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Retention and permeation of hydrogen isotopes through RAFM RUSFER-EK-181

Motivation: Hybrid reactor project in Russia

Strategy 2013 for Fusion-Fission development in Russia

DEMO-FNS(fusion neutron source)
- the key facility in the hybrid branch of the Russian fusion program
- construction planned by 2023

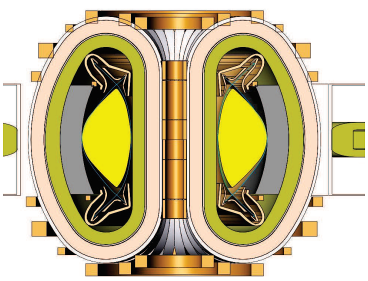
PHP (Pilot Hybrid Plant)
- construction is planned by 2030

Demonstration

DEMO-FNS
- Tritium breeding
- Minor actinides (MA) incineration
- Fissile nuclide production
- Destruction of long life radionuclides
- Heat transfer

PHP
- Tritium breeding and production
- Destruction of MA and long life radio-nuclides
- Electric power production
- Fissile nuclides production

Motivation: Fusion Neutron Source project in Russia



JET – size tokomak

Parameter	DEMO-FNS
R, m	2.5-2.7
R/a	2.5-2.7
Ip, MA	5
B_T, T	5
N, 10^{20} m^{-3}	1
E_b, keV	500
P_b, MW	30
P_F, MW	20-40
S_{wall}, m^2	162-188
V_{pl}, m^3	103-113
Pn/S, MW/m^2	0.2

FNS current status

- This project is realized in collaboration of Kurchatov institute with public corporations NIIEFA, NIKIET, VNIPIET, VNIINM, SPb Polytechnic University and Controlled Fusion Center
- The current level of the design corresponds to conceptual one. The engineering design stage will be completed in 2015
- We have started manufacturing of mockups for VV, divertor

Requirements for materials for fusion reactors and fusion neutron sources:

- Stable properties at fast neutron irradiation
  - DEMO 8-10 MW year/m^2 70 - 80 dpa
  - FNS & FPP 10-15 MW year/m^2 150 - 200 dpa.
- Fast decay of radioactivity
- Small neutron capture cross-section (for fusion neutron source)
- Small n-irradiation influence on properties
- High thermal conductivity
- Low permeation for hydrogen isotopes
- Low hydrogen retention

ITER to DEMO & FPP -

widening of temperature, mechanical and neutron irradiation dose application windows

New structural materials are required

Motivation: Fusion Neutron Source project in Russia

For **FNS** (fusion neutron source) and **PHP** (Pilot Hybrid Plant) construction

native materials are supposed to be used

For **FNS** steel is a wall materials, but in any case retention and permeation of hydrogen through steel are very important topics of investigation

Rusfer (EK-181, Fe-12Cr-2W-V-Ta-B-C)

Manufacturer - A.A. Bochvar High-technology Research Institute of Inorganic Materials (VNIINM), Russia
Composition – Fe-12Cr-2W-V-Ta-B-C.
Available: Almost Industrial: ingots up to 500 kg, rolled sheets, tubes,
Temperature window: (300)350-670(700-750) ^{0}C.
Advantages & disadvantages

+
- reduced activation
- no swelling (<100 dpa)
- ductile
- industry fabrication

-
- low heat resistance
- no high n dose tests (>100 dpa),

Rusfer properties will be investigated in frame of Russian fission programs *(incl. tests in FBR)*

Some additional tests are necessary for fusion application:
- Hydrogen retention
- Gas and plasma-driven permeation of hydrogen
- Influence of fusion neutron spectra on RAFMs properties

γ-phase stab., Impr. Long-term creep
Martencite formation
Strong carbide former, HT strength
γ-phase stab., Ni repl., ↓ crit. cooling rate for martecite formation
Corrosion resistance
Grain refinement, red. ↓-phase
Strong carbide former, stab. γ-phase, Mo replacement

		Ni	C	N	Si	Ti	V	Cr	Mn	Fe	Zr	Ce	Ta	W
ferritic-martensitic	Rusfer (EK-181)	0.03	0.16	0.07	0.4	0.05	0.4	**12**	0.6	BASIS	0.05	0.05	0.15	1.3
	EUROFER		0.1	0.015-0.045			0.15-0.25	**9.2**	0.2-0.6				0.05-0.09	1-1.2
Austenitic	ChS-68	14.0-15.5	0.05-0.08	<0.02	0.3-0.6	0.2-0.5	0.1-0.3	**15,5-17**	1.3-2.0					
	SS316 L(N)-IG	12	0.015	0.06	0.5	0.15		**17**	1.6				0,01	

Institutions involved in our research

NRC 'Kurchatov Institute', Moscow, Russia
- coordination
- exposure in gas and plasma
- permeation experiments

TRINITI, Troitsk, Russia
- exposure to high heat fluxes
- exposure to high density plasma

A.A. Bochvar Institute of Inorganic Materials, Moscow, Russia
- producing RUSFER
- testing physical & mechanical properties

National Research Nuclear University "MEPhI", Moscow, Russia
- retention analysis

Max-Planck-Institut fuer Plasmaphysik, Garching, Germany
- retention analysis

Persons involved in our research

N.P. Bobyr, D.I. Cherkez, A.V. Golubeva, B.I. Khripunov, V.B. Petrov, A.V. Spitsyn,

N.S. Klimov, A. Putrik

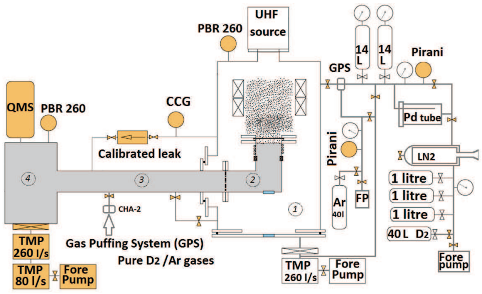
V.M. Chernov, M.V. Leontieva-Smirnova

Yu. M. Gasparyan, V.S. Efimov

M. Mayer, V.Kh. Alimov, O.V. Ogorodnikova

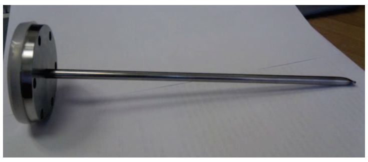
FACILITIES

Deuterium permeation: PIM, Kurchatov institute



Membrane temperature: RT – 1000 K
Gas pressure (D_2 or Ar) $5\cdot10^{-5} \div 1\cdot10^{-3}$ mbar
Plasma composition: ions: 71% (D_3^+:D_2^+:D^+ → 7:2:1) neutrals: 29% D_1^0
Ions accelerating potential: up to -300 V
Plasma density: up to $6\cdot10^{10}$ cm^{-3}
Plasma current on sample: up to 20 $A\cdot m^{-2}$

Investigated samples



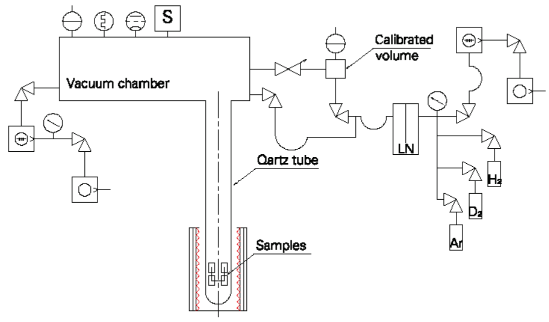
- **Rusfer EK-181**
- **ChS-68**

Tubes

(L=250 mm; d1= 5,85 mm; d2 = 6.95mm;)

Heating - Ohmic

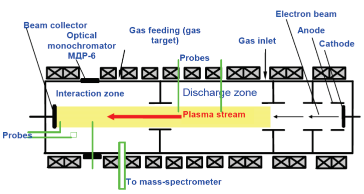
Gas loading: ATLAN, Kurchatov institute



Gas: H_2, D_2, CO, N_2, Ar
Gas pressure: 10^{-4} -10^{4} Pa
Temperature: 290 – 1023 K

LENTA *(linear plasma simulator for high flux plasma irradiation)*, Kurchatov institute

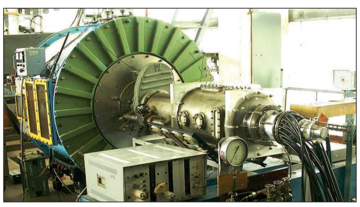
Steady-state plasmas are used to study plasma-surface interactions, divertor physics and test candidate plasma facing materials for fusion application



Electron beam is used to generate plasma in crossed E ⊥ B fields

Axial magnetic field 0,2 T
Injector power 15 kW
Plasma density $10^{11} \div 5\times10^{13}$ cm^{-3}
Electron temperature 0.5÷30 eV
Plasma flux $10^{17} \div 10^{19}$ ion/c × cm^{-2}
Plasma fluence 10^{24} ion/cm^2
Ion energy 10 ÷ 500 eV
Sample temperature RT ÷ 1800 K

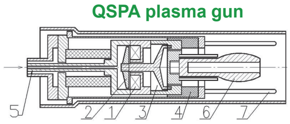
QSPA *(Quasistationary plasma accelerator)*, TRINITI



QSPA plasma parameters (ELMs):

- Heat load 0.5 ÷ 5 MJ/m^2
- Pulse duration 0.1 ÷ 0.6 ms
- Plasma stream diameter 6 cm
- Ion impact energy 0.1 ÷ 1.0 keV
- Electron temperature < 10 eV
- Plasma density $10^{22} \div 10^{23}$ m^{-3}

QSPA plasma gun



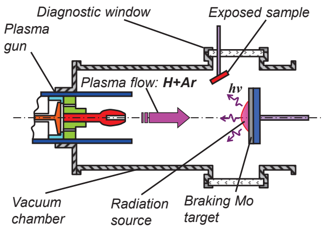
1 – coil of pulse electromagnetic gas valve;
2 – valve disk; 3 – volume of pulse valve;
4 – isolator; 5 – gas supply tube;
6 – cathode; 7 – anode.

QSPA facility provides adequate pulse durations and energy densities. It is applied for erosion measurement in conditions relevant to ITER ELMs and disruptions

QSPA-T heat loads

We used 5, 10 or 50 pulses of
0.5 MJ/m^2 with a duration of 0.5 ms)

In a fusion reactor SS are shielded. Direct contact of plasma with SS is excluded. But the photon flash heating provoked by the mitigation of disruptions at high stored energy can cause repetitive melting of it surfaces.



A. Spitsyn

NRA, IPP Garhing

Tandem accelerator of E2M division

Collaboration in a frame of HGF-RFBR joint research

D+ ^{3}He → p+^{4}He.

D depth-profile up to 14 μm

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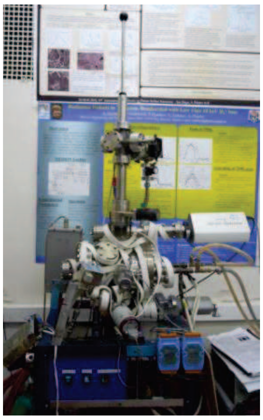
TDS stand, MEPhI

Parameters:

- **Sample temperature** RT ÷ 1700 K
- **Calibration** precision leaks with Baratron
- **Mass spectrometer** Pfeiffer Vacuum Prisma QMS200M1
- **Vacuum pump** Oil-free



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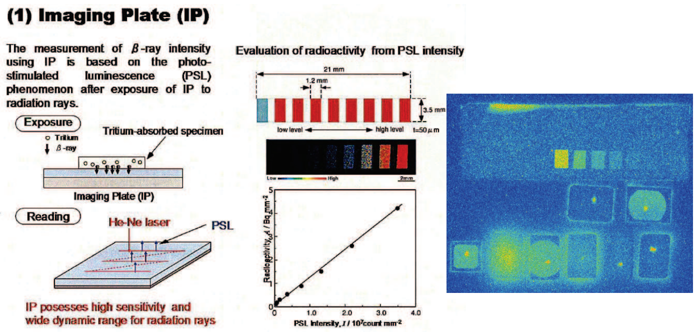
β-ray induced x-ray spectrometry

UNIVERSITY OF TOYAMA
Dr. Yu. Hatano



The method is applicable to the preliminary analysis of tritium trapping in the surface layer. For further investigations more accurate methods can be used

Hydrogen isotopes interaction with RUSFER – What is already done by our group

- **Deuterium retention (from gas and from plasma)**
- **Deuterium retention in damaged material**
- **Deuterium permeation**

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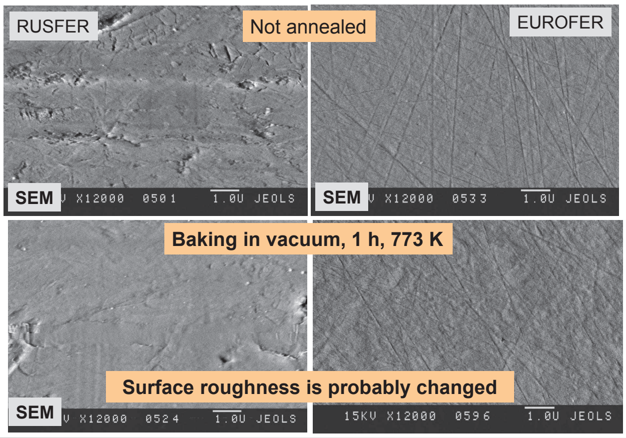
Structure changes of materials at annealing



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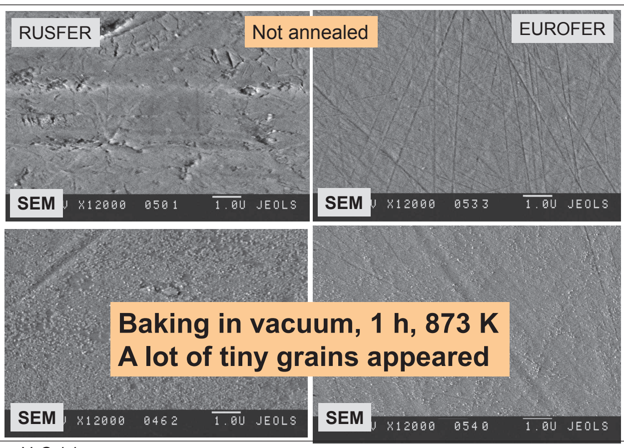
Structure changes of materials at annealing



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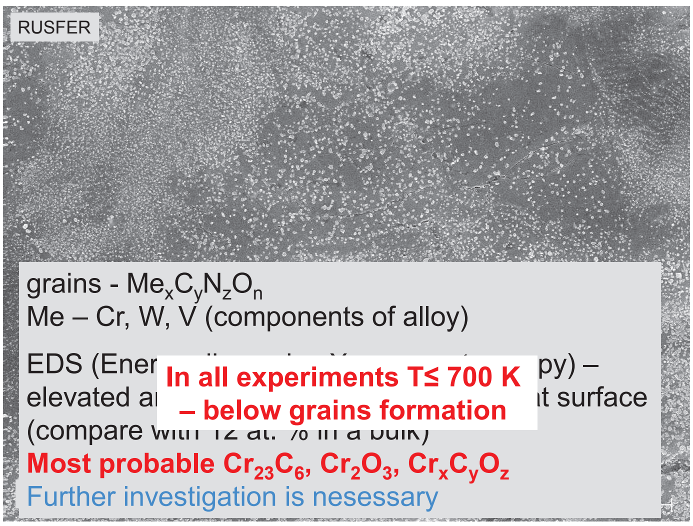


grains - Me$_x$C$_y$N$_z$O$_n$
Me – Cr, W, V (components of alloy)

EDS (Ener... py) – elevated a... at surface (compare with 12 at. % in a bulk)

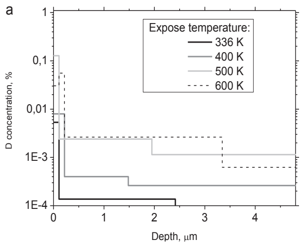
In all experiments T≤ 700 K – below grains formation

Most probable Cr$_{23}$C$_6$, Cr$_2$O$_3$, Cr$_x$C$_y$O$_z$

Further investigation is nessesary

Deuterium retention in RUSFER from gas

Gas loading:
D_2,
10 or 10^4 Pa
1-16 h
RT-600 K



Main peculiarities:

- Concentration of D in RAFMs is relatively low (10^{-3}-10^{-2} at%)
- Deuterium retention is attributed to trapping in the very near-surface layer (~0.2 mkm);
-The dependence of D retention on gas pressure is very weak (at T=693 K the difference between the amount of deuterium retained at P=10 Pa and at P=10^4 Pa is only by about a factor of 2).

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Deuterium retention in RUSFER at plasma irradiation

Plasma-irradiation	
Temperature	RT – 700 K
Gas pressure (D_2)	$5 \cdot 10^{-4}$ mbar
Plasma composition	D_3^+ - 70%, D_2^+ - 20%, D^+ - 10%
Accelerating potential:	- 300 V
Plasma flux	6×10^{19} at/s×m²
Plasma fluence	$10^{23} \div 10^{25}$ D/m²

Plasma-irradiation
- Constant cleaning of surface layer
- Elevated concentrations in near-surface layer
- Defect arise in near-surface layer

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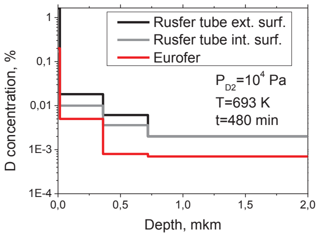
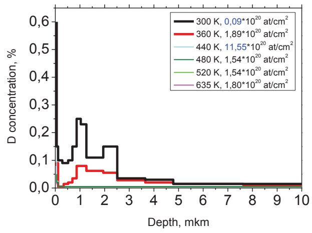
NRA (Depth profiles)

IPP
Garhing

Gas exposure



Plasma irradiation



Much higher concentrations under surface can be achieved as compared with gas exposure

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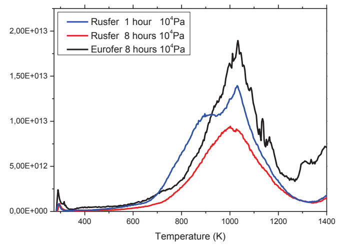
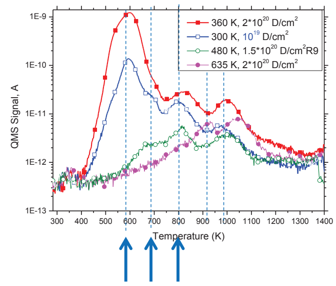
TDS (total retention)

At exposure in D_2 gas (10^4 Pa, 693 K)



At plasma irradiation



trapping sites create by plasma irradiation

! Y - Logarifmic scale

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Deuterium retention in damaged RUSFER

1. Damage:

- 20 MeV W^{6+} ions (0.94 dpa) – modeling of neutrons damage – IPP
- Plasma $5 \cdot 10^{21}$ H/s·m², 10^{25} H/m² - LENTA – Kurchatov institute
- Heat load (10 pulses of 0.5 MJ/m², 0.5ms) - QSPA TRINITI

2. Gas loading

Atlan (10^4 Pa, 8 h, RT-600 K) – Kurchatov institute

3. Retention analysis

- NRA D(³He, p)α – IPP

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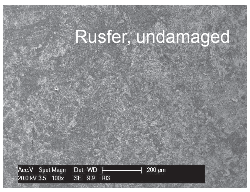
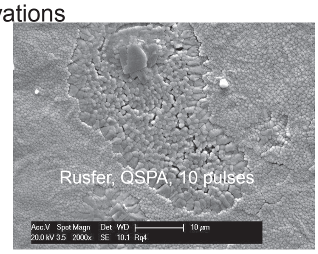
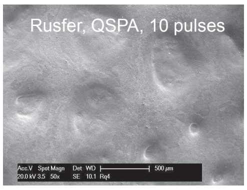
Rusfer Damaged by QSPA-T heat loads

5, 10 or 50 pulses of 0.5 MJ/m² with a duration of 0.5 ms)



SEM observations

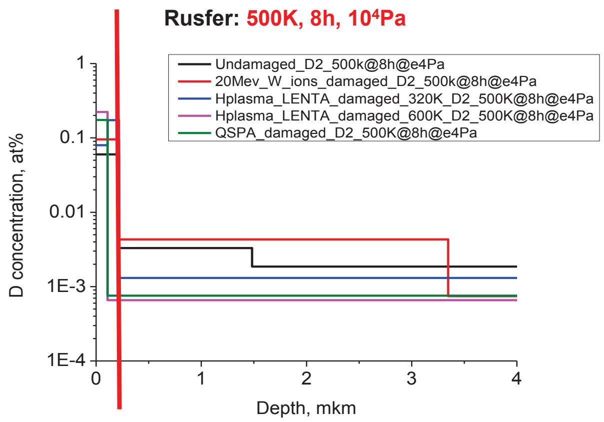




resolidified (recrystallized) layer and cracks are present

A. Spitsyn

Deuterium retention in damaged RUSFER



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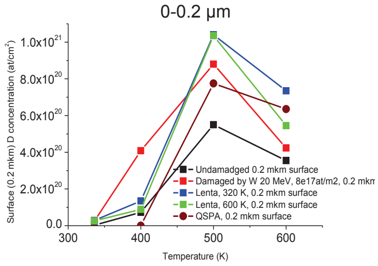
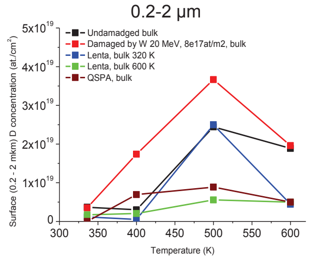
Deuterium retention in damaged RUSFER





- The maximum D retention in all samples were observed after expose to D_2 at 500 K
- D mainly trapped in near-surface layer (~0.2 mkm)
- **D concentrations of deuterium trapped in damaged samples are close to those in undamaged samples**

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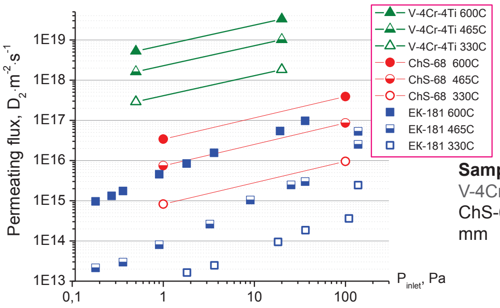
Deuterium permeation



Sample thickness:
V-4Cr-4Ti – 0.1 mm
ChS-68 & RUSFER – 0.55 mm

Tritium leakages for DEMO & FNS [grams/year]:

	S, m²	d, mm	p, Pa
DEMO	1200	10	10
FNS	100	3	

DEMO	T=330C	T=465C	T=600C
V-4Ti-4Cr	2431	13507	44162
ChS-68	29	261	1189
EK-181	1	10	311

FNS	T=330C	T=465C	T=600C
V-4Ti-4Cr	675	3752	12267
ChS-68	8	72	330
EK-181	0,1	3	86

Topics of research of hydrogen interaction with RAFMs in general

- Hydrogen isotopes permeation and retention in RAFMs

influence of neutron effects: high-dpa damage
elements transmutation
He and H formation
helium bubbles formation

With use of both experimental and computation modeling of hydrogen isotopes interaction with materials

- Influence of neutron effects on mechanical properties and thermal conductivity of RAFMs.

Our plans

- Deuterium gas-driven permeation through RUSFER after high heat flux irradiation
- Influence of He production in material on hydrogen isotopes retention

Thank you for your attention!