CAPABILITIES OF A NEW DUAL BEAM EXPERIMENT FOR SIMULTANEOUS IRRADIATION OF MATERIALS WITH TWO ION SPECIES

I. Bizyukov [1], K. Krieger [2], N. Azarenkov [1]

[1]V.N. Karazin Kharkov National University, Department of Physics and Technologies, 31 Kurchatov Ave., Kharkov 61108, Ukraine;
[2]Max-Planck-Institut fьr Plasmaphysik, EURATOM Association, BoltzmannstraЯe 2, D-85748 Garching, Germany

First experiments showed that simultaneous bombardment with fuel particles and impurities leads to synergistic effects, where the erosion rate of a material cannot be explained by superposition of the separate sputtering processes. For the study of these effects a new Dual Beam Experiment setup has been designed and assembled. This paper describes the design and the accessible range of experimental conditions.
PACS: 52.40.Hf

1. INTRODUCTION

All major design studies of future fusion research and reactor devices employ tungsten as plasma-facing component at least in the divertor region (see, e.g. [1-3]) since in general, the erosion rate for low-Z materials like carbon or beryllium is far too high in a steady-state power producing device [1]. Additionally, the use of large area carbon-based materials leads to excessive co-deposition of tritium causing a considerable safety problem [4]. For tungsten, tritium accumulation by co-deposition is not expected to be a problem. High-Z materials offer the advantage of low sputtering yields as compared to low-Z materials like beryllium or carbon, however, their potential of radiative plasma cooling is considerably higher, and, therefore, the maximum tolerable concentrations in the plasma are correspondingly low. The W plasma concentration must for example stay below a limit of approximately 2×10^{-5} for ignited fusion plasmas [5] to avoid excessive energy losses due to the strong specific line radiation power of tungsten [6] in the respective plasma temperature range.

Results from the ASDEX-Upgrade W-divertor experiment show that the erosion of tungsten is dominated by impurities where C, W and O are the most common species and that the erosion yield as well as the transport in the main chamber critically depend on the actual divertor plasma parameters [7]. The simultaneous bombardment of the W surface by hydrogen isotopes and impurities, namely carbon and tungsten, leads to synergistic effects with significantly different plasma-wall interaction properties compared to the ones of pure hydrogen or pure carbon bombardment. This process also leads to formation of mixed surface layers with properties usually different from the original wall material.

Laboratory experiments on simultaneous bombardment of high-Z materials with hydrogen isotopes and impurity projectiles have been reported previously [8, 9]. The simplest way to produce such a flux is a discharge in methane and irradiation of surfaces with CH_3 radicals taking into account that ratio of carbon to hydrogen flux is 1:3 [8]. The experimental results, particularly regarding erosion yields, cannot be explained by the superposition of processes resulting from mutually independent irradiation of tungsten with carbon and hydrogen.

The previous experiments clearly indicate that combination of basic processes do not provide a complete picture of plasma-wall interactions. With respect to fusion devices, synergistic effects have a great impact on impurity wall sources and lifetime of wall components, and, therefore have to be considered for the selection of suitable plasma facing materials. However, only a few particular cases have been studied so far. Sputtering of wall material, particularly high-Z elements, by simultaneous bombardment with different species is a new field of research that is of great relevance for development of future fusion devices. Therefore, the new Dual Beam Experiment (DBE) at IPP Garching has been designed for exploring a wider parameter range. In addition, the new experiment allows in-situ ion beam analysis of irradiated samples, which provides information on the depth distribution of deposited and implanted species. This provides essential data, which were not available in previous experiments where only the weight change of samples could be measured. This paper describes the design and the accessible range of experimental conditions provided by the experimental setup.

2. DESIGN OF THE DBE SETUP

For the detailed investigation of synergistic effects, the equipment of the Dual Beam Experiment includes two ion sources generating beams focused onto the same spot at the target Each part of the setup can be pumped independently of one another and can be separated from the target chamber by shutters.

The MeV Beam Line for ion beam analysis (IBA)

An ion beam line connects the target chamber with a 3 MeV tandem accelerator that provides ion species for different types of ion beam analysis. The beam line is pumped independently by a turbo-molecular pump so that the vacuum is always better than 10^{-7} mbar. It can be sealed by two shutters when IBA is not required. Two quadrupole magnet systems and a beam profile monitor are used for fine adjustment of the high energy ion beam trajectory. The high energy ion beam shares the beam defining aperture system in the target chamber with the low energy ion beam from the Duoplasmatron source. The high energy ion beam is passed into the vacuum chamber through the 60-degree bending magnet of the Duoplasmatron source, which has to be switched off during IBA measurements. In this operation mode the non-deflected low energy ion beam is passing the magnet chamber into a beam dump area.

The Duoplasmatron Ion Beam System (D-IBS)

The ion beam system is capable of producing hydrogen isotope and noble gas (except helium) ion beams with energies varying from 0.5 to 10 keV. The system includes the duoplasmatron source, extraction gap, Einzel lens, beam steerer assembly, beam drift tube and a double focusing 0.5 Tesla 60-degree bending magnet with inclined pole shoes and a curvature radius of 92 mm. Ions are formed in the ion source and are extracted by the extraction gap to the final beam energy with an energy spread less than 25 eV. The filament used in the source is platinum gauze, and a barium carbonate solution is used for increased electron emission. It has a lifetime of many hundreds of hours. The beam focusing on the target position is realized by the Einzel lens and the 60-degree bending magnet, which also provides energy/mass separation. Fine positioning of the beam is performed by a steerer plate assembly. It consists of two orthogonal pairs of deflection plates mounted in a row to eliminate quadrupole focusing effects.

The Cesium Sputter Ion Beam System (CS-IBS)

The Cesium Sputter ion beam system is capable of providing a wide variety of negative heavy ions with energies from 0.5 to 15 keV, which is, however, limited to 10 keV by the present voltage supply. Negatively charged ions are formed in the ion source by sputtering of a target by cesium ions. The ions are accelerated to ground potential and emerge with an energy equal to the cathode voltage and are then mass analysed by a 30-degree magnet. The magnet is capable of separating high-Z elements (e.g. mass 184 from mass 200) but the mass resolution is low enough to pass most isotopes of a given element in order to obtain maximum beam current. Its maximal magnetic field strength is 0.88 Tesla and its radius of curvature is 25.4 cm.

The Target Chamber

The vacuum chamber contains the samples for irradiation fixed on a movable holder, surrounded by a Faraday cup for precise measurement of the beam currents. Beam positions on the target are defined by beam guiding tubes with apertures at the chamber entrance and close to the target respectively. The residual pressure in the vacuum chamber during analysis is $<5\times10^{-7}$ mbar and during low energy ion irradiation $<2\times10^{-6}$ mbar. The spot of the analysing beam is located in the center of the irradiated area avoiding intersection with non-uniformly eroded parts of the surface. The following solid state detectors are used currently for IBA: proton counter, RBS detectors under 165° and 105° scattering angle. To observe the temperature of the samples a thermocouple is attached to the movable holder. To measure beam fluences the charge of the beam is measured by a current integrator. Experimental errors due to secondary electron emission can be corrected using the Faraday cup. The beam tube's system of apertures provides a diameter of the beam trace of 1.5 mm on the target plane. To avid edge effects on IBA measurements the beam tube also includes a movable aperture with a diameter of 1 mm that allows to decrease the diameter of the high energy beam area. Consequently, only the uniformly irradiated region of the target is analyzed by IBA and therefore only depth variations of the elemental concentrations need to be considered in contrast to weight loss measurements where lateral variations of the irradiation current density may lead to significant errors in the results.

3. PERFORMANCE OF THE DBE SETUP

The characteristics of the ion beams were measured by irradiating a-C:H films and then determining the beam profile using optical microscopy and profilometry. A D_3 ion beam is used since it provides the highest beam current and the lowest energy per deuterium atom at the same accelerating voltage. The right side of the graph shows the fluence that can be reached during one working day. Thus, using D_3 ion beam accelerated up to 9 keV the achievable fluence is 1.4×10^{24} D/m^2 that is sufficient for studying the effects connected to sputtering of tungsten and its D retention [10].

The cesium sputter ion beam system has been tested with carbon negative ions since this impurity is the most common in currently existing fusion devices. Because of the principle of operation [11], the system has a time variable beam current. The total collected fluence of carbon atoms is about 6×10^{22} C/m^2 using single negative ions accelerated up to 5 keV. Increase of the C fluence and/or decrease of the energy per atom is possible utilizing various negative molecules of carbon up to C_5^-. Other negative ions of fusion relevant elements which can be obtained using the source and their expected fluxes are listed in the table. One should note that the time variation of the beam current has not yet been fully investigated for every type of negative ions.

The list of negative ion species produced by cesium sputter source and their expected fluxes ($m^{-2}s^{-1}$)

H	$2\cdot10^{17}$	^{56}Fe	$6\cdot10^{16}$
^{9}BeH	$2\cdot10^{16}$	^{58}Ni	$5\cdot10^{17}$
BeO	10^{17}	^{181}TaH	$2\cdot10^{15}$
^{12}C	10^{18}	TaC	$5\cdot10^{16}$
O	10^{18}	TaO_2	10^{17}
^{48}TiH	10^{17}	^{186}W	10^{16}
^{51}VH	10^{16}	^{184}WC	$2\cdot10^{16}$
^{51}VC	$3\cdot10^{16}$	WO_3	$2\cdot10^{16}$
^{28}Si	10^{18}		

Application of thin films as irradiated targets and IBA opens new capabilities for the investigation of plasma-surface interactions, which are not available by other methods. Particularly, thin films of high-Z elements, especially tungsten, are of interest. They have already shown their suitability for such experiments [10]. Apart from D diffusion and retention, usually the penetration depth of plasma particles below the surface in the model experiments is several tens of nanometers. Thin films of high-Z elements with a thickness up to 0.5 μm allow measurement of depth profiles of both low-Z and high-Z element simultaneously by means of Rutherford back-scattering spectroscopy (RBS) and D depth profiling by means of nuclear reaction analysis (NRA). Erosion can be detected as decrease of the film thickness. Since RBS measurements take usually only about ten minutes, it is possible to measure the depth distribution of impurities depending on fluence and to compare the obtained data with results of simulation codes such as the TRIDYN program [12].

4. CONCLUSIONS

Utilization of IBA and experiments with thin films of high-Z materials is a new approach for the investigation of synergistic effects occuring under simultaneous bombardment of plasma facing elements with fuel particles and impurities. At the same time, in these experiments using IBA allows to obtain significantly more details on the plasma-material interactions than in weight-loss measurements. Coupling all the advantages together, it may allow to clarify synergistic mechanisms of erosion which do not occur under bombardment with single species.

REFERENCES

1. G. Janeschitz. ITER JCT and ITER HTs. // *J. Nucl. Mater*. 1 (2001) 290-293.
2. D. Meade, et al. Mission and design of the fusion ignition research experiment. // *Proceedings of the 18th IAEA Conf. on Fusion Energy, Sorrento, Italy October, 2000*. (CD-ROM), pp. IAEA-CN-77/FTP2/16, IAEA, Vienna, 2001.
3. S. Nishio, et al. Conceptional design of advanced steady-state tokamak reactor. // *Proceedings of the 18th Conf. on Fusion Energy, Sorrento, Italy October, 2000*. (CDROM), pp. IAEA-CN-77/FTP2/14, IAEA, Vienna, 2001.
4. G. Federici, et al.// *J. Nucl. Mater.* 266_ 269 (1999) 14. Upgrade Team // *Nucl. Fusion,* 40 (2000) 1441.
5. N. Peacock, R. Barnsley, N. Hawkes, K. Lawson, M. O. Mullane. *Diagnostics for Experimental Thermonuclear Fusion Reactors.* / Ed. P. Stott, G. Gorini, E. Sidoni. Varenna (Italy), Plenum, New York, 1996, p. 291.
6. D. Post, R. Jensen, C. Tarter, et al. // *At. Data Nucl. Data Tables,* 20 (1977) 397.
7. K. Krieger et al.// *J. Nucl. Mater.* 266 –269 (1999) 207.
8. K.Krieger, J.Roth. Synergistic effects by simultaneous bombardment of tungsten with hydrogen and carbon.// *Journal of Nuclear Materials,* 290-293 (2001) 107-111.
9. K.Schmid, J.Roth. Erosion of high-Z metals with typical impurity ions. // *Journal of Nuclear Materials* 313 – 316 (2003) 302 –310.
10. I. Bizyukov, K. Krieger, N. Azarenkov, S. Levchuk, Ch. Linsmeier. Formation of D inventories and structural modifications by deuterium bombardment of tungsten thin films. // *Proceedings of 16th International Conference on Plasma-Surface Interactions, May 27-31, 2004*, in press.
11. G.D. Alton // *Nuclear Instruments and Methods in Physics Research,* B73 (1993) 221-288.
12. W. Moeller, W. Eckstein, J.P. Biersack // *Comput. Phys. Commun*. 51 (1988) 355.

ВОЗМОЖНОСТИ НОВОГО ДВУХ ЛУЧЕВОГО ЭКСПЕРИМЕНТА ПО ОДНОВРЕМЕННОМУ ОБЛУЧЕНИЮ МАТЕРИАЛОВ ДВУМЯ ВИДАМИ ИОНОВ

И. Бизюков, К. Кригер, Н. Азаренков

Первые эксперименты показали, что одновременная бомбардировка изотопами водорода и частицами примесей приводит к синергетическим эффектам, при которых степень эрозии материалов не может быть объяснена суперпозицией распылительных процессов. Для изучения этих эффектов разработана и смонтирована новая двух лучевая экспериментальная установка. Эта статья описывает ее конструкцию и доступные экспериментальные возможности.

МОЖЛИВОСТІ НОВОГО ДВОПРОМЕНЕВОГО ЕКСПЕРИМЕНТУ ПО ОДНОЧАСНОМУ ОПРОМІНЕННЮ МАТЕРІАЛІВ ДВОМА ВИДАМИ ІОНІВ

І. Бизюков, К. Крігер, М. Азаренков

Перші експерименти показали, що одночасне бомбардування ізотопами водню і частками домішок приводить до синергетичних ефектів, при яких ступінь ерозії матеріалів не може бути пояснений суперпозицією розпилювальних процесів. Для вивчення цих ефектів розроблена і змонтована нова двопроменева експериментальна установка. Ця стаття описує її конструкцію і доступні експериментальні можливості.