EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Application of energy resolved neutron imaging at n_TOF EAR2

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M. Bacak[1], O. Aberle[1], M. Calviani[1], E. Chiaveri[2], E. Lehmann[3], and the n_TOF Collaboration[4]

[1]*European Organization for Nuclear Research (CERN), Switzerland*
[2]*University of Manchester, United Kingdom*
[3]*Paul Scherrer Institut (PSI), Lab. Neutron Scattering & Imaging, Switzerland*
[4]*www.cern.ch/n_TOF*

Spokesperson: M. Bacak (michael.bacak@cern.ch)
Technical coordinator: O. Aberle (oliver.aberle@cern.ch)

Abstract:

Neutron radiography plays an important part in the diagnostic repertoire of non-destructive inspection techniques providing information of the inner part of an object often not accessible by any other means. Since the start-up of n_TOF's second experimental area (EAR2), the possibility of diversifying the capabilities of EAR2, profiting from a high instantaneous neutron flux, were exploited. First results with conventional neutron imaging have been published and showed a reasonable performance of the facility with respect to flux and resolution, understandably still short of the performance of dedicated imaging facilities around the world. The potential use of neutron energy resolved imaging was not exploited but the facility's usefulness for imaging of highly radioactive objects, for example AD-targets before and after irradiation proved valuable. During CERN's second long shut down n_TOF upgraded its spallation target, resulting in an increased neutron flux, which, combined with the rise of commercially available time-of-flight imaging detectors, opens the possibility to explore neutron energy resolved neutron radiography at n_TOF EAR2. This Letter of Intent aims at studying the feasibility of a time-of-flight imaging setup at EAR2. The planned experiments willprovide neutron beam profile measurements to validate simulations, as well as to characterize scintillation materials profiting from the wide neutron energy spectrum at n_TOF.

Requested protons: 7×10^{17}.
Experimental Area: EAR2

1 Introduction

Neutron radiography and neutron imaging (NI) is a well-known method to perform non-destructive investigation of materials. Due to the properties of a neutron's interaction with matter it is fully complementary to X-ray analysis, with high-Z materials being essentially transparent for neutrons and with an isotopic dependent interaction neutron cross-section. NI made an important step forward in the last three decades, due to the use of digital data acquisition and processing systems which generally greatly enhanced the image resolution as well as the flexibility of the technique's use. Only a few of the various applications - generally of applied science - shall be mentioned:

- Inspection of (irradiated) bulk material
- Micro-structure analysis of metals
- Application to cultural heritage

Many NI facilities are operating worldwide [1] and are installed at research reactors (e.g. ILL in France, FRM-II in Germany) or at spallation neutron sources (e.g. PSI in Switzerland, J-PARC in Japan). Since its construction in 2014 the neutron imaging capabilities of n_TOF's second experimental area (EAR2) [2, 3] were investigated [4, 5] and showed the technique's feasibility at EAR2 [6, 7]. A sketch of the beam line and photo of the imaging setup is shown in Figure 1. Whilst proven feasible the full characterization of the beam line was not finalized as priority was given to the physics experiments in the last run. During the last long shutdown at CERN n_TOF has upgraded its spallation target [8], optimized for EAR2, resulting in an increased neutron flux of approximately 60 % over the whole energy range, see Figure 2. This reduces the required exposure time

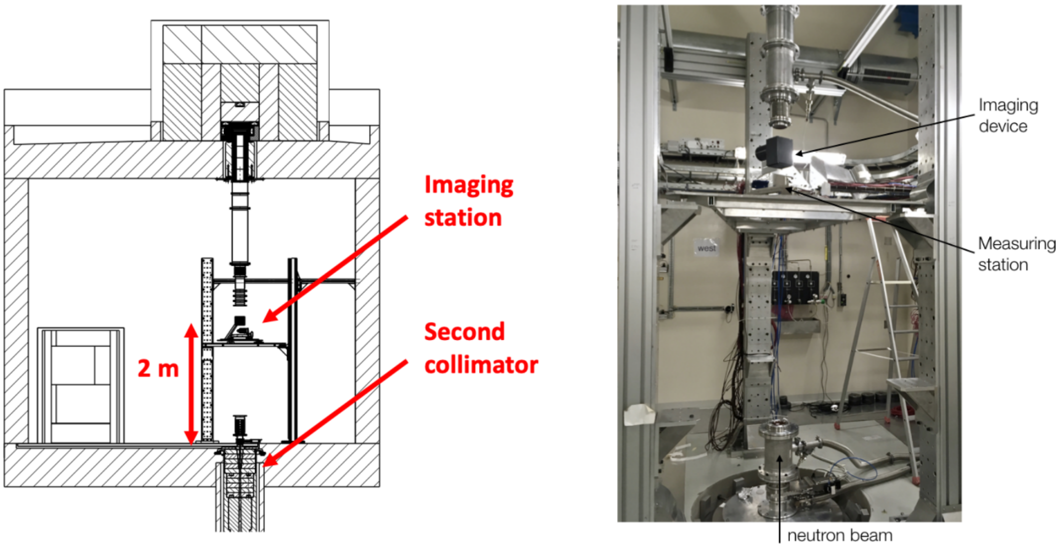

Figure 1: Scheme (left) and picture (right) of the n_TOF EAR2 bunker NI setup used in 2017.

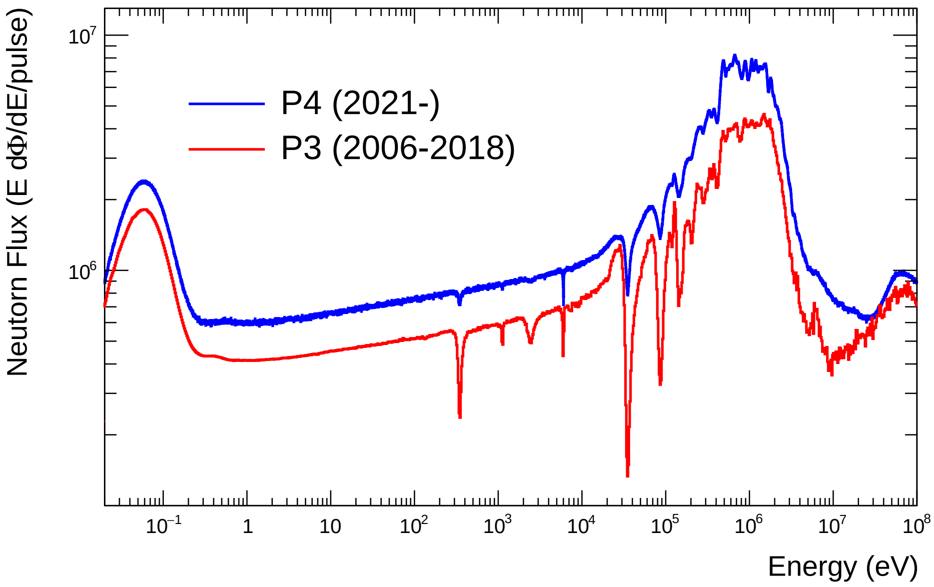

Figure 2: Neutron flux at n_TOF EAR2: evaluated in the previous phase (P3) [3] compared to Monte Carlo FLUKA [9] simulations of the new spallation target (P4).

for images, thus pushing the performance of EAR2, a worldwide exclusive vertical neutron beam line, even closer towards other facilities.

Up to now, conventional neutron imaging has been performed at EAR2, integrating the whole neutron energy range. Recently commercially available neutron imaging systems became available, like the TPX3CAM [10] using the Timepix3 [11] readout technology developed at CERN. The system enables an event driven readout for time-of-flight (TOF) imaging directly integrated into the system with frame rates of up to 500 MHz and a time resolution of 1.6 ns [10, 11]. Furthermore particle discrimination is possible, hence neutron and γ-ray signatures can be distinguished enabling the discrimination of the latter. This system, although not standard yet, is now deployed and investigated at several facilities reflecting the vast interest of the imaging community [12]. The majority of the NI community is using thermal and cold neutron beams for material science studies but fast neutron imaging (MeV range) is emerging [13, 14] which is usually performed at research reactors with inherent epithermal neutron and γ-ray background. In this context n_TOF EAR2 provides the rare opportunity to perform energy resolved neutron imaging with thermal to fast neutrons based on the TOF technique.

With the present Letter of Intent we propose to study the feasibility of energy resolved neutron imaging with a TOF-based camera readout at n_TOF EAR2. We aim to study the general feasibility of TOF imaging at our beam line as well as the capabilities of the TOF camera system in the radiation environment of EAR2. Furthermore we intend to image the neutron beam profile over the neutron flight path accessible in the EAR2 bunker. A characterization of different scintillators for thermal or fast neutrons and γ-rays over the whole neutron energy range available is foreseen. Lastly, a potential application of the TOF imaging technique to test objects as well as potential radioactive specimen – depending on availability – is planned.

2 Programme and beam time request

Generally the detection system will facilitate the characterization of the EAR2 facility with respect to neutron imaging. For an evaluation of the TOF neutron imaging technique at EAR2 we plan to conduct the following experiments and by its application gain useful information either for the n_TOF facility directly or provide the CERN community with first radiographs of radioactive objects.

Feasibility of time-of-flight imaging

The high instantaneous particle flux per proton pulse impinging on the spallation target entails the so-called γ-flash effect, common to all pulsed neutron spallation facilities, which is a mixture of high energy photons and relativistic neutrons which can blind detectors for a detector-characteristic time. The first goal of the test is to study the highest measurable neutron energies, i.e. 1 MeV corresponds to a time-of-flight of approximately 1 µs. Furthermore, the neutron/γ-ray discrimination capabilities of the detector in the EAR2 radiation environment will be investigated. This can be cross-checked with γ-sensitive scintillators. This test will be concluded by neutron radiographs of test objects that will be prepared beforehand, i.e. a disk with different materials in each quarter of the disk. Gating on neutron resonances is expected to allow identification of the different sectors of the disk.

Beam profile measurements

With the new spallation target the connection between the target and the EAR2 beam line was optimized, which was historically not the case due to the fact that the previous target was constructed before EAR2. This had some implications for the neutron beam profile – triangular shape given by the shape of the aluminium window towards EAR2. With the new optimized design an unexpected effect in the beam profile was observed: fast and slow neutrons do not follow the axis of the collimator precisely. Specifically fast neutrons seem to retain a memory from their creation point in the spallation target whilst slow neutrons reach EAR2 mostly isotropically. This effect is shown in Figure 3 for neutrons with energies above 1 MeV, where a shift of the beam profile is observable towards a smaller x-coordinate. The collimators in these simulations are perfectly aligned. The effect can be explained by a shift of the proton beam axis inside the spallation target with respect to the collimator axis. This results in a pin-hole camera like projection of the proton beam axis into EAR2.

The direction of slow and fast neutrons is slightly different, as can be seen in Figure 4. Contrary to the fast neutrons, which originate from close to the proton beam axis, the slow neutrons have been scattering around in the moderator and thus show a more homogeneous spatial profile. This creates a challenge for the physics programme at n_TOF EAR2 with samples with diameters smaller than the neutron beam or irregular samples. The calculation of beam interception factors – overlap of sample and neutron beam – is important and relies solely on simulations. Furthermore, it has been demonstrated that the knowledge of the exact location of such samples is crucial to the analysis and extraction of good physics information due to the position dependent resolution function [15].

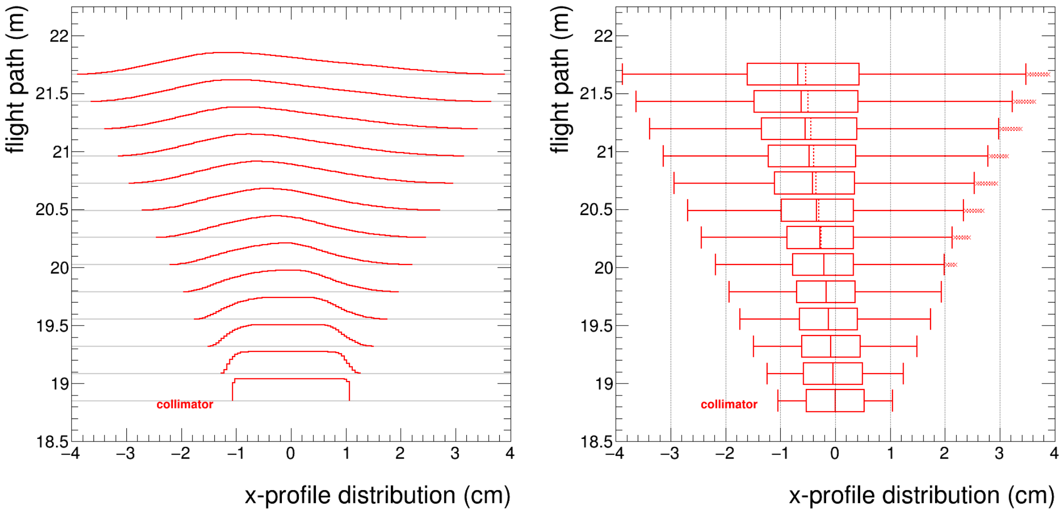

Figure 3: Simulated neutron beam profiles at different flight paths: evolution of the profile with flight path obtained by projection of the central bin of the 2D profile (left); box plot of the statistical parameters of the x-profile distributions from the left panel (right). The location of the collimator exit with a radius of 1.09 cm is indicated.

As the resolution function is calculated exclusively from simulations and depends on the position of the sample in the beam, a validation of the simulated beam profiles is beneficial. By moving the TOF imaging detector along the vertical axis a 4D characterization of the beam profile (x, y, E_n, flight path) will be attempted.

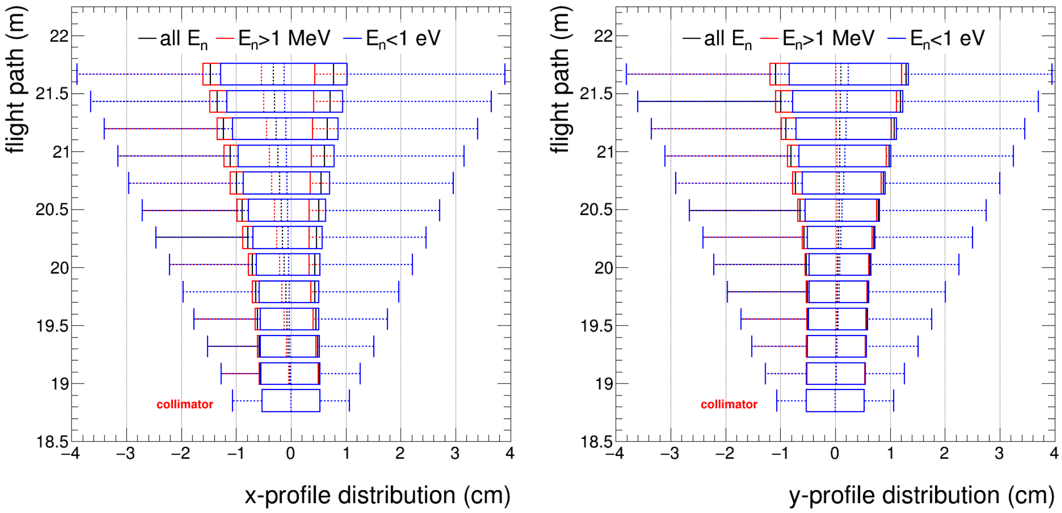

Figure 4: Comparison of the x and y profile (obtained as described in Figure 3) for different neutron energy intervals. The difference in the mean values (dashed vertical line in each box) indicates a shift of the beam center between fast and slow neutrons.

Characterization of scintillators

Neutron imaging requires conversion reactions to detect neutrons and/or to increase the detection efficiency. For thermal and cold neutrons scintillators are commonly doped with ^{6}Li or gadolinium due to their high neutron cross sections. Generally the efficiency will scale with the neutron cross section but little is known about their efficiency and light yield for the epithermal neutron energies. Furthermore, the detection efficiency of fast neutrons with such scintillators is negligible and ongoing research has developed copper doped scintillators [14] capable of detecting fast neutrons with a reasonable efficiency. With the white neutron beam spectrum at n_TOF EAR2 a characterization of the efficiency (number of counts) and light yield (time-over-threshold/charge) is possible over the whole neutron energy range spanning from subthermal energies to several hundred MeV.

Application to radioactive samples/targets

Finally, we plan to dedicate some beam time to the application of the TOF imaging to radioactive samples, e.g. the CERN AD target (exchange 16-17 May 2022) as done in 2017. Using the n/γ discrimination capabilities of the system it should be possible to discriminate the auto-radiographic image caused by the radiation of the sample and obtain a clean image.

The focus of the work will be on the feasibility study, the characterization of the facility and the beam profile measurements. For the purpose of the characterization we will also investigate the possibility to cross-check the TOF imaging results with a reference imaging detector. With this extensive programme, we believe that we cannot only study the feasibility of the TOF imaging setup at n_TOF EAR2 but provide valuable information for the facility and the imaging community as well as provide an imaging service to CERN and thus we request 7×10^{17} protons.

Summary of requested protons: 7×10^{17}.

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