ANNEX 1 - MATERIAL IRRADIATION

As a huge number of high-energy neutrons, in the range from 1 to 40 MeV, are produced in the carbon converter via C(d,xn) reaction, SPIRAL 2 can also be used as an irradiation tool to study the behaviour of materials in the field of fusion machines, as ITER and future reactors.

1. BASIC PARAMETERS

The material irradiation capability of SPIRAL 2 can be compared with the irradiation environment of experimental machines, such as the ITER project, as well as dedicated neutron sources for material testing, as the IFMIF (International Fusion Materials Irradiation Facility) project [1], in terms of available neutron fluxes, energy spectra, material damage rates and irradiation volumes. According to simple estimates, Table 1 provides for example the basic irradiation parameters for IFMIF and SPIRAL 2. A more detailed analysis is given in the coming section. It is worth noting that SPIRAL 2 is able to provide a neutron flux by about two orders of magnitude lower than IFMIF, but with a density lower by a factor ~10 only. Besides, because of the smaller deuteron beam spot on the target, smaller sample volumes (~10 times smaller) are available for irradiation.

Table 1 : Basic irradiation characteristics for IFMIF and SPIRAL 2

Project	IFMIF	SPIRAL 2
Reaction specification	d(40MeV)+Li	d(40MeV)+C
Maximum beam current (mA)	2 × 125	5
Beam spot on the target (cm^2)	~100	~4
Beam density on the target (mA/cm^2)	2.50	1.25
Neutron production over 4π (n/d)	~0.07	~0.03
Neutron source intensity (n/s)	$\sim 1 \times 10^{17}$	$\sim 1 \times 10^{15}$
Neutron flux on the back-plate ($n/(s\ cm^2)$)	$\sim 6 \times 10^{14}$	$\sim 1 \times 10^{14}$
$<E_n>$ on the back-plate (MeV)	~10	~12

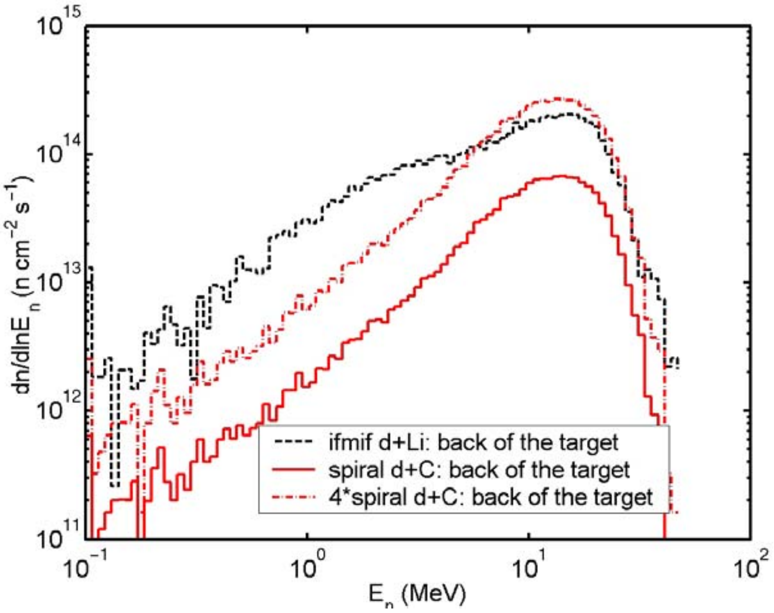

Figure 1: Comparison of neutron energy distributions on the back-plate of the production target for IFMIF and SPIRAL 2

In addition, the energy spectrum of the neutron flux is well suited to the one required for controlled fusion machines. Figure 1 shows the energy distributions on the back-plate of the production target for IFMIF and SPIRAL 2. It is worth mentioning that at forward angles, the d+C reaction results in a slightly harder neutron spectrum than the d+Li reaction. This is due to a higher contribution of neutron production from the target fragmentation and/or compound nucleus evaporation in the case of Li.

2. DETAILED IRRADIATION CONDITIONS

All calculations were carried out with the MCNPX code system, but as it systematically under-estimates the neuton yield, all estimates in this work are given after a re-normalization of the total neutron yield according to the experimental data.

SPIRAL 2 delivers a deuteron beam of 5 mA and 40 MeV interacting with a ~1 cm thick rotating carbon disk. We assume a beam spot of uniform radial distribution with diameters of 4 cm and 2.83 cm. The reaction d(40 MeV) + C will result in ~2.5 % neutron yield per deuteron over 4π. As an example, we consider an irradiation volume (cylinder) filled with ^{56}Fe and ^{4}He with equal occupations (50%-50%) and placed right behind the converter target. Partial occupation of the irradiation volume was chosen to allow for possible cooling (typically He-gas flow). The irradiation zone was of cylindrical shape with length of 6 cm and diameter of 6 cm. Table 2 summarizes the major irradiation characteristics (on the target back-plate over the beam spot dimensions) for SPIRAL-2 in comparison with IFMIF, ITER and DEMO.

Table 2: Maximal neutron flux, displacement rate, gas production and nuclear heating (fpy: full power year, dpa: displacement per atom, appm: atom parts per million)

	Neutron flux n/(s cm^2)	Damage rate dpa/fpy	Gas prod. (He) appm/fpy	Gas prod. (H) appm/fpy	Nuclear heating in ^{56}Fe (W/cm^3)
IFMIF Ref. [1] d-beam 5.0 x 20.0cm^2	1.1 10^{15}	54	562	2622	23
SPIRAL2 (a) d-beam ∅ 4.00 cm	7.0 10^{13}	4	52	205	2
SPIRAL2 (b) d-beam ∅ 2.83 cm	1.1 10^{14}	7	95	378	3
ITER (max)	4.0 10^{14}	12	140	540	12
DEMO (max)	1.3 10^{15}	30	320	1240	35

SPIRAL 2 is able to provide rather comparable irradiation conditions such as ITER. It is also worth mentioning that, although neutron energy distribution of SPIRAL 2 (and also IFMIF) differs from the fluxes predicted for the first wall of ITER (and DEMO), the ratio of gas production over dpa rates is comparable. In the case of SPIRAL 2, we obtain He/dpa = 13, H/dpa = 51, while for ITER, one finds He/dpa = 11, H/dpa = 45.

A comparison between the two diameters assumed for SPIRAL 2 shows that a more focused deuteron beam is preferred to obtain maximal neutron fluxes. Figure 2 shows the spatial distribution of the total neutron flux for both cases. Total neutron flux attenuation is about 30%/cm along z-axis. The useful irradiation volume can also be inferred: for neutron flux and damage rate simultaneously larger than 5.10^{13} n.s^{-1}.cm^{-2} and 3 dpa/fpy, we obtain ~10 cm^3 and ~14 cm^3 for beam spot diameters of 4 cm and 2.83 cm, respectively. In the case of IFMIF, the useful irradiation volume is ~500 cm^3 for neutron flux and damage rate simultaneously larger than 5.10^{14} n.s^{-1}.cm^{-2} and 30 dpa/fpy [1].

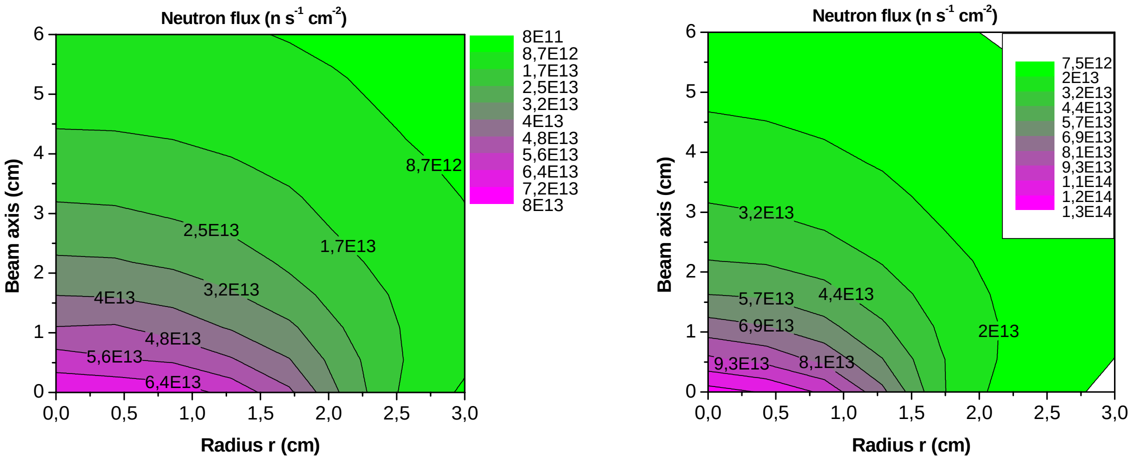

Figure 2: Total neutron flux (n/(s cm2)) in the irradiation region, filled with 50% of ^{56}Fe. Deuteron beam spot on the target-converter is Ø 4.00 cm (on the left) and Ø 2.83 cm (on the right). Irradiation zone (cylinder) dimensions are : L = 6 cm, R = 3 cm

3. EXPERIMENTAL SET-UP

A dedicated plug, very similar to the radioactive ion beam production plug, can be envisaged for irradiation purposes (Figure 3). It will allow accumulating irradiations up to the desired neutron fluence level during successive separate irradiation cycles.

.

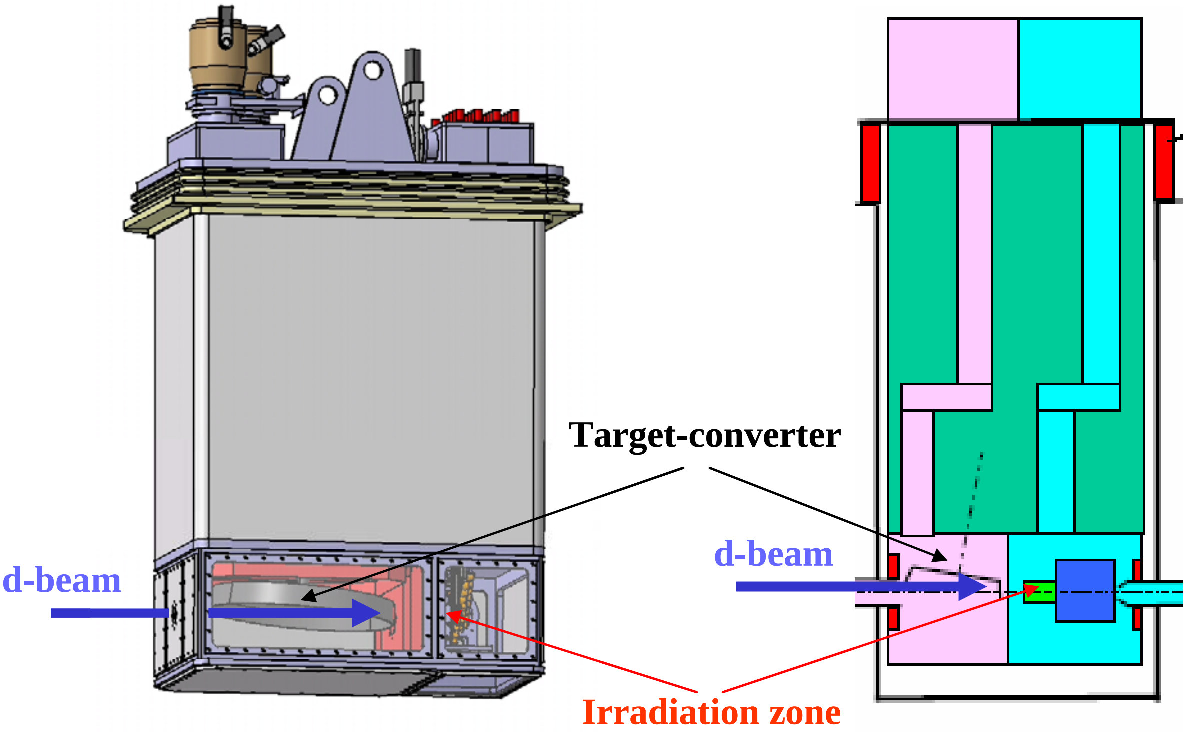

Figure 3: Schematic view of the plug designed for RIB production. Possible zones for irradiation purposes are shown.

The irradiation samples must be placed as close as possible to the target-converter (rotating carbon disk). The irradiated samples need a separate cooling system (e.g. He gas or water flow) to keep their temperature at the desired and controlled level (500-1000°C). The design has to allow the sample container to be easily extracted from the entire plug after the final irradiation and cooling time, and to be finally prepared for the transportation of irradiated material for the final tests and analysis in hot and/or chemistry laboratories. It might be that some preliminary sample examinations on-site will be performed immediately after cooling or/and in between different irradiations. Temporary storage between irradiation cycles and sample cooling will take place in the specific storage silo area.

3.1. Induced radioactivity of samples

Neutron induced activation is only a primary response, which in turn leads to a number of secondary responses such as dose and decay heat. Furthermore, the activation and decay heat are time dependent results, decaying away after shutdown of the neutron source. This information is quite important due to safety, maintenance, transportation and waste disposal issues. Below, we present some estimates related to the activation of natural iron in a typical SPIRAL 2 neutron environment. Our calculations were performed using CINDER'90 activation analysis code.

Table 3 and Table 4 present the time dependence of both the specific activity and decay heat following a one year operation with 70% beam availability (100 days shutdown per year). The activation was calculated for a natural iron irradiated by the SPIRAL 2 maximal available flux (at the back plate). Similar estimates should be performed for all potential materials to be irradiated.

Table 3: Dominant activation products at different periods of cooling

	3 hours cooled	1 day cooled	12 days cooled	116 days cooled
Total, (Bq/kg)	4.21×10^{13}	2.17×10^{13}	2.11×10^{13}	1.78×10^{13}
Cr-51, (%)	3.6	6.7	5.4	0.5
Mn-54, (%)	15.7	30.4	30.6	28.8
Mn-56, (%)	48.3	0.1	-	-
Fe-55, (%)	32.3	62.7	64.0	70.7
Total, (%)	99.9	99.9	100.0	100.0

Table 4: Dominant decay heat sources at different periods of cooling

	3 hours cooled	1 day cooled	12 days cooled	116 days cooled
Total, (W/kg)	9.14	0.92	0.88	0.70
Cr-51, (%)	0.1	0.9	0.8	0.1
Mn-54, (%)	9.7	96.2	97.7	98.3
Mn-56, (%)	90.0	1.1	-	-
Fe-55, (%)	0.1	1.4	1.4	1.6
Total, (%)	99.9	99.6	99.9	100.0

3.2. Thermal conditions

Material irradiation has to be performed at different very stable temperatures, in order to examine in detail the radiation damage as a function of material temperature.

There are two heating sources nearby the irradition zone: the primary beam energy deposition in the rotating graphite target, with a temperature around 1600-1700°C and nuclear heating directly deposited in the samples by interacting neutrons and photons. A preliminary design includes:

a) an intermediate graphite piece (~1 cm thick) between the target-converter and irradiation sample; this graphite piece is cooled separately to the desired temperature (here we used 70°C).

b) a metallic container housing the irradiation samples; this container, located as close as possible to the target-converter, is also heated or cooled separately to reach the required temperature conditions.

Figure 4 shows for example the temperature of the irradiated samples as a function of their location along the beam axis. The temperature variations can be rather flat by using an external heating (black, blue and green curves). Although further optimisation studies are needed, these preliminary estimations are encouraging. Furthermore, a dedicated cooling system (e.g., He-gas flow) of the irradiation samples as it is proposed for the IFMIF project [1] can be used to reach very stable and controlled temperature conditions. Finally, both neutron flux as well as temperature monitoring should be planned during the irradiations.

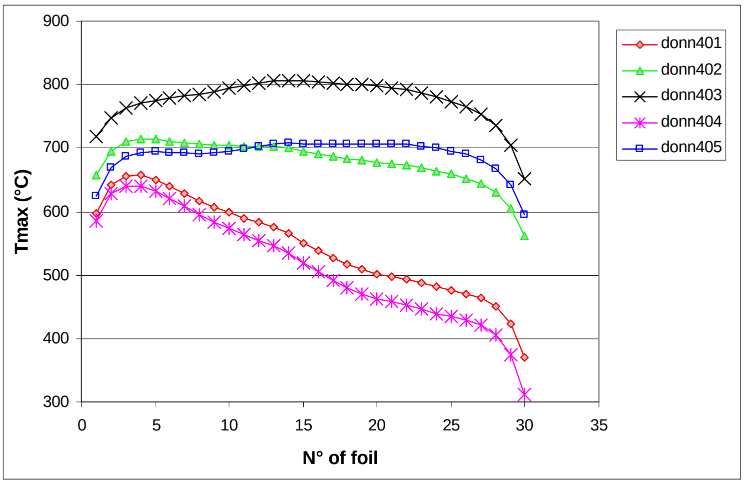

Figure 4: Maximal temperatures of the irradiated samples as a function of their location along the beam axis

4. CONCLUSIONS

Though SPIRAL 2 will deliver neutron fluxes and damage rates by a factor of ~10 lower than IFMIF, it will provide quite comparable neutron flux density and irradiation temperature conditions such as ITER. For neutron flux higher than ~5.10^{13} $n.s^{-1}.cm^{-2}$ and material damage rates greater than ~3 dpa/fpy, the useful irradiation volume will be ~10 cm^3. Assuming 4 months of irradiation per year at full power, the damage rate would then be greater than 1 dpa per year. If one requests for example 3-4 such irradiation campaigns at different irradiation temperatures, the irradiation experiments would last for 3-4 years depending on the beam availability.

There are no particular requirements for the deuteron beam (40MeV and 5 mA continuous wave deuterons) and carbon target-converter (rotating carbon target inside the plug). However, we have shown that a stronger deuteron beam focalisation would increase neutron flux density and useful irradiation volume by ~40%. Finally, the following additional elements and infrastructure will be indispensable for irradiation purposes:

- A dedicated plug(s) for irradiation because irradiation samples should be placed as close as possible to the target-converter (rotating carbon disk). In addition, the irradiation zone might need a separate/different cooling system (e.g. He gas or water flow) to keep sample temperature at the desired level. Finally, a separate-independent plug will allow accumulating irradiations up to a required neutron fluence level during a number of separate irradiation cycles.
- A dedicated radioactive sample handling and storage pit allowing for sample cooling after final irradiations and also for temporary storage between separate irradiation cycles, as well as a sample manipulation system. Similar types of target handling hall and a hot cell for plug maintenance are already designed for the RIB production plugs of SPIRAL 2.
- Transport authorization of irradiated samples should be requested. After final irradiations, the transportation of irradiated material should be feasible for the final tests and analysis in hot and/or chemistry laboratories at CEA Saclay or CEA Cadarache, or elsewhere.

The cost of such an irradiation plug amounts to ~600 k€. The sample cooling system as well as the accelerator operation cost are not included..

5. REFERENCES

[1] S.P. Simakov et al., “Neutronic Chracterization of the High Flux Test Module of the International Fusion Materials Irradiation Facility (IFMIF)”, Proc. of the Int. Conf. on Accelerator Applications/Accelerator Driven Transmutation Technology and Applications (AccApp/ADTTA'03), 1-5 June 2003, San Diego, California, USA.

S.P. Simakov et al., “International Fusion Materials Irradiation Facility (IFMIF): Neutron Source Term Simulation and Neutronics Analyses of the High Flux Test Module”, report FZKA6743 (2002), Forschugszentrum Karlsruhe GmbH, Karlsruhe, Germany.