULATION: ENERGY RESOLUTION

The kinetic energy of primary neutrons coming from a known direction 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.



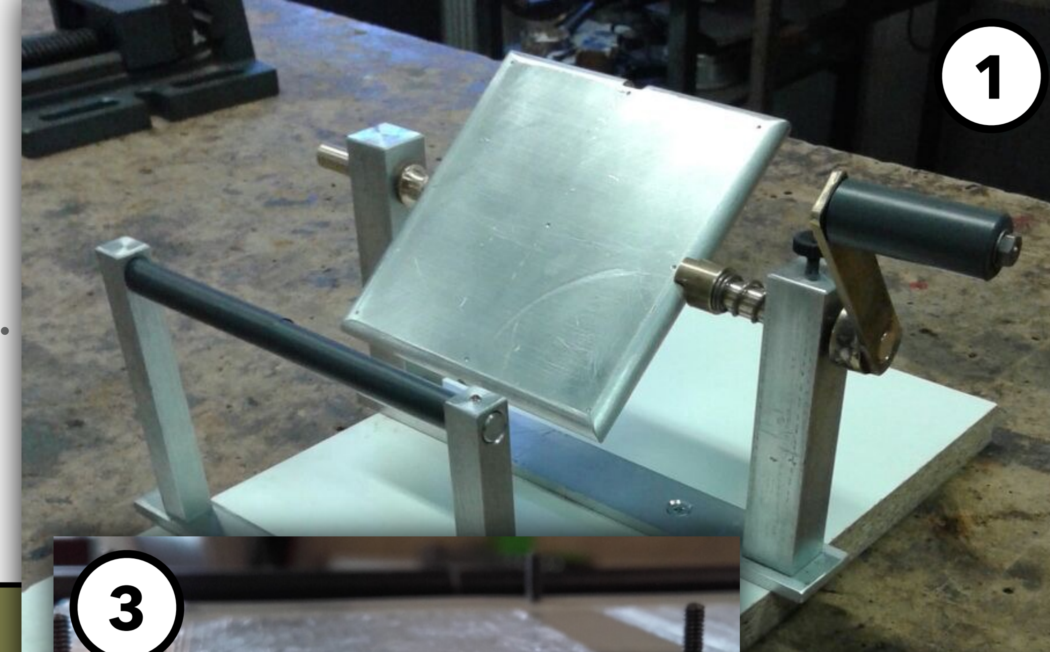
The resolution is reported as a function of the energy applying three different cut on proton energy:

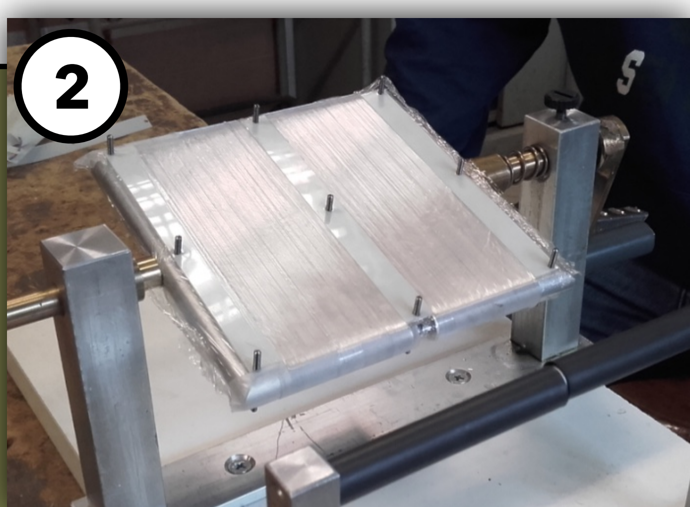
- Secondary protons with $E_{k>}$50 MeV;
- Secondary protons with $E_{k>}$20 MeV;
- Secondary protons without cuts in E_k

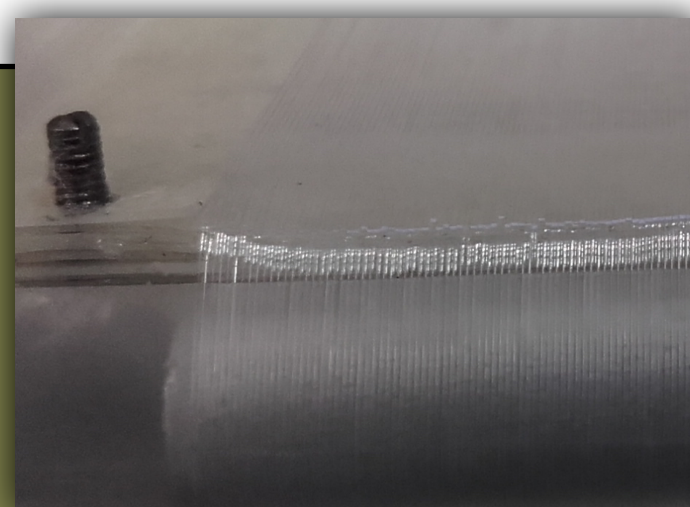
V. Giacometti et al. *Characterisation of the MONDO detector response to neutrons by means of a FLUKA Monte Carlo simulation (in press)*

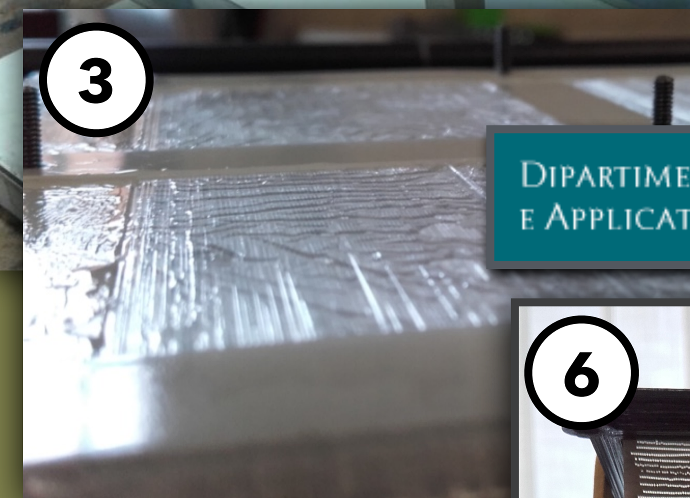
NEUTRONS TRACKER: PROTOTYPE

dimensions: 4 x 4 x 4.8 cm^3

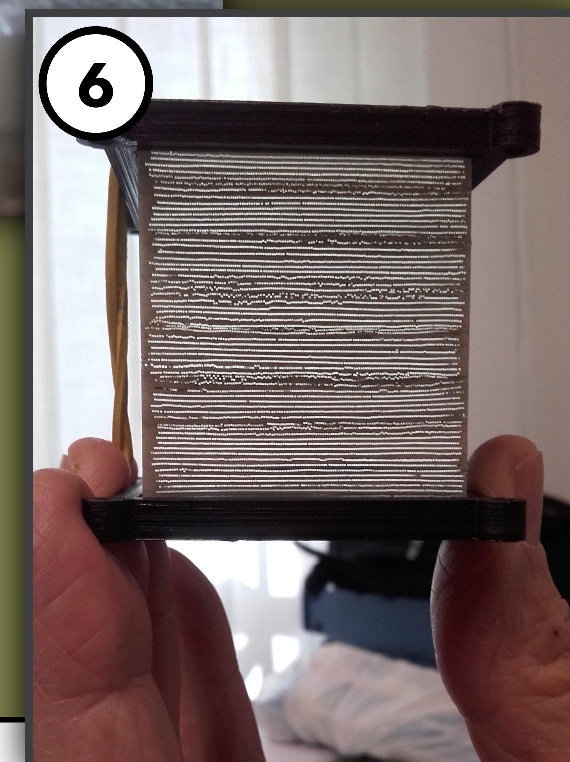




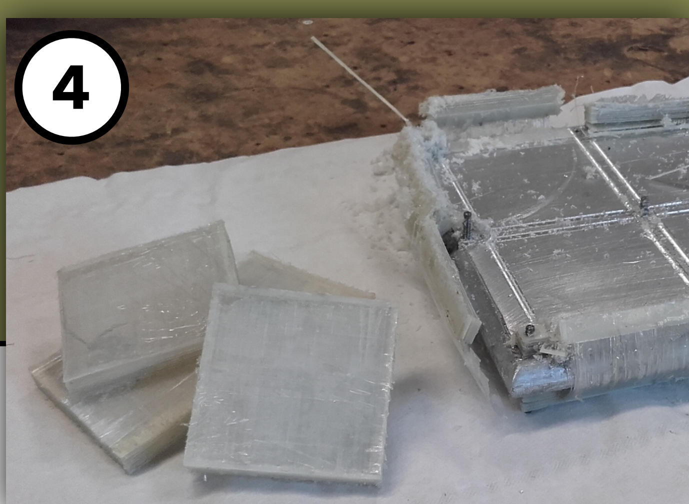


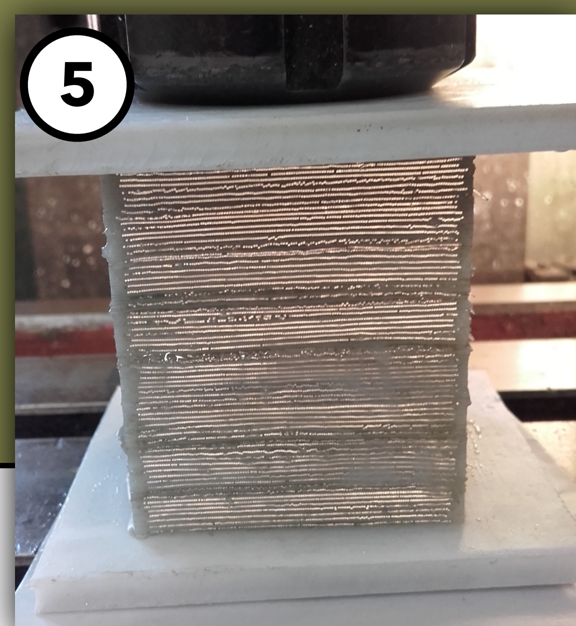


DIPARTIMENTO DI SCIENZE DI BASE E APPLICATE PER L' INGEGNERIA



~ 45 h of work





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: **final matrix will be realized in early 2019**

PROTOTYPE: PENELOPE

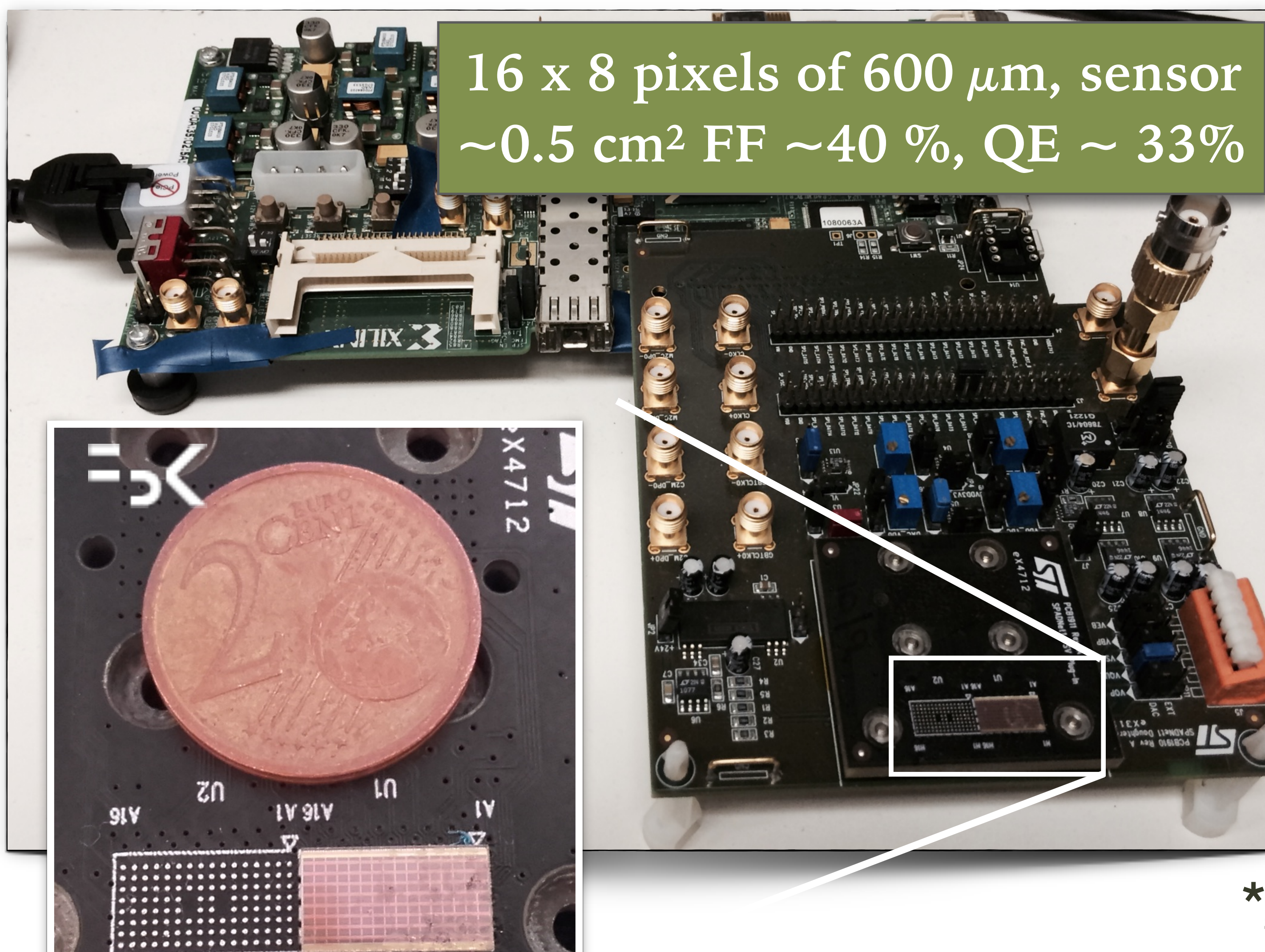
The new sensor SBAM has been developed (FBK-CF) starting from the experience gained using an other sensor prototype: *spad-net**. Practicing with *spad-net* allowed us to point out the critical issues to be addressed in the SBAM development phase.

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)**;

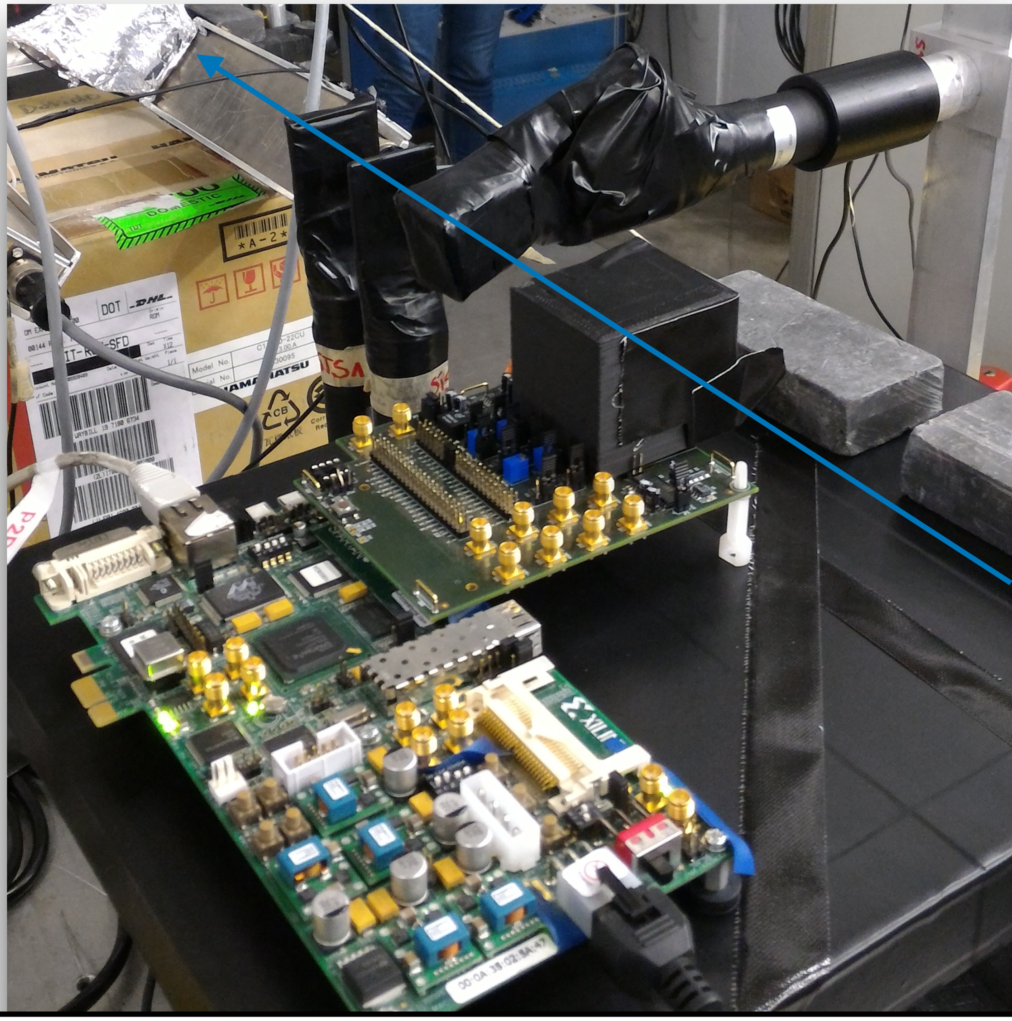
- cosmic rays

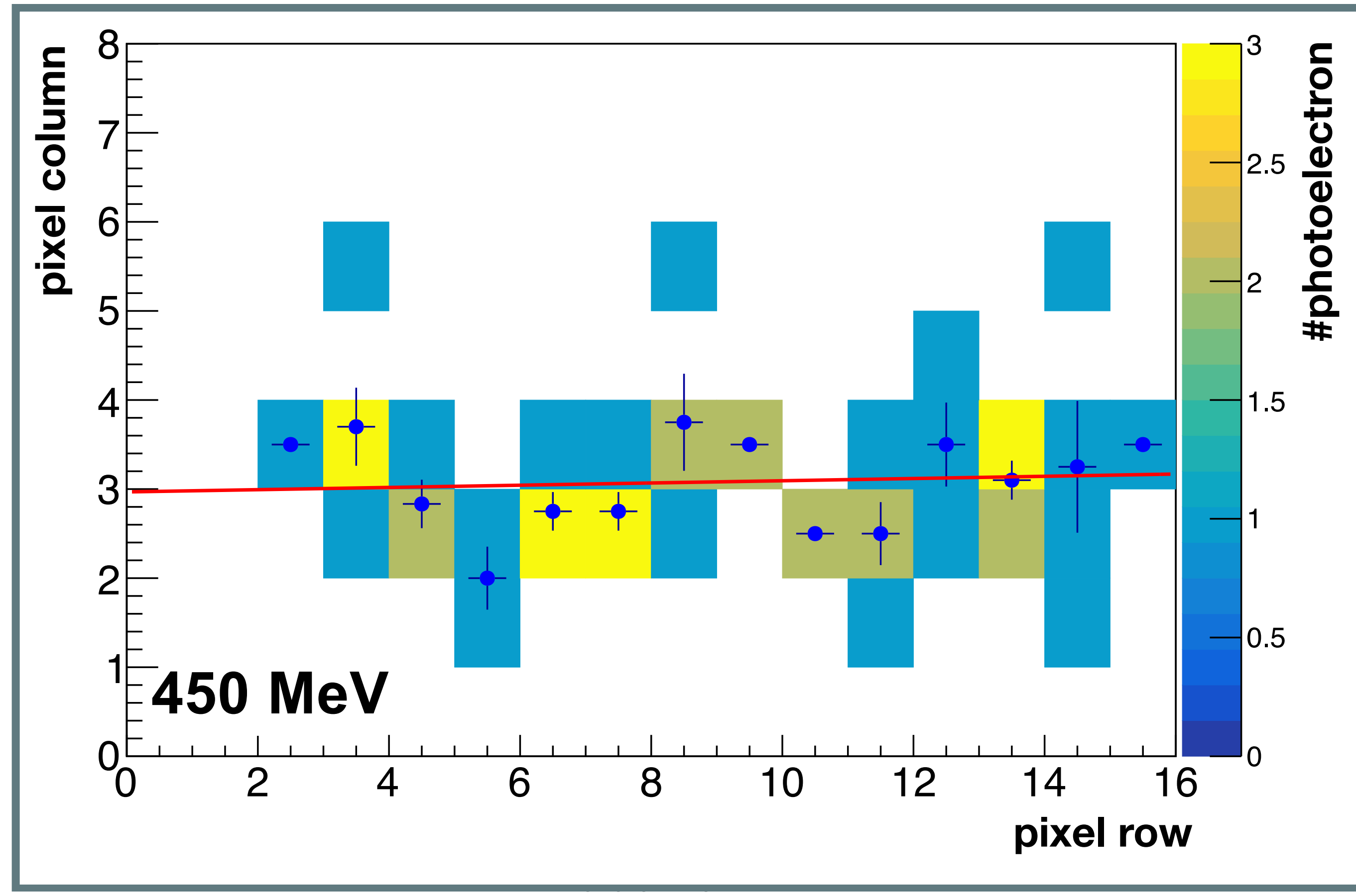
=> electron beam ~ 400 MeV***

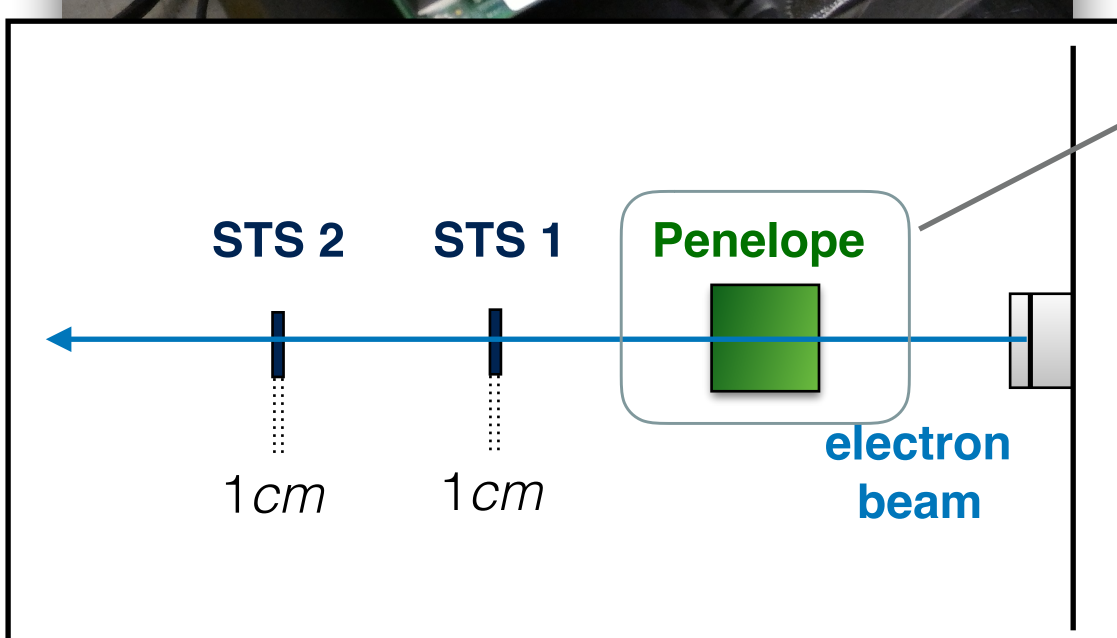
=> protons (60-230 MeV)

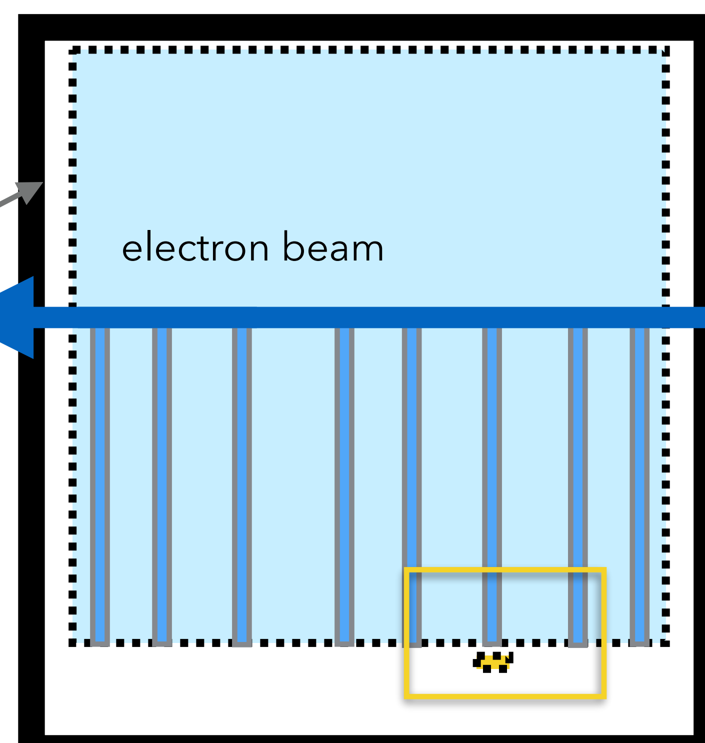
*http://iris.fbk.eu/projects/spadnet

ELECTRONS @ BTF - LABORATORI NAZIONALI FRASCATI









Characteristics:

-Beam Energy: [100 - 450] MeV electrons

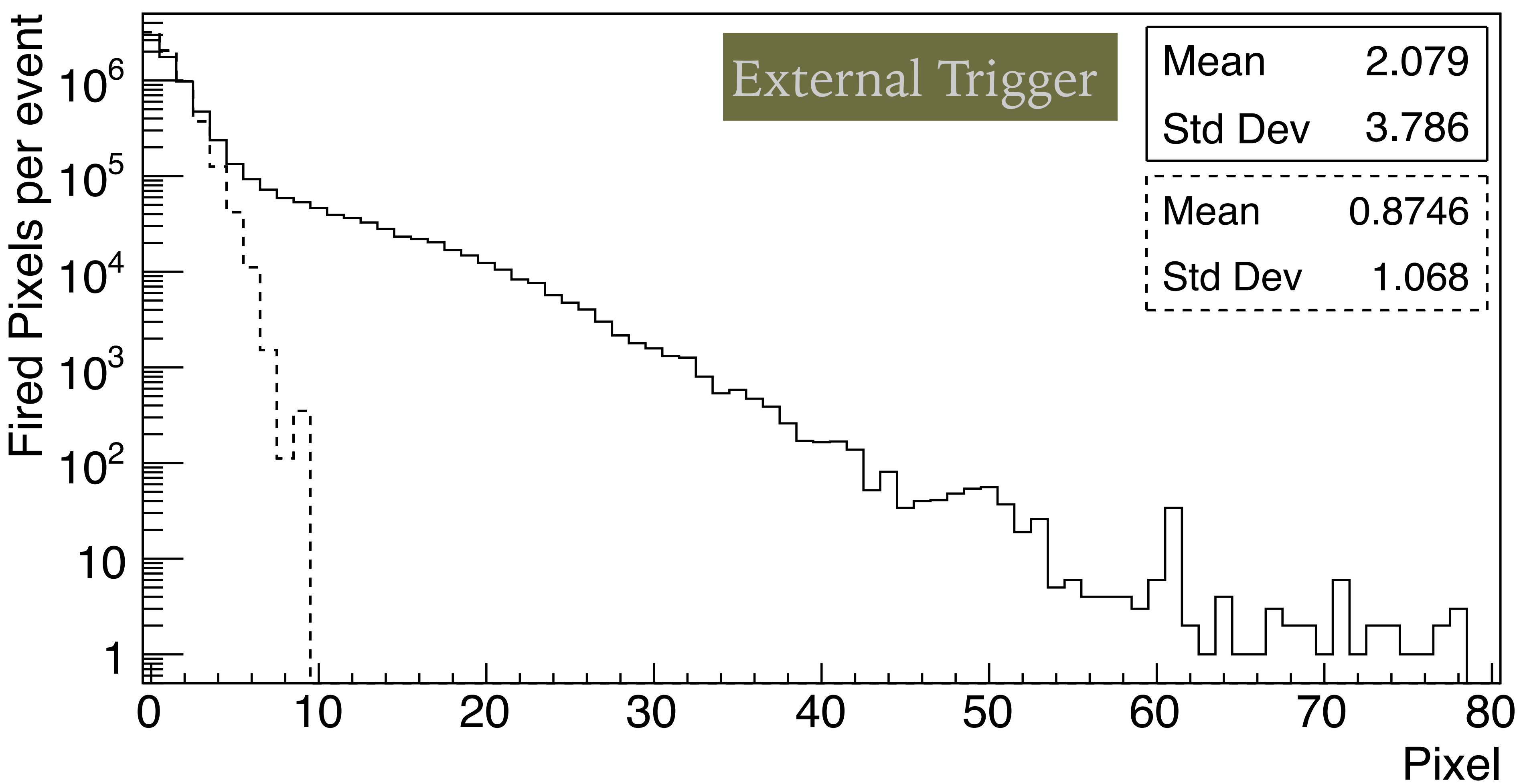
-Beam Size(σ) ~ 1 mm

-External Trigger

ELECTRONS @ BTF - LABORATORI NAZIONALI FRASCATI

Electrons@450 MeV are ~ minimum ionizing particle

Using m.i.p. it has been possible to study the discrimination between signal and noise in the worst case with particles at the minimum of their energy loss.



<u>Evaluation of the trigger threshold</u>

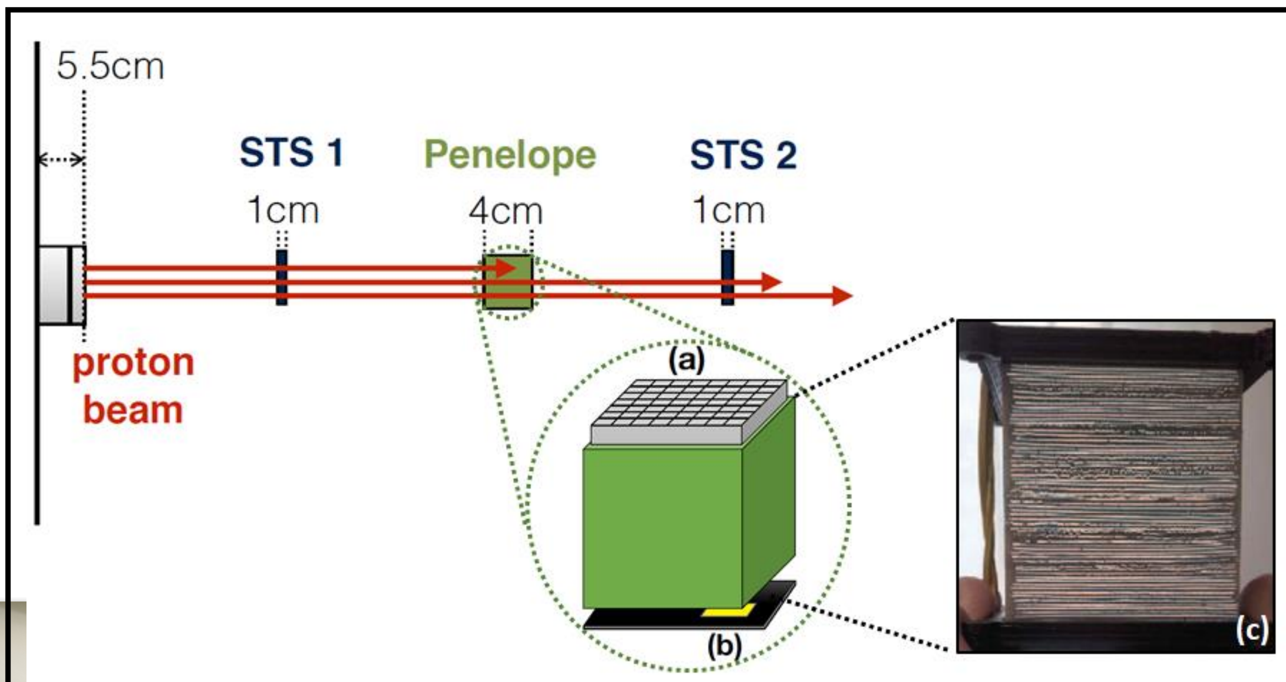
Comparison between the distributions of number of fired pixel :

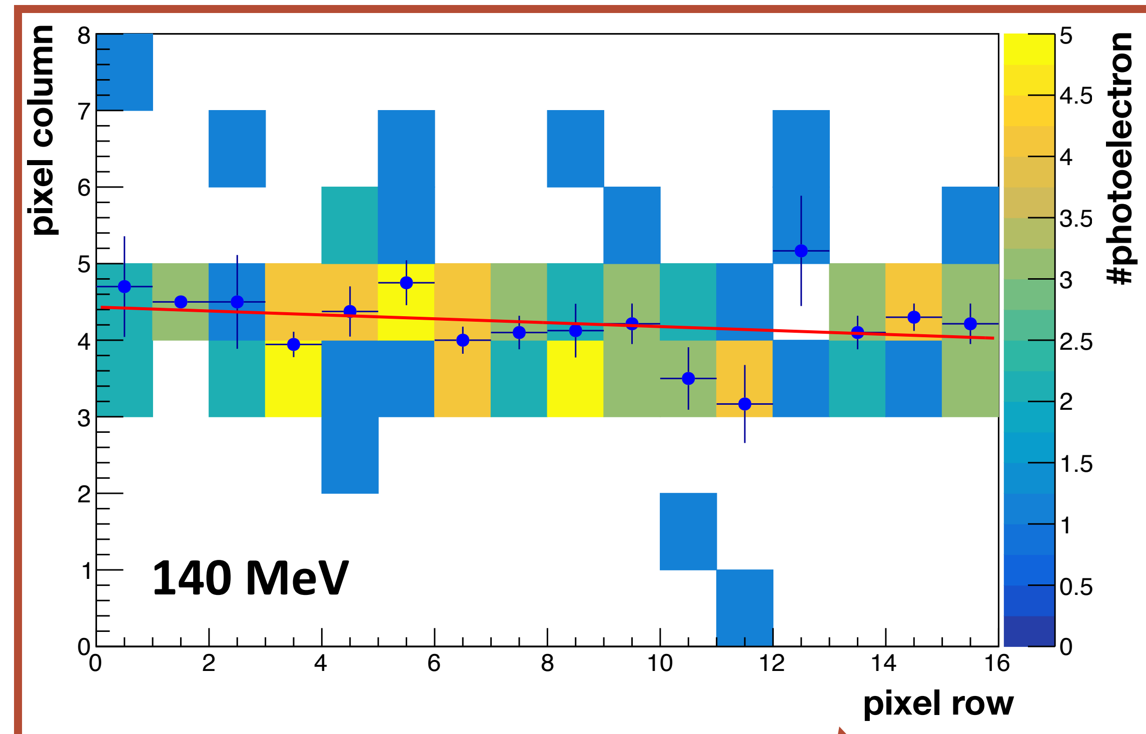
- when the particles of the beam have crossed the tracker
- when the beam has been switched off.

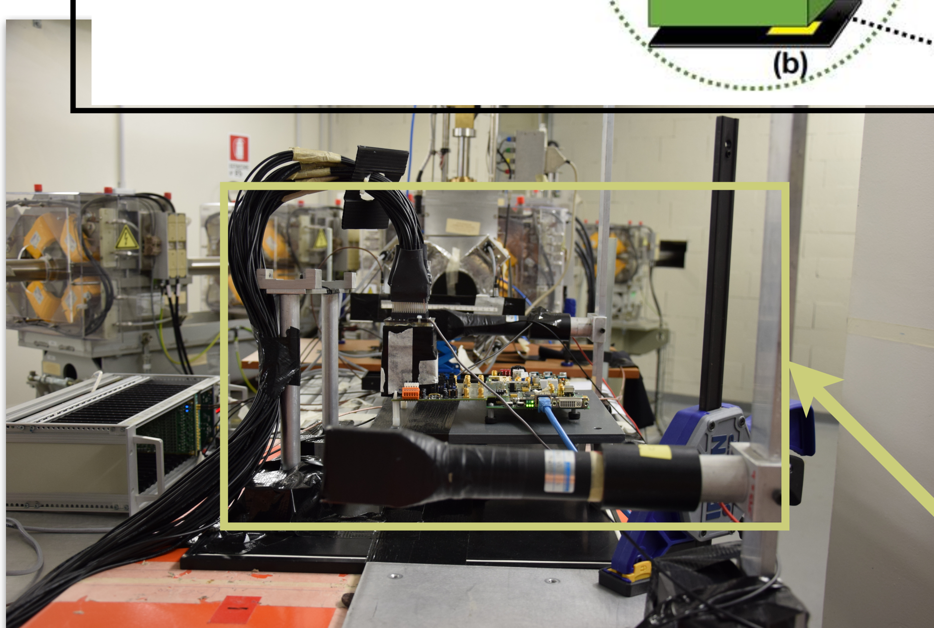
PROTONS @ TRENTO PROTON THERAPY CENTER

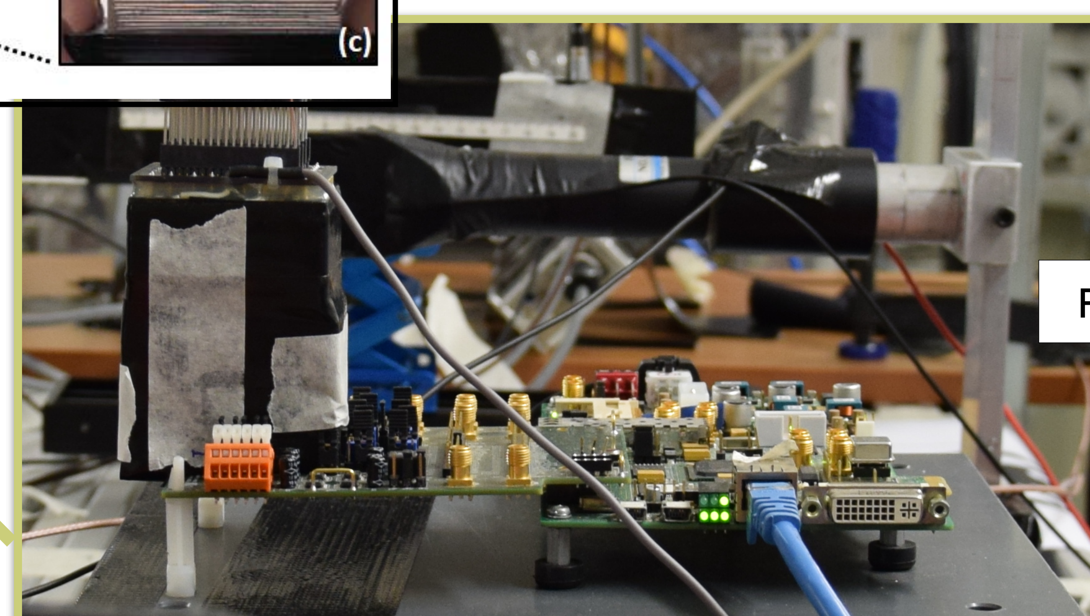
Beam energy: [70-140] MeV protons

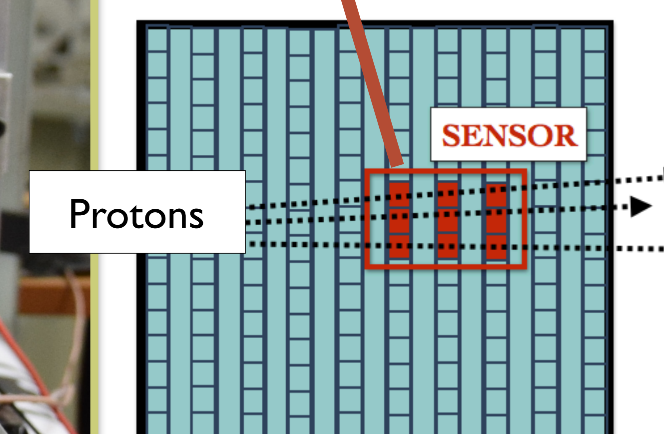
Beam size (σ): [3-7] mm





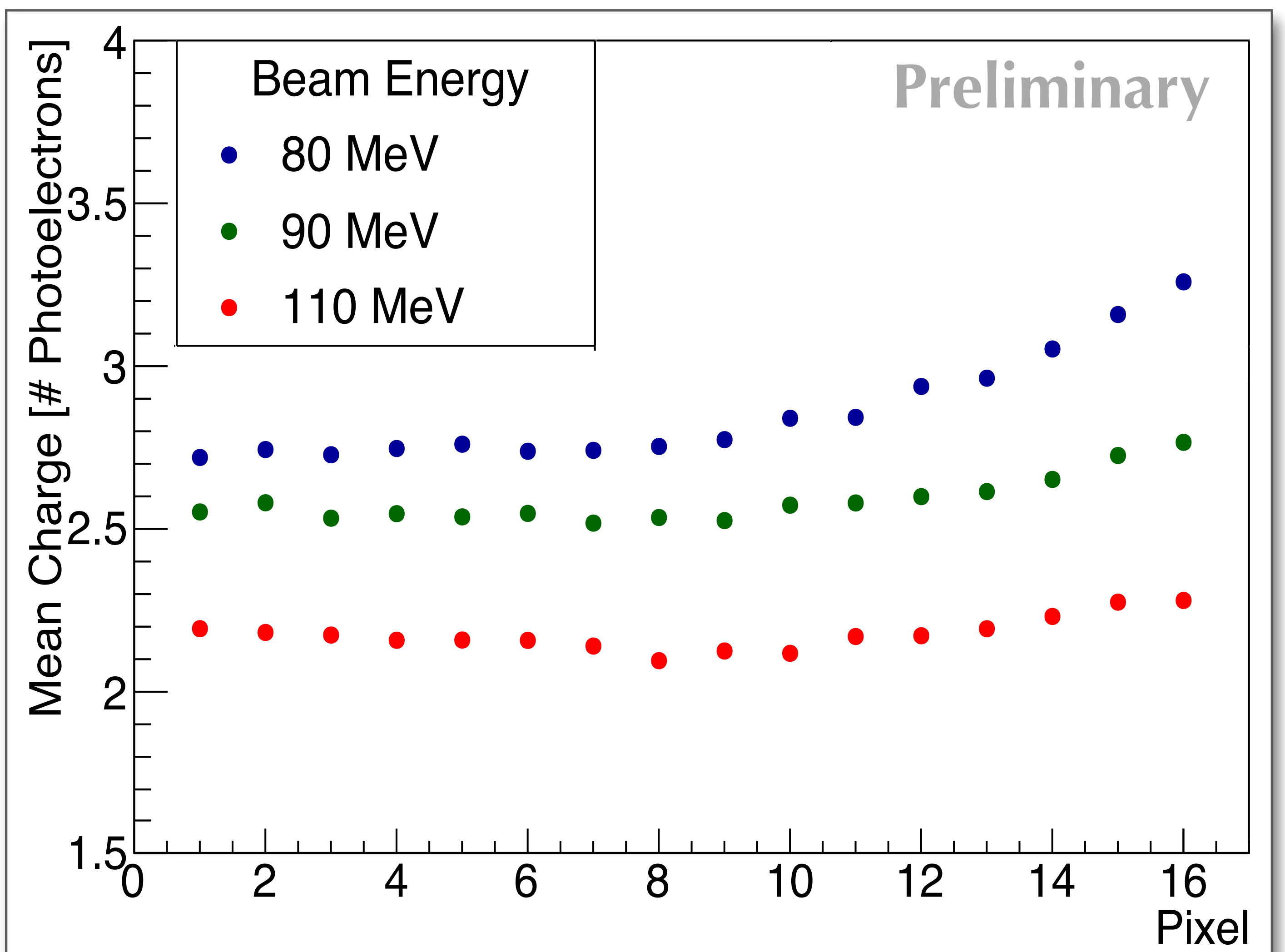


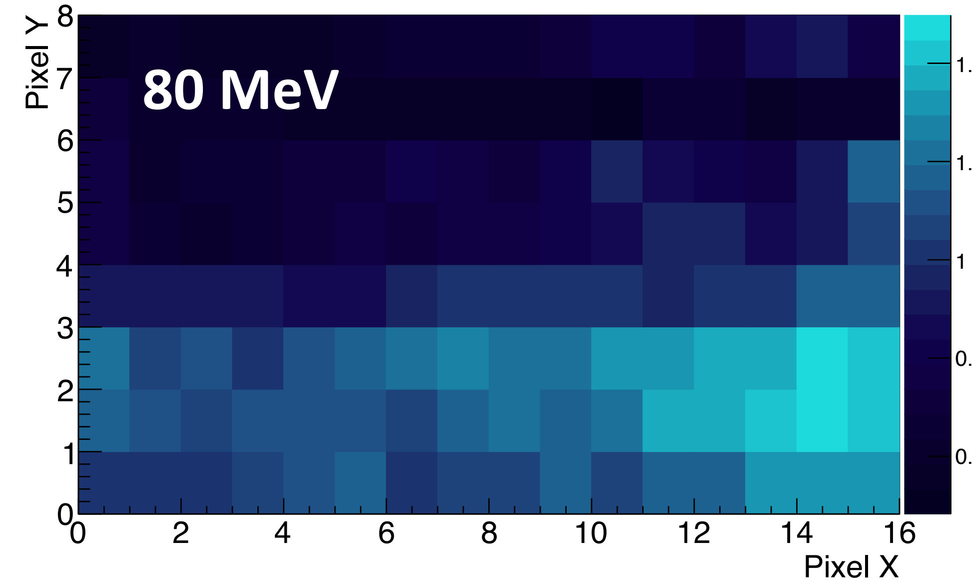


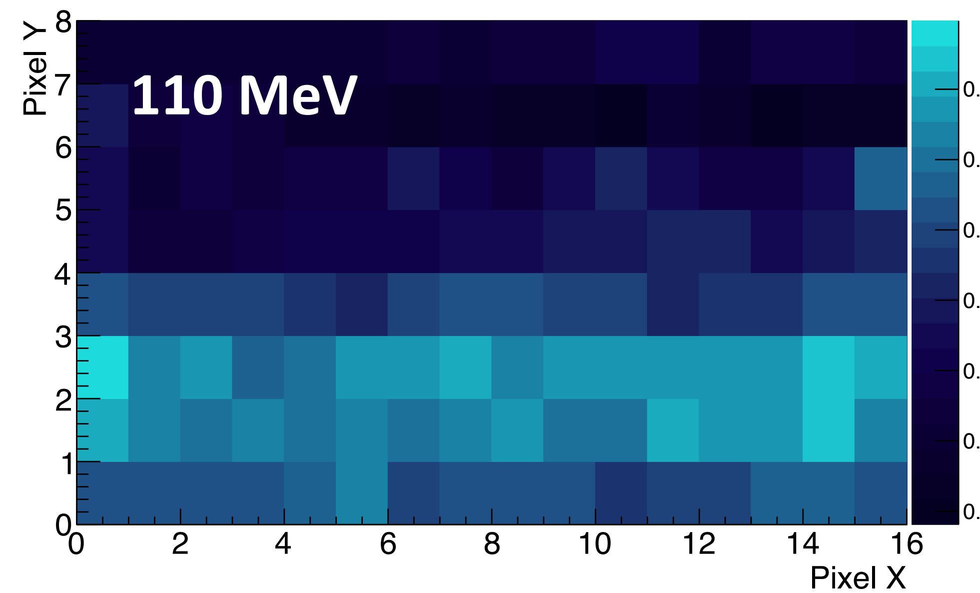


ENERGY LOSS DE/DX INSIDE SPADNET-I

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

CONCLUSION

- In November 2018 the first SBAM chip will be realized at LFoundy. Next months will be dedicated to electronic test that will take place at FBK while the characterization of the chip coupled with Penelope will be realized in Rome;
- In the next period the work on simulation will be focalized on the implementation of the readout system: the pixel structure, the dark counts and the sensor double threshold trigger system will be introduced in the code.

	I year		II year		III year	
Sensor		SBAM design & development		Electronic Test FBK and Rome		Chip Full Run
Tracker	Construction of *Penelope* prototype	Development of the final construction technique		Final Matrix development		
Simulation and Software			Event reconstruction software and detector resolution with ES		Final readout implementation	
Measurements		Calibration of prototypes with Protons				

TALKS AND PRESENTATIONS

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

- 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)

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