THE LUPIN DETECTOR: SUPPORTING LEAST INTRUSIVE BEAM MONITORING TECHNIQUE THROUGH NEUTRON DETECTION

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Abstract

The Long interval, Ultra-wide dynamic Pile-up free Neutron rem counter (LUPIN) is a novel detector initially developed for radiation protection purposes, specifically conceived for applications in pulsed neutron fields. The detector has a measurement capability varying over many orders of neutron burst intensity, from a single neutron up to thousands of interactions for each burst, without showing any saturation effect. Whilst LUPIN has been developed for applications in the radiation protection fields, its unique properties make it also well suited to support other beam instrumentation. In this contribution, the design of LUPIN is presented in detail and results from measurements carried out in different facilities summarize its main characteristics. Its potential use as beam loss monitor (BLM) and complementary detector for non-invasive beam monitoring purposes (e.g. to complement a monitor based on proton beam "halo" detection) in medical accelerators is then examined. In the context of its application as a beam loss monitor for hadrontherapy accelerators, results of measurements performed at the Italian National Centre of Hadrontherapy (CNAO) are presented and analysed.

INTRODUCTION

LUPIN is a state-of-the-art instrument for the detection of pulsed neutron fields (PNFs). In the last years numerous investigations focused on the development of detectors specifically conceived to work in PNF, but limitations were always present in terms of saturation issues, low sensitivity or poor gamma rejection. LUPIN, due to its innovative working principle, overcomes all these limitations and meets four of the requirements needed by an ideal survey meter for PNF:

- It can withstand very high instantaneous neutron fluxes with values of H*(10) up to 16 nSv per burst [1] without showing any saturation effect.
- It has a high sensitivity, comparable to that of commercially available rem counters, i.e. 0.28 nSv/count for the ^{3}He version and 0.48 nSv/count for the BF_3 one.
- It has a measurement capability ranging over many orders of neutron burst intensity, varying from a single neutron interaction up to a reaction rate of $2 \cdot 10^6$ s^{-1} [2].
- It can efficiently reject the photon contribution that accompanies the neutron field [1].

Whilst LUPIN has been developed for radiation protection applications, its unique properties make it also potentially suited to be employed as a BLM and to support other beam instrumentation.

THE LUPIN DETECTOR

LUPIN is a rem counter type instrument consisting of either a ^{3}He, see Fig. 1, or a BF_3, see Fig. 2, proportional counter placed inside a spherical (^{3}He) or cylindrical (BF_3) moderator. The first version shows the advantage of having an isotropic response, while the second one has a much higher sensitivity. The front-end electronics consists of a current-voltage logarithmic amplifier, whose output signal is acquired with an ADC and processed with a LabVIEW© program running on a personal computer. The idea of the analysis software is simple: the voltage signal is converted into a current signal and integrated over a time that can be set by the user. The result of this calculation represents the total charge generated in the proportional counter by neutron interactions. This quantity, divided by the average charge expected by a single neutron interaction, represents the number of neutron interactions occurring during the integration time.

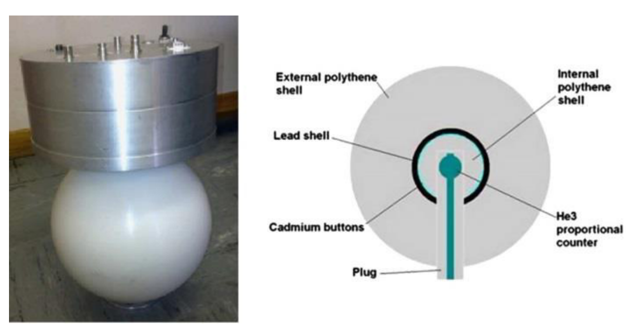

Figure 1: Picture and scheme of the ^{3}He version of LUPIN. The counter is electrostatically shielded with an aluminium tube connected to the electronics case. It is inserted in the moderator from the top. The sphere is placed on a small iron pedestal.

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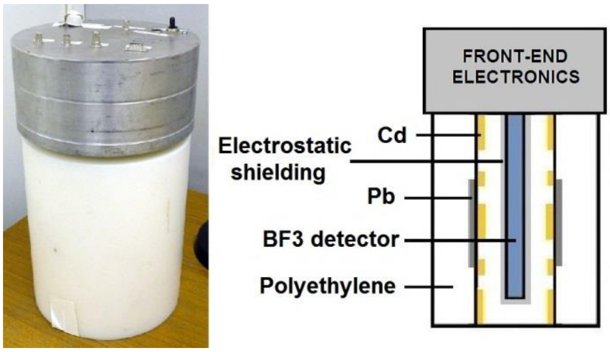

Figure 2: Picture and scheme of the BF_3 version of LUPIN. The counter is electrostatically shielded with an aluminium tube and inserted in the moderator from the top. Dimensions are given in cm.

The absence of an intrinsic dead time allows the detector not to be affected by dead time losses that characterise all conventional rem counters. On the other hand the logarithmic amplification of the signal allows it to work over a very wide dynamic range of neutron bursts, from a single interaction up to $2 \cdot 10^6$ interactions per second.

BEAM LOSS MONITOR

The aim of a BLM is to detect an unintentional interaction of beam particles with media causing radiation. A great variety of BLM types exist: ionization chambers (ICs), scintillators, PIN diodes, secondary emission monitors, Cherenkov light detectors. ICs are the most widely used detectors, even if the optimal detector cannot be defined a priori for a certain accelerator [3].

The potential use of LUPIN as a BLM is considered by evaluating its performances on the basis of the features required by Zhukov [4] for an ideal BLM and by comparing them with the typical features of an IC. An ideal BLM system is a radiation detector that:

- Has a high dynamic range to be used for both regular (low) losses and irregular (high and fast) losses.
- Is sensitive only to radiation caused by a beam loss.
- Allows one to find out the amount of lost beam.
- Resolves the time structure of the loss.
- Resolves the spatial distribution of the loss.

LUPIN easily satisfies the first requirement: it can efficiently measure over a wide dynamic range, being able to detect a neutron burst intensity varying over more than six orders of magnitude. It can detect the presence of a few neutrons generated by a loss of a small fraction of the beam interacting with the accelerator structures, as well as a fast and intense burst generated by an instantaneous and complete loss of the beam in a single impact. An IC can meet this requirement, even if problems can arise when the currents to be measured are too low.

The second requirement refers to synchrotron radiation and cavity X-rays, i.e. sources of radiations that do not involve direct interaction of primary particles with materials. These sources of radiation can be well discriminated by the stray field caused by a beam loss due to the very high gamma rejection of LUPIN. Due to the fact that an IC cannot implement such a powerful rejection property, an efficient discrimination between the two sources of radiation cannot be carried out.

According to the third requirement, the order of magnitude of the beam loss can be conveniently derived from the intensity of the neutron burst revealed by LUPIN. This correlation cannot be achieved with a high precision, but usually the attention is mainly focused on the distinction between small and big losses rather than on the precision of the measurement.

The time structure of the loss is derived from the LUPIN signal by taking into account that the shape of the signal is dominated by the thermalization and drift time of the neutrons in the moderator.

The spatial distribution of the loss cannot be obtained with LUPIN, because it responds to any loss, close or remote, being incapable of an exact determination of the point where the loss originated. However, one could compare the signals obtained by two detectors placed at a given distance to derive information on the loss originating point. The intensity of the signal is in fact much higher than what can be obtained with an IC. This is explained by the neutrons ability to penetrate beam pipes, the usual materials being copper and steel, which effectively attenuate photons but not neutrons. This results in a much higher efficiency of a neutron detector if compared to an IC.

Other potential advantages offered by LUPIN as a BLM are:

- its radiation hardness (significant degradation in the performance have been observed only after operation of 10^{11} registered counts for BF_3 detectors, while no degradation issues are known for the ^3He [5])
- its high sensitivity in terms of nSv per count
- its cost, comparable with a high precision IC
- its calibration factor, that depends solely on the detector geometry and the applied voltage, which is supplied by an internal power supply

APPLICATION AROUND A HADRONTHERAPY SYNCHROTRON

The previous section presented the general advantages of LUPIN as a BLM. This chapter focuses on its use as a BLM around a hadrontherapy accelerator. In fact the original development of LUPIN was triggered by the need of a BLM at CNAO in Pavia, Italy.

In a synchrotron hall LUPIN could become useful both for machine diagnostics and radiation protection, in order to give a posteriori a control on the parasitic beam loss inside the synchrotron vault. In fact two typical loss situations can be encountered around a hadrontherapy accelerator during its functioning [6]: an instantaneous and complete loss of the beam in a single impact or a continuous loss of a fraction of the beam, such as 1% during the beam spill, all around the accelerator. The first

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situation results in the production of an intense neutron flux caused by the interaction of the beam with the accelerator structure and shielding (with a neutron fluence at 1 m from the interaction point that can be as high as 10^5 n/cm^2 [7]), while the second causes neutron fluxes of much lower intensity. LUPIN is able to correctly detect the intensity of the neutron burst in both cases. In the event of a sudden beam loss, the time width of the neutron burst to be detected would be dominated by the thermalization and drift time of the neutrons inside the moderator. The reaction rate in this case can easily reach $4{\cdot}10^5$ s^{-1}, as seen in preliminary measurements carried out with LUPIN in the BF_3 version at CNAO, see Fig. 3. The measurements were performed with LUPIN placed at 1 m from a copper Faraday cup hit by a 7 MeV proton beam accelerated by the injector LINAC.

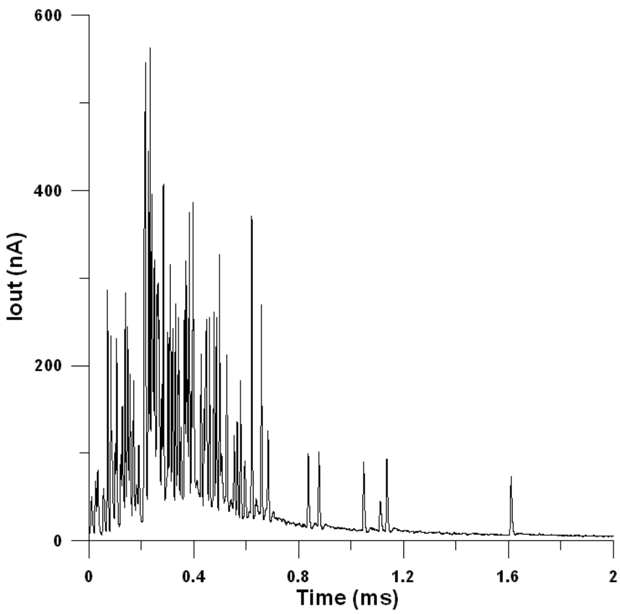

Figure 3: Signal obtained at CNAO with a 7 MeV proton beam accelerated by a LINAC and impinging on a copper Faraday cup.

From the signal it can be derived that most of the interactions occur in the first 500 µs, whereas the rare events that occur later can be ascribed to delayed neutrons. The total charge generated in the detector by the neutron burst is 93.2 nC. By dividing this value for the average charge expected by a single neutron interaction (247 pC) one obtains 378 neutrons. Assuming that all the neutrons have been detected in 1 ms, one derives the reaction rate, i.e. $3.78{\cdot}10^5$ s^{-1}. This neutron interaction rate cannot be properly detected by a proportional counter coupled to a conventional electronics and data acquisition chain due to dead time losses. For example the measured interaction rate of a detector with a 5 µs dead time would introduce a 65% underestimation of the true interaction rate.

LUPIN seems to be an optimal solution for this problem, since its wide dynamic range of operation would allow it to operate in both loss situations listed above, from single neutron interaction up to very intense neutron bursts. Moreover, its operating principle allows it to work without any saturation effects even in presence of very high neutron interaction rates during the radiation burst.

SUPPORT TO NON INTRUSIVE BEAM MONITORING TECHNIQUES

In view of potential applications of LUPIN around hadrontherapy accelerators, its use as complementary detector for non-intrusive beam monitoring techniques should also be considered. In fact one problem still open in hadrontherapy facilities is the development of an effective device for on-line beam monitoring. This device should produce negligible effects on the few nA clinical beam and should have a beam current measurement resolution of few percent [8]. Up to present this has not been possible, since existing interceptive monitors interfere with the beam, causing significant beam disruption at therapeutic kinetic energies. At the same time non-interceptive instrumentation is not sensitive enough to detect average beam intensities from a few pA to a few nA, with extracted beam duration of the order of 1 s [9].

This open issue will possibly lead in the future to the development of a comprehensive system constituted by different detectors to be integrated into the treatment beam line. This system should in principle be able to detect all the beam parameters such as position, intensity and dose profile in a non-intrusive way.

An example of detector to be used as a part of this system could be the one proposed in a recent study by Cybulski et al. [10]. With an innovative method the LHCb VErtex LOcator (VELO) detector has been integrated into a treatment beam line at the Clatterbridge Centre for Oncology, where a 60 MeV proton beam is used for eye cancer therapy. The operating principle is based on the fact that the proton ‘halo’ region hit rate which impinges on the VELO monitor can be related to the absolute beam current. Thereby, halo signal-dose mappings shall be determined to allow for a true online monitoring system during patient treatment However, studies to determine the reliability of this signal cross correlation are still ongoing.

Another part of this system could be constituted by LUPIN that, acting as an efficient BLM, could provide useful information on the beam intensity, and could hence act as a cross-check monitor to complement the information obtained by the main on-line monitoring system, playing at the same time an essential role for beam diagnostics, for radiation protection purposes and for the machine protection system.

CONCLUSIONS

Due to its unique properties, LUPIN seems potentially suitable for use not only in the radiation protection field, but also as a versatile beam loss monitor around particle accelerators. There, and more specifically around hadrontherapy synchrotrons, its potential use has been assessed. The results obtained in the stray field generated by a 7 MeV proton beam impinging on a copper Faraday

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cup at CNAO in Pavia confirmed its reliability in measurements of very intense neutron bursts. At the same time LUPIN could become useful as a complementary detector for a comprehensive on-line beam monitoring system.

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