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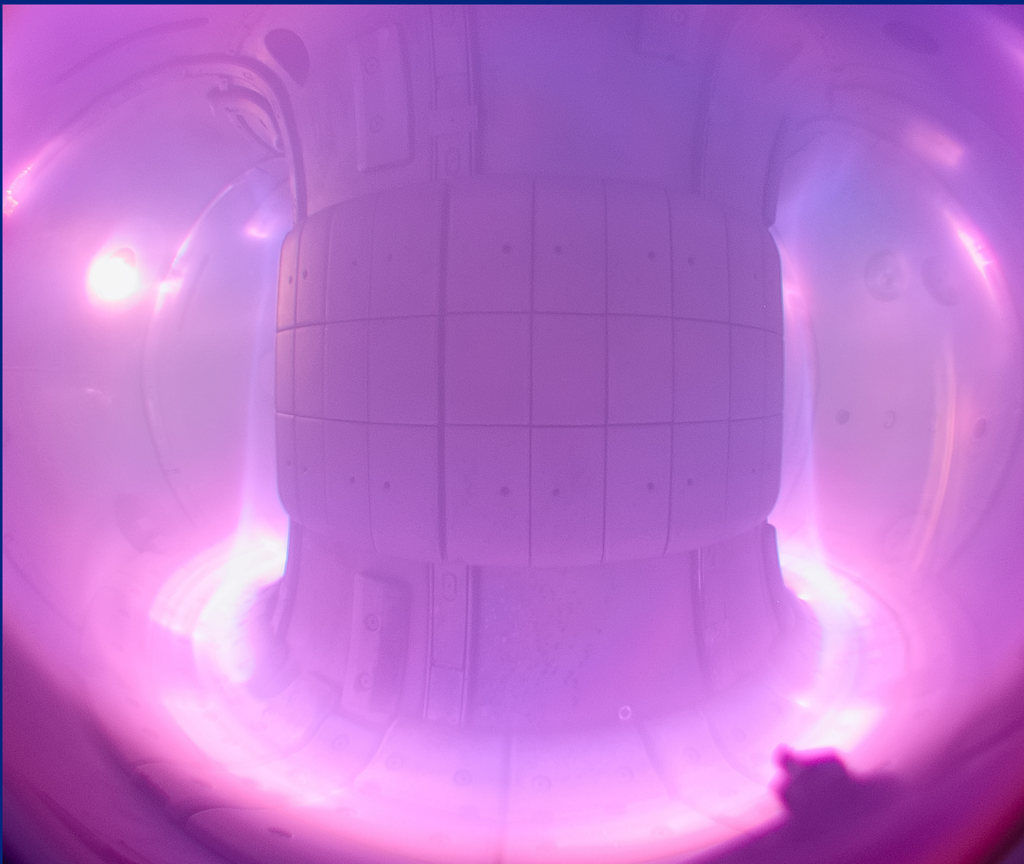
Impurity seeding as an efficient tool for power exhaust solutions in tokamaks



Komise pro obhajoby doktorských disertací v oboru
Fyzika plazmatu a optika

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Praha, 2025

Impurity seeding as an efficient tool for power exhaust solutions in tokamaks

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Nuclear fusion research is focused on the development of the a new type of stable and clear energy source. The need for such type of a power plant is becoming increasingly apparent in light of the ongoing human-induced change of climate, which is already affecting the lives of many people. To achieve a functional fusion reactor based on magnetic confinement, it is necessary to overcome a number of technical challenges as well as to improve our understanding of plasma physics. One of the outstanding issues for future devices is the problem of heat removal from the hot plasma, so-called power exhaust.

The field of power exhaust is surprisingly broad, ranging from various elementary physics processes that can occur in the presence of impurities in the plasma, to advanced diagnostics systems capable of monitoring the plasma conditions, to control systems required to protect the plasma-facing components in future thermonuclear reactors. Impurities play an important role in these investigations, and although they have been traditionally regarded as rather undesirable elements in tokamak discharges, more and more their indispensability for safe operation of future devices is being recognised by the community. Despite several decades of ongoing research, there are still several challenges that need to be addressed. The most important one is the balance between a sufficient effect of impurities on the divertor heat fluxes and a negligible influence on the confinement quality and discharge stability. As it is often the case in plasma physics, the experimental evidence is far ahead of predictive capabilities of both analytical and numerical models. This highlights the importance of the ITER tokamak operation, where the feasibility of $Q = 10$ scenario should be demonstrated. Although ITER is sometimes presented as an engineering project, where the already known physics basis will be solidified into a functional thermonuclear reactor, I believe that it will have to be extensively used for physics research and that impurities will play a crucial role there.

However, even prior to the commencement of operations at ITER, a significantly smaller tokamak COMPASS Upgrade (currently under construction at IPP in Prague) will enable very interesting studies of power exhaust. With its high magnetic field (B $\leq$ 5 T) and plasma current ($I_p \leq 2$ MA) it will be capable of generating huge divertor heat fluxes, in the range of what is expected in ITER. As such, it will create the perfect conditions for tests of various strategies how to mitigate such heat fluxes to levels which are on par with material limits of the PFCs.

Since I started my master thesis studies in 2005, I have been engaged with research topics related to tokamak power exhaust. In that year, I started visiting the Institute of Plasma Physics of the CAS as a master student consulted by Radomir Panek and a year later I got also employed there. Over the course of time, my focus of research has been progressively shifting as new challenges in the fusion research emerged. When I joined the institute, my colleague Renaud Dejarnac had just finished the work on a 2D particle-in-cell code SPICE2, which had been developed in close collaboration with Jamie Gunn from CEA Cadarache. The code was initially intended for interpretation of the tunnel probe measurements [1], however it was quickly recognised that it could be used for investigation of heat flux distribution on the surfaces of the PFCs, most importantly on the exposed leading edges. While the code had all the necessary features for such studies, it was too slow to simulate realistic plasma conditions. My first task was to improve the code performance. This was successfully achieved with a great help of Zdenek Pekarek from MFF UK, who delivered an extremely fast direct Poisson solver.

The heat flux distribution on castellated PFCs then became a topic of my first master thesis at the Faculty of Mathematics and Physics of the Charles University in Prague [2] as well as my second master thesis effectuated within the international programme Erasmus Mundus - Master in nuclear fusion. There, the outputs of SPICE2 were coupled with simulations of plasma-wall interaction in 3D-GAPS performed by Dmitry Matveev from FZ Juelich and cross-checked with experimental results from the TEXTOR tokamak [3]. During my doctoral studies I have developed a full 3D3V code SPICE3 (again aided by Zdenek Pekarek who has delivered another great Poisson solver), which was used to study the heat flux distribution in gap crossings [4] and interpretation of the Katsumata probe [5]. The simulations of heat flux distributions culminated in 2017 with a large set of simulations with ITER-relevant plasma conditions [6]. This work was an essential stepping stone for a largely influential paper on this topic by Jamie Gunn [7] (139 citations at the time of writing).

In the same year I begun working on PIC simulations of thermionic emission from hot tungsten PFCs in collaboration with Svetlana Ratynskaia and Panagiotis Tolias from KTH Stockholm [8][9]. These simulations were targeting an undesired scenario of overheated PFCs, where liquid tungsten would move due to j×B force (the current being driven by the thermionic emission). Within this research, we were able to extend the Tamakura [10] formula which describes the saturation of the thermionic current, so that it could be applied in magnetised plasmas with arbitrary orientation of the magnetic field [11] and later included also effects of secondary electron emission and electron back-scattering [12][13]. Using the input from SPICE2 simulations, it was possible to numerically reproduce experimental observations of motion of molten tungsten in the divertor of ASDEX Upgrade and JET tokamaks. Recently, SPICE2 has been extended with collision operators that allow to study processes in collisional sheaths, which are relevant to the detachment regime as well as the novel inverse sheath regime (subject of my ongoing Czech Science Foundation project *25-17841S*).

Apart from numerical studies focused directly onto power exhaust, I have also been investigating the behavior of diagnostics relevant for power exhaust tokamak experiments, namely electrical probes. These studies included initial simulations of the ball-pen probe behavior [14], calibration of the slit transmission factor of the retarding field analyzer [15], investigations of the collecting mechanism of Katsumata probe [14], electron current attenuation of small flush mounted probes [16] and sheath expansion related to the divertor Langmuir probes in COMPASS tokamak [17].

In parallel to numerical simulations, I have been involved in experimental investigations of SOL and divertor plasmas relevant to the problem of power exhaust. My first participation in an experiment was the ultimate experiment at CASTOR tokamak together with my colleagues Renaud Dejarnac and Jan Stockel. This experiment was using a specially designed *Sandwich probe* to verify the predictions of the SPICE2 code [18]. During my postdoc I was awarded an EFDA fellowship with a 2 year project to the develop an *$E \times B$ analyzer* - a unique and delicate diagnostics for fast measurements of fast ion temperature [19]. Unfortunately, the interpretation of the measured data proved to be rather complicated so it was utilised only briefly at ASDEX Upgrade [20] and COMPASS. However, I have participated in a number of studies regarding ion temperature measurements and filamentary transport in Tore-Supra [21][22] and ASDEX Upgrade [23][24].

At the same time, I got involved in a series of experiments aiming at investigation of the power decay length in limited discharges at COMPASS, which were relevant to the start-up phase of ITER. This concentrated effort brought together an excellent team of external collaborators including Richard Pitts (ITER Organisation), Peter Stangeby (author of the legendary book on SOL plasma physics [25]) and Rob Goldston (Princeton Plasma Physics Laboratory). The result of this activity was a re-design of ITER first wall panels in order to accommodate the variations of the λ_q [26] [27][28]. it has also highlighted the importance of local non-ambipolar effects in plasma-wall interactions.

Later, I was in charge of development of the detachment regime at COMPASS tokamak [29] and studies of impurity seeding in general [30] in collaboration with my colleagues Jiri Adamek and Jordan Cavalier. Although COMPASS was not very well suited for access to this regime, the activity was successful using nitrogen impurity and the detailed measurements of the divertor heat flux footprint allowed to characterise its deformation by the action of impurities. I was able to demonstrate that despite complex spatial variation of the heat flux mitigation effect, the relation between the peak heat flux and the integral power received by the divertor remains linear. Moreover, the robust design of the ball-pen probes allowed for development of a real-time control system for the impacting heat loads, which was used to regulate the influx of the impurities [31].

Meanwhile, I was awarded a standard CSF project on divertor biasing in COMPASS (GA16-14228S) - an attempt to influence the magnitude of the power decay length by external biasing of the divertor tiles. While this method did not work as expected, it lead to a novel concept of electricity extraction from tokamaks [32]. The specially designed divertor tile was subsequently utilised for studies of plasma disruptions [33]. My last task at COMPASS tokamak before its shutdown was commissioning of a new 1 MW neutral beam injection system [34], which was the main goal of the OP VVV project *EF16_013/0001551*, which I was leading. The data from these last measurements were instrumental for the investigations of the power decay length in high confinement mode at COMPASS by my doctoral student Jan Hecko [35]. Moreover, the NBI system, which was acquired in this project, will be used as a basis for development of future in-house similar heating systems for the COMPASS Upgrade tokamak.

In preparation for the installation of the COMPASS Upgrade tokamak, I have investigated the conditions required for access to detachment as well as the feasibility of the alternative ELM free confinement modes [36].

In 2017, I was appointed as a Eurofusion scientific coordinator of a topic relevant to detachment of high confinement mode. This work involved coordination of relevant experiments at European medium-sized tokamaks - namely TCV (Lausanne, Switzerland) and ASDEX Upgrade (Garching, Germany) [37][38][39][40]. This activity has ultimately progressed into the investigation of ELM buffering with multiple experiments at ASDEX Upgrade (2020-2022) and JET (2023) [41].

In 2022 I was appointed as a head of the newly created High-Temperature Plasma Physics department at IPP, which consists of approximately 30 members. In my new role my goal was to maintain the connection between our team and the fusion community. This became increasingly difficult with the recent end of operation of COMPASS in 2021 and the emergence of many design tasks needed for the construction of COMPASS Upgrade. These are of course important, however

I believe that for successful exploitation of this new device we need not only to prepare all required systems but also to be involved in contemporary fusion research in order to make the best use of this unique tokamak. I am promoting this approach also with my PhD students, motivating them to study a joint degree at CTU and Ghent University. I am one of the few people who were approved as external PhD mentors at CTU, so it is common for me to lead students with topics quite outside the scope of my expertise. This is naturally quite demanding, on the other hand it is also a unique option to gain knowledge in various topics related to nuclear fusion research.

Fusion research is specific in the way it is collaborative, rather than competitive. Tokamaks are large scientific infrastructures which are expensive to build and complex to operate. As such, they are always managed by teams, which range from few dozens (COMPASS) to hundreds (JET) of scientists, engineers and technicians. The research topics within Europe are coordinated by the Eurofusion consortium, which defines priority tasks and appoints task force leaders and scientific coordinators to oversee them. ITER Organisation established their own network of specialists within the *International Tokamak Physics Activity*, where topics relevant to future ITER operation are coordinated. So whatever is being done is not performed by a single person but typically in broad collaborations.

I have been dealing with power exhaust research for the past 20 years. As it is described in this thesis, my path has not been straightforward, in fact many things did not work out as expected. Simple concepts were getting more and more complicated, sometimes up to the point where it was not possible to achieve desired goals. However, such shortcomings are a natural part of science and in every case, they allowed me to widen the scope of knowledge of plasma physics, which was often later useful in other research topics either for myself, my students or my colleagues.

There are results, which I believe have already proven to be valuable for the fusion community. The most important one is the revival of the ELM buffering research, with very exciting results from AUG and JET. If proven to be scalable to larger machines, this method could solve one of the very painful issues of nuclear fusion research. The development of SPICE2 and SPICE3 codes over the past 20 years has yielded a number of very interesting results and also established these codes as a reference tool for multi-dimensional particle-in-cell simulations in the domain of magnetised fusion research. One such output is the generalisation of Takamura formula for the magnitude of saturated escaping electron current for magnetised plasmas with arbitrary orientation of the magnetic field. This formula is already employed in modelling for liquid tungsten motion and can have potentially other applications outside fusion research. Also, the proof that surface electric fields can be in fact neglected when predicting the distribution of heat fluxes in the vicinity of poloidal gaps was in important stepping stone for validation of ITER divertor design. Various numerical studies of plasma diagnostics have either improved or validated their design and capabilities to deliver trustable results. From the Eurofusion activities in which I have participated as a scientific coordinator, the most important one is the discovery of X-point radiator regime at AUG, which I believe will be the ultimate solution for power exhaust in ITER and DEMO.

Working on these topics was an exciting experience, not only because of the very interesting physics but also thanks to the great people that I have met along. As mentioned, earlier, fusion research is quite unique in the way it is collaborative and the team work is an essential basis for any serious undertaking. I am grateful that I had the opportunity to share this path with many colleagues - from young students to senior physicists, some of whom are sadly no longer with us. Our shared passion for physics and the intention to make this great source of energy available for mankind is a bond that traverses generations, genders or nationalities. I hope that in the next 20 years of my research we will see the fruit of this effort to see the light of the day. It will be an adventurous journey and I am looking forward to take my part in it.

Abstract

This thesis presents the story of my research related to power exhaust in tokamaks. I have been working on a number of topics related to power exhaust in the past 20 years both in the domain of predictive numerical modelling and experimental investigations at tokamaks CASTOR (IPP), COMPASS (IPP), ASDEX Upgrade (IPP Garching, Germany), TCV (EPFL Lausanne, Switzerland) and JET (CCFE Culham, UK). I have been using 2D3V and 3D3V particle-in-cell codes SPICE2 and SPICE3 to investigate the heat flux deposition onto the surface of castellated plasma-facing components, to improve understanding of the functioning of various types of electrostatic probes and to study emissive sheaths. On the experimental side, I was mainly responsible for experiments with impurity seeded detached plasmas at COMPASS and ELM buffering experiments at TCV, ASDEX Upgrade and JET. I have been a principal investigator of three major projects: (i) Czech Science Foundation standard project on divertor tile biasing (2016-2018), (ii) MYES OP VVV project on the installation of 1 MW NBI system at COMPASS (2017-2021) and (iii) Czech Science Foundation standard project on inverse sheath modelling (2025-2027). Between 2017 and 2020 I have acted as a scientific coordinator within Eurofusion consortium, participating at many power exhaust related experiments at ASDEX Upgrade and TCV tokamaks. Since 2021 I am a head of High-Temperature Plasma Physics Department at IPP, managing a team of more than 30 scientists and engineers.

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