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Challenges for high rate signal processing for the NUMEN experiment

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Abstract. The objective of the research and development activities, regarding the upgrade of the MAGNEX focal plane detector (FPD) and the development of the γ detector array for the NUMEN project, is the construction of new detectors capable to fulfil the requirements of high event rate, radiation tolerance and data acquisition and transmission bandwidth deriving from the upgrade of the Superconducting Cyclotron at INFN Laboratori Nazionali del Sud. The design of the front-end (FE) and read-out (RO) electronics has been performed in parallel with that of the new tracker. The design of the new segmented anode and the architecture of the front-end and read-out electronics are presented.

1. Introduction

The NUMEN project [1, 2, 3] aims at accessing experimentally driven information on Nuclear Matrix Elements (NME) involved in the half-life of the neutrinoless double beta decay ($0\nu\beta\beta$), by high-accuracy measurements of the cross sections of Heavy Ion (HI) induced Double Charge Exchange (DCE) reactions. Particular attention is given to the (^{18}O,^{18}Ne) and (^{20}Ne,^{20}O) reactions as tools to emulate the $\beta+\beta+$ and β-β- decays, respectively. First evidence about the possibility to get information about NME from experiments is found for both kind of reactions [4]. In the experiments, performed at INFN - Laboratory Nazionali del Sud (LNS) in Catania, the beams are accelerated by the Superconducting Cyclotron (CS) and the reaction products are detected the MAGNEX magnetic spectrometer [5, 6, 7]. The measured cross sections are challengingly low, limiting the present exploration to few selected isotopes of interest in the context of typically low-yield experimental runs.

2. Upgrade of MAGNEX detectors

A major upgrade of the LNS facility is foreseen in order to increase the experimental yield of at least two orders of magnitude, thus making feasible a systematic study of all the cases of interest. Frontiers technologies are going to be developed, to this purpose, for the accelerator [8], the magnets [9, 10], the detection systems and the targets[11].

2.1. The new FPD

The electron multiplication region and the segmented readout board of the FPD tracker [12] have to be radically redesigned taking advantage of the possibility to design a brand new full-custom FE and RO electronics, described in the following sections. A new concept for the tracker was developed. The starting point was to extract, for each track, the position of the ions at different depth in the tracker in a fully digital way. The ionization negative charge is driven by the electric field through the gas towards a multiplying stage, a triple GEM. The resulting electron jets are, then, directed towards a first layer of 750 μm pitch strips. Each strip of this layer is capacitive coupled to a twin strip in a second layer. The charge pulse inducted in the twin strip is, then, integrated by the FE and shaped. The shaped signal is compared to a suitable threshold and the logic high output of the comparator identifies the hit strip. In this scenario the position is extracted by only one strip without the need for the calculation of the center of mass. The value of the capacitance for each channel of the tracker is optimized in reference to the selected FE ASIC performances. The drift time is also measured by the FE at sub-ns resolution. An innovative scheme for the connection of FE electronics to the anode board was developed. The main objective was to place the FE in air to simplify the heat dissipation, the maintenance and, above all, the interconnections to RO. An advantage of this strategy is also the possibility to adopt countermeasures respect to high level of radiation during the experiment. The working principle of the new segmented readout board of the FPD tracker is represented in figure 1.

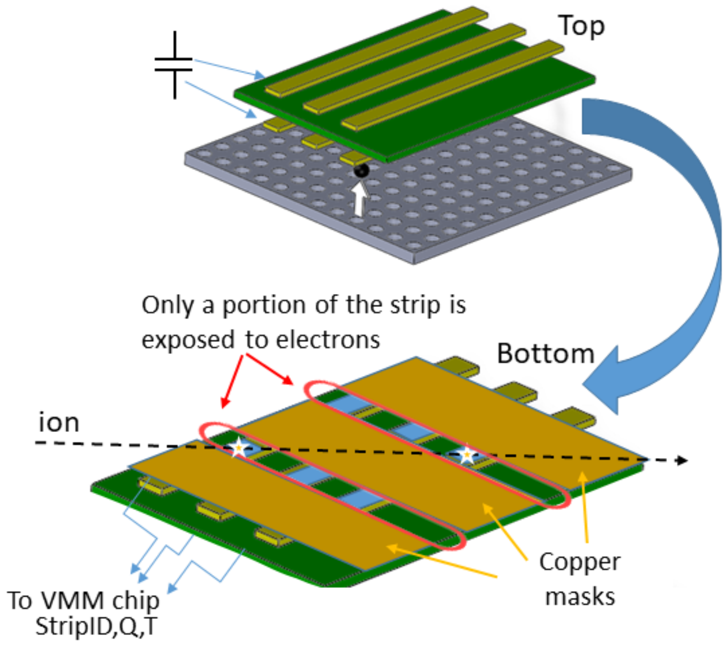

Figure 1. Schematic of the new FPD segmented anode board.

2.2. Stopping wall

The NUMEN project will also investigate promising technologies for stopping detectors, which need also to be upgraded in view of the high detection rate. Standard technologies, based on silicon pad detectors or plastic scintillators, require a high degree of segmentation (and thus high costs) in order to avoid double-hit events. At the beam currents expected for NUMEN the

probability of a double hit at the focal plane is considerable starting for 5 cm^2 area detectors for (^{18}O,^{18}Ne) reaction at 0°. In addition, the radiation hardness of such devices is not enough to avoid a short lifetime of these detectors. For example, in the same reaction (^{18}O,^{18}Ne) the rate limit of about 10^8 ions/cm^2, above which a silicon detector starts to deteriorate will be reached in a few days.
Interesting opportunities arise from the new technology of Silicon Carbide (SiC) crystals, which preserves many of the good properties of silicon detectors, but are much harder to radiation. Improvements in epitaxial SiC growth means that semi-insulating epitaxial SiC layers have recently become available, with thicknesses up to 100 μm. However R&D is still necessary to explore the possibility to build a reliable number of detectors for heavy ions by these epitaxial SiC. INFN is investing resources for R&D, Call SICILIA CSN V [13], in order to explore, characterize and build a wall of telescopes based on thin epitaxial SiC (100 μm thickness) for energy loss followed by thick (about 1 mm) SiC detectors for residual energy. This solution looks like to be promising because it decouples the GEM tracker from particle identification (PID) function and it is based on existing SiC technology, even if not yet implemented in commercial large area detectors. Test of characterization of epitaxial SiC under heavy ion beams are scheduled next months at the LNS in collaboration with colleagues from CNR. An ad-hoc prototype of an epitaxial SiC detector will be also built and characterized in 2018 [14]. Alternative solutions, based on phoswitch detectors, are under considerations [15, 16].

2.3. γ detector array
An important upgrade is the design of a γ calorimeter [17], which is fundamental to separate DCE cascade γ rays. A study on the performances and a prototype based on scintillator and SiPM read-out has been conducted at IFUSP in San Paolo. Particle gamma coincidence measurements are an effective tool for the investigation of nuclear reactions in the cases where the particle spectra energy resolution is insufficient to separate nearby excited nuclear states.

3. FE and RO Electronics
One of the main objectives of the research and development activities, regarding the upgrade of the focal plane detector (FPD) and the γ detector array of NUMEN, is the design and the construction of different prototypes of electronics boards which will act as a test platform for the prototype detectors. The preliminary study for the design and construction of the final electronics consists in the test of the FE board for the pre-amplification, the shaping and subsequent digitization of signals from FPD trackers, designed to be compliant with the for the high event rate and level of exposure to radiations foreseen in the final conditions; With this aim, a front-end ASIC, the VMM chip [18], identified among those documented in the literature and available in the next years, was acquired. The VMM chip is a strong candidate as the front-end of all the types of detectors in FPD, thanks to the high flexibility of its working parameters. A hosting board for the VMM2 chip was designed and constructed [19]. This board was usefull to characterize the response of the chip stand alone, for its evaluation. The board is also a useful test platform in connection with the first prototypes of trackers available. The trigger and calibration strategies, the interface to the temperature and power supply control systems and the mechanical support, will be tested. A new version of the chip, the VMM3, is now under test. We will follow the development of this device in order to evaluate if it matchs the specific requirements of the FPD front-end. The architecture, both hardware and software, is designed modular and scalable and the intelligence on board will allow for great flexibility in the overall data acquisition strategy, i.e. the trigger, the zero suppression, the data communication protocols and the slow control. In the first phase, it will be sufficient the construction, the test and the validation of each modular element ensuring, at the same time, that the built systems already exhibit the characteristics needed for the interconnections and the integration of the

final system. In Fig. 2, the architecture of the FE-RO electronics is shown.

3.1. FE Electronics
The design of the front-end electronics for the new tracker of the NUMEN Focal Plane Detector was performed in parallel with the design of the new FPD. In particular, one of the main objectives was to design a modular, scalable, radiation hard architecture, which, in addition, fulfilled the strong requirements in terms of high event rate, easy maintenance and precise synchronization.The front-end is based on the VMM chip, developed for ATLAS experiment at CERN. The architecture of the front-end electronics was designed as modular and scalable to the final dimensions of the detector. The segmented anode board was designed in order to take advantage of the unique performances of the VMM chip, allowing a digital reconstruction of the track at high event rate. In the VMM chip, each of the 64 channels provides the peak amplitude and time with respect to the bunch crossing clock or other trigger signal in a data driven mode. This is accomplished as follows. Each channel is equipped with a fast comparator with an individually adjustable threshold. When a signal crosses a set threshold a peak detection circuit is enabled. Neighbour-enable logic allows setting the threshold relatively high and yet recording very small amplitudes. At the peak a time-to-amplitude converter is started and stopped by the trigger signal. The two amplitudes are digitized and stored in a de-randomizing buffer and readout serially with a smart token passing scheme that only reads out the amplitude, timing, and addresses of the channels with information, thus dramatically reducing the data bandwidth required and resulting in a very simple readout architecture. In the selected data transfer mode, the continuous (digital) mode, a total of 38 bits are generated for each event in the VMM. The first bit is used as a readout flag, the second is the threshold crossing indicator (allows discrimination between abovethreshold and neighbour events). Next is a 6 bits word for the channel address, followed by 10 bits associated with the peak amplitude, and 20 bits associated with the timing. The 38bit word is stored in a 4events deep de-randomizing FIFO (there is one such FIFO per channel) and it is read out using a tokenpassing scheme where the token is passed firstcome firstserve only among those FIFOs that contain valid events. The first token is internally generated as needed and advanced with the token clock. The data in the FIFOs is thus sequentially multiplexed to the two digital outputs data0 and data1. The first output data0 is also used as a flag, indicating that events need to be read out from the chip. The external electronics releases a sync signal using the token clock as well (i.e. the token clock provides both advancement and data output synchronization), after which the 38bit data is shifted out in parallel to the data0 and data1 outputs using 19 clock edges of the external data clock.

3.2. RO Electronics
The main tasks of the read-out electronics for the new NUMEN FPD is the real-time data collection from the front-end boards and the high bandwidth data transmission towards data acquisition, the remote configuration and the slow control of the front-end electronics and the synchronization of the whole detector. The read-out electronics architecture, thought as modular and expandable to the final size of the detectors, is based on the System On Module (SOM) manufactured by National Instruments [20]. The SOM is a board-level circuit that integrates a system function in a single module. These very versatile devices couple high performance FPGA to powerful processor architecture and allow a graphical approach to the programming and interfacing. The tasks of SOM are the fast serial read-out of the VMM chips, the slow control of the FE and the precise synchronization of all the FE and RO boards [21].

3.3. Data Manager
The NUMEN data rate to be written on disk is estimated to be at maximum 10 Gb/s, depending on the beam configuration and on the trigger settings. Such a rate can be handled (i.e. written

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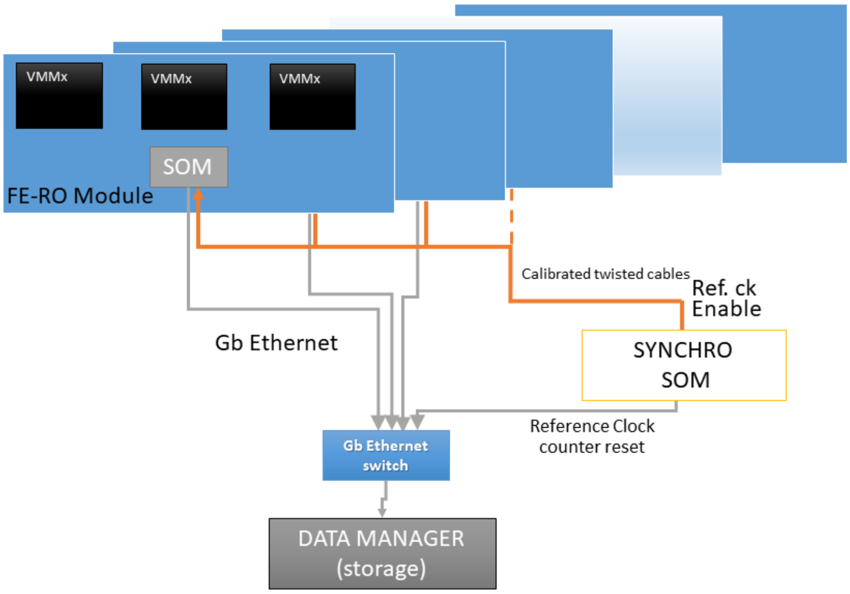

Figure 2. Architecture of FE-RO electronics and DATA Manager.

on disk) by commercial solutions, readily available on the market. The SOM modules of the electronics provide a data stream already formatted according to the TCP/IP standard protocol and transmitted over a standard Ethernet cable. One network switch (10 Gbit/s uplink) is used to collect and route the Ethernet cables coming from the SOMs. Depending on the number of cables coming from the SOMs and on the individual data rate, an additional switch could be necessary. The key component of the system, which suits all requirement and which is easily found on the market, is a one- or two-CPU 32-core server, equipped with two 10 Gbit/s Ethernet cards. Only a small fraction of the cores will be busy with the disk writing. Therefore, the free cores can be used for the event building (i.e. match the information of the same events coming from the different detector systems through different data streams) and/or for other online processing. The online processing could potentially reduce the amount of data written on disk (e.g. by compression), thus saving on the storage costs.

3.4. Radiation Tolerance and SEU

The devices to be accurately characterized from the point of view of radiation tolerance are the VMM chip and the SOM. Atlas collaboration provided the results of radiation tolerance test on VMM chip. The VMM ASIC is expected to be exposed to a total ionization dose of 100 krad according to the simulations done [22]. Deep sub-micron technologies are known to be immune to much higher Total Integrated Dose (TID) because of increasingly thinner oxide layers which can trap smaller amounts of charge. Although not expected to be a problem, the VMM3 will be tested for TID tolerance. However single event upsets (SEU) become increasingly more serious as the technology feature size decreases because of the smaller capacitance in the storage elements that need smaller energy depositions in order to flip their state. In the VMM there are two types of storage elements that require SEU protection, the configuration register, and the state machine control logic. In the data domain perhaps the 12-bit BCID register (under discussion) whereas the FIFOs need not be protected as an occasional data corruption is not an issue. To mitigate the SEU effects in the VMM storage elements two different techniques are used: the Dual Interlocked Cells (DICE) for the protection of the configuration register, and the Triple Modular Redundancy (TMR) for the state machines. The DICE uses redundancy to significantly reduce susceptibility to an upset. D flip flop based on the dual interlocked cell latches have redundant storage nodes and restore the cell's original state when an SEU error is introduced in a single node [23]. The scheme fails if multiple nodes are upset but this is far less likely. The TMR technique is used to protect the small number (less than 20) storage elements of the state machines. No data exists regarding the radiation tolerance of the SOM, despite different tests with neutrons and γ rays have been conducted on analogous devices[24]. The main criticalities are the same described for VMM, related to SEU and integrity of registers. The NUMEN collaboration plans, once accurate simulations results are available, to perform a dedicated test campaign of the overall electronics chain, FE and RO, in order to precisely determine the radiation tolerance performances and, in parallel, a possible strategy for the shielding.

4. Conclusions

Some aspects of the R&D for the upgrade of the MAGNEX detectors, looking at the high rate foreseen for the NUMEN project, has been presented. In particular, the research and development work aiming at the design of the FE-RO electronics for the NUMEN experiment was presented. Preliminary test confirms the design specifications. A complete test of a reduced scale FPD adopting all the new strategies will be performed within the end of 2018. The VMM3A chip will be available starting from spring 2018. The work is still in progress for what regards the particle identification and the γ wall. The plan is to adopt the same solution for the FE-RO electronics. A dedicated measurement campaign, aimed at the characterization of the radiation tolerance of the presented FE-RO architecture, is planned in the same period.

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