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The New Sorgentina Fusion Source-NSFS: 14 MeV neutrons for fusion and beyond

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Abstract. The importance of the design for the realization of an intense 14 MeV neutron facility devoted to test and validate materials suitable for harsh neutron environments, such as a fusion reactor, is well established. The "New Sorgentina" Fusion Source (**NSFS**) is a project that proposes an intense D–T 14 MeV neutron source achievable with T and D ion beams impinging on 2 m radius rotating targets. **NSFS** may produce about 10^{15} n/s at the target and has to be intended as an European facility that maybe realized in a few years, once provided a preliminary technological program devoted to the operation of the ion source in continuous mode, target heat loading/removal, target and tritium handling, inventor as well as site licensing. In this contribution, the main characteristics of **NSFS** project will be presented and its possible use as a multipurpose facility outlined.

1. Introduction

The investigation on structural materials to be used on next generation fusion machines, where intense fluxes of neutrons are expected is of paramount importance. Among all the issues to be addressed, the investigation of structural damages induced by intense fluxes of 14 MeV neutrons emerging from D-T reactions is crucial for the design of fusion reactors for the production of energy. The evaluation of the "atomic reactions-induced" damages in metallic materials upon neutron irradiation is given in terms of the so-called displacement per atom (**dpa**), defined as the number of times (N_d) that an atom is displaced for a given fluence: $N_d = N_0\sigma_d\varphi T_r$, N_0 being the number of atoms in the specimen, σ_d its **dpa** cross section, φ the neutron flunce rate and T_r the irradiation time. The interplay of "atomic damages" and "nuclear damages", e.g. transmutation, affects materials in different way: swelling, ductility loss, increased probability of crack propagation and increased creeping rate, just to mention a few examples. These effects and their correct investigation and evaluation have a deep impact in the choice of the materials and thus on the overall costs of a fusion reactor. The availability of an intense, well calibrated 14 MeV neutron source thus becomes a crucial need towards the construction of a fusion reactor like **DEMO**, and in the mid-term is important as well to test neutron diagnostics (detectors and related electronics) to assess their effective use in intense and harsh neutron environments. The capability of such a neutron source to provide beams for **dpa** and in situ investigation of structural damages after irradiation using neutron-based techniques, such as scattering and/or imaging may be also a useful feature for complete and thorough analyses on the irradiated materials. In this context, the **NSFS** project [1,2] is presented: the main characteristics of the facility are briefly described and the possible use of the neutron beams for experimental activities related to and also beyond fusion are outlined.

2. NSFS main features

NSFS design employs a well-proven neutron source type with existing technology in an innovative plant concept which makes this source brighter, following the relevant experience gained by **RTNSI** and **RTNSII** facilities successfully constructed and operated at **LLNL** [3]. **NSFS** design concept improves such a proven approach, utilizing ion source and accelerator stages from neutral beam injector devices utilized at large experimental tokamaks together with a properly scaled rotating target technology. A twofold water-cooled rotating target of about 2 m radius is operated at rotational speed of about 1000 rpm. Inlet fluid flow of about 110 liters/s is inserted at about 50°C bulk temperature to remove 8 MW thermal power per target (16 MW total power) deposited onto the whole target by a 40A current-200keV energy D and T ion beams imping onto the two rotating targets. Three irradiation volumes are foreseen to accommodate: (i) small specimens (0.5 liter) at high flux; (ii) small material/components samples (1.2 liter) at intermediate flux; (iii) larger volume (several liters) for small mock ups at lower flux. The schematic of **NSFS** and the flux available in the central region are illustrated in figure 1

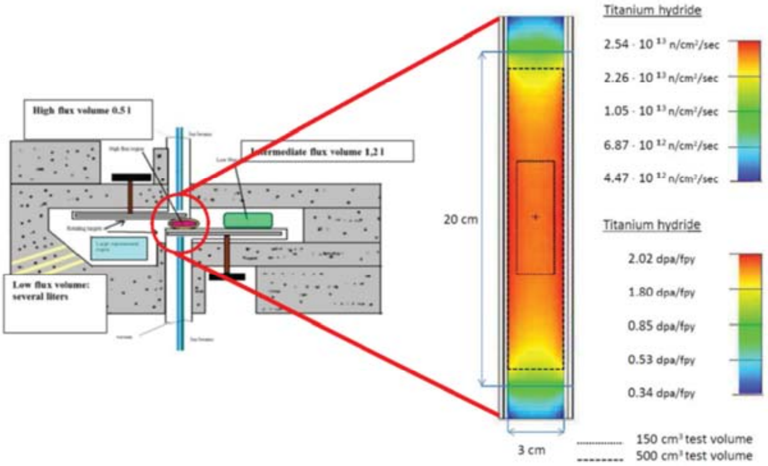

Figure 1: Layout of the NSFS double-wheel target (ion beams on both sides) and neutron flux available in the central region.

3. Possibilities for multipurpose applications

Although **NSFS** is monochromatic, the design of proper moderators could allow at obtaining fluxes of neutrons featuring a wider spectrum. The basic idea relies on the use of a pre-moderator with a high (*n*,*xn*) cross section at 14 MeV, in order to deplete the 14 MeV neutron population, producing lower energy neutrons. These can be then moderated using "conventional" moderators. Just to clarify this approach, figure 2 shows the results obtained with MCNP5-based Monte Carlo simulation [4], where two pre-moderator materials, namely Cu and Pb, are taken into account as test cases. A 4 cm thick water moderator has been placed behind the 5 cm thick pre-moderator. The 14 MeV neutron source used in the calculations is taken from an external routine describing the **FNG** D-T neutron source [5]. The results of the calculations clearly point out an increase of the intensity of the thermal peak using pre-moderators, with respect to the case of the water moderator only, by a factor 4 and 3.5, for the Cu and Pb case respectively. The effectiveness of the pre-moderator in reducing the intensity of the 14 MeV neutron peak is shown in the inset of figure 2. The 14 MeV peak is reduced by a factor 3 with respect to the sole water moderator. A depopulation of neutrons in the 14 MeV region in favor of lower energy neutrons, make them easier to moderate.

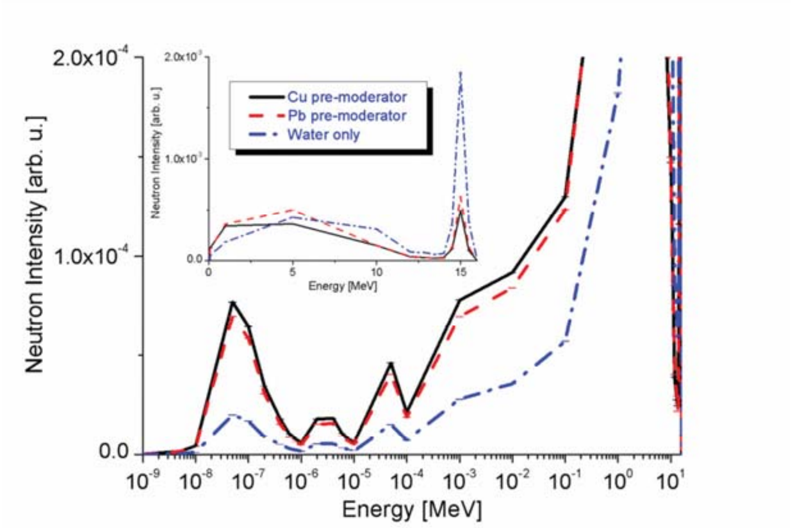

Figure 2: Neutron intensity beyond the moderator system in three different cases: i) only 4 cm water (dashed-dotted line); ii) 5 cm Pb pre-moderator+4 cm water (dashed line); iii) 5 cm Cu pre-moderator+4 cm water (continuous line).

Using a very raw conservative approach, by comparing the neutron production rate of **NSFS** with those of different accelerator-driven neutron sources, and proportionally scaling the fluxes available at the sample position, it is possible to perform an useful exercise providing a first guess of the implementable neutron techniques and their applications for **NSFS**.

3.1. Fusion technology

Fusion reactor materials testing with 14 MeV neutrons is essential before the design of any demonstrator (**DEMO** [6]) can be completed. EUROFER as a breeding blanket structural material, tungsten as the plasma facing component armour, copper alloys for the divertor coolant interface [7] are a few example of main materials. The aim is to deliver 30 **dpa** for structural steels, 10 **dpa** for copper and tungsten. Material investigations for fusion technology concern a broad range of facility components and several property changes under irradiation effects, *e.g.* the influence of nuclear transmutation on the electric characteristics of ceramic insulators, the irradiation effects on window material properties, the selection and test of low activation materials. An important activity will be the assessment of nuclear database and damage cross-section data, as well as the validation of numerical model simulations.

3.2. Electronics and its application

Integrated circuits featuring nanometric dimensions are extremely susceptible to random faults, known as single event effects (**SEE**s), occurring when a highly energetic particle, such as a neutron present in the environment, strikes the sensitive regions of an electronic device [8,9]. Radiation-hardened and radiation tolerant components are often used in military and space applications. Fast neutrons irradiation tests are also important to investigate the nuclear hardness for telecommunication, to assess to which extent the performance of a system, facility, or device is expected to degrade in a given nuclear environment. A potential concern is that mono-energetic neutron-induced single event effects will not accurately represent the real-world effects of broad-spectrum atmospheric neutrons. However, recent studies have indicated that, to the contrary, mono-energetic neutron, and particularly 14 MeV neutrons, can be used to quite accurately measure **SEE** cross sections in modern microelectronics as effectively as white beam, possibly with reduced uncertainties [10].

3.3. Material science

Neutrons provide information on structure and dynamics of materials [11]. Neutron diffraction (ND) and inelastic neutron scattering (INS) provide a thorough description of materials used in many applications ranging from engineering and chemistry, to cultural heritages and life science: the investigation of the structure and physical/chemical properties of materials for fusion reactors is of paramount importance. The measurement of **dpa** described above is just a first aspect of the problem. Irradiation-related defects (of atomic and/or nuclear nature) have to be understood and well characterized. ND at small and wide angles and/or imaging represent the due techniques for these investigations. The identification of stresses, strain, cracks in the bulk of the material as well as morphology is essential in determining the effectiveness of a material for the purpose it was meant for. ND is useful in determining microscopic structure, such as the hydrogen occupancy sites, that in turn may affect macroscopic properties of Pd-based membranes or new and innovative Pd-free compounds (such as electric resistivity [12]) in use for H storage/production. INS represents a very broad spectroscopic area [13], ranging from the study of the slow molecular diffusional regime (≈1 ns) up to that of the fast proton dynamics (≈0.1 ps). Neutron Vibrational Spectroscopy (**NVS**) [14], for example, is a fundamental technique used constantly in educational, research, and industrial laboratories worldwide. It has become an essential tool in medical applications, forensics, environmental compliance, and quality control to cite but a few common uses.

Small-Angle Neutron Scattering (**SANS**) probes structure in materials on the nanometer (10^{-9} m) to micrometer (10^{-6} m) scale. Structure on this length scale is critical to the performance of advanced engineering materials, biological processes in cells, storage of information on magnetic disks, hardness of steels and superalloys, conduction of current in superconductors, and many other materials properties. Possible applications of **SANS** range from biological molecules, polymers and surface properties of catalysts, to colloidal suspensions, metal physics, materials science, nano-crystalline materials, long range spin correlation and flux lines in superconductors [15].

3.4. Fundamental physics

Particle oscillations are familiar phenomena in both classical and quantum mechanics and have provided a wealth of information about the nature of matter and the fundamental forces. The $n-\bar{n}$ oscillation [16] is a unique kind of oscillation phenomenon compared to kaon oscillations as it breaks conservation of baryon number. Another important neutron measurement for fundamental physics is that of the neutron electric dipole moment (**EDM**) [17]. A non-zero electric dipole moment of the neutron (or any fundamental particle) would be a violation of parity (**P**) and time-reversal (**T**) symmetry, implying **CP** violation, already observed in accelerator experiments studying the decays of K and B mesons, but not at a level with can explain the matter-antimatter asymmetry of the universe.

Quantum mechanics fundaments are still subject of debate. Interferometry with massive elementary particles combines particle and wave features in a direct way. In this respect, neutrons are proper tools for testing quantum mechanics because they are massive, they couple to electromagnetic fields due to their magnetic moment, they are subject to all basic interactions, and they are sensitive to topological effects, as well. Recent neutron interferometry experiments based on post-selection methods renewed the discussion about quantum non-locality and the quantum measuring process [18,19].

3.5. Industrial applications

Industrial applications of nuclear analytical methods are useful in metallurgy and coal industries: 14 MeV Neutron Activation Analysis (**NAA**) [20] is capable of determining many light elements that cannot be analyzed using classical **NAA**. One of the most important applications of this technique is the determination of oxygen content in steel during the production phase. Using the reaction $^{16}O(n,p)^{16}N$, where ^{16}N decays with a half-life of 7.13 s, emitting 6.13 MeV, and 7.12 MeV gamma-rays this information can be achieved. Other important applications in metallurgy are the determination of Si, P and Mg in cast iron [21]. Applications can be also found in oil industry (borehole logging), quality assurance and quality controls for nuclear analytical methods, technology for illicit trafficking and anti-terrorism.

3.6. Metrology

Neutron fields can extend over a very wide energy range, this feature setting a challenge for the design of measurement devices and, as a consequence, a parallel challenge of developing measurement standards for their characterization. Neutron standards are required from the lowest energies, (ultra-cold neutrons) up to neutron GeV energies, typical of high-energy accelerators and atmosphere. In the frame of projects such as ITER, a special need is the adequate calibration of neutron diagnostic systems in order to perform accurate neutron emission measurements to determine the fusion power. An intense quite monochromatic neutron reference field, as that expected from **NSFS**, would be of great interest to study instruments in details and asses accurate measurements of neutron emission at 14 MeV. The availability of the intense 14 MeV neutron beam would be a profitable source for metrological concerns, useful to develop improved metrological procedures for fusion applications.

3.7. Neutron radiation biology and therapy and pharmaceutics

In the last decades, studies on the space environment to plan deep space exploration highlighted the the necessity of increase knowledge on the real biological risk of the exposition to low doses of cosmic radiation (mainly energetic protons from solar flares [22] and galactic cosmic rays). These interact with matter producing secondary radiations such as neutrons and gamma rays. Neutrons produced by albedo or interaction with shielding materials could reach 50% of the total radiation [23]. This is a relevant problem since the risks associates to neutron exposure have to be strictly considered for astronauts, beyond the **SEE** discussed above. Cosmic radiation exposure can produce severe damages to astronauts, such as cancer, immune system impairment and neurological damage. The main uncertainty of neutron exposure is the knowledge of the molecular process at low dose exposition [24]. Recently, a molecular approach was performed to investigate the effects of 14 MeV neutron irradiation on living mice [25] using the 14 MeV Frascati Neutron Generator (**FNG**) [26]. It has been shown the capability of neutron radiation, when traversing skin and sub-cutaneous adipose tissue, to induce the release of the Leptin, that in turn reaches the central nervous system likely modifying the lipid metabolism [27]. Radiation therapy is used for the treatment of hyper-proliferative diseases, such as malignant cancer, alone or in combination with surgery and chemotherapy. Neutrons, have potential advantages related to the increased energy deposition in tissues per unit track length. The energy released by neutron delivers a locally multiple damage sites clustered DNA damage far more difficult to repair [28].

In Nuclear Medicine ^{99m}Tc is one of the main radioisotopes currently and extensively used (70% of all radioisotopes diagnostic procedures), with an estimated 10 million medical tests per year. At present, ^{99}Mo, from which the ^{99m}Tc is obtained, is exclusively produced from fission of ^{235}U and in North America this isotope is solely available from Nordion, Canada. A temporary shutdown of two CANDU reactors in Canada in the year 2009 caused so called ‘Tecnectium crisis’. **NSFS** represents an interesting tool to investigate the possibility of producing ^{99}Mo/^{99m}Tc through the $(n,2n)$ reaction, that in the range 11-18 MeV of neutron energy has a cross section of 1.5 barn. The cross sections of (n,α), ($n,n'p$) and (n,p) reactions on ^{100}Mo are lower and produce very low quantity of impurities, so that large amount (> 100 g) of ^{100}Mo can be safely used and managed for irradiation. Very preliminary calculations showed that irradiating 1 kg of natural-Mo in the high-flux region (see Figure 1), taking into account a realistic irradiation time of about 12 h, an activity of 1 TBq could be profitably obtained.

3.8. Training and neutron science testing

The possibility to exploit the high level capability at the large scale facilities is strictly connected to the growth of a strong community, providing training and instrument testing. The availability of several smaller facilities has been the strength of the European neutron scattering community in the last forty years. Some of these smaller facilities are of high level in terms of source and instrumentation (e.g. **LLB**, **HMI**), but they are expected to progressively shut-down due to their aging. On the other hand, the bigger facilities are progressively becoming less and less adequate for the scientist training and instrument development because they must provide a service for a wide and not expert community of users. The role of the small facilities can become even more important in the near future due to the change of the role of the large facilities and their reduced number. Thus smaller facilities having the possibility of a simple access for young scientists willing to learn the neutron scattering techniques are extremely needed. Properly designed beam lines having the appropriate characteristics to perform instrument component tests will be valuable for training and progress of instrument design. A test beam line can be likely deveoted to detector development and testing, including front-end and acquisition electronics in real conditions. This is a particularly important area both because the reduced production of ^{3}He and the need of new more flexible, faster and cheaper detectors. The crystal monochromator development can be also important. Although the existing monochromator design does not need for specific advances the construction of new devices needs for alignment and testing instruments and some improvement can be also possible for specific applications connected to the future development of new instruments specifically designed for the long pulse sources like **ESS** and the future second target station at **SNS**.

4. An overview on possible instrumentation for NSFS

In this section it is briefly presented a reduced selection (with respect to the overall set of applications outlined above) of possible instruments that might be implemented on **NSFS**, starting from a conservative approach for neutron transport capabilities from target to sample position and taking also into account the techniques to date effectively in use in several small-compact neutron sources worldwide with neutron production rate orders of magnitude lower than that available on **NSFS**.

4.1. 14 MeV neutron irradiation station

NSFS offers different possibilities for 14 MeV neutron irradiation experiments, exploiting the irradiation locations sketched in Figure1, already briefly discussed before. Moreover, a dedicated beam line offering the opportunity of irradiating larger systems can be also foreseen by opening line of sight of the target. At a reasonable distance of about 3 m from the target the neutron fluence rate at 14 MeV might be in the order of 10^{9} n cm^{-2} s^{-1}, with the possibility of irradiating large systems of assemblies of devices enhancing statistical accuracy over a single irradiation run.

4.2. ND, SANS, INS and neutron imaging

A basic instrument implementable on **NSFS** could be a medium resolution diffractometer for the study of disordered systems or powders of high-symmetry crystals. The layout is very simple and an example of such instrument is the D20 beam line at **ILL** or 7C2 at **LLB**. focusing on **NVS** applications, basically the same as those relevant in the spectrometers of the latest generation, such as **TOSCA-II** (**ISIS**), **VISION** (**SNS**), and **LAGRANGE** (**ILL**). **NSFS** characteristics place this source in the so-called “low flux class” [29], together with the reactors of Delft (The Netherlands), Řež

(Czech Republic) and Kjeller (Norway), that is about ten or fifteen times below the **NCNR** reactor of **NIST** (USA) and the **PSI** source (Switzerland). Thus a simple conception, such as the so-called "beryllium filter" (BF) [30] might be implemented on **NSFS**. Among the different BF spectrometers currently in operation, one of the most representative is certainly **FANS** [31], installed at the **NCNR** reactor of **NIST** (USA). Although some details are not available, nevertheless the following three operations could approximately recover the factor 10÷15 of lower neutron intensity compared to **NCNR**: 1) doubling of the secondary sector in the spectrometer so to cover about 230° (incidentally, this is also expected from the future phase II of **FANS**) [gain factor=2]; 2) improving the monochromator [for example by using a doubly focalizing Cu(311)]. This too is required by the future phase II of **FANS** [gain factor=4]; 3) decreasing the monochromator-moderator distance (now about 5.3 m), since **NSFS** will certainly need a biological shielding much lighter than that suitable for a nuclear reactor like **NCNR** [gain factor=1.5÷2]. Considering the neutron production rate of **NSFS** and a conservative approach to the neutron delivery at the sample position as compared to existing sources, a possible configuration for a Small Angle instrument may be that of the SANS-I instrument at the **SINQ** spallation source at **PSI** - Villigen (CH). **SANS-I** at **PSI-SINQ** covers the *Q*-range from 6×10^{-3} to 5.4 nm^{-1} and for the detector displaced laterally by 50 cm up to 10.5 nm^{-1}. This allows the investigation of structures ranging from about 1 to 400 nm. The incoming neutrons are monochromatized by a mechanical velocity selector and collimated on a variable length from 1 to 18 m. The two-dimensional ^{3}He-detector with 128 x 128 elements of 7.5 x 7.5 mm^2 can be positioned at any distance between 1.4 and 20 m from the sample. Additionally it can be displaced laterally by 50 cm inside the large vacuum vessel to increase the accessible *Q*-range at any detector position. This option is combined with a rotation around its vertical axes to reduce parallaxes effects. The sample support consist of a remotely controlled xyz and rotation table for mounting devices for working in air (e.g. sample changer, high pressure cell, ...) and a vacuum chamber (able to carry an electromagnet).

An imaging systems for **NSFS** is composed of a few items: a pin hole selector to define flus and resolution, a Li/Gd loaded scintillator and CCD-based digital acquisition. Considering the conservative approach used in this discussion for the neutron transport from target to sample e having in mind the typical measuring times for an imaging beam line an exercise was done to roughly determine the possible performances of **NSFS** for this neutron technique. Assuming a thermal neutron flux in the order of 10^6 n $cm^{-2}s^{-1}$ at the sample position, different experimental configurations can be foreseen. In Table 1 only a couple of examples are reported.

Table 1: possible experimental configuration for an imaging beam line at NSFS

Pin hole diameter [mm]	*Maximum Field of View* [mm]	*L/D*	*Resolution* [mm]
15	100	1133	0.122
30	200	567	0.173

In these configurations the typical measuring times are in the order of a few hundreds of seconds, allowing for a medium-to-high level imaging in reasonable times, also allowing tomographic capabilities.

5. Conclusions and perspectives

New Sorgentina Fusion Source (**NSFS**) is a high intensity 14 MeV neutrons source. Its layout and neutron performance were briefly described and discussed. Main applications of **NSFS** using 14 MeV neutrons have been outlined and possible strategies to obtain moderated (thermal) neutron beams were briefly indicated. In a conservative approach, a prevision was attempted to foresee what kind of techniques could be implemented on hypothetical beam lines operating at the **NSFS**. These range, beyond fusion, from irradiation with 14 MeV neutrons for electronics and biology, to neutron diffraction, imaging and neutron vibrational spectroscopy.

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