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n_TOF New target commissioning and beam characterization

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Abstract

A full characterization of the neutron beam and experimental conditions for measurement with the new spallation target installed at the n_TOF facility is proposed. In a first step, the behavior the target assembly under the proton beam irradiation will be investigated, in order to complete the target commissioning. Subsequently the neutron beam parameters required to analyze the physics measurements, i.e. neutron fluence, beam profile, energy resolution function and beam related backgrounds as a function of the neutron energy, will be determined.

I. INTRODUCTION

The CERN Neutron Time-Of-Flight (n_TOF) facility was constructed [1] with the aim of measuring accurately neutron reaction cross sections of importance for the design of Accelerator Driven Systems (ADS) for the transmutation of high level radioactive waste, for the understanding of the astrophysical processes leading to the synthesis of elements heavier than iron in the Universe, and for the advancement of our understanding of basic mechanisms in nuclear physics.

During the year 2004, after 3 years of successful operation of the original spallation target at the n_TOF facility, an abnormal increase of the radioactivity in the water of the target cooling system could be observed. Following the request of the Radioprotection Group of the CERN Safety Commission the operation of the facility was halted and the causes of the phenomenon thoroughly investigated. After several studies and consultations with external panels an improved target concept has emerged, and after approval by the CERN Directorate, it has been built and installed under the lead of the AB-ATB Department.

The new spallation target (see Fig. 1) consists of a cylindrical Pb block of 60 cm diameter and 40 cm length, cooled by a forced flow of water. The water will be chemically controlled in order to minimize its dissolution capacity. The impinging proton beam will be de-focused, which together with the forced water flow guarantees a target surface temperature well below the water boiling point and an inner temperature well below the Pb melting point. The water and Pb are enclosed in an aluminum container fitting into the old target container, which acts as a secondary containment vessel. A very thin window (with very narrow transversal reinforcements) is used in the forward direction in order to minimize the perturbation on the outgoing neutrons.

The water surrounding the Pb block acts also as an energy moderator material for the neutrons produced in the spallation reactions occurring inside. In particular the moderator volume in the forward direction largely affects the energy distribution of the neutrons arriving to the measurement samples in the experimental area. While a 1 cm thickness of H_2O is enough for cooling purposes a total of 5 cm are considered optimal for a

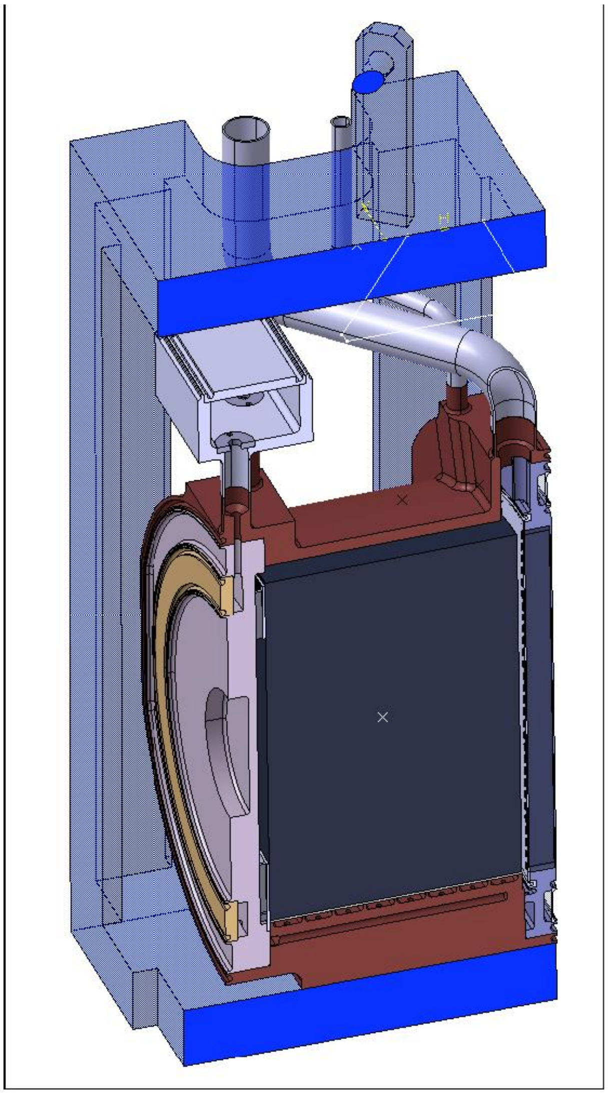

FIG. 1: Computer view of a cut through the new target assembly.

redistribution of the neutron energies. In fact this feature is going to be exploited in the new design in order to reduce the in-beam gamma-rays induced background. These γ-rays are mostly produced in the neutron capture on ^{1}H ($E_\gamma = 2.2$ MeV), travel along with the neutrons and are scattered on the measurement sample. The use of a separate moderator volume of 4 cm thickness allows the use of different moderator material with less harmful γ-ray emission.

The behavior of the target assembly under the pulsed proton beam irradiation as a function of proton beam intensity up to the maximum admissible load, will be verified in order to complete the target commissioning.

The neutron cross section measurements at n_TOF are performed detecting the relevant sample related radiation induced by the neutrons, as a function of the Time of Flight (ToF) measured against the proton beam pulses. The conversion of the measured data into cross sections requires the precise knowledge of the number of neutrons arriving to the sample and of the relation between the neutron energy and the ToF. Since the goal at n_TOF is to make very accurate cross section measurements, the relevant magnitudes were carefully measured for the original spallation target [2] during the starting phase. At the same time we carried out a characterization of the backgrounds present at the installation, which also limit the attainable accuracy. See [3] for some results of the original n_TOF target commissioning. Since all these parameters depend sensitively on the target geometry they must be also carefully measured for the present target configuration.

II. NEUTRON BEAM CHARACTERIZATION

The neutrons produced in the complex spallation reaction originated by the incident PS protons ($E_p = 20$ GeV) loose energy through collisions in the Pb target and more efficiently in the moderator/cooling water and eventually emerge in the forward direction. A fraction of them, after entering the 185 m long vacuum tube and passing through two beam defining collimators situated at 137 m and 178 m, arrive at the sample under investigation. The second collimator can have two different apertures defining beams sizes at the sample of either 4 cm diameter or 8 cm diameter. The former is normally used in capture measurements, the latter in fission measurements. The transversal intensity distribution of the beam is not flat and depends on the collimator in use. Particles non interacting in the sample continue to travel in a 15 m long vacuum tube until they reach a shielded beam dump. Heavy shielding around the target position and at several points along the beam line, serves to reduce the neutron fluence outside the beam by six orders of magnitude. The shielding together with a beam sweeping magnet located at 145 m reduce drastically the number of charged particles arriving to the experimental hall and contributing to the background.

A. Neutron fluence and beam profile

In order to obtain the neutron reaction cross section the quantity which is experimentally determined is the reaction yield. It is defined as the number of neutrons undergoing the specific reaction, signaled by the detection of reaction products, normalized to the total number of neutrons arriving to the sample at different times. In general it is not the absolute number of both quantities which is determined but rather a relative value of the ratio with respect to some standard.

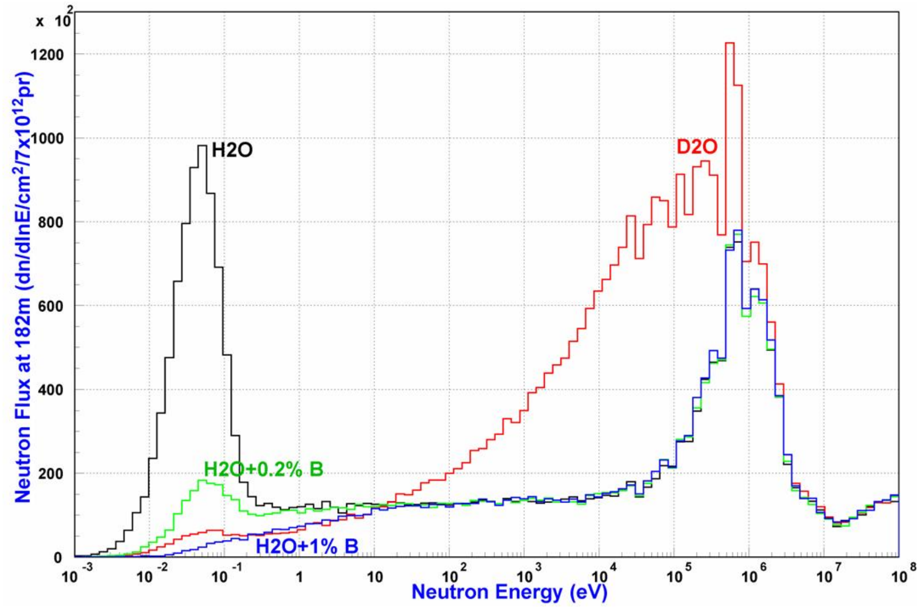

FIG. 2: Monte Carlo simulated flux for the new n_TOF target for different moderator materials.

In order to have a relative measurement of the number of neutrons arriving to the sample, neutron beam monitors are inserted in the beam that continuously register the number of neutrons as a function of the ToF. At n_TOF we have been using [4] a monitor based on the ^{6}Li$(n,\alpha)^3$H reaction consisting of a set of 4 silicon detectors surrounding a thin ^{6}Li deposit on a mylar foil. In the case of fission measurements the multi-detectors in use [5, 6] included ^{235}U and ^{238}U foils which have standard fission cross-sections and are measured simultaneously with the samples of interest. However it is difficult to have a monitor which has high enough differential counting statistics during a specific measurement, since they should be thin in order not to perturb the beam. Moreover in the case of capture measurements the normalization is often done to a single neutron energy value, when the saturated resonance method is employed [7]. Therefore an accurate determination of the shape of the distribution representing the neutron fluence at the sample as a function of the neutron ToF is an essential prerequisite for accurate cross sections.

According to the results of the Monte Carlo (MC) simulations we expect differences of up to around 20 % in the shape of the neutron number distribution (integrated fluence over the sample area) as compared to the original target [8] due to the different target assembly geometry. Fig. 2 shows the calculated flux in iso-lethargic units for different moderator compositions of the new target.

On the other hand the transversal distribution of the fluence, which is mainly determined by the collimators, is expected to vary little from the original one [9, 10]. As mentioned above this distribution is not flat, particularly in the case of the small collimator where it can be represented by a bi-dimensional Gaussian function with width $\sigma_{x,y} \backsim 5$ mm slowly varying as a function of the energy (see Fig. 3). It is important to verify this shape since it is used to calculate the corrections that must be introduced when comparing samples of different size, and to estimate the systematic errors due to sample-beam misalignments and sample thickness variations.

For the neutron fluence determination we propose to use well calibrated fission chambers containing high purity ^{235}U and ^{238}U samples prepared at PTB Braunschweig, similar to the ones employed during the commissioning of the original target [11]. The standard data acquisition system at n_TOF based on Flash-ADC [12] will be used for this and the rest of the measurements.

For the determination of the neutron beam profile we propose to use two different kinds of position sensitive detectors: a new type of Micromegas detector [13] and a MEDIPIX detector [14] originally developed for medical aplications.

B. Energy resolution function and time-energy relation

The properly normalized reaction yield data as a function of the neutron ToF must be analyzed in order to obtain the reaction cross section as a function of the neutron energy.

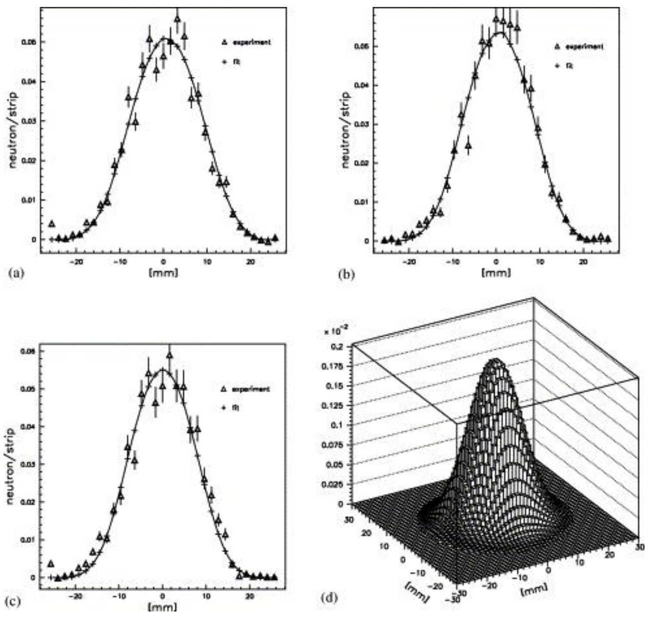

FIG. 3: Measured neutron beam profile at 186 m flight length.

This is usually done using specialized codes as SAMMY [15] or REFIT [16] which not only include, for example, the R-Matrix formalism for the parametrization of the cross section in the Resolved Resonance Region of the neutron energies, but also handles experimental distortions in the spectra as is the one caused by the complex relation between neutron energy and ToF

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After the impact of the PS proton pulses on the Pb target (against which the ToF is measured) neutrons are created at different times of the evolution of the nuclear reaction cascade, each of which suffers a different collision history until they eventually exit the front window and arrive at the sample. The travel time from the exit of the target to the sample depends on the flight path and the neutron velocity, but the time at which the neutron emerges depends on the previous history in such a way that a range of neutron energies emerge at the same time relative to the impact (or equivalently neutrons of a given energy emerge at different times): this distribution is known as the Resolution Function (RF).

Conventionally the resolution function takes into account also the effect of the time distribution of one proton pulse (containing between 4×10^{12} and 7×10^{12} protons) which is a Gaussian with $\sigma_t = 7$ ns, and eventually the time resolution of the detection system

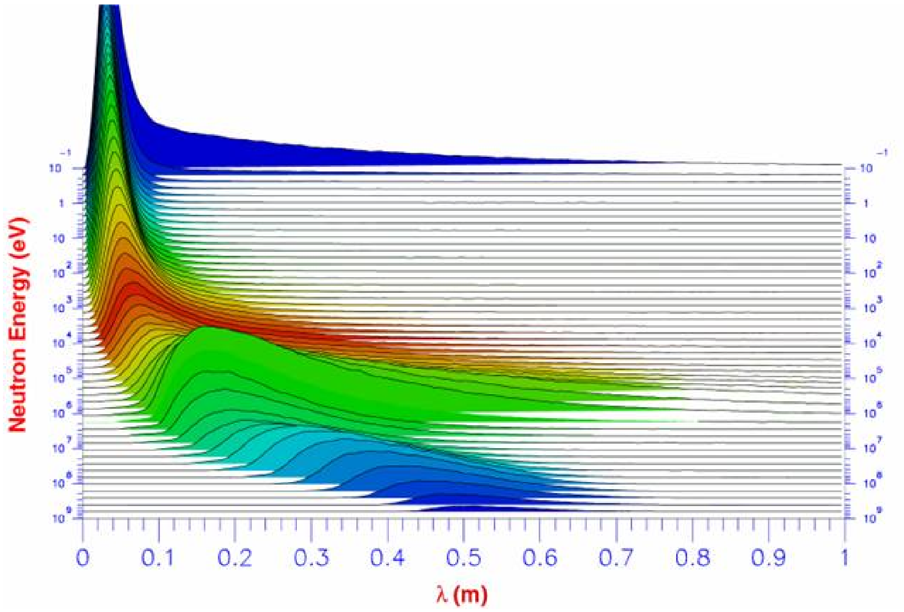

FIG. 4: Monte Carlo simulation of the resolution function for the new n_TOF target, here represented as the equivalent flight length distribution.

should be also included. Monte Carlo simulations of the production-moderation time show (Fig. 4) that the distribution is highly asymmetric, similar to the one obtained for the original target but with a width about 25% larger. In Fig. 5 we can see that the width coming from the proton pulse time width is comparable with this width only above $\sim$ 1 MeV neutron energy. On the other hand the time-energy relation uncertainty introduced by quite another effect, namely that atoms have a temperature dependent velocity distribution affecting the center-of-mass reaction energy, introduces a thermal broadening which dominates at the lower energies up to the keV region (see Fig. 5). Between 10 keV and 1 MeV the effect of the RF is most important and it should be properly determined.

To determine experimentally the resolution function, we will follow an approach similar to the one used previously [17]. The capture (n, γ) yield for a set of known narrow isolated resonances in ^{56}Fe and ^{54}Fe will be measured with good statistics using low neutron sensitivity [18] liquid scintillation C_6D_6 detectors and the Pulse Height Weighting Technique (PHWT) [19]. These resonances will be used to verify the MC simulations of the RF, and eventually to modify the simulated geometry since it has been shown that an optimized MC simulation is able to reproduce accurately the shape of the RF. Fig. 6 shows the agreement

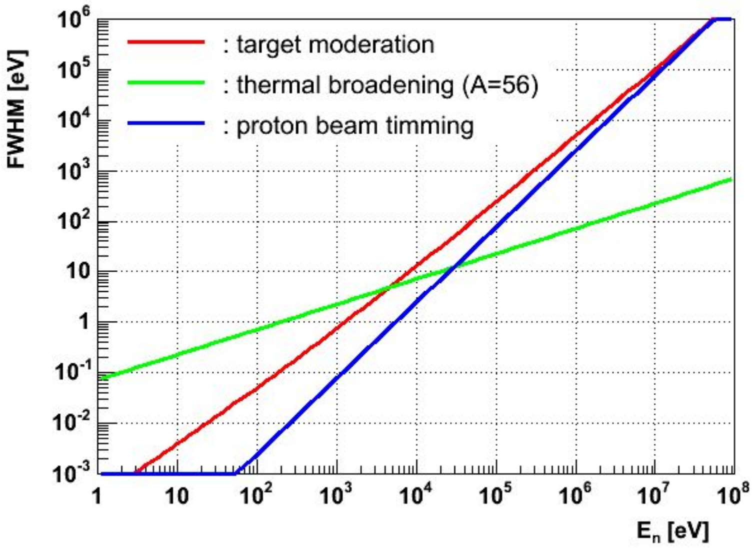

FIG. 5: Different contributions to the neutron beam energy resolution at n_TOF

obtained for the above mentioned resonances in the case of the original n_TOF target assembly. The simulated RF will be subsequently used to obtain a suitable parametrization of the RF over the entire energy range [20].

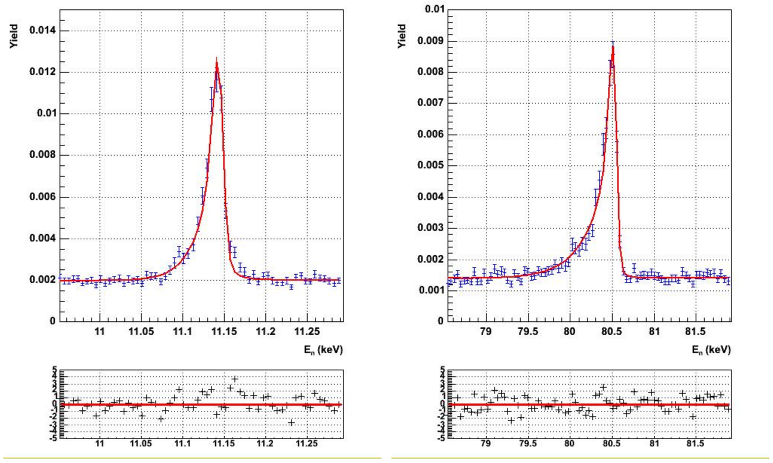

FIG. 6: Comparison of the measured and the calculated shape of two different Fe resonances at n_TOF

In order to determine the absolute neutron energy-ToF relation one measures reaction cross sections of isotopes with narrow symmetric resonances whose energy can be considered as an energy standard. At n_TOF, (n, γ) measurements on ^{193}Ir, ^{238}U and ^{32}S were performed with this purpose and allowed to establish a precise (0.1%) time-energy calibration in the range of 1 eV to 1 MeV [21]. The calibration procedure gave a fixed effective flight path length and a time offset which together correctly describe the time-energy relation. This calibration was used to set the energy of resonances for several measured isotopes with great precision, in particular Au and Fe, which in turn will be used to calibrate the new installation.

III. BACKGROUND STUDIES

In any measurement signals detected but unrelated to the reaction process of interest will limit the sensitivity and precision of the measurement (capacity to measure small resonances) and if unnoticed will limit its accuracy (introduction of systematic errors).

At n_TOF background signals coming from natural sources or from the sample in the case of radioactive ones, which are continuous in time, are greatly suppressed thanks to the particular beam structure of the PS: 7 ns (RMS) beam pulses separated by 2.4 s (prompt target photons arrive to the sample after 620 ns, 1 eV neutrons after 13.4 ms). Other type of background signals are produced by particles accompanying the neutron beam (photons, charged particles and stray neutrons). These are more tricky to handle and great efforts have been spent at n_TOF to reduce them [22]. A third type of background signals are those due to neutrons scattered by the material existing in the beam path (including the sample itself) which produce unwanted signals in the detection system.

A. Beam related backgrounds

At n_TOF one can distinguish three main sources of beam related background signals: 1) neutron beam halo, 2) charged particles and 3) in-beam γ-rays. It has been already mentioned that thanks to the design of the beam collimators and shielding the neutron flux outside the beam is suppressed by six orders of magnitude. On the other hand, at the beginning of the original commissioning phase it was found that charged particles produced in the target and surrounding materials arrived at the experimental area in excessive amount. In a series of posterior interventions the shielding along the beam line was improved and the background greatly reduced. There are no reasons to expect a major change on the level of these background types with the new target assembly, although the source distributions will be different due to the wider proton beam and the new target dimensions. Nevertheless this has to be verified and we are proposing to use a set of CR-39 neutron dosimeters [10] and of scintillation detectors (C_6D_6 and BaF_2) distributed conveniently throughout the experimental area in order to measure the effects of the background components mentioned above.

The third source of background is due to γ-rays produced in the target assembly and traveling together with the neutrons along the beam tube (charged particles are efficiently deflected by the sweeping magnet). When arriving to the sample they could be dispersed and detected, and in fact constitute a mayor source of background in the capture measurements. From MC simulations it was verified that the strongest component are 2.2 MeV γ-rays originated in the $^1\text{H}(n,\gamma)^2\text{H}$ reaction taking place in the cooling/moderator water. Due to this reason in the new target design a separated volume of water for moderation has been included with the idea that in this volume the normal water could be replaced by borated water (^{10}B enriched) which captures neutrons with great probability and produces less harming 0.48 MeV γ-rays. Alternatively, deuterated water where the capture probability is very small could be used in the secondary liquid moderator circuit. Fig. 7 shows the result of MC simulations on the effect of different moderators on the intensity and time distribution of the γ-rays produced. The level of background reduction must be verified comparing the different moderator materials. For the measurement, we will employ samples of low-Z (^{12}C) and high-Z (^{208}Pb) and the scattered γ-rays in the forward and the backward direction will be detected using C_6D_6 detectors.

B. Scattered neutron background

Neutrons scattered by material elements in the beam path, specially those close to the sample or the sample itself, can induce unwanted signals in the detection system. This is the case of the neutron capture measurements using the Total Absorption Calorimeter (TAC), where the effect is particularly large due to its large volume. These neutrons produce γ-rays in the detector or surrounding materials which are then efficiently detected. It has been found

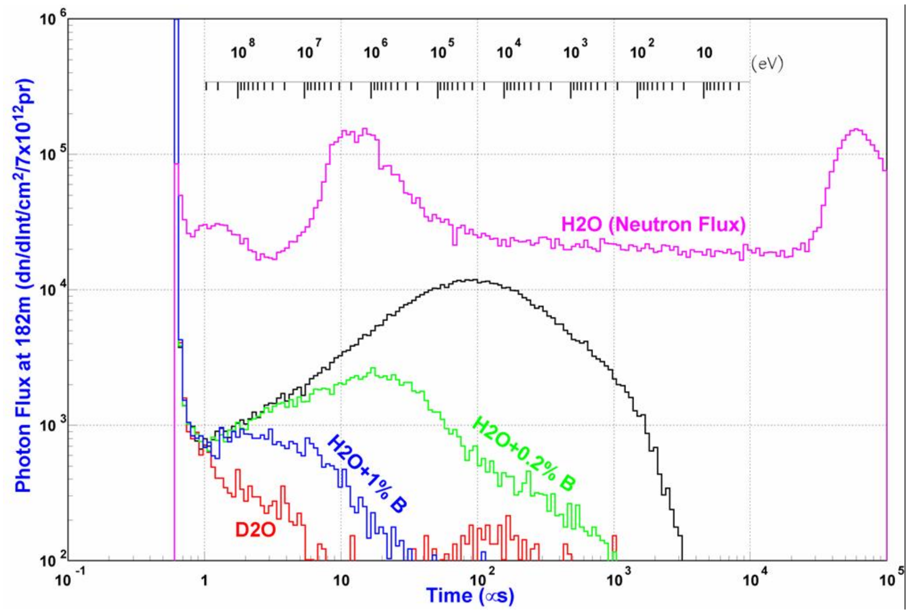

FIG. 7: Monte Carlo simulation of the γ-rays produced for different moderator materials.

that this can become the main source of background for this type of measurements. In order to reduce the overall contribution of the neutron scattering background to the TAC measurements we plan to introduce some modifications in the setup. For neutrons scattered at the sample, a neutron absorber will be placed surrounding the sample in the center of the TAC. Two different absorbers will be compared, one containing ^{6}Li manufactured at FZK (used previously) and another one containing ^{10}B manufactured at CIEMAT. In previous measurements the samples were located in air between the close-by windows of the vacuum tube and it was found that these windows were a major source of scattered neutrons. A new sample system has been designed in which the samples are placed under vacuum at the center of a long canning in such a way that the vacuum windows are located outside the TAC and can be efficiently shielded with borated polyethylene material (see Fig. 8) We plan to quantify the level of background reduction achieved with these improvements.

IV. BEAM TIME REQUEST

General verification of the instrumentation: After the long stop there will be a need to verify the performance of the different detectors with beam (additionally to the verification with radioactive sources, whenever that is possible) and in particular of the DAQ system. We estimate that the total number of protons needed in this phase is 10^{17} in order to test

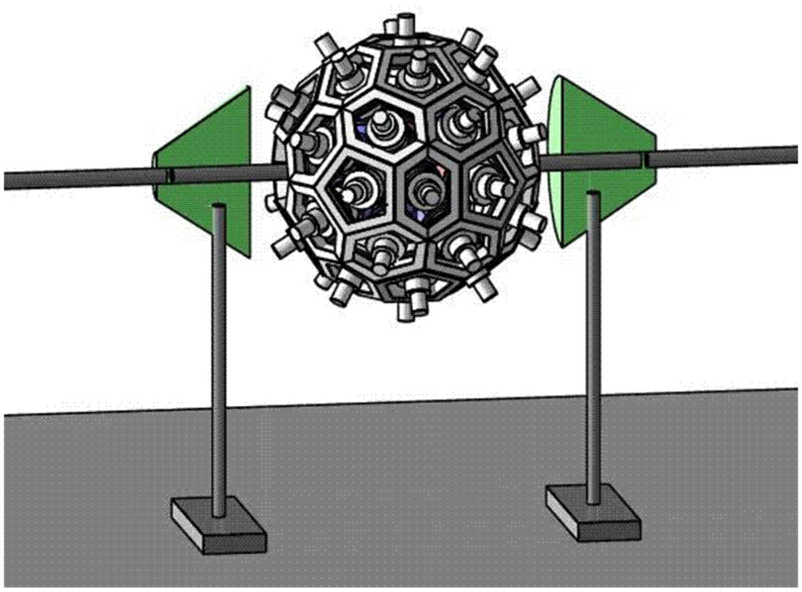

FIG. 8: Schematic view of the TAC with the new sample assembly and absorbers.

the BaF_2 Total Absorption Calorimeter, the C_6D_6 detectors, both the PPAC (Parallel Plate Avalanche Counter) and FIC (Fast Ionization Chamber) fission detectors, and the Si-MON neutron monitor. The verification of the target behavior under the proton beam irradiation conditions will take place also in this phase.

Neutron fluence distribution: We will use two well calibrated fission chambers prepared at PTB Braunschweig, one of them using high purity ^{235}U and the other one high purity ^{238}U samples. The chambers contain 10 parallel plate ionization chambers with deposits of about 0.45 mg/cm^2 allowing an efficient ($> 95\%$) registration of the fission products. Both chambers will be placed simultaneously under the beam and we will accumulate a similar statistics to the one registered during the commissioning phase of the original target [3], requiring a total of 8×10^{17} protons for each moderator-target combination investigated. At present we plan to test two configurations: one using normal water, the other using borated water in the secondary moderator circuit.

Neutron beam profile: We will use two types of detectors. One of them is a new type of Micromegas detector based on the $X - Y$ microbulk technique which was employed recently in the CERN CAST experiment with success. The original design will be modified in order

TABLE I: Estimated counting rate for some selected Fe resonances used to determine the RF.

Isotope	Energy (keV)	Counts/7×10^{12} p
^{54}Fe	9.48	0.27
	11.18	0.98
	30.64	0.21
^{56}Fe	22.80	0.13
	34.23	0.11
	46.05	0.053
	59.23	0.054
	80.84	0.081
	181.18	0.030

to include a thin ^{235}U deposit at the drif electrode. The other detector will be an array of MEDIPIX detectors with the addition of a LiF neutron converter. These detectors will be placed in the beam simultaneously with the PTB chambers, so that no additional beam time is required for this measurement.

Neutron energy resolution function: The measurement will be performed using enriched ($> 97\%$) ^{56}Fe and ^{54}Fe samples with 20 mm diameter and a mass of 2 g using two C_6D_6 detectors with an average γ-ray cascade detection efficiency of 12%. A set of selected narrow isolated resonances up to 200 keV will be analyzed in order to deduce the shape of the RF. In Table I we give the expected integrated counting rate per nominal proton pulse (7×10^{12} p) for the resonances.

If we establish that our goal in statistics is to obtain 10^3 counts in the weakest resonance we will need 3.3×10^{16} protons for the ^{54}Fe sample and 2.3×10^{17} protons for the ^{56}Fe sample for each moderator-target combination investigated.

Background studies: The measurement of the off-beam background will be done using a set of CR-39 neutron dosimeters and scintillation detectors (C_6D_6 and BaF_2) distributed throughout the experimental hall. This measurement will be performed in parallel with other measurements and will not require additional beam time.

The measurement of the in-beam γ-rays induced background will be performed with two C_6D_6 detectors placed in the forward and the backward directions with respect to the sample position. A carbon sample of thickness 6 mm and a lead sample of thickness 1 mm will be placed in the beam. From the comparison of the deposited energy spectra and the ToF distribution the amount of the scattered γ-ray background will be deduced. For our previous experience we estimate that in order to obtain sufficient statistics we will need 2×10^{16} protons for each moderator-target combination investigated.

The measurement of the scattered neutron background with the TAC will be performed comparing the different neutron absorber options and sample configurations using carbon (a pure scatterer) and gold samples. Based on the counting rates recorded during 2004, and assuming a minimum of 100 energy bins per decade with an statistical uncertainty of 2%, a total of 2.1×10^{17} protons are required for the accurate determination of the background conditions in all configurations.

In summary, a total of 2.45×10^{18} *protons is requested to complete the target commissioning and the full beam characterization and background conditions for measurements with the new target installation at n_TOF.*

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