EPFL

SWISS PLASMA CENTER

ANNUAL REPORT 2021

Swiss
Plasma
Center

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Letter of the Director

Our Center has once more demonstrated that commitment and professionalism are essential resources to face difficult situations, such as those imposed by the pandemic and the political difficulties between Switzerland and the European Union, preventing a full association to the new Framework Programme Horizon Europe.

We have lost only a very small number of productive hours in 2021, and have learned to combine smart working with on-site experimentation and exchanges, and new ways of cooperating and communicating, capitalizing the lessons learned during the harshest parts of the confinement forced by the pandemic.

Major results have been achieved across the whole spectrum of the Center's technical and scientific programme, from experimental and theoretical discoveries on tokamak plasma physics, to conception and tests of components and systems for ITER and DEMO, e.g. in the area of millimeter-wave heating and control, to developments and tests of superconductors for advanced tokamak magnet systems, and new applications of plasmas to biology and agriculture.

On the TCV tokamak, after severe travel limitations in 2020, external participation has reached again very high levels, with a share of external usage, primarily in the context of the EUROfusion Consortium, reaching more than one third, and more than 150 external users designing and conducting experiments on site or via virtual connections.

The TCV programme continued to address crucial issues, intersecting both ITER and DEMO needs, including edge and divertor physics, H-mode and alternatives such as negative triangularity plasmas, core transport and fast particle issues, disruptions and runaways, and all of this in view of a possible development of control solutions. An example of the modern approach taken on TCV, and of our openness to innovative groups and institutions, is provided by the collaboration with DeepMind (Google) to develop plasma shape control based on reinforced machine learning.

The multi-annual TCV upgrade project co-sponsored by the Swiss government was completed successfully, with the installation of two megawatt-level dual-frequency gyrotrons, two neutral beam injectors at different energies, providing 1MW each, the in-vessel structures to increase neutral pressure in the divertor chamber, and a number of relevant diagnostic and ancillary systems.

The theory and numerical simulations group has created strong collaborations, not only within the Swiss Plasma Center, but also with other institutes and centers of EPFL on applied mathematics, data science, High Performance Computing (HPC), AI, as well as with material science, and additive manufacturing using liquid metals. An outstanding example of these synergies, in particular between theory and TCV, is the recent discovery of the physical mechanisms behind the so far empirically observed limit to the plasma density that can be obtained in tokamaks.

This year was also marked by the start of the activities of the EPFL Advanced Computing Hub, one of the five selected and financed by EUROfusion across Europe, providing support from HPC code design to implementation, testing and optimization.

Despite the political difficulties, based on previously established contracts with Fusion for Energy, activities on the finalization of the Electron Cyclotron Upper Launcher for ITER have continued, in close collaboration with the international ITER Organization and the Integrator. The FALCON facility for the test of ITER mm-wave components has also been strongly employed throughout the year, serving a variety of stakeholders in Europe and in the US.

Both FALCON and the superconducting test facilities located at the PSI in Villigen have achieved the status of fusion technology hubs for EUROfusion in Horizon Europe. At SULTAN, the final tests for the qualification of ITER conductors are being completed, progressively leaving the floor to the corresponding experiments for a wide spectrum of users, not only for the EUROfusion DEMO concept, but also for China and US in fusion, and CERN for high energy physics.

TORPEX and RAID devices remain the focus of basic plasma studies. A new helicon antenna is presently under development for TORPEX to investigate plasma turbulence, helicon physics, and fast ion-wave interactions.

Beyond fusion, a major advance was obtained by measuring electron temperature and density using Thomson scattering in the plasmas used for wake-field particle acceleration, in the context of the CERN AWAKE project, and major developments were undertaken in the bio-plasmas laboratory for societal applications, to understand how non-thermal plasmas affect biological systems, and to develop industrial-grade plasma-sterilized tools.

Our Center continues to play a very important role in education internationally, with about 33 Master students/year, 40 PhDs and 30 post-docs. We deliver 18 classes on basic physics, plasma physics, fusion and related technologies. More than 100’000 student-hours are taught by members of our Center in one year. The total number of enrolments in our MOOC on Plasma Physics and Applications is approaching 40’000. Quality teaching has become our trademark, as testified for example by the best EPFL teacher award, the *Polysphère d’or*, granted by EPFL students to Prof. Paolo Ricci.

The Swiss Plasma Center is more than ever ready to play a strong role in EUROfusion and in the EU fusion roadmap in *Horizon Europe* and beyond. There are political difficulties, but also a strong will of the Swiss Confederation to support us, and of the European and ITER IO and partners to work with us. As the Director General Bernard Bigot wrote in a letter to the Swiss Secretary of State Hirayama, *“The link between ITER and Switzerland is a prime example of such win-win collaboration, and one that I personally consider extremely important”*.

With such will I am confident that a way to collaborate at all levels will be found. Our Center will continue to make the difference in plasma physics, fusion and other applications, thanks to the competence and dedication of its staff, whom I deeply thank and of whom I am very proud, and also thanks to the generosity of our main 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, the international ITER Organization, Fusion for Energy and EUROfusion, and in particular the German Beneficiary of the latter, to which I to express my profound gratitude.

PROF. AMBROGIO FASOLI

RESEARCH HIGHLIGHTS

TCV Tokamak

The scientific programme of 2021 encompassed a broad palette of subjects, informed by the needs of ITER, the explorations required by DEMO, and the fundamental scientific curiosity that befits academia. Highlights are summarized below by Dr. **STEFANO CODA**, Senior Scientist (MER), who supervises TCV operations and science.

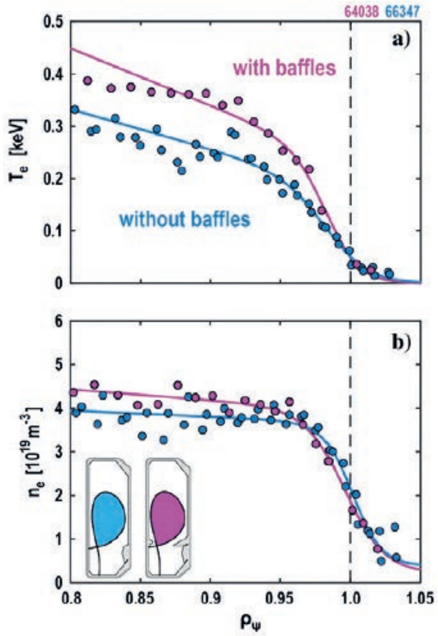
There were no major interruptions in the TCV operational schedule in 2021. The vessel was vented three times for the now-familiar and rapid procedure of alternating among different sets of divertor baffles, accompanied also by necessary repairs and diagnostic upgrades. We started the year with an unbaffled machine, while the so-called SILO (short-inner, long-outer) baffle set was installed in February-March, later replaced by the SISO set in June-July. The baffles were finally removed again entirely in October-November.

The campaign was once again shared between the domestic and EUROfusion programmes, the latter beginning in April under the auspices of the new Tokamak Exploitation Work Package (WPTE). The domestic programme saw the conclusion of the 2019-2021 campaign cycle in May, which was followed by a new call for proposals and the start of a new cycle in August. A total of 2372 completed plasma discharges were performed in 2021.

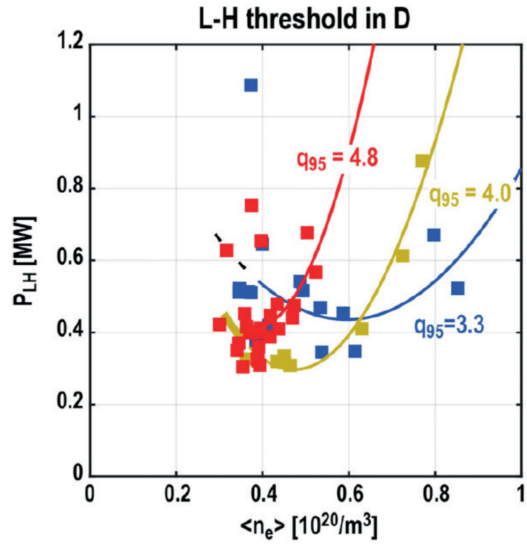
Scenarios compatible with the ITER constraints continue to be studied and painstakingly developed, to eke out incremental improvements in performance and stability. The ITER shape and target physical parameters in terms of plasma pressure (β_N of 1.8), plasma current (safety factor q_{95}=3.0) and good energy confinement (H_{98y2}~1), have now been achieved, using a combination of Neutral Beam Injection (NBI) and third-harmonic Electron Cyclotron micorwaves (X3). The density level remains lower than desired, with a Greenwald fraction of 0.65. As instabilities tend to terminate these scenarios, a higher-q, lower-density case was also developed which benefited from MHD stabilization by well-coupled X3 heating. The optimal compromise is still being sought, with assistance from integrated turbulence and transport modeling.

The all-important edge pedestal region in the high confinement regime (H-mode) has been scrutinized further, with particular attention to any variations caused by the presence of divertor baffles. The known degradation of the pedestal temperature with increased fueling has been found to be tempered considerably in a baffled machine (**Figure 1**). Indeed, in this configuration both fueling and impurity injection can be used to increase radiated power up to threefold without any significant core confinement degradation.

The ITER H-mode regime requires a phase transition from the initial low confinement regime (L-mode), which is governed primarily by a power threshold. The last word about this threshold has not yet been said, as it is characterized primarily by a scaling law which regularly proves inadequate when additional parameters – such as higher shape moments, length of the divertor leg, etc. – are varied. The decoupling between plasma current and heating made possible by high-power NBI has yielded the discovery of an unfavorable dependence of the H-mode power threshold on q_{95}, with a further strong dependence on density (**Figure 2**). These findings fall within standard scalings only in a narrow region in density and q95, and for varying ion species.



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



2 Density dependence of the H-mode threshold in NBI heated discharges at various values of the safety factor.

Edge Localized Modes (ELMs), which are repetitive bursts of plasma ejection at the periphery, pose a problem of high loads on the material surfaces. Therefore the so-called “small-ELM”, or “quasi-coherent exhaust” regime is attractive for a reactor. In the past campaign it was extended to the baffled TCV configuration, where it requires substantially increased divertor fueling. Both this scenario and more standard ELMy regimes have been diagnosed with a novel short-pulse reflectometer, which resolves the outer density profile with μs and mm resolution and has provided direct visualization of the rapid density-profile variations induced by ELMs.

Moving further into the core, fundamental studies of transport have been addressed (see **highlight 1**), as well as the effect on transport of the plasma triangularity, a longtime core subject of TCV research, which is still being pursued in an extensive, multi-year campaign. In parallel, the first global nonlinear gyrokinetic simulation of positive- vs negative-triangularity plasmas on TCV has succeeded in reproducing, in large part, both the transport and turbulence suppression observed with negative triangularity.

TCV has long featured suprathermal electron “tails” (i.e. having a velocity much higher than the average) due to its high-power ECRH and is now also hosting suprathermal ions resulting from ionization of NBI neutrals (see **highlight 2**). A painstaking study of suprathermal electron dynamics was performed with the use of modulated ECRH and with the assistance of quasilinear Fokker-Planck modeling. This study concluded persuasively that data could be explained by substantial radial transport of ECRH-accelerated electrons, concentrated in the resonance region in physical *and momentum* spaces, which suggests wave-induced transport. A second investigation of the effect of ECRH on the plasma focused on the possible role of plasma fluctuations on the propagation of the ECRH waves itself, which can cause the resulting wave-plasma interaction to deviate from the nominal location and lose in efficiency or localization. With results corroborated by simulations in both cases, further experimentation appears needed to separate the two effects.

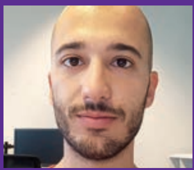
Experiments have continued on the important problem of the mitigation of runaway electrons, focusing on “flushing” a runaway beam with massive injection of neutral hydrogen or deuterium.

A generic plasma control framework has been implemented on TCV to manage multiple control objectives as well as respond effectively to off-normal events (ONEs). This has now been augmented with an advanced supervisor, termed Supervisory control and Actuator Management of ONEs (SAMONE), to provide a general, integrated control strategy. This has already been effectively applied in particular to disruption avoidance in density limit experiments. This framework complements the important set of tools provided by the full discharge modeling and optimization described in **highlight 3**.

Effective real-time control of course requires accurate knowledge of the plasma state, and indicators of proximity to instability or disruptions are particularly important. A change in plasma confinement state is one such indicator, and deep-learning-based confinement-state detectors have accordingly been developed and implemented in the TCV control system.

A more direct approach to mitigating the effects of a disruption, particularly in view of a DEMO reactor, is to constrain the plasma-wall interaction to specific regions of the device. Studies of spatial plasma trajectories during different types of disruptions have been conducted for this purpose on TCV.

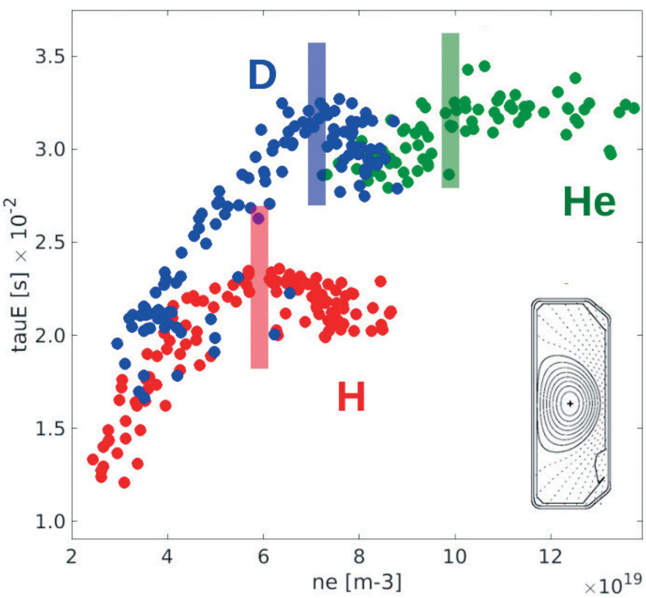
CONFINEMENT REGIMES FOR DIFFERENT SPECIES



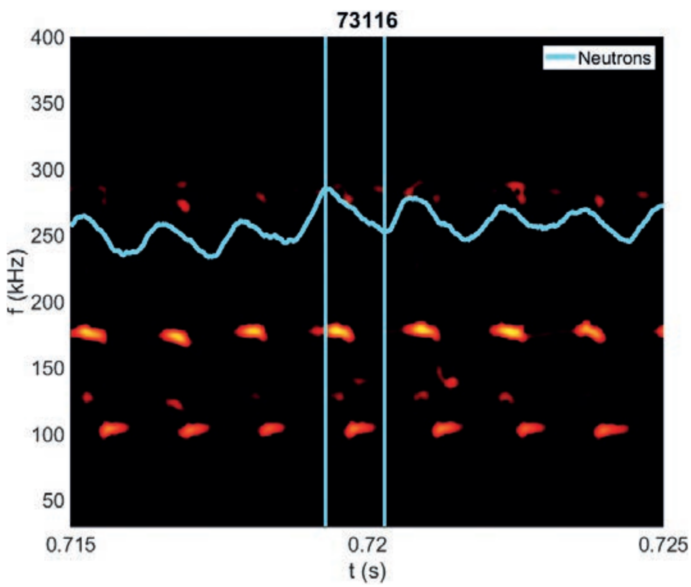
Recent experiments conducted by **FILIPPO BAGNATO**, a Ph.D. student, on the TCV tokamak have focused on the study of plasma confinement and rotation with different hydrogenic species. The confinement time is inversely proportional to the rate at which a system loses energy to its environment. Along with density and temperature, it is the third key factor in the so-called Lawson criterion, a figure of merit employed in plasma science to assess the performance of fusion devices.

The plasma confinement time increases linearly with the density until a critical density value, which divides the confinement into two regimes named Linear Ohmic Confinement (LOC) and Saturated Ohmic Confinement (SOC). The objective of the experiments was to study how confinement, particles and momentum transport change with different species – an important question since the ITER reactor will feature operational phases with different species. **Figure 3** shows how the LOC/SOC transition occurs at different density thresholds for H, D and He, along with significant differences in the confinement time. It is generally believed that a fundamental change in the nature of the underlying turbulence is responsible for the transition.

An intriguing phenomenon often observed during ohmically heated density ramps is the spontaneous reversal of intrinsic toroidal rotation, which is plasma rotation not induced by external torque input. As rotation reversal often occurs in the same parameters region of the LOC/SOC transition in D plasmas, it was suggested that the two phenomena may share the same cause. However, Filippo's work disproved this conjecture. Helium density ramps performed in TCV showed a clear separation of the two phenomena, with rotation reversal occurring before the LOC/SOC transition. At the same time, no rotation reversal was observed in H, despite the saturation of the energy confinement time. A significant correlation was found between the rotation reversal and the electron density peaking, which measures the rate of change of the density profile, possibly shedding some light on this puzzling phenomenon.



3 Plasma confinement time as a function of density. Different colors represent different species: D (blue), H (red) and He (green). The opaque bands indicate the LOC/SOC transition.

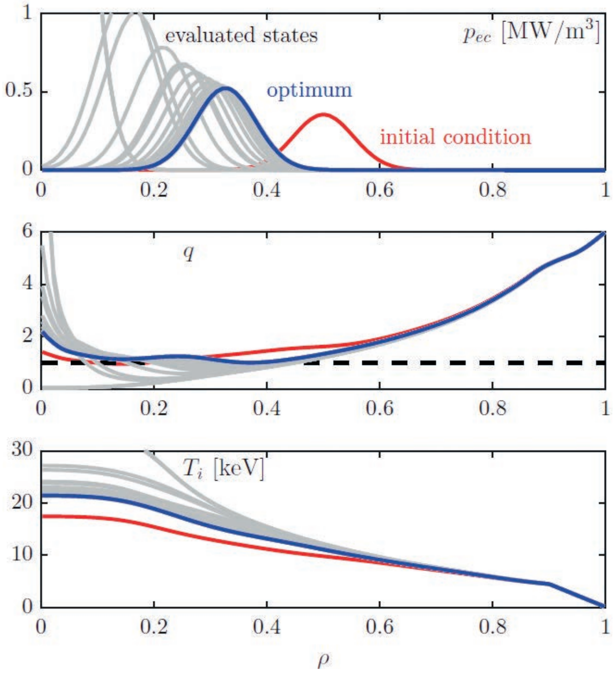


4 Magnetic spectrogram showing the intensity of the modes at different frequencies. The orange bubbles show where the modes are present. The cyan line represents the detected neutrons, and a clear decrease is observed when the mode appears, meaning energetic particles are lost.

FAST PARTICLES

Fast particles are a crucial element of nuclear fusion, since they are an output of the fusion reactions happening in the plasma core. In the TCV tokamak, fast particles are fed directly to the plasma through neutral beam injection. The confinement of such particles is usually good, but some instabilities can develop and cause them to escape the plasma. This results in loss of heat, but can also damage the wall surrounding the plasma. **MATTEO VALLAR**, a post-doctoral fellow at SPC, focuses his work on understanding when such instabilities occur and how to limit the loss of confinement they cause. His activity consists mainly of developing and carrying out experiments in regimes where such instabilities occur and interpreting the observations using modelling tools.

Furthermore, Matteo simulates the neutron production: this helps interpret the fast particles' behavior, since a large fraction of fusion neutrons are generated in TCV by the interaction of the neutral beam with the plasma. These simulations are also important, in conjunction with neutron emission measurements, as neutrons present a direct danger to human safety and their production needs to be carefully monitored. In **Figure 4**, the presence of modes that affect the fast particles is shown and their correlation with the loss of neutrons is clear.



5 The new stationary state solver in RAPTOR was used to find the optimal ECCD deposition for the ITER hybrid scenario, maximizing fusion power, while maintaining the safety factor q > 1. The constrained, non-linear optimization problem could be solved within minutes.

FULL-DISCHARGE MODELING AND OPTIMIZATION

Reliable operation of reactor-class tokamaks like ITER and DEMO will require full-discharge modeling and optimization prior to the discharge, to achieve high-performance plasma regimes and maintain the plasma state within stability limits. Within the PhD thesis of **SIMON VAN MULDERS**, the various phases of tokamak discharges are modeled and optimized, making use of the RAPTOR fast plasma simulator.

A new stationary state solver and optimization scheme was implemented in the RAPTOR code, allowing for the rapid optimization of the flat-top phase. Coupled to a neural network surrogate model of the first-principles-based transport code QuaLiKiz, the potential of fast optimizations was demonstrated for the ITER hybrid scenario (illustrated in **Figure 5**), yielding insights in operational constraints on this scenario.

Dynamic RAPTOR optimizations contribute to the development of a reliable plasma termination strategy for DEMO, optimizing the available actuators to avoid disruptions that would endanger the integrity of the first wall of the machine.

A predict-first approach to perform inter-discharge optimizations on present-day devices allows the validation of the models for ITER and DEMO, while saving valuable experimental time in the development of promising plasma regimes. On ASDEX-Upgrade (Garching, Germany) the RAPTOR code was recently used to inform the ramp-up strategy for a challenging high beta improved confinement scenario. Optimizing the neutral beam onset timing and ECCD radii, a stable and elevated safety-factor profile could be reached early in the discharge

TCV Diagnostics

The TCV Diagnostics group at SPC is headed by Dr MER **BASIL DUVAL**. For TCV diagnostics, 2021 was a year where we started to recover from the COVID19 story and bring several delayed projects into operation.

The Radiation Camera, featuring Bolometer (measuring infrared radiation), photodiodes detector array (AXUV) topographical system and ordinary Soft-Xray diode arrays integrated into one unit, was completed with power balance evaluations automatically available post-discharge.

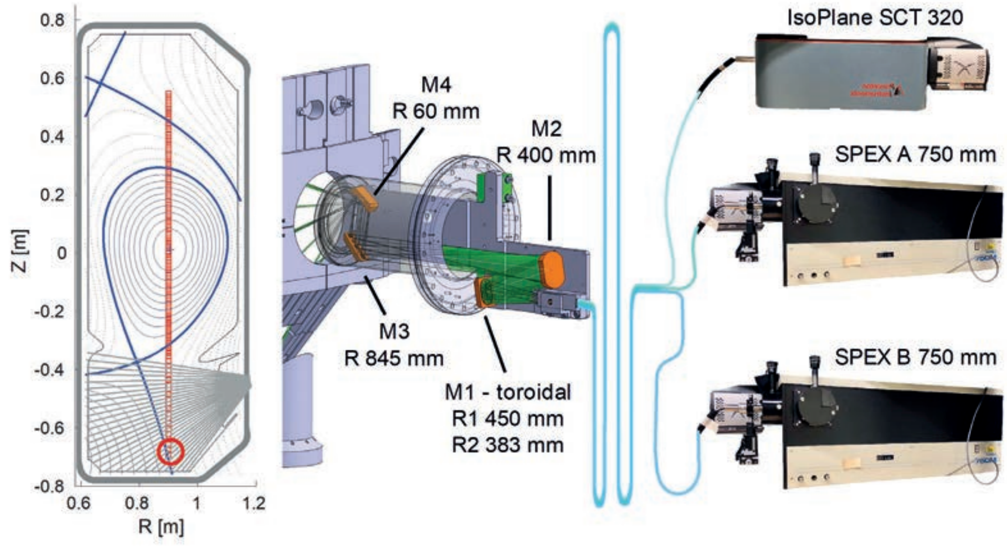
The main Thomson Scattering diagnostic system was further optimised for the lower temperatures that feature in the plasma power exhaust region, called the divertor, and its Real-Time design was finally integrated into TCV's control system, as initially planned (see reports from previous years).

Much effort was dedicated to measuring the neutron emission from the TCV plasma in the presence of our new high power (2x 1MW) neutral beams with a view to reliably monitoring health security. Moving forwards, TCV will be equipped next with a full neutron shield together with calibrated neutron safety monitors that will allow full NBH operation in all discharges, as needed, whilst remaining way below the most arduous safety limits. In the same vein, TCV is now equipped with a fast D-D fusion neutron detector to complement other Fast-Ion detection systems (Fast Ion Loss Detector, FILD, and Fast Ion Detector Array, FIDA) with a bandwidth able to monitor fluctuations up to Alfvén frequencies (100's of kHz).

As for last year, much of the diagnostic development centred upon analysis of the divertor plasma. Following plasma observations by the multi-channel camera system, called MANTIS, that were used to diagnose plasma temperatures and densities across the whole divertor region, new impetuous returned to the divertor spectroscopy system where high-resolution spectroscopy, rather than spectral line ratios, was used on observations chords that traversed the divertor leg radially, see **Figure 1**. Sufficient spectral resolution was obtained to measure ion temperatures down to the 1eV range, albeit after extensive line modelling and corrections for Zeeman magnetic line splitting etc.

A whole new synergy has resulted. As described in previous such reports, divertor Thomson Scattering and MANTIS, multi-spectral-filtered-video-cameras, are already well integrated into TCV's divertor diagnostic assembly. Using TCV's generous, and accurate, poloidal shape control, it was then possible to scan the divertor leg across the Thomson Chords (**Figure 2**) whilst simultaneously monitoring 2D inverted line ratios (from MANTIS) and, now, the ion temperatures and densities from the high-resolution spectroscopy complete the divertor diagnostic, see **Figure 3**. Furthermore, this arrangement can use the Thomson Scattering scan to validate MANTIS line ratio divertor parameter extraction, and, now, the high-resolution data, such that divertor configurations (and this in 2D) inaccessible to Thomson (that form a major part of TCV's divertor research programme) can be diagnosed with high confidence. This, data, rather unique to TCV and a direct result of its open divertor, can be combined with divertor target measurements such as Infra-red cameras and Langmuir probes to construct a well diagnosed 2D (and time changing) divertor parameter space for model validation.

1

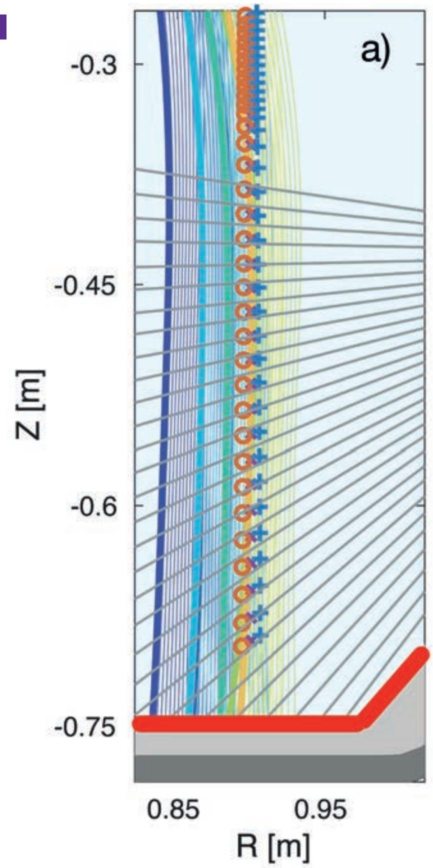


1 Divertor Spectroscopy: IsoPlane survey spectrometer and two High-Resolution spectrometers (observing different spectral lines) observe the same plasma view using 3-fibre bundle relay optics. The Thomson Scattering observation volumes are indicated by red circles and, in the indicated red circle, intercept the divertor leg in this configuration.

2 Vertical line shows Thomson Scattering measurements (3 lasers shown) in TCV's divertor that is scanned (different colours) across Thomson chords.

3 Blue line tracks the position of the CIII radiation front across a density ramp. He II (red) shows the ion temperature (from High-Resolution spectroscopy) at the front position i.e. where the CIII line (often used as a proxy for local plasma temperature ~5-6eV) reduces to ~50% intensity. This measurement shows, for the first time, that the ion temperature, at the CIII front, is near constant as the front moves up the divertor leg across plasma floor detachment.

2



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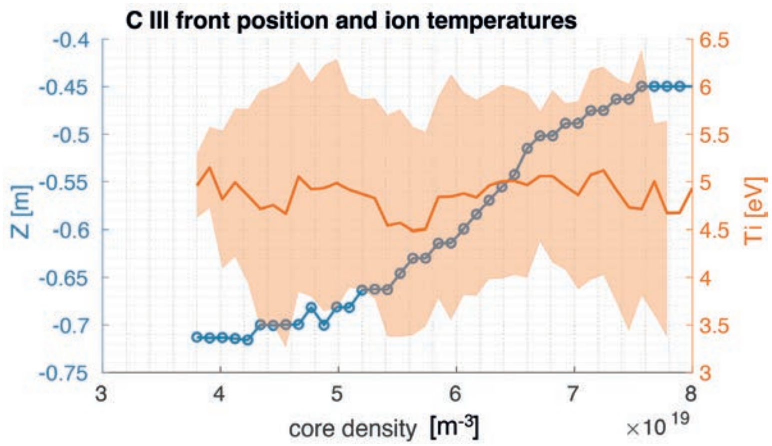


TCV Heating

The upgraded auxiliary heating system on TCV, comprising Electron Cyclotron Heating (ECH) and Neutral Beam Heating (NBH) has entered in its scientific exploitation phase for the TCV experimental campaigns both for the EUROfusion WPTE program as well as the internal SPC program. While scientifically exploiting the auxiliary heating system, a continuing effort is placed for improving its capability, operability, reliability and maintainability in view of reaching the system requirements necessary for operating such a complex system on a future fusion power plant. Dr. **STEFANO ALBERTI**, Senior Scientist (MER), is the leader of the TCV Heating research line and exposes below the main achievements in 2021.

With the aim of further expanding the study of plasma scenarios towards those foreseen for ITER or DEMO, and reaching stationary reactor-relevant discharges sustained by plasma current driven by electron cyclotron waves, a further extension of the ECH system has been devised and is part of the "Swiss Fusion Hub" proposal submitted to the ETH board.

It has been a transition year in 2021 for the ECH system with a large spectrum of activities ranging from completion, consolidation, repair, testing, exploitation up to drafting the design of an upgrade of the present system with a third dual frequency gyrotron.

The first dual-frequency gyrotron, G10, suffered of a cavity failure and was sent back to the manufacturer for repair. The repaired gyrotron has been delivered to SPC in September 2021 and is presently being characterized. The second dual frequency gyrotron characterization has been fully integrated for TCV operation by the end of September.

The top launcher, for the X3 heating, with an optimized optics has been commissioned and is presently characterized on a large variety of plasma scenarios in view to implement a digital real-time control of the injection angle.

Figure 1 summarizes the status of the ECH system in terms of available gyrotrons and launching possibilities with the highly versatile transmission line system connecting the gyrotrons to the various launchers. The proposition for future extension of the system with a 3rd dual-frequency gyrotron is also included in this table with gyrotron G12 and launchers L6 and L12(new).

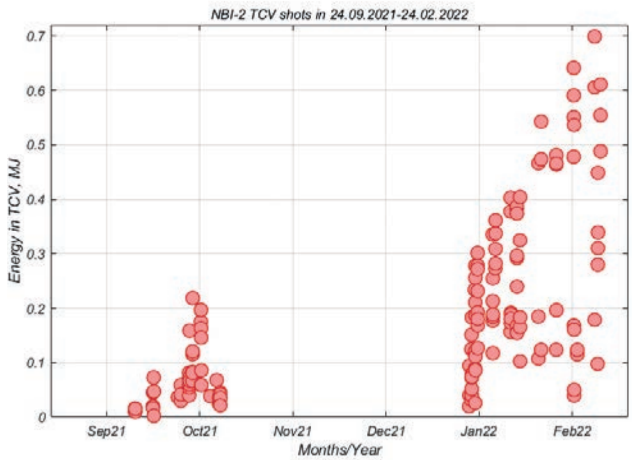
	EQ	UL	EQ	UL	Top-launch			UL
Gyrotron/Launcher	L1	L2	L4	L5	L10	L11	L12	L6
G1(82.7GHz/700kW*)	x							
G2(82.7GHz/700kW)		x						
G7(118GHz/450kW)				x				
G9(118GHz/450kW)			x					
G10(84GHz/900kW)				x	x			
G10(126GHz/900kW)				x	x			
G11(84GHz/900kW)			x			x		
G11(126GHz/900kW)			x			x		
G12(84GHz/900kW)							x	x
G12(126GHz/900kW)							x	x

*All RF-powers are injected power @ TCV

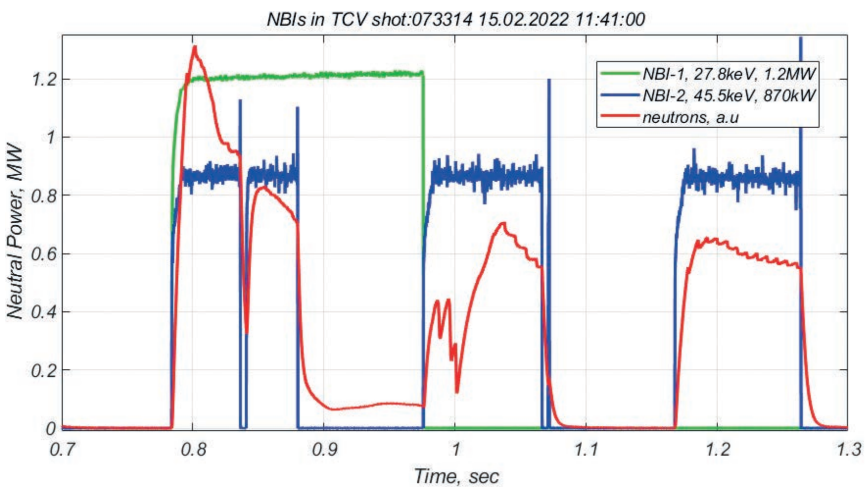
1 Status of the ECRH system with the available gyrotrons at the possible frequencies together with the versatile launching capabilites. For the low-field side launchers, L1/2/4/5/6 are also indicated the launchers position on the vacuum vessel: EQ for EQuatorial and UL for UpperLauncher. In red are shown the extended possibilities with a 3rd dual frequency gyrotro, G12, which is part of the submiited "Swiss Fusion Hub" proposal.

For the NBH system, a 1.3 MW/28 keV low-energy heating neutral beam injector (NBI-1) has been intensively and reliably used on TCV from 2015 mostly for direct ion auxiliary heating in domestic and EUROfusion experimental missions. A second 1 MW/50 keV high-energy neutral beam injector (NBI-2) has been delivered and installed on TCV in July 2021. It addresses plasma physics issues with higher density, in particular fast ion interactions with static and dynamic fields and neutral beam injection - induced plasma rotation. The higher NBI-2 energy will greatly enhance the operating space for fast ion studies. The commissioning of the NBI-2 is ongoing in parallel with TCV experiments using both NBIs. The progress in increase of the NBI-2 energy per TCV shot is illustrated in **Figure 2**. The plan is to extend the existing 0.9 MW, 46 keV, 700 kJ per shot NBI-2 scenario to the nominal 1 MW, 55 keV, 1-2 sec specifications.

The example of the TCV shot with simultaneous NBI-1 & NBI-2 (2 MW in total) injection is illustrated in **Figure 3**, about 10-fold increase of the neutron emission rate has been observed with two beams in comparison with NBI-1 only.



2 Progress in NBI-2 neutral energy per shot injected in TCV.



3 Simultaneous NBI-1 & NBI-2 injection in TCV (0.78-0.88 sec): higher neutron emission in comparison with NBI-1 (0.88-0.97 sec, ~10 times less neutrons) and NBI-2 (1.17-1.26 sec, ~2 times less neutrons).

TCV Boundary

A successful operation of a fusion reactor depends, crucially, upon the boundary plasma. By leveraging TCV's unique magnetic shaping capabilities, operational flexibility and excellent diagnostic accessibility, the TCV Boundary Group, led by Prof. **CHRISTIAN THEILER**, works on advancing the fundamental understanding of the complex, turbulent boundary plasma and developing improved solutions compatible with a reactor.

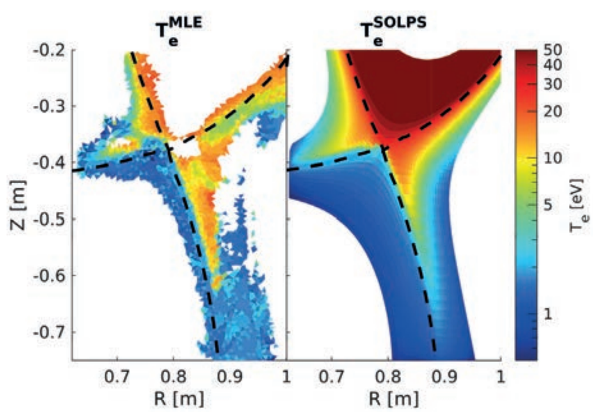
Ideally, one would like to have a cold plasma near the machine walls and reduced plasma-wall contact, thus essentially "detaching" the plasma from any material surfaces, while keeping good fusion core performance. As of today, it remains uncertain whether currently foreseen "conventional" boundary solutions will be adequate for a reactor. New ideas, such as alternative magnetic geometries of the boundary plasma, are being explored. There is a definite need for reliable extrapolations based on experimental observations together with thoroughly validated modeling.

In 2021, we continued to extensively explore the role of neutral particle density in the divertor region, controlled by TCV's interchangeable divertor baffles. A new test baffle of intermediate length provided key information on an optimal baffle closure at the divertor entrance and the effect of baffles on the upstream conditions. In particular, the absence of upstream profile broadening with baffles at high plasma density, known as density shoulder formation, highlights the importance of the upstream neutral density in this process. The study of the divertor plasma and the detachment process as a function of divertor baffling has strongly benefited from improved diagnostic techniques. Probe measurements across a large region, new spectroscopy methods and tomographically inverted multispectral camera imaging, combined with improved collisional radiative models, provide 2D maps of plasma and neutral parameters, including neutral atomic density, ionization and recombination rates, see example in **Figure 1**. These improvements have further strengthened TCV's role as divertor test facility. Detailed comparisons to codes such as SOLPS-ITER have highlighted the important role played by molecular processes in the divertor.

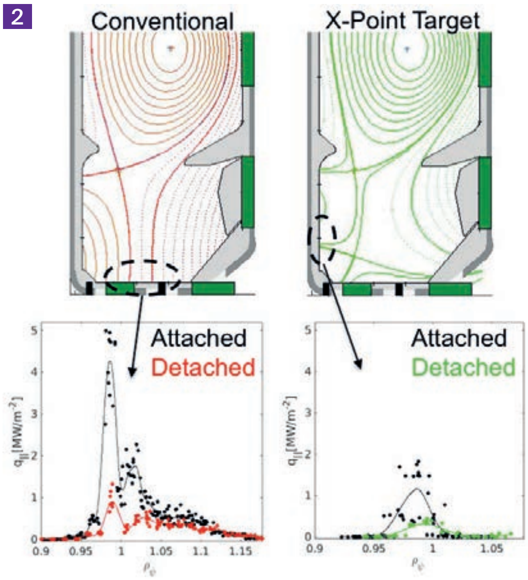
In 2021, there has also been continued progress in the study of optimized power-exhaust solutions, showing some synergetic benefits of target heat flux mitigation by neutral baffling and divertor magnetic geometry in X-Divertor and X-Point Target geometries, see **Figure 2**. Considerable emphasis has been placed on the investigation of X-point radiator regimes, similar to those on the AUG tokamak in Germany, and their manipulation via TCV's generous magnetic geometry control capabilities. Stable X-point radiators were obtained in baffled H-mode snowflake geometries, which retained high energy confinement together with a full suppression of ELMs, opening the way to further studies for a reactor divertor solution. Detachment studies on TCV were also extended, for the first time, to negative triangularity core plasma shapes, a plasma configuration that appears to feature high confinement outside H-mode and, thus, ELMs.

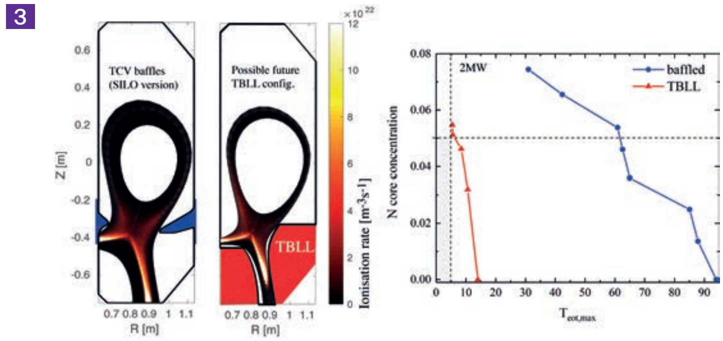
Significant progress was also made in the study of plasma boundary fluctuations (see highlight). In parallel, the work on first-principle turbulence simulations of such plasmas in realistic TCV geometries has substantially advanced. An extensive comparison of real-size TCV turbulence simulations from the GBS and other plasma modeling codes with experiment has been completed, together with all the relevant experimental data to facilitate future code validation studies.

Looking towards the future, long-legged, tightly baffled divertors have been identified as a potentially highly promising reactor solution. TCV is ideally suited for proof-of-principle testing and model validation of this concept and first simulations of such a configuration with the SOLPS-ITER code confirm the great potential of the concept, as shown in **Figure 3**.



1 Example of a 2D map, here of electron temperature, obtained from line-ratio multispectral imaging and comparisons to a SOLPS-ITER simulation.





2 Wall heat flux profiles in an H-mode Conventional and an alternative X-Point Target geometry, demonstrating strong heat flux reductions for the latter, both in the attached and detached plasma phase.

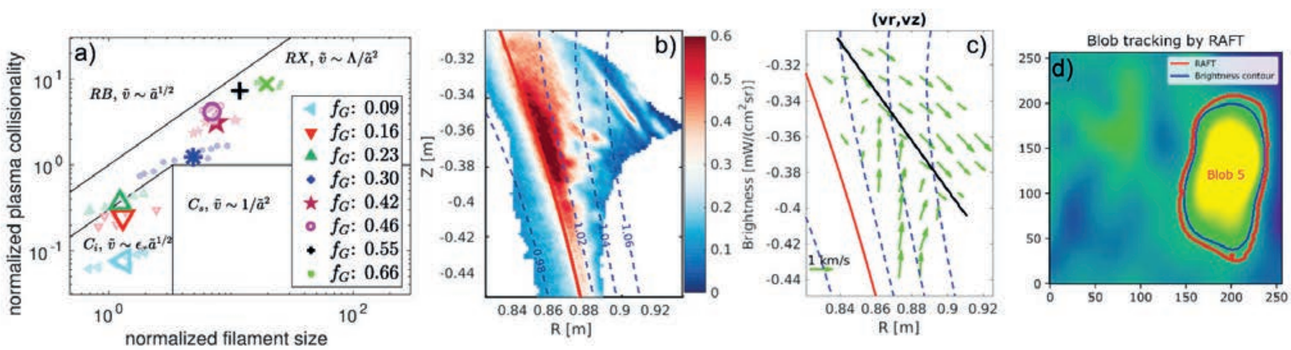
3 SOLPS-ITER simulations in configurations with the existing TCV baffles (blue contours) and a possible future, long-legged, tightly-baffled setup (TBLL, shown by red contours). This predicts substantial benefits for the TBLL in the operating space of safe power exhaust (low enough plasma temperature near the wall) and good core performance (low nitrogen impurity concentration).

GAS PUFF IMAGING OF BLOBS



The PhD students **NICOLA OFFEDDU** (EPFL-SPC), **CURDIN WÜTHRICH** (EPFL-SPC) and **HARRY HAN** (MIT-PSFC) explore a technique called Gas Puff Imaging (GPI) to gain fast (up to 2 MHz), 2D measurements of plasma fluctuations in the boundary plasma of TCV. The installation of a unique setup of several such GPI diagnostics allows them to get measurements in different regions of the plasma, from the midplane, to the X-point region, to the divertor legs.

Filamentary plasma structures, often called blobs, play a prominent role in the dynamics of the boundary region, and their properties are therefore studied extensively. With the help of GPI and other diagnostics, Nicola, Curdin, and Harry have clearly characterized the blob propagation regime defined by a parameter space of normalized blob size and collisionality, see **Figure 4 (a)**. They have shown that blob cross-field motion and their extension along the magnetic field lines are consistent with the prevailing theory. Detailed studies of blobs around the X-point further highlight fluctuations and blobs developing locally in the divertor leg **(b)**. The propagation properties of these structures have been characterized in detail **(c)** and their contribution to heat and particle flux broadening has been estimated. Advanced blob tracking techniques have also been developed **(d)** relying on novel machine learning methods, and, in collaboration with the SPC theory group, a sophisticated synthetic GPI diagnostic is under development, which will allow for stringent comparison of these findings with real-size TCV turbulence simulations.



4 **a)** Identification of blob regime for different core plasma densities, expressed in terms of Greenwald fraction f_G. **b)** Snapshot of turbulence imaging below the X-point, in the divertor leg, revealing both strongly elongated blobs, connected to the midplane, and more circular blobs forming in the divertor. **c)** The different blob types show a different velocity pattern. **d)** Example of a blob identified using object detection neural networks.

Theory and Numerical Simulation

First-principle understanding of the plasma dynamics in magnetic confinement devices for fusion is necessary to interpret the results from current experiments, optimize ITER operation and guide the design of DEMO and future fusion devices. Within the European theory and simulation effort, thanks to the participation in a number of EUROFusion Enabling Research and E-TASC projects, the SPC theory group, led by Prof. **PAOLO RICCI**, gave an important contribution to the understanding of fusion plasmas, through strong collaborations with other research institutes and benefitting from very close ties established with a number of experimental groups.

Since the equations governing the plasma dynamics are generally too complex to solve analytically, the theory group has built a strong expertise on numerical simulations and makes use of some of the most advanced High-Performance Computers worldwide, including Piz-Daint at the Swiss Supercomputing Center (CSCS) and Marconi at Cineca. This expertise on numerical methods has been recognized by the EUROfusion consortium that established one of the EUROfusion Advanced Computing Hub at EPFL (see **highlight** next page). The operation of the Advanced Computing Hub started on July 1st.

PLASMA GLOBAL STABILITY

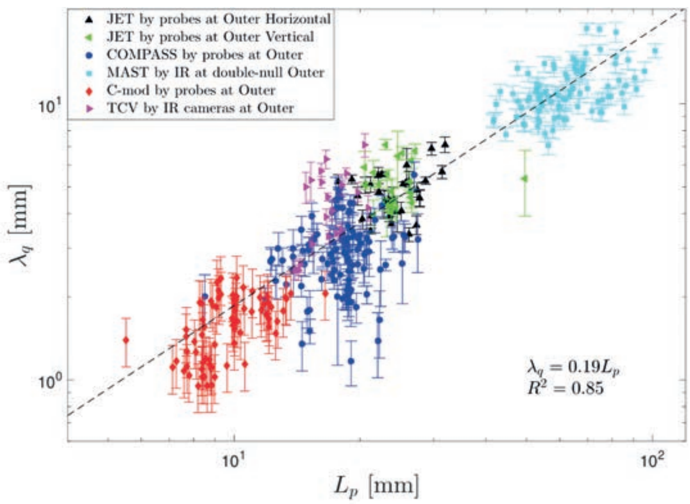
We have progressed in our understanding of the fundamental properties of pressure-driven ideal and resistive instabilities in tokamak plasmas, especially where there are extended regions of low magnetic shear. With this work we will be able to investigate the sensitivity of future tokamak plasma scenarios to performance-limiting instabilities, and ultimately establish the role of plasma rotation, which is likely to be different in fusion grade reactors. Part of this work has concentrated on the existence conditions of edge harmonic oscillations, the associated exfernal modes which are apparently mutually exclusive to ELMs, and therefore hold the key to ELM free H-mode operation in tokamaks. A EUROfusion enabling research project ties these topics together also with a new hybrid kinetic-MHD code that will handle corrections to MHD associated with the long mean free path of particles in a hot reactor plasma.

PLASMA SHEATH

The modeling of magnetized plasma sheaths that forms at the interface between the plasma and the solid walls has been refined by accounting for finite electron Larmor radii effects thanks to a generalized gyrokinetic theory valid for small angles of incidence of the magnetic field to the wall (i.e., conditions relevant for magnetic fusion devices). This allows accounting for the strong deformation of the gyro-rings due to the strong electric fields present in the magnetized sheath. This semi-analytic model was originally successfully applied to account for the kinetic ion dynamics within the magnetic pre-sheath and has now allowed for the accurate kinetic modeling of electrons within the Debye sheath where the plasma becomes non-neutral. This model has been benchmarked with a unique simulation code for modeling the magnetized sheath developed at the SPC in 2021. This code integrates numerically the full particle trajectories and is thus valid for arbitrary angles of incidence of the magnetic field. It provides directly the stationary state of the combined Vlasov-Poisson system of equations via a relatively low number of iteration steps, avoiding the costly time evolution of standard PIC codes that must resolve the plasma frequency over ion-dynamic time scales.

PLASMA DYNAMICS IN THE TOKAMAK BOUNDARY

An increasing effort is being made on the simulation of the tokamak boundary, a crucial region determining the performance of the entire device. Theory-based scaling laws of the near and far scrape-off layer (SOL) widths were analytically derived for L-mode diverted tokamak discharges by using a two-fluid model. The near SOL pressure and density decay lengths were obtained by leveraging a balance among the power source, perpendicular turbulent transport across the separatrix, and parallel losses at the vessel wall, while the far SOL pressure and density decay lengths were derived by using a model of intermittent transport mediated by filaments. The analytical estimates of the pressure decay length in the near SOL was then compared to the results of three-dimensional, flux-driven, global, two-fluid turbulence simulations of L-mode diverted tokamak plasmas, and validated against experimental measurements taken from an experimental multi-machine database of divertor heat flux profiles, showing in both cases a very good agreement (see **Figure 1** for the comparison), allowing the prediction of the heat flux on ITER in L-mode discharges, in fairly good agreement with experimental extrapolation.



1 Comparison of the theoretical scaling law of the SOL width in L-mode single-null diverted discharges to experimental values of λq taken from a multi-machine database.

FAST PARTICLES

Alfvén Eigenmodes can be destabilized by fast particles such as those generated by heating systems and by fusion reactions. They are also damped by various mechanisms, and the balance between the drive and damping will result in overall stable or unstable situations. While unstable modes are sometimes observed in experiments, it is interesting to study the damping of these modes also when they are overall stable, e.g. to try to avoid them becoming unstable. To this purpose, we have equipped the ORB5 code with the possibility to resonantly excite these modes by the application of external perturbations. Various Alfvén eigenmodes could be studied and their damping rate measured. Our simulations also show the nonlinear coupling between different modes.

We have also used modelling methods and experimental data to estimate the structure and dynamics of islands that are coincident with runaway electron beams. Such work is crucial in advance of avoiding runaway electron beams and disruptions in future reactors.

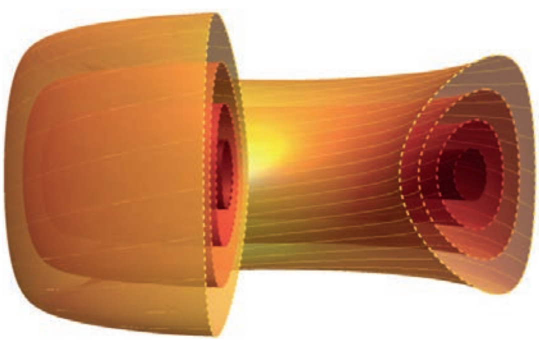
PLASMAS WITH NEGATIVE TRIANGULARITY

Negative triangularity plasmas are attracting considerable attention as an interesting option for fusion reactors, and the SPC leads the EUROfusion Theory, Simulation Verification & Validation (TSVV) task focused on the assessment of their properties. The activities of the theory group on the subject have substantially increased in the past year.

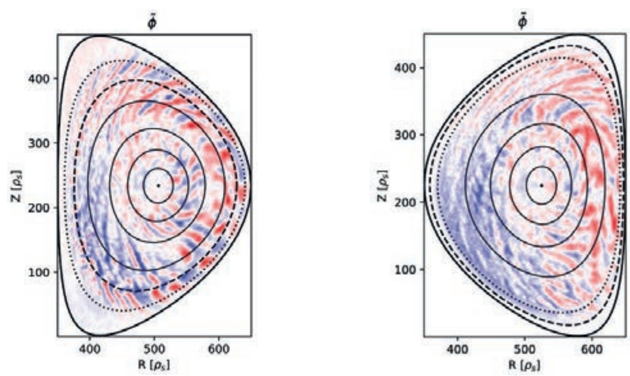
Starting from the plasma equilibrium, A workflow to study the global stability of negative triangularity discharges has been developed using the CHEASE, CAXE and KINX codes. A rather strong dependence of the global stability on the edge value of the safety factor has been found in the preliminary analysis of a first case taken from the TCV database.

The 2D analysis of the local shear with respect to good-bad curvature has been shown to relate well with the access to ballooning 2nd stability access and the H-mode access in negative triangularity plasmas.

High-fidelity computer simulations of turbulence in tokamaks with negative triangularity plasma have been performed with the ORB5 and GENE codes (see **Figures 2 and 3**). Both simulations showed superior energy confinement in negative triangularity plasmas compared with the standard positive triangularity plasma shape, which is consistent with experimental results from TCV. Importantly, the simulations also indicate that the benefits of negative triangularity should hold in the turbulent regime expected for a power plant, which is currently inaccessible to TCV.



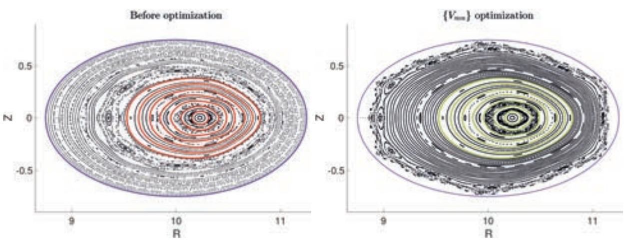
2 Simulaton of plasma Turbulence in a negative triangularity discharge.



3 Contours of potential perturbations in positive (left) and negative (right) triangularity TCV equilibria as computed with the ORB5 code.

3D CONFIGURATIONS

The effort on the simulation of the 3D configurations carried out by the SPC developed along a number of directions. The 3D MHD equilibrium code SPEC has been coupled to the stellarator optimization framework SIMSOPT and used to perform free-boundary stellarator optimization at finite pressure and current, thereby obtaining "healed configurations" (**see Figure 4**), in which the external field produced by the coils is adjusted to reduce the islands and chaos, which are detrimental for confinement.

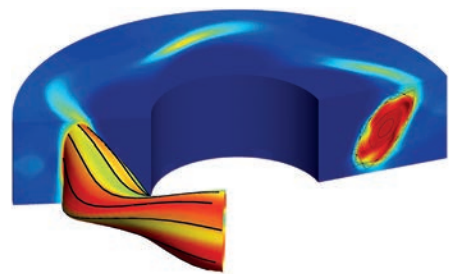


4 Poincaré plots of the equilibrium magnetic field from SPEC before (left) and after (right) optimization of the coils performed with SIMSOPT.

Regarding the heating mechanisms in 3D configurations, the VENUS-LEVIS full-F code has been upgraded to treat various new problems. Inclusion of an effective collision operator for thermalized fast ions has enabled more realistic modelling of synergistic radiofrequency (RF) and Neutral Beam Injection (NBI) heating in the W7-X stellarator.

The modelling of ion based auxiliary heating has been advanced with the SCENIC code, which comprises the VENUS-LEVIS code describing fast particle dynamics, the full-wave code LEMan and a 3D equilibrium code. We have applied SCENIC to help design optimized heating and fast ion generation schemes for the W-7X stellarator, especially synergetic RF-NBI heating, which is also capable of producing a large fraction of energetic particles, required for proving that advanced stellarators are capable of confining fast ions such as alpha particles. These scenarios are now modelled more realistically with the implementation of a collision operator for thermalized minority ions. We have also begun to design a framework for a free boundary axisymmetric equilibrium that will be capable of taking into account the effects of beam ions on plasma rotation and pressure anisotropy in tokamak plasmas.

Finally, the SPC effort has led to the first global, two-fluid, turbulence simulations in a stellarator with an island divertor (**Figure 5**). These simulations, carried out with the GBS code now capable of solving the plasma turbulent dynamics in arbitrary 3D magnetic configurations, have revealed that transport induced by electrostatic fluctuations is associated to the presence of coherent modes, a striking difference when compared to tokamak simulations.



5 Snapshot of the plasma density obtained with GBS for the stellarator configuration in quasi-steady state.

NUMERICAL SCHEMES FOR THE SIMULATION OF CORE TURBULENCE

Reaching quasi-steady-state in turbulence global gyrokinetic simulations is made especially difficult when the temperature or density profiles evolve far from their initial state. This is in particular the case in strong gradient regions near the plasma edge. We have shown that numerical noise accumulation in the zonal flows can result in an unphysical quench of the turbulence. In order to avoid this problem, an adaptive control variates scheme has been implemented in a model gyrokinetic code, showing its capability at controlling the noise in the long term.

Similarly, turbulent eddies interact with themselves when magnetic field lines bite their own tails after a small number of circuits of a tokamak. To study such "turbulent self-interaction", gyrokinetic simulations were used to isolate the effect of changing the field line topology. It was shown that turbulent self-interaction can change energy transport by a factor of 2. Thus, it is very important to properly treat the magnetic field line topology, which is not common practice in the community. Moreover, turbulent self-interaction could play an important role in resolving a mystery concerning the formation of internal transport barriers, which are regions of improved confinement that are sometimes observed in tokamaks.

EUROPEAN HUB FOR HIGH PERFORMANCE COMPUTING

Since July 1, 2021, the EPFL is host of a EUROfusion Advanced Computing Hub (ACH). The ACH is operated by the Swiss Plasma Center (SPC) and leverage the expertise and personnel at the EPFL Scientific IT & Application Support group (SCITAS), at the Swiss Data Science Center (SDSC) and at the EPFL group of Mathematics in Computational Science and Engineering (MATHICSE), while taking advantage of the visualisation capacity of the EPFL Laboratory for Experimental Museology (eM+). It is led by Prof. PAOLO RICCI and Dr **GILLES FOURESTEY** is its executive director.

The EPFL ACH provides a service to the whole EUROfusion community focused on HPC activities. Indeed, the EPFL ACH is addressing an urgent need within EUROfusion by serving as a competence centre for modern computational methods, providing support and expertise to the development of EUROfusion research software through the implementation of state-of-the-art numerical algorithms and its porting to the most advanced computing platforms, developing verification and validation procedures and providing cutting-edge visualization tools. At the same time, the EPFL ACH acts as a competence centre for applications, in particular, for the EUROfusion standard software. After a ramping-up of the ACH activities, we expect to reach the envisaged 10 ppy/y by 2023.

The EPFL was chosen as an ideal host for an ACH, thanks to its expertise on HPC activities, the existing strong links with the entire EUROfusion community through numerous HPC projects, and its infrastructures. Because of its academic environment, the financial support for the ACH will seed a deeper involvement of the EPFL, to the benefit of the entire fusion community. For example, the ACH projects will naturally engage undergraduate and graduate students, as well as a number of professors.

The EPFL ACH already proved very successful in 2021, in that it raised a strong interest from the EUROfusion community: requests for support came from across Europe specifically mentioning the EPFL hub as their preferred choice. As a result, our hub was the most oversubscribed of all five ACHs in Europe.

REAL-TIME CONTROL

Significant progress was made in the development of simulation tools for tokamak real-time control, a field that the SPC has pioneered. The RAPTOR code has been updated to obtain directly the stationary state solution, leading to very fast simulations, which is ideal for optimizations of scenarios. A paper studying hybrid ITER plasmas using the QUALIKIZ surrogate transport model has been published. RAPTOR has also been used to determine the DEMO termination phase, leading to a reduction of the foreseen maximum plasma current ramp-rate to ensure stability. A real-time algorithm for the termination phase in JET plasmas has been shown useful in D, T and DT plasmas. It is based on simulations with RAPTOR and “simple” real-time power balance measures.

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 in the bio-plasmas laboratory exploring applications of low-temperature plasmas in biology and life-sciences. Combining advanced experimental measurements with theory and numerical modelling, we advance the basic understanding of the underlying plasma phenomena towards practical applications. The main activities are summarized below.

RAID: NEGATIVE IONS AND HELICON PHYSICS

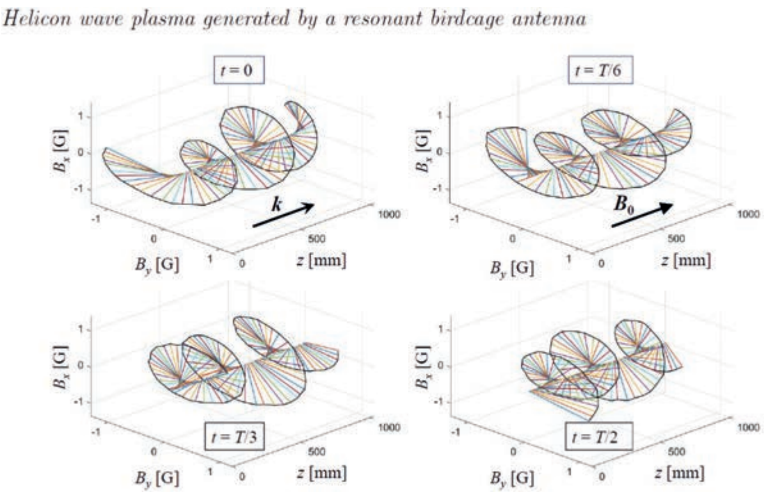
The activities on RAID continued to advance the understanding of the generation of negative hydrogen in helicon plasmas as well as helicon wave physics.

A 1.5D model was developed to understand plasma transport and chemistry in a low pressure hydrogen helicon plasma discharge. We have applied this for a typical case of the RAID helicon plasma device. The method is based on the separation of the ion transport by a fluid model and a MC model for the neutrals. On the basis of electron density and temperature measurements, the neutral equilibrium density profiles as well as the density of H_2 in each vibrational excited state can be found. These values are used as input for the 1.5D fluid transport model. We found that hydrogen plasma discharges are characterized by a H^+ dominated center surrounded by a H_2^+ and H_3^+ halo. We have compared the reaction rate profiles with the steady state equilibrium densities to understand the role of transport; it is found that negative ions are produced at the edge of the plasma column and are transported towards the center. Because of the interest in volume negative ion production in RAID, it is helpful to investigate the interplay of production and destruction processes of H^-. We observe that H^- are mainly destroyed in the plasma center by electron detachment and are mutual neutralized by H_2^+ and H_3^+ at the edge, close to the peak density position. Future developments on H^- volume production in helicon sources should focus on finding a correct balance among these competitive mechanisms to maximize the volume density of H^- close to the extraction region.

We investigated the generation and propagation of helicon waves in RAID, the magnetic wave field was measured along the plasma axis of the device using miniaturized magnetic probes, see **Figure 1**. The observed helical structure and polarization are consistent with helicon waves. The dependence of axial wavelength on the plasma density and external DC magnetic field is smooth and continuous, showing no preferred dependence on the antenna length or the standing wave structure. Furthermore, heavy or light ions had no notable influence on the axial wavelength, which depended only on the electron density and the DC magnetic field, as expected according to helicon theory. Finally, the measured axial wavelengths were compared with semi-analytical and purely numerical models. The semi-analytical model relies on the so-called 'helicon approximation' to calculate the eigenvalues for any radially non-uniform plasma profile, by numerical integration of a second order differential equation. The experimental data and the calculated eigenvalue of lowest axial wavelength are in good agreement with no fitted parameters. Numerical simulation of the self-consistent currents in the antenna and the plasma spontaneously converged towards this same dominant mode. The birdcage helicon source used on RAID represents a new alternative to conventional partial-helix antennas, with technical advantages regarding high internal resonance currents and predominantly-real input impedance, and a wider operational parameter space with improved plasma stability, especially for light ion (hydrogen) plasmas.

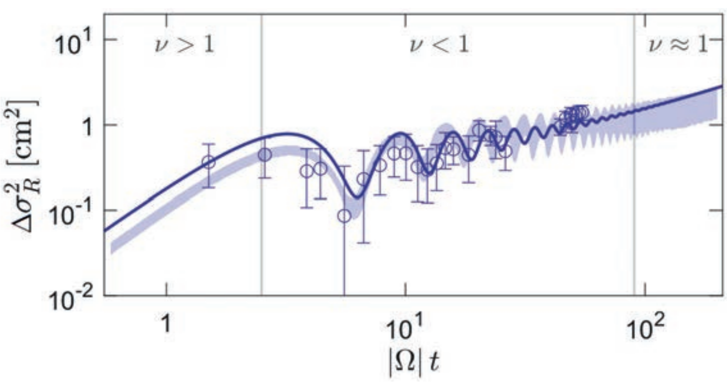
TORPEX: ADVANCED THEORY OF SUPRATHERMAL ION TRANSPORT

The progress made in recent years in the understanding of suprathermal ion transport in TORPEX hydrogen plasmas was consolidated in 2021, both in terms of modeling as well as in experiments. The following three main topics were addressed: intermittency of suprathermal ions, truncated asymmetric fractional Lévy motion model, and the 2D Persistent Random Walk (PRW) model. Time series from non-diffusive transport processes of suprathermal ions in turbulent plasmas were analzyed, on results stemming from the intermittency studies, where a relationship was established between statistics of the time-resolved suprathermal ion detection signals. The main idea was that the variance and skewness of the detection time series can be predicted from knowledge of only the mean and very few additional parameters. Finally, the persistent random walk model of the suprathermal ion transport was applied to TORPEX experimental conditions. The main point was that the



1 Measurements of the transverse components of the wave induction field along the axis (z) of the plasma column, for four equally spaced times of a RF period T (Hydrogen at 0.3 Pa, B_0 = 200 G and P_{RF} = 1.5kW). Spatially the wave field exhibits a left handed helical pitch, and the whole pattern rotates clockwise with time, as expected for helicon modes.

PRW model gives a good description of the experimental observations in TORPEX, see **Figure 2**, and is able to describe transitions between different transport regimes, at different toroidal distances, something that is difficult to model with Lévy motion models.

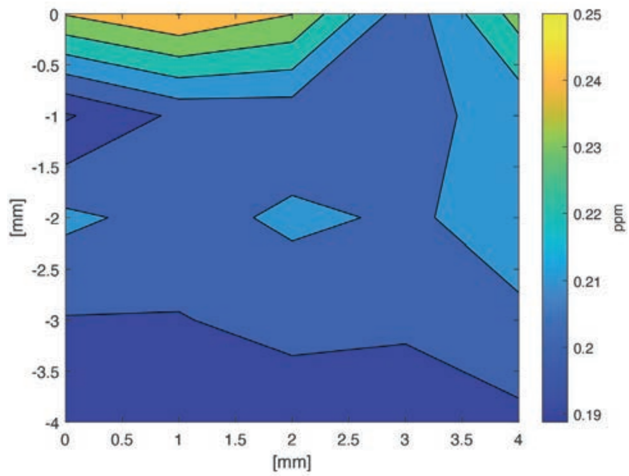


2 Persistent Random Walk model (line) for the radial width change of 70eV lithium-6 ions injected in a turbulent hydrogen plasma, together with experimental data (circles) and simulations (colored band). The horizontal axis is the time evolution in units of the ion cyclotron frequency. The model captures the different cross-magnetic field transport regimes, including super-diffusive (ν >1), sub-diffusive (ν <1) and quasi-diffusive (ν ≈1).

LOW TEMPERATURE PLASMAS FOR BIOLOGICAL APPLICATIONS

The activities in the field of low temperature plasmas for biological applications were conducted along three main research lines detailed below.

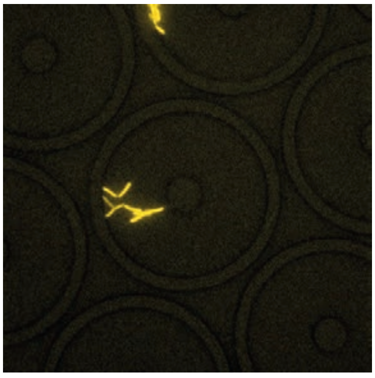
Development of dielectric barrier discharge (DBD) source and plasma characterization



3 NO concentration in ppm in a 4x4 mm square perpendicular to the plasma surface. The measurements were taken at 0% RH, 500 µs after the plasma discharge.

We focused on the design and optimization of dielectric barrier discharges (DBDs) for biological applications, capable to withstand high-humid environment, which is often unavoidable when humid gases or water-containing materials are treated. Several SDBD configurations have been designed, to decouple the effect of the dielectric material from the electrode geometry. We characterized the Reactive Oxygen and Nitrogen Species (RONS) at atmospheric pressure, using a first DBD prototype powered by a nanosecond pulsed power supply. By means of Fourier Transform Infrared Spectroscopy (FTIR) we measured the concentrations of O_3, NO_2, N_2O and HNO_3 and by Laser Induced Fluorescence (LIF) we measured NO, whose concentration is under the detection limit by FTIR in this setup. Thanks to the fast-pulsed picosecond laser we were also able to measure the NO concentration at different humidity, showing an increase of NO at higher humidity. The NO concentration was also measured at different positions in front of the plasma surface with a resolution of around 1 mm³. The results allowed for a 2-dimensional reconstruction of the NO concentration on a 4 mm square region in front of the DBD, see **Figure 3**. The results revealed a clear correlation between the NO concentration and the distance from the plasma. The trend is not only visible on the perpendicular direction from the DBD surface, but also across the electrodes fingers of the DBD. The work was focused not only on the spatial information, but also on the time evolution of the NO concentration between 2 consecutive plasma discharges. The measurements showed a higher concentration of NO at lower plasma discharge frequencies, 100 Hz as opposed to 1 kHz.

Plasma activated water for pathogens sterilization



4 Example of fluorescent acquisition of E.coli cells (100 x magnification).

Leveraging the results obtained in 2020, we investigated the mechanisms at play in plasma-activated water (PAW)-mediated sterilization. We performed time evolution measurements of long-lived species concentrations by vis-spectrophotometry for different samples of PAW. To verify PAW-mediated sterilization efficiency we performed first experiments with E.coli and M.smegmatis bacteria, obtaining the inactivation curves. Thanks to a collaboration with the McKinney Laboratory of Microbiology and Microtechnology at EPFL, first microfluidic experiments were performed for single cells observation of E.coli exposed to PAW. Using genetically-modified fluorescence E.coli, see **Figure 4**, we demonstrated that after PAW exposure, the bacteria were experiencing fluorescence loss, suggesting the perforation of the cellular membrane during the treatment. Experiments on vesicles exposed to a PAW sample were performed at the Bio-photonics laboratory of EPFL using laser induced second harmonic (SH) generation. These showed the evidence of a SH signal, around the vesicles before their collapse, possibly suggesting charge accumulation on the membrane. Future experiments are necessary to assess the nature of this charge accumulation. Atomic force microscopy acquisitions of M.smegmatis exposed to a PAW sample were performed at the laboratory for Bio- and Nano- instrumentation (EPFL). From these first acquisitions it was not possible to identify a degradation of the M.smegmatis membrane. However, PAW showed an inactivation effect on this bacteria strain. Future experiments will help clarifying this aspect.

Plasma agriculture (see also Highlight)

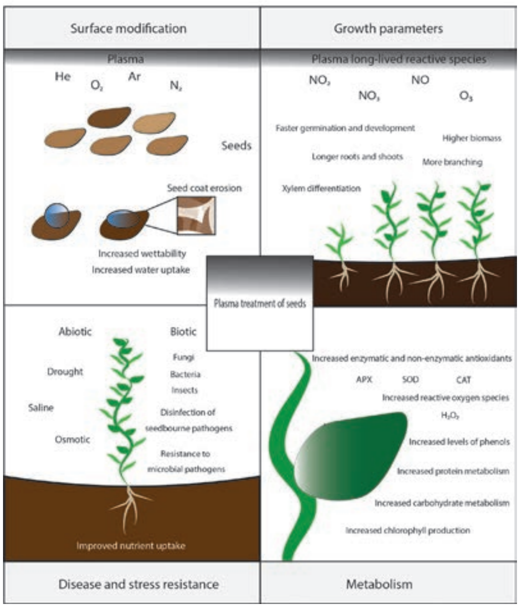
Current agricultural practices are not sustainable. Non-thermal plasma treatment of seeds may be an eco-friendly alternative to alter macroscopic plant growth parameters. Despite numerous successful results of plasma-seed treatments reported in the literature, the plasma treatment parameters required to improve plant growth remain elusive due to the plethora of physical, chemical, and biological variables. In 2021, we investigated the optimal conditions for treatment of Arabidopsis thaliana seeds with a surface dielectric barrier discharge (SDBD) setup, using a parametric study, and attempted to understand relevant species in the plasma treatment. Our results suggest that treatment time and voltage are key parameters for accelerated germination; however, no clear conclusion on causative agents can be drawn. Accelerated germination of Arabidopsis thaliana seeds after plasma treatment was observed. In situ Fourier transform infrared (FTIR) absorption spectroscopy was used to identify the active agent behind the accelerated germination and although it remains unclear, NO remains as a plausible candidate. RNA sequencing was used to look at the gene expression and was among the first transcriptomic studies on plasma-treated seeds in the literature. We provided an overview of all pathways that are differentially expressed where few genes are upregulated and many genes are downregulated. Our results reveal that plasma treatment time is a parameter that can activate different pathways in plant defense. An 80s treatment upregulates the glucosinolate pathway, a defense response to insects and herbivores to deter feeding, whereas a shorter treatment of 60s upregulates the phenylpropanoid pathway, which reinforces the cell wall with lignin and produces antimicrobial compounds, a defense response to bacterial or fungal plant pathogens. It seems that plasma elicits a wounding response from the seed in addition to redox changes. This suggests that plasma treatment can be potentially applied in agriculture to protect plants against abiotic and biotic stresses without discharging residues into the environment.

UNDERSTANDING THE MECHANISMS OF NON-THERMAL PLASMA TREATMENTS ON SEEDS

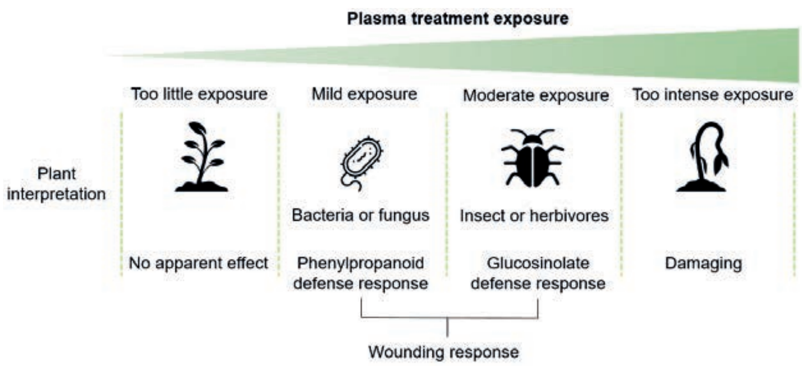
Plasma agriculture is a rapidly emerging interdisciplinary field where non-thermal plasmas are used to treat heat-sensitive biological substrates, such as seeds and plants. When dosed adequately, plasma-treated seeds are observed to have accelerated germination, enhanced growth, reduced water consumption, increased crop yield and disease resistance, and decreased levels of microbial pathogens as shown in **Figure 5**.

Currently, more is known about how non-thermal plasma influences the macroscopic properties of plants but little is known about how plants are affected on a molecular level. Furthermore, it remains unclear which component (reactive oxygen and nitrogen species, heat, electric or magnetic fields, UV, ions, electrons) are responsible for an observed plasma effect on seeds and their subsequent development.

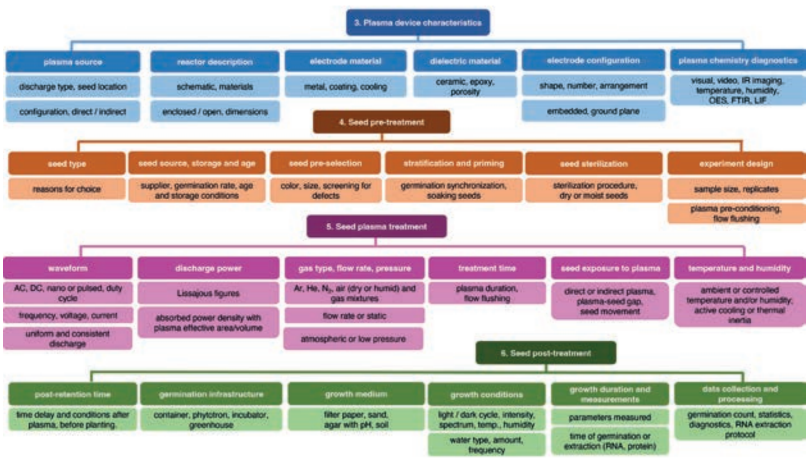
During her PhD thesis work, **ALEXANDRA WASKOW** used Surface Dielectric Barrier Discharge (SDBD) treatments on the model plant organism Arabidopsis thaliana to investigate the underlying molecular effects of plasma treatments. Plant seeds were exposed to SDBD plasmas to identify conditions yielding a phenotypic change, specifically accelerated germination. In collaboration with Dr. Anthony Guihur at the University of Lausanne, she has performed among the first transcriptomic studies on seedlings grown from plasma-treated seeds and has demonstrated that plasma treatment upregulates the plant defense pathways. She has proposed a tentative hypothesis based on the preliminary, pioneering data where plants may perceive plasma as both a wounding and oxidative stress as shown in **Figure 6**. Moreover, she has developed guidelines regarding protocol and diagnostics for plasma-seed treatments in **Figure 7** in an effort to synchronize efforts in plasma agriculture to understand which parameters are important for designing plasma-seed treatments to ultimately transfer this technology into industry. Her work has been appreciated by the biological applications of non-thermal plasma community.



5 Effects of plasma treatment on seeds which includes surface modifications, changing growth parameters, modulating disease, and stress resistance through metabolism.



6 A tentative hypothesis summarizing the findings in the RNA sequencing study where mild plasma exposure and moderate plasma exposure resulted in phenylpropanoid or glucosinolate biosynthesis, respectively.



7 Checklist of a proposed protocol for the plasma treatment of seeds.

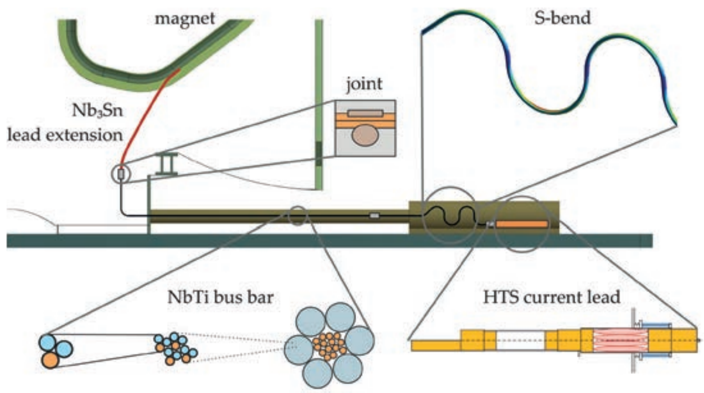
Applied Superconductivity

The main focus of the superconductivity group, which is located in the premises of Paul Scherrer Institute in Villigen and led by Dr **KAMIL SEDLAK**, is on the development and testing of big superconducting cables for fusion magnets. The cables have either circular or rectangular cross-section with a typical diameter of 40 mm. Several km of the cables are wound in a fusion coil, and a tokamak hosts about 30 such coils in total. At SPC, we develop conductors with increased performance compared to those used in ITER. Our prototype conductors for DEMO tokamak achieved performance slightly better than the ITER cables, and did so with a reduced amount of Nb3Sn – the typical low-temperature superconducting (LTS) material used in fusion coils. This way we can save the material costs, and also reduce the radial build of the magnets.

In 2021, our research concentrated on the studies related to high current conductors for EUROfusion DEMO. The motivation is to reduce voltage during the fast (safety) discharge of the coils, and consequently reduce the risk of the coil damage or degradation during their long-term service in a tokamak. We have designed a conductor rated to 105 kA (compare to 68 kA at ITER), whose prototype is now being manufactured in the Italian company Tratos, and shall be tested in 2022.

In addition, we continue investigating high-temperature superconductors (HTS) for fusion. We address mainly the issue of the quench detection and protection. We have studied quench detection based on optical fibers and on the electrically-insulated low temperature superconductor (LTS) wire co-wound with the HTS conductor. We have also continued experiments studying quench evolution in HTS conductors in a dedicated experimental campaign.

In our test facility SULTAN, we tested this year conductor samples for tokamaks ITER, EU DEMO, Chinese CFETR and SPARC (Commonwealth Fusion, USA). The SULTAN facility is unique in the world – nowhere else could these conductors be tested in conditions relevant to the magnet operation. However, the tokamaks designed nowadays shall operate at magnetic fields exceeding the maximum SULTAN field of 10.9 Tesla. For this reason, we are working on the upgrade of the EDIPO test facility that should extend our testing conditions with respect to SULTAN. The aim of new EDIPO is to reach a magnetic field of 15 Tesla in a test well with the aperture larger than that of SULTAN. In 2021, we improved the EDIPO coil design and purchased a helium vessel that will host the new magnets (dipoles). We applied for funding of the EDIPO upgrade, where the major components to be produced are the two dipoles generating the 15 Tesla magnetic field.



1 **Schematic view of a magnet feeder for the EU-DEMO reactor and main components (from top left to bottom right): in-cryostat Nb_3Sn lead extension; schematic cross section of a bus bar joint; proposed cable layout of a NbTi bus bar; simulated deformed shape of a bus bar S-bend under thermal loads; schematic cross section of the HTS current lead.**

DESIGN OF THE MAGNET FEEDERS FOR THE EU-DEMO FUSION REACTOR

Dr. **ROBERTO GUARINO** is working on conceptual design activities for the EU-DEMO fusion reactor. Among these, a particular attention is devoted to the magnet feeders. They must guarantee a safe electrical and hydraulic connection of the superconducting magnets (located within the cryostat and cooled at ~ 4.5 K) to the power supply and cryogenic plant outside of the tokamak.

Low-temperature superconducting (LTS) bus bars, based on NbTi cables joined to the magnets through Nb3Sn lead extensions (see **Figure 1**), have been designed, and their thermal-hydraulic performance has been studied by means of numerical simulations. The structural behaviour of the bus bars, subjected to thermal and electromagnetic loads, has been also evaluated, providing insights for the design of mechanical supports and of S-bends needed to withstand the thermal contractions.

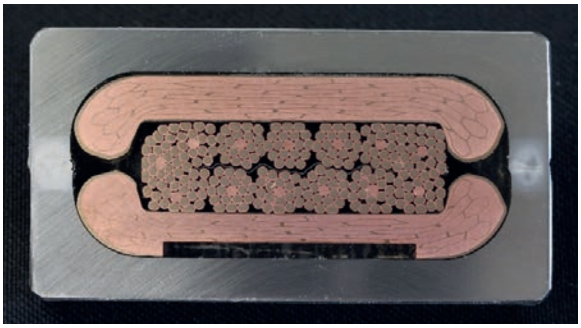
In addition, the design of high-temperature superconducting (HTS) current leads for different operating currents has been outlined. The current leads transfer the electric current from the room-temperature power cables to the superconducting bus bars at 4.5 K. The current leads have been designed considering also worst-case scenario accidents, e.g. a loss of helium flow.

STRAIN CHARACTERIZATION OF NB_3SN SUPERCONDUCTORS FOR EU-DEMO

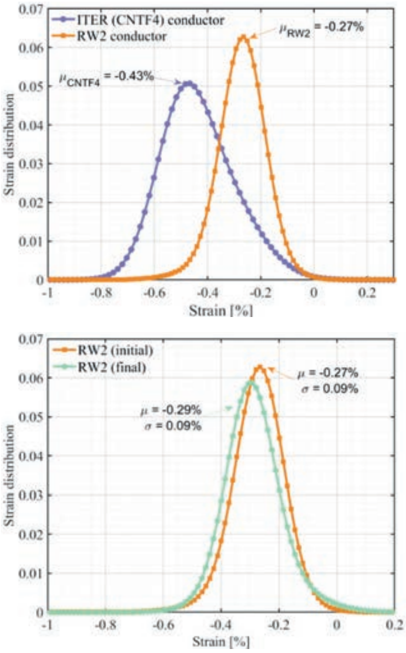
Our PhD student, **CHIARA FRITTITTA**, evaluates experimentally the strain state of Nb_3Sn cables for fusion magnets in the framework of the design, R&D and testing of superconductors for EU-DEMO coils. Nb_3Sn superconducting properties degrade when the material is under compression or tension. For this reason, the knowledge of the strain state of the superconducting filaments within the conductor is important to predict the conductor's performance in operation. One of the predominant sources of strain in Nb_3Sn cables is the thermal strain emerging during the cool-down of the conductor to operating temperature due to the different thermal contraction of Nb_3Sn, copper, and stainless steel, out of which the conductor is made.

The thermal strain distribution is deduced from AC susceptibility measurements using an indirect technique. The technique, applied in the past to several conductors developed for the magnets of ITER, has been applied for the first time to the "react-and-wind" (RW) conductors designed by SPC for the toroidal field coil of the EU-DEMO fusion reactor (**Figure 2**).

The results show that the second RW cable prototype (RW2) exhibits a lower absolute mean strain value, compared to many ITER conductor samples (**Figure 3 - top**). In addition, the analysis highlighted that the assessed thermal strain distribution does not vary significantly before and after the electromagnetic and thermal cycles, confirming the performance stability of the RW2 conductor (**Figure 3 - bottom**).



2 Cross-section of the RW2 prototype conductor assembly with stabilizer and stainless steel jacket.



3 **Top:** Strain distribution assessed for the ITER conductor (CNTF4) and for RW2; **bottom:** strain distribution measured for RW2 at the beginning and at the end of the test campaign.

International Activities - ITER

Research activities at SPC are conducted in the frame of international collaborations with ITER via Fusion for Energy (F4E). Dr **TIMOTHY GOODMAN** leads the area in the field of plasma heating systems, in particular high-power microwaves.

UPPER AND EQUATORIAL LAUNCHER EX-VESSEL WAVEGUIDES

The European component test facility FALCON at SPC, see **Figure 1**, continues to be used to evaluate waveguide components for the first confinement system of the ITER Upper Launcher. Experiments show the importance of higher order modes in the heating of the transmission lines. Measured temperatures exceed the ideal, pure, mono-mode, theoretical expectations by almost an order of magnitude. The mode content arriving at the first confinement system components is predicted by simulations of the transmission line between the gyrotrons and the tokamak, carried out by the US Domestic Agency, to be similar to mode purity measured at the FALCON facility.

Results from the component testing at FALCON are leveraged to provide heat loads on the components as they will be installed at ITER. These loads are used to design all the cooling circuits of the 4 upper launchers and the equatorial launcher for the ex-vessel transmission lines of ITER. All ex-vessel transmission lines are procured by F4E, though the equatorial launcher itself is delivered by Japan.

Additionally, waveguides at a larger diameter are used for the European Gyrotron tests, providing measurements to help better understand scaling of the distribution of heat away from the main sources of mode impurities.

Further prototype testing is planned for 2023 to assist the US Domestic Agency prepare for the procurement of various components of the 54, several-hundred-meter-long, transmission lines that will carry the power from the ITER gyrotrons to the ITER launchers (see **Figure 2**).

EUROPEAN GYROTRON

Testing and development of the European gyrotron for ITER is also carried out. In 2020, The EU gyrotron for ITER was tested at the Karlsruhe Institute of Technology (KIT). The best performance reached was 0.93MW during 180s, limited by the high voltage power supply.

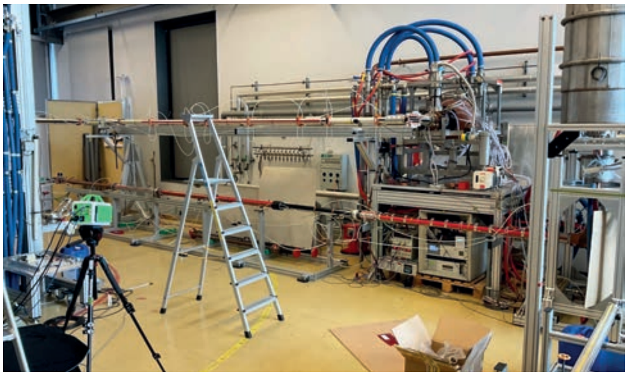
The gyrotron (see **Figure 3**) was dispatched to SPC in the summer of 2021 and tested extensively from August to November to qualify the performance for ITER and the Italian Divertor Test Tokamak (DTT). ITER and DTT will require up to 6 + 24 170GHz gyrotrons, respectively. The gyrotron passed the qualification successfully generating >0.95MW at the gyrotron window, showing stable measurements of output power, beam current, and heating of subsystems for ≥ 100s. The maximum pulse length achieved at full power was 256s, limited by heating in the transmission line waveguide that attaches the gyrotron to the dummy load. This transmission line was uncooled during the experiments. Modifications have now been made to provide sufficient cooling to allow steady-state power pulses. The design of the cooling system is based on tests performed using the RU FALCON gyrotron at half power in smaller diameter waveguide that has twice the power loss, thus an equivalent heat flux.

UPPER LAUNCHER

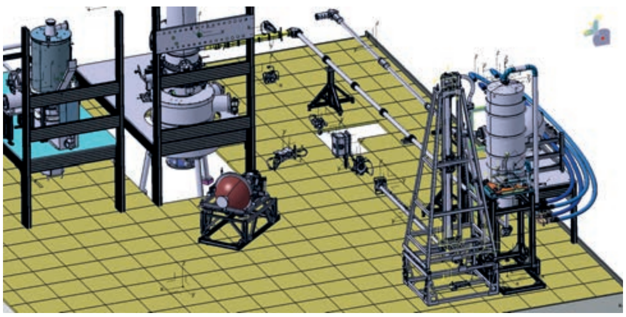
Detailed design activities of the ITER Upper Launcher (see **Figure 4**) were carried out to finalize the design of the ex-vessel waveguide components and the in-vessel steering mirror. The cooling design of the mirrors was modified to ensure lower mirror temperatures and thus lower stresses and higher safety margins. The transmission line components between the tokamak and the diamond window unit are part of the ITER first confinement system and have the most stringent quality, vacuum, and safety class. The in-vessel mirror (see **Figure 5**) that directs the power to the required location in the ITER plasma suffers some of the heaviest loads from nuclear heating, EM forces, mm-wave absorption of all the launcher components. Low levels of stray radiation, which are difficult to quantify, resulting from fabrication and installation tolerances of the entire electron cyclotron system – gyrotron to tokamak – can lead to high temperatures of components that cannot be directly cooled, such as springs and bellows. 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. Mitigation features, such as cooled stray radiation protection caps of the moving parts, have been designed for implementation under extremely challenging geometrical constraints. Additional operational requirements for baking, previously excluded, were given by ITER that required additional design work to be carried out on the ex-vessel waveguide.

DTT & DEMO

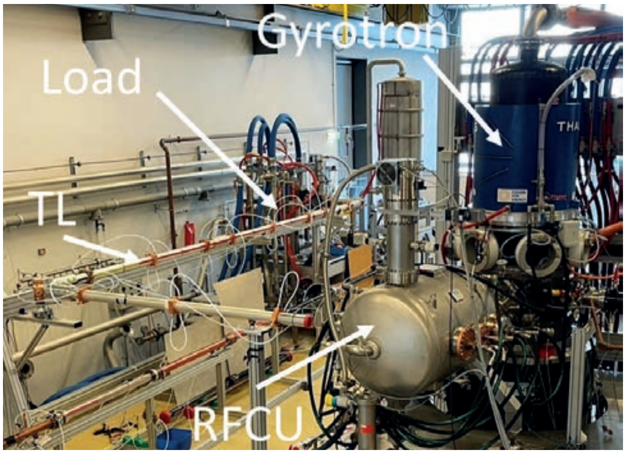
SPC continues to provide know-how and experience to prepare the large EC installations at DTT and DEMO. The DTT prototype gyrotrons (equivalent to ITER) will have their Factory Acceptance and Site Acceptance tests carried out at FALCON, which will also be used as a training center for operators and technicians at DTT. Experience gained from the ITER launcher design is being transferred to DEMO, now including the remote handling features and ever more stringent confinement features required for a Demonstration Reactor.



1 The FALCON test facility horizontal transmission lines (TL) and loads. The EU gyrotron uses the upper TL (with white cooling tubes) and European load (with blue cooling lines). The Russian gyrotron is connected to the lower transmission line covered in black and red tape to permit infrared temperature measurements from the camera (green box on the tripod at the left). It is terminated by the Russian load; the vertical cylinder at the far right of the image.

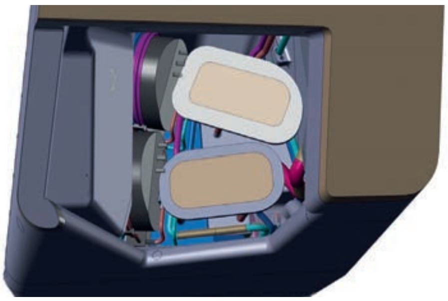


2 This CAD model is used to verify the installation of the US Domestic Agency components for future testing and to help them prepare additional requisite straight sections of waveguide connecting the components.



3 The EU gyrotron installed with the RF conditioning unit (RFCU) whose mirrors focus and direct the output beam into the TL to be propagated to the load where it is absorbed and the power measured.

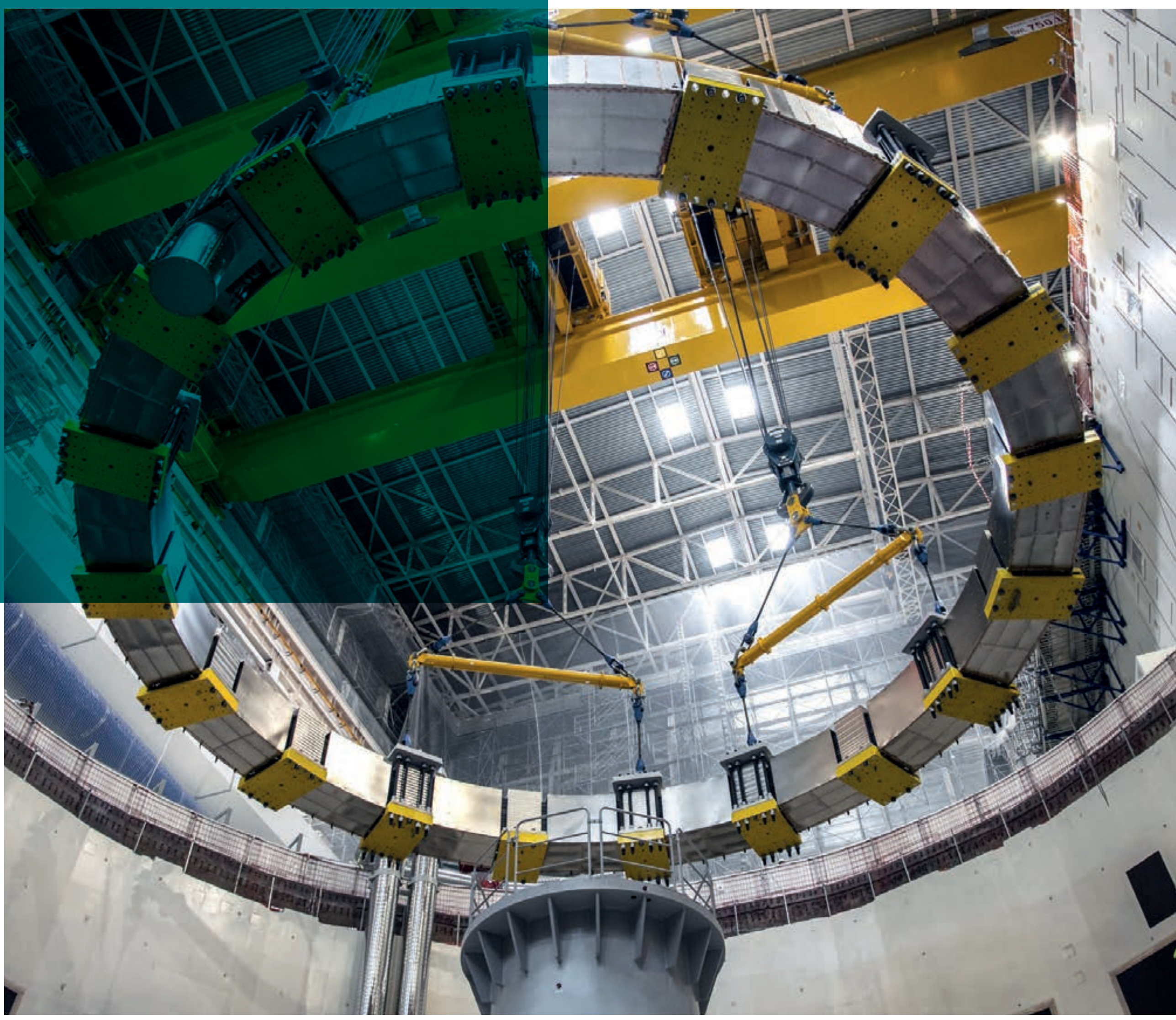
4 The ITER Upper Launcher with ex-vessel waveguide transmission lines (TLs) attached. The last mirrors (M4s) direct 8 beams (4 each) into the plasma to drive current to stabilize the neo-classical tearing modes and avoid potentially damaging plasma disruptions.



5 A view through the output hole of the two M4 mirrors and their actuation units at the left (covered by cylindrical grey caps and cooled by spiral cooling tubes – magenta). These are one of the most complex and demanding components of the ITER tokamak. They suffer the high nuclear radiation load, reflect high power, sustain very high electromagnetic forces and fit into an exceedingly tight space; all while moving with fine precision to direct focussed mm-wave power to the plasma.

ITER, EUROPE AND SWITZERLAND

The second year of the Covid-19 pandemic has confirmed the strong resilience of the fusion community worldwide, and its capability of continuing to push the limit of our knowledge of plasmas and fusion technologies, using all possible public and private funding and support, to pursue the road towards a viable concept of a fusion reactor.



At ITER, major parts produced and shipped from all over the world have been assembled. Such complex exercise has highlighted the importance of nuclear regulations. France's Nuclear Safety Authority has questioned the international ITER Organization on points related to the welding of the vacuum vessel sectors, to the concrete radiological shielding, and to the capacity of the earthquake-resistant foundations in case of a weight increase of the shielding walls. The international ITER Organization is dealing with these questions, the resolution of which will add an extremely valuable experience in view of DEMO and the commercial reactors.

Despite the fact that the work on the ITER construction site has never been halted due to the pandemic, delays with the supply chain of major components add up to the time needed to comply with nuclear regulation aspects. The date of December 2025 for first plasmas is no longer realistic, but all efforts are being deployed to maintain the original schedule for the first real fusion experiments with D-T fuel, in 2035.

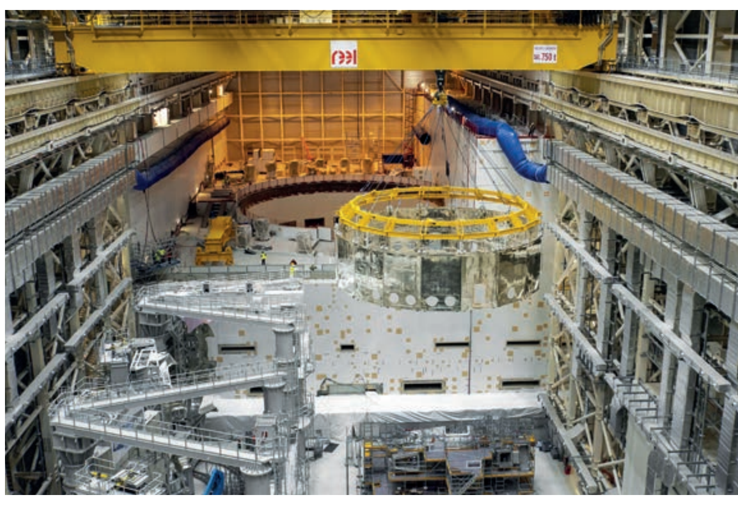
In view of the start of ITER experimental campaigns, all European stakeholders (EUROfusion, Fusion for Energy and the EU Commission) are working on a coherent preparation of ITER operations, as one team, to optimize the return on investment in view of the objectives of the European Roadmap to the realization of fusion energy.

At the European level, the year 2021 marked the beginning of the 9th Framework Programme for research and innovation (*Horizon Europe*, 2021-2027), the second for the EUROfusion Consortium. This follows the first cycle, *Horizon 2020* (launched 2014), that showed remarkable success of the EUROfusion activities. The high-power DT experiments on JET, yielding the world record of fusion energy in one plasma discharge (59MJ, obtained with ITER-like wall materials) were arguably the most visible results, but a number of achievements were praised worldwide, including the joint operation of tokamaks (among which TCV) that provided crucial input for ITER and DEMO, for example in the area of plasma exhaust, and the completion of the DEMO preconceptual design.

Building on its success in *Horizon 2020*, EUROfusion has prepared its R&D programme for *Horizon Europe*, along a natural progression to combine preparations for ITER experimentation with the DEMO conceptual design. After a very positive evaluation by the EU Commission and an international review panel, the EUROfusion R&D programme was accepted, and the Grant Agreement to implement the consortium activities was signed, with retroactive effect from January 2021.

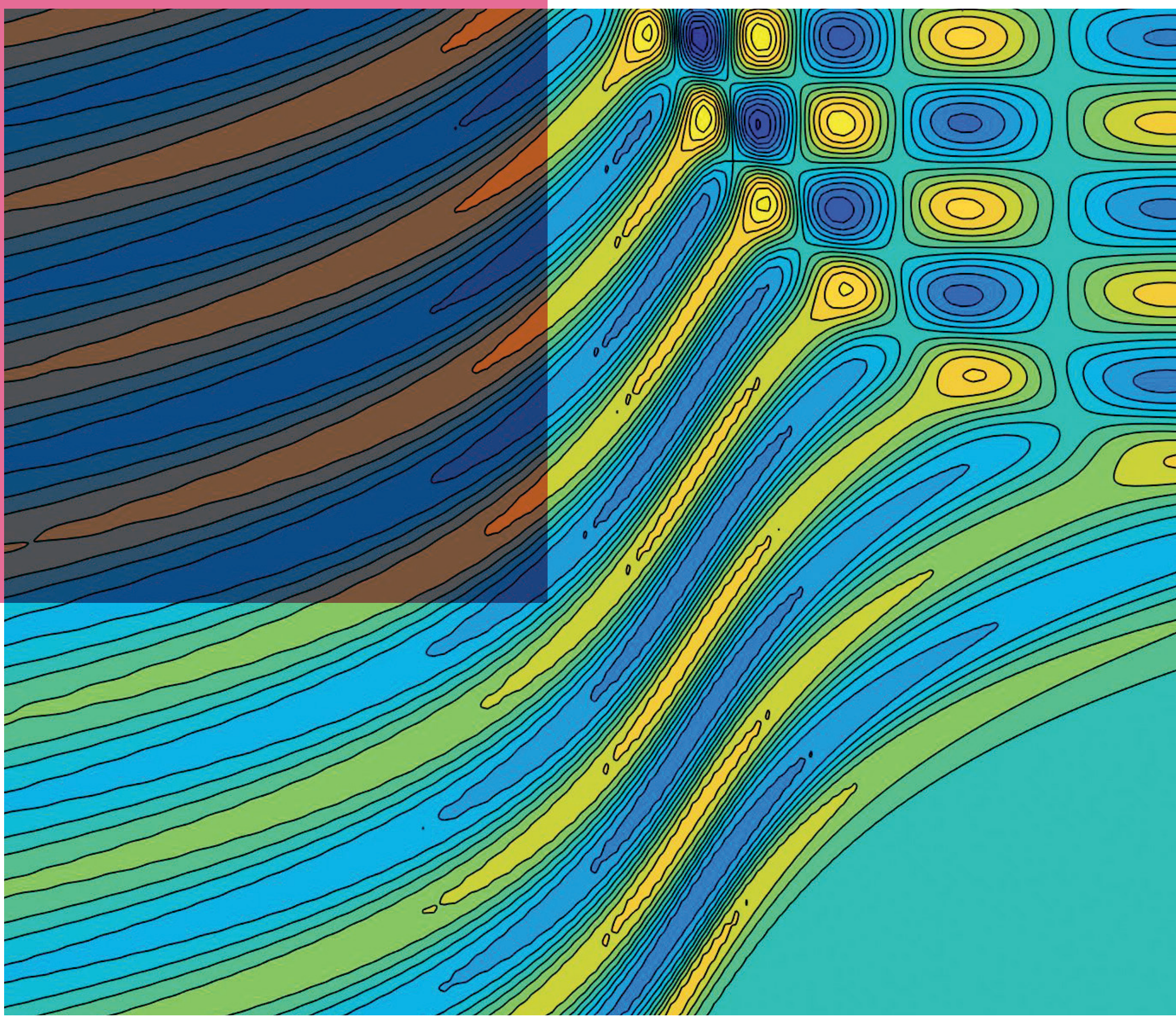
Unfortunately, the political difficulties between the Swiss Confederation and the European Union did not allow an association of Switzerland to Horizon Europe. This prevents full participation of Switzerland, hence of EPFL, to ITER and EURATOM, including Fusion for Energy activities. In particular, Swiss industry and institutions can participate in bids for ITER procurement only as sub-contractors, or if they are the unique holders of a technology, subject to approval by the ITER council on a case-by-case basis.

However, EPFL can and does participate to EUROfusion, with the direct financial support of the Swiss State Secretariat for Research, Education and Innovation (SERI), as an associated partner via the Max Planck Institute for Plasma Physics in Germany – to which goes our gratitude – with similar weight, roles and responsibilities as if it had remained a full member of the consortium. Similar solutions for EPFL to become associated to ITER and Fusion for Energy, and to be enabled to participate to all of their activities, are being explored, before a full re-association will hopefully soon become possible.



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.



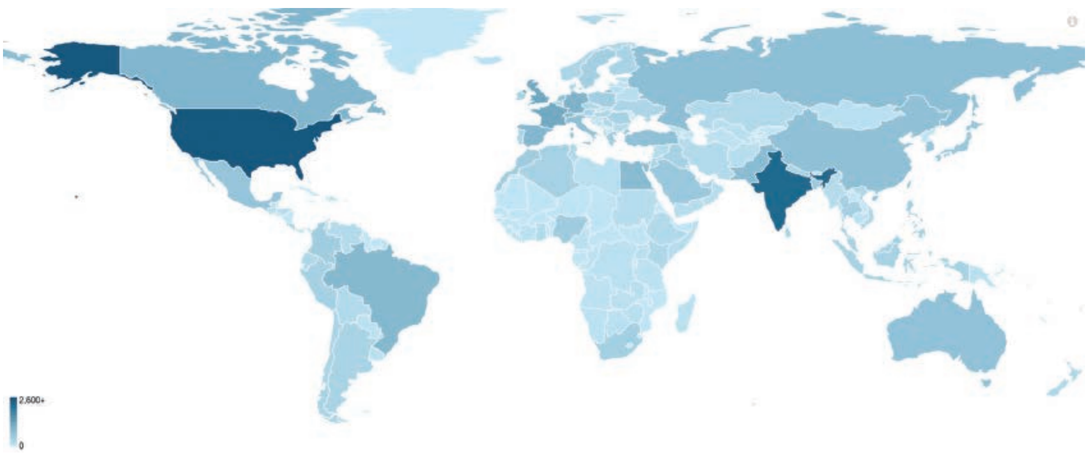
At the end of 2021 the SPC had **41** PhD students enrolled in the Doctoral School of EPFL and **27** Post-Doctoral researchers. In 2021, Carrie Beadle, Lorenzo Stipani, Federico Pesamosca, André Calado Coroado, Mirko Wensing, Francesco Carpanese and Hugo De Oliveira obtained their PhD in Physics.

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 MOOCs on plasma physics are highly successful, with 15564 subscribed learners in 2021 from around the globe, see **figure**.

In addition to plasma physics courses, SPC staff is teaching several classes in general physics, advanced physics, computational physics and mathematical methods for physicists. The reputation of SPC for excellence in teaching has received a further boost with the award of the Polysphère d'Or, see **highlight** below.

16	Number of courses given by SPC staff at Bachelor, Master and Doctoral levels in 2021
113	Average number of students in the classes of these courses
980	Number of hours taught by SPC staff in these classes in 2021
110,376	Number of student-hours taught by SPC staff in these classes in 2021
15,564	Number of subscribed learners in the MOOCs on Plasma Physics of SPC
41	Number of PhD students at SPC by the end of 2021
54	Number of Master students supervised at SPC for semester, specialization and thesis projects in 2021



Map of participants to the MOOCs of SPC per country.

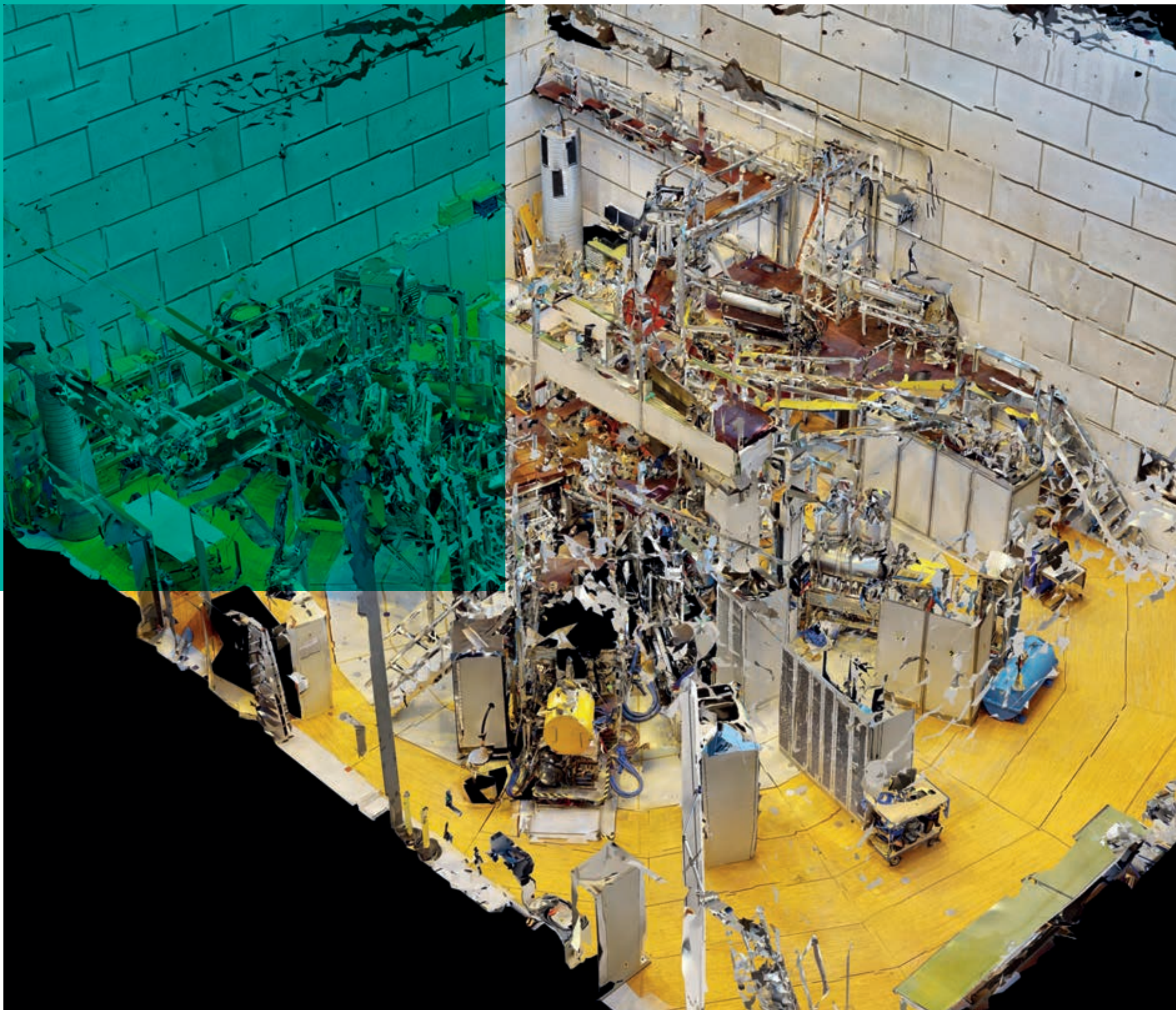
Every year the EPFL students' association, AGEPOLY, supported by EPFL Management, awards the 'Polysphere' to the best teacher of each faculty in recognition of the excellence of their teaching. Among those, the teacher receiving the most votes is awarded the ***Polysphère d'Or***. In 2021, Prof. **PAOLO RICCI** was the recipient of the ***Polysphère d'Or***.

"I teach over 250 students, so it is great to get this sort of recognition. But the "Polypshère d'Or" also belongs to my army of assistants and to the team that sets up the physics experiments we do during classes. During the pandemic we had to adapt our teaching methods to the new circumstances. Our team at the Swiss Plasma Center put a lot of effort into giving high-quality classes remotely and keeping things interactive. Strangely enough, I actually felt closer to the students, even though I couldn't see them. I was really impressed with the students – they demonstrated such resilience despite the difficult conditions they experienced. I want to teach students how to approach problems and think critically. My goal is to instill a way of discerning information that will help them throughout their life. I think the more you put into teaching, the more you get out. It's important to invest time into it."

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. The salient point of 2021 was the publication of virtual tours of SPC spaces, including the TCV tokamak hall, on our web site.

The 3D reconstruction of the TCV hall, obtained from the 360° pictures taken at positions indicated by circles.

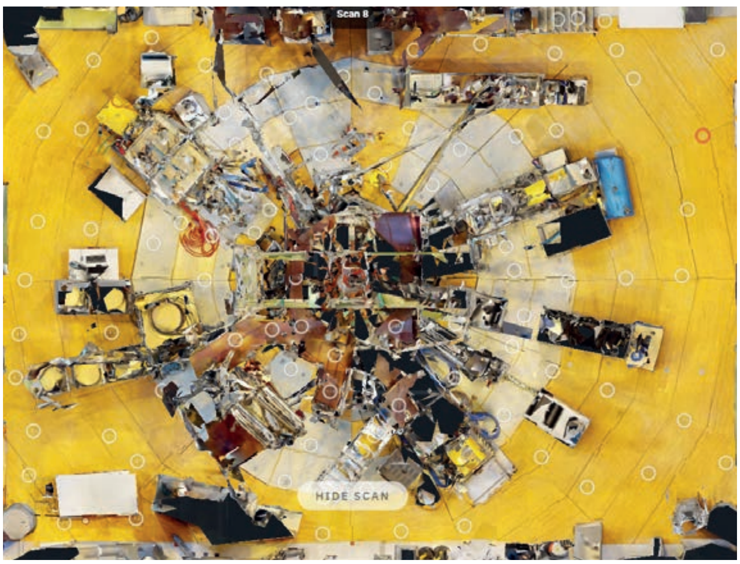


Our main outreach activity, the guided tours of SPC devices (TCV, TORPEX, RAID) was put on hold during the first half of 2021 due to the health restrictions. Visitors began to contact us again in September. Therefore the total number of visitors was only about 900 persons in 44 visits. Considering the small fraction of the year during which visits were possible these figures are reasonable compared to 2019.

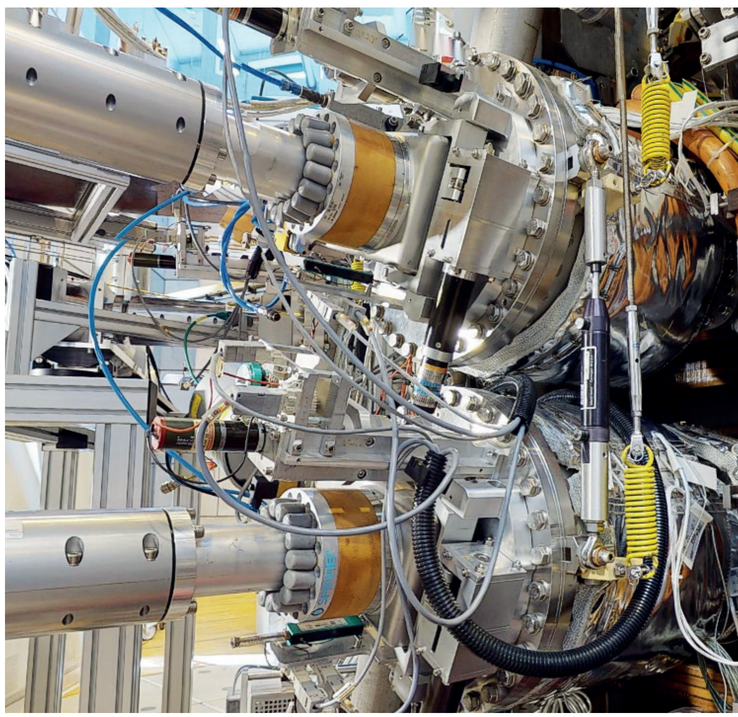
Similarly, external presentations in front of the public resumed at the beginning of the autumn, with, for instance, a TecDay in October in Sion. TecDays are events organized by the Swiss Academy of Engineering Sciences SATW during which each student participates in three interactive presentations chosen among a large variety of scientific or technical topics. On the other hand, the second annual TeacherDay was held in the fall, still with remote participation since this event, organized by FuseNet, gathers participants from all over Europe. In this edition, more than 600 high school teachers had the opportunity to discover the teaching material prepared for them by FuseNet. They were also informed on the progress in fusion research in Europe, in particular through a presentation from ITER.

To improve the experience of our web site users, virtual tours of our laboratories are now proposed. A 360° camera was purchased and used to record the views in different SPC spaces such as the TCV tokamak hall, the RAID hall and the bio-plasmas laboratory. Thanks to an external company, 3D models of these different areas were obtained, which allow visitors to walk around the devices virtually, and directly from our web site (see pictures and QR code).

QR code to access the SPC virtual tours. Try it!



Top view of the TCV hall, with the circles indicating the positions where 360° pictures were taken.



Example of the high quality images that the user can see while walking around in the TCV virtual hall.

SERVICES AND ADMINISTRATION

The Swiss Plasma Center could not have reached 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.

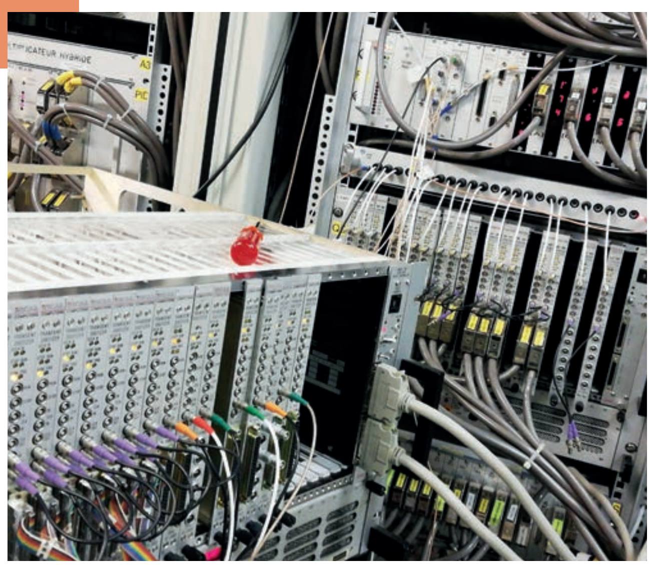
Dr Yves Martin

CAO COMM' & HEAD OF SERVICES

Dr Christian Schlatter

CFO

Installation of the Neutral Beam duct on TCV.



Data acquisition modules at TCV.

Matthieu Toussaint

MECHANICS CONSTRUCTION OFFICE AND WORKSHOP

Frédéric Dolizy

VACUUM TECHNICS

Damien Fasel

ELECTRICAL HIGH POWER INSTALLATIONS

Blaise Marlétaz

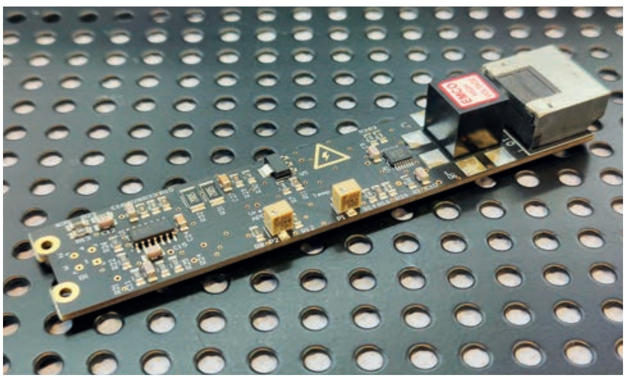
ELECTRONICS

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 persons.

All services have strongly been involved in several interventions on TCV, since no less than three openings occurred in 2021, and with the additional arrival of the second Neutral Beam. The currently more frequent openings are caused by the need to change the baffles or to remove them for a series of experiments. More precisely, the original set of baffles was installed again in February. Low field side baffles were then changed towards shorter ones in June and all baffles removed in November. Moreover, several additional tasks are performed at each opening.



Single channel Avalanche PhotoDiode (APD) detector with temperature compensation and I²C gain control.

Weekly 'service meetings' took place in videoconference all year round.

The installation of the second beam was prepared early in the year with, for instance, the replacement of the diagonal bar with a newly manufactured piece in Titanium to allow the tangential injection of the beam, and performed in July-August, with the participation of the Russian technicians and engineers. The system delivered its first beam in September.

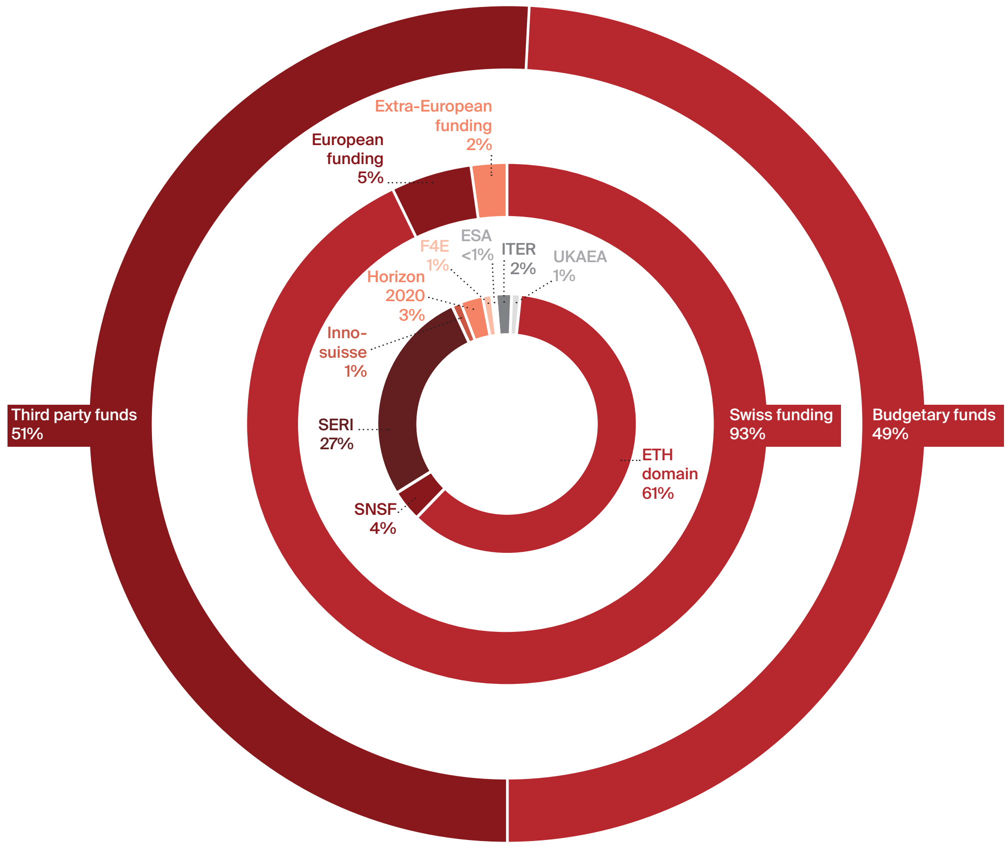
In parallel, services provided the RAID and TORPEX devices, the Bio-plasma experiments and the test-stand for ITER gyrotrons and ECH components, with all kinds of support, without any interruption.

Ready to enter the TCV vessel through the manhole.

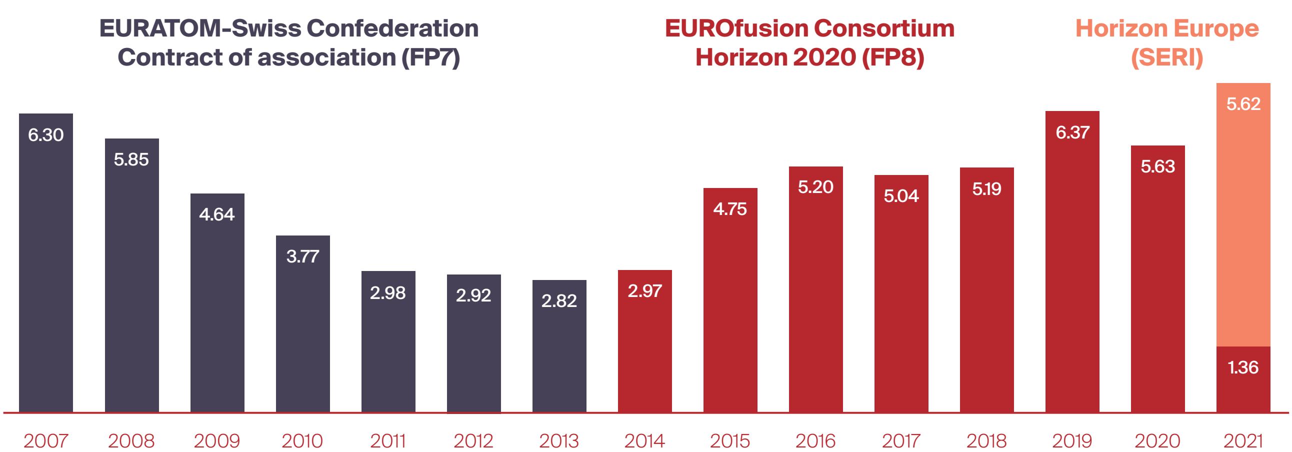
FACTS AND FIGURES

FUNDING 2021

including indirect costs



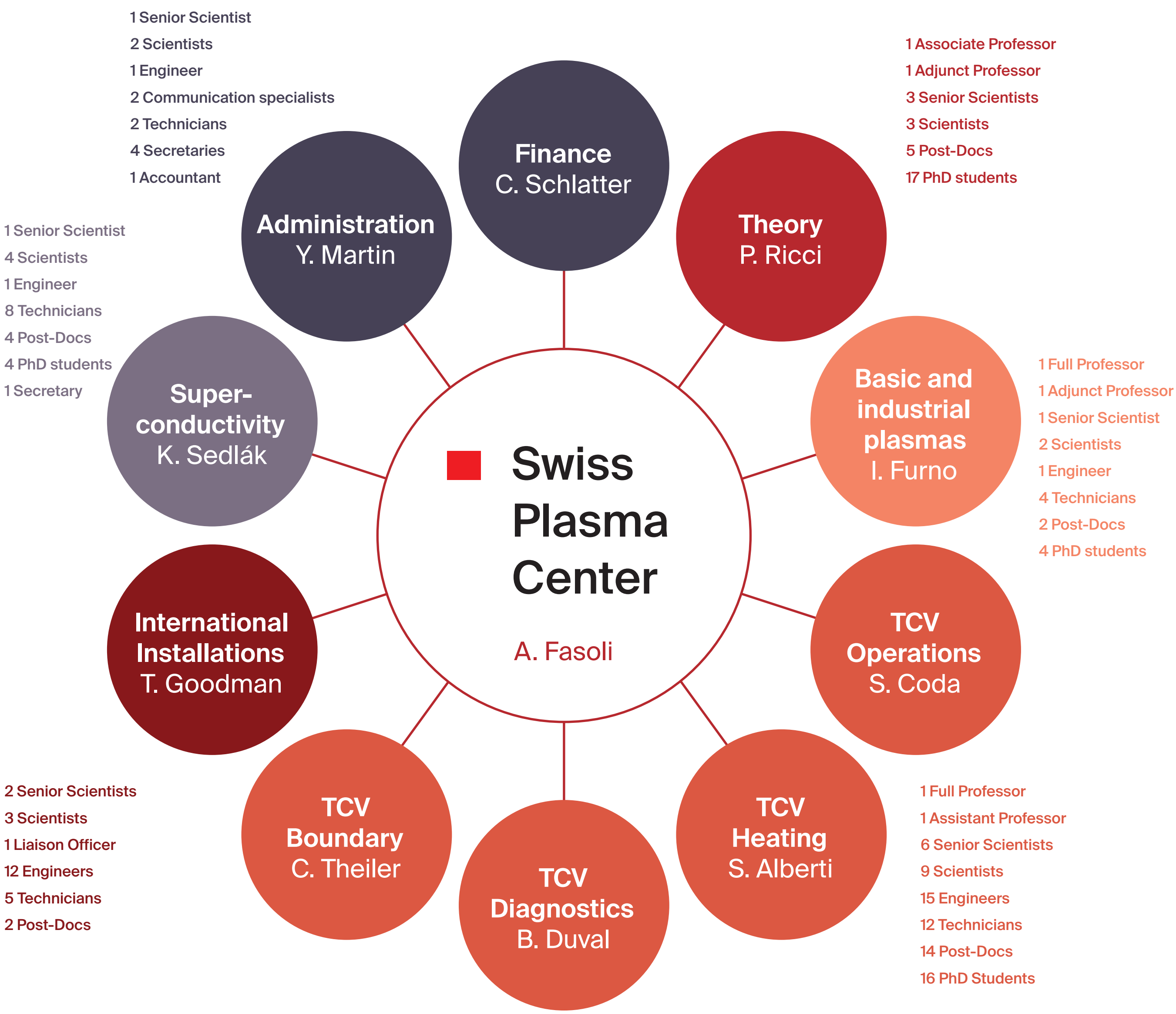
THIRD PARTY FUNDING OF SPC INVOLVEMENT IN EURATOM WORK PROGRAMME [MCHF]



HUMAN RESOURCES

167	Total headcount
163	Full-time Equivalents
41	PhD students (FTE)
27	Post-Docs (FTE)
22	Collaborators joined SPC in 2021
21	Collaborators left SPC in 2021

STRUCTURE



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