Micromegas for beam loss monitoring

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Abstract. The early detection of beam losses and the alarm to the machine protection system in accelerators are crucial for the safe operation of the machine. In the low energy region of the hadron accelerators, only neutrons and photons are produced in the case of a beam loss. However, photons are also emitted by electrons at the RF cavities, becoming a natural background for losses identification. A new kind of beam loss monitors have been conceived to extend the sensitivity to the low energy region of the high intensity hadron accelerators. They are based on Micromegas detectors sensitive to fast neutrons. The appropriate configuration of the Micromegas operating conditions will allow a fast response, a sensitivity to small beam losses and a suppressed sensitivity to photons. In this paper the operation principle and the system developed for the European Spallation Source will be presented, with focus on the results obtained at different irradiation facilities. First time proof of operation in real conditions, with the detection of beam losses, will be also shown with measurements performed at LINAC4 (CERN).

1. Introduction

The detection and control of beam losses is crucial in any accelerator. In high intensity hadron accelerators even low energy beam can be a danger for material activation or for machine damaging in case of beam losses. Therefore the monitoring and early detection of small beam losses is of a high importance, usually demanding to be sensitive to loss levels smaller than 1 \textit{W/m}. The signature of the losses depends on the location where they occur, as different types of secondary particles will be emitted. In the low energy region only neutrons and gammas are produced. The objective of the detectors presented here is to be used as Beam Loss Monitors (BLM) in the low energy part of hadron accelerators detecting the produced fast neutrons to enlarge the sensitivity to small losses while having an appropriate time response for machine protection.

In case of the standard BLM detector, namely ionisation chambers, the production of gammas and x-rays from RF emission represents a challenging background for them. The proposed detector has a very low sensitivity to the gamma background. Moreover, we are interested in the detection of fast neutrons to obtain information of the loss location, and no in thermal neutrons that can be emitted also from the surroundings, so the detectors have been conceived to be almost blind to thermal neutrons. Initial efforts to develop such a detector were done...
at SNS [1]. What we present here is based on Micromegas technology [2, 3]. They offer the advantage to be able to be designed and operated in an almost blind mode for gammas and with a correct combination of neutron convertors and absorbers, to have a high sensitivity to fast neutrons and no thermal. Most of the developments here presented have been done in the context of the in-kind contract between the European Spallation Source (ESS) and the IRFU (Institute of Research into the Fundamental laws of the Universe) at CEA-Saclay. The project consist on the design, construction, validation and commissioning of a system composed by 84 detectors, mainly distributed in the low energy part of the accelerator [4, 5, 6]. In this contribution we focus on the detector development part and in its experimental characterization.

2. nBLM Detectors
Two complementary nBLM modules based on Micromegas detectors as readout have been conceived and tested. Micromegas detector form part of the MPGD family (Multi pattern Gaseous Detectors) offering robustness, high gain, fast signals, high rate capabilities and good ageing properties. It operates with three electrodes: cathode, micromesh and anode. The micromesh and anode are what make up the Micromegas detector itself and the micromesh separates the gas in two regions: between the cathode and mesh is the conversion region where electrons ionize the gas and the region between the mesh and anode is the amplification region. This region is typically of the order of 50-100 µm wide. The conversion from neutrons to charge particles is done at the entrance of the conversion region using a solid convertor layer. Since their invention in 1996 Micromegas detectors have been used in a large list of nuclear and particle physics experiments. Micromegas detectors have been also used before for neutron detection [7, 8]. In this work a new application in the field of beam instrumentation in hadron accelerators is presented.

The two proposed modules have an identical gas chamber, detector, electronics and Faraday Cage but different neutron-to-charge particle converter. In one of them (the "fast") we use as convertor a Mylar foil of 125 µm (aluminized with 50 nm aluminium) glued onto the cathode and in the other (the "slow") we use 10B deposited on the cathode (thickness of 1.5 µm)\(^1\). In addition, one of them, the slow, is surrounded by polyethylene to moderate the neutrons increasing the conversion efficiency in 10B. In this case we have also added a 5 mm layer of borated plastic to absorb the thermal neutrons arriving directly from the surroundings. The moderation process will delay the signal response to \(\sim 200 \mu s\) (slow module) while in the other case the response is very fast, of \(\sim 10 \text{ ns}\) (fast module). The efficiency is higher for the slow detector than for the fast due to the higher cross-section of the thermal neutron capture in boron with respect to the proton recoils production. In combination with the neutron moderation efficiency of the polyethylene in the slow module it will imply one or two orders of magnitude lower efficiency for the fast depending on the initial neutron energy. Therefore both modules have complementary goals: one is more suitable for the monitoring of small losses while the other will give a fast signal in case of a big beam loss. A sketch of the geometry of each module and the final design of the gas chamber and the Faraday cage are shown in Figure 1.

The Micromegas used is a bulk micromegas [9] with an active area of 8x8 cm\(^2\) and the drift gap is small, \(\sim 2 \text{ mm}\) which increases the separation gamma/neutron while staying in a safe operational point. A mezzanine front-end (FEE) card with a fast current amplifier designed at CEA [10] is connected to the PCB board of the detector outside the gas chamber. Therefore the signals from the anode are amplified before sending them to the DAQ card through the long cable. The Micromegas is segmented in 4 pads providing the flexibility to accommodate for different rates or common mode noise suppression. Through jumpers in the FEE the configuration can be chosen to read from 1 to 4 segments together. By default at ESS all pads are connected into

\(^1\) Deposition done by the ESS Detector Coatings Workshop in Linköping, Sweden
Figure 1. (a) Geometry schema of the fast module. In green: the neutron convertor (mylar) placed at the entrance of the conversion region, in purple the Micromegas detector (b) Schema of the slow module. In soft blue the thermal neutron absorber layer (∼5 mm of borated rubber from Mirrotron) in orange, moderator volume (few cm thick) and in black the gas chamber identical than the one for the fast module but the neutron convertor is a deposit of 1.5 µm of $^{10}\text{B}_4\text{C}$. (c) 3D model of the final geometry of the detector chamber and the bottom part of the Faraday cage. The top parts of the Faraday cage and chamber are made transparent. The chamber encloses the PCB board and the FEE and HV power are connected to it as mezzanine cards.

3. nBLM Detectors Characterization

For the past two years, the detectors and the electronics have been tested in different irradiation installations. The response of the detectors have been studied for fast monoenergetic neutrons, gammas, thermal neutrons and in accelerators with pulsed beam. Moreover, the detectors have been tested during the commissioning of LINAC4 at CERN in December 2018 where beam losses were provoked and detected in the nBLM detector. In these section some of the main results obtained are highlighted. Some of them have been presented before in [4, 11] and a full paper with all the results is under preparation.

3.1. Time Response

The time response of the detectors is an important aspect for the safety of the accelerator, as in case of an increase of the detected neutrons, a signal should be sent to the Machine Protection System in a short time. To study this feature we have used the data obtained at the IPHI accelerator at CEA-Saclay, where a 3 MeV pulsed proton beam (of 90 µs) was deviated to arrive to a Be target to produce a neutron flux. Measurements were done triggering with the accelerator to correlate each event with the beam time. Results are shown in Figure 2. For the fast detector 2 (a), the distribution of the detected events (in black) along the time of detection is compared with the variations in the intensity of the source along time (in red). A response of few ns
have been obtained showing the capabilities of the module to react in short times. The relation between the variations in the measured neutron rate with the intensity of the beam in the target proves the capabilities of the detector to also study fine loss structures. In the case of the slow detector a delay produced by the moderation process gives a time response of few hundred of microseconds \(2\) (b). Results are compared in this case with the cumulative distribution obtained from MonteCarlo simulations for a instantaneous pulse (in red).

![Figure 2](image.png)

**Figure 2.** (a) Neutron pulse detected with the final electronics (acquired in the data campaign at LINAC4, CERN with \(V_{\text{mesh}}=550\) V and \(V_{\text{drift}}=1500\) V). The data is smoothed before applying the pulse analysis (green line). In dashed blue line is indicated the maximum amplitude, the dashed magenta line defines the pulse duration and the green’s shows the threshold to trigger the analysis. (b) Time response of the fast module (black) as measured at IPHI following the 90 \(\mu\)s proton beam pulse. It is compared with the measured current on the neutron target (red). (c) Same for the slow detector (black). The response is delayed with respect to the one obtained with the fast module due to the moderation process of the neutrons in the polyethylene. In red the cumulative distribution obtained from MonteCarlo simulations is also shown for a instantaneous pulse.

### 3.2. Gamma response

Efficiency measurements were performed at AMANDE, an IRSN facility in the south of France with calibrated monoenergetic neutron fields. The amplitude spectrum was measured with both detectors for different energies from 565 keV to \(\sim 15\) MeV. In the case of the slow module, as the conversion to charge particles is done in the boron, which emits an alpha particle with constant energy, the same energy distribution is always detected, as the one shown in Figure 3 (b). In the case of the fast detector, as the signal is produced by recoil protons, the energy depends on the initial neutron energy. Thus assuming neutrons with white spectrum, continuous energy distribution of recoil protons can be expected with small differences compared to mono-energetic neutron fields. The efficiency depends on the applied energy cut, while for the slow this dependency is small, for the fast it has a big effect due to the continuous distribution of the emitted protons.

One of the main advantages of the proposed BLM is its low sensitivity to gammas given by the fact that they ionize less than heavy particles, as alphas or protons, in the case of low gamma flux. However detection of neutrons in high gamma flux environments have been also shown possible [12, 13]. With a correct combination of gain and energy threshold, that depends on the gas used as well, we can reduce the gamma contribution to almost negligible values. The first study of the n/gamma discrimination was done in the measurements at the AMANDE facility. In the case of the 565 keV field, the neutrons were produced by a LiF target which
includes a gamma field of 6-7 MeV coming from the $^{19}$F(p,αγ)$^{16}$ reaction. The target can be replaced by a AlF$_3$ to ensure only production of gammas. Data was obtained in both conditions for both detectors and the results can be seen on Figure 3 where both detector types show a clear separation between gammas (red) and neutron+gamma (black) specially if we apply a threshold cut. The gammas amplitude contribution fits very well to an exponential distribution as the produced electrons do not deposit all their energy due to the short drift distance (1.9 mm in the fast and 0.4 mm in the slow). The gamma rejection is strongly dependent on the gain and on the threshold, and as we use current amplifier, it also has a dependency with the drift voltage and drift gap as they affect the pulse shape (width and amplitude). For this particular field conditions (fast: $V_{mesh}$=-500 V, $V_{drift}$=-700 V; slow: $V_{mesh}$=-500 V, $V_{drift}$=-540 V) and threshold (7 keV for the slow corresponding to 0.3 V and 14 keV for the fast corresponding to 2 V in Figure 3) we obtain a sensitivity for gammas with respect to neutrons of $1.8 \times 10^{-4}$ for the slow and of $3.6 \times 10^{-3}$ for the fast detector. In the case of the fast detector, the discrimination gets worst at higher initial neutron energies than this particular one and in the case of a continuous initial neutron energy, due to the shape of the energy deposition spectrum of the emitted protons that will partly overlaps with the gamma energy region for a particular gain. To study further its discrimination potential, measurements were done at Saclay using very intense neutron (AmBe, energies up to 10 MeV) and gamma ($^{60}$Co) sources, varying as well the voltages, which analysis is on-going.

![Figure 3.](image)

(a) Fast detector response to the mixed field of 565 keV neutrons and 6-7 MeV gammas (black) and to the case of only gammas (red). (b) Same for the nBLM slow module.

4. First beam loss detection
In august 2019, one fast nBLM module, with the final mechanics and electronics, was installed at LINAC4 (CERN) between two Drift Tube Linac (DTL) in the 13 MeV proton region. Two data campaigns were done profiting the time of beam during the commissioning of the machine: in the first one the accelerator was operating in normal conditions and serve us to understand the behaviour of the detector. In the second one in the first week of December provoked losses were produced in the vicinity of the nBLM detector location corresponding to uniform beam losses along the accelerator. Results obtained during the second run are shown in the following.

Data was recorded using a fast Teledine Lecroy oscilloscope at 250 Ms/s (the same sampling rate will be used in the ESS-nBLM system). Frames of few ms were registered and then analyzed using ROOT [14]. An event is identified if it exceeds a “noise” threshold (in this case set at 2.5 mV, as seeing in Figure 2 (a)). Then a pulse analysis is performed for each one finding the characteristics of the pulse as amplitude, charge, rise time or pulse duration. The data was taken either using the trigger of the accelerator or in autotrigger mode but recording also the
accelerator trigger signal to correlate then the detected pulses with the beam time. The output signal was the sum of the four segments together. Results obtained at an operation point of $V_{\text{mesh}}=-515$ V, $V_{\text{drift}}=-1000$ V are shown in Figure 5 for two runs: one without losses provoked, i.e. normal operation, and another with losses. The amplitude distributions of all recorded events are shown on figure 4(a) (normal operation) and Figure 5(a) (controlled loss) in black. In the case without losses all the events have low amplitude and fit well to an exponential line (same as observed for the run with gammas in previous section). In fact this has been corroborated to be gammas (low ionization-low energy) produced mainly by the RF as they follow the beam structure of the RF beam. When applying an amplitude cut of 6 mV, in the case of no losses, we reject almost all events. The rate is calculated and shown in Figure 4(b) for this amplitude cut. In the case of losses (Figure 5(b)), on the other hand, we can see how the distribution of events has been populated in the higher energy parts, what we identify as neutrons. And when applying the same amplitude selection the beam structure is then reduced to the beam pulse duration. The rate is also computed applying the same amplitude selection and we can see a clear increase in Figure 5(d). Moreover, a run was taken along all night (Figure 6). Then a blind analysis was done identifying an increase at 21:00 which corresponds to the time when the operators were provoking a loss in the machine. This is the first proof of operation of the detector as a Beam Loss Monitor showing its capability to detect an increase in the neutron rate compared with the operation in normal conditions. In this case we operate the detector at higher gain ($V_{\text{mesh}}=-550$ V, about 50 V higher than the nominal) so the neutron cut was set to 30 mV using a run without losses as in the previous example. The higher gain explains the appearance of sparks produced by the big amount of charge maybe produced by the neutrons when operating at this gain. ”Spark” events are identified if there are strong variations in the baseline or if the charge of the pulse is too large. In fact before the night we saw cross-talk with another system that we were testing at same time and produced events that were misidentified with sparks. However from occurring because we operated at high gains. In nominal conditions the detector will always operate below those voltages.

Figure 4. (a) Amplitude spectrum measured with the fast nBLM module installed at CERN during normal operation. (black) for all events. We can see an exponential fit (in green) to the first part of the spectrum which is mainly populated by low energy events corresponding to the gammas emitted by the RF cavities. In red is the amplitude spectrum of the events surviving an amplitude cut of 6 mV which corresponds to neutrons. (b) Average rate measured along time when selecting the neutrons.
Figure 5. Same as in Figure 4 but in the case of a provoked loss: (a) Amplitude spectrum (black) for all events with an exponential fit (in green) to the first part of the spectrum which is mainly populated by the gammas coming from the RF cavities. In red is the amplitude spectrum of the events surviving the neutrons election cut of 6 mV, with events populating the high energy part of the spectrum above the gamma cut with respect to the case of no losses (Fig. 4 (a)). (b) Average rate measured along time when selecting the neutrons with a clear increase in the neutrons rate with respect to Figure 4 (b).

Figure 6. Measured neutron rate of the fast nBLM module installed at Linac4. Data was recorded over night with a very stable detection rate that suddenly increased at 21:00 in the evening. In discussions with the operators at this hour they produced beam losses during approximately 10 minutes. This serves as first proof of concept of the detector as a reliable Beam Loss Detector. We should note that the detector was operating at a higher gain than nominal which explains the appearance of some sparks produced by the big amount of charge produced by the neutrons. More details in text.

5. Conclusions
A new type of beam loss monitor have been presented in this contribution. This development is done in the context of the future European Spallation Source (ESS), where a system of 84 nBLM modules is foreseen (ESS-nBLM system) to be installed mainly in the normal conductive linac part. The detectors designed and constructed at CEA to fulfil the ESS requirements have been presented here. Based on the operation of Micromegas detectors, their main advantages are the possibility to operate in counting mode to be sensitive to small losses and the capability to discriminate between neutrons (which will be converted into alphas or protons to be detected) and gammas based on different ionisation power of alphas/protons and electrons in the detector sensitive volume. The gammas and x-rays produced by the RF emission represent a background
for beam losses identification, not easily discriminated in the case of the usually used ionization chambers. The detectors have been characterized at different irradiation facilities. In this contribution we have focused in their main specifications: fast time response, neutron/gamma discrimination and in the first operation of the detectors in an accelerator similar to the ESS conditions (LINAC4). During the commissioning of the accelerator, losses were provoked and where clearly identified by the fast nBLM module installed there, showing the potential to discriminate between the gammas from the RF and the neutrons originated in the loss.

For the ESS-nBLM system, 84 detectors (42 slow module and 42 fast modules) are planned to be installed. Half of them will be installed in the region between 3 and 100 MeV proton energy, while the rest will be placed at higher energies. The first 12 detectors will be installed in the accelerator before November 2019 and will cover the MEBT module (Medium Energy Beam Transport) and the first DTL. The rest of detectors will be delivered to ESS before the end of the year and installed later, following the ESS accelerator installation.

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