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New Sorgentina Fusion Source (NSFS) experimental facility supporting materials research

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Abstract. Within the framework of fusion technology research and development, a neutron source has long been considered a key facility to perform irradiation tests aiming at populating materials engineering database – supporting DEMO reactor design and licensing. New Sorgentina Fusion Source (NSFS) has been proposed taking advantage of well-established D-T neutron generators technology, scaled in order to attain a bright source of about 10^{15} n/sec. The provision of an actual 14 MeV neutron spectrum, resembling that of a D-T fusion machined, is a relevant feature. In this contribution, the main facility characteristics are provided, together with a brief discussion on target thermal and mechanical issues.

1. Introduction

Materials testing with fusion relevant neutron source is essential to DEMO design in order to cope with technical (nuclear damage) and regulatory (licensing) issues. In the European roadmap to fusion energy [1-2], testing of materials are scheduled by 2026 up to the following radiation levels: damage of 30 dpa for structural steels, 10 dpa for copper and tungsten. On the other hand, nuclear materials testing is required for a broad range of components e.g. those for auxiliaries and diagnostic.

In this context, the NSFS project provides a potentially unique tool. Indeed, the 14 MeV neutron spectrum offered by Sorgentina facility will closely resemble that of a fusion machine like DEMO, thus providing a very important tool to calibrate and validate displacement per atom (dpa) accumulated in other irradiations facilities such as more readily available fission and accelerator-based facilities. These unique features strengthen strategic relevance for Sorgentina proposal, even within the framework of future powerful plants offering fusion-like spectrum but not exactly DT fusion 14 MeV neutron flux spectrum. The envisaged DT neutron flux spectrum of Sorgentina indeed aims at allowing the study of the influence of nuclear transmutation on the electric characteristics of ceramic insulators, optical fibers, window materials and superconducting cables, selection and test of low activation materials, populating nuclear database and damage cross-section data as well as validation of numerical model simulations. Moreover it will enable to carry out basic studies on neutron damage to materials irradiated with 14 MeV neutrons to validate damage calculation codes and provide a neutron field where damage cross-sections can be tested and/or measured. It would furnish reliable data about the radiation hardness of materials to be used for diagnostics and produce neutron flux and spectra similar to that expected in a tokamak in order to allow for 1) nuclear diagnostics calibration under real spectra, 2) reliable test of electronics equipment and components to be used for diagnostics, remote handling etc. The intense 14 MeV neutron flux will allow to investigate tritium production assessing the behavior of breeding materials working under reactor-like condition as well as methods for tritium handling, extraction and on-line measurement.

Neutron flux spectra and intensities required for materials irradiation must be sufficient to study material damage process. In fact, degradation phenomena such as irradiation creep, volumetric swelling and phase instabilities approach saturation at damage levels above 10 dpa [3].

Material embrittlement onset is more difficult to define. Displacement cascade - consisting in the migration of vacancies and interstitials – produce segregation phenomena, micro-structural evolution, dislocation climb and voids creation. All these processes induce irradiation hardening and embrittlement at relatively low temperatures. By contrast, creation of voids and dislocation climbing produce swelling and irradiation creep – which occurs for doses higher than 10 dpa at higher temperatures.

With a proper design and optimization of the layout, other possible activities of interest in other fields are, for example, irradiation of electronics chips and frontend electronics, neutron imaging (with proper moderation of source neutrons), materials neutron activation studies as well as tests on components for sources large scale neutron facilities.

2. NSFS main components

Sorgentina main design and key feature is the strategy of matching a well-proven neutron source type with existing technology, in an innovative plant concept which makes this source much brighter compared to previously realized facilities [4]. Deuterium-Tritium fusion reaction is currently used in industrial neutron generators in which ion source and accelerator are coupled to a D-T enriched target which turns out to be a planar 14 MeV fusion neutron spectrum source. Sorgentina design concept relies upon ion source and accelerator stages from neutral beam injector devices already utilized at large experimental tokamaks [5] together with a properly scaled rotating target technology. Twofold water-cooled rotating target of about 2 m radius is operated at rotational speed of about 1000 rpm. Inlet fluid flow of some 110 lit/sec is inserted at about 50°C bulk temperature, 8 MW thermal power per target has to be removed – 16 MW total power being deposited onto the whole target. D & T ion beams are delivered to two rotating targets facing each other. Total ion current per each target is about 40A, 20A from deuterium and 20A from tritium. Beam energy is about 200 keV to optimize fusion reaction probability following the reaction $\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} + 17.6\mathrm{MeV}$. Ion beams impinge on both sides of a double wheel target where 14 MeV neutrons are generated. The schematic of Sorgentina is sketched in Figure 1. Three irradiation volumes are foreseen to accommodate: small specimens (0.5 l) at high flux; small material/components samples (1.2 l) at intermediate flux; larger volume (several litres) for small mock ups at lower flux.

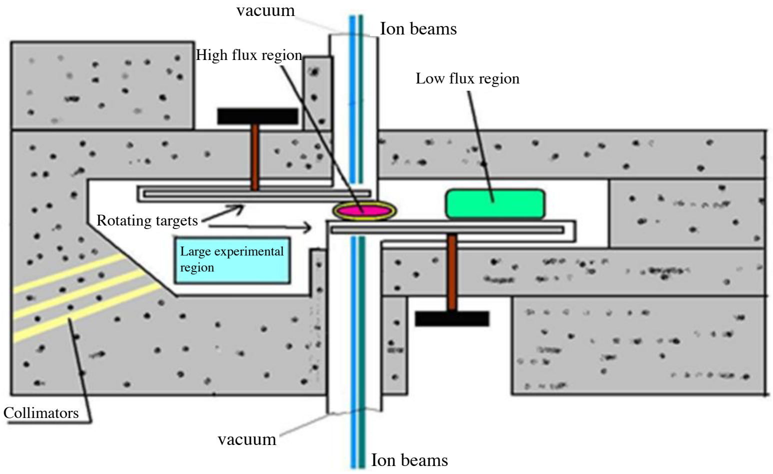

Figure 1: *Layout of double-plate target showing: ion beams on both sides, 0.5 litres irradiation volume in-between and larger irradiation volumes*

Gap between neutron source plates is intended to measure about 3 cm. Irradiation rigs are designed to accommodate specimens in about 2 cm accounting for rotation and mechanical fabrication uncertainty sizes. Sorgentina design results in a very compact layout. In Figure 2, the assembly of the Sorgentina system is shown.

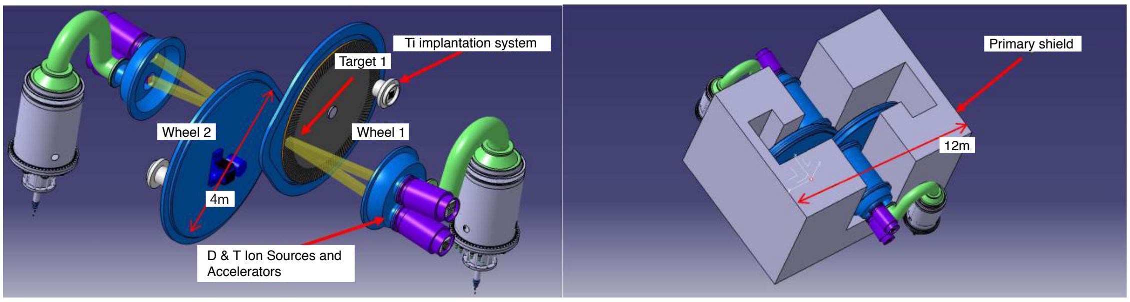

Figure 2: *(a) Layout of double targets showing: ion beams on sides; (b) Sorgentina embedded in the primary neutron shield.*

2.1 Thermal and Mechanical Design

Preliminarily thermomechanical evaluation of target performances were carried out analysing a slice of the interacting plate - using a 2D plain strain finite element (FE) model implemented through the free software package CALCULIX [6]. Only one half of a single tube was modelled due to periodic and symmetry conditions. The heat power deposited by the beam into the metal hydride layer was simulated by imposing a pulsed heat flux on the exposed face with a maximum value of 400 MW/m^2. A water coolant pressure of about 30 MPa was applied on the tube internal surface, corresponding to the maximum pressure induced by the centrifugal forces at the top of the plate (assuming a height of 250 mm) plus the hydraulic head of the circulation pump. A conservative value of 40 $kW/m^2/°C$ for the coolant heat transfer coefficient was adopted. Table 1 summarizes the geometric and operating design parameters. The material properties of CuCrZr-IG specified in the ITER Structural Design Criteria for In-Vessel component (SDC-IC) [7] were used in the analysis. The presence of the hydride layer was properly taken into account in the model.

Table 1: *Geometric and operating parameters of the target*

Heat flux	**400 MW/m^2**
Rotational Speed Water pressure	1000 rpm 30 MPa
Wheel radius	2 m
Plate height	250 mm
Tube diameter	2 mm
Rotation period	60 ms
Beam-plate interaction time	0.48 ms
Heat transfer coefficient	40 kW/m^2 °C
Inlet water temperature	10 °C

Starting from the initial condition, a certain number of beam pulses were applied until the temperature history repeated identically at every cycle. The hydride temperature evolution within the cycle once that equilibrium condition was reached is shown in Figure 3. A maximum value < 300 °C, well below the critical value of 400 °C, is found. It is acceptable from the point of view of hydride stability and tritium retention.

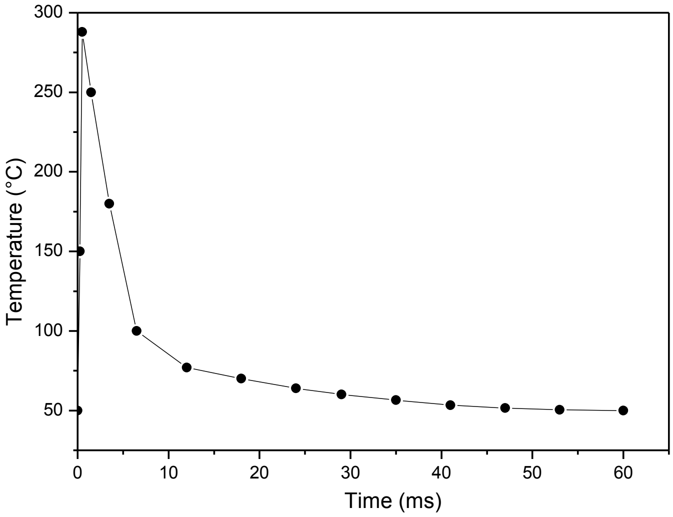

Figure 3: *Hydride temperature evolution within the cycle*

The maximum Tresca stress in the tube area is around 66 MPa (Figure 4), which is safely lower than the minimum allowable stress of the material at the temperature experienced by the tube (~110 MPa at 180 °C), thus proving that the global structural integrity of the plate is assured.

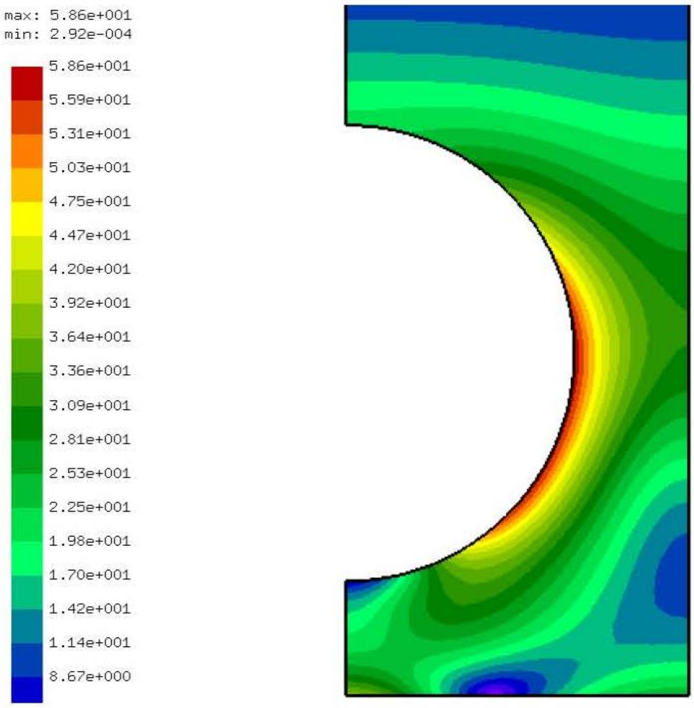

Figure 4: *Tresca equivalent stress in the tube area*

A specific design with a conical structure of the surface exposed to the beam was adopted in order to reduce thermal fatigue effects. The calculated Tresca stress amplitudes at various positions of the considered structure are shown in Figure 5. These values must be compared with the CuCrZr fatigue limit that can be taken around 200 MPa [8] at Sorgentina relevant number of cycles/year (~5x10^8). It is seen that fatigue limits are verified for the operating conditions considered. Thus, it can be stated that the Sorgentina target appears to be feasible and mechanically reliable, even under a conservative analysis.

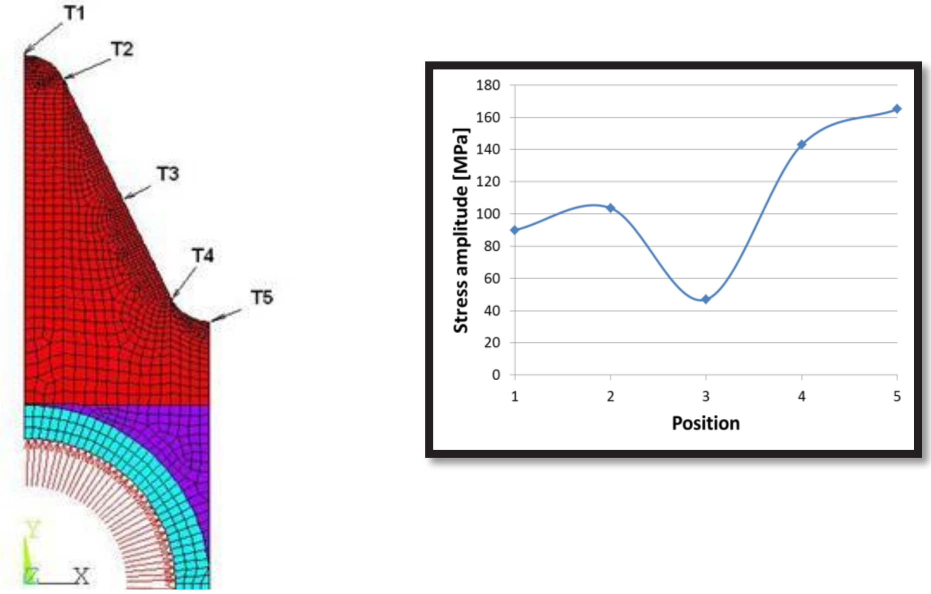

Figure 5: *Tresca stress amplitude (right) at various positions (left) of the exposed surface*

2.2 *Irradiation performance*

Sorgentina irradiation capability is attained through two surface-emitting sources of about 20x10 cm^2 that are ion beams footprints on the rotating target (see Figure 2). Neutron production rate and then source evaluation is related to beam characteristics and lattice properties of the metal in which hydrogen isotopes are implanted. In fact, ions beam energy enhances fusion probability up to reaching a plateau . Different molecular and triatomic species are generated in the ion source and accelerated to the target as well. Neutron yield is calculated starting from design parameters: beam energy, total current, beam composition (monoatomic, molecular and triatomic), metal hydride [9].

Calculated neutron yield assumes 50% deuterium and 50% tritium beams, of monatomic composition (D^+,T^+), impinging on different target coating layers. Calculations reported hereafter considered ion source monoatomic production of about 100% efficiency. Actual ion sources attain performances higher than 95% [10]. Hydrogen-to-metal atomic ratio is taken into account - as a comparison – depending on hydride stoichiometric saturation. Provided implantation regime and saturation achieved, titanium could attain hydrogen loading of about 2 – a conservative hydrogen loading factor which corresponds to no on-line implantation configuration – namely 1.8 for titanium [11].

Neutron transport calculations were performed using the MCNP5-1.6 Monte Carlo code [12]. Each target is hit by the ions beam within a rectangular area which is 20 cm long on target radius and 10 cm in direction of angular rotation. Irradiation volume thickness within rotating targets is taken 3 cm in the present design in order to maximize source flux overlapping.

In the MCNP model, neutrons before reaching the irradiation volume travel through some material layers accounting for both copper-chromium-zirconium alloy as piping and finally water as coolant, as reported in Figure 6.

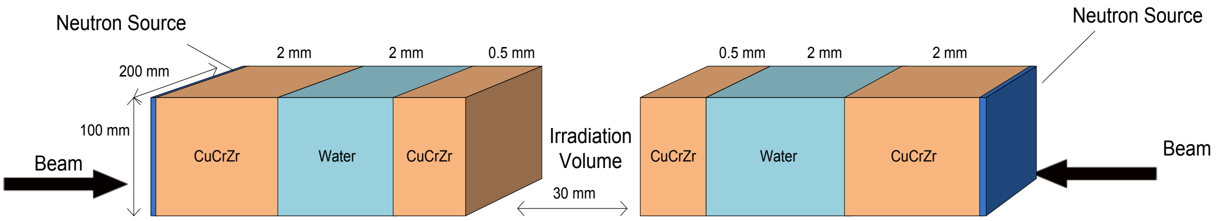

Figure 6: *Monte Carlo model for neutron irradiation evaluations*

Metallic structure gives mechanical frame and contains hydraulic pressure inside cooling pipes. Neutron flux and materials irradiation damage have been evaluated inside the gap by means of neutron cross section data according to FENDL-3 Starter Library, release 4, FENDL-3/SLIB4 [13]. Present nuclear data set is currently considered a robust approach by international agencies and research institutions. The Norgett, Robinson and Torrens (NRT) model [14] has been applied to calculate the dpa rate. Neutron flux (n/cm^2/s) and displacement per atom (dpa /fpy) have been calculated in several irradiation volumes and these values are listed in Table 2. Small gradients for neutron flux and dpa rate occur inside irradiation volume as it can be also noticed in the iso-flux maps shown in figure 7. This means a quite homogeneous irradiation field according to experimental purposes. This is perceived a relevant feature of present source design, aiming at homogeneous irradiation of samples for a solid analysis of future results. Materials irradiation through high energy neutrons gives rise to nuclear reactions (n,p), (n,α), (n,d) etc. which are not triggered in case of low energy neutrons. In fact, 14 MeV neutron flux spectrum has an impact also in the “real” formation of hydrogen and helium atoms which, moving throughout the material lattice yield charged particles reactions, a not negligible problem for materials exposed to energetic and intense neutron flux. Furthermore, presently used theoretical models to predict this effect have never been validated with 14 MeV neutrons. This is another important goal achievable with Sorgentina as the validation of Predictive Tools for DEMO is a fundamental task of the present design.

Table-2 : *Neutron flux and dpa /fpy for candidate layer hydrides*

	Titanium hydride layer	
Test Volume [cm^3]	Neutron flux [n/cm^2/s]	dpa/fpy
10	2.14 10^{13}	2.00
25	2.1 2 10^{13}	1.90
50	2.09 10^{13}	1.87
100	2.04 10^{13}	1.84
150	2.00 10^{13}	1.82
250	1.89 10^{13}	1.77
500	1.54 10^{13}	1.60

As a matter of fact, the mechanical properties of irradiated sample are strongly modified by both helium and hydrogen production rates and Sorgentina has to provide irradiation consistent with fusion machine environments.

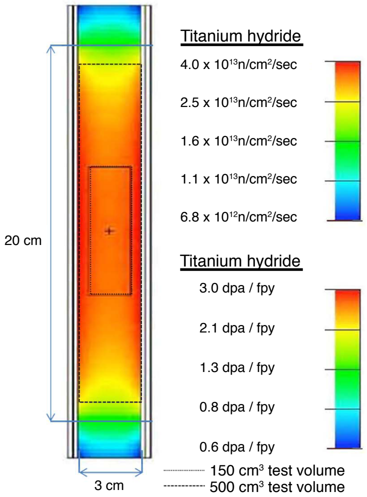

Figure 7: *Neutron flux distribution in test chamber*

Irradiation dpa/fpy values are strictly dependent on the damage energy cross sections contained in the available data libraries. In order to optimize the values of dpa, some parametric calculations have been performed by introducing different external reflectors, with the aim to increase the overall number of neutrons in the irradiation volumes. Materials considered for the reflector calculation were lead, beryllium, graphite, tungsten and depleted uranium. Calculations have been performed considering reflectors with different thickness. Only small differences on the dpa/fpy values as a function of the considered materials were found. The introduction of a reflector determines an increase of the total neutron flux in the irradiation zones that doesn't give an analogous increase in the dpa. This is due to the fact that reflected neutrons have an energy spectrum degrading toward low energy.

Achievable irradiation performances, related dpa rates and available testing volume are satisfactory designed features for Sorgentina, according to experimental capacity envisaged and technological needs for research and development activities.

2.3 Ion Source and accelerator

Sorgentina performances are accomplished through energetic deuterium and tritium ion beams. Deuterium ion beam of 20 A impinges on the target together with 20 A tritium ion beam – yielding a 40 A total current on each plate. Let remember that two rotating plates, facing each other, are forming the twofold rotating target. Power delivered on each target is 8 MW – 16 MW in total. Both deuterium and tritium beam energy is 200 keV in order to induce an optimal fusion reaction rate. High yield monoatomic ion source is required as well. Large-area, multiple-aperture ion sources are currently or have been utilized in main fusion experimental facilities like JET in Europe and JT-60U in Japan. Sorgentina design is meant to utilize powerful positive ion sources developed for JET tokamak. Plasma heating at JET is achieved by means of Neutral Injection Boxes (NIB) in which Positive Ions Neutral Injectors (PINI) are installed to feed plasma through D-T ion neutralized beams. Positive hydrogen ions are produced in a filament driven discharge in PINI ion source and accelerated using a multi-aperture electrostatic accelerator. Acceleration grids are placed within vacuum enclosures; ion source is located on high voltage side of this extraction part. PINI ion source is magnetically confined bucket type with magnetic filter to enhance proton yield. Sorgentina ion source is intended for neutron generation through monoatomic yield enhancement and then PINI technology is expected to be considered in supercusp magnetic field configuration [15]. Radiofrequency driven arc formation is planned to be implemented as well, in order to improve both monoatomic yield of the source and continuous source operation lifetime, reducing maintenance [16]. PINI sources have been successfully operated both with deuterium and tritium ions, provided some dedicated gas loops and insertion flow mechanism modification. Minor design changes concerned use of all-metal seals and provision of pumped interspaces. Conversely, most extensive change regarded installation of a Tritium and Deuterium Gas Introduction System (TDGIS) supplied by a proper active gas handling system that share a secondary containment envelope [1719]. Assuming 200 kV the beam energy, grid gaps are optimized in order to reach current design levels fulfilling best beam perveance. Horizontal and vertical focal lengths may be optimized properly tuning aperture steering off set - in present evaluations they are considered as 10 m and 14 m respectively, as in JET standard configuration. In this regard, JET PINI injectors are currently operated at performances quite close to Sorgentina design parameters. In fact since 2003, octant 4 NBI has been operated with 6 tetrode 80kV/52-58A beam lines, 130 kV/60A and 140 kV/30A triode beam lines. Conversely, NBI at octant 8 has been operated with 8 triode PINIs at 130 kV/60A [1820]. Within the framework of EFDA-JET upgrade programs to increase neutral power injected to plasma, all beam lines are planned to be replaced with triode 125kV/65A PINIs. The reported performances are for the neutral ions injected in the torus. Long pulse beam is a major concern impacting Sorgentina loading factor as well as all neutral heating systems at experimental tokamaks. EFDA reports advances in PINI technology as far as pulse duration is concerned. In fact injection time has been extended from 10 sec to 20 sec and at half power from 20 sec to 40 sec. Studies for next enhancements proved technical feasibility of longer pulses. Critical heat removal reduces global availability impacting several JET PINI beam-line components as neutralizer, ion dumps and beam scrapers. Conversely, in Sorgentina configuration only intermediate grids failure may induce plant performance reduction. Upgrade to continuous pulse is then considered feasible provided a minimum R&D phase. PINI devices are referred to as established technology since installation availability is globally considered very high. PINI operational reports regard also high system reliability that is above 90%, taking advantage of some decades experience. Table 3 reports the main ion source parameters.

Table 3: *Parameters for a single ion source and accelerator*

Parameter	Value
Extraction voltage	200 kV
Extraction current	20 A (per beam)
Current density	0.1 A/cm^2
Current pulse duration	continuous
Ion species	D^+, D_2^+, D_3^+ / T^+, T_2^+, T_3^+
Ion species yield (RF)	~100:0:0
Operational pressure	0.3 Pa
Gas consumption	0.8 Pa m^3 /sec
Focal length in horizontal plane	10 m
Focal length in vertical plane	14 m
Beam divergence	0.5°

For sake of brevity, the reader is referred to a forthcoming paper devoted to the thorough and detailed description of the facility [19].

3. Conclusions

Sorgentina is conceived to contribute in a valuable way to solve the issues of materials development and characterization. 14 MeV neutron irradiation represents a mandatory step in the path towards the understanding of the material damage mechanism in order to validate database derived from different neutron spectra. Also the possibility to make a screening of materials damage up to DEMO relevant dpa in few years from now gives to Sorgentina a great added value.

The design activity made so far demonstrates the soundness of Sorgentina proposal. A considerable neutron generation of about 10^{15} n/sec is expected to be attained and irradiation performances up to about 2 dpa/fpy are possible inside a test volume of about 500 cm^3.

Limited specific R&D activities are deemed necessary to fix and properly validate all design elements. Particularly, continuous RF plasma production has to be demonstrated. All basic technology is anyway well established and proven since it is successfully utilized in other industrial and research frameworks. Rotating target seems adequate to the scope; fatigue lifetime of the substrate will be tested. Operational reliability is then intended to be proved through ad-hoc experimental campaigns on small mock-ups. Tritium reloading of titanium hydride - by means of implantation – does not present in principle any difficulty since it is successfully experimented in sealed-tube neutron sources. Calculations and test performed at JET show that necessary D-T concentration in hydride layer may be achieved, on average, during target thermal cycle.

Preliminary safety analysis has demonstrated the inherent safety of Sorgentina and, therefore, no particular difficulties are expected in finding a suitable site. Moreover, the 14 MeV neutrons allow Sorgentina to provide a source for calibration irradiation and reference material damage tests.

Sorgentina is then proposed as a strategic infrastructure within the European framework to support R&D roadmap towards development of a reliable exploitation of fusion energy.

Indeed NSFS envisaged activity could be devoted to:(a) carry-out basic studies on 14 MeV neutrons induced damage into irradiated materials in turn validating damage calculation codes;(b) verify the influence of nuclear transmutation on the electric characteristics of ceramic insulators, optical fibers and window materials;(c) provide a neutron field were damage cross sections can be tested and/or measured;(d) address basic experimental information for the selection of low activation materials; and(e) furnish reliable data about the radiation hardness of materials to be used for diagnostics. A proper design of the layout and the use of moderators may be useful to obtain intense fluxes of thermal neutrons enabling the test beam lines to be conceived for support in R&D on neutron instrumentation for large scale neutron facilities.

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