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The role and application of ion beam analysis for studies of plasma-facing components in controlled fusion devices

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ABSTRACT

First wall materials in controlled fusion devices undergo serious modification by several physical and chemical processes arising from plasma–wall interactions. Detailed information is required for the assessment of material lifetime and accumulation of hydrogen isotopes in wall materials. The intention of this work is to give a concise overview of key issues in the characterization of plasma-facing materials and components in tokamaks, especially in JET with an ITER-Like Wall. IBA techniques play a particularly prominent role here because of their isotope selectivity in the low-Z range (1–10), high sensitivity and combination of several methods in a single run. The role of ^{3}He-based NRA, RBS (standard and micro-size beam) and HIERDA in fuel retention and material migration studies is presented. The use of tracer techniques with rare isotopes (e.g. ^{15}N) or marker layers on wall diagnostic components is described. Special instrumentation, development of equipment to enhance research capabilities and issues in handling of contaminated materials are addressed.

1. Introduction

An integrated science and technology programme is implemented worldwide to provide operation conditions and to construct a power-generating reactor based on controlled thermonuclear fusion of hydrogen isotopes. Taking into account the reaction cross-sections the most efficient fuel for a reactor is a 1:1 mixture of deuterium and tritium: $D + T \rightarrow \alpha + n + 17.6$ MeV [1]. Strong magnetic fields of several Tesla are used to produce, to confine and to control hot plasmas in toroidal vacuum chambers: either tokamaks [1] or stellarators [2] dependent on the configuration of coils. A tokamak-type configuration has been chosen for ITER (International Thermonuclear Experimental Reactor) being under construction in Cadarache, France. The construction phase is accompanied by a very intense research carried out in several existing fusion devices and also in laboratories and industrial entities engaged in testing and development of materials and components for the plasma-facing wall, diagnostics, various plasma heating systems, magnetic coils, etc.

Material science and engineering are among priority areas of research, because first wall materials in controlled fusion devices undergo serious modification by physical and chemical processes arising from plasma–wall interactions (PWI) [3–6]. The knowledge on material performance under extreme conditions (temperature and radioactivity) is crucial for the development of a power plant reactor. Detailed information is required for the assessment of material lifetime [3,7–9], dust formation [10–16] and accumulation of hydrogen isotopes in wall materials [3,5,6,17–25]. These issues are decisive for the economy and safety of reactor operation. This calls for broad studies on the behavior of wall materials under impact of hot plasmas. There is no ideal element, alloy, composite or compound as a constituent of a plasma-facing wall. For many years carbon (in the form of fiber composites, CFC), beryllium and tungsten have been considered and tested as candidates in

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[1] See Appendix to the F. Romanelli et al., Proc. 25th IAEA Fusion Energy Conf. 2014, St Petersburg, Russia.

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tokamaks and in material research laboratories. The use of all three was planned for different areas of the ITER wall, dependent on the power loads to be deposited. Carbon – the most relevant for power handling and resilient to thermal shocks – has been eliminated from the list because of its affinity to hydrogen isotopes (I) towards the formation of volatile C_xI_y compounds, their transport and re-deposition. As a consequence, it would lead to unacceptable level of radioactive tritium inventory in the reactor [3,26,27]. The decision on the final material choice was preceded by the first large-scale test of the simultaneous use of beryllium and tungsten in the JET tokamak with the ITER-Like Wall (JET-ILW): Be in the main chamber wall and W in the divertor [28–32]. A significant reduction of the fuel inventory has been observed in comparison to the operation with a carbon wall (JET-C).

Knowledge and understanding of material behavior requires broad experimental programme in fusion devices and thorough material analyses before and after exposure to plasma. The aim of this paper is to provide an overview of surface analysis, especially ion beam techniques, in the determination of wall material modification in controlled fusion. Particular emphasis is given to the research programme at JET-ILW. The paper is structured along the points: "*what*" is to be analyzed and "*why*", and then "*how*" the analyses are carried out. This also includes the use of special diagnostic instrumentation, tracer techniques and development of equipment for efficient analysis.

2. Objectives and objects of analysis

Toroidal chambers of tokamaks belong to largest ever constructed and operated vacuum vessels. JET is currently the world's largest tokamak. The volume of its vacuum vessel exceeds 100 m^3 (ITER will be approximately 8 times larger) and the total wall area is several hundred m^2. The wall structure is very diverse, as exemplified in Fig. 1 on which a toroidal view into the JET-ILW is presented. The entire vessel is composed of the main chamber and – at the bottom – the divertor where the greatest power loads are deposited. The main plasma-facing components (PFC) are outer poloidal limiters (OPL), inner wall guard limiters (IWGL), upper dump plates (UDP), all three types made of Be, and the divertor (DIV) plates made either of bulk tungsten or W-coated CFC. Other parts are inner wall cladding (IWC, beryllium coated Inconel) and various types of antennae (AN) for auxiliary plasma heating. On the left there is a remotely handled (RH) robotic arm for all in-vessel operations such as installation, exchange of PFC and diagnostics in the environment containing beryllium and tritium, the latter originates from the fusion reaction $D + D \rightarrow H + T + 4.03$ MeV and the residual amount after the full D–T operation in 1998 [17,19,27].

The ultimate aim of the analysis is to obtain as complete as possible a pattern of material modification and migration arising from erosion–deposition phenomena. It is done by addressing a number of questions: (i) where are the erosion zones; (ii) where is the eroded material deposited; (iii) how are the materials modified; (iv) how much fuel is retained in the wall and, eventually, (v) what is the impact of wall materials on material migration? The aim can be achieved only by studying a set of PFC representative for various areas in the device: tiles from at least one full poloidal cross-section of the divertor and a number of limiter tiles and dump plates. By this one may obtain proper insight into material migration on the main chamber wall (behind the limiters) and in remote areas of the divertor, i.e. zones shadowed from the direct plasma line-of-sight where the greatest fuel inventory occurred in JET with carbon walls [17,19,23]. To deal with such points a large number of erosion–deposition diagnostic tools are used at JET in many locations schematically marked in Fig. 1. Marker tiles (filled rectangles and ovals) are installed in all important locations in the limiter arrays and in the divertor. Wall probes (WP, light filled ovals and circle) such as rotating collectors, inserts in IWC, quartz microbalance (QMB), louvre clips and units with mirrors for the First Mirror Test (FMT) at JET for ITER are in two positions in the main chamber and in shadowed areas in the divertor. All details regarding marker tiles and wall probes in JET-ILW have been described earlier [33].

In detailed analysis of wall materials the interest is in the determination of all species which may be present in the reactor H, D, T, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}Be, ^{10}B, ^{11}B, ^{12}C, ^{13}C, ^{14}C, ^{14}N, ^{15}N, ^{16}O, ^{18}O, ^{19}F, ^{20}Ne, ^{21}Ne, ^{22}Ne, Si, Cr, Fe, Ni, Mo, W, Re. These are hydrogen fuel isotopes, wall constituents (C, Be, W, Inconel components, Mo) or those used in plasma diagnosis systems and/or for wall conditioning (He, B, C, Si), common impurities (C, O), gases seeded for plasma edge cooling (N, Ne) and tracers introduced deliberately to the system in minute quantities to study material migration. The latter category comprises rare isotopes ^{13}C [23,34–36], ^{15}N [37,38], ^{18}O [39] injected in the form of gases or as solids ^{9}Be [40] or Re [36]. The presence of ^{14}C has also been monitored [36]. The main point is the need to characterize qualitatively and quantitatively a mixture of low-Z isotopes and – on many occasions – to resolve a spectrum in which there are simultaneously many of the species listed above.

3. Material analysis: methods and laboratory equipment

Analyses of materials from different devices have been carried out regularly since eighties when several medium and large size devices came to operation: ASDEX, TFTR, TEXTOR, JET and JT-60. More than forty different material research methods have been used over the years for analysis of PFC and probes exposed to plasma in fusion devices and simulators of PWI. A list of the most important methods comprises high-resolution microscopy and techniques providing data on hydrogen isotopes: thermal desorption spectroscopy (TDS), secondary ion mass spectrometry (SIMS), liquid scintillography and IBA methods. The latter group (i.e. IBA) plays a prominent role as the most versatile set of tools: nuclear reaction analysis (NRA), elastic recoil detection analysis (ERDA) including high energy heavy ion variants, Rutherford backscattering spectroscopy (RBS), enhanced proton scattering (EPS), particle-induced X-ray emission (PIXE), and accelerator mass spectrometry (AMS). The importance of IBA in PFC studies was recognized in the seventies [41,42]. Since then the area has grown becoming a well established field of research, but still meeting new challenges related to the operation with both very low-Z and very high-Z materials. NRA based on ^{3}He-induced process has a particular place in the catalogue of methods as the most efficient approach to the quantification and depth profiling of deuterium [43]. Studies of the cross-sections of ^{3}He reactions over a wide range of energies and of the determination of analysis limits in different materials are still carried out to perfect the analytical outcome [44–47]. Nuclear reactivity of that helium isotope is also very broadly used to quantify simultaneously D, Be, C and other light nuclei [17,18,22,23].

There are several specific issues in studies of material from tokamaks, especially in the case of JET where one deals with contaminated specimens: retrieval from the torus, handling and sampling. Wall tiles and probes can be retrieved and replaced by a new set only during major shut-downs with all in-vessel actions done by remotely controlled robots. This is followed by the transfer of items to the Beryllium Handling Facility (BeHF) where all operations (e.g. dismantling from the divertor carriers, packaging) are performed in glove boxes by personnel wearing air hoods or pressurized suits, as shown in Fig. 2.

There are two major categories of items retrieved: those which have spares and can be replaced and those without spares. The cost