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International Workshop
Advanced Neutron Sources and its Applications
IWANS

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An International Workshop on Advanced Neutron Sources and its Applications (IWANS) was held on 4&5 November 2017 in Aomori city hosted by Rokkasho Fusion Institute of the Japanese's National Institutes for Quantum and Radiological Science and Technology (QST). This 1st worldwide workshop on the topic aimed to discuss the required development and potential application of available advanced neutron sources concepts, to build up a global international forum for discussions on the common technological challenges among neutron sources.The present article, co-authored by all speakers and conveners, highlights the technical matters arisen during the fruitful discussions held.

1. Introduction

An International Workshop on Advanced Neutron Sources (IWANS) and its Applications was held on 4&5 November 2017 in Aomori city hosted by hosted by Rokkasho Fusion Institute of the Japanese's National Institutes for Quantum and Radiological Science and Technology (QST), where the IFMIF/EVEDA Project [1] is proceeded under the Broader Approach Activities [2] at the International Fusion Energy Research Centre (IFERC) site, including the validation tests of Linear IFMIF Prototype Accelerator (LIPAc) [3]. The worldwide efforts to promptly develop Accelerator Driven Systems and novel medical concepts is backed by the technological advancements of this decade on both accelerator technologies and beam targets, which approach the readiness of the needed technology.

The 1st IWANS enjoyed the participation of 50 experts from China, Europe and Japan who openly shared their achievements and pending challenges fostering the synergies among projects that share technological frontiers.

The agenda was structured such that it was started from a detailed review of the users' requirements on the neutron sources for materials development [4,5], followed by a session focused on the understanding of the status and R&D expectations for various representative presently planned projects. After this, different technical sessions covered the main technological challenges focusing the discussion in *Accelerator-related issues*, *Target-related issues* and *Irradiation-area related issues*, raising discussions on technical matters spotted either during the sessions detailing individual projects or new ones exploiting participants own expertise on potential shared difficulties and their solutions.

The neutron sources projects involved in the two days workshop and their intended applications were as follows:

A-FNS (Japan) (fusion materials research) [6], BISOL (China) (fusion materials research and general research) [7], HINEG (China) (advanced nuclear systems and general research) [8,9], iBNCT (Japan) (cancer treatment), IFMIF-DONES (Europe) (fusion materials research) [10], ImPACT (Japan) (nuclear waste transmutation), J-PARC (Japan) (general research upon users demand), MYRRHA (Belgium) (general research upon users demand) [11] and SORGENTINA (Italy) (particle physics and fusion materials research) [12].

The Agenda and presentations of this 1st IWANS are public at http://www.ifmif.org/1st-iwans, which included a technical tour to LIPAc.

The aforementioned projects are either in under construction, in a state of prototype validation work or in a planning state; synergies among all of them were addressed. The technical discussions demonstrated that the nowadays maturity of the technologies involved allows the soon materialization, likely next decade, of four decades old ideas like those related with a fusion relevant neutron source based on the neutrons stripping from a beam of deuterons (A-FNS, IFMIF-DONES, BISOL) and the appearance of new challenging ideas related with transmutation of nuclear waste like (ImPACT) or cancer treatment (iBNCT).

2. About readiness of technology

The readiness of involved technologies on the accelerator, beam targets and irradiation area (whenever needed) were thoroughly addressed. The present technological limits and areas for further development were also identified and experiences shared.

2.1 Accelerator related issues

Accelerators technologies have evolved enormously in recent years. Concepts on Accelerator Driven Systems (ADS) relying on high current of hydrogen nuclei (either H^+ or D^+ beams) can be conceived nowadays thanks to the invention last decade of superconducting cavities for light nuclei in low-β energy regions [13]. Proton or deuteron beams of few MeV output of an RFQ can be adequately prepared in bunchers to serve as input of superconducting linacs at energies as low as 2.5 MeV or 5 MeV like in LIPAc. The decade old novel concept of quarter-wave resonators (QWR), as well as the more recent half-wave resonators (HWR) can efficiently accelerate from those low energies. In 2013 in SARAF an H^+ beam of 1.6 mA in CW at 4 MeV through HWR at 176 MHz was achieved [14] In 2015 in IHEP an H^+ beam >2 mA in CW at 10 MeV was achieved [15]. LIPAc aims at a D^+ beam at 9 MeV and 125 mA in CW through HWR at 175 MHz within next years [16]. The current ceiling is not yet determined, but the wide apertures of the cavities available above two orders of magnitude bigger than the typical beam size allow holding optimism; thus the goal of ImPACT of conducting a beam of D^+ at 1 A in CW mode through QWR is theoretically achievable [17]. The recent development of HWRs allows bypassing the main drawback of QWR of exhibiting harmonics providing a slight kick driven by its geometrical asymmetry; in addition the lower threshold of operational energies of HWRs are now overlapping with QWRs [18]. The DTL concept exhibits clear technological showstoppers to conduct high current in CW mode from the typical few MeV output energies of an RFQ given the combination of a twofold drawbacks: 1) the short involved lengths of DTL hardware at low energies that sets a strong limitation on the focusing strength of magnets, which are unavoidably relying on velocity dependent Lorentz forces, and 2) the inherent limiting aperture of drift tubes leading to enhanced losses with high currents [17]. However, it is a reliable and practical solution for currents of few tens mA with duty cycles of typically 20% like BNCT concepts are aiming for.

The feasibility of conducting a beam of H^+ or D^+ through an RFQ from typically below 100 keV to few MeV in CW mode was demonstrated in Los Alamos' LEDA in 1999 thanks to the creative dual cooling system on tips and vanes to tune the RFQ during beam operation [19]. This was allowed by the breakthrough on ion sources taking place in 1991 in Chalk River with the successful application of electro-cyclotron resonance (ECR) to generate a beam of light ions [20]. This fostered a dramatic improvement on beam quality, gas fraction and beam availability if compared with cathode based ion sources. The technology has matured; beam injection at 100 keV for currents above 100 mA, even for D^+, is feasible as has been demonstrated in LIPAc [21]. This is of particular importance in high current linacs since space charge phenomena are mitigated at higher energies improving the beam quality injected in a RFQ with an enhancement of the beam transmission [3,17]. The maturity of ECR ion sources also presents a positive impact on the performance of the D-T neutron sources like HINEG for few hundreds of keV energy [8], and allows an enhancement in the fluence driven by the high currents achievable and potential availabilities above 90%. HINEG-I is equipped with neutron measuring instruments for broad energy spectrum based on characteristic peak detection, and has produced a neutron yield of 6.4 x 10^{12} /s [9].

High current accelerators exhibit a difficulty in beam diagnostics since the high power handled limits the use of interceptive diagnostics, which is particularly relevant at low energies where the beam is difficult to detect. In turn, CW mode also limits the possibilities of detection. Further developments on beam diagnostics must run in parallel. In turn, beam footprints can be tuned in an efficient manner with step-like fields magnets [22] rather than with the traditional non-linear multipole magnets with a positive impact mitigating stray beam irradiating non-wished areas.

Typically, the availabilities of the accelerators are to be maximized to unprecedented values. IFMIF counts with a thorough RAMI analysis developed during its Engineering Design Activities [23] framed by the on-going IFMIF/EVEDA [1]. To achieve the goal of 70% availability, the corresponding one to the accelerator needs to be 87%, which demands suitable redundancy of critical equipment. Though these availabilities are unprecedented, they are actually achievable since the availabilities of accelerators during their operation time, excluding facilities long shutdowns often driven by electricity cost, can easily go beyond these values. A clever program of maintenance activities is essential. A critical point on this respect might be the activation of hardware jeopardizing ‘hands-on’ maintenance. The ‘figure of merit’ used on this respect is 1 W/m as power of beam loss, which in case of high current D^+ accelerators operating in CW mode, could not be any more valid; a reassessment of this criteria for the new generation of accelerators conceived for ADS applications is advisable.

2.2 Target related issues

The target holds the difficult challenge of maximizing the heat absorbed and the neutron generation, being both linked since the higher the impacting beam current, the higher the neutron yield. The power absorbed in the target goes with the square of the beam current and the target is designed such to have a thickness higher than the related Bragg peak to prevent that the beam traverse the target under any condition avoiding risks of accidents. The capability of materials to absorb the heat, and efficiently transfer it, is the main technological limitation on neutron yield for solid targets; conversely the accelerator performance becomes the main limitation regarding the expected neutron yield if the targets are a flowing liquid screen. The surface power densities can reach few MW/m^2 for solid targets [24] and as high as 1 GW/m^2 (for about 100 kW/cm^3) with liquid targets if a suitable flow is implemented [25]; however, technological aspects arise on the solid backplate channelling the liquid. ImPact conceives a free flowing screen bypassing such limitation with a novel concept of a plasma window, but nowadays limited to 6 mm aperture, which is clearly an insufficient aperture to conduct high beam currents reliably. FRIB have demonstrated that electrons in an U beam can be efficiently stripped from a Li free flowing screen with power volumetric densities above 100 MW/cm^3 without observed nucleation [26] given the high surface tension of liquid Li. Anyhow, if the thickness of the backplate is thinner that the Bragg peak, despite the presence of a high beam power, the heat absorbed can be affordable like in IFMIF, where a 1.8 mm Reduced Activated Ferritic-Martensitic (RAFM) steel solid wall channels the flowing lithium where the 10^{18} n/m^{2}s with a broad peak at 14 MeV are generated.

HINEG-II and SORGENTINA rely on fast rotating copper solid targets with the deuterium and tritium present on a thin coated layer of titanium hydride. The Bragg peak involved is only of few μm, which builds enormous volumetric power densities that demand high rotation speeds and active cooling. The beam cross section can be tuned to reduce the beam power densities, enhancing in addition the testing volume. The heat deposition can also lead to blistering of the target as it is expected in the Be target of iBNCT.

The higher heat absorption capability of liquid targets exhibits also performance limitations related with pressure waves, cavitation, corrosion and erosion phenomena. Liquid metal technologies are challenging and, in addition, alkali metals like Li presents safety concerns related with the flammability in contact with water and air. In IFMIF/EVEDA the Li flows at 15 m/s in a concave backplate that increases the boiling temperature through centrifugal forces. The 10 MW deuteron beam is fully absorbed in the 25 mm thick Li screen (Bragg’s peak of 40 MeV deuteron in Li is 19 mm) and the planned <2 mm thick backplate of RAFM steels absorbs a volumetric power density o 17 W/cm^3 and 56 dpa, which seem affordable given the absence of large primary stresses [23]. Nevertheless, a weld free remote removal of the backplate has been developed and is likely indispensable. Unfortunately, with such high powers aimed like in ImPACT with their 1 A D^+ current in CW, the heat absorbed even with very thin walls would be technically unaffordable. In spallation neutron sources like J-PARC or MYRRHA, the pulsed nature of the proton beam induces pressure waves that enhances cavitation phenomena, as well fatigue and thermal stresses on the functional components. This aspect is aimed to be mitigated in MYRRHA facility given its objective of the operation in CW mode. Furthermore, these difficulties seem relieved in J-PARC by technologies of gas microbubbles injection and a double-walled beam window structure concept recently developed [27,28]. In addition, the absence of alkali metals reduces the safety aspects of liquid metal handling. In turn, in IFMIF, essential lessons were learnt in the prototype of the Target Facility, the EVEDA Lithium Test Loop (ELTL), designed and constructed during the IFMIF/EVEDA phase that remained in operation until October 2014 [29]. The ELTL, not only demonstrated the demanding stable liquid Li flow conditions (250 ^{o}C liquid Li flowing at 15 m/s with free surface variations within 1 mm) [30], but also gave lessons on potential cavitation phenomena that were unravelled [31,32] impacting the design of the Li loop to prevent its appearance.

Regarding the corrosion phenomena, experimentation with alkali metals is cumbersome given the dangers involved with their use. The corrosion capability of Li towards RAFM was subject of concerns driven by the high solubility of N in Li and the potentially high Cr depletion through ternary nitrides N-Li-Cr. The Li loop, LiFus6 [33], designed and constructed under IFMIF/EVEDA focused on determining the corrosion rate under IFMIF relevant conditions with successful results in what concerns the specified corrosion limit of 1 µm/y [1,34]. In addition, the methodology for its purification within the required limits was also demonstrated [1].

2.3 Irradiation-area related issues

The degradation of materials exposed to irradiation is particularly severe under neutrons driven not only by their strong capability to impact the bombarded material lattice but also by their transmutation potential, which highly depends on the type of neutron sources [35]. The spectrum of the neutron drives the degradation in materials, which in given cases, like the mono-energetic 14.1 MeV neutrons from D-T fusion reactions, its extent is not yet determined [36]. Mechanical properties are certainly impacted; the increase in the upper limit temperature for brittle behaviour can reach RT regions with certain risks of failure during shutdowns and transient events. The ductile to brittle temperature transition (DBTT) is known to be dependent on the irradiation temperature of the operating material, the higher this is, the lower is the shift of the DBTT thanks to annealing of radiation induced defects. This however does not apply to the transmutation products, as thermal- and radiation-enhanced diffusion may lead to the segregation and precipitation of the low- or insoluble elements, which will further increase the DBTT. It is also known that the He-induced swelling exhibits a substantial higher impact than dpas under high doses (> 10 dpa). Also electrical properties, such as insulation resistance or thermal-electric behaviour, are impacted by in-situ and cumulative irradiation effects.

Not only steels but other materials like W or Cu are impacted, as well as non-metallic ones like composites or ceramics. Bonded areas through welds, brazings and solderings are also affected. Other degradation channels like swelling, thermal and irradiation creep depend strongly in the steel microstructure showing radically different behaviour austenitic steels and ferritic-martensitic ones tentatively used for the blanket of DEMO.

Obviously, the named effects do not only affect the materials under test, but also the equipment used in the irradiation area. Associated challenges for the design of stress bearing (pressurized boundaries, gaskets etc.) and functional components (electrical heaters, instrumentation) have to be addressed.

Typically, the attention provided to the irradiation test region R&D phases is lower than the one provided to the accelerator and beam target; from those presented with irradiation volumes, only IFMIF/EVEDA had devoted prototyping efforts [37-39]. Certainly, the ambition of not being limited to the inherent reduced irradiation volumes of ADS facilities and count with a proper nuclear fusion reactor with multiple irradiation chambers and generous volumes persist in the fusion community [40-42]; where full size specimens, components and equipment could be exposed to irradiation. Unfortunately, neither the technology is ready nor the policy makers could presently be convinced the billions of investment without ITER providing successful results [43]. The limited volume demands the usage of small specimens testing techniques (SSTT) [1,44,45], which is a technique also utilized for decades in fission reactors materials research world [46,47]. The unavailability of experimental fusion reactors demand efforts to accomplish standards on small specimens to ensure the validity of the fusion materials irradiation tests. In this respect, IFMIF community has launched a CRP with the IAEA towards this standardization [48]; which would be usable on other fields.

A correlation between fission and fusion irradiated materials cannot be efficiently done given the transmutation of Fe into Cr releasing α-particles with a threshold n energy of 3.9 MeV, substantially above the average fission neutron energy <2 MeV [35]. The higher He-induced swelling with fusion neutrons leads its faster degradation than with fission neutrons. Conversely, the testing of tungsten in fission conditions is conservative since the thermal neutrons induce tungsten transmutation which is overestimated compared to DEMO-expected conditions. Additionally, material irradiation researches on fusion-fission hybrid systems have been launched, for instance, HINEG-I has been coupled with Lead-based Zero Power Critical/Subcritical Reactor CLEAR-0, which is uniquely featured with the accurate inverse reconstruction ability of neutron energy spectrum based on energy and space discretization technology, and gives a new way for the development of advanced neutron sources [9].

The observed annealing of the degradation and its strong dependence on the irradiated temperature demands the usage of temperature controlled irradiation rigs [38]. The uniformity in temperature in the stack of irradiated specimens for IFMIF is essential and this can only be achieved with heaters and an accurate monitoring of temperatures. Irradiation rigs need to be actively cooled and instrumented to obtain reliable information on the evolution of the material properties. Unfortunately, the anticipated operation lifetime of heaters under irradiation is controversial given the observed drift or resistance when exposed to fission neutrons at degradation levels <1 dpa during tests in the Belgian BR2 framed by IFMIF/EVEDA phase [38,39]. Special efforts shall be devoted to overcome this scenario, which is the potential source of a serious technological problem.

3. Description of facilities

The description of the facilities involved in the workshop is as follows:

A-FNS and IFMIF-DONES [6,10]

A flux of neutrons of 10^{17} /m^{2}s will irradiate a volume of 500 cm^3 that will be filled with above 1000 small specimens distributed in 12 capsules independently cooled. A neutron damage of 20 dpa/fpy for IFMIF and half of this value for A-FNS and IFMIF-DONES is expected. The neutrons are stripped through Li(d,xn) nuclear reactions from a 125 mA CW 40 MeV deuteron beam with a footprint of 200 x 50 mm impacting on a 15 m/s flowing liquid Li screen. IFMIF expects to operate with two equally performing accelerators; however both A-FNS in Japan and IFMIF-DONES in Europe will count with only one accelerator, in correlation with the present under scoping of the DEMO reactor with lower needs of dpa rate. These facilities will fill a gap in the world fusion program.

These facilities are also planned to be used for the realization of experiments in other scientific and technological areas including nuclear physics, isotope production, materials characterization, electronics irradiation or industrial applications [51].

BISOL-MAINS

Based on IFMIF principles, the idea is to reach a lower fluence at the sake of minimizing risks by constructing an accelerator to conduct initially a deuteron beam of 10 mA in CW mode, with an upgrade of this current in two ensuing phases to 20 mA and 50 mA. A flux of 5 X 10^{14} /m^{2}s is expected in a volume of 12 cm^3 capable of reaching 8 dpa/fpy iron equivalent.

iBNCT

Treatment of certain superficial cancers ca be treated through fission reactions of ^{10}B into ^{7}Li and ^{3}He, B would be doped in cancerigen regions and neutron energy modulated to maximize the interesting flux, The neutron can be obtained through with either Li target, ^{7}Li(p,n) or a Be target, Be(p,n) with H^+.

ImPACT

Transmutation of high level radioactive nuclear waste can be efficiently achieved through a deuteron accelerator avoiding long years present storage. A deuteron beam of 1 A in CW mode at 40-200 MeV/u seems the best candidate for an on-going Japanese program promoted by Japan Science & Technology Agency (JST).

HINEG [8]

A 14.1 MeV neutron yield up to 10^{16} /s would be obtained relying on fast rotating copper solid targets with the deuterium and tritium present on a thin coated layer of titanium hydride, and HINEG-II could provide about 4 dpa/fpy [8]. An increase of these fluxes can be achieved through an array of accelerators and a high heating load rotating tritium target.

J-PARC (Japan Proton Accelerator Research Complex)

J-PARC comprises a series of three proton accelerators, a 400 MeV linear accelerator, a 3 GeV rapid-cycling synchrotron (RCS), and a 50 GeV synchrotron as well as three experimental facilities. These facilities include the Materials and Life Science Experimental Facility (MLF) for a wide range of research fields using neutron and muon beams, the Hadron Experimental Facility for nuclear- and particle- physics experiments using K-mesons and other particle, and the Neutrino Experimental Facility for the T2K particle physics experiment using neutrinos. At MLF, a pulsed spallation neutron source using a mercury target has been in operation with 3 GeV protons at 25 Hz, which would generate maximum neutron intensity of 1.8x10^{13}/sr/pulse at the rated beam power of 1 MW.

MYRRHA [11]

A neutron yield of 2 x 10^{17} /s can be obtained by one linear accelerators of 600 MeV protons, with a beam current ranging from 2.4 to 4 mA, impacting on a spallation target. In turn, a lead-bismuth cooled reactor would be ignited by the neutrons generated on the spallation target. The designed thermal power is planned to be between 65 to 100 MW.

SORGENTINA [12]

Two deuteron and tritium beams of 25 A accelerated at 160 keV impinging on a spot of 10 x 20 cm^2 surface onto two rotating and confronted 2 m radius wheels for a neutron flux of 10^{13} /cm^{2}s in the space between both wheels capable to provide 2 dpa/fpy in 50 cm^3.

4. Conclusions

The meeting clearly showed up the renewed international interest in the development of high-intensity high-energy neutron sources for different applications but with special emphasis on nuclear energy and medicine ones. Accelerator technologies able to support high currents will be demonstrated in the short term and power handling technologies based on liquid metals and solid targets are also available. It could be expected that in the next ten years a new generation of neutron sources will be available for the users community interested.

This 1st IWANS has become a success. It accomplished its goals going beyond initial expectations, placing the seed towards a presently non-existing professional network between involved scientific communities due to the lack of a common discussion forum. A consensus on its relevance was shared by all participants with multiple synergies generated during the discussions.

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