The *neutron Time-Of-Flight facility*, n_TOF, at CERN (I): Technical Description

the n_TOF collaboration[a]

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Abstract

The n_TOF facility is a spallation neutron source operating at CERN since 2001. It produces, thanks to the characteristics of the proton driver and of the massive Pb target, a wide energy, very high instantaneous neutron flux, which is employed for neutron-induced reactions measurement. The n_TOF facility resumed operation in November 2008, after a 4 years stop due to radioprotection issues connected with the operation of the spallation target. It features a new lead spallation target with a more robust design a more efficient cooling, separate moderator circuit and a target area ventilation system. In this contribution technical details about this facility and its operation will be given, together with future perspective for the performances of the facility.

n_TOF-PUB-2013-001

1. Introduction

The world-wide increasing energy demand in general, and electricity demand in particular, with the increased concern for the environmental impact of energy consumption and the foreseen limitations of fossil fuel call for a re-evaluation of fission energy as a long-term energy source compatible with the goals of sustainable development. Although present light water reactors (LWRs) are capable of covering the nuclear energy demand for the decades to come, the longer-term need has triggered in the last decades active fields of research looking at innovative options. Important development goals for such advanced systems are environmental friendliness, resource efficiency, and cost-effectiveness, while accounting for socio-political concerns such as proliferation.

Preprint submitted to Nuclear Instruments and Methods in Physics Research Section A February 13, 2013

The design of any innovative prototype requires the complete and precise knowledge of basic nuclear data in the form of cross sections for neutron induced processes. It might be argued that the presently available databases for this application are just adequate for conceptual studies but it is certainly not accurate enough for the design and simulation of innovative 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.

From an astrophysical point of view, heavy elements beyond Fe witness ongoing neutron capture nucleosynthesis in evolved stars and supernova explosions with immediate constraints for the galactic chemical evolution. The difficult task is to understand the formation of these heavy elements, where not only the nuclear physics is complicated but also the mechanisms and thermodynamics are not completely understood yet. Advances in our understanding of these processes and of the astrophysical sites where they occur demand also advances in laboratory measurements of neutron cross sections. Cross section measurements comprising the crucial input for models of those astrophysical processes are also requested. The high precision of new abundance measurements, primarily in meteorites, is a strong motivation for these new, precise measurements of neutron capture cross-sections.

The n_TOF facility entered in operation in 2001, aiming to satisfy the aforementioned demanding research and industrial requirement. The main advancement of the state-of-the-art offered by the n_TOF experiment lies exactly in the dissemination of a complete and consistent set of high accuracy cross-sections, extending over eight orders of magnitude in the neutron energy. The concept of the n_TOF neutron beam [3] makes use of both the specifically high flux of neutrons attainable using the spallation process of 20 GeV protons on an extended lead target containing practically the whole spallation shower and the remarkable beam density of the CERN Proton Synchrotron (PS), which can generate high intensities up to 7 10^{12} ppp (protons per pulse) - high enough to produce the vast number of 2 10^{15} neutrons per pulse - in the form of short (6 ns RMS width) pulses with a repetition time varying from 2.4 s to 16.7 s. The high neutron flux, the low repetition rates and the excellent energy resolution of 3 10^{-4} opened new possibilities to high precision cross section measurements in the energy range from 10 meV to 1 GeV, for stable and, moreover, for non sealed (but however encapsulated) radioactive targets, since the experimental has been converted into a Work Sector Type A in 2009.

2. The CERN PS: characteristics of the proton beam

The n_TOF Facility make use of the spallation mechanism as a strong source for neutrons by using a proton beam impinging a lead target [3]. The spallation mechanism is a remarkably powerful source of neutrons: in an infinite lead spallation target, one 20 GeV/c proton may produce as many as 600 neutrons. Furthermore, lead has a high transparency for neutrons of energy $\leq$1 MeV. The CERN PS accelerator is capable of accelerating $\approx 3\times 10^{13}$ protons per cycle, resulting in as many as 2×10^{16} neutrons at each cycle. This extraordinarily prolific source can be concentrated in short time pulses, which are typically of the order of about 7 ns r.m.s. long, offering the added feature of a tremendous potential accuracy in the time of flight (TOF) determination of the neutron energy. The neutrons produced by spallation are canalized to an experimental area located ~185~~200~~ m downstream through a vacuum pipe, making use of the existing TT2A tunnel Figure 1.

2.1. Proton Beam Line Layout

The geometry of the layout of the proton transfer line associated with n_TOF, FTN, can be summarized as follows [7]:

- three bending magnets (of type MCA) to deflect the beam to the left-hand side of the dump D3. Each magnet generates a bending angle of 2° at the maximum beam momentum of 20 GeV/c;

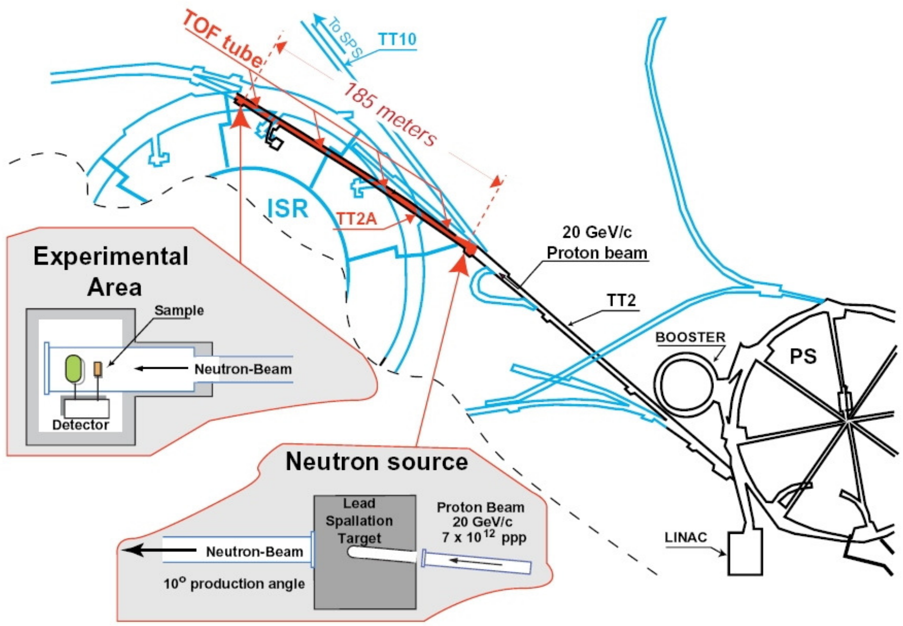

Figure 1: General layout of the n_TOF Facility

- six quadrupoles are used to focus the beam. Three of them (QFS type) are used to focus the beam, the other three (QD type) are used for defocusing. Since the quadrupoles of the same type have the same strength, it is possible to connect them in series;
- three bending magnets (MCA type) are used to deflect the beam to the right by an overall bending angle of 6^o. Each of them generates the same deflection angle;
- two correction magnets (M100 type) are installed to control the beam trajectory.

With this choice of geometry, the proton beam intersects the axis of the TOF pipe at an angle of 10^o. The layout of the FTN transfer line is shown in Figure 2

Such a beam line allows to vary the beam spot size at the target level from $\sim$7x3 mm^2 RMS to $\sim$19x11 mm^2 RMS.

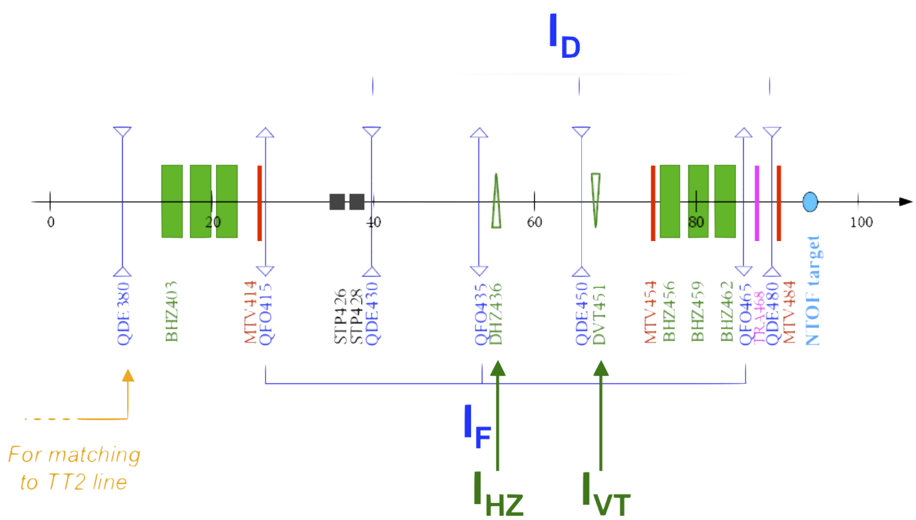

Figure 2: Proton beam line layout

2.2. *Proton Beam Parameters*

The proton beam could be delivered on target in two different operational modes:

2.2.1. *Dedicated mode*

In this mode a 7x10^{12} p bunch at 20 GeV/c is sent to the target during a 1.2 s PS cycle fully dedicated to n_TOF. The bunch time distribution has a Gaussian shape with 7 ns RMS. The beam spot on the n_TOF target is about 8x5 cm^2 (4σs), which can be guaranteed by a limitation in software of the maximum current in the quadrupoles along the FTN line, thus avoiding that the beam is focused on the n_TOF target.

2.2.2. *Parasitic Mode*

During the ramping of a slow ejection cycle for the East Hall, before reaching the 24 GeV flat top, at the 19 GeV energy a $\sim 3.5\times10^{12}$ p bunch is extracted from the PS and sent to n_TOF. The pulse shape and beam profile at the n_TOF target are almost the same as the one in dedicated mode.

2.2.3. Nominal proton Intensity on the Target

The thermal calculations have been done assuming to send on target 4 dedicated bunches of 7x10^{12} p spaced by 1.2 s distributed in a super-cycle 16.8 s long corresponding to an average proton intensity of 1.66×10^{12} p/s. In these conditions the energy deposited in the target every super-cycle is 4×11.4=45.6 kJ (energy deposited by a 20 GeV beam) during a 4.8 s time interval, corresponding to an average power during this time interval of ∼9.5 kW. Since the shortest cycle interval is 1.2 s, this corresponds to the maximum achievable pick power. The average power over a super-cycle 16.8 s long becomes ∼2.7 kW. Any pulse distribution, dedicated or parasitic, distributed over super-cycles of different duration, should not exceed these power values. . By using these assumptions, the thermal simulations are predicting a steady state maximum lead surface temperature of 50°C and an inner temperature of 90°C for a supplying cooling water at 20°C. Assuming to run at the nominal cooling capability (1.66×10^{12} p/s or ~~3.43~~2.72 kW), the nominal integrated intensity for a 200 days run at 100% efficiency is 2.86×10^{19} p, requiring an efficiency of ∼60% to reach the 1.6×10^{19} p expected for the annual runs.

2.3. Proton beam monitoring

The number of protons per pulse is determined pulse by pulse by using a Beam Current Transformer, BCT, [ref?] located about 6 meters upstream with respect to the spallation target in the proton beam line (labeled TRA468 on figure 2). As all the other transformers in the PS complex, the value of the proton intensity is normalized by making periodical calibration procedures. In order to detect any drift of this apparatus, one record, also for each pulse, the signal given by a resistive Wall Current Monitor, WCM, [ref?] mounted immediately after the BCT.

3. The lead spallation target

3.1. Old n_TOF target study

Before designing the new n_TOF spallation target, a complete investigation has been performed on the first one, when it was removed from the pit and brought on the surface for visual inspection and for sample taking. As a consequence of the energy deposition and therefore of the high temperature at the beam interaction point, the mechanical stability was affected. A deformation of the central part of the target was observed, an effect enhanced by the non-monolithic structure and by the presence of creep in lead. A system based on a laser scanning procedure revealed displacements greater than 1 cm around the proton beam spot. During the investigation, a hole was found on the target in the position corresponding to the beam impact point: this has been generated by pitting corrosion, induced by the local boiling of the water close to the impact point, due to insufficient cooling. The latter also inhibited the passivation of the target surface and the stabilization of the Pb oxide layer. Moreover, the lack of control on the water chemistry in the case of the previous target generated the release of spallation products in the water, due to the increased solubility of lead oxides resulting from the corrosion of the lead target.

3.2. New target implementation

Based on our acquired knowledge on lead as spallation target and according with the literature and test on a lead block immersed in an aluminum container [13], the solution to use a cylindrical, 60 cm in diameter and 40 cm length, high purity 99.99% lead target (without cladding) cooled by demineralized water has been adopted. In Figure 3 is sketched the basic principle. A cylindrical lead core is positioned in an AW 5083 H111 aluminum alloy vessel used for the first containment of the cooling water. 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 demineralized water, whilst the moderator volume could be also filled with borated water to improve the background for measurements by reducing the gamma yield produced by the neutron capture in water. The pool and the existing retention vessel are used as second and third containment to avoid uncontrolled release of contaminated water.

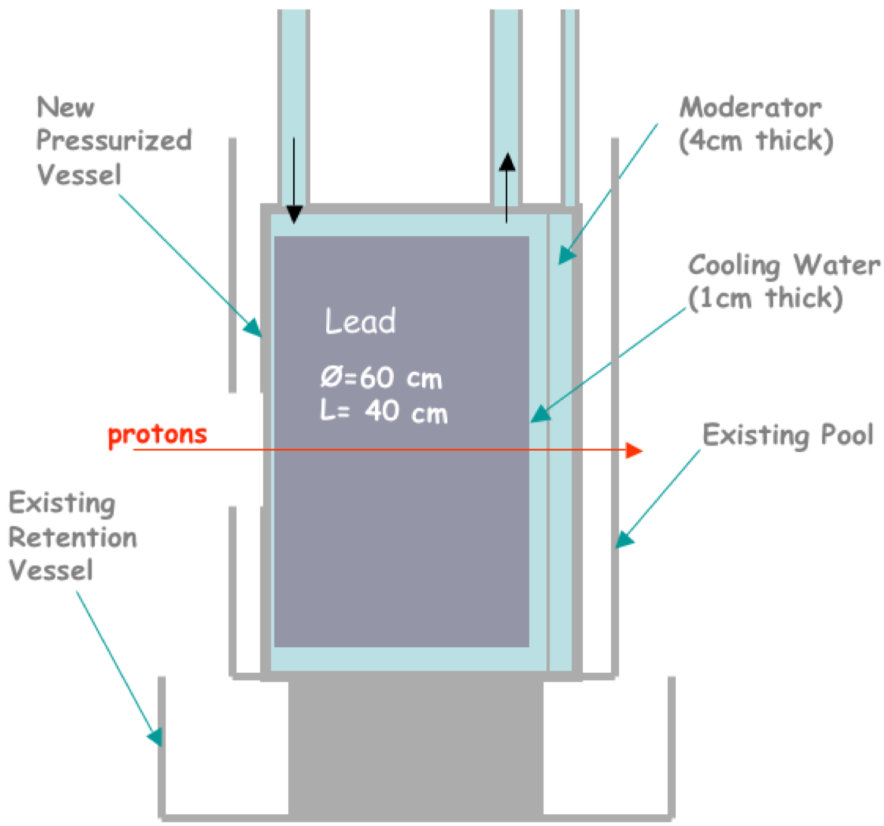

Figure 3: Schematic of the chosen target implementation

This design has been retained mainly for the following reasons:

- Acquired experience with the old lead target,
- possibility to reduce the target dimensions and shape taking into account the target area seen by the neutron collimation system,
- possibility to increase the proton beam cross section. This allow to reduce the hot spot temperature in order to have a sufficient safety margin on water temperature on its vicinity.
- dose rate exposure limitation. The present target has been remotely installed in the old activated pool and retention vessel, allowing to limit the dose exposure to personnel.

3.3. Mechanical stress calculations

Due to the temperature gradient inside the lead block, an initial stress field of 9 times higher than the one due the lead weight has to be considered, so a containment is mandatory to prevents the material from excessive flowing, i.e. less than 2 mm in the neutron and proton surface for the expected lifetime of the target (10 years). The assembly tolerances required to prevent creep of the lead block implied the manufacture of the vessel by machining from aluminum forged blocks. As such, the main cylinder could be largely over-dimensioned without additional cost, however, the entrance and exit widows required an optimization of the material thicknesses traversed by the beam. Mechanical analysis of these windows have been performed [21] following the reference standard NF EN 13445 part 8 (aluminum alloy vessel under pressure). These calculation have shown that the design window deformation remain well in the elastic regime. Maximum displacement of 1.8 mm (1.3 mm) are expected in the neutron (resp. proton) window side. However one have to ensure that the pressure in the moderator circuit will be never higher that the one in the cooling circuit since the plate separating the two circuits does not have its own reinforcements.

Fatigue results ???

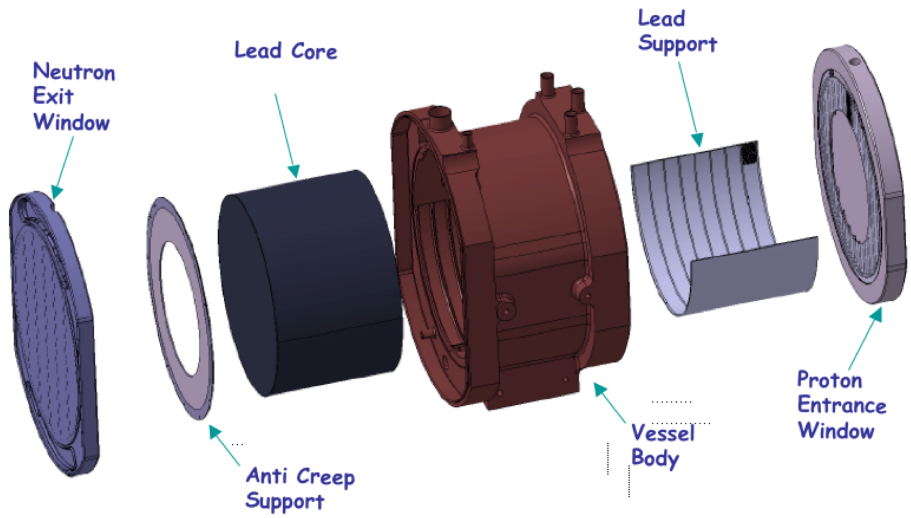

Figure 4: Target assembly layout

3.4. Target decommissioning calculation

3.5. Target Mechanical design

The mechanical design of the new n_TOF target resulting from the constrains and studies reported in this document is shown in figure 4

4. Target area ventilation system

The ISO17873 regulation, which concerns the design and operation of ventilation systems for nuclear installation other than nuclear reactors, recommends the confiment of the Target Areas. The n_TOF Collaboration has therefore implemented a primary target area ventilation system, which is required to ensure the confinement of the target area, capture the aerosols containing radioactive isotopes in absolute filter and allow the monitoring of the released dose to the public. Due to the low energy deposited in the target (¡5 kW) compared to its size and to the ~1200 m^3 volume of the tunnel sector defined as the target area, a cooling system has not been considered necessary. The Target Area volume is continuously flushed out in order to set a negative pressure of roughly 40 Pa between the target area and the adjacent rooms, accomplished with an air flow rate of 500 m^3/h; no fresh air enters the area except through the leak tightness of the static confinement and an adjustment damper. The air is then released in the atmosphere, after having passed from two H10 and H13 HEPA (EN1822 standard) absolute filters and from an activation monitoring systems connected to the CERN integrated radiation monitoring system. The dose rate for the general public outside of the CERN perimeter is estimated to be in the order or less than 1 μSv/year, in agreement with CERN's radioprotection rules.

5. Cooling and moderation system

5.1. Cooling design

5.1.1. Source term

Extensive simulations were done assuming the proton beam cross section impinging the target equal to that used in the past runs, namely σH = 7.8 mm and σV = 5.6 mm RMS. Under this condition, the cooling water flow required to avoid the pitting corrosion in the proton impact area has been estimated at 1 m/s. This value, in itself not particularly high, is large considering risks of corrosion-erosion phenomena, particularly on the lead cylinder. Since the proton beam cross section is not affecting the neutron flux it has been decided to change the proton beam optics in order to produce the largest possible beam cross section. According to the calculations [14] it is possible to tune the proton beam optics to achieve a cross section of σH = 31.2 mm and σV = 22.4 mm on the target face. The following beam energy deposition have been considered: 11.4 kJ per bunch of $7\text{x}10^{12}$ p spaced by 1.2 s, corresponding to $\sim$2.7 kW average power for super-cycle 16.8 s long as explained in §2.2.3. These values have been adopted for the thermal calculations reported hereafter.

5.1.2. Cooling scheme

Cooling calculation have been performed assuming a tangential water flow on both the proton and neutron side of the lead surface. On the cylindrical part of the target one assumed a guided tangential water flow. Water inlet flow, volume flow rate (Q), heat convection coefficient (h) and pressure drop for these flow are reported in table 1

Surface	Cooling type	Inlet speed [m/s]	Q [m^3/h]	h [W/(m^2.K)]	Press. drop [Pa]
Proton	Tangential flow	0,1	2,2	500	13
Neutron	Tangential flow	0,1	10,8	500	13
Cylindrical	Guided tangent. flow	0,02	0,3	120	4
	TOTAL		13,3		

Table 1: Cooling flow parameters considered in the simulation

5.1.3. Results

The results of the numerical simulations are giving the following figures:

- Power to be removed from the proton entrance face: 40 %
- Power to be removed from the neutron exit face: 36 %
- Power to be removed from the cylindrical surface: 24 %
- Maximum temperature rises at the proton face: ∼30 K
- Maximum temperature rises at the neutron face: ∼22 K
- Maximum temperature rises at the cylindrical surface: ∼19 K
- The maximum inner lead temperature: 363 K
- The cooling water velocities: comprised between 2 to 10 cm/s.
- The total water flow rate: 9 m^3/h.

These values are showing that, for a water temperature at the target vessel entrance of 293 K, the lead temperature is far below the water boiling for the external surfaces and far below the melting point (600 K) for the inner volume. Calculations for the real vessel where all the pressure losses in the circuit are taken in account are reported in [19].

5.2. Target cooling system

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. The required water flow is guaranteed

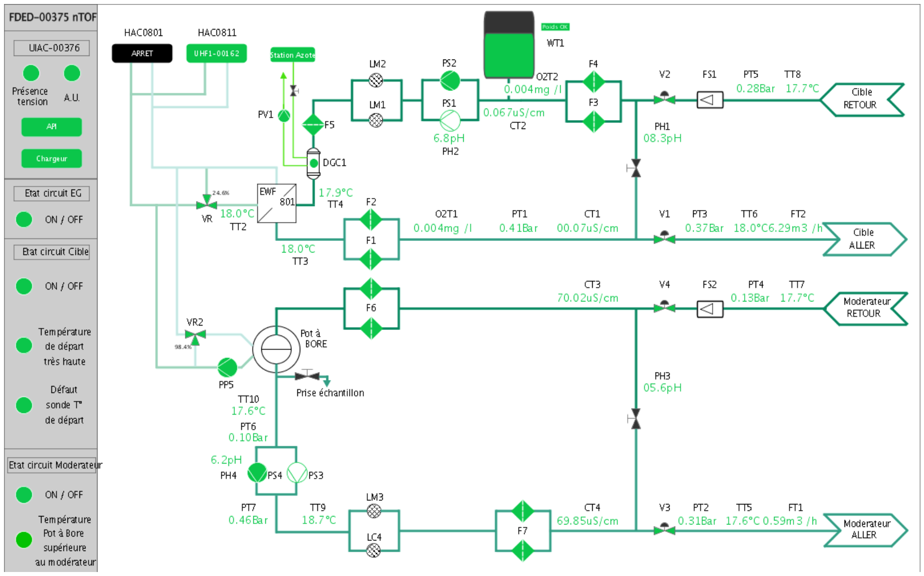

Figure 5: Cooling and moderation station diagram

by design in all critical part. The Cooling Station lay out is sketched in Figure 5

The water flow in the secondary circuit (in contact with the target) is produced by using seal-less pumps (canned motor immersed in the water flow, no shaft seal). A by-pass differential pressure automatic valve controls that the supply-return pressure drop does not exceed preset values in order to protect the thin target enclosure wall (return line) in case of malfunctioning. The system has a further safety device, pressure relief valves (with discharge water collection) on the return lines for the same purpose. The system also features a gas separator to reduce the O_2 contents for minimizing the target corrosion. The degassing system utilizes a microporous membrane acting as a separation between the liquid and gas phases. The transfer of dissolved gas from the liquid phase to the gas one is done by applying vacuum across the membrane. A sweep gas (nitrogen) is used to flush the accumulated oxygen on the gas stream. To reduce in a single pass the O_2 level from ppm to ppb a constant consumption of 1.5 Nm^3/h flush of N_2 is needed. Radiolysis calculations based on FLUKA estimate a total production of O_2 of the order of 1ppm per day for full intensity 20000 pulses, therefore only one flush per day will be needed with a total duration of about 30min. Since steam will pass through the membrane, the gas stream will become saturated with it. A fraction of the vapor will condense and be collected in a liquid trap while the rest will leave the degassing system to be collected by a gas extraction system (hood type) and re-injected into the target area. According to the degassing system manufacturer, solids in the cooling water cannot pass through the membrane and be rejected into the atmosphere; in addition the ion exchange cartridges will be placed upstream the gas separator to decrease the concentration of the different ions before they reach the membrane. The control system monitors the operation variables (temperature, pressure, flow-rates, pH, conductivity, O_2 concentration, ...) and manages the protection of the equipment (pumps, filters fouling, expansion vessel level) transmitting alarms to the control room. The supervision system will allow on-line access to the operational parameters and storage of data recordings for post-mortem analysis and allow remote interaction using standard CERN tools and procedures. To ensure a better control on possible leaks, the system will not have an automatic water refill system. Instead, any leak will provoke the stop of the system and the closure of the safety valves. This will allow for an early detection and prevent the leak to develop for long periods of time. A series of anion-cation de-ionizing cartridges will allow the collection of the activated elements in the water. The main characteristics of the station are:

- Cooling capability: 7 kW
- Water flow rate: 8 m^3/h at 1.5 bars
- Water temperature at the station exit: 18 °C (user programmable)
- Heat exchanger/chiller: 5 kW.
- Primary pumps: one in duty the other in standby.
- Cartridge sieves: one in duty the other in standby.

- Pressurization/expansion vessel: monitored
- Degassing device
- Instrumentation for water chemistry: oxygen content, pH, conductivity on both supply and return line; . [24]
- Water containment under the station: retention basin (1000 liters).
- Gas extraction: degassing device connected to the target depressurized area
- Stainless steel for all components and piping.

5.3. Neutron moderator system

6. Neutron beam line

The retention pool is connected to the neutron beam line thanks to a 800 mm diameter window. This window is made of a 1.6 mm thick aluminum alloy (AA 6082) plate, reinforced by a grid 50 mm thick with sides of 100 mm in length. The struts of the grid have a thickness of 5.5 mm. This window has been machined in one piece from a thick Al alloy plate. The "equivalent" total thickness of the Al alloy is 6.17 mm. The face of the window with the grid is mounted towards the vacuum tube. The deformation of the window amounts to 1.96 mm in the center.

The Time of Flight tube starts directly behind the window and ends 200 m away at the end of the Escape Lane. Due to the geometry of the existing tunnel, the tube is not located in the same position in the cross section. To reach the nominal length of 200 m, the tube has a slope of 1.16% with respect to the flat part of the tunnel. The angle on the horizontal plane between the proton beam axis and the neutron beam is 10^{o} in order to minimize the collection of unwanted secondary particles in the Experimental Area. A Sweeping Magnet at a distance of $\sim$ 150 m is used to remove all the remaining charged particles.

6.1. The n_TOF vacuum tube sectors

The window and the 250 mm long aluminum alloy tube (AA6082) ϕ=800 mm, is directly mounted onto the target pool. Then a 3.9 m sector of the same material and dimension is flanged onto this short tube and traverses the 2 m of marble in front of the target. From there, a stainless steel tube (304 L) with different diameters, as shown in Figure 6, goes up to the end of the Facility. The distances are referred from center of the lead target, to have the Time of Flight path 0.35 m must be subtracted. In one 12 m long sector, three additional windows of diameter ϕ=600 mm are mounted on the side to eventually insert equipment for measurements at very high neutron flux.

At the end of the ϕ=800 mm tube ($\sim$70 m from the target), a reduction piece of ϕ=600 mm is welded. Immediately after there is an iron shielding with a cross section of 1.80X1.80 m2 where the left side (seen in the beam direction) is reduced to the available space to the tunnel wall. This iron shielding is embedded in 40 cm of concrete. At $\sim$140 m from the target, there is the second diameter reduction from ϕ=600 mm to ϕ=400 mm and immediately after is installed the First Collimator with ϕ=110 mm. An iron shielding of 1.20X1.20 m^2 and 1 m long is embedded in concrete with a total thickness of 2 m. In this region the shielding fills the whole tunnel in order to remove the background produced by the Collimator. On the free side of the tunnel, a 1.6 m wide concrete shielding mounted on wheels allow a forklift to go through. Just before and after the Sweeping Magnet the tube is reduced to ϕ=200 mm. After this magnet a 3 m thick Muon Shielding wall has been installed. The ϕ=400 mm section ends with a valve at 175 m. At this point a reduction ϕ=400 mm to ϕ=200 mm precede the Second Collimator.

Starting from this point the TOF tube is made with an aluminum alloy. Before entering in the Experimental Area the tube crosses a 3.2 m deep concrete shielding equipped with a removable part to allow the passage of a forklift. A chicane equipped with a door is used to link these two zones. The Experimental area is defined by two flanges of diameter ϕ=200 mm distant 7.5 m from one another. The lay out in this zone depends on the type of detector installed.

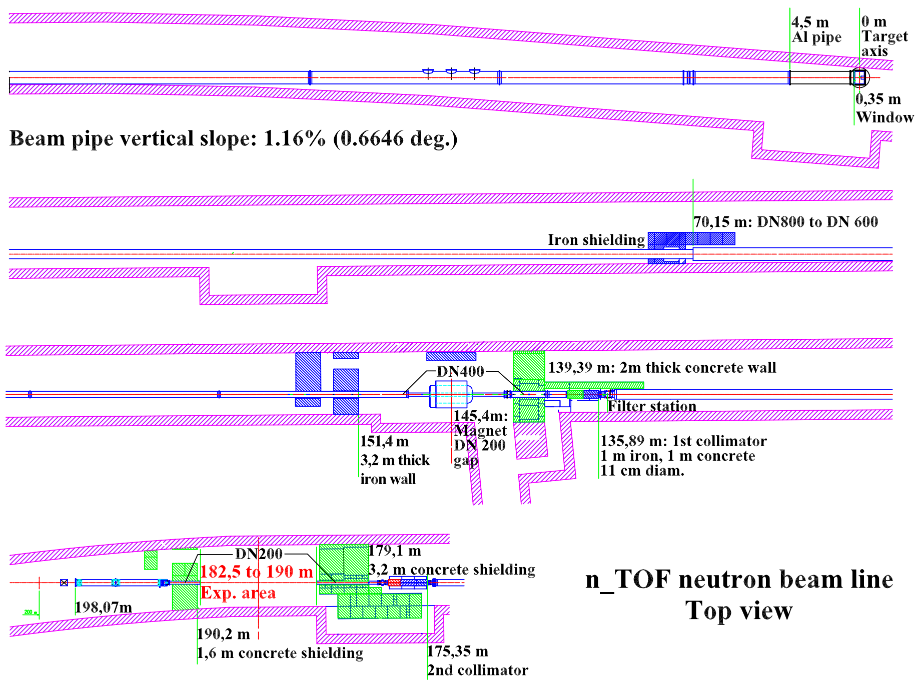

Figure 6: Sketch of the n_TOF neutron beam line

At the exit of the area there is an additional concrete shielding with a simple chicane giving access to the tube end. There, a valve ϕ=200 mm is installed to define the tube sector in the Experimental Area. Finally, the last 8 m of the TOF tube are made with a sector of ϕ=400 mm called the Neutron Escape Line (NEL). For safety reason valves are closed prior to any access in the n_TOF tunnel.

The vacuum inside the pipe is ensured by 6 primary pumps distributed along the neutron beam line. Up to the Second Collimator the vacuum is ensured by 3, double stage, rotary vane pumps (35 m^3/h). After this point vacuum is made by 3 single stage rotary vane pump. The vacuum value inside the TOF tube is typically of few 10^{-2} mbar.

6.2. Shielding and collimation system

The most important elements of shielding along the flying path are:

- shielding at ∼140 m separating the Primary Area from the Secondary Area. This element is a concrete wall 2.4 m deep partially equipped with iron around the tube. A passage for the access of the forklift is available on its right side (in the neutron beam direction). During the run this aperture is obstructed by a removable concrete door mounted on wheels. A closed chicane with a door is used to permit the passage in case of fire;

- Muon Shielding at ∼150 m, few meters after the Sweeping Magnet, made completely with iron covering the whole tunnel cross section, with a chicane to allow people going through. An additional concrete layer of 3.2 m made out of standard blocks is installed after the iron to enhance the efficiency of the shielding;

- shielding at the entrance of the Experimental Area (at ∼175 m), made only with concrete, to separate the area of the collimator from the measuring station. This element is 3.2 m deep again with a passage of the forklift and a closed chicane. Unfortunately in this area the tunnel has a slope of 12% and the aperture can not be mounted on wheels for safety reasons;

First collimator 11 cm internal diameter, 50 cm external side		
Segment material	Length [m]	Initial coordinate [m]
Iron	1	135.89
Concrete	1	136.89

Second collimator: Capture mode 1.8 cm internal diameter, 40 cm external side		
Segment material	Length [m]	Initial coordinate [m]
Iron	2.35	175.35
5% borated polyethylene	0.5	177.7

Second collimator: Fission mode 8 cm internal diameter, 40 cm external side		
Segment material	Length [m]	Initial coordinate [m]
5% borated polyethylene	0.5	175.35
iron	1.25	175.85
5% borated polyethylene	0.75	177.1

Table 2: n_TOF collimators parameters

- shielding at the exit of the Experimental area (at ∼ 190 m), made with concrete 1.6 m deep. The passage of personnel is possible through an open chicane.

The neutron beam is shaped thanks to 2 collimators installed along the flying path. The first located at ∼136 m just after the filter station, and the second one at ∼175 m just before the shielding associated with the experimental area sector. The second collimator is made in such a way that the aperture diameter can be changed from 18 mm to 80 mm in few hours. The capture collimator has been optimized to reduce the neutron halo around the beam. The fission collimator has been optimized to have a flat-top neutron beam spatial profile.

6.3. The sweeping magnet

The natural choice consists in using a dipole magnet to sweep away the charged particles that contaminate the neutron beam. This magnet, that was already used elsewhere in the past, is a standard M200 magnet [ref 18 in performance report] used in the beam transfer lines at the PS. Only the gap has been opened to 210 mm in order to allow the time of flight tube to pass through. This is a 2 m long magnet with a variable height gap. The gap size can be changed by varying the width of a special spacing plate installed in the iron yoke.

7. Measuring station

8. Summary and conclusions

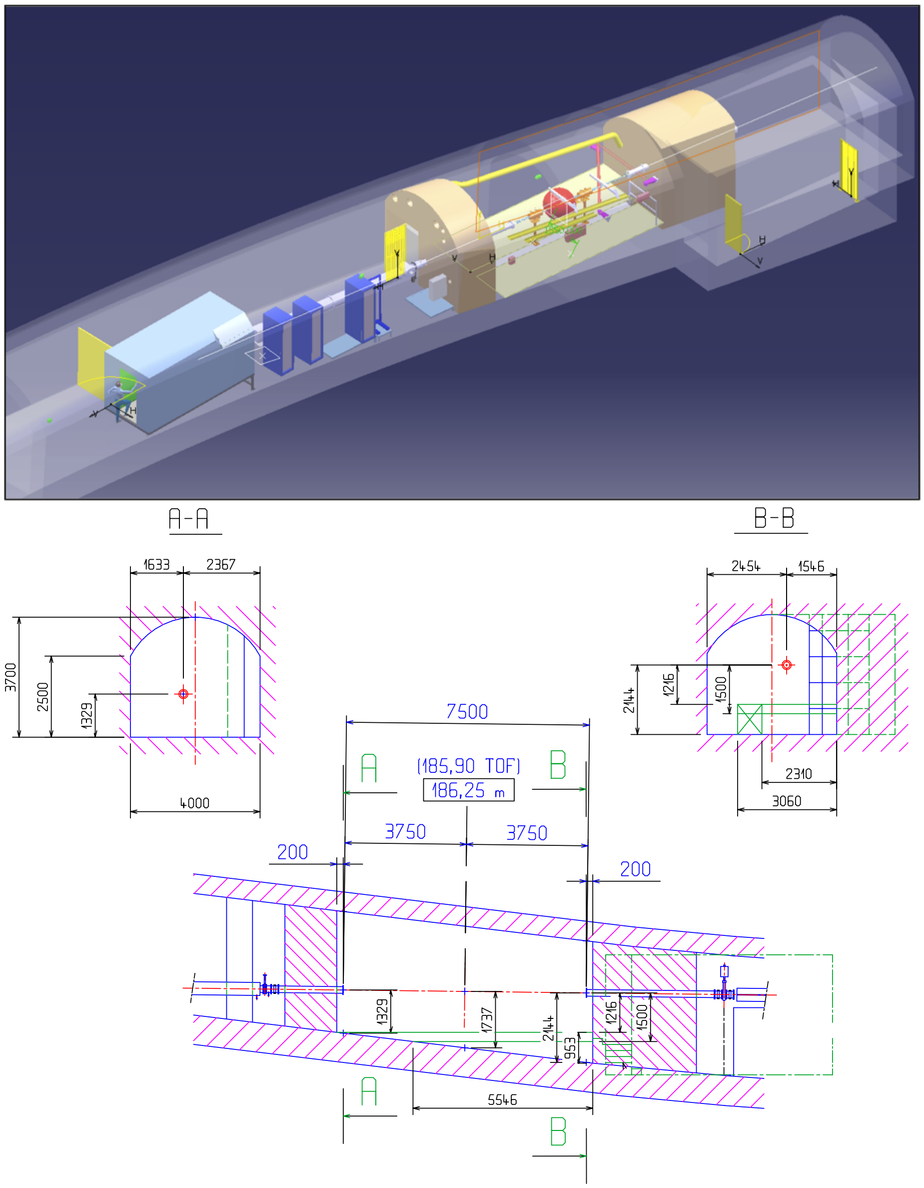

Figure 7: Experimental area layout. Top: 3D artistic view. Bottom: side view and front cross section showing the available space.