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SUJET DE THÈSE 2024

Conditionnement d'un tokamak en tungstène avec chocs longs: de WEST à ITER

Wall conditioning of a long pulse, tungsten tokamak: from WEST to ITER

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Argumentaire

The next generation of magnetic fusion devices, starting with ITER, will have tungsten walls and perform long plasma pulses. These features will qualitatively change the problem of the preparation of optimal vacuum and wall conditions compared to existing experiments. The stronger particle and energy fluences to the reactor walls mandate the optimization of existing wall conditioning techniques as well as the development of new and specific ones. The most conventional conditioning method, called boronization, consists in the deposition of boron coating layers that cover the inside of the vacuum vessel, trapping oxygen and other light impurities. As plasma wall interactions occur, boron and other impurities are eroded and transported by the plasma. How to ensure a constant replenishment such coating layers, as well as their impact on tritium retention during steady state operations are open questions that demand to be answered before the completion of the ITER assembly. In this PhD proposal we leverage both dedicated wall conditioning experiments planned in WEST and a novel numerical modeling workflow to study the transport of boron powder at the boundary of a tokamak plasma in stationary conditions. The candidate will develop key competences (both experimental and theoretical) in the physics of dusts and impurity transport in magnetized plasmas that will lead to a quantitative understanding of the impact of plasma conditions on boron deposition patterns at the wall, enabling the preparation of efficient wall conditioning recipes for ITER.

Résumé du sujet en Français

Les recherches menées pour développer la fusion thermonucléaire contrôlée comme nouvelle source d’énergie utilisent des dispositifs appelés tokamaks, dans lesquels la matière est portée à haute température (plasma) et est confinée par des champs magnétiques. L’interaction du plasma avec les

parois de la chambre à vide d'un tokamak libère des impuretés dont la présence peut affecter ses performances. Différentes méthodes de conditionnement sont alors utilisées pour contrôler l'état de surface de l'enceinte à vide, et donc les flux d'impuretés. Celles-ci utilisent principalement des plasmas basses températures (décharges luminescentes ou radiofréquences) en hydrogène ou en hélium, mais aussi la déposition de couches minces de bore, en raison de sa capacité à piéger par affinité chimique des impuretés telles que l'oxygène. Avec l'avènement des composants face au plasma métalliques et l'allongement de la durée des plasmas dans les tokamaks supraconducteurs, comme ITER et WEST, exploité à l'Institut de Recherche sur la Fusion par confinement Magnétique (CEA-IRFM, Cadarache, France), des nouvelles techniques de conditionnement des parois pour maintenir un état de surface et des performances optimales tout au long de la décharge plasma font leur apparition. L'objectif de cette thèse est de caractériser et d'évaluer sur WEST la pertinence pour ITER de plusieurs méthodes d'injections de bore, a priori comme en temps réel. Le travail consistera d'une part à participer à des expériences sur WEST et à analyser des données expérimentales (localisation et durée de vie des dépôts de bore, effet sur les performances des plasmas). Afin de comprendre le transport du bore, le candidat travaillera aussi avec des modelés numériques de plasma de bord (SOLEDGE, EIRENE, DIS). Ce travail, combinant expériences et simulations, devra consolider la compréhension de la physique du conditionnement en environnement métallique et contribuer à prévoir les conséquences pour ITER et les futurs dispositifs de fusion.

Résumé du sujet en Anglais :
Research on controlled thermonuclear fusion as a new source of energy is carried out in devices called tokamaks, where matter is brought to high temperature (plasma state) and confined by magnetic fields. Interactions between the plasma and the walls of the vacuum chamber of tokamaks releases impurities, which can affect plasma performance. Different conditioning methods are used to control the surface state of the vacuum chamber, and thus impurity fluxes. These mainly use low-temperature plasmas (glow or radio-frequency discharges) in hydrogen or helium, but also deposition of thin layers of boron, because of its ability to trap by chemical affinity impurities like oxygen. With the advent of metallic plasma facing components and the extension of plasma duration in superconducting tokamaks, like ITER and WEST, operated in the Institute of Research on Magnetic Fusion (CEA Cadarache, France), innovative wall conditioning techniques to maintain optimal surface state and performances are under development. The aim of this thesis is to characterize and evaluate in WEST the relevance for ITER of different methods of boron injection, both a priori and in real time. The work will consist on the one hand to participate in experiments on WEST and to analyze experimental data (location and lifetime of boron deposits, effect on plasma performance). In order to understand the transport of boron, the candidate will work with plasma boundary numerical models (SOLEDGE, EIRENE, DIS). This work, combining experiments and simulations, will consolidate the understanding of the physics of wall conditioning in a metallic environment and predicting consequences for ITER and future fusion devices.

Formation recherchée / recommandée

Master en physique des plasmas et /ou interactions plasma-surface. Expérimentation, modélisation. Le sujet requiert une excellente capacité à travailler et communiquer dans un cadre fortement collaboratif avec d'autres instituts de recherche en Europe et aux Etats-Unis.

Description détaillée du sujet

Wall conditioning is a common and established practice in magnetically confined thermonuclear fusion devices like the tokamak. The main goal of wall conditioning is to ensure that the quality of the vacuum in the tokamak chamber is good enough to perform successful plasma discharges. This requires very low vessel pressure (10^{-5} – 10^{-6} Pa) and high plasma purity that would be impossible to obtain after opening the vessel for maintenance or during the commissioning of a new machine. Moreover, throughout an experimental campaign, wall conditions in tokamaks tend to degrade and need to be regularly restored. Besides performing bake and deuterium glow discharges to remove light impurities, like air and water, or

excess fuel from the tokamak wall, a procedure called boronization [1] is often carried out. The main goal of a boronization is to further reduce the oxygen content in the vacuum vessel through the deposition of boron-rich nanometric coating layers where oxygen is trapped due to its strong chemical affinity to boron. In tokamaks sporting a tungsten wall, like WEST [2] or ITER [3], the boronization also has the transient, beneficial effect of reducing/diluting the amount of tungsten eroded at the wall by the plasma and, therefore, of mitigating detrimental radiative power losses due to tungsten ionization.
The boronization is traditionally carried out by adding a boron-rich gas (diborane) to a helium glow discharge. This technique has improved the performance of a large number of machines but presents several downsides: a) diborane is a highly toxic and explosive gas; b) glow discharges require to turn off the magnetic field; c) a boronization takes about a day; d) in long pulse tokamaks the beneficial effect lasts only few plasma pulses. This is why real time wall conditioning methods need to be developed for future devices like ITER where plasma pulses will last hundreds of seconds, the vessel surface will be very large (more boron needed) and it will not be possible to turn the magnetic field off every so often. For these reasons, the Princeton Plasma Physics Laboratory (PPPL) developed an alternative, real time, boron delivery device called impurity powder dropper (IPD) [4]. The dropper is a simple and yet powerful tool as it allows drop chemically inert, boron powder directly into a tokamak plasma. Once evaporated and ionized by the plasma (its peak of radiation occurs below 10 eV, a typical temperature of tokamak boundary plasmas), boron gets sensitive to the magnetic field. Its transport across magnetic surfaces and, therefore, its ability to penetrate in the confined plasma, is then controlled by collisions with the main ions, by velocity drifts and by turbulence. For low Z impurities like boron, the latter usually prevails. Yet, neoclassical (collisional) transport cannot be neglected, especially in plasma scenarios characterized by edge transport barriers with reduced turbulence levels. Most importantly, boron ions are at the same time dragged towards the wall portions wetted by the plasma which are those where wall conditioning is needed the most. Experiments carried out on a number of tokamaks including ASDEX-Upgrade [5-7] and WEST [8-10], showed encouraging results that motivated ITER to adopt the dropper as an alternative or complementary boronization method [3].
The goal of this PhD thesis is to utilize WEST as a platform to study the physics of wall conditioning to prepare efficient and sustainable operations in ITER. The candidate will leverage the unique features of WEST (i.e. the tungsten wall and the long pulse capability) to develop new and optimized conditioning strategies, both a priori and in real time. The candidate will become familiar with analyzing the data of boundary plasma diagnostics to qualify wall conditions and plasma-wall interaction like residual gas analysis, optical emission spectroscopy, ultraviolet spectroscopy and bolometry. In fact, the WEST diagnostics suite has all the necessary tools to study the physics of boron transport in a tokamak plasma. Subsequently the candidate will learn to evaluate the effect of the different wall conditioning techniques on plasma operation, determining the optimal conditioning methods and frequencies for WEST and extrapolating these results to ITER.
Alongside the experimental endeavors, the candidate will leverage an already established numerical modeling workflow developed by IRFM and PPPL [11-13] to perform interpretive simulations of boron transport in the boundary plasma of WEST with SOLEDGE-EIRENE and DIS. By making educated guesses on the main free parameters of the model (boron diffusivity, recycling coefficient, and ablated fraction), the candidate will be able to formulate hypotheses on the outcome of the WEST wall conditioning experiments mentioned above.
This research project builds up on an already established international partnership that led to several WEST experiments dedicated to the boron dropper between 2021 and 2024, leading to the achievement of a successful PhD thesis and several publications already. No additional hardware nor funding is needed for this project to be carried out.

[1] J. Winter et al., Journal of Nuclear Materials, 1989
[2] J. Bucalossi et al., Fusion Engineering and Design, 2014
[3] P. Barabaschi et al., IAEA-FEC, 2023
[4] A. Nagy et al., Review of Scientific Instruments, 2018

[5] A. Bortolon et al., Nuclear Materials and Energy, 2019
[6] R. Lunsford et al., Nuclear Fusion, 2019
[7] K. Krieger et al., Nuclear Materials and Energy, 2023
[8] G.M. Bodner et al., Nuclear Fusion, 2022
[9] R. Lunsford et al., IAEA-FEC, 2023
[10] K. Afonin et al., APS-DPP conference, 2023
[11] N. Rivals et al., Contributions to Plasma Physics, 2022
[12] F. Nespoli et al., Physics of Plasmas, 2021
[13] K. Afonin et al., Nuclear Fusion, 2023

Collaborations scientifiques et/ou partenariats industriels envisagés

- Nom du collaborateur:
  Robert Lunsford, PhD
- Organisme/Société:
  Princeton Plasma Physics Laboratory, Princeton, NJ 08543-0451
- Raison de la collaboration:
  Dr. Lunsford and his team at PPPL lead the conception and development of the impurity powder dropper, now successfully operated on several tokamaks around the world. The exploitation of this device, now available also on WEST, will benefit from a close international collaboration between IRFM and PPPL, allowing the PhD candidate to be trained in a diverse and international high-profile context.