Russian Research Center "Kurchatov Institute"

Influence of Radiation Damage obtained under Fast Charged Particle Irradiation on Plasma-Facing Erosion of Fusion Structural Materials

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Plasma Facing Materials

- The qualification of plasma facing materials is very demanding: They will be exposed to the fusion plasma.
  - High heat flux of energetic particles: 0.1-20 MW/m^2
  - High temperatures: 500-3200℃
  - Electromagnetic radiation
  - Sputtering erosion
  - **High levels of neutron-irradiation: 3-30 dpa/year**
  - Off-normal events: plasma disruptions, ELM (Edge Localized Mode) events
  - Hydrogen trapping

Introduction

- Research of the plasma facing materials (PFMs) for the first wall and divertor in reactor conditions or mostly close to them is of primary importance for the material selection to be made for fusion reactor.
- The materials will be subjected to:
  - plasma particle bombardment,
  - electromagnetic radiation,
  - fusion neutron flux (14 MeV DT).
- Neutron irradiation should be taken into account in the research of PFMs as an important destructive factor inducing damage in materials thus causing degradation of their properties.
- Study of PFMs erosion as a limiting factor for plasma facing components service life should be performed with the account for the radiation damage effect.
- New experimental approach to the study of plasma erosion based on the using fast ions from accelerator for production of damage in materials is developed.
- High level of radiation damage in materials is the most importance in the study of material erosion.
- Erosion study of radiation-damaged materials is performed in deuterium plasma.

Radiation damage in materials. Neutron sources.

- Energetic neutrons induce cascade processes, nuclear reactions.
- Microstructure evolution is resulting in accumulation of structure defects (vacancies, interstitials), impurities.
- Estimation of defect production by neutrons in fusion reactors

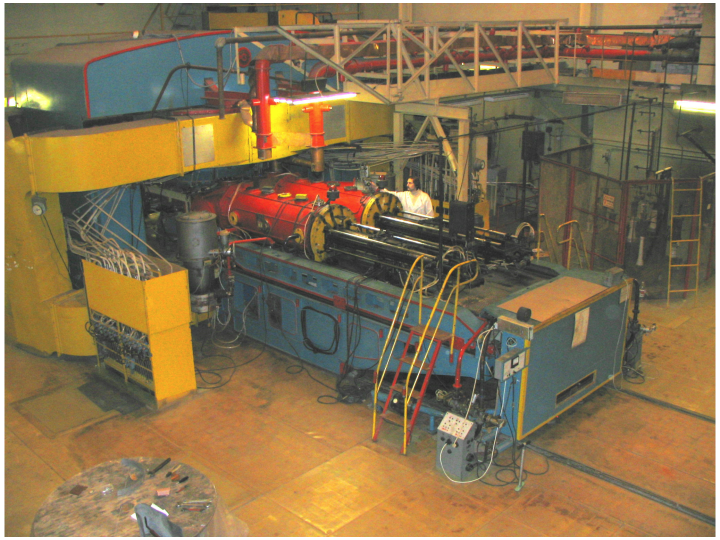
	displacements per atom
ITER	2-4 dpa
DEMO	30-80 dpa
POWER	100-150 dpa

- Preparation of material samples with high level of accumulated radiation damage is a difficult experimental task.
- Neutron sources:

fusion neutron source 14 MeV	not yet available,
fission reactors	energy spectrum and dose limits,
particle accelerators	protons, heavy ions .

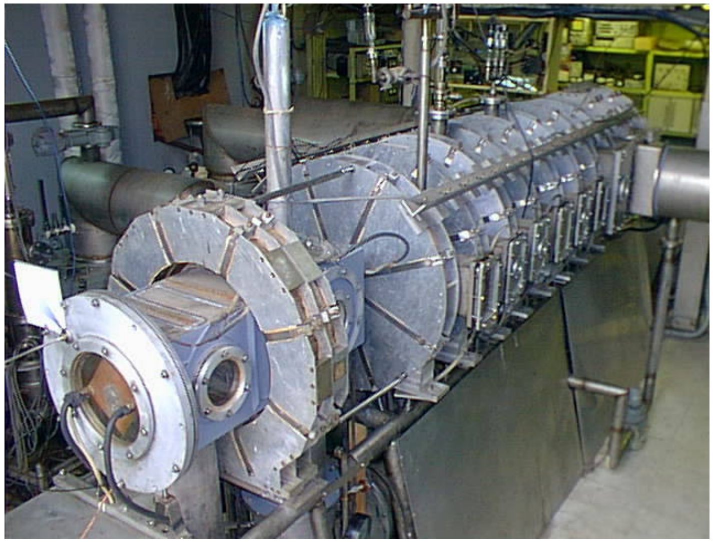
- Production of radiation defects in materials with charged particle beams from accelerator offers a good way to the research of radiation damage effects for fusion.

Combined two-stage experiment



Cyclotron at Kurchatov Institute

- Cyclotron at Kurchatov Institute is used to simulate the PFM's neutron damage
- 1-60 MeV ions H^+, He^+,Li^+,C^+ etc.
- Fusion reactor relevant doses of tens dpa equivalent to neutron irradiation of 10^{22} n/cm^2 are reached in a few days on candidate materials.



LENTA linear plasma simulator RRC KI

- Beam-plasma discharge
- SOL and divertor conditions af a tokamak reactor are simulated
- Exposure of irradiated materials is performed on the LENTA plasma facility in steady-state deuterium plasma
- $N_e=10^{18}-10^{19}$ m^{-3}, $T_e=1-20$ eV, $j_{ion}=10^{21}-10^{22}$ ion/m^{2}s.

Production of radiation damage in materials

Carbon materials

$^{12}C^+$ ions at 5 MeV of the ion energy to get the high level of damage to 5 μm depth irradiation to the total $^{12}C^+$ ion doses 10^{17} ion/cm^2, $5{\cdot}10^{17}$ ion/cm^2 and 10^{18} ion/cm^2 performed during several days

↓

CFC SEP NB-31 ITER divertor target candidate

Fine grane MPG-8 graphite used in Russian fusion devices as limiter

Pyrolytic graphite quasi single crystal

↓

Three levels of radiation damage **1 dpa, 5 dpa and 10 dpa** in average were obtained in the samples of each carbon material.

Tungsten

Irradiation with α-particles ($^4He^{+2}$ ions) at energy of 3.0-4.0 MeV produces defects to 5-6 μm depth .

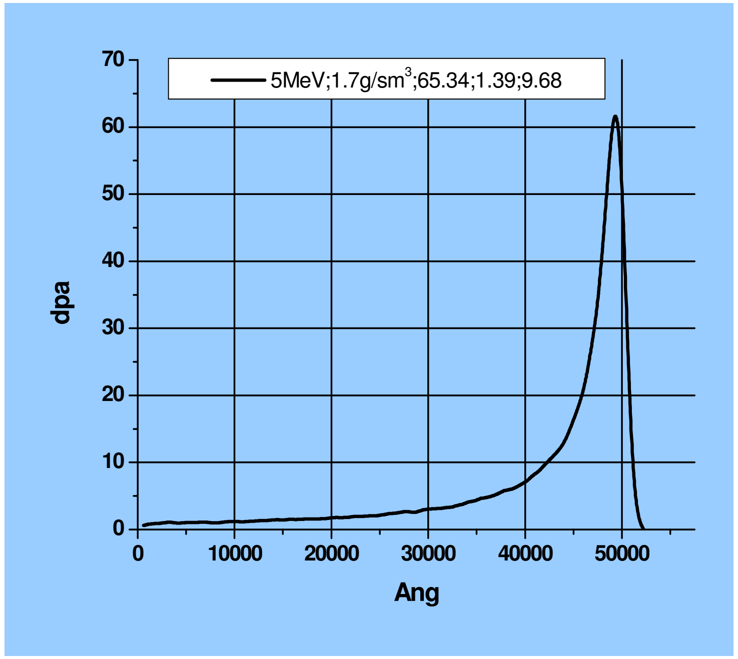
↓

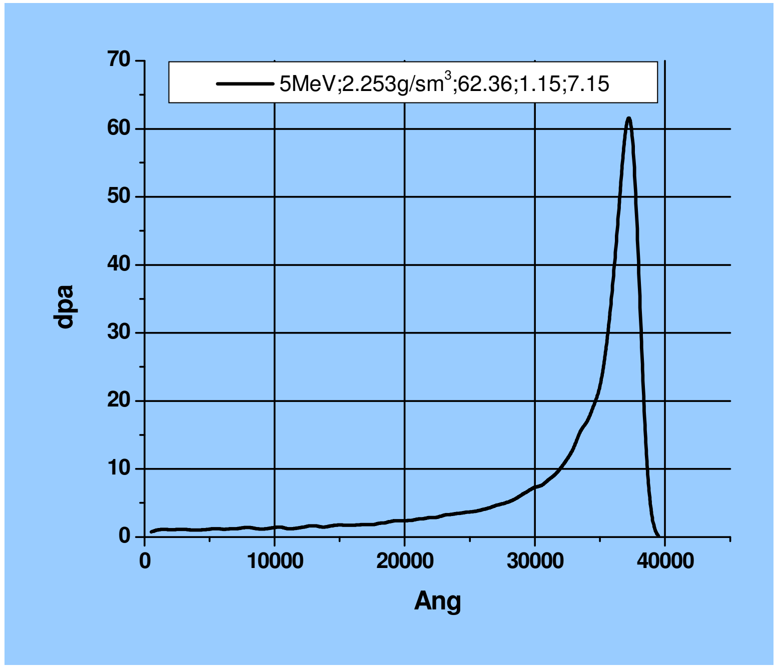
W 99.95% wt.
composition close to that proposed for the ITER application

↓

Three irradiations have done with the ion fluence reached on the samples of $5{\cdot}10^{17}$ ion/cm^2 , 10^{18} ion/cm^2 and $3{\cdot}10^{18}$ ion/cm^2

Characteristics of radiation damage in materials





ρ=1.7 g/cm^3 **<D> = 9.68 dpa**

ρ=2.253 g/cm^3 **<D> = 7.15 dpa**

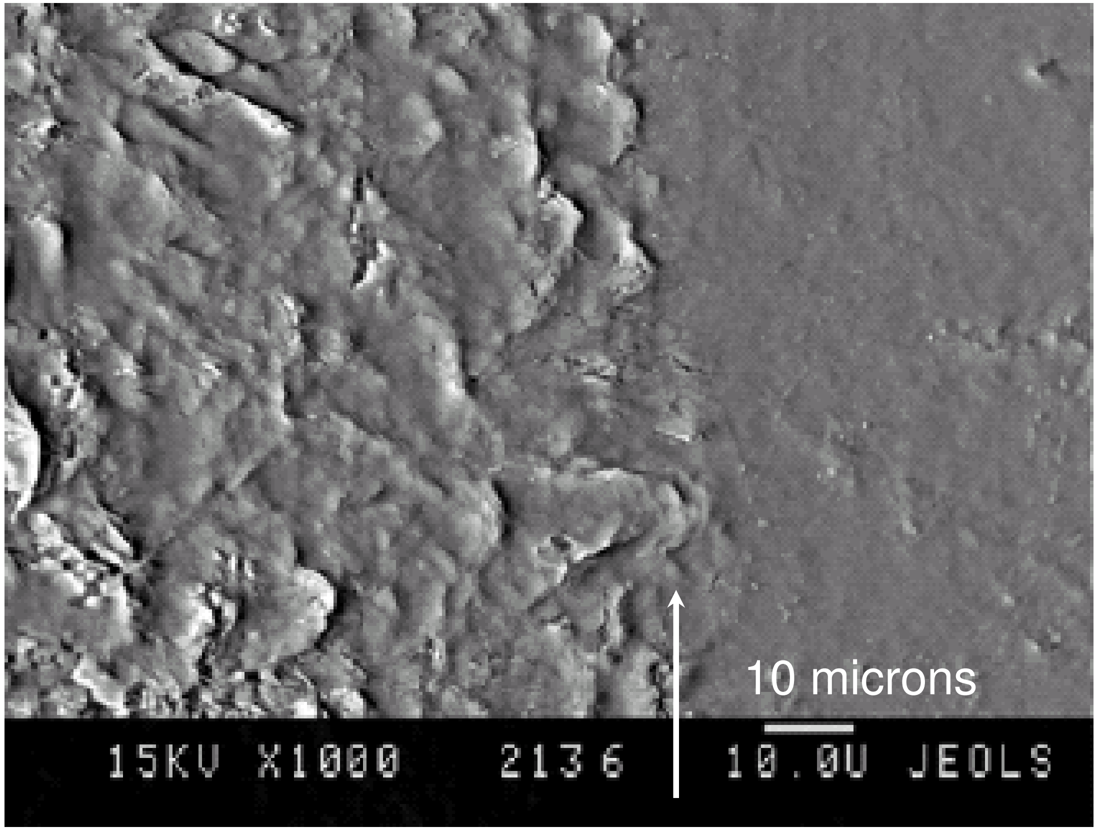
Primary radiation defects D (dpa) vs 5 MeV $^{12}C^+$ ion penetration depth in carbon material for the total ion dose 10^{18} ion/ cm^2

damage profile calculated by SRIM code

Ziegler J.F., Biersack J.P. Littmark U, Stopping and Range of Ions in Solids. NY: Pergamon Press, 1985

Surface evolution after irradiation

MPG-8 graphite **10 dpa**

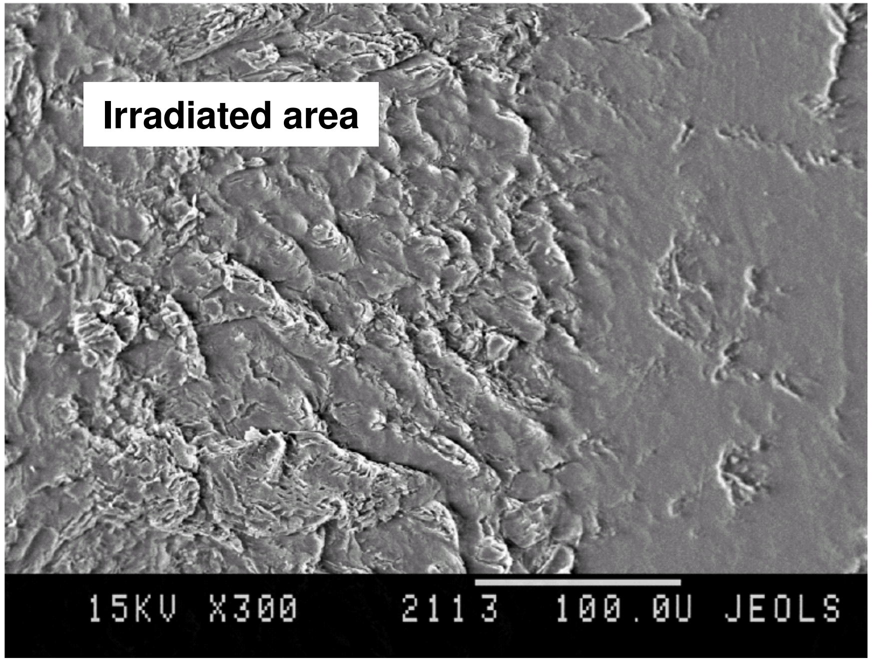


Irradiation border on MPG-8 graphite: area irradiated to the dose 10 dpa is to the left, the non-irradiated surface is to the right (scale in µm).

Surface evolution after irradiation

SEM analysis of SEP NB-31 irradiated to10 dpa around the border of irradiated zone

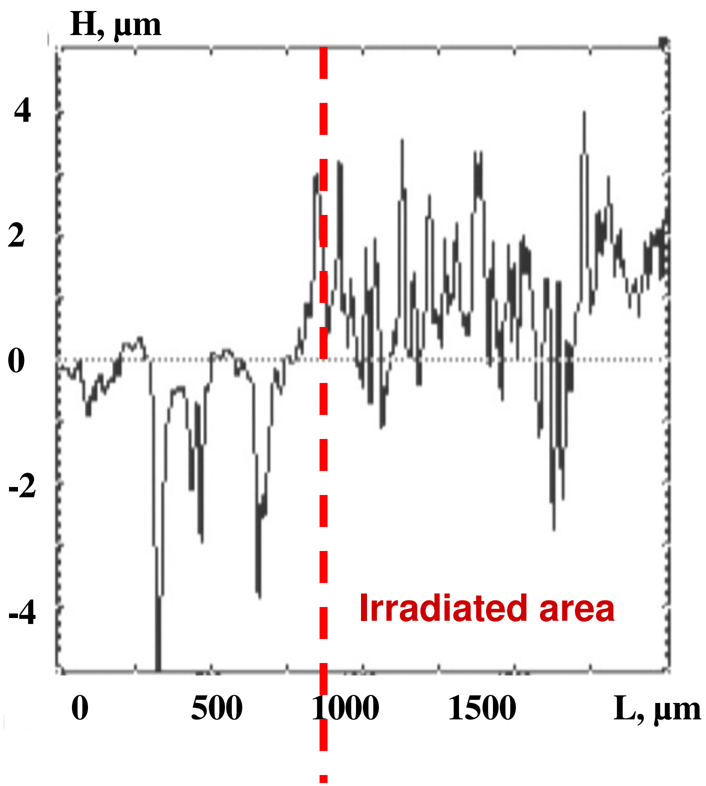
Border of irradiated zone



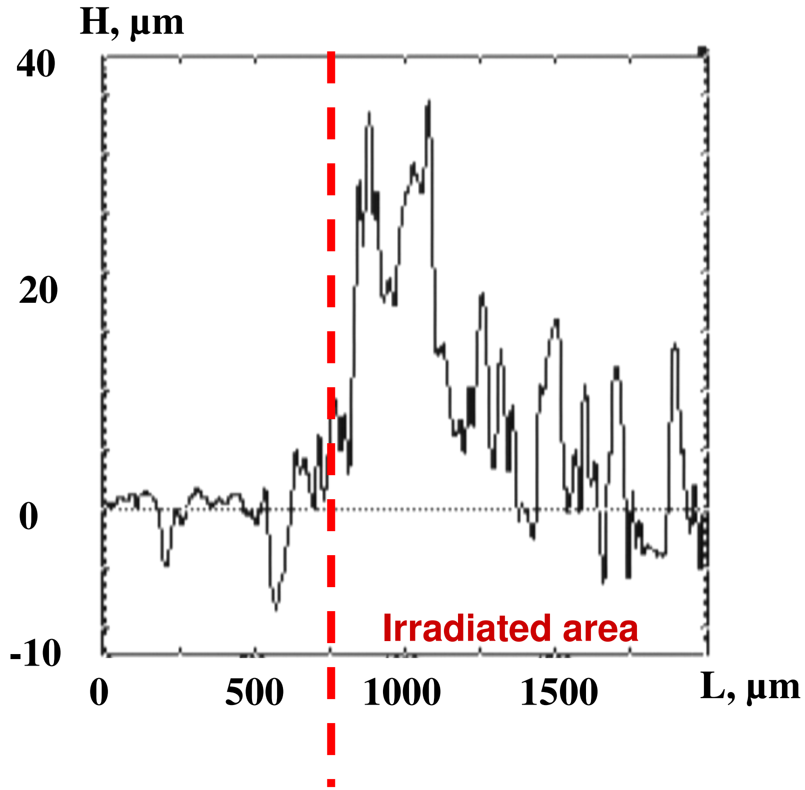
More developed relief structure characterizes the irradiated side

Deformation of radiation-damaged materials

Surface profiles of irradiated materials - swelling

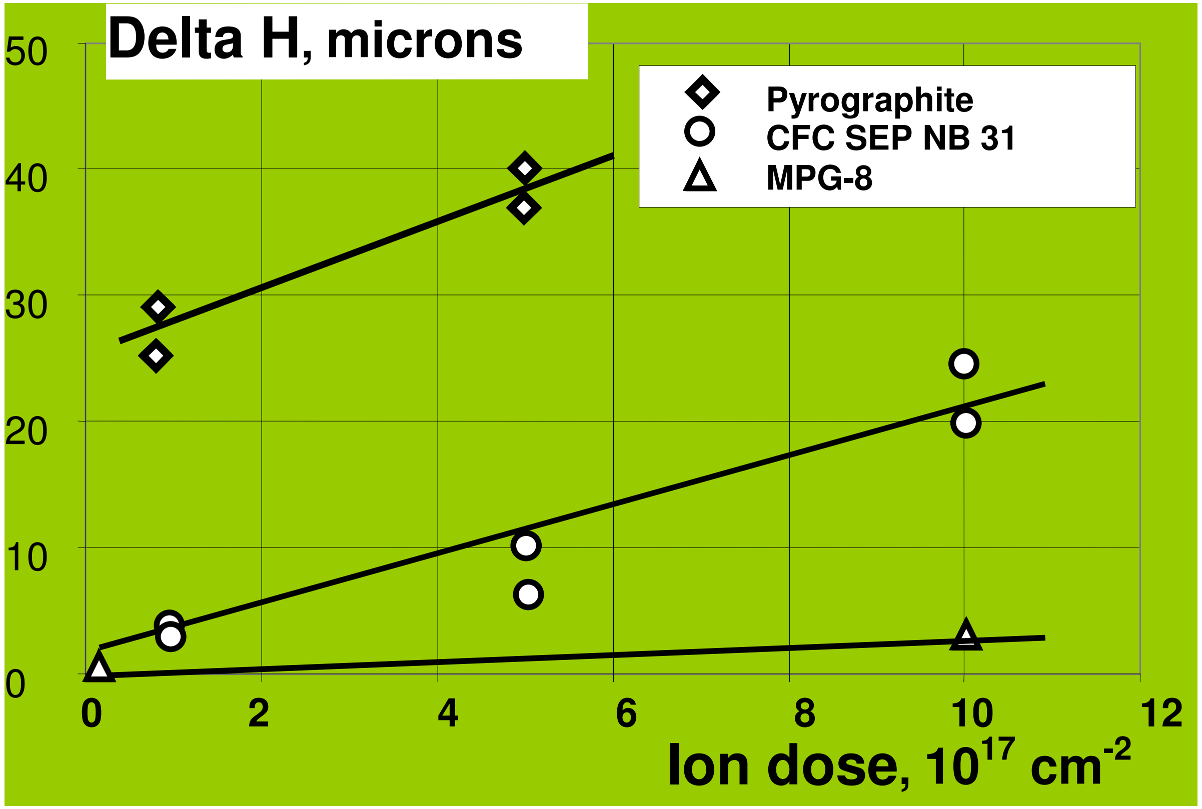


Graphite MPG-8
10 dpa



CFC SEP NB 31
10 dpa

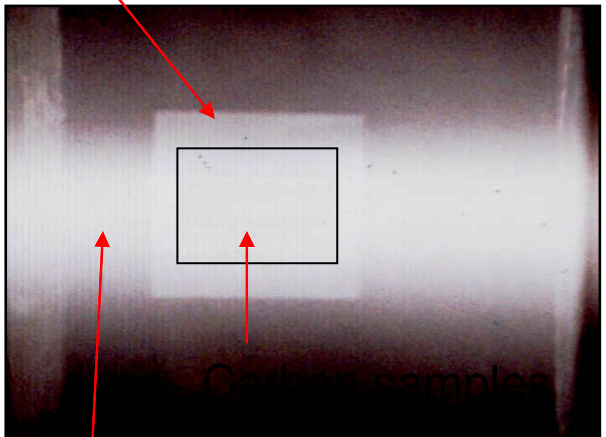
Deformation of radiation-damaged materials



Radiation-induced linear deformation ΔH (swelling) vs dose of the 5 MeV $^{12}C^{+}$ carbon ion for pyrographite, MPG-8 and SEP NB-31 after cyclotron

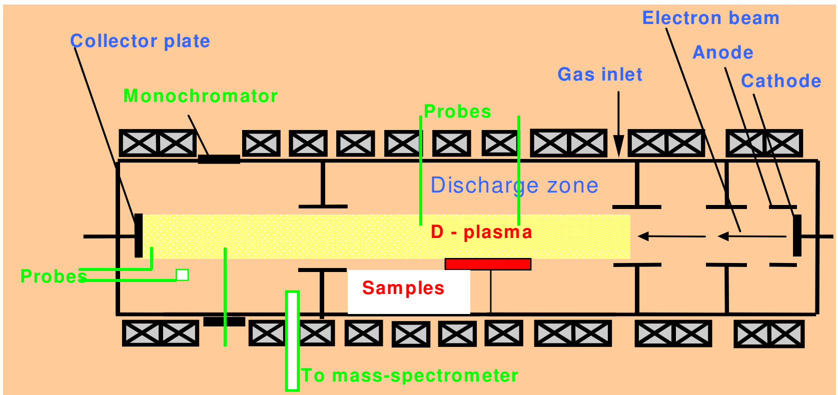
Plasma exposure of irradiated materials – LENTA

Sample holder

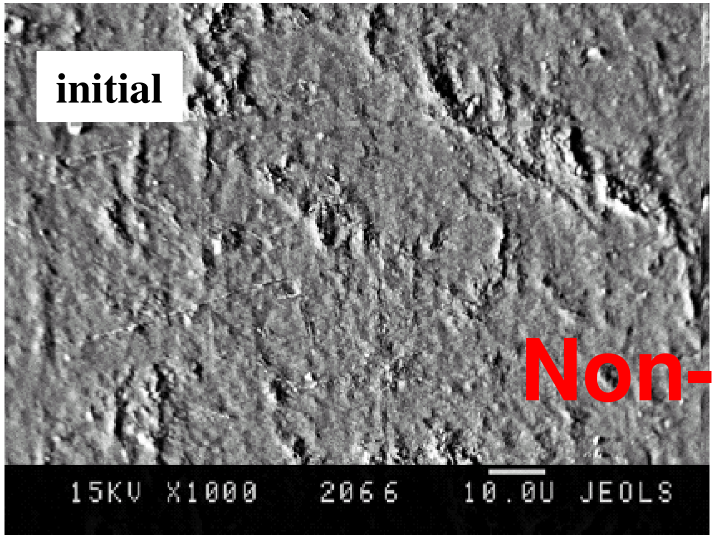


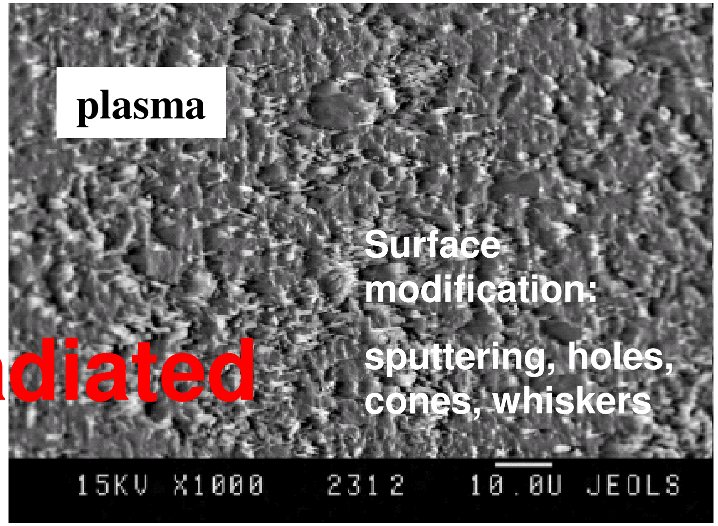
D-plasma

- Deuterium ion current density j = 10 мА/см^2.
- Bombarding plasma ion energy 100 eV
- Exposure time 1 hour
- Material teemperature during plasma operation 40 С.

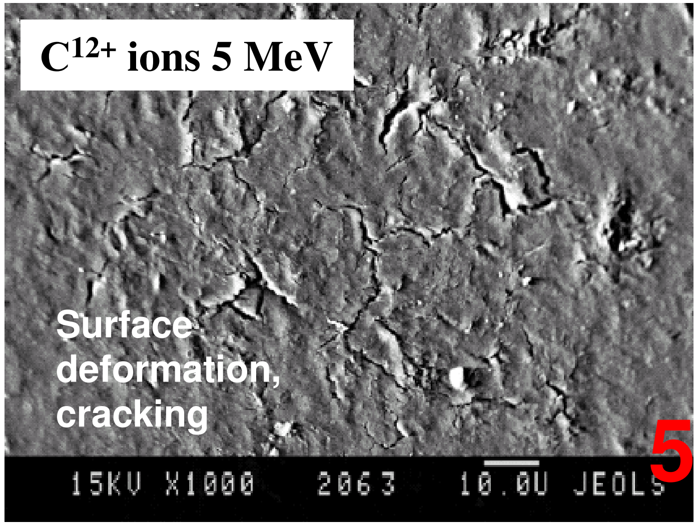


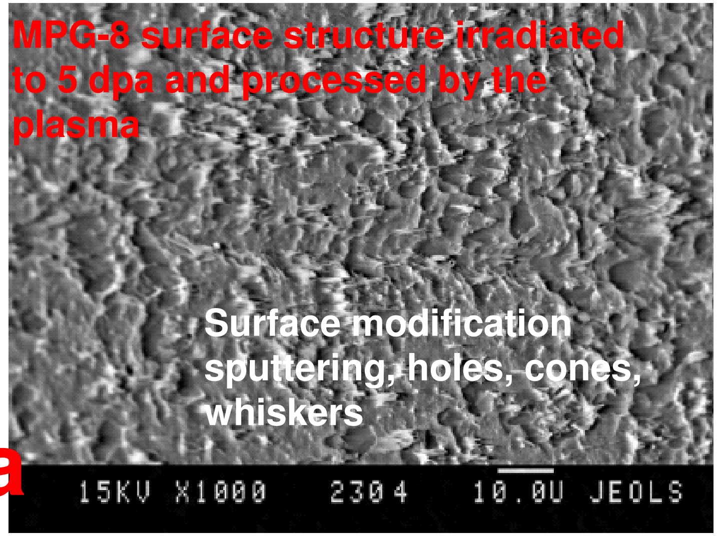
Surface evolution under plasma exposure MPG-8





Non-irradiated

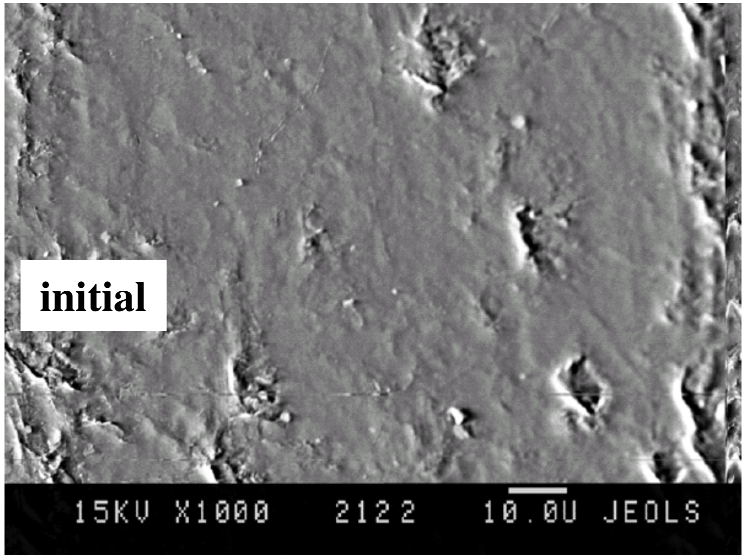


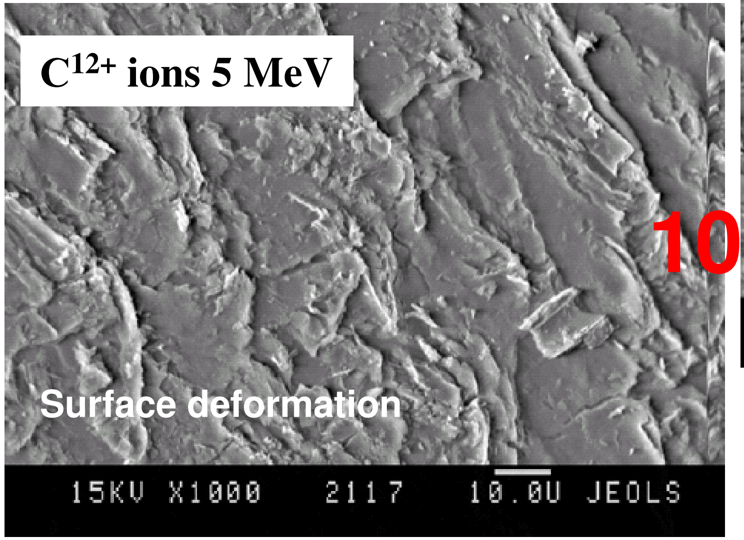


5 dpa

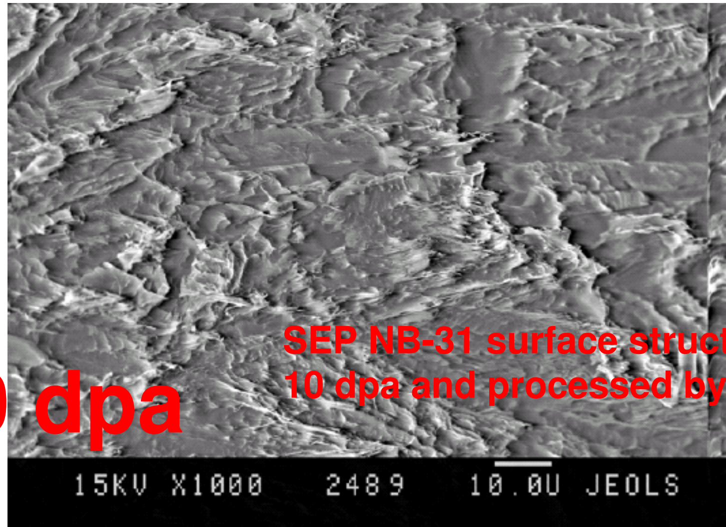
Surface evolution under plasma exposure SEP NB-31

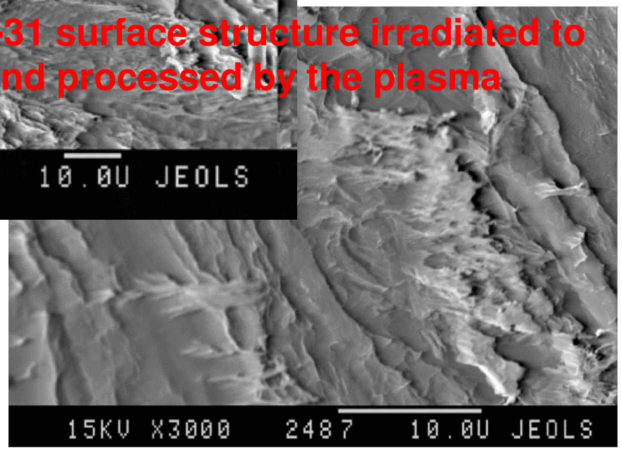
- The effect of plasma on CFC and MPG-8 surface is similar on irradiated materials and on the non-irradiated materials
- cones, pyramids and whiskers appeared on CFC surface after the plasma
- more developed relief after plasma on the irradiated samples compared with those non-irradiated





10 dpa

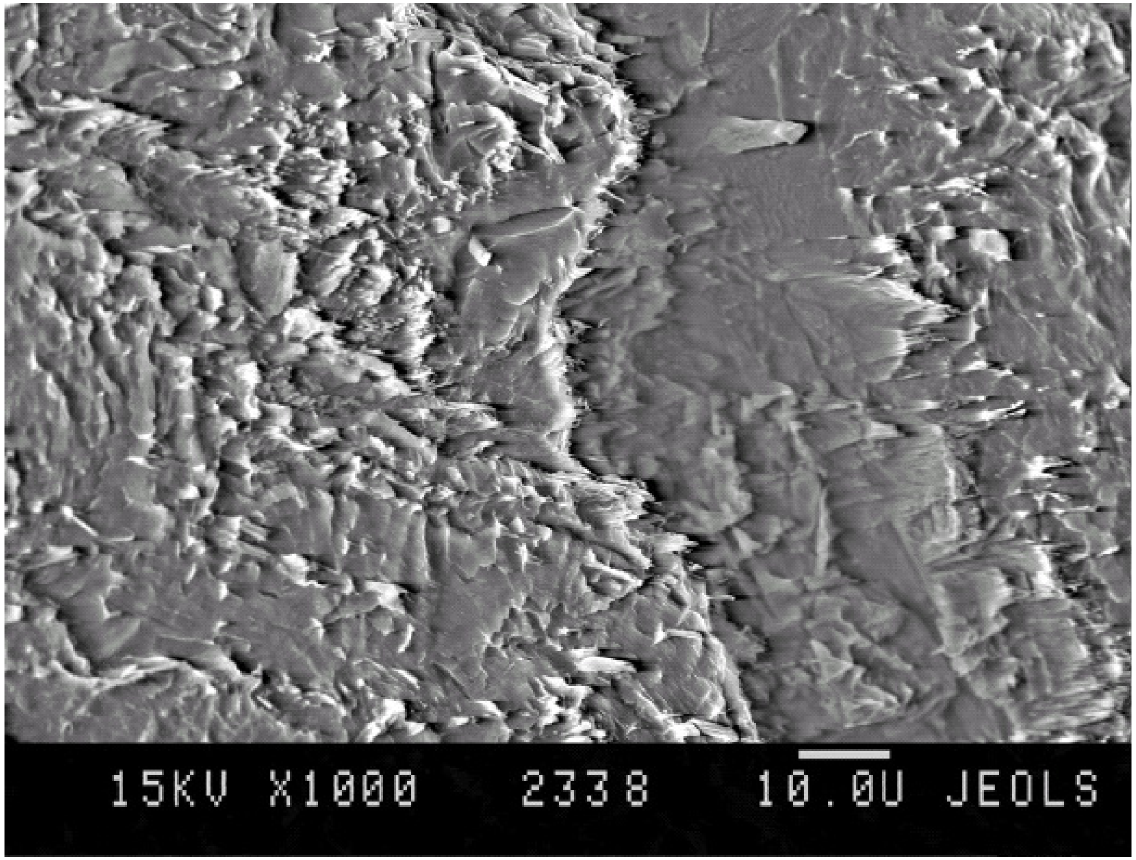




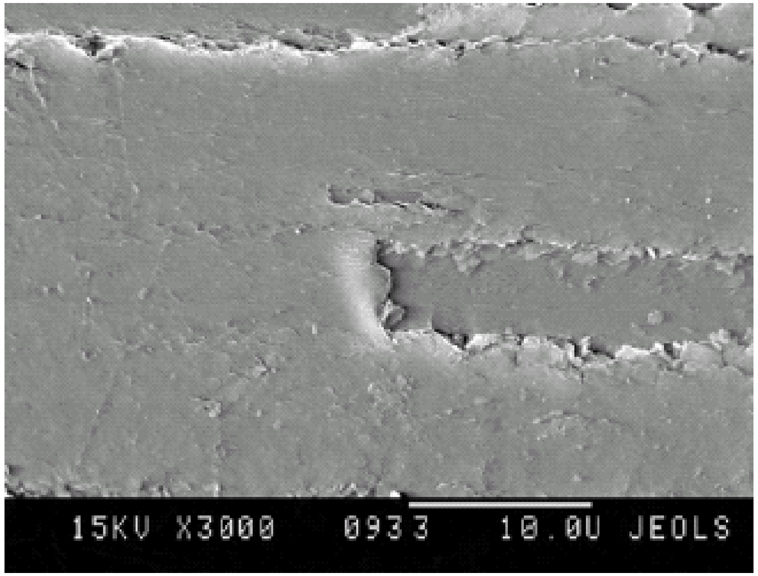
SEP NB-31 surface structure irradiated to 10 dpa and processed by the plasma

Radiation damaged SEP NB-31 after plasma exposure

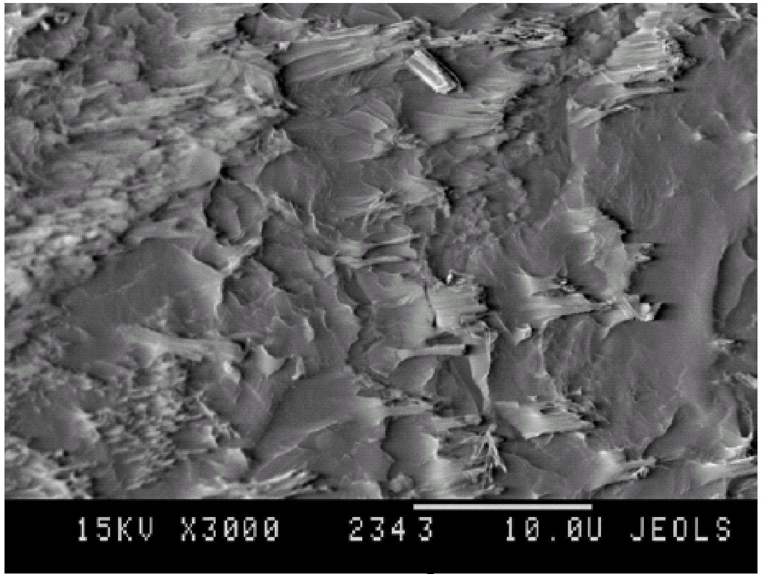
10 dpa



Surface of the SEP NB-31 sample



a



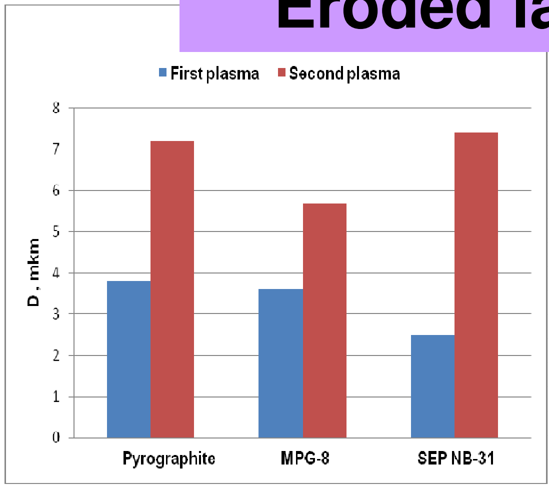
b

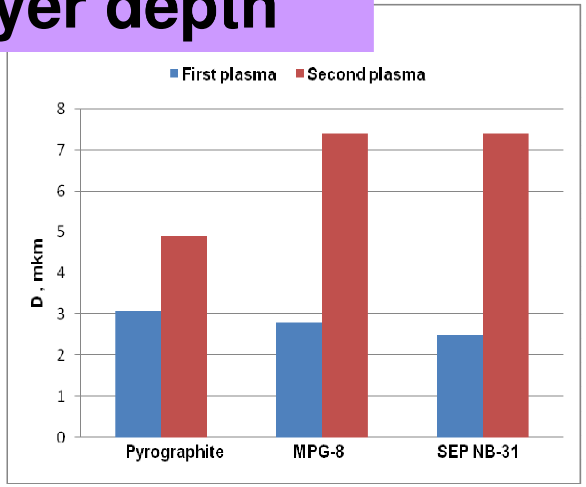
Surface of the SEP NB-31 sample: a) in initial state and b) after irradiation to 10 dpa and plasma exposure (scale 10 μm).

Erosion of irradiated materials in plasma

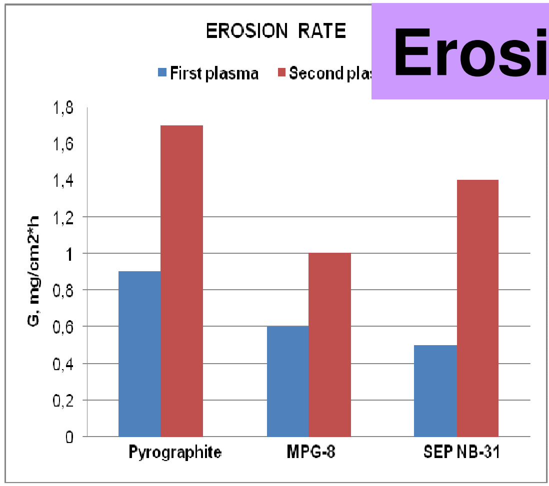
1 dpa **5 dpa**

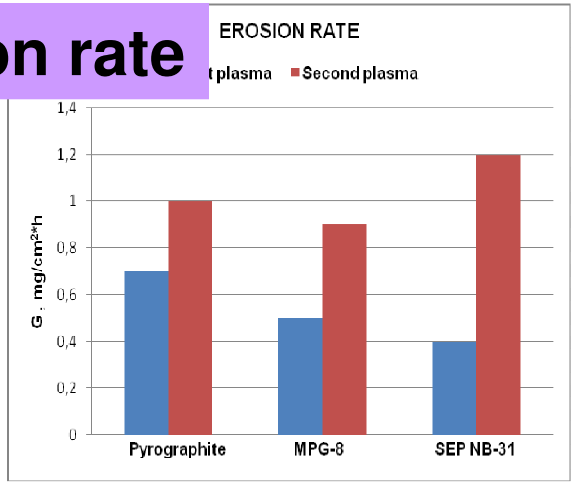
Eroded layer depth





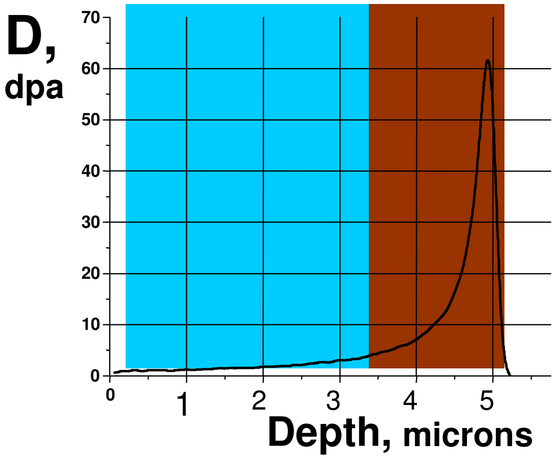
Erosion rate





Pyro MPG SEP

Pyro MPG SEP



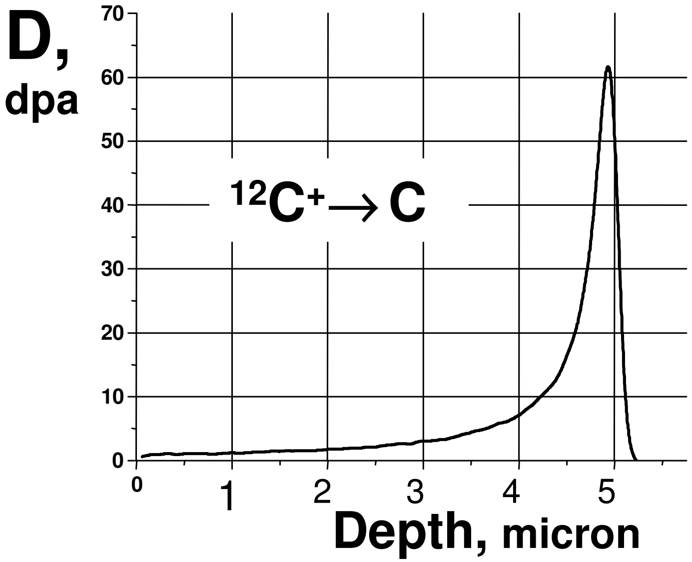
Double plasma exposure experiment:

Damage distribution maximum reached in the second plasma exposure

Increase of erosion rate in the layer of maximal defect density

Radiation damage profiles in materials

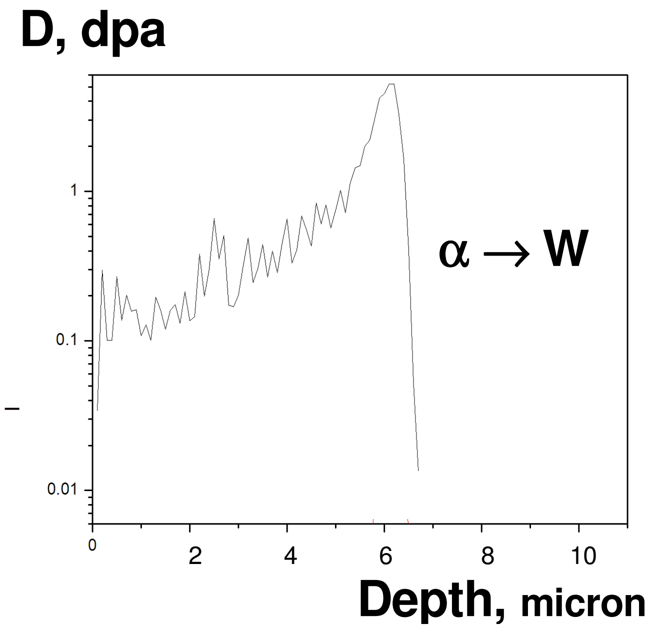
Carbon



$<D> = 9.68$ dpa

Calculated profile of primary radiation defects D (dpa) produced in carbon material (ρ=1.7 g/cm³) irradiated by 5 MeV carbon ions to 10^{18} ion/cm².

Tungsten



$<D> = 0.3$ dpa

Calculated profile of radiation defects produced in tungsten (ρ=19.35 g/cm³, 183.8 amu) irradiated by 4 MeV alpha-particles (He^{+2}) to dose $\Phi = 10^{17}\ \alpha/cm^2$.

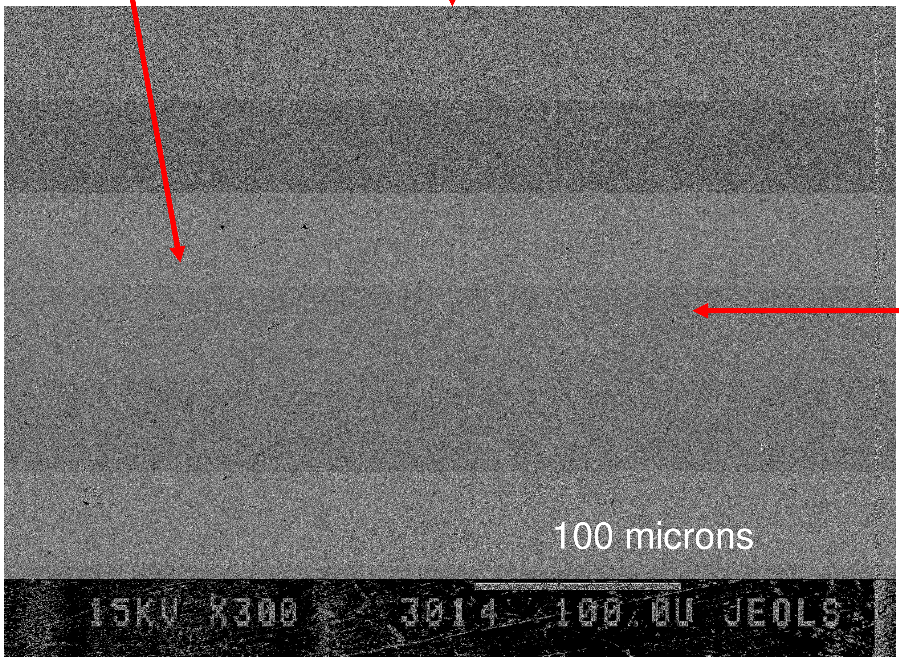
Damage profile calculated by SRIM code
Ziegler J.F., Biersack J.P. Littmark U, Stopping and Range of Ions in Solids. NY: Pergamon Press, 1985

Tungsten surface evolution

Tungsten after irradiation by $^4He^{+2}$ ions 4 MeV

non-irradiated area

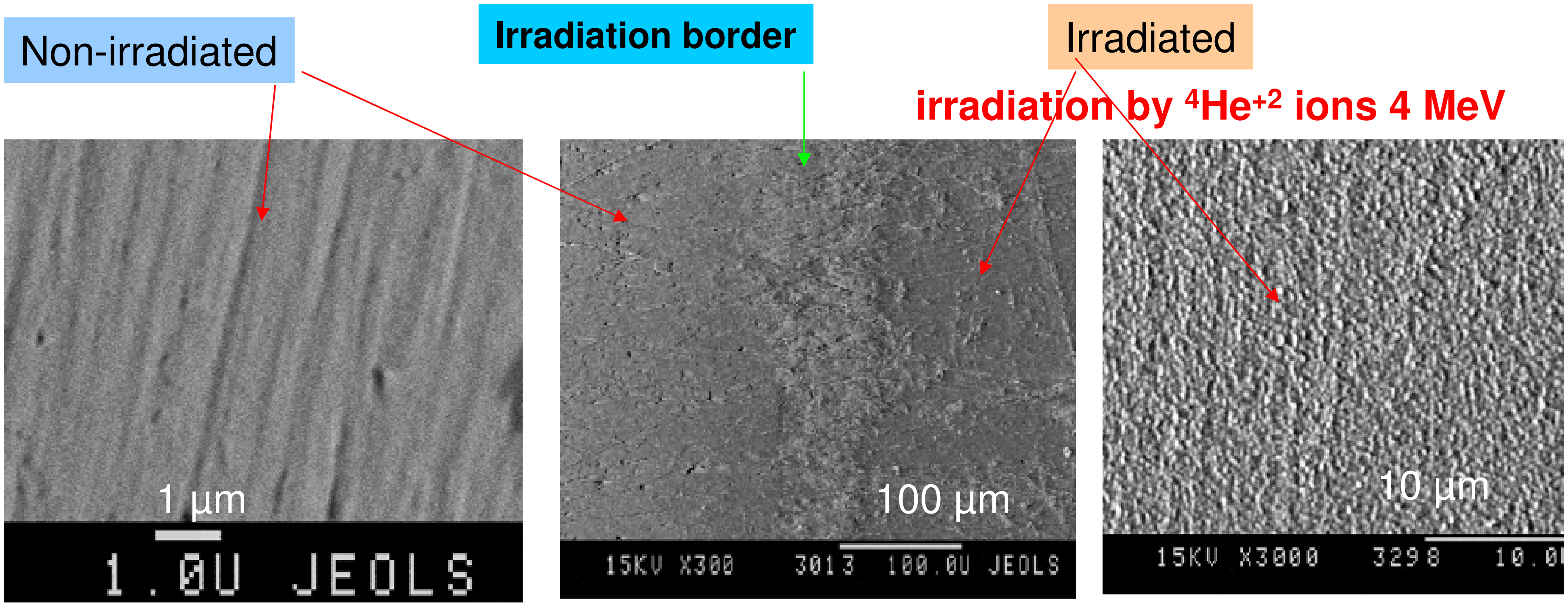
Irradiation border



Linear deformation is notable at 0.1-0.3 micron

Irradiated by α-particle to fluence 10^{18} ion/cm^2

Tungsten surface modification by high-energy α-particles



a

surface as prepared

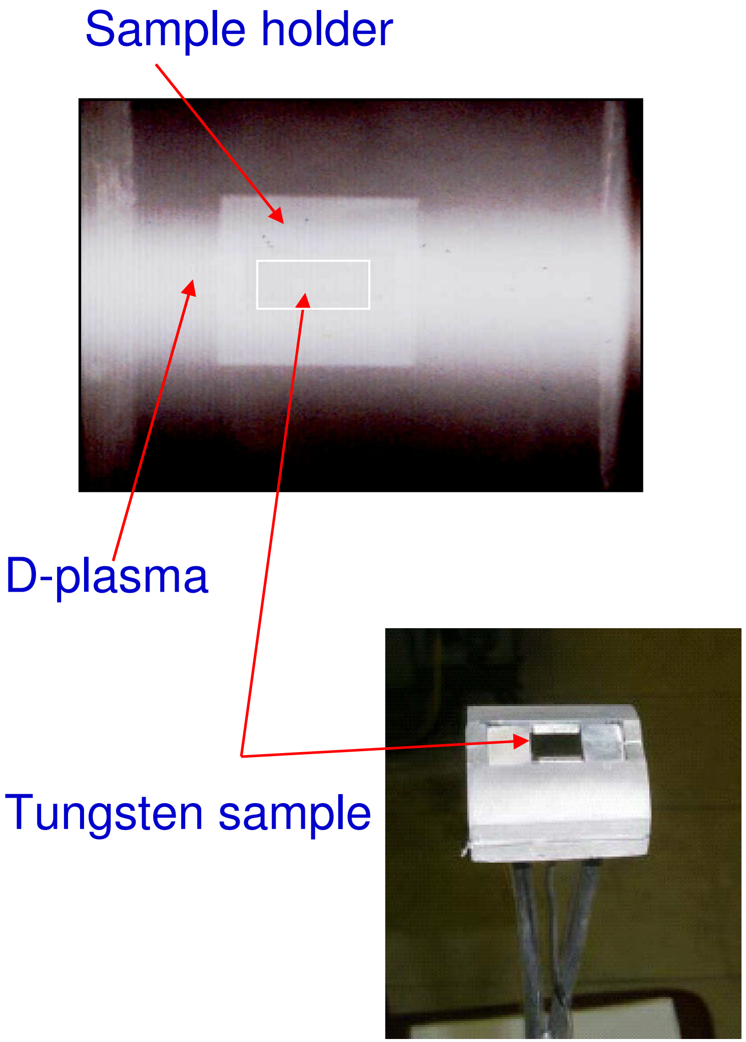
b

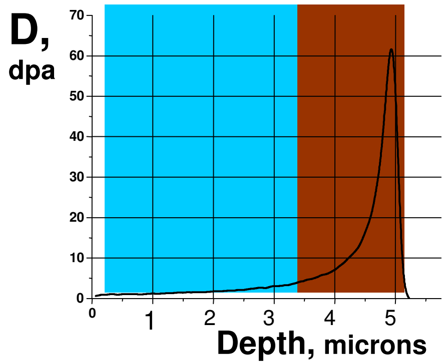
border of irradiation area on tungsten sample having received ion fluence 10^{18} ion/cm^2

c

tungsten irradiated with 4He+2 ions to fluence $3{\cdot}10^{18}$ ion/cm^2 (scale bars in microns)

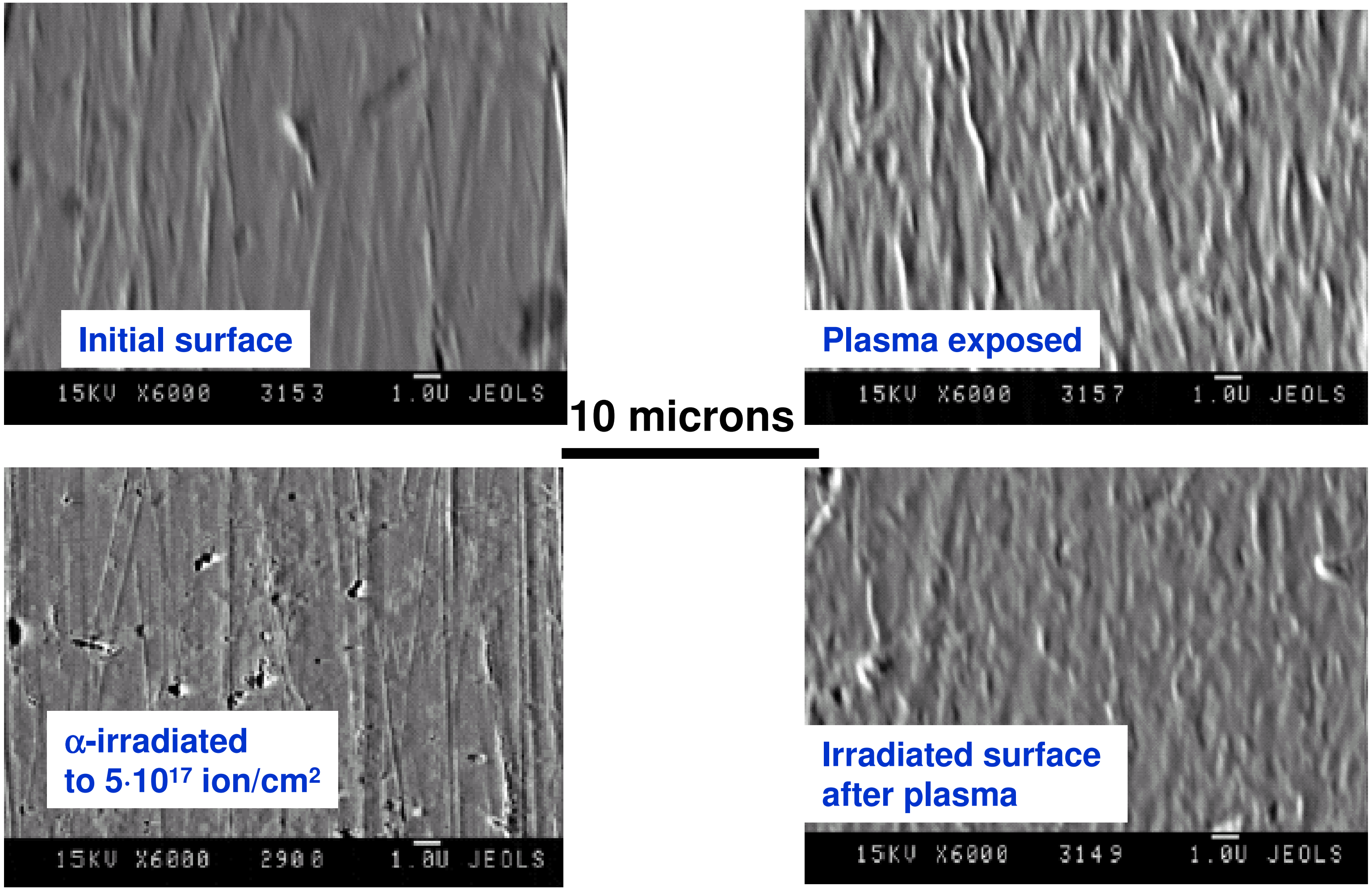
Exposure of materials in deuterium plasma





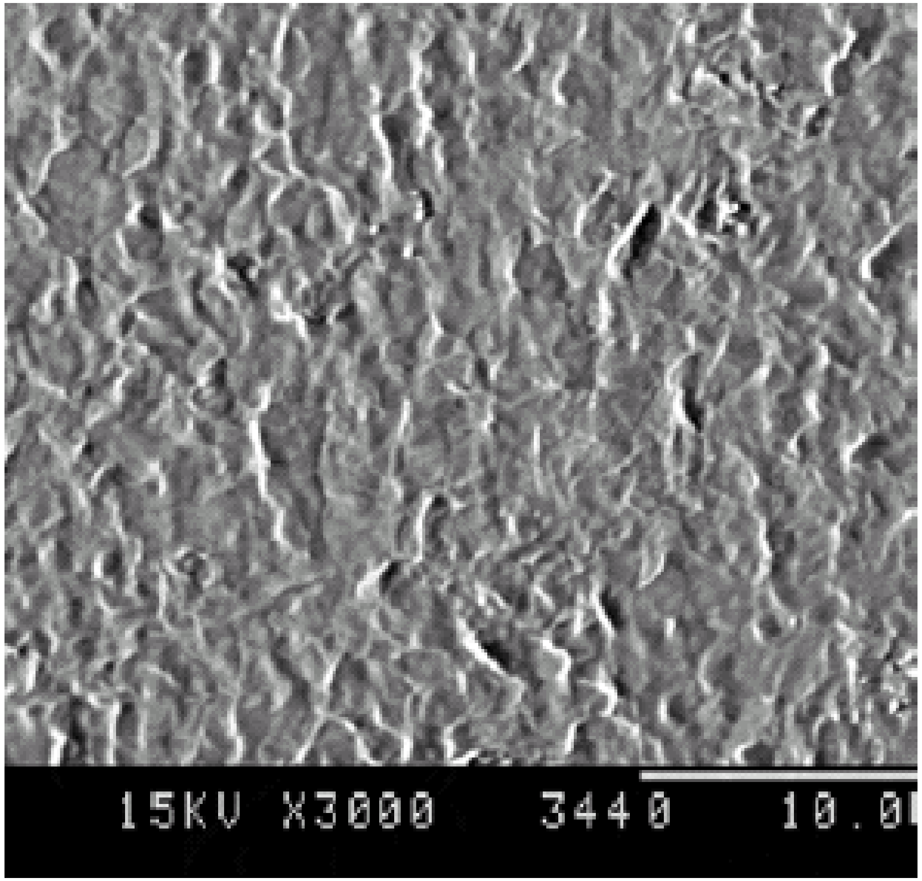
- **Steady-state condition**
- **Ion current density j = 10-20 mA/cm².**
- **Deuterium ion impinging energy 100-250 eV.**
- **Exposure time 1-3 hours**
- **Sample temperature during plasma operation below 40 C.**
- **Some exposures: erosion by layers**

Tungsten surface evolution: fast ion irradiation + plasma exposure



Slightly changed microstructure after alpha-irradiation
Wavy structure after plasma exposure

Tungsten irradiated after plasma exposure



Tungsten irradiated to 10^{18} $^{4}He^{+2}/cm^2$ after plasma exposure to $3.7 \cdot 10^{21}$ D^+/cm^2 (at 250 eV) (scale 10 microns).

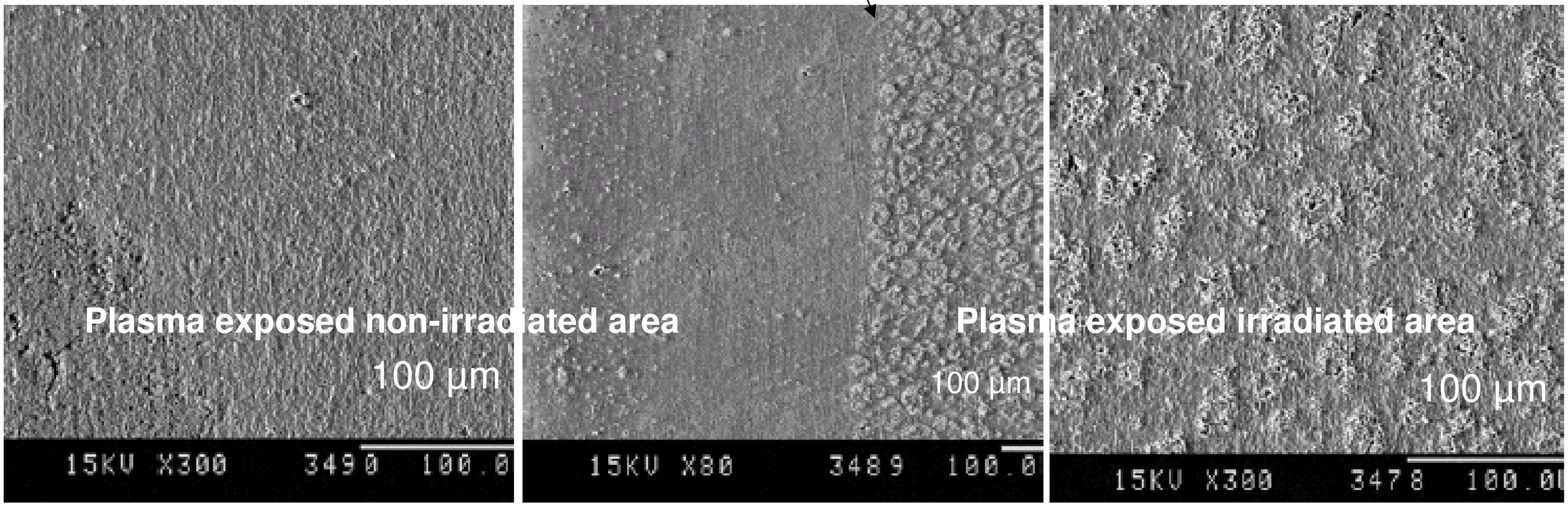
Tungsten surface after plasma exposure

Plasma exposure to $2 \cdot 10^{22}$ D^+/cm^2

6 µm thick layer eroded

Irradiation border

Preliminary irradiation to $^4He^{+2}$ fluence of $5 \cdot 10^{17}$ ion/cm^2



View of tungsten eroded in deuterium plasma – the layer at the maximal damage depth is to the right

Summary

- Experimental approach has been developed aiming at the investigation of the combined effect of neutron irradiation and plasma bombardment on fusion reactor plasma facing materials.
- Radiation damage in materials was produced by accelerated high energy ions simulating the effect of neutron irradiation. $^{12}C^{+}$ ions were taken to irradiate carbon materials and α-particles to produce damage in tungsten.
- Radiation damage level relevant to a fusion reactor has been reached, 1-10 dpa samples were produced.
- Erosion in deuterium plasma was studied on irradiated materials in simulated tokamak SOL conditions (linear plasma simulator LENTA).
- Notable radiation damage effect on the erosion process is found. Enhancement of erosion of irradiated carbon materials and structure damage of irradiated tungsten were detected.
- Efficiency of the proposed method has been demonstrated.

  The progress of the method appears promising for the research of plasma facing materials stability to combined attack of plasma and neutron fluxes.