Fusion Engineering and Design 89 (2014) 2136–2140

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Technical analysis of an early fusion neutron source based on the enhancement of the IFMIF/EVEDA accelerator prototype

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HIGHLIGHTS

- The combination of the three major prototypes produced for IFMIF/EVEDA can form the basis of an early fusion neutron source.
- The elementary option for an early neutron source is conceived to limit the accelerator stages to a beam energy of 26.5 MeV.
- Characteristic ratios of the He to dpa generation can be expected throughout.
- About 75 cm^3 will be available for first studies of the occurrence of a specific Helium effect in the RAFM steels.

ARTICLE INFO

Article history:
Received 13 September 2013
Received in revised form 31 March 2014
Accepted 31 March 2014
Available online 23 May 2014

Keywords:
Neutron source
Fusion materials
Linear accelerator
Liquid lithium
Neutronic analysis

ABSTRACT

In the framework of the Engineering Design and Engineering Validation Activities for the International Fusion Materials Irradiation Facility (IFMIF/EVEDA), three major prototypes have been designed and are being manufactured, commissioned and operated which are firstly the Accelerator Prototype (LIPAc) at Rokkasho, fully representative of the IFMIF low energy (9 MeV) accelerator stage, secondly the EVEDA Lithium Test Loop (ELTL) at Oarai, and thirdly critical components of the High Flux Test Modules to be tested in the helium cooling loop (HELOKA-LP) at Karlsruhe. The present paper analyses possibilities from a technical point of view, for combining, modifying, and enhancing, at limited cost, selected components of the prototypes towards the realisation of an early reduced-flux neutron source, able nonetheless to start the testing of candidate DEMO materials and realising by this a first step towards the construction and operation of a complete IFMIF plant.

Various options of deuteron beam parameters, such as energy, current and shape are analysed with respect to their technical challenges and the neutron yield resulting from the nuclear reaction with the Li target. Related requirements for the liquid Li target with respect to jet parameters are evaluated and the neutron mapping in the high flux region is presented underlying an analysis of the available volume for testing reduced activation ferritic martensitic (RAFM) steels at relevant structural damage levels.

1. Introduction

The International Fusion Materials Irradiation Facility (IFMIF) is projected to provide an accelerator-based, d–Li neutron source to produce high energy neutrons at sufficient intensity and irradiation volume to simulate as closely as possible the first wall neutron spectrum of future nuclear fusion reactors such as DEMO and Power Plants [1]. Structural damage generated by neutrons in the material is quantified in terms of dpa (displacement per atom), so the performance of materials is qualified in terms of dpa per full power year (dpa/fpy), where for Fe 1 dpa equals 1.5×10^{24} n/m^2 (E = 14 MeV) [2].

In conjunction with the development of a DEMO concept, Materials R&D and Breeder Blanket R&D are two high priority issues in nuclear fusion technology [3]. They justify special interest in the following topics:

Topic 1: Proof of feasibility of an efficient cooling concept for ITER Test Blanket Modules (TBMs) by studying the cooling performance in small scale mock-ups under DEMO-relevant nuclear heat load and activation conditions (requiring damage rates of typically 1–5 dpa/fpy);

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http://dx.doi.org/10.1016/j.fusengdes.2014.03.085
0920-3796/

Topic 2: Determination of the occurrence of a specific helium effect for early DEMO conditions by measuring high quality data for the ductile-to-brittle transition temperature and fracture toughness (i.e. well-defined irradiation temperature with no significant temperature excursions) around the expected threshold of 30–50 dpa (requiring damage rates of typically 10–15 dpa/fpy);
Topic 3: Experimental demonstration that the Reduced Activation Ferritic Martensitic steels have the expected radiation resistance well above the helium threshold level. This experiment calls for exploring “terra incognita” in neutron damage well above 50 dpa (requiring damage rates above 20 dpa/fpy).

In the framework of the Engineering Design and Engineering Validation Activities for the International Fusion Materials Irradiation Facility (IFMIF/EVEDA), the IFMIF Engineering Design has been advanced [4] and the IFMIF Intermediate Engineering Design Report (IIEDR) has been completed recently [1]. To validate the developed design features, prototyping sub-projects are continued which consist of the design, manufacturing and testing of the following prototypical systems [5–7]:

Prototype 1: The Accelerator Prototype (LIPAc) at Rokkasho (Japan), fully representative of the IFMIF low energy (9 MeV) accelerator (125 mA of D^+ beam in continuous wave), now under construction and planned to be commissioned by June 2017 (Fig. 1);
Prototype 2: The Experimental Lithium Test Loop (ELTL) at Oarai (Japan), integrating all elements essential to the IFMIF lithium target facility, already commissioned in February 2011 and with a test programme running at least until mid-2014;
Prototype 3: Critical components of the High Flux Test Modules tested in the helium cooling loop (HELOKA-LP), at Karlsruhe (Germany), with testing in 2014 and possibly beyond.

Even though the IFMIF/EVEDA project scope is limited to studies with these prototypes being kept separately, their combination would be appealing, with the potential to obtain an early fusion neutron source, albeit with reduced capabilities in terms of annual fluence, irradiated volume, and overall versatility. There are several options for a step-wise approach towards the final IFMIF plant as well as for the partial use of the infrastructure and components developed for the IFMIF/EVEDA phase. The present paper focuses on an elementary variant of an early neutron source (“ENS”) which can only respond to studies for TBM cooling concepts (Topic 1) and a limited specimen set for materials qualification at 30–50 dpa level (Topic 2). For a more consolidated study of Topic 2 which heads for an engineering and scientific database for DEMO, a variant called “DONES” (DEMO oriented neutron source) is being considered. This variant, which is the subject of another paper [8], is designed to provide a larger available volume for high fluence neutron irradiation, allowing therefore a larger choice of materials and irradiation conditions. The goals set for Topic 3 (investigation of radiation resistance under the extreme damage levels expected in Fusion Power Plants) can realistically only be tackled with the full IFMIF plant.

2. Technical analysis of the ENS variant

In order to reap the potential of three main IFMIF/EVEDA prototypes to realise the ENS variant, technical analysis has been performed on the following aspects:

- Upgrade the LIPAc accelerator to achieve a sufficient level of deuteron energy,
- Adjust the beam footprint to approach the size of the Target Assembly realised in the EVEDA Lithium Test Loop,
- Identify a suitable volume for dedicated R&D studies within the High Flux area.

2.1. Upgrade of LIPAc accelerator

The design of the IFMIF accelerator foresees to have 4 final LINAC stages to boost the 5 MeV beam coming from the RF Quadrupole to 9 MeV, then to 14.5 MeV, 26.5 MeV and 40 MeV.

According to neutronic analysis performed by Fischer et al. [10], the neutron yield would be (in units of 10^{10} neutrons/(sterad μA s)) respectively 0.8–2.5–12–40 when boosting up the energy through the different stages. A deuteron beam of LIPAc alone would then lead to a neutron yield which is only 2% of 1/2 of IFMIF. The situation will improve substantially if at least 3 stages could be realised, as the resulting 26.5 MeV deuteron beam could provide 30% of the targeted neutron yield of a single IFMIF accelerator with 40 MeV deuterons. By this reduction, the broad peak in the neutron spectrum shifts from about 15 MeV to about 10 MeV [11].

The beam has a quasi-Gaussian profile at the entrance of the High Energy Beam Transport (HEBT) line [9] which drives the beam against the Li target. Its typical RMS radius is in the order of 10 mm. As the rectangular footprint of the IFMIF plant design, which has an aspect ratio of 4:1, requires more demanding beam forming magnets, a Gaussian beam footprint at the free surface at the Li target of ENS was considered. However, this simplification was found not to be admissible because of the high power loads generated at outer regions of the Gaussian beam.

LIPAc and thus any energy boosted version has a higher space charge regime (quantified by the generalised perveance parameter) compared to currently designed proton linacs [9]. Taking this into account, moderate reductions of beam current (max. 20%) are considered possible mitigation means for excessive beam halo effects in initial stages of LIPAc upgrades.

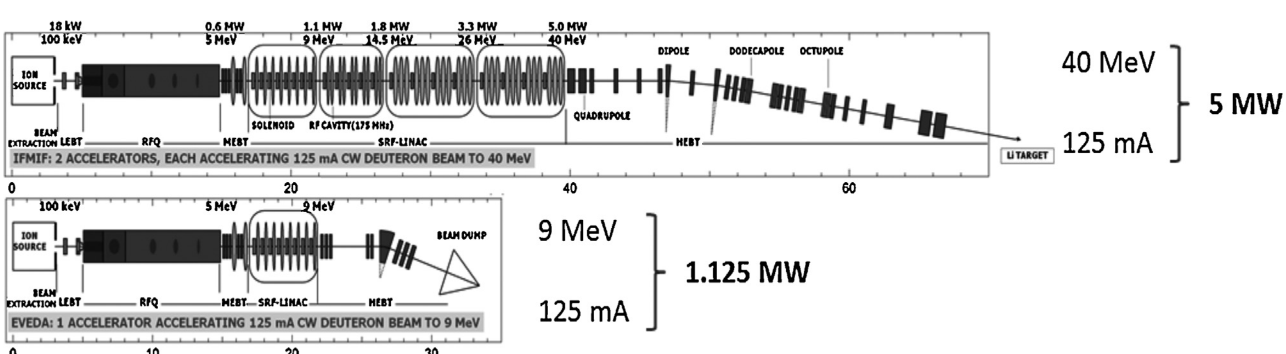

Fig. 1. Features of the 2 accelerator systems designed for the IFMIF plant (top) compared to the Linear IFMIF prototype accelerator (“LIPAc”) being manufactured, installed and commissioned in the IFMIF/EVEDA Project (bottom) [9].