EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Commissioning of the third-generation spallation target and the neutron beam characteristics of the n_TOF facility

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The n_TOF Collaboration

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Abstract

During the CERN's Long Shutdown 2 (LS2), several upgrades of the n_TOF facility have been carried out to improve the performances of the existing experimental areas and further exploit their potentials. The most important one is the construction and installation of a new third-generation spallation target. A thorough commissioning of the target and the experimental areas with beam is therefore proposed. In the first phase, the performance of the new target assembly under proton irradiation at different intensities will be studied in order to complete the target commissioning. In a second phase, a complete characterization of the neutron beam in the two experimental areas will be carried out. The upgrades of the facility will allow increased flexibility in the respective configurations of the collimator and moderator systems in both experimental areas. The commissioning will be carried out at different stages considering such configurations, two for the experimental area 1 (EAR1) and three for the experimental area number 2 (EAR2). The use of protons for measurements in EAR1 and EAR2 during the commissioning will be optimized by combining the commissioning activities with experiments with approved proposals. The results of the commissioning are instrumental for the execution of the n_TOF physics program after LS2.

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Requested protons: $83 \cdot 10^{17}$ (EAR1). $95 \cdot 10^{17}$ (EAR2)

Experimental Area: EAR1 and EAR2

INTRODUCTION

The neutron time-of-flight (n_TOF) facility at CERN was designed and constructed with the aim of measuring accurate neutron-induced reaction cross.sections data and the related physical quantities in a wide energy range [1]. Since the startup of the facility in 2001, the measurements and instrumental developments led to more than 160 publications in refereed journals in several fields [2]. The results of the measurements are continuously disseminated to the scientific community through the EXFOR (Experimental Nuclear Reaction Data) database [3] with more than 116 data sets [4]. Such datasets are often adopted for cross section evaluation by the major nuclear data libraries, such as JEFF (Joint Evaluated Fission and Fusion File) [5], ENDF (Evaluated Nuclear Data File) [6] and JENDL (Japanese Evaluated Nuclear Data Library) [7]. Along the years, the n_TOF physics program has been wide-ranging and, at present, covers several fields [8] [9]. The data provided by n_TOF, the theoretical investigations and the applied studies have been of interest in nuclear astrophysics [10] [11] [12] [13], in advanced fission technologies [14] [15] [16] [17]with several cases covering large energy ranges [18], in fundamental physics [19] and in medical investigations [20] [21]. In addition, new applications of the facility continuously being study [22] and expanding, resulted in the development of the concept for a new measuring/irradiation position. This new station (NEAR Station) will be located less than 3 meters from the target module, just outside the target shielding, with strongly enhanced neutron fluence (see section 1.3).

At n_TOF, neutrons are produced by spallation of a pulsed proton beam of 20 GeV/c momentum from the Proton Synchrotron (PS), impinging on a cooled Pb target. The n_TOF collaboration, jointly with CERN, performed the commissioning of the first generation target [23] [24]. A few years later, the commissioning of the second generation target was also proposed and carried out [25] [26]. Between 2001 and 2014, the n_TOF facility operated with only one experimental area, EAR1, located in the horizontal direction with respect to the proton beam direction, at 185 m downstream from the spallation target. In 2011, a second experimental area, EAR2, with shorter flight path was proposed and constructed taking advantage of the second generation target [27] [28]. The commissioning of EAR2 was proposed and carried out [29] [30]. EAR2 is located at 90º-vertical with respect to the proton beam direction and at 20 m from the target. At the same time, a re-commissioning of the EAR1 neutron beam was proposed and performed [31]. EAR1 and EAR2 have excellent characteristics by themselves but complementary studies can also be carried out providing unique sets of experimental nuclear data [21] [32].

In the present document, the commissioning of the facility with the third-generation n_TOF target is proposed. The second target showed excellent performances, but its aging and the LS2 opportunity motivated the development of a third spallation module and, consequently, a replacement. The new target and related systems have an optimized geometry for both experimental areas, in particular for EAR2. This was not the case for the second-generation target, since EAR2 was constructed few years after its installation. Simulations have shown that a factor of two higher neutron flux in EAR2 (in the keV region) and an improved energy resolution with respect to the second spallation target are expected for the third-generation n_TOF target assembly [33] [34]. In addition, a further reduction of the photon background fluence at EAR1 is expected, while maintaining the previous target performances and the excellent characteristics of the neutron beam [35].

Two steps are envisaged for the commissioning: firstly, an accurate characterization of the performance of the new target assembly and new beam line elements will be carried out, followed by complete and accurate characterization of neutron beam characteristics in both experimental areas will be undertaken.

The programme of measurements to be carried out is detailed in 1 and 2.

1. NEW TARGET AND UPGRADES OF THE BEAM LINES

1.1 Third-generation spallation target

The third-generation n_TOF target is based on six Pb slices. In order to ensure that Pb impurities will have a negligible effect on the facility's physics performances, the base lead material has a minimum purity of 99.9 wt%. The shape and size of the slices have been defined after an optimisation procedure to find the best compromise between the neutron flux towards EAR1 and EAR2, as well as to keep the background conditions low. The slices are 60 cm wide and 5 cm thick. The only exception is the last slice along the beam direction, which is 15 cm thick in order to keep the background low. The flat top helps improving the resolution for EAR2 in comparison with the second-generation target. The Pb slices are cooled down by a forced flow of pure nitrogen.

Switching from the water cooling of the second-generation target to nitrogen cooling in Target #3 reduced the heat removed per unit area. To keep the same peak temperature in the new target, the surface exposed to the coolant must be increased, hence the slicing. The upgrade to nitrogen cooling avoids water contamination issues, while the absence of cladding materials keeps the background low.

Figure 1 shows the target assembly: the lead slices are supported by an aluminium-alloy structure (Al-6082-T6), while the sub-assembly composed of Pb slices and aluminum is hosted inside a low-cobalt (0.078%) stainless steel 316L vessel.

The target will feature two moderators, each one dedicated to each experimental area. The EAR2 moderator is mounted outside the stainless-steel vessel, above the target, while the EAR1 moderator is integrated into it and represents its downstream face. The two moderator casings are made of aluminum alloy 5083. The bond between the EAR1 moderator and the stainless-steel vessel is realized with a bimetallic transition obtained by a process of explosion cladding. Both borated, water as well as light water, will be used – independently - in each of the moderators, enhancing the physics capabilities of the facility. Borated water will be employed in order to reduce the presence of 2.2 MeV photons generated by thermal neutron capture on ^{1}H.

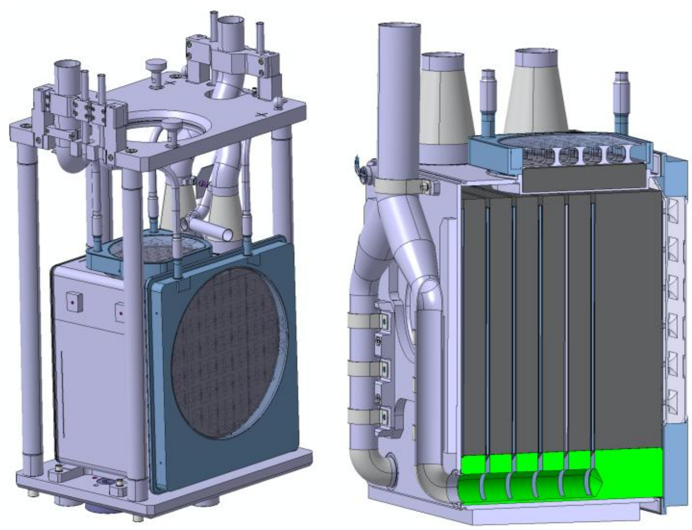

Figure 1: The figure shows two isometric views of the third-generation spallation target. In the left picture the two AW5083 moderator tanks are visible. On the right picture the Pb slices are visible, together with the horizontal Pb wedge required to reduce the photon background in EAR2. The nitrogen cooling distribution manifold is highlighted in green.

The behavior of the target assembly under pulsed proton beam irradiation as a function of the proton beam intensity up to maximum admissible load will be verified in order to complete the target commissioning. The target system is equipped with "K-type" thermocouples in contact with the Pb slices, which are proven to be extremely radiation resistant [36] [37]. In addition, SPND detectors [38] will be installed on the target housing in order to be able to measure directly the neutron fluence.

1.2 Proton and neutron beam line upgrades

During the operation of the first- and second-generation n_TOF spallation targets, the facility lacked the capability to monitor pulse-by-pulse the proton beam impinging on the spallation target. During 2017, the n_TOF Collaboration noted that beam position on target modified the neutron fluence reaching EAR2. As a consequence, a new Secondary Electron Monitor (SEM) grid has been added in the proton transfer line to target (FTN) beam line. This detector will allow reconstructing the beam pulse transversal size for every bunch impinging on the target, without creating beam losses in the area, as well as it will allow reconstructing the neutron fluence as a function of beam centroid position on target. Such a device will have to be commissioned during the early phase of the target-beam recommissioning.

Similarly, a new neutron beam shaping collimator will be installed in the horizontal beam line at around 150 m from the spallation target with the objective of enhancing the positioning reproducibility between capture and fission measurement configurations, while at the same time reducing the time needed for its exchange and improving the photon background conditions in EAR1. A beam-based realignment process will be required in order to minimize the neutron and photon background in EAR1.

1.3 Recommissioning of the consolidated shielding around the spallation target

Operational constraints have also led to a revision of the n_TOF target pit shielding, which is now movable and allows direct access to the target assembly from the side (i.e. parallel to the proton beam). This modification has opened the possibility of exploring the potential for near-target irradiation as well as for a measuring station close to the spallation target (NEAR station) [39]. This would take advantage of the extremely high instantaneous neutron fluence available at around 3 meters from the target. The first step in this new development would be the commissioning of the new shielding around the target with beam, in order to understand the new radiation protection conditions as well as its operational capabilities. A dedicated Letter of Intent has been presented with more details about the NEAR Station.

1.4 Proton request for target commissioning

The target commissioning would involve several steps to be executed in sequence, in order to evaluate the safe and reliable operation of the spallation target systems and the annexed components. The commissioning will include – at the beginning – relatively low beam intensity on target, followed by a ramp-up up to parasitic-like cycles and then later on by high intensity operation. Each ramp-up stage will be followed by stable operation for about 2 weeks, in order to evaluate the stability of target operation as well as the stability of neutron fluence in the EARs. In order to assess these performances, different techniques and experimental means will be employed. These include thermocouples in the target core, extensive instrumentation in the cooling and moderator station, radiation protection detectors (for prompt and dose rate) as well as neutron fluence monitors in the n_TOF Experimental Areas. They will be complemented by proton beam monitors in the proton transfer line in order to measure pulse intensity and to monitor the pulse-by-pulse transversal beam size and position with respect to the target core.

In conclusion, in order to be able to accurately assess the behaviour of the target systems with beam and of the related infrastructures in both the proton and neutron beam lines **$25 \cdot 10^{17}$ protons** are requested. The estimation is based on experience with the commissioning of the previous spallation target and on a list of technical achievements defined in the commissioning plan of similar beam intercepting devices at CERN.

A dedicated and detailed target beam commissioning plan is being redacted by the relevant CERN teams in collaboration with the n_TOF Collaboration.

2. NEUTRON BEAM CHARACTERIZATION

The characteristics of the neutron beam to be determined in both experimental areas are: neutron flux, spatial beam profile, resolution (time-to-energy conversion) and background conditions. In order to provide a highly accurate characterization of the neutron beam, these quantities will be experimentally determined with independent detection systems. We propose to use as main detector systems: PPAC (Parallel Plate Avalanche Counters), which can hold two samples and is used in the detection of fission fragments; SiMon (Silicon

Monitor), based on the $^{6}Li(n,t)^{4}He$ reaction, there is one for EAR1 and another one for EAR2; MGAS (Micro-MEsh Gaseous Structure), which can hold ^{10}B, ^{6}Li or fissionable samples; PTB (Physikalisch-Technische Bundesanstalt fast gas detector), which operates with ^{235}U samples; C_6D_6 (Hydrogen-free deuterated benzene liquid scintillator) detectors and the TAC (Total Absorption Calorimeter, based on BaF_2 crystals) for capture measurements [40]. Figure 3 shows the previous results of the neutron flux or neutron fluence per proton pulse determination in EAR1 (top) [41] and EAR2 (bottom) [30] with the mentioned detector systems.

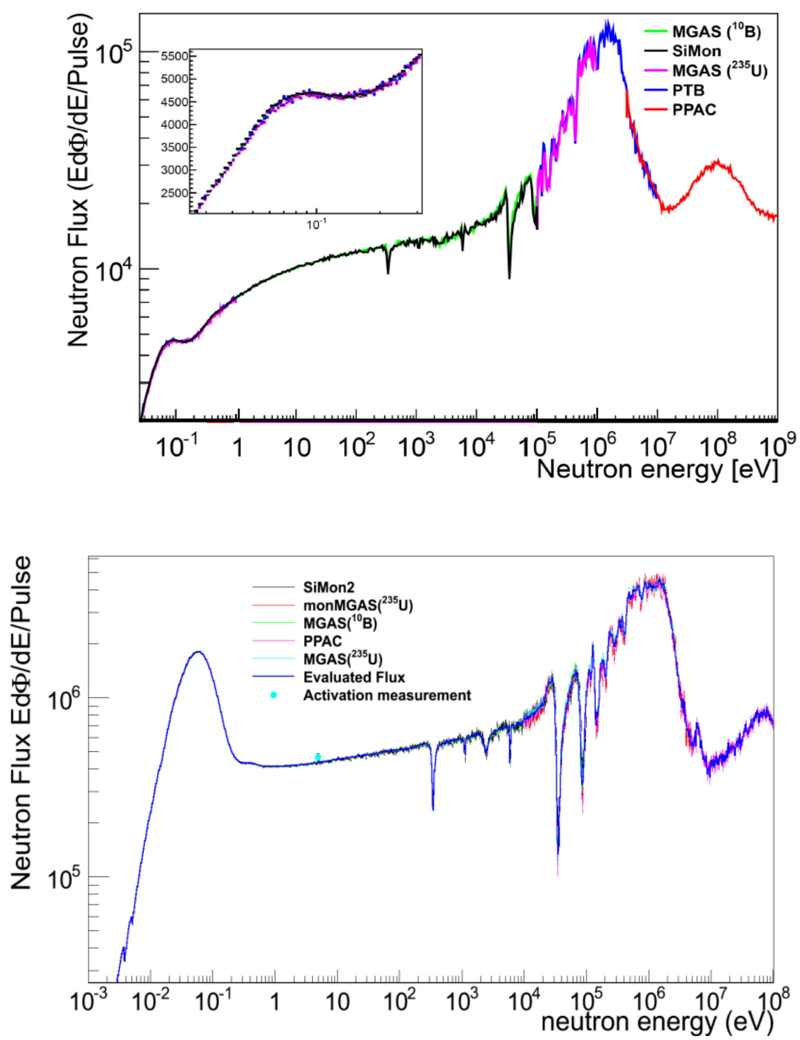

Figure 2: The figure shows the neutron flux or neutron fluence per proton pulse with the second generation spallation target for EAR1 (top) [41] and EAR2 (bottom) [30].

Due to the new target design, FLUKA simulations [33] and the results of the previous commissioning [41] [30] are important references for estimating the number of protons required for each individual measurement. Figure 4 shows the neutron flux or fluence per pulse provided by FLUKA simulations with the new target (named solution #5) in comparison to the previous target (named solution #0), on the left EAR1 and on the right EAR2.

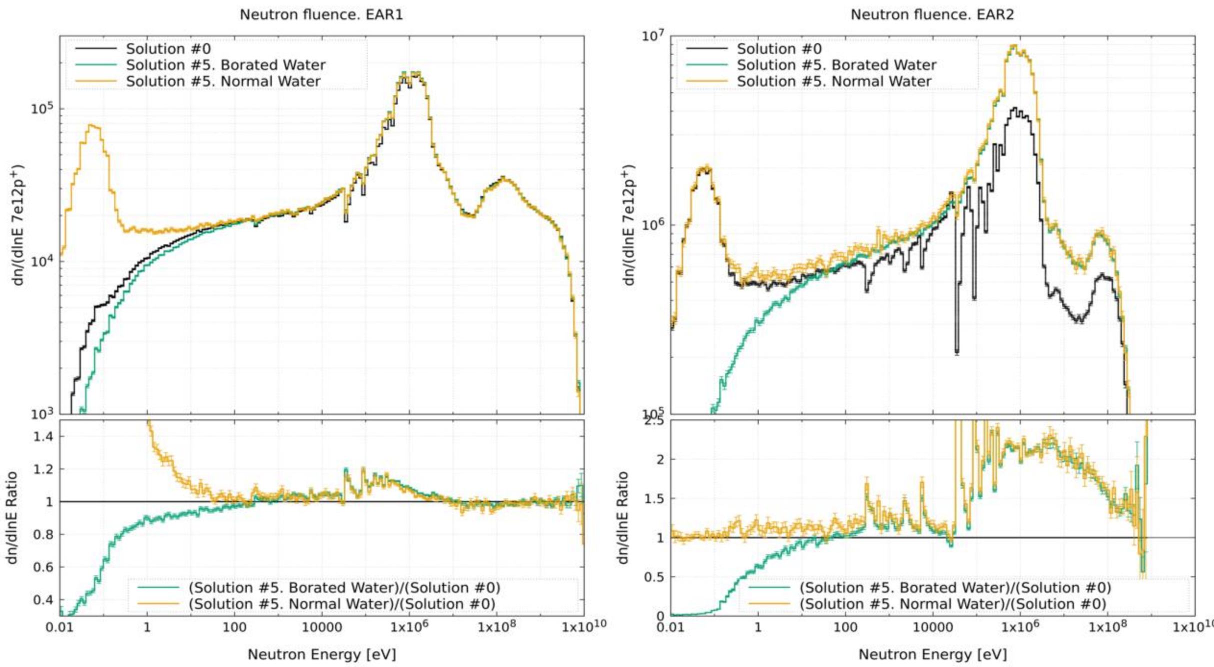

Figure 3: Comparison of neutron fluence per proton pulse ($7 \cdot 10^{12}$ protons/pulse) for EAR1 (left) and EAR2 (right) for the second-generation target (Solution #0 in the figure) and the third-generation target (Solution #5 in the figure).

2.1 Neutron Flux

The neutron flux, defined as the number of neutrons per centimetre squared and per proton pulse ($7 \cdot 10^{12}$ protons), will be determined as a function of the neutron energy using the neutron standard reactions ^{6}Li(n,t)^{4}He, ^{10}B(n,α)^{7}Li, ^{235}U(n,f) and ^{238}U(n,f), with in-beam and off-beam detectors. The shape of the neutron flux as a function of the energy will also be verified with the ^{197}Au(n,γ) reaction and C_6D_6 detectors and TAC (off-beam detectors). Activation measurements using HPGe detectors will be carried out to verify the neutron flux with an alternative technique. As in the previous commissioning, several detectors can run simultaneously due to the high neutron transmission across very thin samples and detector materials. Indeed, the transmission can be accurately determined, and data corrected accordingly. This will allow to optimize the beam time. Table 1 details some characteristics of the detector systems to be used. FLUKA simulations and the results of the previous commissioning have been taken into account for maximizing the count rates while minimizing corrections for dead time and pile-up effects.

Detector	Reactions	Mass - EAR1 (μg/cm^2)	Mass - EAR2 (μg/cm^2)	EAR
PPAC	^{235,238}U(n,f)	280	70	1 & 2
MGAS	^{10}B(n,α)^{7}Li/^{235}U(n,f)	203 / 93	3.03 / 93	1 & 2
SiMoN	^{6}Li(n,t)^{4}He	300	50	1 & 2
PTB	^{235}U(n,f)	264.1		1

Table 1. List of the detectors to be used during the commissioning of the neutron flux.

In EAR1, the goal is to achieve 2% counting statistics uncertainty or lower for neutron energies below 10 MeV and 5% above 10 MeV. In EAR2, the goal of the combined measurements is to achieve 2% statistical uncertainty or lower for neutron energies below 1 MeV and less than 5% above 1 MeV, for 100 bins per decade.

The total number of protons required to achieve these goals is **$15 \cdot 10^{17}$ protons at EAR1** and **$21 \cdot 10^{17}$ protons at EAR2**, estimated using FLUKA simulations of the neutron beam delivered by the new spallation target assembly, the results of the previous commissioning in EAR1 and EAR2 and the properties and characteristics of the setups considered.

2.2 Neutron Beam Profile

The neutron beam profile or the transversal distribution of the fluence as a function of the energy is not a flat distribution. In the commissioning of the facility with previous targets and collimator systems, it showed a modified Gaussian-like shape [25]. The neutron beam profile is a fundamental quantity for the analysis of neutron-induced reactions, since it has to be applied for corrections associated with samples of different size/shape, possible sample-beam misalignments and possible non-homogeneities of the sample thickness.

The neutron beam profile will be measured with different detectors, including PPAC, XYMGAS [42], CR39 and SiMon2D [43]. XYMGAS is a development of MGAS able to determine the beam profile and SiMon2D is a development of SiMon for the same purpose. For this task, **$7 \cdot 10^{17}$ at EAR1** and **$13 \cdot 10^{17}$ at EAR2 dedicated protons** are required. These estimates were made using FLUKA simulations of the neutron beam delivered by the new spallation target assembly, the results of the previous commissioning in EAR1 and EAR2 and the properties and characteristics of the setups considered.

2.3 Resolution Function

The distribution in time of neutrons with a given energy reaching the experimental area is commonly called resolution function (RF). The RF can be determined by Monte Carlo simulations which must be validated with measurements of well-known neutron-induced resonant reactions. The RF considers the time distribution of the proton pulse (Gaussian, with $\sigma = 7$ ns), the moderation time spent by the neutron in the target-moderator assembly and, if relevant, the time resolution (or dimensions) of the detector.

Isolated resonances of well-known or standard reactions are of particular interest for determining the RF. In the commissioning of previous targets, we successfully used C_6D_6 and TAC detectors with the reactions ^{56}Fe(n,γ), ^{54}Fe(n,γ), ^{197}Au(n,γ), ^{238}U(n,γ) and ^{32}S(n,γ), which we plan to use in the present commissioning as well. It should be mentioned that some of the considered reactions for determining the neutron flux, such as the ^{235}U(n,f), can contribute to the resolution function data. As experienced in the previous commissioning, the statistics required are driven by the weak resonance of the ^{56}Fe(n,γ) reaction at 180 keV [29] [31]. For achieving 1000 counts in that resonance, $6 \cdot 10^{17}$ protons in EAR1 and $5 \cdot 10^{16}$ in EAR2 with the C_6D_6 conventional setup are needed. Considering the measurements with all other samples, a dedicated number of protons of **$14 \cdot 10^{17}$ at EAR1 and $14 \cdot 10^{17}$ at EAR2** are required.

2.4 Background

An important background component of neutron capture measurements at n_TOF is related to the neutron scattered in/by different parts of experimental setup. A scattered neutron can undergo a reaction in the detector itself or can react in other parts of the experimental area and produce gamma-rays which induce unwanted signals in the detector. At n_TOF, neutron capture cross section measurements are carried out mostly with C_6D_6 detectors in EAR1 and EAR2, and with the TAC only available in EAR1. The background conditions in both experimental areas can be measured with a C (a pure scatterer), Pb and Au samples of different thicknesses and empty frames used for holding samples. Several detectors can be placed at the same time far away from the sample position and few off-beam detectors will be used close to the sample position to avoid cross-talks. In addition to C_6D_6 detectors and TAC, other detector systems such as i-TED (imaging Total Energy Detector) [44], ^{3}He, HPGe and s-TED (segmented Total Energy Detector) [45] will be used. A dedicated number of **$17 \cdot 10^{17}$ protons at EAR1 and $17 \cdot 10^{17}$ at EAR2** are required for studying the background conditions**.**

3. OVERALL PROTON REQUEST

Table 3 summarizes the dedicated protons for the commissioning of the n_TOF facility which involves the new spallation target and the experimental areas in different configurations. In particular, the following configurations have been considered:

- EAR1 (two configurations): moderator system with borated water and two collimators, for both capture and fission measurements;
- EAR2 (three configurations): moderator system with both demineralised and borated water. For the first configuration, both capture and fission collimators have been considered, while for the second only the capture collimator setup;

The n_TOF Collaboration will optimize the simultaneous use of protons in EAR1 and EAR2. The optimization will consider possible simultaneous measurements in both experimental areas for the commissioning as well as simultaneous measurements with approved physics proposals together with the commissioning measurements.

PROTON REQUEST n_TOF facility		
	EAR1 ($\cdot 10^{17}$)	**EAR2 ($\cdot 10^{17}$)**
Target Commissioning	**25**	**25**
Neutron Flux	15	21
Beam Profile	7	13
Resolution Function	14	14
Background	17	17
Total Neutron Beam Characterization	**53**	**65**
Contingency	**5**	**5**
TOTAL	**83**	**95**

Table 3. Summary of the proton request for commissioning the n_TOF facility.

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