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MONSTER: a time of flight spectrometer for β-delayed neutron emission measurements

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Abstract: The knowledge of the β-decay properties of nuclei contributes decisively to our understanding of nuclear phenomena: the β-delayed neutron emission of neutron rich nuclei plays an important role in the nucleosynthesis r-process and constitutes a probe for nuclear structure of very neutron rich nuclei providing information about the high energy part of the full beta strength (S_β) function. In addition, β-delayed neutrons are essential for the control and safety of nuclear reactors. In order to determine the neutron energy spectra and emission probabilities from neutron precursors a MOdular Neutron time-of-flight SpectromeTER (MONSTER) has been proposed for the DESPEC experiment at the future FAIR facility. The design of MONSTER and status of its construction are reported in this work.

Keywords: Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Instrumentation and methods for time-of-flight (TOF) spectroscopy; Neutron detectors (cold, thermal, fast neutrons)

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Contents

1 Introduction

The β-delayed neutron emission process constitutes a decay mode whose importance increases with the number of excess neutrons, being the dominant decay process towards the neutron drip line. Since the discovery of the process in the fission of Uranium and Thorium isotopes [1], the role and importance of delayed neutrons and their properties has increased its relevance in different nuclear physics fields. In the field of nuclear technologies, the design of new concepts of reactors like Gen-IV fast reactors or accelerator driven systems (ADS) is affected by the evaluation of the contribution of the delayed neutrons to the kinetics of the reaction. Accurate delayed neutron (DN) data, mainly emission probabilities (P_n) and neutron energy spectra, are needed for the design of future reactors, in order to guarantee an adequate control and operation of such systems. In nuclear astrophysics, P_n values constitute together with $T_{1/2}$ and nuclear masses of neutron rich nuclei, the major ingredients in the calculation of the nucleosynthesis r-process path and isotope abundances. Experimental P_n values are sensitive to the structure of parent and daughter nuclei, its value correspond to the β-intensity distribution $I_\beta(E_x)$ in the interval above the neutron separation energy (S_n). The measurement of the P_n values as well as neutron energies is the only way to determine of the full beta strength (S_β) beyond the neutron separation energy and to improve the nuclear models for predicting beta decay properties.

The improvements in the accuracy of DN data are conditioned by the developments in the detection techniques as well as in the production methods of the nuclei of interest. The advent of the new radioactive ion beam (RIB) facilities, where exotic nuclei will be produced with intensities of the order of 10^2-10^4 times higher than present values, will make accessible nuclear species that can not be investigated at the present time. The neutron detection techniques have evolved more slowly and a break through is necessary in the field of new detection methods and material. The experimental techniques have however profited from the developments in photonics, electronics and Monte Carlo simulations. In fact, several projects related to the construction of neutron spectrometers have been started in the framework of the future RIB facilities worldwide. In particular, a MOdular Neutron time-of-flight SpectromeTER (MONSTER) has been proposed at the Facility for Antiproton and Ion Research (FAIR, Germany), for the measurement of the β-delayed neutrons in the framework of the Decay Spectroscopy (DESPEC) [2] experiment. MONSTER will be used to determine the energy spectra and emission probabilities of delayed neutrons with high resolution. In this work we describe the guidelines and simulation work carried out for the design of MONSTER. The status of a demonstrator version of the spectrometer is also reported.

2 Characteristics of a neutron spectrometer for RIB facilities

One of the goals of the DESPEC experiment will be the study of the decay properties of very neutron rich precursors, which are characterized by large Q_β windows and P_n values. At FAIR, these nuclei will be produced in fragmentation reactions and subsequently identified and selected in the super Fragment Recoil Separator (Super-FRS) according to their mass A and charge Z. The slowed down ions will be implanted in a sensitive detector at the focal plane, where the β-decays will take place. The delayed neutron properties of neutron rich nuclei will be investigated through complementary detection systems consisting of an implantation detector for the detection of the implanted ions and their β-decays, and neutron and γ-ray detectors for the delayed neutrons and the γ-rays emitted along the entire de-excitation chain.

The high production rates of very neutron-rich nuclei envisaged at FAIR will still be lower than those for nuclei close to the stability valley. Therefore, the choice of efficient and selective detector setups and techniques is essential. High efficiency Double Sided Silicon Strip Detectors (DSSSD) and germanium detectors have been proposed for the β and γ-ray detection. A high resolution neutron Time Of Flight (TOF) spectrometer has been pointed out as the best device for the measurement of the neutron energy spectra and emission probabilities.

The TOF technique can provide a good neutron energy resolution compared to other spectroscopy techniques. It consists in the measurement of the velocity of an emitted neutron which travels a known flight distance between the implantation set-up and the detection system. The energy resolution of the system depends of the intrinsic time resolution of the detectors and the flight path. The main requirements to be met by an ideal neutron time-of-flight spectrometer can be summarized as follows:

- High detection efficiency
- Large energy resolution
- Good timing resolution
- Good neutron/γ discrimination
- Modularity and cross-talk rejection capabilities

- Minimum interference with other detection systems

The target requirements have been established according to the measurement conditions for very neutron rich nuclei: moderate production rates (⩾100 at/s), large Q_β and large level densities of the daughter nuclei. Therefore, having the largest possible efficiency and the best energy resolution are crucial detector requirements. The modularity is also required for the detection of multiple neutron events. Furthermore, the flexibility in the geometric configuration is also demanded for making the spectrometer compatible with complementary detection setups and for reducing the cross-talk. The neutron/γ separation is crucial for suppressing the coincident γ-ray background.

According to such requirements the organic scintillators are the best candidates to be used because of their large intrinsic detection efficiency and fast time response [3]. Among them, the liquid scintillator as BC501A/EJ301 has been chosen due to its excellent neutron/γ discrimination properties. In the next sections we present the solutions adopted for the design of MONSTER module, considering several aspects such as: the geometry, the light collection and the detection efficiency to mono-energetic neutrons. The evaluation of such characteristics has been made by both Monte Carlo simulations and test experiments, which have led to the construction of a 30 cell demonstrator.

3 Conceptual design

Several Monte Carlo codes, NRESP7 [4] and SCINFUL [5] among others, were developed in the 80's in order to estimate the properties of liquid scintillation detectors in simple configuration setups. However, they show various limitations and therefore we have used the more generalized simulation package GEANT4 [6] which allows the simulation of the interaction with matter of any type of radiation and because its versatility in the definition of geometries and modelling of complex detectors.

A simulation code has been developed [7] for optimizing the design of the BC501A module of MONSTER. The G4EMLow and G4NeutronHP physics packages have been used for modelling the different processes involved in the γ-ray and neutron interactions, respectively. The neutron cross-section data used by neutron physics model are not the standard values distributed with the code but were obtained from the evaluated ENDF/B-VII library, by using a software tool developed at CIEMAT to convert any ENDF-6 format library (ENDF/B, JEFF, JENDL ...) to the G4NDL format [8]. The light production mechanism was modelled as well, thus transforming every energy deposited in the detector into scintillation light according the parameterizations found in literature [3, 9] (and references therein).

3.1 Choice of modular geometry

Following the design of the neutron spectrometers EDEN [10] and TONNERRE [11], among others, two kinds of geometries have been considered for the BC501A detector modules of MONSTER: a cylindrical cell read out with a single photomultiplier tube and position sensitive long bars read out by two photomultipliers placed at the extremes. In the first case, the flight path of a neutron hitting the detector is assumed to be constant, and its uncertainty can be determined from the cell dimensions. For the case of the long bars, the flight path has to be reconstructed, by calculating the position of the first neutron interaction. This is achieved from the time delay between coincident signals in the two photomultipliers.

The optimal geometrical parameters have been calculated for both detector shapes, in terms of the efficiency (detector volume) and the energy resolution (time resolution, detector thickness), showing no clear preference for any of the two geometries. The cylindrical shape was chosen due to its better light collection. The long rectangular bars are more affected by the self-absorption, which worsens the light collection efficiency and leads to an increased detection threshold when the coincidence between two photomultipliers is required. An additional consequence of the lower light collection is the degradation of the neutron/γ discrimination at low neutron energies (i.e. below 500 keV). Such features were confirmed by dedicated tests with prototype modules.

From the point of view of the granularity (i.e. number of modules), geometric efficiency, time resolution, light collection, cost and dimensions of commercially available photomultipliers, cell dimensions with about 20 cm in diameter were considered as a reasonable starting value for the detailed cell design.

3.2 Optical design of detector cell

The optical design of the cylindrical cells for MONSTER i.e. all aspects concerning the transportation of the scintillation light has been performed by means of Monte Carlo simulation in order to optimize the cylindrical cell design. The work performed by Klein and Schölermann [12] and Laurent [10] were taken as a reference. The influence of the geometrical shape, the type of reflective surface (polishing), the presence of a light guide and the optical properties of the materials on the light collection efficiency and uniformity have been evaluated by detailed Monte Carlo simulations with the GEANT4 code [13].

In GEANT4, the wavelike properties of photons in their propagation through matter are taken into account by introducing the optical photon particle definition. The most relevant physical processes for optical photons in scintillators, boundary processes and bulk absorption processes, has been accounted for through the physical properties of the materials and the UNIFIED [14] optical model. In this model the shape of the surfaces are considered as made of planar microfacets with the appropriate roughness given by the probability distribution of heigths. Reflection processes at the interfaces from diffuse to specular type are well described with this model.

The collection efficiency has been studied for a simplified detector geometry: a BC501A active volume enclosed in an aluminum container with the internal walls coated with diffuse reflector or polished surface and coupled to a quartz window. The use of a diffuse reflector paint increases the collection efficiency compared to the polished finishing of the aluminum container internal wall. The effect of the detector shape on the light collection efficiency at the optical window has been investigated. Three container shapes with squared, hexagonal and circular transversal section have been evaluated. All cells were defined with the same transversal section and thickness. The results showed that the collection efficiency converges to the cylindrical container one as the transversal area and the number of corners in the shape increases due to the lower number of lambertian collisions experienced by the photons before reaching the window. The squared and hexagonal shapes favored more compact arrangement of the modules. However, the cylindrical cell was chosen due to its larger collection efficiency. Cell with dimension of 20 cm diameter and 5 cm thickness showed optimal collection values.

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The design of the cell has included a light guide due to the large diameter of the cell and the limited sizes of commercial photomultipliers. A 5” diameter phototube was considered as the largest acceptable one. The effect of the light guide on the light collection efficiency has also been investigated. An enhanced position dependence has been observed and it is related to the size and surface reflectivity of the light guide. Light guides made of poly-methyl methacrylate (PMMA) material has been chosen due to its refractive index close to that of the BC501A, therefore a good transmission is obtained at the interfaces. Diffuse reflector paint with an average reflectivity of 0.92% has been used. Conical light guides of different size with polished and totally coated surfaces have been simulated. The results obtained for polished light guide showed different trend in the position dependence of the collection efficiency for thicknesses of 3, 5 and 12 cm while a similar trend was observed for a totally coated light guides with better uniformity for larger size and increased efficiency for the thinner one. A good trade-off between the light collection efficiency and its uniformity has been achieved for a light guide of 3 cm thickness.

3.3 Simulation of the detector response

The response of the detectors was obtained by Monte Carlo simulations with the GEANT4 code [15]. The results where compared with the well validated NRESP7 code, by simulating the same response functions for several mono-energetic neutron beams in the energy range below 20 MeV. The geometry of the detector consisted in a 20 cm diameter and 5 cm thick cell filled with BC501A, placed inside an aluminium container of 2 mm wall thickness. The back side of the detector was closed by a 2 mm thick quartz window. Other elements have been ignored as contributing to the detector response.

Neutrons with energies of 0.144, 0.250, 0.565, 1.2, 2.5, 8, 10, 12 and 14 MeV were generated isotropically inside the solid angle subtended by the detector surface. The energy deposited by the particles produced in each interaction was converted into light with the light output functions used by NRESP7. The light output spectra were folded with an experimental resolution function for a more realistic appearance.

As it can be seen in figure 1 an excellent agreement between both simulation codes has been obtained. The discrepancies observed at low energies in the response spectra for incident neutron energies higher than 8 MeV are due to missing reactions in the NeutronHP GEANT4 package. Current work is being made for modifying GEANT4, in order to include the two missing reaction channels, ^{12}C(n,n')^{12}C* and ^{12}C(n,α)^{9}Be*, both of them leading to final state with 3 α-particles and one neutron.

We aim to implement the same physical models used in NRESP7 for describing above reactions channels. Two-body relativistic kinematics is applied in NRESP7 for all reactions induced by neutron energies above 5 MeV taking from its own experimental database the necessary cross-section and angular distribution data missing in the ENDF evaluated libraries [4]. A detailed article is being prepared on this implementation in GEANT4 [16].

Taking into account all the design studies, the dimensions of the cylindrical cell which optimize the efficiency and the energy resolution correspond to a radius of 10$\pm$2 cm and thickness of 5$\pm$1 cm. Flight paths in the range of 2 m to 3 m and an intrinsic time resolution of 1ns for each module were assumed. Table 1 summarizes the energy resolution and total efficiencies corresponding to such values for a spectrometer consisting in 200 modules.

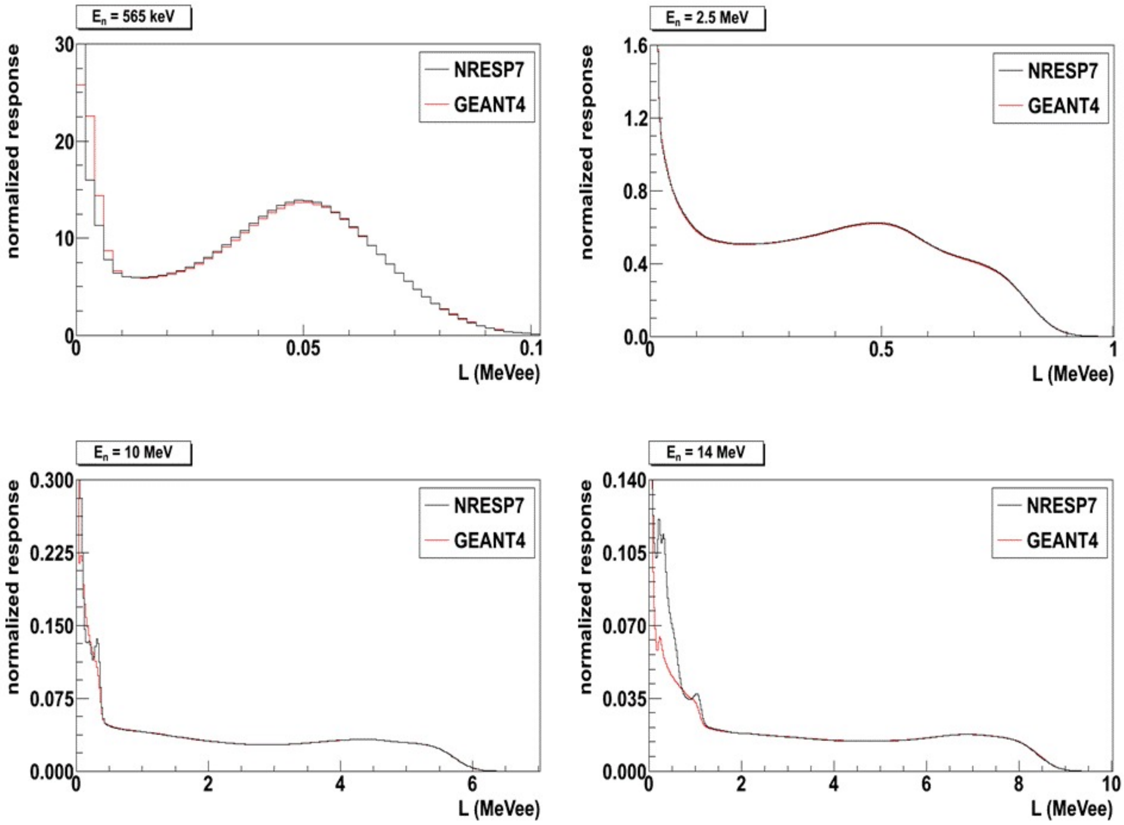

Figure 1. Comparison of NRESP7 and GEANT4 simulated pulse height spectra for selected neutron energies 0.565, 2.5, 10 and 14 MeV.

Table 1. Energy resolution and efficiency of MONSTER calculated for a cylindrical module with 10 cm in radius and a 5 cm thickness.

Number of detectors		**200**
Flight Path (m)	**ΔE/E (%)**	ε_{TOT} **(%)**
2	6.2	6.2
2.5	5.0	4.0
3	4.2	2.8

4 The construction of MONSTER

The MONSTER spectrometer is one of the instruments for the DESPEC experiment of the international NUclear STructure and Astrophysics Research (NUSTAR) collaboration. Several research institutions from Spain, India, Sweden and Finland are involved in its construction. In order to achieve the requirements of efficiency, energy resolution and flexibility, the MONSTER spectrometer will consist of 200 detector cells. As a first step, a demonstrator of 30 cells has been setup by CIEMAT using BC501A detectors built ad-hoc by St. Gobain Crystals. Both CIEMAT

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Figure 2. (Left) Picture of the first detector prototype manufactured by St. Gobain. (Right) Detector components ready for assembling.

and IFIC will contribute with 20 additional modules and VECC in India is planning to build 50 modules. The remaining units will be delivered by the collaboration before the first beam is available at FAIR. The first experiments with the 30 cell demonstrator will be performed at the Cyclotron Laboratory of the Jyväskylä University.

The demonstrator is going to be operated with a specific data acquisition (DAQ) system based on 12 bit resolution and 1 Gsample/s sampling rate digitizers designed and built by CIEMAT. Pulse processing algorithms and routines for on-line and off-line analysis have been investigated [17] and will be programmed on board. The main characteristics of such elements are described in the following sections.

4.1 The MONSTER cell prototype

The optimized detector prototype consists of a cylindrical aluminium cell with a 200 mm internal diameter and a thickness of 51 mm, filled with the BC501A liquid scintillators. The cell is closed with a 6.35 mm quartz window and the internal walls of the cell are coated with BC622A reflector paint. The cell is optically coupled to a 5” fast photomultiplier through a conical PMMA light guide with 30 mm thickness and with diameters 200 mm on the cell side and 128 mm on the PMT side. The cell does have an optical port which allows to plug-in a LED source for gain monitoring purposes. The gain monitoring system is still under development.

Five different photomultiplier tubes with a 5” photocathode diameter have been tested: R877-01MOD, R877-100, R4144, R1250 and E9823B. The R4144 PMT model from Hamamatsu did show the best overall performance (time resolution, linearity, gain, neutron/ γ separation properties). The phototube is shielded from external magnetic fields with a mu-metal cover of 1.0 mm thickness. A modified version of a standard Hamamatsu voltage divider was used.

Two companies, St. Gobain Crystals and Scionix, were contacted for manufacturing the detector according to the specifications. The prototype proposed by St. Gobain (see figure 2) was accepted because the cell design by Scionix is not compatible with the use of the conical light guide.

4.2 Supporting structure

The main requirements for the mechanical support of a neutron detector are to have a low mass and allow an easy positioning and alignment of the neutron detectors. The low amount of material

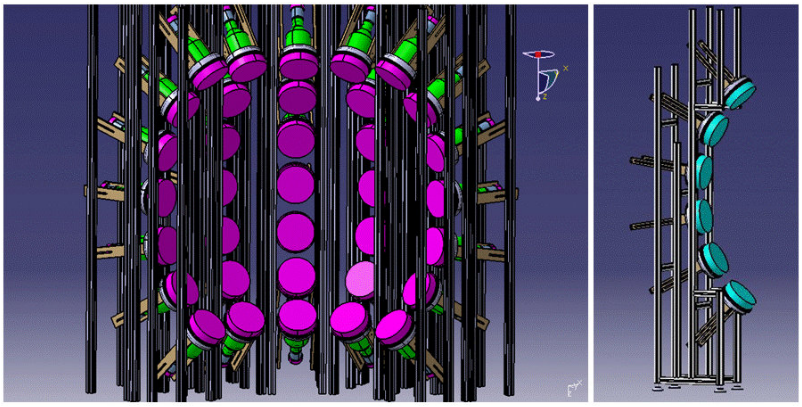

Figure 3. CATIA design of the mechanical structure for the MONSTER demonstrator.

of the whole mechanical structure is intended for minimizing the background induced by neutron and gamma scattering. Modularity and stability is also requested in order to distribute the high number of detectors in the full set-up.

A prototype structure has been built with aluminium profiles arranged as a rack-type structure. The neutron detectors are mounted on the structure by means of a flange with side guides that can be fixed to the columns with the appropriate orientation on the polar angle. The distance of the detector from the implantation point can be adjusted easily by sliding the flange along the side guides. Figure 3 shows a schematic drawing of the structure for a flight distance between 1 and 2 m and a a set-up for up to 35 detectors.

4.3 The digital data acquisition system for MONSTER

The rapid growth of computer performance and storage capabilities at reasonable prices and the development of FPGA and DSP technologies make the use of waveform digitizers as the recommended option for the front end electronics (FEE). Standard electronics modules like amplifiers, discriminators, TAC, etc., can be replaced efficiently by software algorithms in order to extract the relevant information from the digitized pulse signals.

A fast waveform digitizer board is being developed at CIEMAT for the measurements to be performed at the DESPEC experiment and at other possible facilities. The purpose of the board is to digitize signals from fast scintillation detectors (BC501A, BaF_2, etc.) with the best possible dynamic range, signal to noise ratio, time resolution, bandwidth and amplitude resolution.

The digitizer board includes two analog-to-digital converters (ADC) with sampling rates of 500 MSamples/s and 12 bit resolution working in parallel in a time-interleaved mode to achieve an effective sampling of waveforms at rates of 1GSample/s. The management of the sampled data in the prototype is carried out by a FPGA Virtex-4 [18]. The FPGA is responsible for the selection and processing of the data as well as the communication with other devices inside the board. This component can be reprogrammed to modify the processing of sampled data. To improve the performance of the digitizer, several complementary devices have been included. The most relevant is a fast DSP which allows implementing signal processing algorithms for pulse shape analysis with a reduction of the data to be stored, a DDR-II of 2GB which will be used as a data buffer and a TDC which allows time stamping with precision of a few hundred picoseconds.

The combination of a huge amount of memory, advanced time measurement capabilities along with embedded processing is one of the key features of this development. Two data taking modes have been considered for the DAQ . In the first mode, the raw data containing digitized signals with a minimum preprocessing is stored in memory. Up to two seconds of useful data may be recorded and then transferred to the PC for subsequent off-line analysis.

In the second mode, the raw data may be reduced by performing custom user defined data analysis, as for example pulse shape and timing algorithms. This task will be performed on board in real time by the high speed DSP, able to deal with floating points numbers for increased accuracy. The code may be written using standard C++ language and executed in real time for faster observation of results.

The readout to the external PC has been implemented through a USB2.0 bus in the prototype board, but a faster bus will be available in the final digitizer board. The DAQ software has been designed as modular and scalable. Finally, subroutines for an efficient data reading/writing management and on line processing have been developed in C++.

5 Summary and conclusions

The construction of the new RIB facilities has boosted the interest in measuring accurate β-delayed neutron data, emission probabilities and energy spectra, relevant for nuclear structure, astrophysics and nuclear technologies. A high performance modular neutron time-of-flight spectrometer (MONSTER) has been designed for the DESPEC experiment at the FAIR facility.

The liquid scintillation detector NE213/BC501A has been chosen due to its excellent properties: high intrinsic efficiency, good time resolution and excellent neutron/γ discrimination properties. An extensive simulation work with GEANT4 has been carried out in order to optimize the design of the spectrometer according to the experimental requirements: geometry, optical properties, efficiency. The comparison to results obtained with the state of art simulation code NRESP7 has allowed to validate the performance of GEANT4. Several tests were performed at the laboratory for validating the simulations and choosing the adequate detector components. A similar modeling used in NRESP7 of the 3α reaction channels in carbon is being implemented in GEANT4 to reproduce the response function for incident neutron with energies above 8 MeV.

The proposed design of the spectrometer consists of 200 cell detectors of 20 cm diameter and 5 cm length, filled with liquid scintillator BC501A and coupled to a fast photomultiplier, placed at a flight distance of 2–3 m from the implantation setup.

A 30 module demonstrator of MONSTER has been setup at CIEMAT. The cells were manufactured by St. Gobain Crystals. The spectrometer will be operated with a fully digital data acquisition system (DAQ). The DAQ is based on a high performance digitizer board with a 12 bit resolution and 1 Gsample/s. The first experiments with the demonstrator will be performed at the Cyclotron Laboratory of the Jyväskylä University.

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