IAEA Coordinated Research Project (CRP)
"Plasma-Wall Interaction with Irradiated Tungsten and Tungsten Alloys in Fusion Devices"

High flux plasma effect on tungsten damaged by high-energy ions

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Participants in the work

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outline

- Tungsten, fusion neutrons, damage
- Experimental methods, analysis, calculations
- Results
- Participation in CRP

Research of fusion materials as a particular task

- Complex effect of radiation, thermal and mechanical loads on PFMs in a fusion reactor is specific and does not occur in other systems with materials under irradiation.
- Fusion reactor conditions may be reproduced exactly only in a fusion reactor itself.
- Experimental simulations on different facilities (plasma facilities, fission reactors, accelerators, radiation sources) offer solutions for separate tasks.

First wall problem – plasma and neutrons

- **Effect of neutron irradiation is an actual task of experimental research for a steady-state operation fusion reactor with high neutron fluence**
- **Displacement damage supposed levels**

ITER 2-4 dpa

2,4 dpa per MW a/m^{-2} for tungsten in divertor

(Iida H.,Khripunov V.,Petricci L.,Federici G. 2004 ITER Nuclear Analysis Report G 73 DDD 2 W 0)

0.7 –1 dpa with change of components

(J.Linke et al. Fusion Science and Technology, Vol.47, Apr. 2005)

DEMO 30-80 dpa

POWER 100-200 dpa

Neutron sources

- **Fusion reactor (DT neutrons 14 MeV)**
- **14 MeV neutron source on the basis of DT fusion reaction**
- **Fission reactors**

  Dose 10^{22} neutron/cm^2 is achieved for about one year period. Spectrum
- **Proton and heavy ion accelerators.**

Production of radiation damage by accelerated ions

High-energy ions are used to simulate the neutron effect

Displacement **P**er **A**tom –

parameter for evaluation and comparison of accumulated damage produced by different impinging particles (neutrons, ions, electrons), neutrons with different spectra

Damage rate **dpa s^{-1}**

Impurity production rate **appm He/dpa**, **appm H/dpa**

$$dpa = N_{displacement} / N_W$$

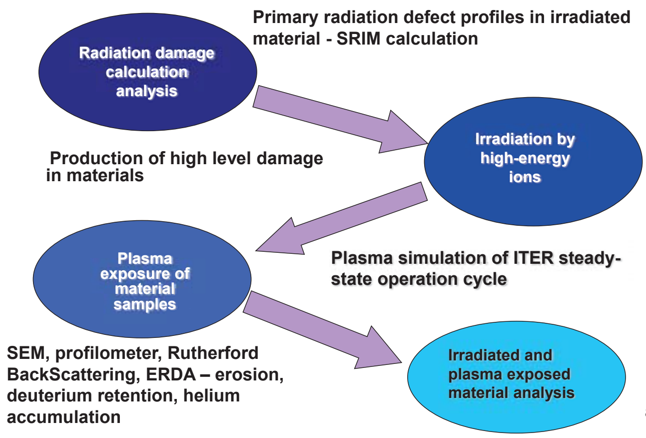
Heavy ion irradiation :

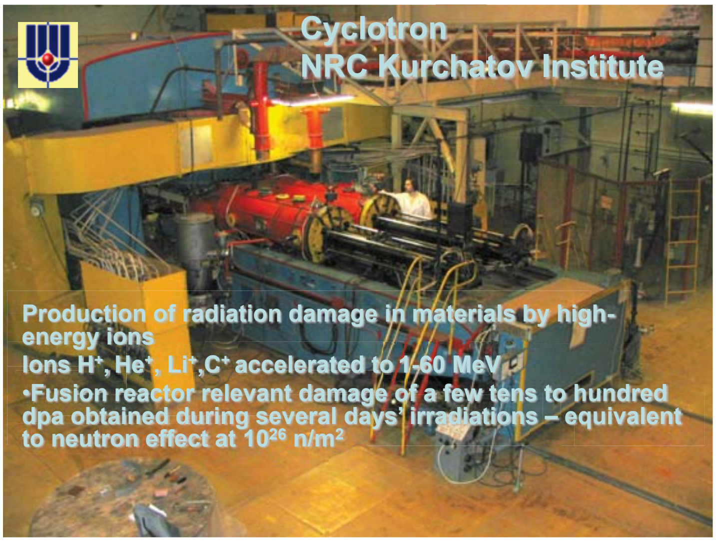
- increased defect production rate 10^{-4}- 10^{-2} dpa/s (10^{-10}- 10^{-6} dpa/s in fission reactors)
- control of chosen irradiation conditions
- impurity generation rate controlled (He, H …)
- no activation of the samples

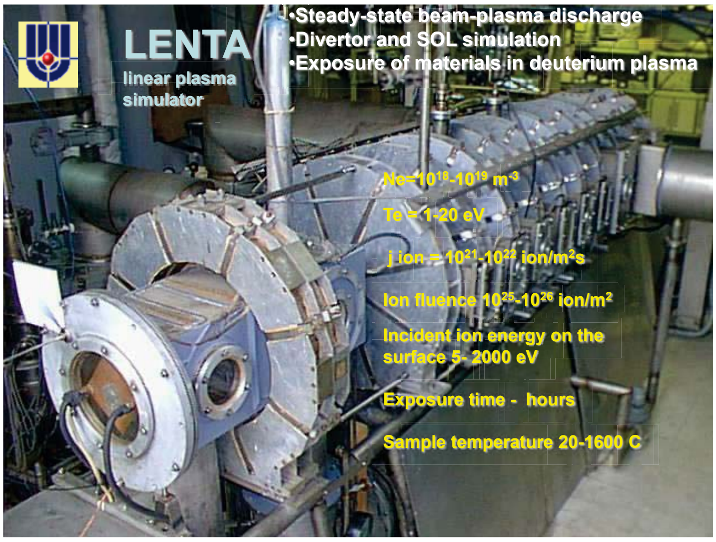
High energy particles generate **cascades and sub-cascades** in the material

Vacancies, interstitials, vacancy clusters, dislocations, loops, pores are generated

Production of radiation damage and plasma exposure of irradiated material







Production of radiation damage in tungsten by high-energy ions

Tungsten W 99.95% wt. close by composition to ITER candidate bombarded by MeV-range ions accelerated with cyclotron

$^4He^{+2}$ ions

D + T → He^4 (3,5 MeV) + n (14,1 MeV)

$^4He^{++}$ ions at energy of 3.0-4.0 MeV produce defects to 5-6 μm depth

$^4He^{++}$ ion fluence
$5{\cdot}10^{17}$ - 10^{19} $^4He{+}{+}$ /cm²

Defect generation rate G_d=$3.7{\cdot}10^{-4}$ dpa/s

Irradiation temperature T = 80-100C

Primary defects **0.1- 600 dpa**

$^{12}C^{+3}$ ions

Accelerated to 10 MeV
$^{12}C^{+++}$ ions produce defects to depth 3.5 μm

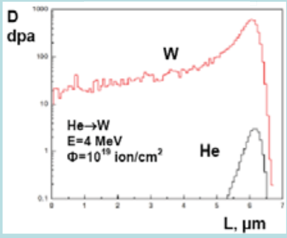
Carbon ion fluence
$2{\cdot}10^{17}$ cm^{-2} $^{12}C^{+++}$/cm²

Irradiation temperature 50 and 600 C

Primary defects **3-120 dpa**

Radiation damage in tungsten

Helium ions



Primary radiation defects in tungsten irradiated by $^4He^{++}$ ions at energy of 4 MeV

Fast ion fluence Φ = 10^{23} $^4He^{+2}$ /m². (ρ=19.35 g/cm³, 183.8 amu)

D_{max} = 607 dpa

D_{min} = 10 dpa
near the surface

<D> = 91 dpa
Average by damaged layer

Damage profile calculated by SRIM-2003 code Ziegler J.F., Biersack J.P. Littmark U, Stopping and Range of Ions in Solids. NY: Pergamon Press, 1985

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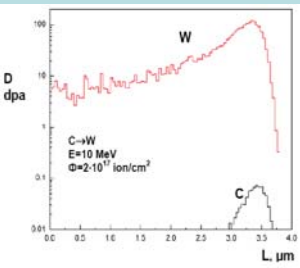
Radiation damage of tungsten

Carbon ions



Primary radiation defects in tungsten irradiated by $^{12}C^{+++}$ ions at energy of 10 MeV

Fast ion fluence
Φ = $2x10^{17}$ C^{+3}/cm².
(ρ=19.35 g/cm³, 183.8 amu)

- D vacancies per atom dpa
  D_{max} = 121 dpa
- near the surface D_{min} = 5.5 dpa
- Average by damaged layer
- <D> = 25 dpa

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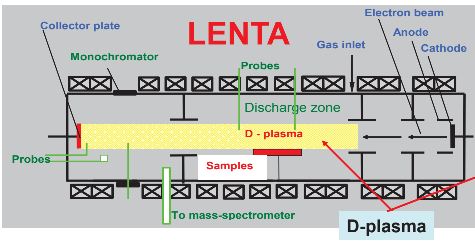
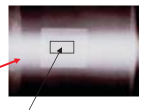
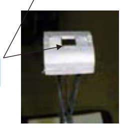
Plasma exposure of irradiated materials

Beam-plasma discharge in axial magnetic field
Steady state operation







W-sample

Optical spectroscopy	Analysis of materials
Electric probes	SEM
Mass spectrometer	Profilometry
Thermometry	Weight loss analysis
Calorimetry	Elastic nuclear backscattering
Pyrometer	Elastic Recoil Detection Analysis

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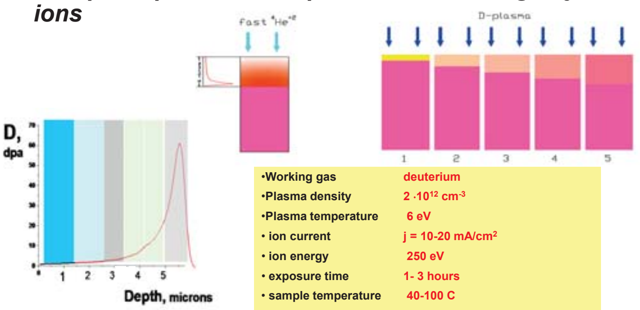
Experimental procedure –D-plasma on damaged tungsten

- *Multiple exposures to D-plasma after damage by fast ions*



•Working gas	deuterium
•Plasma density	2 $\cdot10^{12}$ cm^{-3}
•Plasma temperature	6 eV
• ion current	j = 10-20 mA/cm²
• ion energy	250 eV
• exposure time	1- 3 hours
• sample temperature	40-100 C
• erosion in plasma – step-by-step	
• ion fluence in one exposure step	~10^{21} ion/cm²
•Total ion fluence	$2{\cdot}10^{22}$ ion/cm²

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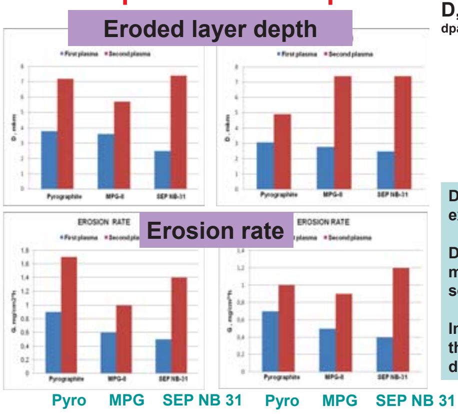
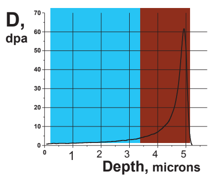
Erosion of irradiated carbon materials in plasma

1 dpa 5 dpa



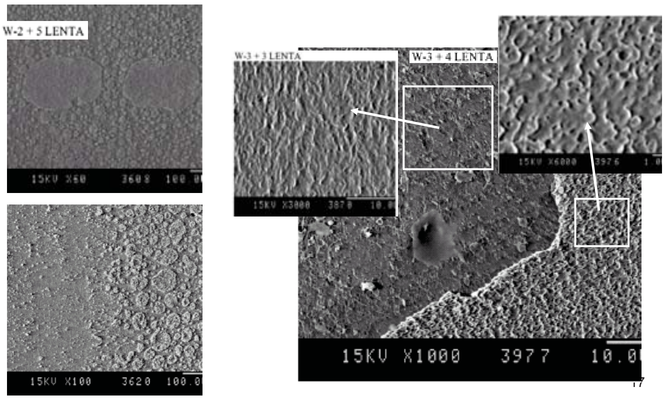


Double plasma exposure experiment:

Damage distribution maximum reached in the second plasma exposure

Increase of erosion rate in the layer of maximal defect density

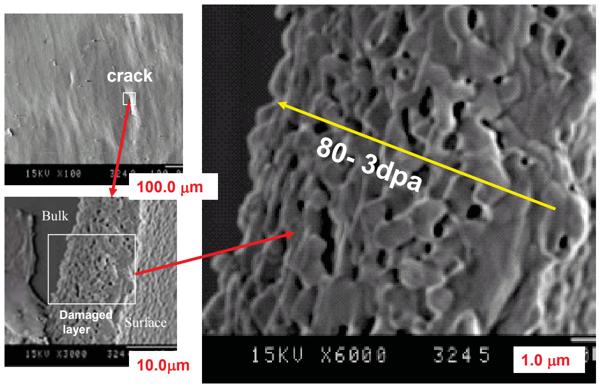
Erosion of irradiated tungsten in D-plasma



Irradiated tungsten - structure

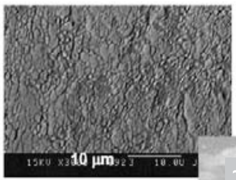
Material structure in damaged layer

$\Phi = 3x10^{18}$ He++/cm^2

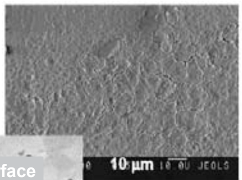


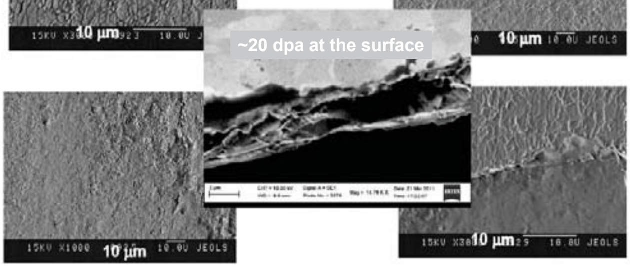
Pores, cracks, delamination

Tungsten surface after irradiation by Helium ions to 10^{19} ion/cm^2

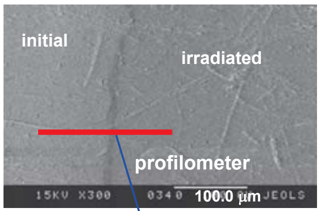


- Micron scale structure formation on the surface
- Cracks
- Delamination
- Cavities

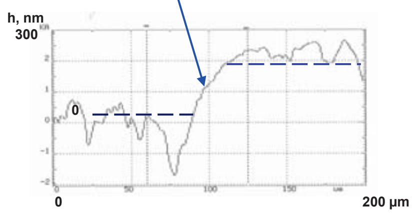




Irradiated tungsten –swelling effect



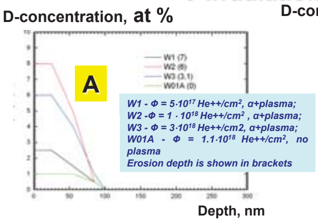
- Irradiated area border on the tungsten sample after irradiation by accelerated carbon ions at 10 MeV

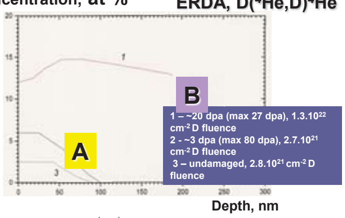


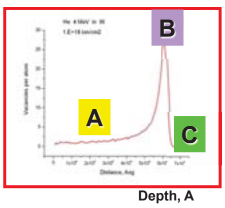
Measurement of radiation swelling effect for tungsten gives 1,5 – 2 %.

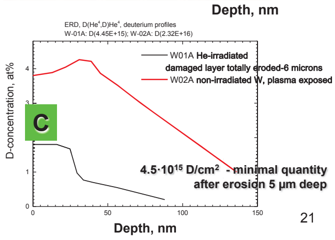
Deuterium retention in tungsten

He-irradiations, 100-150 nm layer









Summary

- **Experimental research of plasma effect on damaged tungsten at Kurchatov Institute based on the use of surrogate ion irradiations and calculation analysis of damage will be developed.**
- **The results will be obtained on tungsten at high level of radiation damage on**
  - **- evolution of microstructure,**
  - **- radiation swelling effect,**
  - **- blistering effect,**
  - **- hydrogen isotope retention.**

Research objectives and anticipated results

- The main objective of the project is to investigate experimentally the complex effect of radiation damage and plasma on tungsten suggested as plasma facing material for long-operating fusion reactor providing high neutron fluence.
- Use surrogate irradiation by charged particles (heavy ions) accelerated to MeV-range energies to produce damage in tungsten to high enough level relevant to those expected in ITER and DEMO reactors.
- Two specific experimental parts: performing experiments on production of radiation damage in tungsten at the level from one to several tens displacements per atom (dpa) of primary defects and exposure of the damaged material to high flux plasma providing conditions of steady-state operating reactor.
- Different ion species will be taken for the damage production, namely, Helium ions and Carbon ions accelerated to energy 3-10 MeV so that the damage will be generated in the surface layer of 3-6 microns at 1-80 dpa.
- The irradiated tungsten will be subjected to steady-state deuterium plasma and the consequences of plasma-surface interaction on tungsten surface will be compared for the damaged material and undamaged one.
- The experimental work will have the computation support of the defects produced and damage effect in the ion-irradiated tungsten to help understanding and interpretation of the experimental results obtained so far.
- The anticipated outcome of the work will be the new direct experimental data on the effect of plasma interaction with radiation-damaged tungsten in fusion reactor simulated conditions.

IAEA CRP on tungsten, 18118/R0 Agreement

Scope of the project

- The changes in tungsten microstructure resulting from the accumulated defects produced by high-energy particle irradiations might give rise to changes in the material response effects to the plasma impact. Therefore, the project will be centered on the analysis of tungsten microstructure at different stages of the experiments - after high-energy irradiation and during plasma exposures.
- Erosion of the irradiated material in deuterium plasma will be evaluated and its relation to irradiation, to the accumulated defect level and to changes of microstructure will be analyzed.
- An important issue of tritium retention in irradiated tungsten will also take place in the project - the analysis of hydrogen isotopes will be performed by nuclear reaction methods to establish the penetration depth and the quantity of the retained isotope after exposure of damaged tungsten to plasma fluence 10^{26} m^{-2}.
- Temperature influence might have a very important role in the production of radiation damage in the irradiated material and in the plasma effect on it, so appropriate experiments are planned at elevated temperatures in order to obtain data on tungsten erosion yield and deuterium retention.

IAEA CRP on tungsten, 18118/R0 Agreement

Work plan 2014-2016

- **The First Year.**
- Irradiation of tungsten on Kurchatov cyclotron by 3-4 MeV Helium ions to fluence $3{\cdot}10^{22}$ m^{-2}.
- Calculation of primary radiation defect profiles in tungsten.
- Exposure of the irradiated samples to deuterium plasma on LENTA linear plasma simulator - erosion.

- **The Second Year.**
- Irradiations of tungsten by carbon ions at 10 MeV to fluence $2{\cdot}10^{21}$ m^{-2}.
- Exposure of carbon-irradiated tungsten on LENTA linear plasma simulator.
- Theoretical models and numerical calculations of radiation swelling of tungsten under fast ions and neutron irradiation

- **The Third Year.**
- Measurements of hydrogen (deuterium) retention in irradiated tungsten.
- Analysis of the helium and carbon irradiation effects.
- Experiments on irradiated tungsten at elevated temperature (500 C).
- Numerical analysis of defect production in tungsten by neutrons and high-energy ions.

Thank you for your attention!