Fast neutron spectroscopy with Mimac-FastN : a mobile and directional fast neutron spectrometer, from 1 MeV up to 15 MeV

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Abstract. In the frame of direct dark matter search, the fast neutrons producing elastic collisions are the ultimate background. The MIMAC (MIcro-tpc MAtrix Chambers) project has developed a directional detector providing the directional signature to discriminate them based on 3D nuclear tracks reconstruction. The MIMAC team of the LPSC has adapted one MIMAC chamber as a portable fast neutron spectrometer, the Mimac-FastN detector, having a very large neutron energy range (10 keV – 200 MeV) with different gas mixtures and pressures. The present paper shows its main features and functionality and demonstrates its potential in the energy range from 1 MeV to 15 MeV.

1. Introduction
In the frame of direct dark matter search, the fast neutrons producing elastic collisions on the nuclei of the active volume of the detector generate the same signals that an eventual WIMP (Weakly Interacting Massive Particle). These events as well as the neutrinos are the ultimate background for dark matter detection. In the frame of the MIMAC project (MIcro-tpc MAtrix Chambers), a directional detector giving the directional signature to discriminate them [ref 1] has been developed. The LPSC MIMAC team has explored the possibility to adapt one MIMAC chamber as a fast neutron spectrometer.

Neutron spectroscopy at high energies (above 1 MeV) is challenging for the present available detector technologies. Indeed, iterative moderation using neutron capture on converters leads to poor energy resolution and requires hypothesis on the expected neutron energy. Besides, the detection in solids through elastic collisions is limited due to the absorption of recoils in the converter, whereas detection in liquid scintillators results in a limited measuring range.

In the present paper, we describe the fast neutron spectrometer called Mimac-FastN, that tackles these issues for high neutron energies, based on the 3D detection of nuclear recoils becoming possible from a very fast sampled, self-triggered and low noise electronics developed at the LPSC [ref.2 and 3].
2. Detection principle

Mimac-FastN is a micro-TPC (Time Projection Chamber) based on a micro-pattern detector coupled to a fast self-triggered electronics [ref.1]. The chamber is filled with a gas that constitutes the converter of fast neutrons into charged particles. In the present paper, we describe the operation of Mimac-FastN with 2 liters of a gas mixture of 95% of $^4$He and 5% of CO$_2$ as a quencher, at 700 mbar, to measure neutron energies between 1 MeV up to 15 MeV. The gas mixture and the pressure can be modified depending on the application energy range [ref.4]. Fast neutron detection is performed through the tracking of the nuclear recoils that result from nuclear elastic scattering between incident fast neutrons and the gas nuclei. The nuclear recoils lose part of their kinetic energy by ionization in the detector gas. The primary electrons resulting from this ionization process are collected by an electrical field of 160 V/cm through a 25 cm long drift chamber, up to the micro-pattern detector (a square bulk Micromegas [ref.5] with a 512 μm gap, and sides of 10.8 cm). A high electrical field of 10.5 kV/cm between the grid and the anode of the Micromegas produces avalanches, that result in the signal amplification. Resulting secondary electrons are collected on the pixelated anode and the ions drifting toward the grid.

The Mimac-FastN electronic board [ref.2] manages two synchronized types of data. The first one is the energy released in ionization by the nuclear recoil, read through a charge preamplifier connected to the mesh of the micro-pattern detector. This preamplifier, developed at LPSC, has a gain of about 100 mV/pC (that is adjustable depending on the energy range required), and a time constant of 2 ms so that the rise time of the signal is small compared to the electronic decay time. The second type of data is the fired strips of pixels on the anode of the micro-pattern detector (512 strips, 256 in X and 256 in Y), which gives access to the 2D position of the charges.

The data on the grid and on the pixelated anode are read out at a sampling frequency of 40 or 50 MHz, depending on the length of tracks to be produced, and managed by the electronic board. In this way, each nuclear recoil track is sliced in samples. In the gas mixture $^4$He/CO$_2$ (5%) at 700 mbar and at 40 MHz sampling, each sample has a perpendicular component to the anode of 241 μm (referring to a Magboltz simulation that gives a drift velocity of 9.65 μm/ns in this gas mixture, which leads to a length of 9.65 μm/ns x 25 ns). So the 3D nuclear recoil track is reconstructed thanks to the composition of the 2D picture on the pixelated anode, and the perpendicular component inferred from the electronic sampling.

The electronic board is coupled to the micro-pattern detector through an interface board that ensures the chamber tightness. This very low noise electronic board manages itself the triggering of each event acquisition through a FPGA. The acquisition triggering is done from the signal on the grid requiring a ionization energy threshold. Once triggered, the acquisition window remains open 25 μs at maximum. The synchronization of the readout on the grid (ionization energy) and the readout on the pixelated anode (track data) is managed by the FPGA. The sampling time is the same for the pixelated anode reading, and for the charge profile on the grid. The two different types of information being the track coordinates and the deposited charges can then be synchronized for each time-slice. The pixelated anode readout is performed by the 8 MIMAC ASICs, specifically developed by the MIMAC team of the LPSC [ref.3].

A dedicated software controls the FPGA through a USB connection, and stores the data event by event in a text file or in a PostgreSQL database. Analysing the event-by-event sampled data from the grid and the pixelated anode, the kinetic energy of the incident neutron can be measured.

The neutron kinetic energy is deduced from the kinetic energy of the nuclear recoil by the following equation:

$$E_n = \frac{(1 + m_R)^2}{4m_R} \times \frac{E_R}{\cos^2(\theta_{RN})}$$

being $E_n$ the incident neutron energy, $E_R$ the kinetic energy of the nuclear recoil, $\theta_{RN}$ the angle between the nuclear recoil track and the incident neutron direction, and $m_R$ the nuclear recoil mass.
The kinetic energy of the nuclear recoil is determined from the measured ionization energy, corrected from the ionization quenching factor ([ref.6] and [ref.7]) in the considered gas mixture. The angle $\theta_{RN}$ is estimated from the 3D recoil track reconstruction, and from the neutron emitter position that gives the incident neutron direction (see Figure 1).

![Figure 1: Drawing of the detector structure on the left, and picture of Mimac-FastN on the right.](image)

3. Special features of nuclear elastic collisions with neutrons above 3 MeV

The angular distributions of the $^4$He recoils, resulting from elastic diffusions with fast neutrons, is a function of the neutron energy. Angular distributions in the laboratory frame have been calculated with the Monte Carlo code Geant 4 [ref. 8], version 10.10.01, with the physics list QGSP_BERT_HP_LIV, and a chamber filled with a gas mixture of $^4$He/CO$_2$ (5%) at 700 mbar (see Figure 2).

![Figure 2: Angular distributions of $^4$He recoils, resulting from elastic diffusions with neutrons of 1 MeV, 3 MeV and 15 MeV.](image)

These angular distributions show that for neutron energies from 3 MeV, angles above 60° are more likely. This has two implications. The first one is that the most probable kinetic energy of the $^4$He recoil is 1.1 MeV for a neutron of 15 MeV. In a mixture of $^4$He/CO$_2$ (5%) at 700 mbar, a recoil track with this kinetic energy is 3.3 cm long according to SRIM [ref. 9], and so remains contained in the...
drift volume as described previously. So the higher the neutron energy is, the more likely it is that the recoil track is small.

The second consequence is that a 3D geometry is required to detect recoils for neutron energies above 3 MeV. The advantage of a gaseous detector like Mimac-FastN with a cylindric or cubic symmetry geometry, is that recoils can be detected whatever their direction is. The pixelated anode could represent a limitation, if the nuclear recoil tracks are parallel to this plane, since in this case, the 3rd dimension calculated by the electronic sampling will be limited to a few samples. However, knowing the position of the neutron emitter, the chamber can be orientated perpendicularly to the mean emission direction. In such a configuration, if the $\theta_{RN}$ angles are above 60°, the tracks’ orientations are optimized compared with the anode plane (see Figure 3).

![Figure 3: Measure configuration for neutron energies above 3 MeV.](image)

In this perpendicular configuration, two groups of nuclear recoils can be detected: recoils directed towards the cathode, and recoils directed towards the anode. Having the head-tail signature of the nuclear recoil tracks is a prerequisite to the neutron energy calculation and diffused neutrons discrimination. In order to determine the track direction of a nuclear recoil track by means of the acquired data the observable described in the following paragraph has been defined.

4. Nuclear recoil track direction

With a time sampling of 25 ns, Mimac-FastN gives access to a high resolution profile of the charges deposited in ionization as a function of time, for each event.

At energies below 1 MeV for $^4$He, the Bragg peak is located in the first half of the track. A symmetry analysis of the charge profile on the grid, compared with its middle point in amplitude, can be performed as illustrated in Figure 4, in order to find the Bragg peak location for which the maximum number of primary electrons have been produced.

![Figure 4: Definition of risetimes 1 and 2 on the charge profile of an $^4$He recoil on the micro-mesh.](image)

The comparison of risetime$_1$ and risetime$_2$ measurements constitutes an observable to define the track direction. The Figure 5 shows a plot of risetime$_2$ as a function of risetime$_1$ for $^4$He recoils from
elastic diffusions with neutrons of 3 MeV, in a perpendicular configuration of the beam. This plot reveals two distinct branches that are assigned to each track direction.

Figure 5: Comparison of risetime, and risetime, measurements for $^4$He recoils resulting from elastic diffusions with neutrons of 3 MeV, in a perpendicular configuration with respect to the beam.

5. Energy calibration

The charge profile is measured through a charge preamplifier connected to the mesh and sent to a Flash-ADC (on the electronic board) that digitizes the signal on 4096 channels. The Flash-ADC energy calibration is done through a natural boron coating fixed on the cathode and by means of the following capture reaction of thermal neutrons by the $^{10}$B isotope:

\[
\begin{align*}
\nu + ^{10}\text{B} & \rightarrow ^{4}\text{He} + ^{7}\text{Li} + \gamma \quad (94\%) \\
\nu + ^{10}\text{B} & \rightarrow ^{4}\text{He} + ^{7}\text{Li} \quad (6\%)
\end{align*}
\]

The boron coating consists in an IBS (Ion Beam Sputtering) deposit of 500 nm of $\text{nat}^{10}$B$_4$C on an aluminum sheet (see picture in Figure 6). The $^{10}$B isotope represents 20% of the natural boron. The coating has a specific shape in order to check the spatial resolution of the boron projection picture on the anode. The energies deposited in ionization by the $^4$He and $^7$Li particles are measured on the Flash-ADC, and their tracks are imaged on the pixelated anode.

Figure 6 shows the anode projection of the detector exposed to a 3 MeV neutron field crossing 5 cm of high density polyethylene. The projection on the anode of the first point of all the tracks directed towards the anode, highlights the boron coating, due to neutron captures, that become predominant with respect to the total elastic diffusions on the gas nuclei, at low energies. The presence on this picture of the specific shape of the boron corner proves the uniformity of the electrical field lines in the field cage and gives an estimation of the spatial resolution.

Figure 6: on the left, picture of the B4C coating used for energy calibration and spatial resolution measurements; on the right, projection on the pixelated anode of the first point of all the tracks, that highlights the boron shaped coating, in a neutron beam of 3 MeV moderated through 5 cm of HDPE.
On a Geant4 simulation, a selection of all the tracks whose interaction points are located on the boron coating projection, leads to the energy spectrum of the particles issued from neutron captures on $^{10}\text{B}$, as presented on Figure 7.

![Figure 7: Ionization energy spectrum of the $^{4}\text{He}$ and $^{7}\text{Li}$ particles resulting from neutron captures on the boron coating; on the left, a simulation with Geant4; on the right, the measured data.](image)

The energy calibration of the Flash-ADC can be done with the end-points or the mean peak values of the peaks issued from the branching ratio of 94%. The peak issued from the alpha particle emitted in the case of a branching ratio of 6% constitutes a checkpoint of the calibration equation.

### 6. Discrimination of species and physical process

Elastic diffusions can occur on all the gas nuclei constituting the gas chamber, so recoils of $^{4}\text{He}$, $^{12}\text{C}$ and $^{16}\text{O}$ are detected. Besides, fast neutrons can interact with all the structures being part of the detector, mostly composed of aluminum, Kapton, PMMA and copper. These interactions have been explored by simulations with Geant4.

Measurements have been performed with Mimac-FastN at the GENESIS facility [ref.10] with the reaction $^3\text{H}(d(220 \text{ keV}), \text{n})^4\text{He}$, that results in the production of neutrons of 15 MeV at 0°. Figure 8 shows a comparison of the simulated and measured track lengths as a function of the ionization energy for all the events detected.

![Figure 8: Track lengths as a function of the energy deposited in ionization, in a configuration parallel to a neutron beam of 15 MeV produced by the reaction $^3\text{H}(d(220 \text{ keV}), \text{n})^4\text{He}$; on the left, a simulation with Geant4; on the right, the measured data at GENESIS facility.](image)
Different structures emerge, that are assigned as follows, as demonstrated by simulations:

**Branch A**: protons issued from Kapton, PMMA, aluminum and copper, that do not release all their energy in the active volume, because their track lengths are much higher than the field cage length. This branch is broad because the length related to the energy deposited depends on the initial energy of the proton and the Bragg peak position.

**Branch B**: protons issued from Kapton and PMMA, that release their energy inside the active volume.

**Branch C**: 

\[
^4\text{He} \text{ recoils with a kinetic energy of more than 6 MeV that are scattered in a head-on collision along the longitudinal chamber axis (perpendicular to the pixelated anode), that release little energy in the gaseous volume with long path length, since the stopping power is small at the beginning of the recoil travel inside the gas (the Bragg peak is at the end of the track).}
\]

**Structure D**: 

\[
^4\text{He} \text{ recoils of low energy that release part of their energy in the active volume before going outside.}
\]

**Branch E**: 

\[
^4\text{He} \text{ recoils that release all their energy in the active volume.}
\]

**Branch F**: 

\[
^{12}\text{C} \text{ and }^{16}\text{O} \text{ recoils that release all their energy in the active volume.}
\]

Given the good separation of all these branches characterizing different physical process and nuclear recoil masses, we can easily select the branch E (\(^4\text{He} \text{ recoils}) that is the main branch of interest for the neutron spectrum measurement.

7. **Gamma – neutron rejection**

Compton electrons resulting from the interaction of few MeV gamma rays with the detector structures also have to be discriminated from the \(^4\text{He} \text{ recoils selected for the neutron spectrum reconstruction. They lose 70 keV at most in the Mimac-FastN gaseous active volume, as attested by a simulation with Geant 4. The energy loss per time-slice of these electrons is so low (0.06 keV/time-slice on average) that the energy deposited by these electrons is not enough to trigger the strips of pixels, and so these events do not leave dense and clear tracks in the active volume, being easily discriminated.**

8. **Experimental results with \(^3\text{H}(d(220 \text{ keV}), n)^4\text{He}**

Spectroscopy of the neutrons produced by the reaction \(^3\text{H}(d(220 \text{ keV}), n)^4\text{He} has been performed at the GENESIS facility [ref.10], with Mimac-FastN placed at 0° degree with respect to the deuteron beam axis. In this configuration, the \(^3\text{H}(d(220 \text{ keV}), n)^4\text{He} nuclear reaction produces neutrons of 15.1 MeV. The target is a solid target, composed of titanium loaded with tritium, and evaporated on a 3 mm thick copper backing [ref.11]. The measurement has been done in one hour, with a deuteron current of 5 \(\mu\text{A}\. The detector was positioned at 1.7 meters from the target. In this directional measurement, we consider the target location as the neutron source position. The spectrometer Mimac-FastN was filled with a gas mixture of 95 % of \(^4\text{He} \text{ and 5 % of CO}_2\text{ at 700 mbar. The selection of \(^4\text{He recoils leads to the construction of the neutron energy spectrum, plotted on Figure 9.**

![Figure 9](https://example.com/figure9.png)

**Figure 9**: Measured neutron spectrum with the reaction \(^3\text{H}(d(220 \text{ keV}), n)^4\text{He at GENESIS, with a binning of 320 keV/bin.**
The measured neutron spectrum reveals a multi-energetic spectrum with 4 structures, explained by the target composition and the interaction of deuterons with all the components of the target. The peak A is the expected production of neutrons of 15.1 MeV resulting from the reaction $^3$H(d(220 keV), n)$^4$He. The peak B is populated by neutrons resulting from $^{65}$Cu(d,n)$^{66}$Zn, $^{64}$Cu(d,n)$^{65}$Zn and $^{49}$Ti(d,n)$^{50}$V. The peak C results from D(d,n) reactions following the implantation of part of the incident deuterons into the target backing. The structure D is a contribution of the residual scattered neutrons on the bunker walls.

9. Conclusion
We have described the ability of Mimac-FastN to measure mono-energetic neutron spectra, with its high spatial resolution 3D track reconstruction associated with its large adjustable measuring range. Using the same gas mixture, this directional fast neutron spectrometer gives a complete multi-energetic neutron spectrum exploring the material and eventual pollutions of the target or neutron sources. This ability to provide multi-energetic neutron spectrum has already been applied to characterize the angular distribution of fast neutrons produced in a nuclear reaction proposed for a radiotherapy called Accelerator-Based Boron Neutron Capture Therapy (AB-BNCT) [ref.12]. Besides this study, preliminary measurements performed at CERF (CERN) [ref.13] with this instrument have recently shown a good potential for spectrometry at neutron energies as high as 200 MeV, a range covering atmospheric neutron production and high energy neutron monitoring.

Further details on Mimac-FastN characteristics and results can be read on the article [ref.14].

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