A. M., Jan 2002

Some considerations of the usefulness of the proposed spallation source ESS for fusion materials irradiations

Introduction

First wall- and structural materials in a future fusion power plant are exposed to a high energy neutron flux up to 14 MeV which does not compare to any other present nuclear technology. Therefore for the design, licensing, construction and safe operation of fusion reactors, materials have to be qualified by radiation exposure in a neutron source simulating the expected fusion neutron spectra and temperatures under fusion relevant conditions.

In the IEA framework different types of neutron sources have been analysed concluding that accelerator-driven d-Li neutron sources are most suitable for fusion materials research. In the course of two development phases in the ninetieths the conceptual design of the International Fusion Materials Irradiation Facility (IFMIF), a source of that kind has been elaborated. It was also recognized that the IFMIF accelerator would be a one-of-a kind, dedicated state-of-the-art machine with a very high availability requirement to enable it to meet the factory production demands of the material testing programme. Two deuteron beams (125 mA each, 40 MeV) operating in parallel are focussed on a single lithium target, producing an intense neutron flux via stripping reactions. If necessary, the neutron energy can be shifted by variation of the deuteron energy. At present a Key Element Phase (KEP) is being performed under the auspices of the IEA with substantial participation of the European Fusion Development Agreement (EFDA) aiming at the reduction of technological risks of key technologies.

Recently it was again proposed to use the ESS spallation source instead or in parallel to IFMIF to qualify structural materials for DEMO. In the proposed ESS spallation source a proton accelerator generates a pulsed beam which hits a heavy metal target and produces neutrons by spallation. The neutron spectrum peaks around 2 MeV with a long high energy tail up to the energy of the primary particles. For the irradiation of fusion material samples it is proposed to insert beam tubes into the high flux- or the reflector region. The spallation source is mainly foreseen for basic science, making use of the pulsed beam structure. It is intended to split the beam and to utilise it for two targets. Consequently the available neutron flux in the material test volumes depends on the beam splitting and on the position of the irradiation beam tubes.

Requirements to be satisfied by a fusion neutron source

A neutron source for the qualification of fusion reactor materials has to meet the following main criteria:

- A neutron spectrum corresponding to the first wall/blanket conditions in a future fusion reactor.
- Operation mode: continuous operation with high availability; almost no unscheduled beam-off gaps
- 20 up to 50 dpa/fpy in the high flux region, allowing accelerated- or at least real-time testing.
- An irradiation volume in the order of 0.5-1 Litre in the high flux region
- Transmutation: He/dpa ratio ~ 10, H/dpa ratio ~ 40 in Fe-based alloys
- Negligible production of impurities affecting material properties
- Reasonable representation of the damage morphology typical for fusion.

IFMIF and spallation sources

In the following a comparison is made to which extent the requirements referred to above could be met by IFMIF and the proposed ESS:

- ***Neutron spectrum***:
  As indicated in Fig. 1, compared to the demonstration power reactor (DEMO) the IFMIF neutron spectrum has its peak close to DEMO and a small tail not exceeding 40 MeV. The neutron flux of the spallation source, however, has an extended high energy tail up to the GeV level. This tail constitutes a *severe problem* because neutrons at energy levels substantially above 50 MeV produce a very large spectrum of *transmutation elements.* Consequently, the initial high purity grade will be seriously deteriorated meaning that its composition would become different from fusion reactor materials and therefore qualification on this basis will become questionable. In particular, besides this complete loss of low-activation capability, transmutation elements like P, S significantly accelerate the material embrittlement in a wide temperature range in a non-fusion specific manner.

- ***DPA rate, He/dpa- and H/dpa ratio***
  In the high flux region of IFMIF a dpa rate of 20-50 dpa/fpy is attainable meaning that the required 80 dpa for the materials qualification for DEMO could be satisfied in a few years time and thus could satisfy well the current road map of future fusion energy R&D. Furthermore the He/dpa- and H/dpa ratios reflect perfectly those expected in a fusion reactor which means that the results on irradiation hardening, ductility loss and embrittlement behaviour of irradiated material are representative for fusion reactors.
  In the target position of the proposed ESS appropriate dpa rates can be attained which would allow accelerated testing. However, the He/dpa ratio are approximately four times as much as fusion relevant ratios thus leading to distorted results regarding the embrittlement behaviour of the irradiated material. This is in particular true for lower temperature (< 350C) applications such as would be the case for water cooled LiPb Planket concepts. The second option in the reflector region offers a retail spectrum which yields less than 15 dpa/fpy . Furthermore, the He/dpa-and H/dpa ratios are only about half as much as fusion relevant ratios leading to a non-representative impact on material embrittlement.
  A major issue is the observed irradiation induced degradation of flow and fracture properties below about 350 °C, though newer results indicate that the recently developed family of low activation ferritic/martensitic 7-9%CrWVTa steels are less sensitive to radiation hardening and embrittlement than conventional ferritic/martensitic steels. However, tiny helium bubbles and hydrogen in combination with helium have shown to accelerate the radiation induced ductility loss and fracture toughness degradation at lower irradiation temperatures. Therefore, any deviation from fusion typical He/dpa and H/dpa ratios has to be avoided to guarantee a solid, fusion specific materials data base.

- ***Recoil energy spectra***
  It is well known that different primary recoil energy spectra can produce completely different damage morphologies. On the one hand, low energy recoils produce with high probability isolated vacancies and interstitials leading to effects like solute segregation, and creep. On the other hand, high energetic recoils generate atomic collision cascades and sub-cascades that can lead to effects like irradiation hardening and embrittlement.
  For the evaluation of the entire recoil energy spectrum, usually a cumulative damage production function (Fig. 2) is calculated that represents the damage energy in all recoils

with energy less than T (x-axis in Fig. 2) . In contrast to mixed spectrum reactors or ESS, the high flux volume of IFMIF (hatched area) meets perfectly the spectrum expected in the DEMO reactor structural materials. To guarantee a fusion specific damage morphology and thus a sound materials database, the shape of the recoil energy distribution should not deviate from DEMO reactor conditions.

- ***Time structure***
  A characteristic of IFMIF is a continuous operation mode while the proposed ESS target operates in a pulsed mode with a duty cycle of 0.06 (~3.5 ms pulses, 16,66 Hz) whereby the dead time is more than an order of magnitude longer than the pulse length. The impact on the irradiated samples up to date has not been experimentally investigated to an extent that a sound conclusion can be drawn on whether the mechanism of damage production and healing is substantially affected. Therefore the question whether irradiation exposure in a pulsed spallation source leads to different material properties than in a continuous wave neutron source is still under discussion.
  In addition, a characteristic feature of intense accelerator sources are unscheduled beam-off periods of typically seconds or minutes. As a consequence, also the nuclear heat drops off leading to temperature fluctuations in the irradiated specimens which in turn can significantly modify the damage morphology in a non-fusion-specific manner as various publications have shown. IFMIF is the only accelerator driven facility having two independent beams striking one single target and thus substantially minimise the probability of a total heat loss.

Furthermore there are some technical issues such as the necessity to perform in-situ experiments like (i) creep-fatigue tests on structural materials or (ii) T-release tests on Be and lithium breeder ceramics which have not been analysed yet for ESS.
A summary of DEMO relevant parameters compared to IFMIF and ESS is presented in Table 1.

Conclusions
As analyses since many years have proven, IFMIF offers an irradiation test bed that fulfils the required criteria. All relevant parameters can be matched, including appropriate neutron spectrum, continuous high availability with practically no beam-off gaps, sufficient dpa production, perfect matching of He/dpa and H/dpa ratios, sufficient volume, excellent access to irradiation test modules and the capacity to perform various voluminous in-situ tests. For the adaptation to any future material, neutron spectrum tailoring is possible by variable source energy and by the free choice of appropriate neutron moderator/reflector materials.

ESS produces a neutron spectrum peaked at relative low energy (comparable to fast breeders), however, with a tail extending to very high energies. Consequently a variety of impurities will be produced which deteriorate materials properties in a fusion-foreign manner during longer term irradiation. If this effect shall be mitigated (place irradiation modules in the reflector moderator) the source flux would decrease considerably with the consequence of practically unacceptable long irradiation times. In addition none of the present ESS test module positions meets fusion specific He/dpa and H/dpa ratios. Also the pulse nature of the source remains a point of future discussions. Obviously a spallation neutron source offers irradiation conditions that are inappropriate for the qualification of a reliable fusion materials data base.

		DEMO 2 MW/m^2	IFMIF 10 MW		ESS 5 MW LPT	
			HFTM	MFTM	Target	Reflector
Total flux	**n/cm^{2}s**	7.1×10^{14}	5×10^{14} - 1.2×10^{15}		2.2×10^{15}	1.2×10^{15}
Flux portion > 15 MeV	**%**	0	14		12	2
Helium production rate	**appm/s**	5.7×10^{-6}	8×10^{-6} 1.9×10^{-5}	3.0×10^{-6}	9.1×10^{-5}	2.2×10^{-6}
Hydrogen prod. rate	**appm/s**	2.2×10^{-5}	3.2×10^{-5} 7.7×10^{-5}	1.1×10^{-5}		1.2×10^{-5}
Displacement rate	**dpa/s**	5.4×10^{-7}	6.4×10^{-7} 1.7×10^{-6}	3.2×10^{-7}	2.0×10^{-6}	4.1×10^{-7}
He/dpa ratio	**appm/dpa**	11	10 - 12	9.2	45	5.4
H/dpa ratio	**appm/dpa**	41	35 - 50	35		30
Displacement per FPY	**dpa**	17	20 - 55	10	63	13
Test volume	**Litre**		0.5	6	0.4	5

Tab. 1: Comparison of different facilities

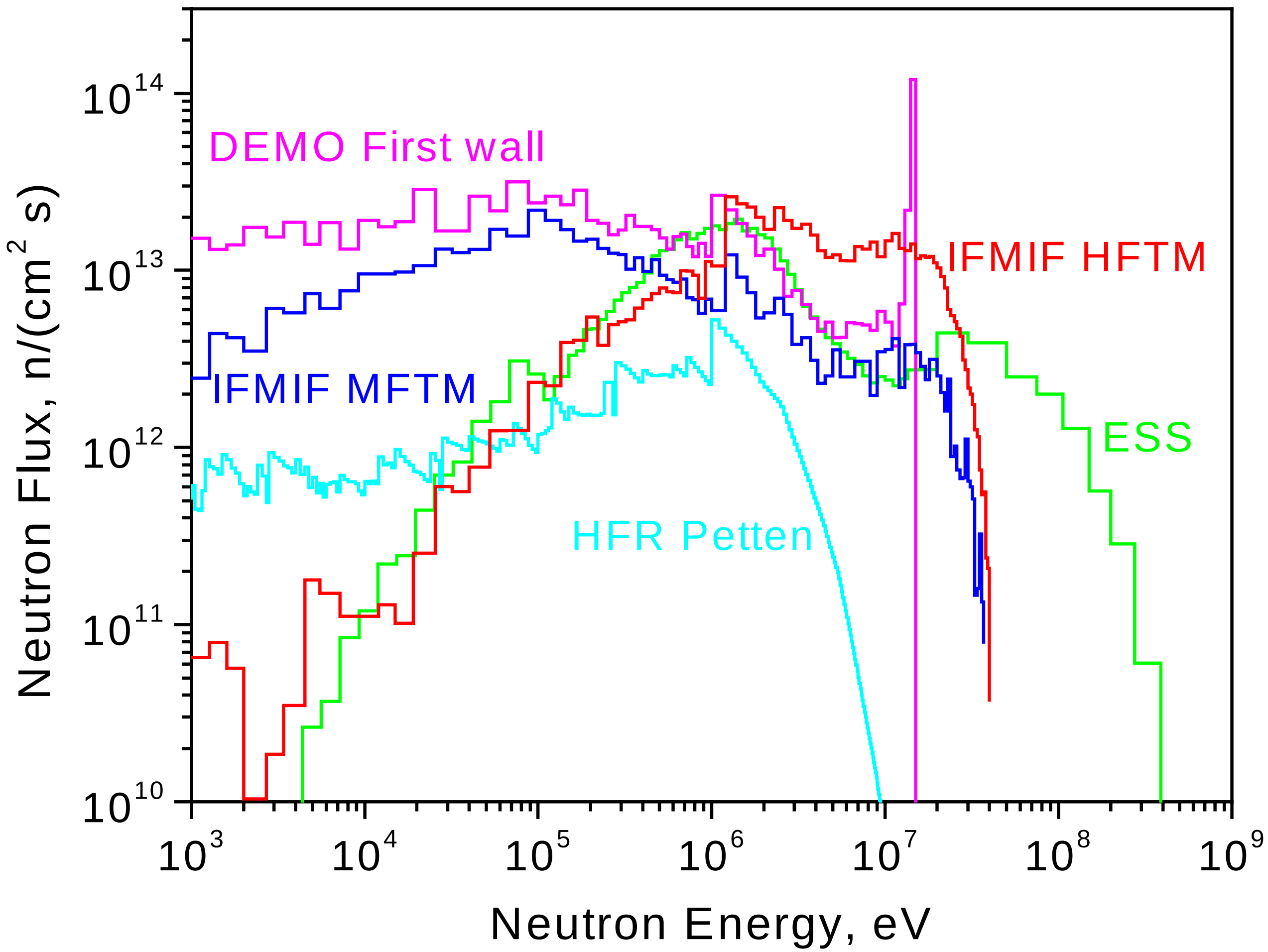

Fig. 1: Typical neutron spectra of (i) DEMO First Wall (HCPB Blanket), (ii) mixed spectrum reactor HFR Petten, (iii) European Spallation Source, (iv) IFMIF High flux test module, and (v) IFMIF medium flux test module.

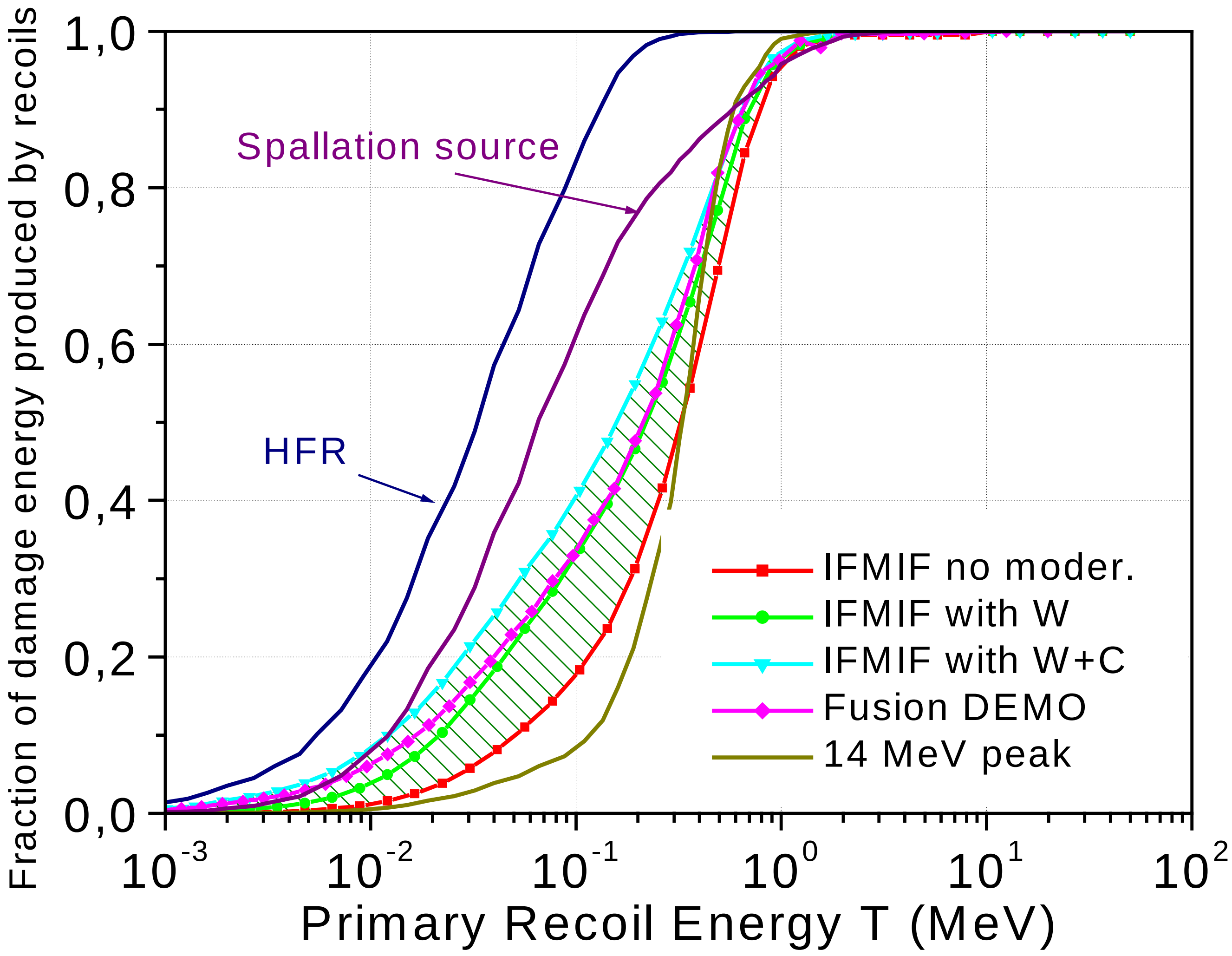

Fig. 2: The IFMIF high flux region meets perfectly (hatched area) DEMO relevant conditions