Survey of Plasma-Material Interaction and Atomic Data Studies for Fusion in Russia

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Decennial IAEA Technical Meeting on Atomic, Molecular and Plasma Material Interaction Data for Fusion Science and Technology,
Daejeon, Republic of Korea, 15-19 December 2014

OUTLINE

1. Introduction

2. PMI data generation for plasma facing components in fusion reactors, data use and needs

3. A+M data generation for integrated modeling of fusion experiments (transport, radiation losses, spectroscopic diagnostics)

4. Application of A+M databases and kinetic codes to fusion plasmas (data use and data needs)

5. Conclusion remarks

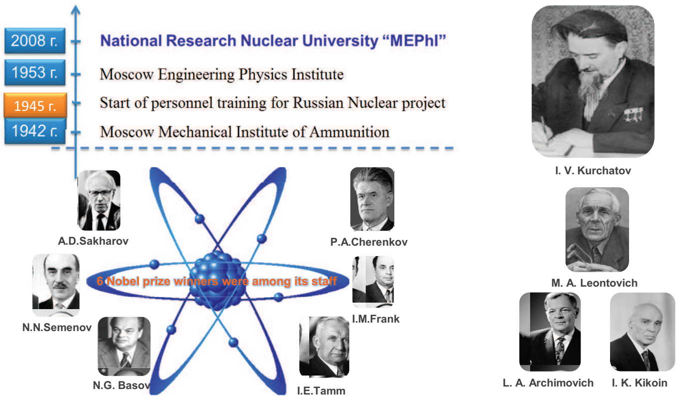
Introduction

My task is
- to take a look at the PMI and A+M data generation battlefield in Russia and main fighters on it.

- to give a brief survey of our experimental and mental possibilities to contribute more effectively to worldwide activity and broaden collaboration in this field.

Listing of studies selectively illustrated with some examples, for a detailed explanation of which, unfortunately, the talk has no enough time.

MEPhI history



MEPhI in Leading International and National University Rankings

Rankings	2012	2013	2014
Times Higher Education (Overscore)	226 - 250		
Times Higher Education (Physical Sciences)		74	
QS. BRICS		65	57
QS (Physics & Astronomy)			251 - 300
Scimago Institutions Rankings (among Russian Universities)	6	5	
National rating of «Interfax» & «Echo of Moscow» agencies	5-6	3	3
Russian rating of «Expert RA» group of rating agencies	7	5	4
Russian rating of «Expert RA» group of rating agencies (among CIS Universities)			group B*
National rating of «National Training Foundation»	1		
Webometrics (among Russian Universities)		3	6
RUR (among Russian Universities)		3	

Rankings 2014

Interfax		Expert RA	
MSU	1	MSU	1
SPSU	2	MIPT	2
MEPhI	3	MSTU	3
MIPT	4	MEPhI	4
PFUR	5-6	SPSU	5
NSU	5-6	HSE	6

** among CIS universities in group A only MSU is included*

- Plasma Physics Department was organized in 1961 by leading scientists of Kurchatov Institute in hot plasma physics.

- We started PMI research 50 years ago due to the help of Kurchatov institution. Now we have powerful experimental base and 4 scientific groups jointed in one of the Leading Russian Scientific Schools in Physics. In total we have ~30 academic stuff and engineers and ~15 PhD students in this field and collaborate closely with Kurchatov Institute, TRINITI and other Russian foreign institutions

2. Plasma-material interaction (PMI) data generation for plasma facing components in fusion reactors + data use and needs

PMI data generation and use

Processes	Method	Data Source \Code	Publication	Verification / Application	Problem
Atoms diffusion on the surface and nanostructure growth	Analytic model and numeric code		Plasma Phys. Rep., 2012, 38, 996-999	Compared with liner divertor simulators experiment (Nucl. Fusion, 2009, 49 095005)	Fuzz formation on a tungsten surface
Stress in films and particle on the surface	Analytic model		Plasma Physics Reports, 2012, 38, 290–294.	Tokamak T-10 dust data	Mobilization of dust and exfoliation of erosion product films in tokamaks
Tungsten recrystallization and cracking under ITER-relevant heat loads	Analytic model		http://vant.iterru.ru/vant_2013_3/3.pdf	Tungsten irradiation by plasma from QSPA-T plasma gun	Test of tungsten for ITER

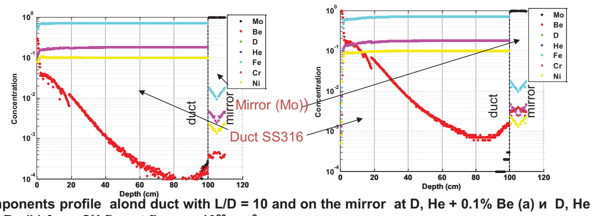
Yu.V. Martynenko et al. (NRC "Kurchatov Institute")

Computer simulation of erosion and deposition

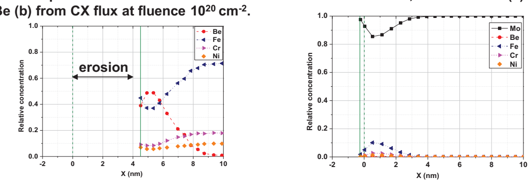
Processes	Method	Data Source \Code	Publication	Verification / Application	Problem
Erosion and deposition of Be PFC under plasma and CX impact	3D Monte Carlo code	SCATTER	J.Nucl.Mater. 2011,415, 1, S1119-S1122	Compared with experiment and TRIM simulations	Tritium accumulation in deposited Be layer , erosion and redeposition in FW cracks and dips
Redeposition of materials in diagnostics ducts of ITER	3D Monte Carlo code	SCATTER	J.Nucl.Mater. 2013,438, 1, S731-S734	Compared with experiment and TRIM simulations	Evaluation of ITER diagnostic mirros erosion and deposition of impurities

D.Kodut, V.Kurnaev, N.Trifonov (MePhI)

Degradation of diagnostic mirror in ITER



Components profile along duct with L/D = 10 and on the mirror at D, He + 0.1% Be (a) и D, He +1% Be (b) from CX flux at fluence 10^{20} cm^{-2}.



Depth distribution at the Mo mirror.

D.K. Kogut, N.N. Trifonov, V.A. Kurnaev.. J. Nucl. Mater., 438 (2013) S731–S734.

PMI data generation

Processes	Method	Data Source \ Code	Publication	Verification / Application	Problem
Fine structure of big carbon molecules (curved-graphene nanoparticles)	Modeling of geometry, electronic and mechanic properties with Density Functional Theory	L.A. Chernozatonskii, Phys. Lett. A 170 (1992) 37 J.D. Gale, A.L. Rohl, Mol. Simul., 29, 291 (2003).	Phys. B: Cond. Matter 2012, 407, 3467-3471	Characterization of big carbon molecules and their agglomerates in the hydrocarbon film deposits in tokamak T-10	Diagnostics of deposits (particles and films) in fusion facilities

PMI DATA USE

Problem	Task	Publication	Processes	Data Source	Data Needs
Diagnostics of deposits (particles and films) in fusion facilities	Characterization of big carbon molecules and their agglomerates in the hydrocarbon film deposits in tokamak T-10	Chem. Phys. Lett., 506, 2011, 265-268	X-ray diffraction by big carbon molecules (curved-graphene nanoparticles)	Phys. B: Cond. Matter 2012, 407, 3467-3471	Curved-graphene nanoparticles and their networks Tritium retention by these structures for fuel control in fusion experiments

A.B. Kukushkin et al. (NRC "Kurchatov Institute")

Hydrogen retention and release (exp.)

Processes	Method	Data Source \Code	Publication	Verification / Application	Problem
D retention in radiation damaged by 20 MeV W	Thermal desorption spectroscopy		JNM, in press, doi:10.1016/j.jnucmat.2014.11.022 (Collaboration with IPP, Germany)	Calculations with TMAP7 and DIFTRAP code	Tritium retention in PFM
D interaction with single defects (heating rate variation technique)	Thermal desorption spectroscopy		Unpublished data	Calculations with TMAP7 and DIFTRAP code	Tritium retention in PFM
High temperature D release from Be	Thermal desorption spectroscopy		I. Kupriyanov et al. FUSION SCIENCE AND TECHNOLOGY, 2014, V.66, P.171		Tritium retention in PFM
Low temperature D release from Li in the presence of H_2O	Thermal desorption spectroscopy		S.A. Krat et al. Vacuum 105 (2014) 111-114		Tritium retention in PFM
D release from Steels with oxidized layers	Thermal desorption spectroscopy		Nuclear Instruments and Methods in Physics Research Section B: Vol . 315(2013), Pages 110–116		Tritium release from SS PFC in fusion devices

12

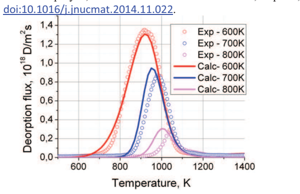
Radiation damage in W

Max-Planck-Institut für Plasmaphysik EURATOM Association

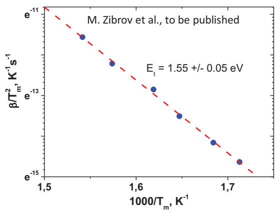
Self-ion damage by 20 MeV W ions (collaboration with IPP):

- ✓ Defects with detrapping energy of 1.7-2.0 eV play the major role at high temperatures.
- ✓ Remarkable retention even at 800 K
- ✓ Standard model does not describe all features of peaks

Yu.M. Gasparyan, et al. Journal of Nuclear Materials, in press, doi:10.1016/j.jnucmat.2014.11.022.



- **Basic experiments (to determine the binding energy with single defect of different types)**
  - ✓ MeV electron damage
  - ✓ Low fluence keV ion damage
  - ✓ Mechanical production of dislocations
- **Set of TDS with different heating rates** (Applicability for traps in the bulk has been demonstrated)



13

Deuterium retention in W with additives of TaC and TiC

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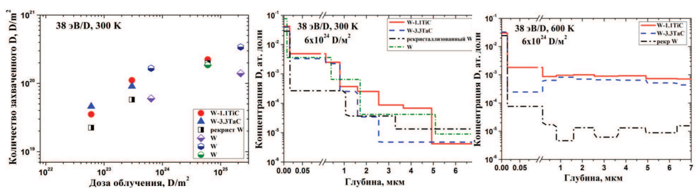
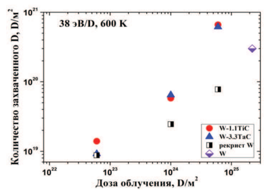
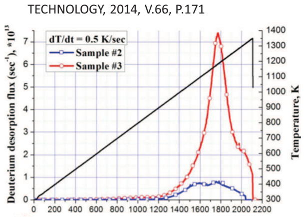


- At RT D retention in W+3.3TaC and W +1.1TiC comparable with retention in pure W.
- Irradiation at 600K and more with 6×10 [24] D/м² **retention in doped W much more and corresponds to the bulk material**



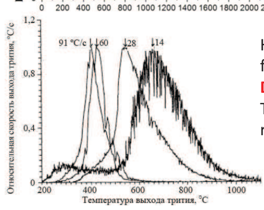
High temperature D release from Be

I. Kupriyanov et al. FUSION SCIENCE AND TECHNOLOGY, 2014, V.66, P.171



TDS data after QSPA plasma heat load (1 MJ/m² at 250μC, 10 shots):

- The main part of deuterium desorbed at high temperatures, in temperature range of **900–1350 K**;
- Some spectra have small peaks at lower temperatures with the maximum at 650–700 K;
- The total deuterium amount in the samples investigated varied from 3x10^{-6} to 6.3x10^{-5} (estimated as N_D/N_{Be})



High temperature tritium release from Be exposed to neutron flux.

Decrease of peak position with increase of the heating ramp

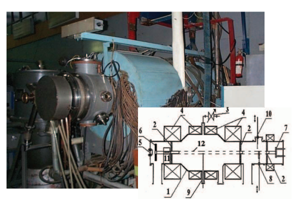
The reason can be cracking of the material at high heating ramps.

B.N. Kolbasov. Problems of Atomic Sci. and Techn., 2013, v. 36, is.4, p.3 (http://vant.iterru.ru/vant_2013_4/1.pdf)

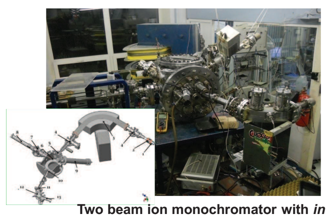
D.V. Andreev et al. : Fusion Engineering and Design 39–40 (1998) 465–475

15

Experimental base of MEPhI for PMI data generation



Linear plasma simulator W_{tot} ~50kW , q > 10MW/m² , B up to 1T, j ~1.0A/cm²



Two beam ion monochromator with *in situ* plasma deposition control with MEIS

The Stand for Coating Deposition and Material Testing (CODMATT) in ITER relevant conditions

Queasy-stationary ion/electron beam with power density ≤ 20 MW/m² Testing cycle frequency ≥ 1ms, T testing ≤ 2200°C

TDS analysis of Li films deposited by magnetron discharge

Deuterium in lithium films

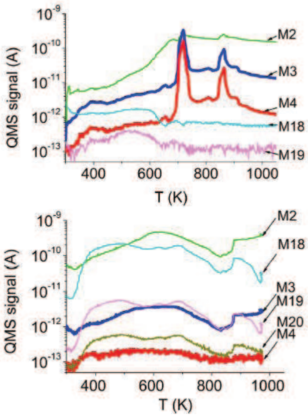
Liquid metals are perspective PFM!
There is a lack of PMI data.

Co-deposition of Li and D in magnetron discharge is investigated in MD-2 device (MEPhI) with in-situ thermal desorption spectroscopy

Main observations:

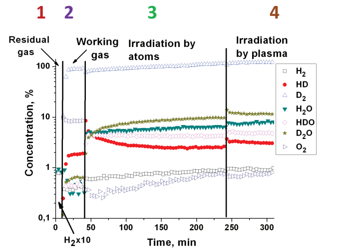
- ✓ Li films can accumulate high amount of D, up to tenths of atomic percent
- ✓ Main desorption in a very sharp peak ~700 K
- ✓ Intensive chemical reactions and deuterium release during interaction with air at RT. There was no deuterium in films after air exposure

S.A. Krat et al. Vacuum 105 (2014) 111-114.



17

Low T hydrogen isotopes release from SS and W coated by Al_2O_3 due to irradiation by ions in O contaminated hydrogen plasma



Irradiation of stainless steel wall of plasma chamber by D-atoms in the (D_2+ xO_2) gas mixture or by ions of (D_2+ xO_2) plasma ($0.5 \le x \le 30\% O_2$) leads to its outgasing at the room temperature. Dissolved hydrogen release appears to be 4-5 times higher than deuterium trapping.

Application. Low temperature outgassing, in particular, tritium release from stainless steel plasma facing and tritium contacting elements of fusion devices.

L. Begrambekov, A Ayrapetov, V Ermakov, A.Kaplevsky, Ya. Sadovskiy, P.Shigin. "Hydrogen and oxygen trapping and retention in stainless steel and graphite materials irradiated in plasma" Nuclear Instruments and Methods in Physics Research Section B: Vol . 315(2013), Pages 110–116

UCSD

Hydrogen retention (theory)

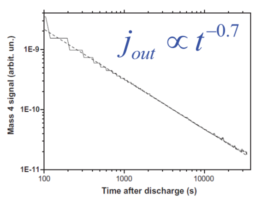
Processes	Method	Data Source \Code	Publication	Verification / Application	Problem
Hydrogen transport in media with a continuous distribution of traps over binding energy	Analytical		[S.I. Krasheninnikov, E.D. Marenkov. Physics Letters A, V. 378, I. 21, P. 1526–1530]	comprision with experiments TORe supra, Jet	Tritium retention in PFM , outgasing rate
H desorption from the first wall during ELMs	Analytical		[Marenkov, E. D.; Smirnov, R. D.; Krasheninnikov, S. I. Plasma physics reports. V. 39, I. 11, P. 867-872]		Tritium retention in PFM
Thermal instability caused by plasma-wall coupling	Analytical		[E. D. Marenkov, S. I. Krasheninnikov et al. Phys. Plasmas 18, 092502 (2011)]		

19

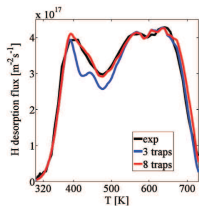
Hydrogen transport in media with a continuous distribution of traps over binding energy

$$\frac{\partial C_s}{\partial t} = D\frac{\partial^2 C_s}{\partial t^2} - \int \frac{\partial f}{\partial t} d\varepsilon$$
$$\frac{\partial f}{\partial t} = K_{tr} C_s (\phi - f) - K_d f$$
$$C_{tr} = \int f(\varepsilon, x, t) d\varepsilon$$
$$\bar{C}_{tr} = \int \phi(\varepsilon, x) d\varepsilon$$

Main equations



Outgasing of JET first wall



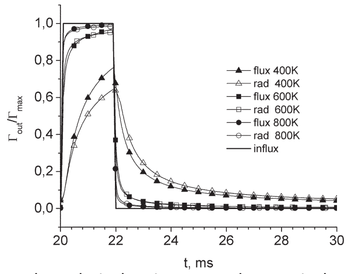
TDS of a W sample

- ✓ We have developed a model of hydrogen transport in media with continuous distribution of traps over binding energy
- ✓ This model is able to describe some experimental observations, such as "anomalous" time dependence of the outgassing flux from tokamak first wall, and broad thermodesorption spectra.

[S.I. Krasheninnikov, E.D. Marenkov. Physics Letters A, V. 378, I. 21, P. 1526–1530] (MEPhI)

UCSD

H desorption from the first wall during ELMs



$$\Omega = \bar{\Gamma}_{in} / \bar{N}$$

$$\Omega t_{burst} >> 1$$

quasi-steadystate regime

$$\Omega t_{burst} << 1$$

sufficient roll of the wall

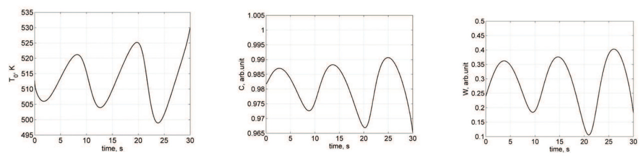
Both analytical estimates and numerical calculations in FACE code have shown that H outgassing from PFMC can play a significant role in pedestal restoration after ELM crush. However, the effect is pronounced only at low enough temperature of the first wall.

[Marenkov, E. D.; Smirnov, R. D.; Krasheninnikov, S. I. Plasma physics reports. V. 39, I. 11, P. 867-872] (MEPhI, UCSD)

UCSD

Thermal instability caused by plasma-wall coupling

Initial increase in the surface temperature of the wall *T* results in a strong increase in the hydrogen desorption rate *J* followed by an increase in heat flux *q* to the wall due to enhancement of charge exchange and radiation losses which prompt further increase in the wall temperature.



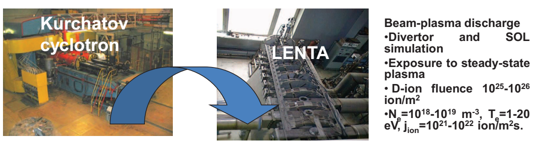
Several models of plasma-wall coupling were used to obtain instability region. In practice, it is possible for definite first wall temperature range, typically 400 -700 K.

[E. D. Marenkov, S. I. Krasheninnikov et al. Phys. Plasmas 18, 092502 (2011)]

Complex experiment – production of damaged materials and exposure in plasma

Ions H+, He+, Li+, C+ at 1-60 MeV.

Equivalent doses to 10^{26} n/m^2 effect for several days irradiation



Beam-plasma discharge
- Divertor and SOL simulation
- Exposure to steady-state plasma
- D-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.

Practically impossible to obtain data on materials behavior in neutron flux of ≥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**

B.I. Khripunov, V.S. Koidan, A.I. Ryazanov, O.K.Chugunov, V.M. Gureev, S.N. Kornienko, S.T.Latushkin, V.B. Petrov, E.V. Semenov, V.G. Stolyarova, V.N. Unezhev, L.S. Danelyan, V.S.Kulikauskas, V.V. Zatekin in
- 23rd IAEA Fusion Energy Conference (FEC-23), 11-18 October 2010, Daejeon, Republic of Korea, CD Rep. FTP/3-3Rb.
- Journal of Nuclear Materials 415 (2011) S649-S652.
- 10th International Workshop on Hydrogen Isotopes in Fusion Reactor Materials, Pleasanton, California, USA, 31 May - 1 June, 2010.
- Physica Scripta, T145 (2011) 014052 (4pp).
- Fusion Science and Technology, V.61, Nr. 2, FUSTE8 (2) 107-117 (2012).
- Journal of Surface Investigation. X-ray, Synchrotron and Neutron Techniques, 2013, Vol. 7, No. 2, pp. 362-365.
- Journal of Nuclear Materials 438 (2013) S1014-S1018.

National Research Center "Kurchatov Institute"

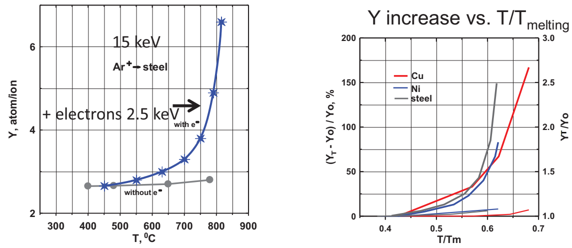
Results on tungsten shortly

- Fast ions from accelerator were used to **produce damage** in plasma facing fusion materials to simulate neutron effect ($^{12}C^{+++}$, $^{4}He^{++}$)
- Damaged materials response to plasma impact was studied.
- Radiation damage level relevant to a fusion reactor reached and **tungsten** samples produced. **1- 600** dpa range of displacement damage was covered
- **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 tungsten.
- **Deuterium retention** in tungsten is analyzed in plasma-induced erosion condition at 250 eV of deuterium energy
- **Deuterium** was found in the layer of **100-150 nm** for different levels of damage. Maximal deuterium concentration **10% at.** was found in **80 dpa** layer
- **Helium accumulation** was detected by nuclear reactions method at the depth of ion range at **8-10% at.**
- **Swelling effect** observed on tungsten with maximal damage. Tungsten showed linear deformation at **2-3 %.**
- Efficiency of the proposed method has been demonstrated. Its further progress appears promising for the research of plasma facing materials stability to combined impact of plasma and neutron fluxes.

New effects and observations

Ion sputtering of metals with simultaneous electron irradiation

Sputtering yield Y, steel Cr18Ni10Ti (components & total)



Parameters of experiment:

Ar^+ - ions energy - **15 keV**

Ion current density - **40-200μA/cm²**

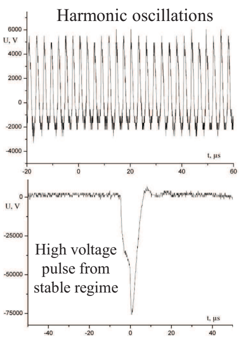
Electron energy - **2. 5keV**

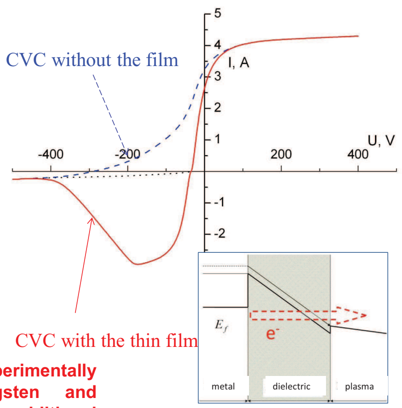
Electron current density ~ **150-1500 μA/cm²**

Yu.V. Martynenko, S.N. Korshunov, I.D. Skorlupkin. Proc. 21st Int. Conf. Ion-Surface Interactions, 22–26 August 2013, Yaroslavl, Russia

Similar evidence: erosion increases in plasma as compared with ion beam only (A. Kirschner, Ibid.) **Need to reassess sputtering under realistic plasma condition**

Unstable plasma-surface interaction





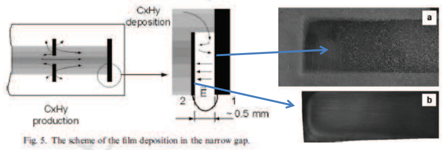
Instabilities were experimentally observed with both tungsten and aluminum electrodes can be additional source of oscillations at the presence of thin oxidized layers.

Fast electrons charges the surface, high electric field in the film, high electron emission

Films formation and cleaning

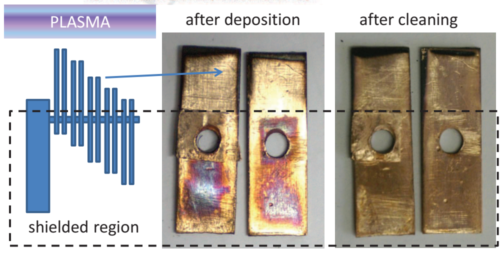
Deposition of C-H films in the gap at the beam collector surface

Al collector, discharge in H_2 with graphite diaphragm



Deposition of C-H films in gaps in open and shielded regions in RF field presence

Cleaning of C-H films in gaps in open and shielded regions in RF field presence in oxygen discharge



✓**The presence of RF fields promotes a C:H films deposition in gaps and shielded from plasma regions, but as well promotes the films cleaning in oxygen discharge**

✓**Experimentally achieved a 1.7 micron film cleaning during 2 hours**

PFM behavior under high heat plasma loads

PMI DATA GENERATION

Processes	Method	Data Source \Code	Publication	Verification / Application	Problem
PFCs erosion under transient plasma events	Experiments on the plasma guns		N. S. Klimov et al., Fusion Science and Technology, V. 66 (2014), #1, P. 118-124	Comparison with experiments on the electron beam facilities and with numerical models	Lifetime of the Be first wall. Lifetime of the divertor plates. Erosion mechanisms of the Be and W. Testing of the ITER PFCs. Eroded materials accumulation and dust formation.
Deposition of the erosion products under transient plasma events	Experiments on the plasma guns		A. B. Putrik et al., Fusion Science and Technology, V. 66 (2014), #1, P. 70-76.	Comparison with experiments on the magnetrons and with theoretical models	Dust problem. Hydrogen isotopes accumulation into deposited materials in ITER. First mirror contamination.

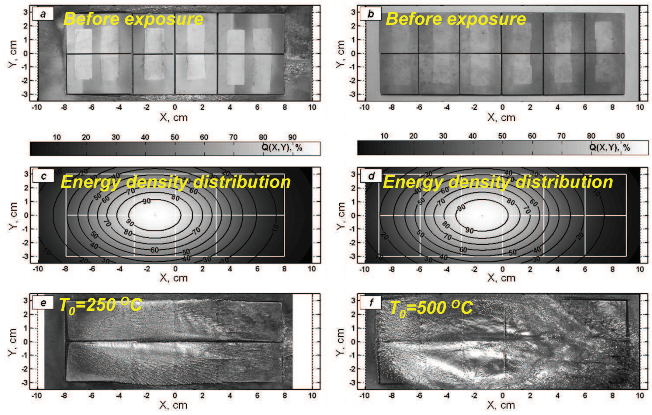
N. S. Klimov et al. (SRC RF TRINITI)

PMI DATA GENERATION

Processes	Method	Data Source \Code	Publication	Verification / Application	Problem
PFMs behaviour under ITER-relevant mitigated disruption photonic heat loads	Experiments on the plasma guns		N. S. Klimov et al., J. Nucl. Mater. 438 (2013) S241-S245 N. S. Klimov et al., Plasma facing materials performance under ITER-relevant mitigated disruption photonic heat loads, J. Nucl. Mater, In press	Comparison with experiments on the electron beam facilities and with numerical models	Lifetime of the Be first wall. Lifetime of the SS diagnostic first wall. Testing of the ITER PFCs. Tritium accumulation by irradiated materials. Detritization techniques.

N. S. Klimov et al. (SRC RF TRINITI)

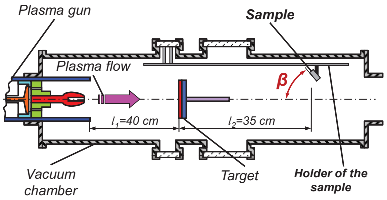
ELMs, disruptions. Exposed Be targets: TGP56-FW, q = 1.0 MJ/m², Δt=0.5 ms



The Be erosion rate significantly increases with initial temperature rising from 250 to 500 ° C. W melted layer behavior is practically independent from initial temperature in the present range (250 – 500 ° C) due to very high melt point (3410 ° C) in contrast to beryllium (1278 ° C). The experimental results indicate that more effective PFCs cooling may be needed in ITER to prevent melt layer movement and splashing.

Hydrogen isotopes retention in deposited erosion products.

The scheme of the experiment



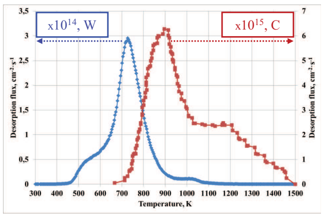
Conditions of the experiment

- Work gas: ***D_2***
- Materials of the targets: ***grafite, W***
- Heat load in the center of the target: ***3 MJ/m²***

Investigated dependences

1. Retention dependence *on the deposition rate:* **β = 0°, 20°, 45°, 90°** *(T = 300 °K)*
2. Retention dependence *on the substrate temperature T, °K*: **300, 450, 600, 750** *(β = 90°)*

Measured average deposition rate for C is 60 μm/s.
Measured average deposition rate for W is 3 μm/s.



Deuterium TDS spectra comparison between deposited C-H and W films

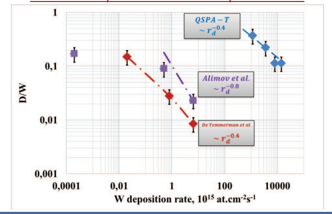
✓ Deuterium retention in W films is more than one order lower, than in C-H films obtained earlier at the QSPA-T [*1. N. Klimov et al. 13th PFMC Workshop / 1st FEMaS Conference, Rosenheim, 2011*]

✓ Retention per pulse at the QSPA-T
for W: **2.7·10¹⁴ at. D** **<<** *for C:* **5.2·10¹⁵ at.**

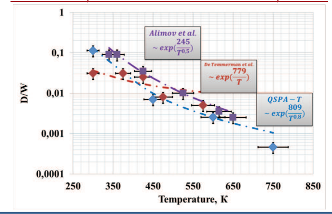
✓ Typical ratios (*T = 300 °K*)
D/W = 0.1 – 0.35 ; D/C = 0.2 – 0.4

Hydrogen isotopes retention in deposited erosion products. Results

D/W ratio dependence on the deposition rate



D/W ratio dependence on the substrate temperature



Scaling equation for describing D/W ratio

1. Equation was proposed by De Temmerman and Doerner [*2. G. De Temmerman, R.P. Doerner, J. Nucl. Mater 389 (2009) 479-483*]:

$$\frac{D}{W} = 5.7 \cdot 10^{-8} \cdot r_d^{-0.4\pm0.1} \cdot E_n^{1.88\pm0.44} \cdot exp\left(\frac{779\pm220}{T}\right),$$

E_n - average energy of the incoming D particles on the substrate

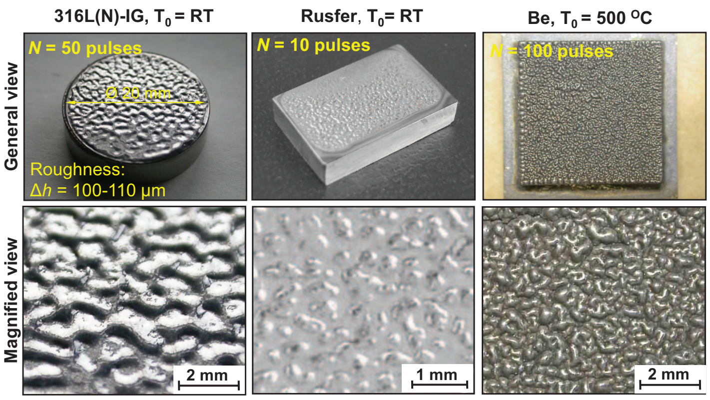
2. Scaling ($E_n = 200\ eV$) in the QSPA-T case ***is almost the same:***

$$\frac{D}{W} = 5.7 \cdot 10^{-8} \cdot r_d^{-0.4\pm0.1} \cdot E_n^{1.63\pm0.4} \cdot exp\left(\frac{809\pm200}{T^{0.8}}\right)$$

Results

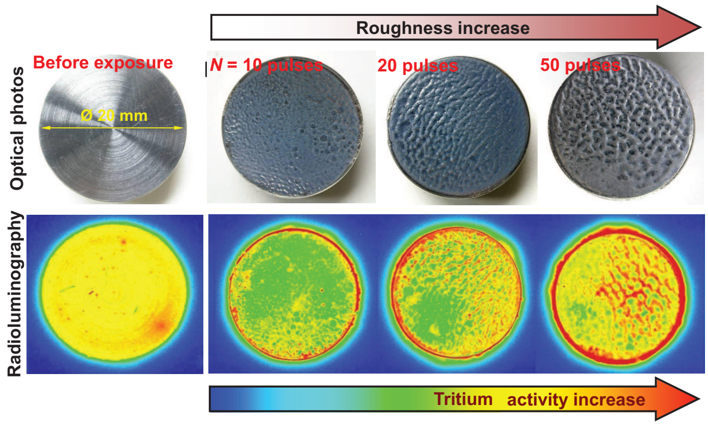
1. Scaling for the QSPA-T is closer to the presented in the work [2], opposite to the work [*3. V. Kh. Alimov et al. J. Nucl. Mater 399 (2010) 225-230*]
2. Deuterium retention at the QSPA-T is approximately two times higher than for stationary processes at 300°K: ***D/W = 0,35***. But it decreases down to ***D/W = 0,1*** with increasing deposition rate.
3. Deuterium retention behavior at high substrate temperature (> 450 °K) ***is lower*** than retention at the magnetron [2,3]: $D/W \sim exp\left(\frac{809}{T^{0,8}}\right)$

Exposed targets: q = 0.5 MJ/m², Δt=0.5 ms



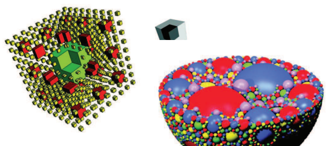
Repeated exposure of the steel leads to a regular "corrugated" surface, with hills and valleys, which was clearly observed already after 5 pulses for all investigated steel grades.

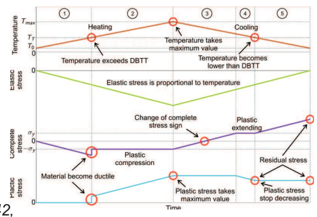
Experimental results



Directions of theoretical modeling in Budker NPI

- Modeling of dust formation during brittle destruction on the basis of scale similarity hypothesis
- Analytical calculation of stresses causes by pulse heat load for crack formation modeling





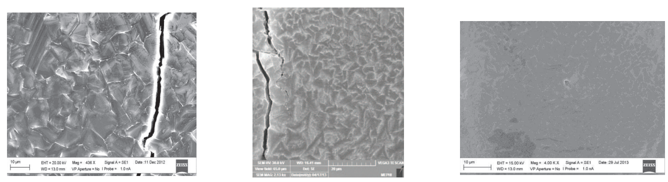
A.Arakcheev et al PSI 2014 A 2012.
A.S.Arakcheev, K.V.Lotov J.Exp.Theor Phys.142, 1012.. 271-278.

Processes	Method	Data Source \Code	Publication	Verification / Application	Problem
Generation and properties of B4C protecting layer on OFC (graphite, W)	Experiments on the plasma guns		A.Barsuk et al. 14th PFMC Intern. Conf. Juelich, Germany, May 13 - 17, 2013	Comparison with experiments on the electron beam facilities and with numerical models	W protection from cracking with renewable low Z coverage resistive to sputtering and H retention.
2. **Tungsten dust/powder behavior under intensive plasma irradiation.**	Experiments at the high plasma density set		L.B.Begrambekov et al., 21st PSI conference (2014J.		Dust mobilization under outgassing and electric field, conglomeration and melting under high heat fluxes

1.N. S. Klimov et al. (SRC RF TRINITI), 2. L.B.Begrambekov et al (MEPhI)

Possibility of protecting renewable B_4C coating for PFC protection

A uniform layer of B_4C safety formation on graphite under multi-pulse irradiation by coaxial gun QSPU-T



a b c

Stoichiometric covering after 15 (a) , 50 (b), 100 (c) pulses (1 GW/m², τ = 0.5 s)

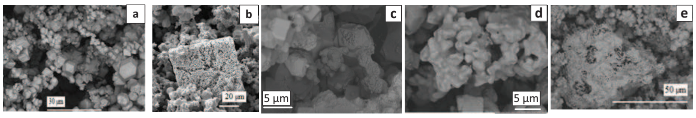
The irradiation power ~ expected full-scale ELMs in ITER
No damage, erosion from sputtering only
The cracks are healed under thermal expansion during subsequent pulse, only new ones appear during cooling
NO DESTRUCTION

A.Barsuk, L.Begrambekov, O.Buzhinsky, A.Zhitlukhin, *et al.* "Behavior of Protecting B4C Coating under Irradiation by Plasma Pulses of QSPA-T". 14th Intern. Conf. on Plasma-Facing Materials and Components for Fusion Applications, Juelich, Germany, May 13 - 17, 2013

Tungsten dust\powder behavior under heat, electric field and hydrogen ion influence

Powder composition (%): ≥ 99.5 W; 0.2 Mo; 0.18 (Al+P+S+C+As+Si+Ca+Ni+K+Fe+Na); 0,12 ($O+H_2O$). The powder comprised of two fractions of crystalline micro particles with dimensions: 5±1.5μ and 1±0.2μ ("large" and "small" particles).

Influence on the tungsten powder, without modification	Phenomena at the surface
Prior any influence (virgin powder)	Three dimensional chains of the large particles (a) and the clusters with geometrical forms of the small particles (b) were observed in the powder
Powder heating with low temperature ramp up (5K/s).	Powder out gassing in the temperature range 550-820 K. Approximately 5×10^{19} molecules/m^2 release from the sorbed layer on powder particles.
Powder heating with high temperature ramp up(100K/s)	Pulse gas release causes emission of dust particles from the surface layers of powder at the temperatures ≤ 1250 K.
Electric field impact without ion irradiation.	Electric field higher than 350 V/mm (independently of its direction) initiate particle emission from the powder surface at the temperatures ≤ 1300 K.
Electric field accompanied with ion irradiation.	The threshold electric field for particle emission decreases down to 290, 260, 220 V/mm, for 5 KeV, 10A/m^2; 6 KeV, 30A/m^2; 6.6 KeV, 50 A/m^2 respectively
Ion irradiation with higher power density	c) small particles pasted all over the large ones (2 keV/at, 100 A/m^2, 1300 K) d) small particles are melted and cover the large ones (2 keV/at, 150 A/m^2, 1500 K) e) Uniform layer is formed on clusters of the small particles (2 keV/at, 300 A/m^2, 1800 K)

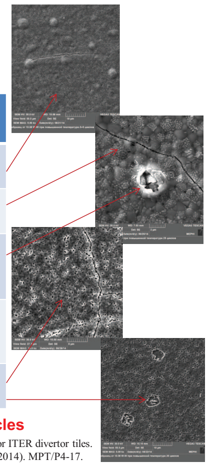


L. Begrambekov*, A.Grunin, S.Vergazov, A. Zakharov Tungsten dust/powder behavior under intensive plasma irradiation. Preceedings of 21st International Conference on Plasma Surface Interactions, P1-032

Deposited W layer modification under thermal cycling

- Temperature of deposition - 500 K.
- Substrate - ITER grade tungsten.
- Deposited layer thickness -200 nm.
- 10s heating up to 1500K and 40 s cooling down to 550^{0}C.

# ofl cycling	Deposited layer modification
5	The surface relief became rough (3-4 μm), cracks 0.1-0.2μm and blisters with diameter 2-5 μm ("big blisters") appeared.
10	Blisters with diameters 0,2-0,4μm ("small blisters") appeared. Their covers had openings. The cracks groove up to 0,2-0,3μm.
15	Covers of some big blisters appeared to be broken. SEM examination of blisters "bottom" showed that they appeared between the deposited layer and substrate
25	Diameters of both small blisters and openings on their covers increased. The neighboring blisters joined each other forming kind of big shapeless blisters
25-60	The covers of "old" and "new" big blisters were flattening. Total destruction of blisters occurred



Deposited W layer practically fully detached within 60 thermal cycles

E.A.Azizov, L.B.Begrambekov, O.I.Buzhinsky, N.S.Klimov, V.A.Kurnaev, I.V.Mazul. Protecting B_4C coating for ITER divertor tiles. Deposition, operation, removal of erosion products. Preceedings of 25th IAEA Fusion Energy Conference (FEC 2014). MPT/P4-17.

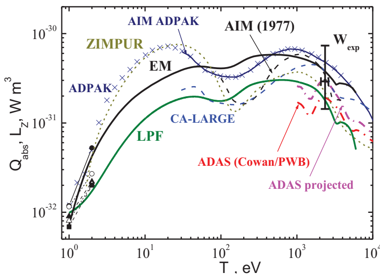
3. A+M data generation for integrated modeling of fusion experiments

A+M DATA GENERATION

Processes	Method	Data Source \ Code	Publication	Verification / Application	Problem
Line emission of W, including multiply ionized	Analytic theory of a quasi-continuous spectrum photon emission by a plasma-like system	W charge-state distributions (IE balance).	JETP Letters, 98 (2013) 786–789	Comparison with first-principle numerical modeling, experimental database on W line emission	Test of W covering (divertor, first wall) in fusion facilities
Ion broadening of Ly-alpha spectral line shape	Comparison of methods	Comparison of all existing codes	E.Stambulchick et al., High Energy Density Phys. 9 (2013) 528-534; Atom 2 (2014) 378-381	Substantial deviations of results	Integrated modeling of fusion experiments (radiative transport + diagnostics, e.g., ITER divertor)

V.S. Lisitsa et al. (NRC "Kurchatov Institute", Moscow, Russia)

Comparison of radiation losses of W impurity in statistical models LPF and EM with results of numerical simulations



Statistical models developed:
A.V. Demura, M.B. Kadomtsev, V.S. Lisitsa, V. A. Shurygin, JETP Letters 98 (2013) 786–789.

electromagnetic model (EM)
local plasma frequency method (LPF)

EM – electromagnetic model (Vlasov kinetic equation), *A.V. Vinogradov , O.I. Tolstikhin, Sov. Phys. JETP 69, 683 (1989);*, **ADPAK** - *D. Post, et al., PoP* **2**, *2328 (1995);* **AIM** - *averaged ion model* , **AIM ADPAK** D.E. Post, et al., *At. Data Nucl. Data Tables* **20**, *397 (1977)*; **ADAS**- H.P. Summers, 1994; ADAS projected, ADAS COWAN/PWB - *R. Neu, et al., Nucl. Fusion,* **45**, *209 (2005)*; CA-LARGE - *T.Putterich, et al., Nucl. Fusion* **50**, *025012 (2010)*; **Wexp** - experimental estimate of radiation losses.

Statistical approach provides an effective data generation for W radiation losses that can be as the fast routine in complex transport codes

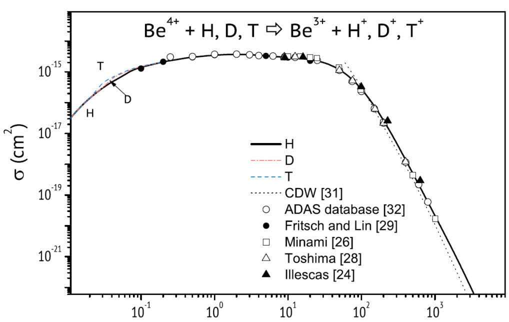
A+M DATA GENERATION

Processes	Method	Data Source \ Code	Publication	Verification / Application	Problem
Charge-changing collisions of tungsten and its ions with neutral atoms H, D, T, He, N, Ar and W	Adiabatic theory of transitions in slow collisions (hidden crossing method.), Born approximation and the classical energy-deposition model.	Codes: ARSENY, CAPTURE, DEPOSIT, RICODE	J. Phys. B: At. Mol. Opt. Phys. 45 (2012) 145201 Physics-Uspekhi, 56, 213 (2013)	Plasma modeling (near-wall, divertor), planning and interpretation of future experiments in fusion devices using tungsten as a material for the plasma-facing components.	Influence of the isotope effect (mass dependence) on the charge exchange cross sections in slow collisions, ionization and charge exchange cross sections in a wide energy range, contribution of the multi electron ionization to the total cross sections
Influence of the isotope effect on the charge exchange in slow collisions of Li, Be, and C ions with H, D, and T			Phys Rev A 84, 012706 (2011)		
Collisions of Be, Fe, Mo and W atoms and ions with hydrogen isotopes: electron-capture and electron-loss cross sections			Submitted to JPB (не нашел публикации)		

Inga Yu. Tolstikhina *et.al.* (Lebedev Physics Institute RAS, Moscow, Russia)

electron-loss: $A^{q+} + H \rightarrow A^{(q+m)+} + H + me^-, \quad m \geqslant 1, \quad A = \text{Be, Fe, Mo, W}$

electron-capture: $A^{q+} + \text{H, D, T} \rightarrow A^{(q-1)+} + (\text{H, D, T})^+, \quad A = \text{Be, Fe, Mo}$



Total electron capture cross sections for Be^{4+} ions colliding with H, D, T atoms as a function of the ion energy. Comparison with other data for reaction with H

Cross section is predicted for extra low energy region

I.Yu. Tolstikhina, M.S. Litsarev, D. Kato, M.-Y. Song, J.-S. Yoon, V.P. Shevelko. J. Phys. B: At. Mol. Opt. Phys. 47 (2014) 035206 (11pp)

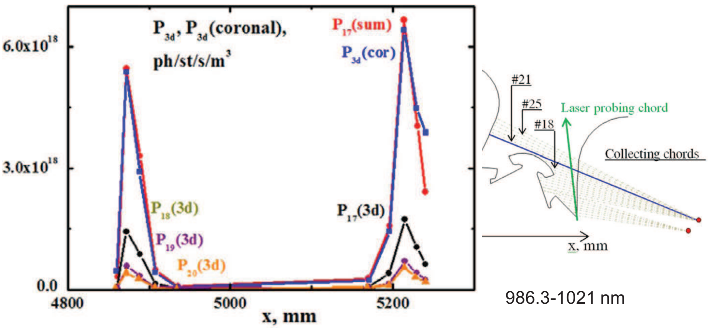
4. Application of A+M databases and kinetic codes to fusion plasmas (data use and data needs)

A+M DATA USE

Problem	Task	Publication	Processes	Data Source	Data Needs
Integrated modeling of ITER scenarios	Fast routine kinetics of hydrogen penetration	Proc. 39th EPS Conference, 2012, P4.093,	All processes with H_2 and H	Data file AMJUEL: Additional Atomic and	H_2 dissociation with H* product,
H-alpha diagnostic in ITER	from the wall in ITER, tested against B2-EIRENE	Proc. 40th EPS Conference, 2013, P1.135.	Charge exchange of neutral H in excited states with protons	Molecular Data for EIRENE	CX(n,l) nl-cascade population
Thomson diagnostics in ITER divertor (E.E. Mukhin et al., Ioffe Physical Institute, St. Petersburg, Russia)	Line and continuum spectral background on diagnostic chords	Plasma Physics Reports, 2012, 38, 138–148	IR Hydrogen lines (P-7), Brems and photorec.	NIST ASD	
	Impurity (nitrogen) line background	Nucl. Fusion 54 (2014) 043007 (13pp)	IR lines, kinetics of 3d levels population	NIST ASD, ADAS	

V.S. Lisitsa et al. (NRC "Kurchatov Institute", Moscow, Russia)

Spectral background for Thomson diagnostics in ITER di



Profiles of local emissivity of most intense lines of neutral nitrogen 0,1% 3d–3p (infrared~986.3-1021 nm) transitions calculated using the coronal model and with the use of ADAS data, for diagnostic chord #23 (*ne* and *Te* profiles obtained from a SOLPS simulation appropriate to ITER *Q* = 10 flat top conditions). *x* is radial coordinate. Good accordance of simple cor. model with ADAS

E.E. Mukhin, R.A. Pitts, et al. Nucl. Fusion 54 (2014) 043007

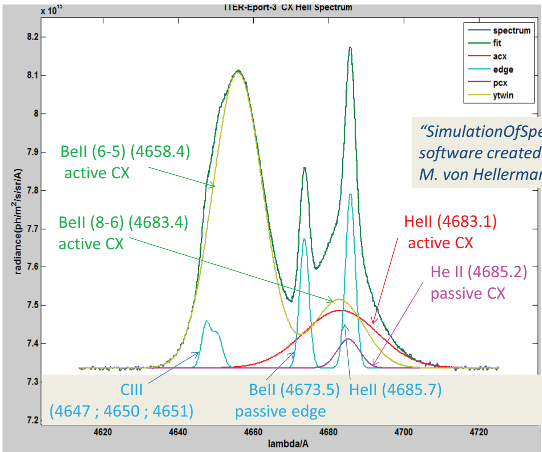
A+M DATA USE

Problem	Task	Publication	Processes	Data Source	Data Needs
Charge exchange recombination spectroscopy in ITER (S.N. Tugarinov, TRINITI, Russia)	Predictive modeling, Data interpretation	25th Meeting of the ITPA Topical Group on Diagnostics, October 2013, IO Cadarache	Selective populations of m sublevels in an atomic beam in a strong magnetic field		Cross sections for W transitions in visible spectral range

S.N. Tugarinov et al. (TRINITI, Troitsk, Russia) ,

ITER CXRS-edge diagnostic

Simulation of spectral profile radiation, based on ADAS data



Using of ADAS for Russian diagnostics

"SimulationOfSpectrum" software created by M. von Hellermann

Continuum radiation 7.33 10^{15} ph/m^2/s/sr/A

A+M DATA USE

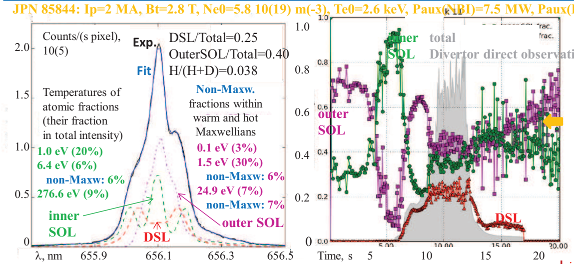
Problem	Task	Publication	Processes	Data Source	Data Needs
H-alpha (and Visible Light) Diagnostic in ITER (A.G. Alekseev, NRC "Kurchatov Institute", Moscow, Russia)	Divertor Stray Light problem, accuracy assessment (ITER Measurement Requirement flow down)	24th IAEA FEC, San Diego, 2012, ITR/P5-44	All processes with D_2 and D All processes with impurities (Be, W, etc.)	B2-EIRENE (SOLPS4.3) simulations of plasma background in divertor+SOL in ITER EIRENE simulations of neutral D velocity distribution in SOL in ITER DIVIMP simulations of impurities	Hydrogen isotope molecules dissociation with excited atoms product
D-alpha diagnostic in JET	Verification of H-alpha synthetic diagnostic for ITER in JET ITER-like Wall experiments	AIP Conference Proceedings 1612, 97 (2014) 25th IAEA FEC, St. Petersburg, 2014, EX/P5-20			

A.B. Kukushkin et al. (NRC "Kurchatov Institute", Moscow, Russia)

Theoretical Model of ITER High Resolution H-alpha Spectroscopy for a Strong Divertor Stray Light and Validation Against JET-ILW Experiments

A multi-parametric inverse problem with allowance for (i) a strong **divertor stray light (DSL)** on the main-chamber lines-of-sight (**LoS**), (ii) substantial deviation of neutral atom velocity distribution function from a Maxwellian in the SOL (a model for line shape asymmetry), (iii) data for direct observation of divertor.

JPN 85844: Ip=2 MA, Bt=2.8 T, Ne0=5.8 10(19) m(-3), Te0=2.6 keV, Paux(NBI)=7.5 MW, Paux(ICRH)=2 MW



Fitting of measured spectrum, time 10.05 s. Asymmetry of Balmer-α spectral line shapes for inner- and outer-wall SOL is due to **non-Maxwellians** (and small admixture of H).

Fractions of **inner-wall SOL**, **outer-wall SOL**, and **DSL**, in total signal vs. time (khord) **Normalized total power of H+D Balmer-α emission in divertor**.

...irect observation of ...e divertor from top ...bservation of main-...hamber inner wall ...long tangential and ...adial LoS (KSRB ...rack 11) from ...quatorial ports ...nalysis of HRS data ...n resolving the power ... D+H Balmer-α ...pectral lines

...he results support the ...xpectation of a strong impact of the DSL upon H-alpha (and Visible Light) Spectroscopy Diagnostic in ITER.

A.B.Kukushkin, V.S.Neverov, M.F.Stamp, A.G.Alekseev, S.Brezinsek, A.V.Gorshkov, M.vonHellermann, M.B.Kadomtsev, V.Kotov, A.S.Kukushkin, M.G.Levashova, S.W.Lisgo, V.S.Lisitsa, V.A.Shurygin, E.Veshchev, D.K.Vukolov, K.Yu.Vukolov, and JET Contributors

A.B. Kukushkin 1 (1) 25th IAEA-FEC 2014, St. Petersburg, Russia, EX/P5-20 16/10/2014

A+M DATA USE

Problem	Task	Publication	Processes	Data Source	Data Needs
D-alpha line shape for ion temperature determination in CXRS diagnostics	Spectroscopic diagnostics in tokamak T-10	Plasma Physics Reports 39, (2013) 632-643	All processes with D atom	ADAS data base Spectra simulation codes	Cross sections energy dependence
C+5 n = 8-7 line intensity in CXRS diagnostics		Problems atom. sci. and technol., ser. Nucl. fusion, 37 (2014) 60-70; Proc. 25th IAEA FEC (2014) EX/P1-44	All processes with C+5 ion All processes with C+5 ion		nl-model for C+5 n = 8-7 line intensity for low energy (100 keV) beam
C^{+5} n = 8-7 line shape for carbon temperature determination with CXRS diagnostics	Design of CXRS for T-15 tokamak				nlm-model for C^{+5} n = 8-7 line shape with allowance for Zeeman and Stark effects

V.A. Krupin , A.Yu. Dnestrovskij et al. (NRC "Kurchatov Institute", Moscow, Russia)

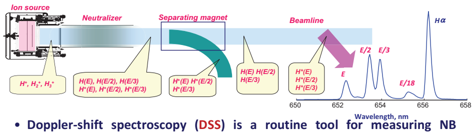
Use of A+M data in the Budker INP

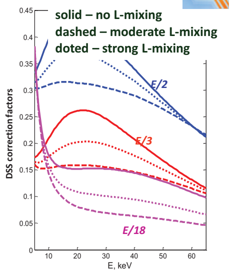
Development of sources on ion and neutral beams for fusion

Task	Publication	Processes	Data source	Data need
Control of impurity content in neutral beams	Instruments and Experimental Techniques 53 (2010) 253	Impurities ionization balance and atomic line emission	NIST ASD, ADAS	Impurities (C,O, Cu…) excitation in collisions with H_2 Isotopic effects in Hα excitation
Doppler-shift measurements of NB species content	JINST 8 P05007 (2013) Rev. Sci. Instr. **85** (2014) 02A707	$H+H_2 \rightarrow H^+ + H_2$ $H^+ + H_2 \rightarrow H^+ + H^+_2$	ALADDIN ORNL-6086	Sublevel-resolved cross-sections of hydrogen excitation in collisions with H_2
Simulation of the beam generation and transport		$H_2 + e \rightarrow H + H^+ + 2e$ $H_2 + H_2 \rightarrow H + H + H_2$		Distribution function of products of dissociation of H_2 (DH, D_2) in collisions with e and H_2

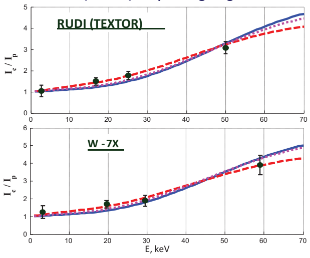
S.V. Polosatkin (Budker Inst. Nucl. Phys., Novosobirsk, RF)

L-Mixing Effects in Hydrogen Neutral Beams Emission





- Doppler-shift spectroscopy (DSS) is a routine tool for measuring NB species content
- Interpretation of DSS measurements depend on excitation cross-sections and de-excitation branching ratios
- Several weak effects can cause L-mixing of n=3 sublevels that result in changes of DSS correction factors
- Model of sublevel population can be clarified by measuring of a ratio of H_α intensities w/ and w/o separating magnet



- The calculations gives the variation up to 30% in DSS correction factors for half- and third- energy atoms for different models of sublevel population.
- Most notable effect that can lead to two-fold overestimation of impurity concentration is found for the correction factors for E/18 species.
- Comparison of experimental data with model calculation points out that traditional coronal model of sublevel population must be rejected on the significance level 10%
- Additional special-purpose measurements with independent control of neutralization efficiency would be useful to confirm this result

S.Polosatkin et al. Rev. Sci. Instr. ***85*** *(2014) 02A707*

Concluding remarks

Conferences in Russia relevant to A+M+PMI data studies for fusion research

1. XLII Zvenigorod International Conference on Plasma Physics and Controlled Fusion, Zvenigorod, Russia, February 2015
2. IX International Conference «Novel methods of plasma diagnostics and their application", November 2014, MEPhI, Moscow
3. XVIII conference "Plasma-surface interactions and plasma technologies", 5-6 February 2015, Moscow, National Research Nuclear University MEPhI http://plasma.mephi.ru/ru/en/psi-2015-en/committees.html

Acknowledgement to contributions and fruitful discussions:

V.S. Lisitsa, Yu.V. Martynenko, V.S. Neverov,

A.G. Alekseev, A.Yu. Dnestrovskii, M.B. Kadomtsev, L.N. Khimchenko, B.I. Khripunov, B.N. Kolbasov, S.N. Korshunov, V.A. Krupin, M.G. Levashova, D.Kh. Morozov, A.I. Ryazanov, V.A. Shurygin, I.D. Skorlupkin, V.G. Stankevich, K.Yu. Vukolov, V.E. Zhogolev (Kurchatov Institute)

S.W. Lisgo, A.S. Kukushkin, M. von Hellermann, E. Veshchev (ITER Organization)

V. Kotov, D. Reiter (Forschungszentrum Jülich)

M.F. Stamp, S. Brezinsek (JET-EFDA, Culham Science Centre)

L.A. Chernozatonskii (Inst. Biochemical Phys., Rus. Acad. Sci. (RAS))

L.A. Vainshtein, I.Yu.Tolstikhina, V.P. Shevelko (Lebedev Phys. Inst. RAS)

L.B. Begrambekov, Yu.M.Gasparyan, K.Gutorov (Moscow Eng. Phys. Inst.)

A.M. Zhitlukhin, O.Buzhinsky, N.Klimov (TRINITI, Rosatom)

S.V. Polosatkin, A.V. Burdakov A.S.Arakcheev (Budker Inst. Nucl. Phys. RAS)

V.V. Voloshinov, A.P. Afanasiev,. (Inst. Inform. Transmis. Problem RAS)

Conclusions

Various PMI data in Russia obtained at different facilities with various methods. Round robin experiments with the same samples started joining experimentalists and theoreticians of all main laboratories.
More broad collaboration with foreign laboratories is welcomed

The existing A+M data (data storage and exchange for elementary processes and basic, simplest kinetic models) correspond to major needs of fusion research. A number of successful applications is shown.

The ways to improve the efficiency of A+M+PMI data use in fusion plasma diagnostics are: (i) creating the simulators (fast-routine simplified computational models), (ii) atomic kinetic models for real-time diagnostics,