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Early Material Qualification for Advanced Magnetic Fusion Energy

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# Objectives

There is no practical experience with materials under the conditions of a steady-state plasma fusion system; damage of 100 to 200 displacements per atom (dpa), and the simultaneous production of helium (10 appm/dpa) and hydrogen (40 appm/dpa). A 14 MeV source of neutrons for achieving the required neutron dose and dose rates does not exist at present. In this sense, the collaboration proposed here will strengthen the materials background needed for the design of the Fusion Nuclear Science Facility (FNSF), identified as a critical element of US fusion energy research in the FESAC [[[1]](#endnote-1)] report. Experiments can be executed today using existing ion beam and spallation neutrons that emulate the fusion environment (Figure 1). Our objectives are categorized by FESAC as, “*conquering nuclear degradation of materials and structures”,* and specifically, *“to develop a rigorous scientific understanding and devise mitigation strategies for deleterious microstructural evolution and property changes that occur in materials exposed to high neutron fluence, and high concentrations of transmutation produced gases from a 14 MeV peaked neutron source*”**.**

# Technical Approach

The focus is on plasma facing materials (PFM) that are candidates in divertor designs. We have also included blanket structural materials as they are used in plasma facing components [[[2]](#endnote-2)]. We will utilize the multiple beam ion sources at CEA Saclay and CNRS Orsay (JANNUS) and materials irradiated with a mixed spectrum of high-energy protons and spallation neutrons at the PSI SINQ-STIP [[[3]](#endnote-3)] target area. This allows us to examine displacement damage at relevant temperatures along with the implantation or generation of transmutation gases of H and He for high dpa rate ion beams and much lower dpa rate neutrons. The simultaneous generation of H is important to describe synergistic effects and because it emulates the behavior of T and T retention. Mechanical testing and atomic scale characterization will be employed in pre- and post-radiation examination of materials. The following three material types will be studied experimentally along with theoretical modeling of the results:

Figure 1. Multi-ion-beam (three beams) sources such as JANNUS (*top*) above and spallation neutron sources (target assembly at SINQ-STIP-PSI *below*) provide the international experimental platforms necessary for the early experimental qualification of materials for fusion energy for fusion energy materials R&D.

1. Refractory metal and refractory metal armored steels (W)
2. RAFM steels *(F82H, EUROFER97, HT-9)* structured as nanograin-sized ferritic
3. Nano-dispersed particle steels *(ODS-14YWT)*

The following task areas are envisioned:

1. Advanced materials and materials synthesis
2. Multiple simultaneous ion beam irradiations (H, He and heavy ion)
3. Identify relevant materials previously irradiated at SINQ
4. Post irradiation examination of evolving microstructure and mechanical properties in 2) and 3)
5. Damage accumulation and material evolution modeling

# Advanced Materials

***Refractory metal and armored steel****.* Pure tungsten exhibits high strength at high temperatures and good surface heat capability (11.3 kW/m at 1275 K). It also shows a good resistance to erosion and does not suffer from high activation. Important issues are its high ductile-brittle transition temperature that preclude its use at low temperatures (water cooled components), T retention in the radiation damaged microstructure, the behavior of He accumulation at or near surfaces, the extensive production of Re and Os under neutron irradiation and phase stability, particularly in the presence of Re. Although an important effort is being made internationally [[[4]](#endnote-4)], recent reviews [[[5]](#endnote-5)] indicate that these issues are not yet resolved and that therefore it is worthwhile to examine in more detail the radiation performance of pure tungsten by a systematic program of irradiations at relevant temperatures (500 to 800 OC) and variable dpa dose and dpa dose rates. There are also important opportunities for the modeling of the overall irradiation microstructure evolution and the irradiation induced phase instabilities.

***Nanograin-sized RAFM’s and Nano dispersed oxide-particle steel*.** Grain boundaries are important point defect sinks and increasing their volume density is a possible path to produce radiation resistant steels. Recent results [[[6]](#endnote-6)] indicate that RAFM steels can be produced with grain sizes of below 100 nm. If stable at high temperatures this would enhance radiation tolerance for the fusion environment. Post-irradiation testing of these steels will provide a measure of their radiation resistance

The oxide dispersion strengthened 14YWT ferritic alloy was developed for extreme neutron irradiation environments encountered in plasma facing components of fusion reactors [[[7]](#endnote-7)].  The processing goal for 14YWT was ultra-fine grains (<500 nm) plus a high concentration of stable nano-size (2-5 nm) oxide particles, or Y-, Ti- and O-enriched nanoclusters, that yield excellent high-strength and creep at elevated temperatures and good fracture toughness at low temperatures.  The microstructure provides high sink strength for trapping point defects, making 14YWT a very promising high tolerance material for fusion neutron irradiation damage.

# Microstructure and Mechanical Properties

One of the techniques commonly used to study the evolution of defect structures and the nucleation and growth of voids utilizes high-resolution transmission electron microscopy (HRTEM) examinations of specimens simultaneously bombarded by heavy ions and helium and/or deuterium ions through so called “dual-beam” and “triple-beam” simulation experiments [[[8]](#endnote-8), [[9]](#endnote-9), [[10]](#endnote-10)] or by spallation neutrons. Together, heavy ions generate atomic displacements and co-implantation of the H and He simulate important aspects of the fusion environment. The ion-beam technique offers the possibility of studying microstructural and defect evolution along with mechanical property variations at various damage rates, helium and hydrogen to dpa ratios, irradiation temperature, and fluences under well-defined experimental conditions. When results for dual beam experiments using He and Fe ions [[[11]](#endnote-11)] were compared with reactor neutron irradiations with He injection they are seen to be identical in almost all respects [[[12]](#endnote-12)]. Spallation source irradiations produce damage at rates similar to the fusion environment and also result in the simultaneous production of H and He in the irradiated specimens. Taken together these two types of radiation studies, ions and spallation neutrons, “bracket” many important aspects of the fusion source irradiation itself, PKA spectra and dpa dose rates.

Tungsten alloys are still at an early stage of their development for fusion applications, despite their large potential for radiation and heat tolerance [[[13]](#endnote-13)]. Ways to circumvent their inherent brittleness, with a high DBTT, are being developed around the world by, for instance, the incorporation of secondary phases, e.g. yttria or TiC, which would improve their ductility, ultra-fine grains stabilized with oxide precipitates or W composites. Whatever the approach their behavior under irradiation is still largely unknown and significant efforts are needed in order to establish these alloys in a fusion device. ODS ferritic materials on the other hand are more mature, with established ways to reduce their DBTT by thermo mechanical treatment (TMT) and data on their radiation and high temperature behavior available today. However, the nature and formation mechanisms of the oxides are still unclear, which complicates the understanding of their behavior under radiation. The interaction of the hydrogen produced by transmutation with the oxygen of the dispersoids is still unknown, while some suggest it might be strong [[[14]](#endnote-14)], and a potential limiting factor. In addition, the fate of Cr in these alloys under irradiation is currently investigated with the expectation of Cr precipitation or ’ would further embrittle the material. Advanced microstructural characterization techniques are foreseen in this area in order to quantify the nature and morphology of the oxides, by energy filtered transmission electron microscopy (EFTEM), aberration corrected scanning transmission electron microscopy (Cs TEM), and atom probe tomography (APT) [[[15]](#endnote-15), [[16]](#endnote-16)]. In addition, TEM in situ irradiation and heating experiments can investigate the behavior of the oxides under irradiation and heat loads and *in situ* mechanical testing (in TEM) allows studying the dislocation-defect interaction. While materials irradiated in the SINQ irradiation program are available, additional ion beam irradiations are needed in order to evaluate the fundamental processes taking place. Small scale mechanical testing can be carried out to a) enhance the statistics on a limited set of SINQ irradiated materials by increasing the number of measurements performed on a single sample and making post irradiation, post mechanical testing, heat treatments accessible and b) gaining mechanical data on ion beam irradiated material to provide a first “glance” at the changes in mechanical properties without the availability of a high dose neutron source.

# Theory, Simulation and Modeling

The proposed experimental strategy must be accompanied by an equally comprehensive theory, modeling and simulation (TMS) effort. The TMS approach must be capable of establishing a hierarchical connection between nanometric causes and continuum consequences, as well as a path for coarse-graining toward a practical computational implementation. The inspiration for the TMS effort comes from the need to unify all the experimental irradiation processes into a framework characterized by a select (although as broad as possible) catalog of fundamental physical mechanisms that are independent of the irradiation mode, temperature, timescale, etc., chosen for a given experiment. In this fashion, TMS can ‘interpolate’ among different experiments for benchmarking purposes, as well as ‘extrapolate’ (only in judiciously-chosen scenarios) outside the range of experimental conditions tested [[[17]](#endnote-17), [[18]](#endnote-18), [[19]](#endnote-19)]. The TMS effort will address the following issues: damage production, defect kinetics including synergistic effects between point and extended defects, helium and hydrogen, as well as their impact on mechanical properties. Validation will be provided by carefully selected experiments of irradiations using ions at JANNUS facility in Saclay/Orsay and spallation neutron irradiation at PSI. JANNUS Orsay offers a unique facility of TEM *in situ* irradiation with dual ion beams, allowing the direct investigation of irradiation induced mechanisms inferred by our TMS approach applied to ODS materials and W alloys.

References

1. Fusion Energy Sciences Advisory Committee Rpt on Opportunities for Fusion Materials Science and Technology Research Now and During the ITER Era Feb. 2012, U.S. DOE, DOE/SC-0149 [↑](#endnote-ref-1)
2. S. Suzuki, K. Ezato, T. Hirose, K. Sato, H. Yoshida, M. Enoeda and M. Akiba: “First wall and divertor engineering research for power plant in JAERI”; Fus. Eng. & Design 81 (2006) 93 [↑](#endnote-ref-2)
3. Y. Dai and G.S. Bauer, Status of the first SINQ Irradiation Experiment, STIP-I, Journal of Nuclear Materials 296 (2001) 43 [↑](#endnote-ref-3)
4. N. Baluc et al., “Status of R&D Activities on Materials for Fusion Power N. Baluc et al 2007 Nucl. Fusion **47** S696 *See references therein*. [↑](#endnote-ref-4)
5. V. Phillips, “Tungsten as material for plasma facing components “ J. Nucl Mater 415 (2011) 52. See also R.A. Pitts *et al* “Physics basis and design of the ITER plasma-facing components”, J. Nucl. Mater 415 (2011) 5957 and T. Tano *et al* “Microstructure development in neutron irradiated Tungsten alloys” Mater. Trans. 52 (2111) 1447 [↑](#endnote-ref-5)
6. M. Landowska *et al* “Structure and properties of nano-sized Eurofer-97 steel obtained by hydrostatic extrusion” J. Nucl. Mater. 386-388 (2009) 499. [↑](#endnote-ref-6)
7. M. K. Miller, D. Hoelzer, and K. F. Russell Towards Radiation Tolerant Ferritic Alloys, [Materials Science Forum](http://www.scientific.net/MSF) (Volumes 654 - 656), pp 23-28 (2010) [↑](#endnote-ref-7)
8. M. Lewis, W. Allen, R. Buhl, N. Packan, S. Cook, and L. Mansur, Nuclear Instruments and Methods in Physics Research, B43 (1989) 243. [↑](#endnote-ref-8)
9. I.–S Kim, J.D. Hunn, N. Hashimoto, D.L. Larson, P.J. Maziasz, K. Miyahara, E.H. Lee, J. Nucl. Mater. 280 (2000) 264. [↑](#endnote-ref-9)
10. K. Yutani, H. Kishimoto, R. Kasada, A. Kimura, J. Nucl. Mater. 367-370 (2007) 423. [↑](#endnote-ref-10)
11. HRTEM study of oxide nanoparticles in K3-ODS ferritic steel developed for radiation tolerance, Hsiung L.; Fluss M.; Tumey S.; et al. JOURNAL OF NUCLEAR MATERIALS  Volume: 409   Issue: 2   Pages: 72-79 [↑](#endnote-ref-11)
12. G.R. Odette, D.T. Hoelzer, Irradiation-tolerant Nanostructured Ferritic Alloys: Transforming Helium from a Liability to an Asset, JOM Volume 62, Issue: 9,  pp: 84-92,(2010) [↑](#endnote-ref-12)
13. M. Rieth, J.L. Boutard, S.L. Dudarev, T. Ahlgren, S. Antusch, N. Baluc, M.-F. Barthe, C.S. Becquart, L. Ciupinski, J.B. Correia, C. Domain, J. Fikar, E. Fortuna, C.-C. Fu, E. Gaganidze, T.L. Galán, C. García-Rosales, B. Gludovatz, H. Greuner, K. Heinola, N. Holstein, N. Juslin, F. Koch, W. Krauss, K.J. Kurzydlowski, J. Linke, Ch. Linsmeier, N. Luzginova, H. Maier, M.S. Martínez, J.M. Missiaen, M. Muhammed, A. Muñoz, M. Muzyk, K. Nordlund, D. Nguyen-Manh, P. Norajitra, J. Opschoor, G. Pintsuk, R. Pippan, G. Ritz, L. Romaner, D. Rupp, R. Schäublin, J. Schlosser, I. Uytdenhouwen, J.G. van der Laan, L. Veleva, L. Ventelon, S. Wahlberg, F. Willaime, S. Wurster, M.A. Yar (2011). "Review on the EFDA programme on tungsten materials technology and science." *Fusion Engineering and Design* ***86****(9-11): 2450-2453*. [↑](#endnote-ref-13)
14. M. Klimenkova, A. Mo ̈slang, and R. Lindau (2008) ,"EELS analysis of complex precipitates in PM 2000 steel." *Eur. Phys. J. Appl. Phys.* ***42****: 292-303*. [↑](#endnote-ref-14)
15. [P. Hosemann](http://www.springerlink.com/content/?Author=P.+Hosemann), [Y. Dai](http://www.springerlink.com/content/?Author=Y.+Dai), [E. Stergar](http://www.springerlink.com/content/?Author=E.+Stergar), [H. Leitner](http://www.springerlink.com/content/?Author=H.+Leitner), [E. Olivas](http://www.springerlink.com/content/?Author=E.+Olivas), [A. T. Nelson](http://www.springerlink.com/content/?Author=A.+T.+Nelson) and [S. A. Maloy](http://www.springerlink.com/content/?Author=S.+A.+Maloy), [Experimental Mechanics](http://www.springerlink.com/content/0014-4851/) [Volume 51, Number 7](http://www.springerlink.com/content/0014-4851/51/7/) (2011), 1095-1102 [↑](#endnote-ref-15)
16. P. Hosemann, E. Stergar, L. Peng, Y. Dai, S.A. Maloy, M.A. Pouchon, K. Shiba, D. Hamaguchi, H. Leitner; J. Nucl. Mat, 417 2011, Pages 274–278 [↑](#endnote-ref-16)
17. D. Kiener, P. Hosemann, et al. (2011). "In situ nanocompression testing of irradiated copper." *Nature Materials* **10**(8): 608-613. [↑](#endnote-ref-17)
18. Chu-Chun Fu, Jacques Dalla Torre, François Willaime, Jean-Louis Bocquet & Alain Barbu, Multiscale modelling of defect kinetics in irradiated iron, *Nature Materials* **4**, 68-74 (2005) [↑](#endnote-ref-18)
19. Arsenlis, A., Rhee, M., Hommes, G., Cook, R., Marian, J. (2012). “A Dislocation Dynamics Study of the Transition from Homogeneous to Heterogeneous Deformation in Irradiated bcc Iron”, *Acta Materialia* **60** 3748–3757. [↑](#endnote-ref-19)