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DONES performance, experimental capabilities and perspectives

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Abstract

The key problems in the development of fusion technology as a possible energy source are linked to the understanding of the behavior of materials, components and systems under working conditions of the fusion environment. As a consequence, it has been recognized that a neutron source able to produce neutrons with a fusion-like energy spectrum associated with a gamma radiation field is necessary. In addition, this source must have an irradiation volume large enough to allow the statistically relevant characterization of the macroscopic properties of materials and components, a cumulated damage level above that expected in the reactor operational lifetime, and an intensity strong enough to allow slightly accelerated testing. In this publication we review the main possible ideas for a fusion-like neutron source, present the concept of the neutron source based on the d-Li reaction, and discuss the stepped approach which led to the design of the DEMO-oriented neutron source (DONES). The mission and top-level specifications of DONES are presented and related to the different DEMO requirements. In a dedicated section, the availability of DONES and the compatibility of its parameters for the experiments in which the main tritium breeding concepts—solid and liquid metal based—can be validated are described. Apart from the development of fusion technology, DONES has the potential to become a multidisciplinary neutron science facility. We discuss the concept of a DONES neutron time-of-flight (TOF-DONES) experiment for nuclear physics experiments such as cross section measurements and nuclear technologies studies (fusion and fission), astrophysics and particle physics. Last but not least, some considerations for a preliminary irradiation programme at DONES are presented to demonstrate a possible timeline for the exploitation of the facility to tackle the foremost problems of DEMO and fusion reactor technology.

[a] See the Appendix in Ibarra *et al* 2025 (https://doi.org/10.1088/1741-4326/adb864) for the EUROfusion WPENS Team.
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Keywords: IFMIF-DONES, fusion-like neutron source, neutron irradiation of materials, tritium breeding technologies, experiments with neutrons, fusion technology

1. Introduction

The development of nuclear fusion reactions as a possible energy source is being receiving renewed interest in the last few years due to several breakthrough results obtained recently in a number of facilities (NIF [1], JET [2], JT-60, Tokamak Energy [3]). This interest coincides with a significant burst of private funds investing in a number of different start-up companies focused on the development of fusion as an energy source (more than 7000 M€ in the period 2018–2024 and more than 45 different companies all around the world [4]).

Irrespective of the specific approach used for the realization of the fusion reactions (although this paper will be focused on the D-T reactions fuel cycle considered as the most feasible one in the short term), the feasibility of fusion as an energy source is controlled by three key parameters:

- The tritium self sufficiency, essential to assure the tritium availability required for the plant operation (in reality it is needed more than just self-sufficiency because, in order to produce fuel for the additional future reactors, some Tritium overproduction is needed).
- The availability of the reactor, i.e. the number of yearly hours the machine is running. This parameter is essential to make a low cost of electricity feasible. It is a complex function of the machine design, in which redundancy can have a significant role; of the lifetime of the used components and materials—linked to the key characteristics that define the performance of the related system—because it defines the mean time to failure (MTTF) and consequently the maintenance operations required; of the planned maintenance schedule and especially the remote maintenance strategy.
- The efficiency of the reactor, i.e. the ratio between the net electric power and the generated nuclear power. This parameter is mainly defined by the internal energy consumption of the plant—for heating, pumping and other plant functions—and the thermal efficiency of the heat extraction system that relies mainly on its working temperature.

All these three parameters require to solve significant technology issues. Without the intention to be fully exhaustive, some of the more relevant ones are strongly related to materials behavior. For example: (i) the tritium fuel cycle, in which it is needed to demonstrate tritium breeding and extraction technologies; (ii) heat and particles exhaust from the plasma; (iii) materials—with special focus on structural ones but also many others—able to survive in the harsh environment of a fusion reactor; (iv) maintenance by Remote Handling devices; (v) high temperature operation, and (vi) fusion safety and environmental impact.

A classical way of evaluating the degree of technology development to address these issues is to use the so-called technical readiness analysis (TRA). TRA was started as a tool for communication of technology maturity and for planning in the 1980′s and it is currently being used to analyze and manage the technical risk in research and development projects. This type of evaluation is increasingly being used in fusion energy development [5–9].

In this approach, the different TRA levels are linked to the different phases of the project development. The lower levels are linked to the understanding of the behavior of individual elements of a system or component under relevant working conditions and the higher levels are linked to the understanding of the behavior of the whole system.

The working environment in a fusion reactor—at least in the areas with harsher conditions—involve significant temperature levels, the presence of magnetic field, vacuum and, most importantly, a very high level of radiation involving a mixed radiation field with relatively high-energy neutrons, high fluxes of charged particles and ionizing radiation. All of the components under the radiation field also exhibit very significant gradients [10].

Taking this into account, one of the key problems in the development of fusion technology is that there is no neutron source available with the required characteristics and, as a consequence, TRA evaluation for the different proposals cannot go over a relatively low TRA level unless the radiation aspect is skipped (and, as a consequence, the developed designs are only relevant for conceptual experimental machines but not for the power plant design).

It is also important to note that the understanding of the behavior of individual elements, components and systems in the working environments as required by the TRA evaluation methods should include the different abnormal situations like, for example, the different types of possible accidental events. That means that, for example, in the case of materials, it is needed to know the full behavior of the material at different temperatures even if they are far away from the ‘nominal’ working conditions.

All these considerations clearly demonstrated already many years ago [11] the need of a fusion-like neutron source in which fusion reactor relevant experiments could be developed in order to qualify system´s components of the future fusion reactors, with special focus on materials.

Key requirements for this neutron source are that it must be able to produce fusion-like neutrons with (i) an irradiation volume large enough to allow the statistically relevant characterization of the macroscopic properties of the materials of interest required for the engineering design of the power plant, (ii) a damage level above that expected in the reactor operational lifetime, and (iii) an intensity high enough to allow slightly accelerated testing. By accelerated testing it is meant that the results are obtained in a shorter time than the expected lifetime in a fusion reactor.

These generic requirements are translated to different numbers depending on the fusion reactor concept and design but generally speaking and without going into more details a neutron source is required which is capable to produce around 10^{17} n s^{-1} or more in an irradiation volume of several hundreds of cm^3 with a neutron flux over 10^{14} n (cm^{-2} s^{-1}) and with a high availability in such a way that an irradiation to the end-of-lifetime of the component under analysis can be obtained in 1–3 years of operation.

2. The d-Li concept history

In this section, the d-Li approach to develop the required fusion-like neutron source will be reviewed, but first it is needed to briefly summarize how the different possible alternatives can be compared.

The interaction of radiation with materials can take place essentially by two different mechanism: in one side, elastic interaction of the incident particle with the ions in the material and, in the other, by nuclear reactions.

In the first case, as a consequence of the interaction, some energy is transferred to the lattice ion giving rise to the so-called primary knock-on atom (PKA). This ion moves inside the lattice possibly displacing a lot of other ions and temporarily creating a region in the material that is fully disordered (called 'cascade') that after some time results in the creation of a number of new defects in the material.

The amount of energy transferred to the PKA and, as a consequence, the extent of the cascade and the final number and type of the defects is a strong function of the type and energy of the incident particle as well as of the materials characteristics, being mainly point defects in the case of 'low' PKA energies and more clusters and dislocation loops in case of 'high' PKA energies [12, 13].

In the second case, due to nuclear reactions, ions of new elements appear inside the material, giving rise to new impurities (in the case of fusion materials main ones are He and H but others can also be of importance—see for example the effect of Os and Re produced in the transmutation of W). Activation of the material can also be induced (some of these new impurities can be radioactive isotopes). The amount and the specificity of new ions are a function of the type of incident particle, its energy, the target ion and the nuclear reaction cross section.

Considering all these aspects, the comparison between the different possible irradiation sources should be made based on the parameter 'dpa' (displacement per atom) taking into account the total dose and the dose rate, and by using some parameters that allow to measure the number and type of nuclear reactions as compared with the number of dpa. The most popular ones are Helium or Hydrogen production rate compared to the dpa rate: the so-called H/dpa and He/dpa ratio. It is also relevant to analyze the production of other impurities, to take into account the nuclear reactions effects, plus other obvious comparison criteria such as the available irradiation volume and environmental conditions with special emphasis on the temperature range available [14].

Due to the very different neutron energy spectra, neither fission reactor irradiations nor spallation sources are able to reproduce the H/dpa and He/dpa ratios required to mimic fusion reactors neutron spectra [15, 16].

The different approaches proposed along the time for building a neutron facility able to fulfill the testing requirements discussed above has been reviewed in [15]. The only concept currently developed into an engineering design phase is the so-called IFMIF-DONES (International Fusion Materials Irradiation Facility—DEMO Oriented Neutron Source) project. It is based on the interaction between a light ion (D+) and a light target (Li).

It has been also proposed to use direct ion irradiations in order to mimic neutron irradiation effects in materials. Simultaneous irradiation with different ion beams, i.e. H, He and Fe in the case of steel, with a similar range in the material can give rise to simultaneous dpa, He and H defects production. Some facilities of this type are running [17] or have been proposed [18]. Main drawback of this approach is the very short range of ions in materials and the very high dose rate in the irradiated area (orders of magnitude different to the one in a fusion reactor). Besides this, there are also basic concerns which still require significant studies about the type of damage that is produced in these experiments and their comparison with the neutron irradiation ones.

Alternatively, it is also possible to irradiate with H ions. Direct proton irradiations also produce displacement damage and, above certain energy, will cause nuclear reactions producing He. Fusion-relevant He/dpa ratios can be obtained with proton energies in the range of 20–30 MeV. Again, main drawback of this approach is the limited affected thickness (even if it is higher than in the previous case) of the irradiated material useful for fusion studies [19–21]. In any case, these techniques could be very interesting to progress in the scientific understanding of radiation damage in fusion materials and as a screening tool to select the most promising alternatives of materials prior to their irradiation in the fusion-like neutron source.

The idea of using the d-Li concept as a fusion-like neutron source came up in the early 80s based on the results obtained in the framework of the FMIT project [22] giving rise to a number of different proposals including ESNIT in Japan [23] based on a variable energy (up to 35 MeV) deuteron beam impinging on a flowing lithium target, or other even more ambitious concepts proposing to reach currents up to 1000 mA by a modular approach combining several 250 mA accelerators as well as different angles of incidence [24].

In the 90s, under the auspicious of the IEA and in the framework of a wide international collaboration involving USA, EU, Russia and JA, the so-called International Fusion Materials Irradiation Facility (IFMIF) conceptual design was developed in different phases including a conceptual design activity [25], the key element technology phase [26] and the IFMIF comprehensive design report [27].

Later on, EURATOM, together with several European countries, has been supporting the preparation for the IFMIF-like neutron source; first, in collaboration with Japan, through the IFMIF/EVEDA (Engineering Validation and Engineering Design Activities) project initiated in 2007 and still running today, implemented by the European Joint Undertaking for ITER and the Development of Fusion Energy (F4E) [28]. In the framework of IFMIF/EVEDA, one of the projects included in the EU-Japan Bilateral Agreement to a Broader Approach to Fusion, the IFMIF Engineering Design was advanced and the IFMIF Intermediate Engineering Design Report (IIEDR) issued [29]. For validating the proposed design features, prototyping sub-projects were developed, including design, manufacturing and testing. The most relevant ones are [28]:

(i) the LIPAc accelerator prototype at Rokkasho (Japan), including a low-energy high-current (9 MeV and 125 mA) D beam fully representative of the IFMIF one with the objective of continuous wave operation;
(ii) the experimental lithium test loop (ELTL) at Oarai (Japan), a lithium loop integrating all elements essential to the IFMIF Lithium Target Facility at a 1:3 scale; and,
(iii) Testing in the helium cooling loop (HELOKA-LP) at Karlsruhe Institute of Technology (Germany) of the critical components of the high flux test module (HFTM).

A second step in the preparation of the IFMIF-like neutron source has been made from 2015 onward, through the EUROfusion Consortium of European research units and industry which develops the advanced engineering design of DONES to be built in Granada (Spain) [30, 31]. Since 2018, the preparation of DONES is also carried also out under the ESFRI (European Strategy Forum on Research Infrastructures) framework [32]. Finally, on March 2023 the DONES Programme Steering Committee was created as the governance body of the Programme, the Programme Team has been established and, formally, the Construction and Integrated Commissioning Phase of the DONES Programme has been started.

The high level schedule of the DONES Programme estimates a construction time of 11 years which is supported by the ongoing construction of several auxiliary buildings (to be completed by the end of 2024) and the planned start of the construction of the main DONES building in 2025. Starting from 2029 the installation, testing and commissioning of components and systems will begin. The integrated commissioning phase and power ramp-up is planned to last until 2034 ending with the starting of full power operation phase in 2034. DONES is designed for 30 years lifetime.

This schedule will allow to produce a first set of samples with fusion-like irradiation effects in the materials relevant to fusion technologies before 2040 and a much more complete database along the 2040´s. Even if the schedule for DEMO construction (either the European one or others) is not yet fully fixed and will evolve with time, this time framework is well aligned to the end of the preliminary engineering design phase of DEMO and the related preparation of the licensing application [33].

Based on the IFMIF-EVEDA results previously mentioned, also the advance fusion neutron source (A-FNS) project is being developed in Japan. Its engineering design is not as advanced as the one of IFMIF-DONES and no formal schedule has been announced for its development [34, 35].

3. DONES: a stepped approach to IFMIF

The IFMIF configuration is based on the interaction of deuterons accelerated up to an energy of 40 MeV deuterons, hitting on a liquid lithium target 25 mm thick and moving in front of them at 15 m s^{-1}. In order to produce enough neutrons and to optimize irradiation volume, the deuteron beams are accelerated in two high −125 mA- current accelerators and shaped to have a nominal footprint of 200 mm × 50 mm [29].

With this design it was possible to fulfill technical specifications and requirements defined by the materials users community and considering the needs of a fusion power plant [36]. It is important to note that the fusion power plant needs, linked to the present understanding of the main characteristics of a generic fusion power plant, are quite clearly defined in the long-term. On the other side, and taking into account the evolving design characteristics of the different DEMO concepts in the world as well as a number of uncertainties, the short term (20 years) irradiation needs are not so well defined [37].

The different ways to manage these uncertainties, as well as other type of considerations i.e. risks related to the construction or performance of the facility systems, budgetary constraints, etc. suggest a stepped engineering approach. The first step focused on the short-term DEMO needs and also on a significant cost-containment effort is the DEMO-oriented neutron source (DONES) to be followed by a second step focused on the development of the full performance IFMIF facility. Thus, the DONES approach leads to the generation of the engineering and scientific data base for DEMO [38].

Based on the previous discussion, the implementation of the stepped approach with a first DONES step assumes a simplification of the IFMIF Engineering design, in order to take profit of the technology validated in the IFMIF/EVEDA project and, at the same time, maintain the capability of a future upgrade to the future full performance IFMIF configuration.

All these aspects can be fulfilled if the DONES facility is built using one of the 40 MeV IFMIF accelerators, together with a strong simplification of some of the systems, the most relevant one being the limitation of the maximum irradiation dose to about 50 dpa in around 2–4 years as well as the specific focus on a single irradiation module (the HFTM) designed

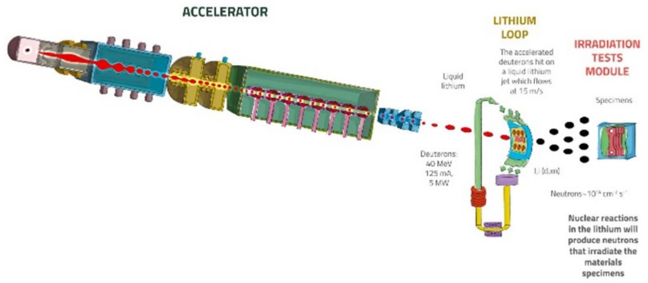

Figure 1. Schematic view of the operational principles of the IFMIF-DONES facility.

to comply with the DEMO low activation structural steels requirements.

Taking these considerations into account, the DONES systems and components have, in some cases, only a quantitative difference with respect to the original IFMIF ones, but in other cases, a redesign work has been required to adapt them to the DONES characteristics [30, 31]. The facility is based on a liquid lithium loop and a 125 mA deuteron accelerator. Deuterons accelerated up to 40 MeV and shaped to have a rectangular footprint in the range from 100×50 mm^2 to 200×50 mm^2, impinge on a 25 mm thick liquid lithium curtain cross-flowing in front of them at a velocity of about 15 m s^{-1}. The D + ^{nat}Li stripping reactions generate at this beam energy a large amount of neutrons that interact with the samples of materials located immediately behind the lithium target, in the test modules. Figure 1 shows a schematic view of the operational principles of the IFMIF-DONES Facility.

The A-FNS project is also based on the same conceptual design of IFMIF and a similar simplification approach has been implemented, although the possible future upgrade to the full IFMIF performance has not been considered as a requirement. Besides this, the A-FNS features a number of design changes, as compared with the IFMIF design, resulting in the experimental area and capabilities being markedly distinct to those of DONES [39].

Figure 2 shows a schematic view of the current configuration of the IFMIF-DONES Plant. Based on this configuration, a fusion-like neutron source capable of producing up to 7×10^{16} n s^{-1} is achieved. Figure 3 displays the neutron spectra in the high flux region of the Test (irradiation) Cell, where fluxes up to 1–5 $\times$ 10^{14} n cm^{-2} s^{-1} can be attained.

The systems dedicated to produce and deliver the high power beam are grouped under the accelerator systems (AS) and they are described in detail in [41]; the systems related to the lithium target management constitute the lithium systems (LSs) [42]; the systems in charge of the irradiation test module(s), the test cell and their support systems constitute the test systems (TS) [43]; the systems overseeing the overall control of the plant are grouped as central instrumentation and control systems (CICS) [44] and finally the site, building and plant systems (SBP) include the buildings and the systems providing power, cooling, ventilation, remote handling of components and services to the other systems [45, 46].

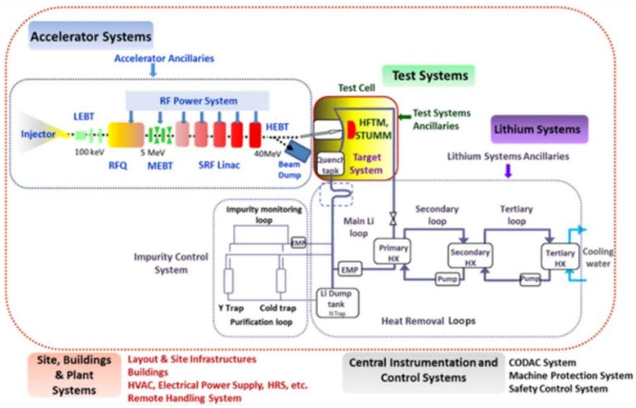

Figure 2. IFMIF-DONES schematic plant configuration (2024 update). Reproduced from [30].

It is important to put emphasis on the previously mentioned flexibility of the design. Different beam size configurations are feasible (in the range from 100×50–200×50 mm^2 as mentioned before) as well as different beam energies (ranging from 25 to 40 MeV). Additionally, both continuous wave and pulsed beam operations are possible.

This flexibility opens the door to tune the irradiation conditions to the requirements of specific experiments. For example, beam size flexibility allows to increase the total dose for a limited number of samples. Figure 4 shows the available irradiation volume vs the minimum irradiation dose in the given volume (dpa/fpy) for different 40 MeV beam configurations.

On the other side, beam energy flexibility allows to modify the He/dpa and the H/dpa ratio at the cost of a lower dpa rate [47, 48]. More details are provided in section 6.

4. DONES missions and top-level specifications

The mission of the DONES Programme was formally approved on March 2023 by the DONES Steering Committee (the committee in charge of the DONES Programme governance) [49]:'*The mission of the DONES Programme is to develop a database of fusion-like neutron irradiation effects in the materials required for the construction of fusion power reactors, and for benchmarking of radiation response of materials. To do so, a neutron source producing high-energy neutrons at sufficient intensity and irradiation volume must be built.*

The main objectives of the DONES Programme are:

(a) *to provide a neutron source producing fusion-like neutrons at sufficient intensity and irradiation volume;*
(b) *to generate materials irradiation test data for the design, licensing, construction and safe operation of a fusion demonstration power reactor;*
(c) *to set up a database for benchmarking of radiation responses of materials hand in hand with computational material science;*

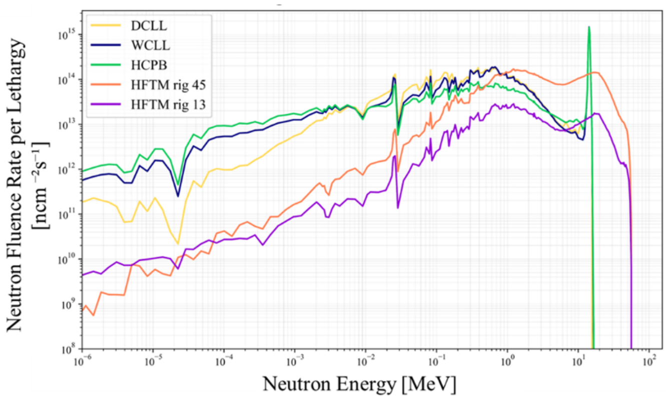

Figure 3. Neutron spectra in the DONES high-flux region compared with the spectra of DEMO first wall under different blanket concept. Reprinted from [40], Copyright (2025), with permission from Elsevier.

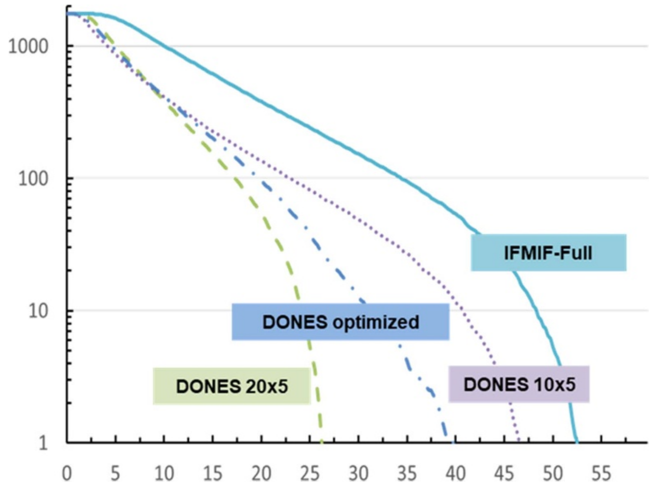

Figure 4. Available irradiation volume (cm^3) vs minimum irradiation dose in the given volume (dpa/fpy) for different beam configurations [47].

(d) *to develop a complementary experiments' work Programme relevant for other scientific and technological areas.*'

Moreover, the material properties dataset generated by DONES will potentially be used also for comparison with larger volumes of irradiations data obtained from other non-fusion installations (like fission reactors, spallation sources, etc.). Given the fact that DONES will be available during ITER operation, the possibility that DONES could assist ITER in some aspects of its nuclear operation phase must also be considered.

According to [49] and in order to achieve its mission and objectives, the IFMIF-DONES Facility has to comply with the following project requirements:

(a) *The neutron spectrum should simulate the neutron spectrum of fusion power plants as faithfully as possible to provide the same response as the one of the material under irradiation in terms of primary recoil spectrum (PKA), important transmutation reactions, and gas production (He, H).*
(b) *The neutron fluence must also be comparable to the ones expected in fusion power plants with accumulation in the high flux region:*
    i. *fluences entailing 20 dpaNRT (displacements per atom calculated by the NRT model) iin less than 2.5 years and applicable to a 0.3 l volume, and*
    ii. *fluences of 50 dpaNRT in less than 3 years applicable to at least a 0.1 l volume.*
(c) *Temperature range: the high flux region needs to be equipped with temperature-controlled test modules that can cover the temperature ranges from at least 250–550 °C.*
(d) *Dpa and temperature gradients in high flux region: over a gauge volume corresponding to standardized miniaturized specimens, the dpa gradient must be less than 15% of the gauge volume and temperature gradient within ±3% with the long-time stability in the same order.*
(e) *Simultaneous irradiation of several irradiation modules must be feasible.*

After irradiation, the DONES Programme will be also in charge of (i) the analysis of the irradiated samples, either on-site or in a network of associated laboratories, and (ii) the production of the related materials database required for the design and licensing of fusion reactors.

Complementary scientific experiments are also considered, beyond materials irradiation. Possible areas of these experiments will be nuclear physics, radioisotope production, medicine or other industrial applications. These experiments will be using the remaining neutron flux behind the HFTM and/or a fraction of the deuteron beam deflected at 40 MeV energy.

The IFMIF-DONES facility shall be designed for a minimum lifetime of 30 years, with at least 20 years of irradiation experiments on a three-shift basis, 24 h/7 d per week. Additionally, an average operational availability goal of 70%

for the whole facility over a calendar year was established as a target.'

The operation of DONES should be defined in such a way that the DEMO needs in fusion materials expressed in previous sections are satisfied. Therefore, DONES operation schedule will be determined taking into account that it is being directly coupled to DEMO schedule.

Aside from the technical objectives, the priority of the DONES design, construction and operation activities is to ensure the safety, security, public health and sanitation, and to protect the environment, by preventing accidents and by limiting their consequences related to radiological and conventional safety. The safety approach of DONES are explained in more detail in [50].

5. Irradiation performances (including flexibility features) for different materials in the HFTM

The neutron and photon flux maps under the nominal condition of a 200 × 50 mm^2 deuteron beam profile are shown in figure 5. In order to develop these calculations, high flux region has been filled with a schematic irradiation module in which samples are distributed in four rows of eight rigs of around 80 × 40 × 10 mm^3 dimensions each one. More details of the HFTM design can be found in [51]. The neutron field is strong in toward the beam downstream, due to the high neutron yield of d-Li at the forward angle dominant neutron energy of 14–16 MeV, with other angles contributed by neutron mainly with 1–2 MeV energy. The gamma flux distribution is more isotropic, as gammas are produced isotropically by deuterons and neutrons in the Li-target and high flux regions. The neutron flux spectra in figure 3 show that the neutrons produced in DONES resemble the 14 MeV fusion neutrons by a broad peak around 14–16 MeV. The impact of changing the nominal beam footprint of 200 × 50 mm^2 to a reduced footprint of 100 × 50 mm^2 does not have a visible effect on the neutron spectra, but more on the local intensities [47].

The damage doses based on NRT model are calculated on the high flux volume in figure 6, assuming the sample material to be EUROFER steel and a specific specimen distribution [40]. The central 4 × 4 rigs provide essential irradiation volume, whereas side-rigs serve as reflectors. Under the nominal beam footprint, the center 4 columns receive high DPA reaching 20 dpa/fpy at the front rigs, which can be further increased to 30–40 dpa/fpy by focusing the beam to the 10 × 5 cm^2 footprint. The reduced beam footprint increases the damage dose rate but limits the relevant irradiation volume. As shown in figure 6, DONES maintains the flexibility of beam footprint dimension, to balance the user's need between the required volume and urgency of data on a particular irradiation campaign.

Reviewing the top-level DONES requirement of 50 NRT-dpa in <3 years, 0.1 l volume can be reach by focusing the beam on 10 × 5 cm^2, which produces damage rates of more than 23 dpa/fpy, thus equivalent to 50 NRT-dpa in <3 calendar years taking into account the target availability of 70%. Similarly, 12–13 dpa/fpy is available for 0.3 l of volume, thus 20 NRT dpa in <2.5 years can be provided.

The gradient of two beam footprints on both the X-axis (beam direction) and Y-axis (transversal direction) are shown in figure 7. Considering the case with nominal footprint (200 × 50 mm^2), for the X-axis, the gradient at the central two columns is in the range of 10%–20%/cm while for the Y-axis, <10%/cm is expected with the value increased to 10%–20%/cm at the next two columns. The higher gradient on the X-axis is due to distance increases from the neutron source location, and the gradient on the Y-axis is lower as a result of using a rectangular footprint of 200 × 50 mm^2 compared

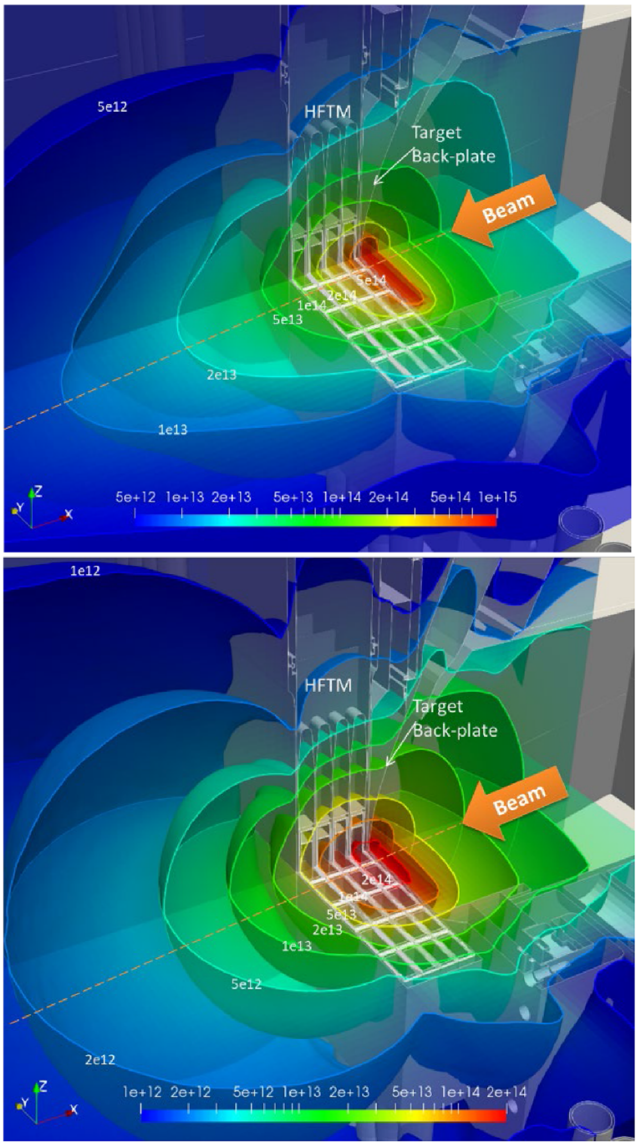

Figure 5. (*a*) Neutron flux (n cm^{-2} s^{-1}) and (*b*) photon flux (γ cm^{-2} s^{-1}) maps at the target and the high flux regions. Reprinted from [52], Copyright (2019), with permission from Elsevier.

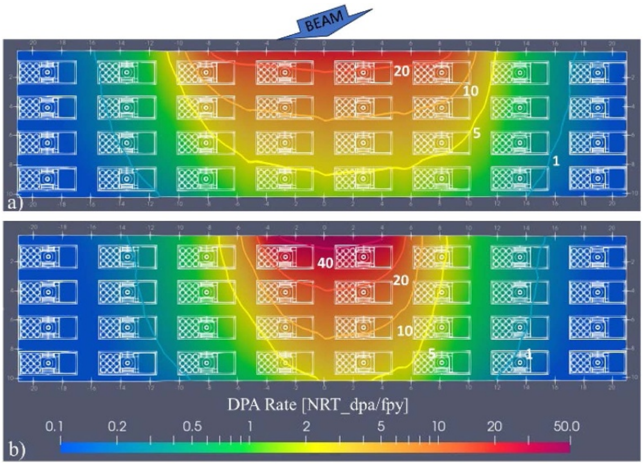

Figure 6. DPA rate in NRT model (NRT_dpa/fpy) for the (*a*) nominal beam footprint of 200 × 50 mm^2 and (*b*) reduced beam footprint of 100 × 50 mm^2. Reprinted from [40], Copyright (2025), with permission from Elsevier.

to the 100 × 50 mm^2 one. High gradient is expected on the edge of the footprint, as well as for the reduced beam footprint size. The samples are loaded with the smallest dimension (e.g. thickness) on the X-axis and the longest dimension on the Y-axis (e.g. length). Therefore, considering the top-level requirement of 15% dpa gradient over the gauge volume and the typical thickness of 2–3 mm and length of 5–7 mm for the specimen gauge dimensions, samples positioning can be optimize to maximize the available irradiation volume.

As already mentioned, the He production is another key parameter of material irradiation and testing, as it has a direct impact on the diffusion of damage effects on materials and a synergistic effect with the primary displacement damage rate. He production in reduced activation ferritic martensitic (RAFM) steel are contributed by threshold reactions of neutrons of several MeV. As shown in figure 8, the nominal beam footprint produces an He/dpa ratio of 12–15 for most of the volume, which is similar to the full IFMIF with the beam current of 250 mA. Instead, the reduced footprint of 100 × 50 mm^2 shifts the peak to a higher value with a flatter distribution. The estimated value for DEMO is between 11–14 He-appm/dpa, which is overlapped with the DONES irradiation conditions.

IFMIF-DONES maintains the flexibility of adjusting the deuteron beam energy up to 40 MeV. As d-Li neutron yield decreases sharply with reducing the beam energy, decreasing the beam energy will reduce significantly the damage dose rate (see figure 9). However, one benefit of reducing the beam energy is that, the He/dpa ratio can be tuned to the specific design features of the DEMO reactor, i.e. at 35 MeV, the He/dpa ratio resembles the condition of the DEMO water cool lithium lead (WCLL) concept (see figure 9). So, for example, it has been shown that the He/dpa ratio can be tuned from around 8–14 appm/dpa if the beam energy changes from 25 to 40 MeV (at the same time the dpa dose rate goes from 8 to 27 dpa/fpy) in the case of EUROFER [47]. Similar results can be obtained for W (He/dpa ratio goes from 4 to 10 appm/dpa if beam energy changes from 25 to 40 MeV) or CuCrZr (He/dpa ratio goes from 4 to 7 appm/dpa for the same beam energy change) [48]. Hence, a dedicated material testing environment can be provided bearing in mind the shortcomings of a lower damage rate.

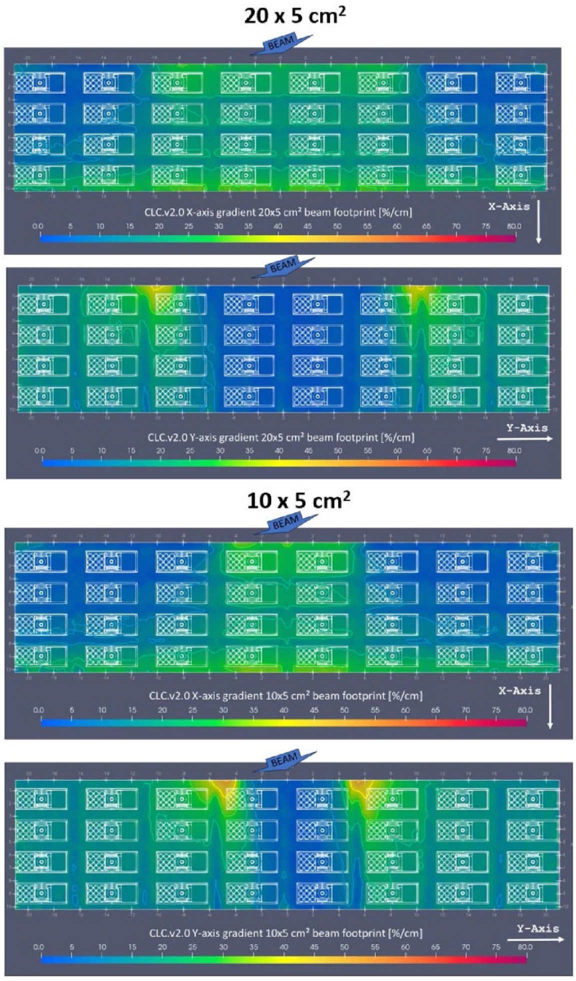

Figure 7. DPA gradient for nominal beam along X-axis (*a*) and Y-axis (*b*). Similarly for reduced beam along X-axis (*c*) and Y-axis (*d*).

Besides structural materials such as RAFM steel, DONES can be used for irradiating functional materials such as tungsten and Cu-alloy which are used for first-wall and divertor heat sinks [53]. The DPA (dpa/fpy) maps of irradiated tungsten and CuCrZr alloy in the HFTM are shown in figure 10.

The DPA on tungsten are in principle factor of 2 lower than that of RAFM steel, directly influenced by the displacement energy, being 40 eV for iron and 70 eV for tungsten [54]. In the case of copper (the heaviest element in the CuCrZr alloy) it has a displacement energy of 33 eV, somewhat lower than the displacement energy of iron, so the DPA data are higher for the alloy than for EUROFER97.

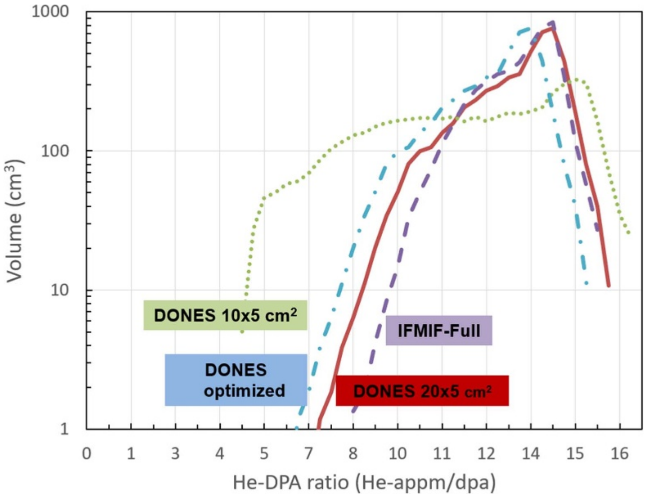

Figure 8. Irradiation volume of different He-DPA ratios under IFMIF (with 2×125 mA beam) and DONES under several beam footprint (200×50 mm^2, 100×50 mm^2 and optimized 140×50 mm^2 beam).

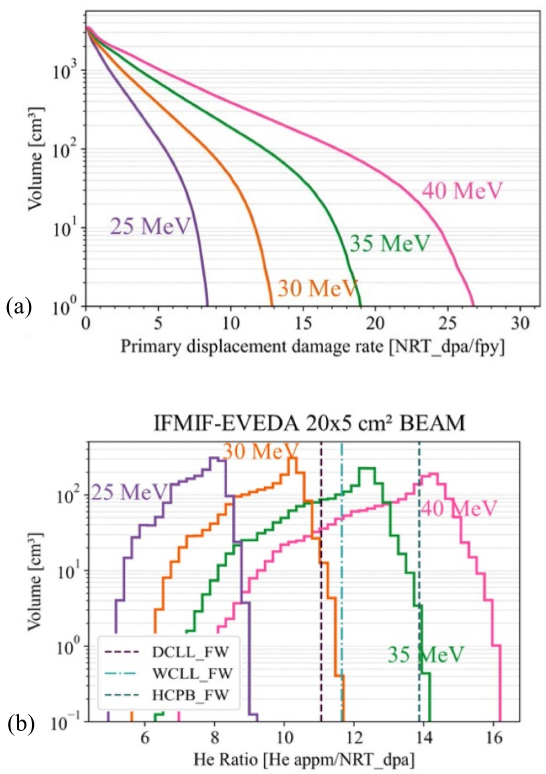

Figure 9. (a) Available irradiation volume (cm^3) vs DPA (dpa/fpy) under different beam energy, (b) He-DPA ratio in the central rigs under different beam energy compared with the DEMO conditions of helium cooled (HCPB), water cooled (WCLL) and dual cooled (DCLL) blanket concept. Reprinted from [40], Copyright (2025), with permission from Elsevier.

The potential drawback of irradiating tungsten in DONES is that the gas production in the center rigs is a factor of 4–5 higher than in the DEMO environment [48], thus making

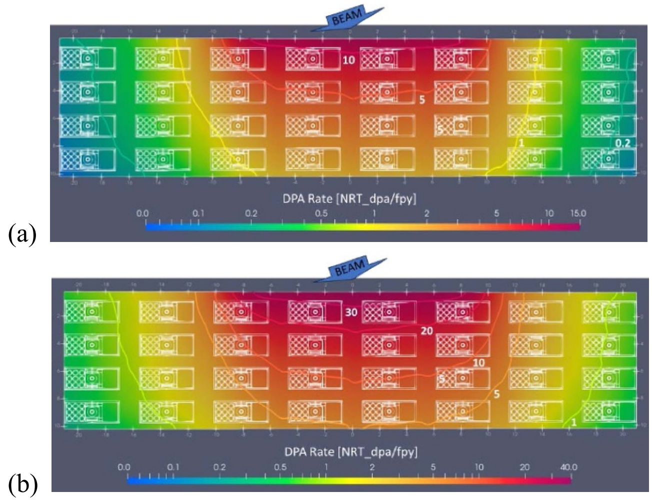

Figure 10. DPA (NRT_dpa/fpy) of irradiated tungsten (*a*) and CuCrZr alloy (*b*) in the high flux region. Reproduced from [48].

it less useful to irradiate tungsten in the central high flux regions. In addition, the transmutation of tungsten to rhenium and osmium is observed in fusion reactors after long-term irradiation, and the transmutation rate could be slightly different in DONES due to the high energy tails above the 14 MeV neutron energy. A dedicated irradiation volume with a tailored neutron spectrum can be designed for tungsten and Cu-alloy, based upon the specific needs.

6. Irradiation performances for tritium technologies

Beyond the performances offered by IFMIF-DONES for critical material testing for DEMO and the future fusion power plants, the facility includes further capabilities for experimental campaigns related to other remaining fusion challenges, one of the most important being the tritium production techniques better known as the breeding blanket (BB) technologies.

The challenging character of tritium production experiments is linked to the very specific and highly complex working environment of the breeding zone (BZ) components which includes multiple fields of neutrons, particles, photons, heat fluxes, etc. with high absolute intensities and steep gradients and transients. In fact, the nuclear heating field and its very sharp gradients drive most of the blanket phenomena [10].

One of the top level goals for the DEMO reactor is the demonstration of tritium self-sufficiency and closed-cycle tritium fuel cycle. To ensure this goal, tritium breeding with a high enough Tritium Breeding Ratio (TBR) is integrated as a functional requirement for the BB, along with the feasible tritium extraction from the breeding components to the fuel cycle.

There are four main BB concepts considered over the time in Europe: WCLL, helium-cooled lead-lithium (HCLL) and dual-coolant lead-lithium (DCLL), all of them based on liquid metal technologies; and Helium-Cooled Pebble Bed (HCPB), which is based on solid breeding components [55].

For all the different breeding concepts mentioned before, some of the following key technical issues needing further technical readiness level (TRL) increase are listed next [10]:

- Ensure tritium self-sufficiency, including adequate control on transport and permeation. In this regard, residence time of tritium as a function of temperature is of particular interest.
- In the case of liquid breeders,
  - o chemical reactivity of liquid breeders with the interfacing materials,
  - o strong interaction between magnetic fields and liquid metals resulting in undesired MHD interactions,
  - o corrosion, transport of activated corrosion products and their deposition in the cold section of the liquid breeder loop.
- In the case of the solid breeder,
  - o thermal-physical properties of pebble beds, e.g. thermal conductivity,
  - o tritium release, inventory and control, e.g. characterization at very low purge gas velocities,
  - o material interaction and thermomechanics, e.g. differential stresses affecting the breeder performance due to strong temperature gradients,
  - o effect of irradiation environment on the pebble bed performance, e.g. irradiation-induced sintering or cracking of pebbles, or porosity distribution changes induced by the working conditions.
  - o Interaction of the pebble beds with the interfacing materials, e.g. dimensional stability with eventually swelling neighbor materials, or variable contact area of pebble with interfacing components along time.

In order to progress in the development of the BB design several validation phases should be developed [55]:

- a phase aimed to investigate single effects at laboratory level (corresponding to level 3 of the TRL analysis) and multiple effects on small scale. A phase in which multiple effects at medium to large scale should be addressed (corresponding to the level 5–6 of the TRL analysis), and
- a phase in which significant prototypes will be tested in real environment and that will accompany the engineering design and the DEMO construction.

Taking into account that IFMIF-DONES will be the only facility able to provide a fusion-like radiation environment in a relatively short time, it is obvious that IFMIF-DONES can provide significant contributions at least to the first two phases mentioned before. According to the needs described so far, the scope of the experiments that should be performed varies from single-effect tests to integrated experiments. For each BB concept and, taking into account the IFMIF-DONES constraints, the scope of the experiments will be different.

On one side, single experiments aim to explore a single-effect phenomenon or the integration of a few phenomenon by means of a dedicated setup which is not significant in terms of the architectural design as compared to DEMO. In this regard, the most promising experimental setups proposed for DONES are focused on the tritium breeding ratio, purge and transport both for solid and liquid breeders:

- Tritium release test module (TRTM) [see [51] for additional details], which is based on the HCPB concept and is focused on the solid breeding components -lithium ortosilicate and metatitanate- performance within a wide range of temperature, amongst other important variables.
- Liquid breeder validation module (LBVM) [see [51] for additional details], which is based on the liquid metal concepts and is focused on the PbLi performance for tritium breeding, purge and transport within a wide temperature range, amongst other important variables.

On the other side, IFMIF-DONES will allow for more advanced validation activities within the space available for experiments inside the test cell (TC), linked to the previously mentioned second phase, focusing on experiments where most of the critical environmental conditions present in DEMO will be closely reproduced. These experiments can include the same architecture as well as most or all the critical components at a scaled or even real-size configuration as proposed for the DEMO BB concepts in question. Indeed, the complexity of such modules is much higher as compared to the single-effect modules, its level of significance for DEMO being as well much higher.

These capabilities are linked with the strong neutron flux and gamma gradient along the X-axis in IFMIF-DONES, that can be made similar to the ones it is possible to find in some regions of the different DEMO BB.

On the other side, gradients in the Y-axis or in the Z-axis are even stronger, making the section perpendicular to the beam direction available for this type of experiments relatively limited (around a few hundred squared cm). Fortunately, this is enough to accommodate typical unit cells of most of the presently proposed BB concepts.

Based on these ideas, a number of experiments have been proposed for functional testing of HCPB BB concept [56] in which an integrated experiment with a dedicated small-portioned, full-scale multi-component irradiation set-up upon an extent limited to 7-breeding, hexagonally-disposed pin assemblies. Similar approaches are being developed for WCLL [57] or DCLL concepts. Concerning the WCLL, its experimental needs would require the IFMIF-DONES facility to provide fast flux neutron fields in the range of 10^{14}–10^{15} n cm^{-2} s^{-1} and 0.2–9 dpa per year.

These capabilities could also be useful for the ITER test blanket modules (TBM) Programme [58] because they allow to check the nuclear performance of an equivalent unit cell component. It is important to note that the expected neutron dose at the ITER TBM's is relatively low [59] and, as a consequence, these results can be obtained in DONES in the very early operation phase.

Last but not least, the IFMIF-DONES baseline design includes a significant space (600 m^2) adjacent to the TC for the accommodation of ancillary systems supporting the operation of the tritium-related irradiation modules. It is therefore concluded, that IFMIF-DONES is very well positioned to provide a highly relevant environment for DEMO tritium technologies validation.

7. Irradiation performances for nuclear physics

The outstanding characteristics of the DONES accelerator open the path to world leading nuclear physics experiments and applications at DONES. Besides the test cell where the material specimens will be irradiated in the HFTM, two additional experimental areas will be available for setting up and running a large variety of experiments:

The neutrons traversing the HFTM can be collimated and used behind the test cell, for producing continuous neutron beam which, at the entrance of the collimated neutron beam experimental area will reach an intensity of 1.5 × 10^{11} n cm^{-2} s^{-1} with a beam footprint of 8 cm diameter [60]. Such a neutron beam can be used for a broad range of experiments and applications with fast neutrons: fast neutron imaging, non-destructive inspection analysis via prompt and delayed gamma activation, isotope production, irradiation of electronics, calibration of sensors, detectors and dosimeters, irradiation of cell cultures for radiobiology studies, or even complex nuclear structure experiments with the combined use of magnetic and γ-ray spectrometers. The beam energy of the beam could also be degraded with cryogenic moderators for producing thermal neutrons for material science studies or coupled to a slowing down spectrometer or a graphite pile. Most of these applications are already in a preliminary design phase [61].

On the other side, the extraction of ∼0.1% of the 40-MeV deuteron beam before reaching the liquid lithium target is currently being investigated. Pulses of deuterons would be extracted by means of a kicker, bunched into 5.3 ns pulses separated by at least 5.7 μs (i.e., 175 kHz or lower frequencies) and directed one floor below. In this area, experiments with pulsed deuterons or pulsed neutron beams produced by deuteron-induced reactions on a secondary target could be carried out.

Neutron time-of-flight facilities are the most flexible installations for performing energy dependent neutron induced reaction cross section and secondary particle emission measurements. The pulsed neutron beams travel along a known flight path and interact with the samples at a given time of flight (TOF) which allows to compute the incident neutron velocity.

A preliminary study shows that the extremely high intensity of the DONES deuteron accelerator could be used for driving one of the most intense neutron TOF facilities worldwide: TOF-DONES. The comparison of the performance of two TOF-DONES beam lines with world leading neutron TOF facilities is shown in figure 11. The results for TOF-DONES correspond to a graphite production target, neutrons travelling along an unmoderated 20 m flight path at 0° (175 kHz repetition rate) and along a 10 m flight path at 20° (88 kHz), after crossing a W degrader, a H_2O moderator and boron filter (for the removal of thermal and epithermal neutrons). As can be seen, both beam lines provide neutron fluxes in the 10 keV to 30 MeV range comparable to or larger than the currently most intense neutron TOF facilities: n_TOF Experimental Area 2 (EAR2) at CERN [62, 63] and neutrons for science (NFS) [64] at SPIRAL-2. Also visible are GELINA (at JRC-Geel) and the 185 m flight path at n_TOF (EAR1), various orders of magnitude below TOF-DONES in the MeV range. One should notice as well that the repetition rates of the particle beams driving the neutron sources vary from 0.8 Hz (n_TOF) to 888 kHz (NFS), thus leading to distinct duty cycles expressed in neutrons/(cm^2·pulse). The lower panel in figure 11 shows the energy resolution at the two flight paths, with and without the combination of degrader, moderator and boron filter. It can be seen that at 20 m the resolution will be better than 3% for both moderated and unmoderated neutron spectra.

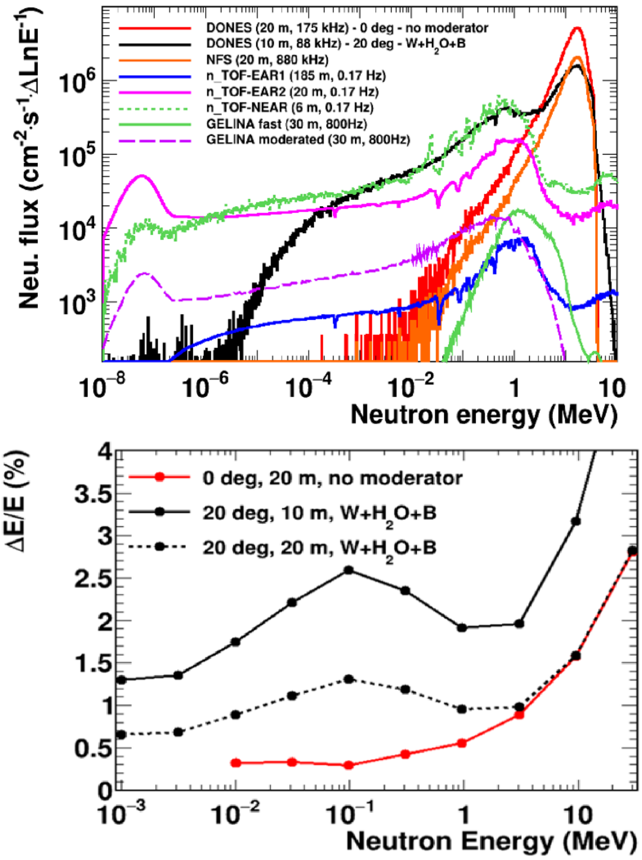

Figure 11. Top: neutron flux as a function of energy at TOF-DONES compared to other TOF facilities. Bottom: expected energy resolution at two TOF-DONES flight paths.

TOF-DONES could cover a large variety of cross section measurements and nuclear structure experiments required for nuclear technologies (fusion and fission), nuclear astrophysics, particle and astro-particle physics: (n,el), (n,γ), (n,n'γ), (n,xn), (n,f), (n,p), (n,d), (n,t), (n,α), (n, charged particles), etc. Details on the nuclear data priorities for nuclear technologies can be found in [65–67] and for nuclear astrophysics in [68–70].

In addition, the pulsed neutron beams could be used for inducing fission and performing nuclear structure studies on the resulting fission fragments [71, 72], by coupling advanced γ-ray detection setups to a high resolution magnetic spectrometer.

The pulsed deuteron beam could also be used for producing valuable (d,x) reaction data for a broad range of applications, including fusion. In particular, ^{6,7}Li(d,xn), ^{12,13}C(d,xn), ^{10}B(d,xn) data for improving the modeling of the neutron sources (including the one of DONES), radiation damage studies or for possible fusion reactor plasma diagnostics. Deuterons could also serve for the production of isotopes via (d,x) reactions and drive nuclear structure experiments based on deuteron induced fission reactions (d,f).

8. Some ideas for a preliminary irradiation programme

This section will focus only on the irradiation program associated with the previously described high flux neutron region that will be reserved for high-priority fusion-related experiments. It is also understood that the initial key experiments related to the fusion program should be focused on the validation of materials properties, although in the long-term experiments related to the validation of some other fusion-related key technologies could be also of interest (for example, validation experiments related to different blanket concepts seem feasible).

8.1. Objectives and key parameters of an irradiation program

Fusion-like irradiation effects must be characterized for materials to be used as structural materials of the reactor (presently the only feasible candidate material for this application is a ferritic-martensitic steels, EUROFER type), materials for heat sink (presently the only feasible candidate material for this application are Cu alloys), materials for first wall (presently the only feasible candidate material for this application are W-based alloys) and different types of functional materials (Li-based ceramics, beryllides, maybe some other ones for diagnostics functional characterization).

In the case of ferritic-martensitic steels, properties to be characterized are:

o with high priority: strength, ductility, fracture toughness
o with lower priority: low cycle fatigue, creep, fatigue-creep interaction, fatigue crack growth and other basic properties required to understand materials behavior.

In order to properly define in a qualitative way the irradiation program it is important to take into account the following aspects:

(i) some key properties of ferritic-martensitic steels show a strong temperature dependence and, as a consequence, several data points are needed at temperatures relatively close;
(ii) evaluation of material properties requires a statistical analysis and the typically assumed Gaussian distribution may not be applicable in the case of irradiation effects (probably a Weibull distribution is more appropriate). The number of samples to fully characterize irradiation effects on some materials is also a function of the assumed statistical distribution;
(iii) as it has been shown previously, DONES irradiation capabilities during operation phase will be in the range of 12–25 dpa/fpy in around 300 cm^3 dpa/fpy. Thus, a typical experiment will last between 1 to 4 years of continuous irradiation depending on the dpa target level, the required volume of irradiated material and the obtained availability (design target is 70% but it is reasonable it will take some time to reach this level);
(iv) irradiation dpa level will not be uniform in all the irradiation volume. For example: based on data included in figure 4, if we target to an irradiation of at least 20 dpa in a volume of around 500 cm^3, it will require 2 full power years of irradiation but it will include 12 cm^3 irradiated over to 80 dpa, or 100 cm^3 irradiated up to 50 dpa. Each irradiation experiment will produce a number of samples irradiated at different dpa levels with higher statistical relevance at 'low' dpa's and lower statistical relevance at 'high' dpa's;

After irradiation, the Irradiation Module must be dismantled, samples extracted, distributed to different labs (on-site and off-site) and characterized. It is estimated this procedure will take around two years (based on the experience obtained in several other fission-reactor irradiations).

Taking into account the time required for the preparation of each irradiation campaign, the decision on the possible experiments to be included and their contents must be taken a few years before the start of the irradiation (steps to be covered are: decision on the scientific contents of the experiments, design -if needed- or adaptation of the irradiation module, preparation of the related safety file, manufacturing and assembly).

8.2. Preliminary draft proposal for an irradiation program

Based on all these considerations, and taking into account only technical aspects, in the following is included a proposal for the irradiation program of IFMIF-DONES for about 10 first years of operation. It is to be noted that this is an early proposal subject to agreement between the scientific community and the DONES Program parties:

- **IR1.** EOL for ITER materials.

The 1st irradiation campaign should focus on EOL ITER materials and possibly the TBM-related mock-ups with the objective to test all the disassembly and characterization procedures.

(1–3 months of irradiation + 2 years PIE)

- **IR2.** Key properties of DEMO structural materials.

The 2nd irradiation campaign should focus on the rough evaluation of key properties of DEMO structural materials up to Early DEMO EOL (a volume of several hundred cm^3 with at least 20 dpa) for engineering design validation:

o Materials to be included: 1 or 2 reference materials -i.e. EUROFER and F82H-. If only one material is irradiated the number of samples will be significant and a relatively large irradiation data set at different dpa levels will be available. If two materials are included, the number of samples for each material will be lower but, on the other side, the comparison of the behaviour of the two materials—if similar- will increase confidence in the obtained results.
o Temperatures: 275, 300, 325, 350 °C.
o Sample types: as many samples as possible for evaluation of the properties relevant at 'low' temperatures and a reduced number for other temperatures.

(2 years irradiation + 2 years PIE)

For the 3rd irradiation campaign and as a function of the fusion program priorities, the following alternatives can be planned:

- **IR3a.** More detailed properties of DEMO structural materials.

The 3rd irradiation campaign could focus on more detailed evaluation of key properties of DEMO structural materials up to Early DEMO EOL (a volume of several hundred cm^3 with at least 20 dpa) for further engineering design validation and increasing the covered temperature range:

o Materials to be included: 1 or 2 reference materials
o Temperatures: 250, 350, 450, 550, 650 °C
o Sample types: wide type of samples for evaluation of a relevant package of different properties. Samples must be produced from a different manufacturing batch than the previous one in order to check reproducibility. Irradiation should include also 'technology' samples (i.e. with welds, etc.) of the ones to used in the future DEMO components.

(2 years irradiation + 2 years PIE)

- **IR3b.** Functional testing of DEMO blanket design.

The 3rd irradiation campaign could focus on a functional testing of the reference BB concept selected for DEMO locating the related irradiation module as close as possible to the neutron source (i.e. excluding the HFTM) that will, probably, allow it to reach neutrons fluxes and gradients very similar to the one in DEMO reactor.

(2 years irradiation + 2 years PIE)

- **IR4.** Rough evaluation of key properties of DEMO advance structural materials.

This irradiation campaign should include ODS steels or some other advanced steels and heat-sink materials up to Early DEMO EOL dpa level for engineering design validation. Due to the wide range of materials and properties considered the number of data points for each property will be limited. Key objective of this irradiation will be to identify 'hot' points that will require further exploration in other irradiations later on.

o Materials to be included: Heat sink reference materials + Advance steel
o Temperatures: TBD
o Sample types: samples for evaluation of key properties of the considered materials. Irradiation should include also 'technology' samples (welds, etc.).

(2 years irradiation + 2 years PIE)

- **IR5.** The 5th irradiation campaign focused on evaluation of key properties, including technology samples, of DEMO structural materials up to EOL of the DEMO second phase (50 dpa) for engineering design validation

o Materials to be included: 1 or 2 reference materials
o Temperatures: 300, 350, 400, 500, 550, 600 °C (to be confirmed depending of results obtained previously)
o Sample types: wide number of samples for evaluation of a relevant package of different properties. Irradiation should include a relevant fraction of 'technology' samples (welds, etc.).

(4 years irradiation + 2 years PIE).

9. Summary

In this paper it has been shown that DONES is the only feasible fusion-like neutron source that is ready to implement and could be available in the next 10 years, with intensity high enough to address the key fusion reactor challenges. High-level requirements of the facility are defined in order to be able to fulfill this role.

The facility has been designed focusing mainly on the problems related to the fusion materials qualification (steels, tungsten, Cu alloys,...) and, after detailed neutronic characterization, it has been shown that dpa ranges over 20 dpa can be achieved in a volume of around 300 cm^3 after 2.5 calendar years of operation.

It is also important to emphasize that the facility design allows some degrees of flexibility either by changing the deuteron beam energy, the beam footprint size or the type of operation (pulsed or continuous), in such a way that the experiments to be developed can be tuned to specific requirements.

Besides fusion materials qualification, the unique neutron environment (very similar to the one in a fusion reactor but limited to a relatively small volume and without magnetic field) allows the possibility of many different types of experiments either focused on functional materials properties (i.e. physical or chemical properties) but also on the validation of other fusion technologies.

More specifically, a significant effort has been reported in the area of tritium technologies. Very different types of experiments related to tritium technologies, that could be developed in DONES, have been proposed, going from individual phenomena identification and characterization to functional small scale tests of complete BB concepts. DONES can become in the future a key tool for the initial validation of some the presently considered BB concepts.

Taking into account the uniqueness of the facility, it has been shown that DONES can be also relevant in other scientific and technological areas with special emphasis on the nuclear physics sector where the possibility to build an n_TOF facility competitive with the best presently available ones has been identified.

Finally, a first very preliminary proposal for an Irradiation Programme is made in which the present understanding of the main priorities of the fusion programme is taken into account.

Taking all this into account it can be said that the successful construction and operation of DONES is on the critical path for the development of fusion as an energy source.

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