Department of Applied Physics
Research Unit Nuclear Fusion

Master thesis topics 2021-2022

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The research on controlled thermonuclear fusion aims at providing stable, baseload electric power by creating “a star on earth”. Magnetic confinement fusion in tokamaks and stellarators is foreseen to result in clean and safe commercial power production by the second half of the century. ITER, the next-step device in this endeavor, is currently being constructed in France in the context of the largest international scientific collaboration ever. In addition, design activities for demonstration reactors are increasing in Europe and worldwide.

The research unit Nuclear Fusion (*infusion*) at the department of Applied Physics offers master thesis topics in the following three areas of fusion research:

- **Fusion data science**
- **Ion cyclotron plasma heating and wall conditioning**
- **Materials for fusion devices**

The topics on offer in each of these areas are described below.

Fusion data science

This research concerns the development of techniques in data science and machine learning with applications to the physics and technology of fusion devices. With the large volumes of complex data being generated at experimental fusion machines around the world, there is a strong need for automated analysis using data science and machine learning methods. The research targets a broad array of applications in plasma control and plasma diagnosis, in increasing the understanding of the physics of magnetized fusion plasmas and in designing new fusion machines. This research combines two of the most topical and challenging issues of our time: sustainable energy supply and data science.

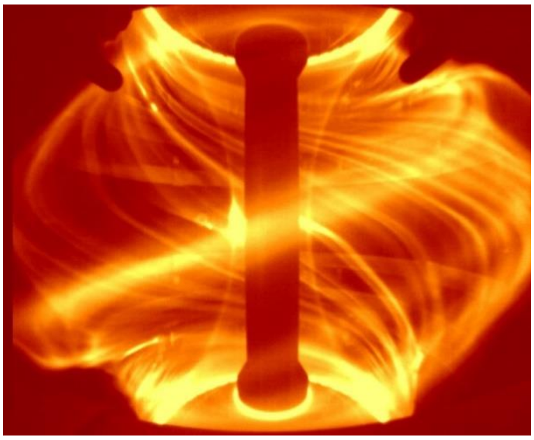
The topics introduced below cover part of the group's research activities, in collaboration with the research institutes operating the tokamaks JET (Culham Centre for Fusion Energy, UK) and ASDEX Upgrade (Max Planck Institute for Plasma Physics, Germany), as well as the Forschungszentrum Jülich (Germany) and the Belgian Nuclear Research Centre (SCK•CEN). The focus of each of the topics can be directed towards either the numerical or rather the physics aspects, depending on the student's interests. A research visit to each of the facilities also belongs to the possibilities.

Topic 1: Probabilistic study of edge-localized instabilities in the JET tokamak

Promoter: Geert Verdoolaege
Supervisors: Jerome Alhage and Geert Verdoolaege
Study programs: Master of Science in Engineering Physics, Master of Science in Physics and Astronomy, European Master of Science in Nuclear Fusion and Engineering Physics
Location: Technicum

Problem statement

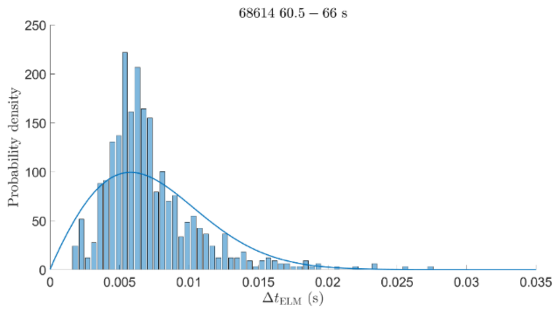
Edge-localized modes (ELMs) are magnetohydrodynamic instabilities that naturally occur in the boundary of tokamak plasmas in the high-confinement regime (H-mode). Acting as a pressure release valve, they lead to a quasi-periodic series of bursts of particles and energy escaping from the plasma (somewhat similar to coronal mass ejections in the sun). Depending on the plasma conditions, different types of ELMs can occur, some of which can be harmful to the machine or its performance. Active control of ELMs is therefore being investigated, using various techniques such as magnetic field perturbations or injection of cryogenic deuterium pellets. However, for reliable performance a better physical understanding of ELMs and the influence of control techniques is needed.



Plasma filament structures aligned along magnetic field lines, observed by fast cameras during an ELM event in the MAST spherical tokamak.

Goals of the thesis

In this thesis the student will work with machine learning techniques for automated ELM type identification based on probability distributions of their properties [1, 2]. In addition, the dependence of the distributions on plasma parameters will be studied. Depending on your interests, you can focus either on development of the methods, based on an exciting geometric approach to probability, and build a system that recognizes and analyzes ELMs at JET (and possibly ASDEX Upgrade). Or, you can contribute to implementation of the algorithms in a new (Python) computer code for ELM recognition that will be deployed at JET.



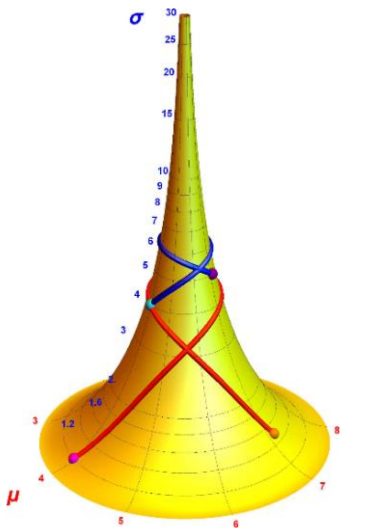
Histogram of inter-ELM times in a JET discharge, fitted by a Weibull distribution.

Topic 2. Prediction of plasma energy confinement for ITER using advanced regression techniques

Promoter: Geert Verdoolaege
Supervisors: Joseph Hall and Geert Verdoolaege
Study programs: Master of Science in Engineering Physics, Master of Science in Physics and Astronomy, European Master of Science in Nuclear Fusion and Engineering Physics
Location: Technicum

Problem statement

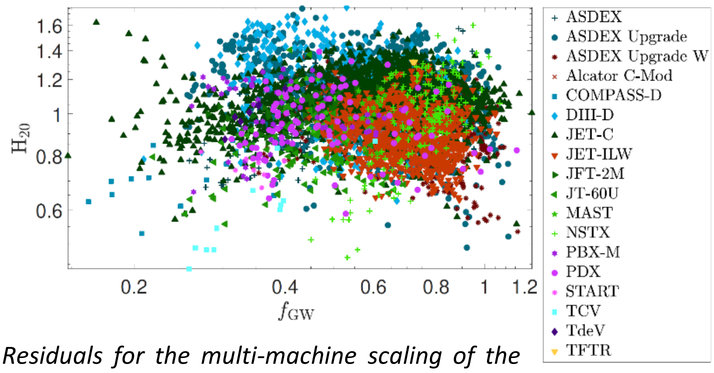
The study of the scaling of key physical quantities characterizing a system, in terms of a number of parameters that can be measured or controlled, is a widespread practice for unraveling the fundamental laws governing complex physical systems in many disciplines such as astronomy, biology, climatology and finance. In controlled nuclear fusion science based on magnetic confinement, scaling laws are essential for establishing design constraints and predicting the performance of fusion reactors. However, due to the complexity and heterogeneity of the data, robustness of the derived scalings is often an issue.



Geodesic curves on a surface representing the family of Gaussian probability distributions.

Goals of the thesis

At UGent a new method has been developed, called *geodesic least squares* (GLS), to robustly quantify trends in physical systems by modeling the data as points in a curved probability space and seeking the shortest path (geodesic) between the modeled and observed probability distributions [3, 4]. The aim of this thesis is to use the GLS method for deriving critical scaling laws related to



Residuals for the multi-machine scaling of the energy confinement time in tokamaks vs. normalized plasma density.

various plasma confinement properties in ITER [5]. This is a very challenging topic involving selection of adequate probability models, calculating geodesic distances in the corresponding probability space, optimization of the scaling surface and prediction for ITER.

Topic 3: Survival analysis of first-wall components under thermal loads in a fusion reactor

Promoter: Wolfgang Biel and Geert Verdoolaege
Supervisors: Leonardo Caputo and Geert Verdoolaege
Study programs: Master of Science in Engineering Physics, Master of Science in Physics and Astronomy, European Master of Science in Nuclear Fusion and Engineering Physics
Location: Technicum, Forschungszentrum Jülich (Germany)

Problem statement

In future tokamak fusion reactors, wall components coming into contact with the plasma (the "first wall") will be exposed to high heat fluxes. Therefore, reactor designs need to take into account reliable estimates of the expected lifetime of the tiles that make up the wall components. However, such estimates are complicated by the strong variation of the heat fluxes in time, as well as from one location to another, that will inevitably occur during reactor operation. The variability of the impinging heat loads will be even more important due to unavoidable variations in the manufacturing and installation of the tiles.

Goals of the thesis

The goal of this master thesis project is to contribute to the design of future reactors by quantifying uncertainties in failure times of wall components and developing a model for predicting achievable component lifetimes. Survival analysis will be applied using probabilistic methods and modern machine learning techniques, based on high heat flux tests carried out on various component prototypes using different materials and designs [6, 7]. During such tests, components are subjected to a series of heat pulses of a specific power and duration, after which the resulting changes are observed of surface properties or structural failures, like crack formation, "burn-through" (mechanical disconnection of coolant tubes from the tiles) or surface melting (see picture).

After a review of existing data of experiments with high heat flux tests in the literature, a systematic and quantitative measure of damage of the observed material samples will be proposed. This measure should be related to the limits of usability of the component, taking into account heat propagation and stress limits in the high heat flux materials. In the next step, a model will be developed for estimating survival probability, transposing the results from the ideal testing under controlled laboratory conditions to the real situation of varying loads during tokamak operation.

This project will be conducted at two locations: the review of experimental data and study of material behaviour will be done at the Forschungszentrum Jülich (FZJ, close to Aachen, Germany), while the mathematical part involving the survival analysis will be carried out in Ghent. Opportunities for funding of expenses will be provided.

Ion cyclotron plasma heating and wall conditioning

Ion temperatures of over 100 million degrees need to be reached in future fusion reactors for the deuterium-tritium fusion reaction to work. Ion cyclotron resonance heating (ICRH) is a method that has the capability to directly heat ions to such high temperatures, via a resonant interaction between the plasma ions and radiofrequency (RF) waves launched in the plasma. Another important application of ion cyclotron waves is wall conditioning, a technique to improve plasma performance by reducing the generation of particles (impurities) released from the wall of the device. The following two topics in this area are offered in collaboration with the Laboratory for Plasma Physics at the Royal Military Academy in Brussels (LPP-ERM/KMS).

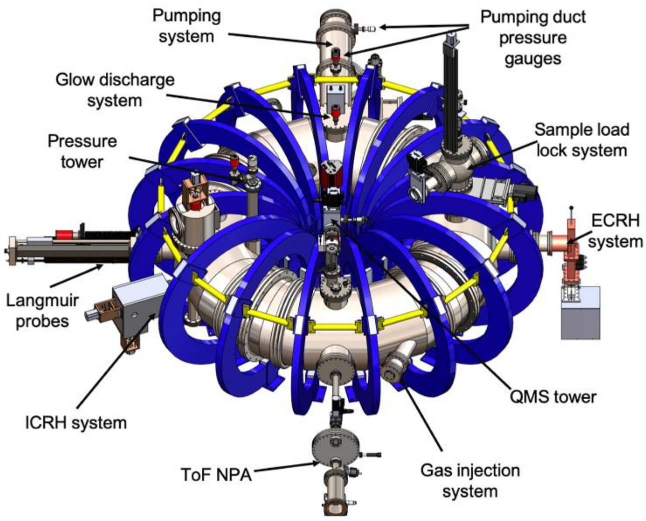
Topic 4: Determination of RF power deposition profiles in a tokamak plasma

Promoter: Kristel Crombé
Supervisors: Johan Buermans and Tom Wauters
Study programs: Master of Science in Engineering Physics, Master of Science in Physics and Astronomy, European Master of Science in Nuclear Fusion and Engineering Physics
Location: Technicum, Royal Military Academy (Brussels), Forschungszentrum Jülich (Germany)

Problem statement
Radio-frequency and microwave (RF) plasmas find applications in tokamaks for wall conditioning and breakdown assistance. These currentless discharges, without equilibrium and typically partially ionised, are produced by resonant or collisional absorption of RF power. Predicting the RF plasma parameters for future large devices such as JT-60SA and ITER requires a good understanding of the power absorption and transport mechanisms of the toroidal magnetised plasmas. The 1D transport oriented model for magnetised toroidal RF discharges, TOMATOR-1D, is developed to provide insight in these phenomena. The code is written in C++. Its robust mathematical implementation with an unconditionally stable temporal discretisation, using the fully implicit backward differentiation scheme of second order complemented by an adaptive time stepping scheme, provides a practical means to benchmark confinement scalings or power absorption modules against experimental data sets. The code describes plasma production by RF waves inside a tokamak using the Braginskii continuity and heat balance equations. The model simulates self-consistent radial density and temperature profiles

for magnetised plasma mixtures of hydrogen and helium. Elementary atomic and molecular collision processes are evaluated at each grid point and time instant in the model. Radiative-collisional models are applied where possible to obtain effective collision rate coefficients, avoiding treating excited states as separate species [8, 9].

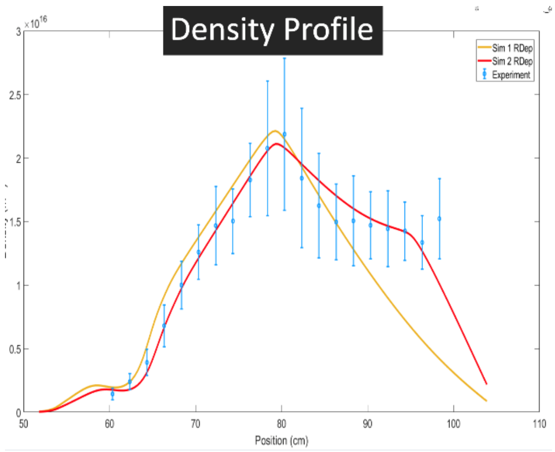
The thesis will contribute to benchmarking this TOMATOR-1D model against experimental data. For that purpose the available database of 1D radial profiles for plasma density and temperature recorded in a toroidal device TOMAS, will be used. TOMAS stands for Toroidal Magnetized System. It is a magnetic confinement device located at the Forschungszentrum Jülich (Germany). It has been built according to specification at the Kurchatov Institute in Moscow, Russia. A detailed description of the machine can be found in the paper by Goriaev, et al. [10]. The code will be applied to both ion cyclotron IC (MHz) and electron cyclotron EC (GHz) plasmas.



Schematic of the TOMAS device with various subsystems and diagnostics indicated.

Goals of the thesis

The TOMATOR-1D model simulates plasma production by RF waves using the continuity and heat balance equations. It is developed to complement experimental data of RF absorption and transport properties. The goal of the thesis is to focus in particular on the development and implementation of a power deposition profile based on theory and experimental findings. The student is encouraged to develop first a theoretical framework, based on existing literature, and then to implement this in the code. Comparison with experimental data will lead to improvements of the model in an iterative way. Recently, radial profiles, measured by Langmuir probes, have become available for the TOMAS device [11]. They have been found to depend on the neutral gas pressure (helium, hydrogen and its mixtures), the coupled RF power and RF frequency, and the magnetic field strength. Additional profiles will be measured in the coming months to complement the available data. The student is welcome to participate in experimental campaigns on TOMAS in Jülich and provide input for e.g. parametric scans that can be useful for the simulations and benchmarking process.



Experimental and simulated density profiles in TOMAS.

The main location and the time division is open for discussion with the student. Simulations can happen at home (with occasional discussions in Ghent or Brussels with the promotor and supervisor).

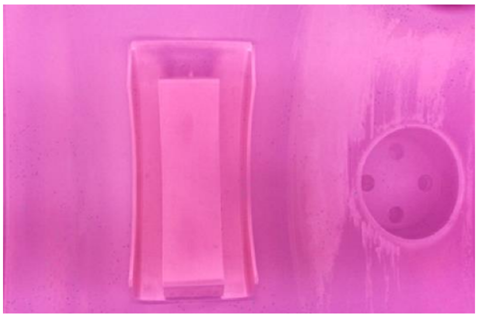
Participation in experiments (if desired) will happen at the Forschungszentrum in Jülich (close to Aachen, Germany), where the experimental device TOMAS is situated.

Topic 5: Experimental study of combined electron and ion cyclotron radio frequency discharges in TOMAS

Promoter: Kristel Crombé
Supervisor: Tom Wauters
Study programs: Master of Science in Engineering Physics, Master of Science in Physics and Astronomy, European Master of Science in Nuclear Fusion and Engineering Physics
Location: Technicum, Royal Military Academy (Brussels), Forschungszentrum Jülich (Germany)

Problem statement

Plasma-surface interactions (PSIs) in controlled fusion devices lead to significant surface modifications at plasma-facing components and contamination of the fusion plasma by species released from the wall due to sputtering, melting, or evaporation. To ensure and provide proper wall conditions for plasma operation or to control the fuel inventory, a number of wall conditioning techniques have been developed: deposition of thin low-Z films by plasma-assisted procedures or evaporation, baking, glow discharge cleaning (GDC), and, recently, operations involving ion cyclotron (IC) or electron cyclotron (EC) plasmas. The two latter methods are being elaborated for use under strong magnetic fields in devices with superconducting magnets, i.e., the stellarator Wendelstein 7-X (W7-X) and ITER. Over the last few years the upgraded device TOMAS - TOroidal MAgnetized System - has become fully equipped for wall conditioning, plasma production, and PSI studies. Technical details of the machine, located at the Forschungszentrum Jülich, are described in [10]. It is located at the Forschungszentrum Jülich. TOMAS is a flexible hands-on study environment. As diagnostic tools to determine the plasma parameters moreover a single Langmuir probe and a triple probe have been installed. Successful first measurements of electron density and temperature profiles have been performed with the probes in both IC and EC plasmas. During this preliminary study the profiles have been found to depend on the neutral gas pressure (helium, hydrogen and its mixtures), the coupled radio frequency (RF) power and frequency, and the magnetic field strength [11]. However detailed scans and a proper physical understanding of the different conditions are still missing.



Inside view of TOMAS during plasma operation, showing the ICRH antenna.

The probe diagnostics on TOMAS.

Goals of the thesis

The purpose of the thesis is to perform systematic parametric scans on TOMAS during IC, EC and combined IC+EC plasmas. Both probe systems (single + triple probes) will be used to determine the density and temperature profiles and to find physical dependencies. The existing data analysis tools as initiated in [11] can be used and possibly improved. In collaboration with modellers and RF specialists also a physical interpretation will be sought. The main goal is to expand the understanding of the discharge properties on TOMAS and to optimise the settings for wall conditioning. The results will be of direct interest for existing and future fusion devices.

The main location will be the Forschungszentrum in Jülich (close to Aachen, Germany), where the experimental device TOMAS is situated. The student should be prepared to spend at least 2 – 3 months in Jülich for the preparation and execution of the experiments. Data analysis can be done from home. Discussions with the promotor and supervisor can happen in Ghent, Brussels or Jülich, as desired.

Materials for fusion devices

Topic 6: Study of anisotropy of plastic properties in pioneering materials for fusion applications

Promoter: Geert Verdoolaege
Supervisors: Alexander Bakaev and Dmitry Terentyev
Study programs: Master of Science in Engineering Physics, Master of Science in Physics and Astronomy, European Master of Science in Nuclear Fusion and Engineering Physics, Master of Science in Sustainable Materials Engineering
Location: SCK•CEN (Mol, Belgium)

Problem statement
Many of the new material grades for fusion applications are anisotropic, i.e. are strong and/or ductile only in one particular direction. Dedicated mechanical testing is currently ongoing to characterize their strength in different directions, at different temperatures, strain rates, etc. The information on the material anisotropy could be very beneficial for the accuracy and robustness of large-scale mechanical computational models, which address the behavior and the structural integrity of fusion reactor components under harsh operational conditions.

Goals of the thesis
The aim of the project is to obtain the anisotropic plastic properties for several fusion-relevant materials via analysis of the existing mechanical testing data or via new dedicated mechanical tests. In addition, the implementation is foreseen of these data into a commercial FEM code to simulate the mechanical tests in order to validate the extracted material properties. This research will contribute to the build-up of a complex virtual model of components of the ITER fusion device.

The work will take place at the Belgian Nuclear Research Centre (SCK•CEN) in Mol.

Recent picture of the ITER construction site.

References

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