Max-Planck-Institut für Plasmaphysik

Studies of Nanostructures Formed in T-10 Tokamak Using Synchrotron Radiation and Neutrons

V.G. Stankevich, N.Yu. Svechnikov, B.N. Kolbasov, A.M. Lebedev, K.A. Menshikov, L.P. Sukhanov, V.A. Somenkov, A.A. Veligzhanin, Y.V. Zubavichus

National Research Center Kurchatov Institute, Moscow 123182, Russia

Introduction

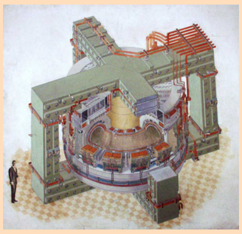
Smooth homogenous hydrocarbon films, or "flakes" (with atomic ratio D/C ≈0.5–0.8, H/C ~0.2, thickness ~30 µm), redeposited under fluctuations of the edge plasma in tokamaks onto the vessel wall regions far from graphite plasma facing components, may accumulate much protium, deuterium and tritium.

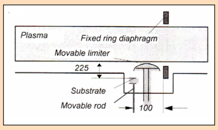
Our goals:
- ✓ Search for ways to decrease D-T accumulation rate inside the vacuum vessel
- ✓ Investigation of structure, electronic and vibrational states of Tokamak erosion products
- ✓ Determination of hydrogen-carbon bonding states for hydrogen isotopes, their thermal stability and accumulation in films

1. Conditions of films' formation

Tokamak T-10 (NRC Kurchatov Institute)

minor radius	0.39 m
major radius	1.5 m
minor radius of plasma	0.35 m
toroidal field	2.8 T
plasma current	200 - 400 kA
discharge time	1 s
electron temperature of core plasma	1 keV
ion temperature	450 - 700 eV





Movable limiter and stationary annular diaphragm, made of a fine grain graphite MPG-8.

The total duration of vacuum vessel conditioning modes and plasma discharges in a 2002 campaign:
- ♦ heating up to 200°C – 897 hours;
- ♦ inductive discharges – 35 hours H2 plus 270 hours 99% D2 + 1% H2;
- ♦ He glow discharges – 86 hours;
- ♦ D- plasma discharges – 1620 s.

2. Samples

Free standing films (flakes) collected in the shadowed areas far from limiter and diaphragm, room temperature.

H/C = 0.1 - 0.2

Thickness 20–30 µm, size S ≈0.5 cm^2

The flakes color strongly varies with D/C ratio: dark-brown D/C = 0.2 - 0.4
reddish-gold D/C = 0.5 - 0.8

Golden flake from a plasma facing side

3. Our previous research results [1,2]

✓ ***RFA analysis*** **(VEPP-3 synchrotron, BINP, Novosibirsk)**

12 microimpurities with concentrations of 50–7000 ppm and a total amount of 1.5%. Dominating impurity Fe = 0.7%.

Element	Ca	Ti	Cr	Mn	Fe	Ni	Cu	Zn	Br	Nb	Mo	Tl
ppm	190	80	2040	140	7000	1720	50	160	20	640	2800	300

They originate from erosion of vacuum chamber walls and chemical reactions in plasma.

✓ ***Luminescence and luminescence excitation*** **of flakes (Siberia-1 storage ring, NRC Kurchatov Institute, Moscow)**
- $E_g \approx 3$ eV
- A large Stokes shift (3.3–2.9=0.4 eV>>kT) → a possibility of nonradiative recombinations on defects inside the optical gap.
- FWHM of luminescence spectrum = 0.5 eV >> kT → strong electron-phonon interaction leading to e-hole localization.
- Excitonic-type photoluminescence due to C π-π^* transitions in the C*sp*^{2} nano-clusters serving as luminescence centers and luminescence quenchers
- the C2p π- and π+σ peaks are common for flakes and fullerenes, since both structures posses C=C aromatic rings

✓ ***Electron Paramagnetic Resonance***

There are defects with unpaired spins which refer to unpaired π- bonds in C*sp2*- nano-clusters with size ~ 4 nm and non-isotropic spin orientation.

✓ ***Thermo Desorption Spectroscopy***

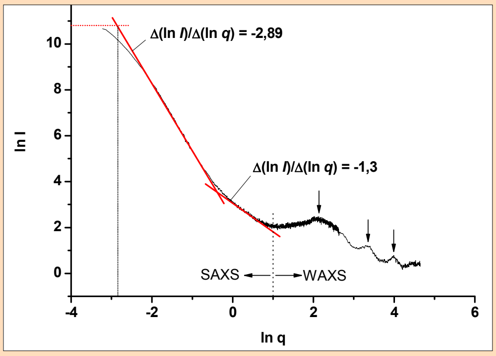
Temperature	450 – 600 K	900 – 1000 K
Adsorption state	Weak ("physisorption")	Strong (chemisorption)
Desorption mechanism	Hopping diffusion	Resonance type mechanism
Characteristic size	3.4 nm (hop)	0.14 nm (C-C distance)
Activation energy	≈ 0.65 eV/H (C-H distance 0.168 nm)	≈ 1.25 eV/H (C-H distance 0.14nm)

✓ ***Current-Voltage Characteristic and Fourier-Transform Infrared Spectroscopy***

There is strong difference between sides of flakes:

	CVC	FTIR
Plasma facing side	ohmic type, ρ ≈ 10^9 – 10^{10} Ω·cm	H, D with C*sp3*, more higher of OH, O concentrations
Wall facing side	semiconductor type, ρ ~ 10^5 – 10^6 Ω·cm	predominance of C*sp2* groups, more fragment structure (may be due metal impurities)

4. Synchrotron Small and Wide Angle X-ray Scattering (Siberia-2 storage ring, NRC Kurchatov Institute, Moscow)

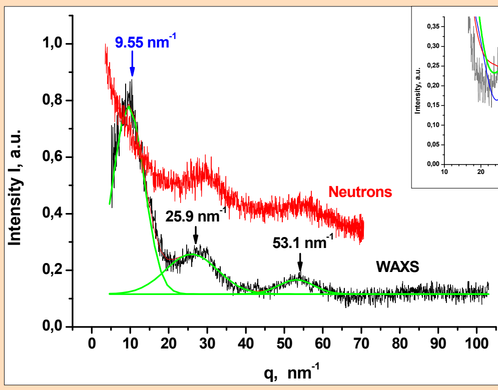


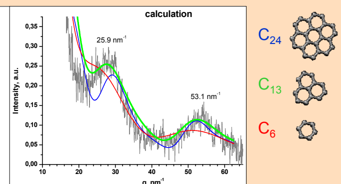
SAXS curve - no any features → multidispersion system with sizes from 1.5 to 80 nm.

Linear parts:
- slope -2.89 - indicate to fractal structure with fractal coefficient 2.89.
- slope -1.3 – very close to cylinder model of scattering center.

WAXS region: 3 peaks.

5. Comparison WAXS and Neutron diffraction (Siberia-2 storage ring and IR-8 reactor, NRC Kurchatov Institute, Moscow)





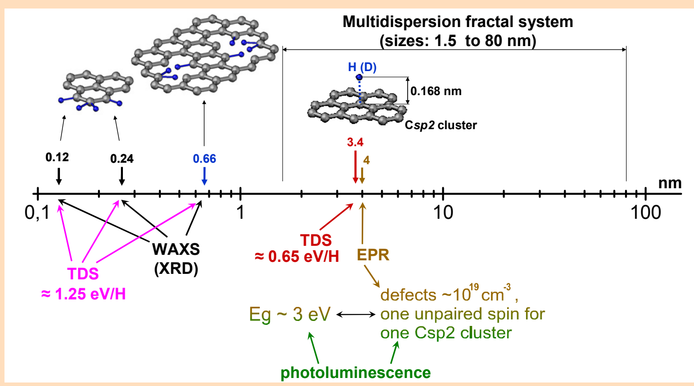
WAXS peaks - average interplane distance between clusters and nanopores d = 2π/q :

q, nm^{-1}	53.1	25.9	9.55
d, nm	0.12	0.24	0.66

Distances 0.12 and 0.24 nm are corresponded to small (several hexagons) fragments of graphene layres.

Main difference - absence of 9.55 nm^{-1} peak for neutron diffraction → due to low C-D contrast for neutrons (coherent scattering cross section σ_D =5.59 barn, σ_C = 5.51 barn), so 0.66 nm – distance between nanopores filled with D.

6. Summary: our present conception of flakes structure in nm scale



[1] N.Yu. Svechnikov, V.G. Stankevich, et al. J. Surf. Invest., 3 (3) 420 (2009).
[2] N.Yu. Svechnikov, V.G. Stankevich, et al. Plasma Dev. Oper. 14 (2), 137 (2006).