SWISS PLASMA CENTER

ANNUAL REPORT 2019

Swiss
Plasma
Center

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Letter of the Director

The Swiss Plasma Center continues to play a key role in the European and international effort in fusion research, and to advance the exploration of plasma applications and related technologies. Our activities are conducted by about 145 staff members, including 36 graduate students and 17 postdoctoral researchers, and are organized in eight research lines: Theory of Plasmas, Basic Plasma Physics, TCV Tokamak Physics, TCV Diagnostics, TCV Heating, TCV Edge Plasma Physics, International Collaborations, Superconductivity for Fusion and Plasma Applications.

As a national laboratory with international facilities in an academic environment, our aims are to contribute to making ITER a success, to develop the science and technology basis of DEMO, to prepare the future generations of scientists and engineers, and to exploit plasma and fusion spinoffs for industry and society.

This year, the ITER project has started the transition from procurement to machine assembly. The scientific goals of the first experimental campaigns are being defined by all of its partners. Our Center, which in this context operates via Euratom in the framework of the EUROfusion Consortium, takes an active part in this.

In 2019, the activities on the TCV tokamak, the main experimental asset of the Center, and the largest scientific facility of EPFL, combined a major upgrade that consisted in the installation of novel in-vessel components with an extensive experimental campaign. The experiments were conducted partly in the frame of the EUROfusion Consortium (44%), from which significant human and financial resources were provided, and partly for our own domestic program (56%), of which an important fraction is devoted to PhD students. A total of 1715 plasma discharges were successfully operated. More than one hundred external collaborators conducted TCV experiments on site.

The in-vessel installation of removable graphite structures, or gas baffles, is an important element of the EUROfusion Plasma Exhaust (PEX) project. TCV has in fact been the first major European device to complete the hardware installations and provide PEX results. With the baffles, a better separation of the hot core plasma from the cold edge region and the wall could be achieved. Better extrapolations of TCV results to future devices such as ITER and DEMO, which rely on high divertor neutral pressure, are now possible.

The multi-annual upgrade project co-sponsored by the Swiss government also includes significant enhancements in the TCV plasma heating systems. This year, one of the two new dual-frequency gyrotrons, first-of-a-kind microwave sources that provide MW-level power at two different frequencies, was installed. For heating the plasma electrons, 900kW of power were injected at 126GHz, i.e. the third harmonic of the electron cyclotron frequency, while for driving current into the plasma, 850kW were introduced at 84GHz, the second harmonic of the electron cyclotron frequency. Two gyrotrons at 82.7GHz, with a power of 750kW each, were also fully commissioned and integrated into the TCV systems, to replace the older 500kW units. On the ion heating front, the performance of the first neutral beam injector on TCV was improved, in terms of beam divergence and power, which can now reach 1.3MW.

Several improvements of the plasma diagnostic systems, in particular for the edge and divertor region, and with real time capabilities, were also installed.

Taking advantage of the unique flexibility in shapes, heating and control, the TCV scientific program addressed a number of crucial issues for ITER experimentation and for the consolidation of the physics basis of DEMO plasma scenarios. In this context, the international fusion community has recognised the potential advantages, observed on TCV for the first time, of a particular (inverted D, also called negative triangularity) plasma shape and is considering this as a serious option for DEMO.

The final phases of the tests of ITER conductors are conducted by the applied superconductivity group, which is also exploring novel concepts for using low- and high-temperature superconductors for parts of the magnets and for joints, both in the context of optimizing the tokamak concept for DEMO, and for the next generation of particle accelerators for high energy physics.

The theory group continues to provide significant contributions to the understanding of fusion plasmas, operating in synergy with its EUROfusion partners, and in close interaction with TCV and other experimental groups. A vast range of topics is covered, from global plasma equilibrium and stability to heating, core and edge turbulence and real time control. High Performance Computing takes an ever increasing importance, and in 2019 one of our flagship codes was successfully ported to the most powerful supercomputer in the world, Summit, in the US. As significant increases in the theory and numerical simulation efforts are foreseen for the next EU framework program , preparations have started within our Center to take a leading role in some of the new EUROfusion initiatives in this area.

More fundamental research activities took place on TORPEX, in particular on developing advanced statistical mechanics concepts to characterize non-diffusive behavior of suprathermal particles in interaction with turbulence. Volume creation of negative ions for efficient neutral beams to heat DEMO plasmas has been explored in the RAID linear plasma device, using optimized wave-driven plasma sources, which are also the basis for our involvement in the plasma-wave particle acceleration concept. For the latter, the Swiss Plasma Center has become an official partner of the CERN-based AWAKE project.

Very encouraging results on the use of plasma-aided sterilization for agriculture were obtained in the recently launched bio-plasma applications laboratory, in collaboration with local companies, the EPFL Life Sciences Faculty, and the University of Lausanne.

As every year, I am proud of the recognition that the collaborators of the Swiss Plasma Center obtain, internally and internationally. In particular, our graduate students were awarded several prizes, which goes to their credit and to that of their direct supervisors, but constitutes also an acknowledgement of the role that is played by all of our collaborators, at all levels, in the collective education and training effort of our Center.

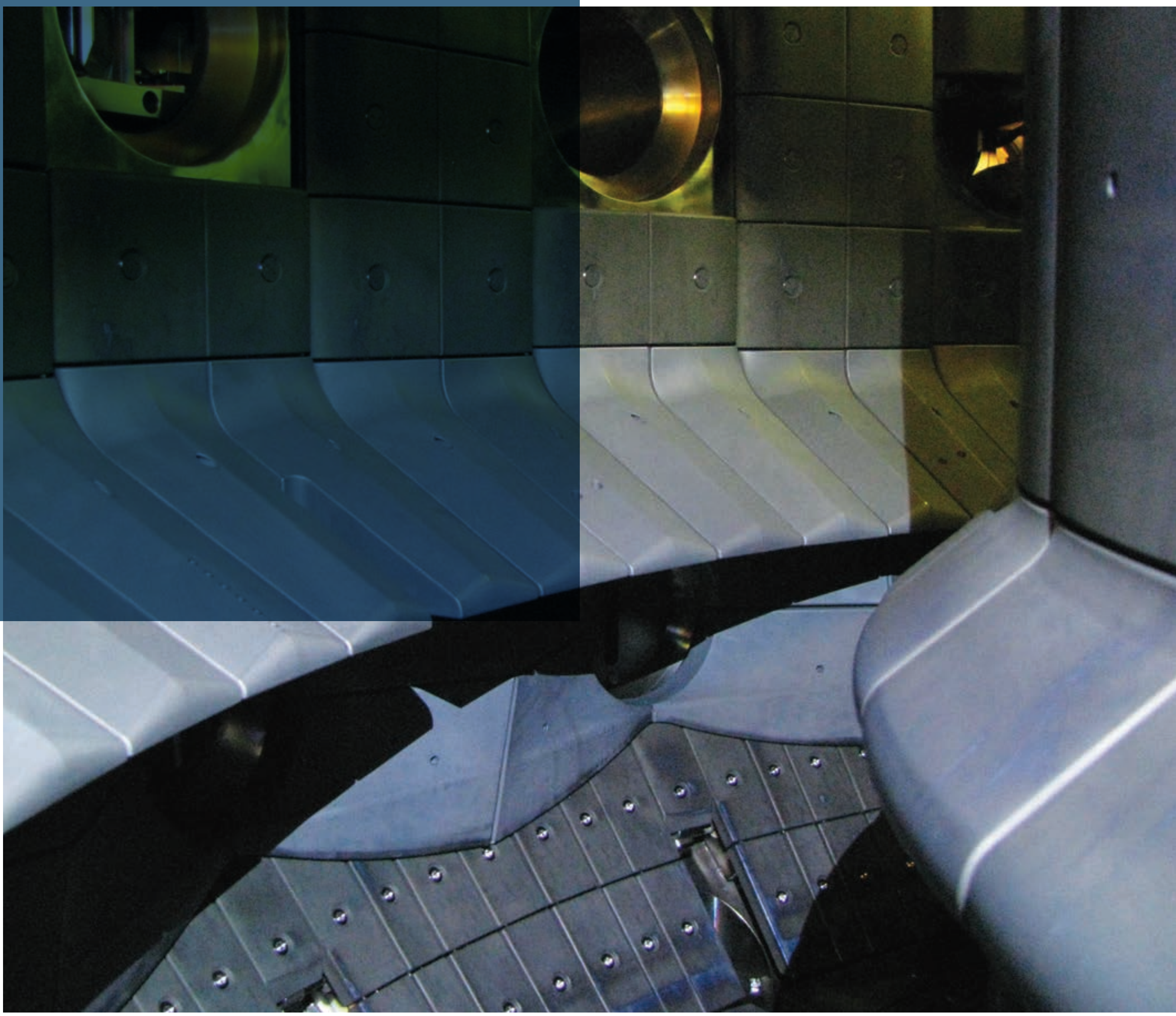
Such a diverse range of cutting-edge research and education activities, and their success, result from the combination of the foresight and generosity of our financial support bodies and partners, including the ETH Board, the SERI, the EPFL Faculty of Basic Sciences and Institute of Physics, the Swiss National Science Foundation, InnoSuisse, ITER International Organization, Fusion for Energy and EUROfusion, and the commitment and proficiency of our teams. I am profoundly grateful to all.

Ambrogio Fasoli

PROF. AMBROGIO FASOLI

RESEARCH HIGHLIGHTS

Rather than giving a comprehensive and exhaustive list of the work items that have been carried out, we describe the highlights that were attained in 2019. These are most often the fruit of a multi-year effort. They are presented in the following pages 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. Success would not have been possible without their commitment.



TCV Tokamak

TCV is the sole Swiss thermonuclear fusion research device and one of three national tokamak facilities in Europe employed and funded by the EUROfusion consortium. It is defined by extreme shaping capabilities and high power density, in the form of electron-cyclotron resonance heating (ECRH: 2.4 MW) and neutral-beam injection (NBI: 1 MW). In spite of a significant shutdown to install a first set of divertor baffles (see the TCV Boundary section), the year 2019 featured an intensive and extensive experimental campaign, 44% of which was EUROfusion-funded (with 114 external participants) and 56% domestically funded, with a total of 1715 completed plasma discharges. Dr STEFANO CODA, Senior Scientist (MER) leads the TCV Operation and describes below the main findings of this research in 2019.

The science programme of TCV continues to be based on a three-pronged approach, covering support and preparation of ITER operations, exploration of alternative scenarios for a DEMO reactor and curiosity-driven research and theory validation. All areas, but particularly the latter, go hand in hand with a fundamental educational mandate that makes TCV a premier training ground for the next generation of fusion scientists.

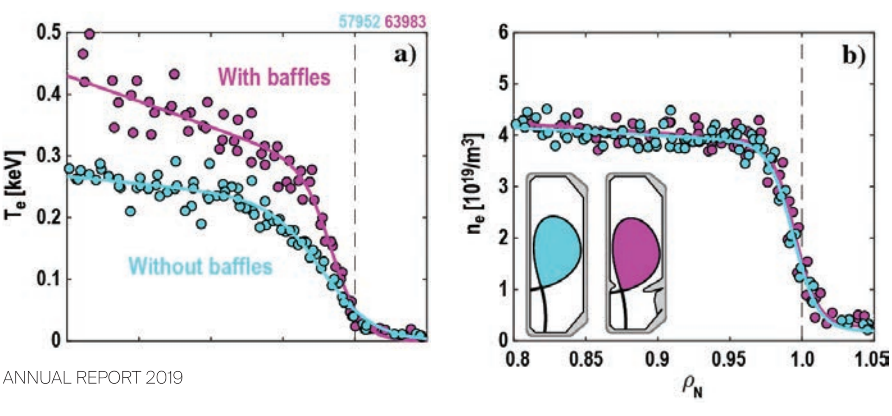
Among the highlights of 2019 is a continually expanding investigation of runaway electrons and plasma disruptions, a crucial concern for reactor wall integrity, see separate text box below, “A CURE FOR DISRUPTIONS AND RUNAWAYS”. Disruptive scenarios using massive gas injection and featuring REs were extended from Ne and Ar to He, Kr and Xe injection, and to negative-triangularity and diverted configurations, increasing the scope for model validation.

Dangerous or performance-limiting phenomena under study include neoclassical tearing modes (NTMs): here, a new analytical model of the classical island stability was successfully validated, which is expected to facilitate NTM pre-emption in future devices. A special class of Magneto-Hydro-Dynamic (MHD) instability, the electron fishbone, was also characterised for the first time, with both its excitation by suprathermal electrons and its reciprocal effect on their confinement demonstrated with assistance from modeling.

Disruption avoidance, as well as performance optimization, is benefiting from a continuous development of real-time control strategies using TCV’s flexible digital control system. With a view to future long-pulse tokamak discharges, a generic plasma control framework has been developed, implemented and applied to avoid density limit disruptions by controlling the NBI power based upon an estimated proximity to the disruptive boundary. An ability to re-assign EC sources to internal-energy or NTM control, based on set criteria, was demonstrated. Plasma exhaust control was explored using an estimate of the radiation profile along the divertor leg, indicative of the local electron temperature, by which feedback control was successfully demonstrated, using gas injection as the actuator, in both Low and High confinement regimes (L- and H-mode, respectively).

H-mode studies for the baffled divertor were facilitated by an apparent reduction in the power threshold for the spontaneous transition from L-mode. Temperatures at the divertor target were lower and nitrogen seeding led to detachment.

H-mode plasma profiles are characterized by a region of steep gradients near the plasma edge, called the ‘pedestal’. Often, this region is subject to repetitive violent relaxations called Edge Localized Modes (ELMs), which can be deleterious to the machine walls. The properties of the pedestal were studied intensively in ELMy H-modes, where the baffles lead to significantly higher pedestal electron temperature and pressure (**Figure 1**). The pedestal degrades with fueling, which increases the separatrix density but decreases the pedestal temperature, consistent

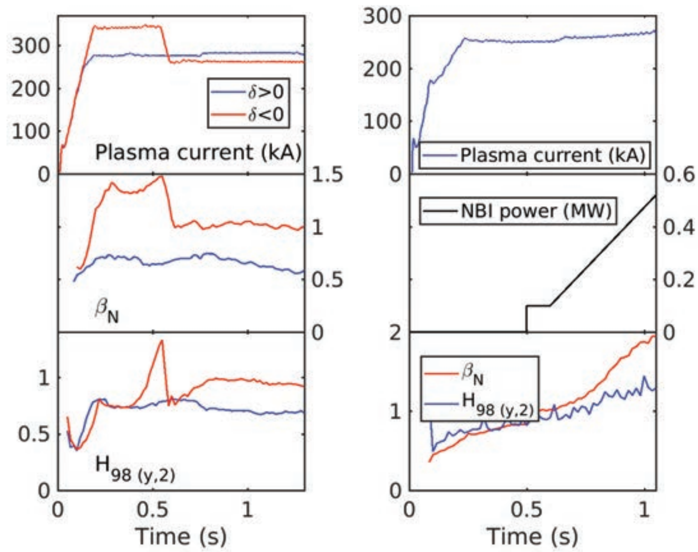


1 Measured (a) electron temperature and (b) pedestal density in unfueled, P_{NBI}=1 MW discharge with (magenta) and without (cyan) baffles.

with previous findings. A broad scan of the major radius of the outer strike point confirms that the pedestal characteristics are almost entirely independent of it, and rather determined by the separatrix density. This highlights the weak effect of alternative divertor geometries on pedestal and core properties.

In a continued effort to extrapolate ELMy H-mode performance to the ITER baseline scenario, NBI and third-harmonic ECRH heated H-modes succeeded in matching the ITER shape, beta, and safety factor targets whilst retaining good confinement.

Negative-triangularity (NT) scenarios, in which the plasma cross section assumes an inverted-D shape, were confirmed as a natural route to ELM-free operation by simply achieving higher confinement than for positive triangularity plasmas in nominally L-mode conditions. Previous results were extended by developing a fully diverted shape (Ohmically heated) and by adding NBI heating to limited scenarios: in both cases ITER-like normalised beta and H-factors in excess of unity were obtained (**Figure 2**). In situ probe and new gas-puff imaging system measurements confirm a reduced turbulent flux extending from the core to the plasma edge in Ohmic NT plasmas.



2 Performances (in terms of normalised beta and H-factor) of negative-triangularity scenarios: (a) Ohmic, diverted; (b) NBI-heated, limited.

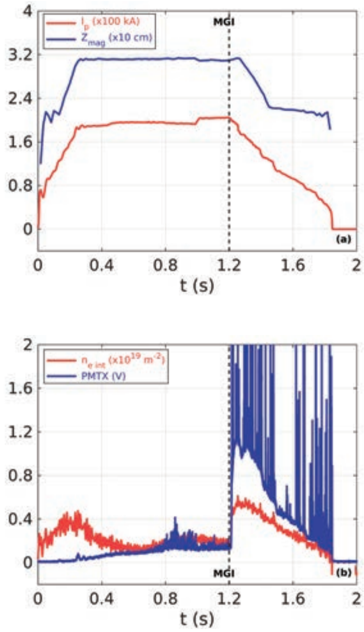
A CURE FOR DISRUPTIONS AND RUNAWAYS

Plasma disruptions are a major concern in the design and operation of reactor-scale tokamaks such as ITER. If the loss of plasma current is too brutal, strong Laplace forces might cause significant mechanical damage. If the loss of plasma current is slower, a fraction of the initial plasma current might be transferred to runaway electrons accelerated to energies in the MeV range by the strong inductive electric field. Controlled mitigation of the resulting multi-MA, multi-MeV runaway electron beam is a crucial challenge to avoid significant melting of the chamber's first wall.

At the Swiss Plasma Center, **JOAN DECKER** and **UMAR SHEIKH** have led an ambitious experimental and theoretical programme dedicated to runaway electron beam mitigation. TCV experiments have demonstrated successful control of the runaway electron beam current ramped down to a few percent of its initial value (**Figure 3**).

An even more ambitious disruption mitigation process designed at the SPC consists of restarting a standard tokamak plasma using the runaway beam as a source of current to maintain the confining poloidal magnetic field. A successful plasma restart has been obtained after a disruption caused by a massive injection of deuterium.

The runaway electron program includes significant efforts in dedicated diagnostics. Equipped with appropriate filters, spectroscopic camera systems capture the synchrotron radiation emitted by the runaway beam. The shape of the corresponding image carries valuable information on the distribution of runaway electrons. Kinetic modelling of the electron population associated with a synthetic diagnostic of the synchrotron emission allows for a quantitative comparison between measured and reconstructed emission (**Figure 4**). The first important result of this comparison is that the runaway electrons carry far more momentum in the direction perpendicular to the magnetic field than was believed initially. This observation will have an important impact in the design of new mitigation techniques.



3 Evolution of (top) plasma current and vertical position; (bottom) integrated density and hard X-ray (PMTX), as a function of time for TCV shot 53644. Massive gas injection of Neon at t=1.2s triggers a plasma disruption and the formation of an electron runaway beam characterized by a strong Hard X-ray emission. A controlled decay of the beam current is obtained by acting on the beam vertical position.

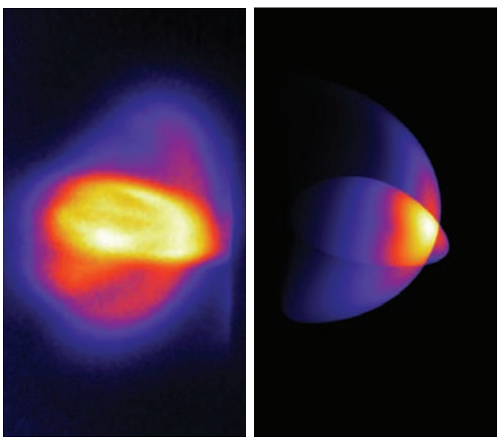
PHYSICS-BASED CONTROL OF NEOCLASSICAL TEARING MODES IN TCV

Neoclassical tearing modes (NTMs) are one class of magnetohydrodynamic (MHD) instabilities in tokamak plasmas. They are located at particular surfaces called "rational", $q=m/n$, with m and n integers, where they perturb the magnetic field into chains of islands. NTMs are known to cause confinement degradation and plasma disruptions. They have to be prevented or stabilized reliably to achieve high-confinement mode plasmas with the required performance on ITER. Research carried out by **MENGDI KONG**, PhD student at SPC under the supervision of Dr. Olivier Sauter, investigated the physics and control of NTMs by means of both experiments and simulations.

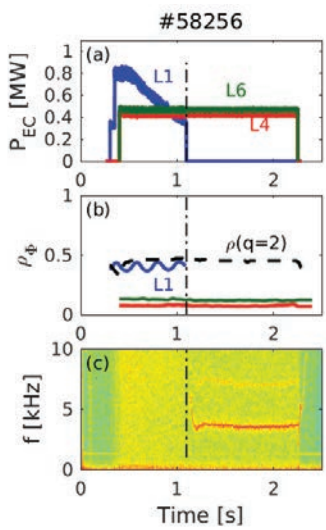
NTMs are metastable, i.e. they require a large enough perturbation, called "seed island", to further grow. Acting on the seed islands provides the possibility of preventing the occurrence of NTMs and highlights the importance of understanding their onset mechanisms. Different sources of seed islands have been identified in various scenarios and tokamaks, for example sawtooth (ST) crashes and fishbone instabilities. Similarly, seed islands can be provided by other instabilities, e.g. the classical Tearing Mode (TM). These are typically called "triggerless" NTMs and have been studied in detail in TCV.

A new *complete* stability model has been developed that clarifies the underlying physics of the onset and evolution of the NTM and of its stabilization with off-axis electron cyclotron (EC) beams. This model has allowed, for the first time, reproducing NTM prevention experiments (**Figure 5**) with off-axis EC beams in simulations (**Figure 6**).

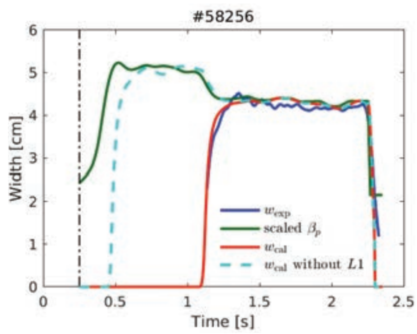
The physics studies have contributed to the development of a comprehensive new control algorithm where simulations are able to estimate in *real-time* the EC power requested to prevent or stabilize NTMs.



4 Synchrotron radiation emitted by runaway electrons at t = 1s during TCV shot 64614. Arc-shaped features observed in the frame taken by the Multicam camera system (left) are related to the superposition of two emission cones, as inferred from the emission reconstructed by the code SOFT (right).



5 Overview of an NTM prevention experiment (TCV #58256) with off-axis EC beams (L1 in blue). (a) Power traces of EC beams from different launchers (L1, L4 and L6); (b) Normalized deposition location (with respect to the plasma minor radius) of different EC beams and the radial location of the 2/1 surface (dashed black); (c) Magnetic spectrogram with 2/1 and 4/2 components.



6 Island width evolution of the 2/1 NTM in TCV #58256. Blue – experimental measurements; green – scaled β_p (ratio of plasma pressure to poloidal magnetic pressure); red – simulation with the new complete model with off-axis EC beams (L1) ; dashed cyan – simulation without L1.

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. Dr **BASIL DUVAL**, MER, is the leader of this research line and exposes below some of the main achievements in 2019.

During 2019, the diagnostic challenge was to install the divertor baffles designed to increase neutral gas compression, and implement the diagnostic changes required to work with these baffles in place. The latter part of the year was then dedicated to running these diagnostics over a wide range of divertor specific and other Tokamak plasma physics research.

This challenge was highly successful with respect to the divertor diagnostics. A new tangential infrared camera completed the view of all our lower divertor strike points and a large number of additional Langmuir probes now provide complete poloidal coverage and, now, include probes on the baffles themselves. A floor reciprocating Langmuir probe array that provides 2D divertor scans was modified to withstand higher temperatures without melting and provided novel data that was particularly useful in validating highly complicated numerical divertor modelling. A video of this diagnostic won an EPS video prize at the 46th Conference in Plasma Physics in Milan. Finally the low temperature Thomson scattering spectrometers were commissioned and have provided statistically meaningful electron temperature and density measurements well into the relatively cold divertor.

Passive spectroscopic diagnostics such as the multi-channel 10-Camera spectrally filtered MANTIS system, together with divertor spectroscopy performed well and are both considerably upgraded for the 2020 campaign. Only the neutral density measurements on the divertor floor and on the TCV midplane were found insufficient and other, more sensitive, systems are being considered since this measurement is fundamental in understanding the baffle efficacity.

In collaboration with colleagues from the PSFC-MIT, a midplane gas puff imaging diagnostic (GPI, **Figure 1**) was installed on TCV in December 2018. During 2019, a second system was installed to probe the X-point and divertor region. With up to 2MHz detector and acquisition bandwidth and ~5mm spatial resolution, edge turbulence features, in particular filamentary transport, can be fully 2D-resolved (**Figure 2**). The midplane GPI covers a 5x4 cm window with a 2D array of optical chords onto 10x12 avalanche photodiodes whereas the X-point GPI records light emission with a fast-framing camera, whose zoom lens can be adjusted to cover a wider region.

In 2019, midplane measurements provided insights into SOL transport and turbulence, in attached and detached plasmas, (**Figure 3**). Using both midplane and floor systems, the study of parallel blob dynamics and extent of turbulent filaments along the magnetic field became accessible (**Figure 4**). Of particular interest, in core plasma negative triangularity studies, where transport appears strongly, and surprisingly, suppressed, it was observed that the turbulent related transport is also strongly suppressed in the SOL.

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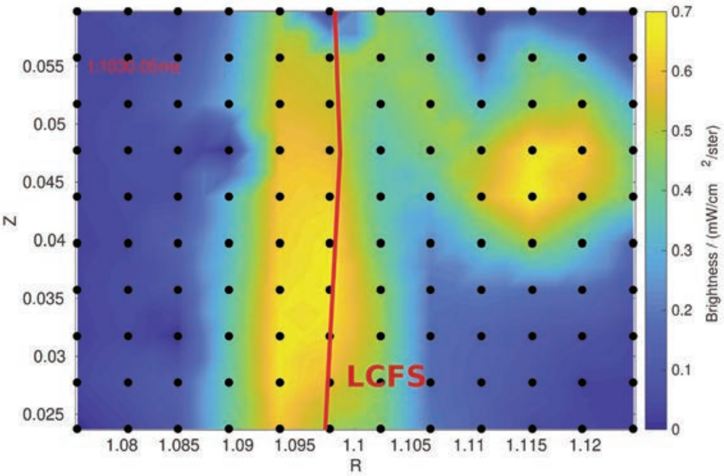

1 View of the midplane gas injection system for the Avalanche PhotoDiode (APD) array Gas Puff Imaging (GPI)

2 Reconstructed blob leaving the plasma LCFS (last closed flux surface) on the APD array GPI

3 Blob Velocities on the APD array GPI for four discharges in attached and detached divertor conditions

4 Signals from the floor(red) and midplane(blue) GPI systems near the same flux surface. The strong correlation provides information on the propagation of the bursty transport seen in the TCV SOL.

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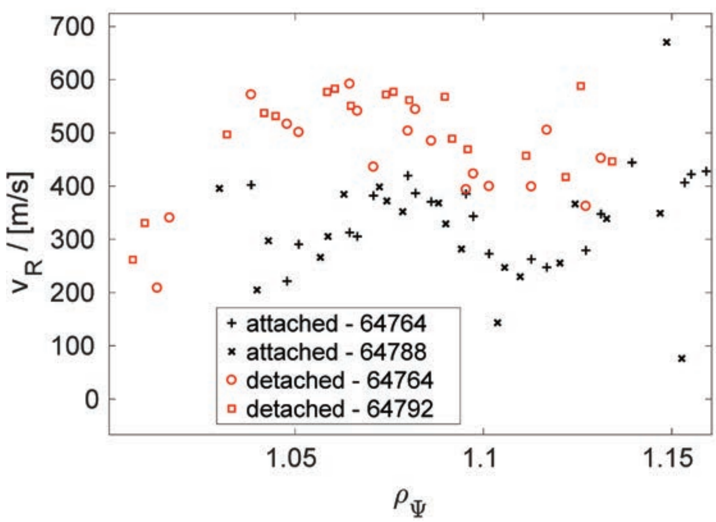

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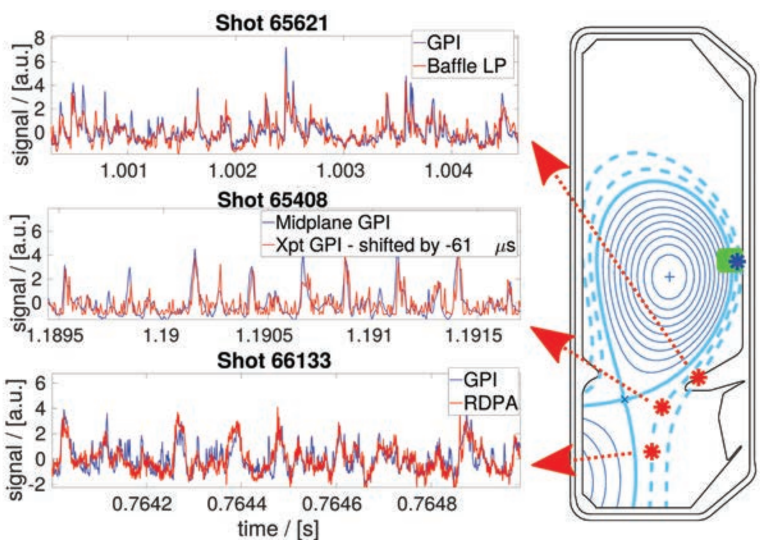


TCV Heating

The two plasma heating schemes used in TCV, the injection of neutral high-energy particles (NBI) and of high-power rf waves at the electron cyclotron frequency (ECH), are the only auxiliary heating systems compatible with the plasma shape control flexibility of TCV. On the one hand, NBI is used primarily to control the ion temperature, and, on the other hand, operating at the shortest natural resonant wavelength of a magnetized plasma, ECH offers the best localization properties of all rf heating methods, which is an essential feature for stabilizing disruptive MHD-instabilities potentially occurring in future fusion experiments such as ITER or DEMO. Dr. **STEFANO ALBERTI**, MER, is the leader of the TCV Heating research line and exposes below the main achievements in 2019.

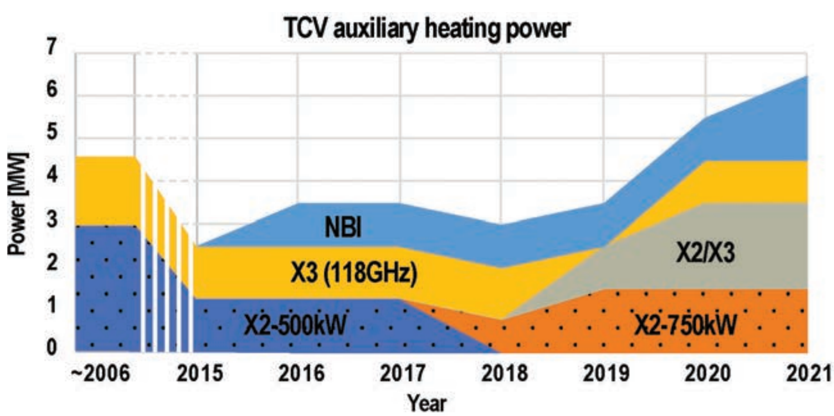
The upgrade of the auxiliary heating systems has reached three important milestones by the end of 2019, with the first injection in the plasma of the rf power generated by the new MW-class dual-frequency gyrotron connected either to the new top-launcher for third-harmonic X-mode heating, X3, at 126GHz, with 900kW of injected power, or connected to a low-field side launcher for X2 heating or current-drive at 84GHz (850kW). The second milestone is the full commissioning and integration of two 82.7GHz/750kW/2s gyrotrons replacing the older 500kW version which failed after 12 years of operation. The third milestone relates to the improved power capability, up to 1.3MW, of the neutral beam injector together with a reduced beam divergence.

The evolution of the auxiliary heating power in TCV is shown in **Figure 1** and is consistent with the three milestones achieved in 2019. By the end of 2019, the second dual-frequency gyrotron, has been delivered to SPC. Its commissioning will be completed in the first half of 2020 followed by first plasma experiments with the fully upgraded ECH system.

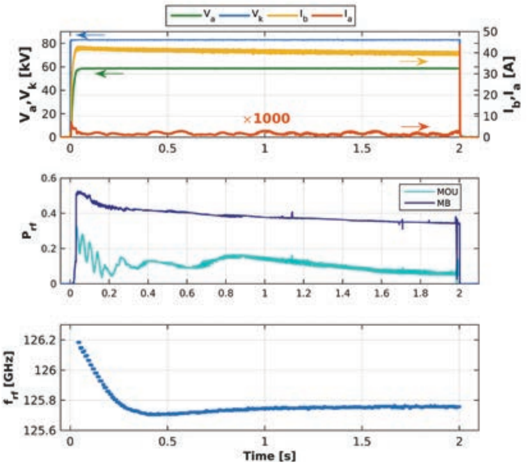
With the first dual-frequency gyrotron fully commissioned, stable monomode ($TE_{26,7}$ @126GHz or $TE_{17,5}$ @84GHz) operation was reached in long-pulse regime (TR_F > 0.5s) and the cavity generated rf-power is well in excess of 1MW at the two frequencies with corresponding electronic efficiencies higher than 35%. The gyrotron operation is extremely robust and reliable. The time evolution of the typical gyrotron parameters when operated at 126GHz are shown in **Figure 2**.

In 2019, the injected power capabilities of the low-energy NBI system have been significantly improved with the delivery of a new low-divergence ion optical system (grids) and with the optimization of the injector characteristics. These two results are illustrated in **Figures 3** and **4**.

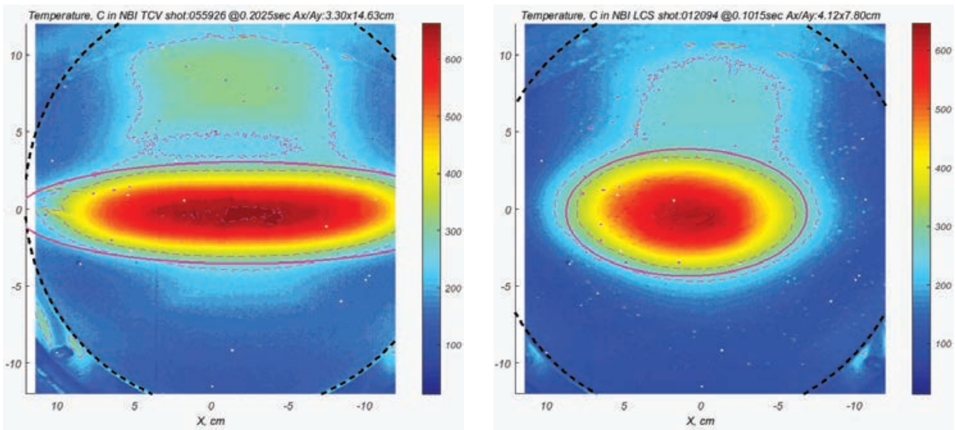
The contract for a second NBI system at higher-energy, 50-60keV/1MW/2s, is being finalized with a foreseen delivery by the end of 2020. The final layout of the upgraded NBI system is shown in **Figure 5**.



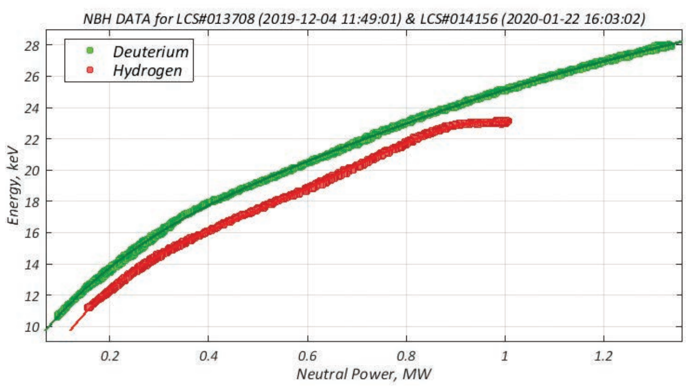
1 Evolution of the installed nominal auxiliary heating power during the ongoing upgrades up to their completion in 2021. The initial EC system, which was fully implemented in 2006, is added as a reference. Dotted areas indicate power that is only available below the X2 cut-off density of $n_e = 4\,10^{19}[m^{-3}]$.



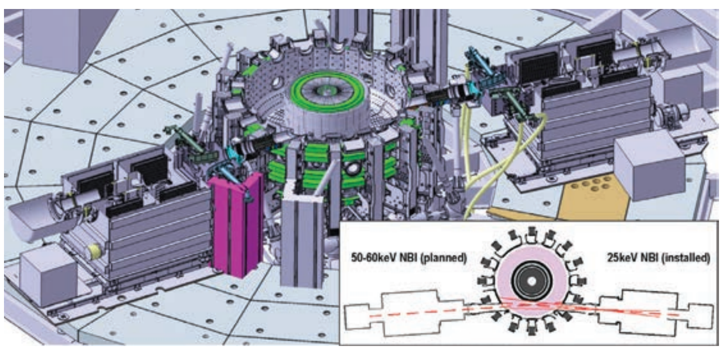
2 Time evolution of typical traces for a 2s shot at 126GHz and a generated power at the gyrotron window of 1.1MW. Top figure: gyrotron external parameters for the triode gun. Anode voltage (V_a) and current (I_a), cathode voltage (V_k) and beam current (I_b). Middle figure: Instantaneous rf-power [a.u] measured by two Schottky diodes at the input (MOU) of the 30m-long transmission line and at its output (MB). Bottom figure: frequency evolution.



3 Temperature profiles on the tungsten target with old (left) and new (right) grids clearly show the decrease of the beam size in horizontal direction. NBI power losses in the beam duct (between injector and tokamak) are reduced and allow for the increase of the energy injected in TCV per shot from 0.5 to 1.3 MJ.



4 NBI operational energy vs power curves. In addition to the improved beam divergence, the optimization of the deuterium beam was extended to 1.3 MW (green curve). The corresponding operation in hydrogen in the power range from 120kW to 1MW has also been demonstrated in 2019.



5 CAD view of the two NBI systems on TCV. The 25 keV system (on the right) was installed in 2015 with an upgrade to 1.3MW in 2019. The 50–60 keV, 1MW system (on the left) is planned to be operational in 2021.

TCV Boundary

The successful operation of a fusion reactor depends crucially on the boundary plasma. On the one hand, adequate confinement of the superhot, 100 million °C plasma core must be ensured. On the other hand, damage to the surrounding wall structures has to be avoided. By leveraging TCV's unique magnetic shaping capabilities, operational flexibility, and excellent diagnostics accessibility, the Boundary Group, led by Prof. **CHRISTIAN THEILER**, works on advancing the fundamental understanding of the complex, turbulent boundary plasma and developing improved solutions for a reactor. Here are the notable achievements in 2019.

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. However, there is a fine line between efficient protection of the wall by a detached plasma and adverse effects on the fusion core performance. Today, it is uncertain whether the currently foreseen "conventional" boundary solution will be adequate for a reactor, and new ideas, such as alternative magnetic geometries of the boundary plasma, might well be required.

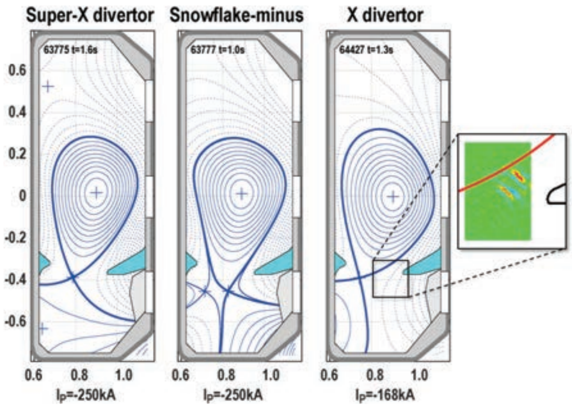
In 2019, we have successfully installed removable graphite structures, referred to as "gas baffles", in the TCV vacuum vessel, **Figure 1**. This upgrade, supported by the EUROfusion Plasma Exhaust (PEX) project and the Swiss government, allows us to better separate the main core plasma above the baffles from the region of strong plasma-wall contact below, called the divertor region. More specifically, these baffles seek to increase the neutral pressure in the divertor and thus to facilitate the extrapolation to future devices such as ITER and DEMO, that will rely on high divertor neutral pressure.

The first experimental campaign conducted in this configuration in 2019 confirmed the main theoretical predictions of how the baffles change divertor performance, i.e. an increase in divertor neutral pressure by a factor of up to 5 and a 30% reduction of the plasma density needed to access detachment, **Figure 2**. Even stronger benefits of the baffles have been identified in the more reactor-relevant high-confinement plasma regime (H-mode). The baffles strongly facilitate the access to this regime and enhance plasma performance once reached. Most importantly, the operational window for detachment, very limited without the baffles, has been shown to increase substantially. Real-time control of this detachment state could be demonstrated through fast processing of visible light emission measurements from the divertor, coupled to active feedback control of gas puffing.

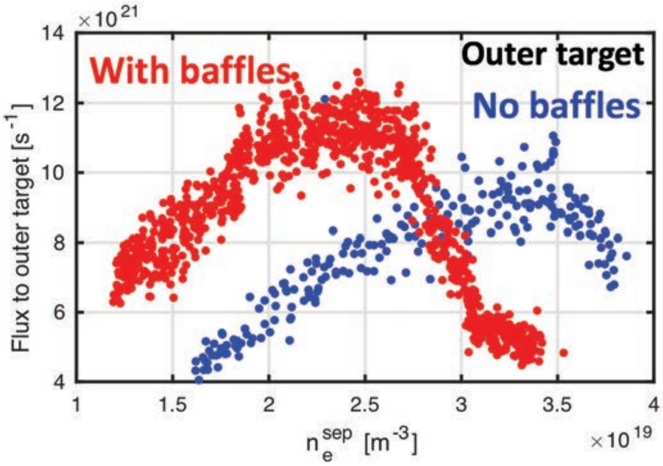
The baffle upgrade and TCV's shaping capabilities now also provide a unique testbed to explore the benefits of alternative divertor magnetic geometries in baffled conditions, such as Super-X and Snowflake configurations, **Figure 1**. In particular, dedicated experiments in the baffled Super-X divertor indicate weaker benefits than expected from modelling, an important puzzle left to solve for 2020.

Clearly, an assessment of the optimal divertor configuration and extrapolation towards a reactor requires validated modelling. Over the past year, the boundary group has substantially enhanced its expertise in this regard (see highlight on the following page). This allowed us in particular to shed light on the processes limiting the benefits of baffles and serves as a guidance for the design of a second generation of baffles foreseen for 2020.

Probably the largest uncertainties in our capabilities to predict operation in a future reactor is related to plasma turbulence and associated particle and heat transport. With the addition of a new turbulence diagnostic in the region of the baffles, see **Figure 1**, the diagnostic coverage of the boundary plasma has been further enhanced in 2019. This in particular allowed us to determine to what extent turbulence "communicates" between the main plasma and the divertor region. The basic plasma device TORPEX in diverted configuration is also being used as a basis for a validation effort, involving five of the leading European turbulence codes.

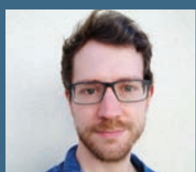


1 Cross-section of TCV with the new baffles highlighted in light blue. Shown are three plasma equilibria with different divertor magnetic geometries. The inset at the right shows a snapshot from the new Gas Puff Imaging diagnostic, providing 2D measurements of turbulence in the vicinity of the outer baffle.



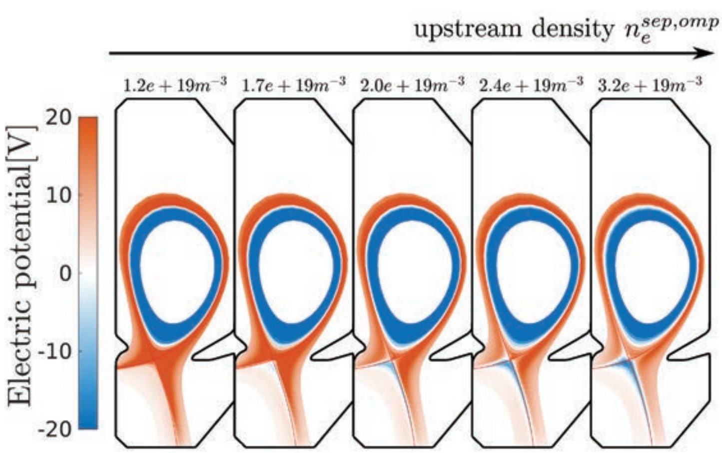
2 Total particle flux to the TCV floor as a function of the plasma density, with and without the baffles. The drop of this flux with increasing density indicates the onset of detachment, occurring earlier in the case with baffles.

DIGGING A POTENTIAL WELL



In November 2016, **MIRKO WENSING** began his PhD thesis project under the supervision of Dr Holger Reimerdes, MER, on computer-aided modeling of the TCV divertor plasma using the SOLPS-ITER code, the code that has guided the design of the ITER divertor. The project focuses on the characterization of cross-field transport in the TCV divertor by accounting for electric currents and guiding-center drifts in close comparison with TCV experiments.

Surprisingly, the work predicted the formation of a potential well structure in the vicinity of the magnetic X-point in detached divertor conditions (**Figure 3**). Its formation is found to be closely related to the evacuation of electric charges accumulated by the grad-B drift, so called Pfirsch-Schlüter currents. Shortly after its prediction, the potential well was indeed observed in TCV experiments using the novel Reciprocating Divertor Probe Array diagnostic (RDPA) indicating a substantially altered divertor flow pattern as compared to what had been anticipated. The simulations indicate that the equilibrium, i.e. non-fluctuating, ExB flows significantly impact the divertor cross-field transport of particles, heat and momentum even in the presence of turbulent transport, contrarily to the cross-field transport in the vicinity of the confined plasma. The work on TCV strengthens the confidence in the predictive capabilities of the codes that aid the design of future machines such as DEMO.



3 Potential profiles predicted by SOLPS-ITER drift simulations. A negative potential well forms below the X-point with increasing density, a prediction explained analytically and verified experimentally.

Theory and Numerical Simulation

The theory and numerical simulation group at SPC is headed by Prof. **PAOLO RICCI**. The main activities and findings of the group are exposed below.

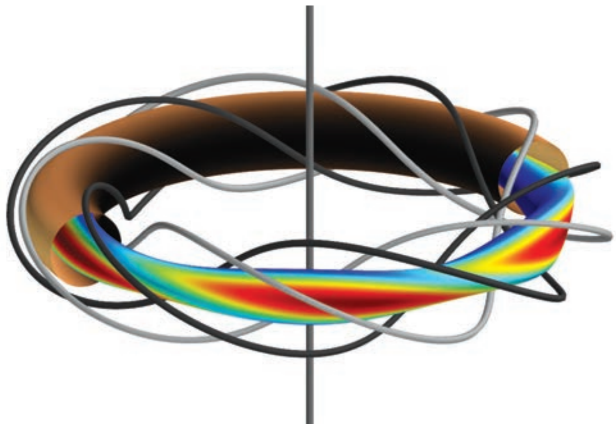
Progress in the first-principles understanding of the plasma dynamics in magnetic confinement devices for fusion is necessary to provide an interpretation of the results from current experiments, and to make predictions for future fusion devices while leading their development.

In 2019, the SPC theory group gave important contributions to the understanding of fusion plasmas, through strong collaborations with other research institutes and within a number of EUROfusion projects. In addition, the theory group maintains very close ties with a number of experimental groups, including TCV and TORPEX at SPC, as well as Asdex-Upgrade and JET. The theory group heavily relies on numerical simulations and makes use of advanced High-Performance Computers platforms, including Piz-Daint at the Swiss Supercomputing Center (CSCS), Marconi at Cineca and, for the first time in 2019, on the most powerful supercomputer in the world, Summit at Oak Ridge National Laboratory.

GLOBAL PLASMA EQUILIBRIUM AND STABILITY

Understanding and controlling the global plasma equilibrium and stability constitute the first step in the design and operation of a fusion device. Following up on our investigations of the past years, linear and nonlinear models have been developed for the solution of global instabilities in strongly rotating plasmas.

Our effort in the analysis of 3D configurations continued. The free-boundary version of the Stepped-Pressure Equilibrium Code (SPEC) is now fully verified in different tokamak and stellarator configurations (**Figure 1**). The SPEC code has been used to demonstrate, for the first time, that the nonlinear saturation of tearing modes in tokamaks can be calculated directly with an equilibrium code without resolving the complex resistivity-dependent dynamics. Finally, we have developed a model for impurity transport during experiments with strong neutral beam heating, and in the presence of internal kink modes. Such kinked strongly rotating plasmas are seen to affect core impurity peaking especially during high performance hybrid scenarios.



1 **Coil configuration used to produce input to SPEC for the verification of vacuum fields. A vertical wire produces the main toroidal magnetic field. The remaining field is produced by two helical windings carrying opposite currents. Colour contours show the magnitude of the magnetic field on an inner surface.**

HEATING

The theory group works on the understanding of the physical processes behind the neutral beam, electron and ion cyclotron resonance heating and supports their developments. One of the missions of the Wendelstein 7-X stellarator is to study the confinement of energetic ions in order to assess the potential of such 3D optimized configurations for a fusion reactor. One of the possible routes for creating a fast ion population is ion cyclotron range of frequency (ICRF) heating. We have identified and optimized a so-called minority regime, whose synergetic effect results in larger concentrations of energetic ions. A number of improvements have been made to the model for the plasma dielectric tensor, which allows us to treat higher harmonic modelling and exotic heating schemes, such as the one shown in **Figure 2**.

Quasi-linear theory and simulations of the JET tokamak indicate that the excellent confinement properties of fast particles are due to increased velocity diffusion from ICRF interaction along the magnetic field lines, and agreement is found with JET experimental measurements for the total neutron rate and the energy distribution of the fast ions.

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. Because of the different levels of plasma collisionality in the core and the edge, the investigations of turbulence in these two regions are most often approached by using different codes and models. An effort started at the SPC to bridge the two descriptions, and it led to the extension of the gyrokinetic model from core to edge conditions, including the formulation of a full nonlinear Coulomb collision operator suitable for numerical treatment.

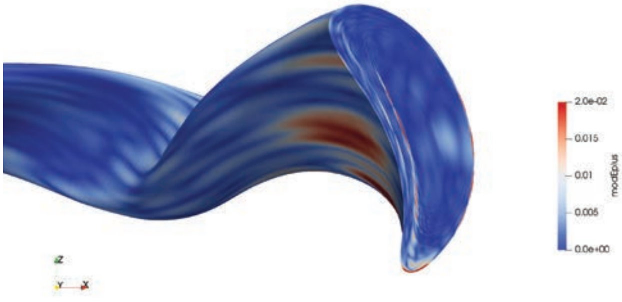
Solving the equations of the gyrokinetic model requires state-of-the-art numerical methods and massively parallelized scalable codes. One such code is the global, electromagnetic, Particle-In-Cell code ORB5, recently refactored and GPU-enabled. The code has been ported to Summit, the most powerful supercomputer in the world at ORNL, and has shown excellent scalability for problem sizes up to 100 billion degrees of freedom.

The ORB5 code capabilities have been enhanced by the addition of an “antenna”, i.e. the possibility to include an external perturbation and investigate the response of the system. Turbulence suppression by steady applied sheared flows by using the antenna was shown to be almost canceled by the nonlinear plasma zonal flow response. The antenna was also applied in an attempt to excite geodesic acoustic modes (GAM). The coherent structures that are observed experimentally e.g. in the TCV tokamak, and as simulated with ORB5, have frequencies below the local GAM frequency and require the plasma nonlinear response to be excited.

Another widely used gyrokinetic code is GENE, which was applied to study how the sharp radial structures localized at the mode rational surfaces of linear eigenmodes of various small-scale instabilities contribute to the drive of zonal flows. This mechanism, called Self-Interaction (SI) has been shown to disrupt the well-established coherent drive resulting from the modulational instability mechanism.

Turbulent transport simulations using GENE simulations, relevant to both the TCV tokamak as well as the upcoming JT-60SA device, have been carried out including a synthetic diagnostic of Phase Contrast Imaging (PCI). This will enable a one-to-one comparison with experimental results in particular the spectral signatures in the PCI diagnostic specific to positive and negative triangularity discharges.

Focusing on the plasma boundary, the capabilities of GBS, the simulation code developed at the SPC to evolve plasma turbulence in the tokamak boundary were further improved. GBS now features an advanced numerical algorithm that allows for simulation in arbitrary magnetic geometry. These include advanced alternative divertor configurations, such as the snowflake, as described in the highlight on page 17.



2 **Absolute value of the left handed polarised component of the fast wave $|E^+|$, in the plasma of the stellarator W7-X. This $|E^+|$ is the main component responsible for RF ion heating. Arbitrary units. The so called 3-ion heating scheme has been used, H-(3He)-4He.**

REAL TIME CONTROL

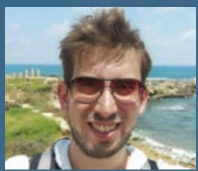
The integrated modelling of tokamaks, including ITER, is quickly advancing thanks to the possibilities to perform simulations of the plasma discharge in real time. This progress leads to the development of fast simulations that are also used to automatize post-shot analysis, which are now systematically compared with experimental results. The feedback of these analyses can lead to a further improvement of the way real-time control can handle off-normal events. An example is the new algorithm proposed for the control of Neoclassical Tearing Modes (NTM). Adaptive real-time simulation can now be used to predict NTM evolution for both prevention and stabilization. It will be tested in TCV and ASDEX Upgrade, for which off-line simulations have been already performed.

Machine learning is also being used to extend our knowledge and test our physics understanding. Machine learning using generative topographic mapping has been developed for disruption prevention and avoidance at JET and is a prime candidate for routine use in this experiment. Work is progressing to extend the results to other tokamaks.

LASER-PLASMA INTERACTION FOR INERTIAL FUSION RELEVANT CONDITIONS

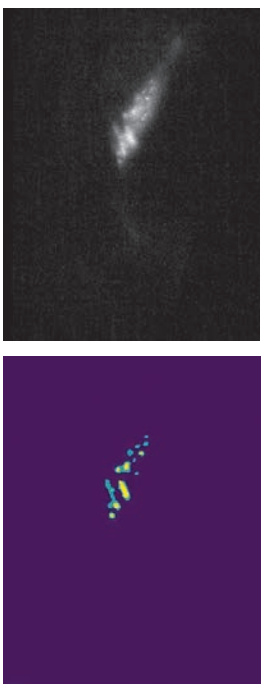
In a collaboration with Lawrence Livermore National Laboratory and Rensselear Polytechnic Institute in the US, the Eulerian Vlasov-Maxwell code LOKI was further developed to include linearized multi-species collision operators with different temperatures and average velocities. Antennas were also implemented, which ensure perfect (to round-off error) uni-directional propagation. The LOKI code was applied to the study of interpenetrating flows, in particular investigating two-stream and Weibel instabilities.

MITIGATION OF PLASMA DISRUPTIONS AND RUNAWAY ELECTRON BEAMS VIA SHATTERED PELLET INJECTION

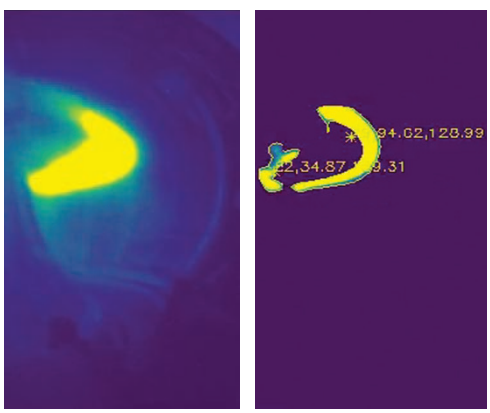


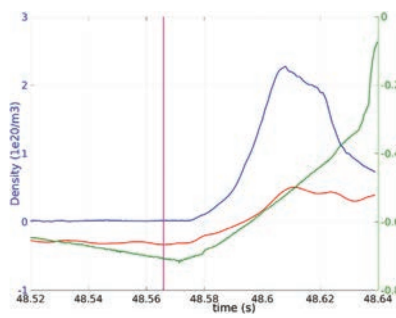
Plasma disruptions are caused by major magnetohydrodynamic instabilities which lead to fast plasma discharge termination. Typically, a disruption is caused by the accumulation of highly radiative impurities, or by the crossing of the plasma operational boundaries. A disruption is composed of two subsequent phases: the thermal quench and the current quench. The thermal quench phase is recognized by a sudden loss (≤1ms) of the plasma thermal energy to the tokamak first wall. During the current quench phase, the plasma current is dissipated up to termination. The fast reduction of magnetic field (~10ms), related to the decrease of plasma current, causes the generation of strong electromechanical stresses in the tokamak conductive structures. Occasionally, a third phase, called the runaway plateau, can be observed at the end of the current quench. The runaway plateau is characterized by the presence of a highly energetic (≥10MeV) electron beam of high current (≥100kA), which, if not controlled, can strike and damage the tokamak first wall. Due to the high risk of damaging tokamak components, strategies are required for softening the high heat loads and stresses taking place during a plasma disruption. Moreover, disruption load intensities scale up with the tokamak size, hence the mitigation of disruptions is a key issue for future large tokamaks such as ITER and DEMO. In this respect, key advancements in the understanding of disruption and runaway electron physics are obtained from experimental campaigns in the JET tokamak, which is the largest working fusion reactor nowadays. Dr **CRISTIAN SOMMARIVA**, Post-doctoral Fellow at the SPC, exposes below his contribution to this important research topic.

The present strategy consists of dissipating most of the plasma energy before the disruption thermal quench phase via radiation (disruption mitigation) and of reducing the runaway electron energy via particle collisions (runaway beam mitigation). This can be achieved by the injection of heavy impurities (e.g. neon or argon) in the form of a solid shard spray into the plasma or the runaway electron beam. This mitigation scheme, called Shattered Pellet Injection (SPI), is the one chosen for the ITER tokamak. For successful disruption mitigation, heavy impurities have to reach the plasma core. Therefore, the shard penetration length into the plasma is considered as one of the figures of merit for evaluating the quality of the injection scheme. Information on the shard penetration can be obtained by identifying and tracking the light emitted by the shard ablation process observed by fast camera videos. A python-based video analysis code has been developed for accomplishing this task. Initial operation capabilities were achieved in 2019, during which the code identified and followed shards injected in multiple target plasmas (**Figure 3**) and runaway beams (**Figure 4**). First results of the SPI into runaway electrons show that shards are ablated at the beam edge. Surprisingly, the shallow shard penetration does not prevent the assimilation of heavy impurities into the beam itself. This is confirmed by the interferometry and polarimetry density measurements (right plot of **Figure 4**) which show a sudden increase in the electron density at the runaway beam core just after the full ablation of SPI shards.

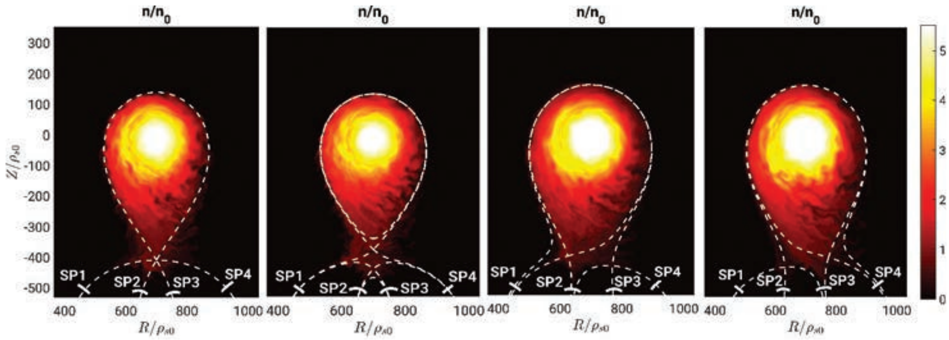


3 Identification and tracking of shards visible in JET Pulse 95150 video. On the top: original frame from fast visible camera showing the shard ablation plume. On the bottom: shard identification (in bright colors) using the video analysis code.

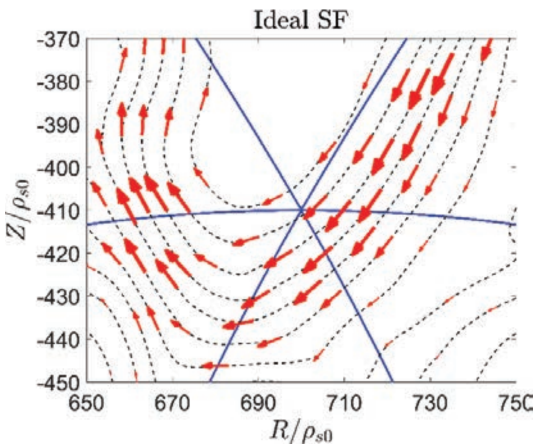




4 Pulse 95729: injection of Neon SPI into JET runaway electron beam. One the left: Neon shard ablation induced by fast electron beam as seen by the JET fast visible camera (false colors). At the center: identification and tracking of the ablation plume moving fronts. On the right: electron density (polarimetry) and runaway current measurements after Neon SPI. Blue and red solid lines are respectively the beam core and edge electron densities. The plasma current is reported using a green-solid line. The magenta line identifies the first time at which shard plume light is visible.



5 Snapshots of density on a poloidal plane for the ideal snowflake (a), the snowflake plus (b), the low-field side snowflake minus (c), and the high-field side snowflake minus (d). The dashed white lines indicates the separatrices and the solid white lines the position of the strike points.



6 Equilibrium convective cell around the null point (red arrows). The solid blue line represents the separatrix, while the dotted black lines represent contour level of the electrostatic potential.

FIRST TURBULENCE SIMULATION IN SNOWFLAKE MAGNETIC CONFIGURATIONS

The power exhausted to the wall in future fusion power plants is expected to be significantly larger than in nowadays experiments, thus questioning the extrapolation of the ITER exhaust solution to larger devices. Alternative exhaust solutions have been proposed by the fusion community to properly address this crucial issue. Understanding the mechanisms behind the heat flux distribution on the tokamak wall in these alternative divertor configurations is therefore of crucial importance. In 2019, **MAURIZIO GIACOMIN**, a Ph.D. student supervised by Prof. Paolo Ricci, together with **LOUIS STENGER**, an EPFL Master student that pursued a semester project at the SPC, carried out the first-ever simulation of plasma turbulence in an alternative divertor configuration, based on a first-principles approach. The work was published as a letter in Nuclear Fusion. Maurizio and Louis considered the snowflake magnetic configurations (see **Figure 5**), a configuration that has been pioneered on the TCV tokamak and is regarded as one of the most promising alternative exhaust configurations. To carry out the simulations, Maurizio and Louis used GBS, a two-fluid code developed at the SPC.

Snowflake magnetic configurations are characterized by the presence of four "legs" that, in principle, distribute the heat flux to the wall on four strike points instead of just two in conventional divertor configurations. This work points out that the activation of the secondary strike points (SP2 and SP3) in the ideal snowflake and snowflake-plus configurations (see **Figure 5 (a)** and **(b)**), experimentally observed in TCV experiments, can be explained by the presence of an equilibrium convective cell around the null point (see **Figure 6**). These simulations highlight the importance of turbulence on the heat flux distribution. For instance, in the low-field side snowflake minus configuration (shown in **Figure 5 (d)**), it was possible to identify the presence of a region of strong cross-field turbulent transport that contributes to the spreading of the heat flux to the wall on a larger area, decreasing therefore its peak value.

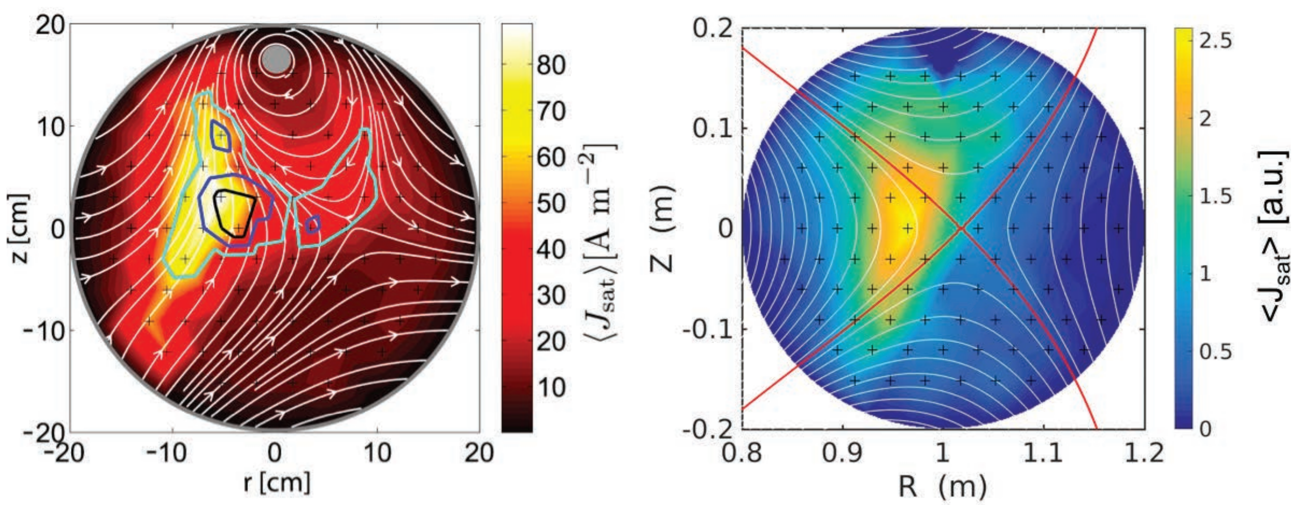
Basic Plasma Physics and Applications

Led by Prof. **IVO FURNO**, the activities of the Basic Plasma Physics and Applications group are performed on the TORoidal Plasma EXperiment (TORPEX), on the Resonant Antenna Ion Device (RAID), as well as a variety of plasma devices for industrial applications. The study of turbulence and associated transport in magnetized plasmas is realized on TORPEX. The physics of helicon waves and helicon-generated plasmas is carried out on RAID. We develop state-of-the-art applications of low-temperature plasmas in a variety of fields by advancing in parallel their fundamental physics understanding. 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.

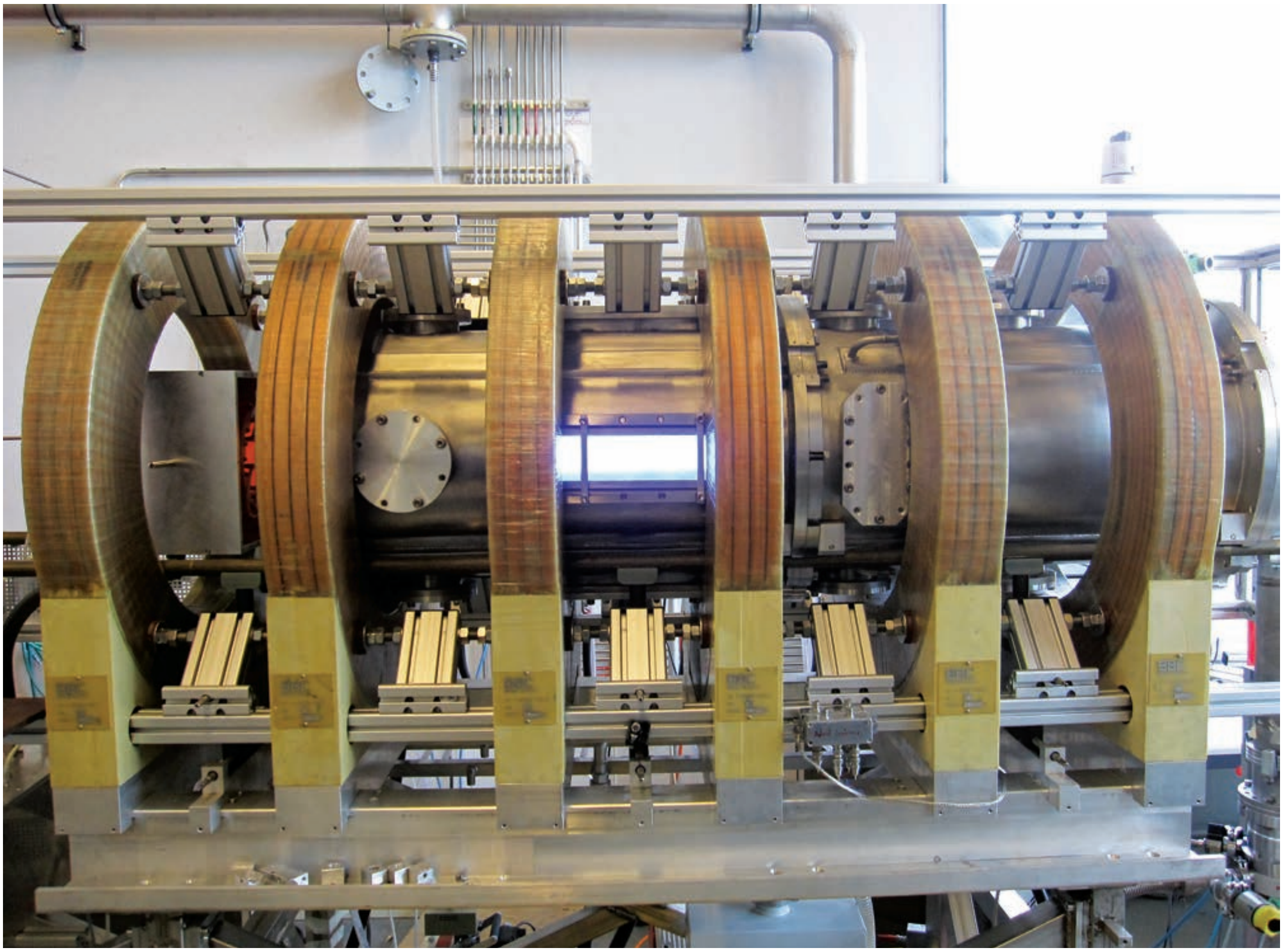
TORPEX

Blob dynamics in advanced magnetic geometries

Exploration of blob dynamics in complex magnetic geometries, which had already started in 2018 in the framework of a EUROfusion Enabling Research project, led by Prof. C. Theiler, has been pursued in 2019. After detailed discussions of the TORPEX scenario originally foreseen for the validation study, some challenges in modelling this scenario have been identified, such as unfavourable strike-point positions and very large values of the poloidal flux expansion. Motivated by these findings, an extensive study of possible alternative X-point scenarios on TORPEX has been performed. This resulted in the development of a new and rather elegant X-point configuration, as shown in **Figure 1**. Up-down symmetric, of minimum complexity, and featuring the main ingredients of SOL and X-point dynamics such as background flows, high levels of turbulence, and blobs, this configuration is a good testbed for X-point codes even in the absence of a confined plasma. Extensive experimental data has been collected in this scenario, including 2D profiles of density, electron temperature, plasma potential, and fluctuation measurements in ion saturation current and floating potential across the entire cross section at two toroidally separated positions. An experimental procedure to determine the plasma density and power source profile, needed as input for the codes, has also been developed and applied.



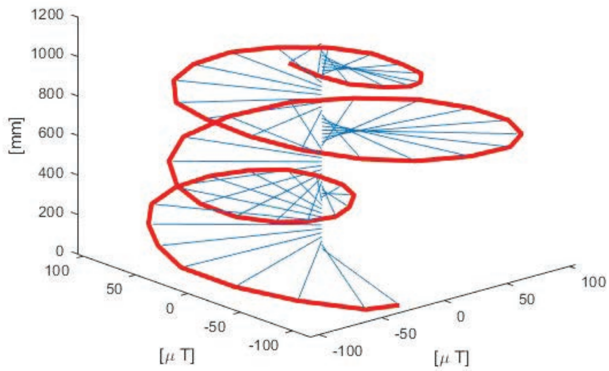
1 Left: X-point scenario originally foreseen for the TORPEX multicode validation work.
Right: New, up-down symmetric TORPEX X-point scenario developed within this project.



2 The resonant antenna ion device (RAID).

RAID

On RAID (see **Figure 2**), helicon plasmas are currently investigated as a way to produce the negative ions for the next generation of Neutral Beam Injectors to be used in future fusion reactors. Helicon plasmas may have advantages compared to Inductively Coupled Plasma (ICP) sources, for instance a reduced power consumption, operation at low pressure (<0.3 Pa) reducing the negative ion losses by electron stripping, and a 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. In 2019, we have continued our investigations on RAID with a particular focus on the physics of helicon waves in high density plasmas. We have equipped RAID with a three-axis magnetic probe, which enables a full three-dimensional characterization of helicon wave propagation. First measurements clearly demonstrate the propagation of helicons along the RAID plasma column, as shown in **Figure 3**. The results are compared with predictions of the most conventional helicon wave theory as well as with numerical simulations of the wave propagation in the RAID experiments.



3 Experimentally measured transverse magnetic field associated with a helicon wave propagating in a hydrogen plasma with 1.5 kW injected power.

Influence of Microstructure on Nanomechanical and Diffusion Barrier Properties of Thin SiOx Films Deposited on Parylene C Substrates

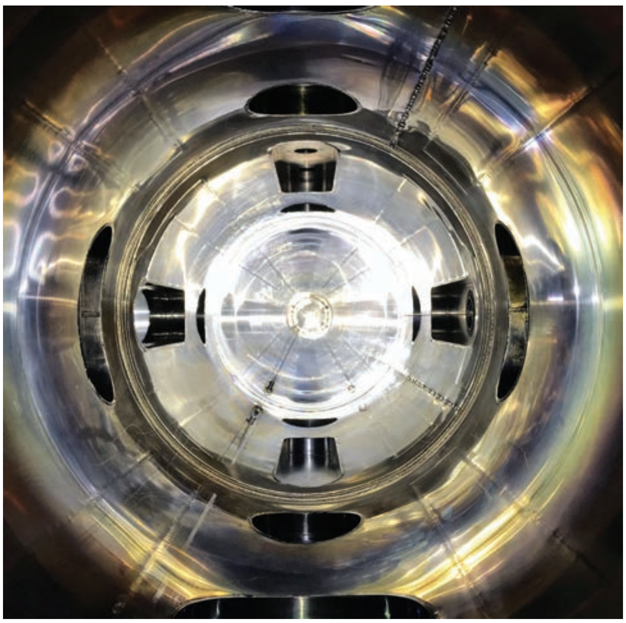
Thin metal oxide films are used as gas and water vapor diffusion barriers for polymer substrates in a variety of fields and purposes, including the food packaging industry, for selective drug delivery in biomedical applications, and microelectronics encapsulation. In collaboration with the Laboratory for Processing of Advanced Composites (LPAC) of EPFL and COMELEC SA, funded by the Swiss Innovation Agency, we have investigated the use of parylene C as a passivation barrier in the medical device field, due to its intrinsically low permeability, good dielectric properties, bio-compatibility, and conformal deposition ability. We used plasma-enhanced chemical vapor deposition (PECVD) to deposit SiOx thin films of varying thicknesses on parylene C substrates. The microstructure of SiOx coatings was analyzed using X-ray photoemission spectroscopy, nano-indentation, and spectroscopic ellipsometry. From this study, we concluded that barrier properties are the result of a complex interplay of microstructural features, with porosity, silanol, and carbon content playing important roles in the final thin film properties.

Plasma agriculture and plasma sterilization

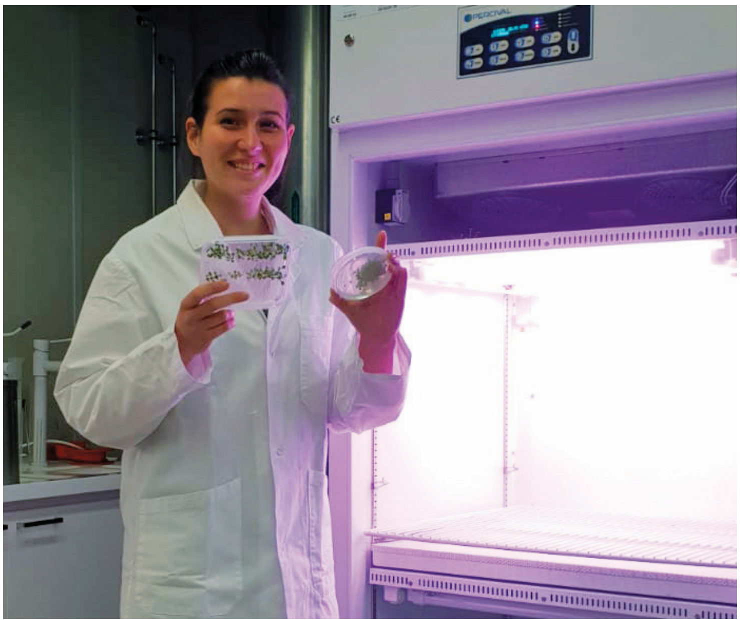
The use of non-thermal plasmas, i.e. non-equilibrium ionized gases, for biological applications such as decontamination, plasma medicine, and plasma agriculture, is a rapidly emerging field. The quasi-room temperatures, typical of non-thermal plasma treatment, make possible the treatment of heat-sensitive biological substrates, such as seeds and plants, to improve germination and growth, increase disease resistance, and decrease microbial contamination. In 2019, the bio-plasmas laboratory has been equipped with an improving set of diagnostics, including a pico-second laser fluorescence system, a Fourier Transform Infrared Spectroscopy system and an Electron Spin Resonance system. First measurements of plasma-generated reactive species, both in the presence and in the absence of biological substrates, have started in the field of plasma agriculture and plasma sterilization. The InnoSuisse-funded project, PhytoClean, in collaboration with Felco SARL, the Ecole d'Ingénieurs de Changins and HES-Yverdon successfully reached the first milestone. Using a high power generator developed by HEIG-VD (600 W with plasma output of 50 W), we have demonstrated disinfection of bacteria on bacterial cultures, using short plasma applications (10-30 s) with electrodes customized to 50 mm petri dishes. Vegetative forms of Bacillus subtilis (BBa4), the non-pathogenic reference bacteria for disinfection, are decreased by more than a factor of 100 within about 10 seconds, independently of the power level. Populations of phyto-pathogens like Pseudomonas (BPs3), and Xanthomonas (BXa1), decrease by 3 to almost 6 orders of magnitude.

Langmuir probes as a converging nozzle with sonic choked flow

Langmuir probes (LP) are one of the most fundamental diagnostics of plasma physics. Leveraging previous investigations of LP theory, we developed a close analogy between a two-fluid plasma description and the classical compressible fluid dynamics description. In this analogy, the simultaneous flows of the ion and electron fluids experience opposite electrostatic body forces in the inward radial flow of the plasma, which behaves as a converging nozzle. The often assumed boundary condition of sonic flow at the probe is explained as choked flow. Using classical fluid dynamics, we provide a physical interpretation of the sonic passage from subsonic to supersonic flow of the attracted species at the sonic radius.



Inside the RAID device



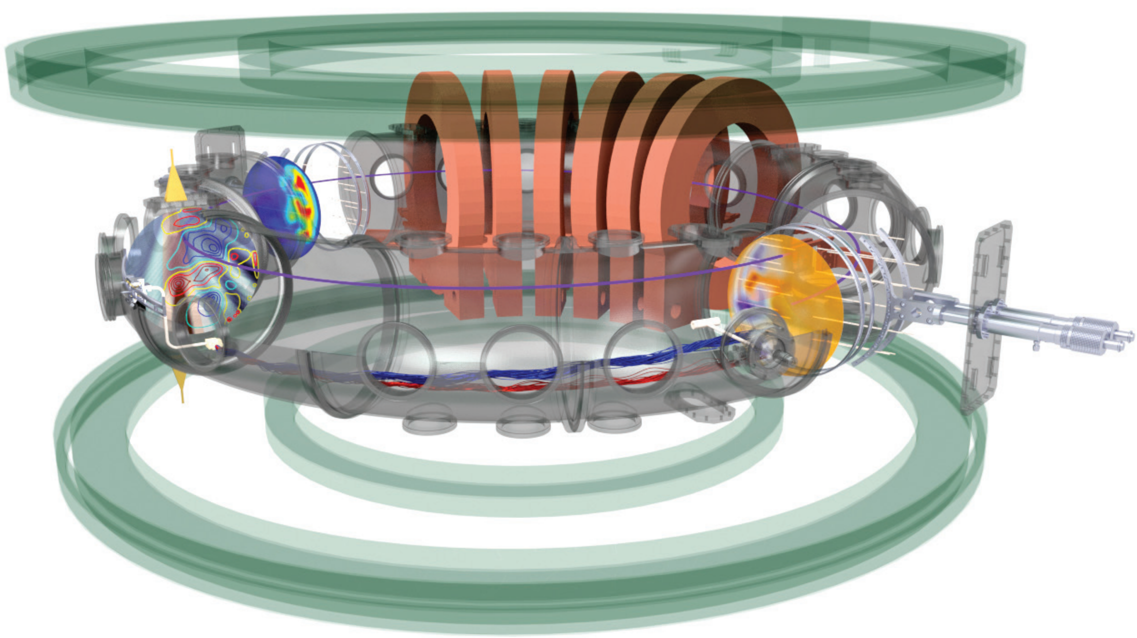
Alexandra Waskow, PhD student, in the Bio Plasma Laboratory

SUPRA-THERMAL ION DYNAMICS ON TORPEX

FABIAN MANKE, PhD student at SPC, supervised by Prof. Ivo Furno, investigates the dynamics of fast ions in turbulent magnetized plasmas in the TORoidal Plasma EXperiment (TORPEX).

Future fusion reactors will be operated in the burning plasma regime, in which the self-heating provided by the α-particles will dominate over the externally provided plasma heating. These α-particles are strongly supra-thermal as they are generated at 3.5 MeV in a quasi-Maxwellian background plasma that has temperatures of the order of tens of keV. Supra-thermal ion dynamics, and in particular their cross-field transport associated with turbulence, have been extensively investigated in TORPEX using a miniaturized suprathermal Li6+ ion source and an electrostatic detector system, shown in **Figure 4**.

Fabian conducted a comprehensive set of experiments to measure the time-intermittency of the supra-thermal ion beam in various non-diffusive regimes, ranging from sub- to super-diffusive. He clearly showed that intermittent supra-thermal ion current signals are determined by the meandering motion of an instantaneous ion beam, displaced by turbulent structures. He also developed, together with Marcelo Baquero, an analytical model to predict local intermittency from the time-average beam, which may be of direct interest for similar systems, e.g., in beam physics, or meandering flux-rope models for solar energetic particle propagation.



4 Schematic of TORPEX with its main elements as well as the fast ion injection and detection system.

Applied Superconductivity

Led by Dr **PIERLUIGI BRUZZONE** and based on the site of the Paul Scherrer Institute in Villigen, the superconductivity group focuses its activities 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 to carry out tests of high-current superconductor cables and joints, in particular for ITER, EUROfusion DEMO and CERN. Notable achievements in 2019 are described below.

DESIGN AND ANALYSIS

Innovative designs are explored for the Central Solenoid (CS) of DEMO to mitigate the impact of fatigue (large number of plasma burn cycles) on the design. Among other options, the separation of structural and hydraulic functions of the conductor jacket is explored, what would make acceptable for a local crack in the jacket material to grow through the wall thickness without compromising the hydraulic integrity of the coil. A variable aspect ratio of the winding pack is considered for the design of the Poloidal Field (PF) coils. A high aspect ratio reduces the peak field and allows for a more effective design. Nonetheless, the field at two of the PF coils exceeds 6T and call for Nb_3Sn technology rather than NbTi.

DEVELOPMENT

The copper for quench protection in the large DEMO conductors based on react&wind Nb_3Sn technology needs high conductivity in longitudinal direction and poorer conductivity in transverse direction to reduce the eddy current loss. In 2019, the fully satisfactory solution was achieved with a cabled stabilizer made of copper wires with CuNi cladding (see highlight on next page)

A novel technique has been set up to assemble Nb_3Sn joints for the inter-grade connections of the layer wound DEMO coils (react&wind technology). (see highlight on next page)

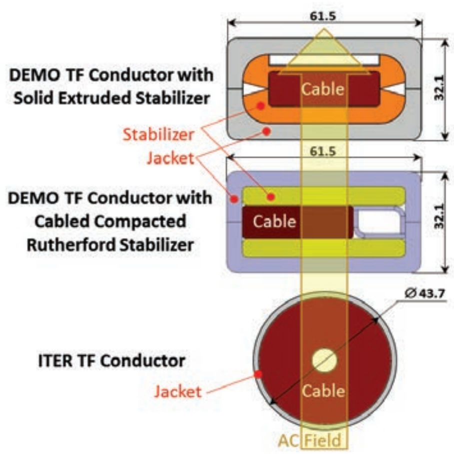
TESTING ACTIVITIES IN SULTAN

Over 20 weeks of SULTAN operation have been used for ITER. For Toroidal Field (TF) conductors, the test campaigns to investigate the performance degradation are completed. More tests are carried out on joint samples prepared at the industrial suppliers for ITER CS and ITER PF coils

Four test campaigns, for a total of 8 operation weeks, have been devoted to the innovative HTS prototype conductors for the SPARC (the compact high field tokamak project in the US), with a rich test program and dedicated instrumentation.

For EUROfusion DEMO, the test campaigns were dedicated to the react&wind conductor prototype with cabled stabilizer and to the novel inter-layer joint, both leading to successful achievements in terms of very low AC loss and very low joint resistance.

1



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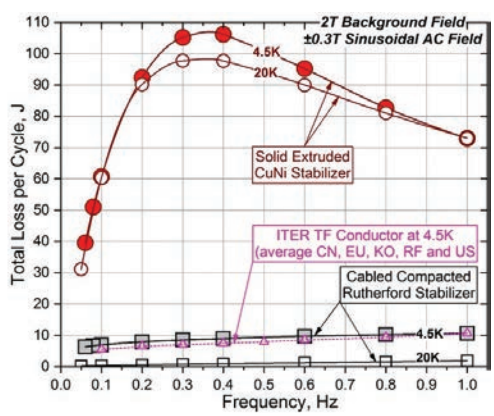


1 Tested conductors and direction of applied AC field

2 Results of AC loss measurements

SIGNIFICANT REDUCTION OF AC LOSS FOR DEMO

Dr. **BORIS STEPANOV** is the leading scientist for all tests at the SULTAN test facility at SPC, including the DC and AC tests of DEMO prototype Toroidal Field (TF) conductors, completed in 2019.

The two DEMO prototype TF conductors are assembled with the same superconducting flat cable but different stabilizers, one with solid extruded Cu/CuNi composite and the other with a Rutherford cable made of CuNi clad copper wires. The AC loss of the conductor with solid extruded composite was at unacceptable high level. Thus, to reduce AC loss, a cabled Rutherford stabilizer was developed. The cooling pattern has been modified in the conductor with cabled Rutherford stabilizer to provide a pre-compression of cable, see **Figure 1**.

The AC loss tests have been performed at 2T SULTAN background field, with sinusoidal AC field at a frequency range of 0.05-1 Hz, applied perpendicular to the wide surface of the conductor. The AC results are shown in **Figure 2**.

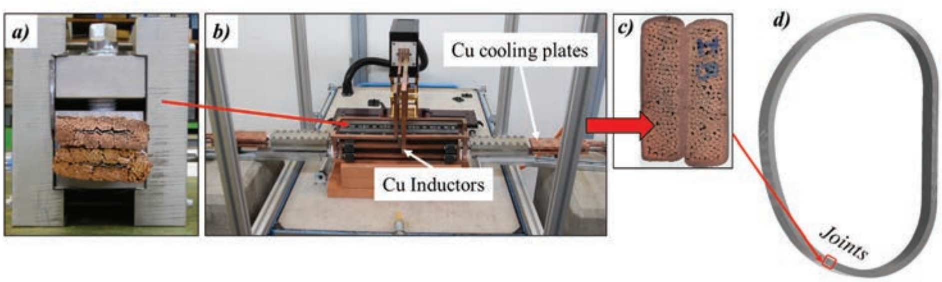
The total AC loss in the conductor with cabled stabilizer (gray squares) is over one order of magnitude smaller than in the conductor with solid stabilizer (red circles). The contribution of the eddy current loss (empty symbols from test at 20K) is less than 10% of the overall loss of the conductor with cabled stabilizer. whereas it is 90% with solid. **Figure 2** includes also the AC loss of the ITER TF conductor (average of tested CN, EU, KO, RF and US conductors) for comparison.

The cabled stabilizer has now become the baseline for the DEMO generation of conductors.

SUCCESSFUL TEST OF JOINT PROTOTYPE FOR DEMO TF MAGNETS DEVELOPED AT SPC

In September 2017 **VINCENZO D'AURIA** started his PhD under the supervision of Dr Pierluigi Bruzzone. His objective is the development of low-resistance joints between Nb_3Sn cables for high-field and high-current superconducting magnets. Nb_3Sn is a commonly used LTS material if high magnetic field is requested and becomes brittle after heat treatment at 650 °C. Vincenzo reached in 2019 the goal of manufacturing and testing in SULTAN the joint for the Toroidal Field (TF) coils of DEMO designed by SPC. Our TF design is based on the react-and-wind (R&W) technology, in which the cable is first heat treated and then wound to the coil final shape. This is possible despite Nb_3Sn brittleness thanks to the big DEMO TF bending radius and gives advantages in terms of Nb_3Sn performance. Our manufacture originally combines several technological tools to obtain the final joint (see **Figure 3**). For wider contact between the cables, we start by coating the cable ends using copper thermal spray and we mill the surface until it is flat. The overlap of matching cable ends is fitted into an Inconel-steel clamp, which exploits the thermal expansion coefficient of different materials to raise the pressure to 30 MPa when the temperature is 650 °C. A customized inductive heater rises the clamp temperature to 650C during 2 hours, in an inert nitrogen atmosphere that avoids the oxidation of the cable, while the cable ends are water cooled at 20 °C. In a real magnet, this would avoid the propagation of heat to the rest of the layers being at ambient temperature.

The joint, characterized by the excellent resistance of 0.84 nΩ at 10.9 T and 63.3 kA, is now the baseline for the DEMO R&W magnets.



3 (a) Inconel-steel clamp with a copper dummy joint. (b) Diffusion-bonding setup, including Inconel-steel clamp, inductive oven and cooled terminations. (c) Cross-section of copper coated dummy cables after diffusion bonding. (d) TF coil winding pack.

International Activities - ITER

Among the many research activities at SPC conducted in the frame of international collaborations, special efforts are carried out for ITER, for which Dr **TIMOTHY GOODMAN** leads the area of high power microwaves.

The European component test facility FALCON has been used intensively in 2019; first, to test the European 170GHz 1MW ITER gyrotron, and second for characterisation of guided components to be used in the ITER Upper Launcher. **Figure 1** shows the EU gyrotron RF conditioning unit (RFCU) and waveguide (WG) leading from the EU gyrotron to the EU RFL and the continuation of the WG through a General Atomics mitre bend (GA MB) to the spherical copper RF load (RFL).

The EU gyrotron was returned to the factory for refurbishment and the transmission line (TL) was removed to allow for installation of the ITER components to be tested. The refurbished gyrotron will be returned to FALCON in 2020 for continued testing. Two campaigns were carried out during the year for testing EU components: waveguides (WG), mitre bends (MB) and the RF load (RFL); though the latter is not strictly part of the EU delivery for the ITER Upper Launcher, its characterisation is vital to successful testing and interpretation of results for the components.

In addition, the facility was operated for several weeks in August under a Memorandum of Understanding between SPC and General Atomics (GA), and with the consent of Fusion For Energy (F4E), to test equipment that could be chosen by the United States ITER Project Office (USIPO) as part of their delivery to ITER.

Prior to 2019 testing, the power monitor mitre bend (PMMB) mirror - used to measure the instantaneous power and to protect the gyrotron in case of a change in operation mode - was identified as the source of a vacuum leak and was therefore replaced. The cooling of the mirror was also increased at that time, and the PMMB has functioned successfully for all of 2019. **Figure 2** shows the RU FALCON gyrotron that provides high power long pulses. The large box at the end of the source TL is used for measuring beam pattern in free space to allow retrieval of the phase and amplitude, while simultaneously providing personnel protection against stray RF radiation. The projection of the deduced beam on the mouth of the waveguide allows the mixture of propagating modes to be determined. This is essential information for ensuring that the mode purity meets the specifications so that the tested components will function properly.

Figures 3 and **4** show the setup of the first EU waveguide testing. During the first campaign, it was shown that the thermocouples that are inserted into the mirror of the mitre bend just behind the reflecting surface not only proved the high efficiency cooling of the mirror - stabilisation is reached after 3-4s, as predicted - but also showed a very good linearity with the calorimetric power. Once cross-calibrated, the thermocouples provide an easy, reasonably fast, and reliable power measurements when calorimetry is not available (e.g. when firing into a plasma). In the first campaign, excessive heating was seen in the waveguide. This was further investigated in the November campaign once more cleaned components were available.

Between the two EU campaigns the GA equipment was tested. First, a 3D printed 63.5mm mitre bend mirror was tested, comparing its behaviour with that of the standard one. Improved cooling with more-rapid temperature stabilisation, equivalent vacuum behaviour and heat loss closer to theoretical values were observed. The 3D printed mirror has remained in the transmission line since August without incident.

Figure 5 shows the parallel GA testing line, including the down taper, attenuator and tank load next to the EU gyrotron tower. Visiting scientists from GA participated in the testing.

The final campaign, at the end of the year, used various combinations of the waveguides shown in **Figure 6** to elucidate the discrepancy between theoretical and measured losses.

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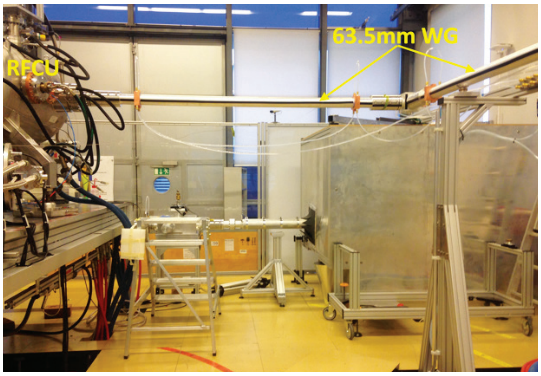
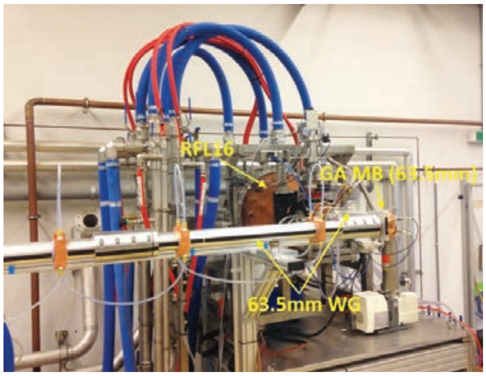


1b



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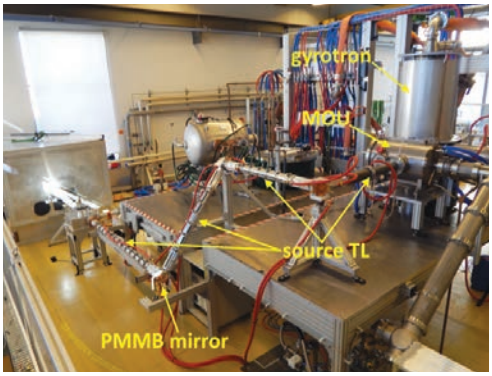

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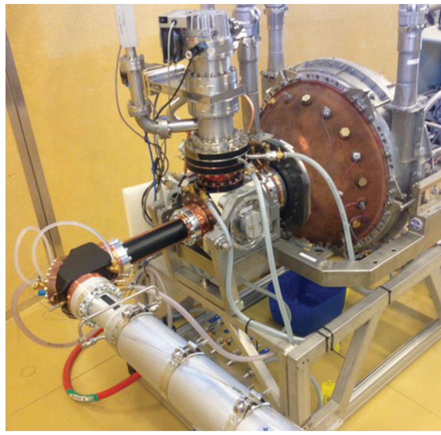

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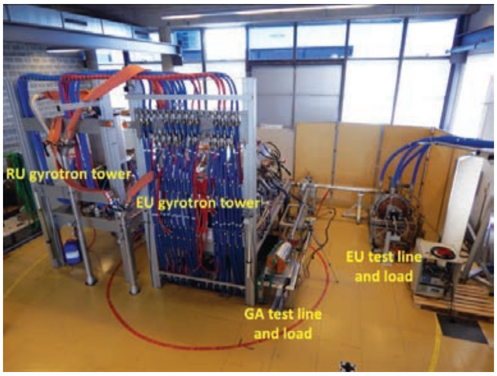

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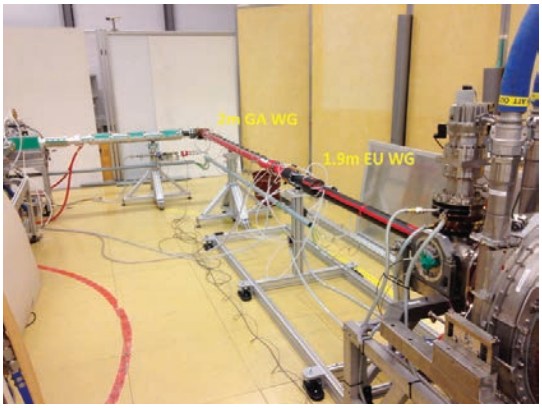


1 (a) The Transmission line leaving the RF Coupling Unit (RFCU) of the EU gyrotron, (b) the arrival of the transmission line at the 16-channel RF load (RFL16) for calorimetric power measurements.

2 The FALCON source consists of the gyrotron, Matching Optics Unit (MOU), 63.5mm transmission line (TL), high power switch and 50mm downtaper.

3 The SPC mitre bend, waveguide and RF load have been installed for the first EU transmission line campaign.

4 A closer view of the output end of the source transmission line.

5 The Russian and EU gyrotron towers are seen from the water cooling manifold side. The water manifold and high voltage connections allow switching between the EU and GA test lines within a few hours.

6 The waveguides of the second EU campaign consist of a water-cooled, 2m-long, Cu-coated, stainless-steel waveguide provided by GA and three EU WGs.

ITER, EUROPE AND SWITZERLAND

Fusion efforts worldwide continue to intensify, with focus on the completion of the ITER construction. To maintain momentum in the project and guarantee continuity in the transition from procurement to machine assembly, the ITER Council has reappointed Bernard Bigot to second term as Director-General.

Several countries are launching very ambitious fusion projects in addition to ITER, in view of the DEMO step, involving plasma experiments, materials and technology facilities. Some of these efforts involve private investors, and approaches that are complementary to those taken in publicly funded projects.

With the approach of the first operation of JT60-SA in Japan, the largest superconducting tokamak before ITER, several laboratories around the world and in Europe, among which our Center, are developing ideas and tools to extract as much information as possible from its scientific exploitation.

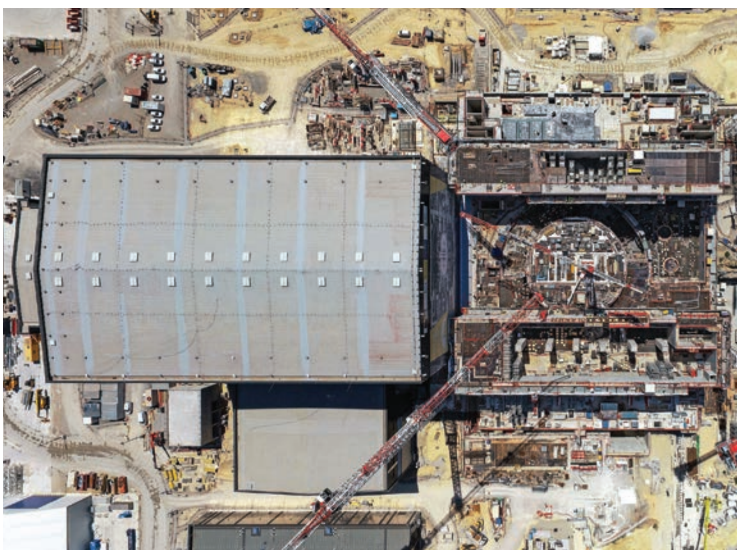
Europe plays a crucial role in the ITER project, via the procurement agency Fusion for Energy, the national laboratories, and industry. As an example of the European contribution to ITER, two landmark achievements in 2019 can be mentioned: the completion of the construction of the tokamak building, which is now ready to receive the various components of the device, and the delivery of the first piece of equipment for the heating of ITER plasmas to thermonuclear temperatures. The latter, a power supply for microwave sources, was in fact produced by a Swiss firm, which has developed its market and its capabilities also in conjunction with the activities of our Center.

In parallel with the ITER construction, the crucial role of Europe in fusion is manifest in the high-level R&D for ITER and DEMO conducted in the frame of the EUROfusion Consortium to progress along the European Roadmap to fusion energy.

This year, EUROfusion and Fusion for Energy have signed an agreement that will facilitate and intensify mutual collaborations for the benefit of the European fusion program, in view of both ITER and DEMO.

Preparations for the Deuterium-Tritium experiments on JET are continuing. For this, record neutral beam power was achieved this year, with up to 31MW injected into the plasma.

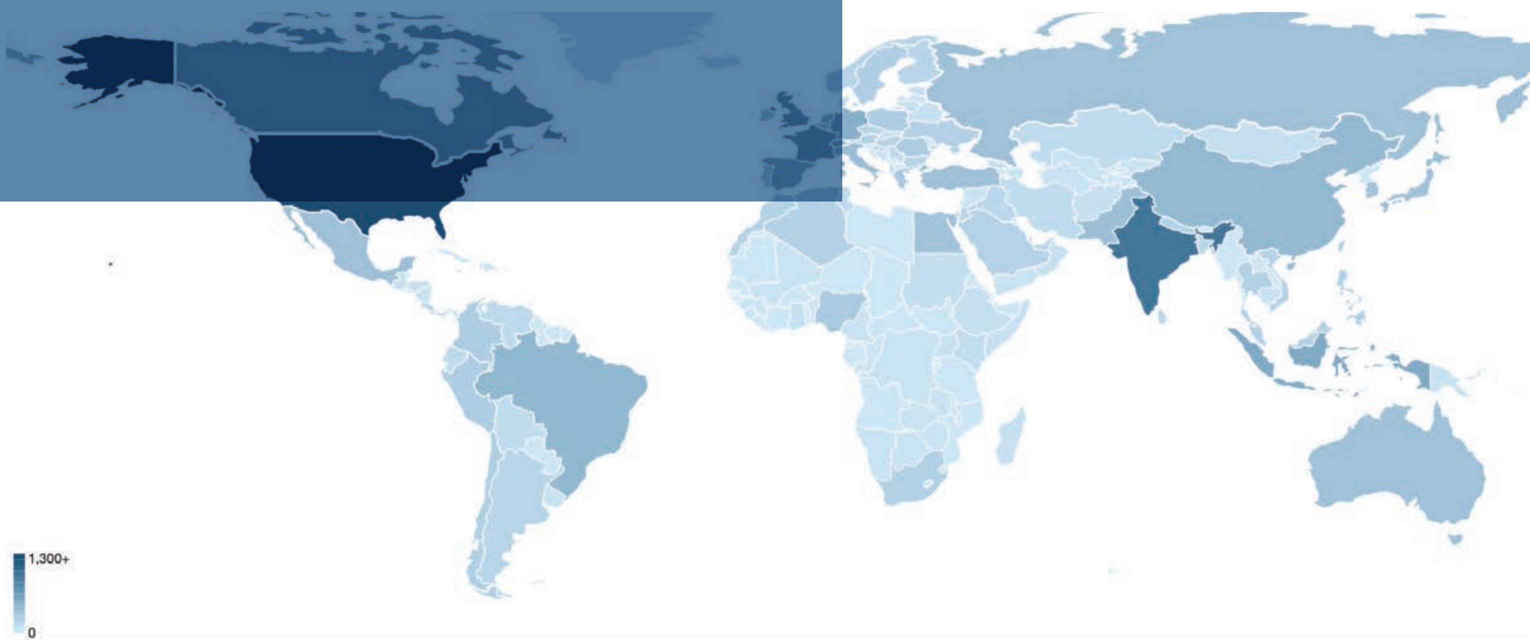
In parallel with the exploitation of the existing devices, the members of EUROfusion are preparing the strategy for Horizon Europe, the 2021-2027 European Research and Innovation Framework Programme. We count on the fact that the association of Switzerland to the research framework programme of Horizon Europe will be secured soon, as this will enable our Center to play a key role in EUROfusion, in ITER, and, over a longer time scale, DEMO.



TEACHING

One of the essential missions of the Swiss Plasma Center is to educate the future generations of plasma physicists and fusion scientists. They are the ones who will participate to the full power operation of ITER, design and construct DEMO and ultimately bring fusion power to the grid. Fulfilling this role is greatly facilitated by the fact that SPC is fully embedded in the Faculty of Basic Sciences of the EPFL, which includes in particular the Section of Physics and the Doctoral Programme in Physics.

Number of participants to the MOOC of SPC per country.



At the end of 2019 the SPC had 36 PhD students enrolled in the Doctoral School of EPFL and 17 Post-Doctoral researchers. In 2019, Rogerio Cabete, Oulfa Chellai, Jeremy Genoud, Emmanuel Lanti, Andreas Kleiner, Pedro Molina and Hamish Patten obtained their PhD in Physics.

The SPC is providing a complete curriculum of plasma physics courses at all levels: Bachelor, Master and Doctoral School, at the EPFL and within the European-wide education initiative FUSENET.

The SPC is giving a Massive Open Online Course (MOOC) on Plasma Physics Introduction and Applications. This course also includes lectures on plasma medicine, superconductivity for fusion and laser-plasma interaction, together with experts from Sorbonne University in Paris and Ecole Polytechnique in Palaiseau. The SPC MOOC on plasma physics is highly successful, with 10010 subscribed learners in 2019 from around the globe, see figure.

Besides plasma physics courses, SPC staff is teaching several classes in general physics, advanced physics, computational physics and mathematical methods for physicists.

18	Number of courses given by SPC staff at Bachelor, Master and Doctoral levels in 2019
76	Average number of students in the classes of these courses
1,070	Number of hours taught by SPC staff in these classes in 2019
95,282	Number of student-hours taught by SPC staff in these classes in 2019
10,010	Number of subscribed learners in the MOOCs on Plasma Physics of SPC
36	Number of PhD students at SPC by the end of 2019
33	Number of Master students supervised at SPC for semester, specialization and thesis projects in 2019

In 2019, three of our PhD students at SPC received awards for their thesis.

The 2019 winner of the Culham Thesis Prize is **KEVIN VERHAEGH** for his thesis on “Spectroscopic investigations of detachment on TCV: Investigating the role of atomic physics on the ion current roll-over and the dynamics of detachment in TCV”, which he conducted at SPC under the supervision of Prof. Bruce Lipshutz at the University of York and Dr MER Basil Duval at SPC. The Culham Thesis Prize, jointly coordinated by the Culham Centre for Fusion Energy (CCFE) and the Institute of Physics (IoP), is awarded to the candidate who has displayed the highest degree of excellence in the execution of the scientific method as witnessed by the award of Doctor of Philosophy in plasma science from a UK or Irish university in the last two calendar years.

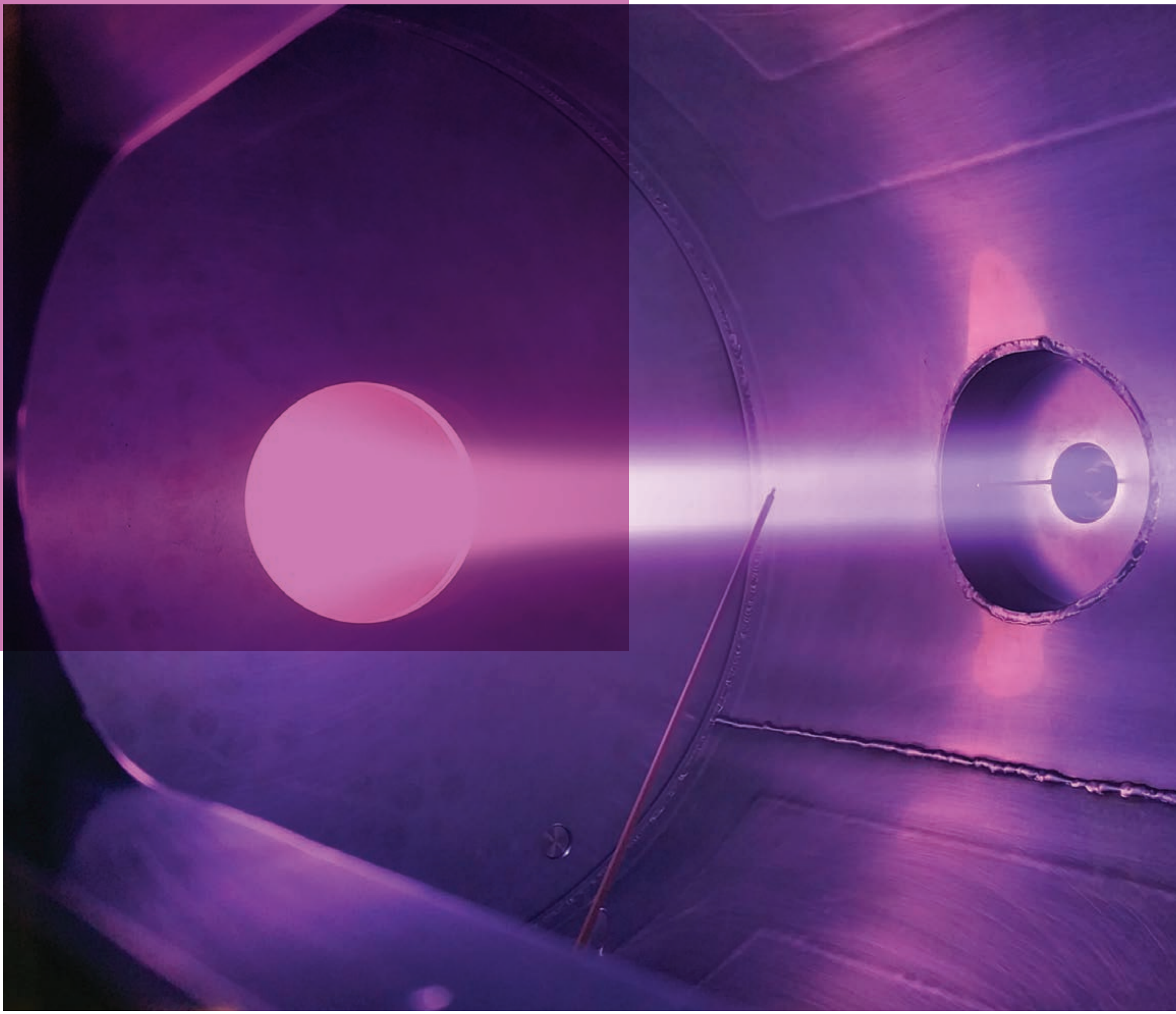
At the 2019 edition of the European Physical Society Conference on Plasma Physics, **AYLWIN IANTCHENKO**, who is supervised by Dr MER Stefano Coda, received the high recommendation of the Kyushu University Itoh Project Prize for his work on “Modeling of turbulent fluctuations measured in the TCV tokamak with gyrokinetc simulations and a synthetic phase contrast imaging diagnostic.” This acknowledges the substantial progress that was achieved in modelling localised measurements of turbulent electron density fluctuations, obtained with the tangential phase contrast imaging (TPCI) diagnostic installed on the TCV tokamak. The modelling is done in two steps. First, nonlinear flux-tube gyrokinetic simulations are performed taking into account realistic TCV geometry and profiles. A synthetic diagnostic is then applied to the simulated density fluctuations to model the experimental measurement procedure, allowing detailed comparison between simulation and experiment.

ROGERIO JORGE, who made his PhD thesis under the joint supervision of Prof. Paolo Ricci at SPC and Prof. Nouro Loreiro at MIT, received the 2019 EPFL Physics Thesis Distinction. This award is given to the best 8% PhD theses within the EPFL Doctoral Program in Physics (EDPY). It recognizes the PhD students who have distinguished themselves by a research of the highest quality in physical sciences. In Rogerio Jorge’s thesis, “A moment-based model for plasma dynamics at arbitrary collisionality”, drift-kinetic and gyrokinetic models able to describe the plasma dynamics in the tokamak periphery have been developed, which take into account electrostatic fluctuations at all relevant scales, allowing for comparable amplitudes of background and fluctuating components. In addition, the models implement a full Coulomb collision operator, and are therefore valid at arbitrary collisionality regimes.

OUTREACH

The Swiss Plasma Center recognizes the importance of outreach activities and conducts a variety of initiatives, encompassing visits of the Center, conferences given on-site or outside, as well as the publication of printed or electronic documents for the general public.

Visitors can view the plasma inside the RAID device.



The Center welcomed about 3200 persons in more than 120 visits to discover its activities. Most visitors were students aged from 12 to 20, but visits for senior scientists were also organized. For instance, professors of Tokyo University or Alumni from Harvard University or simply EPFL professors had the opportunity to visit the Center including walking around the TCV tokamak.

In addition, between 2000 and 3000 persons visited the Center during the Open Doors which were held in the frame of the 50th anniversary of EPFL.

In 2019, the World Conference of Scientific Journalism took place at the Swiss Tech Convention Center. Journalists then had the opportunity to visit EPFL labs, including the Swiss Plasma Center, and meet scientists during so-called Lunch@Labs guided tours.

A Swiss German TV crew came to interview Prof. Christian Theiler about his research. All together they visited ITER as well. It resulted in a 15 minutes program broadcast in prime time on present and future prospects for fusion energy.

The movie 'Let There Be Light' has been presented in the city of Lausanne on the occasion of a large public event organized by the Cantonal and University Library of Lausanne. Visits of the Swiss Plasma Center were also proposed to the public for those who wanted to deepen knowledge about the subject.

SERVICES AND ADMINISTRATION

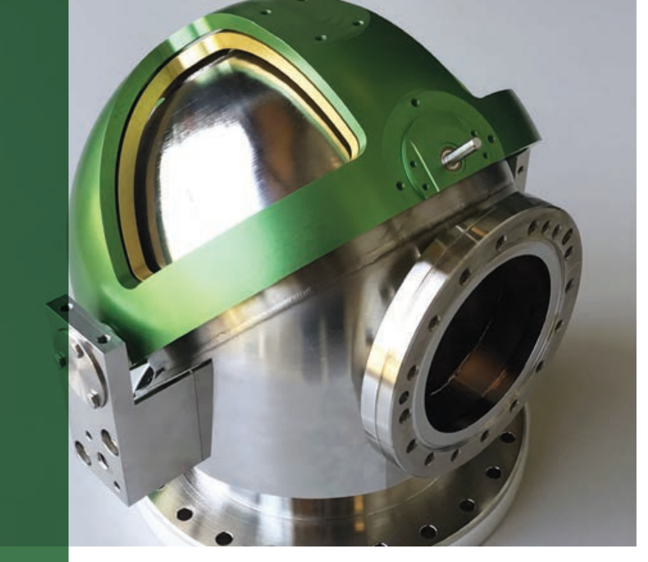
The Swiss Plasma Center could not reach its objectives without a strong technical and administrative support.

Dr Yves Martin

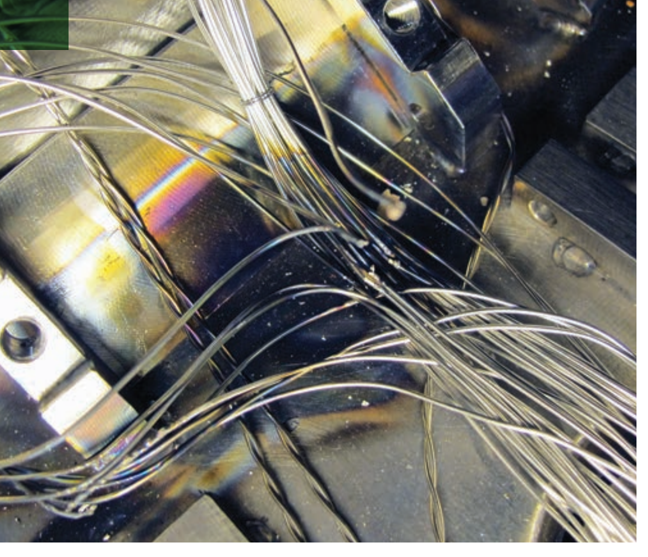
CAO & HEAD OF SERVICES

Dr Christian Schlatter

CFO



ECH Launcher to be installed on top of the TCV vessel



Langmuir probes wiring on the TCV floor to be covered by C-tiles

Technical support is provided by some 50 engineers and technicians distributed to five services

Matthieu Toussaint

MECHANICS CONSTRUCTION OFFICE AND WORKSHOP

Frédéric Dolizy

VACUUM TECHNICS

Damien Fasel

ELECTRICAL HIGH POWER INSTALLATIONS

Blaise Marlétaz

ELECTRONICS

Joan Decker

IT

The administrative and financial team is composed of 7 persons.

All technical services are continuously solicited to provide the physicists with support of various kinds and are requiring a broad range of competences.

2019 was marked by a major opening of TCV which lasted from January to July. The main goal of this opening was to install the baffles. On this occasion, all existing tiles were removed and cleaned before being re-installed in the machine for most of them, the remaining ones being replaced by the baffles. In the meantime, several tiles underwent modifications for holding dozens of new Langmuir probes. Several diagnostics, the gas injection valves and glow antennas had to be moved to more appropriate positions for operation with baffles. Eventually, high field baffles were successfully installed, and while waiting for the late arrival of the low field side baffles, TCV has been closed and operated for a few weeks, before being able to install the second part.

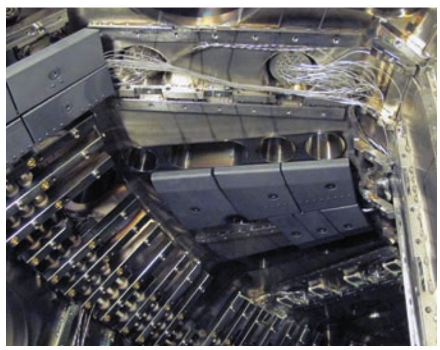
In parallel, the ECH system of TCV evolved with wide progress in the installation and start of the new 1MW gyrotrons. The first 1MW dual-frequency gyrotron has been tested and the preparatory work for the second one, such as stand, table and matching optics unit (MOU), was performed.

In the area of Basic Plasmas and Applications, the RAID was upgraded with new diagnostics and the Bio-plasma lab was improved with several innovations.

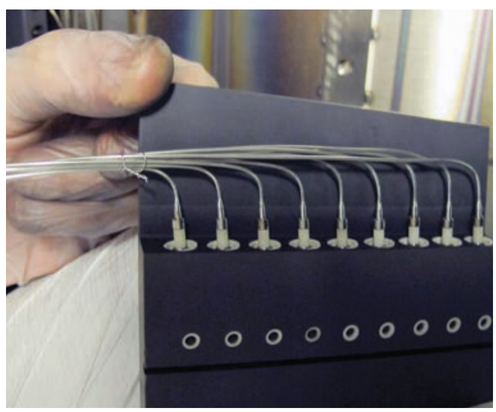
For its part, the European gyrotron and ancillary systems test stand was upgraded according to the delivery of the material and requests related to the contracts with Fusion for Energy.

C-tiles, with Langmuir probes passage, before and after sandblasting

New 1MW dual frequency gyrotron and new waveguide arrangement



TCV ceiling during Langmuir probes and C-tiles installation



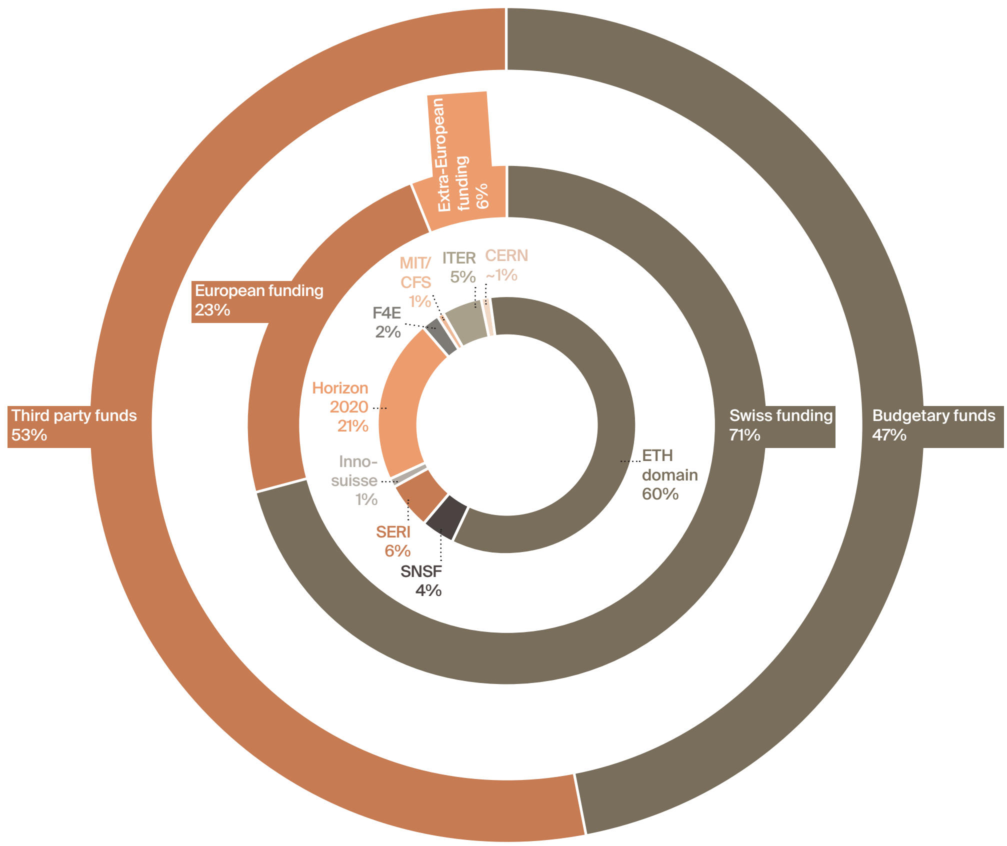
C-tile equipped with Langmuir probes cabling and connections

FACTS AND FIGURES

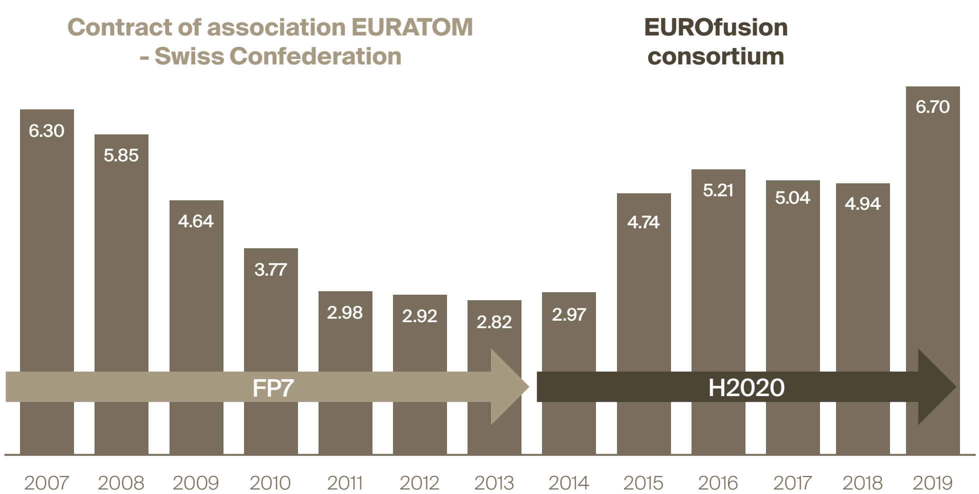
SPC staff with Bernard Bigot (middle, with the orange tie), Director-General of the ITER Organization, during a visit in October 2019

FUNDING 2019

including indirect costs



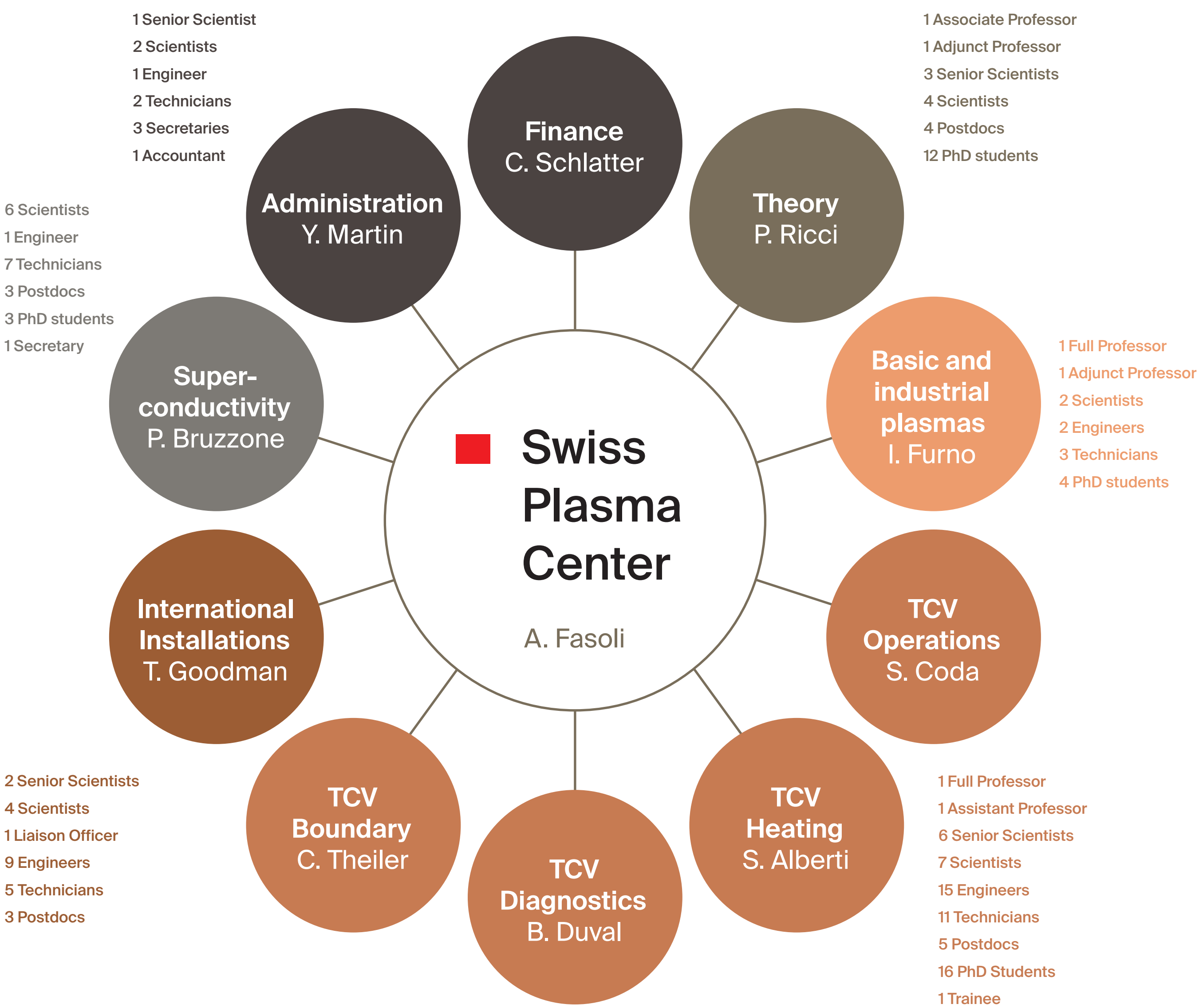
EUROPEAN COMMISSION CONTRIBUTION [MCHF]



HUMAN RESOURCES

169	Total headcount
141	Full-time Equivalents
37	PhD students (FTE)
14	Post-Docs (FTE)
28	Collaborators joined SPC in 2019
22	Collaborators left SPC in 2019

STRUCTURE



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