Commissioning of the New Spallation Target for the n_TOF facility at CERN

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Abstract. The neutron Time of Flight (n_TOF) facility at CERN is a source of high flux of neutrons obtained by the spallation process of 20 GeV/c protons onto a solid lead target and the remarkable beam density of the Protons Synchrotron (PS). From Nov 2008 the n_TOF facility resumed operation after a halt of 4 years due to radio-protection issues. It features a new lead spallation target with a more robust design, more efficient cooling, separate moderator circuit and most important without any loss of the unique neutron performances of the previous target. The outstanding characteristics of this facility: high neutron flux 10^6n/cm^2/s.c. at 185 m, wide spectral function from thermal up to GeV, low repetition rates 1.2 s^{-1}and the excellent energy resolution of 2 x 10^{-4}open new possibilities for high precision cross section measurements, using radioactive samples of modest mass. Moreover the separate moderator circuit will permit in the future the use of borated or heavy water instead of normal water to reduce the 2.2 MeV gamma background for the neutron capture measurements. The facility has been commissioned in November 2008, with performances similar of the previous target and predicted by Monte Carlo simulations.

1. Introduction

Progress in particle accelerator technology makes it possible to use a proton accelerator to produce energy and to eliminate nuclear waste efficiently. An example is the innovative Accelerator Driven Systems technique (ADS) that has emerged at CERN [1] and elsewhere [2]. Two experiments have been done at CERN to demonstrate these ideas.

The first one concerns the First Energy Amplifier Test (FEAT) [3], to test experimentally the proposal of Carlo Rubbia and his group [1]. And the second one concerns the demonstration of the efficiency of this system for destroying long-lived fission fragments using the concept of Adiabatic Resonance Crossing (ARC) the TARC experiment [4]. The ARC concept can be extended to several other domains of application (production of radioactive isotopes for medicine and industry, neutron research applications etc.) [5].

The design of any ADS prototype requires the complete and precise knowledge of basic nuclear data in the form of cross sections for neutron induced processes. The presently available databases for this application are just about adequate for conceptual studies but are certainly not accurate enough for the design and simulation of ADS devices. Nuclear data contained in these databases stem from compilations of numerous distinct experiments, which by being inherently dedicated to specific energy domains and elements each time, are often not in perfect agreement or even mutually incompatible. The discrepancies are worse in the case of minor actinides, fission products and the isotopes of the Th cycle, their intrinsic radioactivity being one of the reasons.

To fill this hole, from the experience acquired in the TARC experiment and taking the opportunity available at the CERN Accelerator complex, we have proposed to perform a new spallation neutron beam facility named n_TOF at CERN [6].

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new lead spallation target with a more robust design, more efficient cooling, separate moderator circuit and most important without any loss of the unique neutron performances of the previous target. The outstanding characteristics of this facility: high neutron flux 10^6n/cm^2/s.c. at 185.307 m, wide spectral function from thermal up to 1 GeV, low repetition rates 1.2 s^{-1} and excellent energy resolution of 2 10^{-4}, open new possibilities for high precision cross section measurements, using radioactive samples of modest mass. Moreover the separate moderator circuit will permit in the future the use of borated or heavy water instead of normal water to reduce the 2.2 MeV gamma background for the neutron capture measurements. The facility has been commissioned in Nov 2008, with performances similar of the previous target and predicted by Monte Carlo simulations.
In this paper we describe first the concept of n_TOF. After a short description of the n_TOF facility, the summary of the result obtained in the first phase, we describe the new improvements that were made to avoid all radioprotection problems.

2. The n_TOF facility at CERN

2.1. Description of the facility

The neutron beam at n TOF is produced by spallation of a 20 GeV/*c* proton beam from the CERN proton synchrotron (PS) onto a massive natural Pb target (see Figure 1). The main characteristics of the proton beam are summarized in Table I. The PS is delivering 7-ns-wide bunches of 7x10^{12} protons with a maximal repetition rate of 0.8 Hz, but presently only five bunches can be accepted within the PS supercycle of 14.4 s owing to limitations set by the cooling system. The High energy of the proton beam and the high proton intensities in the bunches yield a high instantaneous neutron flux of ~10^5 per pulse and per energy decade at the experimental station 185.3 m from the target. The n TOF neutron spectrum covers a wide energy range from thermal up to 1 GeV. A more detailed description of the technical features of the facility and its performance is given elsewhere [7,8].

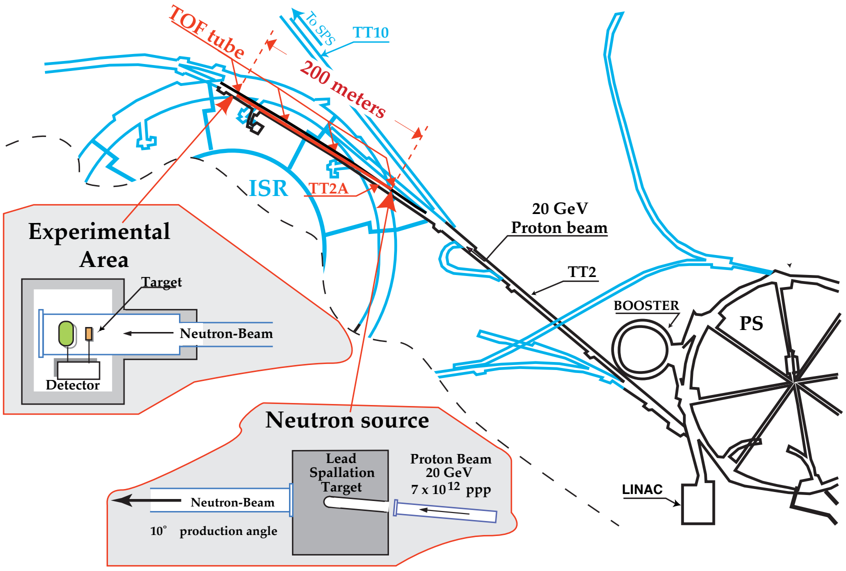

FIG.1. General layout of the n_TOF facility. The proton beam is extracted via the TT2 transfer line and hits the lead target. At the end of the TOF tunnel (TT2-A), neutrons are detected about 185.3 m from the primary target.

Two collimators in the evacuated flight path define the neutron beam profile. For all capture cross section measurements, an aperture of 18 mm in diameter is used for the second

collimator just upstream of the experimental area, resulting in an approximately Gaussian beam profile at the sample position with a FWHM of 11.75 mm [9].
A very low background level has been achieved in the experimental area owing to several massive concrete and iron shielding and by means of a strong sweeping magnet. The start signal for the time-of-flight (TOF) measurement is accurately defined by the so-called prompt flash, resulting from ultra relativistic particles such as electrons, muons, and γ rays produced by the impact of the PS proton pulse on the spallation target.

TABLE I. MAIN CHARACTERISTICS OF THE n_TOF FACILITY.

Proton beam	20 GeV/*c* momentum, pulse width 7 ns (rms), repetition frequency 0.8 Hz, Intensity 7 x 10^{12} protons/pulse.
Neutron beam	300 neutrons/proton generated in the spallation process, energies from 0.1 eV to 250 MeV, Sweeping magnet, two collimators, and shielding walls for background reduction, Neutron filters for background definition Neutron flux at 185.3 m, $\Phi = 10^5$ neutrons/ pulse/energy-decade Resolution in neutron energy, $\Delta E/E = 10^{-3}$ at 30 keV

2.2. The results obtained in n_TOF Phase 1

Before the capture and fission measurements, the performance and the characteristics of n_TOF have been performed using a dedicated Fission Chamber from the PTB laboratory [7], it is completed with the measurement of the Gold with C_6D_6, the profile of the beam have been measured using an innovative detector based on the Micromegas concept [9]. During the period between 2002 and 2004 several measurements of neutron cross sections relevant for Nuclear Waste Transmutation and related Nuclear Technologies have been performed and published. These concern : the Th/U fuel cycle (capture & fission), the Transmutation of MA (capture & fission). These measurements clarified the discrepancy observed in the previous measurements and the evaluation of the Transmutation of fission products (capture). In addition, **C**ross sections measurements were performed relevant for Nuclear Astrophysics: s-process: branching and s-process: pre-solar grains. There were also measurements performed using the neutrons which as probes for fundamental Nuclear Physics, where the Nuclear level density & n-nucleus interaction have also determined.
The list of the experiments is summarised here:
For Capture : ^{151}Sm, ^{204,206,207,208}Pb, ^{209}Bi, ^{232}Th, ^{24,25,26}Mg, ^{90,91,92,94,96}Zr, ^{93}Zr, ^{139}La, ^{186,187,188}Os, ^{233,234}U, ^{237}Np, ^{240}Pu, ^{243}Am.
For Fission: ^{233,234,235,236,238}U, ^{232}Th, ^{209}Bi, ^{237}Np, ^{241,243}Am, ^{245}Cm.
The measurements have been done using different detectors such as PPAC [10] and FIC [11] for the fission measurement. For the capture measurement, in addition of the C_6D_6 already mentioned, the n_TOF collaboration have been constructed a Total Absorption Calorimeter (TAC) [12,13]. The Total Absorption calorimeter is based on 40 BaF_2 crystals shaped as hexagonal and pentagonal pyramids forming a spherical shell with 10 cm inner radius and 15 cm thickness. Each BaF_2 is covered by a Teflon light reflector layer, an aluminium foil and a final cover with ^{10}B loaded carbon fibber capsule. The TAC has High detection efficiency for capture events 95% and an acceptable energy resolution, typically 10% at 661.5 keV to 6% at 6.15 MeV. Targets are placed at the centre of the TAC and surrounded by a neutron absorber made of $C_{12}H_{20}O_4(^6Li)_2$. A small-mass device has been designed for the monitoring of the n_TOF neutron beam facility at CERN for the phase 1 [14]. This detector was based on a thin Mylar foil with a ^{6}Li deposit, inserted in the beam. Four Si detectors placed outside the beam were viewing the foil and were detecting the reaction products.
The high instantaneous neutron flux at n_TOF is of great advantage, especially for the measurements of small radioactive samples. However, it represents a challenging problem for

data acquisition and signal processing because of pileup and dead-time effects. These difficulties are solved by an innovative data-acquisition system based on fast digitizers, which records the full analogue waveform of the detector signal during the entire transit time of the neutron burst. The sampling is performed by means of flash analogue to digital converters (FADCs) with maximal sampling rates of 10^9 s−1. The raw data taken in this way consist of a series of signals, preceded and followed by a defined number of samples for baseline determination. These signals are analyzed off-line by determining the corresponding information on TOF, charge, amplitude, and particle type [15].

3. The renewed n_TOF facility at CERN

3.1. Preamble

After four years from 2000 to 2004 the CERN n_TOF facility was running well without any problems. For unknown reasons a drastic increase of the radioactivity of the cooling water have been observed (see Figure 3). Due to this problem the CERN management has decided to stop the n_TOF facility. A long discussion between the n_TOF collaboration and the CERN management took place during about three years under the supervision of the external panel expert to find the solution for starting again the n_TOF facility.
Taking in account: - the potential capability of the Facility; - the worldwide recognized results obtained during four years of running; - the approved physics program ; - the request of the n_TOF Collaboration. In June 2007 a presentation to an External Panel Reviewers was done to assess the Facility status and provide recommendations for the restart. According with the Reviewers reports the restart is justified but the necessity of an upgrade was underlined, in particular concerning the target cooling system and the ventilation of the target area.

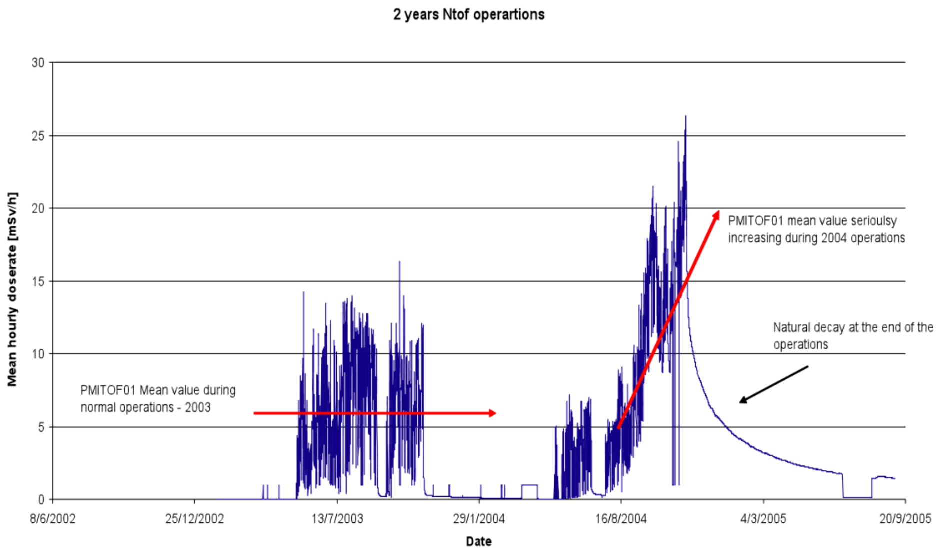

FIG. 3. n_TOF Cooling circuit activation in 2004

After the positive assessment of a second External Panel Review in February 2008, the CERN management decided to implement the necessary Facility upgrade to make possible the restart in 2008 under three conditions: 1) to replace the old target by a new one, 2) to carried out a very efficiency circuit cooling with automatic control of the pH, the Oxygen production and the conductivity of the demineralised water, 3) to perform a ventilation system of the lead target area. The two systems will be equipped each by a sophisticated radioprotection system.

These three items constitute the renewed CERN n_TOF facility, which was commissioned in November 2008.

3.2. The Old target removal and inspection

After removal of the old target, a detailed inspection has been performed. The following result have been observed: - a pitting corrosion caused a hole at the proton impact location (see Figure 6 b) - important surface oxidation due to rupture of protection layer when the drying was performed (flush). The conclusion was that the target shape didn't allow for a correct water flow at the entrance face and the used modular assembly lead to a mechanical instability and deformation.

3.3. Design and construction of the Lead target

Several options were investigated for the design of a new target. One of them was Aluminium cladded Lead Target water cooled used in other facilities, has been investigated before the visual inspection of the old target. The use of the cladding was intended for the containment of the spallation products in order to keep the water contamination at reasonable limits. Intensive studies were performed to optimize the target shape and volume, to evaluate the thermal behaviour at the interface lead/cladding and investigate the structural problems of the cladding due to lead deformation with temperature (creep). This solution was envisaged in view of the use of the existing cooling system.

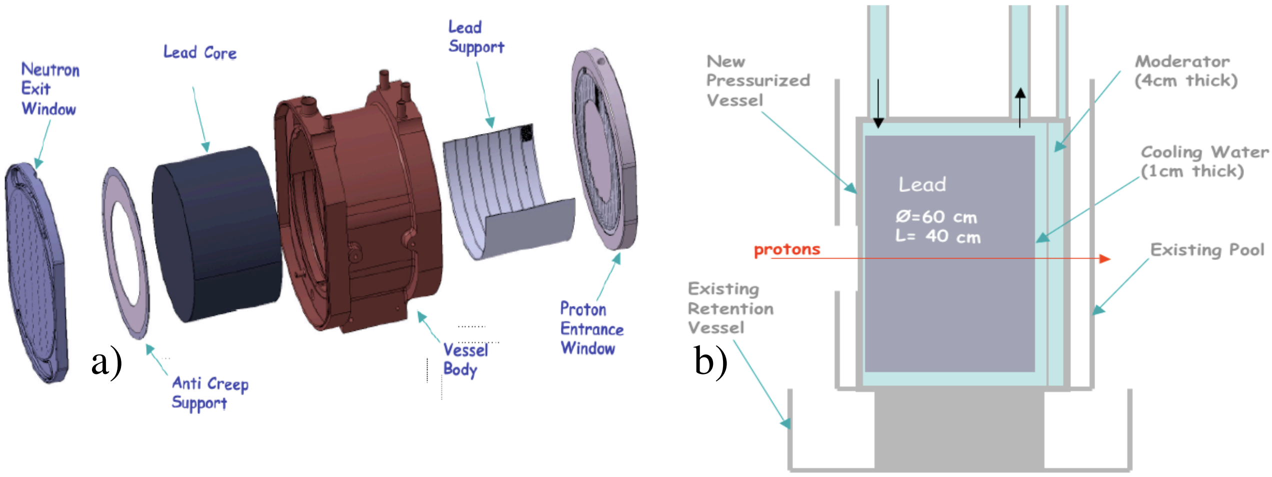

FIG. 4. The conceptual design of the new Lead target a) View of the different part of the lead target b) schematic view of the lead target placed inside the cooling system. The cooling water is separated with Aluminium foil.

After the old target removal and inspection of the pool, it has been decided to not adopt this option for two main reasons: i) the need to use a pressurized water cooling system instead of the open circuit used in the past, ii) the structural constraints on the cladding due to creep.
Based on these arguments and according with the literature and test on a lead block immersed in an aluminium container, the solution to use a cylindrical lead target cooled by water has been adopted. In Figure 4 is sketched the basic principle. A cylindrical lead core is positioned in an aluminium alloy vessel used for the first containment of the cooling water (Figure 4 a). The vessel is separated in two parts: the cooling container and the moderator container. The two volumes are connected to the Cooling System by four pipes allowing the separate circulation of the cooling liquids. The volume dedicated to the target cooling is filled with

demineralised water, whilst the moderator volume could be also filled after the commissioning with borated water to improve the background for measurements by reducing the gamma flash produced by the capture in water (Figure 4 b). The local heat load has been reduced significantly by increasing the spot size of the incident beam by a factor of about 16.
The vessel with the lead core mounted inside, is loaded down in the existing pool via the shaft. The pool and the existing retention vessel are used as second and third containment to avoid uncontrolled release of contaminated water in the tunnel.

3.4. The cooling and ventilation

The cooling System is a pressurized circuit ensuring a water flow in the Target Vessel sufficient to keep the temperature of the lead surface at a value sufficiently below the water boiling point, in particular on the proton entrance face of the target where the damage was observed in the old target. This solution is based on the acquired experience on the old target and the studies made to understand the pitting corrosion discovered after the inspection of the previous target. In the new Cooling Circuit the required water flow is guaranteed by design in all critical part. The monitoring and control of the water chemistry is implemented according with the suggestions expressed in the reports made by the External Panel. The Cooling Station lay out is sketched in Figure 5 a).

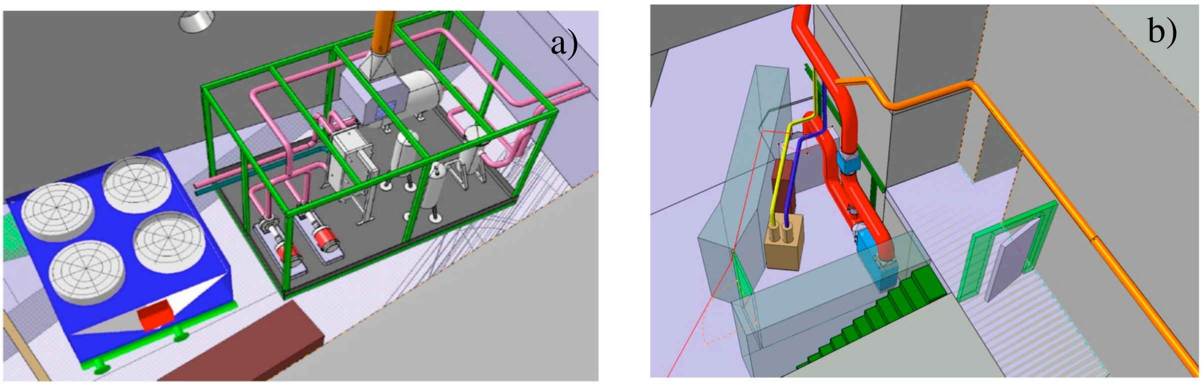

FIG. 5. *a) Lay-out of the n_TOF cooling system, b) Lay-out of the n_TOF ventilation system*

The target area Ventilation (Figure 5 b) is required for the following reasons:
- Ensure the confinement of the target area; - Capture of the aerosols containing radioactive isotopes in the absolute filters; - Allow the monitoring of the released dose to the public.
Since the energy deposited by the proton beam in the target area is low (<5 kW) compared to the 1200 m^3 volume of the tunnel sector defined as the target area, it is considered that a cooling system for the air is not needed. Based on the air measurement done during the previous runs and extensive simulations, a strategy has been defined to minimize the released dose to public (critical group) and the direct exposure of personnel inside CERN. The calculations were done assuming the lay out given in Figure 5 b.

4. Commissioning of the renewed facility

To avoid the encountered problems in the previous Lead target, a special study and transformation of the proton beam have been done. The goal is to decrease the local heat load by increasing to the maximum the transverse dimensions of the proton beam impinging on the

Lead target. The maximum dimension obtained in the November test is about 6 cm x 6 cm as shown in Figure 6 a)

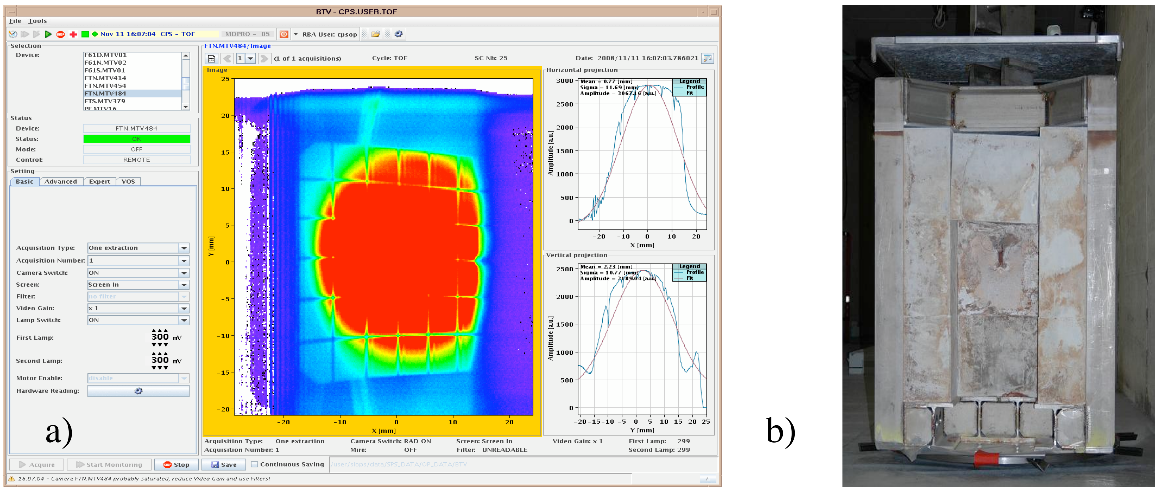

FIG.6. a) The new proton beam spot on the Lead target, b) view of the old Lead target (the hole is clearly seen in the central part of the target assembly).

5. Preliminary result obtained with the very short commissioning of the n_TOF facility

The commissioning in November 2008 was dedicated especially to the test of the behaviour of the new target w.r.t. the cooling system. Very short beam time had been given by CERN RP (only in total four hours of beam time). Benefitting maximally from this short beam time we have succeeded to measure the neutron flux. Two detectors have been used. The first one is constituted by a Fast Ionisation Chamber equipped with ^{235}U sample. The flux is extracted from the counting of the produced fission fragment. The second detector is constituted by a Micromegas chamber [16]. The very preliminary results are shown in Figure 7.

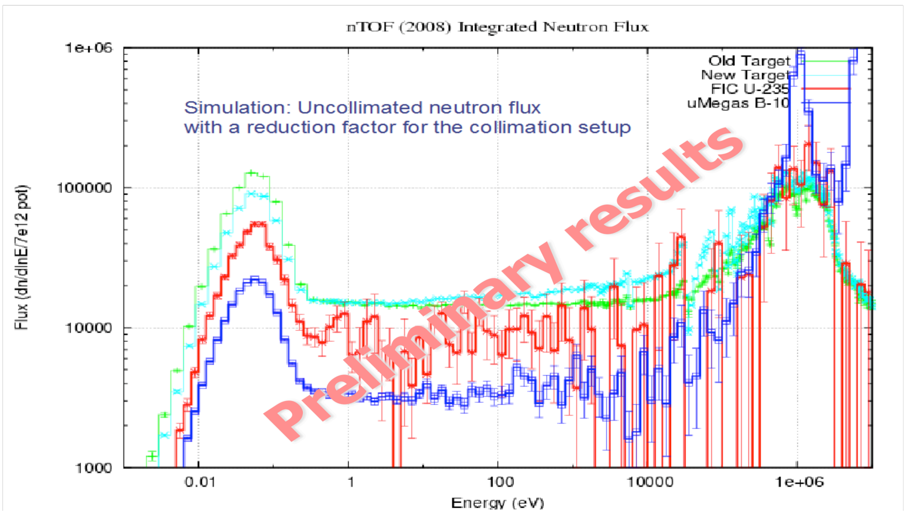

FIG.7. *Preliminary result of the neutron flux measurement during the short November 2008 commissioning compared with the FLUKA simulation.*

Due to the very limited beam time, for the reason mentioned before, the statistics accumulated were rather poor but sufficient to give an idea for the new characteristics of the renewed CERN n_TOF Facility. The results obtained with FIC and Micromegas for the ^{235}U sample are in good agreement. But the flux is around 40% low compared to the simulation. This discrepancy is due to the bad alignment of the collimator (0.9 mm offset was found for the new alignment). The discrepancy observed with the result obtained with the Micromegas for the ^{10}B sample is due to the uncertainty of the mass of ^{10}B.

6. Final Remarks

A new Lead target has been designed and fabricated for the n_TOF facility. In addition of the Fluka simulation, the conceptual design has helped from the experience gained from the previous target help us on the construction of the new Lead target for the n_TOF facility at CERN. The short commissioning performed in November 2008, showed that the values are consistent with the simulations. The work is in progress and will be finished before the middle of May 2009. After the commissioning planed for the determination of the new characteristic and performance of the updated n_TOF facility a new campaign of measurements will be performed. The following proposals have already been accepted by the CERN Research Board: - "The role of Fe and Ni for s-process nucleosynthesis in the early Universe and for innovative nuclear technologies" (CERN-INTC-2006-012); - "Proposed study of the neutron-neutron interaction at the CERN n_TOF facility" (CERN-INTC-2006-006); "Angular distributions in the neutron-induced fission of actinides" CERN-INTC-2006-016; - "n_TOF: New target commissioning and beam characterization" (CERN-INTC-2008-035). Two of them will be performed in 2009. In the future it is planned to use: Borated water and Heavy water.

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