EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Letter of Intent for a neutron imaging station at n_TOF EAR2

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Abstract

Neutron radiography is a well-developed diagnostic tool for nondestructive testing and to obtain images of an inner part of an object. Neutrons can act as probes for nondestructive testing since, due to their peculiar interaction with matter, can penetrate thick-walled samples and provide an image of the transmitted radiation. As X-rays interact very differently with matter with respect to neutrons, the two imaging methods are complementary to investigate the properties of an object's internal structure. Several dedicated facilities are operating worldwide in order to provide high performance neutron imaging stations, in particular at research nuclear reactors and at spallation sources. This Letter of Intent aims at studying the feasibility of a neutron radiography testing station in the new n_TOF Experimental Area 2 (EAR2), taking advantage of the beam structure and intensity as well as the intrinsic capability to handle very radioactive samples. If successful, this technique could be exploited for several ongoing activities at CERN and pave the way for multidisciplinary use of EAR2.

Requested protons: $6*10^{17}$ protons on target
Experimental Area: EAR2

Introduction

Neutron radiography is a well-known method to perform non-destructive investigation of materials. The method employs the unique properties of neutron interaction with matter and 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. During the last two decades the method has known an important step forward, due to the use of digital techniques and new detection methods, which greatly enhanced the image resolution as well as the flexibility of use.

Several facilities worldwide are proposing such kind of instrumentation, with performances and capabilities different for each installations. In general these stations are installed at research reactors (i.e. Orphee at LLB in France or BER-2 and FRM-II in Germany) or at spallation neutron sources (e.g. PSI in Switzerland or J-PARC in Japan).

The method is employed for a variety of different applications – generally of applied science – of which few examples are listed here below:

- Inspection of irradiated material (1)
- Microstructural analysis of metals
- Application to cultural heritage (2)
- Moisture dispersion analysis for building materials or sandstone (3) (4)

With the construction of the n_TOF Experimental Area 2 (EAR2) (5), CERN has now a neutron source which provides a white beam with very high neutron intensity (in the range of 10^6 n/cm^2/pulse, i.e. within tens of ms), coupled with the possibility to perform time of flight with very high resolution.

This Letter of Intent aims at studying the feasibility of a neutron imaging test station in the n_TOF EAR2. The possible applications could be manifold and quite unique for CERN, and could open the way for multidisciplinary physics applications at n_TOF.

The capability of the n_TOF EAR2 to be classified as a Class-A laboratory allows for the use of highly active samples or samples with contamination risks. The goal would be not to compete with similar installations but rather to give the possibility for neutron imaging on CERN-originated samples in those cases where access to dedicated external facilities could be complex and/or expensive.

In particular, possible applications could entail:

- Analysis of post-irradiated samples at the CERN's HiRadMat facility, presently lacking a dedicated hot-cell for damage inspection. Experiments will profit from having a tool for non-destructive inspection to check the integrity of materials after irradiation or to evaluate corrosion;
- Analysis of possibly damaged antiproton decelerator (AD) production target, being the present design completely welded with no easy inspection possibilities and essentially opaque to X-rays;
- Inspection of equipment associated to the n_TOF target cooling and moderator station, like the device which maintains boron at a constant level (so called "pot-a-bore");
- Complementary inspection of welding with energy-selective neutron radiography in order to identify inhomogeneity due to variations in the crystals lattice properties of the material in the weld zone;
- Measure humidity transport in soils or concrete, due to the sensitivity of the neutron radiography to small amounts of hydrogenous compounds in a matrix;

Imaging at n_TOF EAR2: beam characteristics and possibilities

Conventional neutron-imaging techniques are based on mapping the attenuation of a neutron beam when transmitted through a sample. The resulting intensity map can be represented as an image with two main parameters, spatial resolution and contrast. The quality of a neutron radiography station is essentially dominated by the ratio between the collimator-sample distance (L) and the neutron source collimator diameter (D). In particular, the achievable resolution (d) – for the part associated to the neutron beam – is given by:

$$d = \frac{l}{L/D}$$

Where "l" is the distance between the sample and the imaging detector. The higher the L/D ratio, the better the resolution that can be reached at the imaging station. Typical values range from 100 to 1000. Optimal spatial resolutions for imaging range from 100 to 500 μm, which – for a fixed L/D – dictates the maximum distance between the sample being measured and the detection systems.

This Letter of Intent assumes no modifications of the n_TOF vertical beam line, in particular would keep the present collimator with a D=2 cm diameter at its end. As presented in Figure 1, two detector stations could be foreseen at various heights, at 200 cm (where no modification of the present detector system would be needed) and at 500 cm (on top of the EAR2 hall, which would require the temporary removal of the upper vacuum pipes up to the last flange before the beam dump). In the first case the imaging system would yield an L/D of 100, while for the latter the L/D would be 250.

Figure 1: The photo shows a photo of the n_TOF EAR2, with the two possible location of the imaging detector and the L/D characteristics.

FLUKA Monte Carlo (6) simulations were performed to evaluate the characteristics of the neutron beam at the proposed experimental locations (see Figure 2). In particular, at 500 cm from the collimator pinhole, a 6-7 cm diameter neutron beam is expected, with ~1.3*10^5 thermal neutron/cm^2/pulse. In the optimistic case of 1 pulse every 1.2 seconds, ~10^5 thermal neutrons/cm^2/s can be expected on the samples.

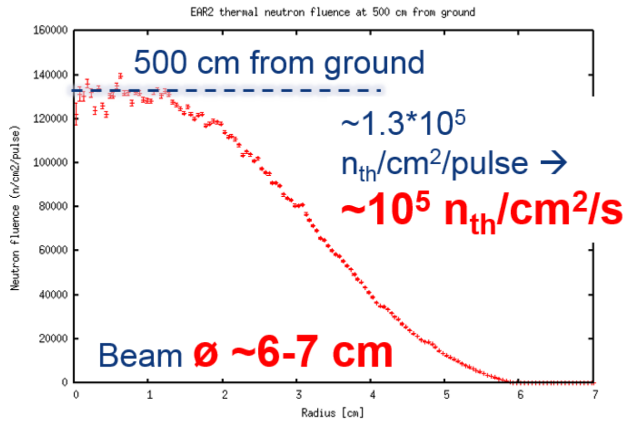

Figure 2: The figure shows simulated thermal neutron beam profile at 500 cm from the end of the collimator.

Figure 3 summarized the properties of the proposed neutron imaging station at n_TOF EAR2 as compared to an existing dedicated and high performance facility at PSI (NEUTRA (7)). It is worth underlining that the fluence assumed for n_TOF considers only the thermal part, where known neutron imaging is mainly based on. The exposure required for a good neutron image is to be considered only as an order of magnitude, as it has been extracted based on the NEUTRA data.

	n_TOF EAR2 (proposed)	NEUTRA@PSI
D (cm)	2	2
L (m)	5 (*)	11
L/D	250	550
Flux (cm^{-2}s^{-1})	10^5 (**)	5*10^6
T (min)	*25 (***)*	0.5

* = maximum height for EAR2
** = only thermal flux
*** = extracted from NEUTRA data

Figure 3: The table shows a comparison between the neutrons imaging station characteristics of the proposed station at EAR2 compared with one possible configuration of an existing dedicated installation at PSI.

Several different types of neutron imaging detectors exists, but few examples can be highlighted for possible use at n_TOF:

- A camera-based imaging system, where neutrons are converted into an image by a scintillator screen loaded with ^{6}LiF embedded in a ZnS:Ag(Cu) powder, mixed with an organic binder and deposited on a thin (~0.4-0.5 mm in order not to spoil too much the spatial resolution) Al foil. The emitted photons will then be reflected by 90 degrees by an aluminium first-surface mirror and then captured by a dedicated CCD camera sensitive to the light emitted by the scintillator screen. The whole apparatus will be embedded in a light tight box.
- Another camera-based system, similar to the previous one, but where the neutron converter is a ^{6}LiF foil deposited onto an aluminium foil. Such a foil, also acting as light reflector, is then

placed into a 5x5 cm^2 Scintillating FiberOptic Plate (SFOP), which allows a position resolution below 10 μm (8).

- A system based on MediPix or a X-Y MicroMegas – already widely employed at n_TOF – where neutrons are detected by the direct production of light charged particles on a ^{10}B sample. With such kind of devices, a spatial resolution up to 50 μm can be reached (9).
- A system based on Microchannel Plate (MCP), now being developed within the n_TOF Collaboration.
- The design and realization of an imaging beamline in EAR2 will enable a R&D activity on novel imaging detection systems capable to perform time resolved (or equivalently wavelength resolved, thanks to the time-of-flight technique) imaging with in beam systems rather than conventional scintillator-reflecting plus CCD detection systems.

Beam time requirements

The goal of this Letter of Intent is to prepare a basic experimental setup to prove the feasibility of a neutron imaging station at the n_TOF EAR2 during 2015, with a minimal perturbation of the measurement configuration (i.e. collimator and supports).

The detection system would be based either on a standard detection system composed by a standard camera-based device equipped with a scintillator, a mirror and a CCD camera (to be borrowed by ILL, France) either by employing a pixelated MediPix or an X-Y MicroMegas.

Two devices would be imaged:

- A test device composed by an iron or steel hollow cylinder (of roughly 5x5x2 cm^3) with and without an internal polyethylene cylinder (potentially borated), in order to evaluate the capability of the apparatus to identify light materials;
- A spare Antiproton Decelerator production target (see Figure 4), composed by an external Ti-6Al-4V shell few cm thick, an internal ~2 cm thick graphite container and a 55 mm, 3 mm diameter iridium core. The external dimensions are ~15 cm length for ~8 cm diameter.

Both of them will also undergo X-ray imaging, to understand the complementarity of the methods. We will also consider the possibility to insert bismuth γ-filters to understand the role of background photons in the imaging system.

Figure 4: The figure shows the external container of a spare Antiproton Decelerator production target. The outer shell is made by Ti-6Al-4V alloy, while the inner core is composed by graphite with an iridium core.

The estimated beam time requirement for this Letter of Intent is roughly $6*10^{17}$ protons on target, roughly equivalent to 6 days of beam time, in addition to the preparatory works and installation in the experimental area.

Outlook

This Letter of Intent has the objective of studying the feasibility and the preliminary performances of a neutron imaging station at the n_TOF Experimental Area 2. A set of objectives to be reached during the required beam time has been identified.

An imaging proposal at the n_TOF facility would have several unique characteristics:

- It would allow the use of highly radioactive or contaminated samples produced at CERN, thanks to the classification of the EAR2 as a class-A laboratory
- It could open the way to new techniques for TOF-selective images up to several MeVs;
- Once the technique is proven, neutron tomography could be considered as well, allowing 3D object reconstruction. The method uses a composition of single radiographic projection images from many views to reconstruct the material internal composition;
- The repetition rate of 1.2 seconds of the PS machine allows to mitigate issues associated with image transfer and long scintillator decay times;
- Possibility to couple neutron imaging with PGNAA (prompt neutron activation analysis);
- Future development could see the construction of a dedicated "imaging" collimator to improve – if needed – the L/D ratio;

If the tests will be successful, a dedicated proposal for neutron imaging commissioning and validation will be proposed towards the end of 2015. Dedicated FLUKA simulations of the setup will accompany the proposal.

Summary of requested protons:

The present Letter of Intent requires $6*10^{17}$ protons on target.

References:

1. *The fourth SINQ Target Irradiation Program, STIP-IV.* **Y. Dai et al.** 1-3, s.l. : Journal of Nuclear Materials, 2012, Vol. 431. doi:10.1016/j.jnucmat.2011.11.004.

2. *Application of X-Ray and Neutron Tomography to Study Antique Greek Bronze Coins with a High Lead Content .* **M Griesser, R Traum, K Vondrovec, P Vontobel, E. H. Lehmann.** s.l. : IOP Conference Series: Materials Science and Engineering, 2012, Vol. 37. http://iopscience.iop.org/1757-899X/37/1/012011.

3. *Diffusivity and Sorptivity of Berea Sandstone Determined using Neutron Radiography.* **M. Kang et al.** 3, s.l. : Vadose Zone Journal, 2013, Vol. 12. doi: 10.2136/vzj2012.0135.

4. *Neutron radiography, a powerful method to determine time-dependent moisture distribution in concrete.* **P. Zhang et al.** s.l. : Nuclear Engineering and Design, 2011, Vol. 241. doi:10.1016/j.nucengdes.2011.02.031.

5. **E. Chiaveri for the n_TOF Collaboration.** *Proposal for n_TOF Experimental Area 2 (EAR-2).* Geneva : CERN, 2012. CERN-INTC-2012-029 / INTC-O-015.

6. **A. Ferrari, P.R. Sala, A. Fasso' and J. Ranft.** *FLUKA: a multi-particle transport code.* 2005. CERN 2005-10 (2005), INFN/TC_05/11, SLAC-R-773.

7. *PROPERTIES OF THE RADIOGRAPHY FACILITY NEUTRA AT SINQ AND ITS POTENTIAL FOR USE AS EUROPEAN REFERENCE FACILITY.* **E. H. Lehmann, P. Vontobel & L. Wiezel.** s.l. : Nondestructive Testing and Evaluation, 2001, Vols. 16:2-6. 10.1080/10589750108953075.

8. *Scintillating screens sensitivity and resolution studies for low energy, low intensity beam diagnostics.* **J. Harasimowicz, L. Cosentino, P. Finocchiaro, A. Pappalardo, C. P. Welsch.** s.l. : Review of Scientific Instruments, 2010, Vol. 81. doi:10.1063/1.3488123.

9. *Spatial resolution of Medipix-2 device as neutron pixel detector.* **J. Jakubek, T. Holy, E. Lehmann, S. Pospisil, J. Uher, J. Vacik, D. Vavrik.** 1-2, s.l. : Nuclear Instruments and Methods in Physics Research Section A, 2005, Vol. 546. doi:10.1016/j.nima.2005.03.112.