Available online at www.sciencedirect.com
ScienceDirect
Journal of Nuclear Materials 363–365 (2007) 1087–1092
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Accommodation of prompt alpha-particle loss in a compact stellarator power plant

A.R. Raffray *, T.K. Mau, F. Najmabadi, The ARIES Team

University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0438, USA

Abstract

Alpha loss is an important issue in stellarators, where the inherent non-axisymmetry of the magnetic geometry causes an appreciable magnetic field ripple along the flux surfaces inside the plasma. This results in a non-negligible fraction of alpha-particles being promptly lost from the plasma and hitting the plasma facing components (PFC) at energies close to their born value of 3.5 MeV. The PFC armor must not only accommodate the heat load from the alpha-particle flux but it must also accommodate the He implantation resulting from the high-energy alpha fluxes while providing the required lifetime. An effort is underway as part of the ARIES-CS study to characterize the alpha-particle loss for a compact stellarator and to explore engineering solutions to accommodate the impact of these alphas on the PFC's. This paper summarizes the initial results from this effort.

PACS: 28.52; 52.55.H; 52.40.H; 66.30

Keywords: Diffusion; Helium; Ion–surface interactions; Power deposition; Tungsten

1. Introduction

Alpha loss is an important issue in magnetic fusion energy (MFE), governed by the magnetic field ripple. It can impact tokamaks, where size and aspect ratio constraints can result in coil placement inducing significant ripple, and more importantly stellarators, where the inherent non-axisymmetry of the magnetic geometry causes an appreciable magnetic field ripple along the flux surfaces inside the plasma. In this case, a non-negligible fraction of the alpha-particles will either be born or 'kicked' into orbits that are trapped in these ripples, resulting in rapid outward diffusion and quick exit from the last closed magnetic surface (LCMS) before they are thermalized. Depending on the magnetic topology, a fraction of these particles are promptly lost from the plasma and hit the plasma facing components (PFC) at energies equal to or close to their born value of 3.5 MeV. The alpha loss not only represents a loss of heating power in the core, but, more importantly, impacts the PFC behavior. The PFC armor must not only accommodate the heat load from the alpha-particle flux but it must also accommodate the He implantation resulting from the high-energy alpha fluxes while providing the required lifetime.

* Corresponding author. Tel.: +1 858 822 2120.
E-mail address: rraffray@ucsd.edu (A.R. Raffray).

0022-3115/$ - see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.jnucmat.2007.01.167

This paper describes the initial ARIES-CS effort in this area. The expected alpha loss is first discussed. The effect of these alphas on the first wall armor is then highlighted. Possible engineering solutions to accommodate the impact of these alphas on the plasma facing components are discussed and the findings summarized.

2. Alpha Loss in ARIES-CS

As part of the ARIES-CS study, several class of stellarators were considered including NCSX-based configurations, as illustrated in Fig. 1 [1]. Initial results indicated a high fraction of prompt alpha-particle loss (>10%) due to the appreciable magnetic field ripple associated with the non-axisymmetry of the magnetic geometry. Subsequent optimization studies with the inclusion of a bias in the magnetic spectrum helped to reduce the ripple and associated alpha losses to <5%. This is still a relatively high number, which would require special measures in designing the PFC area being impacted depending on the resulting alpha loss footprint and peaking factor on the first wall. An effort is underway to determine the location and density of the alpha-particle fluxes on the PFC using two particle orbit codes: ORBIT3D is used to follow the guiding-center or drift orbits of the alphas inside the plasma; outside the LCMS, the GYRO code is used, taking into full account the gyro-orbit of the particles, which is needed to accurately determine the strike point locations since for MeV alphas, the gyro-radius is of the same order as the scrape-off layer width [2].

Fig. 2 shows an example energy spectrum of the alpha loss [1], which ranges from a few hundreds keV to 3.5 MeV. The resultant footprints on the LCMS show that the bulk of these particles are lost in a region below the mid-plane on the outboard edge of the plasma cross-section. Initial findings

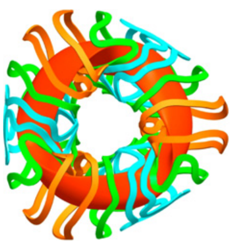

Fig. 1. Example of NCSX-like 3-field period configuration considered in the ARIES-CS study.

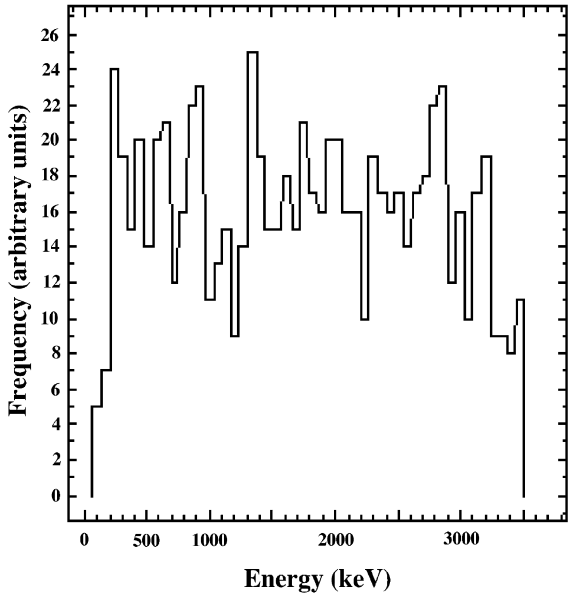

Fig. 2. Example energy spectrum of alpha-particle loss from ARIES-CS physics study.

appear to indicate that part of the lost alpha population will intersect the first wall and another part the divertor plate. These predictions remain to be confirmed by numerical studies. This paper reports on the effort launched to explore the impact of the high-energy alphas on the PFC's and to look into possible engineering solutions.

3. Effect of prompt alpha irradiation of PFC

The PFC surface must not only accommodate the heat load from the alpha-particle flux but also the resulting He implantation while providing the required lifetime. The heat load resulting from the alpha flux can be accommodated by utilizing divertor-like modules, capable of handling heat fluxes of ~10 MW/m^2. Such a divertor concept has been developed for ARIES-CS utilizing a He-cooled jet configuration with W-alloy as structural material and a thin W armor, as illustrated in Fig. 3 [3]. For power plant relevant inlet and outlet He temperatures of ~600 °C and ~700 °C, the maximum W alloy temperature is <1300 °C and the total stress intensity <370 MPa for a maximum heat flux of 10 MW/m^2 and an outer W-alloy tube thickness of 1 mm (on top of which would be added a ~1-mm thick W armor layer). Issues requiring further R&D effort include fabrication methods, W alloy development and experimental thermo-fluid performance verification.

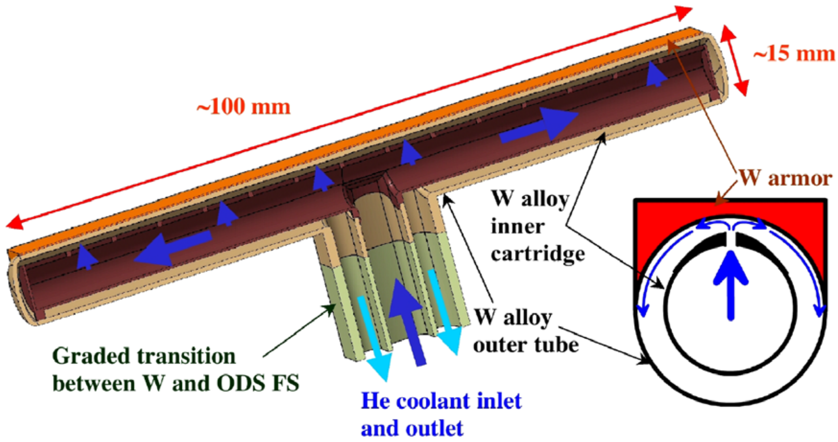

Fig. 3. Cross-section of ARIES-CS divertor T-tube, illustrating He coolant flow [3].

For such high alpha energies as shown in Fig. 2, erosion by sputtering is less of a concern; for example, the threshold for sputtering of W by He ions is about 100 eV, the sputtering yield then increasing to a maximum value at about 10 keV before falling down at higher energies [4]. For the high-energy alpha case, the armor lifetime would be governed by some other mechanism, such as exfoliation, resulting from the accumulation of He atoms in the armor (the penetration depth of a 1 MeV He ion in W is ~1.5 μm). Much information can be found in the literature on the effect of low energy He ion bombardment on different armor including tungsten (e.g. Refs. [5–7]); some information is also available on the effect of the high-energy (~1 MeV) He ions on the armor (e.g. [8]) but it is rather limited.

In the case of ARIES-CS, for an example fusion power of ~2350 MW, a first wall surface area of ~572 m^2, a conservative assumption of 10% alpha loss and a 5% alpha footprint, the average heat flux on the PFC is ~2.2 MW/m^2 and the maximum heat flux would be <10 MW/m^2 for a peaking factor <4.5. The corresponding ion flux on the PFC is $\sim 3\times 10^{18}$ ions/m^2 s (corresponding to a generation rate of $\sim 2\times 10^{24}$ ions/m^3 s). This is in the range of the average dose rates expected under some IFE conditions, and information from IFE R&D in this area could prove useful. For example, a pulsed He implantation and release experimental study was performed recently with 1 MeV He ions on a W armor as part of an effort on assessing the possibility of a W-based dry wall armor in an inertial fusion energy (IFE) chamber [9]. These results are used below to help provide some more insight on the possible impact of high-energy alpha implantation in a W armor in a compact stellarator.

4. He behavior in W

From the literature, a fairly good theoretical understanding of the possible behavior of He in W can be inferred. Due to their high heat of solution, inert-gas atoms are essentially insoluble in most solids. The He atoms would occupy either substitutional or interstitial sites. As interstitials, they are very mobile, but they will be trapped at lattice vacancies, impurities, and vacancy–impurity complexes. The following activation energies are associated with the different He processes in tungsten [10]:

$$\left.\begin{array}{l}\text{Helium formation energy}: 5.47\ \text{eV}\\ \text{Helium migration energy}: 0.24\ \text{eV}(1)\\ \text{He vacancy binding energy}: 4.15\ \text{eV}\\ \text{He vacancy dissociation energy}: 4.39\ \text{eV}\end{array}\right\} \quad (1)$$

The behavior of helium in tungsten can be represented through the following simplified processes. the implanted he would diffuse through the bulk of the W and then be trapped in a vacancy, defect or other trapping sites. if sufficient energy is available the trapped atom can be set free and diffuse further through W. Eventually at the W surface interface, He would desorb to the surrounding atmosphere. These overall processes might include more than one mechanism. All these processes are governed by activation energies which might also change with the He concentration and with the possible formation of He bubbles. The material thermo-mechanical conditions would also impact the overall He behavior. For example, the implantation of high-energy He would result in defects or high dpa's (thousands). High temperature operation would tend to anneal out these defects except for those occupied by He already.

5. Cyclic he implantation and release in W

Recently, as part of the HAPL program, an experimental study of the cyclic implantation and release of He in W was performed by the University of North Carolina (UNC) and ORNL (high base temperature, ~850 °V, high-energy, ~1.3 MeV, pulsed implantation and anneals at 2000 °C over ~1000 cycles to fluences of ~10^{20} He/m^2) [9]. The results are summarized in Figs. 4 and 5; they indicate that He retention decreases drastically when a given helium dose is spread over an increasing number of pulses, each one followed by W annealing to 2000 °C, to the extent that there would be no He retention below a certain He dose per pulse. For example, from Fig. 5, for single crystal tungsten, this threshold would be of the order of 10^{16} ions/m^2 per shot. Detailed modeling of He behavior under these conditions is highly challenging due to lack of well-defined parameters over the anticipated range of operation (for MFE and even more so for the cyclic IFE operation). Such modeling effort includes the work performed at UCLA for both MFE conditions [11] and IFE conditions [12]. For the scope of this work and in order to obtain some preliminary insight on the application of experimental results to MFE conditions, it was decided to derive an effective diffusion coefficient, ($D_{\text{eff}} = D_0 \times \exp(-E_{\text{eff,diff}}/kT)$), which would be based on the combination of processes and which would be applicable for the same range of conditions. It is clear that in doing so the effective activation energy ($E_{\text{eff,diff}}$) derived from the experiment would not be that of bulk diffusion but of the rate-controlling mechanism, much probably some form of trapping/detrapping mechanisms. The pre-exponential constant for diffusion was set to the same value as for the bulk diffusion case, $D_0 = 4.7 \times 10^{-7}$ m^2/s [7]. The diffusion length was set at 1.5 μm consistent with the implantation depth of he ions with energies ~1 MeV energy (used in the experiment). The 1-D analysis proceeded by assuming a step He implantation concentration (in atoms/m^3 based on the dose and the implantation depth) as source term followed by diffusion over the temperature history shown in Fig. 4 for the anneal process; the boundary conditions assumed zero concentration gradient at one end of the diffusion domain and zero concentration at the other end. This procedure is repeated over the given number of cycles with the aim of finding the value of $E_{\text{eff,diff}}$ which would yield the final retention value measured experimentally in each case (i.e. for 1, 10, 100, 167, 333 and 1000 cycles) [13]. The overall results are summarized in Fig. 6, and a possible interpretation of the results follows.

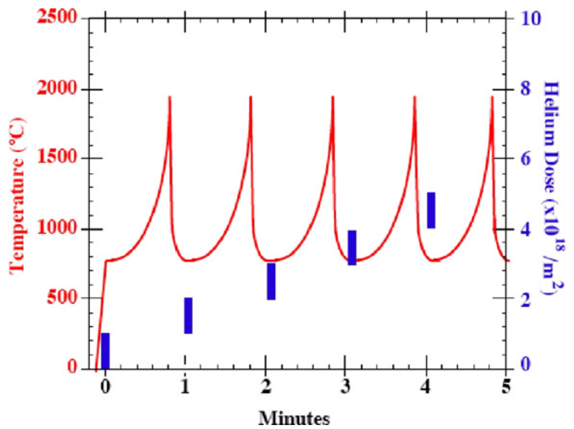

Fig. 4. He dose implantation and temperature anneals for experiments simulating He retention in tungsten under IFE conditions [9].

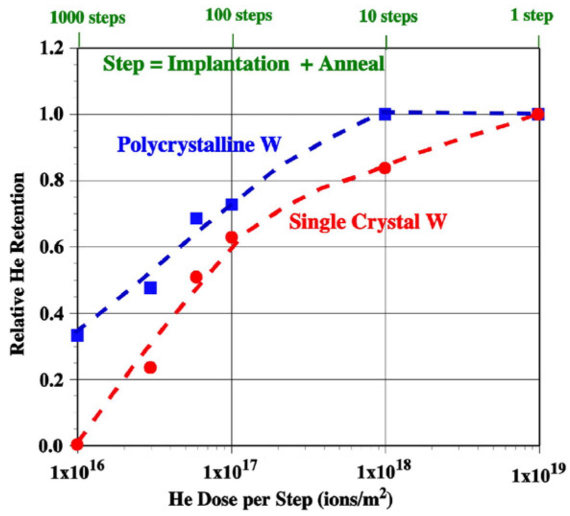

Fig. 5. Relative He retention in polycrystalline and single crystal W samples as a function of He dose per cycle for different number of pulses based on He implantation and temperature anneals illustrated in Fig. 4 [9].

The basic assumption is that trapping in general increases with the He irradiation dose or concentration which creates sites through dpa's and formation of vacancies (followed by an anneal of

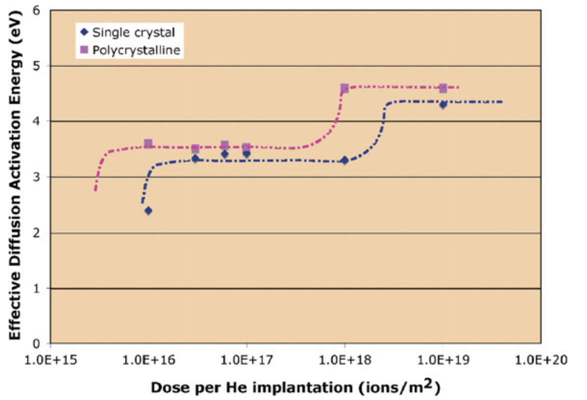

Fig. 6. Effective diffusion activation energy required to reproduce the experimental results for single crystal and polycrystalline W. The curve fits have been drawn to suggest a possible variation of the activation energy with the He dose (or concentration).

the unoccupied trapped sites during the ensuing temperature transient). At very low dose, only a few trapping sites are activated by the irradiation and the helium transport should be governed by bulk diffusion (with an activation energy of ~0.24–0.28 eV as shown in Eq. (1)). As the dose per cycle increases, an increasing number of trapping sites are formed or activated and the activation energy increases. It seems that there is a near-threshold of He dose at which the activation energy increases rapidly to about 3.3–3.6 eV and stays at this value over a dose of $\sim 2\times10^{16}$ to $\sim 5\times10^{18}$ ions/m^2 for single crystal W and about $\sim 5\times10^{15}$ to $\sim 5\times10^{17}$ ions/m^2 for polycrystalline. Above this range, the activation energy increases rapidly to ~4.2–4.8 eV, indicating an increase in trapping perhaps due to He build up in vacancies (the vacancy dissociation energy is ~4.4 eV from Eq. (1)). Overall the dependence of activation energy with dose is about the same for single crystal and polycrystalline W except that it is shifted to lower doses for the latter case.

6. Application to ARIES-CS case

For the ARIES-CS case, both the He irradiation and temperature are steady-state as opposed to the cyclic experimental results previously described. Effective He inventories under steady-state temperatures can be parametrically calculated. However, the choice of $E_{\mathrm{eff,diff}}$ for a steady-state dose is not so straightforward as the results were obtained for cyclic conditions with a finite He dose per implantation. As a rough guide, the experimental temperature anneal from Fig. 4 was used to estimate the uniform temperature which would result in the same characteristic diffusive length (assumed as $(D_{\mathrm{eff}}t_{\mathrm{cycle}})^{0.5}$) as the integration of the diffusion characteristic length over the temperature and time increments (for $t_{\mathrm{cycle}} = 60$ s). This temperature was found to be 1625 °C, and the corresponding maximum dose rate would be 1.6×10^{17} ions/m^2 s. Increasing this temperature for a given diffusive length would result in shorter effective times and larger maximum dose rates (e.g. ~3.5 s and 3×10^{18} ions/m^2 s for a ~1825 °C temperature) and reducing it would have the opposite effect. For the ARIES-CS case, the steady-state alpha dose rate from the example case shown is $\sim 3\times10^{18}$ He ions/m^2-s and the experimental results would be best applied for high temperature cases with $E_{\mathrm{eff,diff}}$ corresponding to the maximum dose. Parametric analyses would then be performed to evaluate the sensitivity of the results to this assumption. From Fig. 6, this value of $E_{\mathrm{eff,diff}}$ is ~4.8 eV.

The results in term of the steady-state He inventory estimated in W for different characteristic diffusion distances are shown in Fig. 7. It is not clear what is the maximum allowable He concentration limit in W to avoid exfoliation and continuous loss of armor. Ref. [9] indicates about 4% to avoid blistering and ~20% or more to avoid exfoliation; Ref. [14] indicates about 15% to avoid exfoliation. Clearly higher W temperature and shorter diffusion distances are needed, e.g. 50–100 nm at ~1800 °C.

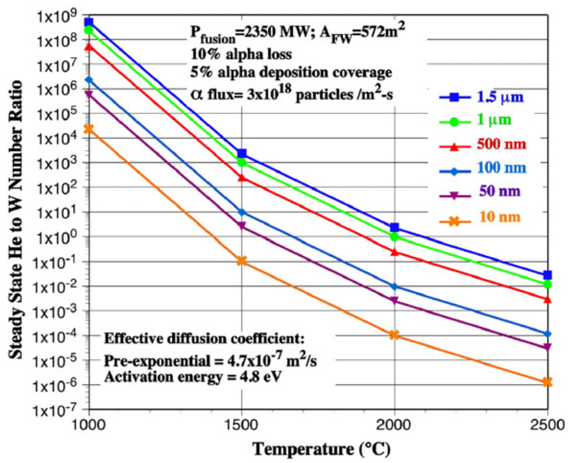

Fig. 7. Implanted He retention in W armor as a function of operating temperature and characteristic diffusion distance for an effective diffusion activation energy of 4.8 eV.

One possibility is to used porous W with very fine microstructure. For example, Plasma Technology Incorporated in the USA has produced nano-sized tungsten powders by plasma flame vaporization and rapid quenching; the product is ultra pure with an average particle size of <50 nm. This powder can then be used to fabricate by vacuum plasma spray a porous W armor with ~50 nm microstructure and interconnected porosity to enhance the release of implanted He [13].

A reduction in $E_{eff,diff}$ would also have a major effect. For example, for a diffusion distance of 100 nm and a temperature of 1800 °C, the steady-state He to W inventory ratio changes from ~0.1 for $E_{eff,diff} = 4.8$ eV, to $\sim 4 \times 10^{-5}$ for $E_{eff,diff} = 3.4$ eV and all the way down to 8×10^{-13} for $E_{eff,diff} = 0.24$ eV. An interesting question is whether at such a high W operating temperature some annealing of the defects might further help helium release.

7. Conclusions

Alpha loss is a major issue in stellarators, impacting the survival of the first wall. The armor lifetime under the alpha flux would depend on a number of parameters, including the α-particle energy spectrum, the armor material configuration and temperature, and the activation energies for the different processes governing the implanted He behavior in the armor; changes in these can result in orders of magnitude variation in the trapped He inventory. Use of a nano-sized porous W armor and high operating temperature would help to enhance the release of implanted He. Clearly, further R&D is required in this area to make sure that a credible solution exists for the accommodation of alpha loss in a compact stellarator.

Acknowledgement

The work at UCSD was supported under US Department of Energy Grant No. DE-FC03-95-ER54299.

References

[1] F. Najmabadi, A.R. Raffray, L.-P. Ku, J.F. Lyon, et al., Phys. Plasmas 13 (2006) 1.
[2] T.K. Mau, H. McGuinness, A. Grossman, A.R. Raffray, D. Steiner and the ARIES Team, in: Proceedings of the 21th IEEE/NPSS SOFE, Knoxville, TN, September 26–29, 2005, (CD-ROM).
[3] T. Ihli, A.R. Raffray, S. Abdel-Khalik, M. Shin and The ARIES Team, Fus. Eng. Des., 2007, in press.
[4] W. Eckstein, Sputtering, reflection and range values for plasma edge codes, IPP-Report, Max-Planck-Institut fûr Plasmaphysik, Garching, Germany, IPP 9/117, March, 1998.
[5] D. Nishijima, M.Y. Ye, N. Ohno, S. Takamura, J. Nucl. Mater. 329–333 (2004) 1029.
[6] M. Ye, S. Fukuta, N. Ohno, S. Takamura, et al., J. Plasma Fus. Res. 3 (2000) 265.
[7] K.O.E. Henriksson, K. Nordlund, J. Keinonen, et al., Phys. Scripta T108 (2004) 95.
[8] R. Behrisch, B.M.U. Scherzer, Radiat. Eff. 78 (1983) 393.
[9] S.B. Gilliam, S.M. Gidcumb, N.R. Parikh, D.G. Forsythe, et al., J. Nucl. Mater. 347 (2005) 289.
[10] M.S. Abd El Keriem, D.P. van der Werf, F. Pleiter, Phys. Rev. B 47 (22) (1993) 14771.
[11] N.M. Ghoniem, S. Sharafat, J.M. Williams, L.K. Mansur, J. Nucl. Mater. 117 (1983) 96.
[12] S. Sharafat, personal communication, HEROS.
[13] A.R. Raffray, Engineering analysis of He retention and release in porous W armor, UCSD Technical Report, UCSD-CER-05-09, September 27, 2005.
[14] G. Lucas, personal communication.