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**White Book
on the Complementary Scientific Programme
at IFMIF-DONES**

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Introduction

IFMIF-DONES - a powerful neutron irradiation facility for studies and qualification of materials is planned as part of the European roadmap to fusion-generated electricity. Its main goal will be to study properties of materials under severe irradiation in a neutron field similar to the one in a fusion reactor first wall. It is a key facility to prepare for the construction of the DEMO Power Plant envisaged to follow ITER.

At present, as the construction of ITER is well under way, it has been considered to accelerate the design and construction of DEMO, which should start during the 2030 decade. Thus, the decision to start the building of IFMIF-DONES is imminent. IFMIF-DONES must start operation in mid 2020's in order to provide results on material properties from the first batches of irradiated samples in time to be used for the design of DEMO. Assuming a minimum period of 5 years for the construction process the design and validation activities for IFMIF-DONES must be completed by 2020. Other preparatory activities such as site preparation and licensing must also start before 2020.

As part of those activities EUROfusion, the European Consortium for the Development of Fusion Energy, which manages and funds European fusion research activities on behalf of EURATOM, has started the Early Neutron Source work package (WPENS) with the main goal to prepare by 2018 the Engineering Design of IFMIF-DONES. At the same time, Fusion for Energy, the European Union's Joint Undertaking for the Development of Fusion Energy, which will be responsible for the construction of IFMIF-DONES, has asked member states to express interest in the siting of the facility.

Poland is one of the countries, which have declared interest to host IFMIF-DONES. The ELAMAT (European Laboratory for Material Science) consortium was founded in 2014 by the Rzeszów University of Technology and the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) as a bottom-up initiative of the science community to prepare the proposal to site IFMIF in the Podkarpackie region of Poland [1]. Its members are the leading universities, research institutes, high technology companies and business environment institutions active in Poland. Consortium participants seek to combine economic and scientific potential of business and research and development institutions for building in Poland an international research infrastructure for advanced materials research.

One of the decisions of the Consortium was to establish the ELAMAT Scientific Council with the aim to study possible extension of the objectives of the IFMIF-DONES facility beyond its standard programme of material studies for fusion reactors [2]. The Scientific Council whose members represent the fusion, nuclear physics, medical physics and technology research communities organised two open meetings to discuss the opportunities offered by the new facility. At the workshop "Town Meeting on IFMIF/ELAMAT Complementary Scientific Programme", which took place in April 2016 [3], it was decided to prepare a collection of science cases for the future facility in the form of a White Book. At the same time, this activity was met with interest and received support from the Early Neutron Source work package (WPENS) of EUROfusion.

The possible science cases, discussed in this White Book, require certain modifications of the IFMIF-DONES facility layout (see Fig.1). The considerations and conclusions presented in the White

Book are independent of the site of the future facility. The intention of the authors of this report was to demonstrate that many foremost topics and questions of today's science in several active fields of research could be addressed and investigated at the IFMIF-DONES without compromising its main role of a material irradiation facility for the fusion programme. It is hoped that such demonstration will raise interest and bring support for the construction of IFMIF-DONES and that elements of the complementary science programme will be incorporated into the original programme of the facility.

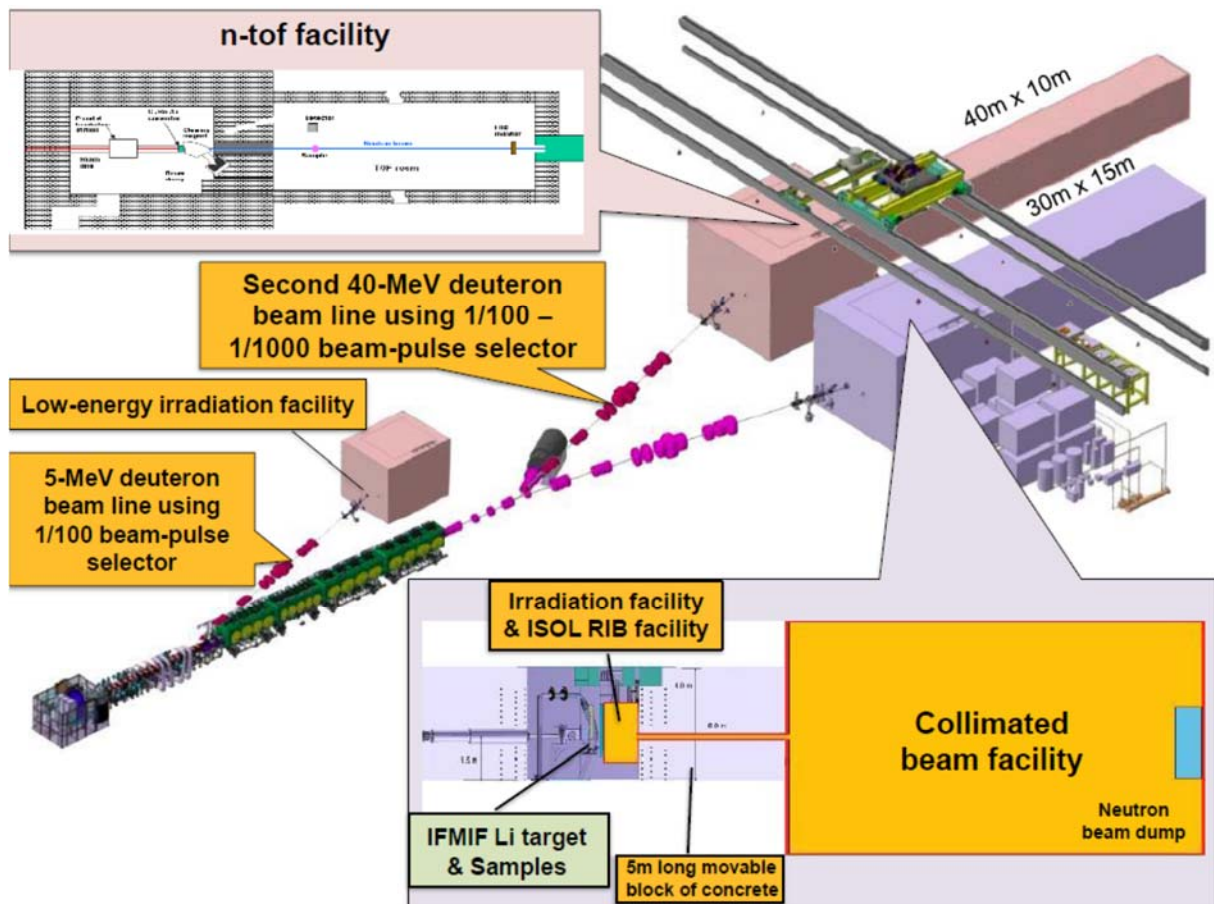


Figure 1. A schematic drawing of the IFMIF-DONES facility showing the baseline IFMIF accelerator with the irradiation cell (in blue and yellow) and additional parts of the facility dedicated to the research topics described in the White Book (in yellow and mauve). The proposed installations consist of an irradiation facility for materials, backed by a setup for producing radioactive ion beams with an additional setup for a collimated beam facility, for a neutron time-of-flight facility, and a low-energy irradiation facility. The last two installations require two additional beam lines (in red) and beam-pulse selectors to deviate a 0.1-1% of the primary deuteron beam to the dedicated setups.

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Chapter 1: Description of IFMIF-DONES neutron facility

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Introduction

The irradiation environment in future Fusion Power Plants (and obviously also in DEMO independently of its specific design) is characterised by the presence of an intense 14 MeV neutron radiation field in the first wall region. Understanding the degradation of the materials and components properties throughout the reactor operational life is a key issue to allow the design, the licensing and the subsequent reliable operation of the facility.

The presence of radiation-induced structural damage in the reactor materials together with He and H gases produced during irradiation can significantly affect their properties and it is also well known, from a qualitative point of view, that there are very significant synergetic effects. Unfortunately, the depth of understanding these effects, needed for the engineering design of DEMO as well as for a fusion Plant, is incomplete, especially for structural materials, mainly due to the lack of a consolidated database that should be generated by irradiation tests under conditions [1] that are as close as possible to a typical fusion environment.

These experimental data can only be produced in an irradiation facility, and there is consensus that the available (fission, spallation and ion beam) irradiation sources do not have the proper characteristics to fulfil the observed needs [2]. Although all the different types of irradiation experiments are being used, and must continue to be used in the future in order to improve the basic understanding of radiation effects in materials, the need for a dedicated fusion neutron facility has been widely identified by the fusion materials community more than 30 years ago and confirmed all along.

The main requirement for this neutron source is to produce a fusion-characteristic neutron spectrum with enough intensity to allow accelerated testing, up to a level above the expected operational lifetime, with an irradiation volume large enough to allow the characterisation of the macroscopic properties of the materials of interest required for the engineering design of DEMO and the Power Plant.

The need for a fusion-relevant neutron source was clear from the start of the nuclear fusion developments. Intense discussions over the years, driven by the material scientist community, concluded in consensus that an accelerator-based source utilising deuteron-lithium nuclear reaction with a broad energy spectrum peaked at around 14 MeV would be the best choice for a materials-irradiation facility [3]. The International Fusion Materials-Irradiation Facility (IFMIF) was proposed to be such a dedicated facility. IFMIF can achieve all these objectives using two 40-MeV deuteron linear accelerators, each delivering a 125-mA beam current with 100% duty cycle. Both beams strike a liquid-lithium target, thus providing an intense neutron flux density of about 10^{18} to 10^{19} n/m²s with a broad energy peak near 14 MeV.

IFMIF design and engineering validation has been developed since 1990. In the period from 1990 to 2006, IFMIF was a joint effort of the European Union (EU), Japan, the Russian Federation (RF), and the United States of America (USA) within the framework of the Fusion Materials Implementing Agreement of the International Energy Agency (IEA) [4, 5, 6, 7, 8, 9]. Since 2006, it was agreed to address the so-called Engineering Validation and Engineering Design (IFMIF/EVEDA) phase as one of the main three projects of the Bilateral Agreement between EU and Japan for the Broader Approach (BA) to Fusion.

The roadmaps towards fusion power developed in different countries commonly foresee the construction of two fusion machines before the industrial prototypes: ITER and DEMO. It has also been recognised that materials development and validation under irradiation are not only of highest importance for the economic success but are on the critical path for early use of fusion power. Consequently, IFMIF, or an equivalent neutron source, is also considered an indispensable element of international roadmaps to fusion power. In the last few years, new Fusion Roadmaps have been developed in a number of countries [10, 11, 12, 13]. A general tendency is apparent to speed up the design and construction phase of DEMO (in the case of EU it is foreseen to start its construction during the 2030 decade) and, at the same time, to reduce the neutron dose requirements on the materials. For example, in the case of the EU Roadmap an initial DEMO phase is foreseen with a maximum dose around 20 dpa, for components integration testing, and a second DEMO phase with a maximum dose around 50 dpa [14]. On the other hand, the specifications and requirements on materials irradiation data for the Power Plant are maintained as before [15]. This new approach reduces the requirements for the early phase of the neutron source, maintaining the long-term ones, and opens the possibility of a staged approach to IFMIF in which its construction can be developed in two phases:

- A first one focused on DEMO needs, that is called IFMIF-DONES (DEMO Oriented Neutron Source)
- A second one oriented to the Power-Plant needs

This staged approach allows a wider distribution of the required investments over time as well as some relaxed specifications for the neutron-source design during the first phase. The IFMIF-DONES project will be able to provide in a short time (around 2 years) a set of around 200 SSTT specimens (following the small-specimen-testing-techniques standards) irradiated up to 30 dpa with a neutron spectrum similar to the one in the fusion reactors. Furthermore, an additional set of around 1000 samples irradiated up to 40-50 dpa will be produced in a longer timeframe - and much higher number at lower irradiation doses - that will provide the relevant set of materials-properties data required for DEMO design.

Because of this set of requirements, the DONES neutron source shows unique characteristics that could also be of interest in other scientific and technological areas. Therefore, the objective of this White Book is to identify these other possible areas of application for the DONES neutron source and to evaluate qualitatively the feasibility of their implementation in the DONES facility.

The document has been written based on the inputs obtained from a Workshop on the IFMIF-DONES Complementary Scientific Programme, held in Rzeszów (Poland) in April 2016 in which contributors from all around EU elaborated a number of different scientific proposals.

Plant Configuration

The Plant will produce a 125-mA deuteron beam, accelerated up to 40 MeV and shaped to have a nominal cross section of 100 mm × 50 mm or 200 mm × 50 mm, that will impinge on a liquid-lithium curtain 25 mm thick cross-flowing at about 15 m/s in front of it. The stripping reactions generate a large amount of neutrons that interact with the materials samples located immediately behind the lithium target.

The different systems in IFMIF-DONES can be grouped in four different groups: i) the systems devoted to produce the high-power beam named Accelerator Systems (AS), ii) the systems related to the lithium-target management named Lithium Systems (LS), iii) the systems in charge of the irradiation modules handling and management named Test Systems (TS) and iv) the systems named Conventional Systems (CS) that provide power, cooling, ventilation, rooms and services to the Plant. In Figure 1, a schematic view of the Plant Configuration is displayed.

The IFMIF-DONES Accelerator Systems main function is to deliver a properly sized and stabilised deuteron beam to the lithium target and mainly consists of a Continuous-Wave (CW) 175 MHz linear accelerator, providing a 125-mA, 40-MeV deuteron beam. The accelerator conceptual design assumes utilisation of superconducting RF Linacs. Most of the DONES accelerator involved technologies are being manufactured and tested during the IFMIF/EVEDA phase at LIPAc. This technological approach is cautiously aggressive with respect to the previous capabilities of RF Linac technology.

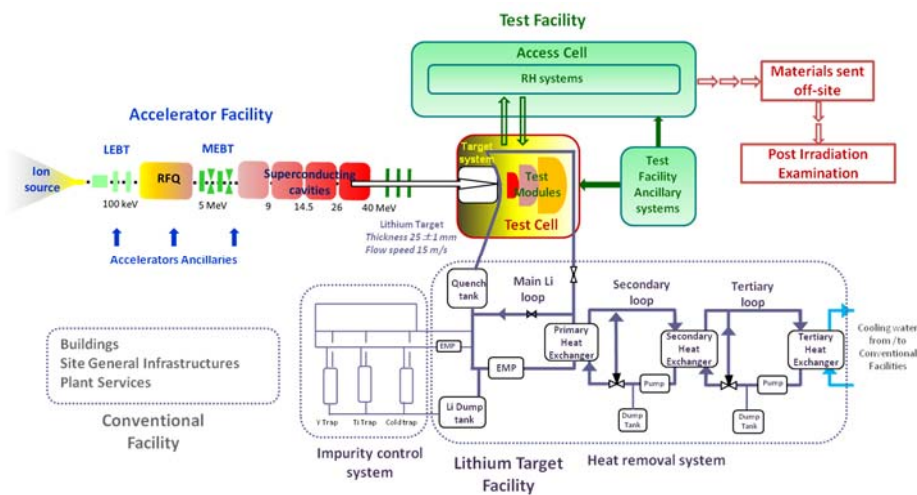


Figure 1. DONES Schematic Plant configuration

The IFMIF-DONES accelerator is a sequence of acceleration and beam-transport stages. A CW 140-mA deuteron beam is produced and extracted from an Electron Cyclotron Resonance ion source at 100 keV. A Low-Energy Beam Transport (LEBT) section guides the deuteron beam from the source to a RFQ accelerator. The RFQ bunches the beam and accelerates 125 mA to 5 MeV. The RFQ output beam is injected through a Medium-Energy Beam Transport (MEBT) with two rebuncher cavities to be conditioned, and then transferred to a superconducting RF Linac where it is accelerated to a final energy of 40 MeV. All the accelerating RF cavities are powered by a radio-frequency system based

upon the use of 175 MHz high-power tetrode-based amplifiers with a CW output power level of up to 200 kW. A total of 50 such amplifiers are needed. Additionally, the MEBT is powered by two smaller solid-state amplifiers rated at 16 kW CW. An innovative alternative based on solid-state power amplifiers is being developed and could be of interest for the whole RF system, in order to increase overall availability. Figure 2 shows a preliminary accelerator arrangement.

The magnetic optics elements of the beam line condition, expand, and bend the beam to project a fully overlapped, uniform distribution of rectangular shape onto the free surface of the lithium target. This produces a forward-peaked source of fusion-like neutrons, which stream through the target into the Test Cell, where high-fluence testing is accomplished. Virtually all of the beam energy is deposited in the target, creating an extremely high CW power density in the flowing lithium. The accelerator and target share a common vacuum boundary. Back-streaming radiation from the target and test cell is minimised by use of radiation shielding and by bending the beam in the HEBT. Therefore, back-streaming radiation does not have a direct path to the active elements of the HEBT (with the unavoidable exception of the final HEBT elements, which must have a direct line of sight to the target). Additionally, the beam profile must be tailored in the vertical direction so that the lithium flow is not shocked by a sudden step increase in the deposited power density. The beam profile must also be tailored in the horizontal direction to eliminate heating of adjacent structure due to the beam fringe.

On the other hand, the angle at which the beam intercepts the target represents a compromise between two important considerations: (1) maximising the high-flux volume in the test cell (favours smaller angle), and (2) minimising machine activation due to neutron back-streaming into the active beam line components (favours larger angle). The 9° beam-bending half-angle is acceptable for the current target/test cell configuration and for the reduction of neutron back-streaming.

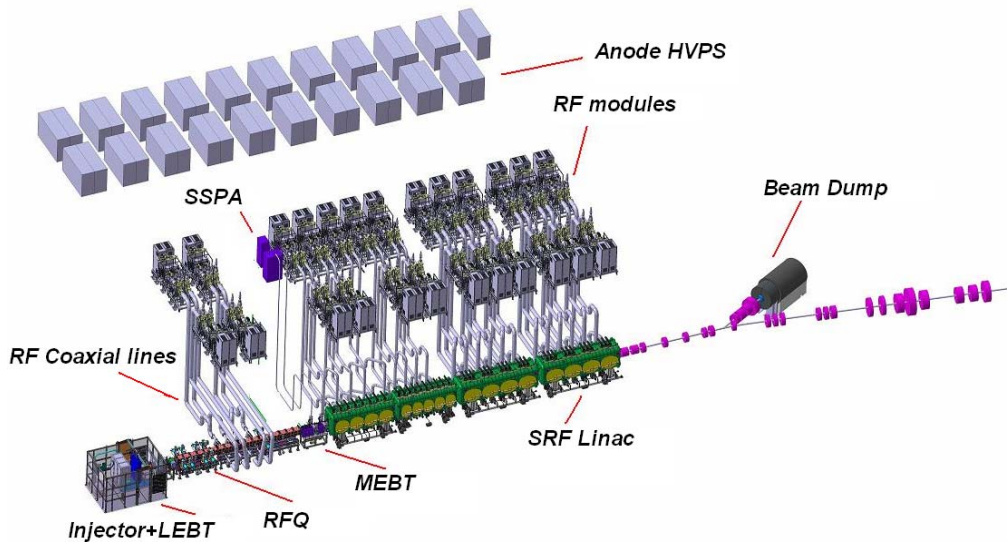


Figure 2. Accelerator Facility general arrangement

The main function of the Lithium Systems is to provide a neutron field for the irradiation of Test Modules placed in the Test Cell. The characteristics of this field have been defined as flux, spectrum, damage rate and damage distribution in the High-Flux Test Module. The neutron flux is generated by the injection of one *d* beam as previously described. The main component is the Target Assembly,

which includes the concave-shaped open channel (Back plate) exposed to the accelerator vacuum, where the beams impinge on the liquid metal. One d beam with a power of up to 5 MW (40 MeV, 125 mA) is injected on a common beam footprint with a height of 50 mm and a width of 200 mm on a free surface of liquid-Li flow. To avoid boiling and significant vaporisation of the liquid Li even under the high power density deposited and a vacuum condition for the accelerator, a concept of liquid-Li target flowing at high speed along a concave channel increasing the boiling point due to a centrifugal force has been employed. Heat is removed by a Li loop, re-circulating the lithium between the Target Assembly and a heat exchanger; a secondary and a tertiary oil loop transfers the heat to the Plant general cooling water system. Figure 3 shows the CAD model of the LS for IFMIF-DONES, based on the IFMIF Lithium Target Facility (IIED Report).

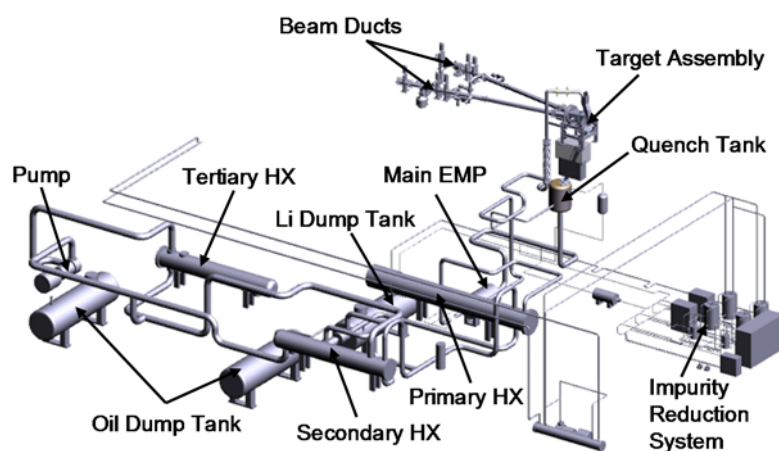


Figure 3. Isometric view of the CAD model of the Lithium Systems

The Test Systems (TS) include the systems required to accommodate a High-Flux Test Module (HFTM) under controlled environment and conditions for irradiation as well as all the systems required for handling the HFTM and transporting irradiated HFTM for further external processing and post irradiation experiments.

The Test Systems consist mainly of two systems: the first one is the Test Cell (TC) where the nuclear reactions take place, and the second one is the hot cell allowing the replacement of the Target Assembly (TA) and the HFTM, transferring irradiated TA and the HFTM to outside of IFMIF-DONES. The basic layout of the Test Systems is shown in Figure 4. This is a cross-section view from the beam direction. In this configuration, the TC is the centre of the Test Systems, the Access Cell (AC) is arranged above the TC, and the Test Systems Ancillaries System is arranged at the same level of the TC and at the right lateral side of the TC (oriented towards the beam direction). The HFTM, not shown in Figure 4, is installed inside the TC. The Remote Handling subsystems for the TC operation are installed in the AC.

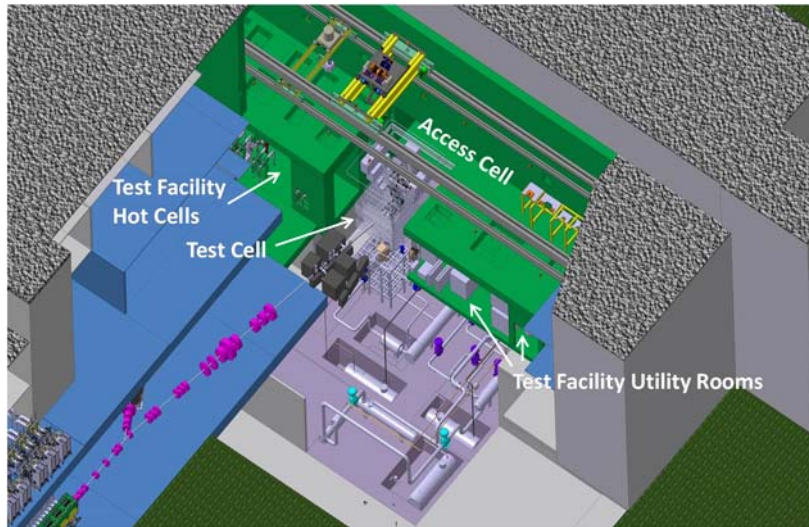


Figure 4. Arrangement of the Test Systems (in green colour) in the building

The TC is the central location where the deuteron beam from the accelerators meets the lithium at the place of the TA and the HFTM. A cross-section view of the TC is shown in Figure 5. The TC is a blind hot cell with an opening at the top. The surrounding biological shielding walls around the TC and the bottom of the TC are part of the IFMIF-DONES building. The internal surfaces of surrounding shielding walls are covered with a liner, which provides together with the upper cover plate a vacuum-tight enclosure. Inert atmosphere is maintained inside during beam operation. Furthermore, the liner and cover constitute a “second barrier” for containing the radioactive inventories on the one hand in the lithium loop and on the other hand in the cavity with the HFTM. Stainless steel liner and biological shielding made of concrete are cooled with chilled water. The TC structure serves as checkpoint for the orientation or fixation of the TC internals in relation to the beam axis.

The shielding plugs and the surrounding shielding walls complete the biological shielding of the TC. The top closure of the TC is split into two top shielding plugs and piping and cabling plugs (PCPs). Two top shielding plugs have to be removed every time for access to the TC. The lower shielding plug is actively cooled by helium whereas the upper one is un-cooled. By this split, the maximum weight load for the crane is limited. The plug shape corresponding to the TC opening results in the requirement that in case of a load drop no plug may fall into the TC cavity. The PCPs accommodate all of the pipe and cable penetrations that connect inside and outside the TC. They are kept in position for standard module or target replacement. Only failure of one/more PCPs will lead to a replacement. The shape of the PCP's reduces radiation streaming. The biological shielding, in particular the upper and lower shielding plugs, ensures that the dose rate in the Access Cell remains at a lower level, even at beam full power, so that access for the operators is possible.

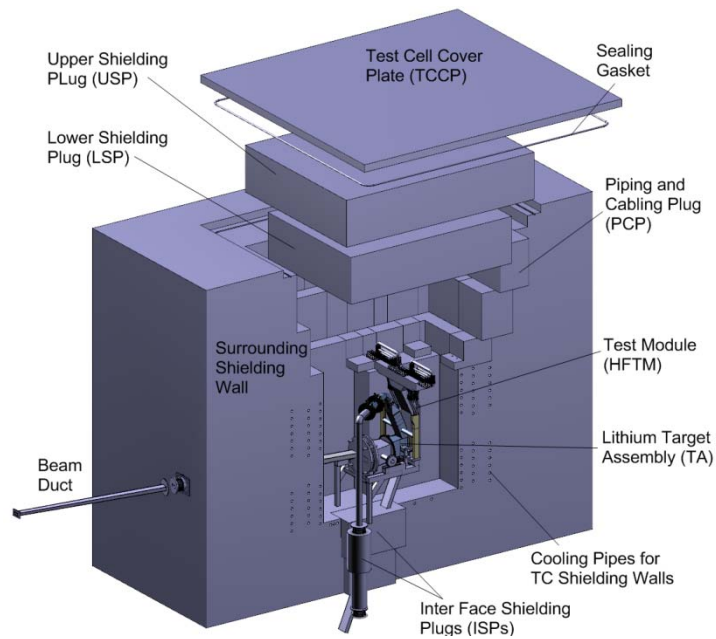


Figure 5. Test Cell with internals and penetrations for beam tubes as well as Li loop inlet and outlet pipes

In the TC layout, six PCPs are designed to provide shielding and pipe/cable accommodations. Two of the PCPs are used for the pipes and cables from the HFTM while another one is for the TA and other in-cell components. The rest three PCP positions are occupied by dummy PCPs (without cabling and piping), which are replaced by cabled PCPs in case of need; e.g., the upgrade to IFMIF or other applications. All of the reserved PCPs have no connection to the components inside the TC but are equipped with embedded active cooling systems using low-pressure helium (at 0.3 MPa) as coolant.

Inside the TC, the HFTM is supported by two vertical walls, which are parts of the biological shielding. By separating the HFTM from the top shielding materials, the HFTM can be operated independently and open-cell testing during beam-off is possible.

The final tightening of the TC is achieved by a TC covering plate. It closes the TC over the shielding plugs, as shown in Figure 5. The cover sheet, and in particular the sealing against the liner, is outside of the high-dose radiation field.

Liner and cover are designed for an inner sub-pressure of at minimum 1 hPa. The free volume of the TC cavity and the volume of all gas/helium loops connected to the TC in total are related in so far as no over pressure of the TC may occur in case of a leak. Consequently, an over-pressure design is excluded. The internal dimensions of the TC are 4 m in length, 4 m in height, and 2.8 m in width. A detailed description of the IFMIF TC (which is the basis for the design of the IFMIF-DONES TC) can be found in [16].

A high-flux test module (HFTM) is foreseen to be installed behind the BP in the TC for irradiation. A start-up monitoring module (STUMM), which is only used during the commissioning phase of IFMIF-DONES, is also included in TC. In the IFMIF-DONES design, the HFTM is the only Test Modules (TM), which is directly behind the TA. The HFTM is a module that allows irradiation of different materials. It is conceived for the irradiation of steels in the temperature range of 250-550°C, with an option to provide irradiation up to 650°C for ODS steels.

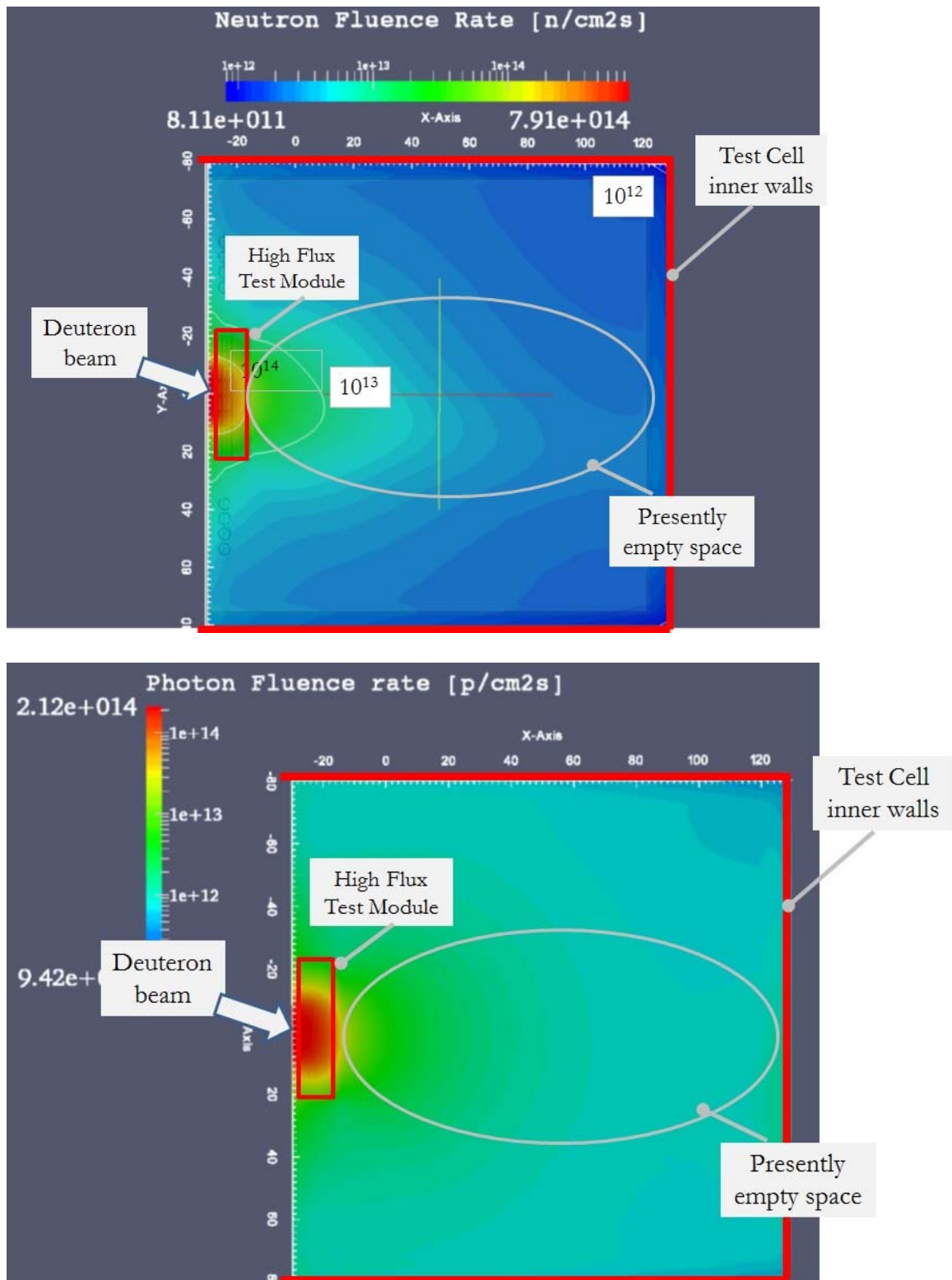


Figure 6. Maps of the neutron (upper figure), and photon flux densities (lower figure), in the Test Cell, calculated across the horizontal mid-plane of the deuteron-beam incidence.

Finally, Figure 6 shows the neutron (a) and gamma (b) flux maps expected in the TC during nominal operation. A region with a neutron dose rate up to $5 \cdot 10^{14}$ n/s/cm², in which the HFTM will be located, can be observed. In addition, other regions can be observed with dose rates in the range from

10^{14} n/s/cm² to 10^{12} n/s/cm² that can be used for other irradiation modules or different types of experiments not presently included in the IFMIF-DONES baseline design. Relevant information for the discussion on the complementary scientific programme can also be found in Figure 7, in which the neutron and gamma spectra inside the TC are shown.

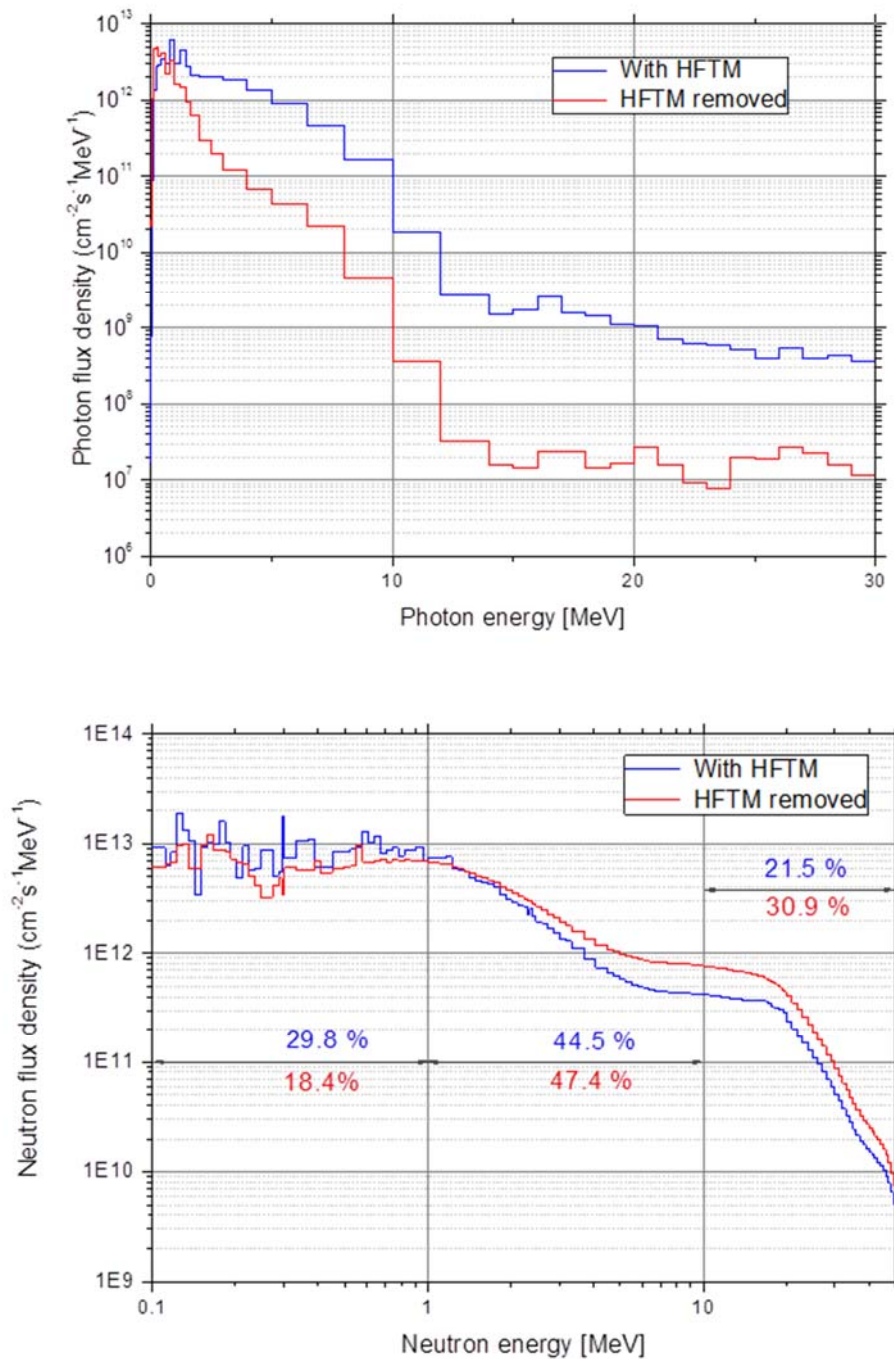


Figure 7. Neutron (upper figure) and photon (lower figure) flux spectra, calculated in the region of the HFTM in the Test Cell.

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Chapter 2: Applications of medical interest

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Summary of the chapter

The possibility of producing neutron beams by conversion of the deuteron beam of the IFMIF-DONES accelerator, in order to substitute nuclear reactors with accelerator-based neutron sources for the production of medical isotopes, is investigated. The possibility to skim off a few percent of the deuteron beam for Boron Neutron-Capture Therapy clinical investigations is also discussed.

Introduction

Nuclear medicine describes the use of pharmaceuticals, which consist of radioactive materials either in elemental form or coupled to a molecular vector.

Nowadays, over 30 million procedures per year based on radioisotope compounds are used in nuclear medicine worldwide. Most of them are produced in research reactors like the Maria reactor in Poland. The neutron-flux characteristics of this reactor are suitable for the production of a wide range of radioisotopes except those requiring fast-neutron fluxes. Examples of radioisotope production, like ^{47}Sc , requiring fast-neutron fluxes are examined in the attached contributions. ^{47}Sc , with a half-life of 3.35 days and decaying by the emission of β and γ rays, is considered as an excellent candidate for targeted radionuclide therapy. Similarly, the production of medically useful α -emitters radionuclides could benefit from the high-energy and high-intensity neutron flux. For example, the $^{226}\text{Ra}(n,2n)^{225}\text{Ra} \rightarrow ^{225}\text{Ac}$ reaction is unique in the production of ^{225}Ac free from contamination by ^{227}Ac . The fast-neutron flux of the future IFMIF-DONES facility, 1000 times more intense than the flux of any existing facility, will be used to study the production of these radioisotopes and in general the production of radioisotopes requiring fast-neutron fluxes.

One of the most used radioisotopes worldwide is the $^{99\text{m}}\text{Tc}$ isomer. This radionuclide is produced by irradiation of highly enriched uranium targets in nuclear research reactors to obtain molybdenum-99 (^{99}Mo), a precursor of $^{99\text{m}}\text{Tc}$ by radioactive decay. However, the worldwide supply of ^{99}Mo is mainly ensured (more than 90%) by only five ageing nuclear research reactors. An alternative solution for obtaining $^{99\text{m}}\text{Tc}$ is via the reaction $^{100}\text{Mo}(n,2n)^{99}\text{Mo}$. The 14-MeV neutron energy flux of the IFMIF-DONES facility of $\sim 10^{14} \text{ cm}^{-2}\cdot\text{s}^{-1}$ is perfectly suited to the production of ^{99}Mo . Within this framework, the production of ^{99}Mo will be investigated at the IFMIF-DONES facility.

BNCT (Boron Neutron-Capture Therapy) is a binary tumour therapy. A ^{10}B carrier, with high tumour-cell specificity, is injected into the patient either locally or through the circulatory system. The tumour region is then irradiated with thermal or epithermal neutrons inducing an exothermic nuclear reaction in the ^{10}B nuclei. The short-range nuclear reaction fragments destroy the tumour cells sparing

the surrounding healthy tissues. However, for a reasonably short treatment the neutron fluence rate in the tumour volume has to be rather high ($\approx 10^9 \text{ cm}^{-2}\cdot\text{s}^{-1}$). So far, only research nuclear reactors have been able to provide such neutron rates with satisfactory clinical results.

The possibility of substituting nuclear reactors with accelerators will allow the installation of BNCT centres inside hospitals. Indeed, 10% of the IFMIF-DONES deuteron beam could be skimmed off after the MEBT and transported into the BNCT hall, where the beryllium target would convert the deuterons into $\sim 6 \times 10^{12}$ neutrons/(MeV·sr). After appropriate energy moderation, the neutron field would be properly shaped, ready for in-air advanced BNCT studies. Eventually, larger clinical studies will allow better exploitation of this therapy, which is able successfully to treat deadly infiltrating tumours.

Physics topics

- Radiopharmaceuticals for therapy: Investigation of the possibility of substituting nuclear reactors with accelerator-based neutron sources for production of medical isotopes; examples, which may be investigated, are ^{47}Sc via the (n,p) reaction ($^{47}\text{Ti}(n,p)^{47}\text{Sc}$), technetium-99m ($^{99\text{m}}\text{Tc}$) via the $(n,2n)$ reaction $^{100}\text{Mo}(n,2n)^{99}\text{Mo}$ and ^{225}Ac via the $^{226}\text{Ra}(n,2n)^{225}\text{Ra} \rightarrow ^{225}\text{Ac}$ reaction. (Contributions A, B and C).
- Accelerator-based boron-neutron-capture therapy: Investigation of the possibility of substituting nuclear reactors with particle accelerators for installing BNCT centres inside hospitals. (Contribution D).

List of contributions

- Perspectives on the production of ^{99}Mo in the framework of IFMIF-DONES facility**
Marchix, CEA, Centre de Saclay, DRF/IRFU/SPhN, 91191 Gif-sur-Yvette, France
- Radionuclides and radiopharmaceuticals for therapy**
R. Mikołajczak, Radioisotope Centre POLATOM, National Centre for Nuclear Research, Otwock, Poland
- The use of neutron source from IFMIF: Production of ^{225}Ac for targeted alpha therapy**
M. Łyczko, Institute of Nuclear Chemistry and Technology, Warsaw, Poland
- Accelerator-based boron-neutron-capture therapy**
P. Colautti; LNL INFN viale dell'Università 2, I-35020 Legnaro, Italy

Facilities (by order of complexity in implementation)

- **Irradiation facility** (just behind IFMIF samples)
- **Extraction of a 5-MeV d beam** (10% of deuteron beam pulses kicked-out to a dedicated converter room)

Summary table

Topic	Facility	Instrumentation	Comments
Radiopharmaceuticals for therapy	The samples have to be located just behind the irradiation module	Space requirements behind the IFMIF samples Positioning and transfer system (based on the pneumatic transfer system called "Rabbit"). Gamma-spectrometry system with HPGe detectors, shielding containers for transporting radioactive materials, and radiochemistry processing hot-cell	Flux of fast neutrons > 1000 times more than any existing facility and > 10 times at ToF facility. For the production of (^{99m} Tc) no other facility can provide neutron beam of ($10^{14} \text{ cm}^{-2}\cdot\text{s}^{-1}$) in the 14-MeV neutron energy range.
Accelerator-based boron-neutron-capture therapy	Specific beam line	Extraction of a 5-MeV beam. ⁹ Be thick target. Experimental hall containing a neutron moderator and shaper and a remote system for the Be target maintenance	No other facility can produce a 2-MeV neutron beam of: ($\sim 6 \times 10^{13} \text{ (MeV}\cdot\text{sr}\cdot 125 \text{ mA)}^{-1}$)

Perspectives on the production of ^{99}Mo in the framework of IFMIF-DONES facility

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Scientific case

Radioactive isotopes have an important role in nuclear medicine for imaging, therapy, biokinetics and pharmaceutical research and development (R&D). The most important one is the technetium-99m ($^{99\text{m}}\text{Tc}$), which is used worldwide more than 80% in diagnostics. However, technetium has no stable isotope and $^{99\text{m}}\text{Tc}$ has to be artificially produced; for few decades, the usual route has been the irradiation of highly-enriched uranium targets (HEU) in nuclear research reactors to obtain molybdenum-99 (^{99}Mo), a precursor of $^{99\text{m}}\text{Tc}$ by radioactive decay. The worldwide supply of ^{99}Mo is mainly ensured (more than 90%) by only five nuclear research reactors that are more than forty years old. In 2009, extended shutdowns of two of them, Chalk River in Canada and Petten in the Netherlands [1,2], led to a shortage of isotopes, which raises an important concern regarding the production of $^{99\text{m}}\text{Tc}$ and its supply.

Following this medical isotopes crisis, international agencies (IAEA, OECD) mandated groups of experts to find solutions for improving the reliability of $^{99}\text{Mo}/^{99\text{m}}\text{Tc}$ supply. One of the alternative solutions proposed in refs. [3,4] is the use of accelerator-based neutron source using a deuteron beam to produce fast neutrons that induce the production of ^{99}Mo via the reaction $^{100}\text{Mo}(n,2n)^{99}\text{Mo}$. The IFMIF-DONES facility fits perfectly with the neutron-source characteristics required since it leads to a most probable neutron energy of 14 MeV coming from the primary interaction of 40-MeV deuterons with a liquid-lithium target. Within this framework, the production of ^{99}Mo has been assessed at very close proximity to the lithium target in order to take advantage of the hard-radiation environment in parallel with the primary goal (material irradiation for fusion).

The mean neutron flux passing through the molybdenum sample has been assessed at 10 cm behind the lithium target (just behind the irradiation module) and has been estimated to be about $10^{14} \text{ cm}^{-2} \cdot \text{s}^{-1}$. According to the facility size defined in ref. [3] for the production of ^{99}Mo , IFMIF-DONES facility might be a “small-scale facility” (<200 6-days Ci/week) by assuming 6-days irradiation of 125 grams of highly-enriched ^{100}Mo sample. For the medium- (>200 6-days Ci/week and <1000 6-days Ci/week) and large- (>1000 6-days Ci/week) scale facilities, one has to irradiate 250 grams and 1250 grams of ^{100}Mo , respectively. Note that a highly-enriched ^{100}Mo sample is much more efficient for the production of ^{99}Mo than any other molybdenum sample type (natural isotopic abundance, highly-enriched ^{98}Mo). This is also true for the radiological purity obtained with a ^{100}Mo sample as it provides less radiological contaminants than the other Molybdenum sample types.

Beam characteristics

The molybdenum sample has to be located just behind the irradiation module (in beam axis) in order to take efficiently advantage of the high-energy part of the neutron spectrum (14-MeV neutrons). The molybdenum sample has also to be as close as possible to the lithium target to obtain the largest neutron flux.

Equipment required

In order to fit with weekly demand, a maximum irradiation time of 6 days has to be considered (3-day irradiation to optimise the production). For this purpose, a transfer system has to be considered in order to be able to place the molybdenum sample just behind the irradiation module in operation (without stopping the accelerator and opening the test cell). The well-known technology is based on the pneumatic transfer system called “Rabbit”.

Space required

The space requirement for the production of ^{99}Mo depends on the foreseen producer facility size and consequence on the minimum sample mass. The sample volume required for each facility size is provided below (for a sample located 10 cm behind the lithium target):

- Small-scale facility (125 grams of ^{100}Mo): 12.5 cm³,
- Medium-scale facility (250 grams of ^{100}Mo): 25 cm³,
- Large-scale facility (1250 grams of ^{100}Mo): 125 cm³.

These values refer to the minimum volume needed at the irradiation location. The volume of the transfer system is not taken into account in this estimate.

Specific considerations

One needs to consider discontinuities in the concrete walls, constituting the test cell, for the transfer system. Radiological shielding has to be adapted in consequence.

Uniqueness or benefits doing this at IFMIF-DONES (compared to existing facilities)

The exploitation of the reaction $^{100}\text{Mo}(n,2n)^{99}\text{Mo}$ for the production of ^{99}Mo is very promising and has been identified by the international agencies as an attractive solution to ensure the reliability and the diversity of $^{99}\text{Mo}/^{99\text{m}}\text{Tc}$ supply. However, a high-intensity neutron source is required in the 14-

MeV neutron energy range. No other facility in the world, except IFMIF-DONES, can provide such high-intensity neutron beam (10^{14} cm⁻².s⁻¹) in the 14-MeV neutron energy range.

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- [4] OECD Nuclear Energy Agency, “The supply of medical radioisotopes: Review of potential molybdenum-99/technetium-99m production technologies”, (OECD Publishing, Paris, 2010).

Radionuclides and radiopharmaceuticals for therapy

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Scientific case

Investigation of neutron cross-sections for (n,p) reactions useful for production of medical isotopes.

Beam characteristics

Neutron flux of not less than $10^{13} \text{ cm}^{-2}\cdot\text{s}^{-1}$.

Equipment required

Positioning system for the target material to be irradiated.

Space required

White rabbit for transfer of the irradiated target to the radiochemistry lab (either at the IFMIF-DONES facility or to the facilities of NCBJ), gamma-spectrometry system with HPGe detectors, shielding containers for transporting radioactive materials, and radiochemistry processing hot-cell.

Specific considerations

Longer irradiation cycles (in the range of 100-200 h) should be considered.

Uniqueness or benefits doing this at IFMIF-DONES (compared to existing facilities)

The neutron-flux characteristics of Maria Research Reactor are suitable for production of a wide range of isotopes. However, there are reactions requiring high contributions of fast neutrons, which are not available at the Maria Research Reactor, e.g., $^{47}\text{Ti}(n,p)^{47}\text{Sc}$.

^{47}Sc is a radionuclide emitting β^- radiation suitable for therapy. In addition, there are other scandium radionuclides: ^{44}Sc and ^{43}Sc , which are positron emitters suitable for diagnostic imaging in Positron Emission Tomography technique, PET. The wide availability of ^{47}Sc would increase its use in therapy of disease using the same targeting vector molecules.

The use of neutron source from IFMIF Production of ^{225}Ac for targeted alpha therapy

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Radionuclides that decay with the emission of α -particles are of considerable interest for targeted radionuclide therapy. Because of the unique properties of α -particles, they are well suited for treatment of diseases such as micro-metastases or residual tumours after surgical resection of a primary lesion, hematologic cancers, and compartmental cancers.

Unfortunately, current supplies of medically useful α -emitters remain limited as isolated by-products from nuclear weapons processing within USA and Russian Federation. Hence, the actual production level of ^{225}Ac (main therapeutic α -emitter) is sufficient only for preclinical studies and limited number of clinical trials.

Preparation of ^{225}Ac in cyclotrons by the $^{226}\text{Ra}(p,2n)^{225}\text{Ac}$ and $^{232}\text{Th}(p,\text{spall})$ reactions is difficult, because considerable amounts of ^{226}Ac and ^{227}Ac are formed in parallel through (p,n) and proton-capture reactions. The only possible way of producing ^{225}Ac uncontaminated by ^{227}Ac is its production by the $^{226}\text{Ra}(n,2n)^{225}\text{Ra}\rightarrow^{225}\text{Ac}$ reaction using high-energy and high-intensity neutron flux. The calculations indicate that the optimal neutron energy for this reaction should be between 5-25 MeV. Unfortunately, fast-neutron flux in research reactors has a too-low intensity (up to 10^{14} n \cdot cm $^{-2}\cdot$ s $^{-1}$) and a too-broad energy range to be useful in this context. The proposed source of fast neutrons based on the linear accelerator (IFMIF) should produce neutrons with sufficient energy and intensity for the production of GBq levels of ^{225}Ac .

Accelerator-based boron-neutron-capture therapy

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BNCT (Boron Neutron-Capture Therapy) is a binary tumour therapy. First, ^{10}B nuclei are introduced in the patient intravenously by using a ^{10}B carrier; then the tumour region is irradiated with thermal or epithermal neutrons. The ^{10}B -carrier cell absorption has to have more specificity for tumour cells than healthy cells. Two ^{10}B carriers are already commercial. For a reasonable short treatment, the neutron fluence rate in the tumour volume has to be rather high ($\approx 10^9 \text{ cm}^{-2} \text{ s}^{-1}$). So far, only research nuclear reactors have been able to provide such neutron rates with satisfactory clinical results. Recently, several AB-BNCT (Accelerator-Based Boron-Neutron-Capture Therapy) centres have been planned. The substitution of nuclear reactors with particle accelerators allows for installing BNCT centres inside hospitals. Moreover, the neutron source size will be much smaller, allowing for replaceable neutron-sources. Eventually, larger clinical studies will allow better exploitation of this therapy, which is able to treat successfully treat deadly infiltrating tumours.

The IFMIF-DONES project accelerates 125 mA of deuterons at 40 MeV of energy by using SRF linacs. An RFQ accelerator pre-accelerates the beam up to 5 MeV of energy. Such a beam could be used to construct an intense neutron source, by using a beryllium target. The $^9\text{Be}(d,n)$ thick-target spectra show a large peak at an energy of about 2 MeV, when 5-MeV deuterons are used. The neutron-yield production at 0° is $\sim 6 \times 10^{13} (\text{MeV} \cdot \text{sr} \cdot 125 \text{ mA})^{-1}$.

After the MEBT a 10% of IFMIF-DONES deuteron beam could be parasitically extracted and transported into the BNCT hall, where the beryllium target would convert the deuterons in $\sim 6 \times 10^{12}$ neutrons/(MeV·sr). After appropriate energy moderation, the neutron field would be properly shaped, ready for in-air advanced BNCT studies.

The BNCT experimental hall has to contain the neutron moderator and shaper, as well as the remote system for the Be target maintenance. Such facility will be available for international dosimetric and radiobiological experiments, which will aim to define a protocol for further AB-BNCT clinical studies.

Chapter 3: Nuclear physics and radioactive ion beam facility

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Summary of the chapter

In this chapter, the use of the high-intensity fast-neutron beams, produced at the future IFMIF-DONES facility, in several research areas and applications is presented. Neutron-induced reactions of particular importance to a number of nuclear-technology applications are discussed together with the limitations of the high-flux beam. Furthermore, production of high-intensity radioactive ion beams with neutron-induced fission employing the ISOL technique is delineated. This in turn would allow nuclear structure studies very far from the island of stability, which, aside from their intrinsic interest, could help shed light onto the astrophysical *s*- and *r*-process paths. Study of β - ν correlations in tests of the Standard Model require high precision and consequently high yields of the light radioisotopes ^{23}Ne and ^6He , which can be produced with the high-flux neutron beams and their decay can be measured in ion and atom traps.

Introduction

Reactions induced by fast neutrons such as fission, multiple neutron emission and light charged particle emission are very important for fusion technology, accelerator-driven systems, fission reactors, study of electronic damages under neutron flux, as well as for medical applications. The study of these reactions can be efficiently pursued with the high-flux, fast-neutron beams at IFMIF-DONES. Furthermore, the activation technique allows circumventing the limitations of the high-flux neutron beam due to its time structure and induced high neutron and gamma-ray background.

In the last two decades, radioactive ion beam facilities based on the ISOL (isotope separation online) or IFF (in-flight fragmentation) have provided opportunities to study nuclear structure far from the island of stability. This allowed studying the evolution of nuclear shell structure as function of N/Z , and delivered evidence for the emergence of new magic numbers and for shape coexistence. Furthermore, the availability of very neutron-rich isotopes paved the way for delineating the paths of the *s*- and *r*-processes assumed to be responsible for nucleosynthesis of elements heavier than Fe and Ni. Several other new phenomena were observed as well such as neutron and proton radioactivity. The promise of new discoveries in going even further away from the island of stability gave a push towards having more intense neutron beams that would increase the yield of highly exotic nuclei. In this respect, the IFMIF-DONES facility can play a key role through its high flux of fast neutrons. State-of-the-art equipment have to be developed to allow for measurements under such extreme conditions.

In the same vein, the high-flux, fast-neutron beams of the IFMIF-DONES facility can produce in neutron-induced reactions high yields of light radioactive isotopes. This is needed to reach the high precision with which the Standard Model (SM) of Particle Physics can be tested in the low-energy

regime. In contrast to measurements at very high energies, the tests here are made by measuring parameters of β - ν correlations in β decay of light radioisotopes in ion or atom traps with very high precision to observe small deviations from the predictions of SM. This would point then towards Physics beyond SM.

Physics topics

- Nuclear Structure & Astrophysics (evolution of nuclear shell structure; structure of nuclei in the r-process path; shape coexistence; search for neutron radioactivity in neutron-induced fission products around doubly magic ^{78}Ni) (Contributions B, C, D)
- Mechanism of nuclear fission (Contributions D, E)
- Cross-section measurements for applied physics ((n,γ) , (n,xn) , (n,lcp)) (Contribution A)
- Test of the Standard Model (Contribution F)

List of contributions

- A. **Study of neutron-induced reactions at IFMIF-DONES**
X. Ledoux, GANIL, Caen, France
- B. **Production of radioactive ion beams of fission fragments by the ISOL method**
P. Delahaye, with contributions from X. Ledoux and M. Fadil, GANIL, Caen, France
- C. **Production and study of the most exotic neutron-rich nuclei via fast-neutron induced fission**
Blanc, ILL, Grenoble, France; B. Fornal, IFJ PAN, Kraków, Poland; J.N. Wilson, IPN Orsay, Orsay, France
- D. **Spectroscopy of neutron-rich isotopes produced in neutron-induced fission reaction**
J. Kownacki, Warsaw University, Warsaw, Poland
- E. **Nuclear fission studies at IFMIF-DONES**
Blanc, ILL, Grenoble, France
- F. **β - ν Correlations in light radioisotopes: Production of radioisotopes by fast neutrons - SARAF-I (and II) and projections for IFMIF**
M. Hass¹, O. Heber¹, D. Melnik¹, M. Rappaport¹, S. Vaintraub^{1,3}, D. Schwalm^{1,4}, Zajfman¹, Y. Mishnayot^{1,3}, G. Ron², T. Segal², T. Hirsh³, K. Blaum⁴
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Facilities (by order of complexity in implementation)

In Fig. 1, a schematic drawing of the following facilities that will be used in the foreseen scientific programme is shown.

- **Irradiation facility** (just behind IFMIF samples)
- **Collimated beam facility** (5 m concrete wall with collimator)

- **ToF facility** (1/100-1/1000 deuteron beam pulses kicked-out to a dedicated converter room, additional ToF room)
- **RIB facility** (just behind IFMIF samples but physically separated by a thin wall from irradiation cell, additional experimental & service areas)

Summary table

Topic	Facility	Instrumentation	Comments
Nuclear Structure & Astrophysics	Collimated beam, RIB	Dedicated experimental area, γ -ray spectrometers, traps, charge-particle detectors, ionisation chambers, FIPPS magnetic spectrometer, neutron detectors	Flux of fast neutrons > 1000 times more than any existing facility, RIB yields comparable to the most ambitious RIB facilities (SPES, SPIRAL2 Phase 2, ARIEL)
Mechanism of Nuclear Fission	Collimated beam, ToF	Dedicated experimental area, γ -ray spectrometers, charge-particle detectors, ionisation chambers, FIPPS magnetic spectrometer	Flux of fast neutrons > 1000 times more than any existing facility and > 10 times at ToF facility
Cross-section measurements for applied physics	Collimated beam, ToF, Irradiation	Dedicated experimental area, γ -ray spectrometers, charge-particle detectors, neutron detectors	Flux of fast neutrons > 1000 times more than any existing facility and > 10 times at ToF facility
Test of the Standard Model	RIB	Magneto-Optical Trap (MOT) and an Electrostatic Ion-Beam Trap (EIBT)	60 times higher yield of ${}^6\text{He}$ and ${}^8\text{Li}$ than at existing facility

Study of neutron-induced reactions at IFMIF-DONES

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The IFMIF-DONES (DEMO Oriented Neutron Source) is a future facility designed for the irradiation of material by a very intense flux of fast neutrons. This equipment could also be used for experiments in nuclear physics. Actually, the neutron energy distributions, extending up to 40 MeV with a most probable energy around 14 MeV, allow covering several domains of interest in the study of neutron-induced reactions. Among the reactions of interest, we can mention:

- (n,n') and (n,xn) with x up to 5
- Neutron-induced fission
- The production of light charged particles (lcp)

Each of these reactions plays an important role in several applications like the development of a new generation of fission reactors, the fusion technology, the accelerator-driven systems, the study of electronic damages under neutron flux and the medical applications.

The very high flux available at IFMIF opens undoubtedly new possibilities for the study of these kinds of reactions up to 40 MeV. Very small cross-sections could be measured and samples of very small mass could be used. This is particularly interesting for experiments requiring targets of enriched isotopes, which are sometimes available only in small quantities. This is the case for radioactive targets for which small samples have to be used because of safety constraints or detection issues. In such cases, only a huge neutron flux allows obtaining a significant counting rate.

However, if the high flux available at IFMIF is an important parameter, there are structural limitations that will make some experimental techniques unusable.

- The beam frequency (150 MHz) is not adapted to the time-of-flight (TOF) technique. Since the neutron spectrum is continuous, some experiments require the TOF technique to measure the neutron energy. An adaptation of the frequency (down to about MHz) is necessary to use the TOF technique. A decrease of the primary frequency by selecting one burst over N ($N > 100$) would make the TOF technique applicable but would also decrease the neutron flux on the target by a factor of N. In addition to the adapted beam frequency, a flight path of several meters between the neutron production source and the sample is needed.
- The second limitation comes from the background (gammas and neutrons) in the irradiation area of IFMIF. The high neutron and gamma fluxes forbid the use of several detection setups

(neutrons and gamma detectors, for example) except if the facility is equipped with optimised shielding. The best way is probably a dedicated room separated from the neutron source by a wall pierced with a hole (collimation system) to define the neutron beam. The room design will depend on the foreseen experimental setups to be used. The collimation system must be carefully studied in order to optimise the ratio of beam flux over background.

The two previous limitations do not concern the measurements by activation technique.

For this experimental method, the sample is put in the irradiation cell and removed after irradiation for activity measurement. Only a pneumatic system remotely controlled is required. No dedicated time structure is required. This setup seems quite easy to be adapted to the IFMIF facility.

The IFMIF-DONES facility will be an interesting and valuable facility for the study of neutron-induced reactions up to 40 MeV. Needed adaptations of the facility will depend on the experimental techniques, which will be used. Cross-section measurements by activation technique could be realised “easily” while in-flight measurements would require bigger modifications of the facility to have a collimated beam and adapted time structure.

Production of radioactive ion beams of fission fragments by the ISOL method

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Scientific case

The IFMIF-DONES Facility would provide intense neutron fluxes comparable in energy and intensity to what is projected for the SPIRAL2 phase 2 facility [1]. In this respect, one could imagine producing radioactive ion beams of fission fragments with comparable intensities to what is predicted for SPIRAL2 phase 2.

The physics case of such an ISOL facility using the neutron flux provided by IFMIF-DONES is very rich and has been detailed in many documents for SPIRAL2 phase 2 and for EURISOL (see for instance [2], the numerous LoIs for SPIRAL2 phase 2, and [3]). In essence, the production of very neutron-rich nuclei far away from stability would permit a number of studies of nuclear structure along the astrophysical s- and r-process paths, which are believed to be responsible for the nucleosynthesis of isotopes of masses beyond Fe. A choice would have to be made concerning the possible reacceleration of the beams. With low energy (keV) ISOL beams, the facility would be limited to different studies of the ground and isomeric states properties (such as masses, spins, moments and charge radii using ion traps and laser collinear spectroscopy) and to some excited states using beta decay (with the possibility to measure the Gamow strengths, B_n , and half-lives using tape stations, γ arrays, total-absorption γ spectrometers, and neutron detectors, for example). A post-acceleration up to 10-20 A-MeV would permit in addition to study nuclear structure via Coulomb excitation, transfer reactions, deep-inelastic collisions, and fusion-evaporation reactions. The study of post-accelerated beams would benefit from the use of different types of spectrometers and a wide variety of detectors including γ arrays, active targets, etc.

Beam characteristics

The non-moderated neutron flux as calculated in the irradiation cell would be perfectly suited for the production of radioactive ion beams by neutron-induced fission in an ISOL SPIRAL2-like target; see Fig. 2 for the calculated distribution of the neutron flux in the irradiation cell and an estimate of the fission yield at the fusion irradiation module. Alternatively, if a few percent (corresponding to a few 100 kW) of the primary deuteron beam could be redirected onto a secondary Li loop, the ISOL target station could be placed at this spot.

Equipment required

The production of radioactive ion beams by the ISOL method requires an adequate infrastructure, including a long list of equipment such as:

- Target front ends and dedicated hot cells and storage rooms for the actinide targets,
- Appropriate shielding, possibly inert atmosphere, nuclear ventilation and gas storage.
- A remote handling in the target front end, storage room and hot cells.
- Mass separators and beam lines in order to transport the beam to experimental areas.
- Services such as power supplies, cooling water, etc.
- Appropriate shielding and radioprotection monitoring, and access controls for the experimental rooms.
- Spectrometers, traps, detectors in the experimental areas, and other instrumentation.
- Possibly a compact linac with an EBIS or ECR charge breeder for radioactive ion beam preparation.

Space required

While the target front-end containing the target and ion source and first beam optics can be quite compact (a few m²), the whole infrastructure described above requires significantly more space. As an order of magnitude, the SPIRAL2 phase 2 production building, containing the target bunkers, hot cells, storage, first beam lines for beam separation, and all the services occupy some 1000 m² to be multiplied by several floors (3 to 4). The surface of the experimental areas would have to be of the same order of magnitude.

Specific considerations

The ISOL target front ends could be either placed in the irradiation cell, or further away in a dedicated building if coupled to a secondary Li loop. The advantage of the irradiation cell is the large volume where high neutron flux would be available, permitting the use of several targets in parallel. On the other hand, the continuous operation of the irradiation cell, over several months, would complicate the regular target exchange and maintenance operations. The lifetime of a SPIRAL2 phase 2 target was estimated to be of the order of 1 month. Maintenance operations at the front ends are done every year at ISOL facilities. Repair interventions have to be done sometimes before in case of failures. A remote handling permitting replacing the targets and front-end sensitive parts during irradiation would have to be conceived.

Uniqueness or benefits doing this at IFMIF-DONES (compared to existing facilities)

Regarding the neutron fluxes predicted at the irradiation cell, which are of the same order of magnitude as expected for SPIRAL2 phase 2, but for a larger volume, unique intensities of radioactive ion beams could be produced. The use of a parasitic deuteron beam impinging on a secondary Li loop would also open unique perspectives for the ISOL beam intensities, as the ISOL target(s) could be placed closer to the beam interaction point. These efforts would have to be accompanied by dedicated target and ion source R&D, which has shown to be highly beneficial for the production of short-lived isotopes with the ISOL method. In addition to the production of unique intensities of fission fragments from a UCx target, the high neutron flux would allow the production of unique beam intensities of some isotopes via (n,α) reactions, for example. This is the case for ${}^6\text{He}$ and ${}^8\text{Li}$, which could be produced in targets such as BeO or B_4C , respectively. The intense production of these isotopes is of interest for different tests of the Standard Model (see as an example contribution of M. Hass) and for material science.

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DONES. Neutron map in the Irradiation Cell (Horizontal Plane $-z$ -axis position $z=-220$ -)

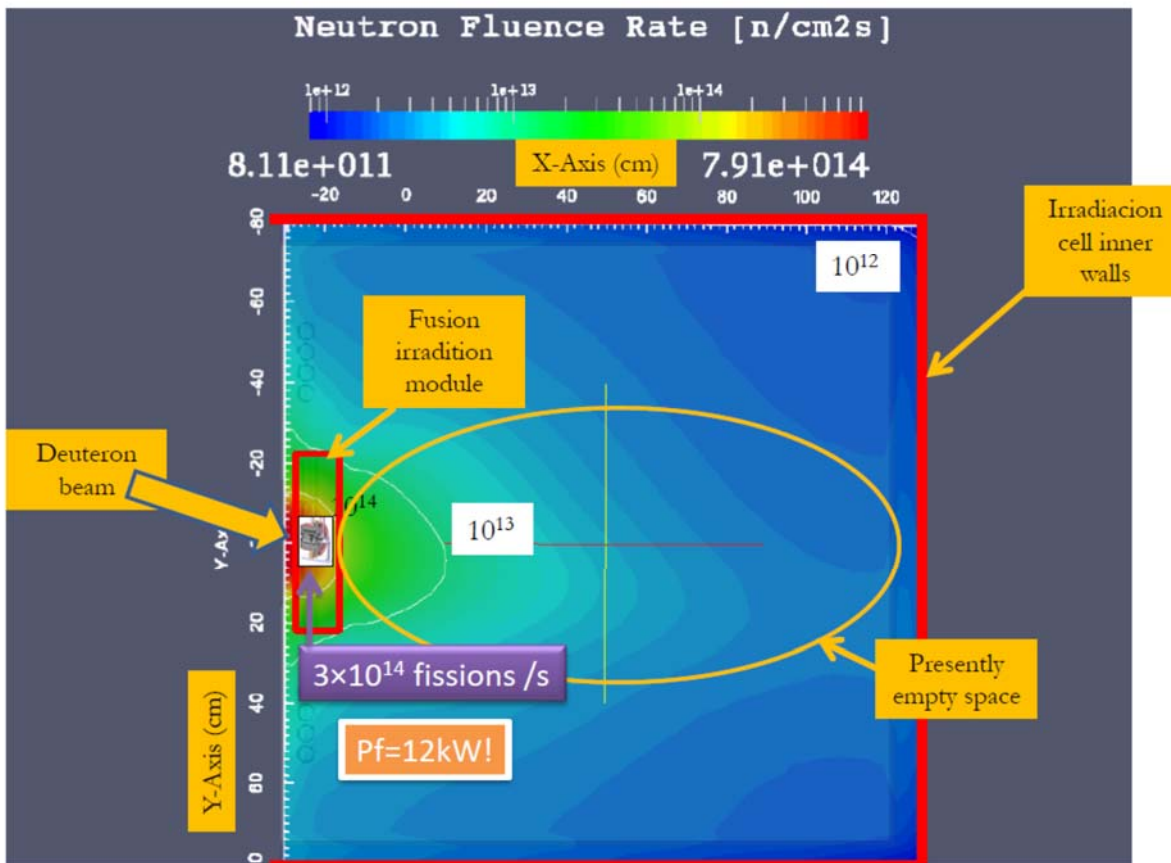


Figure 2. A drawing of the irradiation cell of the IFMIF-DONES facility showing the distribution of the neutron fluence rate (in units of $n \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$) over the cell. The fusion irradiation module is indicated and the number of fissions/s that could be produced at that location is shown.

Production and study of the most exotic neutron-rich nuclei via fast-neutron-induced fission

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Introduction

Nuclear matter accounts for 99.9% of the mass of the visible matter in the universe. The study of the fundamental forces, which hold it together and the way it chooses to organise and arrange itself in atomic nuclei are thus important to study, and give rise to a wealth of diverse structures and complex phenomena. The proposed IFMIF-DONES facility will provide a unique opportunity to gain interesting new information on the nuclear structure of exotic neutron-rich nuclei via the fast-neutron-induced fission of various actinide targets. The decay of the resulting excited fission fragments produced in these nuclear reactions can be studied in-beam via high-resolution gamma-ray spectroscopy.

Scientific case

The high fluxes of ~14 MeV neutrons available at the IFMIF-DONES facility will produce high fission rates even in small actinide samples (milligrams of material), allowing the most neutron-rich (fertile) actinide nuclei to fission (e.g., ²³²Th, ²³⁸U, ²⁴⁴Pu), which are very highly improbable to fission with thermal neutrons. This will give unprecedented access to a diverse range of exotic nuclei on the neutron-rich side of the nuclear chart. At least four particular areas of study in the field of nuclear structure have been identified as key to the scientific case for the IFMIF-DONES facility. These are detailed in the following section.

Evolution of nuclear shell structure

The properties of nuclei lying close to the valley of stability are relatively well studied allowing nuclear models and effective interactions to be introduced and experimentally verified. This allows the understanding of general nuclear properties for species not too far outside of the valley of stability. An important fraction of nuclear-structure studies nowadays is devoted to the question of how nuclear

potential parameters change when neutrons are added to the nucleus. By adding neutrons, the characteristics of the nuclear surface will change, leading to a modification of the spin-orbit interaction and the pairing forces. These parameter changes have consequences on the ordering of the nucleon orbitals and on the sequence of magic numbers, as they appear in stable nuclei.

A large number of experimental observables are needed to resolve the problems mentioned above. Such quantities are nuclear masses, excitation energies, transition strengths, lifetimes and nuclear moments. An excellent production scheme for nuclear excitation far from stability is fast-neutron-induced fission, which produces a large variety of neutron-rich fission fragments. It is possible to populate nuclei with more than 12 neutrons in excess of the stable isotope. Fission products have excitation energies up to 15 MeV, and angular momenta with mean values of about 6 to 8 units of angular momentum. The spin-distribution is very broad, and spins up to about 17 units of angular momentum can be investigated.

Structure of nuclei in the r-process path

The nucleosynthesis of the elements on earth between ^{56}Fe and ^{238}U occurs in astrophysical environments (stars and galaxies) and is thought to proceed mainly by the r-process (rapid-capture process), which is understood to occur in violent conditions such as those in type II supernova explosions. New elements are synthesised by rapid successive neutron captures leaving no time for a subsequent nuclear decay and creating nuclei very far from stability, which are the precursors of the stable elements found here on earth and in our solar system. The study of the nuclear structure of nuclei in the r-process path often provides important complementary information for determining r-process reaction rates and thus helps to understand the origins of abundances of the elements in the periodic table. In particular, the IFMIF-DONES facility may be able to produce and study nuclei at the r-process waiting point at the $N=82$ shell closure (e.g., ^{130}Cd , ^{128}Pd), where currently little or no information is available on excited nuclear states.

Shape coexistence

Certain atomic nuclei have the remarkable property of possessing different geometrical configurations, which are energetically similar, yet have very different surface shapes (e.g. prolate and oblate). This phenomenon appears to be unique for finite many-body quantum systems. It is thought to arise due to the delicate interplay between macroscopic (collective) and microscopic (individual nucleon) effects. Dramatic shape changes can occur with the addition of only one or two extra nucleons, causing a complete rearrangement of the quantum configuration. For certain nuclei, such as the neutron-rich Kr, Sr and Zr isotopes around $A\sim 100$, two different kinds of shape configurations co-exist at the low energies. Such nuclei would be easy to produce and study at the IFMIF-DONES facility, particularly with the use of fast-timing detectors, which would allow nuclear-lifetime measurements and deduction of the quadrupole moments of excited nuclear states of exotic neutron-rich nuclei.

Search for neutron radioactivity in neutron-induced fission products around doubly magic ^{78}Ni

High-spin isomers located above the neutron binding energy, in theory, might decay via emission of a neutron. Such decay would proceed to low-lying states of the daughter nucleus what implies a rather large change of angular momentum. The high centrifugal barrier, which is felt by the neutron in this case, strongly inhibits the decay. The existence of the phenomenon described above, often referred to as neutron radioactivity, was suggested already in the seventies by Peker et al. [1] who pointed out that for neutron-unbound high-spin isomers in nuclei close to the neutron drip line, the angular-momentum barrier could delay neutron emission, making it to compete with gamma decay.

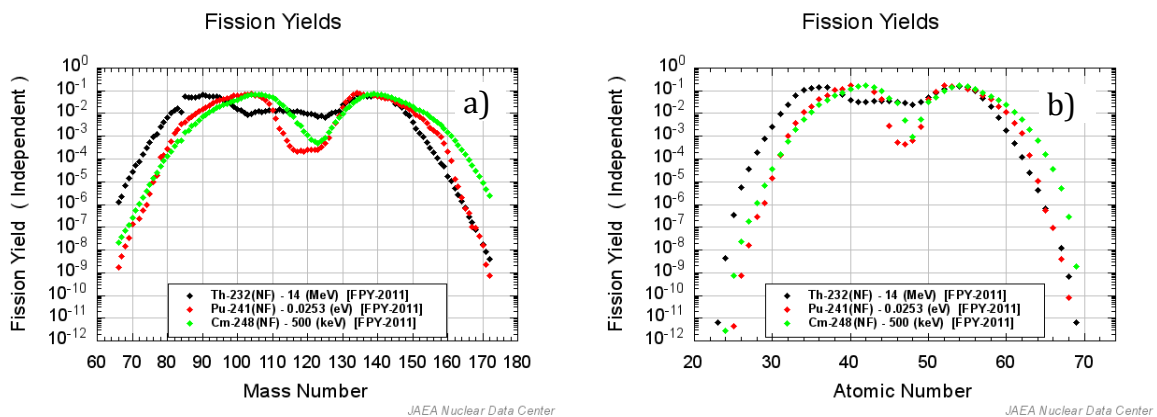


Figure 3. Fission yield distributions as a function of: (a) mass number and, (b) atomic number. Data for spontaneous fission of ^{248}Cm , thermal-neutron-induced fission on ^{241}Pu , and 14-MeV-neutron-induced fission on ^{232}Th are shown (taken from Japan Atomic Energy Agency).

Several high-spin isomers, which are neutron unbound, are known in the region of doubly magic ^{208}Pb ; however, neutron radioactivity has not been observed in their case. This is understandable because neutron decay would have to involve spin change of the order of 18-20 spin units.

For the search for neutron radioactivity nuclei lying in the yet unexplored region of doubly magic ^{78}Ni , where spin isomers should be abundant, offer conditions that are more favourable. Here, above the $N=50$ shell closure, neutron binding energy is low and, as a result, spin isomers would become neutron unbound at relatively low spin. In these cases, the amount of angular momentum which would have to be carried away by a neutron would be of the order of only 5-10 units thus making the probability of neutron emission comparable with that of gamma decay.

In spontaneous or thermal-neutron-induced fission, the region of neutron-rich species close to ^{78}Ni is not populated with yields sufficient to perform measurements of gamma rays from the isomers decay. This can be overcome by using fission induced by fast, 14-MeV neutrons on light actinide targets. Fig. 3 shows product yield distributions as a function of mass A (Fig. 3(a)) and atomic number Z (Fig. 3(b)) for three processes: spontaneous fission of ^{248}Cm , thermal-neutron-induced fission of ^{241}Pu and 14-MeV-neutron-induced fission on ^{232}Th . It is clear that fission induced by 14-MeV neutrons gives rise to a sizeable population of nuclei with $Z=28-34$ and $A=76-88$, i.e., in the neighbourhood of ^{78}Ni . In particular, production of $A=82-87$ Ga, Ge and As isotones, i.e., $^{82-85}\text{Ga}$, $^{83-}$

^{86}Ge and $^{84-87}\text{As}$ nuclei, increases by more than one order of magnitude reaching the level of 5×10^{-4} , 5×10^{-3} , 2×10^{-2} for Ga, Ge and As, respectively, which is suitable for gamma-ray spectroscopic studies of isomers with lifetimes of hundreds of nanoseconds and longer. Bearing in mind that in the nuclei mentioned above the existence of spin isomers at excitation energy of the order of a few MeV is almost certain and, considering that neutron separation energy is of the order of 3.0-3.5 MeV for odd- N ones and 4 - 5 MeV for even- N ones, this provides optimal conditions to search for neutron radioactivity.

The high intensity of the neutron beam available at IFMIF-DONES and the possibility of conducting very long experimental runs will permit to look for very weak neutron-decay branches from high-spin isomers. This will also permit investigations to be extended to short-lived (tens to hundreds ns) isomers as well as to very weakly populated (with relative production yield lower than 10^{-4}) neutron-rich species around ^{78}Ni . *The IFMIF-DONES facility will thus be a unique place, where, by using fission induced by fast neutrons on light actinide targets, one can reach new spin isomers in the ^{78}Ni region, study their gamma decay and search for neutron radioactivity from those states.*

Beam characteristics and space requirements

The reaction target and detection system consisting of the magnetic spectrometer coupled to a germanium array positioned around the spectrometer's focal plane, should be located in an experimental room, which is well shielded from the neutron production area. This could be accomplished by building a 5 m thick wall of concrete. The 5 m thick wall reduces the neutron flux by more than 12 orders of magnitude, bringing it to an acceptable level in the experimental hall. This is shown in Fig. 4. A collimator (composed of several materials arranged in ring type geometry) placed inside this wall will define the neutron beam in the experimental hall. A reduction of 3-4 orders of magnitude in the neutron-flux intensity is expected between the production area (where the neutron flux is of the order of $10^{13} \text{ n/cm}^2/\text{s}$) and the reaction-target position (at the exit from the collimator), yielding the neutron beam intensity on target of the order of 10^9 - $10^{10} \text{ n/cm}^2/\text{s}$.

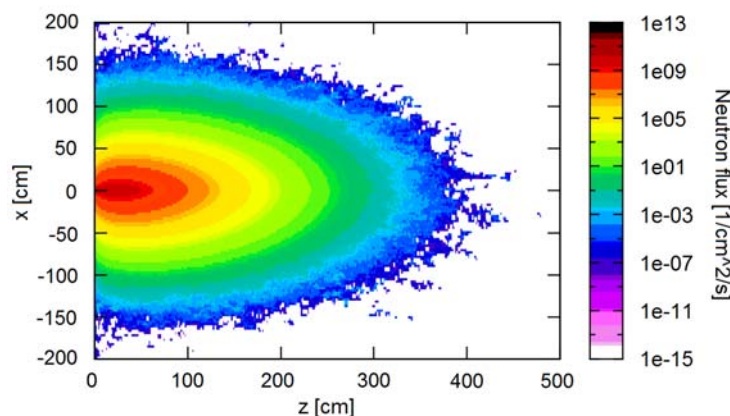


Figure 2. Simulations of neutron flux rate attenuation in the wall of concrete separating the neutron production area from the experimental room (B. Wasilewska, private comm.).

The neutron beam should be stopped at the end of the experimental room in a beam dump designed to reduce the neutron backscattering and the additional gamma production. The beam dump should be located far from the reaction target, at a distance of at least 30 m.

Equipment required

High-resolution, high-efficiency gamma-ray spectrometer

To study the excited states of the exotic fission fragments produced in the neutron-induced fission reactions of actinide nuclei would require a high-resolution gamma-ray spectrometer [2]. Such a spectrometer would comprise many large-volume Ge detectors and has a total photopeak efficiency at 1 MeV of at least 5% to be able to collect large numbers of triple coincidence events, where three or more gamma rays from the same cascade are detected simultaneously. Conditions, or gates, placed on gamma rays in these events would then be used to cleanly disentangle the multiple decay paths in the hundreds of different nuclei produced during the experiment. The average multiplicity of gamma rays emitted in fission is around eight. Therefore, the granularity of the array would need to be sufficiently large (> 20 detectors) to minimise the probability of two gamma rays entering the same detector.

Ionisation chamber

The high fluxes of fast neutrons would permit the use of small actinide samples (milligrams), which could be placed inside a twin Frisch-grid ionisation chamber [3]. The mass, kinetic energy and emission angle of the fission fragments can subsequently be deduced from measurements of the signals detected on the cathode, grids and anodes. Such devices are commonly used at neutron production facilities to study nuclear fission and have a mass resolution of ~ 4 mass units. Their cost is relatively low for the advantages in selectivity that they would provide.

FIPPS

FIPPS (Fission-Product Prompt gamma-ray Spectrometer) is a new instrument under construction at the ILL in the context of ILL ENDURANCE programme. The new instrument will be positioned at an external thermal neutron beam to study neutron-induced reactions. FIPPS addresses two fundamental domains of nuclear physics: fission of heavy elements and structure of neutron-rich matter. FIPPS consists of a high-efficiency γ detector array coupled to a fission-fragment spectrometer based on a gas-filled magnetic (GFM) device. During the fission process, two fragments are emitted back to back. The first one will be stopped in the target backing. The γ -rays from the decay of the fragment will be detected using the high-efficiency Ge detector array. The second fragment will fly to the gas-filled magnet (GFM). The magnet will be instrumented with a time-projection chamber (TPC) for individual 3D tracking of the fragments. Hence, the angular acceptance of the spectrometer can be maximised without compromising the mass resolution. This unique instrument, in combination with a TOF measurement, will allow identification of the mass and kinetic energy of the second fission fragment. In addition, the GFM can be used in “focalisation” mode where individual tracking is not used and where fission fragments are “extracted”. Such mode would allow studies of isomeric states with lifetime between 100 ns and 1 μ s at the focal plan of the magnet. The GFM-spectrometer and its

associated instrumentation will be designed such that it can be moved to other facilities where beams of fast neutrons (such as at IFMIF-DONES), light charged particles and photons are available to induce fission reactions of targets ranging from the heaviest elements down to the rare earth region.

Advanced fission studies require the determination of mass and kinetic energy of the fission fragments combined with a simultaneous detection of prompt gamma rays and possibly also fission neutrons. Nuclear spectroscopy of very neutron-rich isotopes can be performed via gamma-gamma or triple-gamma coincidences with efficient Ge detector arrays. Mass and nuclear charge are usually identified via coincidences with known gamma rays of complementary fragments. Where this is not possible additional mass information from an ancillary spectrometer can improve the overall resolving power to identify new, weak gamma rays.

Uniqueness of IFMIF-DONES compared to existing facilities

The uniqueness of the IFMIF-DONES facility would be the extremely high fluxes of fast neutrons available (> 1000 times more than any existing facility). This allows studies with milligram samples and the fission of actinide nuclei which are very highly improbable to fission with thermal neutrons (e.g., ^{232}Th , ^{238}U and ^{244}Pu) giving access to the study of a diverse range of neutron-rich atomic nuclei between masses ~ 75 to ~ 170 . In addition, the facility would allow very long experiment durations (months) making possible extremely high-statistics experiments and the gathering of unique information on nuclear structure of interesting nuclear systems up to moderate spins.

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Spectroscopy of neutron-rich isotopes produced in neutron-induced fission reaction

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Scientific case

Spontaneous and induced fission are so far the main means used to populate and study in detail the excited states in neutron-rich nuclei in the region of mass 90 ~ 160. Gamma-ray data supported by fission-fragment detectors can be used to determine spin, mass, and charge distribution of the fission products and other information relevant to how a heavy nucleus splits into two fragments of nuclear matter. The main goal of this proposal is the study of the nuclear structure of states in neutron-rich isotopes (e.g., heavier than ^{108}Rh), as well as the spin distribution in fission fragments in neutron-induced fission reactions.

Spin generation in fission products is a topical subject of study aiming to throw light on the fission mechanism. Another engrossing topic is connected to the search of new isomers in the neutron-rich nuclei region. It would be interesting to gather systematic information on the properties of the excited states and determine their quasi-particle configurations and the shapes of the associated nuclear potential using several different targets.

Beam characteristics

In order to carry on the proposed experiment efficiently one would need a neutron flux of the order of $\sim 10^{15}$ n/s/cm² to get $\sim 2 \times 10^{12}$ fissions/s (e.g., 4 mg of ^{239}Pu , 742 b).

One has to remember that in the fast-neutron region the cross section at 1 MeV is 1/1000 of the thermal value for $^{235}\text{U}(n,f)$ reaction.

Experimental setup

The beam section should be reduced to a disk of roughly 1.5 cm diameter at the target position in order to:

- allow a compact arrangement of the γ -ray detectors around the target to maximise the detection efficiency,

- perform precise spectroscopic studies like angular correlations, and
- avoid radiative-capture reactions on the infrastructure items surrounding the detectors, which would cause a large background. The neutron-beam collimation can be realised by using a series of lithium and boron collimators mounted upstream the target in a similar way as described by W. Urban [1]. The advanced HPGe detector array (like at least the Eagle array at Heavy-ion Laboratory of Warsaw University) is necessary to conduct the scientific project.

With such a setup up to 10^9 $\gamma\gamma$ and up to 10^8 triple- γ coincidence events can be collected in a relatively short-time measurement.

The high sensitivity of modern arrays allows the identification of weak transitions in nuclei of interest, even in neutron-rich nuclei produced with relatively low yield. The charge of newly observed nuclei can be identified by γ -X ray coincidence measurements. Therefore, low-energy Ge detectors (LEGe) are also needed. Linear polarisation of prompt γ -rays can be measured using clover detectors as Compton polarimeters (as it was done in EUROGAM2 array).

Methods of mass identification is very important and is described in ref. [2]. The electron conversion spectrometer would also allow determination of spins of the observed excited states.

Space required

The whole apparatus, i.e. power supply, electronics, computer, detectors with ancillary equipment etc., would occupy a space of at least about 30 m².

Other information

The neutron collimation line and beam-spot dimension is a source of concern. How to avoid effectively a high background?

Uniqueness or benefits

High total neutron production and high beam current.

Unique and important is the concept for location of IFMIF-DONES in Poland, and especially in Rzeszów, the capital of the Sub-Carpathian Voivodship.

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Nuclear fission studies at IFMIF-DONES

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Introduction

Nuclear fission has been discovered in the late 30's and widely used worldwide in the last decades in nuclear power plants to produce electricity. However, the fission process itself is still poorly known. For instance, the mechanism of angular momentum population of fission fragments is still not well understood. To overcome this issue, setups combining the determination of mass and kinetic energy of the fission fragments and the detection of prompt particles are needed.

Scientific case

Up to now, we have good data on fission yields as distribution functions for fragment mass, and a programme is ongoing to determine also the nuclear-charge distribution of the fragments. The observed distributions reflect the interplay of collective motion and (deformed) shell structure. It is now clear that neither of the extreme models (scission-point model and mean-field model, respectively) can describe the observations adequately. Despite enormous efforts towards a dynamic microscopic calculation (TDHF model, CEA Bruyères-le-Châtel), the experiments cannot be reproduced yet. The main deficiency resides in the incomplete description of the dynamics of the fission process, i.e. the path from initial excitation energy to the partition of final excitation energy and spin distribution. For practical applications, phenomenological models (CGMF Los Alamos, GEF CENBG Bordeaux, FIFRELIN CEA Cadarache ...) are today experiencing an important renaissance. Multi-parametric studies on correlations between fragment distributions and their excitation and spin distributions are essential for a validation and improvement of these codes and for the fundamental understanding of the fission process.

Neutron-induced fission, and especially the measurement of prompt particles following the reaction, allows testing the different nuclear models involved in the fission modelling in terms of their parameters: excitation-energy repartition, deformation energy of the nascent fragments, level density, nuclear cascade process, fission-induced spin distributions, etc. The separation of a recoiling fragment would allow the identification of short-lifetime states, which give indirect information on the γ cascade and the spin populated after neutron emission. In addition, neutron-induced fission gives access to a wide range of fissioning systems allowing systematic studies as a function of various parameters.

Such kind of experiments requires thin actinide targets and high fission rates. The ~ 14 MeV neutrons available at the IFMIF-DONES facility will allow studying fissioning systems that are not accessible via thermal-neutron-induced fission. The high flux will compensate the low cross section expected at such high energy.

Beam characteristics and space requirements

The beam characteristics and space requirement for fission studies are the same requirements as for nuclear-structure studies given in the “Production and study of the most exotic neutron-rich nuclei via fast-neutron-induced fission” part.

Equipment required

FIPPS (FISSION-Product Prompt gamma-ray Spectrometer) is a new instrument under construction at the ILL to study nuclear structure and nuclear fission by means of thermal-neutron-induced reactions. It consists of a high-efficiency γ detector array coupled to a fission-fragment spectrometer based on a gas-filled magnetic (GFM) device. The spectrometer is being designed such that it can be moved to other facilities such as IFMIF-DONES. A more accurate description of the instrument is given in the “Production and study of the most exotic neutron-rich nuclei via fast-neutron-induced fission” part.

Uniqueness of IFMIF-DONES compared to existing facilities

The uniqueness of IFMIF-DONES for fission studies are the same as for nuclear-structure studies given in the “Production and study of the most exotic neutron-rich nuclei via fast-neutron-induced fission” part.

β - ν Correlations in light radioisotopes Production of radioisotopes by fast neutrons - SARAF-I (and II) and projections for IFMIF

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The Standard Model (SM) of particle physics [1] is currently the most comprehensive theory to describe the myriad interactions between the known fundamental particles in nature. Experimentally, the standard model is one of the best-tested theories in modern-day physics. It is therefore disconcerting to note that the standard model is undeniably incomplete [2]. Most strikingly, the standard model contains no reference to Gravity, Dark Matter, or Dark Energy, which together make up nearly all the mass-energy balance in the universe. Additionally, the standard model is “hand-tuned” in that most of the parameters are taken from experiment, rather than from a-priori arguments.

There must therefore be other physics beyond the Standard Model, and there have been many attempts to describe such physics theoretically (string and SUSY theories, to name but a few). Experiments testing for beyond SM (BSM) physics must either operate at the highest available energy regimes (such as with the LHC) or search at lower energies with extremely high precision for signatures which may be forbidden within the SM, but allowed in theories beyond the SM. These low-energy approaches seek tiny deviations from the Standard Model that may be caused by the new physics. Low-energy tests explore regimes of BSM theories, which cannot be tested at high energies [3, 4].

Low-energy experiments cannot make use of the strong interaction since comparing experimental results to theory is severely limited by the proper interpretation and calculation of strong confinement effects. We are inevitably led to test the SM using electroweak interactions, for which the theoretical calculations may be precisely performed and interpreted. In general, these efforts include several broad groups: electron-scattering experiments, neutrino-scattering experiments, atomic parity-violation experiments, and beta-decay experiments, the topic of this research proposal.

In the Standard Model description of the electroweak interaction, the photon has heavy, spin-1 partners, the Z^0 and W^\pm bosons, which mediate the weak interaction. Due to the large mass and vector nature of these bosons, the Lorentz transformation properties of the effective low-energy four-fermion

contact interaction operators compared to the rest masses of the W bosons are vector and axial vector. Phenomenologically, the weak interaction is completely chiral, coupling only left-handed neutrinos and maximally violating parity. However, there is no a priori reason for these properties of the weak interaction, and Beyond SM theories may be (and have been) constructed in which a small deviation from these properties is introduced. A measurement of the correlation coefficients in the beta decay of radioactive nuclei is a sensitive probe for any such small deviations.

In the proposed project, we will precisely measure several of the beta-decay correlation coefficients, using complementary experimental techniques. Any deviation from the SM model values is a clear indication of physics beyond the standard model. These measurements are an extremely powerful test of the standard model since the accuracy of the measurement constrains new physics as, $(M_W/M_{New})^2 \sim Acc$, where M_W is the W boson mass, M_{New} is the mass scale of the new physics, and Acc is the accuracy. Thus, a 1% measurement translates to a constraint on physics beyond the SM at the TeV scale, which is essentially the LHC scale. This project will measure the correlation coefficients **at least to the 0.1% level**, leading to constraints beyond the current reach of high-energy experiments.

Proposed Measurements

To measure angular-correlation coefficients one must have a localised, non-interacting radioactive sample. This is impossible in solid samples, since angular information is washed out by the interaction with the solid matrix. Beam-decay experiments, where radioactive decay is detected in a beam of radioactive atoms or ions, is also challenging, due to the large region, which must be instrumented with detectors in order to obtain a reasonable statistical sample. The advent of efficient traps for ions and atoms has initiated a programme of such measurements [5-7]. Traps present an almost ideal system to measure such decays since they are well localised, low-density (i.e., non-interacting), and highly isotope selective.

This project will use two different traps, a Magneto-Optical Trap (MOT), and an Electrostatic Ion Beam Trap (EIBT) to trap radioactive isotopes and measure these decays. In particular, we focus on the Ne and He isotopes, each exhibiting specific properties making them attractive systems for study. Since these rare isotopes are short-lived they must be produced in an accelerator facility and trapped online immediately after production.

Schematics of radioisotopes production by fast neutrons

Expected yields for a BeO target: ${}^9\text{Be}(n,\alpha){}^6\text{He}$

SARAF (40 MeV, 2 mA): $8 \times 10^{12}/\text{sec}$

Expected yields for a BN target: ${}^{11}\text{B}(n,\alpha){}^8\text{Li}$

SARAF (40 MeV, 2 mA): $2 \times 10^{12}/\text{sec}$

Also: ${}^{16}\text{O}(n,p){}^{16}\text{N}$, ${}^{23}\text{Na}(n,p){}^{23}\text{Ne}$

With IFMIF – 60 times higher yield!!

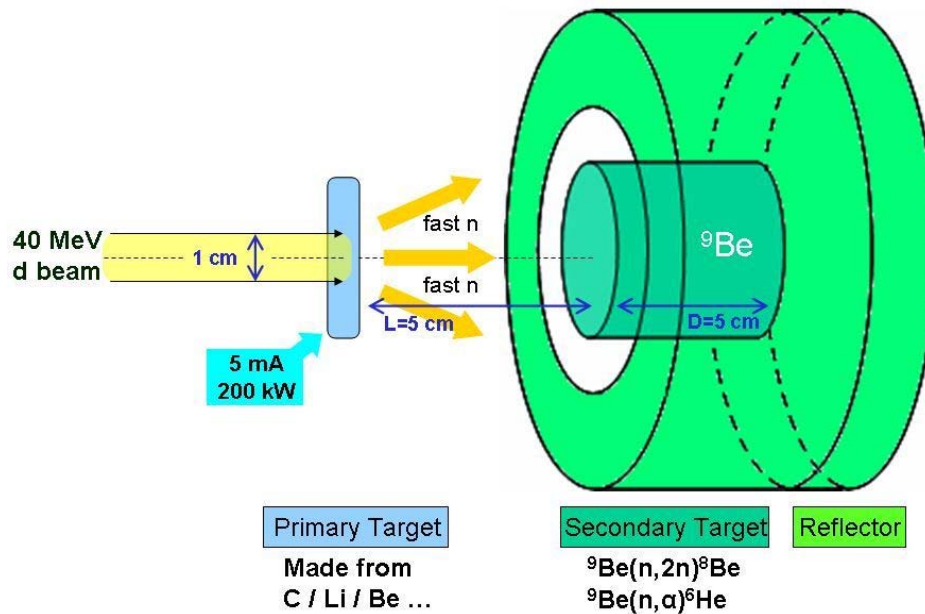


Figure 3. Experimental setup.

Needs:

- Access to fast-neutron flux; even at not-optimised geometry (depending on configuration) – vast yield improvement.
- High-temperature oven (to hold the production target) with transfer of produced radioisotopes to a remote location with a radiation-free environment.
- At the remote location, instalment of ion or atom-trap devices such as a MOT (for ^{23}Ne) and electrostatic trap (for ^6He).

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Chapter 4: Basic physics studies

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Summary of the chapter

While IFMIF-DONES is predominantly a facility for applications, the available high neutron flux can be used for basic studies as well. However, it should be kept in mind that any additional modification in the original setup will increase the costs. Furthermore, special care should be taken to preserve the excellent characteristics of the facility. In that respect to use the high-intensity neutron field via (n,α) reactions to produce special long-lived isotopes seems to be very feasible. The determination of the half-lives of several isotopes is interesting for different fields, like astrophysics, reactor physics and medical applications. It is also important that the available neutron energy is adequate for such an isotope production.

A step beyond is to build up a cold-neutron beam line. Once it is established, particle physics problems can be studied such as the neutron-antineutron oscillations and neutrino oscillations. Here, also a sophisticated tracker detector setup is necessary to be built.

It is foreseen that in the next 15 years several major research reactors in Europe will be closed. Therefore, the reactors serving for material science in Europe will be very limited and the neutron-scattering community in Europe will be forced to use pulsed sources only.

IFMIF-DONES, owing to the high-intensity neutron yield, can remedy this problem after a modification of the facility. Two important steps are required to apply the neutron beam for studies in the area of solid-state physics, i.e. energy moderation and monochromatisation. The latter one can be achieved either through time-of-flight method, or through Bragg diffraction. It should be investigated in details whether the above modification of the facility still allows the primary aim of the system, i.e. ultra-high neutron dose in a given volume for material testing. Once the system is ready, theoretical studies, e.g., ab-initio approaches in material sciences, can be verified experimentally.

Physics topics

- Half-life measurements on long-lived isotopes (A)
- Neutron and neutrino oscillations (B)
- Solid-state physics studies (C,D)

List of contributions

- A. **Half-life measurements on long-lived isotopes**
R. Reifarth, Goethe University, Frankfurt, Germany

B. Neutron and Neutrino oscillations in the framework of IFMIF-DONES facility

A. Letourneau, Irfu/SPhN/LEARN, CEA-Saclay, Gif-sur-Yvette, France

C. Neutrons in solid-state physics

W. Szuszkiewicz, Faculty of Mathematics and Natural Sciences, University of Rzeszów, Poland

D. Ab-initio modelling of materials studied at IFMIF-DONES

P. Piekarczyk, Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland

Facilities (by order of complexity in implementation)

- Irradiation facility
- Cold neutron beam
- ToF facility/monochromator

Half-life measurements on long-lived isotopes

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The determination of half-lives in the range of 10^4 - 10^8 years is a very challenging task. The reason is that the half-life can only be determined from the ratio of activity and number of nuclei. Therefore, the activity must be determined, which is difficult, since usually no gamma ray is emitted and, even more challenging, the number of atoms has to be determined. The determination of the number of atoms is difficult, because the material has to be freshly produced since it is not naturally abundant on earth. This means, it will only be available in minute amounts. This typically results in huge systematic uncertainties, which is reflected in contradicting data from different measurements.

One possibility to address this problem is to produce a short-lived isotope, which decays to the long-lived isotope. Since the half-life of the short-lived isotope is known, the total amount produced can easily be determined from the activity. This means, the task of determining the long half-life is reduced to the measurement of two activities.

In particular, the hard-energy spectrum of the IFMIF-DONES facilities is ideal to use the described approach in combination with (n,α) reactions. The following cases are interesting for different fields, like astrophysics, reactor physics and to some extent medical applications:

Isotope:	^{93}Zr ($1.5 \cdot 10^6$ years)
Production path:	$^{96}\text{Zr}(n,\alpha)^{93}\text{Sr}(\beta^-)^{93}\text{Y}(\beta^-)$ (10 h)
Isotope:	^{79}Se ($3 \cdot 10^5$ years)
Production path:	$^{82}\text{Se}(n,\alpha)^{79}\text{Ge}(\beta^-)^{79}\text{As}(\beta^-)$ (8 min)
Isotope:	^{107}Pd ($7 \cdot 10^5$ years)
Production path:	$^{110}\text{Pd}(n,\alpha)^{107}\text{Ru}(\beta^-)^{107}\text{Rh}(\beta^-)$ (22 min)
Isotope:	^{135}Cs ($2 \cdot 10^6$ years)
Production path:	$^{138}\text{Ba}(n,\alpha)^{135}\text{Xe}(\beta^-)$ (9.1 h)
Isotope:	^{129}I ($1.5 \cdot 10^7$ years)
Production path:	$^{132}\text{Xe}(n,\alpha)^{129}\text{Te}(\beta^-)$ (33 d / 1 h) (see Fig.4)

It is necessary to monitor the beam with a time resolution significantly better than the short half-life. Only a relative flux monitor is needed, no absolute information is required. In addition, it is necessary to irradiate the sample not much longer than 2 times the short half-life. After that, the

freshly produced gamma-activity should be measured with Ge-detectors. If not enough material is produced, the procedure can be repeated.

It is necessary to be able to extract the sample without interference with the main programme. Ideally, the irradiation times can be chosen solely based on the shorter half-lives. In addition, a gamma-ray detector is necessary. The most general type is a Ge-detector combining high resolution with reasonable efficiency and timing.

The samples will be small, typically 1 g. The only space needed is for the rabbit system and the activation analysis. The latter will require a somewhat shielded environment of $\sim 4\text{m}^2$.

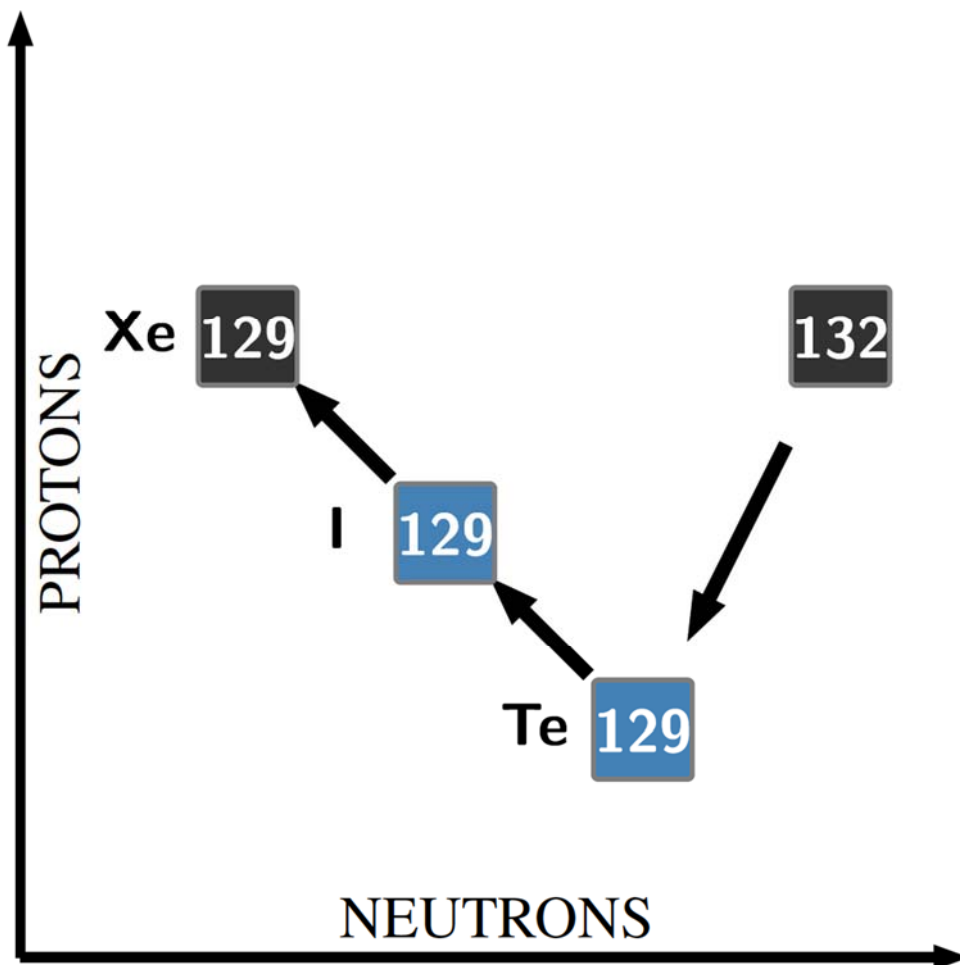


Figure 4. Illustration of the production path of ^{129}I .

This programme is uniquely suited to IFMIF-DONES setup, since it takes advantage of the high neutron flux and the spectrum. The (n,α) channel typically opens around 1 MeV, which means all the available neutrons contribute to the production. The neutron flux in this energy regime is much higher than at reactors, hence this approach is much more feasible. The absence of thermal neutrons in the meV-regime ensures that neutron captures on other isotopes do not occur. This keeps the systematic uncertainties small.

Neutron and Neutrino oscillations in the framework of IFMIF-DONES facility

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Scientific case

- Why is there more matter than anti-matter in the universe?
- What is the character of the neutrino?

These two fundamental questions can be addressed using very intense neutron sources.

The observed predominance of matter over antimatter in the universe cannot be explained based on the symmetries of the Standard Model (SM) of particle physics. A violation of the baryon number (B) conservation is one of the conditions required to explain such asymmetry [1]. Such violation is included in various grand unified theories, wherein B-violation occurs through the exchange of massive ($M \gg M_{\text{WEAK}}$) particles. In the SM, the baryon (B) and lepton (L) numbers are accidentally conserved at the renormalisable level, but both are broken by non-perturbative effects [2] with only the combination B-L conserved. If neutrinos are of the Majorana types (neutrino is its own anti-particle) they provide evidence for B-L violation, via $\Delta L=2$ operator. The conservation can be restored if B-violation occurs by two units ($\Delta B=2$). One experimental test for such $\Delta B=2$ violation is the search for the existence of neutron-antineutron oscillation ($n \rightarrow \bar{n}$). The present limit on $n \rightarrow \bar{n}$ transition is slightly above 10^8 s and has been obtained for bound neutrons in the super Kamiokande detector [3]. The best limit for free neutrons was obtained in the 90's at the ILL research reactor with a value slightly below 10^8 s [4]. Regarding the latter experiment, two parameters can nowadays be improved to increase the sensitivity of the experiment: the neutron flux and the propagation time of the neutron in quasi-free conditions (without interaction). A gain of two or three orders of magnitude on the neutron flux will immediately allow testing supersymmetric models predicting a baryon-violation around 10^{10} s.

Neutrino oscillation experiments have clearly established the existence of a non-vanishing neutrino mass. The PMNS matrix relating flavour eigenstates to mass eigenstates is now well constrained with the latter results from Daya-Bay, Double-Chooz and Reno [5]. Despite such high-statistics measurements, some incoherency exists between predictions and measurements that could be attributed to the existence of light sterile states. An important research effort is now devoted to search for new oscillations at short distances [5]. Using intense decay-at-rest neutrino sources would be very profitable to explore short-range neutrino oscillations and possibly discover new physics.

Beam characteristics

An intense cold-neutron beam is needed to measure the neutron-antineutron oscillation. The neutron divergence should be reduced first before it propagates over several tens of meters (~70 m or less depending on the neutron velocity) in a beam tube surrounded by mu-metal to reduce the earth magnetic field influence. At the end of the beam tube, a tracker detector of about 2*2*2 m³ of overall footprint will be placed to detect antineutrons in the neutron beam. Neutrons should be moderated first in the irradiation cell with a compact high-brightness cold-neutron moderator (20*20*20 cm³) and extracted to a hall where the experiment could be placed.

For electron-anti-neutrino production, an enriched lithium blanket to favour the ${}^8\text{Li} \rightarrow {}^8\text{Be} + e^- + \bar{\nu}_e$ reaction by radiative neutron capture on ${}^7\text{Li}$ could be placed around the moderator. Direct production of electron anti-neutrinos in the lithium target should also be explored.

Equipment required

A cold high-brightness moderator is needed to moderate neutrons and collimate them into a direction. Such features can be obtained with very compact cryogenic moderators as those developed to enhance the brightness of existing neutron sources (see for example the 20*30*3 cm³ cold moderator for ESS [6] using para-H₂ at 20 K). A cryogenic hydrogen system supplying super-critical hydrogen consisting of a helium refrigerator system and a hydrogen circulation system would then be needed. This system can be placed in a separate room.

This has still to be studied but one advantage of such compact moderator is that it could be placed off-axis of the deuteron beam allowing fast neutrons to be extracted from the irradiation cell for specific studies using fast neutrons.

Space required

Regarding the planned [6] or J-PARC [7] cold moderators, a volume of 20*20*20 cm³ in the irradiation cell as close as possible to the irradiation module would be sufficient. A dedicated room for the cryogenic hydrogen system should be anticipated and a hall for experiments where the cold neutrons beam could be extracted.

Other information

The influence of moderated neutrons and the irradiation materials should be addressed.

Uniqueness or benefits doing this at IFMIF-DONES (compared to existing facilities)

Cold neutrons are used for a wide spectrum of basic science. Dedicated installations in Europe like ILL or ESS are/will be in operation in the next decades. Regarding the neutron flux in the irradiation cell and with a dedicated high-brightness moderator, we could expect one or two orders of magnitude more intense cold-neutron beam than ESS. In that case, it is clear that for specific studies of rare processes like neutron-antineutron oscillation IFMIF-DONES will be unique in Europe and in the world.

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Neutrons in solid-state physics

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The development of the nuclear reactors (continuous sources of neutrons) first and the accelerator-based spallation neutron (pulsed) sources subsequently allowed beams of neutrons for materials research to become routinely available. However, it is foreseen that in the next 15 years several major research reactors in Europe will be closed. It is the case of Helmholtz Zentrum Berlin (HZB, 2019), Laboratoire Léon Brillouin in Saclay (2019) or Institute Laue-Langevin in Grenoble (probably after 2023). Several other reactors have been closed in recent years (Risø in Denmark 2000, Jülich in Germany 2006 and Geestacht in Germany 2010). Some other medium-flux smaller facilities in the Netherland, Czech Republic or Hungary will be probably closed by 2030 or even faster. The construction of new reactors dedicated to studies in the area of a general material science including both solid-state physics and industrial applications is no more planned. The Jules Horowitz Reactor in Cadarache (France) which is the only research reactor under construction now in Europe, cannot be applied for the studies above mentioned because it is dedicated to very selected, well defined other important purposes related to materials and nuclear fuel used in nuclear industry. There is a real risk that at least in 2030 the last reactor serving for research in material science in Europe will be closed and after this date, the neutron scattering community in Europe will be limited to the use of pulse sources. In spite of the fact that the list of such sources will be rather short (which will result in much more limited access to neutron beams) they will not be able to fill the gap in experimental possibilities offered by continuous sources. What is the reason for it?

Two important steps are required to apply the neutron beam for studies in the area of solid-state physics. First of all, it is crucial to moderate high-energy neutrons created by the neutron source and to reduce their velocity by five orders of magnitude from the speed of light to the speed of sound. Under the circumstances, neutrons applied in solid-state physics are not relativistic, but classical particles. The second necessary step would be a monochromatisation of the neutron beam by proper selection of the neutron's velocity (time-of-flight method) or the neutron's wavelength (by the use of Bragg diffraction). In the first case, typically a fraction (up to 10%) of the neutrons can be used in a scattering instrument. The European Spallation Source (ESS) is an exception because all the neutrons of an ESS pulse can be used thanks to its time structure. In the second case, the crystal monochromator diffracts only a specific neutron wavelength (with a wavelength spread of typically 1%), so with this technique only 1% of the initial neutron flux is used to perform the scattering experiment on the sample.

All interactions of slow neutrons with matter are weak and generally each neutron scatters only once within the sample volume. The neutron mass gives to the thermal neutron a de Broglie wavelength comparable to interatomic distances in crystals, allowing an interference effect, used to determine both the nuclear structure and the magnetic ones. An even more important consequence of

the mass is the energy of thermal neutrons (10-80 meV), particularly suited to study both nuclear and magnetic thermal excitations. It should be highlighted that the neutron scattering is a unique experimental technique in magnetism since the interaction with the electronic magnetic moment is of the same order of magnitude as the interaction with atomic nuclei. Neutrons are sensitive to the electronic magnetic moment or fluctuations amplitude perpendicular to the momentum transfer. Moreover, an application of polarized neutron beams allows one to separate the nuclear and the magnetic scattering and gives access to a more detailed picture of the structure of the investigated sample.

In order to get a general picture of dispersion of given excitations a monochromatisation of an incident neutron beam by the time-of-flight method is an optimal choice. This method of monochromatisation can be applied both using the continuous neutron source (reactor) and the pulse source like a spallation source or an accelerator-driven compact neutron source taking advantage of the stripping effect. Because of the application of an array of neutron detectors which covers a wide range of scattering angles and simultaneous measurements of scattered neutrons with various energies the determination of dispersion does not take a long time. A disadvantage of the time-of-flight method apart from the relatively high price of an array of neutron detectors is the limited accuracy in determination of fine details of dispersion under study. The neutron beam monochromatisation taking advantage of Bragg diffraction can be applied only when using the continuous source. In this case, due to the necessity of a change of single, point detector position in a step-like manner the experiment is more time-consuming, but one could expect much higher precision in determination of dispersion details.

The experiments, serving for the determination of crystal magnetic structure, are related to relatively high neutron scattering cross sections. The measurements mentioned above do not require high neutron flux and can be realized using even compact (of medium size) accelerator-based neutron sources. Such neutron scattering techniques as the small-angle scattering, imaging or powder diffraction do not need extreme neutron flux. The situation is quite different when considering inelastic neutron scattering serving for studies of excitations in solids. Such measurements require either continuous neutron source or a high-intensity pulsed source (in practice – spallation source only). According to the latest news, the ESS could be fully operational in 2023 but the users programme will start in 2025. Moreover, as it has been pointed out before, even the experimental opportunities offered by ESS could not replace completely similar opportunities offered by a continuous source.

The planned construction of IFMIF could completely change the situation. The important point to be taken into consideration is a continuous in practice operation mode of IFMIF and a high neutron flux, which can be obtained with this facility. What we propose is to complete the present IFMIF project by a moderator in order to get an access to low energy neutrons and to construct the separate beam line equipped with a monochromator, a triple-axes spectrometer and neutron polarizers. As we do not plan to take advantage of the time-of-flight technique, it does not require a lot of space because for the neutron energy selection the Bragg diffraction on Si or pyrolytic graphite monochromator will be applied. After 2030, it could be the only experimental facility in Europe for high accuracy studies of excitations in solids. The point is that the precise knowledge of details of such excitations gives access to proper understanding of relevant interactions in solids, which is extremely important from point of view of both basic physics and material-science applications. It concerns a variety of materials not only limited to more or less classical superconductors, metals or semiconductors, but also concerns multiferroics, ferroelectrics, topological insulators etc. Expected further development of the modern

technologies will result for example in a consecutive progress within the area of methods and means of transport, the transportation and storage of energy as well as the anticipated growth of the space industry. It will clearly require further development of experimental methods of research with the use of the neutron beams. Even under assumption that the development of an additional cold-neutron beam line in the IFMIF that would take advantage of the time-of-flight monochromatisation method is established, it would be certainly desirable to keep some space for the further development of this line by a crystal monochromator. The cost of such a monochromator should correspond to a minor part of the total cost of the moderator, shielding, detector system etc. Possible neutron scattering studies of solids, to be performed in IFMIF after 2030, would be a valuable complement to the experimental opportunities of another European large research infrastructure ESS.

Ab-initio modelling of materials studied at IFMIF-DONES

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IFMIF, the International Fusion Materials Irradiation Facility, will generate a high flux of neutrons for fusion-power-plant materials testing. The main objective of the project is to investigate changes in materials properties due to high concentration of crystal defects induced by neutron irradiation. The first principles (*ab-initio*) calculations can be very helpful to understand the basic processes of defects formation, their migration and clustering, which lead to material damages.

Crystal defects modify the basic physical and chemical properties of materials. This effect is enhanced in materials with tendency to accumulate a large number of defects. The accuracy of *ab-initio* modelling, involving no experimental input parameters, is now sufficient for the meaningful analysis of materials properties. First principles calculations based on the density functional theory (DFT) provide relevant information about the formation energies of defects, the structure of nanoscale defects, the nature of short-range interactions between defects, clustering of defects, and their migration [1,2]. Often this information is not available from experiments. The *ab-initio* studies can explain the influence of defects and their clusters with high concentration on the structural, electronic, magnetic and dynamical properties of materials [3]. DFT calculations can provide also the input parameters to other theoretical methods: Monte Carlo simulations, molecular dynamics or cluster expansion approach.

A number of problems in the development of nanoelectronics are tightly connected with the understanding of defects, usually associated with harmful effects on device operation (trapping free carriers, reducing the carrier lifetime). The electronic properties of epitaxial layers also strongly depend on the material quality. The presence of intrinsic defects and impurities which arise during crystal growth process substantially limit applications of materials such as silicon carbide (SiC) - a promising material in fusion power plant: use of SiC flow channel inserts (FCI) as electrical and thermal insulator in the Dual-Coolant Lithium-Lead (DCLL) blanket of fusion reactor systems. However, some properties such as the vacancy-induced magnetism in SiC can be enhanced in samples irradiated by neutrons [4], and could be investigated using the IFMIF-DONES facility.

The DFT calculations provide the means for evaluating the structure of radiation defects and basic characteristics such as the energy of interaction between radiation defects and impurities, activation energies characterising reaction rates and dynamics of migration and clustering of radiation defects. Higher neutron fluxes and higher average neutron energies in fusion reactors give rise to new processes like the transmutation production of gas atoms (He, H) that have severe consequences for materials [1]. It generates also fundamental questions, which can be addressed within the *ab-initio* studies: diffusion of gas atoms in the crystal, their clustering and accumulation at vacancies, dislocations or grain boundaries, and their influence on structural and elastic properties of materials.

These examples confirm the general importance of basic studies on crystal defects by the *ab-initio* methods.

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Chapter 5: Industrial application of neutrons

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Summary of the chapter

This chapter summarises the results of an initial study on feasibility of using the IFMIF-DONES facility for other industrial applications beyond its main objective, which is to examine mechanical properties of materials expected to be used in future fusion reactors. Three different areas of industrial applications have been identified: (a) investigation of properties of irradiated materials from miniaturised samples, (b) computed tomography imaging using fast neutrons, and (c) transmutation doping of silicon and radiation-damage testing of electronic devices. The requirements for additional infrastructures to be added to baseline IFMIF-DONES facility have been outlined.

Introduction

The use of IFMIF-DONES facility will be a unique source of fast neutrons and gamma radiation, which potentially can be used for some industrial applications beyond the main goal to study materials for future fusion reactors. For each of such an application there are two important issues to be considered carefully, namely: compatibility of additional needed infrastructure with the baseline design of the IFMIF-DONES, and compatibility of such a programme with the main programme of the facility. Additional infrastructure for specific applications can be added providing the funding is available but it should not interfere with the current design of the facility. Similarly, using neutrons or gamma radiation for other applications should not compromise the main programme of the facility.

Applications

- Mechanical properties of irradiated materials from miniaturised samples
- Computed tomography imaging using fast neutrons
- Transmutation doping of silicon and radiation-damage testing of electronic devices

List of contributions

- A. **Mechanical properties of irradiated materials from miniaturised samples**
J. Jagielski, National Centre for Nuclear Research, Świerk, Poland

- B. **The potential use of fast neutrons from IFMIF-DONES to perform computed tomographic imaging**
J.N. Wilson, Institut de Physique Nucléaire d'Orsay, Orsay, France
- C. **Neutron-transmutation doping of silicon and testing of radiation effects in electronic devices**
W. Dąbrowski, AGH University of Science and Technology, Kraków, Poland

Facilities (by order of complexity in implementation)

- Material engineering laboratory and hot-cell laboratory
- Mixed radiation, fast neutrons and gamma, irradiation facility for testing electronic devices (just behind IFMIF samples)
- Collimated beam facility and advanced high-granularity detection system
- Moderator and thermal neutron irradiation facility for transmutation doping of silicon

Summary table

Topic	Facility	Instrumentation	Comments
Miniaturised samples	Collimated beam		
Fast neutron CT			
Radiation effects in electronic devices	Irradiation space outside IFMIF box	Cabling to connect external electronic power supplies and testing equipment	Precise dosimetry in the irradiation area needed
Transmutation doping of silicon	Moderator, large irradiation space	Standard electronic testing equipment	

The potential use of fast neutrons from IFMIF-DONES to perform computed tomographic imaging

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The possibility for using high fluxes of fast neutrons at IFMIF-DONES for producing 2D and 3D computed tomographic (CT) images of the internal structure of objects is examined. An evaluation is made of what this new technological development could add with respect to x-ray CT, a widely used and relatively cheap method of imaging, and thermal neutron CT, which is a more recently emerged technique.

Introduction

The use of ionising radiation to make images first started with the x-ray radiographs of Röntgen for which he was awarded the first Nobel Prize in 1901. Imaging techniques then reached a higher level of sophistication in the early 1970s. It was demonstrated that a collimated beam of x-rays and a detector system could be used to probe the attenuation of x-rays through solid objects at different angles and positions. By combining attenuation data for many different angles and positions, 2D and 3D images of the internal structure of the object could be produced using computational techniques. Allan M. Cormack and Godfrey N. Hounsfield won the Nobel Prize in medicine for these developments in 1979 and they have since proved hugely important in the field of medical imaging but have also found wide application in fields as diverse as engineering, archaeology and materials testing.

The principal limitation of x-rays, however, is the lack of penetration into dense objects with high atomic numbers (Z) meaning that there are whole classes of objects, particularly those composed of thicknesses of high- Z materials, which cannot be imaged with x-rays (see Fig. 5). Neutrons, with their high penetrability, afford an alternative means of imaging since they have absorption properties, which are highly complementary to those of photons. While thick high- Z materials are capable of strongly absorbing both x-rays and gamma rays, they are much more transparent to fast neutrons. On the other hand, organic materials containing large amounts of hydrogen are well penetrated by photons, but easily scatter neutrons.

Scientific case

Very little research work has been performed for tomography with accelerator-based fast-neutron sources due to the difficulty of producing finely collimated neutron beams and high enough fluxes simultaneously. However, at the proposed IFMIF-DONES high fluxes of accelerator-generated fast neutrons (peaked at around 14 MeV) will be available which may provide an ideal environment for the development of fast-neutron tomographic techniques and possibly also their commercialisation.

There is currently no facility dedicated to computed tomographic imaging with fast neutrons. However, fast neutrons are the most effective radiation type to penetrate the thickest and most dense objects. While a handful of thermal-neutron imaging facilities exist [1,2], there are some drawbacks to using thermal neutrons such as the potential activation of the sample, the fact that the attenuation in matter varies wildly as a function of atomic number and the difficulty of building a high-efficiency detection system. These drawbacks do not exist for fast neutrons since neutron radiative-capture cross sections are very small and they have sufficient energy to be detected with high efficiency. A further advantage of using fast neutrons for imaging purposes is that the neutron energy is sufficiently high to excite nuclei inside the object via inelastic scattering reactions. The nuclei excited in this way will then emit gamma rays as they de-excite which are highly characteristic of the isotope in question.

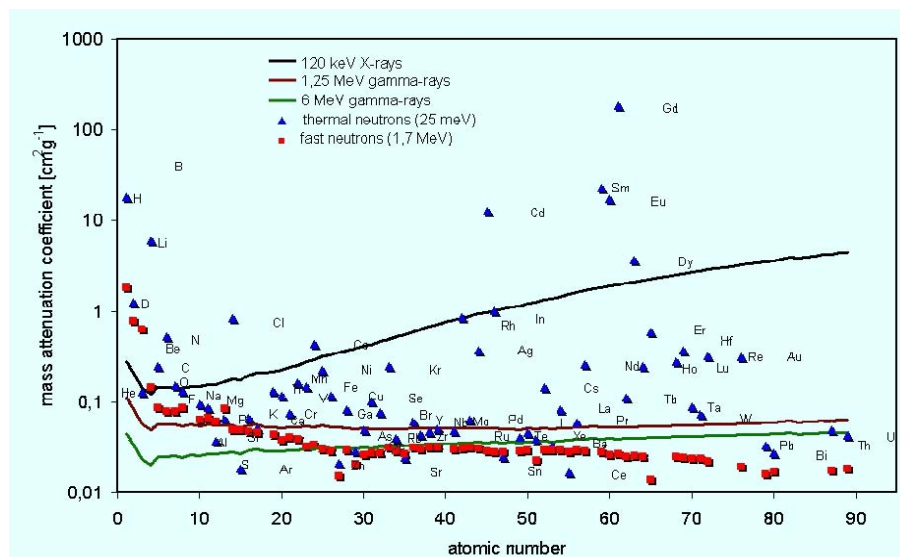


Figure 5. Mass attenuation coefficients for x-rays, gamma rays, thermal neutrons and fast neutrons (1.7 MeV) as a function of atomic number.

If a high-efficiency gamma-detection system was placed around the object, it may be possible to produce images for the spatial distribution of each individual isotope in the interior of the object, giving extremely useful information about the elemental composition inside the object that no other technique would have access to. The kinds of imaging that might be envisaged at the proposed IFMIF-DONES facility are in the following diverse scientific domains:

- **Precision quality control for industry:** (e.g., fault inspection of large and expensive industrial components)

- **Nuclear materials and safeguarding:** (e.g., non-destructive methods for characterising the contents of nuclear-waste containers)
- **Border Security:** (e.g., detection of actinide material in containers passing through a port or detection of explosives in air-passenger baggage)
- **Cultural heritage and archaeology:** (e.g., non-destructive testing of large archaeological objects)
- **Planetary science:** (e.g., non-destructive examination and assay of meteorites, which frequently include metallic inclusions, and isotopic ratios of included materials often differ importantly from terrestrial material).

Needed beam characteristics and space requirements

The spatial resolution achievable depends largely upon the degree of collimation of the neutron beam in terms of the L/D value, the ratio of the distance to the object, L , and diameter of the neutron beam, D . The higher the degree of spatial precision required the more collimation is necessary but the lower the flux and the greater the exposure time to obtain an image. Thermal-neutron facilities have typical L/D values of around 100-500 and can achieve a spatial resolution of a few micrometres. This means that the object needs to be at least tens of metres away from the source and collimation requiring at a minimum several metres thickness of borated concrete. In addition, precise simulations would need to be carried out to determine an imaging station room and collimator design where the fast-neutron, thermal-neutron and gamma backgrounds at the imaging station are sufficiently low. A method of remotely plugging the fast-neutron beam line would also be essential since access to the imaging station to maintain detectors and to position new objects to be imaged would be required regularly.

Finally, a highly granular neutron detection system would be mandatory. This would ideally be a highly segmented liquid scintillator array of a dimension of the order of $1\text{m} \times$. Individual pixels allow attenuation of neutrons for many trajectories through the object simultaneously.

In addition, a segmented and efficient gamma-ray detector array placed perpendicular to the beam axis would allow detection of gamma rays emitted from the object and additional information to be gathered about the spatial distributions of different isotopes inside the object.

Uniqueness of the IFMIF-DONES facility

For non-medical application, numerous x-ray CT scanning facilities exist and the technology is already widely used and commercialised. For thermal neutrons, there are currently a handful of facilities in Europe based around nuclear reactors [2]. Therefore, a necessary criterion for the development and commercialisation of fast-neutron tomography is that it must provide an additional benefit over the existing imaging techniques that are cheaper, better developed and more widespread. The unique appeal of IFMIF-DONES is then firstly the penetrating power of the ~ 14 MeV fast neutrons that may allow imaging of objects, which are particularly large and/or particularly dense containing significant thicknesses of high- Z materials. In addition, there will be the unique possibility

to detect emitted gamma rays allowing additional information about the spatial distributions of isotopes within the objects to be collected.

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Mechanical properties of irradiated materials from miniaturised samples

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Scientific case

Main objective of the IFMIF-DONES is to examine the role of irradiation with fast neutrons on mechanical properties of materials expected to be used in future fusion reactors. Most of the tests used for this purpose has to be carried out according to commonly accepted standards, and consequently, the samples used are described by international protocols. Typical size of the sample is in the order of 10 cm³. Taking into account that the highest flux of neutrons is obtained in roughly 300-cm³ volume, each test has to be repeated several times and the expected dose accumulated in one year of continuous operation of the facility can be estimated to be 10-30 dpa. One may conclude that the use of standard samples will limit the number of tests roughly to one test of one material per year. This is hardly acceptable and points to the critical need for the implementation and validation of a new generation of mechanical tests that may be performed on much smaller samples than the ones currently used. Such tests should first be developed, then executed and the results obtained should be compared to currently used protocols. The influence of irradiation on materials properties should be analysed for new and current generation of tests. The results obtained for both inactive and irradiated materials should be compared for both tests.

Beam characteristics

The highest possible neutron flux should be used. Studies of the influence of accumulated dose would require the possibility to extract the samples from the irradiation capsule. The samples should either be analysed in an adjacent hot-cell laboratory or packed and shipped to an external hot-cell lab, presumably similar to standard TSO (technical support organisation) laboratory.

Equipment required

The project can be started well before the IFMIF-DONES operational phase. In the first stage, a standard material engineering laboratory equipped with structural and mechanical test facilities will be used. The objective of the first stage is to analyse mechanical properties of materials by using samples of the reduced size and compare the results to standard methodology. In the second stage, the role of irradiation on measurements performed on small-sized samples will be assessed. One may use a

standard material testing reactor (MTR) for this purpose. In the third stage, the comparison between standard methodology and small-sized sample tests will be performed using fast neutrons. Only this stage will require the use of IFMIF-DONES accelerator.

Space required

Depending on final configuration of IFMIF-DONES facility the samples may be measured either in the adjacent hot-cell laboratory or packed and transferred to an external hot-cell lab. Standard tests, such as hardness, toughness, strength will be required. New, small-sized tests may be installed either in IFMIF-DONES or in external hot-cell labs. In a first approximation, three standard hot cells would be required for this purpose.

Other information

The proposed programme answers the needs of both fusion and fission communities. Development of fusion devices and of IV Generation fission reactors requires numerous new materials able to withstand high temperatures, corrosive environments and high doses of irradiation with fast neutrons. In both cases, new samples of much smaller size and irradiation devices able to accumulate high irradiation doses in relatively short time are critically needed. It is worth to point out that studies of sample miniaturisation have been already initiated in the frames of the Joint Project Nuclear Materials of EERA.

Uniqueness or benefits doing this at IFMIF-DONES (compared to existing facilities).

IFMIF-DONES appears today as the only one device able to irradiate materials with fast neutrons in a reasonable time what actually means faster than dose accumulation in real nuclear installations. Currently used MTR allows one to accumulate roughly one dpa per year, however, in much larger volumes than the ones expected for IFMIF-DONES. On the other hand, IFMIF-DONES will allow for the accumulation of about 10-30 times higher dose in the same time than MTR.

Neutron-transmutation doping of silicon and testing of radiation effects in electronic devices

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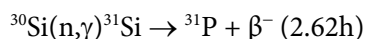
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The IFMIF-DONES facility can be potentially suitable for two important areas of electronics industry, namely: neutron-transmutation doping of silicon and testing of radiation effects in electronic devices, where currently research reactors and high-activity gamma sources are used.

Neutron-transmutation doping of silicon

The neutron-transmutation doping is a technique that allows one to obtain large volumes of silicon with uniform distribution of dopants that is not achievable by other methods. There is continuously growing demand for neutron-transmutation doped silicon in electronics industry driven mainly by applications of high-power devices in hybrid electric cars, wind power and solar-cell power plants.

The method is based on thermal-neutron capture reaction to produce phosphorus (donors) dopants in silicon



The abundance of ^{30}Si isotope in natural silicon is 3.10%.

Absorption of fast neutrons leads to the direct or indirect production of Al (acceptor dopant) or Mg isotopes and this effect should be suppressed. Fast neutrons cause also displacement damage in the silicon lattice, which can degrade electronic parameters of silicon. Thus, a transmutation doping facility should deliver high flux of thermal neutrons with low background of fast neutrons.

Depending on the target doping concentration (resistivity of silicon) the required neutron flux may vary from $2 \times 10^{16} \text{ cm}^{-2}$ to obtain silicon resistivity of $1 \text{ k}\Omega \cdot \text{cm}$ up to $86 \times 10^{16} \text{ cm}^{-2}$ to obtain resistivity of $30 \text{ }\Omega \cdot \text{cm}$. The trends in electronics industry are to use as large wafers as possible. Currently, power devices are processed by leading manufactures on wafers of 8-inch diameters but there is a strong demand for 12-inch wafers. Silicon ingots to be irradiated can be up to 1-m long and preferably, one would like to irradiate several ingots simultaneously. Considering all these requirements it becomes clear that incorporating a facility for transmutation doping of silicon into the IFMIF-DONES facility would require a major additional technical and financial effort to add a dedicated moderator.

Testing of radiation effects in electronic devices

According to physics phenomena, which are responsible for radiation damage in semiconductor devices radiation resistance of semiconductor (and other electronic devices) is defined in three categories:

- damage caused by ionisation effects characterised vs. the total ionising dose
- damage caused by displacement effects characterised vs. 1 MeV equivalent neutron fluence,
- single-event effects caused by charge generated in active volume of semiconductor devices by single particles.

The three categories are not completely independent; however, qualification criteria and qualification procedures are defined separately for each category.

The IFMIF-DONES irradiation facility can be suitable for investigation of ionisation and displacement damage effects in electronic devices as well as for qualification testing. The ranges of required total ionising doses and 1 MeV equivalent neutron fluences are, respectively, the following:

- Total Ionising Dose (TID) up to 10 MGy (SiO_2) with no particular requirements on gamma radiation spectrum provided that the dosimetry is accurate within 5-10%.
- 1 MeV equivalent neutron fluence up to 10^{16} cm^{-2} with no particular requirement on neutron spectrum provided that the spectrum is known.

Additional requirements:

- Single device must be biased during irradiation and more complex integrated circuits or boards comprising components of different types must be irradiated under nominal working conditions, i.e. biased, clocked and supplied with specific digital test patterns. The bias and control equipment can be placed remotely provided electrical connections to the irradiated devices are available.
- The dimensions of irradiated devices may vary from single centimetres for single devices up to tens of centimetres for electronic boards.
- For specific test of ionisation damage and displacement damage, we would prefer gamma-radiation field without neutron background and vice versa neutron-radiation field without gamma background. However, for some tests combined gamma/neutron radiation field will be useful.

Conclusions

The IFMIF/DONES project has as main objective the examination of the effects of irradiation with fast neutrons on mechanical properties of materials expected to be used in future fusion reactors. This research is of crucial importance for the presently under construction International Thermonuclear Experimental Reactor (ITER) as well as future demonstrators for commercial use of nuclear fusion energy. The IFMIF/DONES project provides also truly unique opportunities for Polish and foreign scientists in various research and innovation fields enhancing the performance of cutting-edge research in these fields and bringing their impact to unprecedented level. This goes from the fields of basic science research such as exploring and understanding the very exotic isotopes that have been produced in the early phases of the creation of the universe as well as in stellar processes thereafter, to a large number of applications in medicine, material science and industry.

For medicine, opportunities arise for offering Boron Neutron-Capture Therapy (BNCT) for clinical investigations and therapy, and for production of radioisotopes, such as β - and γ -ray emitters like ^{47}Sc and the worldwide highly in demand $^{99\text{m}}\text{Tc}$ isomer through its ^{99}Mo precursor, and the radiopharmaceuticals from these for medical imaging and/or medical therapy. In some cases, useful α -emitter radionuclides, such as ^{225}Ac , which have high therapy potential, can be produced free from contamination from other radioisotopes.

The availability of high-energy neutrons allows studies of neutron-induced reactions, e.g., (n,γ) , (n,xn) , (n,lcp) , for applications in nuclear technology and accelerator-driven systems. They provide also the possibility to produce radioactive beams through fission. The radioactive fission-fragment beams can in turn be used for nuclear structure and nuclear astrophysics studies. This will make IFMIF/DONES one of the few facilities worldwide that can deliver intense radioactive beams by means of the ISOL technique. The astrophysics programme that can be pursued will allow studies of structure of nuclei along the r-process path, and neutron-capture reaction on long-lived radionuclides thereby delineating the nucleosynthesis of elements, including the elements that are available and made life possible on our planet. Furthermore, certain particle-physics problems can be investigated at the IFMIF-DONES facility once a cold-neutron beam line is built, which allows for studies of the neutron-antineutron oscillations and neutrino oscillations. Physics beyond the Standard Model can be pursued with β - ν correlations in light radioisotopes, the production yields of which at IFMIF-DONES will be one to two orders of magnitude higher than what can be achieved at present neutron-beam facilities.

For material science and industrial applications, the investigation of mechanical properties of irradiated materials - expected to be used in future fusion reactors - from miniaturised samples, the computed-tomography imaging using fast neutrons, and the transmutation doping of silicon and radiation-damage testing of electronic devices are some of the promising opportunities.

The involvement of Polish universities and scientific institutes in the IFMIF-DONES project is expected to be very high and extremely beneficial both in the high research potential and in the opportunities for training future generation scientists.

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Glossary / List of Acronyms

AB-BNCT	Accelerator-Based Boron Neutron-Capture Therapy
AC	Access Cell
AGH	Akademia Górniczo-Hutnicza (AGH University of Science and Technology)
ARIEL	Advanced Rare Isotope Laboratory
AS	Accelerator Systems
BNCT	Boron Neutron-Capture Therapy
BP	Back-Plate
BSM	Beyond Standard Model
CAD	Computer-Aided Design
CEA	Commissariat à l'énergie atomique et aux énergies alternatives
CENBG	Centre Etudes Nucléaires de Bordeaux Gradignan
CS	Conventional Systems
CT	Computed Tomography
CW	Continuous Wave
DCLL	Dual-Coolant Lithium-Lead
DEMO	Demonstration Power Plant
DFT	Density Functional Theory
DONES	DEMO-Oriented Neutron Source
EBIS	Electron Beam Ion Source
ECR	Electron Cyclotron Resonance
EERA	European Energy Research Alliance
EFDA	European Fusion Development Agreement
EIBT	Electrostatic Ion-Beam Trap
ELAMAT	European Laboratory for Material Science
ENSAR	European Nuclear Science and Applications Research
ESS	European Spallation Source
EURISOL	European Isotope Separation On-line Facility
EURATOM	European Atomic Energy Community
EUROfusion	European Consortium for the Development of Fusion Energy
F4E	Fusion for Energy – European Union's Joint Undertaking for ITER and the Development of Fusion Energy
FCI	Flow Channel Inserts
FIPPS	Fission Product Prompt Gamma-ray Spectrometer
FNCT	Fast Neutron Computed Tomography
GANIL	Grand Accélérateur National d'Ions Lourds
GFM	Gas-filled Magnet
HEBT	High-Energy Beam Transport
HEU	Highly-Enriched Uranium
HFTM	High-Flux Test Module
HPGe	High-Purity Germanium
HVPS	High-Voltage Power Supply
HZB	Helmholtz-Zentrum Berlin
HX	Heat Exchange
IAEA	International Atomic Energy Agency

IFF	In-flight Fragmentation
IF PAN	Institute of Physics Polish Academy of Sciences
IFJ PAN	Institute of Nuclear Physics Polish Academy of Sciences
IFMIF	International Fusion Materials Irradiation Facility
EVEDA IFMIF	Engineering Validation and Engineering Design Activities
IIEDR IFMIF	Intermediate Engineering Design Report
ILL	Institut Laue-Langevin
ISOL	Isotope Separation On-line
ISP	Interface Shielding Plug
ITER	International Thermonuclear Experimental Reactor
J-PARC	Japan Proton Accelerator Research Complex
LEBT	Low-Energy Beam Transport
LEGe	Low-Energy Ge detectors
LHC	Large Hadron Collider
LINAC	Linear Accelerator
LIPAc	Linear IFMIF Prototype Accelerator
LS	Lithium Systems
LSP	Lower Shielding Plug
MEBT	Medium-Energy Beam Transport
ODS	Oxide Dispersion Strengthened
OECD	Organisation for Economic Co-operation and Development
MOT	Magneto-Optical Trap
MTR	Material Testing Reactor
NCBJ	Narodowe Centrum Badań Jądrowych (National Centre for Nuclear Research)
NCNR	National Centre for Nuclear Research
PCP	Piping and Cabling Plug
PET	Positron Emission Tomography
PMNS	Pontecorvo–Maki–Nakagawa–Sakata
POLATOM	National Centre for Nuclear Research Radioisotope Centre
R&D	Research and Development
RF	Radio Frequency
RFQ	Radio Frequency Quadrupole
RIB	Radioactive Ion Beam
SARAF	Soreq Applied Research Accelerator Facility
SM	Standard Model
SPES	Selective Production of Exotic Species
SPIRAL2	Système de Production d'Ions Radioactifs Accélérés en Ligne (Linearly Accelerated Radioactive Ion Production System)
SRF	Superconducting Radio Frequency
SSPA	Solid State Power Amplifier
SSTT	Small Specimen Test Technology
STUMM	Start-up Monitoring Module
SUSY	Supersymmetry
TA	Target Assembly
TC	Test Cell
TCCP	Test Cell Cover Plate
TDHF	Time-Dependent Hartree-Fock

TID	Total Ionising Dose
TM	Test Module
ToF	Time-of-Flight
TPC	Time-Projection Chamber
TS	Test System
TSO	Technical Support Organisation
USP	Upper Shielding Plug
WPENS	Early Neutron Source work package