EPFL

SWISS PLASMA CENTER

ANNUAL REPORT 2020

Swiss Plasma Center

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Letter of the Director

We all know that the year 2020 has been severely marked by the Covid-19 pandemic. In spite of very dramatic and demanding circumstances, it is an element of pride to notice, retrospectively, that the activities of the Swiss Plasma Center, and, in general, of fusion research, have progressed very successfully.

All core activities of the Swiss Plasma Center in plasma physics and fusion energy have continued, with a combination of home working and on-site technical and experimental activities, in the modality that was allowed by the Swiss and EPFL rules. These activities contributed to enlarging our physics understanding of plasmas of interest for magnetic fusion, both in the core of confinement devices and at their edge, and to advance the exploration of plasma applications and related technologies.

The projects discussed in this report are coordinated in the frame of eight research lines and involve about 170 staff members, including 39 graduate students and 27 postdoctoral researchers.

The operation of the TCV tokamak, the main experimental facility of the Center, was for a part integrated into the EUROfusion consortium for the development of fusion energy, and partly done for the domestic programme, of which a significant part is dedicated to PhD thesis projects.

In 2020, the TCV vacuum vessel was vented from January to March for maintenance and installations, and primarily to remove the divertor baffles that were used in the previous campaign to explore the physics of plasma exhaust, a significant part of the EUROfusion tokamak physics programme. Then, an EPFL campus-wide shutdown during the first phase of the pandemic delayed the restart of operations by two months, but the adoption at the Swiss Plasma Center of novel practices relying strongly on remote working and videoconferencing allowed us to recover a robust stride on TCV, as well as on TORPEX and in theory and numerical simulations.

The TCV tokamak was operated intensively from June to December 2020 and we ended the year with a total of 2356 completed plasma discharges. The EUROfusion share of the programme was smaller than usual (12%), largely as a consequence of the difficulty or impossibility to travel for our international partners.

The analysis of the results obtained in the first part of the year confirmed that with the baffles, the hot core plasma is efficiently separated from the cold edge region with a substantially enlarged operational window.

We also probed and documented the advantages that characterise plasmas with an inverted D shape, referred to as negative triangularity, with equal ion and electron temperatures and high normalised pressure, necessary conditions for being of interest for DEMO.

These results, and others obtained in the course of the year using advanced plasma and magnetic configurations in the plasma edge region, provide invaluable input for the operation of ITER and for the conceptual design of the DEMO device.

The final phase of the multi-annual upgrade project co-sponsored by the Swiss government was undertaken, including the initial commissioning of the second of the two new dual-frequency gyrotrons, first-of-a-kind microwave sources that provide MW-level power at two different frequencies. Significant improvements in the TCV diagnostic systems were implemented, in particular for the plasma edge and the divertor.

Further crucial tests of ITER conductors were conducted on the SULTAN device at the PSI Villigen site within the applied superconductivity group, which also focused on advanced novel concepts for high-temperature superconductors for parts of the magnets and for joints, both for DEMO and for the next generation of particle accelerators for high energy physics.

Given the size, costs and timescales of fusion experiments, the role of theory and numerical simulations in the European and international fusion community is continuing to grow. The theory group of the Swiss Plasma Center is at the forefront of this effort.

In 2020, such prominent role was testified by the attribution to EPFL of one of only five Advanced Computing Hubs of EUROfusion. This research hub will be led by the Swiss Plasma Center and bring together a diverse group of scientists from EPFL's Institute of Mathematics, the SCentific IT and Application Support (SCITAS), the Swiss Data Science Center, and the Laboratory for Experimental Museology.

These experts will provide scientific and technical support to European fusion researchers for enabling and optimizing their applications.

Fundamental research activities continue to be undertaken on the TORPEX device, in particular on disentangling basic elements affecting the trajectories and the transport mechanisms across magnetic fields of suprathermal particles interacting with plasma turbulence.

The physics of helicon plasmas, produced in the RAID device using novel birdcage resonant antennas, has been investigated for applications to negative ion beam sources for fusion as well as for wake-field particle acceleration in the framework of the CERN-based AWAKE collaboration.

In the bio-plasma laboratory, we continued the investigation of the interaction between plasmas and living organisms, with plasma-based treatments for agriculture applications and experiments with plasma-activated water revealing huge potential to kill different bacteria strains.

Among the national and international prizes that the members of the Swiss Plasma Center have won last year, I am particularly proud of the 2020 Nuclear Fusion best paper award that was granted to Christian Theiler by the IAEA and the Nuclear Fusion journal's Board of Editors, as this recognizes not only an outstanding piece of work that is central to our scientific effort, but also the importance of collaborative efforts within our teams and with all of our European and international partners.

Finally, I wish to reiterate my appreciation for the generosity, foresight and flexibility of all 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 I would like to express my deep gratitude to all of the members of our teams, at all levels, who have shown not only extreme professionalism, but also a commitment and dedication that allowed us to continue to strive despite the exceptionally enduring circumstances that we all lived in 2020.

PROF. AMBROGIO FASOLI

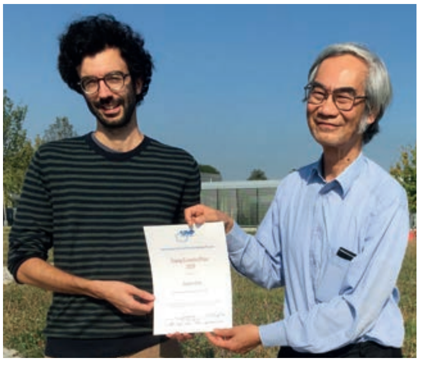
RESEARCH HIGHLIGHTS

In the following pages, the main highlights that were achieved in 2020 are presented by the respective heads of the research lines at SPC. We emphasize that these are the result of the commitment of teams of physicists, supported by strong and dedicated technical and administrative staff, without whom success would not have been possible.

AWARDS

The Nuclear Fusion Award is celebrating papers of the highest scientific standard that make a significant contribution to their field. In 2020, this award was attributed to Prof. **CHRISTIAN THEILER**. He is the lead author of the paper “Results from recent detachment experiments in alternative divertor configurations on TCV”. The Board of Editors notes in particular that: ‘this impressively detailed and systematic work presents detachment studies across a variety of divertor geometries. [...]. This work is important as future devices such as DEMO will require a thorough understanding of the detachment processes in order to choose the optimum divertor solution.’

Prof. Christian Theiler receiving the 2020 Nuclear Fusion Award from Prof. Ambrogio Fasoli



Dr Joaquim Loizu receiving the IUPAP2020 Young Scientist Prize from Prof. Minh Quang Tran

The IUPAP’s (International Union of Pure and Applied Physics) 2020 Young Scientist Prize in plasma physics was awarded to Dr **JOAQUIM LOIZU**, researcher in the theory group of SPC. This prize is awarded each year to a young international scientist for outstanding research. The prize was attributed to him ‘in recognition of his seminal work in the fundamental understanding of three-dimensional magneto-hydrodynamic equilibria and of the interaction of a plasma with a solid wall.’

TCV Tokamak

The TCV tokamak was operated intensively from June to December 2020, in spite of the challenging constraints imposed by the Covid-19 pandemic. Dr **STEFANO CODA**, Senior Scientist (MER) leads the TCV Operations and describes below the main findings of this research in 2020.

The vacuum vessel was vented from January to March for maintenance and installations, and primarily to remove the divertor baffles that were used in the previous campaign - and that are now being reinstalled in early 2021. A campus-wide shutdown during the first phase of the pandemic delayed the restart of operations by two months, but the adoption of new practices relying strongly on remote working and videoconferencing allowed us to recover a robust stride and we ended the year with a total of 2356 completed plasma discharges. The EUROfusion share of the programme was smaller than usual (12%) but is due to climb considerably in 2021.

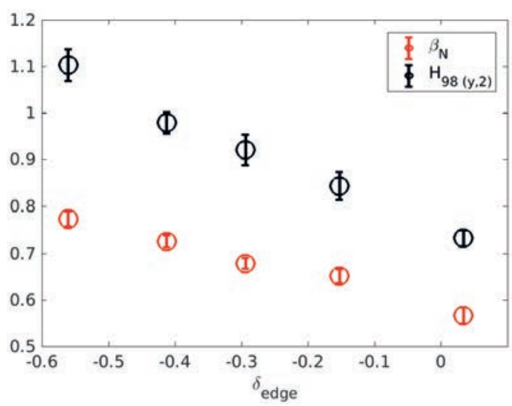
The core-physics portion of the domestic programme was characterized by a greater-than-usual emphasis on plasma configurations alternative to the standard ones around which the ITER experimental reactor is being built. These alternatives are explored as risk mitigation strategies for a future energy-producing reactor, DEMO.

Negative-triangularity shapes, pioneered by TCV in the 1990s, were revisited extensively in this campaign, taking full advantage of the device's shaping flexibility to explore a broad range of shapes, both diverted and limited, in particular by varying the upper and lower triangularities independently. This work confirms the enhanced confinement of this configuration, with a record $\beta_N \sim 3$ reached with NBI heating. (The quantity β_N is a measure of the capacity of the tokamak to hold a certain plasma pressure). This is opening the tantalizing prospect of operating a DEMO reactor free from deleterious Edge Localized Modes (ELMs) while having, although in a nominally "low" mode of confinement (L-mode), a confinement as good as nominally 'high' (or H-mode) in a standard, positive triangularity plasma.

The study mapped out the detailed dependence of transport and confinement on shape (**Figure 1**), the macroscopic stability limits, and the exhaust properties and particularly access to divertor detachment. The associated physics, pertaining especially to turbulence, fast-ion dynamics, and scrape-off layer (SOL) properties, was investigated in parallel.

A second, more exotic alternative is the doublet, featuring two magnetic axes and an internal separatrix, and carrying a long-held theoretical promise of enhanced performance. Following encouraging results obtained in 2017, new, systematic attempts were made to obtain stationary doublet plasmas. To this aim, a new procedure was developed to achieve a reliable and reproducible breakdown and early ramp-up with two separate current channels. The insertion of feedback controllers allowed us, for the first time, to maintain two separate, stable plasmas in the chamber. While attempts to slowly merge these separate plasmas into a stationary doublet (**Figure 2**) have not yet met with success, they did result in the validation of new control tools and improved physics understanding, which constitute a strong basis for pursuing the concept further in future campaigns.

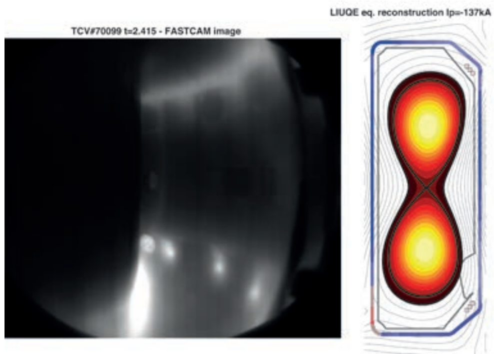
In the mainstream of ITER-relevant scenarios, systematic work was performed to study the variation of L-H transition properties with the main ion species (see **Highlight 1**, next page). A comparison was also made between the pedestal properties in the presence and absence of the gas baffles, in discharges with strong ELMs. While the pedestal density is similar in the two cases, the pedestal temperature is somewhat higher with baffles; this behaviour seems correlated with a lower separatrix-to-pedestal density ratio in the latter case.



1 Dependence of Ohmic L-mode confinement and β_N on edge triangularity.

Particle transport and its dependence on the ion species were investigated in L-mode through modulated gas puffing, over a broad density range to explore different turbulent transport regimes. The species dependence of both diffusive and convective transport is being analyzed in concert with modelling.

With a high-power-density neutral beam, a rich phenomenology of fast-ion-related instabilities has been observed in recent years, including several Alfvén modes and geodesic acoustic modes. Notably, the modes do not appear with a hydrogen beam or at low elongation. The effect of current drive by electron cyclotron waves (ECCD) on the modes was investigated, with strong differences observed between co- and counter-ECCD. A newly installed Fast Ion Loss Detector was usefully employed to delineate the reciprocal effect of these modes on the fast-ion population.



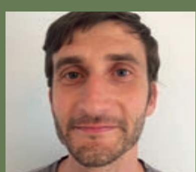
2 Visible-light camera image and equilibrium reconstruction of a transient doublet.

One of the direct concerns for a fusion reactor is the generation of runaway electrons by disruptive events. Their potential for damaging the device structure motivates a muscular research programme on TCV. The past year saw the first development of diverted runaway discharges, and a study of the possible formation of a runaway population during plasma start-up. In addition to applying multi-spectral imaging of synchrotron radiation to tomographic reconstructions, more diagnostics were brought to bear on the runaway problem, including vertical ECE radiometry and rf detection of emitted whistler-type waves. A wealth of data is now available to constrain modelling. A specific experiment was performed to explore whether a runaway discharge could be refueled to convert it into a thermal plasma discharge, effectively restarting the scenario. This was fully successful, with complete elimination of the seed runaway population.

Further studies were performed on the disruption problem itself, in particular to assess the predictability of the location of maximum plasma-wall interaction, which was found to depend primarily on the plasma shape.

The development of real-time control tools remains a mainstay of our programme, as evidenced in **Highlight 2**. Various machine learning methods were also tested for identification of TCV confinement regimes.

EXTENSION OF THE HIGH CONFINEMENT REGIME TO HYDROGEN AND HELIUM PLASMAS



For ITER operation in the high confinement mode (H-mode) it is important to understand the dependence of the H-mode power threshold, $P_{L\text{-}H}$, on the main ion composition. Not only will fusion operation be performed in mixed deuterium-tritium (D-T) plasmas, but also the initial pre-fusion phase will use helium (He) or, preferentially, hydrogen (H) plasmas.

Recent experiments on the TCV tokamak have been conducted by **BENOIT LABIT**, staff scientist at SPC, to document the L-H power threshold for different plasma parameters (magnetic field, plasma current, plasma density) for hydrogen and helium plasmas and to compare these with the deuterium case. To determine the threshold, the power injected through a neutral beam (operated in either D or in H) is progressively increased until the L-H transition occurs. In agreement with the scaling laws from an international database, $P_{L\text{-}H}$(H) is about twice as large than $P_{L\text{-}H}$(D) (**Figure 3**). This might be a concern for the pre-fusion power operation of ITER, when only limited auxiliary heating will be available. Therefore, ways of decreasing $P_{L\text{-}H}$(H) are desired and helium doping is one possibility.

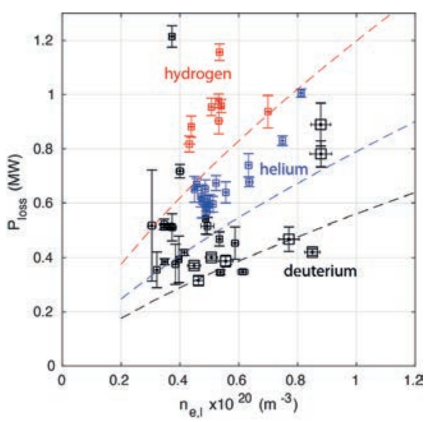
To monitor the helium concentration, **DMYTRY MYKYTCHUK**, post-doctoral researcher at SPC, employed a high-resolution spectrometer to measure charge-exchange (CX) reactions of helium ions (He++) with the atoms of the neutral injector. Due to the integration along the line-of-sight, the measured spectrum contains the 'active' He++ emission originating from the CX reactions in the core plasma, as well as 'passive' emission from other atomic processes occurring mainly at the plasma edge. To correct for the unwanted 'passive' emission, the background measurement recorded in similar plasma conditions but with the neutral beam off (**Figure 4**) is subtracted. By comparing the absolute intensity of the He++ emission with collisional-radiative calculations he is able to estimate the helium density in the plasma.

IMPROVED MAGNETIC CONTROL OF PLASMA SHAPE AND POSITION

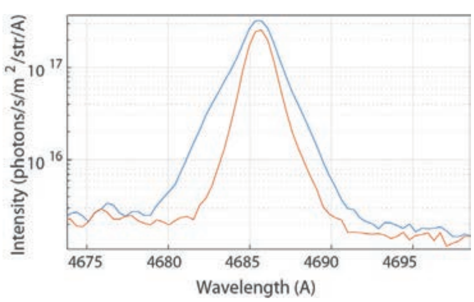
Magnetic control of tokamak plasmas refers to the ability of estimating, stabilizing and regulating the position and shape of a tokamak plasma in real-time. This is crucial to confining the plasma, regulating its interaction with the surrounding solid structures, and improving fusion performance. Simulation and experimental tools for real-time magnetic control are being optimized for the TCV tokamak in order to fully exploit its extreme shaping flexibility and its state-of-the-art digital control system.

Research carried out by **FRANCESCO CARPANESE** in his PhD thesis allowed him to improve the estimation of the plasma shape, position and internal profiles using an approach called Kinetic Equilibrium Reconstruction. In this approach, together with the external magnetic measurements, information about the internal distribution of plasma current and pressure, obtained through a combination of diagnostics and modelling, is used as an additional constraint. This yields a more accurate picture of the internal state of the plasma. A real-time implementation was demonstrated in TCV for the first time. In addition, a new free-boundary tokamak simulator, named 'FGE' (Forward Grad-Shafranov Evolution), was developed which allows accurate and efficient simulation of plasma magnetic evolution on TCV, see **Figure 5**, providing a useful tool for designing vertical stability and shape controllers.

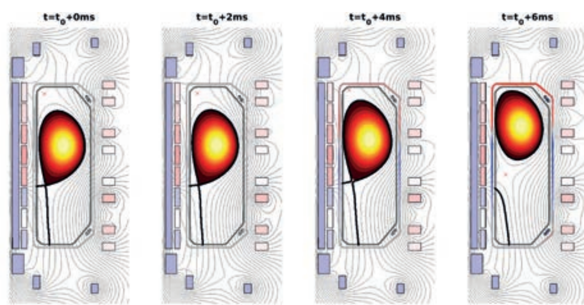
These new developments provided valuable input for the PhD thesis work of **FEDERICO PESAMOSCA**, which focused on improving the magnetic control on the TCV tokamak. Specifically, the decoupling of the plasma shape and position control problems - which share the same poloidal field coils as actuators - was studied using multivariable control techniques. This led to a separate design of the position and shape control loops combining a frequency separation approach and optimal selection of actuators. The stabilisation of the plasma vertical position, a necessary requirement of all high-performance plasmas, was optimised with a model-based algorithm applying techniques from modern control engineering. Improved control performance was demonstrated in dedicated experiments in TCV, see **Figure 6**, showing the ability of the position controller to stabilise different plasmas with a reduction of the control actions.



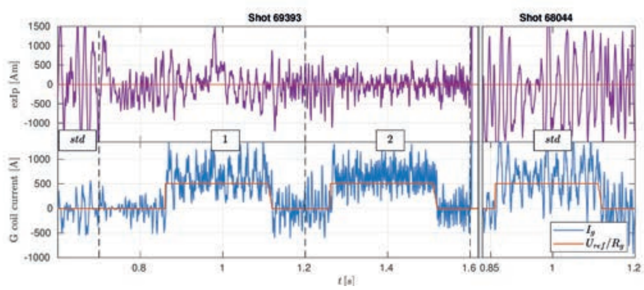
3 L-H power threshold as a function of plasma density (same plasma current, plasma shape and magnetic field) for 3 different main ions. For medium densities, experimental findings agree with scaling laws (dashed lines).



4 Absolute emission intensity of the He++ n=4 – n=3 transition at λ = 4686 Å, measured in the plasma core. The blue spectrum is measured with the neutral beam ON and the red one when the beam is OFF. The "active" signal i.e. the difference between the two spectra is used to infer the helium density.



5 Simulation of uncontrolled vertical displacement in TCV using the new FGE free-boundary tokamak simulator. The rapid upward movement of the plasma is clearly visible including the (color-coded) time-evolving currents in the coils and vessel structure surrounding the plasma.



6 Demonstration of improved vertical position control on TCV: a reduced oscillation in the plasma position (top) and actuator action (bottom) is visible in phases (1) and (2), which used the optimised controller, with respect to phase 'std' which used the standard TCV vertical controller.

TCV Diagnostics

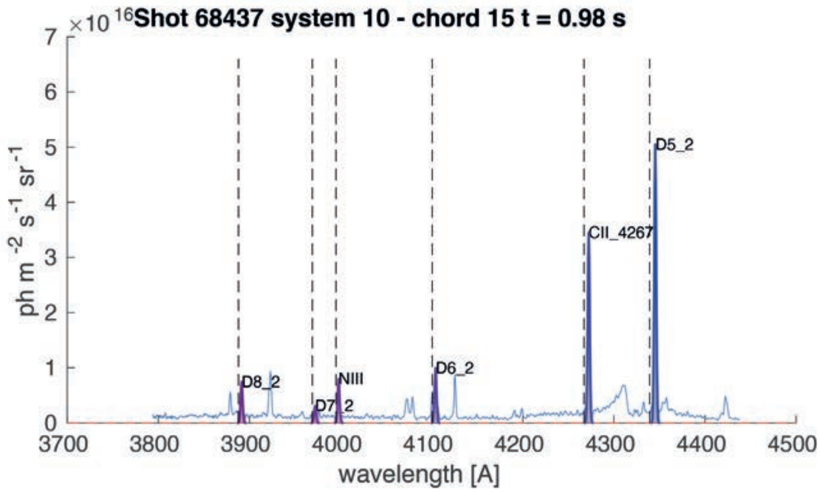
The TCV Diagnostics group at SPC is headed by Dr MER **BASIL DUVAL**. As he explains, the year 2020, as for most things, was dominated by dealing with the Covid-19 story as it unrolled. Our collaborations with external laboratories were reworked using video conference and other communication vectors such that TCV's diagnostic array could continue operations whilst completing the PEX upgrades described in previous reports, which consisted primarily in installing a new divertor configuration with baffles in the TCV chamber. With TCV operations only suspended for a couple of months, this approach proved extremely effective with many diagnostics reaching full operation albeit with some small delays and remote collaborators able to contribute strongly to daily operations.

New diagnostic work remained centred upon analysis of the divertor plasma in, and without, the presence of neutral gas confining internal TCV baffles. These new diagnostics required strong developments in multiple chord spectroscopic devices and full arrays of Langmuir probes, either mounted on the machine walls, or mounted on moving probe heads. This year also saw the re-introduction of high resolution divertor spectroscopy with the return to use of two SPEX spectrometers, previously employed from Charge Exchange Spectroscopy. Replaced by in-house higher throughput systems, these spectrometers feature a bigger Rowland Circle (3x) and aspherically corrected mirrors resulting in state-of-the-art spectroscopic resolution. Coupled with a pair of new high sensitivity Andor 888 CCD cameras, these spectrometers were connected to supplementary fibre bundles that, with mirror optics, now cover a wide part of TCV's divertor region.

While the three divertor survey spectrometers (DSS) covered a wide spectral region across multiple chords, single, relatively strong, spectral lines were selected for tracking. **Figure 1** shows the wide spectral region on one of TCV's survey spectrometers where particular regions of interest are monitored but whose spectral resolution is insufficient to measure temperatures from Doppler broadening reliably. **Figure 2** shows an example spectrum for He II (singly ionised helium) where, after accounting for Zeeman splitting, one can resolve a spectral line with a "cold" component, from ionisation of neutral gas, and a "hot" component from hot plasma ions.

Figure 3 shows a comparison of the ion temperature, deduced from the spectral width of the "hot" component and the Electron temperature measured by the Thomson divertor spectroscopy system. The temperature profiles with, here, the divertor leg aligned with the Thomson scattering laser, show more or less equal ion and electron temperatures and represent the first direct comparison of plasma particle temperatures in the divertor region. By analysing other spectral lines, such as CIII (doubly ionised carbon), whose radiation front displaces as divertor detachment is approached, or nitrogen lines from injected impurities, the ion temperature and/or the line contribution from neutral species can be monitored over the wide range of divertor configurations studied on TCV.

1



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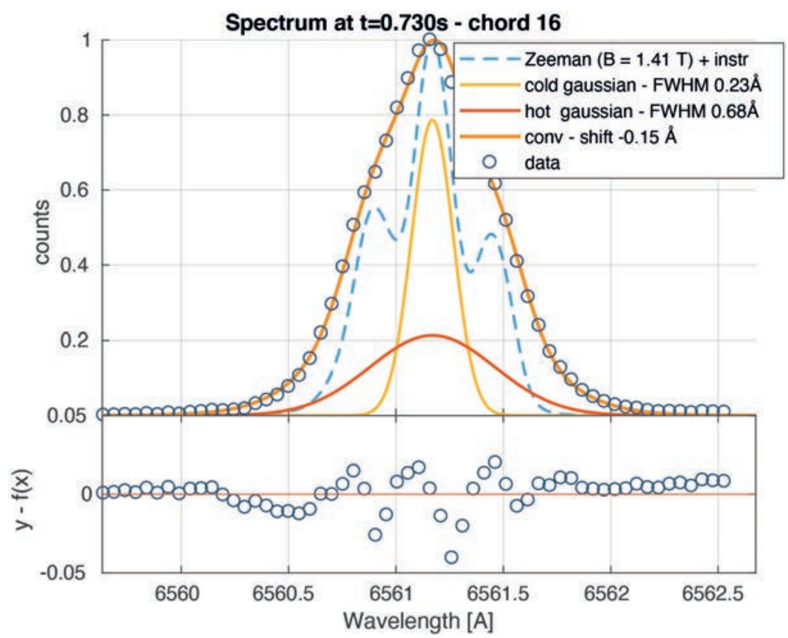
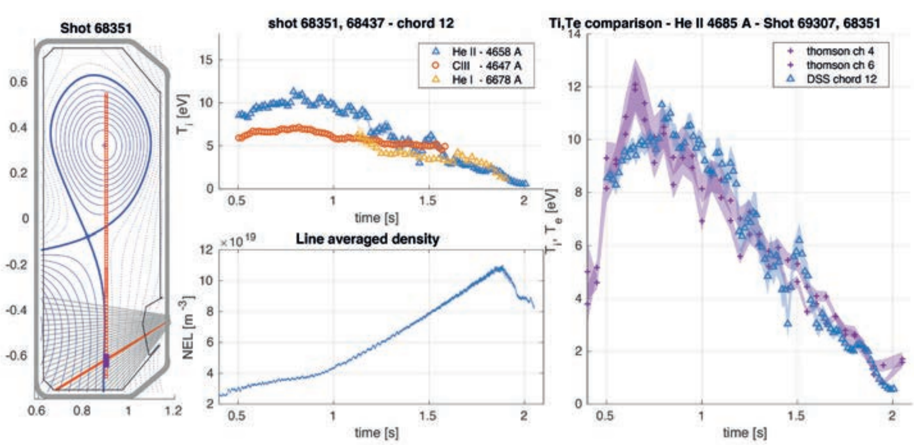


1 Spectrum from one chord of a survey DSS spectrometer system showing good spectral range but limited resolution. Particular lines, meritorious of high resolution acquisition are indicated.

2 High resolution from SPEX of HeII spectral line showing contributions from spectrometer, Zeeman splitting and deduced Ion temperatures for the "cold" (neutral gas) and "hot" (plasma ion) contributions.

3 Thomson vertical laser line (Te) (red) and SPEX chords (Ti) (lower divertor) with deduced temperatures are in indicated region compared during a strong TCV density ramp (bottom-middle insert).

3



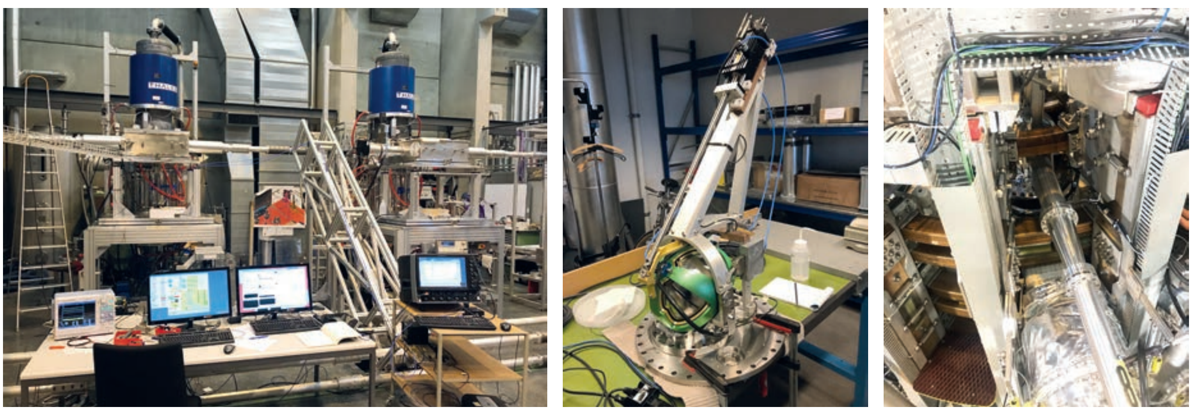
TCV Heating

The versatile shaping capabilities of the TCV plasmas, together with the wide range of plasma density, electron and ion temperatures, imply that auxiliary heating based on Electron Cyclotron Heating (ECH) combined with Neutral Beam Heating (NBH) is a natural choice. The operation conditions of both NBH and ECH strongly depend on the plasma scenario, shape and parameters. On TCV, the ongoing upgrades of the NBH system, with two sources at different energies, and the multi-gyrotron ECRH system, including two new dual frequency gyrotrons, an upgraded transmission line system and launching antennas, allows one to significantly extend the range of plasma scenarios that can be investigated: from novel and innovative confinement concepts such as doublets, to high-performance plasmas at ITER-relevant parameters and negative triangularity plasmas of potential interest for DEMO. Dr. **STEFANO ALBERTI**, MER, is the leader of the TCV Heating research line and exposes below the main achievements in 2020.

Despite the limited accessibility to the experiment due to covid-19, the upgrade of the ECRH system has significantly progressed in 2020. The first dual-frequency gyrotron has been extensively used for plasma experiments with X2-mode injection (84GHz/850kW) from the low-field side or with X3-mode injection (126GHz/900kW) from the newly commissioned top-launch antenna. By the end of 2020, the second dual-frequency gyrotron has been fully characterized by reaching the same level of performance as the first one. In parallel, the complex transmission line system with different rf high-power switches has been nearly completed. The highly versatile switching capability allowing us to connect given gyrotrons to different launchers significantly extends the experimental scenarios using ECRH on TCV.

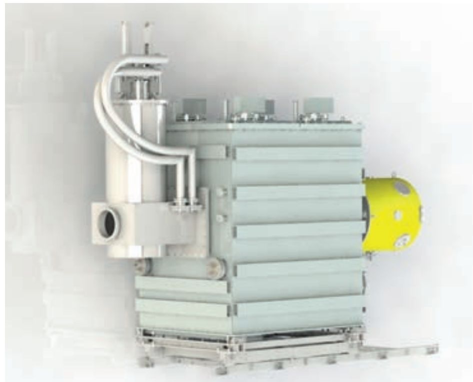
The low-energy heating neutral beam (10-28 keV, 90 kW-1.37 MW) has been intensively and reliably used on TCV in 2020 for direct ion heating in domestic and EUROfusion experimental missions. The TCV's flexible real-time digital control system has been routinely used for control of NBI power to access the pre-programmed plasma ß, which is a measure of the capability of the magnetic field of the tokamak to hold a plasma of high enough pressure.

A second 1MW/55keV/2s high-energy neutral beam is being procured, for addressing burning plasma physics issues with higher plasma density, in particular fast ion interactions with static and dynamic fields and plasma rotation. The high-energy NBI has been designed and manufactured by a commercial company; injector tests started on the manufacturer premises; the delivery, installation and first experiments with plasma are

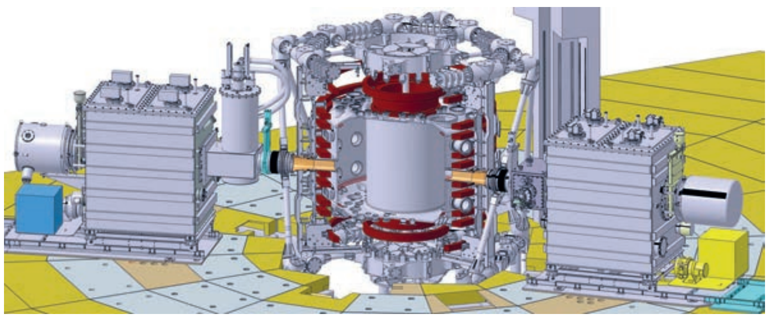


1 **Left:** two dual-frequency gyrotrons installed in the TCV ECRH system. **Middle:** new top launcher before being mounted on TCV. **Right:** transmission line connected to the top launcher mounted on TCV. Thanks to the highly versatile switching capability of the upgraded ECRH system together with the control of the wave polarization it is possible to inject from the top-launcher either 126GHz in X3/O3-mode or 84GHz in X2/O2-mode scheduled for the second half of 2021. The final layout of the second NBI is shown in **Figure 2** and the TCV with two NBIs is shown in **Figure 3**. The operational ranges of the two neutral beams are shown in **Figure 4**.

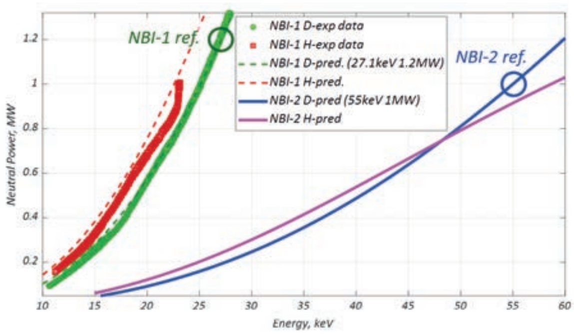
A new beam duct (**Figure 5**), connecting the injector with TCV, has been designed in order to resolve the overheating of beam-facing components encountered in the previous version. Thermo-mechanical modeling of the CuCrZr duct with B4C coating confirm the capability for extension of maximal beam energy per shot delivered in the TCV from the present maximum of 1.3MJ to 2.0 MJ. The manufacturing of the new beam duct is ongoing and installation for both high and low energy beams is planned during the 2021 TCV shutdown when the high-energy NBI will be installed.



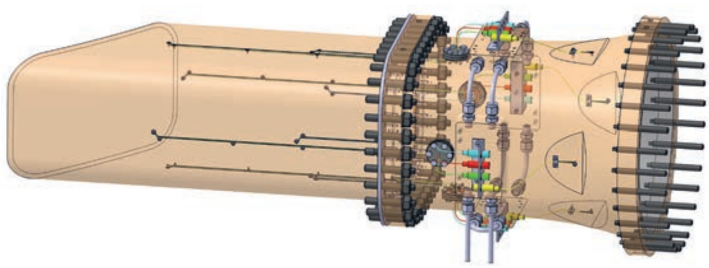
2 High-energy neutral beam for TCV.



3 CAD view of the two NBI systems on TCV with the operational low-energy system (10-28 keV) on the right and the to be delivered high-energy system (55keV) on the left.



4 Operational neutral power vs energy curves for low-energy (NBI-1) and high energy (NBI-2) beams both for deuterium(D) and hydrogen(H) neutrals. References: NBI-1 – 27.1 keV, 1.2 MW; NBI-2 – 55 keV, 1 MW both in deuterium.



5 New part of the NBI duct: insert in TCV port (to left) and conical part (to right). The new duct is equipped with a set of thermocouples for temperature monitoring and active water cooling.

TCV Boundary

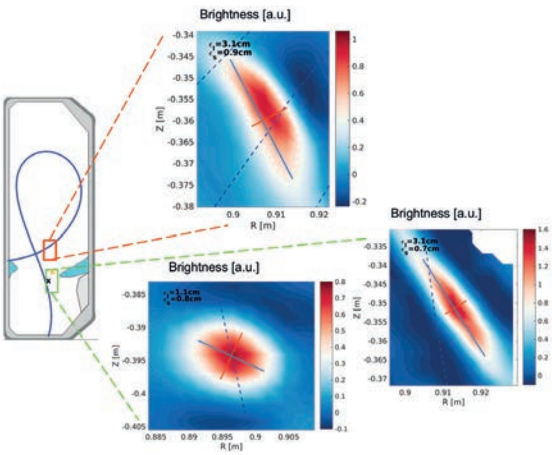
Any successful operation of a fusion reactor depends crucially on the boundary plasma. Adequate confinement of the superhot, 100 million °C plasma core must be ensured while avoiding damage to the surrounding wall structures. By leveraging TCV's unique magnetic shaping capabilities, operational flexibility, and excellent diagnostic 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 some notable achievements from 2020.

Ideally, one would like to have a cold plasma near the machine walls and reduced plasma-wall contact, thus "detaching" the device from the hot plasma core. However, there remain many possible compromises between efficient protection of the wall by a detached plasma and possible resulting adverse effects on the fusion core performance. Today, despite substantial progress in our understanding of the boundary plasma, quantitative predictions for future reactors are accompanied by uncertainties. There is, therefore, an urgent need for reliable extrapolations based on experimental observations together with thoroughly validated modelling. As of today, it remains uncertain whether currently foreseen "conventional" boundary solutions will be adequate for a reactor. New ideas, such as alternative magnetic geometries of the boundary plasma, therefore need to be explored.

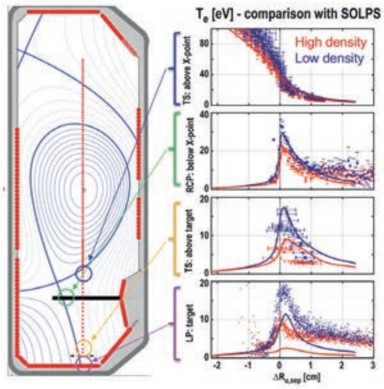
In 2020, we focused extensively on using TCV's removable gas baffles (the blue structures in **Figure 1**), designed and first installed in 2019 to better decouple plasma and neutral dynamics to further enhance TCV's role as a testbed for boundary plasma solutions. The effects of baffles were further elucidated in 2020 by a detailed divertor particle balance study and their potential benefits for high-confinement plasma operation in regimes with a high divertor neutral pressure was demonstrated. The new flexibility provided by the baffles furthermore allowed for increased understanding of the mechanisms governing the formation of the "density shoulder" and to experimentally retrieve, albeit to a lesser extent than predicted, benefits of "Super-X" alternative divertor geometries. Detailed studies of other alternative geometries, with and without baffles, demonstrated, in particular, lower heat fluxes to the floor in high-confinement X-Divertor and X-point target geometries, an almost full suppression of plasma interaction with the outer wall in plasmas with strongly negative triangularity, and higher radiation levels and facilitated detachment access in Double-Null plasmas (**see highlight**).

The measurement capabilities in the TCV divertor were enhanced in 2020, in particular regarding spectroscopic and imaging diagnostics. This provides greatly improved 2D maps of the radiated power levels and high-resolution measurements of neutral density, plasma density, electron temperature and ion temperatures. Real-time processing of such imaging data, combined with TCV's state-of-the-art control system, allowed for a proof-of-principle demonstration of active feedback control of divertor detachment, published in Nature Communications. Measurements on the fast time scale, using a new Gas Puff Imaging diagnostic, provided detailed insights into turbulent structures in the divertor, **Figure 1**.

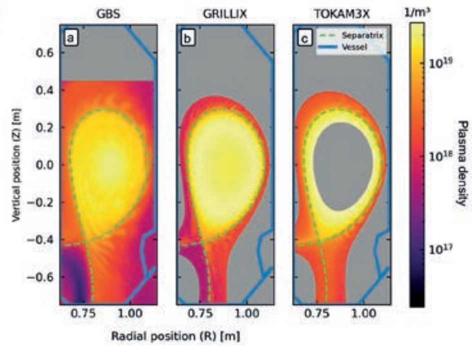
Considerable effort has been dedicated to the validation of the leading tokamak boundary modeling tools. A quantitative validation of the SOLPS-ITER edge transport code against an extensive set of measurements in TCV L-mode experiments was achieved. While simulations show excellent qualitative consistency, quantitative differences to the experiment have been identified, challenging aspects of the underlying model (see **Figure 2**). Part of this may be related to an incomplete treatment of molecular effects, as identified through novel spectroscopic analysis. Strong progress was also achieved in the validation of first-principles boundary turbulence codes. As part of a collaboration with leading turbulence modeling groups from the SPC-EPFL, IPP Garching, and CEA Cadarache, the first real-size turbulence simulations of diverted TCV L-mode plasmas were obtained, see **Figure 3**, enabling a detailed validation against an extensive set of experimental measurements. In parallel to these modeling efforts, comparison of heat flux channel widths in TCV H-mode plasmas with leading empirical, cross-machine scaling laws show clear deviations, indicating a more complex parameter dependency, justifying further research with other divertor configurations and a wider range of plasma parameters.



1 Conditionally-averaged images of turbulent structures (blobs) in the divertor region, revealing both strongly squeezed blobs due to magnetic shear and more circular blobs.

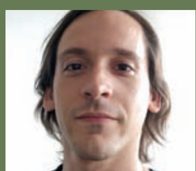


2 Results from an in-depth validation of SOLPS-ITER drift simulations. Temperature profiles from experiment (data points) and simulation (lines) at different distances from the wall agree well, but differ, for currently unknown reasons, in close vicinity of the floor.



3 First full-size simulations of the TCV boundary plasma in diverted geometry, achieved with the GBS, GRILLIX, and Tokam3X turbulence codes and used for a rigorous validation against the experiment

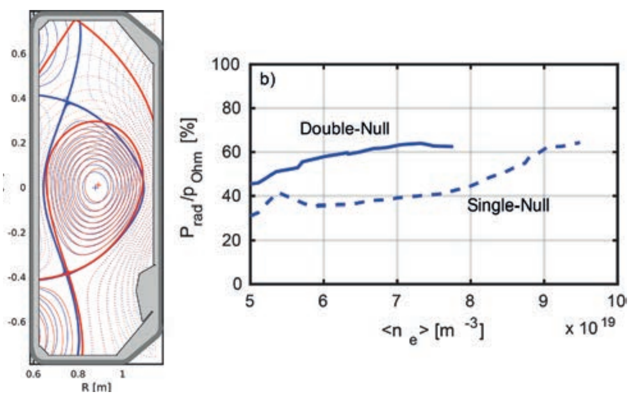
THE BENEFITS OF A SECOND X-POINT



In January 2017, Dr. **OLIVIER FÉVRIER** joined the boundary group at the Swiss Plasma Center as a post-doctoral fellow. His research focuses on the understanding of divertor detachment, a regime in which the heat flux reaching the divertor targets is significantly reduced. In particular, he focuses on how alternative divertor geometries can improve the access to such a regime and enhance its properties.

In the framework of a EUROfusion Researcher Grant, he investigated the prospects of Double-Null (DN) configurations (**Figure 4**, left panel) as an exhaust solution for a reactor. By magnetically separating the outer and the inner legs, DN configurations allow sharing most of the power between two outer legs, and, possibly, between two radiation fronts. This allows, depending on the balancing of the DN, to distribute the power more equally among the two exhaust legs as compared to a single-null configuration. In addition, alternative geometries can then be applied to both active legs, further increasing the expected benefits. DN configurations are being considered for several reactor concepts, such as the European DEMO, the Korean K-DEMO, or ARC.

Dedicated experiments on TCV reveal considerable benefits of the DN, such as a substantially facilitated access to a detached regime (by approximately 10-20%) and typically a 50% increase in radiated power levels (**Figure 4**, right panel), thus proving DN as viable candidates for an exhaust solution.



4 **Left:** cross-section of TCV with a single-null (red) and a double-null (blue) configuration. **Right:** fraction of radiated power for double-null (plain lines) and single-null (dashed lines) configurations as a function of averaged plasma density.

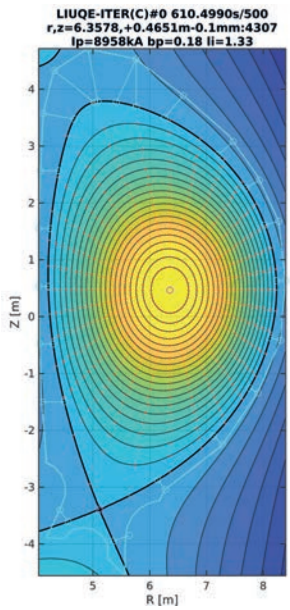
Theory and Numerical Simulation

Fully embedded in the EUROfusion programme through the participation to E-TASC (Theory and Advanced Simulation Coordination), Enabling Research and several collaborative code development projects, the SPC theory group goal is to advance the first-principle understanding of fusion plasmas. This is necessary to interpret the experimental results from current devices and make predictions for ITER and DEMO. For this reason, the SPC theory group, led by Prof. **PAOLO RICCI**, strongly collaborates with the TCV group and with the other major European and international experiments. 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) and Marconi at CINECA. Within the effort to optimise the performance of the simulation codes developed at the SPC, strong ties have been established in 2020 with the SCITAS (Scientific IT & Application Support) group of the EPFL.

PLASMA EQUILIBRIUM

The tokamak equilibrium reconstruction code LIUQE, developed at the SPC, has been evaluated as a potential candidate for reconstruction of ITER plasmas in a contract under the supervision of F4E. Following the positive outcome of the evaluation, LIUQE is now ready to be included and tested within the newly developed ITER Plasma Control System. LIUQE will play a crucial role for the magnetic control of ITER plasma, including shape and gap control, which will help provide stable operation and achieve high performance.

LIUQE managed to satisfy most of the precision and latency time requirements imposed by ITER. These included demanding specifications for the reconstruction of global plasma quantities such as the total plasma current, poloidal beta, internal inductance, as well as the reconstruction of equilibrium profiles such as the safety factor profile and the location of several rational surfaces where harmful MHD instabilities might develop, and of the plasma shape through the definition of a number of wall gaps and the reconstruction of full flux-surface contours in the confined plasma, as shown in **Figure 1**.



1 Contour plot of the reconstrution of a synthetic ITER equilibrium using the LIUQE code. The magenta open circles indicate the estimated position of the axis and active X-point, the red dots that of the different closed flux surfaces, the cyan dots the location of the ITER limiter. Finally the different wall gaps are represented by the cyan segments terminated by open circles.

REAL TIME CONTROL

We have demonstrated, for the first time, real-time kinetic equilibrium reconstruction combining kinetic profiles obtained from the real-time control RAPTOR code and the equilibrium reconstruction code LIUQE. Data-driven algorithms that can provide physics insights have been developed and tested across various tokamaks, opening the way towards disruption predictors valid across machines, which can lead to considerably faster developments on a new device like ITER. Avoiding disruptions is also obtained through relevant predictive simulations. Specific DEMO simulations have shown that a safe termination can be obtained if the current ramp rate is not too fast. These simulations have also supported the development of a new real-time algorithm used on the JET tokamak for safe discharge termination and the control of the H- to L-confinement transition. A new reduced model for the time evolution of neoclassical tearing modes (NTM) has also been developed and validated with TCV experiments and simulations. This opens the path towards a change in the strategy for the real-time control of neoclassical tearing modes, using physics-based observers in this area as well.

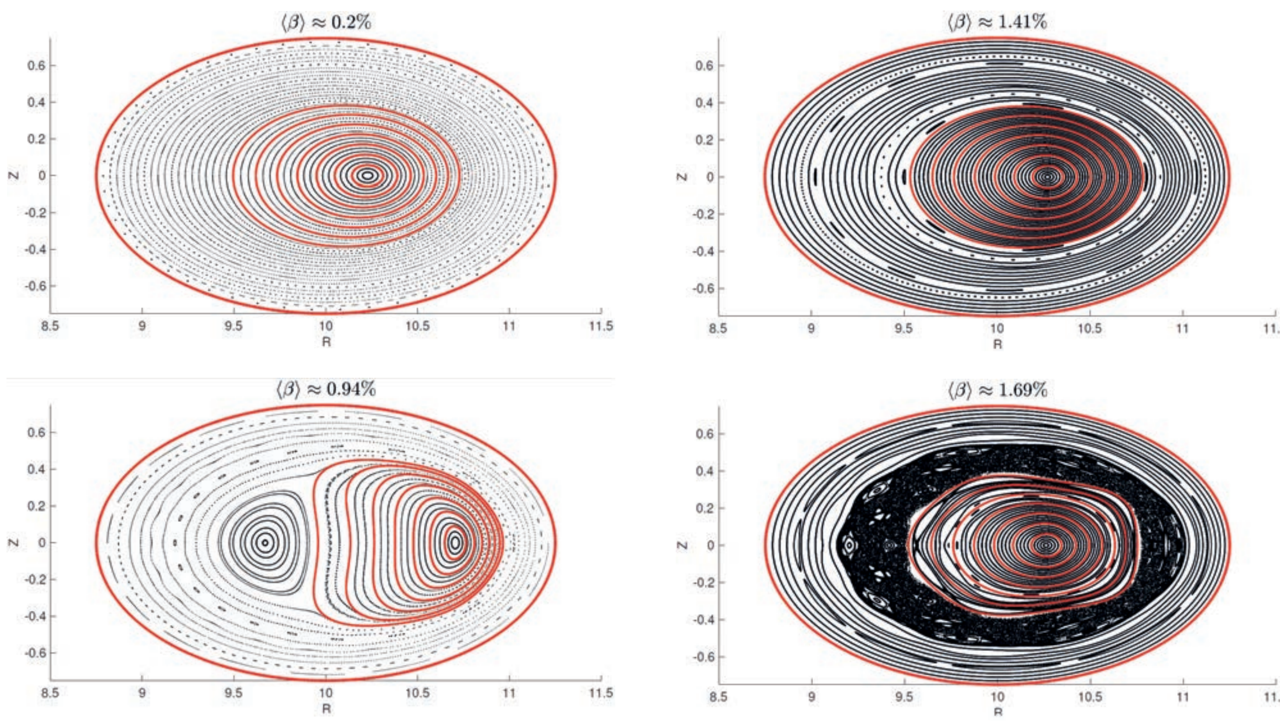
THREE DIMENSIONAL CONFIGURATIONS

Focusing on magnetic equilibria in three-dimensional configurations such as stellarators, the free-boundary MHD equilibrium code SPEC co-developed at the SPC has been extended to allow prescribing the profile of net toroidal current. This has enabled a first exploration of the effect of the bootstrap current on the magnetic topology in classical stellarators, see **Figure 2**, and paves the way to understanding and optimizing the equilibrium pressure-limits in stellarators. The SPEC code has also been applied to study the nonlinear saturation of tearing modes in a cylindrical tokamak, comparing the predicted saturated island size to the results of resistive MHD simulations.

Modelling of ion-cyclotron resonance heating is undertaken with the SCENIC code package, which comprises the VENUS-LEVIS particle following code, the 3D full wave code LEMAN and the 3D equilibrium code ANIMEC. We have applied SCENIC to help design optimised heating and fast ion generation schemes for the W-7X stellarator. Advanced schemes with higher harmonic heating exploit recent advances in our modelling capability in SCENIC which can handle hot dielectric tensor physics.

A new research avenue started at the SPC, focused on the understanding of turbulence in the stellarator boundary. The GBS code has been extended to describe the plasma dynamics in three-dimensional magnetic equilibria and is currently being applied to study plasma turbulence in stellarator vacuum fields with different topologies of the boundary.

We have also exploited the synergy between stellarator and tokamak physics. The VENUS-LEVIS code has been applied to various physics problems, including heavy impurity transport in tokamak plasmas that display plasmas equilibria with three-dimensional features and runaway electron physics (see **highlight** on page 17). Regarding impurity transport physics, a new formulation has been developed to model experiments with long living internal kink modes and strong flows induced by neutral beam injection. The synergy between the 3D magnetic fields, strong flows, and neoclassical toroidal viscosity induced electric field is seen to influence core impurity accumulation. The simulated impurity densities shown in **Figure 3** are broadly in agreement with experimental measurements.



2 Poincaré plots of different classical stellarator equilibria computed with SPEC. **Left:** low boostrap current, **right:** large bootstrap current. **Top:** low plasma beta, bottom: large plasma beta. At low bootstrap current, a separatrix forms and a (m,n)=(1,0) island opens above the (ideal) beta limit. At large bootstrap current, magnetic field lines become chaotic above the (chaotic) beta limit.

Concerning runaway electron physics, the VENUS-LEVIS code has been enhanced to include a simplified model for three-dimensional time varying MHD perturbations. The perturbations are consistent with patterns visible in the synchrotron electron radiation beams of JET, which have been analyzed via a newly developed computer vision code.

TURBULENCE

Global gyrokinetic simulations with the ORB5 code have benefited from three recent additions to its functionality and performance, which have largely opened the feasibility of global electromagnetic simulations, which are known for being particularly challenging and numerically very costly. First, the optimization and GPU-enabling of the code has resulted in an overall acceleration by a factor of about eight. Second, a novel mixed representation and 'pullback' scheme, developed in collaboration with the Max-Planck-Institut für Plasmaphysik, has been implemented in the ORB5 code, allowing for much larger time steps for electromagnetic simulations. Third, an external 'antenna' perturbation was shown to be able to excite electromagnetic modes such as Toroidal Alfvén Eigenmodes (TAEs), opening the way to studies of their damping and drive by fast particles.

Another improvement has been brought to the ORB5 global gyrokinetic code, namely the implementation of a novel nonlinear collision operator for both intra- and inter-species collisions, based on an expansion on suitable polynomials. The new operator has been thoroughly verified, in particular for its conservation properties, as well as for neoclassical physics. This extends the range of validity of the code, in particular towards the plasma edge, which is typically much more collisional than the plasma core. Also, the new operator has been GPU-enabled.

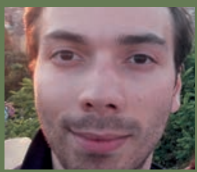
Also in collaboration with the Max-Planck-Institut für Plasmaphysik, the SPC contributed to the development of the GENE gyrokinetic code. In 2020, we devised a new coordinate system for local gyrokinetic simulations: the non-twisting flux tube. In a conventional flux tube, the boundaries of the simulation domain are field-aligned, meaning the corners of the domain follow particular field lines. Notably, if the magnetic shear is very large, as the conventional domain extends along the field line it becomes very strongly twisted, thereby preventing it from efficiently resolving the turbulence. In contrast, the non-twisting flux tube retains a rectangular cross-section at all locations along the fields, enabling it to properly resolve turbulence with few computational grid points.

Regarding the physics studies carried out with GENE, we mention the investigation of turbulence in the parameter regime where internal transport barriers have been experimentally observed: equilibria with very low values of the magnetic shear. Linear simulations have revealed a sharp increase in the parallel extent of the modes as the shear is lowered, which was found to be in agreement with prior analytic calculations and appears to be associated with a transition from toroidal to slab turbulence. In addition, we studied how non-adiabatic passing electron dynamics affects the drive of zonal shear flows and the associated saturation of ion temperature gradient-driven turbulence. Making use of novel statistical analysis of the simulation data, it was shown how the non-linear self-interaction of microinstability eigenmodes effectively acts as random kicks on the zonal flow drive and can at least partially disrupt the coherent drive from the modulational instability mechanism.

The SPC is focusing on the extension of gyrokinetic models to the boundary region by adopting different strategies. For instance, a low noise PIC scheme has been developed to carry out the time evolution of the full distribution function, considering a simplified slab geometry with steep profile gradients for mimicking edge conditions. A moment approach has also been developed that consists in developing the ion and electron full distribution functions over a Hermite-Laguerre polynomial basis. The coefficients of the basis functions are then evolved over the three-dimensional space. Numerical results show that a small number of basis elements are needed to describe the plasma dynamics in typical collisional conditions of the tokamak boundary.

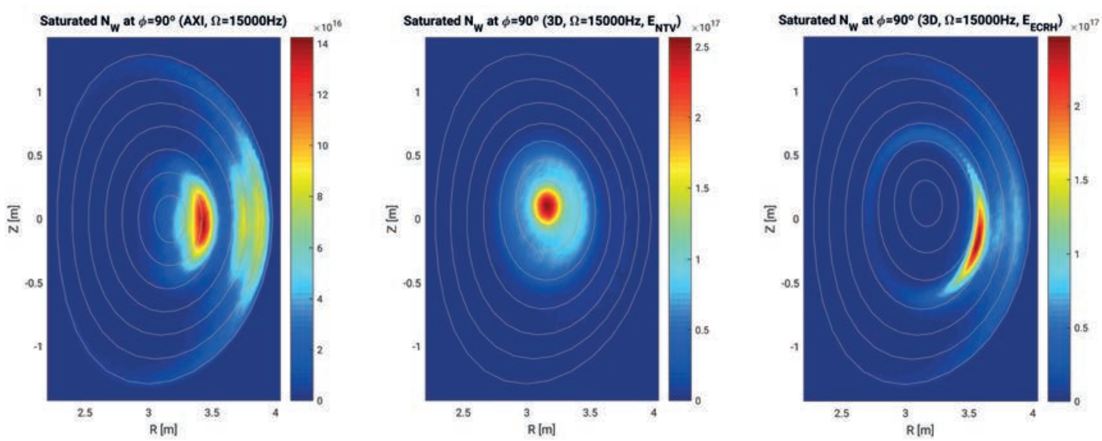
Finally, the GBS turbulent fluid code has been used in order to study turbulent regimes in the tokamak edge. It has been pointed out that turbulence can be suppressed by strong shear flows at low plasma resistivity and large heat source, a process that we have associated with the L-H transition. On the other hand, disruptive large transport has been observed at large density, a feature that recalls the density limit observed in tokamaks.

HEAVY IMPURITY TRANSPORT IN THE PRESENCE OF STRONG FLOWS, SYMMETRY BREAKING AND VISCOSITY



Tungsten is the main choice of plasma-facing wall material in tokamak reactors due primarily to its capability of sustaining the high heat loads of fusion reactor plasmas, while preventing unwanted absorption of tritium. The JET and ASDEX-Upgrade tokamaks feature a tungsten divertor, as will ITER and the EU-DEMO. Unfortunately, the tungsten divertor is a source of heavy impurities (high-Z ions) which typically radiate strongly inside the plasma. During plasma operation the heavy tungsten ions detach from the wall and are transported through the plasma, potentially reaching the core. The emission of radiation by these ions causes a loss of thermal plasma energy, which can result in significant decrease in the plasma temperature near the axis. In the best scenario, a mild decrease in plasma temperature profile ensues, but if the impurities gather in sufficient number in the plasma core, the core temperature collapses, ultimately leading to termination of the plasma. It is therefore crucial to understand the physics mechanisms involved in core impurity accumulation in order to develop better operational scenarios for ITER and EU-DEMO. Experiments in both JET and ASDEX-Upgrade show that the heavy tungsten ions flow supersonically due to strong rotation induced by Neutral Beam Injection (NBI), and are thus subject to strong centrifugal forces. These centrifugal forces are known to impact tungsten transport due to the generation of poloidal impurity density asymmetries in axisymmetric tokamak configurations. However, tokamaks are often not purely axisymmetric configurations. Both externally applied 3D perturbations and saturated long-living ideal 3D perturbations are a frequent, and sometimes desired, feature of tokamak operational scenarios. This breaking of symmetry is often seen to greatly impact tungsten transport.

In 2020, **EDUARDO NETO**, a Ph.D. student supervised by Dr MER Jonathan Graves, developed a model to study the effects of strong flows, symmetry-breaking 3D saturated long-living perturbations and ambipolar electric fields induced by neoclassical toroidal viscosity (NTV) on heavy impurity transport. The theoretical framework is partly based on impurity transport physics deployed in the stellarator community, but it is necessarily adapted to include strong equilibrium flows. Strong flows, and associated centrifugal effects, are never a feature of stellarator plasmas, but they remain important in NBI heated tokamak plasmas, even those with long-living 3D magnetic structures. The model has been primarily applied to the case of a JET-like m=1, n=1 internally kinked magnetic configuration. Simulations were performed with the VMEC equilibrium code and the VENUS-LEVIS code which can be used to follow the tungsten particles in a suitable background configuration. The saturated tungsten density was obtained for an axisymmetric equilibrium (**Figure 3, left**) and a m=1, n=1 internally kinked magnetic equilibrium (**Figure 3, middle**) obtained from a JET hybrid scenario. The axisymmetric simulation shows an off-axis accumulation due to the strong centrifugal radial force and the kinked case shows on-axis accumulation. These results agree with experiments in JET which show that strong impurity accumulation coincides with the growth and saturation of large and long living m=1, n=1 kinked magnetic fields, rotating strongly due to NBI. The agreement between theory and experiments gives confidence that it is the synergy between the 3D magnetic fields, strong flows and NTV that is important for explaining the observed accumulation. Finally, **Figure 3, right,** shows the saturated tungsten density for a similar m=1, n=1 kinked case where the sign of the electric field from NTV was reversed. This simulation was chosen as an initial way of modelling the effect of ECRH heating on the ambipolarity condition. In complete contrast to the case of **Figure 3, middle,** an impurity density “hole” is observed in **Figure 3, right**. This favourable effect of continuous m=1, n=1 kink modes on impurity screening in ECRH heated plasmas with strong NBI driven rotation is sometimes observed in ASDEX-U experiments, and has been promoted as a favourable way to operate the tokamak.



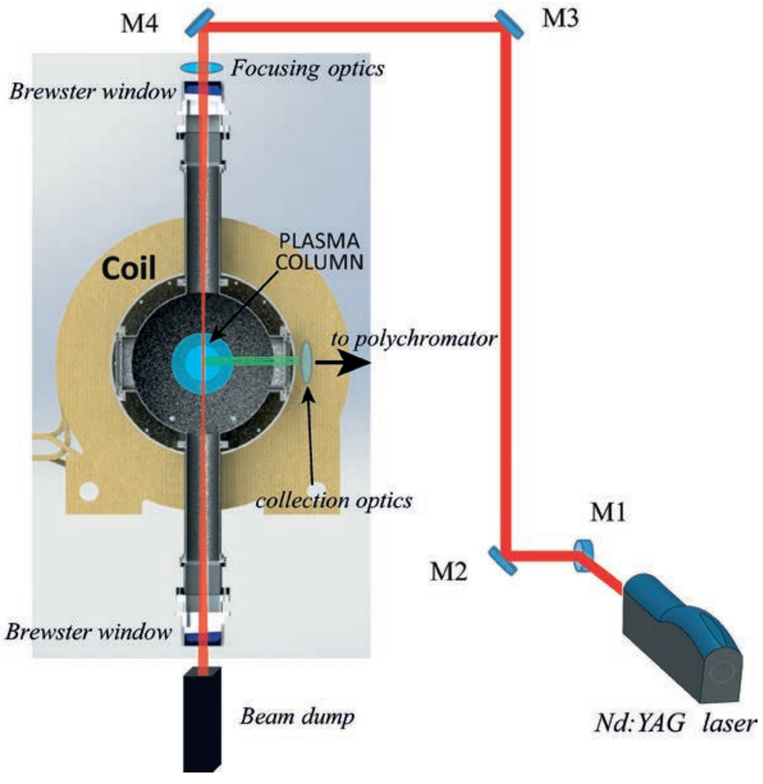
3 Poloidal contour plots of steady state impurity densities in JET-like plasmas obtained with VENUS-LEVIS simulations. In an axisymmetric case the impurity density peaks off-axis (left). In the presence of 3D internally kinked perturbation and electric field induced by NTV, impurities are accumulating on-axis (middle). In the presence of 3D internally kinked perturbation but reversed electric field modelling the effect of ECH, an impurity density hole is observed (right).

Basic Plasma Physics and Applications

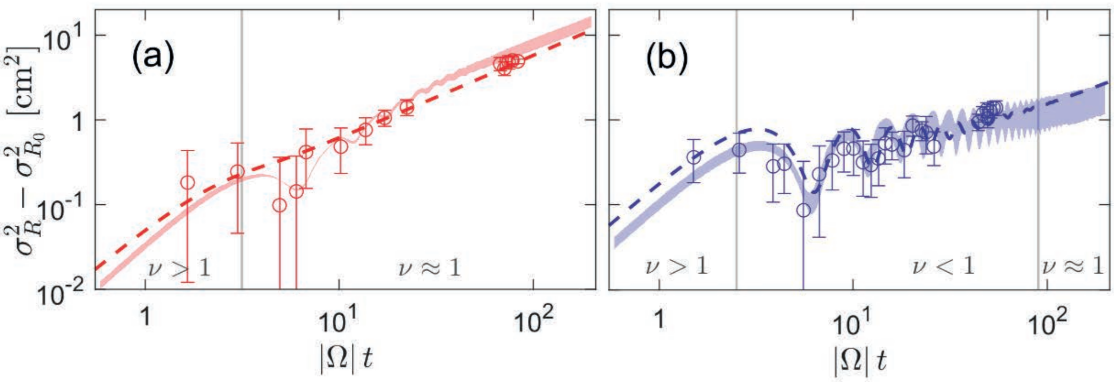
The Basic Plasma Physics and Applications group is headed by Prof. **IVO FURNO**. The activities are conducted on two basic plasma devices, the TORoidal Plasma Experiment (TORPEX) and the Resonant Antenna Ion Device (RAID), as well as on a variety of dedicated plasma devices for industrial applications. Combining advanced experimental measurements with theory and numerical modelling, we advance the basic understanding of underlying plasma phenomena towards practical applications. The main activities are summarized below.

RAID: A THOMSON SCATTERING SYSTEM FOR AWAKE

The SPC participates to the AWAKE (Advanced WAKefield Experiment) project, which aims at developing the next generation of particle accelerators for high energy particle physics based on wakefield acceleration in plasmas. A challenging goal for the development of an AWAKE plasma source is the achievement of a large electron density near 10^{21} m^{-3}, with high homogeneity over a 1 m plasma cell, which is required for wakefield acceleration and electron bunch focusing. A helicon plasma cell is a promising candidate to generate the plasmas needed for AWAKE and is presently under development at CERN. Measuring such high densities with the required temporal and spatial resolution is a diagnostic challenge in itself. In 2020, we demonstrated the use of a Thomson scattering (TS) system for electron density and temperature measurements in helicon plasmas, see **Figure 1**. The TS system was installed and successfully tested on RAID, which produces a helicon plasma column with characteristics similar to those of the AWAKE helicon source, and is therefore an optimal testbed for application to the AWAKE device. These results suggest that, when used on the AWAKE helicon cell at CERN with electron densities of the order of 10^{20} m^{-3}, the contribution to measurement error due to coherent scattering would be ~2.5%.



1 Laser path and optical arrangement of the Thomson Scattering diagnostics in RAID (not to scale). Before entering the vacuum vessel, the beam is focused by lenses and passes through a window tilted at the Brewster angle to minimize back reflections.



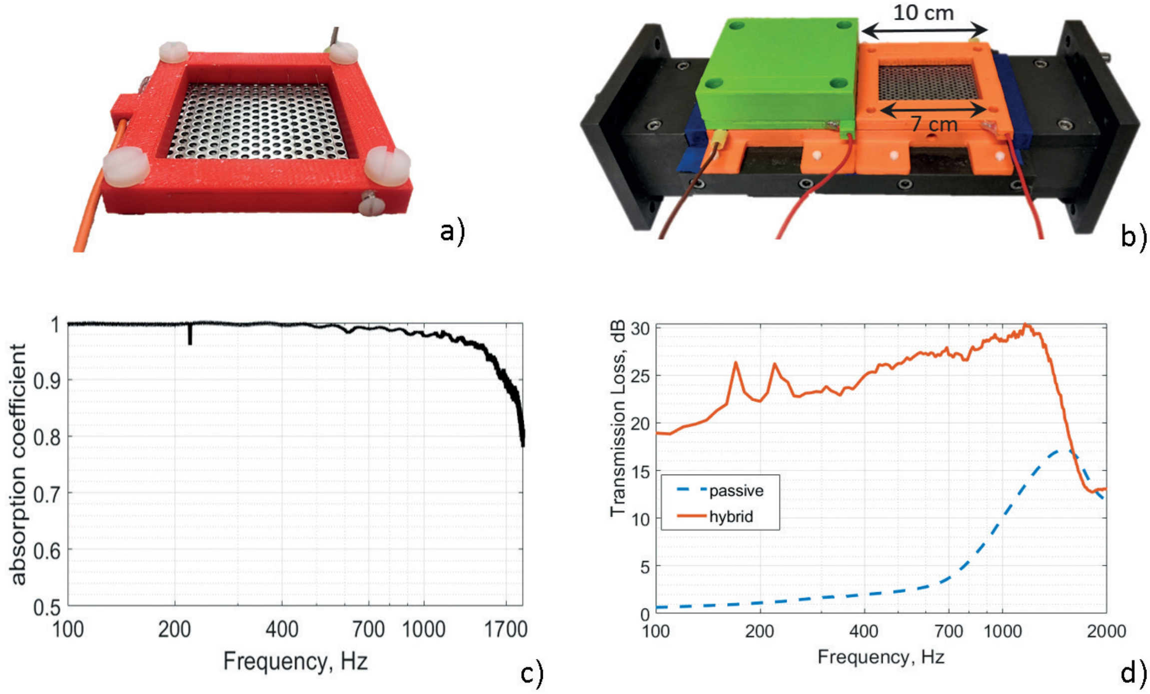
2 Time evolution of the variance of suprathermal ions injected at **(a)** 30 eV and **(b)** 70 eV in TORPEX. experimental data (points), simulations based on GBS (bands), and from a persistent random walk model (dashed lines) . Error bars are 1σ uncertainties of the experimental data. The model can recover the different cross-field transport regimes observed in the experiments and simulations.

TORPEX: ADVANCED THEORY OF SUPRATHERMAL ION TRANSPORT

In the TORPEX device, we have been studying for a few years the transport of suprathermal ions induced by plasma turbulence. Using detailed experimental measurements and numerical simulations, we showed that a Lévy motion approach can properly describe the suprathermal ion transport across magnetic field lines in the simple magnetized configuration of TORPEX. Through appropriate choices of parameters, the Lévy motion models reproduce results both from turbulence simulations and experiments. In 2020, we studied transport without resorting to a random forcing in the form of noise, a friction term, or a memory kernel. Instead, we used a persistent random walk (PRW) approach where particles feature continuous trajectories and finite propagation velocities that lead to correlations in location at short time scales. The random dynamics arises from random instantaneous velocity changes, or collisions, which follow a Poisson distribution with constant rate. The new model captures the main features of transport across magnetic field lines as well as the evolution of the character of transport over time, see **Figure 2**. While previous models based on Lévy motion can describe asymmetrical and non-diffusive behavior in a single regime at all times, the new PRW model is successfully able to incorporate a variety of transitions between different transport regimes, while always converging to diffusion in the long term limit. The PRW model therefore offers a consistent method to describe transient non-diffusive transport, without the requirement of invoking non-Markovian or nonlocal assumptions. The PRW and Lévy motion approaches can therefore complement each other, depending on the specific system and time frames under investigation.

Development of a plasma electroacoustic actuator for active noise control applications

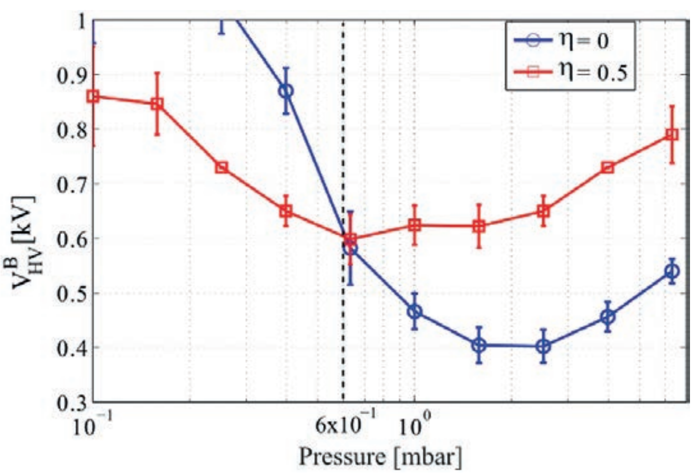
Funded by a Horizon 2020 grant lead by the Signal Processing Laboratory LTS2 of EPFL, we developed a plasma electroacoustic actuator for active noise control applications. The need for a breakthrough in the noise reduction technologies is pushing many industries, especially in the aircraft sector, to develop new solutions beyond the conventional passive noise control materials, which are limited in their performance and frequency range. Our study focused on the experimental development and modelling of sound generation phenomena in a positive corona plasma discharge to gain physics understanding and to develop a dedicated actuator with a geometrical configuration for further implementation in active control systems. We demonstrated that a positive corona discharge actuator in a wire-to-mesh geometry (**figure 3 a**) can generate sufficient sound pressure levels with limited signal distortion, with a limited total electrical power consumption. The numerical and analytical model of corona discharge actuator describing its electroacoustic dynamics was derived and further implemented in the active noise absorption system. In the measurements under normal sound incidence the system behaves as a broadband perfect sound absorber up to 1700 Hz where the passive methods are rather inefficient (**figure 3 c**). The corona discharge based system was implemented and tested as a novel aircraft acoustic liner concept. We tested the 2 cell prototype in the duct (**figure 3 b**) and obtained high transmission losses for travelling sound in the wide frequency range down to 100 Hz, which is not achievable yet with passive solutions (**figure 3 d**).



3 **a)** Corona discharge actuator in a wire-to-mesh geometry; **b)** two active cells containing the corona discharge actuators are wall-mounted in a duct, as an acoustic liner prototype; **c)** normal incidence sound absorption is achieved with active impedance control of corona discharge actuator using analytical model; **d)** sound transmission losses in the duct are obtained with active control of corona discharge actuators compared with passive behavior.

Slip ring assembly with increased breakdown voltage limit for high-voltage bus satellites

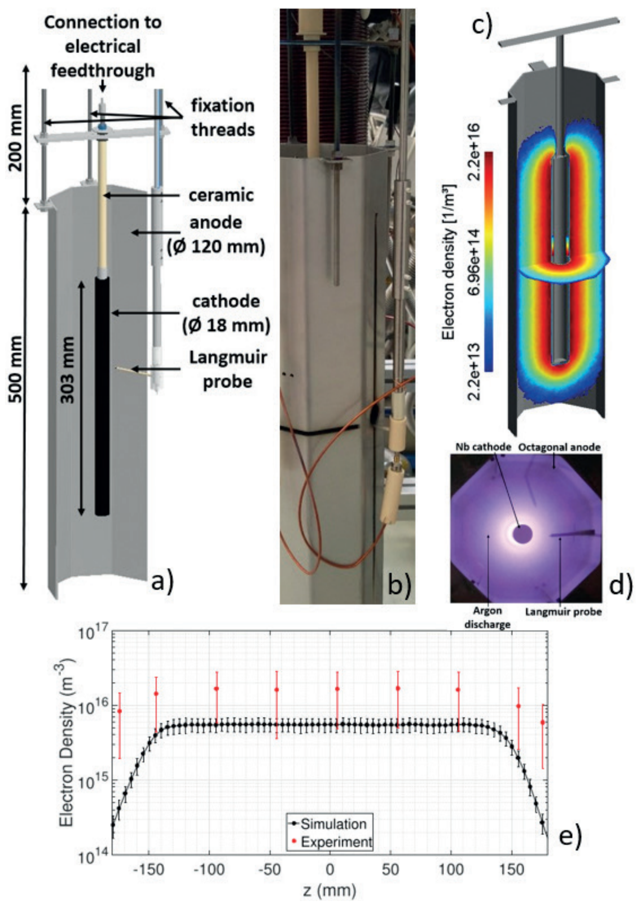
A large effort is presently devoted to the development of high-voltage (HV) bus systems for satellites in the 300-600 V range to meet the requirements of new generation high-power electrical plasma thrusters. The risk of electrical breakdown for solar panels and for slip ring assemblies (SRAs) is a crucial aspect to develop reliable satellite components. In collaboration with Ruag Space Nyon and in the framework of the H2020 EPSA project, we developed a new passive gas breakdown mitigation solution for satellite SRAs, which meets the 600 V requirement of safe operation. A series of resistances is used to passively bias two conducting limiting discs (LDs) that enclose a central HV ring. In this way, the voltage of the LDs rises together with that of the central ring, which allows one to raise the minimum voltage of the characteristic breakdown curve of the SRA. This approach has been tested both on a basic assembly with three discs featuring the basic elements of a SRA, as well as on a test-SRA, see **Figure 4**, composed of all the main components of a real cylindrical slip ring, including gold plated discs and brushes.



4 Breakdown curves of the high voltage ring for the test slip ring assembly with 54 mm limited discs (LDs): in blue circles, the case of grounded LDs ($\eta = V_{LD} / V_{HV} = 0$), in red squares the curve measured with the passively biased LDs ($\eta = 0.5$).

SPEEDING UP THE DESIGN OF RADIO-FREQUENCY CAVITY AT CERN

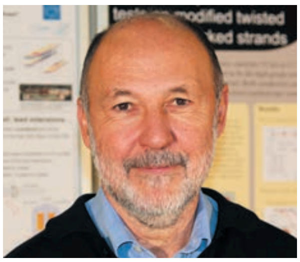
Niobium thin films are used at CERN for coatings of superconducting radio-frequency (SRF) accelerating cavities. Numerical simulations can help better understanding the physical processes involved in such coatings and provide predictions of thin film properties.
In collaboration with CERN, Dr **THIBAUT RICHARD** (EPFL PhD 2020) carried out Particle-in-Cell Monte Carlo (PICMC) 3D plasma simulations of a coaxial cylindrical system allowing both DC diode and DC magnetron operation, see **Figure 5**. An experimental test bed was developed to benchmark the numerical simulations by measuring profiles of electron density and temperature by Langmuir probes over the whole plasma volume. A proper choice of ion induced secondary electron emission parameters enables to match experimental and simulated discharge currents and voltages, with argon as the process gas and niobium as the target element. The choice of argon gas with a niobium target is driven by CERN applications, but the methodology can be applied to other discharge gases and target elements. Validation of plasma simulations is the first step towards developing an accurate methodology for predicting thin film coatings characteristics in complex objects such as SRF cavities.



5 **a)** Schematics and **b)** picture of the experimental setup. **c)** Simulated electron density [m-3] displayed in the horizontal and vertical mid-planes at pAr = 0.3 mbar, 20 W. **d)** Picture of the argon plasma taken from a viewport below the chamber. **e)** Comparison of simulation and Langmuir probe profiles of axial electron density [m-3].

Applied Superconductivity

Based on the site of the Paul Scherrer Institute in Villigen, the activities of the superconductivity group are focused on design studies, R&D and testing for magnet technology. Both Low-Temperature and High-Temperature Superconductors (LTS and HTS) are investigated, with a primary focus on future fusion devices. The main experimental tool is the SULTAN test facility, a unique equipment that allows SPC to carry out tests of high current superconducting cables and joints, in particular for ITER, EUROfusion DEMO and CERN. In December 2020,



Dr. **KAMIL SEDLAK** (left) took the lead of the group previously assumed by Dr **PIERLUIGI BRUZZONE** (right). Despite the limitations imposed by the pandemic crisis in 2020 and beyond, some notable achievements were obtained.

DESIGN AND ANALYSIS

- With the aim of reducing the peak voltage during fast discharge of the TF DEMO coils, innovative winding pack designs have been explored with reduced number of turns and high operating current.
- The electromagnetic design of the 15 T dipole coils to restore the EDIPO facility made significant progress, using a two-stage flat cable, with high operating current and faster discharge, and a stack of three coils, reducing the peak stress on the superconductor.
- The pre-compression structure for the CS column of EUROfusion DEMO is designed and analyzed for the operating scenario.
- On behalf of EUROfusion industrial feasibility studies have been carried out with companies to assess technical aspects, logistic and cost for the DEMO magnets.

DEVELOPMENT

- For the manufacture of next react&wind prototype conductor, 80 kg of Nb3Sn strand and 300 kg CuNi clad copper wires have been procured at KAT (Korea) and WST (China).
- Two kinds of clamps are developed for the bent joints of accelerator magnets to promote diffusion bonding between the two Rutherford cables during the Nb3Sn heat treatment.

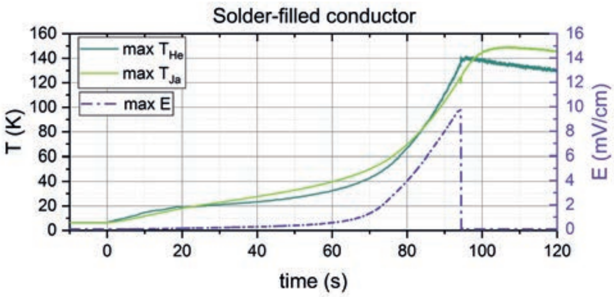
TESTING ACTIVITIES IN SULTAN

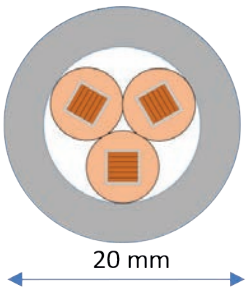
- The SULTAN test facility was down during four months in 2020 due to the lockdown at PSI and a leak repair in the main vacuum vessel.
- In support of the ITER project four samples were prepared and tested: two NbTi samples of PF coil joints provided by F4E, one Nb3Sn sample of CS coaxial joint provided by US and one Nb3Sn TF conductor sample provided by IO.
- Under agreement with the CFETR project (China), one Nb3Sn conductor sample for the CS model coil was assembled and tested over a period of six weeks.
- For EUROfusion DEMO, two Nb3Sn TF samples from ENEA were assembled and tested.
- In the scope of the development of Nb3Sn internal joints for CERN accelerator magnets, two samples of bent joint were tested, obtained by diffusion bonding into a custom clamp.

1 From left to right: cross-section of multifilamentary Bi2212 strand; established high-pressure and high-temperature furnace; and critical current vs. applied field dependences at 1 and 50 bar.

DEVELOPMENT OF Bi2212 COILS FOR MAGNETS IN NMR APPLICATIONS

Dr. **ROBERT SOBOTA** is working on a project focused on high-temperature superconductors (HTS) together with an industrial partner. The goal is the development of a novel coil technology based on multifilamentary $Bi_2Sr_2CaCu_2O_8$ (Bi2212) round wires. A high field insert coil by Bi2212 should eventually be part of a superconducting magnet system for nuclear magnetic resonance (NMR). To produce high magnetic fields over a long period of time, a high critical current is required. High-temperature annealing up to 900°C in overpressure up to 50 bar, with a partial pressure of oxygen as the working atmosphere is needed. This type of annealing increases the critical current of Bi2212 strands up to 8 times, when compared to standard low-pressure annealing used in the past. Such an annealing environment is extremely demanding. A custom-made high-pressure furnace was specially designed in collaboration with SPC, delivered, and assembled at our industrial partner. We successfully and repeatedly obtained sufficient critical current density above 600 $A.mm^{-2}$ at a field of 15 T, see **Figure 1**, which demonstrates the high performance of the strand type and its high potential for application to NMR magnets.





2 **Right:** Cross-section of one of the three strands of the HTS quench experiment cable. The HTS tapes form a stack, that is enclosed by a round copper shell. **Top:** time traces of temperature of helium and jacket (green curves) and electric field (purple). The Jacket is the stainless-steel tube in which the superconducting cable is placed, used as mechanical structure and to contain the flowing Helium.

QUENCH EXPERIMENT ON HIGH TEMPERATURE SUPERCONDUCTORS FOR FUSION MAGNETS

In the scope of an international collaboration between EUROfusion and China, our PhD student **ORTENSIA DICUONZO** led a quench experiment on high temperature superconductor (HTS) samples.

Large magnets of existing fusion machines as well as those under construction, e.g. ITER, are all based on low temperature superconductors (LTS). HTS are too expensive to be employed on a large scale. However, their price decreases over time, and we must be ready to exploit their advantages – reaching twice higher magnetic fields and a higher operating temperature of 20 K compared to 5 K for LTS.

One of the key challenges for magnets based on HTS conductors is the quench protection. The transition into the normal-conducting state is not sudden, and there is always a region of the so-called current-sharing mode, in which part of the current still flows through the superconductor, while the other part runs through a resistive material, usually copper. While in the LTS the current-sharing mode spans over just a few Kelvins above the operating temperature and the quench fully develops within a fraction of second, in the HTS conductors it spans over 50 K, which makes the quench behaviour very different, i.e. very slow voltage growth with very large temperature raise.

The quench experiment for HTS high current conductors was set up in the SULTAN test facility. In order to sustain the operating current in the HTS sample during the quench, we have replaced the current source of the SULTAN test facility. This way, we have been able to study for the first time quench evolution in HTS conductors of the size relevant for fusion magnets. Five HTS conductors made by SPC with relevant layout variations were tested in 2020. **Figure 2** illustrates a quench run, during which the temperature reached 150 K – a value that is considered to be the highest tolerable in a fusion magnet.

International Activities - ITER

Research activities at SPC are mostly conducted in the frame of international collaborations, in particular ITER. Dr **TIMOTHY GOODMAN** leads the area in the field of plasma heating systems, in particular high-power microwaves, while other activities are focused on neutral beam injectors.

The European component test facility FALCON has been used in 2020 to evaluate guided components to be used in the first confinement system of the ITER Upper Launcher (UL).

Waveguides were provided by F4E, manufactured by a consortium led by Tiefbohrbär GmbH, Rothrist, Switzerland. They are made of CuCrZr, Aluminum 6061 T6 and 316L stainless steel to allow comparison of their cleanliness, loss rate and mechanical characteristics. Ten campaigns were carried out during 2020. Infrared (IR) images combined with thermocouple measurements were used to determine the temperature rise in the components and verify that losses are significantly larger than predicted for the desired hybrid transmission mode (HE11). Most of the experiments carried out in 2020 were aimed at finding the source of these discrepancies: it is crucial to know whether there is a problem with the manufacturing of the components or whether there is another explanation for the higher losses.

One possible explanation would be that the components are poorly aligned. To exclude this possibility, the F4E metrology department performed measurements on FALCON and confirmed that the installation was within the present ITER requirements.

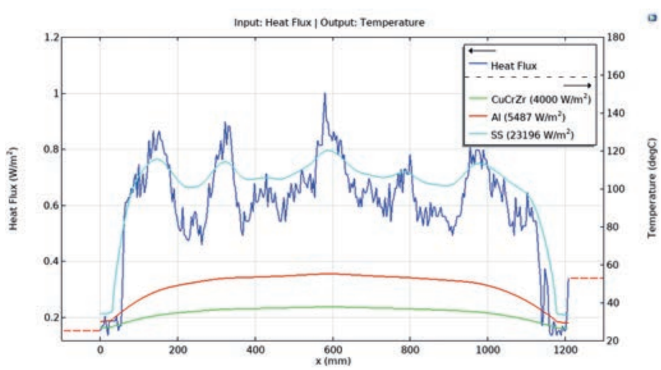
Stainless steel (SS) is not usually considered for use as a waveguide (WG) material due to the much higher electrical resistivity compared with other and shows higher losses than the preferred CuCrZr waveguide; but, they also result in strongly non-uniform IR images. Numerical simulations verify that SS WG can be used effectively as a diagnostic for the presence of higher order modes in the transmitted beam. A non-uniform heat flux profile on the inner diameter of the cylindrical WG produces a concomitant nonuniform temperature profile on the outer diameter of the WG (See **Figure 1**).

The experiments thus strongly suggest that the higher losses can be attributed to the poor mode purity in the transmission line, and as such might be eliminated by a better control of the modes in the line.

In addition, the facility was operated for several weeks under a Memorandum of Understanding (MOU) between SPC and General Atomics (GA), and with the consent of F4E, to test equipment that could be chosen by the US ITER Project Office. Power measurements were made with completely independent sensors, using an alternative method (waveguide surface waves) for absorbing most of the mm-wave power.

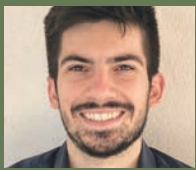
In 2020, The EU gyrotron for ITER related activities were kept to a minimal level as the tube was refurbished by Thales in France and sent to KIT for an initial testing period that started in August 2020. The best performance reached there was 0.93MW during 180s, limited by the high voltage power supply. The gyrotron will shortly be dispatched to Lausanne, and the pulse length will be extended to >1000s.

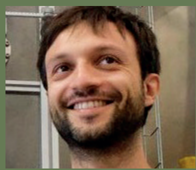
Detailed design activities of the ITER Upper Launcher were pursued in order to finalize the ex-vessel waveguide components and the in-vessel steering mirror. These activities were driven by continually more advanced simulations of the ITER neutronics and off-normal load cases, particularly disruption forces, that led to updates in the load specifications for these components.



1 Numerical simulations using the COMSOL package of the temperature at the WG outer diameter for different WG materials (SS - cyan, CuCrZr - green, Al - red), given an axially non-uniform heat flux on the inner diameter (blue) for a pulse of a certain RF energy transmitted.

NEGATIVE ION SOURCE FOR ITER



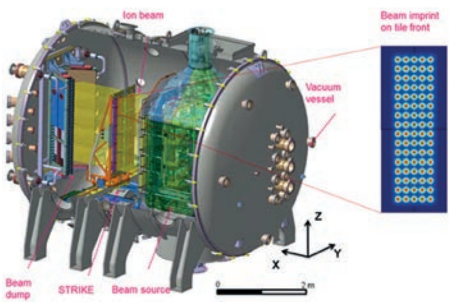


Two staff members of SPC, **BASILE POURADIER** and **RICCARDO AGNELLO**, started working at the Neutral Beam Test Facility (NBTF) in Padova, Italy, through a joint programme of the members of the EUROfusion consortium. Their research contributes to investigate the physics of the negative ion source SPIDER and could help to drive its optimization for ITER.

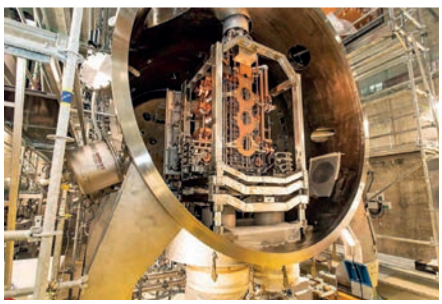
To reach fusion conditions and to control the plasma configuration in ITER, two heating and current-drive neutral beam injectors (NBIs) will supply a total power of 33 MW, by accelerating negative deuterium ions to 1 MeV. The NBTF was created to study and optimize the performances of the ITER NBIs. It hosts two key experiments for the achievement of fusion energy: the full-scale negative ion source SPIDER, shown in **Figures 2** and **3**, which produces and accelerates H−/D− ions up to 100 keV, and MITICA, the full-scale ITER NBI prototype.

To enhance the negative ion production, the surface of the acceleration system grid facing the source, where most of the H−/D− are produced by means of a surface reaction, is to be coated with Cs to reduce its work function. Basile's objective at the NBTF is to study the role of Cs in the source, both in terms of its interactions with the surfaces and its behavior in the plasma. He took part in the design and installation of several diagnostics, such as a TPD device (Temperature-Programed Desorption, **Figure 4**) which can be used to study the formation of Cs compounds on the surfaces, and he expanded a collisional radiative model to investigate the distribution of Cs in the source in conjunction with Optical Emission Spectroscopy.

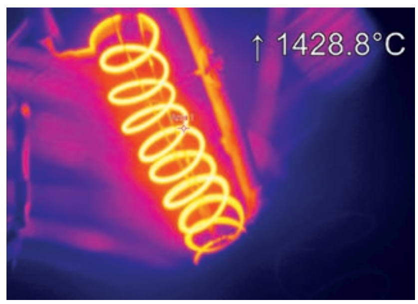
Crucial issues being investigated in SPIDER are the mechanisms of negative ion production in the source volume and the extracted beam properties. To study the density of negative ions in the plasma volume, the Cavity Ring-Down Spectroscopy (CRDS) recently became fully operational. CRDS consists of a high finesse optical cavity in which a laser pulse performing multiple reflections can strip off the extra electron from the H−/D− ions. Riccardo participated in the installation and in the first CRDS measurements, see **Figure 5**, which demonstrated efficient negative ion production. To investigate the features of the negative ion beam, he also contributed to the exploitation of the Beam Emission Spectroscopy (BES) diagnostic, which relies on the measurement of the emission spectra of the accelerated H−/D− beam interacting with the residual background gas (see **Figure 6**).



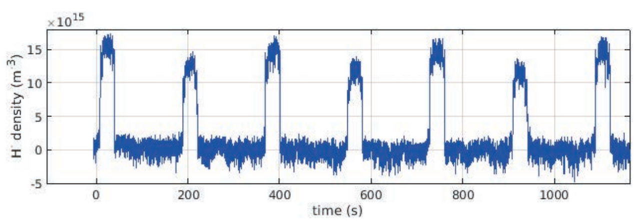
2 Cutaway view of the SPIDER source.



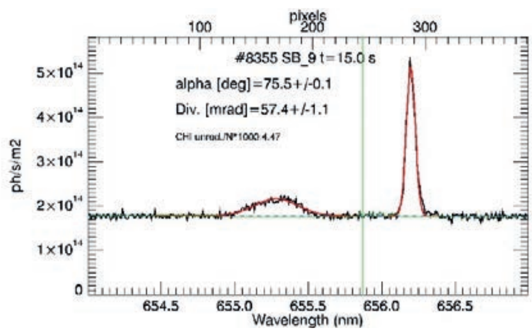
3 The vessel and the SPIDER source (from NBTF website).



4 Thermocamera image of the TPD diagnostic during operation.



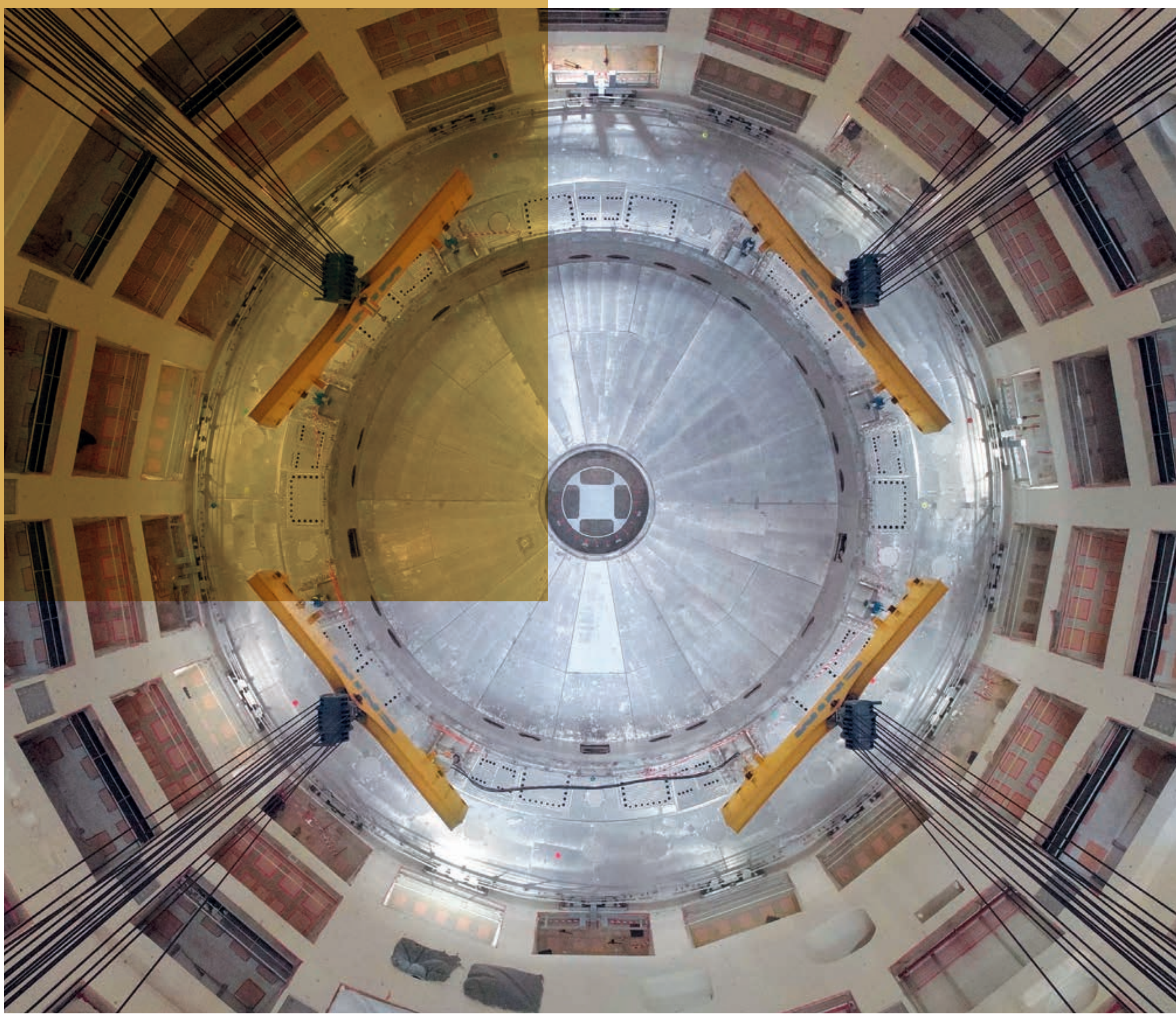
5 Volumetric production of negative ions during operation with short RF pulses.



6 Emission spectrum of a H- accelerated beam showing the H-alpha emission from the background gas (peak on the right) and the Doppler shifted H-alpha emission of the H- beam (left peak).

ITER, EUROPE AND SWITZERLAND

The worldwide fusion community has demonstrated an impressive degree of cohesion and resilience in 2020, an unusual year marked by the Covid-19 outburst and dramatic consequences. Fusion collaborative R&D has in fact continued at levels that were not dissimilar to those before the outbreak of the pandemic.



The ITER construction site kept swarming with activities even during the most rigid lockdown period. The official ceremony of the beginning of the assembly phase took place on July 28, with Heads of State as testimonials, confirming once more a very strong political support for fusion.

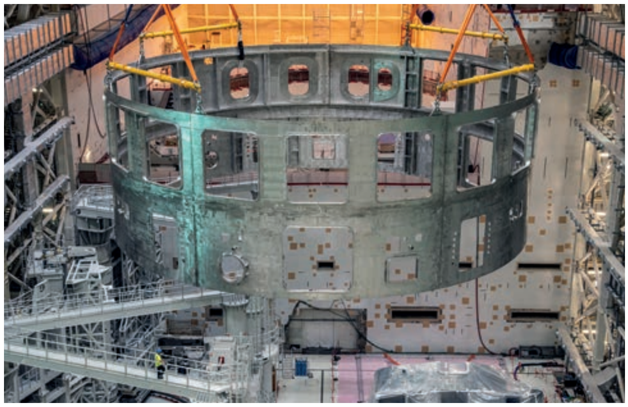
New fusion projects are being undertaken in different places around the world, with both public and private funding, and significant efforts are being devoted not only to finalize the preparations for ITER experimentation but also to advance towards the DEMO step, involving plasma physics, materials and technology.

In Europe, the procurement for ITER is under the responsibility of the Fusion for Energy agency, which has also managed to pursue its mission in an efficient way despite the various sanitary constraints. As an example, important elements of the magnetic field system have been completed, including the first two European Toroidal Field coils, which will carry 68'000A of current, producing a magnetic field up to 11.8T, and one of the main coils for the production of the poloidal field.

In addition, the construction of the largest superconducting tokamak, JT60-SA, conducted in a collaboration between Japan and Europe, was completed, and the tokamak coils were brought to cryogenic temperatures, on the path to first operations.

In parallel with the ITER construction, Europe is forcefully following its Roadmap to fusion energy, with ITER and DEMO as the major milestones, in the frame of the EUROfusion Consortium. Experiments using Tritium have started successfully on JET, in view of the full power Deuterium-Tritium experiments foreseen for 2021, and a variety of studies across Europe, including at EPFL, have provided significant information both to optimize ITER operation and to complete the physics basis for DEMO design.

In 2020, EUROfusion has finalized its R&D strategy and programme for Horizon Europe, the 2021-2027 European Framework Programme for Research and Innovation. Despite the complex political negotiations between the EU and the Swiss Confederation, we hope that some kind of association of Switzerland to the research framework programme of Horizon Europe, or parts of it, will be secured soon, so that our Center will continue to provide critical contributions to EUROfusion, ITER, and, for the next decades, DEMO.



TEACHING

Educating the future generations of plasma physicists and fusion scientists is at the heart of the missions of the Swiss Plasma Center. They are the ones who will bring ITER to full fusion power operation, 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.

At the end of 2020 the SPC had **39** PhD students enrolled in the Doctoral School of EPFL and **27** Post-Doctoral researchers. In 2020, Riccardo Agnello, Ajay Chandrarajan Jayalekshmi, Dahye Choi, Mengdi Kong, Fabian Manke, Roberto Maurizio and Noé Ohana obtained their PhD in Physics.

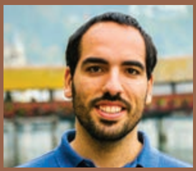
The SPC is providing a complete curriculum of plasma physics courses at all levels: Bachelor, Master and Doctoral School, at the EPFL and within the European-wide education initiative FuseNet.

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 12390 subscribed learners in 2020 from around the globe.

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

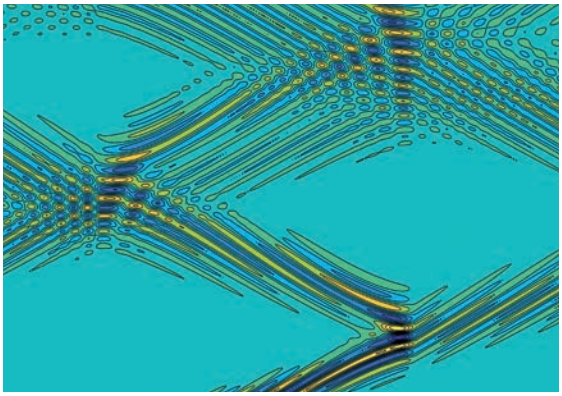
17	Number of courses given by SPC staff at Bachelor, Master and Doctoral levels in 2020
91	Average number of students in the classes of these courses
1,036	Number of hours taught by SPC staff in these classes in 2020
105,168	Number of student-hours taught by SPC staff in these classes in 2020
12,390	Number of subscribed learners in the MOOCs on Plasma Physics of SPC
39	Number of PhD students at SPC by the end of 2020
44	Number of Master students supervised at SPC for semester, specialization and thesis projects in 2020

Every year, up to four prizes are granted by the Plasma Physics Division of the European Physical Society (EPS) to young scientists from 38 European countries in recognition of truly outstanding research achievements associated with their PhD study. In 2020, two of these prizes were awarded to PhD students for their work accomplished at the SPC: **ROGÉRIO JORGE** and **KEVIN VERHAEGH**.



ROGÉRIO JORGE made his PhD thesis under the joint supervision of Prof. Paolo Ricci at SPC and Prof. Nuno Loureiro at MIT. His thesis, entitled "A moment-based model for plasma dynamics of arbitrary collisionality", develops drift-kinetic and gyrokinetic models of particular relevance to describe the plasma dynamics in the tokamak periphery. Turbulence in this region is characterized by both short and large scales and fluctuation amplitudes that are as large as background values. The full Coulomb collision operator implemented allows for the description of all collisionality regimes.

KEVIN VERHAEGH conducted his PhD thesis under the joint supervision of Dr MER Basil Duval at SPC and Prof. Bruce Lipschultz at the University of York. He got the award for his thesis entitled "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". The physics leading to divertor detachment, whereby heat and particle fluxes to divertor surfaces are strongly reduced, has been explored with a combination of measurements of divertor ionization and hydrogenic radiation along the divertor leg.



$$\frac{\partial^2 f}{\partial t^2} = \nabla \cdot \left(u^2 \nabla f\right) + a_{\mathrm{ext}}(x, y, t)$$

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.

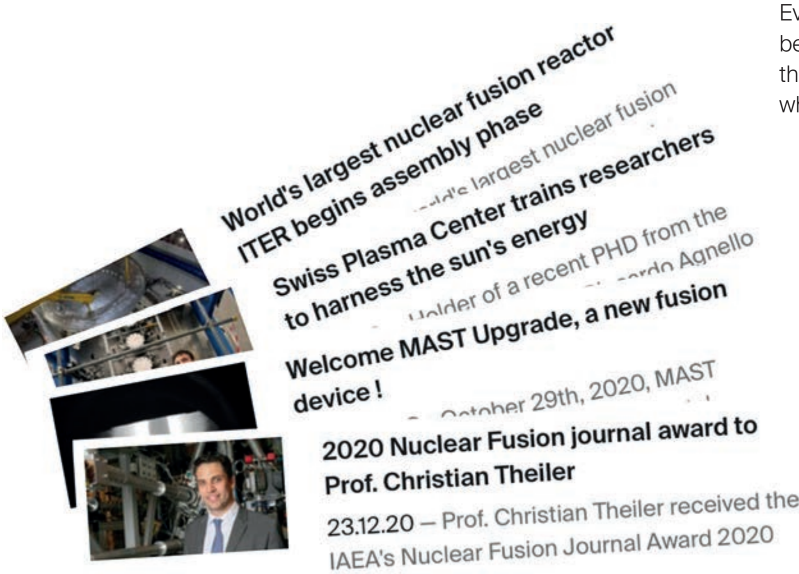
2020 was marked by the launching of the assembly phase of ITER. A major event took place on July 28th in the ITER Assembly Hall, with the participation of President E. Macron of France and dignitaries from the seven ITER members. This event gave rise to a significant recrudescence of the media coverage of fusion activities in Switzerland.

Event marking the start of the assembly phase of ITER (28.7.20)

Our main outreach activity, the guided tours of SPC devices (TCV, TORPEX, RAID) started well in 2020, with 22 visits totaling 515 persons up to March 11th, a slight increase compared to 2019 (19 visits for 363 persons over the same period). From March 16th to mid-July no visits were allowed due to the COVID crisis. During the Summer and until mid-October, some visits were again possible as far as they were considered as important for the EPFL activities. In this period, 7 visits totaling 100 persons have been organised. On the other hand, 33 visits had to be cancelled.

Similarly, external presentations have been performed, as usual, face-to-face, until mid-March, all others have been cancelled or turned into remote events, while not originally planned as such, as, for instance, the Teacher Day organised by FuseNet. This first of the kind EU-wide event offered the possibility of good local contacts with teachers and global connections within EU with the presentation of FuseNet teaching material and a view of the EU salient research activities. FuseNet is an association for the coordination of fusion education in Europe (https://fusenet.eu/).

Eventually, as teaching at high school level in Switzerland has been maintained throughout the pandemic, we received more than half a dozen of requests for matura projects mentorships, which have been honored as usual.



News from the SPC

New web pages for the SPC web site

SERVICES AND ADMINISTRATION

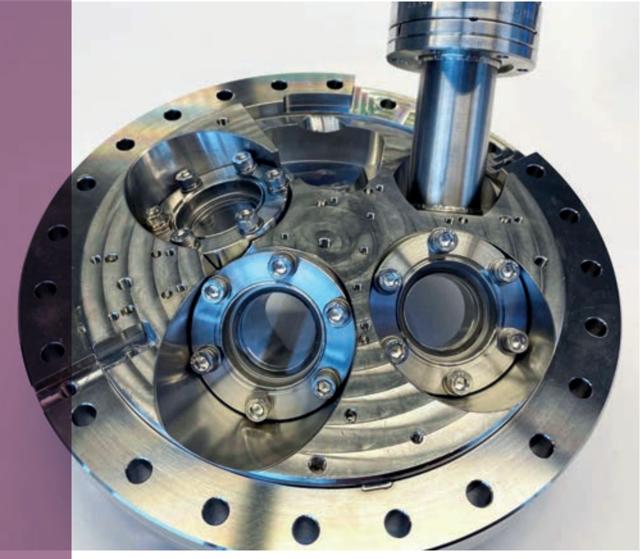
The Swiss Plasma Center could not reach its objectives without a strong technical and administrative support. All services are continuously solicited to provide the physicists with support of various kinds and are requiring a broad range of competences.

Dr Yves Martin

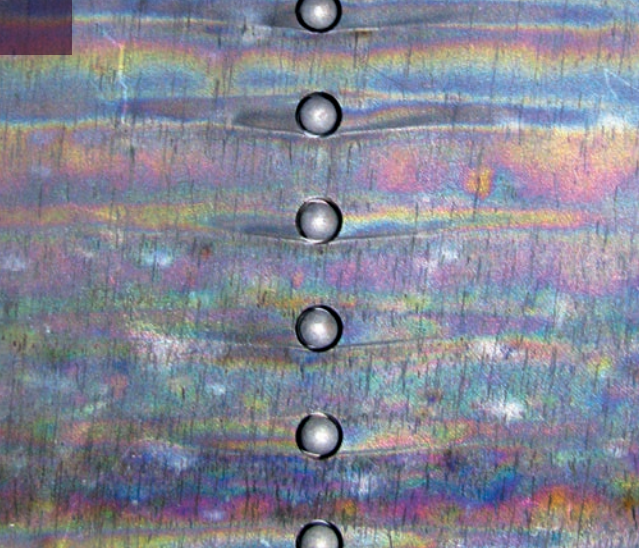
CAO & HEAD OF SERVICES

Dr Christian Schlatter

CFO



Sophisticated arrangement of view-ports dedicated to the observation of the neutral beam ducts and neutral beam dumps for both neutral beam injection systems



TCV Carbon tile equipped with a series of Langmuir probes looking as small domes. The colored streaks are the results of a long exposure of the tile to the plasma.


Matthieu Toussaint

MECHANICS CONSTRUCTION OFFICE AND WORKSHOP


Frédéric Dolizy

VACUUM TECHNICS


Damien Fasel

ELECTRICAL HIGH POWER INSTALLATIONS


Blaise Marlétaz

ELECTRONICS


Joan Decker

IT

Technical support is provided by some 50 engineers and technicians distributed to five services led by the above persons. The administrative and financial team is composed of 7 people.

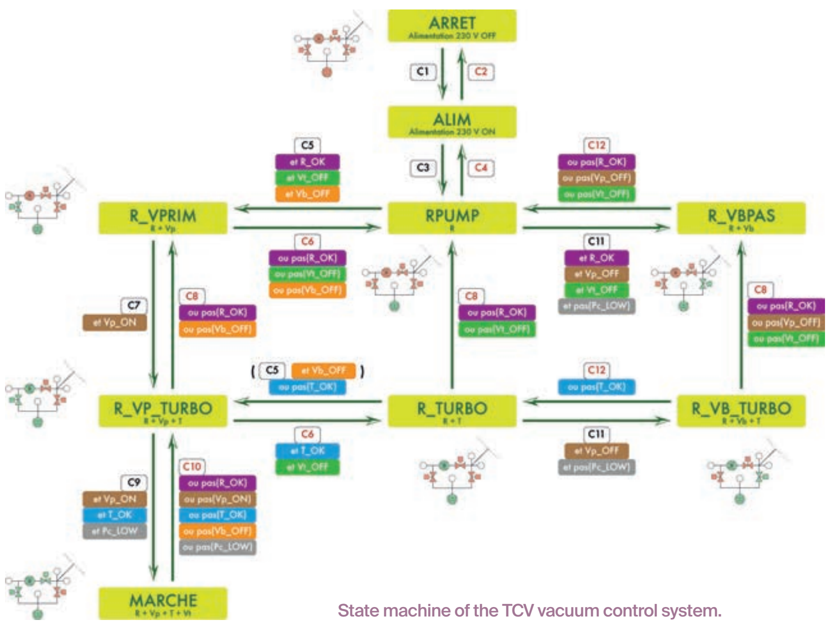
The beginning of 2020 was mainly devoted to a brief shutdown of the TCV exploitation in particular for removing the baffles. On this occasion, several diagnostics have been calibrated, especially those requiring access to the interior of TCV to do this. A full row of electronic and IT cabinets in the N-E corner of the TCV zone have been replaced, displaced and their interior reorganized to accommodate the move of the fast reciprocating probe and other diagnostics to prepare the arrival of the second neutral beam. Several dozen meters of waveguides and other microwave components such as mitre bends have been installed to connect the new bi-frequency gyrotrons to the new ECH launchers located on the top of the TCV vessel.


Copper alloy part to be used to connect the Neutral Beam Injector to the TCV tokamak

The machine was closed but kept at the atmospheric pressure during the lockdown and finally the full restart occurred in May.

All services then contributed to the upgrades of TCV heating systems, namely the two new bi-frequency gyrotrons and the second neutral beam injector. A new gas injection system was also developed, based on new valves and controllers, to feed the plasma and the divertor regions through a series of new nozzles located at different positions in the TCV vessel. A similar system was built for the Gas Puff Imaging (GPI) system. A strong effort was also dedicated to the development of the real-time control of plasmas using new observers such as the electron temperature profile.

In parallel, services provided support to the RAID and TORPEX devices, the Bio-plasma experiments and the test-stand for ITER gyrotrons and ECH components. Among the many tasks executed, let us point out the construction and installation in the RAID device of the measurement of the electron temperature by Thomson diffusion, developed by the laser group.

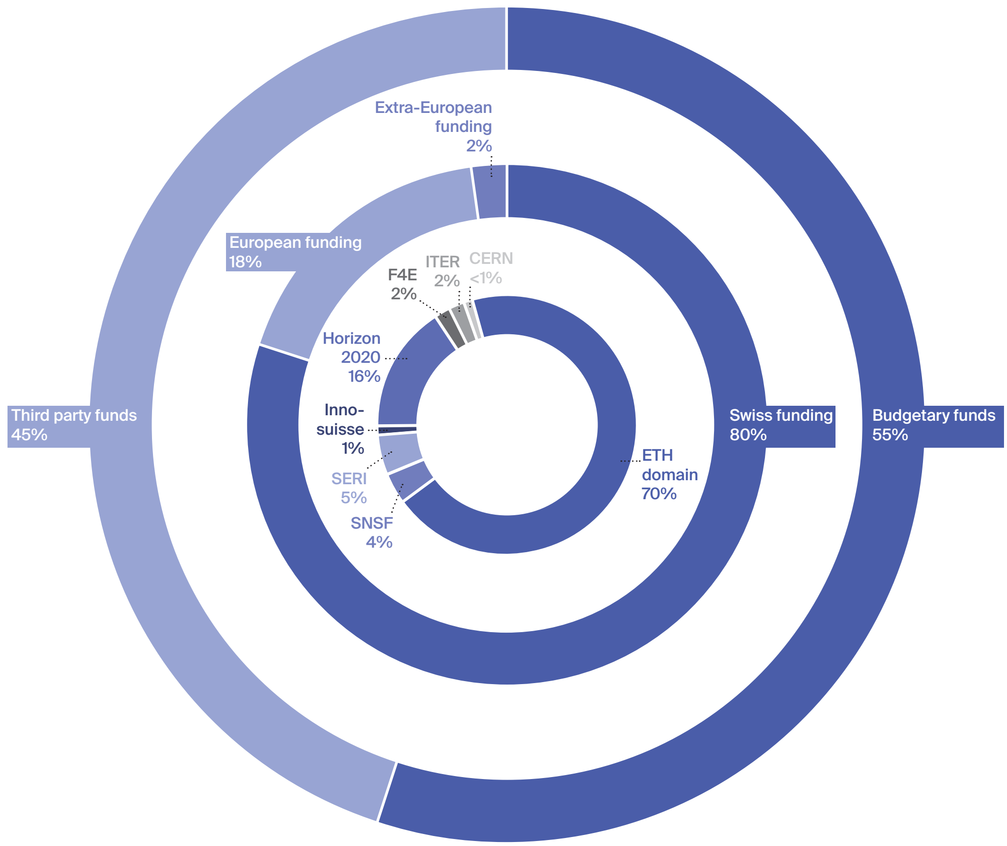


State machine of the TCV vacuum control system.

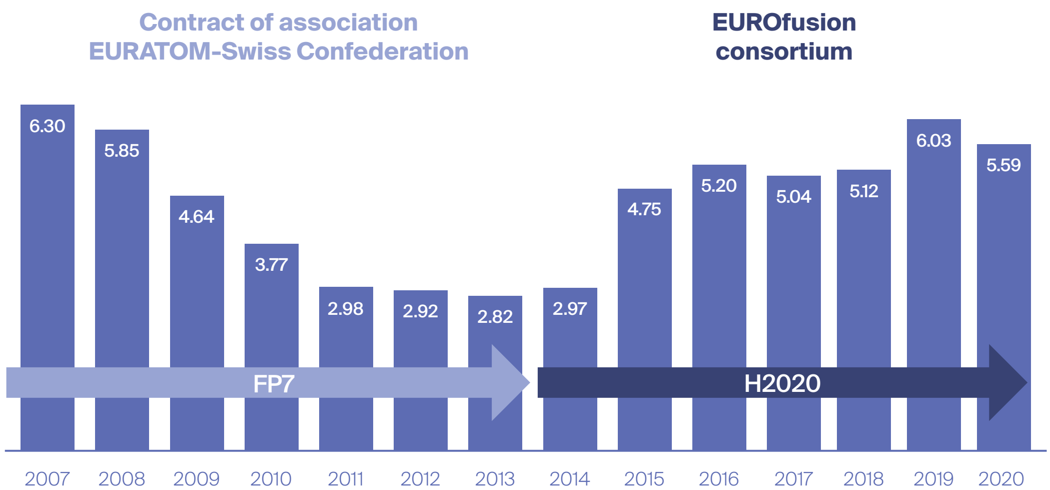
FACTS AND FIGURES

FUNDING 2020

including indirect costs



EUROPEAN COMMISSION CONTRIBUTION [MCHF]



HUMAN RESOURCES

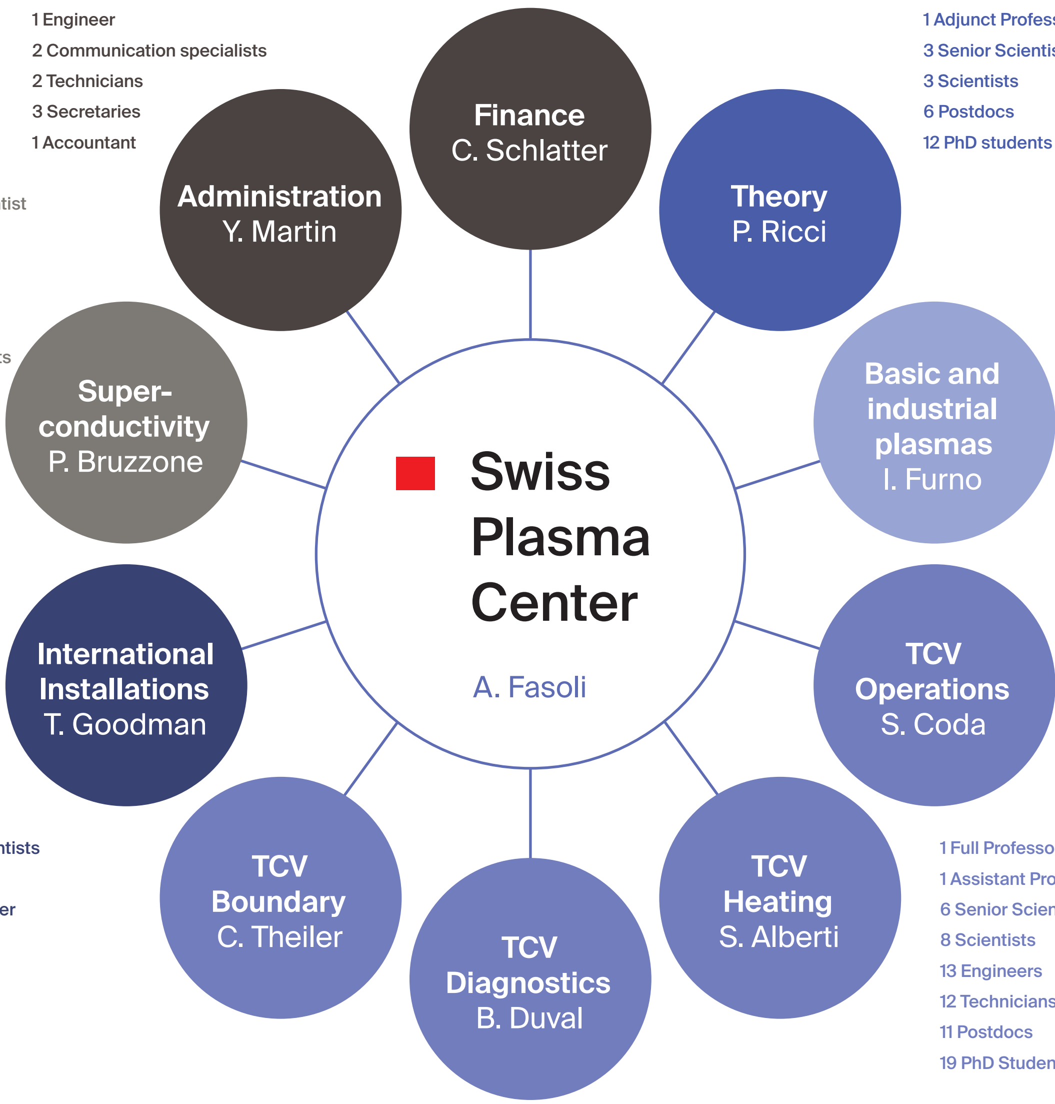
161	Total headcount
156	Full-time Equivalents
39	PhD students (FTE)
27	Post-Docs (FTE)
31	Collaborators joined SPC in 2020
16	Collaborators left SPC in 2020

STRUCTURE

1 Senior Scientist
2 Scientists
1 Engineer
2 Communication specialists
2 Technicians
3 Secretaries
1 Accountant

1 Associate Professor
1 Adjunct Professor
3 Senior Scientists
3 Scientists
6 Postdocs
12 PhD students

1 Senior Scientist
4 Scientists
1 Engineer
8 Technicians
4 Postdocs
4 PhD students
1 Secretary



1 Full Professor
1 Adjunct Professor
1 Senior Scientist
1 Scientist
1 Engineer
4 Technicians
4 Postdocs
4 PhD students

3 Senior Scientists
3 Scientists
1 Liaison Officer
10 Engineers
5 Technicians
3 Postdocs

1 Full Professor
1 Assistant Professor
6 Senior Scientists
8 Scientists
13 Engineers
12 Technicians
11 Postdocs
19 PhD Students

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