HIGH DYNAMIC RANGE DISCRIMINATOR FOR MEASUREMENTS WITH FRAGMENTED HEAVY IONS

Jorge Llacer, Donald A. Landis and Norman W. Madden
Engineering Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

Abstract

This paper describes the design of an event discriminator with a practical dynamic range of at least 2000:1 and its application to measurements in fragmented heavy ion beams. Such beams are formed by particles with a wide range of values of dE/dx and the determination of fragment composition by a simple, portable instrument that can be used under a variety of experimental conditions requires the measurement of the dE/dx of all particles in a single experiment. Histograms of dE/dx vs. residual energy for a 20Ne fragmented beam, showing events with Z ranging from 1 to 10 are shown.

I. INTRODUCTION

Accelerated heavy ion beams with sufficient energy to penetrate the human body are being used in biological research and in cancer therapy trials at Lawrence Berkeley Laboratory and are expected to be used in similar endeavors in a number of other installations in the near future. Such beams have a very interesting characteristic in that the energy deposition and cell killing power is relatively uniform and low along most of the path of the ions in living tissues, but becomes very high in the last few millimeters of the trajectory.[1] That characteristic makes heavy ions a promising alternative for radiation cancer therapy when compared to accelerated electrons or energetic gamma rays because it allows the delivery of a concentrated radiation dose to a tumor, with little damage to surrounding healthy tissues.

As they penetrate matter, heavy ion suffer a number of collisions that result in the fragmentation of the original nucleus into a number of lighter nuclei. The most common kinds of fragmentation collisions of interest from a biomedical point of view have been shown in [2]. Chatterjee et al [3] have described the general characteristics of the complex beams that can be used in biomedical applications based on information obtained from cosmic-ray data. Since the cell killing power of the nuclei is dependent on their atomic charge, Z, and on a number of other parameters,[4] the interpretation of biological and medical experiments cannot be done correctly unless the true composition of a fragmented beam is known with sufficient accuracy at the depth of penetration where the intended target is located. For that reason, techniques have been developed to measure beam composition "in situ", in the large variety of experimental setups that are used in biological and medical experiments. A simple two-detector solid state instrument, the Berklet,[2] was originally developed for those measurements. Later,[5] a small scintillator detector was added to the system in order to define the active area of the two solid state detectors and to provide a time coincidence signal that increased the certainty with which low dE/dx events (like fast protons) could be detected in the presence of high dE/dx fragments (like Si ions near their stopping point), in a single measurement.

In the course of the development of the latter version of the Berklet, it became clear that the approximately 200:1 dynamic range of commercially available fast discriminators was inadequate for the desired measurements. The needed dynamic range when using Neon beams (Z = 10), for example, was approximately 2000:1 and it was necessary to insure that low dE/dx events occurring a few microseconds after a large dE/dx event would not be lost because of overload recovery problems in the fast amplifier preceding a discriminator. Also, no false triggers should be generated during the recovery from such an overload. Those requirements led to the design, construction and testing of a High Dynamic Range Discriminator (HDRD) whose circuits and characteristics are described in this paper.

II. EXPERIMENTAL CONFIGURATION

A. Detector System

Figure 1 describes the detector system used for the study of fragmented heavy ion beams. The first detector encountered by the particles is a 0.5 cm diam plastic scintillation which is coupled to a highly sensitive photo-multiplier tube (PMT) by a light guide. The PMT (Hamamatsu R1213) was selected for single photo-electron pulse height resolution of 150%. The dE/dx detector, located 1 cm past the scintillator, consists of a 400 micrometer thick, 1.1 cm diam, fully depleted silicon p-n
Fig. 1: Description of the Berklet detectors

junction, without a guard ring. Finally, a high-purity Germanium detector of 5.5 cm length and a cross section of 2.25 cm² in its cryostat acts as a residual energy detector for those particles that can stop fully in it, or as a thick dE/dx detector for sufficiently energetic particles that traverse it.

B. Electronic System

Figure 2 shows schematically the Berklet electronics. In order to achieve the large dynamic range necessary for the measurement, each of the circuit elements employed must exhibit a nearly perfect response. The preamplifier of the dE/dx detector must exhibit a monotonic rise and a single exponential recovery, both of which are free of overshoot and ringing which could cause ambiguous response in the discriminator. The location of the HDRD and the two main amplifiers for the Si detector in the experimental area, with long cables to the data acquisition area after those units, has been found necessary in order to avoid small cable reflections due to imperfect terminations from triggering the HDRD. The dE/dx signals from the Si preamplifier were taken to two amplifiers, one at high gain in order to record signals originating from the lighter ions, and the other at low gain to cover the higher dE/dx events. Two amplifiers are required because of the large range of the energy signals in the Si detector and a practical limit on the number of channels in the CAMAC ADCs (2048 channels were used). An event must trigger both the scintillator and silicon discriminators and have no pile-up within the width of the silicon amplifier’s shaping time to be recorded.

C. Data acquisition and analysis

The data corresponding to the individual events detected are stored in a disk and placed in a 2-dimensional histogram on-line. The histogram has the dE/dx values obtained from the Si detector as its ordinate and the residual energy obtained from the Ge detector as its abscissa. Events entering the histogram can be selected among those passing a number of tests. Histograms of other data-pairs can also be obtained.

The 2-dimensional histograms of dE/dx vs. residual energy have the characteristic that events corresponding to fragments of different values of Z cluster along specific loci, making the histograms useful in analyzing experimental data in a rapid manner, without having to resort to event-by-event calculations. The detailed method of analyzing the results in terms of beam composition is described in [5] and [6]. Some results obtained with a 20Ne beam are shown below.

III. DESCRIPTION OF THE DISCRIMINATOR CIRCUITS

A block diagram of the HDRD is shown in Fig. 3 and a detailed schematic in Fig. 4. The HDRD has a topology similar to a network developed earlier for Si(Li) X-ray detectors in a Tokamak (magnetically confined fusion reactor) environment.[7] A triangular shaped waveform with a well-defined return to the baseline is generated by combining an asymmetrical bipolar delay-line pulse shaper with a known RC integrator. The triangular shape waveform will return precisely to the baseline if the amount of asymmetry of the bipolar waveform and the value of the RC integrator are correctly chosen. A convenient solution is to make the RC integrator time constant equal to the delay-line length, and make the amplitude of the second lobe of the bipolar waveform to be 1/e of the amplitude of the first lobe. The second (short term) pole/zero
Fig. 3: Block diagram of the High Dynamic Range Discriminator

control makes this adjustment. This shaper produces a pulse that has a nearly ideal shape, very close to a symmetrical triangle, which is the shape for best signal/noise when delta noise dominates.[7] The resolving time (pulse width) reaches a maximum of only two times the RC integrator time constant for the entire energy range. In order to achieve the large dynamic range, the discrete transistor amplifiers have been made capable of a linear 18 V unipolar excursion. A gated baseline restorer has been used in the circuit, although we anticipated a low duty cycle. Diode limiters precede the selected high quality voltage comparator (CMP-05). With these circuits we have measured a dynamic range of 3500:1 on the workbench.

IV. EXPERIMENTAL RESULTS

A. Discriminator adjustment

Apart from the selection of its threshold, the HDRD only requires the setting of the long and short pole-zero cancellation adjustments before an experiment. With the careful design of the charge-sensitive preamplifier feeding signals to the HDRD, indicated above, the long term pole-zero cancellation presents no special problems. A random true charge injection pulser, without long time constant tails, is a requirement for that task. The adjustment is carried out by observing the analog output of the amplifier in the HDRD and adjusting the long...
Fig. 4: Schematic of the High Dynamic Range Discriminator
Fig. 5: Two-dimensional histogram of Linear Energy Transfer (LET) in water vs. Residual Energy for a 670 MeV beam of $^{20}\text{Ne}$ after traversing 20.67 cm of water absorber. LET is proportional to $dE/dx$ and is given in KeV of energy deposited in one micrometer of water. Clusters for particles ranging from $Z = 10$ down to 3 are displayed.

The short term pole-zero cancellation potentiometer until the output baseline is stable. Some temperature dependence of the position of the pole in the preamplifier and/or that of the zero in the HDRD has been observed and we have found it advantageous to leave the electronics always powered and carry out the adjustment just before a series of measurements is to begin.

The short term pole-zero cancellation requires triggering an oscilloscope with the logical output signals from the HDRD and observing the short term behavior of the analog output. The signal from the charge injection pulser should be varied over the complete range of operation of the HDRD and the short-term pole-zero cancellation potentiometer should be adjusted so that the only triggers that occur are caused by the leading edge of the analog signals. This adjustment, as well as the long term one, will remain correct for experiments lasting several hours, at least.

**B. Measurements with $^{20}\text{Ne}$ beams**

Figure 5 shows the 2-dimensional histogram of $dE/dx$ vs. residual energy for a $^{20}\text{Ne}$ beam of 670 MeV/amu after traversing 20.67 cm of water absorber. The cluster of data points at top, right, corresponds to Ne ($Z = 10$) and, in decreasing value of $Z$, the clusters below correspond to the different fragments, down to $Z = 3$. The cutoff between low and high gain channels for the $dE/dx$ measurements had been placed approximately between $Z = 2$ and $Z = 3$ by the analysis software. Figure 6 shows the 2-dimensional histogram for protons and He obtained in the same measurement in the high gain channel.

Sets of data similar to those of Figs. 5 and 6 have allowed the analysis of a number of beams of heavy ions under a variety of experimental conditions. Reference 6 describes in detail the measurements carried out with $^{20}\text{Ne}$ beams of 670 MeV/amu.

**V. CONCLUSIONS**

In this paper we have shown that, with some care in the design, it is possible to construct and operate discriminators that have one order of magnitude higher dynamic range than those currently available. We have indicated which are the important details that have to be taken into consideration during the design and calibration of the units. It remains to be mentioned that not all commercially available NIM bins and power supplies live up to the requirements of the HDRD, particularly when the units are placed adjacent to main amplifiers. Very low level coupling between modules has been observed in some NIM bins, resulting in spurious triggers, even in the absence of signals.
VI. ACKNOWLEDGMENTS

The heavy ion beam analysis and the development of the HDRD and other electronics were funded, in part, by the National Cancer Institute under grant No. CA-15184, and by the Department of Energy under Contract No. DE-AC03-76SF00098. The encouragement of C. Tobias during all parts of the work is gratefully acknowledged.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

VII. REFERENCES


