AMS MEASUREMENTS OF FUEL RETENTION ON THE SURFACE OF MATERIALS USED IN FUSION EXPERIMENTS

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This paper presents the experimental data obtained with the Accelerator Mass Spectrometry analyzing method, concerning the surface retention of hydrogen isotopes in carbon materials under the conditions when at the same time with the fuel retention phenomenon other eroded materials are deposited. Tungsten surface covered for carbon tiles were also investigated.

Keywords: Tritium, deuterium, AMS depth profiling.
PACS: 25.45.-z, 52.55.-s, 52.55.Gj, 07.75. +h, 07.77.-n

1. Introduction

Today, in order to finalize the construction of the first International Thermonuclear Reactor (ITER) in Cadarache-France (see fig.1) there is a high and very special interest for research of materials used for the construction of the fusion facilities.

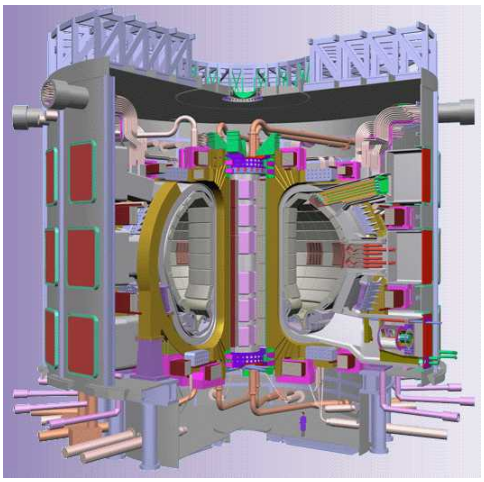

Fig. 1: The ITER tokamak under construction in Cadarache France that will be the first testing fusion reactor in world.

To collect the data necessary to solve the last problems related to the design, to the construction materials and to the all subsequent operations, several

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tokamaks around the world are currently performing detailed experiments. Between them, we mention the Axially Symmetric Divertor Experiment (ASDEX –Upgrade) and the Joint European Torus (JET) - the largest existing Tokamak.

An important issue of this research is the interaction of the plasma with the main wall components of the vessel. Hot plasma causes erosion and formation of the deposited/co-deposited layers of the mixed materials and of the spatially non-uniform tritium retention. An accumulation of hydrogen isotopes in the First Wall Materials (FWM) of the vacuum vessel may create problems for the operation of future fusion devices such as ITER, from both perspectives of safety and of economy.

The amount of retention depends on the nature of the FWM of a fusion device and also on the plasma operation conditions. Carbon based materials suffer from erosion even at low plasma temperatures and co-deposition of the eroded carbon with tritium and deuterium may lead to high fuel inventories in the wall structures. For these types of analyses, Accelerator Mass Spectrometry (AMS) is a powerful and highly sensitive analyzing method that selects and detects the atoms individually. The AMS measurement of hydrogen isotope retention within the plasma facing components (PFC) goes more than 10 years back [1, 2]. It is able to perform the depth profiling of fuel elements in the bulk or materials of different components in the tokamak and it is also able to provide information on material migration, erosion/deposition and finally on fuel retention.

This paper will present the AMS experimental data obtained from the fusion experiments with respect to the surface fuel retention in the plasma facing components and results of experiments of simulation performed in the laboratory reproducing the same conditions as in a real tokamak system. This issue is important for determining the role and the effect of the practiced deposition layers (W or Be) on tokamak protection tiles.

The first chapter describes an introduction to the AMS method. The second chapter describes the experimental results obtained by AMS depth profile measurements concerning surface fuel retention of protection tiles under real and simulated conditions of a fusion experiment. They are followed by conclusions. Last chapter will make a summary and draw the conclusion of these experiments.

1. The ams method

The Accelerator Mass Spectrometry is a highly sensitive analysing method that selects and detects the atoms individually. The AMS selects and counts the number of impurity atoms of an element in a sample (e.g. D/C or T/C). It is able to measure all different kinds of energetic particles that are impinging on the plasma facing components and that are retained into the surface or into the bulk. The AMS can perform the depth profiling of the hydrogen concentrations in

different host materials and therefore it represents a powerful analyzing method for the very serious task of studying the fuel retention inside the tokamak. In Fig. 2 the schematic view of our AMS machine at IFIN HH [3] is shown.

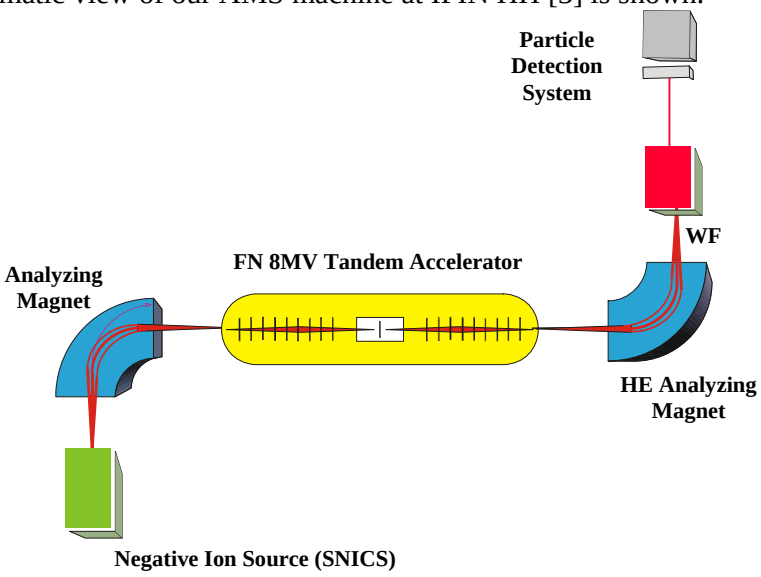

Fig. 2: Schematic view of the AMS machine at the 8 MV tandem accelerator at IFIN HH, Bucharest.

In a nutshell, the analyzing machine consists of an ion source, a tandem particle accelerator, several electromagnetic filters and a sensitive charged particle detector. The samples to be analyzed are loaded into the ion source, where they are collided by a $^{133}Cs^{+}$ accelerated ion beam in order to produce sputtered ions from the target.

The depth profiling of the concentration of elements (D, T etc.) in the bulk of the sample is performed by taking advantage of the sputtering process performed by the focused Cs beam onto the material of the sample. The analysis is done step by step, as the sputter beam is advancing into the bulk of the sample, producing a crater. The released atoms can be selected and detected with a time resolution corresponding to 20 nm of depth. This is also the lowest resolution that can be attained. The sputtered beam aria on the target is no more than 2 mm^2.

Experimentally AMS depth profiling (DP) is performed by sputtering the sample material in the ion source with the Cs beam and by measuring the element concentration in relation to the lapsed time. The time scale can be later converted to depth value if one performs, at the end of the in-beam experiment, an optic profilometry that determines the total crater depth. These optic data will also be used to calculate the correction of the rim effects into the depth profile [4]. In this way the AMS-DP provides a detailed scan of hydrogen isotopes distribution

inside of the bulk of the investigated sample material. Of course, such DP represents a "snap shut picture" of the concentration distribution in the depth that is taken at the moment of the experiment. Due to inherent diffusion the T or D concentration will vary further on.

Quantitative depth profiling of material concentrations also requires reference samples. Their structure must be identical (same atomic matrix) with the material under investigation and this is not always a simple task (e.g. T/ C, T/Si, T/W, T/Be, D/C etc). Reference samples were made in our laboratory [5]. The measured data is expressed in units of ion concentration, in atoms/$cm^{3.}$ It can be easily converted using the optic profilomerty to bulk inventories expressed in atom/cm^2. The overall errors never exceeded 30 % and were typically bellow 15%.

Since the AMS-DP analyses are performed for light nuclei, the particle detection is done with a simple detector array composed of three sequential PIN diodes. Such a set-up eliminates possible molecular interferences.

2. Results and interpretation

To produce the fusion of light nuclei (a gas mixture of H, D and T) the tokamak performs the confinement of the fuel plasma. Discharge currents up to 5 million amperes are induced into the plasma in order to produce fusion. These current discharges lead to burning plasma and the fusion occurs during the plasma confinement in a magnetic "cage". The duration of plasma confinement and fusion reaction is of tens of seconds up to few minutes. The huge current inherently heats up the plasma and due to radiation a significant fraction of energy will be lost. On the one side, these energy losses have to be recovered by additional heating while on the other side one has to protect the walls from the enormous heat of the plasma core. The protection of the tokamak vessel (inner and outer) wall, until end of 2009, was made out of the so called CFC (Carbon Fiber Composite) carbon protection tiles**.** This material has similar structure with the material used for the heat shields of the cosmic rockets [6].

For the future fusion reactor, ITER was planed to be equipped with beryllium and tungsten materials that would better reject the penetration of hydrogen isotopes and would be much easier to be decontaminated from the radioactive tritium [7]. Unfortunately, experimental results concerning the behavior of such materials exposed to hydrogen fluxes are very sparse.

Divers analyses methods of plasma facing components, like Rutherford Backscattering (RBS) , Proton Induced X-ray Emission (PIXE) , Secondary Ion Mass Spectrometry (SIMS) etc. are performed on slices cut from those materials. Usually, tokamak protection tiles are drilled to extract cylinder like samples which are then cut to thin slices suitable for the analyses. Such kind of samples can also

be used for AMS analyses however, it is more suitable to use separated prepared samples of pyrolitc carbon that can be mounted in-between of the protection tile or in other important locations. Such samples, called Test Samples (TS), were used to perform the AMS–DP analyses. TS are made of small carbon slices (8 x 12 mm) loaded on a frame provided with a mobile shuttle that is opened by magnetic field during the discharge in the tokamak vessel. In this way, the carbon TS remains untouched during the sputter cleaning procedures applied for periodic decontaminations. They can be mounted in-between the protection tiles in each desired location without perturbing the inner magnetic field geometry. The TS can be efficiently used for measurement without any dismounting and cuts of the protection tiles. They do not depend on the material structures of the tiles (that can be used between the Be and W tiles). Also, they have an uniform and compact internal structure and a flat mirror-like surface providing unperturbed information on the energy and concentration of the implanted particles.

Finally, the TS are used by the AMS-DP similar to a particle track detector, determining from the penetration range the energy of the incident particles and from the width of the concentration peak an estimate of the outspread of particles incident angles. To illustrate the resolution of this method an example is given Fig. 3, showing the deuterium depth profile measured by AMS in TS placed on the inner wall of the tokamak in a position opposite to a neutral beam injector (NBI) of 140 keV deuterium.

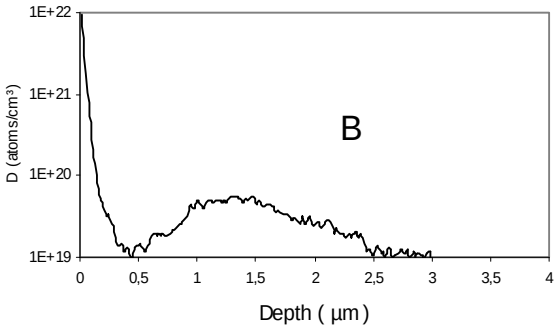

Fig. 3: Deuterium depth distribution displaying a broad second maximum of the concentration that corresponds to the penetration in carbon of energetic deuterium atoms (140 keV) produced by the Neutral Beam Injection system.

The “surface” peak, starting at zero depth, corresponds to the absorbed deuterium with energy in thermal equilibrium with the plasma energy. The second peak corresponds to the penetration range in carbon of the injected 140 keV neutral deuterium in the tokamak vessel by the NBI system of the tokamak. It represents the fraction of injected particles that is not interacting with the plasma

and is implanted into the opposite wall of the tokamak. The broad peak shows that the incidence angular distribution of incoming particles is large (approx. 100^0). A tailing on both sides of the concentration DP corresponds to diffusion of the hydrogen isotope in carbon.

The aim of this research is to study deposition, penetration and surface retention of the hydrogen isotopes (D and T) in the tokamak protection tiles that happens during the fusion experiments. The hydrogen isotopes are implanted into the plasma facing materials and into the vessel walls with the thermal energy of the plasma (10 up to 20 keV). Their energy can be higher when these particles are repelled from interactions with other energetic particles injected as neutrals (see below, NBI), or up to 1.01 MeV, when tritium escapes from the DD fusion reaction produced in the confined plasma. Fig. 4 shows concentration DP spectra of tritium colliding on the TS with energies higher than the plasma temperature. These are T ions with energies of 50-60 keV that were partially decelerated form the initial energy of 1.01 MeV by rotating in the plasma enclosure and were finally lost but before the end of the discharge, when all produced tritium comes to equilibrium with the hot plasma and have thermal energies.

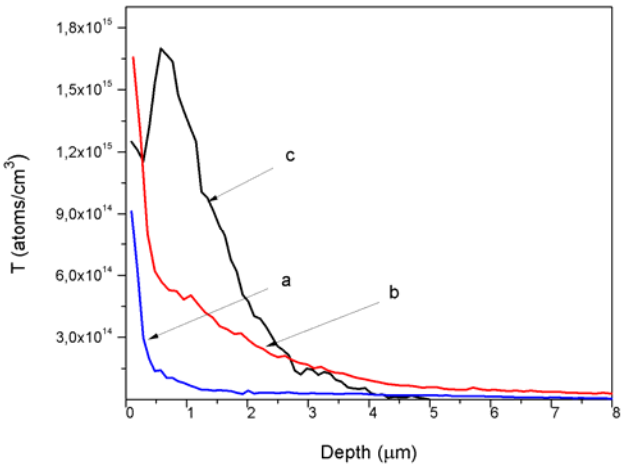

Fig.4: AMS depth profile spectra of tritium penetrations in TS carbon substrates: a) depth profile with centroid at 10 keV, corresponding to particles in equilibrium with the plasma temperature, b) depth profile revealing an overlap of low energy tritium accumulation (10 keV) and of tritium escaping with 60 keV and large incidence angular outspread, c) peak of the depth distribution at 50 keV indicating a grouped bunch of incidental particles escaping the plasma confinement.

However, in order to investigate the surface fuel retention only low energy particles have to be able to bombard the TS. For this reason TS were placed in hidden locations of the tokamak vessel that are not directly exposed to the plasma, far away form the confinement region. The hydrogen isotopes, will

reach these locations at the end of the discharges when thermal expansion of the plasma will take place. Since in a tokamak fusion experiment it always exist erosion and transport of intrinsic impurities (Be and C) and fuel (D), followed by depositions and re-erosion, an investigation of a low-energetic deposition of fuel on different plasma facing materials would reveal the aspects of such a behaviour.

Fig. 5, below, presents tritium and deuterium concentration depth profiles measured by AMS-DP for particles with energies below 10 keV retained on the surfaces of the measured TS. These spectra reveal the details of the retention of low energetic hydrogen isotopes on a carbon substrate in the context of co-deposition of Be and C impurities.

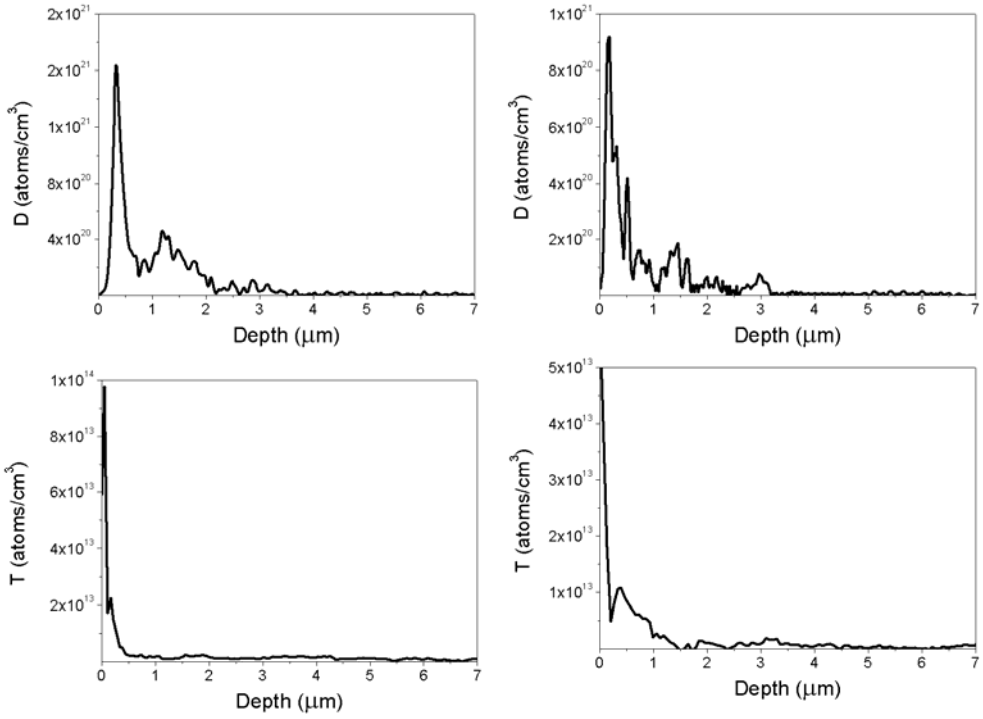

Fig. 5: AMS depth profiles of hydrogen surface depositions on carbon substrates. Deposition accompanied by carbon and beryllium co-depositions on carbon substrate of deuterium (upper spectra) and tritium (lower spectra).

Typical for such composed multi-material deposition are the oscillations visible in the concentration depth profile spectra. The oscillations are caused by the depositions of the different materials (^{13}C, ^{12}C, ^{9}Be, ^{1}H and ^{2}H) and occur

regularly in a tokamak vessel due to erosion. Sandwich-like structures are formed by intercepting hydrogen isotopes in-between the deposited layers. Such formed structures are not compact, are loosely bound on the surface of the tiles and modify the properties of the PF materials. In the hidden location from high energetic particles neither deuterium nor tritium would have had sufficient energy to penetrate more than 0.3 μm in the carbon substrate of the TS. As can be seen from Fig. 5 concentrations of D and T are visible until few microns of depth. This is the height of deposited material. Correspondingly, the DP of hydrogen isotopes concentrations will be measured shifted to a deeper depth, where the particles could not penetrate with their small thermal energy.

Besides the retention of fuel elements in carbon, another crucial issue for the reactor walls of the future ITER is the retention of fuel elements that occurs in tungsten and beryllium. Therefore, preserving the exposure of TS to low energetic hydrogen isotopes we investigated the fuel surface retention in tungsten. The exposed samples were carbon slices 3 mm thick with a 20 μm tungsten layer deposition on the surface. The AMS-DP of retention for the two samples exposed to deuterium and tritium gas in laboratory simulations are shown in Fig. 6.

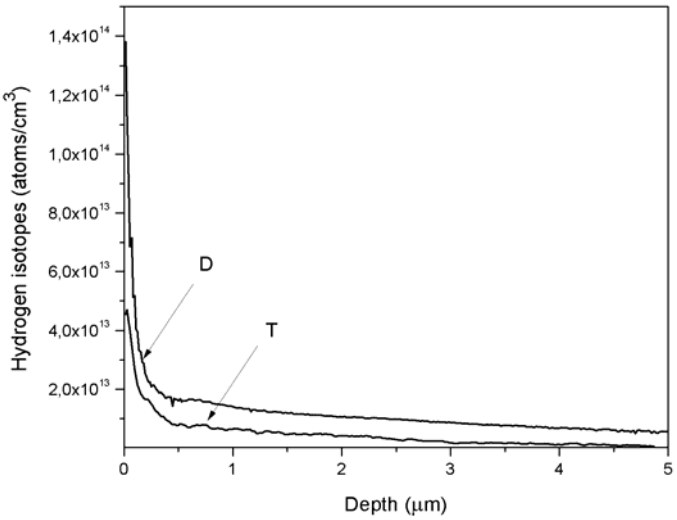

Fig. 6: Low energy deuterium and tritium retention on tungsten substrate.

As can be seen from these DP the entire retention is strictly on the surface of the sample. The tungsten layer is 20 μm thick and the tritium retention is vanishing rapidly after 5-6 μm. The deuterium retention is in some extent more persistent. Responsible for the long tailing of the distributions is the roughness of the W-coated sample that is enhancing the diffusion,

The depth profile spectra integrated over the explored depth give the inventory of the retained hydrogen isotope, expressed in at/cm^2. Such inventories of D and T were compared for carbon and tungsten substrates, showing an important reduction in the later substrate by factors between 8 and 11. Same measurements have shown that the drop of the hydrogen isotopes concentrations in tungsten is more rapid than in carbon showing that tungsten has lower affinity than carbon to retain hydrogen isotopes. However, at this moment is not clear if this reduction is due to the opacity of tungsten to hydrogen penetration or if W is highly permeable to hydrogen and the entire hydrogen inventory will be found into the bulk of the exposed material. The same considerations might be valid for Be coatings of the tokamak wall protection tiles. Such studies are continuing in the frame of the ITER like Wall experiment, in order to demonstrate the plasma compatibility with the metallic wall and with aim of the reduction in the fuel retention [7, 8, 9].

4. Summary and conclusions

More then twenty years ago it was recognized that AMS and the Full Combustion Method followed by scintillation detection (FC-SD) are the only analyzing methods capable to perform sensitive measurements of tritium in carbon materials. In the last decade the rapid progress in fusion technology opened a large area of new applications that required inherently an evolution and upgrading of the AMS-DP experiments and complimentary by FC measurements to obtain information of the bulk concentration of T [10].

Unfortunately, the protection tiles used in the tokamak are made of CFC that is a loosely bound carbon structure, with many holes and caverns. Independent of the incident particles energy the fuel retention is high in these plasma facing components. Therefore, tungsten and beryllium depositions on the surface of the PFC were the hope of stopping the retention of D and T. During the last major shutdown performed during 2009-2011, JET has been completely equipped with beryllium and tungsten materials. The new lining is called the “ITER-Like Wall” because the materials are the same as the ones chosen for ITER. With this idea many other fusion experiments around the word have started to replace the classical carbon protection tiles with tungsten or beryllium tiles or only by covering the carbon tiles with such metals.

In this paper AMS depth profiling technique was applied to investigate the affinity of carbon and tungsten substrates to the retention of low energy hydrogen, when the energetic implant is excluded. Retention in carbon was studied in conditions were co-deposition of eroded materials from the tokamak vessel (^{13}C, ^{12}C, ^{9}Be, ^{1}H, ^{2}H) is present. It was shown that at low energies sandwich-like structures are formed on the sample surface by intercepting hydrogen isotopes in-

between the deposited layers, modifying the properties of the protection tiles in a tokamak.

An inter-comparison of retention in carbon and tungsten was also investigated by using simulated conditions in the laboratory and it was shown that hydrogen isotopes have better affinity on carbon substrates than on tungsten.

Nevertheless, it is still to be investigated if the tungsten and beryllium are reducing the fuel retention by blocking the material deposition, solely, on their surface, or if such materials are permeable to hydrogen isotopes and their screening effect to fuel retention would small. Experiments to clarify this important issue are continuing on JET samples exposed during the JET-ILW operations (using tungsten coated plasma facing materials) in comparison with previously performed JET-C references under various plasma conditions.

R E F E R E N C E S

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