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Studies of irradiation-induced defects in materials

P. Horodek, K. Siemek

2nd Workshop on Research & Innovation in Poland
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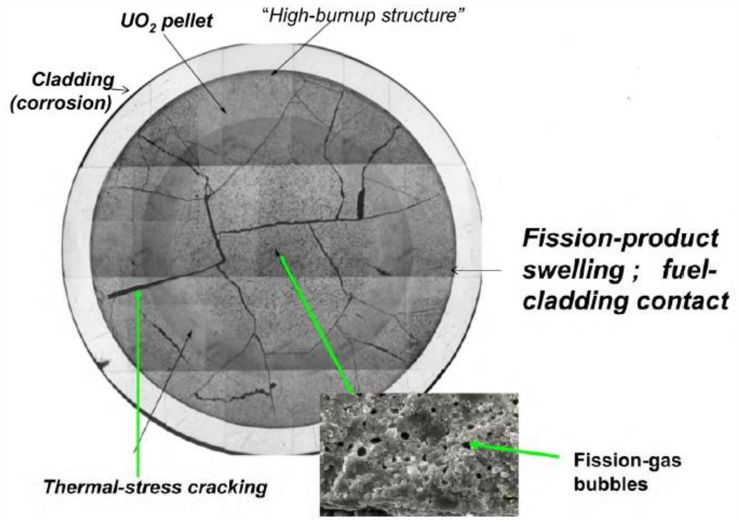
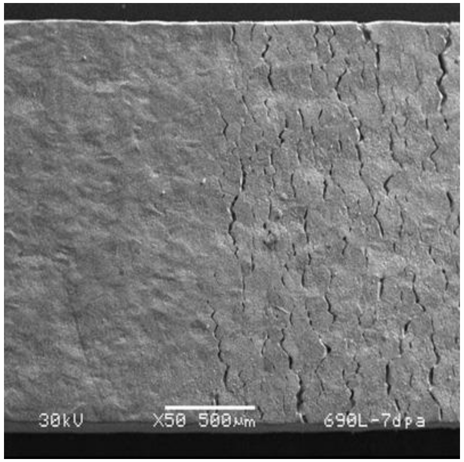
Outline

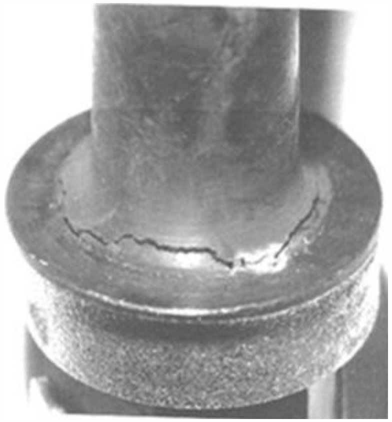
- ☐ Introduction
- ☐ Description
- ☐ Importance
- ☐ Required beam: particle, energy and properties
- ☐ SWOT analysis for the project
- ☐ Conclusions

Introduction

Irradiation induces a large number of structural defects, such as vacancies, their clusters, dislocation loops, voids etc. As a result, swelling, hardening, creep and embrittlement appear and lead to a faster wear







Amaya, M. et al., J. Nucl. Sci. Technol. 45(3) (2008) 244

Introduction

Irradiation modifies properties of material

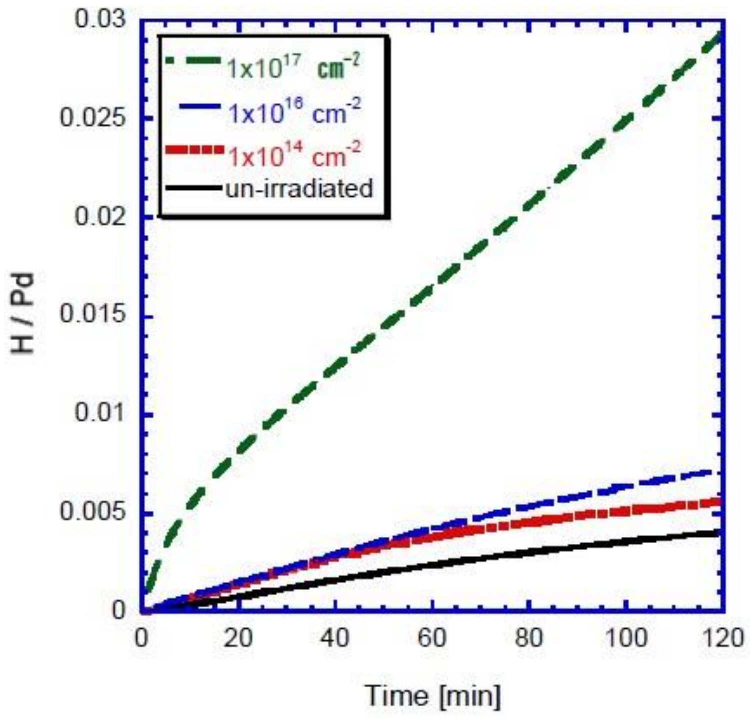
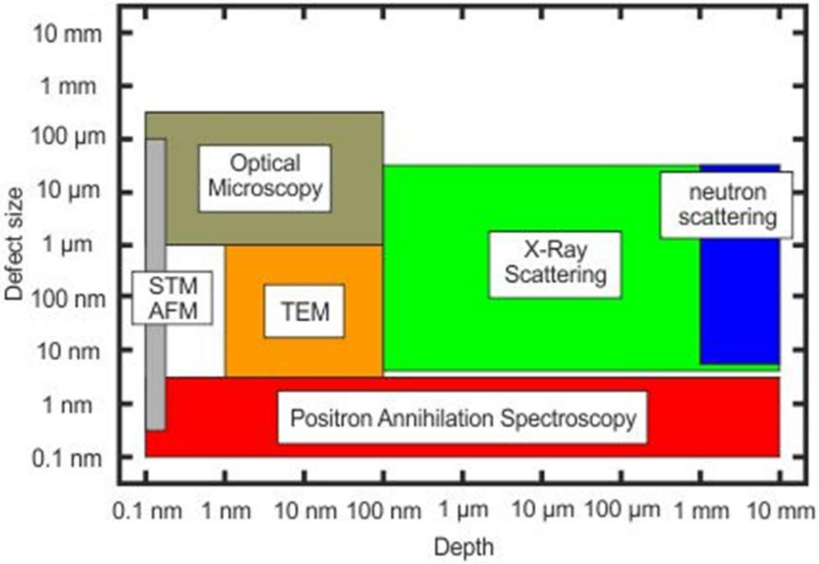


Fig. 1. Hydrogen absorption reaction rate, 5 cycles, curves of irradiated Pd by 350 keV Cr^{+} at fluence from 1 x 10^{14} to 1 x 10^{17} cm^{-2}.

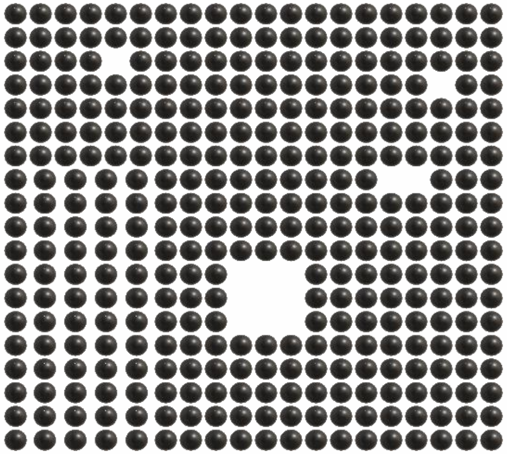
H. Abe, et. Al.. *Trans. Mat. Res. Soc. Japan* **36** (2011) 133

Description

- PAS techniques allow us to find defects with the size ranging from 0.1 to 3 nm with the concentration up to 10^{-7}
- PAS enables the detection of defects in the wide range of depths from single nanometers up to milimeters



https://www.hzdr.de/db/Cms?pNid=3581



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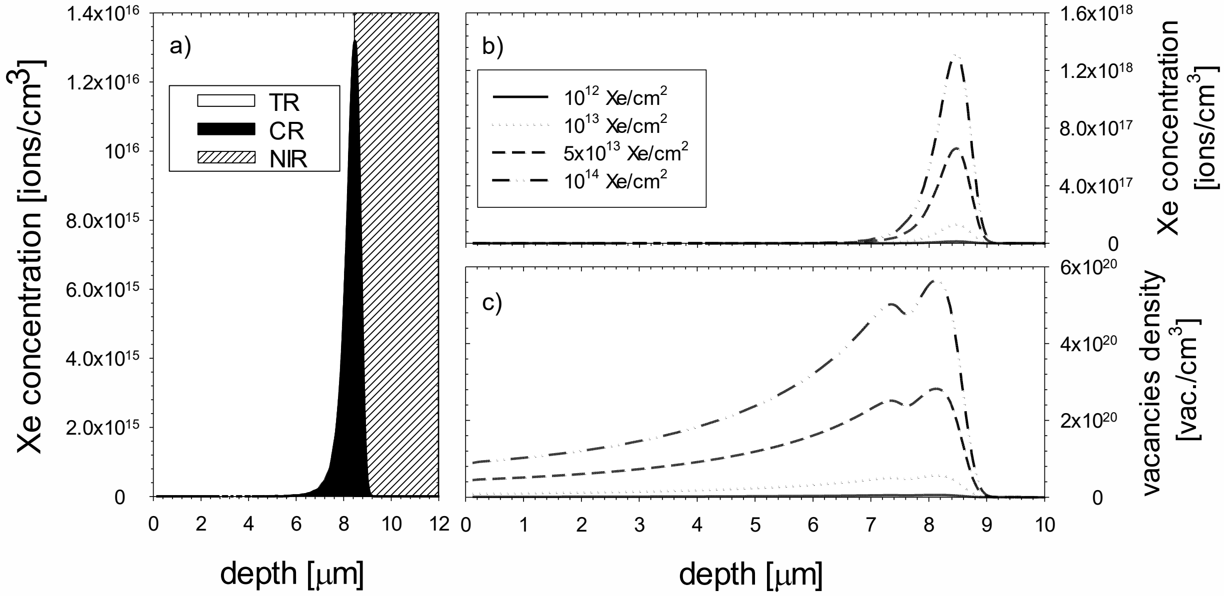

P. Horodek, et al., Rad. Phys. Chem. 122 (2016) 60

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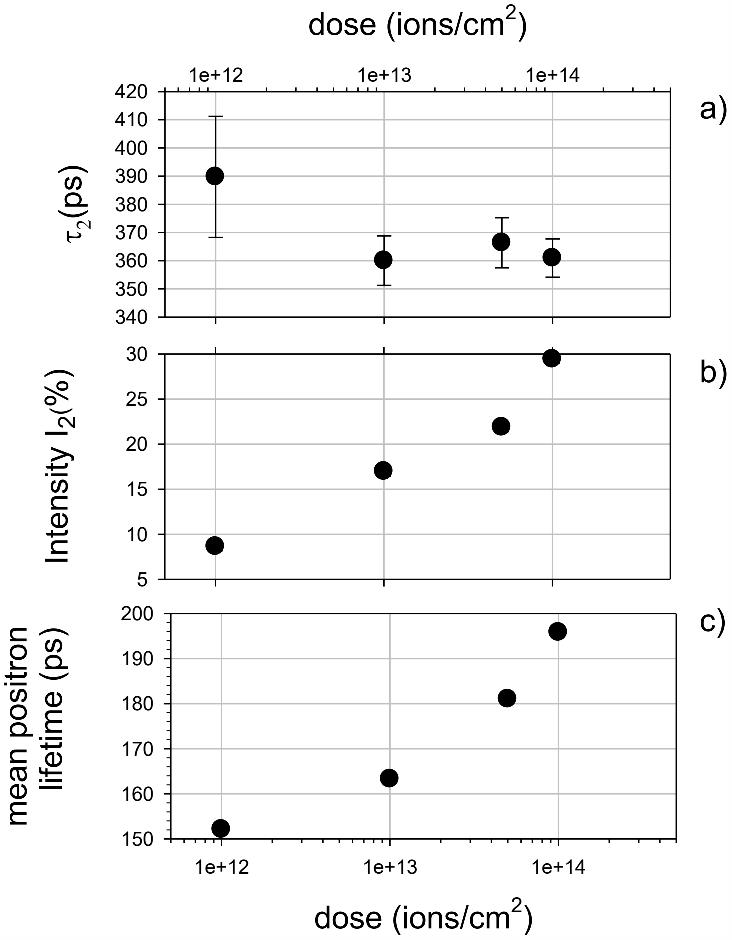
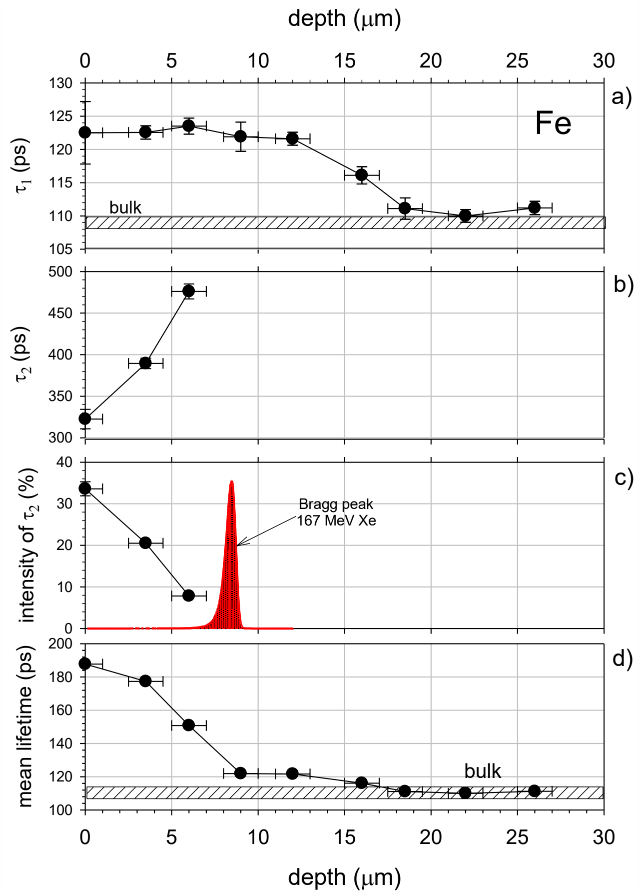


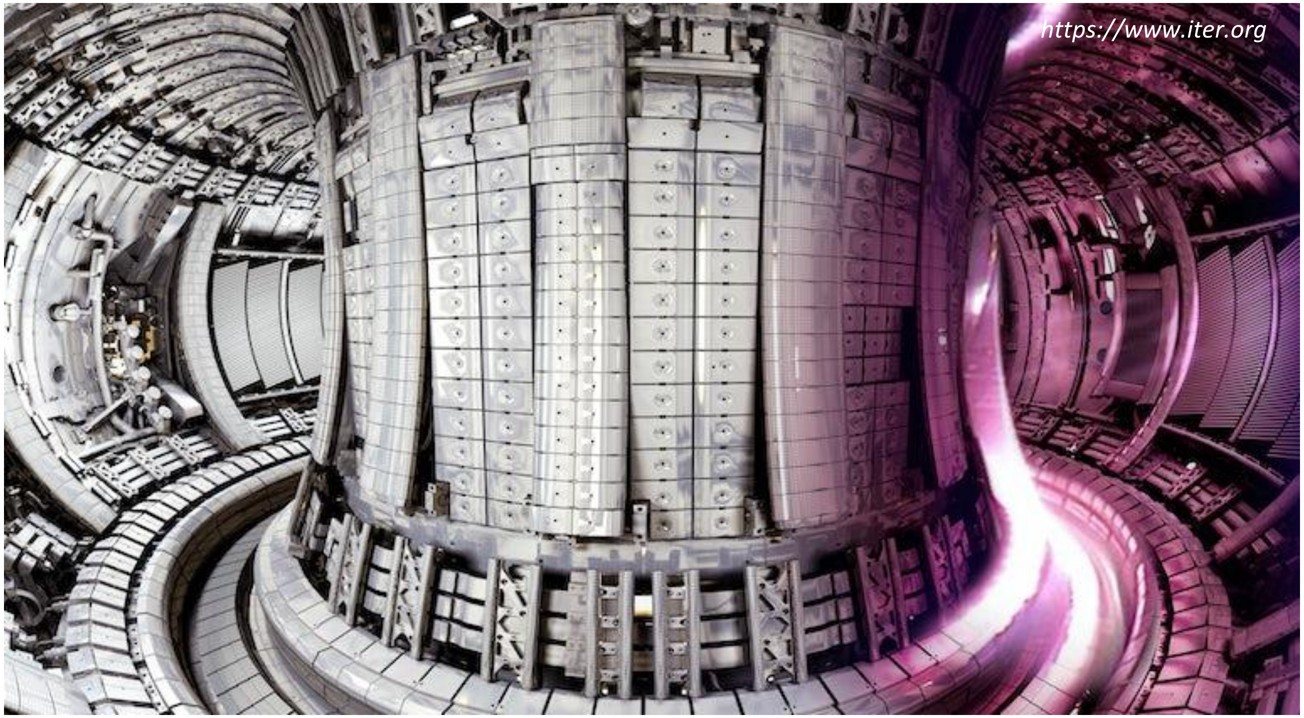
P. Horodek, et al., Rad. Phys. Chem. 122 (2016) 60

Description

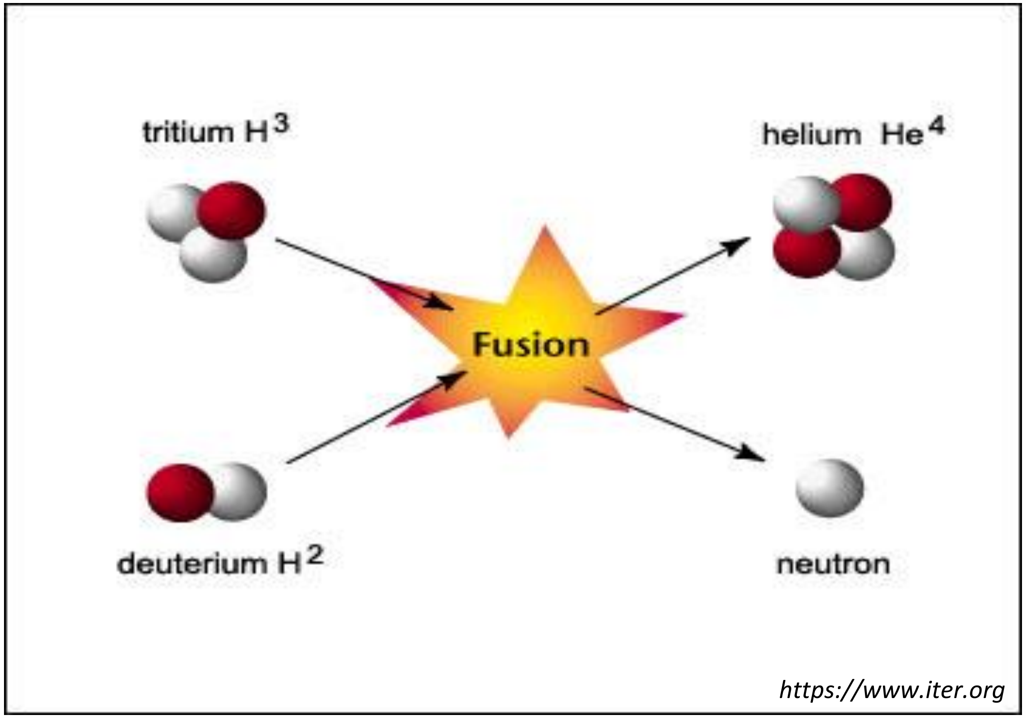


P. Horodek, et al., Rad. Phys. Chem. 122 (2016) 60

Importance

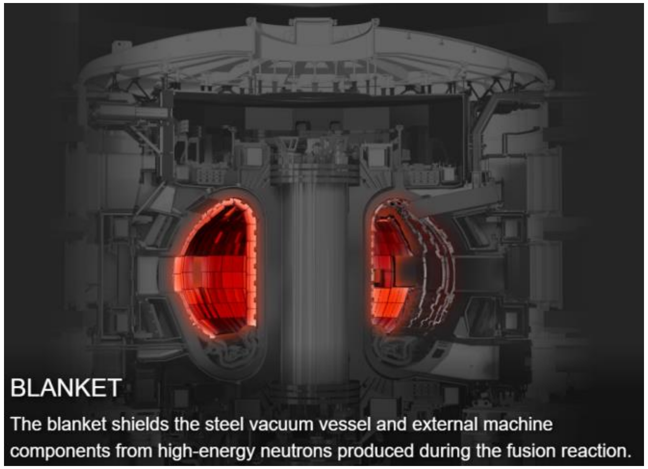

https://www.iter.org

Importance



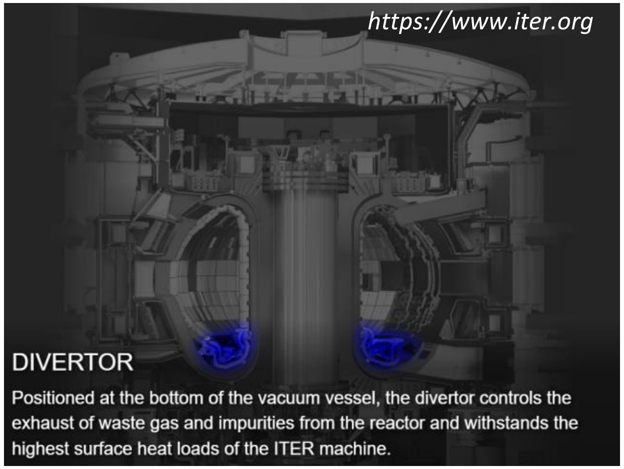
https://www.iter.org

Importance



BLANKET

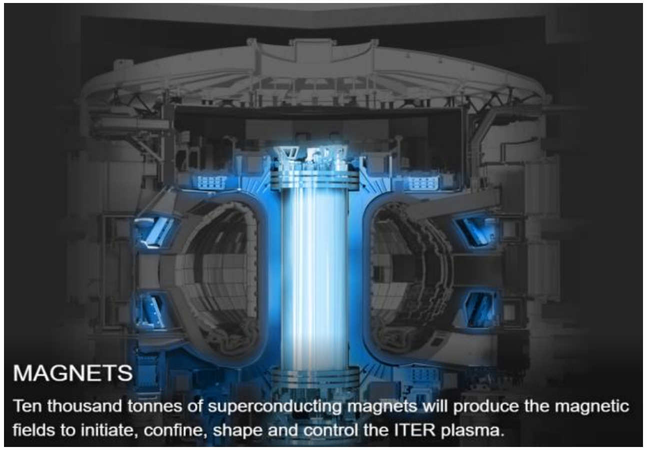
The blanket shields the steel vacuum vessel and external machine components from high-energy neutrons produced during the fusion reaction.



https://www.iter.org

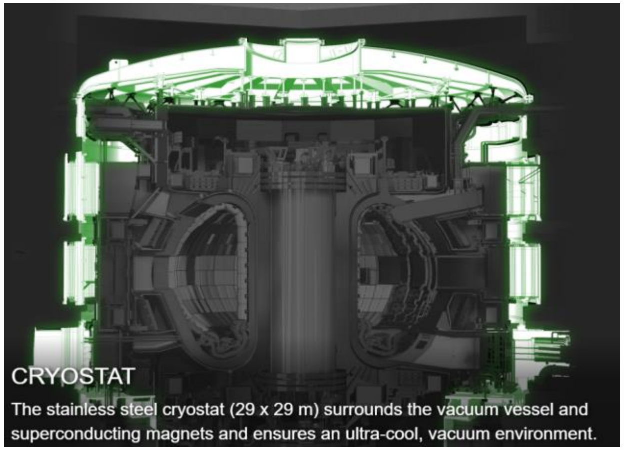
DIVERTOR

Positioned at the bottom of the vacuum vessel, the divertor controls the exhaust of waste gas and impurities from the reactor and withstands the highest surface heat loads of the ITER machine.



MAGNETS

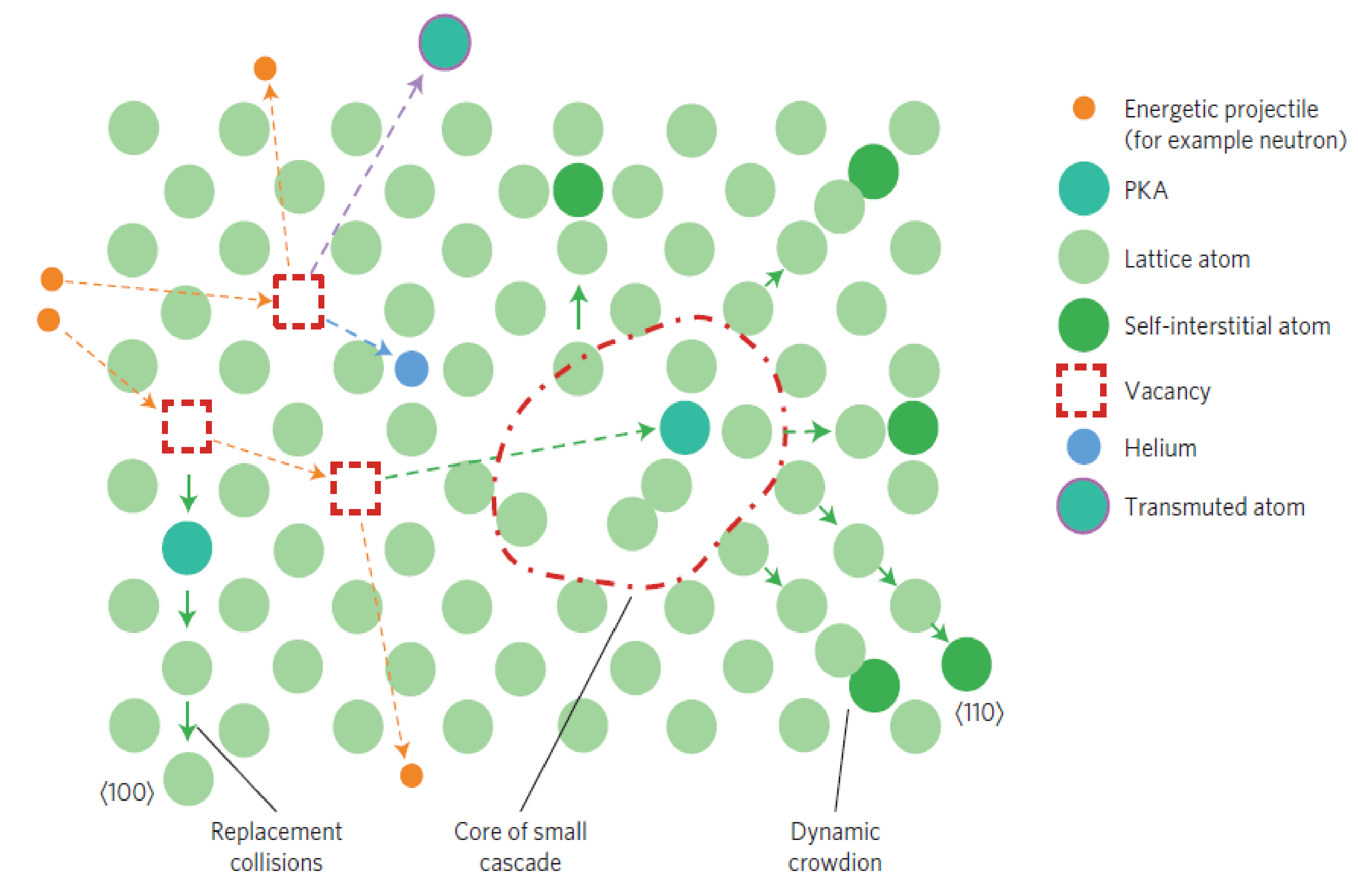
Ten thousand tonnes of superconducting magnets will produce the magnetic fields to initiate, confine, shape and control the ITER plasma.



CRYOSTAT

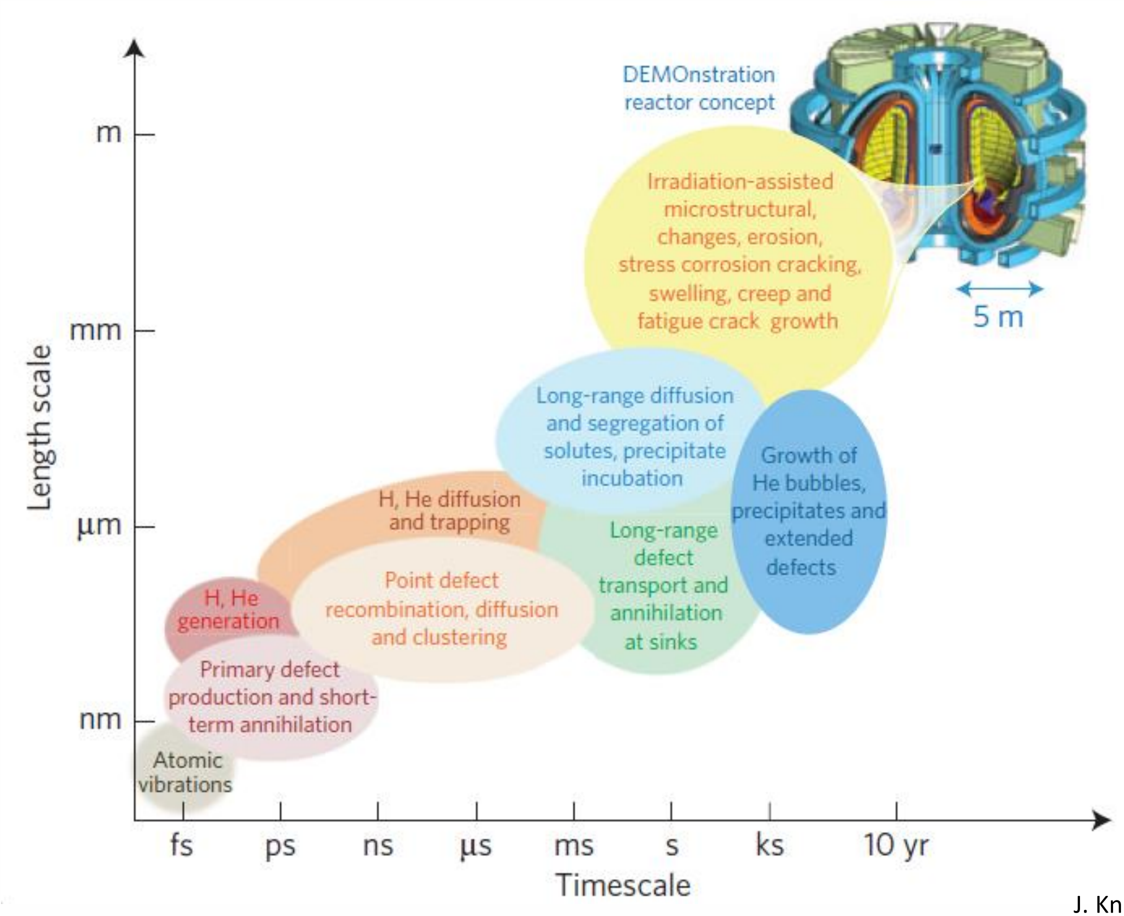
The stainless steel cryostat (29 x 29 m) surrounds the vacuum vessel and superconducting magnets and ensures an ultra-cool, vacuum environment.

Importance



J. Knaster, et al. Nat Phys 12 (2016)424–434

Importance

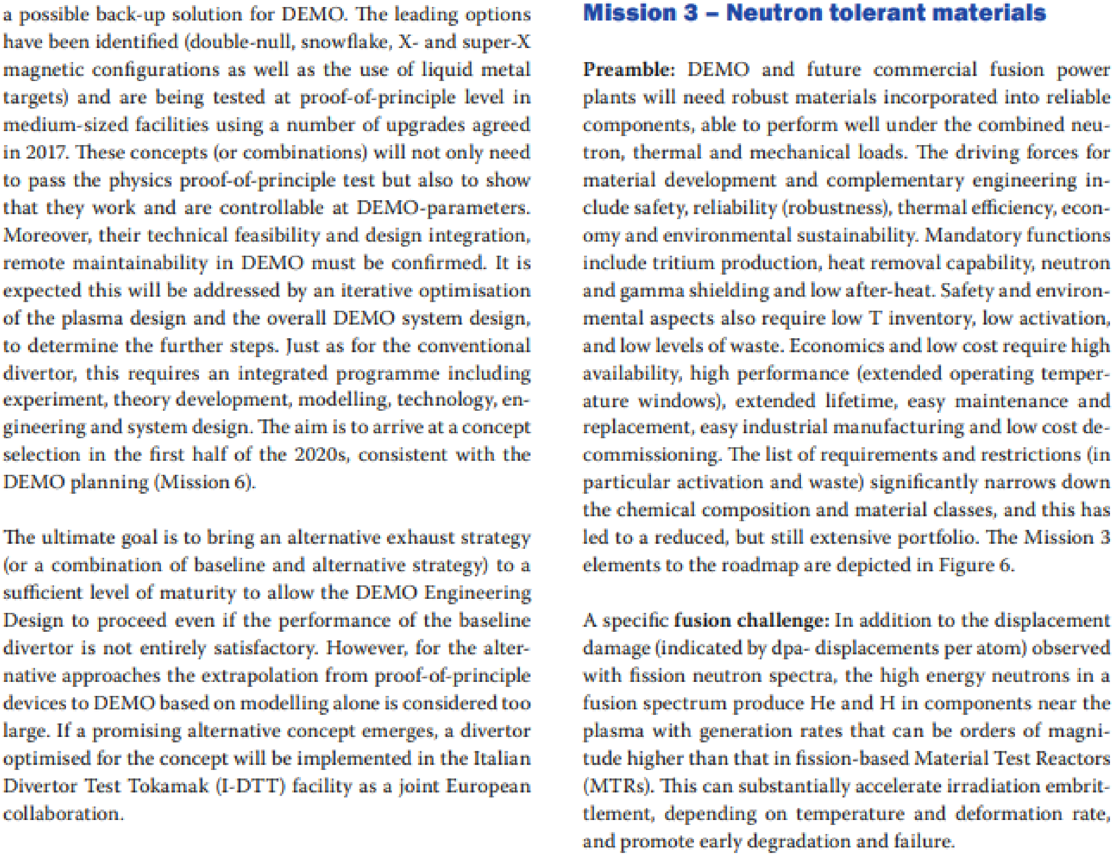


J. Knaster, et al. Nat Phys 12 (2016) 424–434

Importance

European Research Roadmap
LONG VERSION to the Realisation of Fusion Energy

EUROfusion



a possible back-up solution for DEMO. The leading options have been identified (double-null, snowflake, X- and super-X magnetic configurations as well as the use of liquid metal targets) and are being tested at proof-of-principle level in medium-sized facilities using a number of upgrades agreed in 2017. These concepts (or combinations) will not only need to pass the physics proof-of-principle test but also to show that they work and are controllable at DEMO-parameters. Moreover, their technical feasibility and design integration, remote maintainability in DEMO must be confirmed. It is expected this will be addressed by an iterative optimisation of the plasma design and the overall DEMO system design, to determine the further steps. Just as for the conventional divertor, this requires an integrated programme including experiment, theory development, modelling, technology, engineering and system design. The aim is to arrive at a concept selection in the first half of the 2020s, consistent with the DEMO planning (Mission 6).

The ultimate goal is to bring an alternative exhaust strategy (or a combination of baseline and alternative strategy) to a sufficient level of maturity to allow the DEMO Engineering Design to proceed even if the performance of the baseline divertor is not entirely satisfactory. However, for the alternative approaches the extrapolation from proof-of-principle devices to DEMO based on modelling alone is considered too large. If a promising alternative concept emerges, a divertor optimised for the concept will be implemented in the Italian Divertor Test Tokamak (I-DTT) facility as a joint European collaboration.

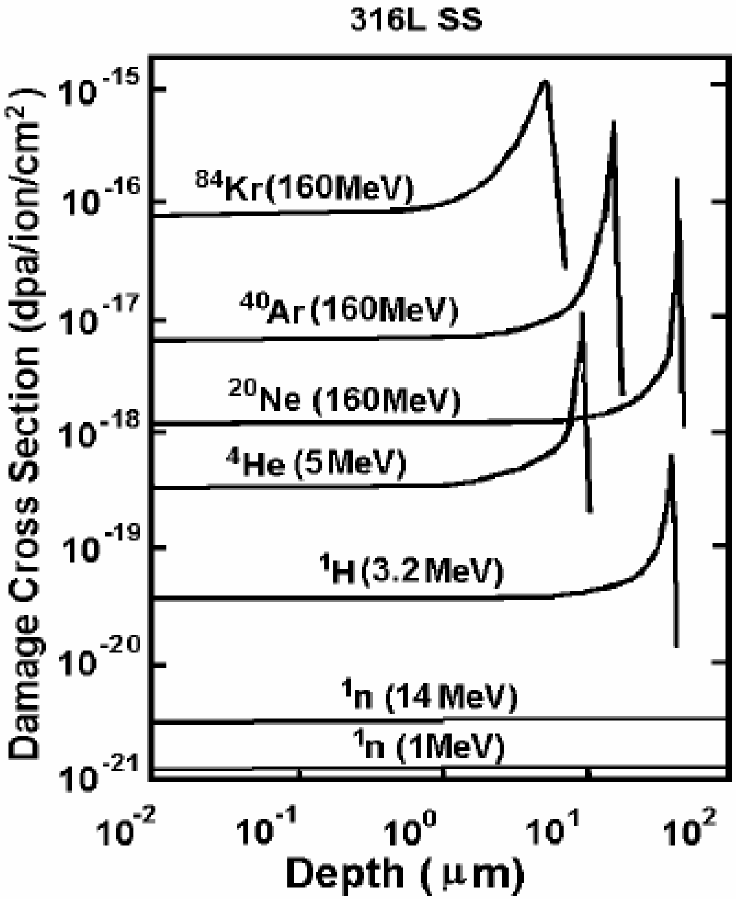
Mission 3 – Neutron tolerant materials

Preamble: DEMO and future commercial fusion power plants will need robust materials incorporated into reliable components, able to perform well under the combined neutron, thermal and mechanical loads. The driving forces for material development and complementary engineering include safety, reliability (robustness), thermal efficiency, economy and environmental sustainability. Mandatory functions include tritium production, heat removal capability, neutron and gamma shielding and low after-heat. Safety and environmental aspects also require low T inventory, low activation, and low levels of waste. Economics and low cost require high availability, high performance (extended operating temperature windows), extended lifetime, easy maintenance and replacement, easy industrial manufacturing and low cost decommissioning. The list of requirements and restrictions (in particular activation and waste) significantly narrows down the chemical composition and material classes, and this has led to a reduced, but still extensive portfolio. The Mission 3 elements to the roadmap are depicted in Figure 6.

A specific **fusion challenge:** In addition to the displacement damage (indicated by dpa- displacements per atom) observed with fission neutron spectra, the high energy neutrons in a fusion spectrum produce He and H in components near the plasma with generation rates that can be orders of magnitude higher than that in fission-based Material Test Reactors (MTRs). This can substantially accelerate irradiation embrittlement, depending on temperature and deformation rate, and promote early degradation and failure.

https://euro-fusion.org/

Importance



S. Das, Applied Sciences (2019) 1:1614

Required beam: particle, energy andd properties

Primary Particle: Proton, Deuteron, Alpha, Lithium-7

Acceleration Stage (Energy):

Section 1: 2.5 MeV/u

Section 2: 12.5 MeV/u

Intensity / Current: 1 nA to 5 nA

Temperature control: required

Beam scanning mode: required

SWOT analysis for the project

S (Strengths):

- defects similar to neutron-induced ones(m_p~ m_n)
- H and He as transmutation products
- damage range suitable to conventional PAS
- no-activation for Section 1

W (Weaknesses):

- activation for Section 2

O (Opportunities):

- upgrade the laboratory
- expanding research collaboration
- independence

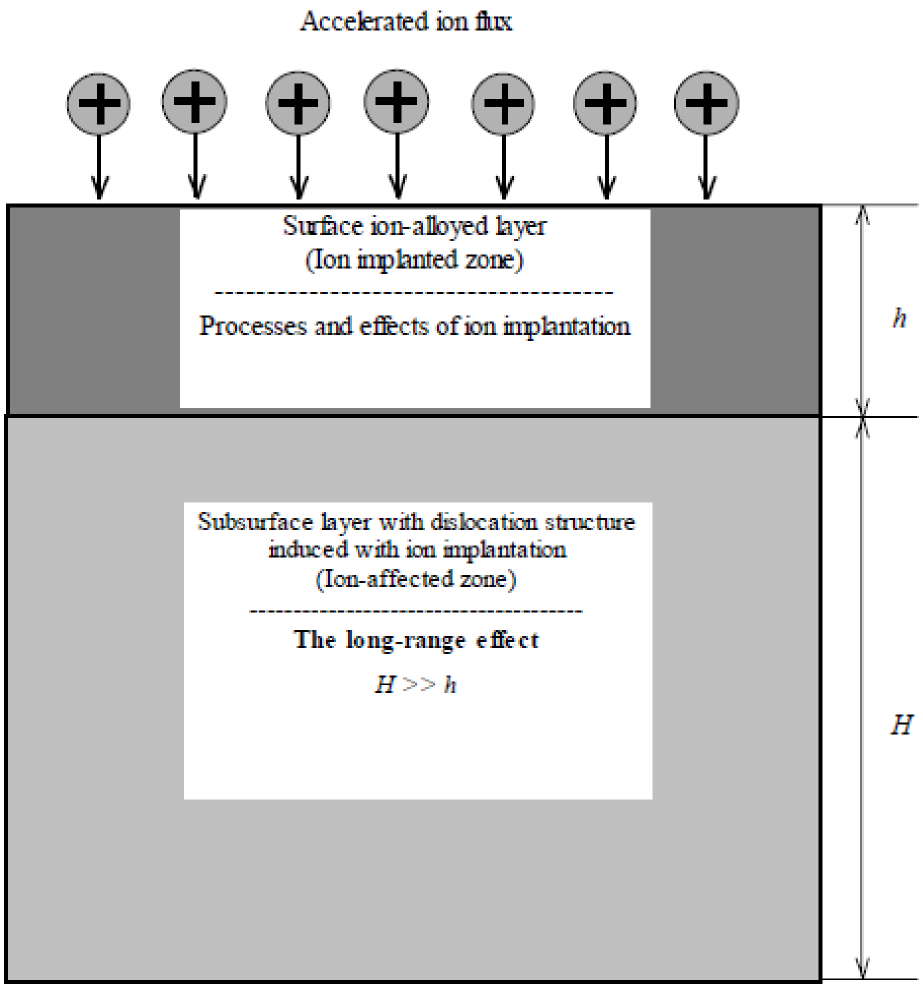
- **T (Threats):**
  - time to deactivate the samples

Conclusions

- ✓ ion beams can be used to introduce irradiation-induced defects
- ✓ the proposed ion energies are suitable for structural modification at depths relevant to conventional PAS experiments

Introduction

The long range effect

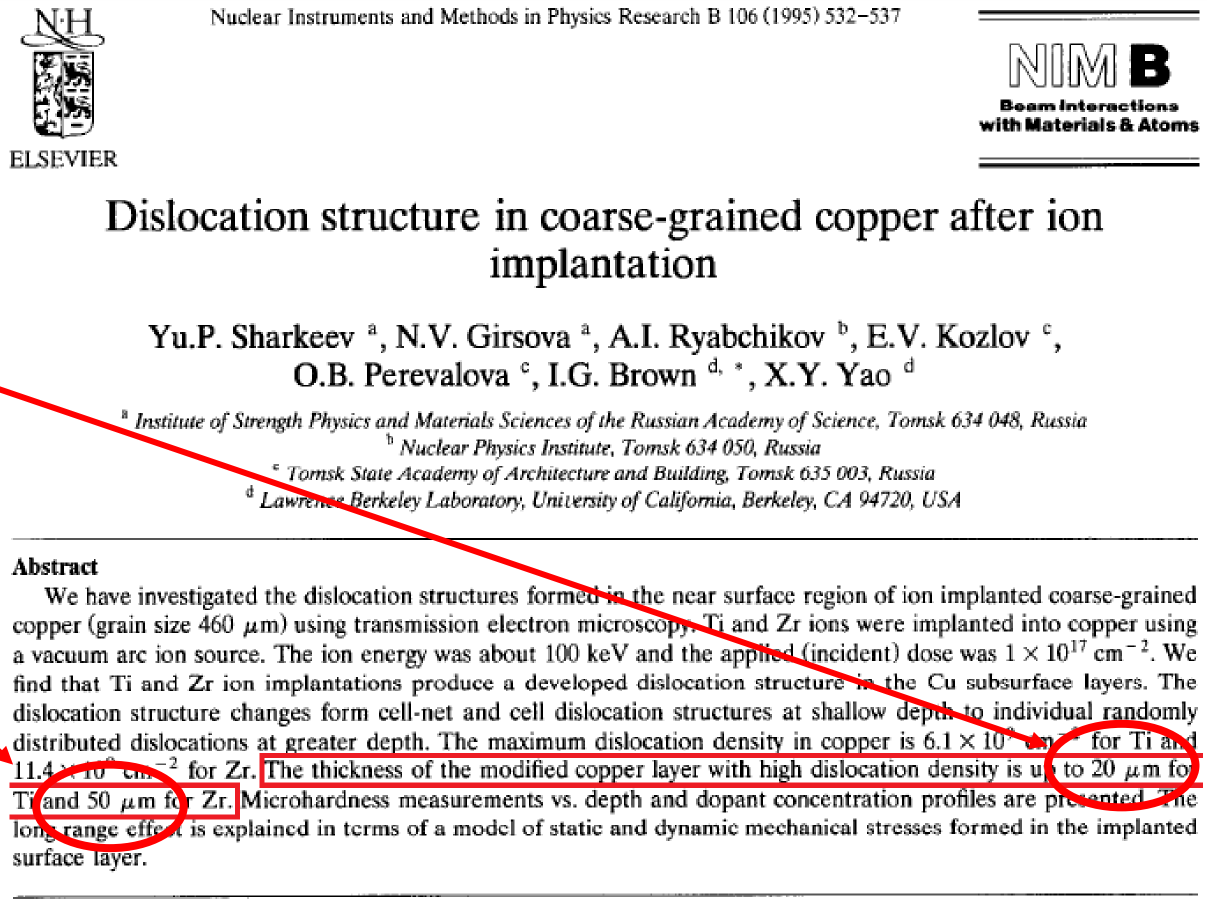


The long-range effect in metal materials at ion implantation

Yu.P. Sharkeev, E.V. Kozlov, Surf. Coat. Technol. 158-159 (2002) 219

Introduction

0.5 µm



ELSEVIER

Nuclear Instruments and Methods in Physics Research B 106 (1995) 532–537

NIM B
Beam Interactions with Materials & Atoms

Dislocation structure in coarse-grained copper after ion implantation

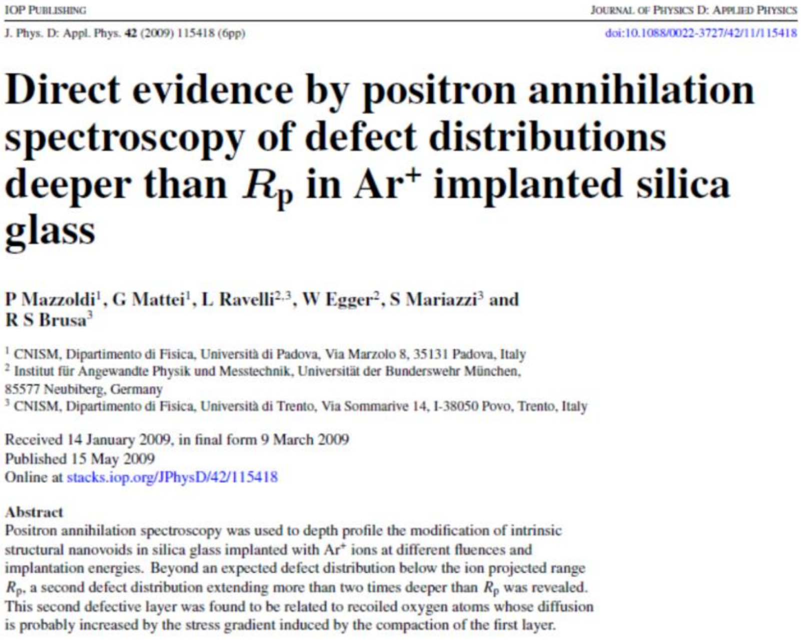
Yu.P. Sharkeev [a], N.V. Girsova [a], A.I. Ryabchikov [b], E.V. Kozlov [c], O.B. Perevalova [c], I.G. Brown [d, *], X.Y. Yao [d]

[a] *Institute of Strength Physics and Materials Sciences of the Russian Academy of Science, Tomsk 634 048, Russia*
[b] *Nuclear Physics Institute, Tomsk 634 050, Russia*
[c] *Tomsk State Academy of Architecture and Building, Tomsk 635 003, Russia*
[d] *Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA*

Abstract

We have investigated the dislocation structures formed in the near surface region of ion implanted coarse-grained copper (grain size 460 µm) using transmission electron microscopy. Ti and Zr ions were implanted into copper using a vacuum arc ion source. The ion energy was about 100 keV and the applied (incident) dose was 1×10^{17} cm^{-2}. We find that Ti and Zr ion implantations produce a developed dislocation structure in the Cu subsurface layers. The dislocation structure changes form cell-net and cell dislocation structures at shallow depth to individual randomly distributed dislocations at greater depth. The maximum dislocation density in copper is 6.1×10^9 cm^{-2} for Ti and 11.4×10^9 cm^{-2} for Zr. The thickness of the modified copper layer with high dislocation density is up to 20 µm for Ti and 50 µm for Zr. Microhardness measurements vs. depth and dopant concentration profiles are presented. The long range effect is explained in terms of a model of static and dynamic mechanical stresses formed in the implanted surface layer.

Introduction



IOP PUBLISHING — JOURNAL OF PHYSICS D: APPLIED PHYSICS
J. Phys. D: Appl. Phys. **42** (2009) 115418 (6pp) — doi:10.1088/0022-3727/42/11/115418

Direct evidence by positron annihilation spectroscopy of defect distributions deeper than R_p in Ar^+ implanted silica glass

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[2] Institut für Angewandte Physik und Messtechnik, Universität der Bunderswehr München, 85577 Neubiberg, Germany
[3] CNISM, Dipartimento di Fisica, Università di Trento, Via Sommarive 14, I-38050 Povo, Trento, Italy

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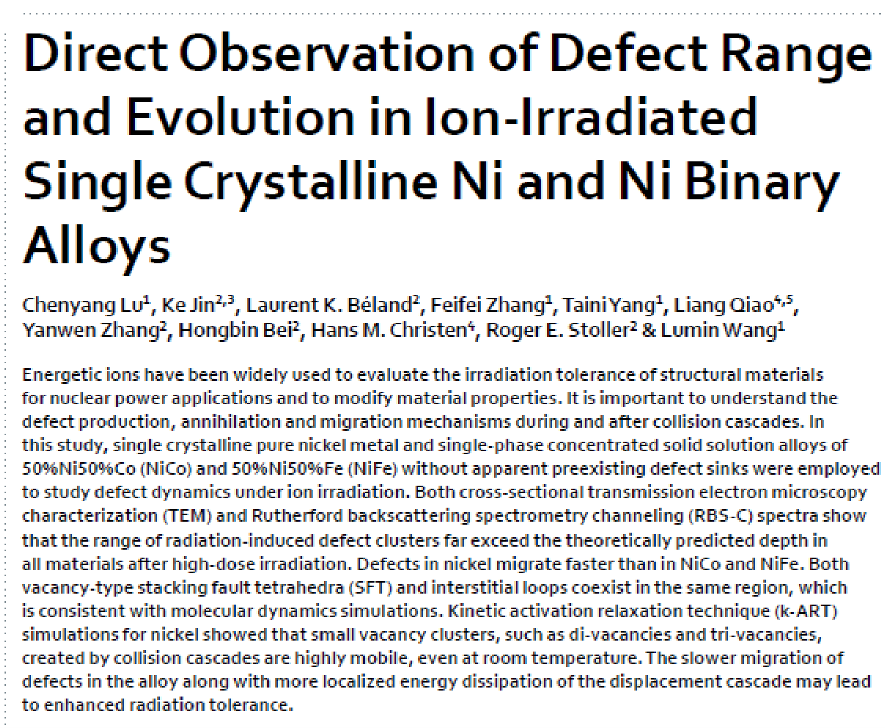
Online at stacks.iop.org/JPhysD/42/115418

Abstract
Positron annihilation spectroscopy was used to depth profile the modification of intrinsic structural nanovoids in silica glass implanted with Ar^+ ions at different fluences and implantation energies. Beyond an expected defect distribution below the ion projected range R_p, a second defect distribution extending more than two times deeper than R_p was revealed. This second defective layer was found to be related to recoiled oxygen atoms whose diffusion is probably increased by the stress gradient induced by the compaction of the first layer.

SCIENTIFIC REPORTS



Direct Observation of Defect Range and Evolution in Ion-Irradiated Single Crystalline Ni and Ni Binary Alloys

Chenyang Lu[1], Ke Jin[2,3], Laurent K. Béland[2], Feifei Zhang[1], Taini Yang[1], Liang Qiao[4,5], Yanwen Zhang[2], Hongbin Bei[2], Hans M. Christen[4], Roger E. Stoller[2] & Lumin Wang[1]

Energetic ions have been widely used to evaluate the irradiation tolerance of structural materials for nuclear power applications and to modify material properties. It is important to understand the defect production, annihilation and migration mechanisms during and after collision cascades. In this study, single crystalline pure nickel metal and single-phase concentrated solid solution alloys of 50%Ni50%Co (NiCo) and 50%Ni50%Fe (NiFe) without apparent preexisting defect sinks were employed to study defect dynamics under ion irradiation. Both cross-sectional transmission electron microscopy characterization (TEM) and Rutherford backscattering spectrometry channeling (RBS-C) spectra show that the range of radiation-induced defect clusters far exceed the theoretically predicted depth in all materials after high-dose irradiation. Defects in nickel migrate faster than in NiCo and NiFe. Both vacancy-type stacking fault tetrahedra (SFT) and interstitial loops coexist in the same region, which is consistent with molecular dynamics simulations. Kinetic activation relaxation technique (k-ART) simulations for nickel showed that small vacancy clusters, such as di-vacancies and tri-vacancies, created by collision cascades are highly mobile, even at room temperature. The slower migration of defects in the alloy along with more localized energy dissipation of the displacement cascade may lead to enhanced radiation tolerance.

Ch. Lu, et al. Sci. Rep. (2016) 19994