Contribution ID: **940** Type: **Regular Poster**

Plasma-Surface Interaction in the Stellarator W7-X: Conclusion Drawn from Operation with Graphite Plasma-Facing Components

Thursday 13 May 2021 18:25 (20 minutes)

Wendelstein 7-X (W7-X), the currently largest operating stellarator in the world, finished successfully its first operational phase in divertor configuration using the so-called test divertor unit (TDU) [Klinger]. Plasma-facing components (PFCs) made of fine grain graphite, designed to sustain without active cooling power loads of $10MWm^{-2}$, were used to exhaust the plasma particle and power in the 3D-geometry of the toroidal device with five-fold symmetry. No significant damage occurred to the 10 divertor modules in the executed $3.6h$ of integral operation in hydrogen (H) and helium (He) plasmas; performed in two timely separated campaigns. The carbon (C) divertor with a total area of $25m^2$, received peak heat loads up to $10MWm^{-2}$ and up to $200MJ$ energy was coupled into the ECRH-heated plasma discharges with a maximum duration of $100s$. The corresponding particle exposure with peak fluxes up to few $10^{23}ionss^{-1}m^{-2}$ to the divertor and $10^{21}ionss^{-1}m^{-2}$ to the first wall - consisting of graphite heat shields, baffles, and stainless steel panels - resulted in a manifold of plasma-surface interaction (PSI) processes in the complex geometry with the island divertor. W7-X superseded the expected plasma performance with adiabatically cooled divertor, demonstrating plasmas at high central density beyond $1.5 \times 10^{20}m^{-3}$, high neutral compression in the divertor, and discharge durations up to $30s$ at an input power of $5MW$ and detached divertor. Access to this operational regime was only possible owing to dedicated wall conditioning with boronisation in the second operational campaign where the oxygen (O) impurity content in the plasma was reduced by more than one order of magnitude with respect to the first one (fig. 1). The latter is consistent with a reduction of Z_{eff} from typically 3.5 to 1.5 due to a drop of the O and associated C content in H plasmas.
The PSI processes in the full-C W7-X device will be discussed and relations to the predicted long-pulse operation of up to $1800s$ as well as first consequences for the need to control PSI processes will be drawn. Important with this respect is a) the balance of C in W7-X, namely the identification of erosion and deposition areas as well as the material transport paths between those; b) the balance of fuel (H and He) in W7-X, namely the balance of injection, retention, release, and recycling. In view of steady-state operation, these processes determine the lifetime of divertor PFCs, the fuel cycle and plasma control, as well as the C dust production. The studies include in particular also impurities like O, resulting from leaks and water release, B, resulting from boronisation in B_2H_6/He glow discharges, as well as $Ne,\ N_2,\ CH_4$ from impurity seeding for radiation cooling or diagnostic purposes.
The footprint of C migration and the H content in PFCs has been assessed via two main paths since start of W7-X operation with TDU, which is now completely extracted from the W7-X vessel.
(i) Post-mortem analysis of extracted PFCs provides the integral H and C pattern for one campaign and includes all kind of plasma conditions and configurations. Embedded marker layers provide access to net erosion and deposition at specific locations in the divertor and first wall. Complementary, invasive techniques like colourimetry reveal global pattern information for the complete vessel surface. A typical example of the erosion and deposition pattern in poloidal direction on a single C/Mo/C marker tile of the divertor horizontal target plate at the strike-line shows fig. 2.
A number of analysis techniques like EBS, EDX, LIA-QMS, and LIBS is applied to determine the erosion of and the retention in graphite tiles. Peak erosion rates of $2.5 - 5.0nms^{-1}$ were determined by EDS and LIBS leading to an overall peak C erosion of $\simeq 10m$ in the standard configuration with five magnetic islands. Extrapolation to all divertor modules and thus, to the integral C source in W7-X leads to $\simeq 50g$ eroded C in this predominant configuration ($\simeq 2500s$) of the first campaign [Mayer].
The local retention rate varies depending on the relevant physics mechanisms: implantation, co-deposition the application of He plasmas. Retention up to $1 \times 10^{22}Hm^{-2}$- was found via LIA-QMS in co-deposits with up to $1.5m$ C layer thickness after the first campaign.
(ii) Dedicated experiments with $^{13}CH_4$ marker injection allow the study of ^{13}C transport and global migration in a carbon device utilising both carbon spectroscopy and post-mortem analysis. The first marker experiment in W7-X has been carried out as last experiment before tile removal in a series of consecutive discharges [temperature $T_e = (2.8-3.2)keV$, density $n_e = (5.0-6.0)\times 10^{19}m^{-3}$, input power $P_{input} = (3.4-3.9)MW$ with attached divertor [temperature $T_{e,OSP} \simeq 25eV$, density $n_{e,OSP} \simeq 1.0\times 10^{19}m^{-3}$) accumulating $330s$ of plasma with identical conditions in standard configuration. 4.5×10^{22} ^{13}C atoms were introduced as methane through gas inlets located in one horizontal divertor module. The injected ^{13}C is intended to mimic the erosion of ^{12}C at the TDU and allows to follow-up C transport paths. In-situ optical emission spectroscopy of methane break-up products (CH, C, C^+, C^{2+}) is used to characterise the local interaction at the

target plate. Post-mortem nuclear reaction analysis is applied to determine the local ^{13}C footprint on the horizontal and vertical target plates. The marker experiment provides a test bed for global erosion and deposition modelling with the 3D material transport codes ERO2.0 [Romazanov] and WallDYN3D [Schmid] coupled to an EMC3-EIRENE plasma background. Both codes are currently benchmarked against carbon spectroscopy and surface pattern of ^{13}C and deconvolute the migration paths from the divertor target plate to other areas for a given plasma and magnetic configuration. Fig. 3 describes initial results from ERO2.0 regarding the net C erosion and deposition pattern for the standard plasma background, but without ^{13}C injection activated.

The presented results about PSI processes in W7-X show peak erosion rates at the strike-line and the net migration pattern of C as well as the associated fuel retention. ERO2.0 and WallDYN3D modelling reveal the actual migration pathways with sources (net erosion areas like strike-lines) and sinks (net deposition areas like baffles). Extrapolation towards the anticipated $1800s$ discharges in attached plasma conditions suggest critical peak erosion up to $10\mu m$ at the strike-line and associated deposition of about $1\mu m$ on shadowed areas of the divertor and the baffle tiles per discharge. The deposited layers can with time become instable and induce C dust as observed before in Tore Supra long-pulse discharges. Counter measures will require adaption of the divertor operation regime and reduction of impurity levels by wall condition techniques.

[Klinger] T. Klinger et al 2019 Nucl. Fusion 59 112004
[Wang] E. Wang et al., Phys. Scripta T171 014040 (2020)
[Mayer] M. Mayer et al., Phys. Scripta T171 014035 (2020)
[Romazanov] J. Romazanov et al., NME 18, January (2019) 331
[Schmid] K. Schmid et al., - to be presented at PSI conference 2020

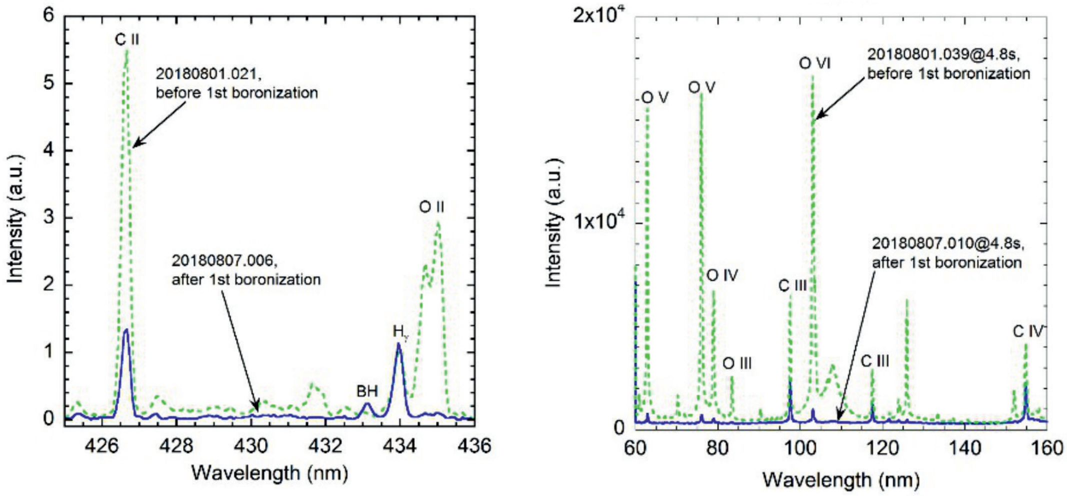

Figure 1: Impact of the first boronisation on impurities in the divertor (left) and in the confined plasma (right). [2]

Figure 1:

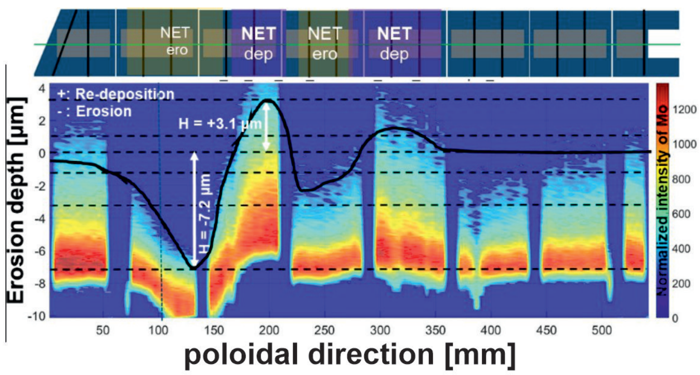

Figure 2: Poloidally resolved erosion and deposition pattern on a graphite tiler of the horizontal target determined by LIBS.

Figure 2:

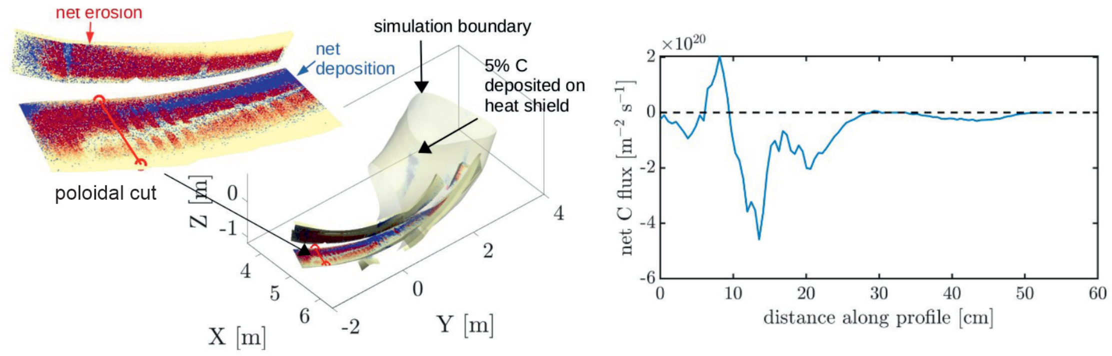

Figure 3: First ERO2.0 results on C erosion and deposition in W7-X plasmas in standard divertor configuration [left]. C erosion/deposition pattern in poloidal direction at the location of the LIBS measurements [right].

Figure 3:

Country or International Organization

Germany

Affiliation

Forschungszentrum Jülich, Institut für Energie- und Klimaforschung –Plasmaphysik, 52425 Jülich, Germany

Authors: NAUJOKS, Dirk (Max-Planck-Institut für Plasmaphysik Teilinstitut Greifswald); JAKUBOWSKI, Marcin (Max-Planck-Institut für Plasmaphysik); MAYER, Matej (Max-Planck-Institut für Plasmaphysik); SCHMITZ, Oliver (University of Wisconsin - Madison, Department of Engineering Physics); BREZINSEK, Sebastijan (Forschungszentrum Jülich); Dr MASUZAKI, Suguru (National Institute for Fusion Science)

Co-authors: GORIAEV, Andrej (ERM-KMS); HAKOLA, Antti (VTT Technical Research Centre of Finland Ltd.); Dr BUTTERSCHOEN, Birger (Max-Planck-Institut für Plasmaphysik); Dr DHARD, CP (Max-Planck-Institut für Plasmaphysik); Dr ZHAO, Dongye (Forschungszentrum Jülich - IEK-4); FORTUNA-ZALESNA, Elzbieta (Warsaw University of Technology); Dr WANG, Erhui (Forschungszentrum Jülich - IEK4); Dr EFFENBERG, Florian (Princeton Plasma Physics Laboratory, Princeton, NJ, 08543 USA); MOTOJIMA, Gen (National Institute for Fusion Science); Dr OELMANN, Jannis (Forschungszentrum Jülich - IEK-4); Dr ROMAZANOV, Juri (Forschungszentrum Jülich - IEK-4); SCHMID, Klaus (Max-Planck-Institut für Plasmaphysik); Dr KRYCHOWIAK, Maciej (Max-Planck--Institut für Plasmaphysik); Dr RASINSKI, Marcin (Forschungszentrum Jülich - IEK-4); RUBEL, Marek (KTH, Royal Institute of Technology); Dr BALDEN, Martin (Max-Planck-Institut für Plasmaphysik); Dr NEUBAUER, Olaf (Forschungszentrum Jülich - IEK-4); Dr FORD, Oliver (Max-Planck Institut für Plasmaphysik); Dr PETTERSON, Per; DREWS, Philipp (Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung – Plasmaphysik, Partner of the Trilateral Euregio Cluster (TEC)); Dr YI, Rongxing (Forschungszentrum Jülich - IEK-4); BRAKEL, Rudolf (Max-Planck-Institut für Plasmaphysik); NEU, Rudolf (Technische Universität München & MPI für Plasmaphysik); SEREDA, Stepan (Institut für Plasmaphysik - IEK-4); Dr KREMEYER, Thierry (University of Wisconsin - Madison); PEDERSEN, Thomas Sunn (Max Planck Institute for Plasma Physics); Dr DITTMAR, Timo (Forschungszentrum Jülich - IEK-4); WAUTERS, Tom (Laboratory for Plasma Physics - ERM/KMS, 1000 Brussels, Belgium, TEC Partner); Dr WINTERS, Victoria (Max-Planck-Institut - IEK-4); Dr GAO, Yu (Forschungszentrum Jülich - IEK.4)

Presenter: BREZINSEK, Sebastijan (Forschungszentrum Jülich)

Session Classification: P6 Posters 6

Track Classification: Magnetic Fusion Experiments