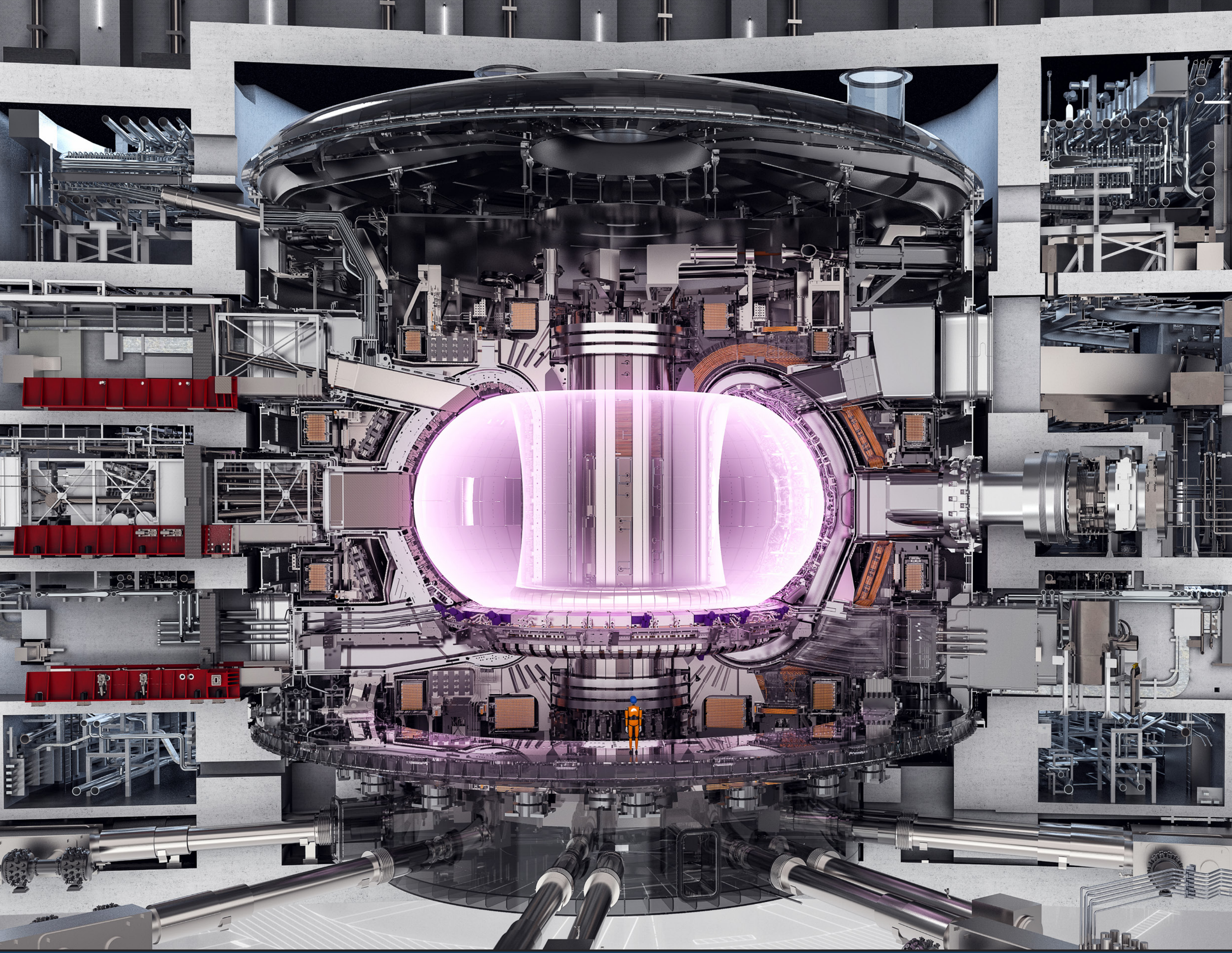

Fusion

Energy Source of the Future

EUROfusion Research Progamme in Austria
2014 - 2020

EUROfusion

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

Impressum

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EUROfusion

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Executive Summary

This brochure intends to present the Austrian contribution to the European fusion research programme 2014 to 2020. At the end of 2013, the Austrian Academy of Sciences was appointed by the Federal Ministry of Science and Research (now Federal Ministry of Education, Science and Research) as programme manager of the Austrian contribution to the EUROfusion Consortium for the duration of H2020. The upcoming renewal of this contract for the period of the next EU Framework Programme (Horizon Europe 2021 - 2027) is now under consideration. The budget assigned to ÖAW by the Ministry during 2014 - 2020 was 2.6 Million EURO. With these funds and national in-kind contributions additional 5.4 Million EURO could be raised from Austria's participation in EUROfusion.

The energy demand of mankind, which has been growing for decades, is increasingly reaching its limits due to both dwindling resources and the environmental impact associated with their use. Therefore all renewable ("sustainable") energy sources are in particular demand, especially the use of solar energy, water and wind energy. A new, practically inexhaustible, clean and CO_2 free energy source is promised by nuclear fusion. Almost 100 years ago it was recognized that fusion reactions of light atoms are the energy source of our sun and all stars. The goal of worldwide fusion research is therefore to make the energy released by the fusion of hydrogen nuclei to form helium usable for mankind. Since its beginnings in the 1950s, fusion research has been moving towards its ambitious goal of developing this clean and environmentally friendly source of energy. At present, the fusion reactor ITER is being built in the south of France, which for the first time will produce about 10 times more energy from fusion than is needed to heat the (hot) plasma. ITER is an international undertaking and the most impressive energy project in human history to date. Within the framework of the H2020 project EUROfusion of the EU, research groups from Austria have also made their contribution to this ambitious goal. **The main objective of this brochure is to present the scientific achievements of the Austrian participation in EUROfusion in the period 2014 - 2020 in a compact and clear form in order to provide a basis for the continuation and further development of the Austrian participation in the next EU Framework Programme**.

The Association EURATOM-ÖAW was founded in 1996, shortly after Austria's accession to the European Union, and concentrated the research efforts in the field of plasma and fusion physics, which at that time were scattered among several Austrian universities and non-university research institutions. Since then, the Austrian contributions to the European fusion programme have been reoriented in accordance with the scientific priorities defined by the European Commission and within the framework of the European Fusion Development Agreement (EFDA). Increased cooperation and exchange with other European research institutions in the field of fusion led to a much stronger integration of Austria into the European fusion research programme.

In 2006, the European Union, India, Korea, the Republic of China, the Russian Federation and the United States of America signed an agreement for the construction of the international fusion experiment ITER in Cadarache in southern France. With ITER on the horizon, European fusion research activities have been further streamlined, first until 2013 under EFDA and then from 2014 under EUROfusion, in order to focus on research, education and training relevant to ITER and the planned power plant prototype DEMO. As a result, in H2020 the activities of the Austrian fusion research unit (Fusion@ÖAW) shifted from more theory and basic research-based activities to active participation in the experimental campaigns of the major European fusion facilities (JET, ASDEX Upgrade, TCV, Wendelstein 7X, etc.). A special focus was placed on topics that EUROfusion had identified as priorities in line with the European Research Roadmap to the Realization of Fusion Energy.

Fusion@ÖAW currently comprises five institutions: Austrian Academy of Sciences (Fusion@ÖAW Coordination Office in Vienna and Erich Schmidt Institute for Materials Science in Leoben), TU Graz (Institute for Theoretical and Computational Physics), TU Wien (Institute for Applied Physics and Atomic

Institute), University of Innsbruck (Institute for Ion Physics & Applied Physics and Department of Mathematics) and the Research Studios Austria in Salzburg. At the participating universities, education on fusion-related topics is part of the curriculum of the physics faculties. The specialization on fusion-related topics starts at the level of master theses and is deepened at the level of PhD theses. Despite the lack of an institution entirely dedicated to fusion research, fusion-related education and training has a long tradition at the participating universities. The number of doctoral students specializing in fusion-related topics and funded by EUROfusion has remained more or less constant since the beginning of the 7th Framework Programme with an average total number of 20 ongoing doctoral theses per year. This success is due to the constant adaptation of research topics to the priorities of the Roadmap.

The topics of the PhD theses are closely related to the core competences of Fusion@ÖAW: modelling and simulation of plasma phenomena in tokamaks and stellarators, investigation of the processes of plasma-wall interaction, controlling edge-located modes (ELMs) in tokamaks, development of suitable wall materials, high-temperature superconductors and accompanying socio-economic studies. Young researchers benefit from an attractive mobility programme that offers numerous opportunities to work temporarily in renowned European fusion laboratories and gain valuable professional experience.

From early 2014 to September 2020, a total of 85 publications with a first author from Fusion@ÖAW were published in peer-reviewed international journals focusing on plasma physics and fusion technology. In addition, co-authors from Austria have contributed to further 75 articles. Open Access is a prerequisite for H2020 projects and thus also applies to publications resulting from work within the EUROfusion work programmes. The total number of conference contributions with authors from Fusion@ÖAW is about 165 over the same period.

From 2014 onwards, outreach activities were also intensified, with a new focus on the upper grades of secondary schools in order to increase interest in the development of fusion energy in general and to motivate high school students to consider a possible career in this field. Statistical data on a possible success rate are currently not available, but the reactions to the regular newsletters of Fusion@ÖAW and the participation in corresponding lectures show an increased interest among teachers. Compared to previous periods, we have seen an increasing interest among female students in choosing a technology-oriented subject in recent years. Fusion@ÖAW encourages female students to specialize in fusion-related topics and supports all efforts to promote the careers of qualified women.

The construction of ITER in the South of France offers attractive business opportunities for European companies. The exploitation of fusion energy is also an industrial effort that must be supported by targeted research. The network of Industrial Liaison Officers (ILOs) is raising awareness among qualified companies and advising them on ways to participate in the ITER project. In Austria, the function of the ILO is performed by the Chamber of Commerce, which acts as a contact forum for Austrian companies qualified to participate in industrial high-tech projects. In cooperation with Fusion@ÖAW, appropriate information events are organized time and again. Fusion@ÖAW regularly publishes newsletters with information about upcoming events and tenders to interested companies. The European Domestic Agency Fusion for Energy (F4E) is responsible for the European contribution to ITER and offers large-scale business opportunities. The success of Austrian industry in international F4E tenders from 2008 to 2019 is presented in chapter 8 of this brochure.

Looking ahead to Horizon Europe, Fusion@ÖAW is well prepared to continue its activities in line with the future EUROfusion work programmes. As the first plasma in ITER is planned for the end of 2025, training for the “Generation ITER" of young scientists and engineers remains the main priority of Austrian participation. The outreach activities directed at schools, universities and industry will be continued and intensified. We expect that the first plasma in ITER will create new incentives for existing and potential participants and considerably raise the interest of the general public.

Zusammenfassung

Mit dieser Broschüre soll der österreichische Beitrag zum europäischen Fusionsforschungsprogramm 2014 bis 2020 vorgestellt werden. Ende 2013 wurde die ÖAW vom Bundesministerium für Wissenschaft und Forschung (jetzt Bundesministerium für Bildung, Wissenschaft und Forschung) für die Dauer von H2020 zum Programmmanager des österreichischen Beitrags zum EUROfusion Consortium ernannt. Die bevorstehende Verlängerung dieses Auftrages für den Zeitraum des nächsten EU Rahmenprogrammes (Horizon Europe 2021 - 2027) wird derzeit geprüft. Das Budget, das der ÖAW vom Ministerium für die Jahre 2014 - 2020 zugewiesen wurde, betrug 2,6 Millionen EURO. Mit diesen Mitteln und nationalen Sachleistungen konnten aus der österreichischen Beteiligung an EUROfusion zusätzlich 5,4 Millionen EURO aufgebracht werden.

Der seit Jahrzehnten wachsende Energiebedarf der Menschheit stößt sowohl durch schwindende Ressourcen als auch durch die mit ihrer Nutzung verbundenen Umweltbelastungen zunehmend an seine Grenzen. Besonders gefragt sind deshalb einerseits alle erneuerbaren ("nachhaltigen") Energiequellen, vor allem die Sonnenenergienutzung inkl. Wasser- und Windenergie, andererseits ein neuer, praktisch unerschöpflicher Energieträger, der durch die Kernfusion in Aussicht gestellt wird. Bereits vor nahezu 100 Jahren wurde erkannt, dass Verschmelzungsreaktionen leichter Atome die Energiequelle von Sonne und Sternen sind. Ziel der weltweiten Fusionsforschung ist es daher, die Energie, die bei der Verschmelzung von Wasserstoffkernen zu Helium frei wird, für die Menschheit nutzbar zu machen. Die Fusionsforschung hat sich seit ihren Anfängen in den 50er Jahren des letzten Jahrhunderts in kontinuierlicher Detailarbeit auf ihr anspruchsvolles Ziel zubewegt, eine saubere, umweltfreundliche, und praktisch unerschöpfliche Energiequelle zu entwickeln. Gegenwärtig wird in Südfrankreich der Fusionsreaktor ITER gebaut, der erstmals etwa zehnmal mehr Energie aus der Fusion erzeugen wird, als zur Heizung des (heißen) Plasmas notwendig ist: ITER ist ein internationales Unternehmen und das bisher beeindruckendste Energieprojekt in der Geschichte der Menschheit. Im Rahmen des H2020-Projekts EUROfusion der EU haben auch Forschergruppen aus Österreich ihren Beitrag zu diesem ehrgeizigen Ziel geleistet. **Das Hauptziel dieser Broschüre ist es, die wissenschaftlichen Erfolge der österreichischen Beteiligung an EUROfusion im Zeitraum 2014 – 2020 in kompakter und klarer Form darzulegen, um so die Grundlage für die Fortsetzung und den weiteren Ausbau der österreichischen Beteiligung im nächsten EU Rahmenprogramm zu liefern**.

Die Assoziation EURATOM-ÖAW wurde 1996, kurz nach dem Beitritt Österreichs zur Europäischen Union, gegründet und bündelte die damals an mehreren österreichischen Universitäten und außeruniversitären Forschungseinrichtungen verstreuten Forschungsanstrengungen im Bereich Plasma- und Fusionsphysik. Seit damals wurden die österreichischen Beiträge zum europäischen Fusionsprogramm im Einklang mit den von der Europäischen Kommission und im Rahmen des European Fusion Development Agreement (EFDA) definierten wissenschaftlichen Prioritäten neu ausgerichtet. Die verstärkte Zusammenarbeit und der Austausch mit anderen europäischen Forschungseinrichtungen im Bereich Fusion führte zu einer wesentlich stärkeren Einbindung Österreichs in das europäische Fusionsforschungsprogramm.

Im Jahr 2006 unterzeichneten die Europäische Union, Indien, Korea, die Republik China, die Russische Föderation und die Vereinigten Staaten von Amerika ein Abkommen zum Bau des internationalen Fusionsexperiments ITER in Cadarache in Südfrankreich. Mit ITER am Horizont wurden die europäischen Fusionsforschungsaktivitäten zuerst bis 2013 im Rahmen von EFDA und dann ab 2014 im Rahmen von EUROfusion weiter gestrafft, um sich so auf Forschung, Ausbildung und Schulung zu konzentrieren, die für ITER und den geplanten Kraftwerksprototyp DEMO relevant sind. Dadurch verlagerten sich in H2020 die Aktivitäten der österreichischen Fusionsforschungseinheit (Fusion@ÖAW) von eher theorie- und grundlagenbasierten Aktivitäten auf die aktive Teilnahme am Experimentierprogramm der großen europäischen Fusionsanlagen (JET, ASDEX Uppgrade, TCV, Wendelstein 7X, etc.). Dabei konzentrierte man sich besonders auf Themen, die EUROfusion im Einklang mit der europäischen Forschungs-Roadmap zur Realisierung der Fusionsenergie als vorrangig eingestuft hatte.

Fusion@ÖAW umfasst derzeit fünf Institutionen: Österreichische Akademie der Wissenschaften (Fusion@ÖAW-Koordinationsstelle in Wien und Erich-Schmid-Institut für Materialwissenschaften in Leoben), Technische Universität Graz (Institut für Theoretische und Computational Physics), Technische Universität Wien (Institut für Angewandte Physik und Atominstitut), Universität Innsbruck (Institut für Ionenphysik & Angewandte Physik und Abteilung für Mathematik) und die Research Studios Austria in Salzburg. An den beteiligten Universitäten ist die Ausbildung zu fusionsrelevanten Themen Teil des Lehrplans der Fakultäten für Physik. Die Spezialisierung auf fusionsrelevante Themen beginnt auf der Ebene von Masterarbeiten und wird auf der Ebene von Dissertationen vertieft. Trotz des Fehlens einer eigenständigen Institution, die sich gänzlich der Fusionsforschung widmet, hat die fusionsrelevante Aus- und Weiterbildung an den beteiligten Universitäten eine lange Tradition. Die Zahl der Doktoranden, die sich auf fusionsrelevante Themen spezialisieren und von EUROfusion gefördert werden, ist seit Beginn des 7. Rahmenprogramms mit einer durchschnittlichen Gesamtzahl von 20 laufenden Doktorarbeiten pro Jahr mehr oder weniger konstant geblieben. Dieser Erfolg ist auf die konstante Anpassung der Forschungsthemen an die Prioritäten der Roadmap zurückzuführen.

Die Themen der Doktorarbeiten stehen in engem Zusammenhang mit den Kernkompetenzen von Fusion@ÖAW: Modellierung und Simulation von Plasmaphänomenen in Tokamaks und Stellaratoren, Untersuchungen der Prozesse bei der Plasma-Wand-Wechselwirkung, Beherrschung der Edge-Localized Modes (ELMs) in Tokamaks, Entwicklung geeigneter Wandmaterialien, Hochtemperatur-Supraleiter und begleitende sozio-ökonomische Studien. Junge Forscher profitieren von einem attraktiven Mobilitätsprogramm, das zahlreiche Möglichkeiten bietet, vorübergehend in renommierten europäischen Fusionslabors zu arbeiten und dabei wertvolle Auslandserfahrung zu sammeln.

Von Anfang 2014 bis Juni 2020 wurden insgesamt 85 Publikationen mit einem Erstautor von Fusion@ÖAW in begutachteten internationalen Fachzeitschriften mit Schwerpunkt Plasmaphysik und Fusionstechnologie veröffentlicht. Darüber hinaus haben an weiteren 75 Artikel Co-Autoren aus Österreich mitgearbeitet. Open Access ist eine Voraussetzung für H2020-Projekte und gilt somit auch für Publikationen, die aus Arbeiten im Rahmen der EUROfusion-Arbeitsprogramme resultieren. Die Gesamtzahl der Konferenzbeiträge mit Autoren aus Fusion@ÖAW liegt im gleichen Zeitraum bei rund 165.

Ab 2014 wurden auch die Outreach-Aktivitäten intensiviert, wobei ein neuer Schwerpunkt auf die Oberstufe der Sekundarschulen gelegt wurde, um das Interesse an der Entwicklung der Fusionsenergie im Allgemeinen zu erhöhen und die Schülerinnen und Schüler der Sekundarstufe zu motivieren, über eine mögliche Karriere in diesem Bereich nachzudenken. Statistische Daten über eine mögliche Erfolgsquote sind derzeit nicht verfügbar, aber die Reaktionen auf die regelmäßigen Newsletter von Fusion@ÖAW und die Teilnahme an entsprechenden Workshops zeigen ein verstärktes Interesse der Lehrkräfte. Im Vergleich zu früheren Perioden konnten wir in den letzten Jahren ein zunehmendes Interesse von Studentinnen beobachten, sich für ein Technologie-orientiertes Fach zu entscheiden. Fusion@ÖAW ermutigt weibliche Studierende, sich auf fusionsbezogene Themen zu spezialisieren und unterstützt alle Bemühungen, die Karrieren von qualifizierten Frauen zu fördern.

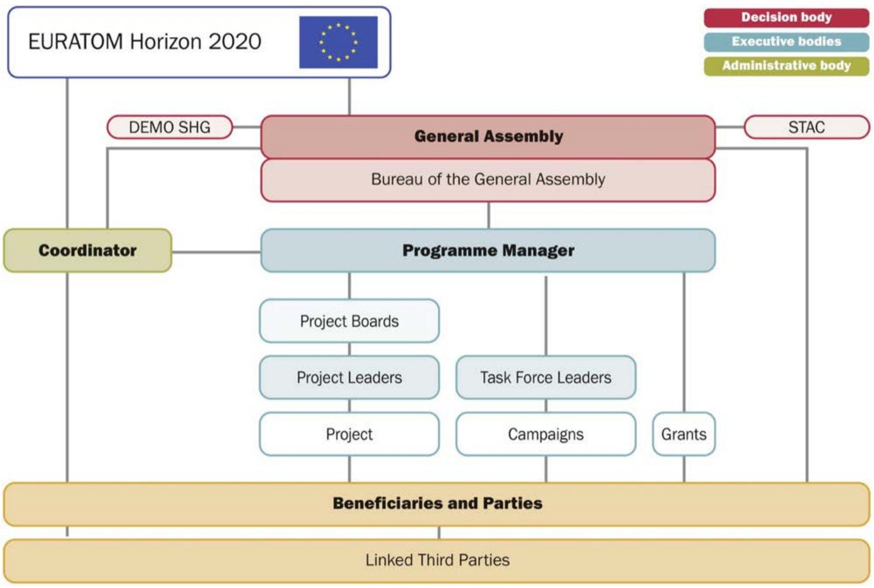
Der Bau von ITER in Südfrankreich bietet attraktive Geschäftsmöglichkeiten für europäische Unternehmen. Die Nutzbarmachung der Fusionsenergie ist auch eine industrielle Anstrengung, die durch gezielte Forschung unterstützt werden muss. Das Netzwerk der industriellen Verbindungsbeamten (Industrial Liaison Officers - ILOs) sensibilisiert qualifizierte Unternehmen und berät sie über Möglichkeiten, sich am ITER-Projekt zu beteiligen. In Österreich wird die Funktion des ILO von der Wirtschaftskammer wahrgenommen, die als Kontaktforum für österreichische Unternehmen fungiert, die für die Teilnahme an industriellen High-Tech-Projekten qualifiziert sind. In Zusammenarbeit mit Fusion@ÖAW werden immer wieder entsprechende Informationsveranstaltungen organisiert. Fusion@ÖAW gibt regelmäßig Newsletter mit Informationen über bevorstehende Veranstaltungen und Ausschreibungen an interessierte Unternehmen heraus. Die European Domestic Agency Fusion for Energy (F4E) ist für den europäischen Beitrag zu ITER zuständig und bietet groß angelegte Geschäftsmöglichkeiten. Der Erfolg der Österreichischen Industrie bei internationalen F4E Ausschreibungen von 2008 bis 2019 wird in Kapitel 8 dieser Broschüre dargestellt.

In Hinblick auf Horizon Europe ist Fusion@ÖAW gut darauf vorbereitet, seine Aktivitäten im Einklang mit den zukünftigen EUROfusion Arbeitsprogrammen fortzusetzen. Da das erste Plasma in ITER für Ende 2025 geplant ist, bleibt die Ausbildung für die Generation „ITER“ die wichtigste Priorität der österreichischen Beteiligung. Die Outreach-Aktivitäten, die sich an Schulen, Universitäten und die Industrie richten, werden fortgesetzt und intensiviert werden. Wir gehen davon aus, dass das erste Plasma in ITER neue Anreize für bestehende und potenzielle Teilnehmer schaffen und das Interesse der breiten Öffentlichkeit wecken wird.

1.Management Structure and Core Competencies

1.1. EUROfusion Consortium

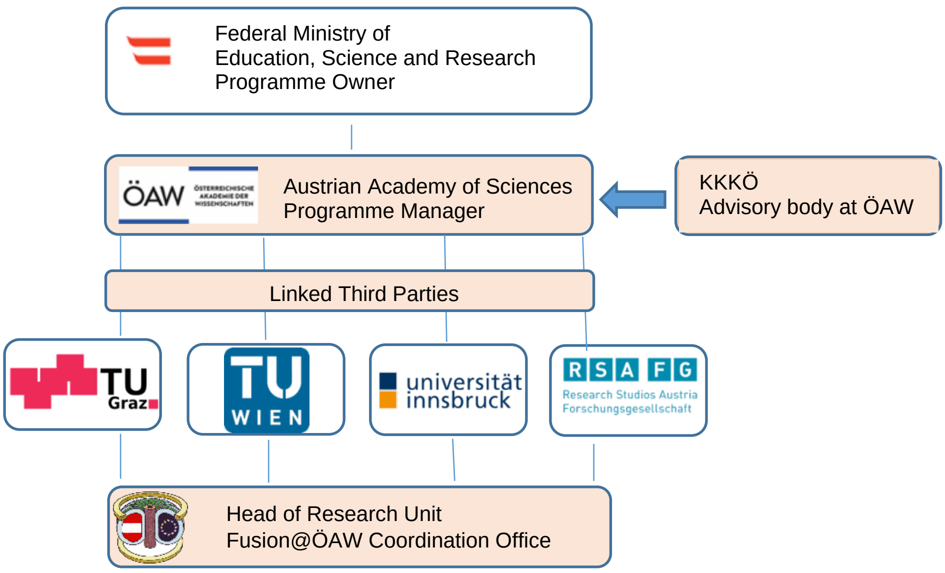
The EUROfusion Consortium is funded by a co-fund action within the H2020 EURATOM Programme (Grant Agreement No. 633053; 2014 - 2020). EUROfusion funds and manages all fusion research activities across Europe (www.euro-fusion.org). The present management structure of the EUROfusion Consortium is shown below:



Graph: EUROfusion

1.2. Austrian Beneficiary ÖAW and its Linked Third Parties

The Austrian Academy of Sciences (ÖAW) acts as the official beneficiary with the EUROfusion Consortium and coordinates the participation of Austrian research groups in the European Fusion research programme. Fusion@ÖAW is structured as shown below:



Austrian Beneficiary: Austrian Academy of Sciences (ÖAW)

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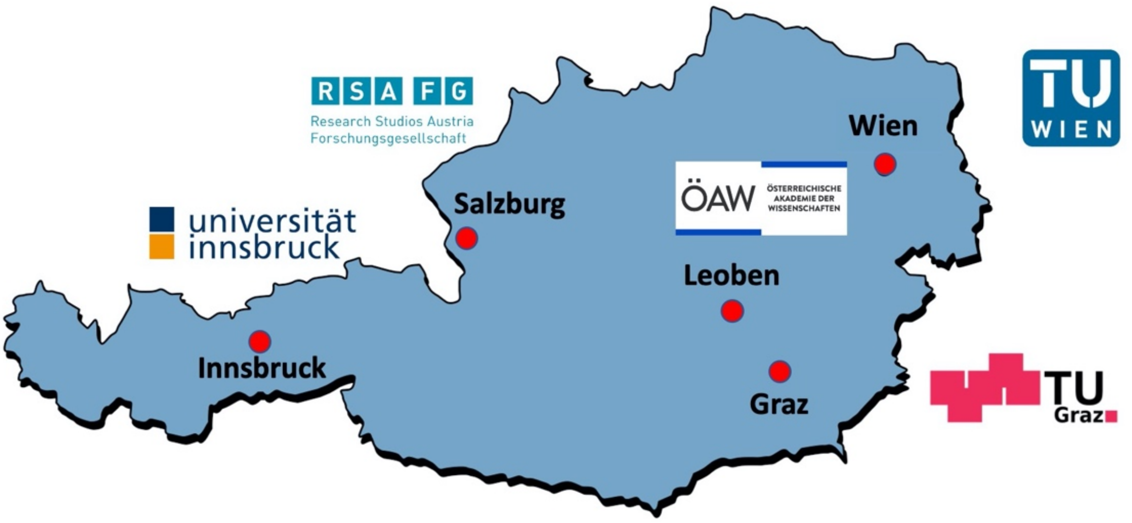
Core competencies of the Austrian Participants in EUROfusion

Building on expertise developed over many years in cooperation with international partners and focusing on primary topics under the European Fusion Development Agreement (EFDA, 1999 - 2013) and EUROfusion (2014 - 2020), Fusion@ÖAW concentrates its research and educational efforts on the topics shown in the table below. Scientific highlights from these areas are presented in chapter 2.

Core competences

ÖAW Österreichische Akademie der Wissenschaften	Optimization of structural materials Divertor materials for DEMO
TU Graz	Modelling of plasma phenomena Plasma transport, current drive, Stellarator optimization
TU Wien	Plasma edge physics, ELM instabilities Plasma-wall-interaction High temperature superconductors
universität innsbruck	Plasma-wall-interaction Plasma turbulence Gyrofluid simulations
RSA FG Research Studios Austria Forschungsgesellschaft	Socio-economic studies (energy scenarios)



2. Scientific Highlights

2.1. MODELLING OF PLASMA DYNAMICS AND TRANSPORT IN TOKAMAKS AND STELLARATORS

Short summary of main fields of activities

Confinement of fusion plasmas relies on tolerably low and controllable transport losses of heat and particles. Undesirable effects such as collapse of the plasma or damage to the first wall due to heat loss bursts or by energetic particle populations need to be studied and avoided. European experiments are carried out in JET (UK), which is presently the most advanced tokamak in the world, and in medium-size tokamaks such as ASDEX Upgrade (Germany) and TCV (Switzerland), as well as the advanced stellarator W7-X. The obtained data are used to improve the accuracy of predictive modelling and the scaling of expected properties towards future plasmas of ITER and DEMO. Fusion@ÖAW is contributing to this effort through fundamental theoretical modelling and applied numerical simulations, specifically by gyrofluid models of edge turbulence and flows, performed at Univ. Innsbruck, kinetic models of resonant magnetic field perturbations for ELM mitigation and simulation of electron cyclotron resonant heating and current drive in tokamaks and stellarators, performed at TU Graz and a study of new properties of the divertor plasma sheath performed at TU Wien.

Selected scientific examples & highlights

Nonlinear dynamics of plasma edge turbulence and flows[1]

Turbulence in general develops nonlinearly in driven fluids towards a three-dimensional spatio-temporal chaotic state with interacting tornado-like vortex tubes. But in particular situations, turbulence can obtain a quasi-two-dimensional character with rather different statistics: this is the case for thin films, like in soap bubbles, or for geostrophic flows in layers of planetary atmospheres that determine weather patterns. Turbulence in plasmas also can become quasi two-dimensional, and show similar characteristic vortex and flow structures, in the plane perpendicular to a background magnetic field.

In contrast to ordinary fluids, there is no ”standard model“ like the Navier-Stokes equations to describe turbulence in magnetized plasma. Particle dynamical and electromagnetic field effects are included at various levels of detail. In magnetically confined fusion research, effective ”gyrokinetic“ and ”gyrofluid“ theories were developed, which treat gyration of charged particles in magnetic fields with dynamical models for the distribution function or its fluid moments. Mostly such models rely on assumptions of small fluctuation amplitudes. In many space or laboratory plasmas, especially in the edge of fusion experiments, however, we encounter strong turbulence and transport with large relative amplitudes.

In the last years, we have pioneered novel ”full-f“ gyrofluid models and simulations, which consistently include fluctuations at arbitrary amplitudes. This generalization has allowed new insights into strong turbulence and nonlinear structure formation in magnetized plasmas by theory and computation.

We have developed two separate code implementations (FELTOR and TOEFL) which are both based on similar model sets, but use different numerics, which allows to cross-verify our codes throughout the development, but they for example also have optimized applicability for different magnetic field geometries. The well CPU-GPU hybrid parallelized FELTOR code is also openly available [1].

---

1 Principal Investigator: Alexander Kendl, University of Innsbruck (alexander.kendl@uibk.ac.at)

A strong impact of arbitrary-amplitude "full-f" versus small-amplitude "delta-f" models can be expected for scrape-off layer (SOL) filamentary transport, which is demonstrated by simulations including consistent finite Larmor radius (FLR) effects that lead to weaker acceleration of pressure "blob" perturbations with large amplitudes [2]. Around the separatrix not only blobs with positive perturbations appear, but also holes as local pressure depletions. Delta-f models predict that outward motion of blobs is exactly anti-symmetric to inward motion of holes. This symmetry is broken in a proper full-f treatment of blobs and holes, which show different propagation, especially when pressure profiles steepen around their origins near the tokamak separatrix [3].

Turbulence in magnetised fusion plasmas is intrinsically influenced by gyroscale effects across ion Larmor orbits. We have shown that fundamental vortex interactions like merging and co-advection in gyrofluid plasmas are essentially modified under the influence of gyro-induced vortex spiraling. For identical initial vorticity, the fate of co-rotating eddies is decided between accelerated merging or explosion by the asymmetry of initial density distributions. Structures in warm gyrofluid turbulence are characterised by gyrospinning enhanced filamentation into thin vorticity sheets [4]. These important novel gyrospinning effects are more pronounced in gyrofluid (or gyrokinetic) models that treat the full wavelength spectrum, whereas so far all full-f models have made use of a long-wavelength approximation in the treatment of polarisation. We recently have proposed a new full-f model for arbitrary fluctuation wavelengths [5], which we are going to implement in future simulation studies.

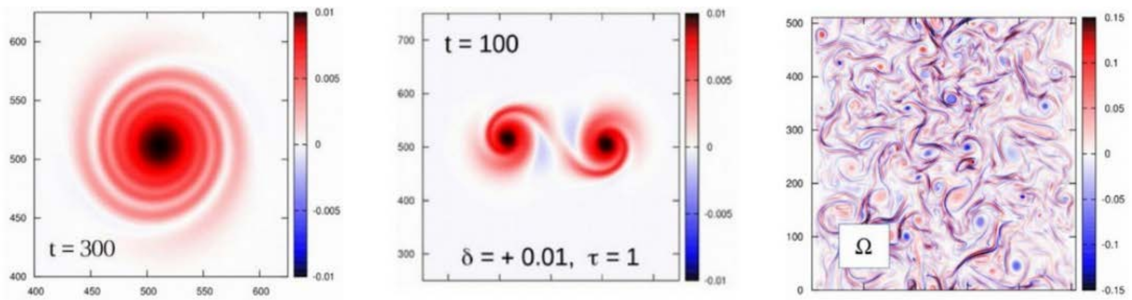


Fig. 1

Full-k (delta-f) gyro-spinning - a new twist on vortex motion [4]. **Left**: FLR-induced spiraling of **E**×**B** vorticity (Ω) in an asymmetric vortex. Middle: Effect on vortex interactions. **Right**: Resulting vorticity filamentation in fully developed drift wave turbulence. (All figures reproduced from Ref. [4]).

Several turbulence and transport properties change when we go from delta-f to full-f models. We have so far demonstrated this for drift wave instabilty in steep edge density gradient regimes [6] and for zonal flow generation [7] by means of theory and 2-d simulations. We have also started first (long wavelength) delta-f vs. full-f comparisons for 3-d electromagnetic isothermal edge turbulence simulations: transport is significantly larger for large gradients and amplitudes, but consistently converges towards the long-wavelength delta-f solution for small variations. All of these recent results from our reduced long-wavelength full-f gyrofluid models motivate the development and application of complete full-k (i.e. arbitrary wavelength) full-f models and codes [5] as a next step.

[1] M. Wiesenberger, L. Einkemmer, M. Held, et al., Computer Physics Communications **238**, 145 (2019). [Code source (open data): feltor-dev.github.io, https://doi.org/10.5281/zenodo.596442]

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[4] A. Kendl, Plasma Physics and Controlled Fusion **60**, 025017 (2018), https://doi.org/10.1088/1361-6587/aa9f94.

[5] M. Held, M. Wiesenberger, A. Kendl, Nuclear Fusion **60**, 066014 (2020), https://doi.org/10.1088/1741-4326/ab7a68

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Interaction of 3D magnetic field perturbations with tokamak plasmas and perturbation Induced neoclassical transport[2]

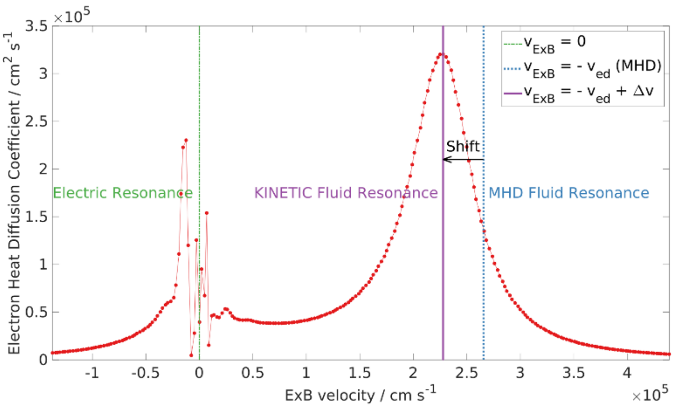
Neoclassical transport (particle and energy transport in a quasi-static electromagnetic field) can be comparable or even dominant over turbulent transport in toroidal fusion devices with 3D magnetic field geometry (stellarators, tokamaks with broken axial symmetry). For evaluation of this transport as well as for the computation of the generalized Spitzer function (a particular kind of particle distribution function which is required for computation of current drive efficiency by auxiliary heating methods) we have developed two branches of the drift kinetic equation (DKE) solver NEO-2 [8] and applied them for the modelling of transport and current drive in experimental devices [9, 10]. In contrast to most other DKE solvers, NEO-2 treats realistic magnetic field geometries and uses full linearized Coulomb collision integral without model simplifications. In addition, it has unique features compared to other codes. Namely, adaptive velocity space discretization allows to efficiently model regimes with very low collisionality (important for the studies of peculiarities of bootstrap current in stellarators), quasi-local approach used in the quasilinear tokamak branch [11] correctly treats toroidal banana precession in tokamaks (feature available up to now only in Monte-Carlo or bounce-averaged codes), collision operator in the stellarator branch [9, 12] is fully relativistic (required, in particular, for the modelling of electron cyclotron current drive, ECCD). Besides NEO-2, for the computation of perturbation induced neoclassical transport in resonant regimes, we have developed the code NEO-RT [13] which is based on the Hamiltonian approach for the realistic tokamak geometry and allows for finite orbit widths .

The quasilinear branches of the NEO-2 and NEO-RT code have been used for the modelling of transport induced by non-axisymmetric magnetic field perturbations in ASDEX-Upgrade [15]. Main sources of these perturbations in ASDEX Upgrade are toroidal field (TF) ripples appearing due to the discreteness of the main coil system, resonant field perturbations induced for the purpose of mitigation of Edge Localized Modes (ELMs) by a special coil system (RMP coils), and perturbations induced by MHD modes. In contrast to axisymmetric neoclassical and turbulent transport, 3D neoclassical transport is not ambipolar in the leading order over the Larmor radius and therefore it induces a significant radial electric current which changes the equilibrium radial electric field and, respectively, toroidal plasma rotation (this phenomenon is called neoclassical toroidal viscosity (NTV). This change, in turn, may affect MHD plasma stability with respect to resistive wall modes and also affect the anomalous transport. Computations of NTV for the perturbations from RMP coils have shown that toroidal torque due to NTV is not negligible but is still a few times smaller than the torque induced by the neutral beam injection (NBI). In particular, spin-up of plasma rotation at the edge observed in RMP experiments during the transition to suppressed ELMs cannot be explained by NTV what indicates that plasma reconnection at resonant magnetic surfaces is the main reason for this phenomenon. In turn, NTV in presence of MHD modes (kink and tearing modes) can result in torques comparable to the NBI torque and may strongly break plasma rotation if such mode is locked to the wall. For rotating eigenmodes (intrinsic modes which are not interacting with the outer conductors) the condition of vanishing mode-induced toroidal torque onto the plasma determines the mode's frequency. Computations of this frequency using the NTV torque for the combination of electromagnetically coupled kink and tearing modes observed in ASDEX Upgrade showed that this frequency is consistent with the experimentally measured one in case of comparable amplitudes of the two modes [13]. The quasilinear version of the code NEO-2 has been recently coupled with the transport code ASTRA and is presently applied for the modelling of plasma rotation and tungsten impurity transport in the experiments with helical core formation where expulsion of tungsten from the vicinity of the magnetic axis has been observed in presence of static helical magnetic field perturbation in the plasma core.

[2] Principal Investigator: Winfried Kernbichler, TU Graz, (winfried.kernbichler@tugraz.at)

We have also studied ELM mitigation with the help of RMPs in ASDEX Upgrade using the kinetic cylindrical quasilinear balance model based on the Maxwell solver KILCA. Some observations at the tokamak DIII-D and modelling of those experiments with the help of the MHD approach suggested that suppression of ELMs is caused by bifuraction of RMPs from the shielded to the unshielded state where RMPs create an island structure affecting plasma pressure profiles in the pedestal region at the plasma edge. In our study, a quasilinear balance model [14] has been coupled to the ideal MHD code GPEC which treats the realistic tokamak geometry and has been used for the calculation of bifurcation thresholds (amplitudes of the coil current sufficient for the bifurcation). Computed thresholds agree by order of magnitude with those observed at ASDEX Upgrade transitions to the plasma state with suppressed ELMs. In particular, density scaling of the bifurcation threshold obtained in the modelling agrees with observation observation of the density limit for ELM suppression at ASDEX Upgrade.

Finally, in order to facilitate kinetic modelling of RMP interaction with tokamak plasmas for realistic device and particle orbit geometries we introduced an iterative approach where 3D perturbation electromagnetic fields and plasma response currents to these fields are computed self consistently using the finite element method for the fields and test particle method for plasma response [15]. For efficient test particle modelling, a new geometric integration method has been developed which is stable with respect to the statistical noise in electromagnetic fields and which is an order of magnitude faster than usual guiding center orbit integration methods.



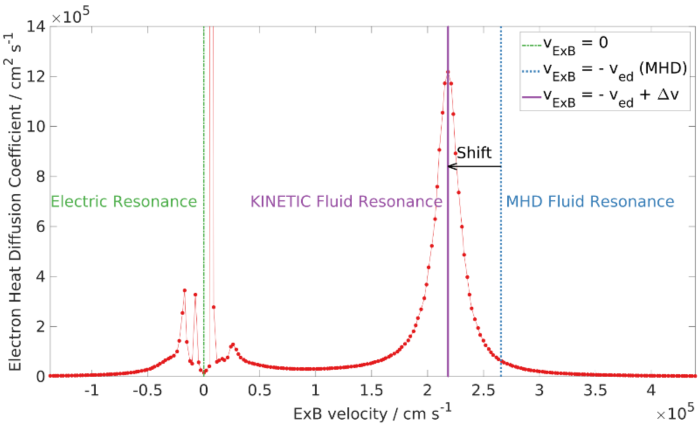


Fig. 2

Results of quasilinear kinetic modeling of RMP shielding in AUG (top) and at ITER collisionality (bottom) show a shift and broadening of the MHD fluid resonance. This discrepancy is more severe for ITER than for present-day devices. For reactor-relevant plasmas it is therefore expected that kinetic modeling is necessary for effects previously treated by MHD theory.

Stellarator Issues (ECCD, bootstrap current, fusion alpha particle losses)[3]

The stellarator branch of the code NEO-2 has been applied for studies of finite collisionality effects on ECCD efficiency in Wendelstein-7X (W-7X) [9]. Usually this efficiency is modelled in the long mean free path (LMFP) limit using the bounce-averaged kinetic equation because finite collisionality introduces relatively small correction to the LMFP limit in standard electron cyclotron current drive (ECCD) scenarios. However, in advanced ECCD scenarios realized at higher cyclotron harmonics (second harmonic for ordinary-mode and third harmonic for the extraordinary mode) where wave absorption is weaker, and a significant power is absorbed by thermal particles, finite collisionality effects are important. Moreover, current generation by waves with a symmetric spectrum in parallel wave numbers (feature which is absent in the LMFP limit) becomes important. In order to include relativistic effects in the stellarator branch of NEO-2, we have derived a new, numerically stable representation of the relativistic Coulomb collision operator in the form of usual (1D) integrals [12]. This form is better suitable for the numerical modelling than fully analytical form of Braams and Karney which may become unstable because of strong numerical cancellations.

The stellarator branch of NEO-2 has also been used for studies of peculiarities of the parallel equilibrium (bootstrap) current at low plasma collisionalities. Effective evaluation of bootstrap current is required in the optimization of stellarator configurations for reactor design. However, the commonly used asymptotic Shaing-Callen formula for the LMFP regime results in significant deviations of the bootstrap current from the results of DKE solvers (which are too slow to be used in optimization) even at very low collisionalities. A comparison of modelling by NEO-2 with an analytical LMFP solution showed that these deviations are caused by barely trapped particles which traverse many field minima between reflection points and which can be de-trapped by collisions during a single pass between these points at any low collisionality. This has been demonstrated in a model case with a closed field line, where such particles disappear at certain low enough collisionality and the Shaing-Callen limit is reached by NEO-2. Proper account of such particles within a modified Shaing-Callen approach is planned in future in order to provide a better tool for the calculation of bootstrap current within stellarator optimization.

Another important measure required in stellarator optimization is the loss fraction of fusion alpha particles during their slowing down time. This fraction must be minimized in a fusion reactor in order to sustain self-heating of the plasma, and, even more importantly, to avoid the damage of the first reactor wall by those particles. Direct computation of this fraction by integration of collisionless guiding center orbits so far has been costly and therefore was limited in optimization algorithms only to prompt losses. In order to accelerate direct computations of alpha particle losses we have developed a symplectic orbit integration method which uses a special kind of flux coordinates – canonical flux coordinates where equations of guiding center motion take a canonical form without simplifications of the guiding center Lagrangian, and where quadrature points are computed in non-canonical variables [16]. In addition, an orbit classification algorithm based on the Minkowsky dimension method has been developed in order to quickly identify „regular“, well confined orbits which cannot be lost (and which are the majority of the orbits in modern advanced stellarator configurations) and trace only stochastic orbits which produce the delayed losses [17]. These methods have been implemented in the code SIMPLE [17] which, in addition, is parallelized within OpenMP and which permits evaluation of the loss fraction during the full slowing down time using the representative ensemble of test particles within a few minutes of computation time. Presently SIMPLE is being implemented in the stellarator optimization packages STELLOPT (PPPL) and ROSE (IPP Greifswald), and it is planned to be used in the future European stellarator optimization tool.

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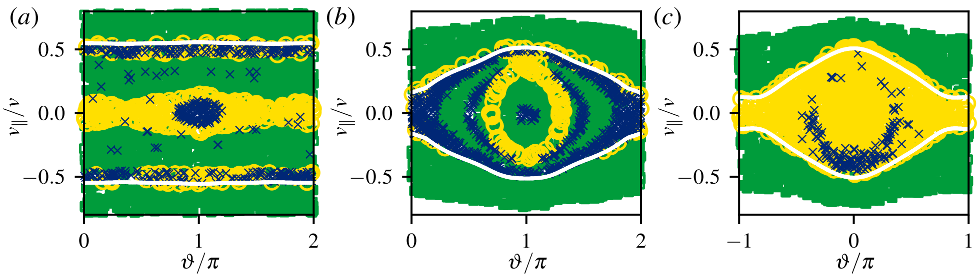

Fig. 3

Fusion alpha particle orbit types over initial condition in pitch parameter and poloidal angle at the symmetric cross-section of the flux surface with normalized toroidal flux equal to 0.6 for (a) quasiisodynamic, (b) quasihelical and (c) quasiaxisymmetric configuration. The background (green) is filled by regular orbits, early losses before t=0.1 s are marked as yellow circles, and chaotic orbits potentially causing late losses after t=0.1 s as blue crosses with some 'false positives' visible that remain confined. The trapped–passing boundary is marked by a white line (Figure reproduced from Ref. [17]).

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Modelling of fast ion loss from tokamak plasmas[4]

Evaluating the loss of fast ions from tokamak plasmas is important for studying the impact of fusion alphas and NBI ions on the plasma facing components as well as for developing diagnostics of fast ion losses. We developed a Fokker-Planck (FP) method for the assessment of distributions of the collisional loss of fast ions as depending on the coordinates of the first wall surface and the velocities of lost ions. It was shown that the complete 4D drift Fokker-Planck approach for the description of fast ions in axisymmetric tokamak plasmas can be reduced to a 2D FP problem for lost ions with a boundary condition delivered by the solution of a 3D boundary value problem for confined ions. Based on this new method the poloidal distribution of neoclassical loss of fast ions from tokamak plasmas can be examined as well as the contribution of this loss to signals in fast-ion loss detectors such as the scintillator probe at JET. The loss distributions obtained with this novel FP treatment may serve as an alternative approach to Monte-Carlo models commonly used for simulating fast ion loss from toroidal plasmas.

Typically, relevant simulations are based on Monte-Carlo approaches delivering detailed information on confined and lost fast ions as a result of expensive time consuming calculations. On the other hand, simplified methods (e.g. focussing on poloidal distributions only, neglecting the real first wall shape or/and effects of gyromotion) will provide a qualitative rather than quantitative information on loss distributions. Former FP treatments of the radial fluxes of fast ions from tokamak plasmas focused primarily on the description of confined fast ions and ions lost via scattering into a loss cone, but did not deliver the appropriate poloidal distributions of the fluxes of ions lost as a result of radial transport.

In [18] a technique is established for assessing the distributions of energetic ion loss induced by Coulomb collisions in tokamaks, which extends former FP treatments of the poloidal distributions of collisional fast ion loss to an arbitrary poloidal shape of the first wall and accounts for the effects of finite gyro radii. It focuses on the losses due to collision-induced radial transport of fast ions, which is expected to be the substantial mechanism of losses of energetic charged fusion products in ITER.

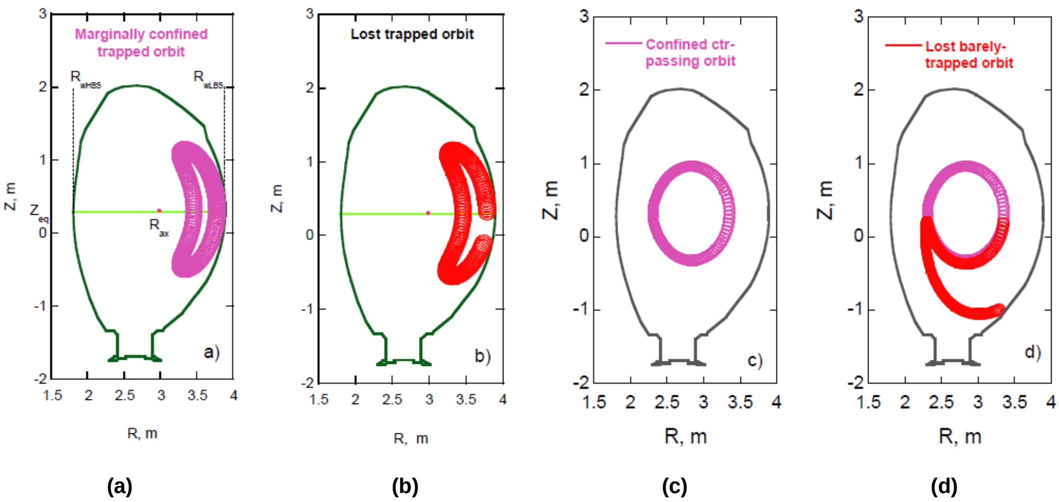

Fig. 4

Orbits of fast ions lost as a result of radial diffusion (a) (b) and via scattering into a loss cone (c) → (d)

As an example we present here results of our numerical evaluation of the poloidal and pitch-angle distributions of the convective-diffusive collisional loss of 130 keV deuterons to the first wall from a JET-like tokamak plasma with a=0.95 m and R_c= 2.95 m, $n_e(0)=n_i(0)=7\times10^{19}m^{-3}$, $n_e(a) = n_i(a) = 2\times10^{19}$ m^3,

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$T_e(0) = T_i(0) = 5.0$ keV, $T_e(a) = T_i(a) = 1.0$ keV. Also used was a model magnetic configuration with Shafranov shift 0.2 m, elongation k(0) = 1.3, k(a) = 1.7, triangularity = 0.15 and plasma current I = 2.5*MA*.

In fig. 5 the calculated distribution function of lost 130 keV deuterons with pitch-angle cosine ζ_l=0.5 is displayed as dependent on the poloidal angular variable and poloidal coordinate at the wall Z_l. As expected, $f(\theta_l, Z_l)$ is localised in a rather narrow range of *Z* below the mid-plane $-0.2m < Z_l < 0.3m$. Fig. 6 represents the distribution of lost co-circulating deuterons over the pitch angle cosine ζ_l and the poloidal coordinate Z_l at the first wall. The maximum loss is observed at Z_l = 0.1m for marginally trapped ions with ζ_l = 0.65

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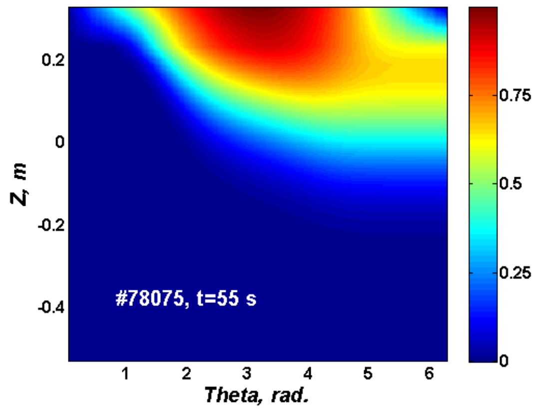

Fig. 5
Fast ion distribution function of co-circulating lost 130 keV deuterons with ζ_l=0.5 vs poloidal angular variable θ_l and poloidal coordinate Z_l at the first wall.

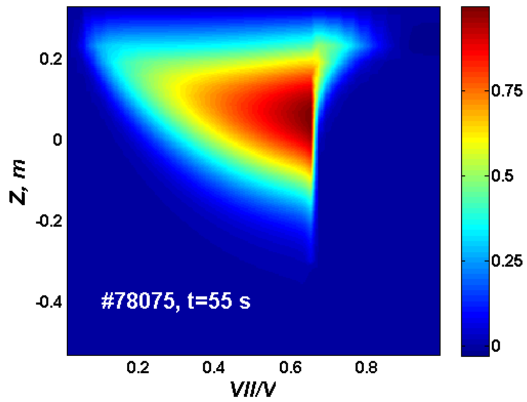

Fig. 6
Contours of the convection-diffusion collisional flux of trapped and co-passing beam deuterons in the plane spanned by the pitch angle cosine ζ_l and the poloidal coordinate Z_l at the first wall.

In our study we demonstrated that in drift approximation the distribution function of fast ions lost from axisymmetric tokamak plasmas as a result of collisional convection-diffusion transport can be treated by a 2D Fokker-Planck kinetic equation, i.e. 1D in COM space and 1D in poloidal angular coordinate, with a boundary condition resolved from a 3D boundary value problem for confined ions. The solution of this FP equation allows for direct evaluation of the spatial and velocity distributions of the flux of lost ions to the tokamak first wall.

Modelled collisional loss of fast ions in a JET-like tokamak are found to be localized in a rather narrow range of the poloidal coordinate *Z (0.2m < Z < 0.3m)* below the plasma midplane. The solution of the boundary value problem for lost fast ions allows to extend the Fokker-Planck code FIDIT (V. Yavorskij et al., Nucl. Fusion **43** (2003) 1077), predominantly describing confined fast ions (only velocity distributions of total loss and of cone losses of fast ions are calculated), to a detailed description of ions lost due to radial collisional transport (including loss distribution over the tokamak first wall). It is noted that this approach accounts for effects of gyromotion and the real poloidal shape of the plasma facing surface and thus constitutes a viable alternative method to Monte-Carlo models which are commonly used for the simulation of fast ion loss from toroidal plasmas.

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Development of a new model of the divertor plasma sheath[5]

The plasma sheath is a narrow plasma layer forming in front of the conductive wall. The classical model of the sheath is commonly used for the estimation of plasma particle and heat fluxes to the wall, for plasma-surface interactions and plasma probe diagnostics. Using heavy numerical simulations, new properties of the divertor plasma sheath have been studied. We found that the normalized power loads to the divertor plates might exceed the classical ones by an order of magnitude [19]; also the energy and the angular distribution functions of the plasma ions impinging on the divertor plates differ strongly from the classical ones (see fig. 7). These new effects can have significant consequences for plasma-surface interactions and overall plasma discharge performance in next generation tokamaks.

Two main reasons of these deviations have been identified: strong temperature gradients in the SOL and finite collisionality of the divertor sheath. The findings of this work are highly relevant for ITER and are therefore continuing in the framework of the ITER Scientist Fellows' Network.

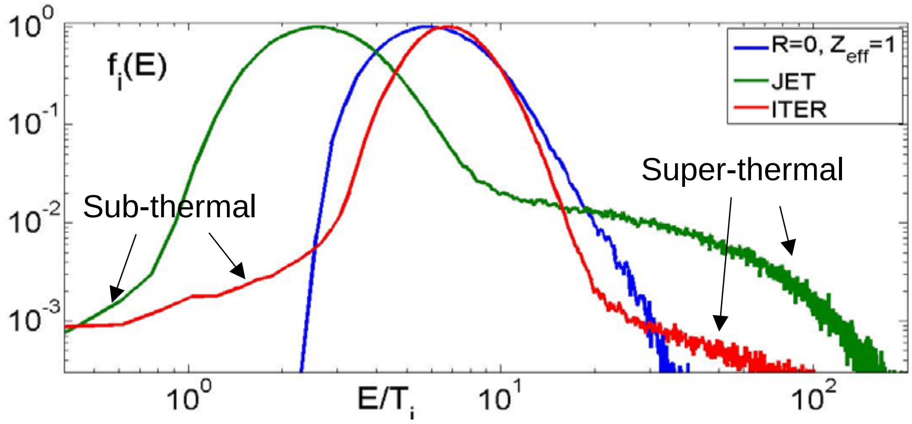

Fig. 7

Energy distribution of D^+ ions absorbed at the divertor plates, for the classical sheath, and divertor sheath in JET and ITER. Non-Maxwellian sub-thermal ions originate from the diffusion inside the sheath; super-thermal particles correspond to the hot upstream SOL ions reaching the divertor without collisions [20].

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[5] Principal investigator: D. Tskhakaya, formerly TUWien and UIBK (tskhakaya@ipp.cas.cz)

2.2. MATHEMATICS AND ALGORITHMS FOR GYROKINETIC AND KINETIC MODELS

Short summary of main fields of activities

Computer simulation plays an essential role in investigating the plasma dynamics relevant for the efficient and safe operation of fusion devices. While many of the traditional methods are based on fluid models (such as magnetohydrodynamics or gyrofluid models), it is increasingly realized that in order to accurately describe many physical phenomena, a kinetic description is required. Since kinetic equations are posed in an up to six-dimensional phase space, their numerical simulation is extremely expensive. In the framework of the Enabling Research Project MAGYK (Mathematics and Algorithms for GYrokinetic and Kinetic models) Fusion@ÖAW contributes to the development of new numerical methods and algorithms for the next generation of fusion codes. This work is performed at the Department of Mathematics at the University of innsbruck.

Selected scientific examples & highlights

Exponential methods for plasma simulation[1]

To be able to perform the kinetic simulation necessary to understand the plasma dynamics relevant for fusion devices requires the use of large supercomputers (with all the cost and difficulty that this entails). This limits the amount of physics that can be done. For example, extensive parameter studies common for simpler, but less accurate fluid models, are usually not possible. Thus, there is a large incentive to develop more efficient numerical methods that reduce the cost and run-time of such simulations.

A major problem in performing computer simulation of fusion devices is the separation of timescales. For example, the ion cyclotron frequency is on the nanosecond range while confinement has to happen on the seconds range (a gap in timescales of 10^9). Furthermore, a small number of particles is often much faster than the bulk of the plasma. The problem for numerical simulations using traditional algorithms is that the fastest time scale in the system dictates the largest time step that can be taken and thus the computational cost.

We have developed a numerical integrator that can decouple the fast timescales in such systems from the timescales at which the relevant physical phenomena are observed [1, 2]. Such an exponential integrator is thus able to take much larger time steps, which dramatically reduces the cost of computer simulations. This is accomplished by treating the fast dynamics, which is often linear, by either an analytic solution or to specifically design a heavily optimized numerical algorithm. This requires intimate knowledge of the underlying physical systems. In fig. 1 we show a computer simulation for an ion temperature gradient instability using a drift-kinetic model.

Breaking the curse of dimensionality with dynamical low-rank approximations

A fundamental problem of performing computer simulations of kinetic equations is the up to six-dimensional phase space. If twice the accuracy is desired, the computational cost increases by a factor of 64. This is commonly referred to as the curse of dimensionality. Many numerical methods have been put forward to alleviate this, but to date none is universally applicable in plasma physics.

[1] Contributor from Fusion@ÖAW: Lukas Einkemmer, University of Innsbruck (lukas.einkemmer@uibk.ac.at)

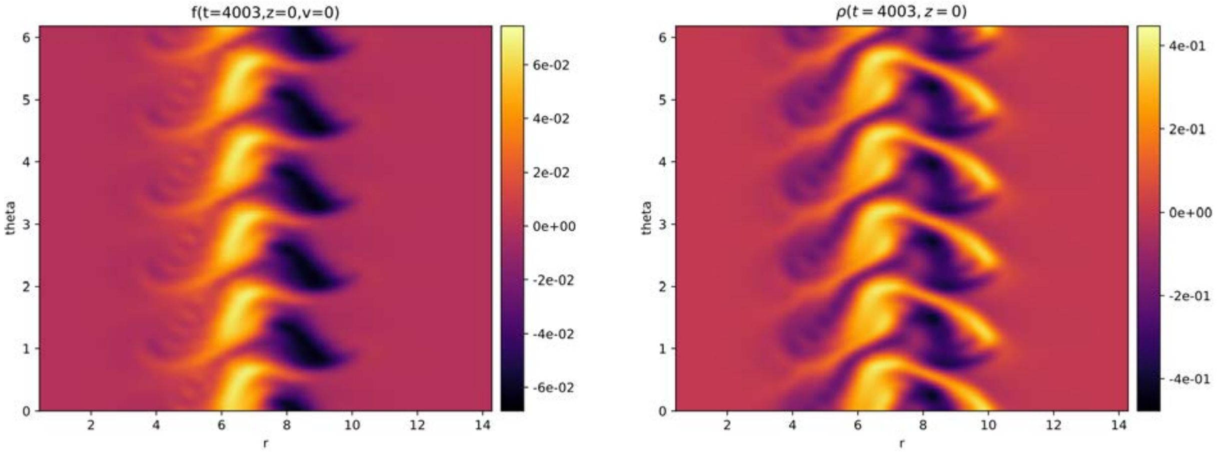

Fig. 1

Simulation of an ion gradient temperature gradient instability using the Lawson (RK(4,4)) scheme. A slice through the particle density function is shown on the left and the corresponding density is shown on the right.

The projector splitting based dynamical low-rank approximation is a recently introduced technique that holds great promise in this regard. It is able to resolve many important phenomena in plasma physics (such as Landau damping or the two-stream instability) without effort and to faithfully treat filamented structures, while reducing the dimensionality of the problem from six to three [5]. This makes it possible to run simulations on single workstations or small clusters, which has previously only been possible on large supercomputers.

In a series of papers [3-5] we have laid the groundwork to develop dynamical low-rank methods for plasma physics applications. Within the EUROfusion Enabling Research project MAGYK we are developing an implementation of numerical methods of this type that can be easily used by physicists. Together with researchers at the Max Planck Institute of Plasma Physics a set of representative benchmark examples are currently being developed on which a range of numerical methods, including the dynamical low-rank approach, will be tested and compared with each other. The lessons learned and the developed algorithms and implementations will build the foundation for the next generation of codes that will be used to simulate tokamak devices.

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2.3. PLASMA EDGE PHYSICS

Short summary of main fields of activities

The outermost centimeters of a tokamak plasma are crucial for machine performance and serve two important purposes. Firstly, the boundary conditions for the core-plasma are defined there. For a reactor-like device, this requires ion temperatures in the core of exceeding 10 keV (100 million °C) at densities around $10^{20}m^{-3}$. Secondly, the plasma edge provides conditions for safe operation without damaging the plasma facing components. A fundamental understanding of the physical processes taking place in the plasma edge region is therefore necessary to ensure a long lived, safe and high-performance fusion reactor. Fusion@ÖAW / TUWien contributes to these efforts by supporting the EUROfusion MST1 Task force with control room expertise and data analysis for both ASDEX Upgrade and TCV.

Selected scientific examples & highlights

Edge localized mode studies[1]

The high confinement H-mode is the foreseen operational scenario for ITER as it provides high enough core temperatures and densities to achieve the promised energy gain factor of Q=10. The confinement improvement in H-mode originates from an edge transport barrier, which is accompanied by steep gradients of the plasma pressure, which elevate the core profiles onto a so-called pedestal. The maximum sustainable pedestal, i.e. the maximum pressure gradient, is usually set by an ideal magnetohydrodynamic limit, which if exceeded leads to so-called edge localized modes (ELMs). ELMs are instabilities that relax the pedestal and can lead to a loss of plasma stored energy on the order of 10%. Especially large, so-called type-I ELMs result in high particle and heat fluxes towards the wall which extrapolated to future fusion devices would exceed the material limits.

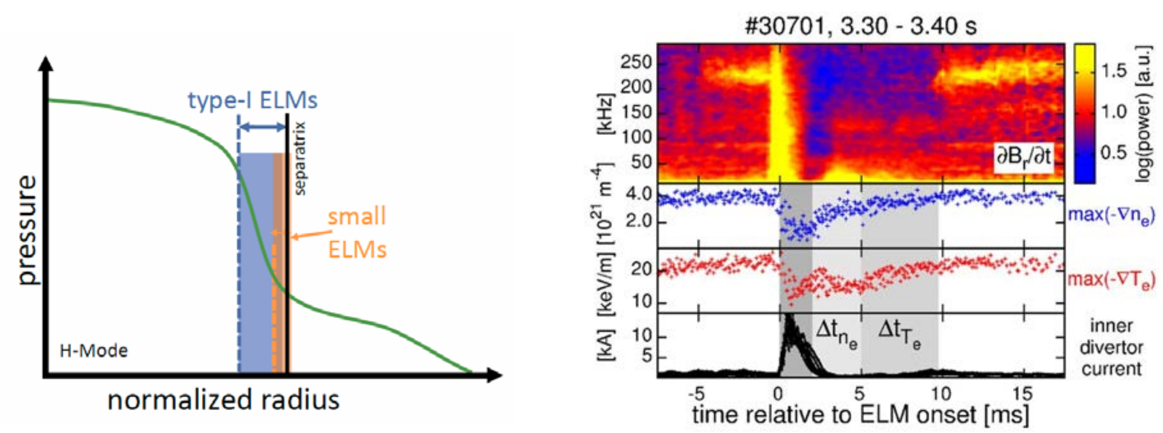

Fig. 1

left: Sketch of the relevant regions for type-I ELMs and small ELMs depicting the narrowing of the pedestal.

right: Temporal evolution of the magnetic activity (∂Br/∂t), edge electron density gradient, max($-\nabla n_e$), and temperature gradient, max($-\nabla T_e$), and the divertor current relative to the ELM onset: The burst in the divertor current indicates the ELM crash. When max(-∇ne) as well as max(-∇Te) saturate, high frequency magnetic fluctuations set in, visible as yellow band at 220 kHz from 10 ms relative to ELM onset on or, equivalently, just before the ELM. [1]

In cooperation with the Pedestal and Edge Physics group of IPP Garching the TU Wien group has studied mechanisms which set the pedestal structure before an ELM crash and keep the pedestal stable up to this point. Just milliseconds before the ELM crash characteristic high frequency magnetic fluctuations in the kilohertz region have been identified as a sign of the imminent instability (see fig. 1).

[1] Principal investigator: Friedrich Aumayr, TU Wien (aumayr@iap.tuwien.ac.at)

The corresponding publication [1] has been selected by IOP science as a Plasma Physics and Controlled Fusion highlight of 2016.

In its first non-nuclear phase ITER will rely on H and He plasmas. To ensure machine safety we also studied the ELM behavior in plasmas with different main ion species [2]. Furthermore, the TU Wien – IPP collaboration was able to show that the ELM stability can be influenced by plasma shaping especially by the so-called triangularity [3].

As mentioned before, when unmitigated, large type-I ELMs can cause damage to the plasma facing components. In recent years the focus therefore shifted from investigations examining the physical principles underlying ELM stability [4] to the search of plasma scenarios with smaller, more tolerable ELM types [5]. Several factors suspected to be responsible for this smaller ELMs stability have been studied [6]. And indeed, a promising operation mode for the plasma of a future power plant has been developed recently with strong participation from TU Wien at ASDEX Upgrade. By properly adjusting the plasma shape and injecting hydrogen to ensure a sufficiently high particle density at the plasma edge, type-I ELMs cannot develop. Instead, many small particle bursts appear which flatten the pressure profile at the plasma edge again and again before a too steep pressure increase leads to a type-I ELM instability [6]. In up to 500 small pulses per second, the power from the plasma arrives quasi-continuously at the divertor plates – without impairing the good thermal insulation of the central plasma. With an enhanced perpendicular transport and a broader heat-flux profile the small ELM scenario looks particularly promising for future fusion reactors [IPP Press release July 2020].

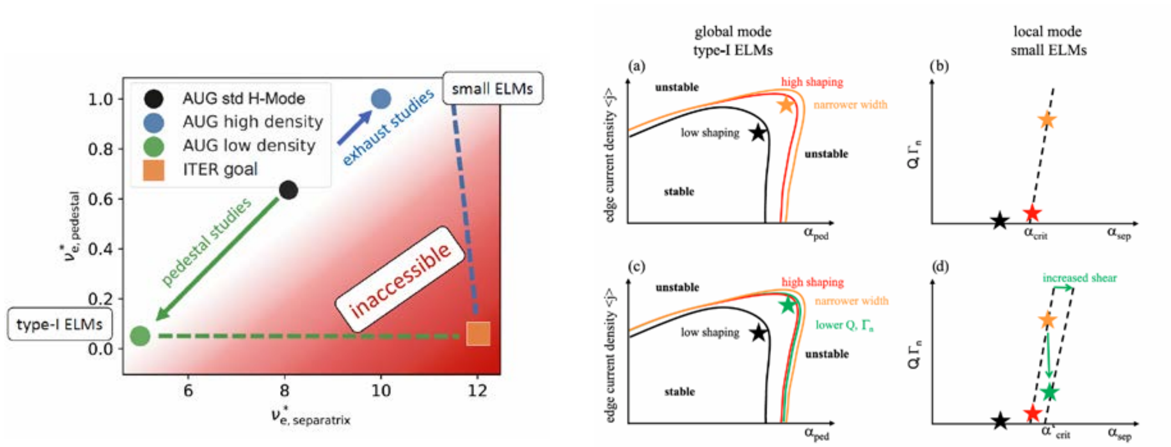

Fig. 2

left: Electron collisionality operational space diagram: collisionality at the pedestal top as a function of separatrix collisionality.

right: Schematic description of small ELM occurrence. Type-I ELM mechanism on the left (a) and (c), small ELM mechanism on the right (b) and (d).

[1] F. M. Laggner et al. Plasma Physics & Controlled Fusion **58** (2016) 065005, http://dx.doi.org/10.1088/0741-3335/58/6/065005

[2] F. M. Laggner et al. Physics of Plasmas **24** (2017) 056105, http://dx.doi.org/10.1063/1.4977461

[3] F. M. Laggner et al. Nuclear Fusion **58** (2018) 046008, https://doi.org/10.1088/1741-4326/aaaa43

[4] F. M. Laggner et al. Plasma Physics and Controlled Fusion **60** (2018) 025002, http://dx.doi.org/10.1088/1361-6587/aa90bf

[5] G. F. Harrer et al. Nuclear Fusion **58** (2018) 112001, https://doi.org/10.1088/1741-4326/aad757

[6] G. F. Harrer et al. subm. to Nuclear Fusion (preprint available on EUROfusion pinboard repository)

Lithium beam diagnostics at ASDEX Upgrade[2]

The lithium beam emission spectroscopy (Li-BES) has become a powerful diagnostic to resolve the plasma edge density in a fusion experiment with high temporal and spatial resolution. Over the past decades the TU Wien has developed the foundations of this diagnostics by providing an accurate atomic database and developing an accurate modeling of the beam attenuation in the plasma.

Up to this date TU Wien contributes to the routine operation of Li-BES at the Tokamak experiment ASDEX Upgrade (IPP Garching). Within H2020 the Li-BES diagnostics at ASDEX Upgrade has been upgraded with the help from TU Wien [7] by installing a new observation system (fig. 3).

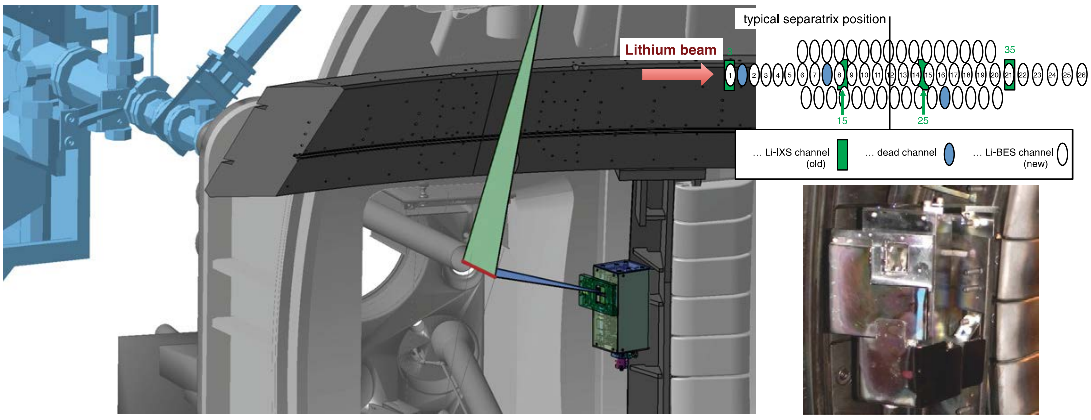

Fig. 3
The new lithium beam diagnostic setup at ASDEX Upgrade: The lines of sight of the old poloidally placed optical head are in green and the lines of sight of the new toroidally placed optical head are in blue. The lithium beam is injected from the low field side and the beam position is indicated by a red line. The lithium beam injector is light blue colored.

The resulting gain in photon flux now allows the plasma edge density to be determined with an advanced level of accuracy. Furthermore, electron density fluctuations can be performed using Li-BES. The Li-BES is well suited to characterize electron density turbulence in the scrape off layer (SOL) with decreasing sensitivity towards the plasma core and an excellent tool to study transport phenomena in the SOL over a wide range of plasma parameters due to its robustness and routine usage.
Together with interferometry diagnostics the Li-BES is now part of the integrated data analysis (IDA) and routinely used for the evaluation of electron density profiles in ASDEX Upgrade [8].

[7] M. Willensdorfer et al., Plasma Physics and Controlled Fusion **56** (2014) 025008, http://dx.doi.org/10.1088/0741-3335/56/2/025008

[8] M. Willensdorfer et al., Journal of Nuclear Materials **463** (2015) 1091, http://dx.doi.org/10.1016/j.jnucmat.2015.01.035

[2] Principal investigator: Friedrich Aumayr, TU Wien (aumayr@iap.tuwien.ac.at)

2.4. TURBULENCE MEASUREMENTS IN THE EDGE REGION OF MEDIUM-SIZE TOKAMAKS AND DEVELOPMENT OF SUITABLE PLASMA PROBES

Short summary of main fields of activities

Together with the Research Units at ENEA-RFX, Padua, the Technical University of Denmark (DTU) and the Jožef-Stefan-Institute (JSI), Ljubljana, the Experimental Plasma Physics Group at the University of Innsbruck (IEPPG) has participated in comparative density profile measurements in the SOL of AUG and TCV. The purpose was to clarify the conditions for filamentary transport and subsequent density shoulder formation, which also increases the edge plasma losses. Plasma probes are suitable diagnostic tools for measuring plasma potential and electron and ion temperature However, cold Langmuir probes (CLP) can only derive these parameters with low time resolution from the current-voltage characteristics. Also the floating potential of CLPs is not a satisfactory parameter, because it strongly depends on the electron temperature. Based on the long-standing experience of the Innsbruck group and their European cooperation partners listed above new types of probes were developed which have a floating potential close to the plasma potential so that the latter parameter can be measured directly and with high temporal resolution. Such plasma potential probes (PPP) can either be electron-emissive probes (EEP) or – in strong magnetic fields –electron-screening probes (ESP).

Selected scientific examples & highlights

Edge plasma turbulence and transport phenomena[1]

By the strong gradients of plasma temperature and density in the edge regions of toroidal magnetic fusion devices, in particular in H-mode, plasma turbulence is excited giving rise to high plasma and energy losses. The motivation for this work is to clarify the mechanisms of this frequently filamentary transport and its properties.

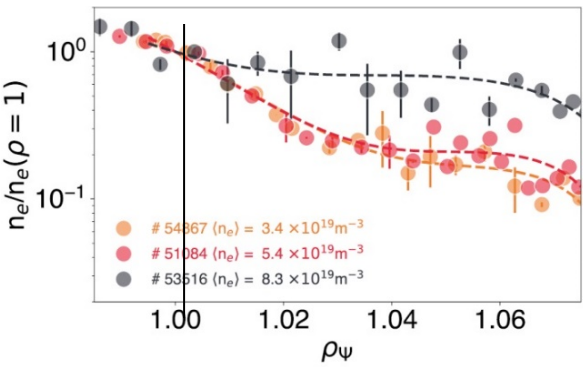

Fig. 1
Normalized density profiles in TCV in poloidal flux coordinates (ρ_Ψ):
Shots without density shoulder formation:
Shot #54867 (**orange**) and shot #51084 (**purple**).
Shot with density shoulder formation: Shot #53516 (**grey**).

Comprehensive measurements mainly with plasma probes have been undertaken for comparison in the SOL of AUG and TCV. Our main efforts have been directed, on one side, to apply cold Langmuir probes suitable for the edge region of toroidal magnetic fusion experiments, and on the other side, to develop electron-emissive probes which are strong enough to function and withstand the plasma conditions in the SOL and also further inside the plasma (see e.g. [1]). Also a new type of electron screening probe has been developed [2]. Both types have in common that their floating potential is close, or – ideally equal – to the plasma potential [5]. The most relevant development of the IEPPG is the new probe head (NPH) combining several different plasma diagnostics [4].

[1] Principal Investigators: Roman Schrittwieser, University of Innsbruck (roman.schrittwieser@uibk.ac.at)
Codrina Ionita-Schrittwieser, University of Innsbruck (codrina.ionita@uibk.ac.at)

Fig. 1 shows radial density profiles in TCV with and without formation of a density shoulder at inner and outer divertors in L-mode plasma [3]. The time evolution of the current densities at three different positions in the TCV wall showed that without shoulder formation the current densities are slightly increasing during the discharge. During shoulder formation the current density was found to drop significantly at the inner wall (i.e. inner divertor) while current densities to floor and outer wall remain constant and similar [6].

Fig. 2

Lateral view of the front side of the NPH with the three probe pins in red. The probe pin in the center is the electron emissive probe. The two retarding field analysers (RFAs) are inside the protruding part. The two triple magnetic pick-up coils (MPC) are further inside.

Fig. 2 shows a side view of the NPH [4]. It carries three probe pins of graphite of which the two lateral pins have 1 mm diameter each and a protruding length of 3 mm; these pins act as cold Langmuir probes. The center pin has a diameter of 0.6 mm and is coated by titanium carbide to increase electron emission. The three probe pins are mounted in a row, slanted by 10° with respect to the total magnetic field in the edge region to avoid mutual shadowing. While the two outer probe pins will not be heated, the centre pin will be heated, thus acting as an EEP. Without heating the EEP the three probes can be used as triple probe for direct measurements of the electron temperature. The NPH also contains two retarding field analysers facing upstream and downstream to measure the ion flux, as well as two triple magnetic pick-up coils to measure magnetic fluctuations in all three directions of space. Also the thermal response of the NPH was successfully simulated [7].

[1] F. Mehlmann et al., Contrib. Plasma Phys. **54** (2014), 273-278, https://doi.org/10.1088/0029-5515/54/6/064005

[2] S. Costea et al., Rev. Sci. Instrum. **87** (2016), 053510, https://doi.org/10.1063/1.4951688.

[3] N. Vianello et al., Nucl. Fusion **57** (2017), 116014, https://doi.org/10.1088/1741-4326/aa7db3

[4] B.S. Schneider et al., Plasma Phys. Controlled Fusion **61** (2019), 054004, (https://doi.org/10.1088/1361-6587/ab0596).

[5] C. Ionita et al., European Phys. J. D **73** (2019), 73, https://doi.org/10.1140/epjd/e2019-90514-5

[6] N. Vianello et al., Nucl. Fusion **60** (2020), 016001, https://doi.org/10.1088/1741-4326/ab423e

[7] B. Končar et al., A, Fusion Engin. Design **156** (2020), 111744 (https://doi.org/10.1016/j.fusengdes.2020.111744)

2.5. PLASMA-WALL-INTERACTION

Short summary of main fields of activities

Particle and power exhaust is a key area of current fusion research and mandatory for the successful operation of ITER and DEMO - the first reactor-like device. Especially the inner wall of such a reactor, which is the first boundary between the extremely hot plasma and the reactor vessel, must withstand harsh conditions. The extremely high heat loads, the excessive neutron radiation and severe sputtering by particle impact cause erosion and reduce the lifetime of wall components. The importance of this area, as well as the need to provide a solution for the plasma-facing components, has been identified in Europe in the so-called European Roadmap to the Realization of Fusion Energy resulting in a special work program PFC (Plasma facing components). Fusion@ÖAW is contributing to this effort by dedicated high precision laboratory experiments and advanced simulation calculations performed at TU Wien and Univ. Innsbruck.

Selected scientific examples & highlights

Erosion of plasma facing components by ion impact[1]

Despite the magnetic confinement in a Tokamak reactor, charged particles (ions) and fast neutral atoms from the fusion plasma can strike the wall of the reactor with high kinetic energy. This results in the removal of wall material ("erosion"), the implantation of fuel into the wall ("fuel retention") and the release of impurities into the main plasma ("plasma dilution" and "radiation cooling"). The interaction of particles from the plasma with the reactor walls must therefore be investigated in detail in order to select suitable materials for the first wall of a fusion power plant and in particular for the so-called divertor. For this purpose, fusion relevant plasma-wall-interaction processes are studied under controlled laboratory conditions at TU Wien. In the laboratory, the basic interaction processes between energetic ions and atoms with solid surfaces can be studied much more precisely than would be possible inside a fusion reactor. A high-precision quartz crystal microbalance (QCM), developed in-house at the Institute of Applied Physics, is particularly helpful in this respect: a small piece of fusion relevant material is bombarded with energetic ions, and its change in weight (due to either implantation or sputtering) is measured extremely accurately by the frequency change of the quartz microbalance. In-situ measurements with the QCM method, in combination with surface investigations using atomic force microscope (AFM) and scanning electron microscopy (SEM), as well as elemental depth profile measurements via ion beam analysis (IBA), made it possible to reveal the dynamic process of erosion under ion bombardment in high detail. This allows the comparison with and benchmarking of erosion modelling by newly developed dynamic codes, which can take into account elemental composition, surface morphologies (e.g. roughness) and even nanostructures.

One of the fusion relevant projectile-target combinations investigated was the erosion of tungsten-nitride (WN) by deuterium (D) ions. In a future fusion device, impurity seeding into the plasma is required to reduce the power flux to the divertor. Nitrogen (N) seeding is an effective coolant at the plasma edge as demonstrated on ASDEX Upgrade. In combination with a tungsten (W) divertor, the formation of WN surface layers can be expected. The erosion of well prepared WN and W (for comparison) films was therefore studied under D ion bombardment at 500 – 1000 eV/D. For W a constant erosion rate was measured with increasing D fluence, while for WN an initially enhanced erosion rate was observed, until steady state conditions are reached. SDTrimSP simulations showed that the initially higher erosion rate for WN can be linked to radiation-induced diffusion [1].

[1] Principal investigator: Friedrich Aumayr, TU Wien (aumayr@iap.tuwien.ac.at)

A highly interesting target surface was iron-tungsten (FeW), because it is a model system for heavy element containing steels, like EUROFER, which are considered as possible material for recessed areas in a future fusion reactor like DEMO. In particular, fluence dependent sputter experiments were carried out for thin FeW films, containing 1.5 at% W, under low energy (250 - 1000 eV/D) ion bombardment. The incident angle of the ion beam was additionally varied and the sample's topography and roughness was investigated by AFM (Atomic Force Microscopy) before and after the exposure to a total fluence of $3{\cdot}10^{23}$ D/m^2. For all kinetic energies a decreasing sputtering yield with increasing D fluence was observed, which could be correlated to a W surface enrichment measured with IBA. The AFM measurements showed a significant surface roughening and (depending on ion impact angle) formation of nanodots or nano-ripples which could be well reproduced by the advanced TRI3DYN code [2, 3].

Furthermore a new experimental setup was developed and put into operation, where a QCM is placed beside the target holder acting as a catcher for material that is sputtered at the target surface. The new setup is able to overcome the limitations of the existing QCM technique to thin film targets directly deposited on the quartz crystal. A proof-of-principle experiment demonstrated that the sputtering yield can be reconstructed from the measured (catcher-) QCM signal [4]. With the new catcher method the erosion of nanostructured tungsten (so called W-fuzz) under argon irradiation was investigated. Although W-fuzz was previously suspected to have a high erosion rate, it could be demonstrated experimentally that such nanostructures show only about 5% of the sputtering yield of bulk tungsten [5].

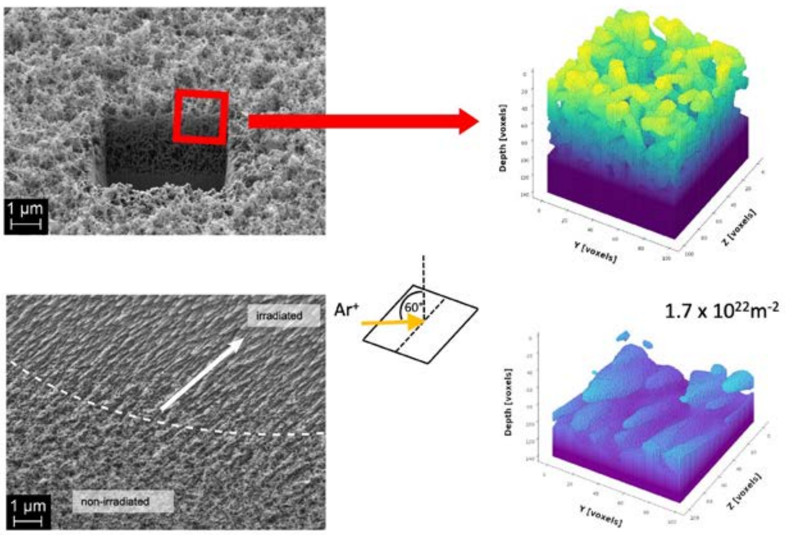

Fig. 1
left: SEM picture of unirradiated (top) and partially irradiated W-fuzz (bottom); The sputtered region shows a scale-like structure, where the tips are pointing in the direction of the incident ion beam (beam direction indicated as white arrow). Ar ion Fluence: 1.7 x 10^{22} m^{-2};
right: Random W-fuzz structure generated as input for TRI3DYN (top); result of the dynamic erosion modelling with TRI3DYN, after a simulated fluence of 1.7 x 10^{22} m^{-2}, revealing a cone-like surface morphology pointing in the direction of the incident ion beam. [5]

The high quality of the experimental results made it possible to compare and benchmark state-of-the-art fully dynamic Monte Carlo - BCA codes just recently developed for the plasma-wall-interaction community, like the 2D- and 3D-version of SDTrimSP or the 3D-version of the code TRIDYN. On several examples we could successfully demonstrate, that SDTrimSP-2D or TRI3DYN are indeed capable to forecast the outcome of complex erosion experiments, if precise surface morphologies and elemental sample compositions are available [3, 5, 6].

[1] B. M. Berger, et al. Nucl. Instrum. Methods Phys. Res B **382** (2016) 82, https://doi.org/10.1016/j.nimb.2016.04.060
[2] B. M. Berger, et al. Nuclear Materials and Energy **12** (2017) 468, https://doi.org/10.1016/j.nme.2017.03.030
[3] R. Stadlmayr, et al. Physica Scripta **T171** (2020) 014021, https://doi.org/10.1088/1402-4896/ab438f
[4] B. M. Berger, et al. Nuclear Instruments and Methods in Physical Research B **406** (2017) 533, https://doi.org/10.1016/j.nimb.2016.11.039
[5] R. Stadlmayr, et al. Journal of Nuclear Materials **532** (2020) 152019, https://doi.org/10.1016/j.jnucmat.2020.152019
[6] R. Stadlmayr, et al. Nuclear Instruments and Methods in Physical Research B **430** (2018) 42, https://doi.org/10.1016/j.nimb.2018.06.004

Reactive ion - surface collisions at low impact energies[2]

For a nuclear fusion reactor, the only reaction currently in reach is the formation of ^{4}He via a collision of the heavy isotope deuterium (D) and tritium (T) in the core plasma at temperatures of around 100 million K. Tritium is a radioactive isotope of hydrogen and would readily exchange with protium (H) in water, when released into the environment. Inside a water molecule, this isotope could be introduced into organisms including humans. For safety reasons the maximum amount of T in ITER is limited to 0.7 kg. If T is lost due to chemical or physical processes other than nuclear fusion, this so-called tritium retention is a severe problem and might lead to a complete shutdown of the reactor. In contrast to the high energy ions mentioned above, we investigate chemical processes between hydrogen and wall materials of ITER at much lower kinetic energies, typically expected for ions that will collide with the first wall material or divertor under normal operation conditions. With a newly designed instrument [7] we investigate the formation of BeD^+ and BeH^+ in collisions of deuterium molecular and atomic ions with a beryllium surface at hyperthermal energies. Our experiments show, that BeD^+ and BeH^+ can be formed in nearly all conditions comparable to an expected wall temperature of ITER.

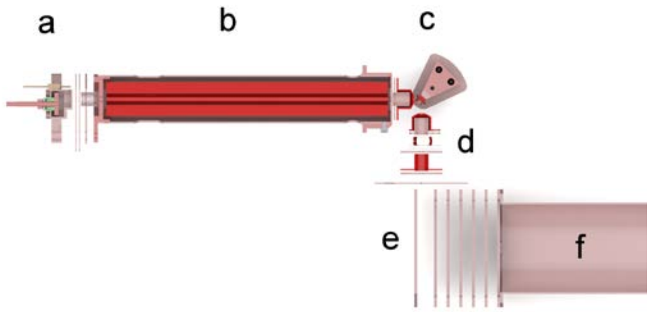

Fig. 2
Schematic of the apparatus SurfTOF with the major parts labelled; a: electron impact ion source, b: quadrupole mass filter, c: heated Be target surface, d: ion optics and second electron impact ion source, e: orthogonal extraction region of a reflectron TOF-MS, f: drift tube of the TOF-MS

The new experimental setup is a tandem mass spectrometer with a surface sample placed between the two mass spectrometers (compare fig. 2). A detailed description of the setup can be found in [7]. Briefly, a quadrupole mass filter selects a specific projectile species, i.e., D^+ or D_2^+, formed upon electron ionization of D_2 introduced into the ion source. The kinetic energy of these projectile ions can be varied from close to zero eV to a few 100 eV by setting a potential difference between ion source and target surface. Secondary ions formed upon reactive ion surface collisions are analyzed in an orthogonal extraction reflectron time-of-flight mass spectrometer), which records all product species simultaneously. The projectile ion current for D_2^+ can reach several 10 nA, which is high enough to keep the surface sputter cleaned during the measurements. Due to a very compact design of the instrument, the ion yield of product ions is more than four orders of magnitude higher than with the predecessor instrument utilized for many years [8].

For the formation of BeD^+ and BeH^+ in collisions of deuterium molecular ions with a beryllium surface at hyperthermal energies, we could assign two different reaction pathways. The first pathway is the direct reaction of the D_2^+ projectile with the Be surface. The relative yield of the product ions BeD^+/Be^+ is very sensitive to the kinetic energy of the projectile and quite insensitive to surface adsorbats, such as water or hydrocarbon molecules that we introduced to the surface chamber. Formation of BeD^+ at low impact energies is of interest for detached plasma conditions of future fusion reactors as a potential channel for tritium retention. BeD^+ can be seen as a marker for a chemical erosion channel and the projectile reaction identified in this work exhibits different properties as an implantation-based model.

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A second reaction channel, forming BeH^+ from surface adsorbates was clearly identified and shown to be independent from the projectile reaction. The product ion yield does not depend on projectile kinetic energy. But the surface temperature, surface ion flux and adsorbate pressure had a strong influence on the yield of this product ion.

Surface ablation of tungsten, known as a plasma-facing material in fusion devices, was investigated mass-spectrometrically in ion beam-type experiments by exposing a tungsten surface in the presence of H_2/D_2 to fast atomic and molecular projectile ions with high electron-recombination energies (Ar^+, He^+ and N_2^+) [10]. The sputtered product ions were monitored by high resolution mass spectrometry (see fig. 3). Bare monatomic and diatomic tungsten ions were seen to be sputtered, more so at elevated ion impact energies and increasing surface temperatures. The relative yield of deuterated WD+ ions was enhanced at higher impact energies and increased partial pressures of D_2, but diminished with increasing tungsten temperature. Our results suggest the occurrence of physical sputtering of bare tungsten ions, W^+ and W_2^+, as well as a novel form of chemically assisted physical sputtering of WD^+ with concomitant dissociation of D_2. Our measurements also provide insight into the influence of the surface temperature of tungsten and the kinetic energy dependence of the impacting ions that cause the physical sputtering. The results clearly indicate an energy onset for the sputtering of the atomic and molecular tungsten ions as well as a minimum energy requirement for the chemically assisted sputtering of WD^+ accompanied by the dissociation of D_2. The latter may be "good news" for fusion research, as the kinetic energy of the ions in the divertor of a tokamak reactor is very low. Our results also suggest that raising the temperature of the plasma-facing material in fusion devices could be useful in preventing chemically assisted sputtering.

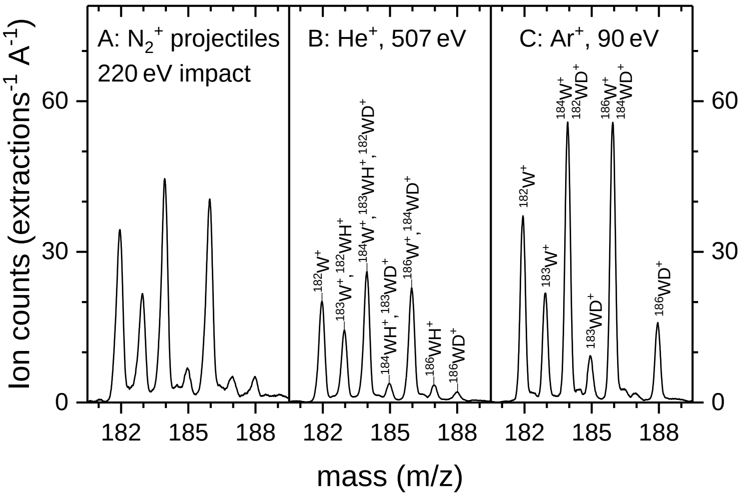


Fig. 3
Mass spectra obtained using various projectile ions at different impact energies. Left: N_2^+ projectiles, impact energy 220 eV, D_2 partial pressure in surface chamber is 3.2 mPa, surface temperature 300 K. Middle: He^+, 507 eV, D_2 pressure 2.3 mPa, surface temperature 300 K. Right: Ar^+, 90 eV, D_2 pressure 2.3 mPa, surface temperature 320 K

[7] P. Ballauf et al., Rev. Sci. Instrum. **91** (2020) 19, https://doi.org/10.1063/1.5145170
[8] M. Harnisch et al., Int. J. Mass Spectrom. **365–366** (2014) 316–323, https://doi.org/10.1016/j.ijms.2014.02.013
[9] L. Ballauf et al., Nucl. Mater. Energy **22** (2020) 100722, https://doi.org/10.1016/j.nme.2019.100722
[10] L. Ballauf et al., Int. J. Mass. Spectrom. **448** (2020) 116252, https://doi.org/10.1016/j.ijms.2019.116252

Computational studies of plasma-exposed metals and alloys[3]

Plasma-wall interactions in ITER cannot be studied by experiments on a 1:1 scale, due to the sheer size of ITER, its high particle flux and the unique design incorporating beryllium and tungsten. Modelling techniques get increasingly helpful to augment experimental data. At the macroscopic level, differential equation-based methods comparable to the finite-element codes in civil engineering can be used to describe surface degradation on the macroscopic scale. These methods require material-specific data like sputtering coefficients and electron-impact cross sections. Such physical constants can be derived from on the microscopic scale with atomistic simulations and with few approximations.

We are developing a multiscale approach to model surface sputtering. At the highest level we use classical molecular dynamics simulations, allowing an atomistic approach to sputtering. Its details differ somewhat from molecular dynamics (MD) simulations for studying modelling system thermodynamics or (bio)molecules in solution. It is intrinsically necessary that bond breaking and bond formation events are covered correctly. It is also necessary to deal with a large range of kinetic particle energies from 0 to 100 eV and more, which would correspond to ~10^6 K in terms of temperature. We typically study infrequent events which requires to perform statistics on thousands of individual trajectories. Our parameter space is about 10-dimensional. In the ideal case we want to know sputtering behaviour as a function of surface temperature, incident angle, incident kinetic energy, type of particle, surface roughness and other parameters. Our approach to combine computational speed and accuracy is based on machine learning: The force expression which is input for all molecular dynamics simulations is derived from all-electron quantum chemical calculations [11, 12] with the information stored in a neural network as a mathematical expression [13]. This allows to (nearly) keep the accuracy of the quantum chemical calculations – which have no problems with bond breaking and bond formation – and perform the MD simulations much faster than 'direct MD' without the intermediate step of building the neural network can do. A feedback algorithm [14] checks if quantum chemical and analytical forces and energies are the same and issues a retraining of the neural network, if necessary. Analysis of the trajectories gives us a variety of material and plasma-related information: Sputtering yields under different conditions, surface degradation, formation of hydrides, composition of the plasma close to the surface and more. With respect to the last item, we also calculated the energy balance in the plasma by determining its electron-impact cross sections [15-17].

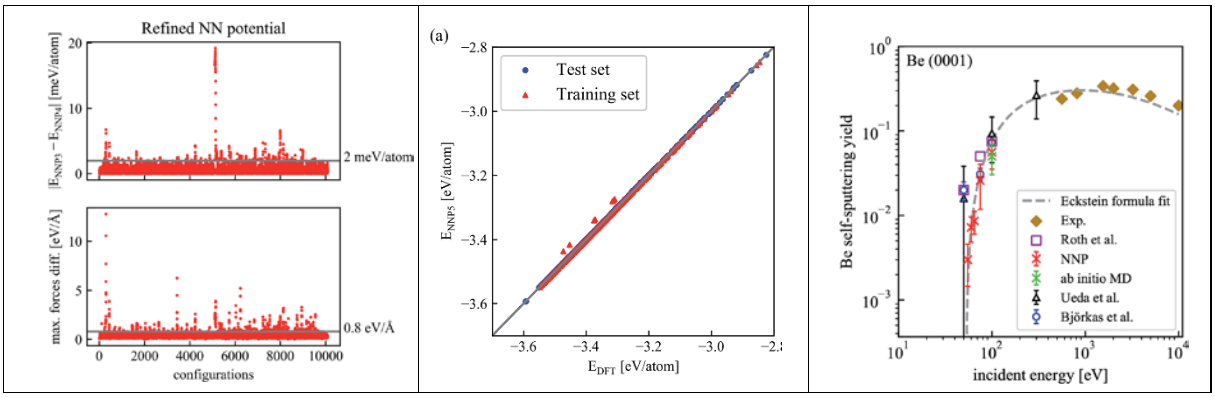


Fig. 4

Left: From the molecular dynamics (MD) trajectory, configurations are identified where energies (top) or forces (bottom) deviate between the neural network and density functional calculations.

Middle: Problematic configurations are incorporated in the training data for an improved neural network potential energy function.

Right: After successive cycles of improvement, the production run is started and sputtering yields are calculated. Our NNP values are compared with literature data.

[3] Principal investigator: Michael Probst, University of Innsbruck, (michael.probst@uibk.ac.at)

We studied the self-sputtering of Be atoms from a Be surface (fig. 4, [14]). The sputtering yield as a function of the energy or the impinging particle is calculated by a series of molecular dynamics simulations using the protocols described above [12]. For this system, literature data are also available for comparison.Further, we try to cover the multidimensional parameter space relevant to sputtering, reflection and deposition of particles as much as we can computationally effort by simulation and, beyond that, by interpolation. Of second importance after the particle energy is the angle of impact. We analyzed how this angle determines energy and outgoing angle of the sputtered or reflected particles (fig. 5).

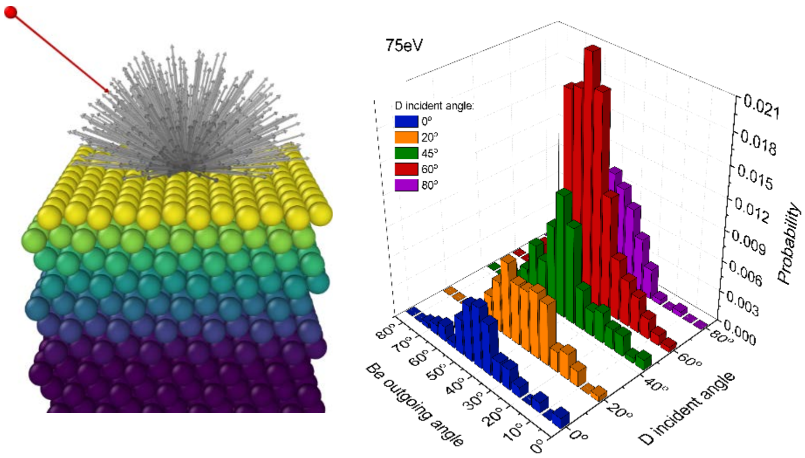


Fig 5:
Left: Particles impinging at a certain angle to the surface with a kinetic energy of 75 eV cause atoms to be sputtered from the surface with various directions and energies.
Right: Angular distributions of the sputtered particles. The maxima of the distributions are around 50° in all cases, but the sputtering efficiency depends strongly on the incident angle (0° = perpendicular to the surface).

The distribution of the angles of the sputtered beryllium atoms (Be) is shown as a three-dimensional histogram. As an example, the energy of the incoming deuterium particle is 75 eV. For other energies the distributions are quite similar, except that below 30 eV the low sputtering rate causes few events to be sampled.

If one looks instead at the reflection of deuterium, which ist the dominant channel in the energy range from 0-100 eV, the angular distribution is also broad: The angle of the outgoing particle is rather independent of the incident angle, both in case of sputtering and reflection events - an indication that predominantly inelastic processes take place.

[11] L. Chen et al., Nuclear Materials and Energy **16** (2018) 149–157, https://doi.org/10.1016/j.nme.2018.06.021

[12] L. Chen et al., Nuclear Materials and Energy **22** (2020) 100731, https://doi.org/10.1016/j.nme.2020.100731

[13] I. Sukuba et al., Molecular Simulation (2018), https://doi.org/10.1080/08927022.2018.1560440

[14] L. Chen et al., RSC Adv. **10** (2020), 4293 (issue in progress)

[15] S.E. Huber et al., J. Chem. Phys. **150** (2019), 024306, https://doi.org/10.1063/1.5063767

[16] I. Sukuba et al., J Mol Model (2017) 23:203, https://doi.org/10.1063/1.5063767

[17] S.E. Huber et al., Probst; Eur. Phys. J. D (2017) 71: 335, https://doi.org/10.1140/epjd/e2017-80308-2

2.6. NUCLEAR DATA

Short summary of main fields of activities

Nuclear data evaluations of high quality are required for transport simulations, uncertainty assessments, activation and radiation damage calculations affecting the design and performance of fusion technology facilities, as well as safety, licensing, waste management and decommissioning issues. A corresponding programme on the nuclear data development (NDD) and qualification is conducted within the Power Plant Physics and Technology (PPPT) programme of EUROfusion supporting the development of the DEMO fusion power plant and the IFMIF-DONES neutron source [1]. H. Leeb et al. (TU Wien) focus on the development and implementation of an R-matrix method for three-body reaction channels to create evaluated nuclear data files requested by EUROfusion.

Selected scientific examples & highlights

R-matrix-based formalism for three-body reaction channels[1]

The availability of reliable nuclear reaction data of light nuclear systems is an important prerequisite for the development of novel nuclear technologies and in particular for the design of fusion facilities. In general the evaluation of reaction data of light nuclear systems is rather challenging due to limitations in experiments and the lack of quantitatively reliable microscopic model calculations. Consequently the available evaluated nuclear data files for light nuclei are not satisfactory and subject of worldwide efforts for improvement. Many evaluations of neutron-induced reaction cross section data of light nuclei make use of the R-matrix theory (Lane et al., Rev. Mod. Phys. **30**, 257, 1958) which is sufficiently flexible and satisfies conservation laws applicable in the collision process. The concept of standard R-matrix theory assumes a finite interaction volume (fig. 1) and is thus limited to two-body channels. Consequently breakup-channels with three or more outgoing particles cannot be described properly [2]. In several light nuclear systems dominant breakup channels occur at low energies and hamper a proper R-matrix description. A typical example for a dominant breakup reaction is the process n+^{9}Be→ a+a+n+n which opens at 1.66 MeV (fig.2). This breakup can be considered as an effective three-body reaction n+^{9}Be → (^{8}Be)+n+n because (^{8}Be) is a long-lived resonance (~10^{-17} s) of two a-particles at E_x=92 keV. The only derivation of a three-body R-matrix formalism was presented by Glöckle (Z. Phys **271**, 31, 1974),

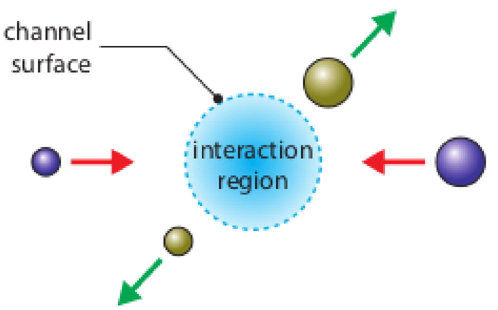


Fig. 1
Separation of space assumed in standard R-matrix theory. At the channel surface the form of the asymptotic solution of the wave function of relative motion is matched to the internal wave function given by an expansion of basic functions.

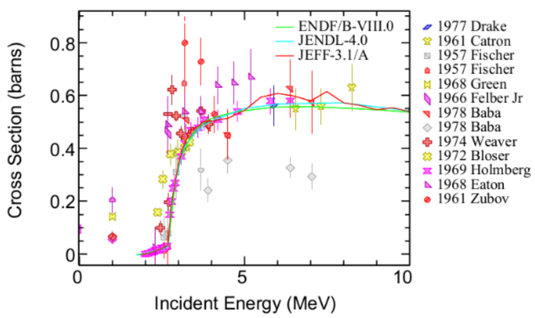


Fig. 2
Comparison of available experimental data of the breakup cross section by the reaction n+^{9}Be → α+α+n+n with the corresponding cross sections provided by recent nuclear data libraries.

[1] Principal Investigator: Helmut Leeb, TU Wien (helmut.leeb@tuwien.ac.at)

but neither numerically implemented nor applied to examples. In the absence of any extension of the R-matrix formalism, three-body channels are frequently treated in approximations. However, these approaches do not yield a fair description of the reaction n+^{9}Be→α+α+n+n. The development of an applicable R-matrix formalism for three-body channels is urgently needed and the goal of the current activity at TU Wien. The work follows two directions: (i) the numerical implementation and extension of the formalism of Glöckle as well as (ii) the development of a novel three-body R-matrix formalism directly based on the Faddeev equations (L.D. Faddeev, Soviet Phys. JETP **12**, 1014, 1961).

The R-matrix formalism of Glöckle starts from the Faddeev equation which splits the scattering quantities in three components each containing two interacting particles, while the third one is freely moving. Glöckle reinterpreted the separation of space in terms of different regions in the three pairs of Jacobi coordinates. Similarly to the standard R-matrix formalism the internal three-body wave function is described by an expansion in two-dimensional basis functions. For the external three-body wave function the asymptotic form of the breakup amplitude is used. Similarly to the standard derivation of the R-matrix the wave functions are matched at the border between internal and external space which leads to a system of equations which is quite similar to the two-body formulation. In order to make the procedure applicable to treat effective three-body channels an extension to unequal masses was performed by the group. Furthermore the formalism was modified with regard to imperfections and implemented numerically. Thus the group succeeded to implement the three-body R-matrix algorithm of Glöckle for the first time and obtained for the rearrangement channels reasonable and almost stable results. For the breakup channels the method proved very sensitive to the integration grids and the set of functions used in the expansion. A major problem is the transfer of the separation to the domain of Jacobi coordinates which leads to strict conditions for consistent matching radii. In addition the method deviated from the standard Faddeev formalism, thus hiding the off-shell contributions of the two-body interactions. In summary the method of Glöckle bears some problems and tends to instabilities which can be cured by regularization. Hence there remain some doubts whether the algorithm based on the idea of Glöckle could be efficiently applied for nuclear data evaluations.

In parallel a new concept for a three-body R-matrix was developed at TU Wien. It is fully based on the Faddeev equations assuming separable two-body interactions between the particles which significantly simplifies the solution of this system of coupled integral equations. The interactions enter via the corresponding two-body *t*-matrices into the Faddeev equations. Formally these two-body *t*-matrices are three-body operators but reflect all features of two-body operators because the associated third particle is free and enters only as unity operator. Furthermore one makes use of the fact that a separable two-body interaction results in a separable *t*-matrix. The form factors of the separable interactions determine the momentum dependence, while the energy dependence is given by the energy denominator. This property allows a complete description of the two-body *t*-matrix, i.e. on- and off-shell behaviour, via a two-body R-matrix although the latter contains only on-shell information. Thus the novel three-body R-matrix formalism is a straightforward extension of the standard R-matrix theory which requires three sets of R-matrix parameters (one for each subsystem) in order to describe the complete two-body *t*-matrix. Contrary to the algorithm of Glöckle the novel three-body R-matrix method does not require any conceptual change of the R-matrix. In addition it completely follows the established formalism for the solution of Faddeev equations with separable potentials and no significant problems are expected for the solution of the system of coupled Faddeev equations. At the moment the numerical implementation of the novel formalism is in progress. A manuscript for publication in a peer-reviewed journal is in preparation which will also include an example to demonstrate the feasibility of the novel method.

[1] U. Fischer et al., Engineering and Design **136 Part A** (2018), pp162-267, https://doi.org/10.1016/j.fusengdes.2018.01.036
[2] B. Raab et al., EPJ Web of Conferences **211** (2019), 07006 https://doi.org/10.1051/epjconf/201921107006

2.7. HIGH-HEAT-FLUX MATERIALS FOR FUSION APPLICATIONS

Short summary of main fields of activities

Applications in fusion technology require materials with high thermal conductivity and acceptable ductility and strength both at room temperature and higher temperatures. Additionally, the materials must be resistant to activation by neutron bombardment. Studies carried out at the Erich-Schmid Institute of Materials Science (ÖAW-ESI) are focusing on the optimization of the fracture behavior of various tungsten alloys, investigating the respective materials on the nanometer scale.

Selected scientific examples & highlights

Fracture toughness and microstructural stability of heavily deformed tungsten materials[1]

Tungsten and tungsten-based materials are leading candidates for the divertor and plasma facing components of future nuclear fusion devices. However, a significant drawback for the structural application of tungsten is its poor fracture toughness and low ductility at room temperature along with a high ductile-to-brittle transition temperature (DBTT). Therefore, the use of tungsten for structural components will strongly depend on the elucidation of toughening mechanisms allowing an adequate fracture resistance in this material class. Hence, a comprehensive understanding of the fundamentals of fracture of tungsten-based materials is essential. The focus of recent investigations was on the fracture behaviour and microstructural stability of heavily deformed tungsten materials in the shape of sheets of foils and wires [1–6].

The crack resistance of pure and potassium doped tungsten foils was tested as a function of testing direction and temperature in the range from -196°C to 800°C. A positive effect of deformation-induced grain refinement was found enabling high fracture resistance and a reduction of the DBTT to room temperature. The grain shape anisotropy and a rotated cubic texture were found to control the orientation dependent fracture properties. The mechanical changes were accompanied with a change of the failure mode going from brittle, transcrystalline fracture at -196°C towards pronounced delamination at intermediate temperatures and ductile failure at highest temperatures.

In addition, microstructure-property relationships of differently annealed pure tungsten and potassium doped tungsten wires were investigated. Pure tungsten wires recrystallize fully in the temperature range of 1300-1500°C accompanied with tremendous coarsening and a complete loss of the initial fibrous, elongated grain structure. In contrast to this, potassium doped wires show superior high temperature properties with retarded recrystallization and grain growth at even higher temperatures. The occurrence of either a brittle or a ductile response in the as-received state of both materials is a strong indication that the ductile-to-brittle transition temperature is around room temperature. Pure annealed tungsten wires experience a tremendous deterioration of the fracture toughness with a very prominent transition of the failure mode. The observed embrittlement by annealing can be related to the loss of the fibrous

[1] Principal Investigator: Reinhard Pippan, ÖAW-ESI (reinhard.pippan@oeaw.ac.at)

elongated microstructure. In contrast to this, the results of the annealed, doped wires demonstrate that the microstructural stability and preservation of the initial, beneficial grain structure is directly reflected in the crack resistance of the material. Predominately ductile behaviour, with characteristic knife-edge necking, is seen even after annealing at 1600°C.

So far the quasi-static properties were in the focus of the investigations at the Erich Schmid Institute. Beside strength and fracture toughness, the cyclic behaviour is of essential importance for the lifetime of a future fusion reactor. Current and future research will therefore concentrate on the fracture resistance under cyclic loading conditions, i.e. the fatigue crack propagation behavior (these experiments on tungsten alloys are the worldwide first investigations of these important properties).

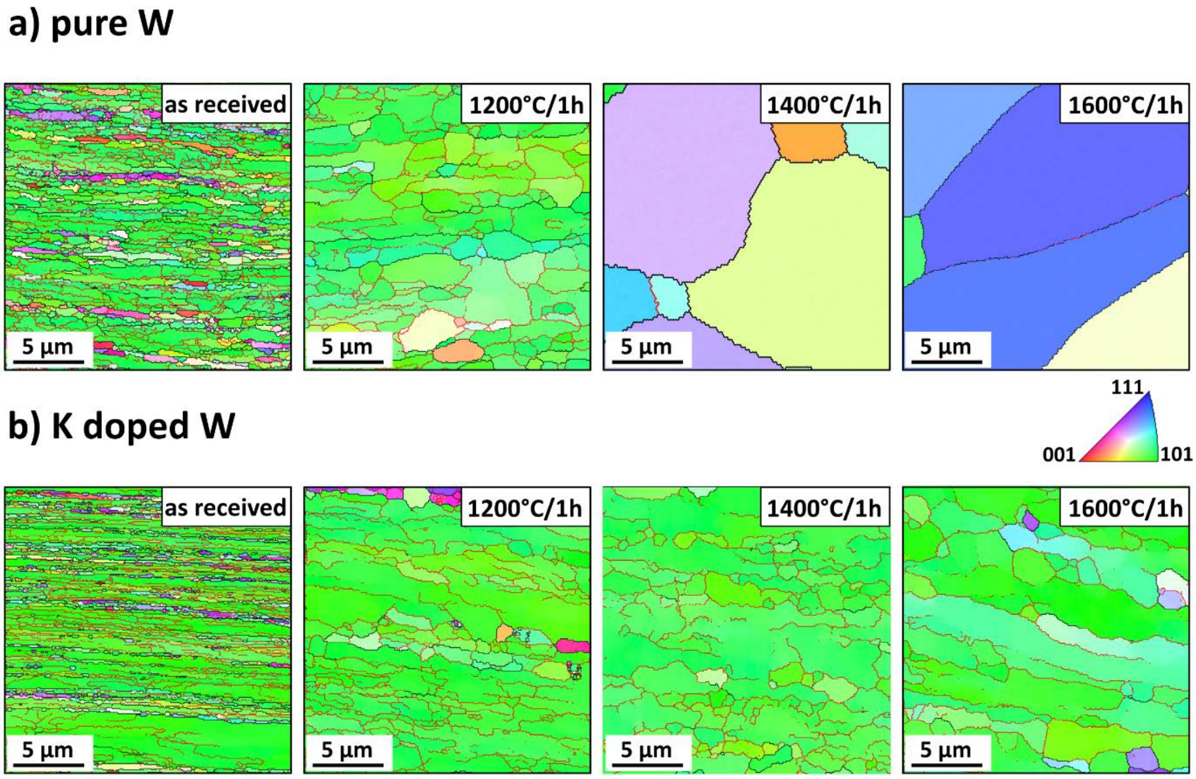


Fig. 1

Comparison of the thermal stability of pure (a) and K-doped tungsten different annealing temperatures. The beneficial elongated microstructure is lost at high annealing temperatures and directly impacts the fracture behavior.

[1]. V. Nikolic et al., Nucl. Mater. Energy **9**, 181 (2016), https://doi.org/10.1016/j.nme.2016.06.003

[2]. V. Nikolić, et al., J. Refract. Met. Hard Mater. **69**, 40 (2017), https://doi.org/10.1016/j.ijrmhm.2017.07.017

[3] V. Nikolić, et al., Int. J. Refract. Met. Hard Mater. **76**, 214 (2018), https://doi.org/10.1016/j.ijrmhm.2018.06.008

[4}. V. Nikolić, et al., Mater. Sci. Eng. A **737**, 434 (2018), https://doi.org/10.1016/j.msea.2018.09.029.

[5]. V. Nikolić et al., Mater. Sci. Eng. A **737**, 422 (2018), https://doi.org/10.1016/j.msea.2018.09.027

[6]. M.J. Pfeifenberger et al., Acta Mater. **176**, 330 (2019). https://doi.org/10.1016/j.actamat.2019.06.051

2.8. HIGH-TEMPERATURE SUPERCONDUCTORS FOR FUSION APPLICATIONS

Short summary of main fields of activities

A future fusion device has to operate with superconducting magnet coils for obtaining a net energy gain. Superconductors do not consume energy, but they need to be cooled down to low temperatures. Superconductors for ITER will be made of niobium-tin and operated at around 5 K. High-temperature superconductors are favorable for future fusion power plants because they allow for higher magnetic fields and temperatures, which reduces the cooling costs and simplifies magnet construction. In any case, the superconductor will suffer from the neutron radiation inherent to fusion. M. Eisterer et al. (Atominstitut, TU Wien) investigate the effect of neutron irradiation on industrial superconductors.

Selected scientific examples & highlights

Superconductors for future fusion power plants[1]

Nuclear fusion based on magnetic confinement of the plasma relies on strong magnetic fields generated by huge magnets surrounding the plasma chamber. These magnets have to be superconducting for a net positive energy balance because conventional magnets, such as the ones in JET, dissipate too much energy. State-of-the-art superconducting magnets are made of low temperature superconductors, which are well-established as a conductor technology, but need cooling with liquid helium. This is expensive, and helium is an exhaustible resource. In addition, there is little margin in enhancing the magnetic field compared to ITER or DEMO. High-temperature superconductors are an immature technology, but very promising because they can be operated at higher temperature, which enables more energy efficient cooling with cheaper and inexhaustible gases. Much higher fields can be achieved offering the possibility of smaller and consequently much cheaper fusion plants. The magnet system is a big portion of the overall costs in ITER and DEMO. All superconductors will suffer from the neutron radiation arising from the fusion reaction which in turn might limit the lifetime of the power plant.

The work at Atominstitut / TU Wien focuses on the radiation resistance of commercial superconductors. Both, conventional niobium-tin superconductors and high-temperature superconducting tapes, were sequentially irradiated in the TRIGA reactor. The changes in properties were assessed by magnetic and resistive measurements. The facilities at Atominstitut are ideal for this purpose because the irradiation and characterization can be done at the same place. Safe handling of the radioactive samples is ensured by the staff of the radiation protection and appropriate laboratories. This makes our studies world-wide unique.

All investigated superconductors basically behave in the same way under relevant operation conditions (field and temperature). The critical temperature, below which the material is superconducting, decreases with increasing neutron exposure. On the other hand, the critical current, which defines the maximum loss-free current initially increases, reaches a maximum, and declines at high fluences. The left panel in fig.1 shows a typical example at 30 K and 15 T, where the critical current was normalized to its value before irradiation. Although this behavior is qualitatively universal, the height and the position of the maximum as well as the fluence where the currents become smaller than in the pristine conductor

[1] Principal Investigator: M. Eisterer, TU Wien (michael.eisterer@tuwien.ac.at)

depend on the material and the operation conditions. Superconductors are more robust against neutron radiation at low operation temperatures [1] and conventional superconductors are less sensitive. The original defect structure, which is important for the performance of the unirradiated conductor, has an important influence as well. Defects are important to impede the movement of the quantized flux in a superconductor, which would otherwise lead to losses. Hence, so-called artificial pinning centers (APCs) are induced by particular preparation techniques in high-performance conductors. Flux pinning is also the reason for the initial increase of the critical currents upon irradiation because of the created defects. On the other hand, if the number of defects becomes too high, the critical current degrades, which happens at lower neutron fluences if the pristine conductor contains APCs.[2] This is sketched in the right panel of fig. 2.

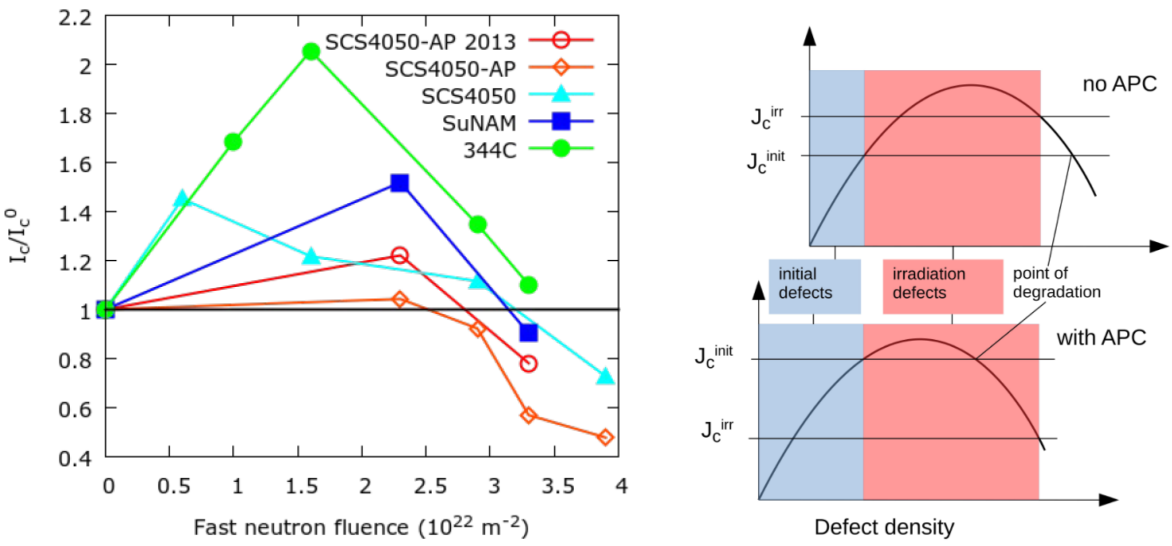


Fig. 1

Left: Change of the critical currents at 30 K, 15 T after fast neutron irradiation (E>0.1 MeV) in various commercial coated conductors. The currents are normalized to the value in the pristine tape for better comparison.

Right: Sketch of the influence of artificial pinning centers (APC).

[1] R. Prokopec, et al., Supercond. Sci. Technol. **28** (2015) 014005, https://doi.org/10.1088/0953-2048/28/1/014005

[2] D X. Fischer et al., Sci. Technol. **31** (2018) 044006, https://doi.org/10.1088/1361-6668/aaadf2

2.9. SOCIO-ECONOMIC STUDIES ON FUSION

Short summary of main fields of activities

One topic of Socio-Economic Studies on Fusion is the development of future energy scenarios, with shares of fusion energy depending on external factors such as environmental responsibility, in particular in terms of the stringency of CO_2 emission targets. Fusion@ÖAW contributes to this effort with special input to the scenario models, elaborated at Research Studios Austria in Salzburg.

Selected scientific examples & highlights

Energy scenario modelling[1]

Our global energy system is facing a transition. The phase-out of nuclear fission and fossil fuels – not at least due to climate change mitigation – in many parts of the globe means a significant challenge for our supply system. In addition, the electrification of the mobility and heating sectors bring new challenges for our future energy system. Therefore, the future development of our global energy system is simulated with the EUROfusion Times Model (ETM) under varying assumptions on cost developments, climate policies and further external constraints. In order to forecast under which circumstances fusion power is able to enter the market, the globe is divided in several regions (see fig. 1 - left), which are modelled with individual parameter settings. Next to fusion power, renewable energies are the most promising option for a sustainable future energy system. However, covering high shares of the energy demand with renewable resources would also mean a high spatial impact since solar, wind and biomass potentials are quite space-intensive.

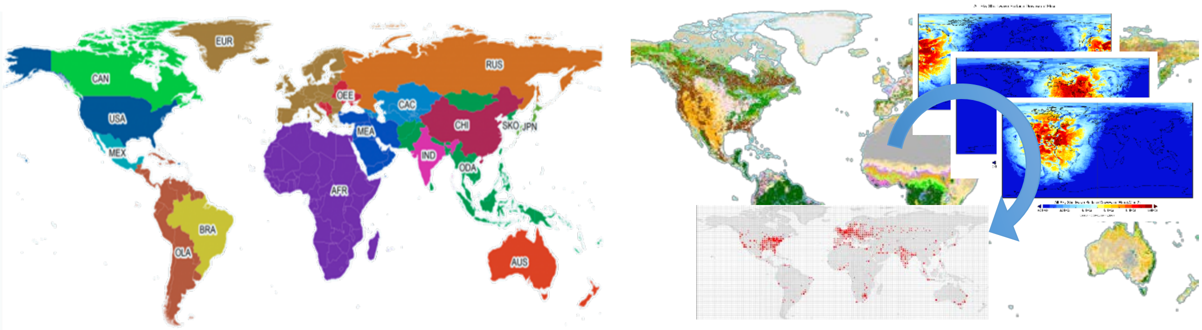


Fig. 1
left: break-down oft he globe in individual homogeneus regions in ETM; **right:** landcover dataset merged with temporal discrete solar insolation maps in order to identify PV potential in settlement areas.

With GIS methods and tools the correlated spatial availability and impact is calculated in a high spatial resolution for the complete globe by merging spatial datasets on climate, soil, land use, topography, population density, weather data, etc. in complex models. This includes for instance the model-based calculation of photovoltaic (PV) production on suitable areas (see fig. 1 - right).

With these spatially discrete calculations, a breakdown to the concrete ETM model regions is done in order to estimate the usable renewable energy potential coming from biomass, wind, solar or hydropower. It allows also the identification of possible coverage rates related to temporal demand

[1] Principal Investigator: Markus Biberacher, Research Studios Austria (markus.biberacher@researchstudio.at)

profiles by paying attention to spatial balancing streams between demand and supply within individual ETM regions.

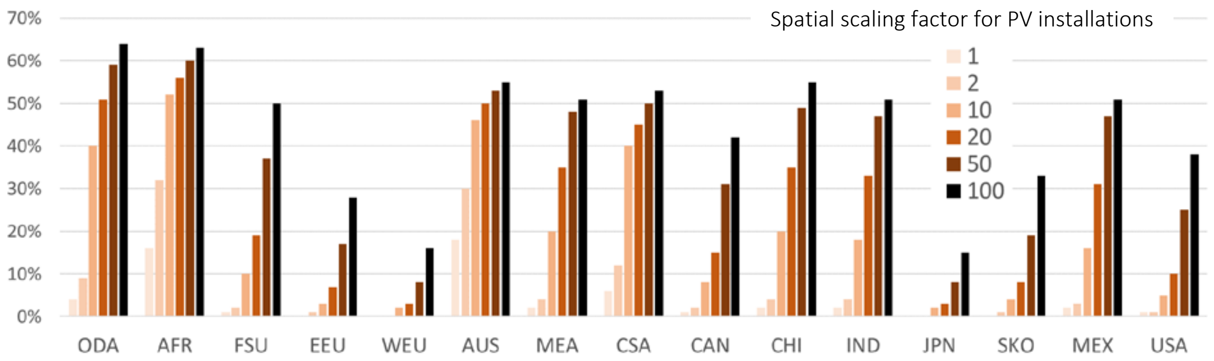


Fig. 2

Possible demand coverage rates in % by solar PV installations in individual ETM regions by paying attention to temporal aspects in load balancing if installations are scaling up spatially by a factor of 100.

Results serve as input for ETM as upper constraints for renewable energy shares in relevant model regions. In cooperation with ENEA in Rome/Padova, CIEMAT in Madrid and the JRC in Petten, scenarios on the future development of the global energy system until the year 2100 are calculated by finding an optimal market equilibrium under varying storyline assumptions (see fig. 3).

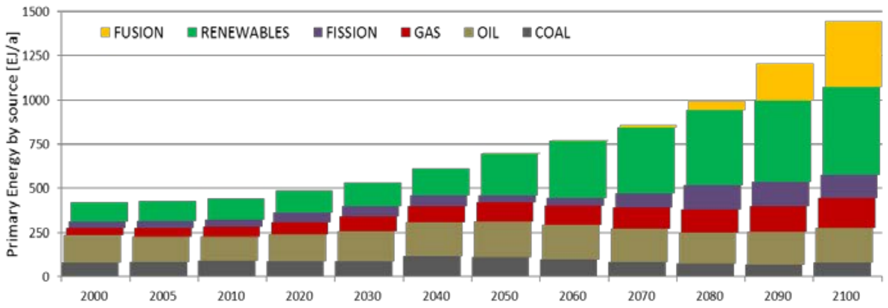


Fig. 3

Possible market shares of different sources (including fusion power) until 2100 for a 550ppm climate constraint scenario.

The outcome of these scenarios – especially on the regional scale of ETM regions – are subject to an ongoing review process in which Fusion@ÖAW / RSA is supporting the partners ENEA and CIEMAT. Model parameters are continuously updated to actual technology developments and political streams on a global scale in order to adapt and improve ETM successively.

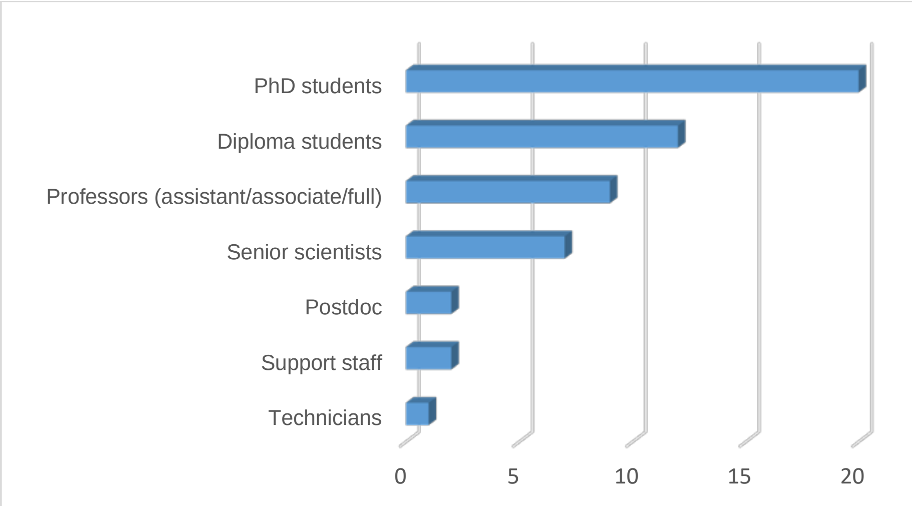
Besides these scientific tasks, Fusion@ÖAW / RSA also takes responsibility for the publication of SES activities and results on the EUROfusion collaborators website. On this website economic studies as well as the social studies are presented separately and for each study a description of the relevant contents, the realized work and relevant publications is provided.

3. Statistical Information

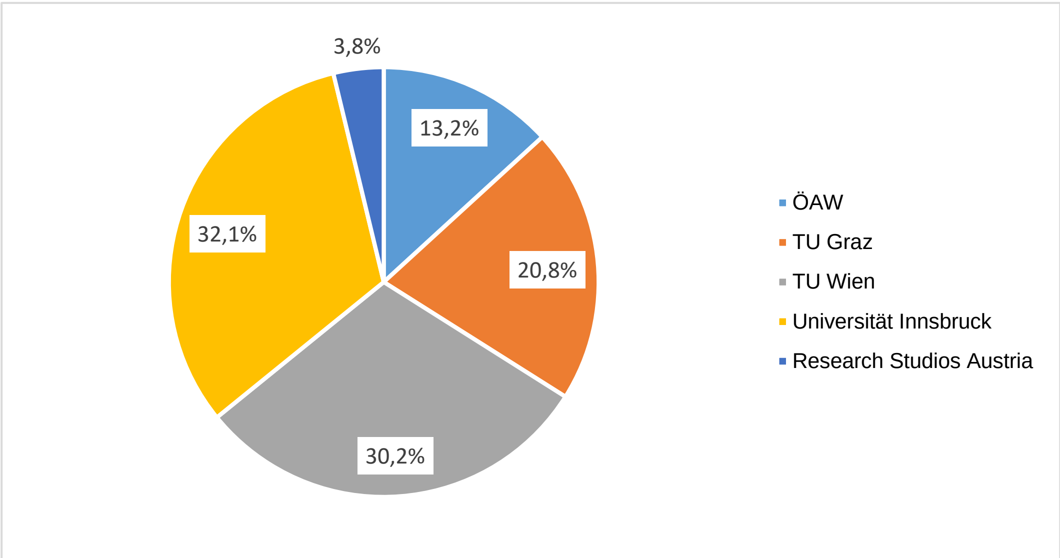
3.1. EUROfusion Participation

The Austrian Fusion Research Unit (Fusion@ÖAW) comprises research groups at the Austrian Academy of Sciences, three universities (Technische Universität Graz, Technische Universität Wien, Universität Innsbruck) and Research Studios Austria Forschungsgesellschaft (RSA). In addition, ÖAW hosts the Fusion@ÖAW Coordination Office led by the Head of Research Unit which provides administrative support and advice to the participating scientists. The total number of staff members by category and the distribution of personnel among ÖAW and its Linked Third Parties (snapshot as of 31 December 2019) are shown below.

Fusion@ÖAW: staff members by category
(as of 31 December 2019)



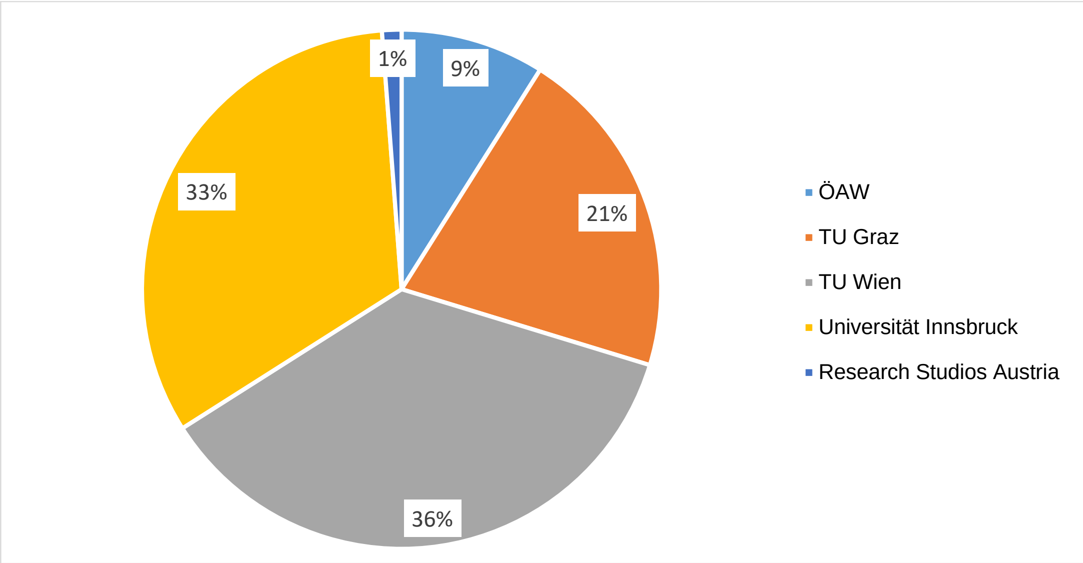
Distribution of personnel among ÖAW and Linked Third Parties
(as of 31 December 2019)



3.2 Total Expenditure and EURATOM Cofunding

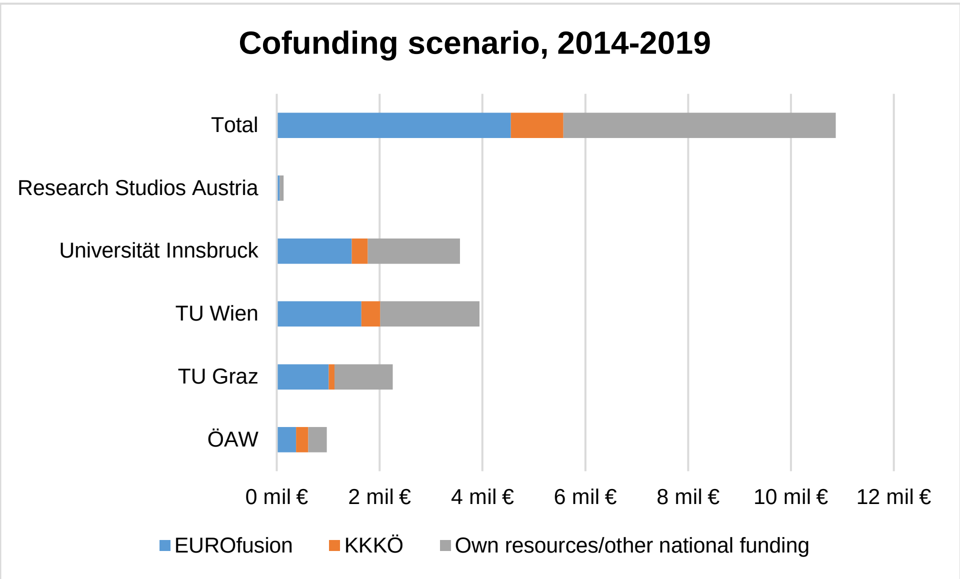
During the period 2014-2019, the total average annual expenditure of Fusion@ÖAW's participation in EUROfusion was EUR 1.8 million. In the same period, the average EUROfusion funding per year was kEUR 770, i.e. approximately 43 % of total expenditure came from EUROfusion.

Share of total expenditure - ÖAW and Linked Third Parties

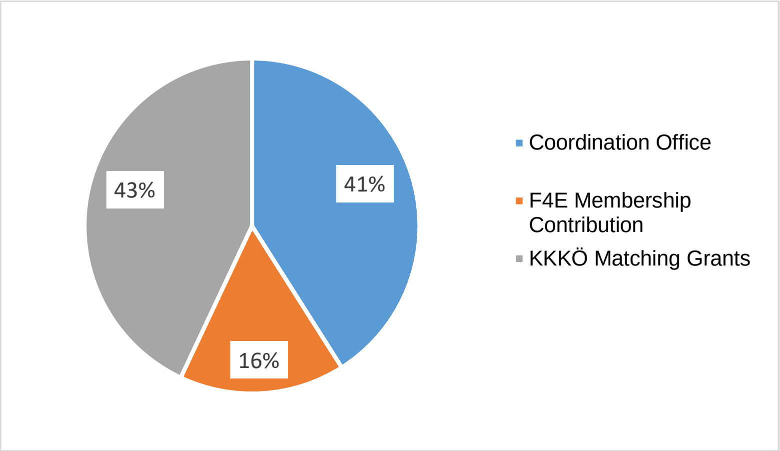


National co-funding of the remaining 57% of total expenditures is acquired from various sources (see graph below):

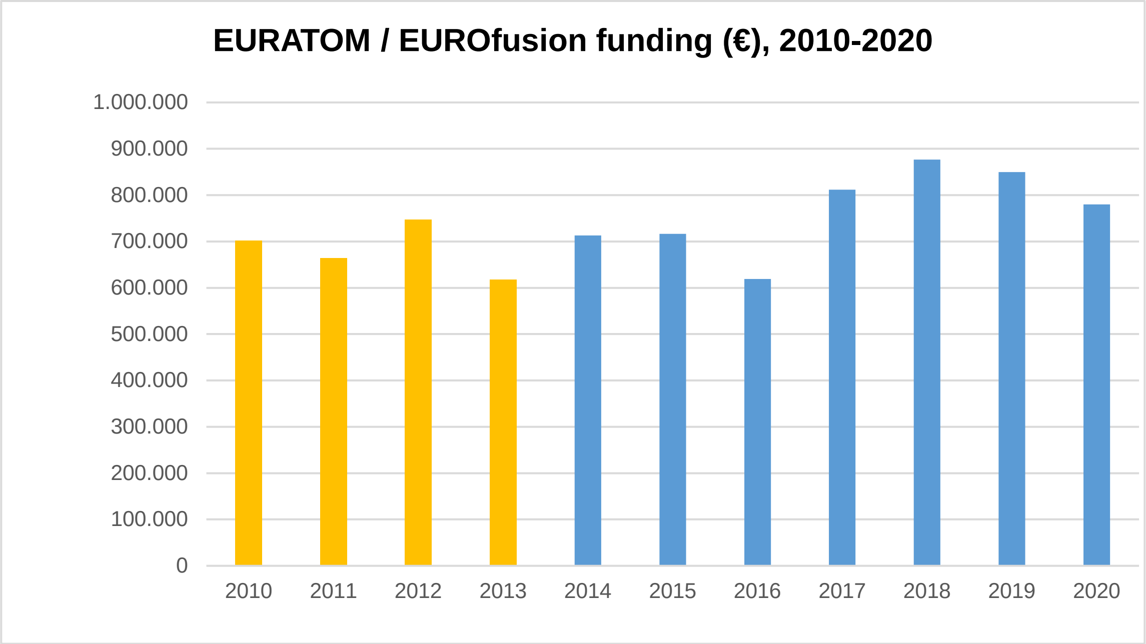
KKKÖ - funds dedicated to fusion research by the Federal Ministry of Education, Science and Research (bmbwf) and administered by ÖAW (365 k€/year)
Own resources (including university budgets and salaries) and other national funding



Annual budget assignment for fusion research
(bmbwf to ÖAW, based on average figures 2014-2019)



Contrary to the baseline support which was granted under the Contract of Association (2007-2013) for annual work programmes defined by the national members in consultation with the European Commission, EUROfusion (2014-2020) supports specific contributions to its annual work programmes at internally defined funding rates weighted according to goal-oriented priorities. The graphs below show a comparison between EURATOM funding from 2010 to 2020. It must be noted that there is a remarkable difference in the average annual funding rate (≈ 22 % in FP7 and ≈ 43 % in H2020). In line with EUROfusion priorities, Austrian fusion research activities moved from more theory-based activities to active participation in the experimental programme and focused even stronger on the education of young researchers. This strategy not only enabled Fusion@ÖAW to avoid drops in funding in the first years of H2020, but to even increase its participation from 2017 onwards.

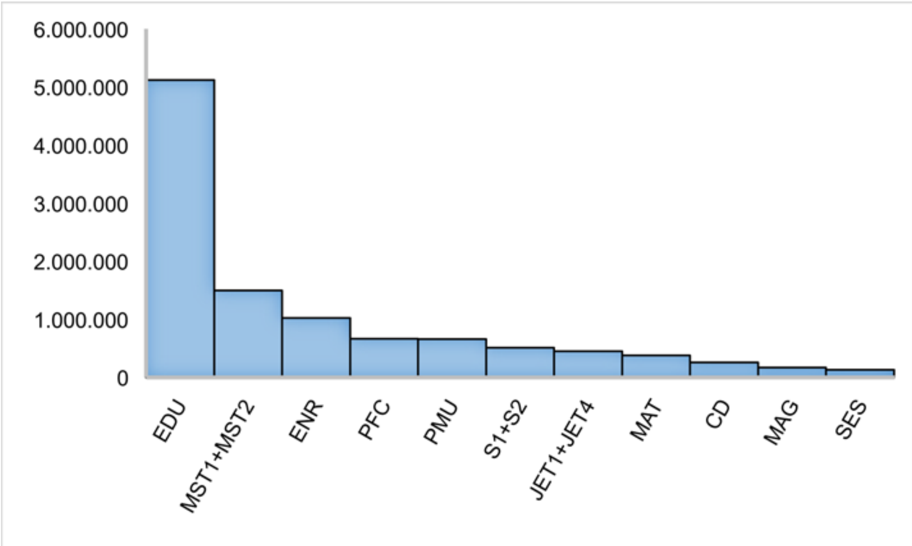


Data for 2014-2018 reflect funding based on the financial statements approved by EUROfusion. Data for 2019 and 2020 are based on budget figures assigned by EUROfusion.

Work packages

Fusion@ÖAW comprises three large universities and two research institutions. It is therefore not surprising that “Education” (i.e. partial support of PhD salaries) is the most important priority, followed by participation in the Medium-Size Tokamak Program MST. The topics of PhD-theses supported under “Education” are closely linked to the activities in the remaining work packages displayed in the graphs below.

Total expenditure (€) per work package
(Fusion@ÖAW 2014-2019)

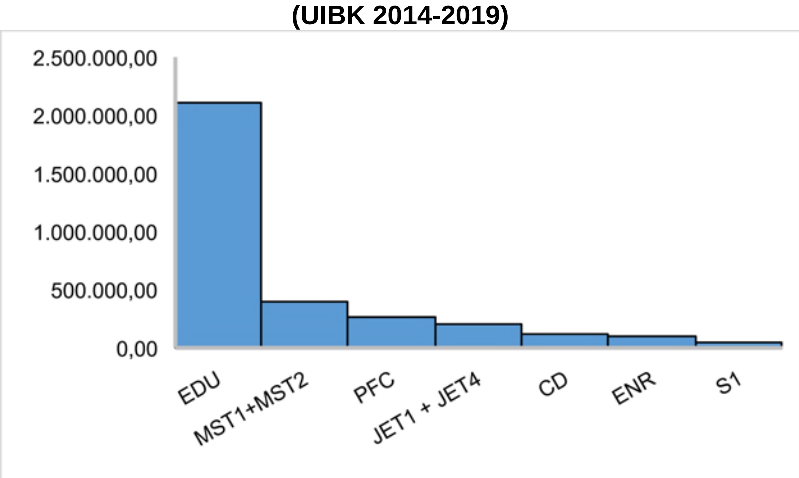


EUROfusion work packages – legend

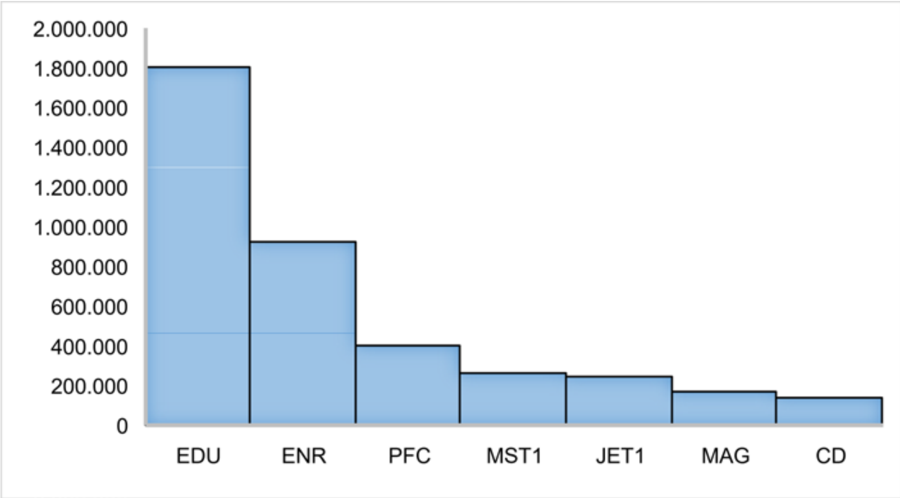
EDU Education	PMU Management at beneficiary and EUROfusion level	MAT Materials
MST1 Medium-Size Tokamaks	S1 Preparation and Exploitation of W7X-Campaigns	CD Code Development
MST2 Preparation of Exploitation of MSTs	S2 Stellarator optimization	MAG Magnet System
ENR Enabling Research	JET1 JET Campaigns	SES Socio-Economic Studies
PFC Preparation of efficient PFC operation for ITER and DEMO	JET4 JET enhancements	

In terms of total expenditure, the University of Innsbruck accounts for the highest share attributed to the work package Education, followed by TU Wien and TU Graz.

Total expenditure (€) per work package
(UIBK 2014-2019)

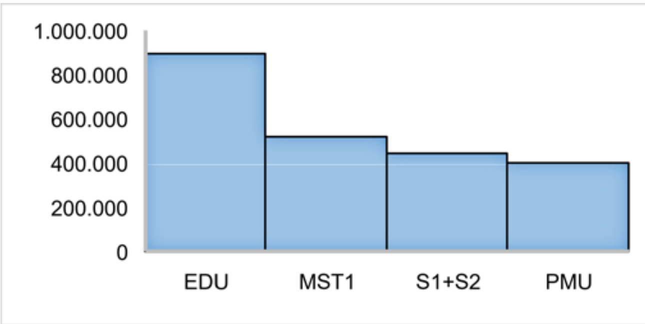


Total expenditure (€) per work package
(TU Wien 2014-2019)

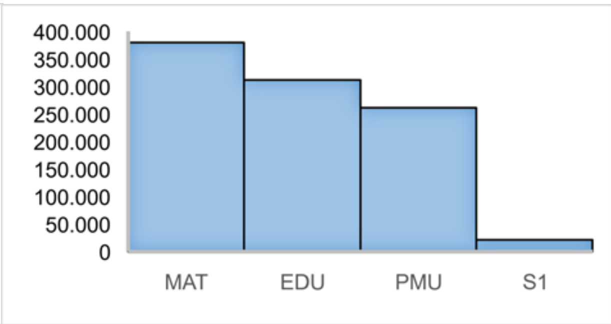


Total expenditure (€) per work package

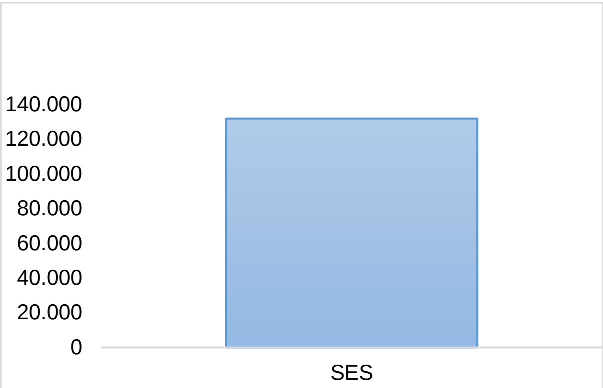
TU Graz 2014-2019)



ÖAW 2014-2019



Total expenditure (€) per work package
(RSA Salzburg 2014-2019)

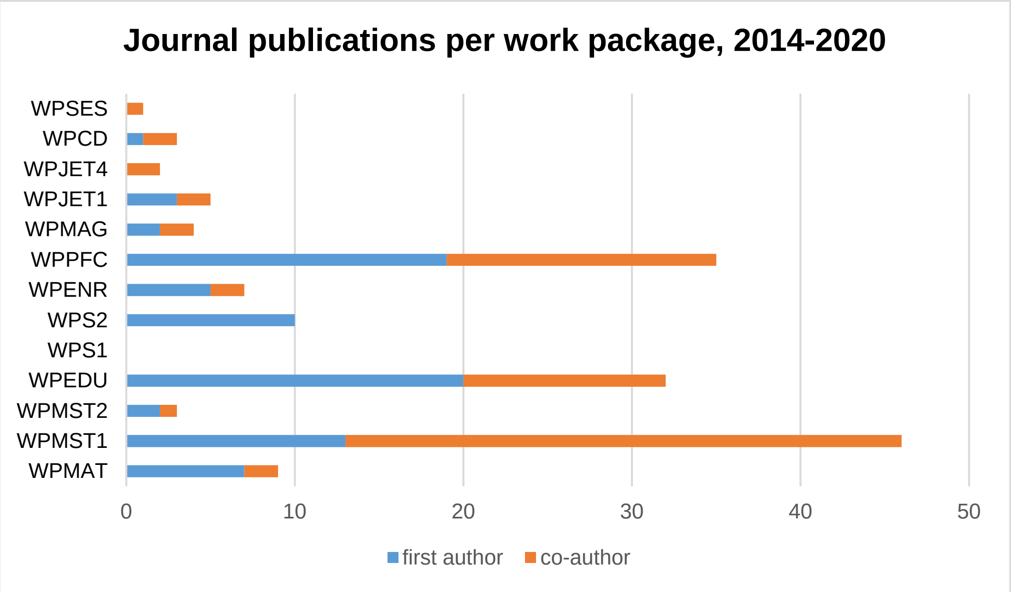


3.3. Publication Output

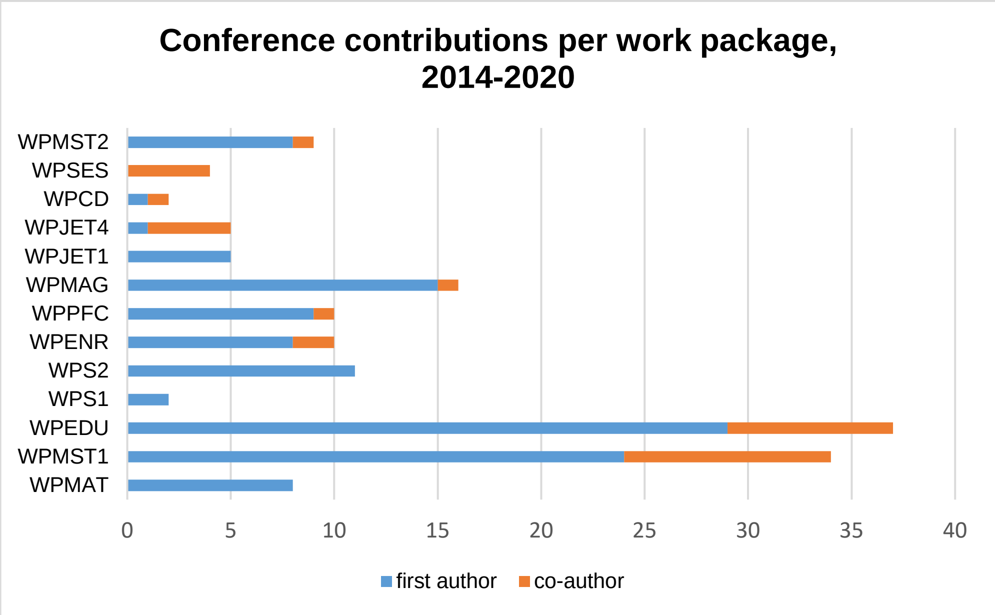
From 2014 to September 2020 a total number of 160 publications have been published in international, peer-reviewed scientific journals 39 papers appeared in the most prestigious fusion-specialist journal *Nuclear Fusion,* 21 papers were published in *Plasma Physics and Controlled Fusion*. In addition 165 conference contributions have been published (of which a considerable fraction has also undergone peer review, especially all the contributions to the annual EPS Meeting on Plasma Physics and Controlled Fusion).

All publications related to the EUROfusion work programme have to pass a **mandatory clearance procedure** (internal review process). For this purpose journal manuscripts and conference contributions have to be uploaded to the so-called “EUROfusion pinboard” at least 3 weeks before submission for internal discussion. Submission can only take place after receiving clearance from the respective task force leader. After acceptance by the journal or conference the papers are transferred from the pinboard to the EUROfusion preprint server to fulfill the EU requirements of (green) **open access**.

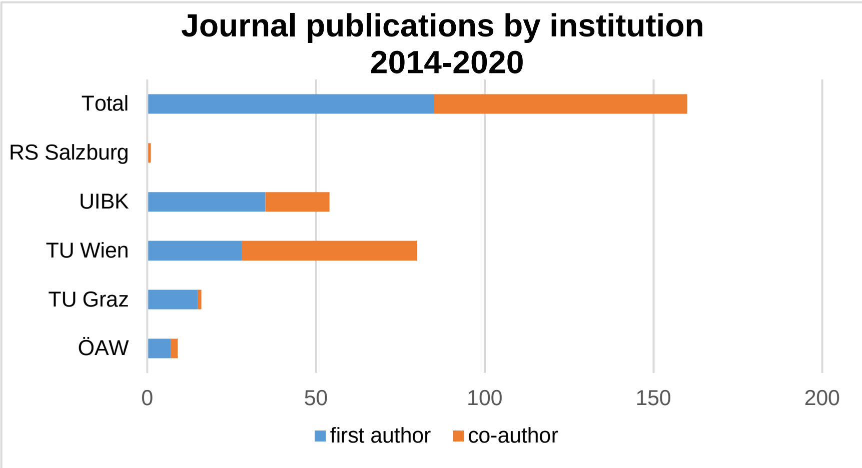
An overview on the output of scientific publications from 2014 until 2020 per work package is shown below. In line with the core competences described in chapter 1, most articles by Austrian authors and co-authors have been recorded under the EUROfusion work packages Education (EDU, with topics closely connected to the technical work packages), Medium-Size Tokamaks (MST1), Plasma-Facing Components (PFC), Stellarator Optimization (S2) and Materials (MAT).

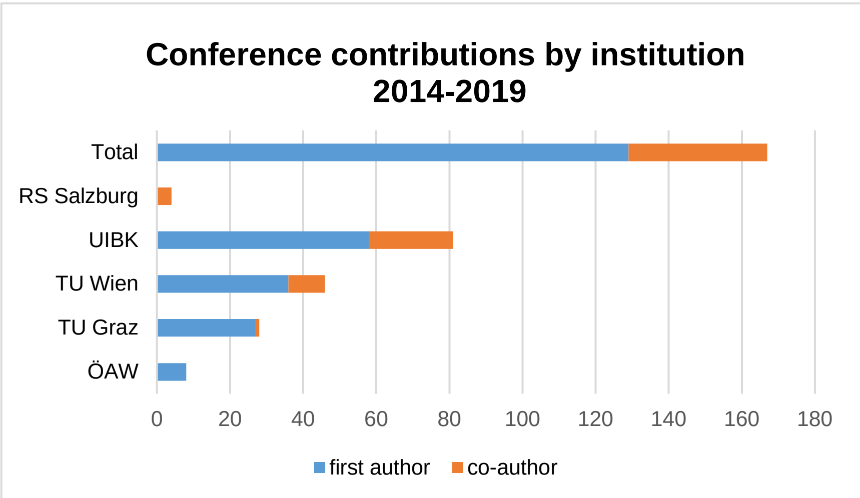


Besides Education (EDU), the highest number of conference contributions has been attributed to MST1, which highlights the highly cooperative nature of this work package.



The distribution of journal articles and conference contribution by institution is shown in the following graphs:





A complete list of publications as well as conference contributions from 2014 to June 2020 with authors from Fusion@ÖAW underlined is attached in **Annex 1**.

4. The Mobility Programme in Horizon 2020

The EUROfusion Mobility Programme enables international cooperation between all EUROfusion project partners. Mobility funding supports the participation of European scientists in joint fusion activities and experiments at research facilities in other Member States. When researchers (in particular also PhD students) participate in this programme, they receive an allowance for each day of travel.

Fusion research in Austria is being conducted in cooperation with renowned European fusion laboratories and partners at European universities. Austrian scientists take part in experiments at big fusion devices.

- **Max Planck Institute of Plasma Physics (IPP Garching near Munich and Greifswald)**

  Two different fusion facilities run by the Max Planck Institute of Plasma Physics are visited most frequently:

  - ASDEX Upgrade, also called the "Axially Symmetric Divertor Experiment", is the largest German fusion device. The core issues of fusion research are being investigated here under power plant-like conditions and the physical foundations for ITER and DEMO are being elaborated. Dedicated workpackages: MST 1 AUG, MST 2 and Li-Beam Diagnostics.
  - Wendelstein 7-X in Greifswald is the world's largest device of the stellarator type. Austrian scientists participate in experiments within the work packages S1 and S2 (Wendelstein 7-X campaigns and Stellarator Optimization).

- **École Polytechnique Fédérale de Lausanne**

  The medium size tokamak TCV (Tokamak à Configuration Variable) is located at the École Polytechnique Fédérale de Lausanne (EPFL), a university in Switzerland. TCV's aim is to investigate the physics of magnetically confined plasmas in order to support the ITER and the future DEMO project. Austrian scientists participated in experiments performed at TCV: work package MST1

- **Culham Centre for Fusion Energy**

  The Joint European torus (JET) is the world's largest tokamak. It is located at the Culham Centre for Fusion Energy, which is the UK's national fusion research laboratory. JET has similar conditions like those needed for a power plant and the research results are indispensable for future ITER operation. Dedicated workpackages: JET 1 and JET 4.

- **Forschungszentrum Jülich**

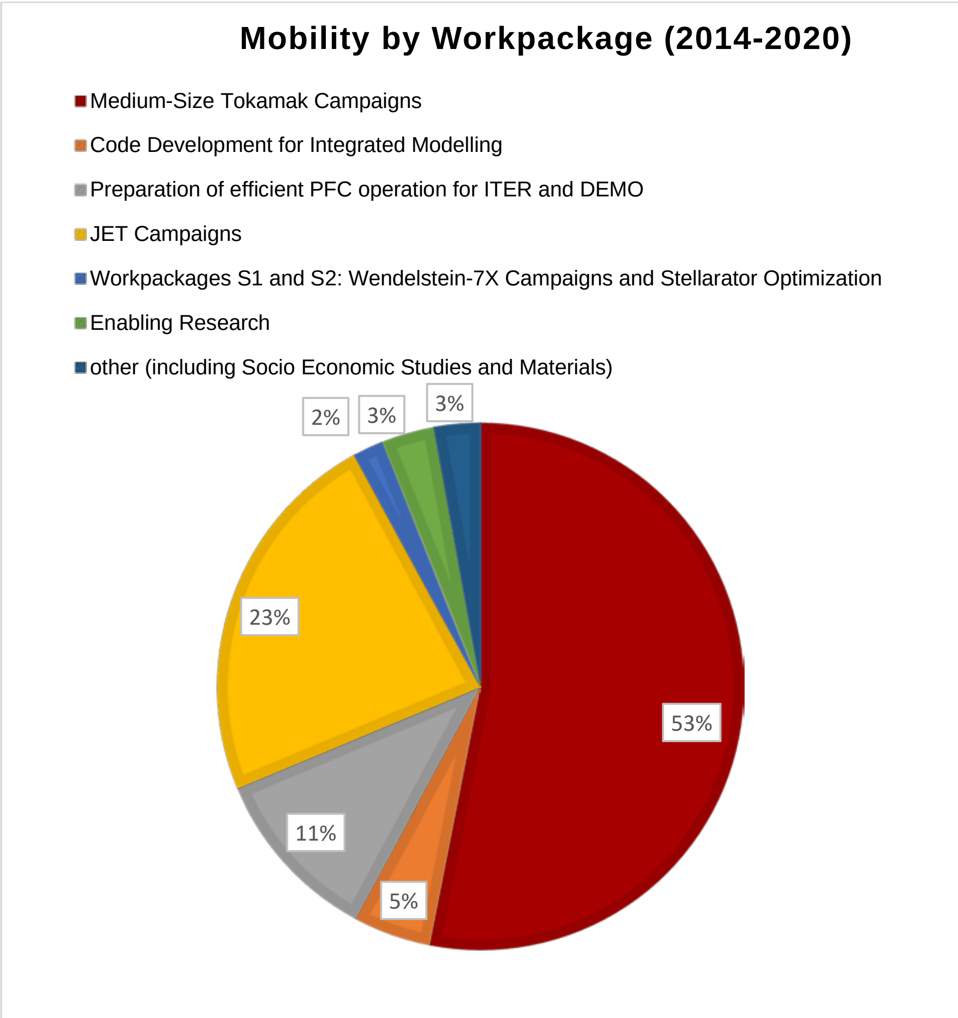
  FZJ is based in Germany and is one of the biggest research centers in Europe. The research fields encompass energy, environment and health. During their travels, Austrian scientists study the erosion of different plasma-facing components for ITER and DEMO. Dedicated work package: PFC

- **Ion Beam Center of the University of Uppsala**

  As part of the PFC work package, Austrian scientists visit this research center in Sweden to conduct ion beam-based materials studies. Dedicated work package: PFC.

Further universities and research centers which are frequently visited by Austrian Fusion Researchers within the mobility programme:

- Comenius University in Slovakia
- Institut Jožef Stefan in Slovenia
- Poznan Supercomputing and Networking Center in Poland
- CEA (French Alternative Energies and Atomic Energy Commission) in France
- DIFFER (Dutch Institute for Fundamental Energy Research) in the Netherlands
- CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas) in Spain
- ENEA (Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo economico sostenibile) in Italy
- IPP.CR (Institute of Plasma Physics of the Czech Academy of Sciences) in the Czech Republic
- VTT Technical Research Centre of Finland
- IST (Instituto Superior Técnico) in Portugal

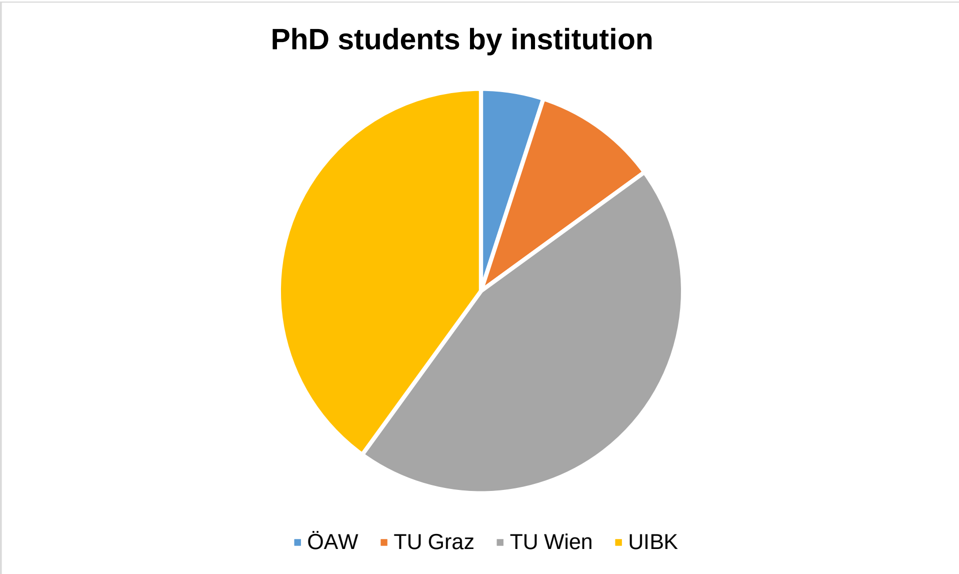


This graph shows the distribution of EUROfusion missions by work package. As of July 2020, total mobility funds of **€ 328.805,71** were approved by EUROfusion for Austrian visiting scientists for the period 2014-2020. Please mind that EUROfusion mobility/mission does NOT cover any travel to conferences, but working visits to other partners only! As can be seen from the graph above the medium-size tokamak (MST) campaigns account for the largest share of the mobility programme in Austria and are followed by travels to JET (Joint European Torus in Culham, UK)**.**

5. Fusion Education

"Fusion laboratories and universities play a key role in providing general training and education in fusion science and technology by **selecting and forming the *Generation ITER***, through theoretical and experimental work on relevant facilities." (Quotation from A. Wagner et al., Strategic orientation of the EU Fusion Programme with emphasis on Horizon 2020).

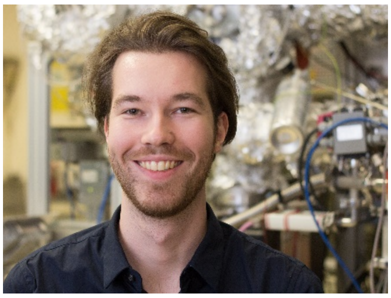
At Austrian universities education on fusion-relevant topics is mainly part of the curriculum of the faculties of physics. Specialization on fusion-relevant topics may start at the level of master theses and can be consolidated at the level of PhD-theses. Fusion-related education and training at the participating universities has a long tradition, although it is limited by the lack of an independent institution dedicated to fusion research. The number of PhD students specializing in fusion-relevant subjects has remained more or less constant at an average total number of **20 running PhD theses per year** since the beginning of FP7. This success is due to constant focusing on topics prioritized within the European Roadmap to the Realization of Fusion Energy.



A comprehensive list of completed and currently ongoing PhD theses from 2014 – 2020 can be found in **Annex 2**.

As part of their PhD thesis, candidates participate in experiments under the relevant EUROfusion work packages and contribute to scientific publications and conferences. Fusion@ÖAW conducts regular interviews with PhD candidates and publishes them on its website. Selected extracts from these interviews are shown on the following pages.

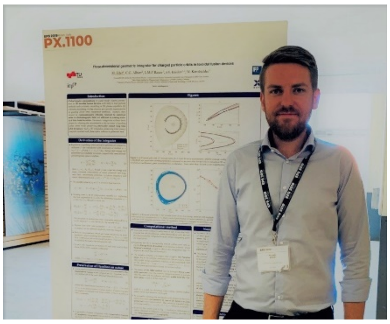
Fusion@ÖAW PhD Interviews



"Climate change and the ever-increasing energy consumption are problems that have been present for a very long time. Nuclear fusion aims to help solving both of these challenges and I find it inspiring to contribute to this cause."

Paul Szabo, doctoral candidate at the Institute of Applied Physics (TU Wien)

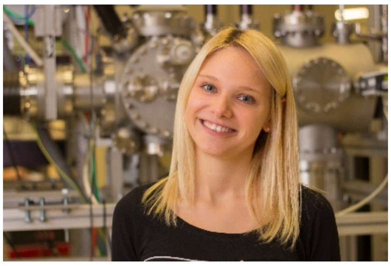
Thesis: “Ion interaction with realistic surfaces: case studies for nuclear fusion and space weathering research”



"In my opinion, plasma physics, especially controlled nuclear fusion, will be extremely exciting in 5 years, since the first ITER plasma is scheduled for December 2025. This important milestone will mark a historical event in the development of fusion devices."

Michael Eder, doctoral candidate at the Institute for Theoretical Physics (Computational Physics) at TU Graz

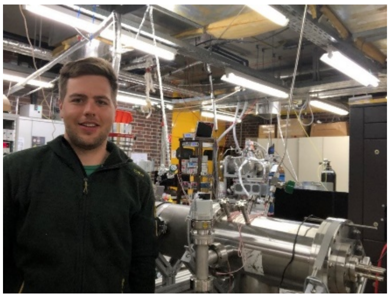
Thesis: “Kinetic approach to computation of plasma equilibria in 3D magnetic fields with general topology”



“I just liked the idea to be able to contribute some small pieces to the large and challenging puzzle.”

Janine Schwestka, former doctoral candidate at the Institute of Applied Physics (TU Wien)

Thesis: “Ion irradiation of thin carbon films - from fundamental understanding to material properties”



“Nuclear fusion has clearly the potential to provide unlimited amounts of clean (CO_2 free) energy.”

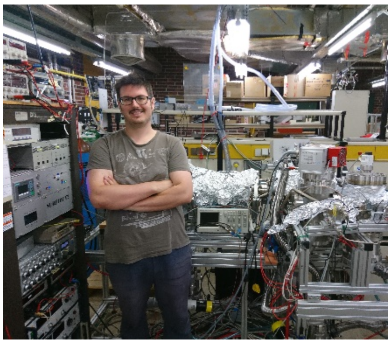
Faro Hechenberger, doctoral candidate at the Institute for Ion Physics and Applied Physics (University of Innsbruck)

Thesis: “Reactive low energy ion surface collisions on fusion relevant surfaces focusing on the formation of molecules”

"The aspect I like the most in the nuclear fusion field is the opportunity to be involved in cutting-edge science while tackling such a crucial problem of humanity – energy crisis. In addition, the entire research is done in an international, multicultural environment where thousands of scientists are gathered around the same goal, sharing their ideas and scientific achievements while overcoming cultural differences. In my opinion, this is simply amazing!"

Vladica Nikolic, former doctoral candidate at the Erich Schmid Institute of Materials Science in Leoben

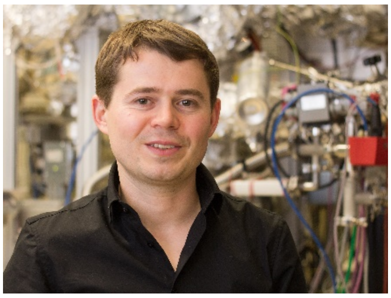
Thesis: “Mechanical properties of fusion relevant materials”



"It is fulfilling to be part of a research effort which will aid everyone."

Lorenz Kranabetter, doctoral candidate at the Institute for Ion Physics and Applied Physics (University of Innsbruck)

Thesis: “Construction and design of a new experimental set-up to study reactive ion surface collisions with fusion relevant surfaces”



"I am very interested in nuclear fusion, because this is the only way to bring the power of the sun to earth."

Reinhard Stadlmayr, doctoral candidate at the Institute of Applied Physics (TU Wien)

Thesis: “Impact of surface roughness on erosion and retention”

"Nuclear fusion is the most promising source of clean, safe and sustainable energy that can power the world."

Lei Chen, doctoral candidate at the Institute for Ion Physics and Applied Physics (University of Innsbruck)

Thesis: “Computational studies of beryllium, tungsten and their mixed systems”

Find the whole interviews on our Fusion@ÖAW website and Facebook page: www.oeaw.ac.at/fusion/

6. Outreach Activities 2014-2020

- *Fusion@ÖAW website* http://www.oeaw.ac.at/fusion/
- *Newsletter for industry, schools, fusion scientists and other stakeholders*
- *Facebook page* https://www.facebook.com/FusionatOEAW/
- *Fusion Day once a year*
- *Magazine every two years*

The Fusion@ÖAW Coordination Office maintains the **website** http://www.oeaw.ac.at/fusion/ and **Facebook page** https://www.facebook.com/FusionatOEAW/ and sends regular **newsletters** to teachers, industry and other stakeholders. School news bulletins include a link to multimedia resources on our website and the industry letter gives an insight into business opportunities and events. Furthermore, we periodically circulate news to scientists and students contributing to the Austrian Fusion Research Programme.

Examples of Fusion@ÖAW webpage, facebook page and newsletters sent to teachers and industry.

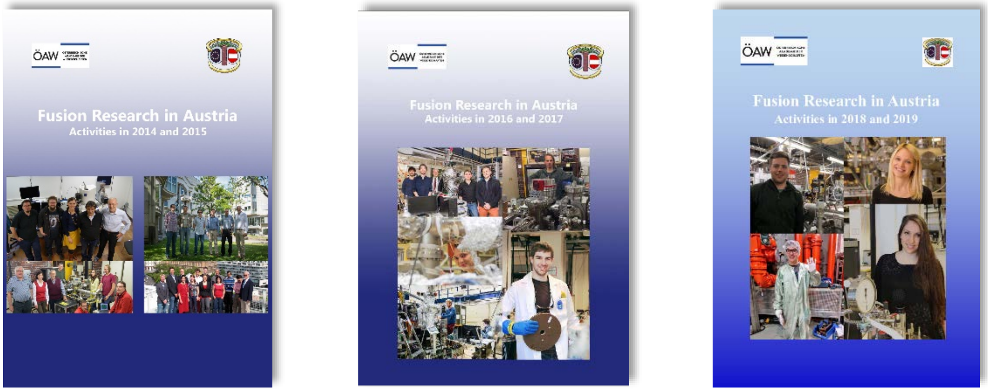
Once a year we organize the event "**Fusion Day**" with researchers and students from all over Austria to come together and exchange knowledge. As plenary speaker we invite high level fusion researchers.

Fusion Days 2014 – 2019

1st Fusion Day:	21.11.2014 Graz
2nd Fusion Day:	20.11.2015 Wien
3rd Fusion Day:	18.11.2016 Innsbruck
4th Fusion Day:	17.11.2017 Leoben
5th Fusion Day:	16.11.2018 Wien
6th Fusion Day:	15.11.2019 Salzburg

6th Fusion Day at the Research Studios Austria in Salzburg, 15.11.2019 (Photo: Lätitia Unger)

Moreover, the magazine “**Fusion Research in Austria**” is produced bi-annually. The target groups are researchers at Austrian universities as well as members of the Austrian Academy of Sciences and the Federal Ministry of Education, Science and Research.



Three issues of the magazine “Fusion Research in Austria”. The full text of the magazines can be found here

In addition, the following activities were part of the communication work in the period 2014-2020:

Education – outreach to Austrian teachers and students

The aim of these communication activities is to bring knowledge about fusion research into the classroom in order to spark the interest of students and teachers and perhaps win future fusion scientists.

Prof. Friedrich Aumayr (Head of Research Unit, Fusion@ÖAW) held a nuclear fusion seminar for Austrian teachers at TU Wien in 2019. In the same year he also gave a lecture for students of the Bundesoberstufenrealgymnasium St. Pölten. As already mentioned, we send out newsletters three times a year, which contain links to teaching materials, events and other current information.

Nuclear fusion seminar for physics teachers in Austria at TU Wien, November 2019
(Photo: TU Wien)

Media

Articles and interviews appeared online and in print media. There was also a number of radio broadcasts which included interviews of Austrian fusion research scientists.

Print media: OÖNachrichten, Die Presse, Kleine Zeitung, derStandard;

online media: futurezone.at

radio: Ö1 „Dimensionen – die Welt der Wissenschaft“

Examples

2020-06-01
Energie erzeugen wie die Sonne
ÖIAZ – Österreichische Ingenieurs- und Architektenzeitschrift
https://www.oiav.at/wp-content/uploads/2020/06/Energie-erzeugen-wie-die-Sonne.pdf

2019-11-07
Energie erzeugen wie die Sonne – geht das?
Planetarium Wien – VHS
https://tinyurl.com/y6zv9zn7

2019-02-20
Die Kraft der Sonne im Reaktor? (Interview über Fusion mit Tageszeitung DerStandard)
Printausgabe vom 20.02.2019 (Forschung spezial)
http://www.iap.tuwien.ac.at/www/_media/atomic/fusion_standard_interview_20022019.pdf
online (23.02.2019): https://derstandard.at/2000098234340/Kernfusion-Energie-der-Zukunft-oder-grosse-Illusion

2019-01-02
Energie der Zukunft: Wo bleibt mein Fusionsreaktor? (Interview)
Futurezone.at
https://futurezone.at/science/energie-der-zukunft-wo-bleibt-mein-fusionsreaktor/400344988

2018-04-25
Die Erben des Prometheus - Energie erzeugen wie die Sonne
Festival "WissensDurst" der österreichischen Wissenschaft
im Pub-Lokal "Bierteufel" 1030 Wien, 25.04.2018
https://www.wissensdurst-festival.at/archiv-2018?pgid=jz71fcap-3f8f9ab7-ddbd-46cf-9b36-4b81b17418d5

Artikel in den OÖ Nachrichten Magazin Seite 7 (print) und online unter
http://www.nachrichten.at/nachrichten/weltspiegel/Die-teuren-und-verschlungenen-Wege-zur-Kernfusion;art17,2212496

2016-02-22
Plasma Spenden
Artikel zur Inbetriebnahme von Wendelstein 7-X im Magazin “Profil” Nr. 8 p. 76 - 79

2015-03-10
Dimensionen – Die Welt der Wissenschaft: Sonne, wie imitiert man dich?
Das Problem mit der Kernfusion
Studiogespräch in der Wissenschaftssendung von Radio Ö1
https://www.youtube.com/watch?v=UYCBZkjs56w

2014-02-13
Ein Stern im Fusionsreaktor!
Interview im Ö1 Mittagsjournal

Information material

We regularly produce new information material: flyers, leaflets, brochures, postcards.

Presentations at events

Austrian scientists have given lectures at various locations and events: Rotary Club Vienna and St. Pölten, Munich Science Slam, WissensDurst-Festival Vienna, Austrian Federal Economic Chamber, Planetarium Vienna Prater, Volkshochschule Science in Vienna, IAEA (International Atomic Energy Agency) and presentations at the Vienna University of Technology, Johannes Kepler University Linz, University of Innsbruck, Graz University of Technology.

Exhibition

The Technical Museum Vienna has dedicated a small part of the permanent exhibition "Energy of the Future", which started in 2017, to nuclear fusion. We supported the museum with the organization of this part.

Photo: Technisches Museum Wien
https://www.technischesmuseum.at/

7. Participation of Industry in the ITER Project

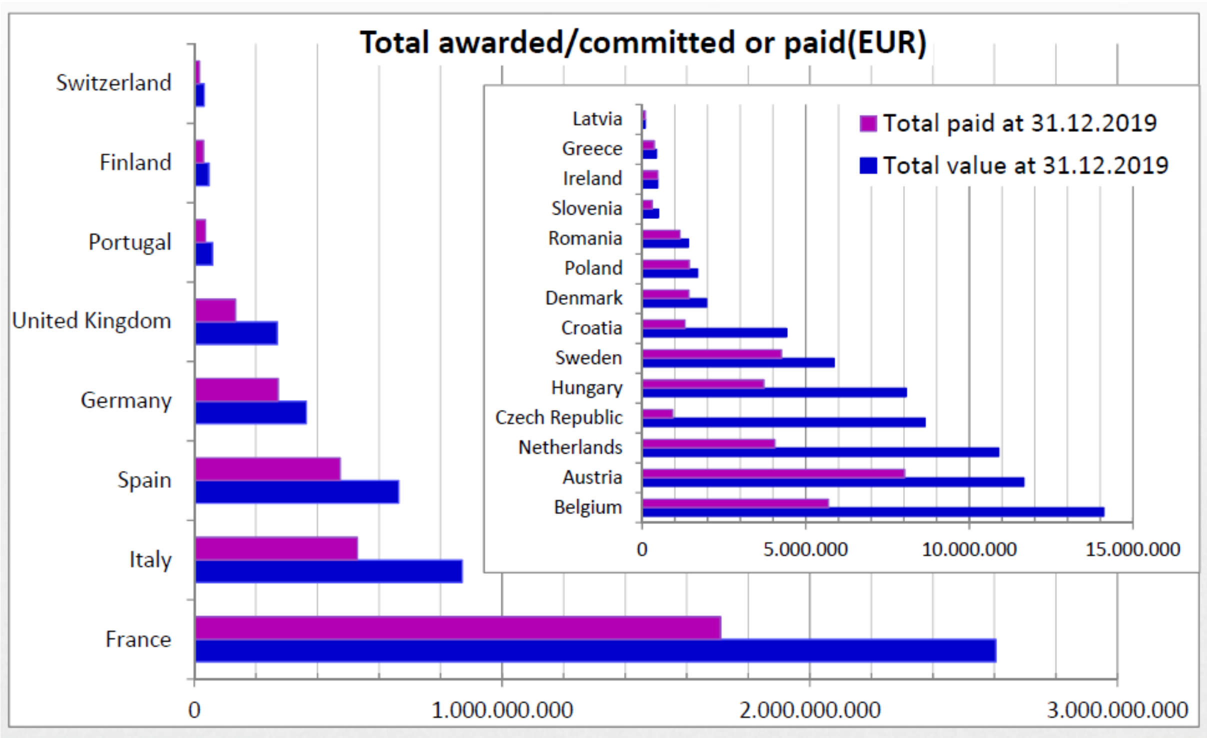
Information for Austrian industry

Harnessing fusion energy within the ITER project is an industrial effort backed by targeted research. The network of Industrial Liaison Officers (ILOs) raises awareness among qualified companies and advises them on ways to get involved in the ITER project. In Austria the function of ILO is performed by the Austrian Chamber of Commerce which acts as a contact forum for Austrian companies qualified for participating in high-tech industrial projects and organizes information events in cooperation with Fusion@ÖAW. Regular workshops on ITER Technology Transfer and Supply take place at the place at the Austrian Chamber of Commerce.

Fusion@ÖAW issues regular newsletters with information on forthcoming events and tenders to interested companies.

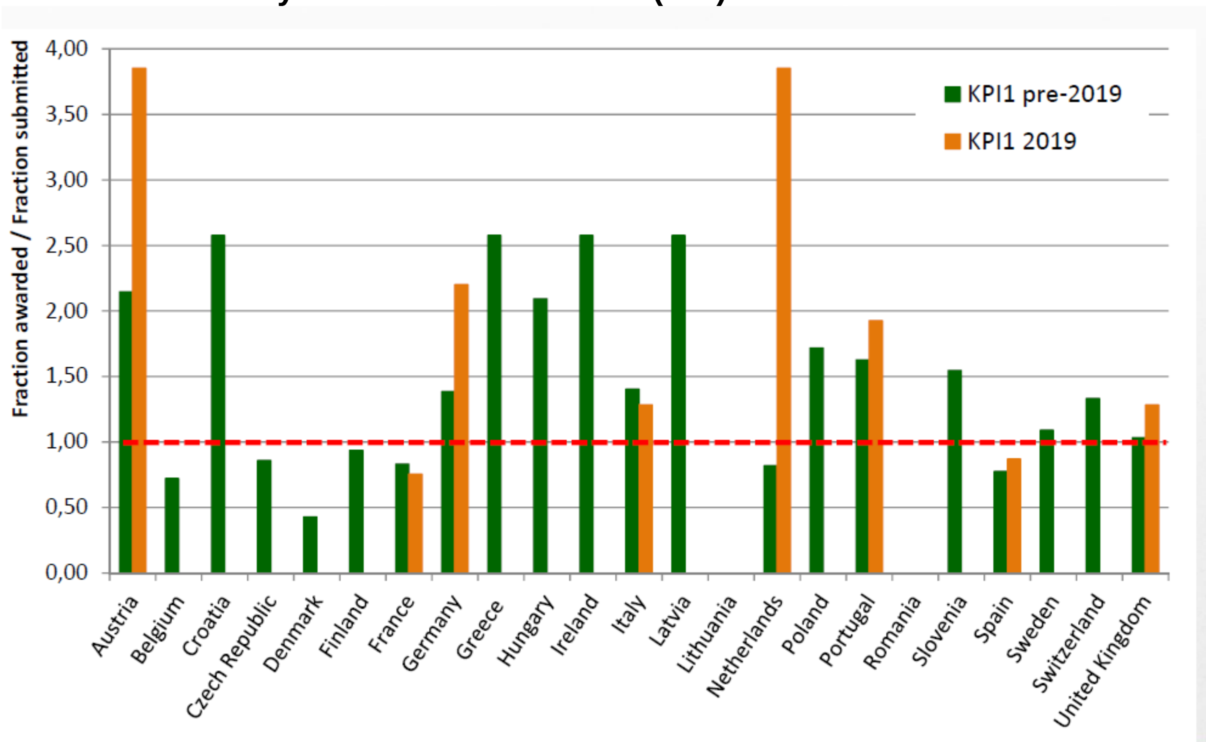
The role of Austrian industry in the European contribution to ITER

The European Domestic Agency Fusion for Energy (F4E) is responsible for the European contribution to ITER and offers large-scale business opportunities. The graphs below are taken from a geographical distribution report recently issued by F4E and show Austria's success in international tenders from 2008 to 2019. The tender process has resulted in contracts with Austrian companies exceeding 11 Mio € (ranking Austria among the 10 most successful EU countries in absolute numbers). The relative success rate is even better.



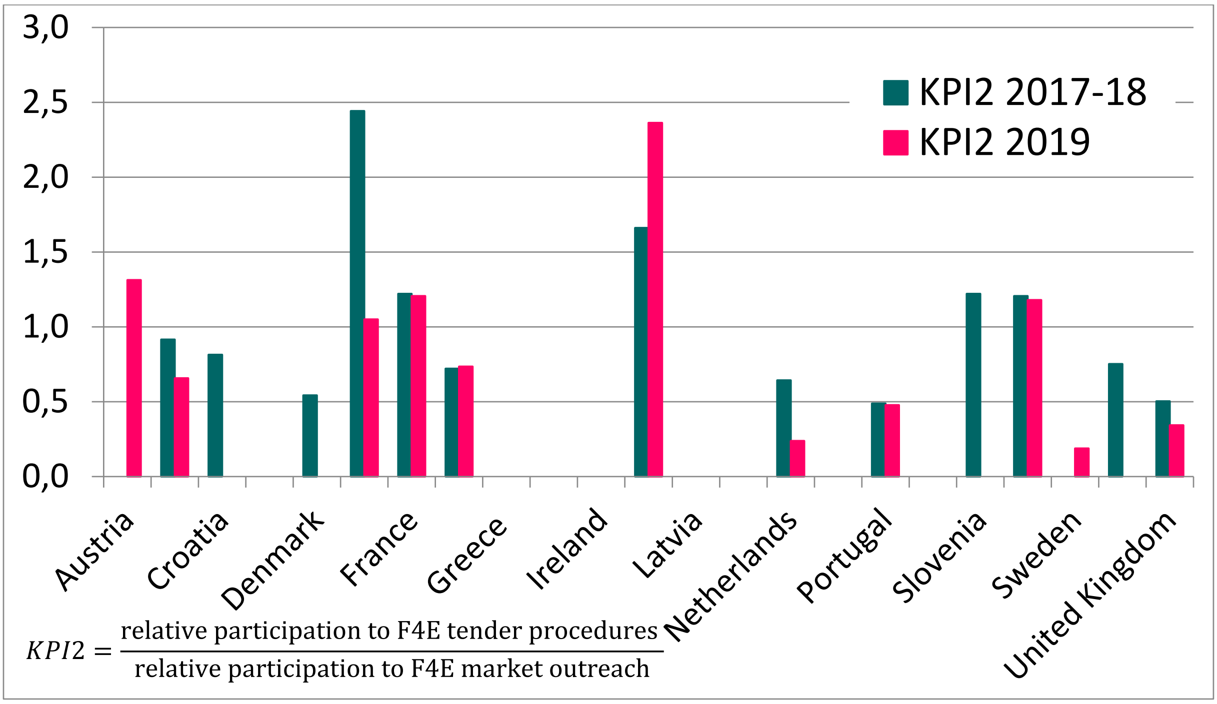
Geographical distribution of F4E's procurements and grants with industry in € (Source: F4E)

Key Performance Indicator (KPI)1: success ratio



$$KPI1 = \frac{\text{relative success in F4E tender procedures}}{\text{relative participation to F4E tender procedures}}$$

Key Performance Indicator (KPI)2: participation ratio



$$KPI2 = \frac{\text{relative participation to F4E tender procedures}}{\text{relative participation to F4E market outreach}}$$

Geographical distribution of relative success (Source: F4E)

8. Outlook to Horizon Europe

Looking ahead to Horizon Europe from 2021-2027, Fusion@ÖAW is well prepared to continue its activities in line with future work programmes defined within the European Fusion Research Programme. Like in H2020, we expect that the ***education of the generation ITER*** (i.e. training of PhD students and young researchers) will remain a major priority of the Austrian partner.

Outreach activities will continue and may even be intensified, addressing schools, universities and industry. We expect that the first plasma in ITER scheduled for the end of 2025 will provide new incentives for existing and prospective participants and raise interest by the general public.

The members of the EUROfusion Consortium have undertaken a concerted effort to intensify the cooperation with industry and make industrial partners actively participate. Given the structure of the Austrian research unit, direct participation by industry is difficult. Nevertheless, the long-standing co-operation with the Industrial Liaison Office at the Federal Economic Chamber will continue and advice and information will be provided to interested companies.

Of course, all of this is subject to the final agreement by the political bodies in charge, including the final decision on the EURATOM budget within Horizon Europe by the European Council and Parliament, the signing of the EUROfusion Grant - and Consortium Agreement and the renewal of the mandate of ÖAW as programme manager of the Austrian contribution to EUROfusion by the Federal Ministry of Science and Research. **This brochure shows that Austrian fusion research is internationally competitive and that further participation in the European Fusion Research Programme is expected to result in substantial Austrian contributions within Horizon Europe**.

LIST OF ABBREVIATIONS AND ACRONYMS

Fusion experiments

AUG	ASDEX Upgrade, facility at IPP Garching
DIII-D	Tokamak operated by General Atomics (San Diego) for the U.S. Department of Energy
ITER	"The way" (under construction at Cadarache, France)
JET	Joint European Torus, UKAEA, Culham, UK
MAST	Mega Amp Spherical Tokamak
TCV	Tokamak à Configuration Variable, EPFL, Lausanne, Switzerland
W7-X	Wendelstein 7-X, IPP Greifswald, Germany

University Institutes and research institutions

CCFE	Culham Centre for Fusion Energy (United Kingdom)
EPFL	École polytechnique fédérale de Lausanne
EUROfusion	European Consortium for the Development of Fusion Energy
F4E	Fusion for Energy
ILOs	Industrial Liaison Officers
IPP	Institut für Plasmaphysik, Garching (Germany)
ÖAW	Österreichische Akademie der Wissenschaft
ÖAW-ESI	Erich-Schmid Institute of Materials Science at ÖAW
RSA	Research Studios Austria
TU Graz	Technische Universität Graz
TU Wien	Technische Universität Wien
UIBK	Universität Innsbruck

Scientific and technical abbreviations

AFM	Atomic force microscope
ECCD	Electron cyclotron current drive
ELMs	Edge localized modes
IBA	Ion beam analysis
NBI	Neutral beam injection
NTV	Neoclassical toroidal viscosity
PFC	Plasma-facing components
QCM	Quartz crystal microbalance
RMPs	Resonant magnetic perturbations
SEM	Scanning electron microscopy
SOL	Scrape-off layer
WN	Tungsten nitride

GLOSSARY OF SCIENTIFIC AND TECHNICAL TERMS

Organizations and institutions

ITER

The world's largest magnetic fusion deice (currently being built in Cadarache, France), designed to proof the feasibility of fusion as a viable and sustainable source of energy www.iter.org

F4E (Fusion for Energy)

Responsible for providing Europe's contribution to ITER (established in 2007 for a period of 35 years) www.fusionforenergy.europa.eu

EUROfusion

H2020 Co-fund Action (2014-2020), grant no. 633053. Funds and manages all fusion research activities across Europe within the H2020 Euratom programme. www.euro-fusion.org

Fusion@ÖAW

Coordinates the participation of Austrian research groups in the European fusion research programme www.oeaw.ac.at/fusion

Scientific and technical terms

DEMO

DEMO is the successor of the international fusion experiment ITER and the next step on the way to realise fusion energy. Its purpose is to develop and test technologies, physics regimes and control routines for operating a fusion reactor not as a scientific experiment, but as a power plant. One of the key criteria for DEMO is the production of electricity (albeit not at the price and the quantities of commercial power plants).

Divertor

A magnetic field configuration affecting the edge of the confinement region, designed to divert impurities and helium ash to a target chamber. Often this chamber is also called 'divertor'. Handling the heat fluxes at the divertor of fusion power plants is one focus of fusion research. It is tackled by developing more resistant materials and by developing magnetic configurations (e.g., snowflake and Super-x divertor) that reduce the heat load at the divertor.

ELMs

Edge localized modes - instabilities which occur in short periodic bursts during the H-mode in divertor tokamaks. They cause sudden outbursts of the plasma thus expelling particles and depositing large heat flux onto the vessel wall. The plasma loses severe amounts of energy. In high-power fusion devices such as ITER or DEMO, powerful ELMs will cause erosion at the vessel wall. Finding methods to mitigate or suppress ELMs is therefore an important topic in present-day fusion research.

Fluence

The total number of particles per unit area with which a material is irradiated.

H-mode

A high confinement regime develops when a tokamak plasma is heated above a characteristic power threshold, which increases with density, magnetic field and machine size. It is characterized by a sharp temperature gradient near the plasma edge (resulting in an edge “temperature pedestal”).The H-mode typically doubles the energy confinement time compared to the normal L-regime. ELMs are often observed in this regime.

L-mode

As opposed to the H-regime. The “normal” low confinement regime of additionally heated tokamak operation.

Scrape-off layer (SOL)

The term scrape-off layer (SOL) refers to the plasma region characterized by open field lines (starting or ending on a material surface).

Separatrix

Boundary separating magnetic field lines that intersect the wall (open lines) and the closed magnetic field lines that never intersect the wall (closed lines). Defines the plasma edge.

TRIGA Reactor

The TRIGA Mark-II reactor at Atominstitut / TUWien was installed by General Atomic (San Diego, California, USA) and started operation in 1962. Operation of the reactor since that time has averaged 220 days per year, without any long outages. The TRIGA-reactor is purely a research reactor of the swimming-pool type that is used for training, research and isotope production.

Annex 1. List of Publications 2014 – September 2020

Austrian Academy of Sciences

Publications in scientific journals

First author

Nikolic, V., S. Wurster, D. Firneis and R. Pippan, "Improved fracture behavior and microstructural characterization of thin tungsten foils", *Nuclear Materials and Energy **9** (2016), pp.181-188,* WPMAT, https://doi.org/10.1016/j.nme.2016.06.003

Nikolic, V., S. Wurster, A. Savan, A. Ludwig and R. Pippan, "High through-put study of binary tungsten thin-film tungsten alloys", *International Journal of Refractory Metals and Hard Materials **69** (2017) 40,* WPMAT, https://doi.org/10.1016/j.ijrmhm.2017.07.017

Nikolic, V., J. Riesch, M. Pfeifenberger and R. Pippan, "The effect of heat treatments on the microstructure and fracture toughness properties of drawn tungsten wires, Part I - Microstructural characterization", *Materials Science and Engineering: A **737** (2018), pp. 181-188,* WPMAT, https://doi.org/10.1016/j.msea.2018.09.027

Nikolic, V., J. Riesch, M.J. Pfeifenberger and R. Pippan, "The effect of heat treatments on pure and potassium doped drawn tungsten wires: Part II – Fracture properties", *Materials Science and Engineering: A, **737** (2018), pp.434-447,* WPMAT, https://doi.org/10.1016/j.msea.2018.09.029

Nikolić, V., S. Wurster, D. Firneis and R. Pippan, "Fracture toughness evaluation of UFG tungsten foil", *International Journal of Refractory Metals and Hard Materials **76** (2018), pp. 214-225,* WPMAT, https://doi.org/10.1016/j.ijrmhm.2018.06.008

Pfeifenberger, M.J., V. Nikolic, S. Žak, A. Hohenwarter and R. Pippan, "Evaluation of the intergranular crack growth resistance of ultrafine grained tungsten materials", *Acta Materialia **176** (2019), pp.330-340,* WPMAT, https://doi.org/10.1016/j.actamat.2019.06.051

Scheiber, D., L. Romaner, R. Pippan and P. Puschnig, „Impact of solute-solute interactions on grain boundary segregation and cohesion in molybdenum", *Physical Review Materials **2** (2018) 093609*, WPMAT, https://doi.org/10.1103/PhysRevMaterials.2.093609

Co-authors

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Annex 2. List of PhD Theses (2014 – 2020)

Name	Institute/University	Title of thesis	Supervisor	Year of completion
Albert Christopher	ITPCP/TU Graz	Resonant magnetic perturbations in tokamaks	Kernbichler Winfried, Heyn Martin	2017
Aradi Matyas	ITPCP/TU Graz	Neoclassical transport modelling in tokamaks with external magnetic perturbations	Kernbichler Winfried, Heyn Martin	left before completion in 2018
Bader David	ATI/TU Wien	Granular high temperature superconducting wires	Eisterer Michael	ongoing
Ballauf Philipp	IAP/Universität Innsbruck	Construction and characterization of an experiment to investigate ion-surface interactions	Scheier Paul	ongoing
Berger Bernhard	IAP/TU Wien	Laboratory work on plasma-wall-interaction processes relevant for fusion experiments / PWI	Aumayr Friedrich	2017
Chen Lei	IAP/Universität Innsbruck	Computational investigation of the physics and chemistry in plasma-facing components	Probst Michael	2020
Cupak Christian	IAP/TU Wien	Investigation of ion - solid interaction processes relevant for plasma facing components in nuclear fusion devices	Aumayr Friedrich	ongoing
Dobes Katharina	IAP/TU Wien	Erosion of fusion relevant surfaces under Ion impact	Aumayr Friedrich	2014
Duensing Felix	IAP/Universität Innsbruck	Ion impact induced chemical ablation of Be and W in contact with seeding gases	Scheier Paul	ongoing
Eder Michael	ITPCP/TU Graz	Kinetic approach to computation of plasma equilibria in 3D magnetic fields with general topology	Kernbichler Winfried, Heyn Martin, Buchholz Rico;	ongoing
Fischer David	ATI/TU Wien	Superconductors for nuclear fusion magnets	Sauerzopf Franz, Eisterer Michael	2019
Gruber Elisabeth	IAP/TU Wien	Ion- induced nanostructures on surfaces	Aumayr Friedrich	2017
Harrer Georg	IAP/TU Wien	Origin and transport of small ELMs	Aumayr Friedrich	2020
Hechenberger Faro	IAP/Universität Innsbruck	Investigation of ion surface collisions and plasma wall interactions	Scheier Paul	ongoing

Name	Institute/University	Title of thesis	Supervisor	Year of completion
Held Markus	IAP/Universität Innsbruck	Gyrofluid edge/SOL turbulence in tokamak and stellarator geometries	Kendl Alexander	2016
Holleis Sigrid	ATI/TU Wien	Development of Tl-based high temperature superconductors	Eisterer Michael	ongoing
Kapper Gernot	ITPCP/TU Graz	Neoclassical transport and related issues of current drive	Kernbichler Winfried, Heyn Martin	2017
Kranabetter Lorenz	IAP/Universität Innsbruck	Construction and design of a new experimental set-up to study reactive ion surface collisions with fusion relevant surfaces	Scheier Paul	2019
Laggner Florian	IAP/TU Wien	Inter ELM pedestal structure development in ASDEX Upgrade	Aumayr Friedrich	2017
Lainer Patrick	ITPCP/TU Graz	Hybrid kinetic/MHD modeling of plasma response to 3D magnetic perturbations in tokamaks	Kernbichler Winfried, Buchholz Rico, Kasilov Sergei;	ongoing
Meyer Ole	IAP/Universität Innsbruck	Kinetic and multi-species effects in gyrofluid computations of tokamak edge turbulence	Kendl Alexander	2017
Nikolic Vladica	ÖAW/ESI	Mechanical properties of tungsten alloy	Pippan Reinhard	2018
Pfeifenberger Manuel	ÖAW/ESI	Implementation of femtosecond laser processing for materials testing and research	Pippan Reinhard	2019
Raab Benedikt	ATI/TU Wien	Semi-microscopic description of fusion-relevant reactions in light nuclear systems	Leeb Helmut	ongoing
Raggl Stefan	IAP/Universität Innsbruck	Experimental and numerical plasma-analytics of magnetron sputtering processes	Scheier Paul	2018
Reiter Eduard	IAP/Universität Innsbruck	Gyrofluid modelling of turbulent impurity transport	Kendl Alexander	ongoing
Schneider Bernd	IAP/Universität Innsbruck	Investigations of turbulent transport in the edge plasma of tokamaks by means of emissive and armoured probes	Schrittwieser Roman, Ionita-Schrittwieser Roman	left before completion in 2019

Name	Institute/University	Title of thesis	Supervisor	Year of completion
Schwestka Janine	IAP/TU Wien	Ion irradiation of thin carbon films - from fundamental understanding to material properties	Aumayr Friedrich	2020
Stadlmayr Reinhard	IAP/TU Wien	Impact of surface roughness on erosion and retention	Aumayr Friedrich	2020
Süß Daniel	IAP/Universität Innsbruck	Assessment of electronic structure methods for the calculation of properties of molecules	Probst Michael	ongoing
Szabo Paul	IAP/TU Wien	Sputtering of composite materials - Experimental investigations and comparison to simulations with SDTrimSP-2D	Aumayr Friedrich	ongoing
Unterrainer Raphael	ATI/TU Wien	Radiation robustness of technical superconductors	Eisterer Michael	ongoing
Vasilovici Ovidiu	IAP/Universität Innsbruck	Investigations of high density magnetized plasmas by means of electric probes	Schrittwieser Roman, Ionita-Schrittwieser Codrina	left before completion in 2019

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