A new compact tracker for ultrafast secondary neutrons produced in light ions therapy

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CHARGED PARTICLE THERAPY

PT is a modern technique of non-invasive radiotherapy mainly devoted to the treatment of tumours untreatable with surgery or conventional radiotherapy

Light ions advantages (\(^{12}\text{C}\) ions):
- better spatial selectivity in dose deposition (Bragg Peak) sparing healthy tissues (less MS than p);
- suited for deep-seated radio-resistant solid tumours:
  - relative biological effectiveness (RBE)
  - oxygen enhancement ratio (OER)

Light ions disadvantages:
- more fragmentation (secondary products);

Increasing interest in other ions, ex. \(^{4}\text{He}\) and \(^{16}\text{O}\).
Neutral and charged secondary particles are largely produced during the patient irradiation:

- it is crucial to characterize the secondary production in order to evaluate its contribution to the total energy deposit;

- **treatment planning system** has to take into account their contributions to the additional dose;

- .. but.. charged fragments can be exploited for monitoring.

- RESULTS - CONCLUSION

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See Poster n. 178
SECONDARY NEUTRONS

Secondary neutrons has to be deeply investigated because they can release addition dose also far away from the treated volume.

Secondary malignant neoplasm (SMN): possible complication induced neutrons, one of the main concern in PT, especially in paediatric cases.

The incidence (also years after the treatment) of SMNs impacts directly in the quality and the expectation of life of the patient.
SECONDARY NEUTRONS

Neutrons are produced (as protons) in the beam nuclear interactions with the matters, in particular with the patient tissues.

Secondary neutrons interact also with the treatment room (and with the patient!) degrading their energy: moderation process.

It is therefore important to develop a detector capable of fully reconstruct neutrons in order to characterize their emission profile ($\theta$) and spectra ($E_{\text{kin}}$) and of rejecting the background contribution due to moderation processes (tracking device).

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**THERAPEUTIC BEAM**

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![Graph showing neutron yield vs. neutron energy](image-url)
Tracking the neutrons with high efficiency

Double elastic scattering

1. First neutron interaction: elastic scattering (ES)
2. Proton recoil ($E_{\text{kin}}$ from range)

\[ \vec{p}_n = \frac{\vec{p}_p}{\cos \theta_p} \hat{n} \]

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

\[ \vec{p}_{n'} = \frac{\vec{p}_{p'}}{\cos \theta_{p'}} \hat{n}' \]

Hydrogenated target
Double elastic scattering

**SCINTILLATING PLASTIC FIBRES**

- squared 250 µm (to maximise the granularity)
- plastic (high neutron interaction probability on H)

**Final tracker size:** 10 x 10 x 20 cm³

more than 6x10⁵ channels

=> silicon readout system
A Monte Carlo simulation has been developed using FLUKA code to optimize and study the detector. The energy release of the protons in the fibers as a function of the neutron (and proton) energy has been evaluated.

Ex. of the proton spectrum for 100MeV neutrons


M. Marafini et al., PMB (2017) doi: 10.1088/1361-6560/aa623a
Digital silicon diode (Silicon Photon Avalanche Diode -SPAD) allows to build a sensor with customized 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.

- Need to keep the space granularity of the fibres
- Few photons (few ph. electrons)
- Fast signals: typically ~5ns
Main characteristics of the new sensor:

- Pixel 125x250 µm
- Side-by-side sensors
- Fill Factor ~33%
- Trigger logic tuned for plastic scintillation signals
- Quantum efficiency ~40%
- Possibility to turn-off noisy SPAD (Dark Current reduction)
- Possible EXT. Trigger
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 3 layers 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)
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.

- 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.**

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

A tracker prototipe (4 x 4 x 4.8 cm³) has been realized as a proof of principle for proton trading and in order to test the assembling procedure.

The new sensor SBAM has been developed 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.

Test PENELOPE prototype:
- $^{90}$Sr (electrons ~2 MeV)*
- cosmics rays (mip)
- electrons@BTF (30-510 MeV) (~mip)**
- protons@Trento (60-230MeV)

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

* S.M. Vallie 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
Beam energy: [70-140] MeV protons
Beam size ($\sigma$): [3-7] mm

PENELOPE readout FBK spad-net sensor (128 ch., 600 $\mu$m per pixel)

A second readout with a commercial multi-anode PMT has been used to cross-check the tracking efficiency.
Sensor response: map of the average number of ph.el per pixel (75k events)

Example of a 140 MeV proton track reconstructed by the SPAD-net sensor.

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
Simulated energy deposited in the fibres as a function of the primary proton kinetic energy (only the volume covered by the SPAD-net sensor was considered).

As expected, the Bragg Peak is clearly visible for 83 MeV protons.

CONCLUSION

NEXT FUTURE:

1. New sensor SBAM:
   1. test chip (may 2018 @LFoundery, under test @FBK summer 2018)
   2. full run (2019);
2. Full matrix assembling and instrumentation;
3. Calibration and test beam (protons at TIFPA, neutrons ?);

Measurements with secondary neutrons produced by Carbon ions (CNAO) beams on different targets;

Evaluation of the impact of the secondary neutron emissions in TPS, in particular for Paediatric Particle Therapy.
BACK UP SLIDE
RESOLUTION

For single elastic scattering

Preliminary