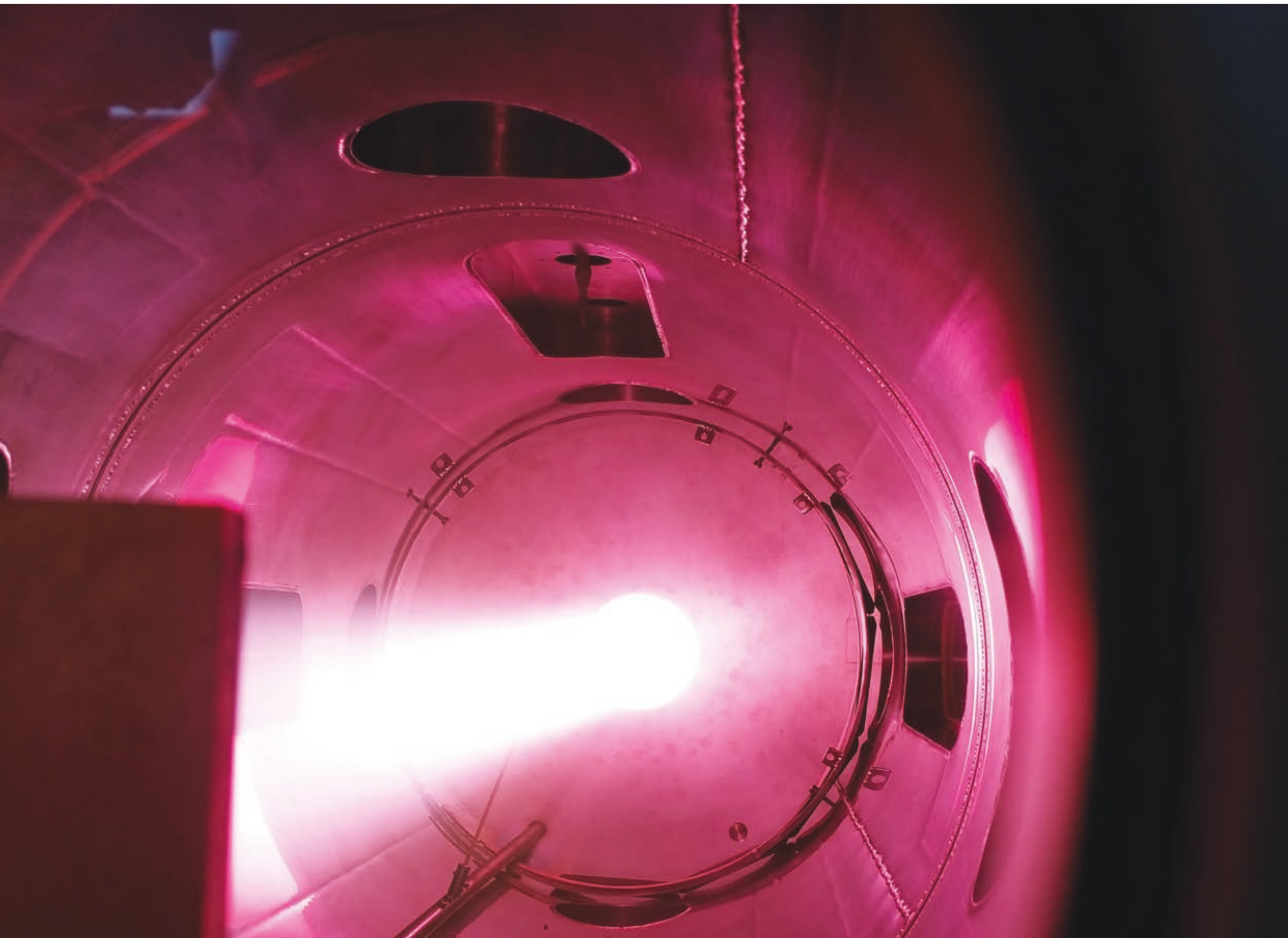
2018 SYNTHESIS REPORT

Controlled Thermonuclear Fusion Research Programme



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Cover page:
Hydrogen steady state plasma discharge in RAID vacuum vessel.

IEA classification:	4.2 Nuclear Fusion
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Research programme nuclear fusion
Annual report 2018

Editors:
Dr. Laurent Villard (SPC), Dr. Laurent Marot (University of Basel), Dr. Patrice Soom (SERI)

Programme manager:
Dr. Patrice Soom (SERI) (patrice.soom@sbfi.admin.ch)

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Introduction

Nuclear fusion is the process bringing a star's core to life, fusing light elements into heavier ones to release unequalled amounts of energy per fuel mass. The development of the science and technology required to enable the industrial and commercial exploitation of this type of energy-producing reaction represents a major opportunity for the humanity's energy future as nuclear fusion carries the promise of a virtually unlimited source of safe, clean and CO_2-free energy. The fuel required is available in large quantities and in many parts of the planet. Fusion reactors of the future will be intrinsically safe and the energy produced could be used for multiple purposes, including electricity generation and hydrogen production. The product of fusion reaction is helium, which is not a greenhouse gas and is not radioactive. The radioactive products, essentially in the vessel of the power plant, are short-lived (50-100 years). Fusion energy would ideally complement the current renewable energy sources. The advantages of nuclear fusion motivate the international R&D effort that addresses the major challenge of creating the extreme conditions necessary to initiate, sustain and convert the energy arising from fusion reactions.

From the outset, the European Fusion Research Programme has focused on developing nuclear fusion as a source of electricity. This strategy has been closely pursued by the European Atomic Energy Community Euratom for nearly 40 years, in particular since 1979 with the construction and commissioning of the Joint European Torus (JET) in the United Kingdom. The highly successful operation of this facility led to significant progress in controlling the deuterium-tritium fusion reaction. In 1997 an unprecedented fusion power of 16 MW and an energy output factor of Q=0.65 were achieved.[1]

These developments brought the European Union, the United States, China, South Korea, Japan, India and Russia to the launch in 2007 of the international ITER Project. The main objective of ITER is to demonstrate that nuclear fusion is technically feasible and a viable option for producing energy on an industrial scale. Currently under construction at the Cadarache site in France, ITER is designed to generate 500MW of fusion power out of 50MW of injected power, i.e. to reach an energy output factor of Q=10. In parallel to ITER construction, several of the same partners already started to take steps towards the use of nuclear as a commercial source of power. The design of a demonstration fusion reactor capable of producing large amounts of power that can be fed into the electricity grid is already in preparation. This step, known as DEMO, is planned to start operation in the 2050s.

ITER DEVELOPMENTS

Worldwide activities in nuclear fusion research are currently focused on the realization of the International Thermonuclear Experimental Reactor, ITER. In 2018, the ITER Organization consistently pursued the implementation of the new operational and financial construction schedule that was adopted *ad referendum* by the ITER Council in November 2016. This new baseline foresees the start of operation in 2025 with a first plasma and the decisive nuclear experiments in 2035. At the end of 2018, 59.7% of all physical work activities required to achieve the First Plasma milestone were completed. Design activities were completed at a level of 95.8% whereas manufacturing reached 67.2%.

ITER construction highlights of 2018 include the tokamak bioshield completion, allowing for the installation of the first mechanical and electrical components in the tokamak complex. Half of the equipment was installed in the cryoplant facility and commissioning is expected to start in 2020. Final activities in cryostat workshop are ongoing and acceptance test are planned in 2019. As Assembly Phase I shall officially begin in March 2020 under its sole responsibility, ITER Organization proceeded in 2018 to several institutional adjustments. A unique Holistic Integration Team now supplements the Project Teams that integrate ITER Organization and Domestic Agencies staff to manage complex tasks in all complex areas. It shall ensure installation sequences are adequately planned for all tasks in the Tokamak Complex. The ITER Organization took over the lead in several complex areas that were initially foreseen to be completed by domestic agencies.

At the institutional level, 2018 saw a major step towards the formal approval of the new operational and financial construction schedule. Stressing the fundamental importance of ITER and reaffirming the continued correlative commitment of Euratom, the Council of the European Union adopted positive Conclusions[2] on the European Commission's Communication "EU Contribution to a reformed ITER project"[3]. Therein, Euratom Member States mandated the European Commission to ap-

1 Q is defined as the ratio between the power emitted in the reaction and the external power fed into the plasma by the reactor heating system.
2 Council conclusions on the reformed ITER project (adopted on 12/04/2018)
3 Communication from the Commission to the European Parliament and the Council EU Contribution to a Reformed ITER Project (COM/2017/0319 final)

prove the new ITER baseline on behalf of Euratom at an ITER Council meeting at Ministerial level. Even though the financial resources beyond 2021 are yet to be granted in the frame of the European multiannual financial framework 2021-2027, this political decision of the ITER Host Party opens the way for the other Members to move forward towards the final approbation of the ITER new baseline.

EUROPEAN DEVELOPMENTS

The priorities and strategic directions in European nuclear fusion research are set out in the "European Research Roadmap to the Realisation of Fusion Energy".[4] The updated version of this document released in 2018 focuses on three main pillars: the completion of the international ITER experimental reactor, the construction of a neutron source facility for fusion materials development and qualification DONES, and the realization of a demonstration power plant DEMO, which will deliver hundreds of megawatts of electricity to the grid and operate with a closed fuel cycle. These infrastructures and projects are supported by a strong research and innovation programme that already looks towards commercial fusion power plants. Although it focuses on the tokamak concept, the roadmap includes the development of an alternative type of reactor architecture, the stellarator. Finally, the roadmap stresses the need of training new generations of scientists and engineers.

At an institutional level, European research into nuclear fusion has a dual framework: the Euratom fusion research programme, currently implemented by the EUROfusion consortium, and the European Joint Undertaking for ITER, Fusion for Energy (F4E), responsible for the European contribution to the construction of ITER.

Euratom fusion research and training programme

The Euratom research and training programme was established in December 2013 for the period 2014-2018. The EUROfusion consortium implements the fusion side of this programme with a budget of EUR 857 million for the years 2014 to 2018. Half of this amount is granted by Euratom while the other half has to be provided by participants in the frame of a co-funded action. In October 2014 Euratom and EUROfusion signed a co-financing contract worth EUR 424.8 million, completing the process of restructuring the European Fusion Research Programme. In order to keep synchronization with the multiannual financial framework of the European Union, the Euratom research and training programme was renewed by the European Council in October 2018 to cover the years 2019 and 2020, with a total budget of EUR 770.2 million, out of which 349.8 are available for fusion research. As a signatory of the Consortium Agreement establishing the consortium, the EPFL is an official member of EUROfusion. The University of Basel is affiliated as a linked third party. The activities of these institutions in 2018 under the EUROfusion umbrella are summarized below.

The spectrum of R&D conducted under the auspices of the EUROfusion consortium covers the scope of the eight missions defined in the roadmap for fusion energy: the development of plasma regimes of operation, the heat exhaust systems, neutron-resistant materials, the infrastructure needed for tritium self-sufficiency, the implementation of intrinsic safety features, the integrated design of DEMO, and the competitive cost of electricity from fusion power plants. The backbone of the medium term programme is the ITER device, but many existing facilities are deemed essential, including the joint EU tokamak JET and the three national Medium Size Tokamaks, one of which is the EPFL TCV tokamak. Emphasis is also put on theory and numerical simulations and on education and training, as an essential element of a trans-generational effort such as that of the quest for fusion energy.

Fusion for Energy activities

In 2018, F4E activities focused on the timely and costly implementation of the consequences of the new ITER construction schedule. With good operational performance, F4E implemented a commitment budget of EUR 694.99 million, representing 113% of its initial 2018 budget. It realized payments for a total amount of EUR 813.99 million. 90% of payments appropriations went the construction of ITER, i.e. all activities associated with construction at the Cadarache site. 2% were dedicated to operational expenditures arising from further technological development both for ITER and for the collaboration with Japan in the frame of the Broader Approach. The remaining 8% corresponds to the administrative and running costs of F4E.

In 2018, F4E achieved 93% of all its internal milestones compared to 91% in 2017, 70% in 2016 and 75% in 2015. Amongst many activities, F4E completed in particular the massive concrete bioshield encircling the tokamak pit. The casing of the superconducting toroidal field magnets started, bringing 26 European companies to work together. Three full-sized prototypes of blanket first wall prototypes were realized while the full-sized Inner Vertical Targets of the Divertor successfully passed thousands of cycles of high-heat flux testing.

F4E implements the European participation to the Broader Approach agreement, concluded between the European Atomic Energy Community (Euratom) and Japan to complement the ITER project and to accelerate the realization of fusion energy. Three main projects of the Broader Approach made substantial progress in 2018. In Naka, the construction of the JT60-SA tokamak reached 95% completion, F4E having delivered all TF coils, the cryostat and further equipment. The subsystems for

4 European Research Roadmap to the Realisation of Fusion Energy
https://www.euro-fusion.org/fileadmin/user_upload/EUROfusion/Documents/2018 Research_roadmap_long_version_01.pdf
Formerly "EFDA roadmap to the realisation of fusion energy".
https://www.euro-fusion.org/wpcms/wp-content/uploads/2013/01/JG12.356-web.pdf

short pulse beam transmission through the Radio Frequency Quadrupole of the International Fusion Material Irradiation Facility IFMIF-EVEDA in Rokkasho were successfully commissioned, bringing the project to 90% completion. Finally, the International Fusion Energy Research Centre IFERC is reaching completion.

SWITZERLAND'S ROLE IN INTERNATIONAL NUCLEAR FUSION RESEARCH

Swiss research into nuclear fusion is part of this European and international framework. Its involvement in international research into nuclear fusion goes back to the 2nd International Conference on Peaceful Uses of Atomic Energy held in Geneva in 1958, at which it was agreed to declassify fusion research. Three years later, in 1961, Switzerland set up its own Plasma Physics Laboratory,[5] becoming a pioneering nation in this field. In 1979, Switzerland became fully associated to the European Fusion Research Programme under a cooperation agreement with Euratom. In 2009, the Swiss Parliament ratified the agreements with the EU involving Switzeralnd in the construction of ITER through its membership in the European Joint Undertaking for ITER and the Development of Fusion Energy, Fusion for Energy (F4E). Since 2014, Switzerland has a seven-year long association agreement with the EU regulating its participation in the Horizon 2020 Framework Programme, in the Euratom programme, as well as the financial aspects of its participation in F4E.

Switzerland's strong implication in international fusion research brings its stakeholders to endorse various institutional responsibilities. In July 2018, Prof. Ambrogio Fasoli was elected as Chair of the General Assembly of EUROfusion, the highest decision body of the European Consortium for the development of fusion energy, for the period 2019-2020. His nomination at the highest level in the fusion community in Europe constitutes not only an acknowledgment of his personal competence and commitment but also a proof of the prominent role that EPFL and Switzerland play in this field.

Representatives of the Swiss State Secretariat for Education, Research and Innovation SERI in the F4E governance endorse since 2018 extended responsibilities as member of the Governing Board Bureau as well as Vice-President of the F4E Administration and Management Committee.

SWISS RESEARCH HIGHLIGHTS

Swiss fusion research is today mainly conducted at the Swiss Plasma Center SPC (based at the Ecole polytechnique fédérale de Lausanne, EPFL, and including the group on Superconductivity at the Paul Scherrer Institute, PSI, in Villigen) and at the University of Basel, providing specific skills and expertise that are globally recognised. Directed by Prof. Ambrogio Fasoli, the SPC has about 160 staff including 40 graduate students, working along six research lines: TCV Tokamak Physics, Theory and Numerical Simulation, Basic Plasma Physics, International collaborations, Superconductivity for Fusion and Plasma Applications. It contributes to the ITER project via contracts with the ITER International Organization and F4E, by strengthening the participation of Swiss industry to the procurement of important components, and by advancing the ITER physics basis and optimizing its chances of success via experimentation on specific facilities, in particular the TCV tokamak. The operation of this facility on the EPFL campus proved to be very intense during 2018: 543 plasma discharges were conducted in the frame of the EUROfusion Consortium, for which a significant input of human and financial resources is granted by EUROfusion, and 1609 for the SPC's own program, of which an important fraction is devoted to PhD students. About 150 external collaborators have come to EPFL to perform experiments on TCV, and the overview paper summarising the results for 2017-2018 was signed by 274 co-authors, a record number for the SPC.

The TCV program ranges from conventional to advanced tokamak scenarios and alternative divertor configurations, exploiting the device unique shaping capabilities. New results were obtained in a number of areas, e.g. on how to control instabilities in real-time that can otherwise lead to disruptions, which are sudden losses of plasma confinement that could be deleterious for reactors, and on how to use gas injection to dissipate the runaway electrons that could still result from these violent events. The new 1MW Neutral Beam Injector has expanded the parameter range, now encompassing plasma scenarios that are akin to those foreseen for ITER, and stationary discharges sustained by the current driven by electron cyclotron waves. These intense experimental campaigns will be followed by a major shutdown, to implement infrastructure upgrades that will further enhance the capabilities of the TCV tokamak to investigate crucial issues for ITER, DEMO and fusion reactors. An important element of the TCV upgrade plan is the construction of an in-vessel structure, with mechanical baffles, several gas injection valves and an enhanced pumping system, together with an updated set of diagnostic systems. This will create a divertor volume of variable closure with a high degree of control of the plasma and neutral gas conditions. The divertor upgrade will also capitalise on the ongoing installation of additional, multi-MW electron cyclotron wave and neutral beam heating systems, and will enable the investigation of important aspects of the plasma exhaust issue in conventional and innovative magnetic configurations. Tests of ITER conductors are continuing in the applied superconductivity group, in parallel with innovation on specific aspects of high temperature superconductors, for DEMO and for particle accelerators,

5 Renamed the Centre de Recherches en Physique des Plasmas in 1968 and Swiss Plasma Center in 2015. http://spc.epfl.ch.

in the context of EUROfusion and of the Swiss collaboration on advanced particle accelerators, CHART.

Significant progress was also achieved in basic studies and theoretical models, which, starting from first principles, address the crucial issue of the coupling between the thermonuclear core and the plasma periphery, where complex interactions with the surrounding material surfaces take place. Theory and numerical simulation are aligned onto the new EUROfusion initiatives that aim at significantly increasing the joint efforts to simulate and predict ITER and DEMO grade plasmas. Advanced analysis of the intermittency of turbulence and related suprathermal ion transport continued in TORPEX, while studies for the optimization of wave-drive plasma sources for DEMO neutral beam injectors, as well as for the plasma wake accelerator concept for CERN were conducted in the linear plasma device RAID. The SPC also exploits fusion and plasma spin-offs for societal applications. In 2018, first results from the novel SPC's bio-plasma laboratory were obtained in the area of plasma-aided sterilization, in collaboration with local companies and the EPFL Life Sciences Faculty. This large set of activities and their success are made possible by the long term vision of the SPC wide platform of financial support bodies, including the ETH Board, the SERI, the EPFL Faculty of Basic Sciences and Institute of Physics, the Swiss National Science Foundation, InnoSuisse, ITER, Fusion for Energy and EUROfusion.

As for ITER the formation of tritiated ammonia may pose some issues with regards to tritium inventory and duty cycle, the research at the University of Basel was focused on understanding the formation of ammonia in a hydrogen/nitrogen plasma with tungsten catalyst. Rather than giving an exhaustive list of all progress made, the following pages presents a selection of 2018 research highlights at the SPC and the University of Basel. These are presented by the respective heads of the responsible research units. As SPC Director Prof. Ambrogio Fasoli emphasizes: behind each of these achievements, there are teams of physicists, supported by strong technical and administrative staff, without whom success would not have been possible.

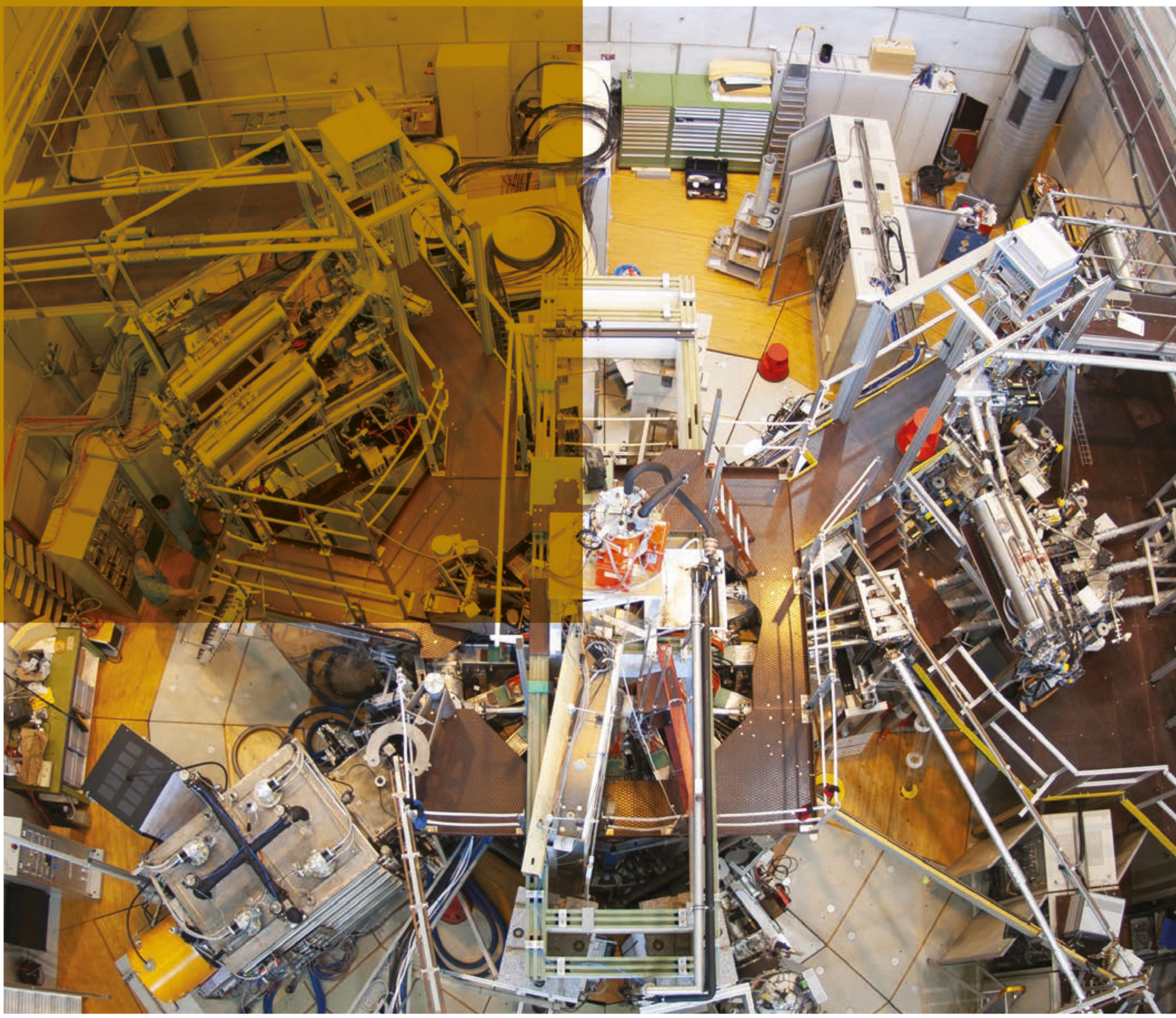
In July 2018 Prof. Ambrogio Fasoli was elected as Chair of the General Assembly of EUROfusion, the European Consortium for the development of fusion energy. His nomination at the highest level in the fusion community in Europe constitutes not only an acknowledgment of his competence and com- mitment, but also a proof of the prominent role that EPFL and Switzerland play in this field. The General Assembly is the highest decision body of EUROfusion, the European Consortium for the development of fusion energy.

FROM LEFT TO RIGHT Prof. Tony Donné, CEO of EUROfusion; Dr Jérome Pamela, Chair of the EUROfusion General Assembly until July 2018; and Prof. Ambrogio Fasoli, the newly elected Chair.

SWISS RESEARCH HIGHLIGHTS

In the frame of this short Annual Report, it is impossible to give a comprehensive and exhaustive list of all the work that has been carried out. Rather, we describe the highlights that were attained in 2018, which in reality are most often the fruit of a multi-year effort. These are presented by the respective heads of the research lines of the SPC, with the understanding that behind each of these achievements there are teams of physicists, supported by strong and dedicated technical and administrative staff, without whom success would not have been possible.

Prof. Ambrogio Fasoli, Director of the Swiss Plasma Center of EPFL



TCV Tokamak

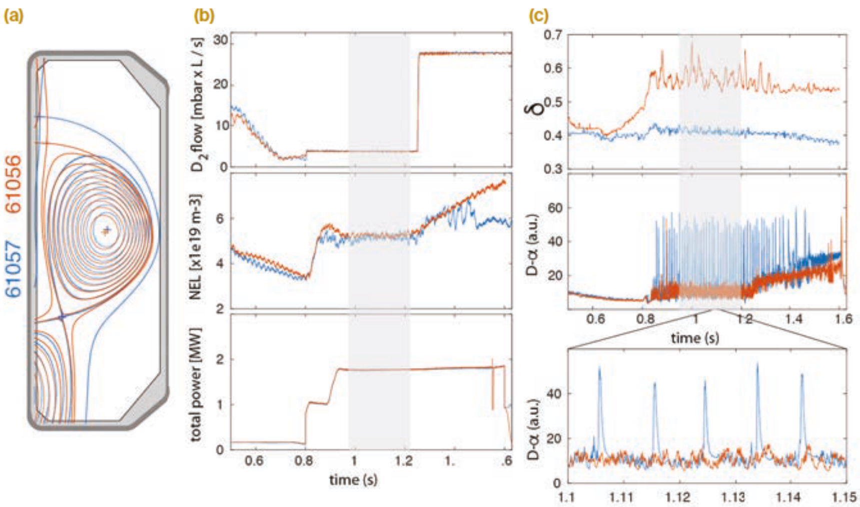
As the largest experimental facility of the Swiss Plasma Center, the TCV Tokamak continues to pursue its mission to explore the physics of nuclear fusion by magnetic confinement, in support of experimental reactors under construction (such as ITER and JT-60SA) and also investigating new and alternative avenues in view of future prototype power plants (DEMO). The device is operated partly as a shared European facility and has hosted 149 external visitors from 41 institutions in 2018. Fully embedded in the EPFL campus, TCV has served also - and continues to serve - as a training ground for generations of students, many of whom have gone on to fill the ranks of the worldwide fusion research community. Dr STEFANO CODA, Maître d'Enseignement et Rercherche (MER, Senior Scientist), is leading the TCV operations and is describing below what the main findings of this research were in 2018.

The year 2018 was operationally intensive for TCV with considerable progress being made on several important topics. Here are a few highlights.

Abnormal discharge termination events, called disruptions, continue to garner focused attention as they present the highest risk to device integrity. Disruptions were systematically induced in TCV by injecting impurities, in the form of a noble gas, which alter the current density profile and result in a violent instability. Methods to control or suppress this instability were tested, using microwave power that is absorbed resonantly at the location of the instability. Both full performance recovery and soft landing paths were explored and documented. A side effect of disruptive events is the appearance of ultra-fast, so-called "runaway", electrons that travel essentially at the speed of light and can cause deep damage to the metallic structures of a reactor. In addition to studying and documenting the generation and dynamics of these electrons, TCV scientists also successfully demonstrated methods of control and attenuation of the runaway electron beam by using applied magnetic fields.

More generally, real-time control is strongly emphasized in TCV research, with recent focus on optimizing the entire philosophy underpinning its architecture. In particular, a highly modular structure is now being promoted, (see next pages), where the detection of events and the evaluation of the state of the system are carried out by a layer that is machine-independent (or "tokamak-agnostic") and kept strictly separate from the layer that governs the actuators that intervene to modify that state.

After disruptions and runaway electrons, reactor designers fear Edge Localized Modes (ELMs) the most. These are periodic instabilities occurring in the so-called H-mode (the low-loss or high-confinement mode in which ITER is expected to operate) that expel particles and energy in violent fashion and can also damage the wall of the device. In an ongoing effort to avoid large ELMs, in 2018 we developed in TCV an attractive, robust regime (already found in ASDEX Upgrade) with small and frequent ("grassy") ELMs, with no compromise in performance, see **Figure 1**.



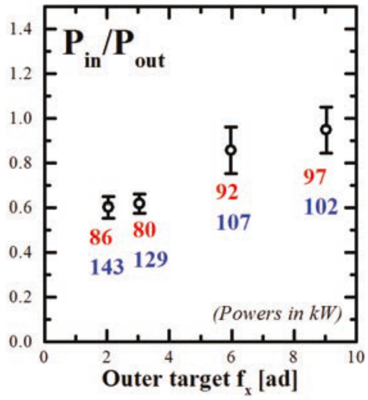
1 The ELM character changes drastically from large to small and frequent ("grassy") with a small change in shape (triangularity) of the upper part for otherwise similar discharges: (a) equilibrium reconstructions; (b) from top to bottom: injected gas flow, line-integrated density, total power; (c) from top to bottom: average edge triangularity and D_alpha emission, with a zoomed-in detail showing the semi-periodic ELM instabilities.

The problem of particle and energy exhaust, more generally, constitutes a central concern of tokamak physics and is intimately related to the physical processes at play in the plasma edge region. TCV plays a prominent role in these studies, partly, but not exclusively, because of its unique ability to create exotic magnetic topologies such as "snowflake" and "super-X" divertors that could offer better exhaust solutions than are possible in ITER. The physics of "detachment" took center stage in this topic in 2018. This refers to a state in which the plasma edge region effectively becomes detached from the material wall, such that the peak power load to the wall is greatly reduced.

This is experimentally achieved by increasing fueling and/or injecting impurities. Novel spectroscopic analysis techniques have been developed and applied to edge line radiation measurements to yield remarkably quantitative results on the origin of detachment, which is attributed to power "starvation", i.e., a reduction of the power available for gas ionization.

The shaping flexibility of TCV was applied to scan the magnetic flux at the plasma-wall impact points ("strike points") and to document its effect on the detachment process in both low- and high confinement mode, finding a weak correlation in both regimes. On the other hand, the commonly observed asymmetry in power flux between the two strike points (larger at the outer point) is found to become less pronounced with decreasing magnetic flux, **Figure 2**, an effect that was reproduced successfully with a simple analytical model. One of the several variants of snowflake divertor, the so called low-field-side snowflake-minus, was found to exhibit a broader - that is, more favourable - heat-flux profile than all the others.

Experiments have been carried out to assist the preparation of the operation of the new Japanese tokamak JT-60SA. In particular, we documented how the initial plasma creation was affected by the reduced electric field expected in JT-60SA, by the presence of impurities, and by the application of microwave power.



2 Ratio of power fluxes to inner (red) and outer (blue) strike points vs flux expansion (a quantity inversely proportional to the magnetic flux). The numbers refer to the individual power exhausted to the inner (red) and outer (blue) targets, in kW.

INTEGRATED REAL TIME CONTROL OF TOKAMAKS

In fusion plasma control, the single control goal (control task) approach has been applied systematically for decades to face diverse control challenges. However, to fulfil a global physics goal, particularly in long-pulse experiments, integrated control is valuable for simultaneously dealing with multiple control tasks and handling off-normal events. By "off-normal" we mean undesired plasma events or hardware failures, which can suddenly and unexpectedly occur and deteriorate the plasma or damage the plasma facing components. Dr **TRANG VU**, Post-Doc at SPC, describes an innovative approach to integrated control and its implementation in TCV.

Due to the fact that some control tasks need to share a limited set of actuators during an experiment, there will be conflicts on actuator requests. For this reason we have developed a generic *Plasma Control System* (PCS) architecture **(Figure 3)** including a tokamak-dependent layer and a tokamak-agnostic layer. In the tokamak-agnostic layer, a plasma supervisory controller and an actuator manager make high-level decisions on how to handle the required control tasks, using generic actuator resources and controllers. The tokamak-agnostic layer is independent of the tokamak subsystems (diagnostics/ actuators) and can therefore be independently developed and maintained, while only the tokamak-dependent layer should be adapted for each tokamak. Moreover, the tokamak-agnostic layer is modular, i.e. the components are clearly defined and separated, which facilitates independent testing and further developments.

The same tokamak-agnostic layer has been tested on both ITER and TCV scenarios, adapting only tokamak-related configuration parameters, demonstrating the value of this generic design. The integrated control scheme has also been successfully implemented in TCV and has been applied to various scenarios. For example, simultaneous control was successfully achieved of total plasma pressure and of a localized instability called the Neoclassical Tearing Mode (NTM) known to deteriorate confinement. In this experiment, two actuators were used, consisting of Electron Cyclotron Waves (ECW) injected to generate plasma current either in the centre of the discharge or at the position of the NTM. This platform will serve as a test bed for the rapid development of integrated control scenarios in complex tokamaks like ITER.

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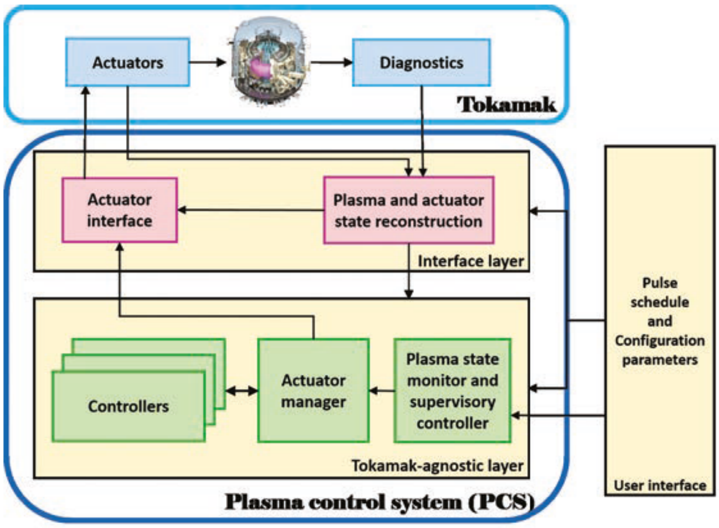

3 Overview of the generic tokamak control system architecture including the tokamak system and the plasma control system (PCS). The components in the PCS are split into two layers: the tokamak-dependent layer and the tokamak-agnostic layer. The latter is independent of the particular device and can thus be applied to different tokamaks.

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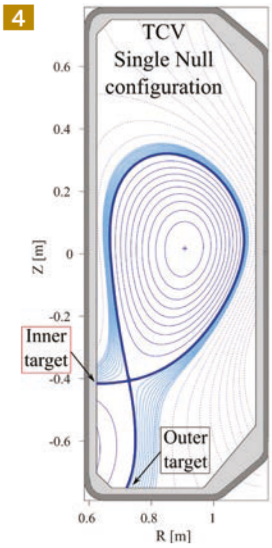

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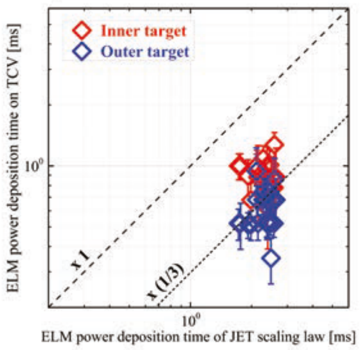

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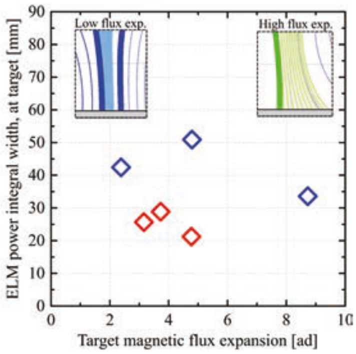

4 The conventional Single-Null magnetic configuration, used in this study and foreseen for ITER. 5 Measured duration of ELM power deposition, compared to expectation using a scaling law developed at the JET tokamak. 6 The ELM power integral width at the target, which is a proxy for the total deposition area, does not increase when the spacing between magnetic surfaces, the so-called flux expansion, is increased by more than a factor four. The inlet show cases with small and high flux expansion.

INVESTIGATING POWER LOADS ON THE WALL DURING ELMS

In ITER and in a future fusion reactor such as DEMO, the plasma is planned to be in the so-called high-confinement mode (H-mode), as it guarantees high plasma core pressure and, thus, high nuclear fusion gain. Unfortunately, the H-mode comes with regular Edge-Localized-Modes (ELMs) events, periodic plasma instabilities that expel hot particles into the Scrape-Off Layer (SOL), colder plasma surrounding the confined plasma. Most of these hot particles follow the SOL open magnetic field lines and impact onto the divertor targets, causing large heat loads and potential target melting.

Research carried out by **ROBERTO MAURIZIO**, PhD student at the SPC under the supervision of Dr. Holger Reimerdes, investigated in detail the characteristics of ELM power loads in conventional divertor configurations, **Figure 4**, and how they can be affected by changes in the geometry of the magnetic configuration.

A first result is that the ELM power deposition duration, at the target, is three times shorter than observed, for similar SOL plasmas, in the larger JET tokamak, **Figure 5**. The ratio of the ELM durations in TCV and JET also corresponds to the ratio of the SOL magnetic field line lengths, suggesting that the ELM energy can be dilated over a longer time, with beneficial reduction of target surface thermal stresses, simply by increasing the SOL magnetic field line length. A second, rather unexpected, result is that the ELM power deposition area at the target does not increase when increasing the spreading of magnetic surfaces, i.e. their relative distance, **Fig. 6**. This observation reveals for the first time how the ELM power load responds to changes of the magnetic divertor geometry and may give new insights into the dynamics of cross-field transport during ELMs.

TCV Diagnostics

Plasma diagnostics are the scientists' eyes and ears in observing the experimental behaviour of the plasmas we are investigating. As such, on an exploratory machine such as TCV, these diagnostics are under constant evaluation and improvement as technology or experimental need provides or requires. With TCV's upcoming divertor upgrade, these systems must not only be maintained but modified to suit the upcoming requirements. Dr BASIL DUVAL, MER, is the leader of this research line and exposes below some of the main achievements in 2018.

Through the planning and early execution time of TCV's divertor upgrade, diagnostic effort has been divided between ensuring existing systems will be optimised for the new internal configuration and developing new diagnostic systems specifically for the augmented divertor chamber. The development of diagnostics with an increasing number of multi-viewing chords is increasingly used on Tokamaks to provide profiles of plasma parameters such as temperatures and densities. During 2018, a major revision of multi-chord plasma radiation diagnostics was undertaken. These systems diagnose rapid changes in the confined and peripheral plasma's radiated power losses and, when calibrated absolutely, measure one of the plasma's main power exhaust mechanism to be compared with the total power input. These are complemented by high spectral resolution multi-spectral chords that analyse specifically selected atomic line transitions and visible light continuum intensities that have been briefly described in previous years.

TCV has array of X-ray (diodes, Be foil filtered), AXUV (bare diodes that age erratically) and Bolometers (thin gold-foil thermometers) whose observation cords cover the whole TCV volume, see **Figure 1**. Each detector's performance is governed by a mix of advantages and disadvantages (mostly compromises between spectral response and temporal response) but all have been found useful in diagnosing TCV. Of the 15 toroidal sectors around TCV, each of these systems occupied a complete, and separate, sector.

Whilst scoping out new detectors and electronics to enhance these arrays, it became apparent that, all three systems could be merged into a single sector whilst even increasing the number of chords of each system. A detailed view of these combined camera systems can be seen in **Figure 2**. Furthermore, by modularising the array and entrance slit designs, each system's view-chords through the plasma may be modified. A final problem with Bolometer operation in the presence of high power heating ECH power, extensively used on TCV, will be palliated by inserting conducting metal grids at the entrance slit positions. This may, for the first time on TCV, allow bolometers (that are, by nature, absolutely calibrated) be available for strongly EC heated experiments.

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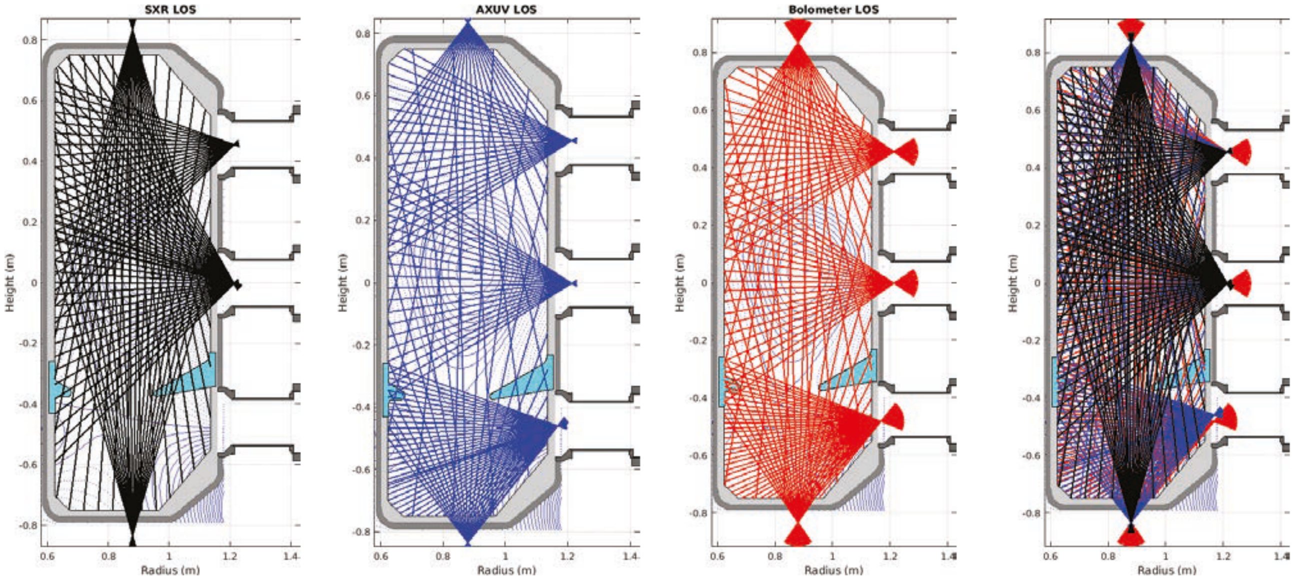

Soft X-ray chords | AXUV chords | Bolometer chords | All together

1 Line of sights of three diagnostics in the TCV tokamak (Soft X-ray, AXUV and bolometer), as well as the superposition of all three together.

2 Detailed view of one the combined camera systems. Left: view from plasma side without entrance slits showing the three detector arrays. Right: Modular detector arrays (diodes on both sides, bolometers in the middle) and backplate with electrical connections (shown underneath).

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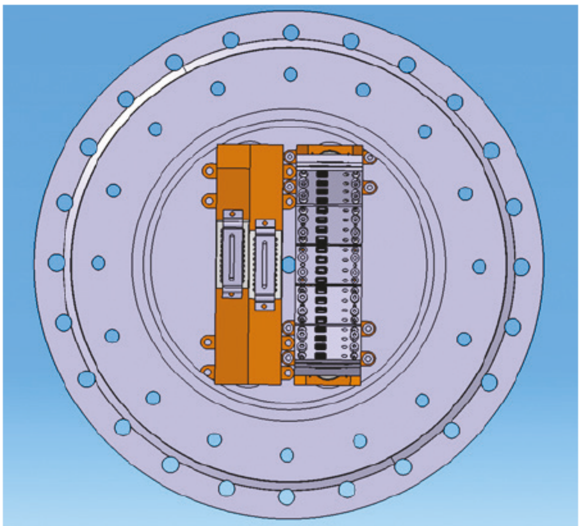
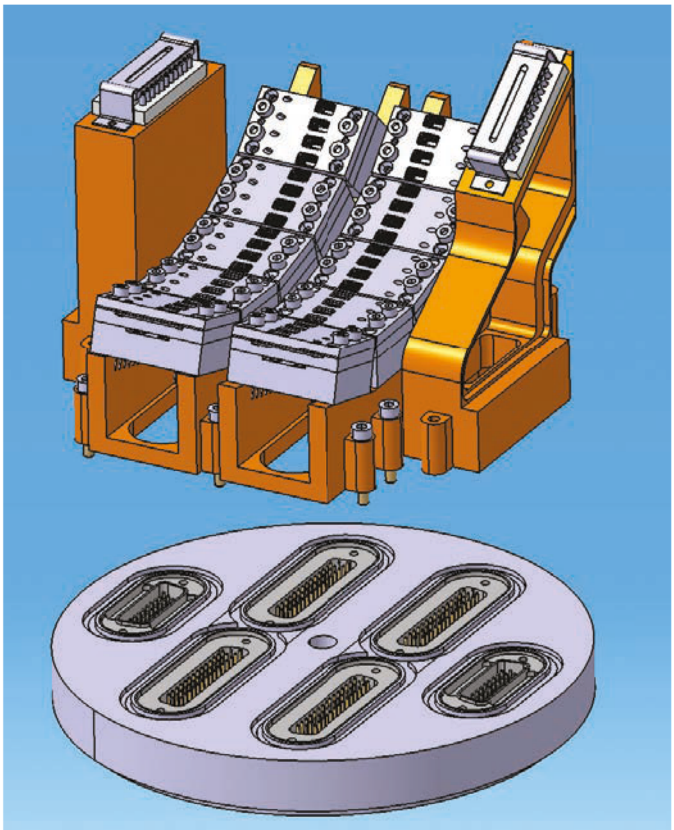




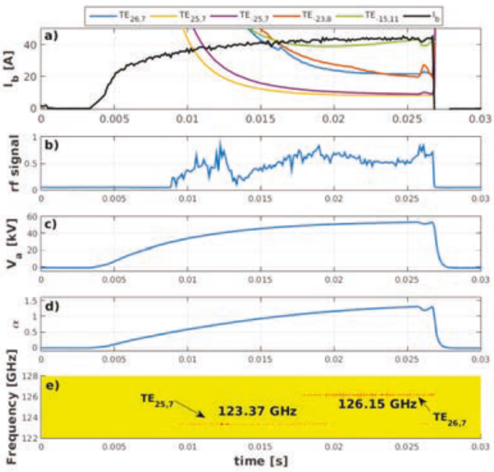
TCV Heating

In addition to the so-called Ohmic heating due to the presence of the plasma current, two auxiliary plasma heating schemes are used in TCV: the injection of neutral high-energy particle beams and of high-power mm-waves at the electron cyclotron waves (ECW) frequency. These heating schemes are complementary, since the former primarily interacts with the plasma ions and the latter with the electrons, hence allowing the independent control of the two species temperature which is of paramount importance in a future fusion reactor such as ITER and DEMO. Dr **STEFANO ALBERTI**, MER, is the leader of the TCV Heating research line and exposes below what were the main achievements in 2018.

Within the ongoing upgrade of the TCV ECW-system, the first dual-frequency MW-class gyrotron (84 or 126GHz/1MW/2s) has been delivered and partially integrated into the existing ECW-system. The gyrotron design is the result of a collaborative effort between SPC and Karlsruhe Institute of Technology and its manufacturing is made by Thales. All commissioning steps performed at SPC, from short-pulse (≤20ms, **Figure 1**) to long-pulse operation (≥500ms) have been accomplished without facing any issues and the gyrotron optimization was essentially guided by extensively using the numerical modelling tools developed at SPC. In long-pulse operation (>0.5s) stable mono-mode operation was reached and the generated rf power is well in excess of 1MW at the two frequencies with corresponding electronic efficiency higher than 35%, fully in agreement with the theoretical prediction.

This is a very remarkable result since a one-step development strategy was adopted (no prototype development). It is also an excellent sign for the qualification of the modelling and industrial tools developed in the EU over several decades.

The pulse length extension to 2s is ongoing. Based on these results, the 2nd gyrotron will be identical to the 1st gyrotron and its delivery is foreseen in the current of June 2019. The upgraded ECW-system will be operational for plasma experiments by the end of 2019.



1 Test set-up of the dual frequency gyrotron on the left. On the right, short-pulse results (≤20ms, during the start-up phase) obtained at the higher gyrotron operation frequency, 126GHz. The time traces show the evolution of different parameters during the start-up: a) electron beam-current, b) rf-signal, c) anode voltage, d) pitch angle, e) measured frequency spectrum evolution with the nominal mode being the TE26,7 mode at 126.15GHz. The sequence of mode excitation shown in e) is very well predicted by the code TWANGlinspec (see next page) shown by the calculated starting current curves indicated by the colored curves in a). This is an additional validation of the modeling tools developed at SPC.

PARASITIC OSCILLATIONS IN GYROTRON BEAM-DUCTS

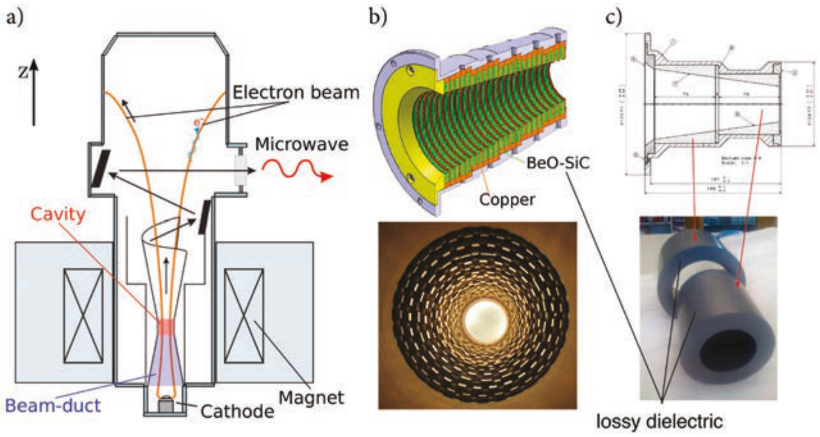
Research carried out by **JÉRÉMY GENOUD**, PhD student at SPC under the supervision of Dr. Stefano Alberti, MER, aimed at developing a self-consistent numerical model for studying parasitic instabilities potentially occurring in high-power megawatt gyrotrons.

In a gyrotron, the parasitic oscillations, can be excited by the intense magnetized electron beam in a region, called beam-duct (shown in **Figure 2**), located before the extraction cavity where the kinetic energy of the electron beam is very efficiently converted in high-power electromagnetic waves via the cyclotron maser instability. The efficiency of the interaction strongly depends on the electron beam quality at the cavity entrance which, in the ideal case, is considered to be mono-energetic and mono-velocity. In case an instability develops before the cavity (in the beam-duct for example), the electron beam distribution function deviates from the mono-energetic distribution, causing a very significant decrease in interaction efficiency.

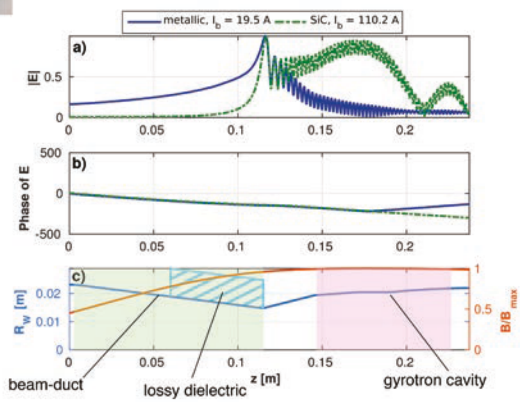
In present day high-power gyrotrons, a variety of beam-ducts have been partially successfully implemented for suppressing parasitic oscillations. However, due to the very complex beam-duct geometry **(Figure 2b)** and the strong non-homogeneity of the system parameters, no self-consistent model was available so far for systematic parasitic oscillation studies.

For the extended interaction space, which includes the *beam-duct & cavity*, several hundreds of parasitic modes need to be considered. For a given set of system parameters and considering a single $TE_{m,n}$ mode, the excitation of this given mode is characterized by the *starting current* which is defined as the threshold in the electron beam current above which the parasitic mode is excited.

Thanks to the development of a novel self-consistent model (TWANGlinspec code, also used in **Figure 1**) based on a minimal number of assumptions, it has been demonstrated that by properly placing a lossy dielectric layer, in a *smooth-wall beam duct* **(Figures 2c and 3c)** and for an electron beam without initial velocity spread, nearly all potential parasitic modes have their starting current above the nominal gyrotron beam current. For the remaining modes, it has been shown that an initial velocity spread further significantly increases the starting currents of the parasitic modes above the gyrotron operating current, hence no excitation of parasitic oscillations. The experimental validation of the models will be made in the near future.



2 On the left, a), schematic of a high-power gyrotron with highlighted the beam-duct in which parasitic oscillations might be excited. On the right, different types of beam-duct geometries presently used for suppressing parasitic oscillations in high-power gyrotrons. The beam-duct geometry in c) satisfies the smooth-wall approximation.



3 a) and b) amplitude and phase of the $TE_{19,3}$ mode electric field profile for the case with a 10mm dielectric SiC layer (dashed green line) and with a fully metallic boundary condition (continuous blue line). c) Wall radius: in blue a metallic wall with indicated the position of the lossy dielectric layer. The normalized magnetic field profile is shown in red. For the considered mode and assuming no initial velocity spread, the starting current with a dielectric layer (I_{start}=110A) is increased by more than a factor of five compared to the full metal beam-duct (I_{start}=19.5A). The nominal electron beam current is I_b = 40A.

TCV Boundary

The TCV Boundary Group is led by Prof. CHRISTIAN THEILER. He explains us below what the main objectives of his group are, and what the notable achievements in 2018 were.

The tokamak boundary plasma plays a crucial role for the successful operation of a fusion reactor. On the one hand, it has to ensure adequate confinement of the superhot plasma core, 100 million °C, and, on the other hand, avoid damaging the surrounding wall structures. By leveraging TCV's unique magnetic shaping capabilities and excellent diagnostics accessibility, the Boundary Group works on advancing the fundamental understanding of the complex, turbulent boundary plasma and developing improved solutions for a reactor.

Ideally, one would like to have a cold plasma near the wall and reduced plasma-wall contact, thus 'detaching' the periphery from the hot plasma core. Increased transport across magnetic field lines, high density, and the controlled addition of impurity species such as nitrogen all help accessing this detached regime of operation. Unfortunately, there is a fine line between efficient protection of the wall by a detached plasma and adverse effects on the fusion core performance. Over the past few years, it has become ever clearer that alternative magnetic geometries of the boundary plasma have a large potential to address these critical issues.

In 2018, two new diagnostics for the boundary plasma have been commissioned on TCV, providing key measurements of turbulence and time-averaged quantities for an extended diagnostic coverage and in particular for more stringent model validations. The first new tool is Gas Puff Imaging (GPI), which visualizes plasma turbulence in a two-dimensional region near the confined plasma with 4mm spatial and 0.5 microsecond temporal resolution. A sequence of GPI frames, revealing the formation and propagation of a turbulent plasma structure, is shown in **Figure 1**. The other new diagnostic is the Reciprocating Divertor Probe Array (RDPA), probing the boundary plasma closer to the machine wall, as discussed in the highlight on the following page. In addition, in 2018, the number of wall-embedded Langmuir probes has been nearly doubled, providing key measurements of plasma parameters right at the wall for almost any magnetic geometry in TCV.

An emphasis in the experimental campaigns has been put on detachment studies using nitrogen impurity seeding, extending the previous focus on detachment via density ramps. A detailed study in low confinement (L-mode) plasmas highlighted similarities and differences in the turbulence dynamics between the two methods and quantified the level of achieved radiation levels and heat flux mitigation. Similar studies in more reactor-relevant high confinement (H-mode) conditions have also significantly progressed in 2018. For the first time on TCV, a partly detached plasma was achieved during ELMy H-mode operation. These studies have been extended to different magnetic geometries, including so-called X- and Super-X divertors, revealing no significant effects on H-mode access conditions and modest changes in terms of detachment characteristics. Recent simulations suggest that the true benefits of alternative magnetic geometries will only become effective once the TCV divertor neutral baffles are in place. The performance of these baffles, which will substantially increase the reactor relevance of the TCV boundary plasma, has been simulated with two complementary edge transport codes. These simulations in particular predict higher levels of volume recombination of the plasma near the floor in the presence of baffles, **Figure 2**. These and other predictions will be confronted with first baffled experiments in 2019.

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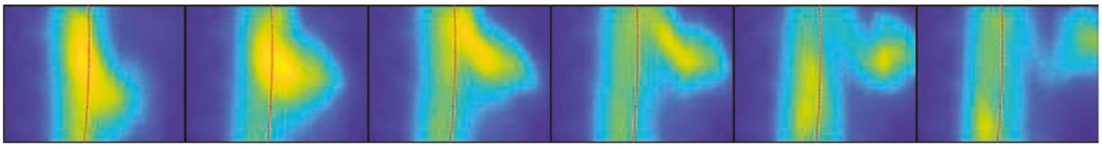

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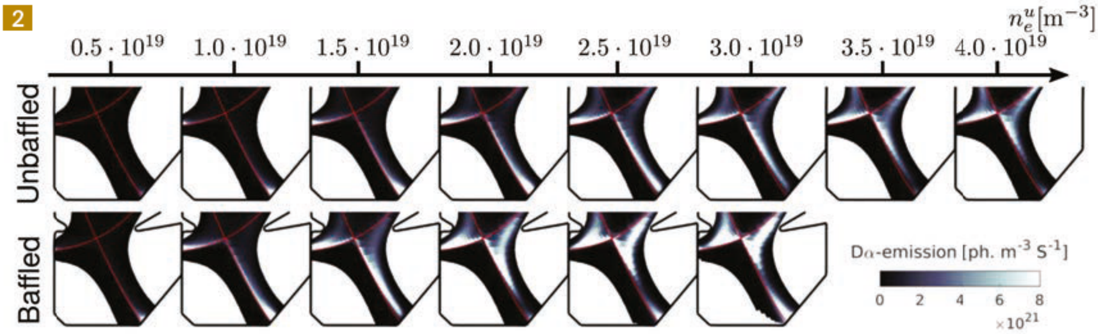


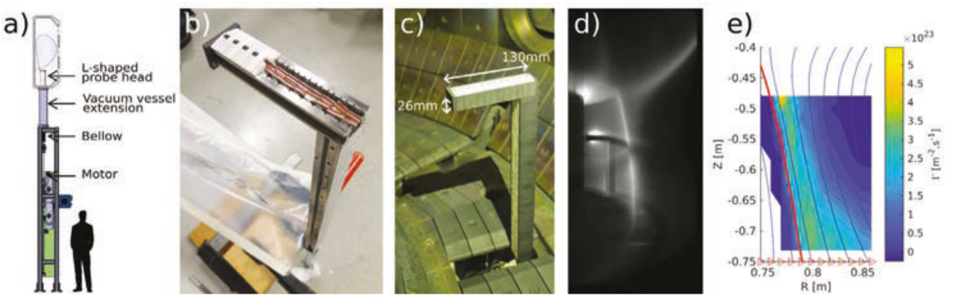
1 **Sequence of Gas Puff Imaging frames, showing the formation and subsequent propagation of a turbulent structure, called "blob", in the TCV boundary plasma. The red line represents the outermost boundary of the confined plasma.**

2 **Numerical simulations of a TCV plasma with and without the new divertor baffles, using the SOLPS-ITER code. Shown here is the D_α light emission (an experimentally easy to measure quantity) predicted by the code for different plasma densities indicated on top. The high emission near the floor in the baffled case and at high density is the result of high levels of plasma recombination.**

A NEW PROBE AIMING AT THE DIVERTOR OF TCV

In December 2016, **HUGO DE OLIVEIRA** accepted an ambitious PhD thesis subject under the supervision of Prof. Christian Theiler: to design, build and operate a fast-moving probe in order to scan an extended, two-dimensional region in the TCV divertor plasma and obtain unprecedented insight into this plasma region. This new tool would become the Reciprocating Divertor Probe Array (RDPA) diagnostic, shown in **Figure 3**.

After two years of design, drawing, assembling and testing activities, in December 2018 the diagnostic made its first measurement in the plasma. Fifteen successful discharges were obtained in the very last day before the Christmas holidays and the probe stayed 10s in total in the plasma. The Langmuir probe measurements were reliable and plasma profiles could be successfully reconstructed. The RDPA plays a specific role among other edge diagnostics by providing in situ measurements of time-averaged (temperature, density, plasma potential) and fluctuating (saturation current, floating potential, particle flux) quantities. The diagnostic is now ready for the upcoming experiments, in particular for an international code validation project and the baffled experimental campaign.



3 **a) Drawing of the diagnostic structure mounted on the TCV basement floor. b) Assembly phase. c) RDPA at the highest position in the torus. d) D4->2 light emission snapshot recorded with the MANTIS camera system during a discharge. e) 2D profile of the particle flux density Γ measured with the RDPA across the divertor region.**

Theory and Numerical Simulation

Prof. PAOLO RICCI is heading the Theory and Numerical Simulation group at SPC. The main activities of the group and main achievements in 2018 are exposed below.

The main goal of the theory group at SPC is to make progress in the first-principle understanding of the plasma dynamics in magnetic confinement devices for fusion. This understanding is necessary to provide an interpretation of the experimental results coming from current fusion experiments, and to make predictions for future experiments while leading their development. Since the equations governing the plasma dynamics are generally too complex to be solved analytically, we heavily rely on numerical simulations and the SPC theory group makes use of some of the most advanced High-Performance Computers worldwide.

In 2018 the activities of the SPC theory group have focused on the global plasma equilibrium and stability in tokamaks and 3D magnetic configurations, exploring their interaction with fast particles and impurities. Studies the simulation and analysis of plasma turbulence in the tokamak core and periphery were pursued. Activities on real-time simulations and predictions, pioneered by the SPC, continued.

The SPC theoretical activities are well embedded in the European theory and simulation effort, through strong collaborations with other research institutes and the participation to a number of EUROFusion Enabling Research and Code Development projects. In addition, the theory group maintains very close ties with the experimental groups, in particular at the SPC. Work on the development of new TCV scenarios and the interpretation of simulation results constitutes one of our continuous activities. For example, in 2018 an I-mode scenario for TCV has been developed at the maximum allowed magnetic field, discriminating the effect of improved confinement due to a transition to a different regime from the effect of improved absorption of EC heating.

GLOBAL PLASMA EQUILIBRIUM AND STABILITY

Understanding and controlling the global plasma equilibrium and stability is of the utmost importance on the way to fusion energy. Following up our investigations on global plasma equilibrium and stability, we have developed a novel analytic expression for the effect of the plasma shaping, in particular triangularity, on global geodesic acoustic modes, a mode associated with the plasma rotation and supported by plasma compressibility. We showed that our theoretical findings agrees with observations in TCV. In addition to these modes, we have recently isolated the effect of parallel magnetic field fluctuations on pressure driven plasma instabilities so that the limitations of typical assumptions used in gyrokinetic codes can be identified.

Our effort in the analysis of three-dimensional configurations continued. We opened a new research avenue at the SPC, focused on the calculation of stellarator magnetic equilibria by using the free-boundary version of the Stepped-Pressure Equilibrium Code (SPEC) code. Its solutions have been rigorously verified for stellarator vacuum fields with regions of islands and stochastic field-lines **(Figure 1)**. Also, it has been shown that SPEC can be used to retrieve exactly the tearing stability criterion in force-free plasmas. By leveraging our expertise in three-dimensional configurations, in particular a code ordinarily used for free boundary ideal MHD equilibrium calculations in stellarators, we were able to model edge harmonic oscillations associated with important ELM-free H-mode plasma scenarios. This three-dimensional equilibrium approach has been verified with analytic solutions to current driven and pressure driven external instabilities.

Finally, advances have been made into impurity ion transport modelling in tokamak plasmas under the influence of saturated non-linear MHD instabilities and poloidal and toroidal plasma flows.

TURBULENCE

Turbulence is the main reason for which transport of heat, particles and momentum across the magnetic field is much higher than that due to collisional processes alone. It generally results in a detrimental degradation of the quality of the confinement in the core and, in the periphery, a beneficial spreading of the heat flux on the vessel walls. Because of the different properties of the plasma and in particular the level of collisionality, the investigations of turbulence in these two regions have been approached by using different codes and models. To overcome this limitation, a large effort started at the SPC to bridge the two descriptions, and a model valid at arbitrary values of collisionality developed by our group was for the first time applied to the study of basic plasma instabilities, such as the drift waves.

Indeed, the need of a global simulation of turbulence is becoming evident. For example, our studies carried out with the global gyrokinetic code ORB5 have shown that turbulent heat flux in the plasma core is strongly affected by the value of temperature gradients in the pedestal region **(Figure 2)**. This non-local behaviour is characterised by the appearance of avalanche-like structures propagating radially mostly inwards from the pedestal to the core **(Figure 3)**, associated with modulation of outward heat flux, at a frequency that matches very well that observed in the TCV tokamak.

Focusing on the core, the physics behind the suppression of turbulence and transport, due to the presence of strong sheared flows continued. We pointed out that the non-adiabatic passing electron response leads to reduced levels of sheared flows and associated shearing of turbulence and thus to increased transport levels. In addition, a new algorithm for modeling background shear flows in the commonly used flux-tube approximation has been implemented and tested. This new scheme corrects a flaw in the standard algorithm that has been implemented in most gyrokinetic flux-tube codes, which leads to a non-physical smearing of non-linear mode coupling and has significant effects in turbulence simulations. The corrected algorithm is thus based on a continuous remap approach that avoids any unphysical nonlinear couplings.

REAL TIME CONTROL

Our simulation capabilities were developed with the objective to provide better integrated physics information for real-time control and for the benefit of the analysis of TCV shots. More precisely, the automatic suite of analysis codes that we use for the analysis of TCV shots, in particular the coupling of transport equations with equilibrium reconstruction, has been improved to provide self-consistent reconstructed magnetic equilibria and plasma profiles with driven and bootstrap current densities. As a consequence, we now obtain routinely, for example, the correct profiles of the most important plasma quantities and the ray-tracing Electron Cyclotron results from the Toray-GA code. The advanced model that are now used in RAPTOR, the simulation code developed at SPC for real-time control and now used in many European devices, has been benchmarked in the ramp-down studies within an international effort under the ITPA group. The successful benchmark gives confidence in our general effort to provide faster than real-time prediction of the discharge evolution in order to avoid disruptions. We have also developed a new strategy for integrated control in order to better act on detected or predicted events, and on a failure of a diagnostic or actuator. Our real-time control algorithms are becoming tokamak independent and have physics-based inputs and outputs. This is important for long pulse control and to test same controllers in different tokamaks.

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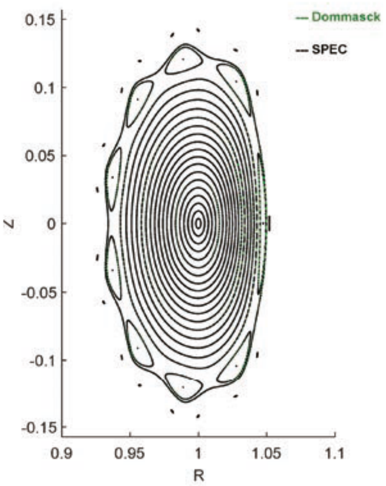

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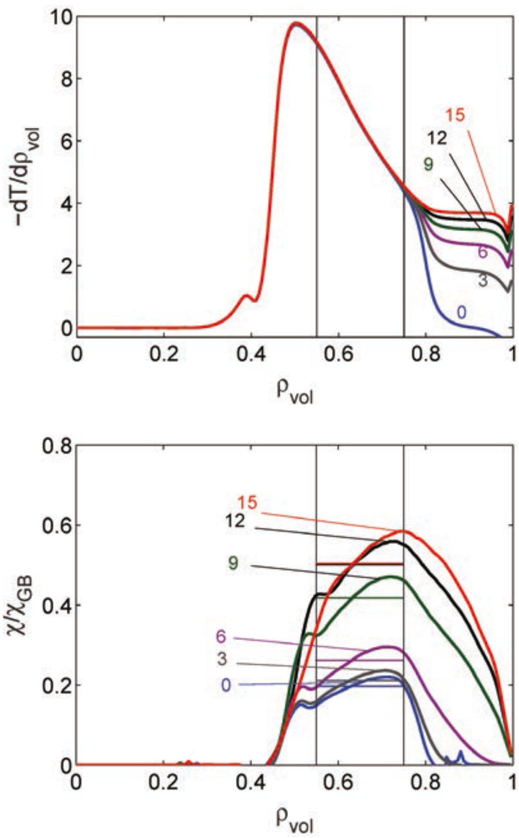
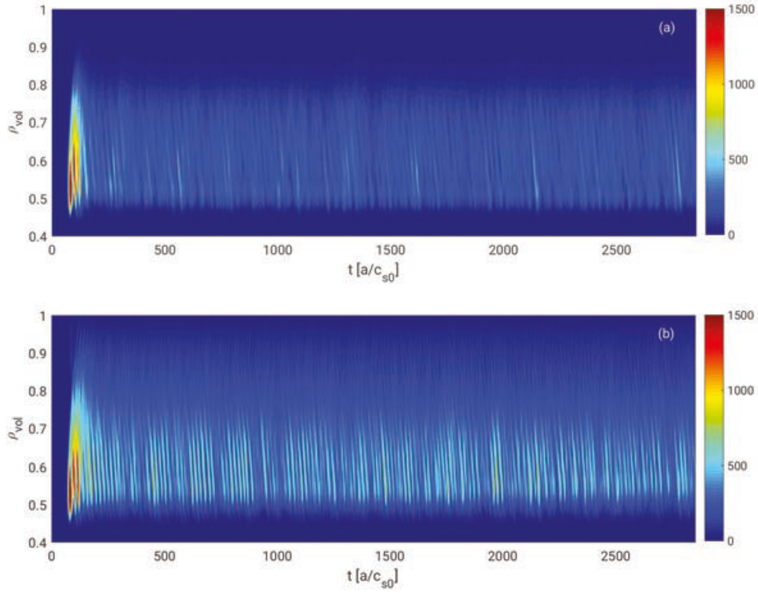


1 Poincaré cross-section of a 3D magnetic equilibrium with island chains computed with the newly developed SPEC code. The numerical solution almost perfectly matches the analytical solution (Dommasck).

2 For different temperature gradients in the pedestal (top), heat transport (bottom) is modified not only in the pedestal but also in the core.



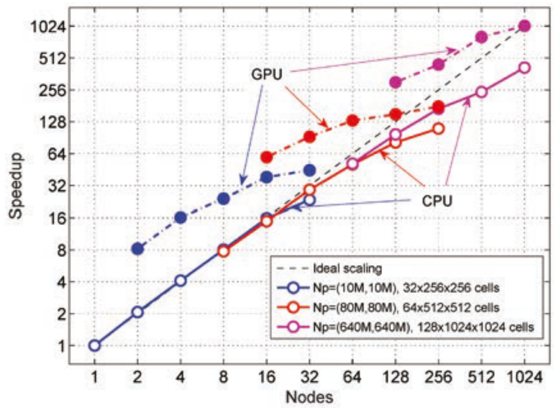
3 Contours of turbulent heat flux versus radius and time. The top case (a) and the bottom case (b) have identical temperature profiles in the core (for rho_vol<0.8), but lower temperature gradient in the pedestal (for rho_vol>0.8) in case (a) than in case (b). Heat transport in the core can be modified by the gradients in the pedestal, through the propagation of avalanches (oblique features) from the pedestal to the core.

BOOSTING A TURBULENCE SIMULATION CODE PERFORMANCE ON GPUS

NOÉ OHANA and **EMMANUEL LANTI**, PhD students supervised by Dr Stephan Brunner and Prof. Laurent Villard, have achieved a major milestone in 2018 with the complete refactoring of the ORB5 code, combining the functionalities of several code versions originally distributed on different versions into a single code base, while at the same time introducing hybrid parallel programming, boosting the code performance.

First-principle based approaches of plasma simulation such as gyrokinetic theory require massive amounts of computing resources. Indeed, our codes typically run on some of the most powerful HPC platforms in the world, such as the Piz Daint at the Swiss National Supercomputing Centre (CSCS). This supercomputer is built with hybrid architecture, consisting of thousands of compute nodes, each equipped with a conventional CPU and a GPU (Graphics Processing Unit) accelerator. Using the power of the GPU has required a complete refactoring of the ORB5 code which, incidentally, has also benefited the code when run on CPUs only. This effort was completed in 2018, with the successful porting of the code to GPUs. The code executes about 4 times faster when using the GPUs than when not using it. Its parallel scalability has been measured (see **Figure 4**). The typical operating point for our scientific production runs makes use of 4 times less nodes and still executes 1.5 times faster, meaning a reduction in resource consumption (i.e. the amount of node-hours to get to a solution) by a factor of 6.

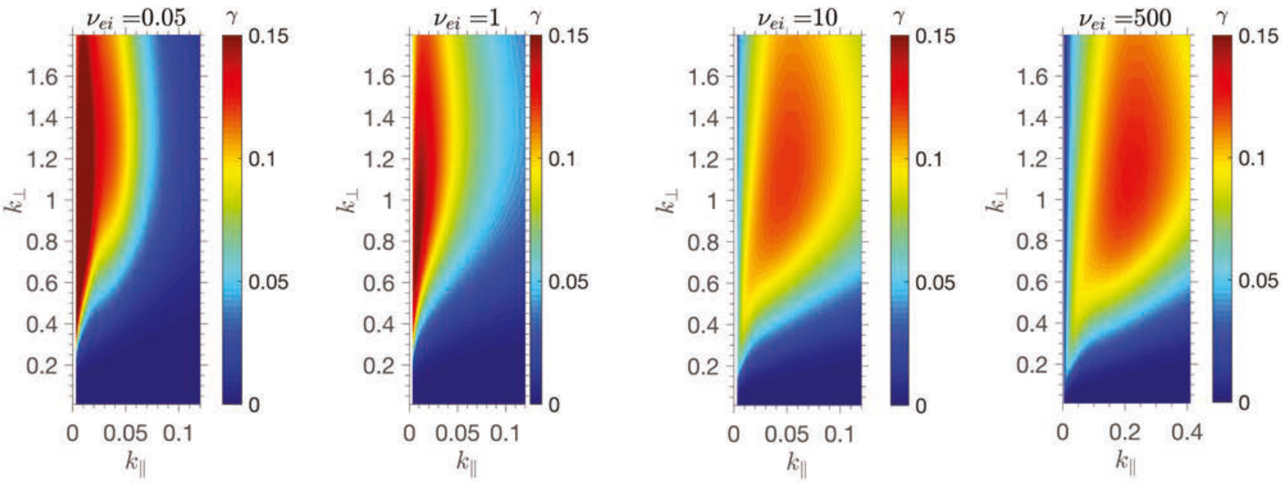
4 Speedup of the ORB5 code on the Piz Daint GPU-equipped partition, relative to the single node, CPU-only case.



MAGNETIZED PLASMA INSTABILITIES CAN NOW BE STUDIED AT ARBITRARY COLLISIONALITIES

The inclusion of the effect of collisions occurring among plasma particles in the description of magnetized plasma has proven to be extremely challenging and has remained an open issue for decades. While models have been developed to study efficiently plasmas either in the high collisionality regime or in the absence of collisions, the intermediate collisionality regime could not be properly approached and simplistic assumptions are often used, with no possibility to compare them against more accurate models. It turns out that an intermediate collisionality is the regime of interest in the edge region of fusion devices, where some of the most crucial phenomena that regulate the performances of a tokamak take place. Ultimately, this undermines our predictive capabilities of future fusion devices. In 2018, **ROGÉRIO JORGE**, Ph.D. student jointly supervised by Prof. Paolo Ricci at the SPC and Prof. Nuno Lourerio at MIT, developed a novel model of plasma dynamics directly derived from the theory of Coulomb collisions, which was shown to be both accurate and numerically efficient.

This work was published in *Physical Review Letters*, with a particular focus on the drift-wave instability (also called universal instability) (see **Figure 5**). The drift-wave instability plays an important role not only in magnetic fusion devices, but also in astrophysical, space, and dusty plasmas. Rogerio's work has shown that previously used simplifying assumptions to describe particle collisions can provide a misleading picture of the plasma dynamics, i.e. different from what Coulomb collisions actually dictate. While questioning our current basic understanding of plasma turbulence, Rogerio's model may lead to important progress in the evaluation of the level of turbulent transport in fusion devices.



5 Growth rate of the drift wave instability γ obtained from the newly developed model at the Swiss Plasma Center, as a function of the parallel ($k_\parallel$) and perpendicular ($k_\perp$) wavenumbers, for four different regimes of increasing collisionality (from left to right).

Basic Plasma Physics and Applications

Led by Prof. **IVO FURNO**, the activities of the Basic Plasma Physics and Applications group are focused on two topics: first, turbulence in magnetized plasmas is studied on the TORoidal Plasma EXperiment (TORPEX) device; second, the physics of helicon waves and helicon-generated plasmas is investigated in the Resonant Antenna Ion Device (RAID) device. Combining a full set of plasma diagnostics together with theory and numerical modeling we advance the basic understanding of the underlying plasma phenomena to a level where quantitative comparison between theory and experiments are possible.

FAST IONS ON TORPEX

Transport of fast ions has been an important subject of study in TORPEX due to its relevance for fusion plasmas, astrophysics and other fields of physics. In our experiments, we inject a beam of lithium ions into a turbulent, low temperature, hydrogen plasma. We let the ions propagate and we then detect them using a small gridded energy analyzer which outputs a current measuring the number of lithium ions per unit time arriving at the detector. Early studies focused on the time average of the detection signal and lead to important results, most notably the observation of different transport regimes depending on the energy and propagation distance of the lithium ions. More recently, improved detection electronics have allowed us to study the time variation of the detected current. We have developed a theoretical model that establishes a relationship between the time average and higher order moments of time variation of the current, such as the variance and skewness. We have seen that intermittence, as measured with the skewness, is not exclusive to any particular transport regime but can be observed in diffusive, subdiffusive and superdiffusive situations. The model has been applied to particle tracer simulations and has been seen to give a correct description of the detection currents. The next step is to evaluate the compatibility of the model with an extensive set of experimental data.

FLUORESCENT PROBE IN TORPEX

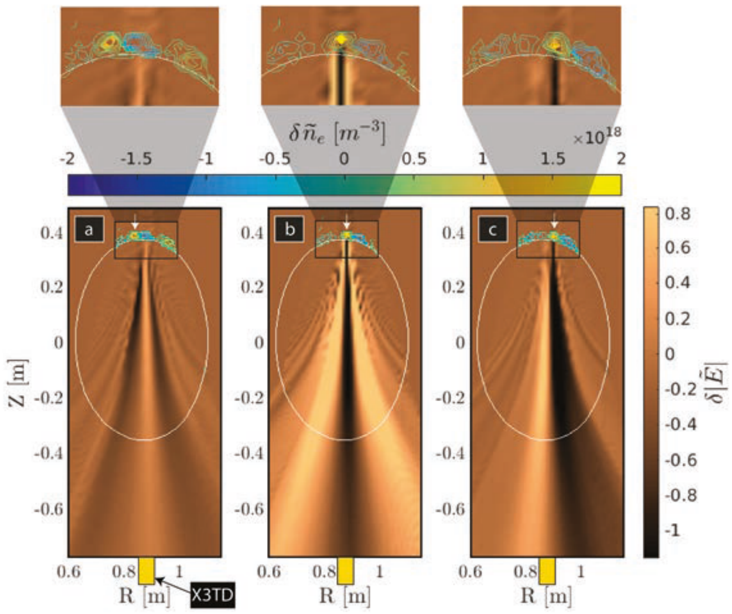
Pursuing ways of increasing the spatial resolution of the TORPEX plasma diagnostics, we continued our work in imaging with a cathode-luminescent coating. We use a fast camera to image the light produced by the coated surface when struck by plasma electrons. With the addition of a light intensifier, we can acquire images at up to 100'000 frames per second, which has allowed us to track blobs and individual plasma structures. A main focus of our work has been the development of image analysis routines, which now enable us to study structure propagation properties and the evolution of shape over time. The routines work in conjunction with data from other diagnostics, notably the dual 2D Langmuir probe array.

BLOB DYNAMICS IN ADVANCED MAGNETIC GEOMETRIES

Exploration of blob dynamics in complex magnetic geometries has started in 2018. The first scenarios explored include the presence of an X-point, which allows us to investigate turbulence of relevance for magnetic fusion geometries. First measurements with multiple arrays of Langmuir probes reveals spatial regions with substantially different statistical properties of the turbulent fluctuations associated with blobs. An extensive numerical simulation programme, involving the major state-of-the-art SOL turbulence codes available in fusion research in Europe has started to understand the observed blob dynamics in TORPEX and at the same time to leverage the experimental data for code validation.

TURBULENT SCATTERING OF MICROWAVE BEAMS ON TORPEX AND TCV

Understanding the effect of edge plasma turbulence on high-power millimeter-waves (mmw) beams at the electron cyclotron range of frequencies in future fusion devices, such as ITER, is of major importance to guarantee their intended use. Leveraging previous experiments on the TORPEX device, a joint international effort was undertaken using state-of-the-art numerical codes and experiments to model the propagation of millimeter-waves in the turbulent plasmas of the Tokamak a Configuration Variable (TCV). Using a set of well-embedded Langmuir probes, filaments of locally-enhanced electron density located in the upper part of the turbulent plasma periphery are found to be responsible for time-dependent fluctuation of the transmitted beam power. Numerical simulations in good agreement with the experiments reveal that the filaments defocus the mmw-beam. In TCV the turbulence located at the edge of the plasma is identified to be responsible for a broadening of the mmw-beam of about 50% (see **Figure 1**), supporting previously raised concerns about beam broadening in ITER and associated core confinement degradation. The result of this study is laying the foundations of validated modelling of wave propagation in fusion plasmas to reach predicting capabilities for ITER.



1 Microwave beam injected into the simulated turbulent field in TCV geometry, Snapshots taken at times (a), (b) and (c), around the passage of a blob (arrows in insets, zoomed on top) on the path of the beam. The elliptic white curve is the main TCV plasma boundary (last closed flux surface).

INDUSTRIAL PLASMAS

The Basic Plasma Physics and Applications group continues to develop new applications of low temperature plasmas in many different fields by advancing in parallel of with their fundamental physics understanding.

INCREASING THE LIFE-TIME OF SATELLITE COMPONENTS

Direct current (DC) gas breakdown was experimentally investigated for high-voltage circular conductors and insulators that reproduce the main features of a satellite slip ring. The measured breakdown curves show clear similarities with Paschen's curve, which is generally associated with parallel plate electrodes. We demonstrated that the low-pressure branch of the measured curves is determined by breakdown between the high-voltage ring and the grounded vacuum chamber, whereas the high-pressure branch is due to discharges between the high-voltage ring and the adjacent grounded rings. A technical solution is introduced to inhibit the gas discharges at low-pressures in a slip ring assembly: The diameter of the grounded conducting discs is extended, strongly increasing the measured breakdown voltages by modifying the electric field distribution. The safe operating pressure range of the satellite slip ring is thereby increased by two orders of magnitude.

SOCIETAL APPLICATIONS OF NON-THERMAL PLASMAS

Non-thermal plasmas are non-equilibrium ionized gases that can be used for biological applications such as food decontamination, plasma medicine, environmental remediation and, plasma agriculture, a rapidly emerging field. Non-thermal plasmas can maintain temperatures as low as room temperature and therefore, be used to treat heat-sensitive biological substrates like seeds and plants. When dosed adequately, plasma treatment is considered to be a timely, economical and environmentally friendly method that has been reported to improve germination and growth, increase disease resistance, decrease microbial contamination and reduce water consumption. In 2018, we continued equipping the bio-plasmas laboratory, which will explore the huge potential of non-thermal plasmas in a variety of societal applications. Two projects, which started in 2017, have been continued: plasma agriculture in collaboration with UNIL and the development of a new plasma-based sterilization method within an InnoSuisse project and in collaboration with Felco, the Ecole d'Ingénieurs de Changins and HES-Yverdon.

NEW LANGMUIR PROBE THEORY

Motivated by practical difficulties in interpreting experimental probe data, we have developed a new theory, which provides solutions for the classical one-dimensional (1D radial and Cartesian) problem of Langmuir probes in a collisionless, isothermal plasma. In contrast to commonly used approximations, electron inertia and ion temperature are not neglected, so that the fluid equations are symmetric in terms of electrons and ions. The single radial solution applies continuously over the whole region from the probe up to the unperturbed plasma, in contrast to theories which separate the probe boundary region into a charged sheath and a quasi-neutral pre-sheath, and is valid for all values of probe bias potential. Current-voltage characteristics are computed for cylindrical and spherical probes, which exhibit non-saturation of the ion and electron currents.

A RAID ON NEGATIVE IONS

RICCARDO AGNELLO, PhD student at SPC, supervised by Prof. Ivo Furno and Dr Alan Howling, works on the Resonant Antenna Ion Device (RAID), a prototype of negative ion source for future neutral beam injectors (NBIs) for fusion plasmas. The schematic of RAID can be seen in **Figure 2**, and a typical plasma produced in **Figure 3**.

Helicon plasma sources are currently investigated as a way to produce the negative ions for the next generation of NBIs due to less power consumption compared to Inductively Coupled plasma (ICP) sources, the operation at low pressures (<0.3 Pa) reducing the negative ion losses by electron stripping, and the considerable amount of negative ions produced in the plasma volume. Overall, the use of helicon sources could increase the efficiency of DEMO generation of fusion power plants.

An important milestone result in RAID is the first application of Cavity Ring-Down Spectroscopy (CRDS) in a helicon plasma source to measure negative hydrogen and deuterium ions (H^- and D^-). The design of the diagnostic was developed in collaboration with Consorzio RFX, Italy, and the tests on RAID showed the production of negative ions in a Cs-free source. CRDS is routinely employed in fusion machines but the technical implementation on such a compact source like RAID was a challenge. The promising results of CRDS have been published on Review of Scientific Instrument and recognized as "Editor's pick".

In the framework of a collaboration with the Laboratory of Subatomic Physics & Cosmology of Université Grenoble-Alpes, the Langmuir Probe photodetachment diagnostic was implemented in RAID. By combining this technique with CRDS it was possible to determine that H^- and D^- are concentrated in a shell like shape, see Figure 3. These results are the first steps towards the realization of a negative ion extractor. Numerical simulations have been initiated to support experimental results and predict the behavior of the source at higher powers.

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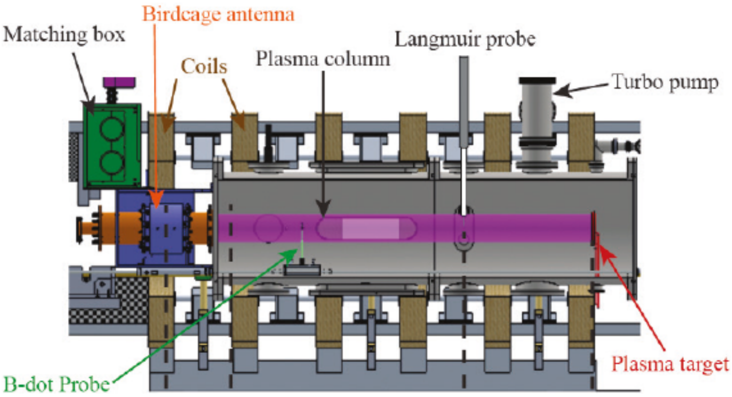

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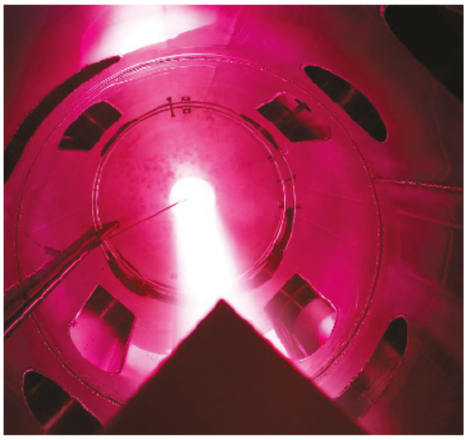

2 Schematic of RAID, a prototype negative ion source for future Neutral Beam Injectors.

3 Hydrogen steady state plasma discharge in RAID vacuum vessel.

4 Radial profile of negative ions of hydrogen (left) and deuterium (right) measured by combining Cavity Ring-Down Spectroscopy and Langmuir Probe photodetachment.

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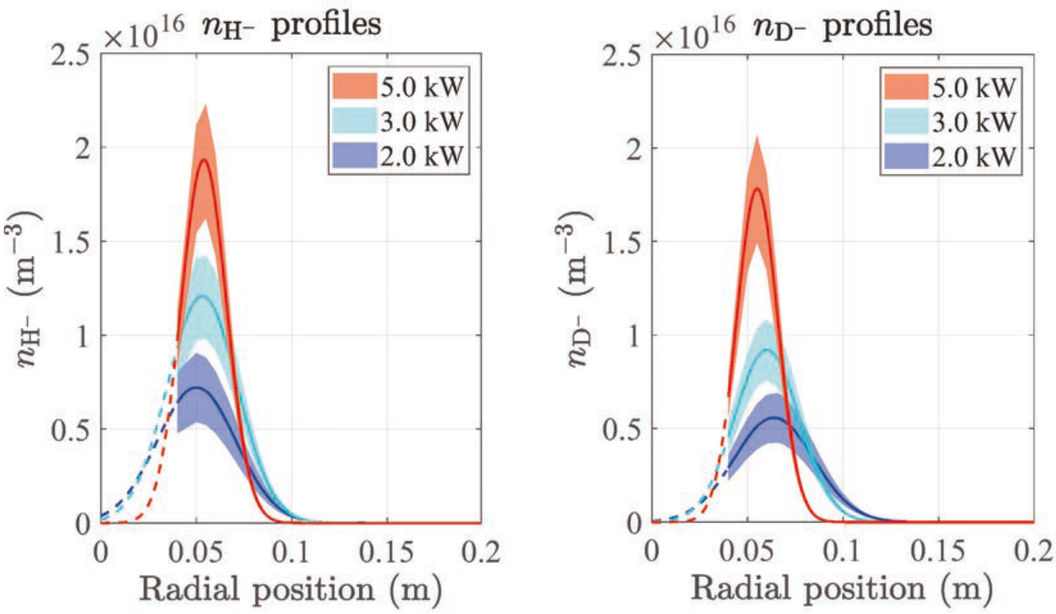
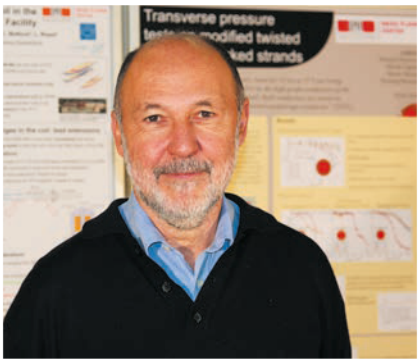


Applied Superconductivity



Based on the site of the Paul Scherrer Institute in Villigen, the activities of the superconductivity group, led by Dr **PIERLUIGI BRUZZONE**, are focused on design studies, R&D and testing for magnet technology. Both Low Temperature and High-Temperature Superconductors (LTS and HTS) are investigated, with a primary focus on future fusion devices. The main experimental tool is the SULTAN test facility, a unique equipment that allows SPC experts to carry out tests of high current superconductor cables and joints, in particular for ITER, EUROfusion DEMO and CERN. Notable achievements in 2018 are described below.

DESIGN AND ANALYSIS OF SUPERCONDUCTING MAGNETS

The mechanical analyses for the Central Solenoid (CS) and Poloidal Field (PF) coils for DEMO have highlighted the strong impact of the number of plasma burn cycles on the design. The fatigue load criteria for structural material call for very large steel cross section in the winding and drastically limit the overall performance of the CS, even when HTS is used. The design of the PF coil systems for DEMO has been updated. The design optimization leads to Niobium-Tin (Nb_3Sn) technology rather than Niobium-Titanium (NbTi).

DEVELOPMENT

The copper for quench protection for the second prototype of DEMO TF conductor based on react&wind Nb_3Sn technology was developed as a large, solid composite of copper and CuNi (mixed matrix), in order to get high conductivity in longitudinal direction and poorer conductivity in transverse direction, reducing the eddy current loss. In collaboration with the industry, the mixed matrix was developed to the required shape and assembled with the last version of the TF prototype conductor.

In the frame of the collaboration with CERN, Nb_3Sn joints have been developed for the inter-grade connections of the accelerator dipoles for the Future Circular Collider project (wind&react technology). Two different approaches have been investigated and proved to be feasible, achieving low resistance, in the range of 0.5-0.8 nΩ in reproducible way.

TESTING ACTIVITIES IN SULTAN

Over 20 weeks of SULTAN operation were used for the tests of ITER TF conductor samples, addressing the degradation rate for all the ITER strand manufacturers. The test procedure starts with partial load (medium field and current) to identify a load threshold at which the degradation starts.

Other tests for ITER in 2018 were carried out for PF and CS joint samples manufactured in industry. The test of the CS co-axial joint, to connect the CS module terminal with a Nb_3Sn lead extension, pointed at a high resistance, in the range of 20 nΩ, increasing with load cycles. The issue is now discussed at top level and SPC is helping with dedicated trials and advanced instrumentation.

For DEMO, the rectangular react&wind TF prototype for baseline 2015, named RW2, was tested in various campaigns with different stabilizers, including the newly developed mixed matrix, and in different field orientations.

The Central Solenoid (CS) and Poloidal Field (PF) coils in a pulsed tokamak are intrinsically subjected to cyclic mechanical loads. ITER will experience 30,000 plasma cycles during its lifetime, and this number is likely to be 100,000 for a fusion power plant. This imposes severe limitations in the design of the CS and PF coils: mechanical fatigue becomes the main driver. In the case of the DEMO CS coil, the radial component of the Lorentz force is a few Giga Newton per module. The design of the winding packs has to ensure that this stress does not cause a small initial defect to grow through the jacket wall, leading to a leak of the helium coolant. For a given material of the jackets (typically a stainless steel alloy), the number of mechanical cycles determines the allowable stress in the jackets, which in turn determines the amount of stainless steel in the coil. The larger the required steel fraction, the lower the overall current density of the coil, limiting the effectiveness of the superconductor.

SUCCESSFUL TESTS OF PROTOTYPE SUPERCONDUCTORS FOR DEMO TF MAGNETS DEVELOPED AT SPC

Dr **KAMIL SEDLAK**, together with Dr Pierluigi Bruzzone, is leading the development of the superconductors for DEMO at SPC. The huge toroidal field (TF) coils of ITER are made of Nb_3Sn, which is a commonly used low-temperature superconducting material if high magnetic field is requested. One peculiarity of Nb_3Sn is its brittleness after heat treatment at 650°C. To cope with the brittleness, ITER TF coils were first wound to their final shape, and then heat-treated. This technology is called wind-and-react (W&R). In the superconductivity group of SPC, we are designing the TF coil for DEMO tokamak. Our design is based on the react-and-wind (R&W) technology. The key factors that allows us to opt for R&W are the big bending radius of the DEMO TF coil together with very flat cable design, so that when the cable is bend, it will not be damaged.

The second peculiarity of Nb_3Sn is the reduction of its critical current when Nb_3Sn is compressed. In W&R technology, the thermal shrinkage of steel conductor jacket from 650°C down to 4.5 K (the magnet operating temperature) brings Nb_3Sn strands into compression, and subsequently reduces its ability to carry electric current, typically by 50%. In the R&W, where the jacket is applied on the cable after the heat treatment, the Nb_3Sn is compressed much less, and less Nb_3Sn material is needed to carry the same electric current compared to a W&R conductor.

Figure 2 shows the cross-section of the R&W conductor designed by SPC for the DEMO TF coil. This is already the second prototype of this kind, called RW2. Three samples of RW2 were tested in the SULTAN test facility, and we were more than encouraged by their performance, which we found ways to improve by tightening the cable inside the steel jacket. Not only did it increase the value of the current-sharing temperature T_{cs} (the temperature at which a conductor stops being fully superconducting), but also the degradation of T_{cs} with the number of operating cycles has become negligible, as can be seen on the graph in **Figure 3**. In the end, the DEMO RW2 conductor has significantly higher T_{cs} temperature (7.6 K) than an ITER TF conductor (around 6 K after 1000 cycles, see figure). The cross-section of Nb_3Sn in DEMO RW2 is only 132 mm², to be compared with 238 mm² in the ITER TF conductor. As the price of large magnets is driven by the price of Nb_3Sn, the material saving is of a great importance for the economic feasibility of a fusion reactor.
In addition, the fact that the steel jacket and the welds do not have to undergo the heat treatment provides additional coil manufacturing simplifications, relieves data quality assurance, and leads to additional savings.

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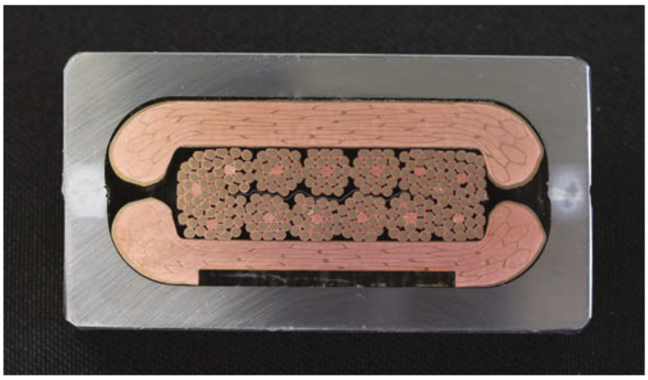

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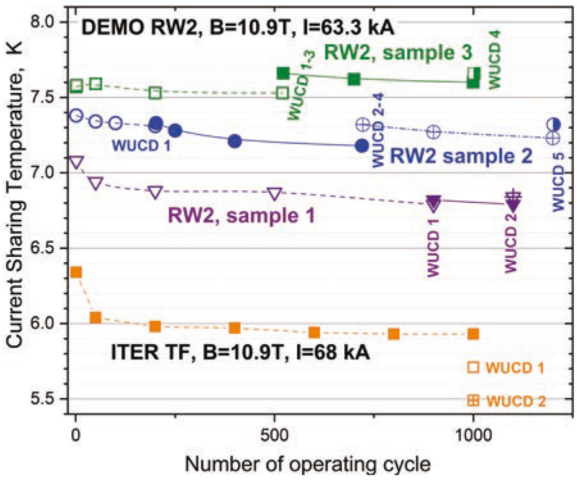


1 Cross-section of the RW2 sample with Nb_3Sn strands (round wires in the center) surrounded by copper-matrix stabilizer and steel jacket providing mechanical stiffness. The voids are filled by coolant, i.e. helium at 4.5 K and 6 bar.

2 Current-sharing temperature T_{cs} (the temperature, at which a conductor stops being fully superconducting), as a function of number of operating cycles. Three RW2 samples, gradually improving from sample 1 to sample 3, are compared to an ITER TF conductor "ITER TF Insert Sample" that has been used in the test of ITER TF sub-sized coil in Japan in 2018. Relatively high T_{cs} of DEMO TF conductors provides high margin for the coil operation

International Activities - ITER

The research activities at SPC are mostly conducted in the frame of collaborations at the European level and also worldwide, in particular ITER, for which SPC efforts, led by Dr TIMOTHY GOODMAN, are devoted to two main areas, namely the field of high power microwaves and the testing of superconductors, the latter being reported in the section on Superconductivity.

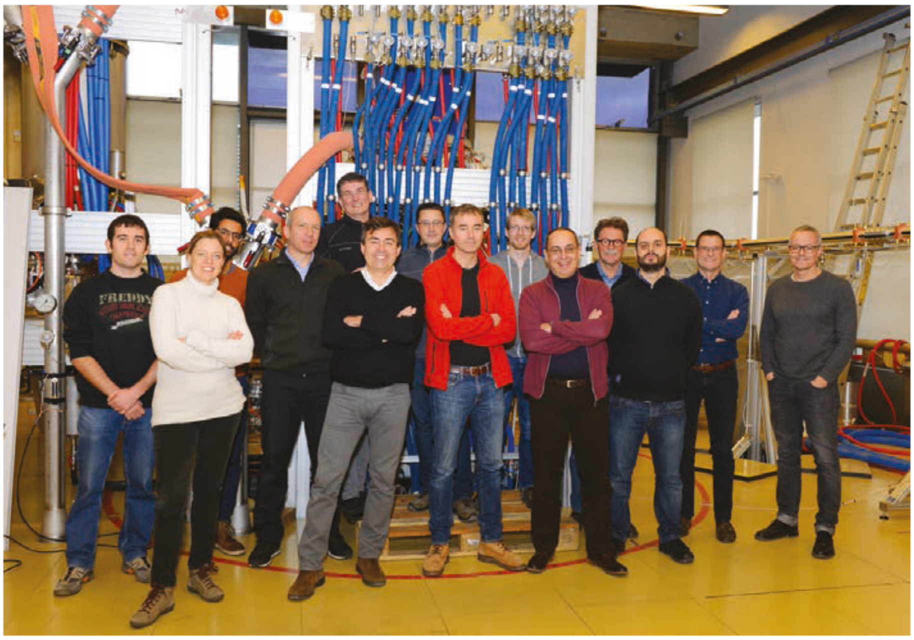
SPC's unique test facility for high power mm-wave sources and transmission components has been used in 2018 to perform final design tests of the 170GHz, 1MW, 3600s gyrotron, which is a contribution of the European partner (EU) for ITER. A key feature of the facility is the use of the full complement of electron cyclotron (EC) subsystems that are needed for a heating system on future fusion reactors - the source (gyrotron), matching optics unit (MOU), transmission line (TL), RF load (RFL), vacuum systems and control system - since weaknesses in any of these integrated parts can reduce the on-line availability of heating power.

Recent confirmation of mm-wave beam broadening by edge turbulence in TCV X3 transmission experiments suggests that more power must be reliably available on ITER than originally conceived without beam broadening.

In April 2018, reliable high power operation (0.745MW, 170GHz, 51s; 0.377MW, 170GHz, 215s) of the EU gyrotron was achieved. A second experimental campaign took place during the third quarter, with an MOU with improved cooling, an 8m-long evacuated TL and an RFL with low reflectivity and good cooling characteristics. The experiments were stopped due to a problem with the Body Power Supply that necessitated modifications of the modules. At the planned end of the experimental campaign, the gyrotron source used for this setup will be returned to the factory to incorporate new design features aimed at improving the output power and efficiency.

Similarly, a second gyrotron source, used for testing components, has produced 1000s 420kW pulses at 170GHz. A vacuum leak in one component of the source TL has been identified and repaired to allow higher energy testing in the 2019 experimental campaign.

ITER partners are welcomed at the SPC facility to test improvements to equipment planned for ITER. To that end, installation began for testing of a second type of RF load. Initial tests were carried out to confirm the alignment of the load subcomponents - a critical requirement to ensure long pulse, low-loss operation. Measurements of the beam profiles in atmosphere at several distances from the end of the various load subcomponents were made in a specially-prepared absorbing box fitted with a measurement target and infra-red and visible cameras. From these measurements the electric field (phase and amplitude) is "retrieved" and subsequently projected onto the waveguide to provide an estimate of the mode content in the subcomponent. These showed a very high level of the required HE11 mode, in most cases. The presence of other modes in one component led to a re-alignment of that component to reduce the wrong modes and improve the long pulse behaviour. The methodology for both identification and correction of misalignments has thus been validated.



The team of the EU gyrotron

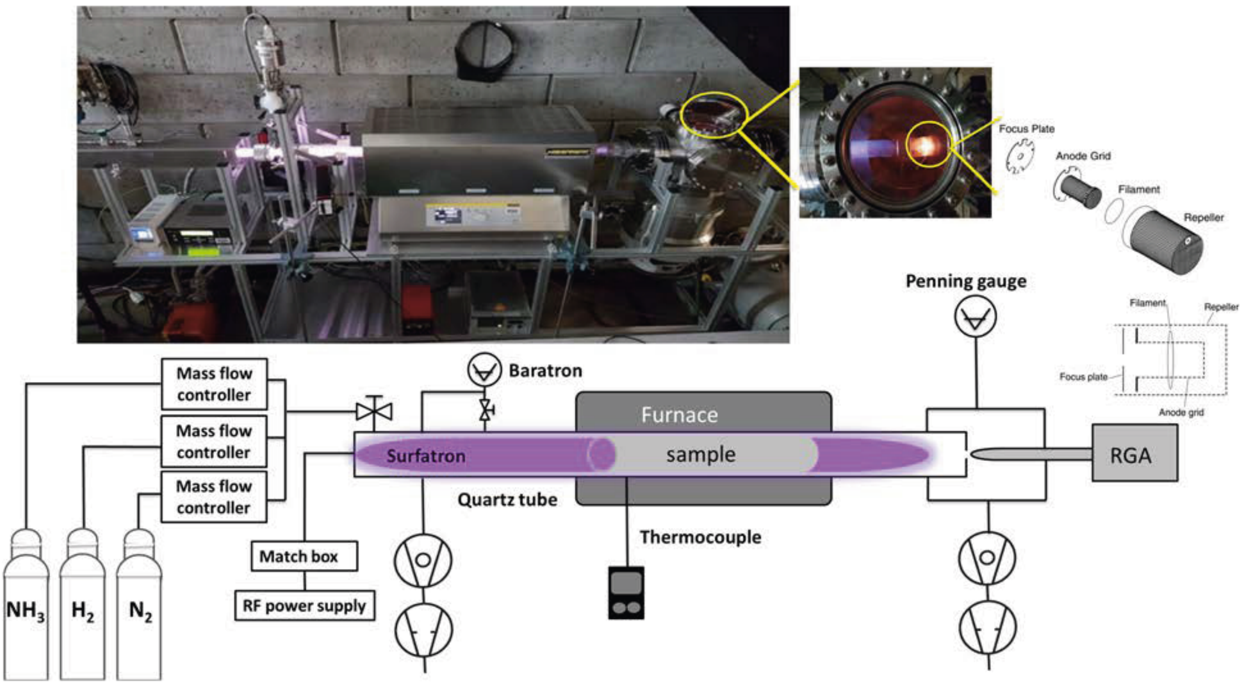
The EU gyrotron

PLASMA-WALL INTERACTION STUDIES RELATED TO FUSION REACTOR MATERIALS

University of Basel

In the frame of plasma-wall interaction for ITER, a specific topic is studied at the University of Basel by a group led by Dr LAURENT MAROT: the formation of ammonia in a nitrogen/hydrogen plasma.

In fusion devices such as tokamaks, extrinsic impurities are typically injected in the edge region of the confined plasma to help dissipate the intense power exiting the plasma before it reaches nearby surfaces. Nitrogen is the preferred species for existing devices because of its beneficial effect on plasma performance. In this context, ammonia formation resulting from fusion plasma and plasma-facing components' interaction with nitrogen gas is an increasingly important subject of research for the nuclear fusion community including ourselves over the past few years. Nitrogen injection leads to the formation of ammonia. The formation of tritiated ammonia in future fusion devices such as ITER may pose some issues with regards to tritium inventory and duty cycle. Tungsten is envisaged as a material for the plasma facing components of fusion reactors and, using our newly built metal-free setup, see **Figure 1**, we established the effect of the presence of a tungsten surface on ammonia production for different nitrogen/hydrogen plasma compositions experimentally. We demonstrated that the presence of the tungsten surface is acting as a catalyst and highly increases the formed ammonia percentage by increasing mainly the formation yield and slightly the nitrogen cracking efficiency.



1 Schematic and real picture (on top) of the RF plasma reactor and surrounding equipment for gas inlet and outlet.