National Research Center “Kurchatov Institute”

Plasma Impact on Materials at Displacement Damage Condition

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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.

ITER Tungsten in divertor 2.4 dpa/(MW $a^{-1}m^{-2}$)

0.35×10^{-7} dpa/FPS *(Iida H.,Khripunov V.,Petricci L.,Federici G. 2004 ITER Nuclear Analysis Report G 73 DDD 2 W 0)*

0.7 –1 dpa for changing components *(J.Linke et al. Fusion Science and Technology, Vol.47, Apr. 2005)*

DEMO 30-80 dpa

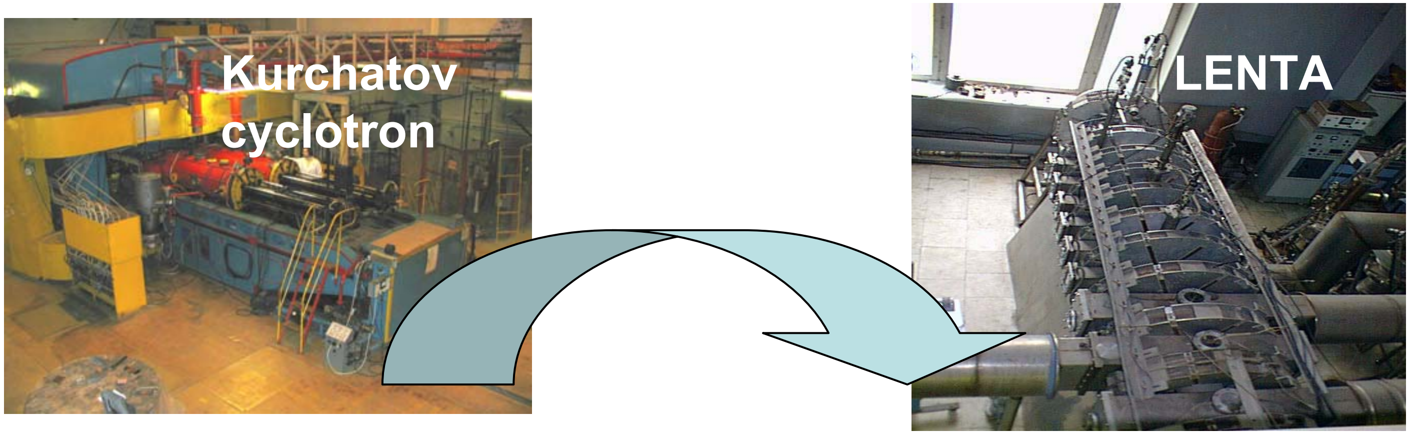
POWER 100-200 dpa

Table 1-1. Advanced fission and fusion operating conditions

	Fusion	Fission (Gen-IV)
Coolant	H_2O, He, Li, PbLi, FLiBe	H_2O(SC), He, Pb, PbBi, Na
Particle Energy	< 14 MeV	< 1–2 MeV
Temperatures	300-1000°C	300–1000°C
Max displacement damage	~ 200	15–200
He/dpa	10 appm/dpa	~ 0.1 appm/dpa
Stresses	Moderate, nearly constant	Moderate, nearly constant

Workshop on Advanced Computational Materials Science: Application to Fusion and Generation IV Fission Reactors

Complex experiment – production of damaged materials and exposure in plasma



Practically impossible to obtain data on materials behavior in neutron flux of $\geq 10^{16}$ neutron/cm^2s (fusion reactor case) on actually existing fission reactors

- Experimental simulation of neutron effect on fusion reactor PFMs by irradiation with high-energy ions
- Produce materials at high level of radiation damage – carbon-based and tungsten
- Study effect of plasma on damaged materials – erosion and deuterium retention emphasized

- Ions H^+, He^+, Li^+, C^+ at 1-60 MeV
- Equivalent doses to 10^{26} n/m^2 effect for several days irradiation

Beam-plasma disacharge
- Divertor and SOL simulation
- Exposure to steady-state plasma
- Ion fluence 10^{25}-10^{26} ion/m^2
- $N_e=10^{18}$-10^{19} m^{-3}, T_e=1-20 eV, $j_{ion}=10^{21}$-10^{22} ion/m^2s.

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 grain 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 ($^{4}He^{+2}$ 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

Four irradiations done with the ion fluence reached on the samples of $5 \cdot 10^{17}$ ion/cm^2 , 10^{18} ion/cm^2, $3 \cdot 10^{18}$ ion/cm^2 , 10^{19} $^{4}He^{++}$ /cm^2

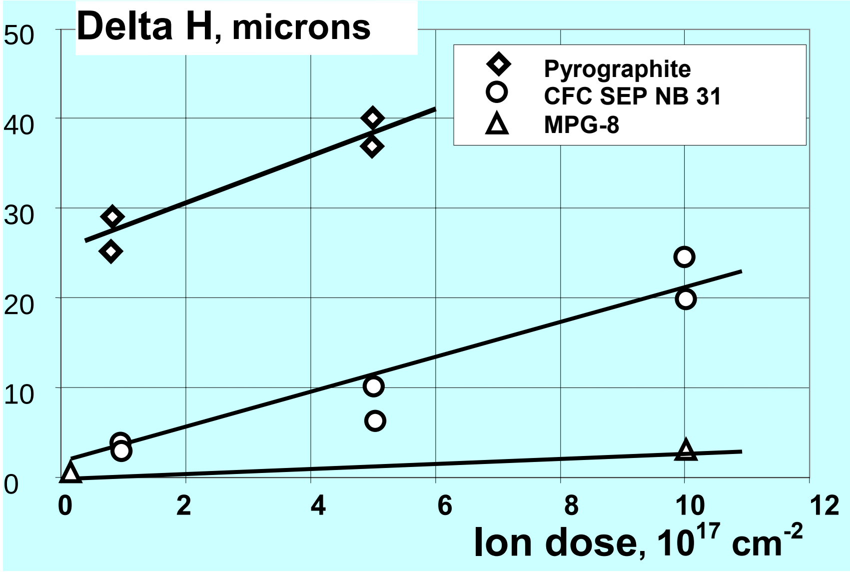
Defect generation rate

$G_d = 3.7 \times 10^{-4}$ dpa/s

Irradiation at T = 80-1000 C

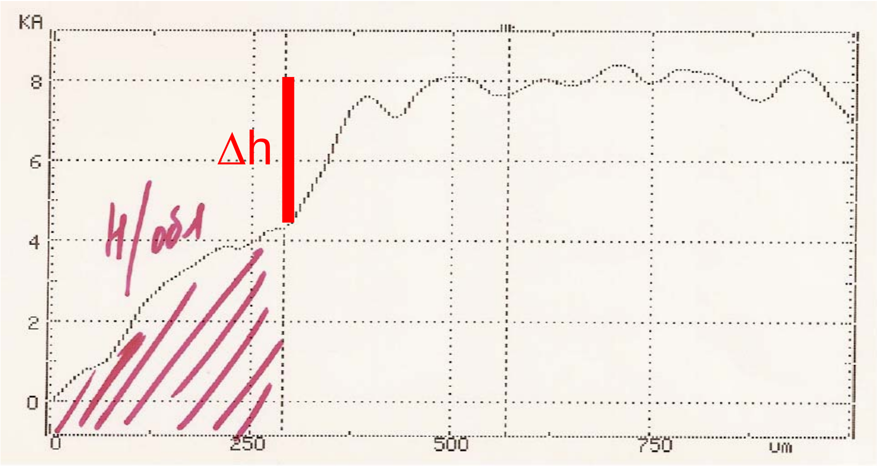
Deformation of radiation-damaged materials

C



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

W

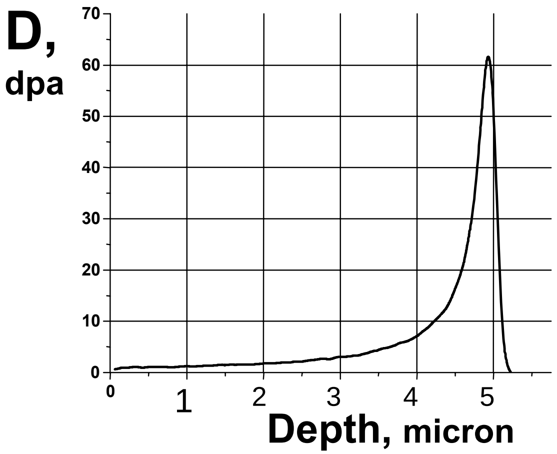


Swelling effect:
Δh = 0,15 – 0,3 **μm**
Up to 5% in average over damaged layer

Radiation defects in carbon and tungsten

Carbon

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.

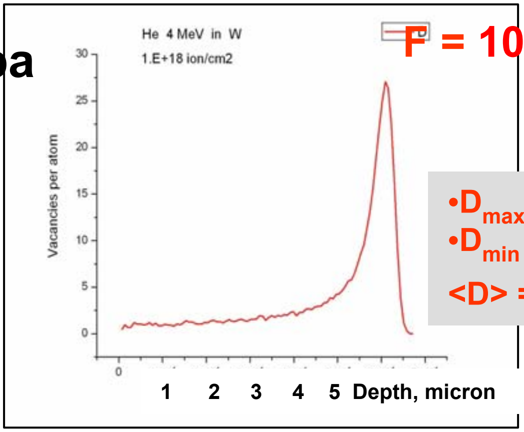


$^{12}C^{+} \rightarrow C$

Tungsten

Primary defects in tungsten at $^{4}He^{+2}$ 4 МэВ (ρ=19.35 g/cm3, 183.8 amu)

D, dpa



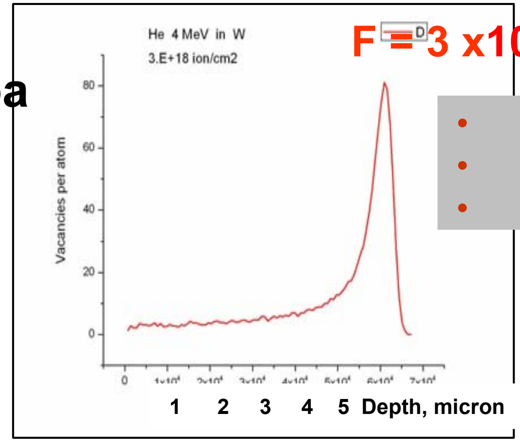
F = 10^{18} He^{++}/см^2

- D_{max} = 27.04 сна
- D_{min} = 9.2x10^{-1} сна

<D> = 4,03 сна

$He^{++} \rightarrow W$

D, dpa



F = 3 x10^{18} He^{++}/см^2

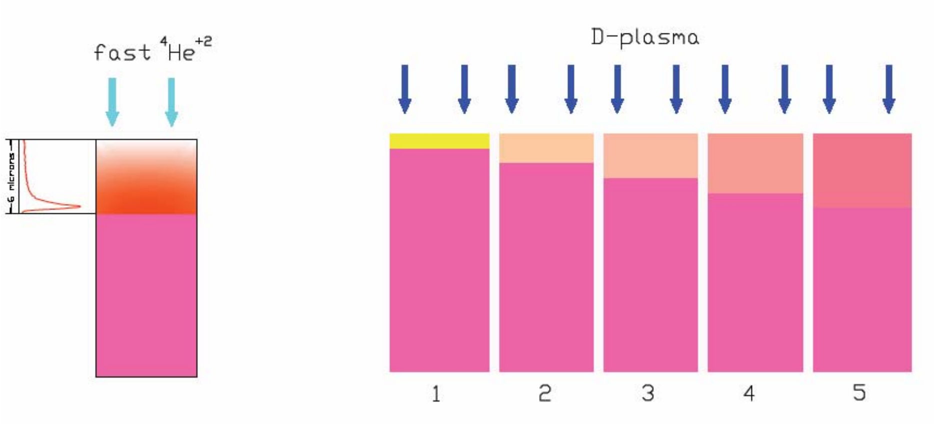
- D_{max} = 81.11 dpa
- D_{min} = 2.76 dpa
- <D> = 12.09 dpa

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

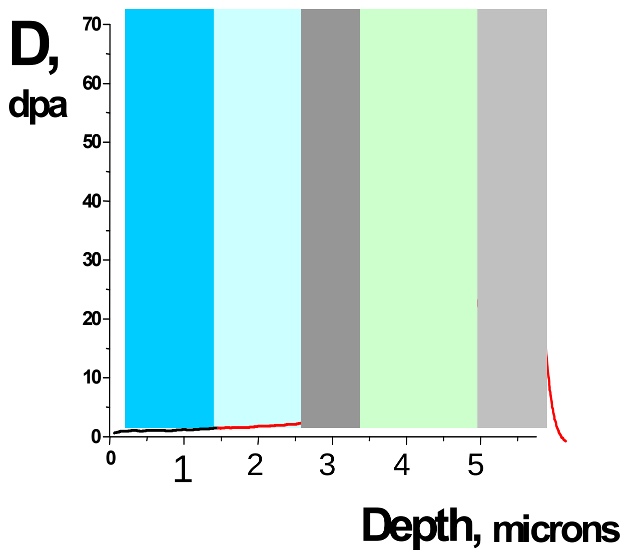
Tungsten exposure in plasma

Successive expositions of materials in steady-state deuterium plasma

LENTA



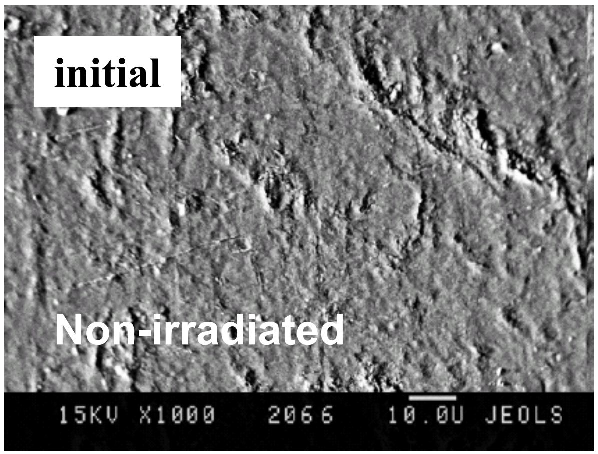
Working gas **deuterium**
Plasma density **2 ·1012 cm-3**
Electron temperature **6 eV**
Ion current **j = 10-20 mA/cm2**
Incident ion energy on the surface **100-250 eV**
Exposure time **1- 3 hours**
Sample temperature **40-100 C.**
Experimental scenario – multiple exposure
Ion fluence in one exposure step 1021 ion/cm2
Total Ion fluence **2·1022 ion/cm2**
Analysis after each exposure step

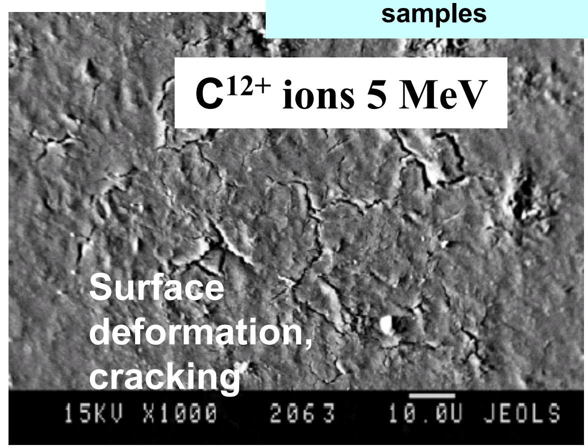


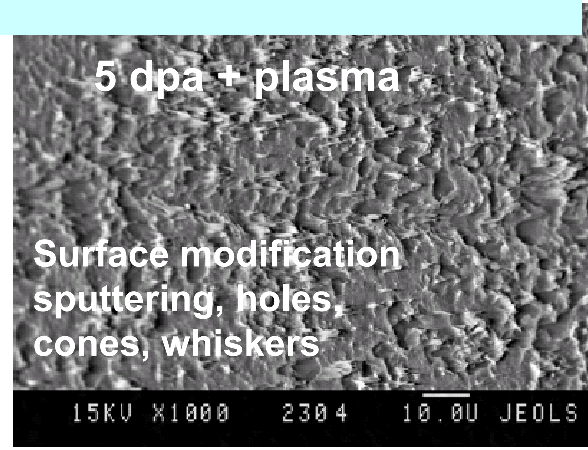
Surface evolution under plasma exposure

- 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 after the plasma
- more developed relief after plasma on the irradiated samples

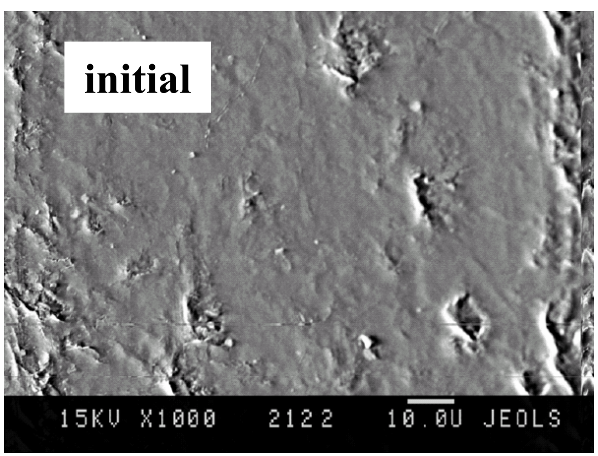
MPG-8

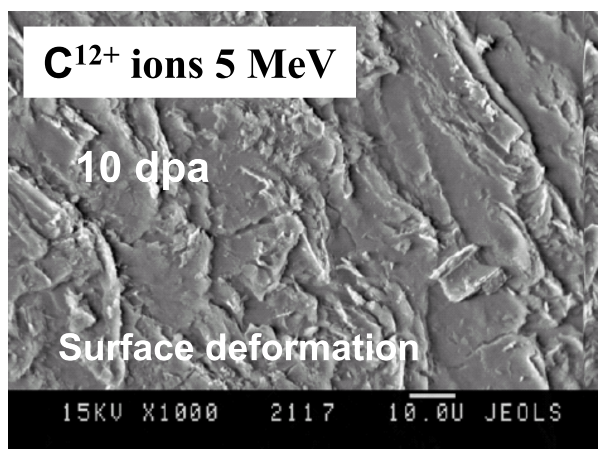


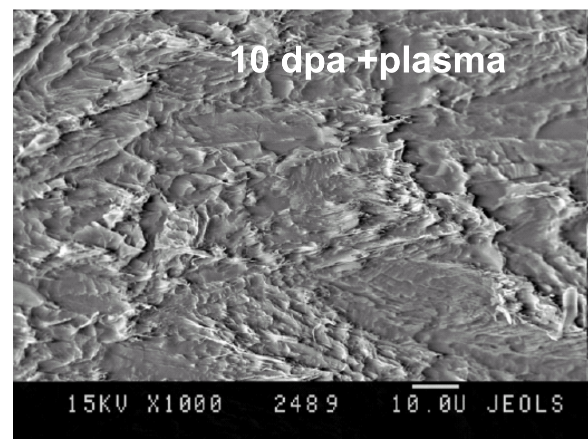




SEP NB-31

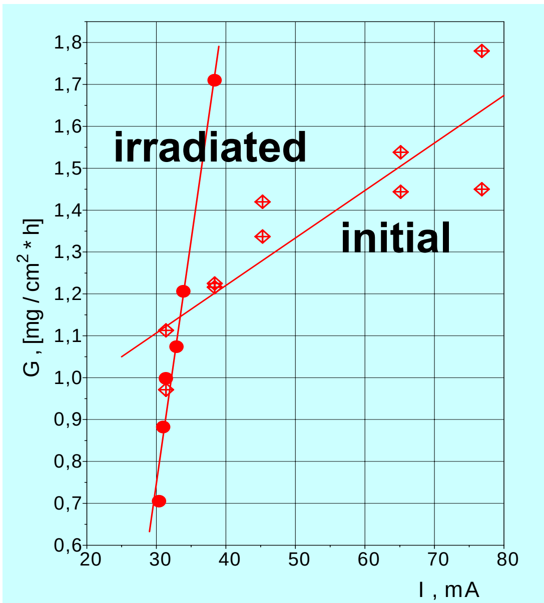




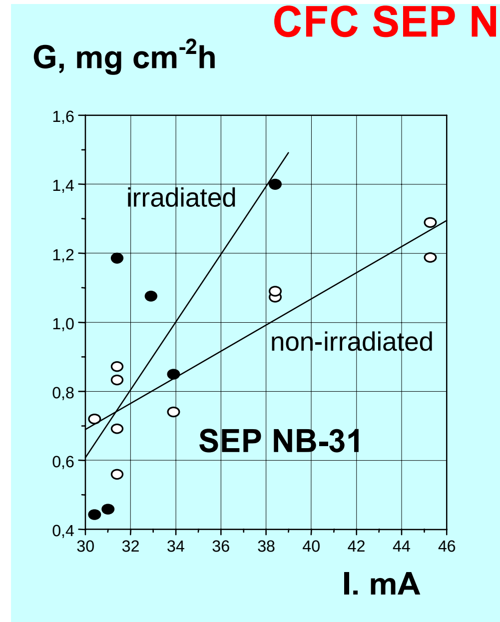


Erosion in deuterium plasma

Pyrographite



CFC SEP NB 31



Pyrographite initial state

Y_1 = 0.2 at/ion

Increase of erosion yield on irradiated material

$Y_{pyro\ irrad}/Y_{pyro} = 4.8 \pm 0.4$

$Y = dj_{at}/dj_{ion} \propto dG/dI$

- **SEP NB-31 in initial state**

  Y_1 = 0.2-0.3 at/ion

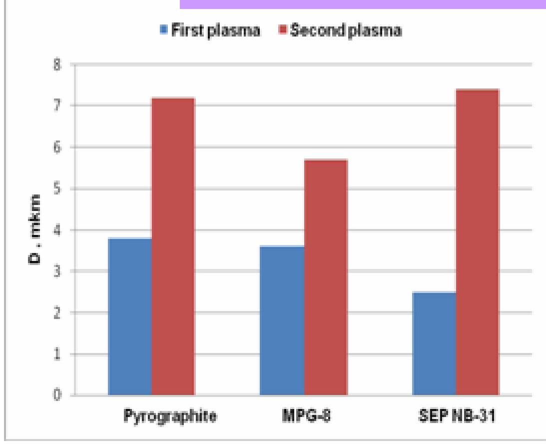
Increase of erosion yield on irradiated material

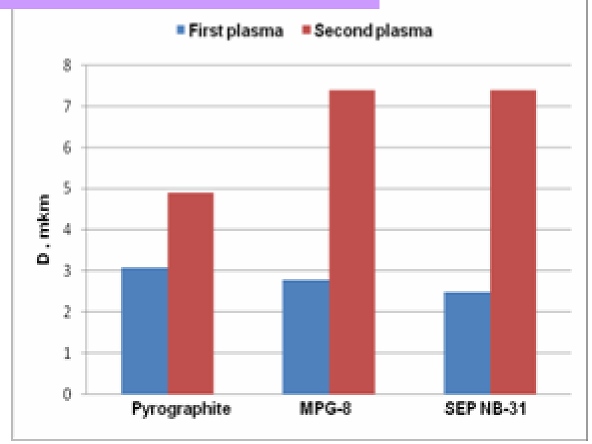
$Y_{SEP\ irrad}/Y_{SEP} = 2.6 \pm 0.6$

Erosion of irradiated materials in plasma

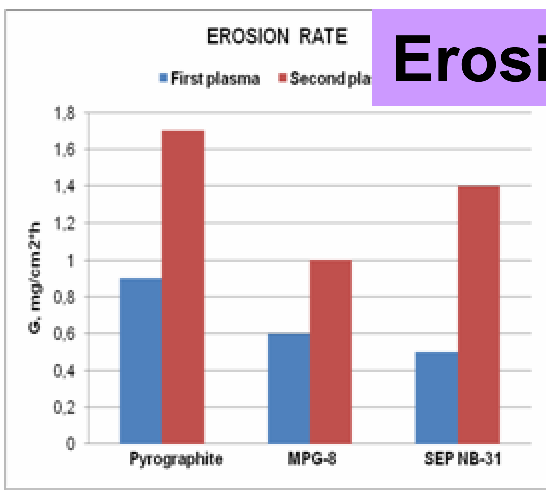
1 dpa **5 dpa**

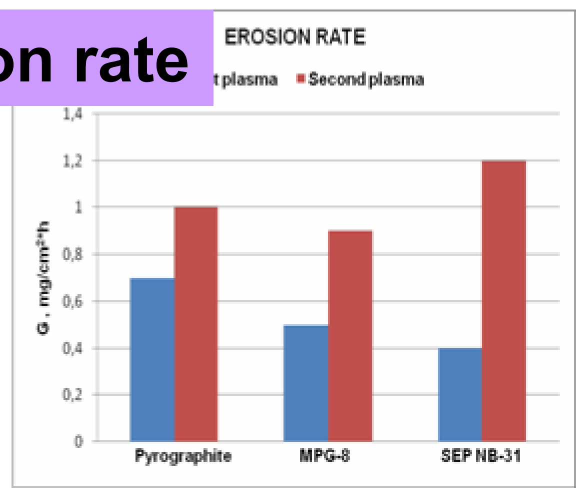
Eroded layer depth



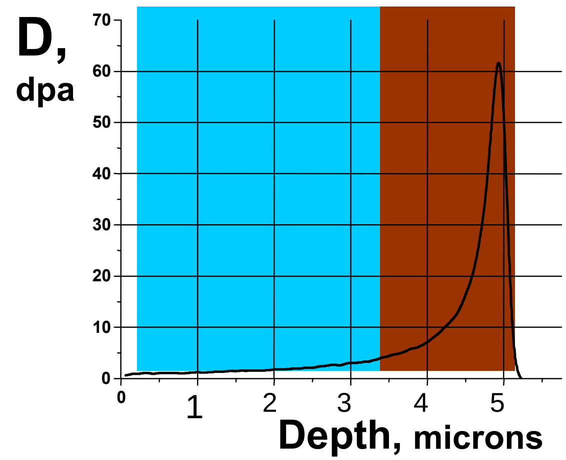


Erosion rate





Pyro MPG SEP **Pyro MPG SEP**

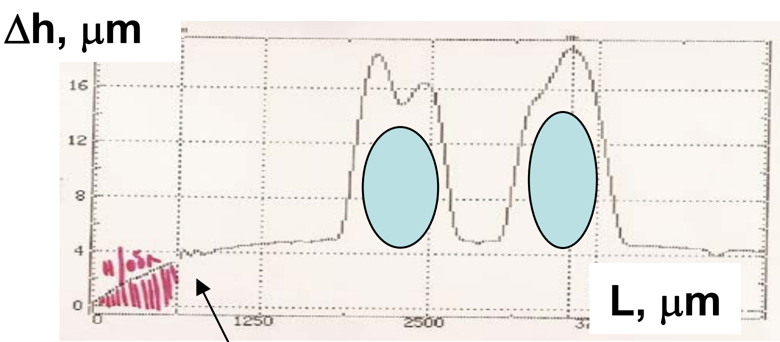


Double plasma exposure experiment:

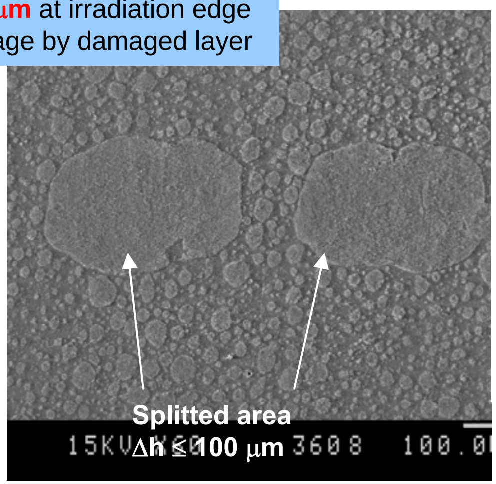
Damage distribution maximum reached in the second plasma exposure

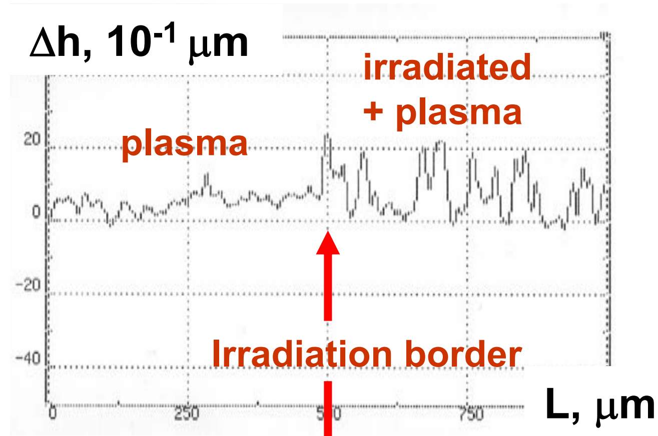
Increase of erosion rate in the layer of maximal defect density

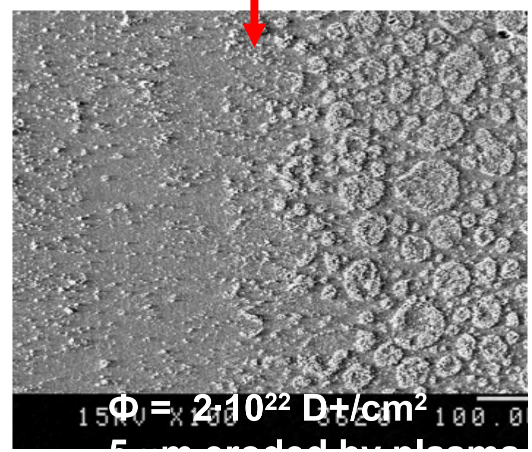
Irradiated tungsten erosion in plasma



Swelling effect:
Δh = 0,15 – 0,3 μm at irradiation edge
up to 5% in avarage by damaged layer

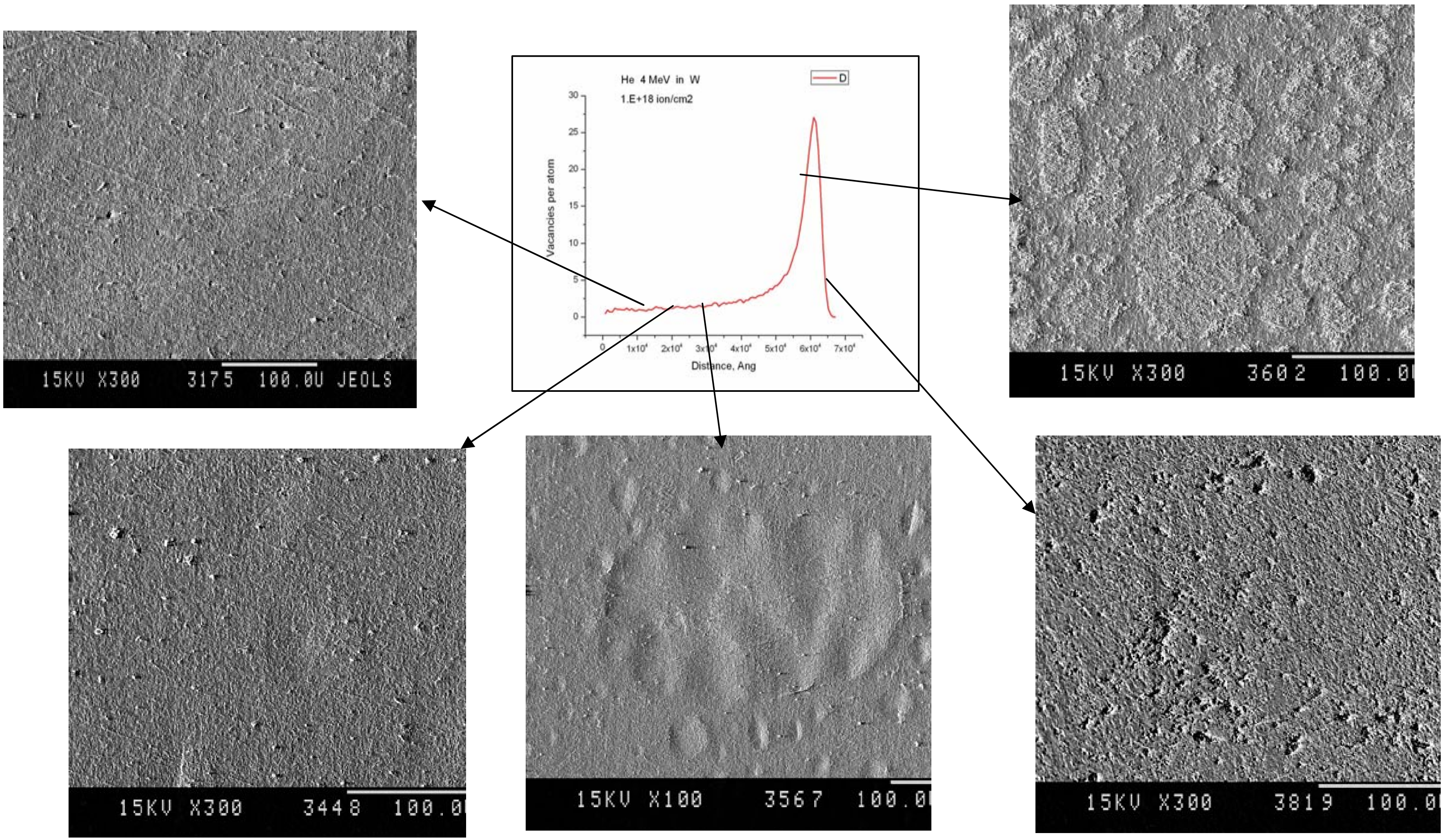






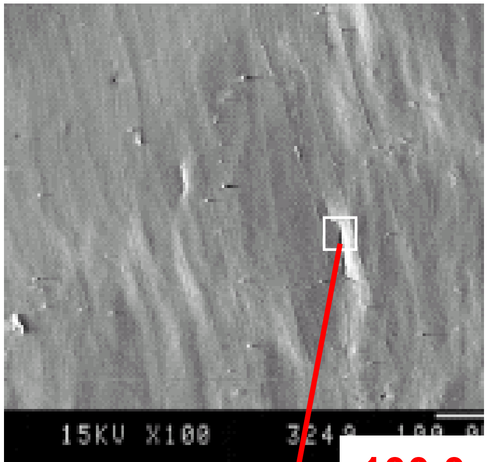
- Developed structure after erosion to end-of-range depth
- Stucture column elements Δh ~ 2 μm
- Коэффициент эрозии вольфрама в дейтериевой плазме Y = 3·10-3 at/ion

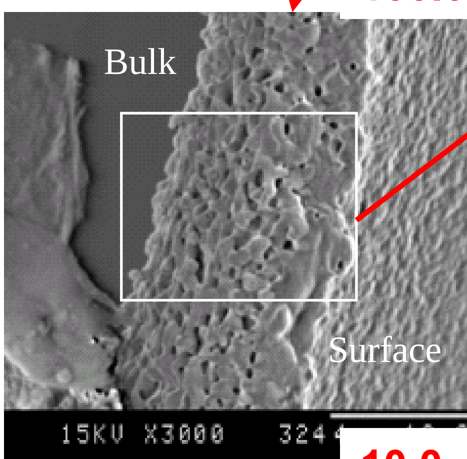
Erosion dynamics of irradiated tungsten in plasma

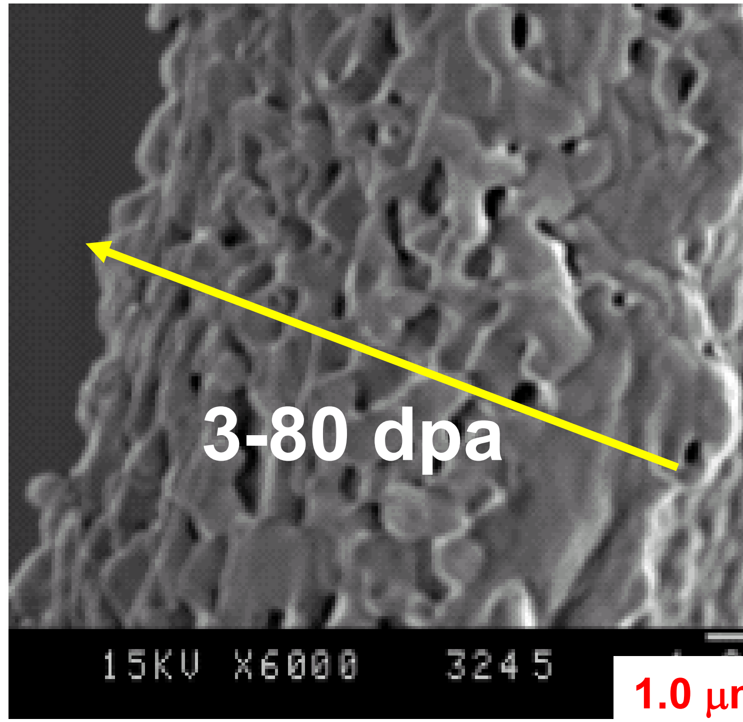


Irradiated tungsten microstructure

Structure of damage layer in a rupture $\Phi = 3x10^{18}\ He^{++}/cm^2$



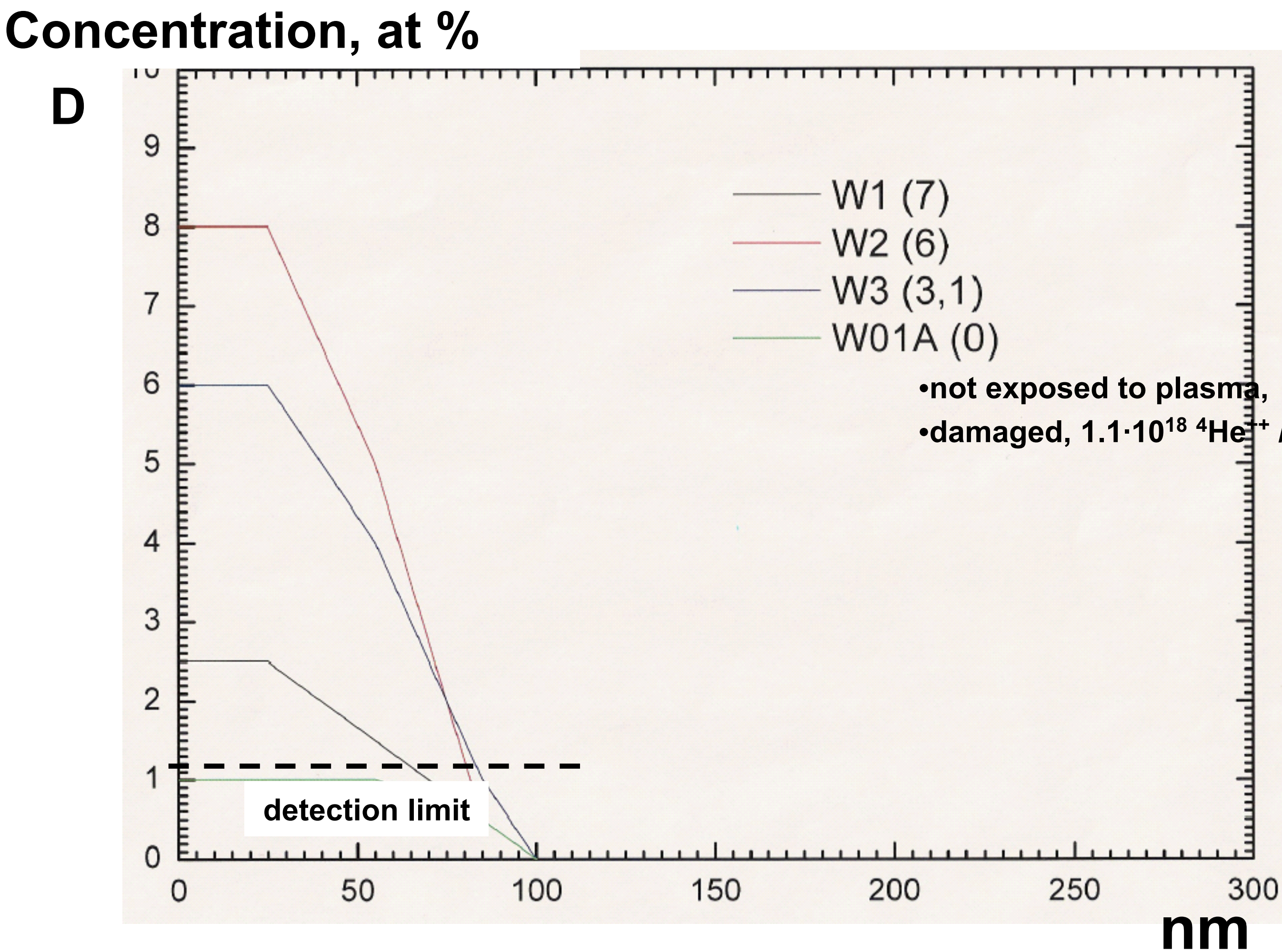




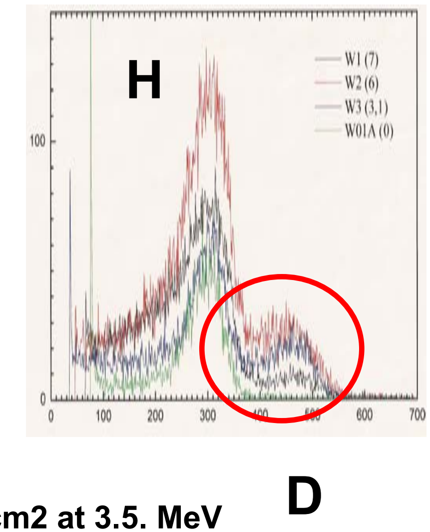
Pores, fractures, splitting

Swelling effect:
$\Delta h = 0{,}15 – 0{,}3\ \mu m$
Up to 5% in average over damaged layer

Deuterium depth profiles in tungsten

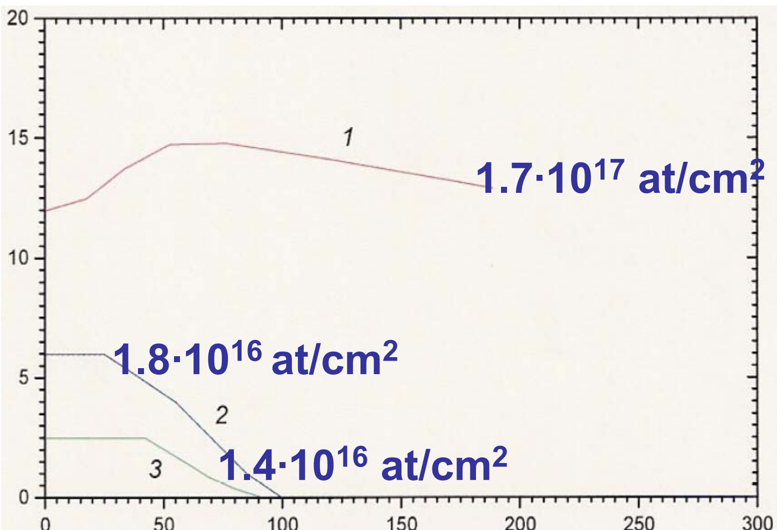


- not exposed to plasma,
- damaged, $1.1 \cdot 10^{18}$ $^{4}He^{++}$ /cm2 at 3.5. MeV



Deuterium depth profiles in plasma exposed tungsten

Concentration, at %

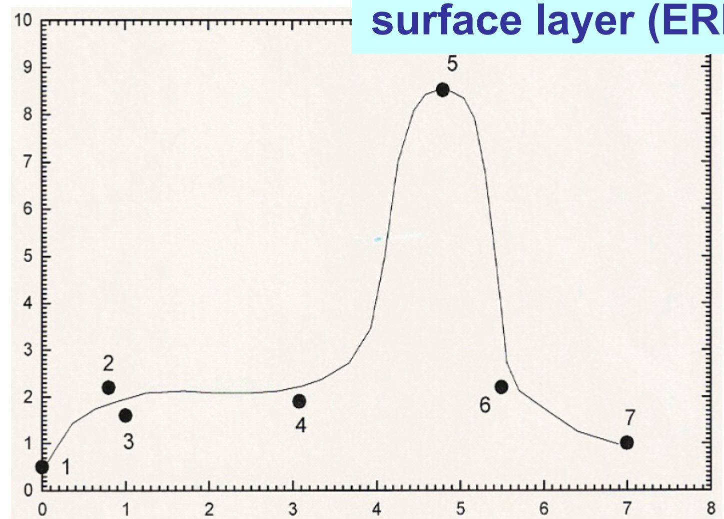


nm

1 – ~20 dpa (max 27 dpa), 1.3.10^{22} cm^{-2} D fluence
2 - ~3 dpa (max 80 dpa), 2.7.10^{21} cm^{-2} D fluence
3 – undamaged, 2.8.10^{21} cm^{-2} D fluence

D, 10^{16} at/cm^{-2}

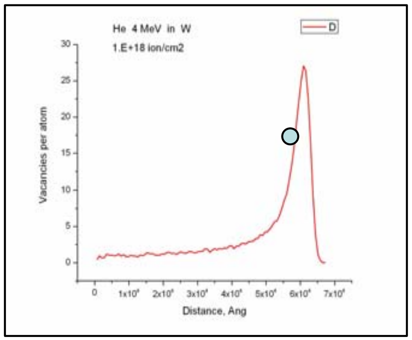
Areal density in 100 nm surface layer (ERDA)

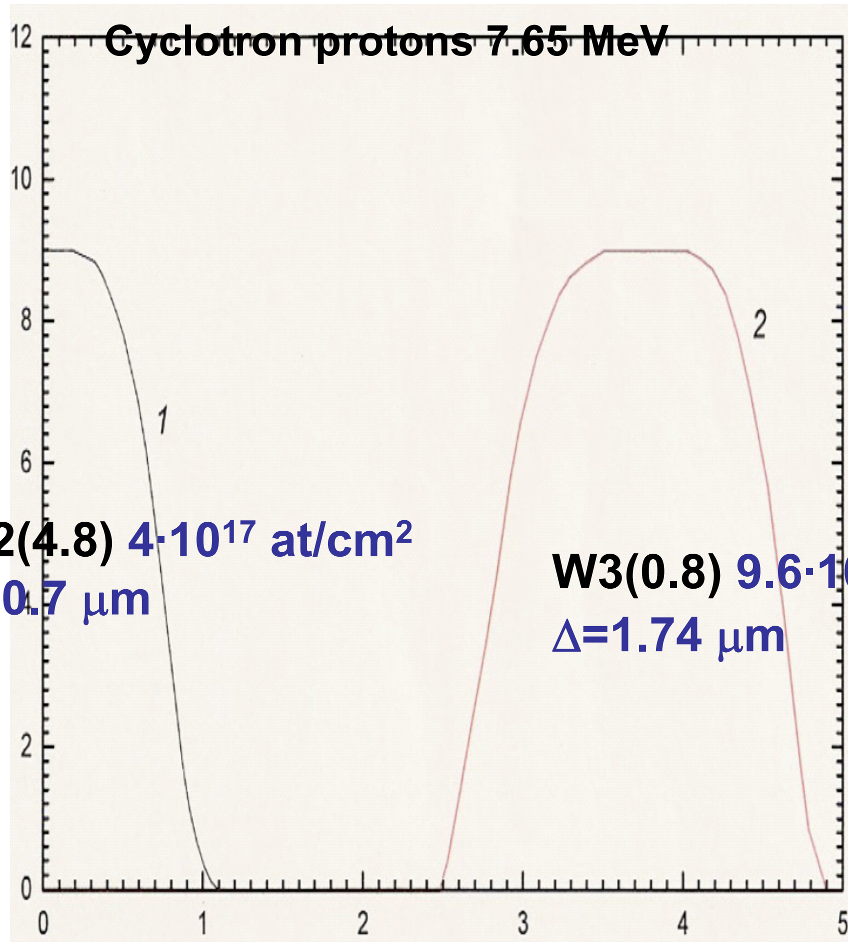


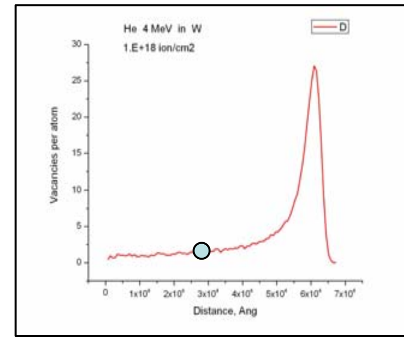
μm

- 1- not exposed to plasma, damaged, 1.1·1018 He++/cm2 at 3.5. MeV
- 2 - 3 dpa, plasma exposed
- 3 – undamaged, plasma exposed
- 4 – damaged, plasma exposed
- 5 – damaged, plasma exposed
- 6 – damaged, plasma exposed
- 7 – damaged, plasma exposed

Helium in irradiated tungsten

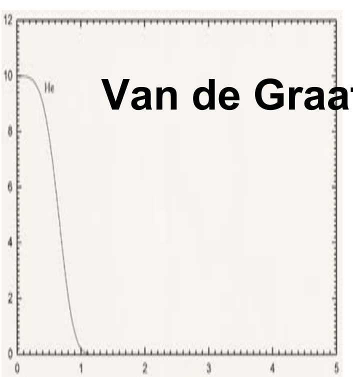






W2(4.8) $4 \cdot 10^{17}$ at/cm^2
Δ=0.7 μm

W3(0.8) $9.6 \cdot 10^{17}$ at/cm^2
Δ=1.74 μm



Helium is concentrated at the fast ion range region

W2(4.8) $^4He(p,p)^4He$ 2.4.MeV 4.1 10^{17}at/cm^2

Deuterium retention and helium in irradiated tungsten

Areal density of retained deuterium and implanted helium in tungsten for various damage levels and erosion depth

Elastic nuclear backscattering, α-particles. E=2.4 MeV						ERDA, α-particles E=1.9 MeV	
Sample Nr	4 MeV α-fluence, cm^{-2}	dpa, max	D-ion fluence, cm^{-2}	Erosion depth, μm	He, aт.%; at/cm^2	D, cm^{-2}	H, cm^{-2}
W-3	$3\cdot10^{18}$	81	$2{,}7\cdot10^{21}$	0,8	-	$2\cdot10^{16}$; $2{,}4\cdot10^{16}$	$1{,}6\cdot10^{17}$
W-2	$1\cdot10^{18}$	27	$1{,}3\cdot10^{22}$	4,9	10%; $4{,}1\cdot10^{17}$(0,7 μm wide)	$1.7\cdot10^{17}$	$7\cdot10^{16}$
W-1	0	0	$2{,}8\cdot10^{21}$	1,17	-	$1.6\cdot10^{16}$	$1.5\cdot10^{17}$

Increased retention in the damaged layer

Summary

- Fast ions from accelerator used to produce damage in plasma facing fusion materials to simulate neutron effect ($^{12}C^{+}$, $^{4}He^{++}$)
- Damaged materials response to plasma impact studied
- Radiation damage level relevant to a fusion reactor reached and 1-10 dpa carbon samples produced.
- 1- 80 dpa range of displacement damage covered on tungsten samples
- Erosion in deuterium plasma was studied in simulated tokamak SOL conditions on irradiated materials
- Displacement damage influence on the erosion found by analysis of deformation, surface modification and erosion data on carbon materials including SEP NB 31. Erosion tended to increase on the radiation-damaged carbon materials.
- Deuterium retention in tungsten analyzed in plasma-induced erosion condition at 250 eV of deuterium energy
- Deuterium found in the layer of 100 nm at the levels of damage of several dpa.
- Important increase of deuterium retention to 10% at. observed in the depth of fast ion end-of range at peak damage in extended depth more than 200 nm where helium is accumulated.
- Helium accumulation observed at this depth was 10% at. about 2 μm wide
- Important swelling observed on carbons. Tungsten showed linear deformation at 1 – 5 %.