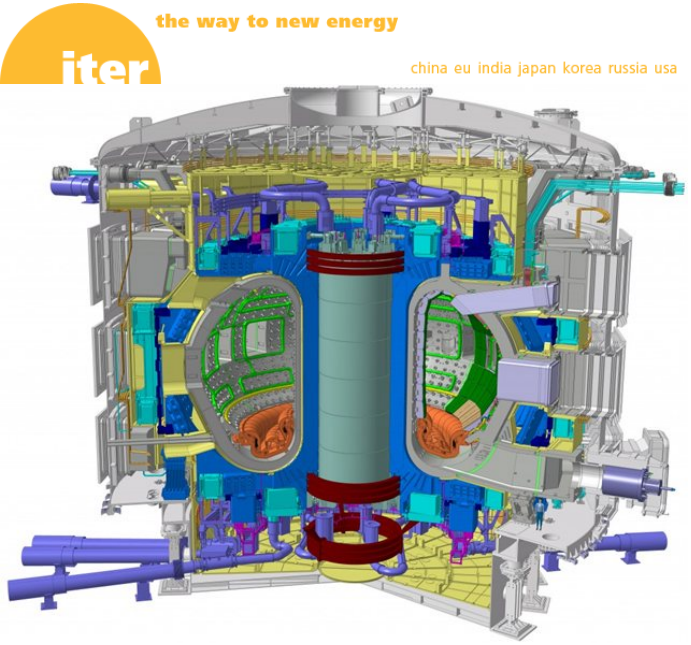
V.N. Karazin Kharkiv National University

School of Physics and Technology

Mass-Separated High Flux (>10^{22} $m^{-2}s^{-1}$) Ion Beam for Fusion Oriented Material Research

O. Girka,
I. Bizyukov, A. Bizyukov, K. Sereda, S. Herashchenko



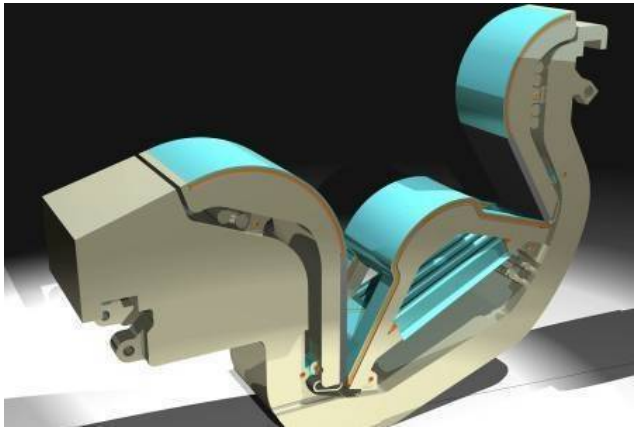
Economical efficiency of fusion power station strongly depends on lifetime of the first wall.

Erosion of the first wall as well as other ion-surface interaction issues critical for fusion program are under intensive research.

The ion-surface interactions are investigated either in tokamaks or using laboratory setups.

While general trend in Europe is closing the tokamaks in favor of ITER funding, many laboratories have started to focus on fusion oriented research of ion-surface interactions and related material properties.

However, modern laboratories aimed on the material research face essential dilemma



The laboratories have to split their budget between tools for surface analysis and equipment, which provides ITER relevant particle and heat fluxes.

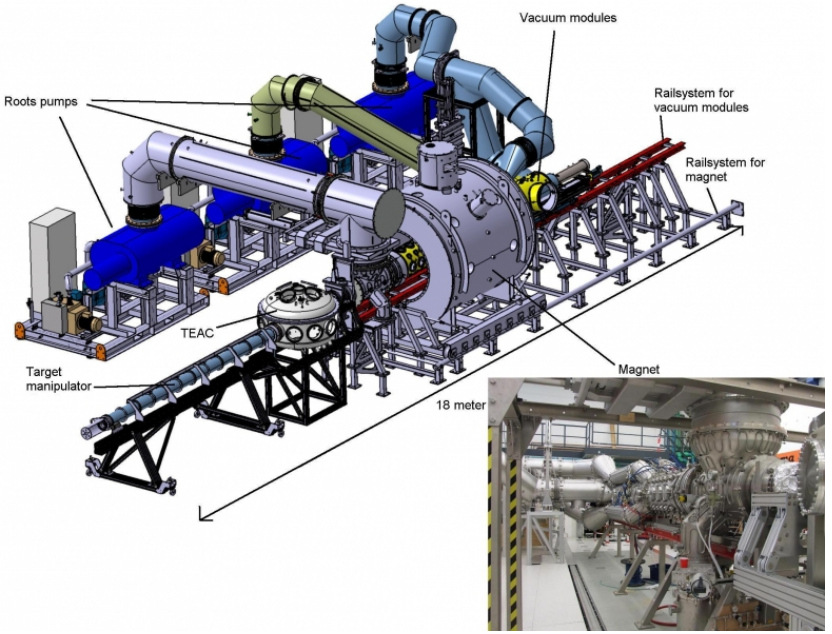
Tools for surface analysis are well known and costs for their ownership are well established.

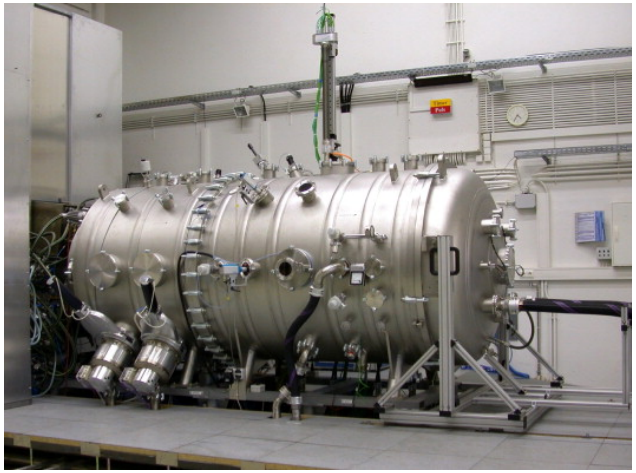
In contrast, equipment for steady-state and high heat and particle fluxes has not been yet standardized and represents “state-of-the-art” devices.

Actually, there are only few of them available in Europe: MAGNUM-PSI, PILOT-PSI, GLADIS.

There are also few in Japan (HiFiT, NAGDIS) and USA (DIONISIS, PISCES).

A number of ion beam devices with magnetic mass separation available, however, typical ion fluxes are well below 10^{20} $m^{-2}s^{-1}$





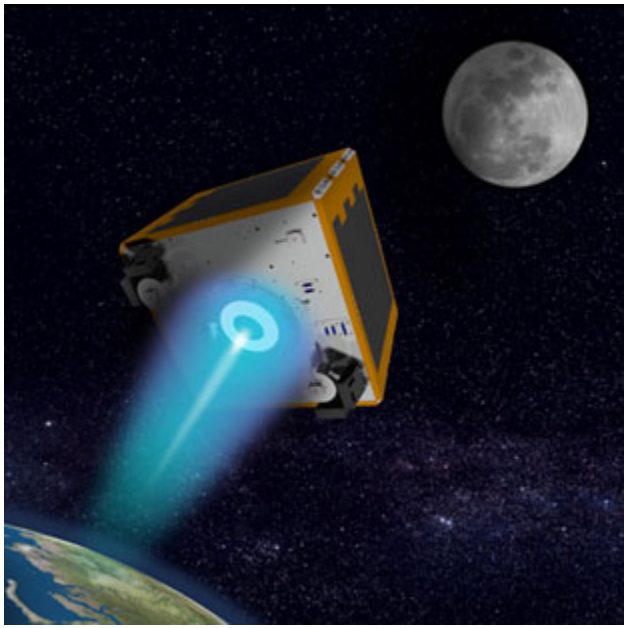
Therefore, fusion community requires standard and affordable tool, which helps to wide-spread fusion oriented material research over small and medium laboratories.

Its size and cost should be similar to ion beam sources

It should provide ITER relevant steady-state ion (>10^{22} $m^{-2}s^{-1}$) and heat (>1 MW m^{-2}) fluxes to the sample surface

It should provide continuous operation over many days to achieve high enough particle fluence (10^{26} m^{-2} and above)

Typical properties of conventional anode layer thruster for space propulsion



Satellite propulsion has to be compact and reliable in order to fit the space program

To drive the satellite the space propulsion has to generate powerful and stable ion beam

Typical anode layer thruster provides the ion beam current in the range of 5-300 mA

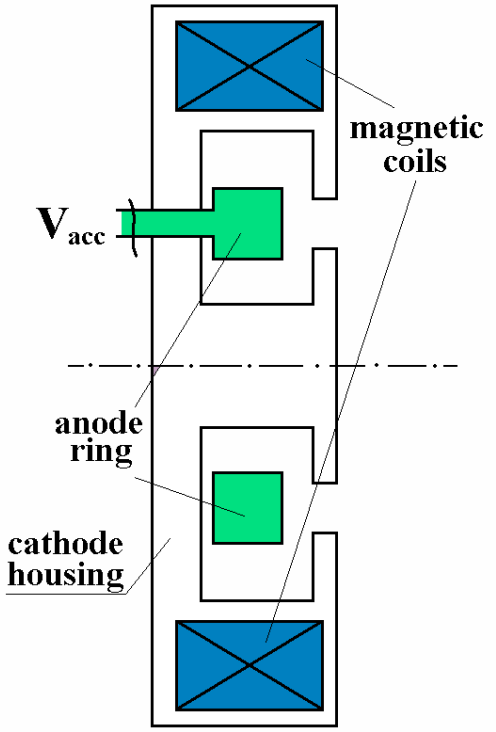
Ion beam is steady-state (≈200 h of continuous operation)

Its typical working pressure range is ≈10^{-5}-10^{-4} mbar

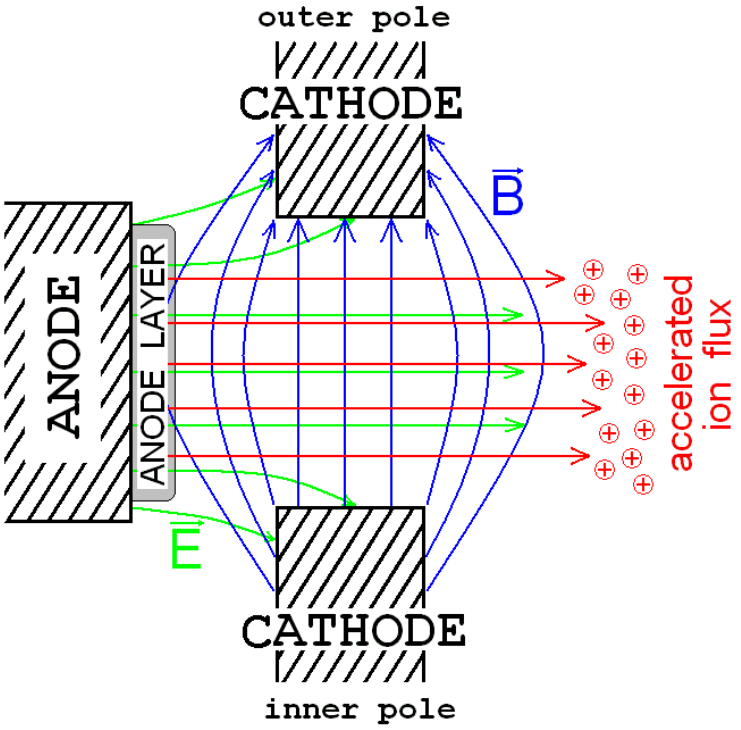
Converted and modified space propulsions could be used for fusion oriented material research!

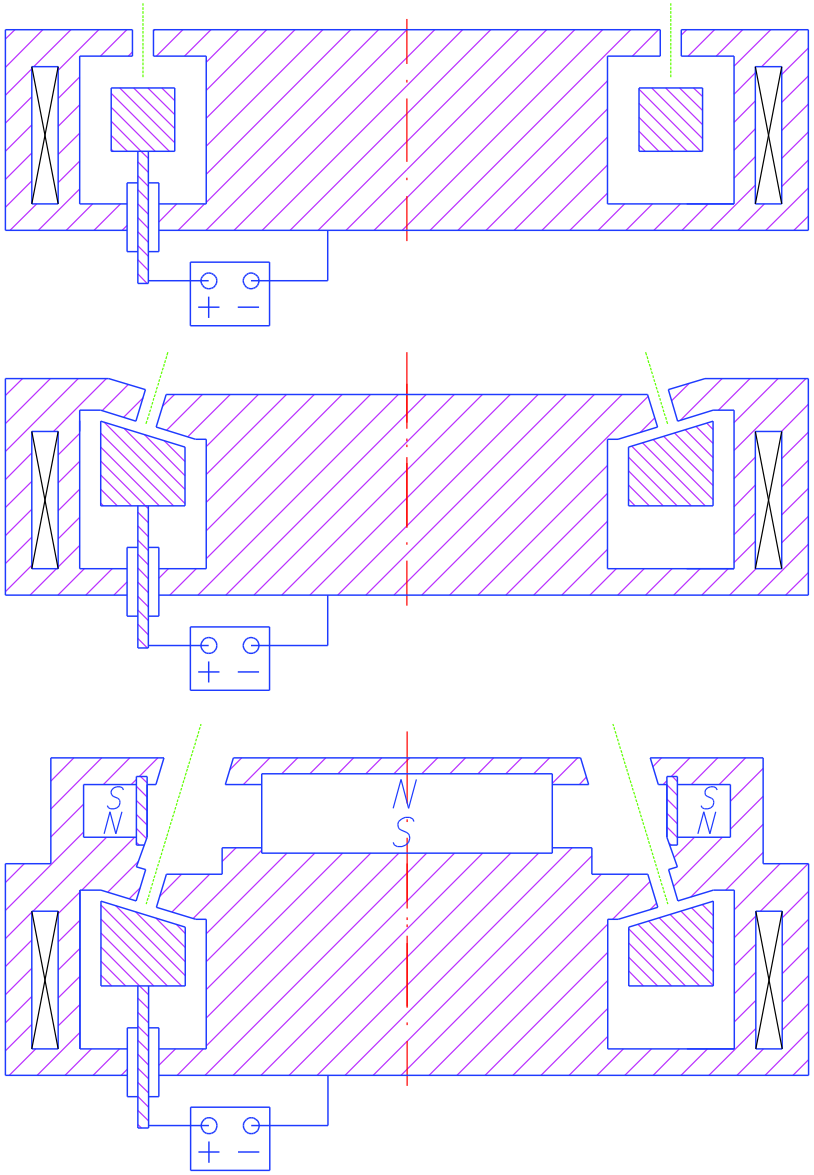
Principal scheme of anode layer thrusters

Cross-section



The discharge gap





To adopt the thruster for fusion research it is necessary to convert cylinder-type ion beam to cone-like

This conversion should increase ion beam current density

To implement the ballistic focusing usual plane cathode and anode were replaced by the new units of special shape with channels which provide cone-like beam

To improve the focusing, it was proposed to use the magnetic system with reversible magnetic field

The new modification of the anode layer thruster has been titled FALCON and patented in USA

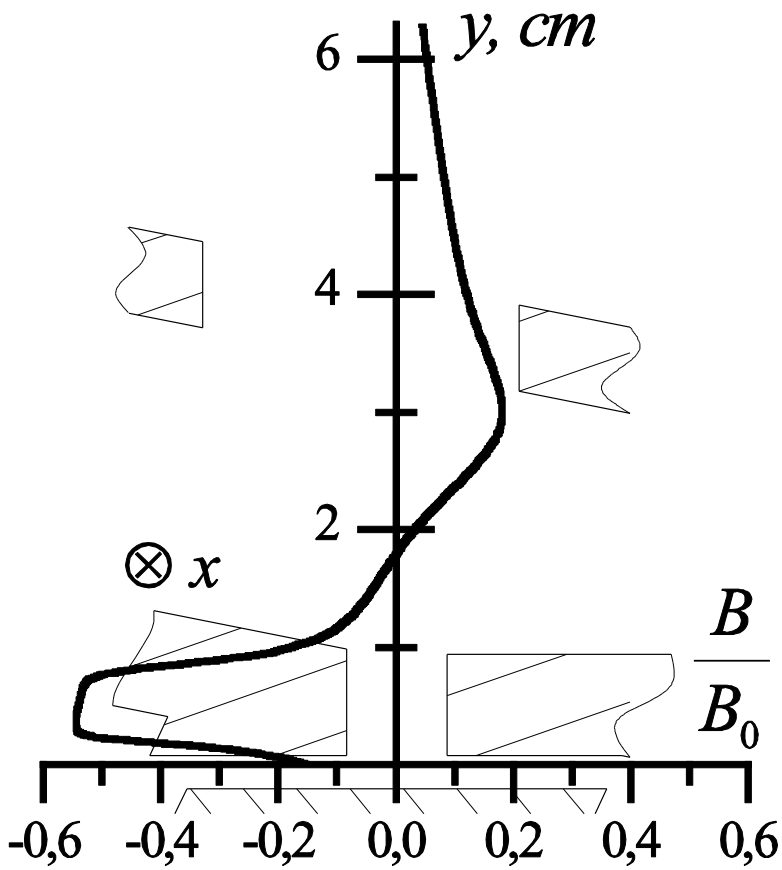
(12) **United States Patent**
Gutkin et al.

(10) **Patent No.: US 7,622,721 B2**
(45) **Date of Patent: Nov. 24, 2009**

(54) **FOCUSED ANODE LAYER ION SOURCE WITH CONVERGING AND CHARGE COMPENSATED BEAM (FALCON)**

4,886,969	A *	12/1989	Knauer	250/427
5,359,258	A	10/1994	Arkhipov et al.	
5,716,500	A *	2/1998	Bardos et al.	204/192.12
5,763,989	A	6/1998	Kaufman	

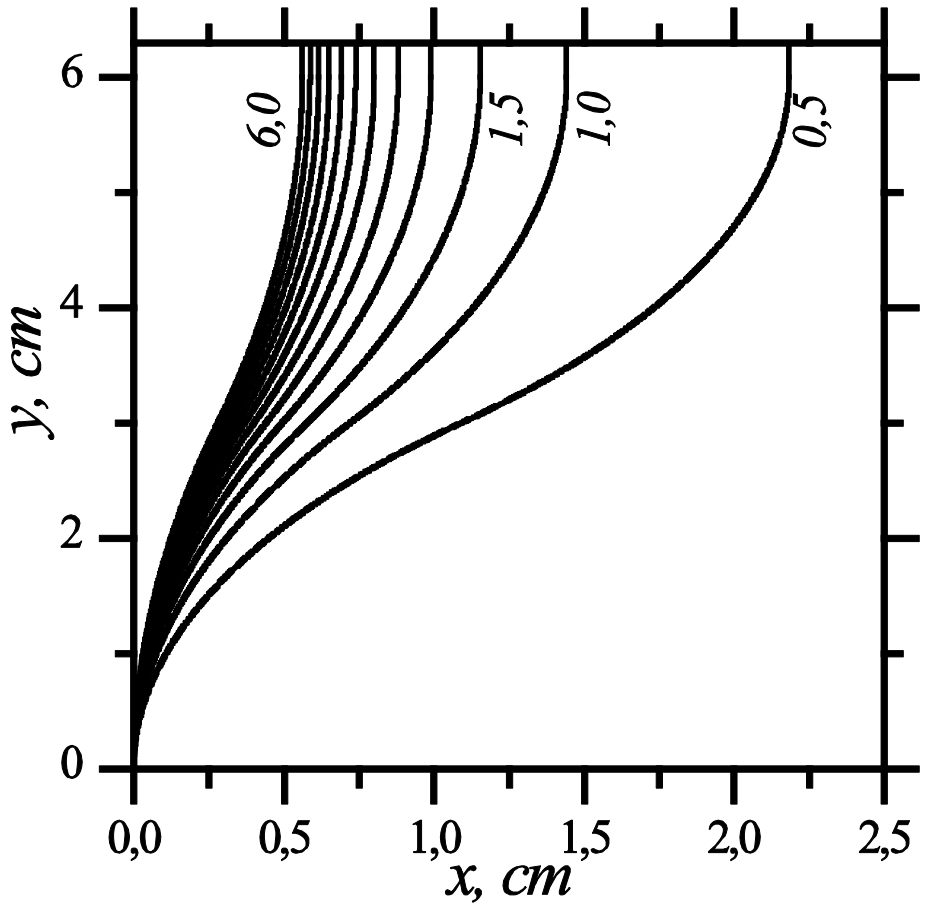
M. Gutkin, A. Bizyukov, V. Sleptsov, I. Bizyukov, K. Sereda
Focused Anode Layer Ion Source With Converging and Charge Compensated Beam (FALCON).
US Patent #US 7,622,721 B2, 2008/0191629 A1 (2009)



Actual distribution of the B (perpendicular) of the magnetic induction perpendicular to the ion flux direction

To find out the trajectories of the ions in the FALCON ion source with the ballistic and magnetic focusing analogue of the Bush theorem for paraxial beams and the energy conservation law were used:

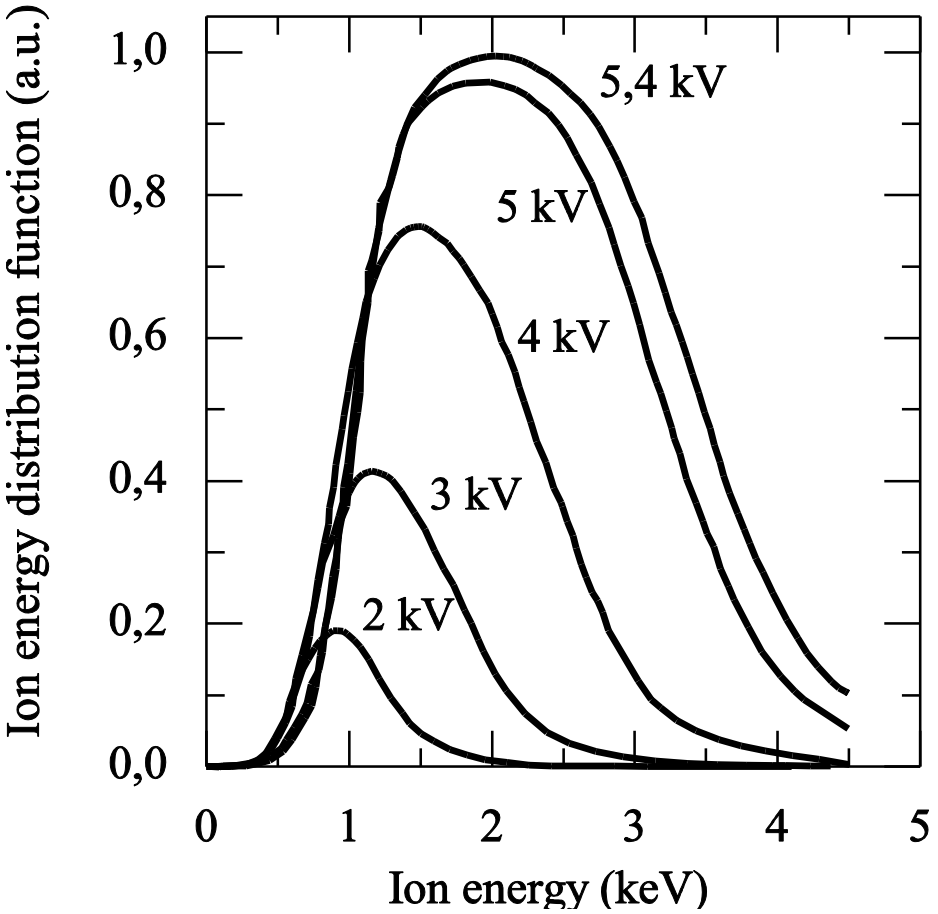
$$\begin{cases} m\dot{x} - m\dot{x}_0 = -e(\psi - \psi_0) \\ \dfrac{m\dot{x}^2}{2} + \dfrac{m\dot{y}^2}{2} = \varepsilon_i = \dfrac{m\upsilon_0^2}{2} \end{cases}$$



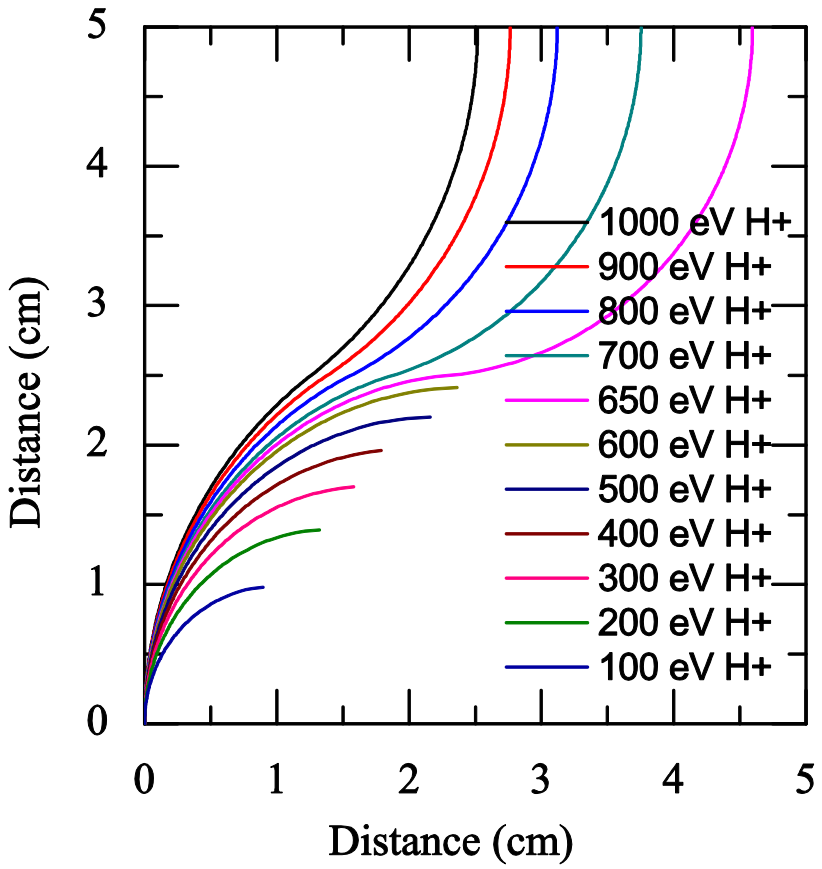
The H ions trajectories in FALCON ion source.

Curve marked with
“0.5” corresponds to the 0.5 keV ion trajectory
and “6.0” corresponds to the 6 keV

O.I. Girka, I.O. Bizyukov, O.A. Bizyukov, K.M. Sereda, O.V. Romashchenko.
Focused ion source for the microelectronics thin films processing
// Uzhhorod University Scientific Herald. Series: Physics, Issue 30, 2011, p. 45-51



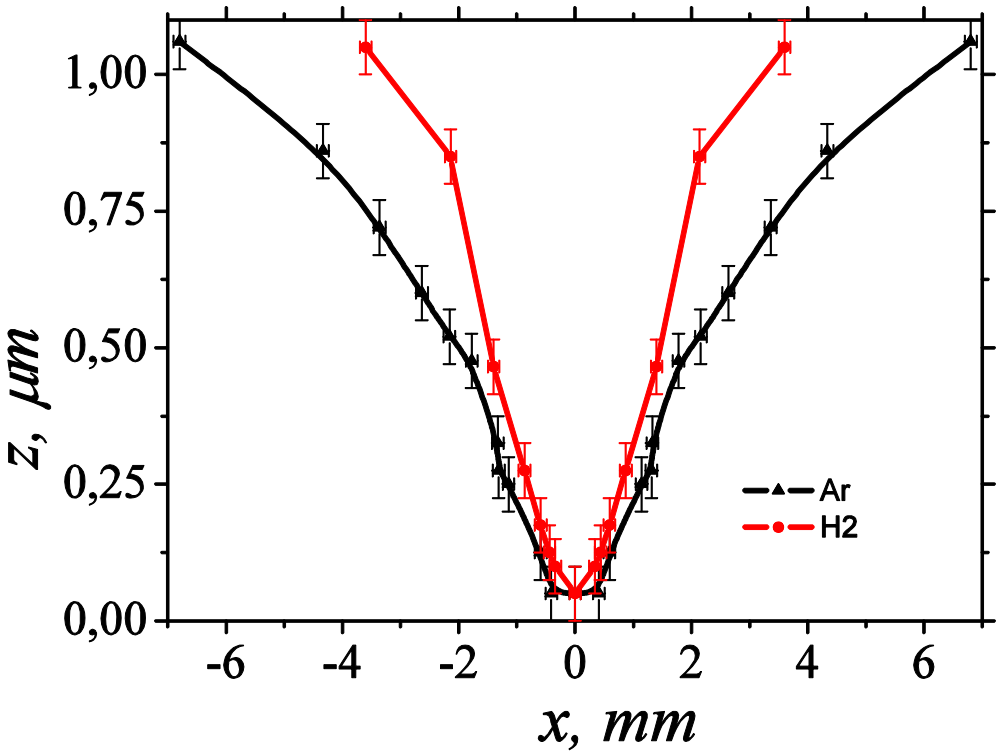
The ion energy distribution function of the beam measured by energy analyzer. The resolution of energy analyzer is 30 eV.



The strong magnetic field in the discharge gap affects the trajectories of the slow hydrogen ions, bending them towards the cathode

Therefore, low energy part (0 ÷ 650 eV) of distribution function is cut off

O.Girka, I. Bizyukov, A. Bizyukov, K. Sereda, S.S. Gerashchenko.
Impurities mass-separation in optimised Falcon ion source for high-flux and high-heat material tests //
Programme & Contributions of 11th Kudowa Summer School, "Towards Fusion Energy",
June 11-15, 2012 Kudowa Zdrój, Poland, P. 92-95



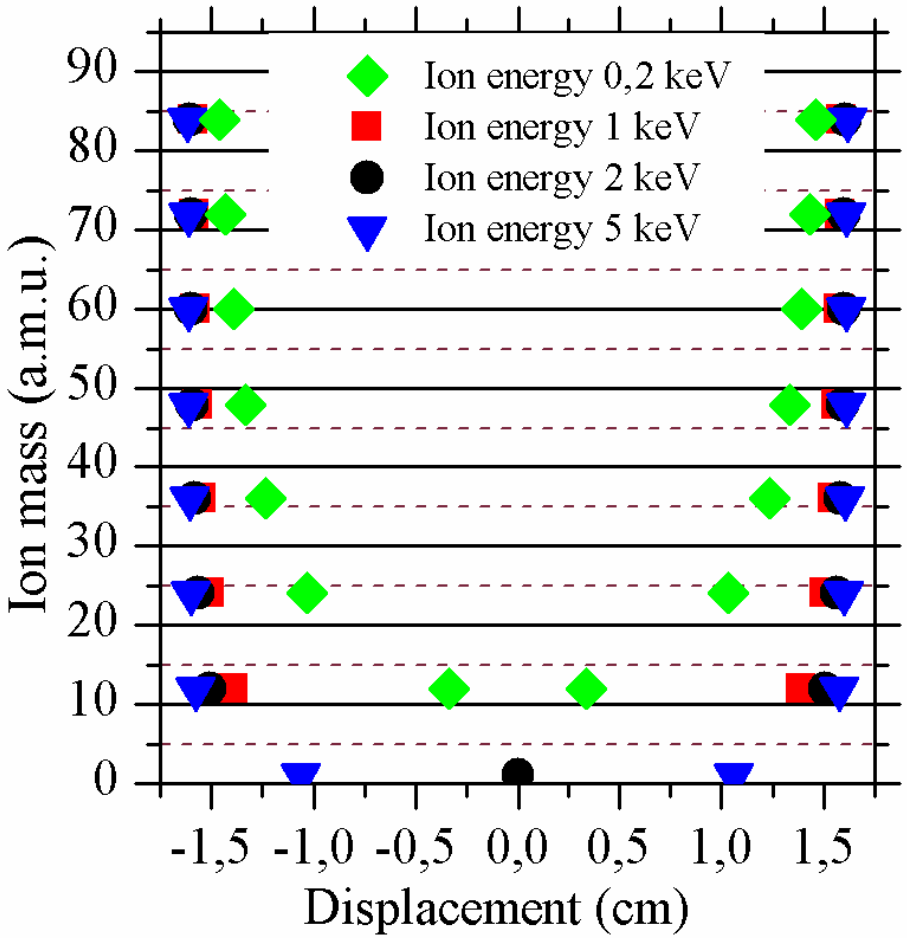
The ion beam intensity measured by sputtering the SiO_2 layer with *Ar and H* ion beam

Ar ion beam current was 40 mA with average ion energy of 2 keV

H ion beam current was 10 mA with average ion energy of 2 keV.

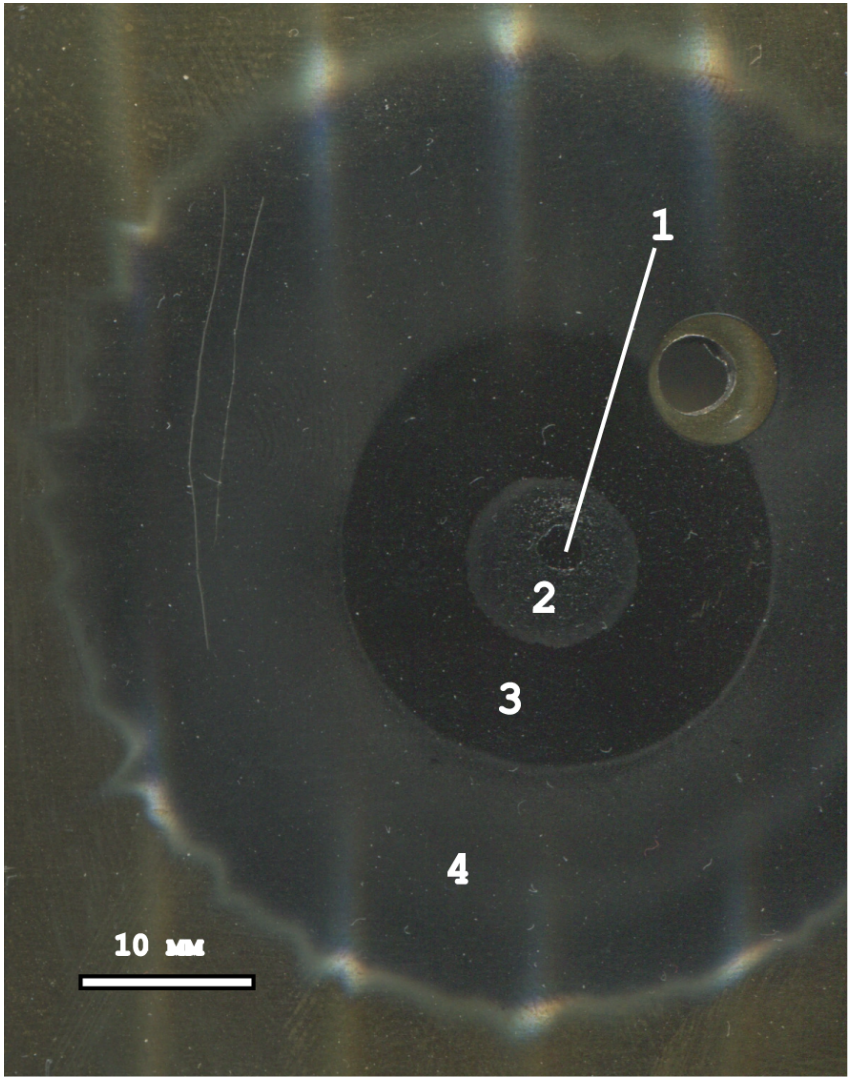
Beam intensity is well concentrated within the spot with a diameter of ~3 mm

Small beam spot provides high heat and particle fluxes
yet the cost of the pumping system remains relatively low



Results of numerical calculations of beam impurities mass-separation

Due to magnetic focusing the impurities can be separated providing pure H, D or T beam spot in the center



The surface of SS304 with TiN coating after bombarding

Cyclohexane was used as a working gas

1 – area sputtered by hydrogen ions;

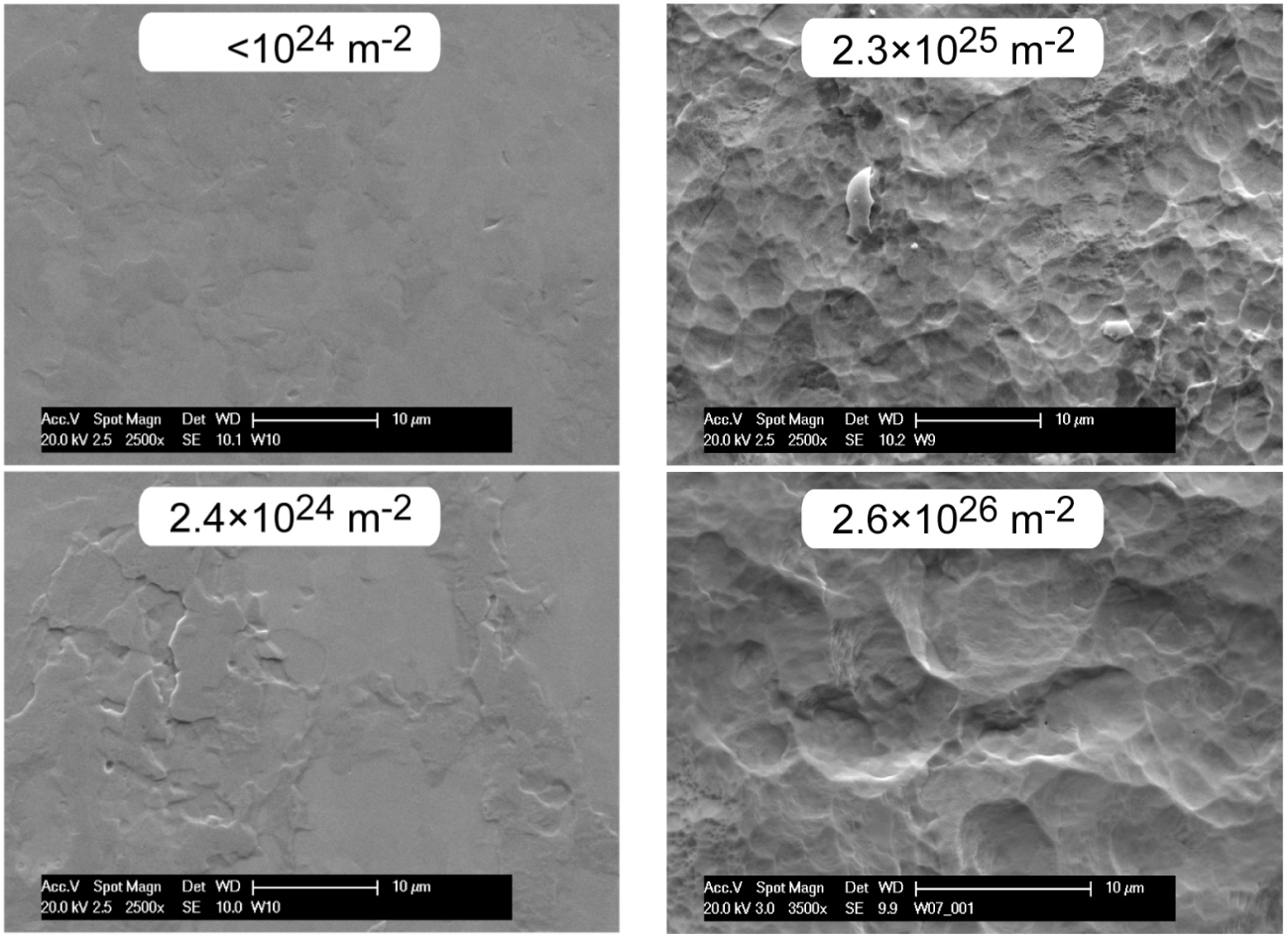
2 and 4 – film deposited by scattered ions

3 – direct deposition with C_XH_Y ions

Application of the FALCON ion source for fusion-oriented material research

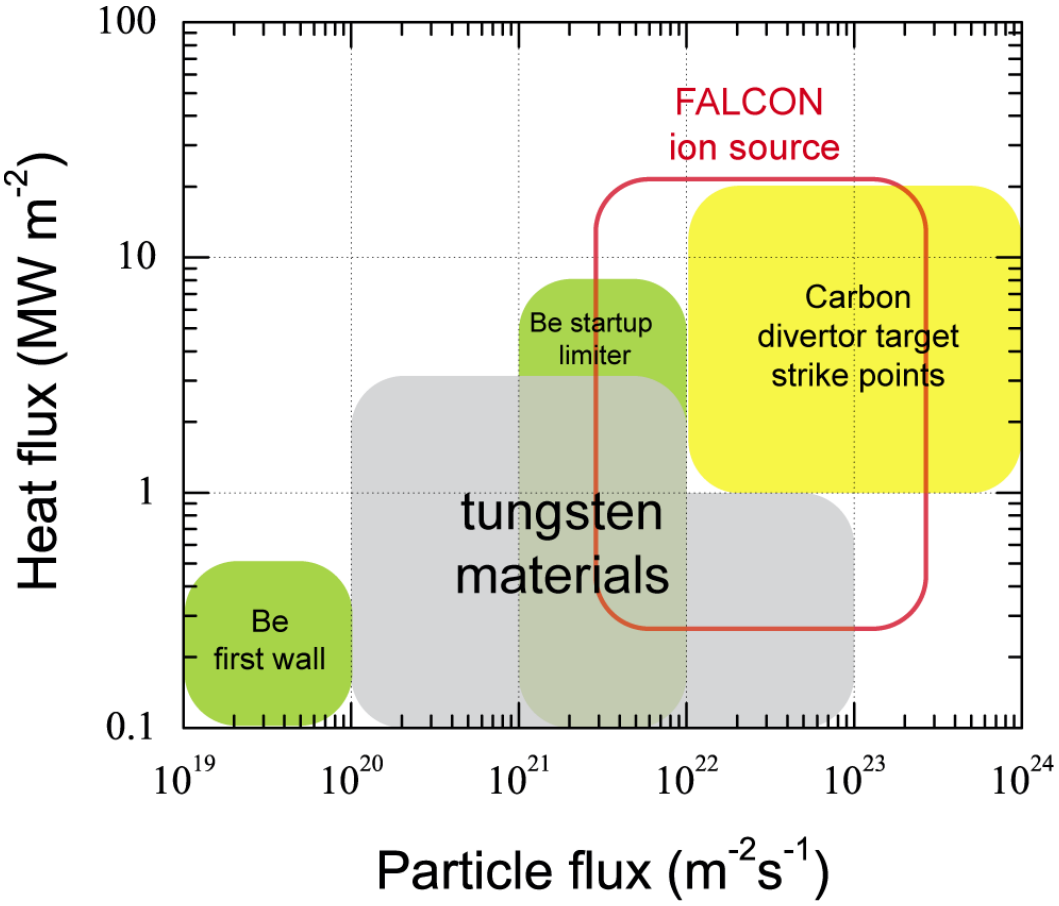
FALCON ion source application
for fusion-oriented material research

After the exposure, the samples were examined in SEM.



I. Bizyukov, O. Girka, T. Schwarz-Selinger, M. Balden, A. Bizyukov, N. Azarenkov.
Tungsten Erosion under High-Flux and High-Fluence Hydrogen Ion Beam Bombardment //
20th International Conference on Plasma Surface Interactions 2012, Eurogress, Aachen, Germany, 21. – 25.05.2012, P2-097

CONCLUSIONS



The FALCON ion source is designed for material research for ITER and future DEMO reactor. It could be used either for steady-state irradiation or for combined steady state and pulse irradiation of the samples

*Range of parameters taken from G. Federici et.al. Nuclear Fusion vol.**41**, pp. 1967-2137, (2001)

CONCLUSIONS

•The key advantages of FALCON ion source are very compact size, affordability, intrinsic capability for impurity separation and absence of re-deposition.

• long time 200 h of continuous operation allows reaching the fluence >10^{28} m^{-2}

• The beam is focused into a spot of ≈3 mm in diameter to reduce costs for pumping system.

•The "impurity" ions are separated to form the circle with a diameter of ≈6 mm. Therefore, the central part of the spot is free of impurities due to magnetic separation.

•Small volume of beam transportation makes the source suitable for the investigation with hazardous materials (tritium, beryllium, etc.)

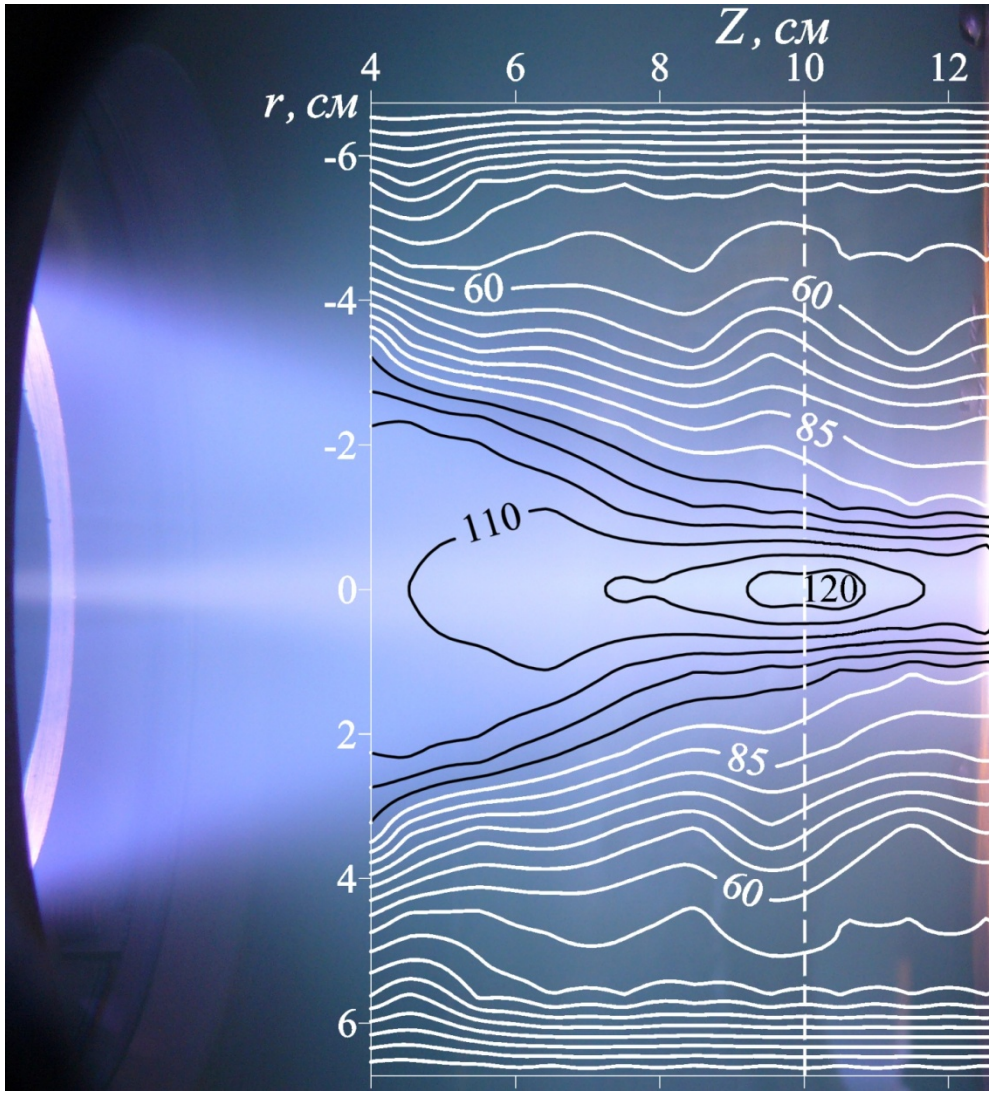
•FALCON design is simple for maintenance and operation makes it suitable for students work.

Thank you for your attention!

Find details about FALCON ion source

on www.micronst.com

or in my Ph.D. thesis



Ion beam potential distribution was measured via single Langmuir probe. Longitudinal potential asymmetry was observed during the measuring experiment. Essential longitudinal potential gradient after the beam crossover plane can initiate significant deviation of ions trajectories. Average transversal ion beam energy is

$\varepsilon_{\perp}=\varepsilon_i \cos 2\varphi =$ 130÷170 eV

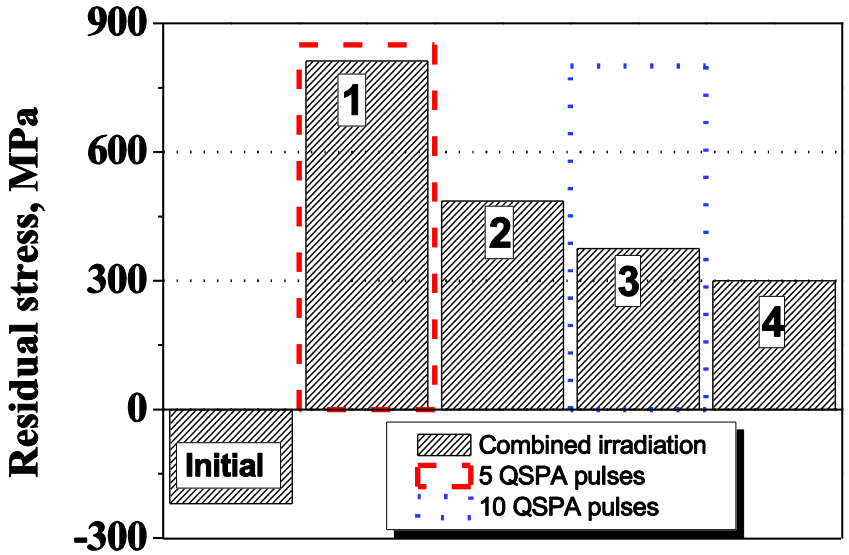
under our experimental conditions and is comparable to maximum measured potential ~120 eV. And beam glow points that ion trajectory deviate from ballistic ones.

An electric potential well for compensating electrons was shown to be formed near the beam crossover region. It allowed to explain the anomalous distribution of the brightness and glow of gas as well as ion deviations from ballistic trajectories.

Influence of combined hydrogen plasma exposures on tungsten behavior was studied in QSPA Kh-50 facility and steady-state FALCON ion beam system

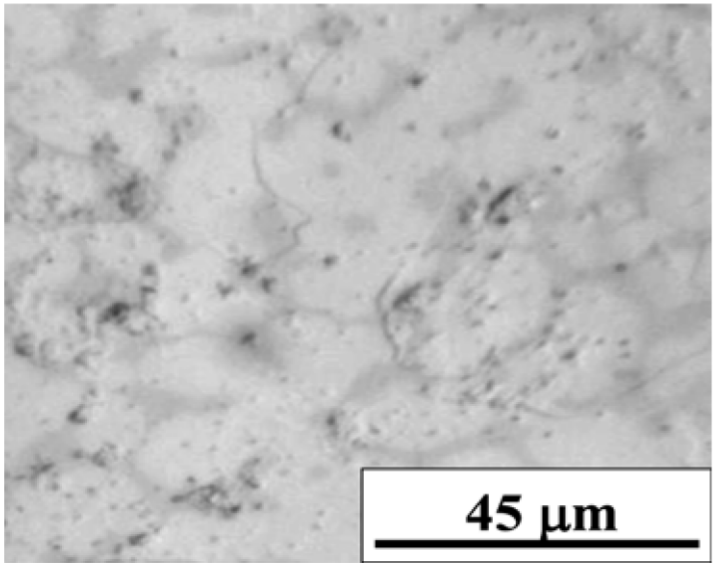
The main parameters of the QSPA Kh-50 plasma streams were the following:
- ion impact energy about 0.4 keV;
- maximum plasma pressure 3.2 bar;
- stream diameter 18 cm;
- surface energy load 0.45 MJ/m2, that (corresponded to ITER type I ELMs);
- plasma pulse shape – triangular;
- pulse duration 0.25 ms.

The main parameters of FALCON ion beam were the following:
average ion impact energy 2 keV;
particle flux 0.53x10^{22} $m^{-2}s^{-1}$;
Heat flux 0.43 MW/m^2;
Exposure time 900 sec;
Fluence 4,8x10^{24} m^{-2} ;

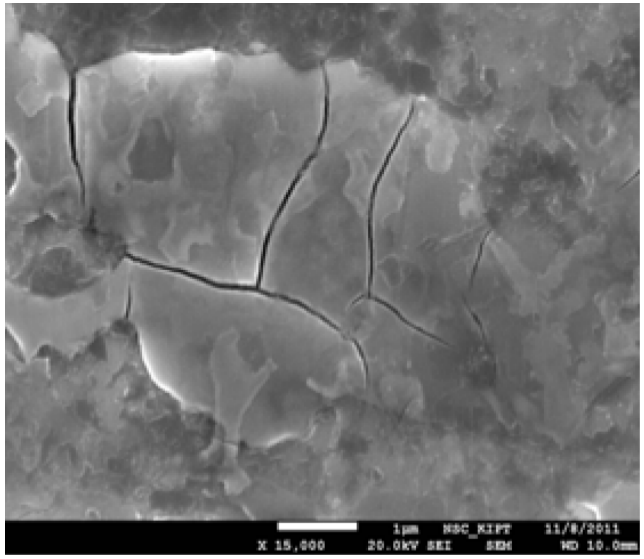


Results of residual stress measurements: combined irradiation:
- *first stage of single cycle (1),*
- *single cycle (2),*
- *after first stage of second cycle (3),*
- *second cycle (4)*

V.A. Makhlaj, N.N. Aksenov, O.V. Byrka, I.E. Garkusha, A.A. Bizyukov, I.A. Bizyukov, O.I. Girka, K.N.Sereda, S.V. Bazdyreva, S.V. Malykhin, A.T. Pugachov. Combined Exposure of Tungsten by Stationary and Transient Hydrogen Plasmas Heat Loads: Preliminary Results // Problems of Atomic Science and Technology. # 1. Series: Plasma Physics (83), p. 70-72 (2013)



View of exposed surface after two cycles of plasma irradiation



SEM view of exposed surface

The roughness of exposed surface was caused by distinguished boundary of grains as result of plasma ions bombardment and also by some isolated intergranular cracks due to the thermal stresses. Development of cracks caused the stress relaxation after plasma irradiation.

Symmetrical tensile stresses were created in tungsten surface layer in result of plasma irradiation. The maximal stresses in plasma affected layer were formed after the first plasma pulses. Diminution of residual stresses was observed with increase of exposition dose.

Faster relaxation of residual stresses in comparison with only pulsed plasma exposures was registered as a result of the combined influence. The correlation of cracks development with stress relaxation was demonstrated