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Summary Report of a Consultancy Meeting in preparation of a Coordinated Research Project on Properties of Tungsten Ions in Fusion Plasmas

29 – 30 August 2024
IAEA Headquarters, Vienna, Austria

Prepared by

K. Heinola and C. Hill
Nuclear Data Section, International Atomic Energy Agency

January 2025

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ABSTRACT

The preparatory Consultancy Meeting for Coordinated Research Project (CRP) on Properties of Tungsten Ions in Fusion Plasmas was held from 29 – 30 August 2024 as an in-person event at IAEA headquarters. Meeting was attended by seven participants representing six Member States. Meeting discussed the current status and unknowns related to collisional-radiative properties and processes of W impurities in fusion plasmas and set priorities for topics to be addressed by this CRP. Potentially interested and relevant participants were discussed and recommended for further contact making.

January 2025

Contents

1. Introduction

Impurities in fusion plasmas are known to play an important role in the physics of the core and edge regions of magnetically confined plasmas. For example, noble gas impurities neon, argon, krypton and xenon have been studied and injected deliberately in the edge region of the plasma at the divertor for protecting the armour materials at the target. The most favorable material solution for armour materials is tungsten (W) due to its high thermal conductivity and its ability to withstand various intense plasma-wall interactions. However, the powerful plasma fluxes from edge-localized modes (ELMs) or the particle bombardment by the injected impurities may lead to ejection of W particles into the plasma. Having these heavy element impurities as a plasma impurity may lead to massive power losses through radiation of the plasma, which can lead to operational instability and plasma termination.

The International Fusion Research Council Subcommittee on Atomic and Molecular Data for Fusion (IFRC A+M Subcommittee), in its biennial meeting in June 2024, advised that the Atomic and Molecular Data Unit initiate a Coordinated Research Project (CRP) to recommend fundamental data concerning the collisional-radiative processes of W impurities in fusion plasmas; participants should be drawn from the fusion plasma modelling community and the network of computational and experimental plasma physicists working on the calculation and measurement of the collisional and spectroscopic properties of W species under relevant conditions of temperature and density.

A Consultancy Meeting (CM) was held on 29 and 30 August 2024 with seven external experts plus three Agency staff to discuss the scope and parameters of the proposed CRP; see https://amdis.iaea.org/meetings/tungsten-ions-cm/ for further details. This CM, which is summarised in the present report, included experts in relevant data development and evaluation together with specialists in fusion plasma diagnostics and fusion plasma simulations representing the intended users of the data.

2. Background

2.1 Scientific Context

A viable nuclear fusion reactor will be operated with a magnetically confined hydrogen plasma as its fuel. The energy is gained by fusing hydrogen isotopes, deuterium (D) and tritium (T) with a release of 14 MeV neutrons and 3.5 MeV heliums. These fusion processes take place in the core of the plasma at temperatures of 10^8 K (about 175 million K or 15 keV). However, the conditions inside the plasma are far from homogeneous and near material boundaries (in the plasma edge region) the plasma temperature is typically 100 eV or less and down to about 1 eV. The significantly cooler outer regions of the D-T plasma will be interacting with the reactor inner walls. The wall materials, i.e. the first wall materials or also known as armour materials, must therefore withstand heat and particle loads from the plasma. Currently the most favorable material to withstand these incomparable conditions is tungsten (W), which has the highest melting point of all metals, very good durability against high heat and plasma particle loads and the retention rate of hydrogenic fusion fuel species (D, T) is very low in W-based materials. Therefore, W is planned to be used in the next-step fusion device ITER and in several future DEMO-scale and pilot plant fusion reactors around the world.

Regardless of these favorable properties of W, during high flux plasma particle bombardments situations may occur where varying amounts of W particles are being ejected from the first wall components through erosion and sputtering processes. W particles entering the plasma and especially its core can be extremely detrimental for the stability and lifetime of the fusion plasma. Impurity species entering the plasma contaminate the plasma and emit radiation through radiative-collisional processes, such as bremsstrahlung and recombination radiation. These power losses depend in addition to the plasma electron temperature and density also on the proton number Z of the impurity species as Z2. W being a heavy metal element with Z=74 can create severe plasma power losses in the form of disruptions or other plasma instabilities and thus its presence in the plasma must be avoided and its collisional processes with the plasma as well as the subsequent transport properties must be understood.

It is important to know as much as possible about the behavior of W at different charge states in different regions of the fusion plasma. Of particular concern are the ionization processes and collisional properties of W at electron temperatures between 1 keV and 10 keV, which are currently subject to large uncertainties and disagreements between theory and experiments. Collisional processes of neutral atoms and protons with low ionization stages of W play a critical role as well as the ionization processes of low-charge metastable states of W.

The overall objective is to provide evaluated experimental and computational collisional data on W ion properties at fusion-relevant plasma conditions. The significance of these results will be to any fusion reactor operating with W-based armour materials.

2.2 Organisational Context

Project 1.4.1.003 of the Agency's present Programme and Budget is concerned with provision of atomic, molecular and plasma-material interaction data for fusion energy research and other plasma applications. The Subcommittee on Atomic and Molecular Data of the International Fusion Research Council ("the Subcommittee") makes recommendations to the IAEA Nuclear Data Section as to this project.

At its 23rd biennial meeting, held in June 2024, the Subcommittee discussed plans and provided recommendation for CRP proposal for F43028 on "Properties of Tungsten Ions in Fusion Plasmas". The Subcommittee endorsed the plans for this CRP with the objective "[to] establish a trusted repository of evaluated data concerning the collisional-radiative properties of tungsten ions in fusion energy devices". Further it was endorsed "the data production and other activities undertaken over the course of this CRP will directly assist in the modelling of the behaviour of tungsten ions which enter the plasma in fusion devices through sputtering and erosion mechanisms."

The last time the topic of tungsten ions in plasma was addressed was in CRP F41027: "Spectroscopic and Collisional Data for Tungsten from 1 eV to 20 keV" (2010 – 15) and progress in experimental and computational techniques motivates another project in the near future, particularly given the importance of this temperature range at the pedestal region of tokamak devices. This new CRP is also intended to complement the ongoing Technical Meeting series on tungsten and hydrogen in edge plasmas (which focuses on lower plasma temperatures).

3. Discussion Summary and Recommendations

The agenda and list of participants in this meeting are provided as Appendices A and B to this report.

Meeting presentations can be found at https://amdis.iaea.org/meetings/tungsten-ions-cm/ .

As the members of the IFRC Subcommittee discussed, the CM participants acknowledged the ionization balance and spectroscopic and collisional properties of W at temperatures between 1 keV and 10 keV are subject to large uncertainties and disagreements be-tween theory and experiment. The last time the topic of tungsten ions in plasma was addressed 10 years ago in CRP F41027: "Spectroscopic and Collisional Data for Tungsten from 1 eV to 20 keV" (2010 – 2015).

The CM identified three principal activities as having a high priority to the central goal of the CRP, to address data needs in the area of the ionization balance and spectroscopic and collisional properties of tungsten at temperatures between 1 keV and 10 keV, which are currently

subject to large uncertainties and disagreements between theory and experiment. These activities are described below, with potential participants identified during the meeting and who will be contacted directly, provided the CRP is successfully approved by the IAEA's internal CCRA committee (probably in autumn 2024, with the aim of holding the first Research Coordination Meeting in Q2 2025).

3.1 Ionisation from metastable states of low ionisation stages of W

This process has been found to play a substantial role in ionisation equilibrium. Up to now, only ground state ionisation has been included in the collision calculations. One of the CRP objectives is to perform collisional calculations of ionisation cross sections and rate coefficients from metastables of the first ionisation stages (e.g. from W^0 to W^{9+}).

Possible participating institutions:
Queen's University Belfast (QUB), UK
Auburn University, USA
Department of Physics, University of Strathclyde, UK
Malmö University, Sweden
Fudan University, China
Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa (FCT, Nova University of Lisbon), Portugal
Vilnius University (Vilniaus universitetas), Lithuania
Korea Atomic Energy Research Institute (KAERI), Korea
National Institute for Fusion Science (NIFS), Japan
Northwest Normal University (NWNU), China
University of Mons (Université de Mons), Belgium
University of Delhi and Delhi Technological University, India
National Institute of Standards and Technology (NIST), USA
Lanzhou School of Nuclear Science and Technology, Lanzhou University, China
Tokyo University of Science, Japan
National Center of Nuclear Sciences and Technologies (CNSTN), Tunisia

3.2 Neutral and proton collisions with low ionisation stages of W

Charge exchange plays an essential role in the plasma edge of fusion devices. Room temperature neutrals come from such fueling methods as gas puffing or supersonic gas injection. There is also a population of 'hot' neutrals resulting from charge exchange between the cold neutrals and the outgoing H^+/D^+ flux from the plasma. The same goes for H^+/D^+: two populations must be included in the calculations. Those calculations must be accompanied with experimental measurements for validation.

It is expected that the results will modify the ionisation balance. This in turn can change the evaluation of the prompt redeposition of W, sputtering, plasma facing component lifetime and W transport in the scrape-off layer of fusion devices.

Possible participating institutions:
Lebedev Physical Institute, Russia
Kyoto University, Japan
North Arizona University, USA
Fudan University, China
Institute of Applied Physics and Computational Mathematics (IAPCM), China
Lawrence Livermore National Laboratory (LLNL), USA
Niigata University, Japan
Tokyo Metropolitan University, Japan

3.3 Spectroscopic analysis of low and medium ionisation stages of W

Many fusion devices use W as a plasma-facing material or inject it for spectroscopic investigations. The spectra measured in those devices are very complex. In several wavelength intervals, particularly in the EUV domain they show a superposition of individual spectral lines and so-called quasi-continuous features emitted by a range of W ionisation stages. The line assignment is extremely complex and time-consuming. It involves a detailed knowledge of the plasma conditions and scenario, including the recent experimental history and conditioning techniques of the device. Despite intensive work, lines from important ionisation stages (namely W IX to W XXVII) are still missing. As far as the quasi-continua are concerned, the interpretation by sophisticated atomic models need improvement before the measurements can be used to provide information about the behaviour of W. The objectives of the CRP will be the following:

- to make (structure and collisions) calculations to provide line wavelengths of W IX–XXVII in the EUV and visible ranges;
- to make a thorough line assignment for wavelength intervals of particular interest from existing measurements in various fusion devices and EBITs.

Possible participating institutions:
Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP), China
Institut de Recherche sur la Fusion par confinement Magnetique (IRFM), CEA Cadarache, France
National Institute for Fusion Science (NIFS) / Tohoku University, Japan
Max Planck Institute for Plasma Physics (IPP), Garching, Germany
Culham Centre for Fusion Energy (CCFE), UK
Max Planck Institute for Plasma Physics (IPP), Greifswald, Germany

Korea institute of Fusion Energy, Korea
National Institute of Standards and Technology (NIST), USA
Fudan University, China
Institute for Laser Science (ILS), University of Electro-Communications (UEC), Japan
Max Planck Institute for Nuclear Physics (Max-Planck-Institut für Kernphysik, MPIK), Germany
Auburn University / Compact Toroidal Hybrid, USA
Toyama University, Japan
Oak Ridge National Laboratory (ORNL), USA
Institute of Plasma Physics of The Czech Academy of Sciences, Czech Republic
General Atomics: DIII-D, USA
Southwestern Institute of Physics (SWIP), China

4. Related CRPs and Technical Meetings

The following CRPs and Technical Meetings, previously run by the Atomic and Molecular Data Unit are of direct relevance to the present project:

CRP F41027 "Spectroscopic and Collisional Data for Tungsten in Plasma from 1 eV to 20 keV", from 2010 – 2015.

Technical Meeting series "Collisional-Radiative Properties of Tungsten and Hydrogen in Edge Plasma of Fusion Devices":

- 1st meeting from 29 March – 1 April 2021
- 2nd meeting from 28 November – 1 December 2023.

Technical Meeting of "Global Network on Atomic and Molecular Processes in Plasmas", from 6 – 10 December 2021.

Appendix A: Agenda

Thursday, 29 August 2024

10:00 – 10:30 Meeting Opening; welcome and introductions; administrative information.

10:30 – 11:00 Christian HILL (IAEA): *Atomic and Molecular Data Activities at the IAEA*

11:00 – 11:30 Ling ZHANG (Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP), China): *Tungsten atomic data needs in ASIPP*

11:30 – 12:00 MURAKAMI Izumi (National Institute for Fusion Science, Japan): *Tungsten ion data needs and tungsten spectral data compilation at NIFS*

12:00 – 14:00 Lunch

14:00 – 14:30 Rémy GUIRLET (IRFM, CEA Cadarache, France): *Tungsten EUV lines and quasi-continua: identification and relation to tokamak plasma physics*

14:30 – 15:00 Coffee Break

15:00 – 15:30 Inga TOLSTIKHINA (Lebedev Physical Institute, Russia): *Mechanisms of non-adiabatic charge-exchange transitions in slow collisions of W ions with He, Ar and Kr atoms*

15:30 – 16:00 Connor BALLANCE (Queen's University Belfast, United Kingdom): *R-matrix as part of the fundamental atomic structure and collisional data required for tungsten ions*

19:30 – 21:00 Social Dinner: MODI 1080, Alser Straße 11, 1080 Wien.

Friday, 30 August 2024

09:00 – 10:30 Discussion

10:30 – 11:00 Coffee Break

11:00 – 12:30 Meeting Report CRP Proposal drafting; Meeting conclusion.

Appendix B: List of participants

Seven participants from six Member States and IAEA staff.

Connor BALLANCE	Queen's University Belfast, United Kingdom
Rui DING	Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP), China
Rémy GUIRLET	IRFM, CEA Cadarache, France
KATO Daiji	National Institute for Fusion Science, Japan
MURAKAMI Izumi	National Institute for Fusion Science, Japan
Inga TOLSTIKHINA	Lebedev Physical Institute, Russia
Ling ZHANG	Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP), China
Christian HILL	IAEA
Kalle HEINOLA	IAEA
Khadidja BENYAHIA	IAEA

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