# EURAC : a concept for a EURopean ACcelerator Neutron Source

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## Abstract

The Joint Research Centre (JRC) has conducted studies on the feasibility of spallation neutrons to simulate the Tokamak fusion reactor first wall conditions. It can be shown that spallation neutrons, produced by 600 MeV protons impinging on a thin lead target are simulating the fusion reactor first wall conditions as well as, or even better than neutron sources based on the D-Li stripping or D-T fusion reaction. Comparing an optimized spallation neutron source of equal beam power with a D-Li neutron source, we find the following Figure of Merit:

$$FM = \frac{\langle dpa \times volume\rangle^{EURAC}_{dpa \geq 60}}{\langle dpa \times volume\rangle_{FMIT}} = \frac{\langle 93162\rangle}{\langle 83\text{x}10\rangle} = 111,$$

reflecting the fact that the proton beam generates about 100 times more neutrons than the deuteron beam.

## Introduction

A D-T fusion cycle produces five times more neutrons per unit of energy released than a fission cycle, with about twice the damage energy and the capability to produce ten times more hydrogen, helium and transmutation products than fission neutrons. They determine, together with other parameters, the lifetime of the construction materials for the low plasma-density fusion reactors (Tokamak, Tandem-Mirror, etc.), which require a first wall.

The Fusion Community [1] is well aware that the construction of an economic fusion power reactor requires a first wall material that can withstand 40 $MWy/m^2$ or 400 dpa**. Mattas et al. [2] predicted that the lifetime of SS 316 in Starfire (First Wall: 1 mm (Be) - 1.5 mm (SS), 3.5 $MW^n/m^2$ and $T_{max}$ = 415°C) will be about 20 dpa or 0.6 years, because of excessive swelling. This theoretical prediction has been based on data sets from fast fission rectors and HFIR* and their respective swelling equations. If First Wall - Liquid Metal Coolant interactions are also considered, the situation will become worse. Therefore, an advanced alloy, such as PCA (Prime Candidate Alloy), has still to be developed and tested adequately. For these reasons the Senior Advisory Panel of Materials for Fusion [3] of the International Energy Agency recommended on October 13, 1986:

- that the selection, the detailed design and the construction of a high flux high energy neutron test facility be initiated immediately with the highest priority.

In the following we comment on the shortcomings of the various simulation techniques and the need for an intense spallation neutron source.

## Simulation with charged particles : dpa-rates $\gtreqless 10^{-2}$ dpa/sec**

Charged particle experiments are an excellent tool to study the underlying basic physical phenomena of radiation damage, particle transport, micro-structural and micro-chemical evolution, swelling and the changes of mechanical properties as a function of dose, dose rate and injected impurities; hence these data can be used to calibrate theoretical models that can, in turn, guide-line the PCA program. However, they have limited reliability if the primary recoil energy spectrum, the production of transmutation products (impurity atoms), dpa-rate effects, segregation and precipitation phenomena, as well as typical bulk properties are important parameters in the evolution of the mechanical properties towards end-of-life [4]. In general bulk properties and weldings cannot be tested.

## Simulation with HFIR* and EBR-II* : dpa-rates $\approx 10^{-6}$ dpa/sec

These reactors have the same dpa-rate as Starfire [5], a Commercial Tokamak Fusion Power Plant Study. This is the dilemma: How to test a PCA material with a dpa-generator that has a source strength more than 10 times lower than the required life time dose [1]. A problem similar to the quadrature of the circle. However, it is due to the existence of HFIR, EBR-II, FFTF* and other reactors that a deep insight into the complex and competing processes for the onset of swelling in the incubation period has been obtained. Garner [6] and Brager and Garner [7] have shown that at high fluence ($\approx$30 dpa) and high temperature ($\approx$400 to 600°C) a relatively temperature-independent swelling rate of 1%/dpa is typical for neutron irradiations of a wide variety of austenitic, solution-strengthened alloys, annealed or cold-worked, with nickel contents below 35%. However, we are on the search for a material whose incubation period must be about 200 to 300 dpa before that steady-state swelling rate may onset, otherwise the material will fail as in Starfire where the swelling limit was set to 5%. This limit will stay unless an ingenious engineer finds a way to design around the problem.

## Simulation with accelerator-based intense neutron sources

It can be shown [8-10] that only accelerator-based neutron sources can provide the necessary source strength with the required neutron energy distribution. There are only two competing nuclear reactions that might be used for the production of an intense neutron source: they are based on the $D^+$-Li stripping, or on the spallation reaction. 35 MeV deuterons, imping-

* HFIR and EBR-II are acronyms for the High Flux Isotope Reactors at Oak Ridge Nat. Lab. and the Experimental breeder Reactor II at Argonne Nat. Lab. in Idaho Falls, respectively; FFTF stands for Fast Flux Test Facility at Richland, U.S.A.

** dpa is displacements per atom.

ing on a lithium target, produce a considerably harder neutron spectrum (average neutron energy: $\tilde{E}_n \approx 9$ MeV) than in a first wall fusion reactor ($\tilde{E}_n \approx 4$ MeV). On the contrary, spallation neutrons, produced by 600 MeV protons impinging on a reflected lead target, have a somewhat softer spectrum ($\tilde{E}_n \approx 4$ MeV) than the $D^+$-Li neutrons. Both neutron spectra deviate strongly from the one in the first wall of a fusion reactor. However, for simulating first wall conditions, it is sufficient to show that the ratio of the spectrum averaged properties:

$$<\sigma\emptyset>_{n,p} : <\sigma\emptyset>_{n,d} : <\sigma\emptyset>_{n,t} : <\sigma\emptyset>_{n\alpha} : <\sigma\emptyset>_{n,2n} : \ldots$$

$$\ldots : <\sigma\emptyset>_{n,\text{rest nuclei}} : P(T)$$

are similar to the one in the fusion reactor. $\sigma$ stands for $\sigma(E)$, the energy-dependent production cross section; $\emptyset \equiv \emptyset(E)$, the neutron spectrum; and P(T) stands for the primary recoil energy spectrum; and T for the recoil energy in the laboratory system.

For the original exploration of the validity of the spallation neutron source concept [10] we had chosen an iron reflected high leakage lead target. For the actual design concept [10] a lead or a $^{17}LiPb^{83}$ reflected non-leakage lead target had been chosen and neutron contour calculations have been performed for the zones and sections as sketched in Figure 1. These zone sections are actually accessible for irradiations. In Figure 2 the results are plotted for the different sections and zones. Due to the non-leakage target we obtain 800 dpa/6 mA year for a 600 MeV proton beam. Note that even in Zone III and Section 8 a dose of 13 dpa can be obtained, equivalent to the 1 MW year/m$^2$ of the fusion reactor dose. Comparing this optimized spallation neutron source with FMIT, we obtain the following Figure of Merit:

$$FM = \frac{<\text{dpa x volume}>^{\text{EURAC}}_{\text{dpa} \geq 60}}{<\text{dpa x volume}>_{\text{FMIT}}} = \frac{93162}{83\text{x}10} = 111,$$

reflecting the fact that the proton beam generates about 100 times more neutrons than the deuteron beam in FMIT for the same beam power. Similar to FMIT a coolant fraction of 50% has been assumed in the irradiation space.

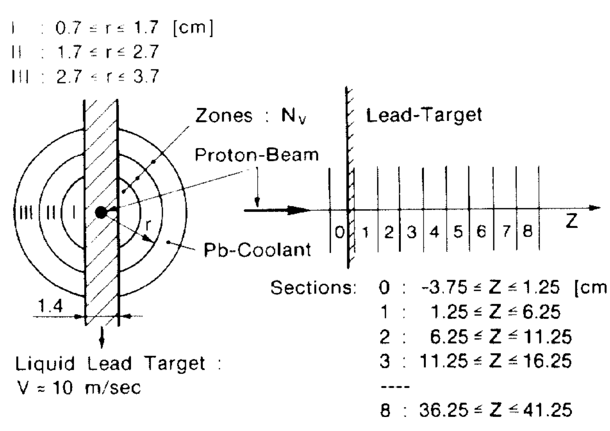


FIGURE 1 Target cross sections perpendicular and parallel to the beam axis (Z) with there respective zones and sections.

In the first three zones we have a total volume of 2352 cm$^3$, allowing a coolant fraction of 50%, we obtain 1170 cm$^3$ of actual sample space of which 653 cm$^3$ have a yearly dose of $60 \leq$ dpa $\leq 800$. This is the kind of volume and dose/year that is required for an Alloy Development Programme. Note also that the dpa-rate effects can be studied simultaneously in identical samples placed at different positions in the EURAC target over a range of two to three orders of magnitude in order to obtain the correct correlations from low to high fluence data in fusion reactors.

Most important: bulk properties and weldings can be studied with samples having a diameter of 1 cm with the appropriate temperature gradients, thermal and swelling induced stresses and the adequate liquid metal coolant-sample interaction to test corrosion and leaching phenomena simultaneously. Such experiments can provide the necessary technological data base to evaluate the economic feasibility of fusion power reactors.

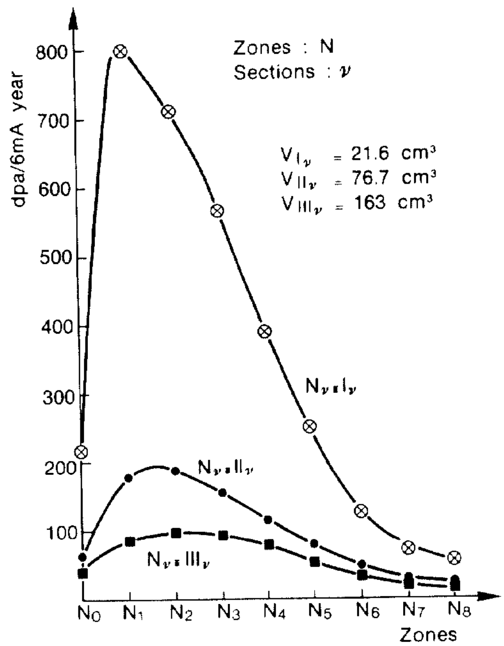


FIGURE 2 Irradiation dose in dpa per 6 mA year in the different zones and sections of the lead reflected lead target.

There are three problems connected with spallation neutrons and the EURAC target geometry and material composition:

1) the high energy neutrons and protons, present in the irradiation space, so close to the impinging proton beam, do they produce damage structures representative for fusion conditions ?
2) neutrons and protons are interacting with the sample nuclei producing (n;n,2n,...,nxp,x$\alpha$) and (p;n,2n,...,xp',x$\alpha$) reactions; is the resulting ratio of total hydrogen and helium production representative for fusion first wall conditions ?
3) high energy neutrons and protons that are interacting with sample nuclei produce a different distribution of transmutation products than fusion neutrons. Is the build-up of the "undesired" transmutation products small enough that they do not influence the mechanical properties of the test samples towards end of life ?

In the following, answers are given to the questions:

1) 14 MeV neutrons in Fe produce recoiling Fe atoms with a maximum recoil energy $T_{max} = 1$ MeV. 100 MeV neutrons and protons can produce $T_{max} \approx 7$ MeV. One can show that the damage energy density per unit track length as a function of Fe-recoil energy in Fe is a steady decreasing function with recoil energy, reflecting the fact that high energy ions produce more heat than damage. Therefore, we do not expect any new damage structures from high energy recoils. Merkle [11] showed already in 1974 that 14 MeV and fission neutrons are producing the same damage structures but two times more per 14 MeV than per fission neutron. Merkle's result confirms our view.
2) 600 MeV protons produce neutrons and protons in the intranuclear cascade and the residual highly excited nucleus

evaporates n, p, d, t and $\alpha$-particles. Therefore, neutrons and protons arrive in our irradiation space of zone I to III. Sinha [12] has calculated the fractional deposition of protons slowed down in an Fe-sample of 2 mm thickness positioned in zone I at Z = 3.75 cm and r = 1.3 cm. He found for the different contributions for the different production terms (p,xp') : (n,xp for $E_n \leq 40$ MeV) : (n,xp for $E_n \geq 40$ MeV) = $1.29 \times 10^{-3}$ : $0.31 \times 10^{-3}$ : $0.48 \times 10^{-3}$ hydrogen/cm$^3$ proton. 62% of the deposited hydrogen originates from slowed down protons leading to a hydrogen to helium ratio of 10. This is twice what we expect in a fusion reactor first wall, see Table 1. However, it is known [13] that the HETC underestimates the He-production by a factor of two, hence we are very close to fusion conditions. Since hydrogen has a high solubility in metals compared to He, the H:He ratio is not too sensitive a quantity and a factor of 2 is in any case acceptable.

TABLE 1 Neutron source flux values and their production of H, He and dpa in AISI 316.

| | $\phi_{max}$ n/cm$^2\cdot$sec | Neutrons / cm$^2\cdot$dpa | dpa / sec | He (appm) / dpa | H (appm) / dpa | H:He |
|---|---|---|---|---|---|---|
| HFIR | $5.9 \times 10^{15}$ | $5.71 \times 10^{21}$ | $\sim 10^{-6}$ | $\sim 60$ | 12 | 0.2 |
| EBR-II | $2 \times 10^{15}$ | $2.29 \times 10^{21}$ | $\sim 10^{-6}$ | $\leq 0.6$ | 30 | 50 |
| Fusion 1 MW total/m$^2$ | $2.6 \times 10^{14}$ | $0.9 \times 10^{21}$ | $\sim 3 \times 10^{-7}$ | $\sim 10$ | 50 | 5 |
| EURAC 6 mA - 600 MeV | $\leq 2 \times 10^{16}$ | $0.64 \times 10^{21}$ | $\leq 3 \times 10^{-5}$ | $\sim 10$ | 100 (total) | $\leq 10$ |

3) Sinha [14] has evaluated the production cross sections for transmutation products and calculated the production rate by the neutron and proton flux in the Fe sample positioned at Z = 3.75 cm and r = 1.3 cm. He could show that the production rate falls off exponentially with decreasing atomic number values, contrarily to the case of 600 MeV protons. The main contributions are coming from (n,p), (n,$\alpha$), (n,xp+x$\alpha$) and (p,xp+x$\alpha$) reactions. On the basis of these evaluated production cross sections, the evolution of the composition of PCA can be calculated as a function of dose and compared with fusion reactor conditions. Sinha and Srinivasan showed [15] that the contribution of "undesired" transmutation products is small, hence, no influence on the mechanical properties of a PCA is expected.

## Choice of accelerator

As discussed by Kley and Bishop [10], three different types of accelerators could be considered depending on the overall programme on which the Scientific Community and the interested Countries could agree. The most reliable and straight forward solution would be based on a 600 MeV, 6 mA, 600 m long proton continuous wave accelerator [10] or a more efficient modification: a 400 MeV, 10 mA, 1000 m long version [16]. The least expensive single purpose machine would be one isochronous cyclotron of the SIN type (Villigen, CH).

However, at present, a limit of the extracted beam current is set to 2 mA [17]. This limit might be overcome in a new design [18] after running the upgraded SIN-isochronous cyclotron at 2 mA some time in the near future.

## Conclusion

We have indicated that charged particle beam experiments are an excellent tool to study the basic physical phenomena of evolving damage structures with dose. High flux reactors have a dpa-rate similar to fusion power reactors and, consequently, are strongly limited for end-of-life tests for prime candidate alloys that must withstand 300 to 400 dpa for the construction of economic fusion power reactors. We showed that an optimized spallation neutron source based on a continuous beam of 600 MeV, 6 mA protons is the desired neutron source for a fusion reactor materials test and development programme. The construction and operation of such a materials test facility will cost about 10% of a fusion engineering test reactor such as NET, FER or ITER. Hence a simultaneous decision is indicated.

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