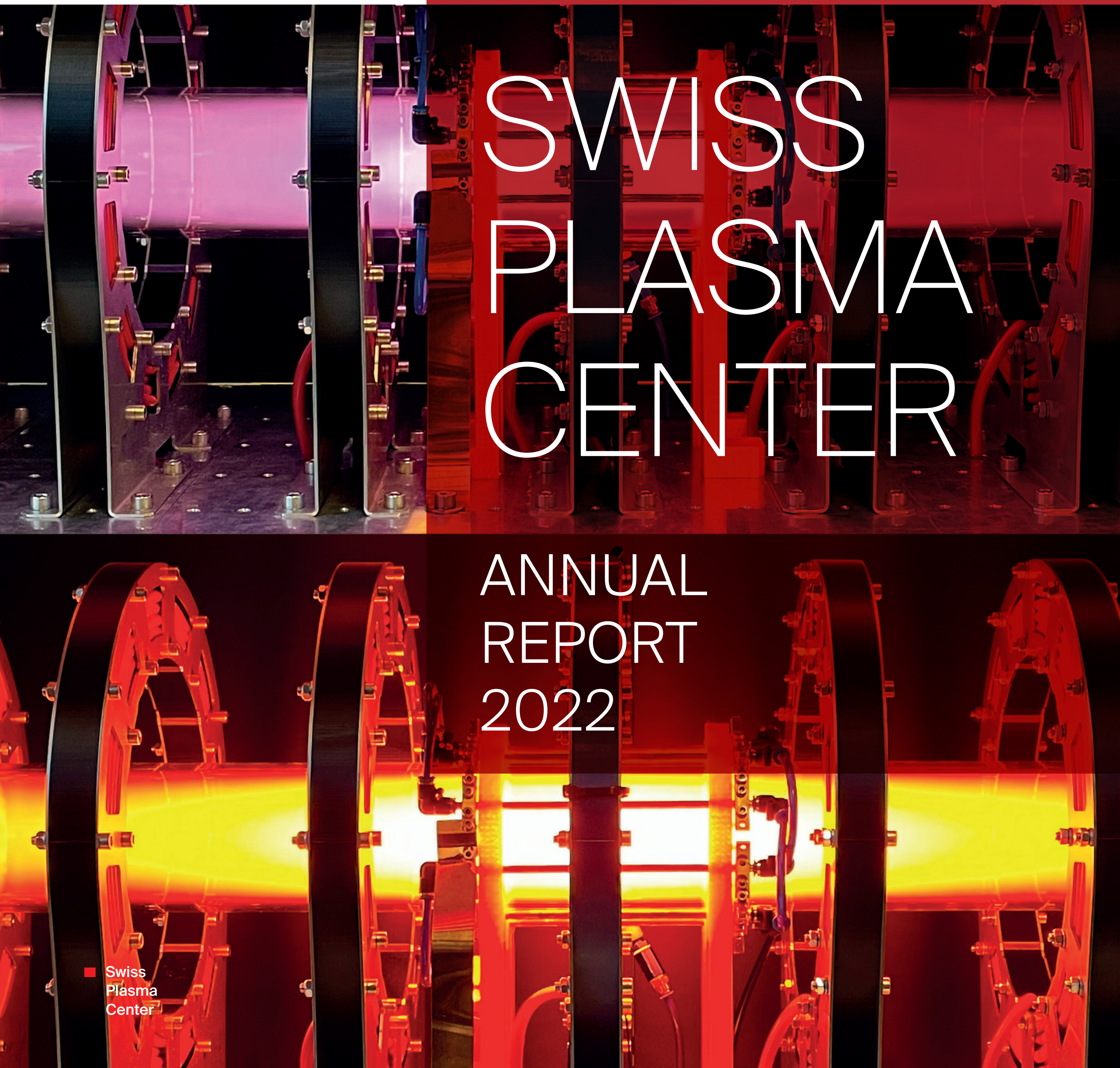
EPFL

SWISS PLASMA CENTER

ANNUAL REPORT 2022



Swiss
Plasma
Center

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Letter of the Director

Our Center is continuing to grow, in terms of its impact on fusion, on plasma science for industry and society, and in its educational role, and has reached a record number of collaborators, approaching 200. The number of graduate students and post-doctoral researchers has never been so high, neither have their geographical origin ever been so diverse and their gender almost balanced.

We have adapted to a 'new normal' after the pandemic, combining home working with on-site activities, enjoying direct interactions and travel only when necessary and always as sustainable as possible.

Results of great impact have been obtained in all of our research lines, including new approaches to tokamak magnets that combine low and high temperature superconductors, effective elimination of bacteria in plants using atmospheric pressure plasmas, plasma avoidance in satellite launching, crucial validation for microwave systems for ITER, crucial advances in plasma simulations in the core and the edge of present and future tokamaks, and extended experimental campaigns addressing key tokamak physics questions, from core confinement in various plasma shapes to advanced divertor configurations and the mitigation of transient events and their consequences.

For the TCV tokamak, the year 2022 was a very significant one. It was its 30th year of operation, an achievement that will be celebrated in the course of 2023. But it was also a record year in terms of intensity in operation, with 4599 plasma discharges, operated both for the domestic program and in the frame of international collaborations, with a full spectrum of multi-MW heating capabilities, including 2nd and 3rd harmonic electron cyclotron heating and two heating neutral beams operational together for the first time.

The enhanced plasma performance and interactions brought by the new plasma heating systems lead to a generation of a significant number of fusion reactions, hence of neutron emission. This motivates the installation of a new shielding around the machine, mostly made of blocks of polyethylene.

The resulting reduction in the neutron flux will be sufficient to maintain, even in conditions of highest plasma performance, the present level of access, with no restrictions outside the TCV area, and no need for any of our team members to become radiation worker.

To install the new shielding and conduct a complete revision of the dedicated flywheel generator, a necessity after several years of operation, TCV has gone into a shutdown phase that started in the second half of 2022 and will continue until next summer. During this operational break, preparations for the subsequent experimental campaigns, of which a significant part will be in the context of, and supported by, the EUROfusion Consortium, will be completed.

In 2022, the initiative we launched to further modernize our infrastructure, named Swiss Fusion Hub, was integrated in the 2025-2028 Swiss Roadmap for Research Infrastructures produced by the State Secretariat for Education Research and Innovation (SERI). This initiative consists in a set of upgrades to the TCV tokamak, including additional microwave heating, a new divertor structure and improved diagnostics and real-time control apparatus, and to the superconductors' test facility, with the new high-field EDIPO2 coil, extending the impact of our research in the decades to come. Our state-of-the-art facilities, and, more importantly, the commitment, competence and flexibility of our team will allow our Center to maintain, and even reinforce, its central position in the rapidly evolving international fusion scene.

Challenges and opportunities are expected at European level in 2023, with the Facilities Review exercise and the revision of the approach to the Roadmap to fusion energy. We will strive to position ourselves in this context, in spite of the difficulties related to the non-association of Switzerland to the European Research Framework Programme, hoping that this situation will be soon solved and, at the same time, taking advantage of the welcoming attitude of our European partner institutions and colleagues.

We are prepared to play an important role in the transition of the European program from the ITER construction to the operation phase via our R&D program, our education & training contributions, and our readiness to participate to the public-private partnerships that will be launched in view of DEMO developments. We will need to navigate carefully through a delicate financial situation at the Swiss and EPFL levels, generated mostly by the pandemic and the energy crisis. Given the urgency of achieving fusion energy, we will strive to avoid major disruptions to our activities, and any limitation to our ambitions. Collaborations with European and international partners, and across EPFL and the rest of Switzerland, and our internal cohesion will be even more important in these transition times.

I wish to warmly thank all the staff of the Center for their professionalism and commitment, and for the forthcoming additional effort in maintaining this cohesion, and express my deep gratitude to our stake holders and sources of support, including the ETH Board, the SERI, the EPFL Faculty of Basic Sciences and Institute of Physics, the Swiss National Science Foundation, the ITER International Organization, EUROfusion and Fusion for Energy.

Ambrogio Fasoli

PROF. AMBROGIO FASOLI

RESEARCH HIGHLIGHTS

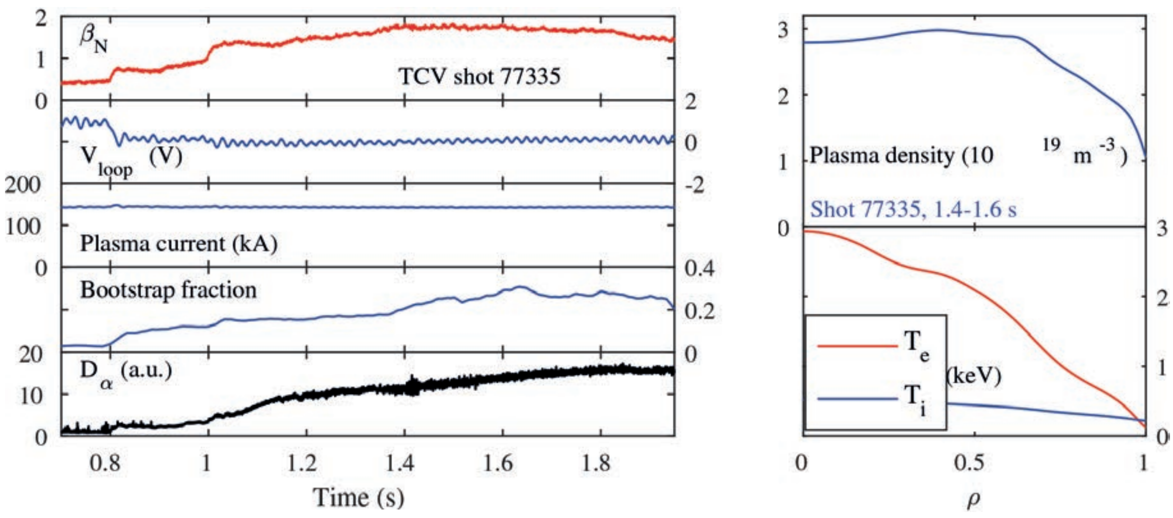
TCV Tokamak

The year 2022 was an extraordinarily intensive and productive one for TCV, with the largest number of plasma shots ever fired in a single year, namely 4599. The device was operated nearly continuously for the entire year, with only two short openings in June and August, to install and then remove the so-called LILO (long-inner, long-outer) set of baffles, used then for the first time. During most of the year the machine was unbaffled. The campaign was shared between the domestic programme and the EUROfusion Work Programme on Tokamak Exploitation as usual, and featured a broad range of experimental themes. Highlights are exposed below by Dr. **STEFANO CODA**, Senior Scientist (MER), who supervises TCV operations and science.

The high confinement mode (H-mode), the reference scenario for ITER, received considerable attention. Plasmas in H-mode are characterized by a transport barrier near the edge, resulting in temperature and density profiles forming a 'pedestal'. Different versions of the so-called ITER baseline (IBL) shape have now been developed for the sake of comparative studies: ones emulating the closest versions created in JET and ASDEX Upgrade, in addition to one truly approaching the prospective ITER case. The influence of the upper triangularity (δ_{top}) on the pedestal height and on the characteristics of Edge Localised Modes (ELMs) was documented, with ELM mitigation observed at smaller δ_{top}. ELMs are repetitive bursts of plasma ejection and are a typical feature of H-mode operation. A novel result was that large ELMs can trigger another type of instabilities, called Neoclassical Tearing Modes (NTMs), although even the most potentially detrimental NTMs can be survived by the plasma at sufficiently high q_{95} (>3.5). NTMs are also alleviated by Electron Cyclotron Resonance Heating (ECRH) at second or third harmonic. Seeding with nitrogen was attempted to achieve detachment, in which a cold plasma is obtained near the machine walls, resulting in reduced plasma-wall contact, but no detachment was observed even between ELMs, with the ELMs themselves becoming more virulent as a result. At high triangularity and strong fueling, the JET-like IBL entered a quasi-continuous exhaust (QCE) regime.

The pedestal properties were investigated at both low and high effective collisionality (ν^*). At low ν^*, gas fueling scans with ECRH were performed to seek the transition from a peeling to a ballooning limited regime, with results closely following modeling predictions; the ratio of separatrix to pedestal density was found to remain constant during the scan, in contrast with the high-ν^* case, in which this crucial parameter (a good descriptor of the link between the pedestal and Scrape-Off Layer (SOL) plasma regions, independent of divertor closure) increases with the fueling rate. Interesting, transitions from Low- to High-confinement mode (L-H) were obtained with the divertor detached throughout.

Studies of the species dependence of the L-H threshold and H-mode confinement were also carried out. Salient results, potentially worrying for early ITER operation, are a stronger scaling of the threshold with density in helium than in hydrogen or deuterium, and a lower confinement in helium. A study of the H-L back-transition was also conducted to test models: the transition power threshold was found to increase with fueling and decrease with divertor closure.



1 Time traces of relevant quantities (left) and density and temperature profiles at the time of maximum β_N (right) for TCV shot 77335.

The alternative reactor option of negative-triangularity (NT) L-mode has been vigorously pursued in parallel. The L-mode existence range was characterised and, in accordance with growing theoretical consensus, the H-mode was shown to be fully inhibited at sufficiently large NT, where access to the second ballooning stability region is precluded. Divertor detachment has remained elusive and possible only with impurity seeding (see **highlight p. 7**). A detailed study of the SOL heat flux profile (lq) has been carried out and data are currently being analysed. The increase in momentum and particle confinement, and attendant impurity retention, was thoroughly documented.

The high β_N (β_N is a measure of the capacity of the tokamak magnetic field and current to contain a certain plasma pressure) obtained at NT in the previous campaign primarily through Neutral Beam Injection (NBI) heating was revisited with β_N control to achieve semi-stationary conditions, in some cases with the addition of X3 ECRH. Above a β_N limit (still below ideal limits) NTMs develop and often terminate the discharge through coupling with an axisymmetric displacement.

A dedicated emulation of planned NT shapes for the new DTT device under design was performed, with results confounding initially pessimistic simulations and showing that the confinement improvement with NT fully compensates the loss of pedestal due to the avoidance of H-mode.

The first internal transport barriers (ITBs) in NT configurations were also developed, with modest synergy thus far in terms of achieved performance. Investigations of MHD activity and of MHD control schemes in NT plasmas proceeded in parallel.

In addition to NT - which is intrinsically ELM-free - other avenues for ELM mitigation were explored further. These included the QCE regime as well as ELM control with edge-localised ECRH; the latter was attempted for the first time with NBI heating and found to be as effective as in Ohmic H-modes.

The Advanced Tokamak route to high performance with high non-inductive current fraction was studied with two parallel approaches: applying off-axis Electron Cyclotron Current Drive (co-ECCD) to an established NBI-heated H-mode, or applying NBI to an established ITB sustained non-inductively by co-ECCD. Ideally the two approaches would merge, possibly with the establishment of a double-barrier scenario. Fine-tuning of the available actuators has led to β_N in the 1.6-2.0 range, with in particular the first instance of a fully non-inductive ITB heated by NBI (β_N=1.8, 35% bootstrap current fraction, see **Figure 1**). The ECRH power available is believed to be marginal and planned ECRH upgrades may permit this scenario to be pushed to higher performance.

The subject of core turbulence has been somewhat subdued, with diagnostics not always available owing to ongoing upgrades. Some limited studies have nonetheless taken place, namely comparisons between negative- and positive-triangularity plasmas, a preliminary characterization of the QCE regime, and a search for filamentary structures near rational surfaces. Data analysis is underway.

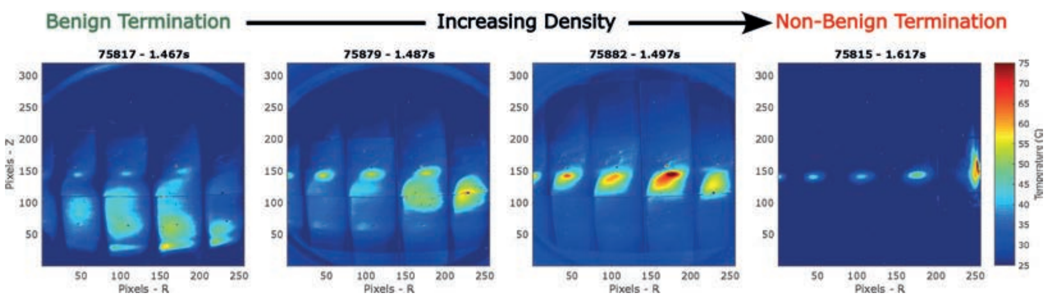
A new modeling framework has been developed to study the increased transport of ECRH-accelerated fast electrons, caused by turbulence generated by the wave-plasma interaction itself. Experiments have been carried out to study the fast-electron dynamics and characterise the turbulence at the same time. Analysis and model validation are ongoing.

The successful commissioning of the second NBI system at Alfvén-wave-relevant energy and the deployment of a Fast Ion Loss Detector have benefited the investigation of fast-ion physics. In particular, the excitation of Toroidal Alfvén Eigenmodes (TAEs) by NBI has been documented, as well as their suppression by ECCD. The effect of ELMs on fast ions has been probed as well.

The availability of two counter-propagating neutral beams has also permitted more thorough control of the toroidal torque, with zero rotation obtained using an appropriate balance of the two beams. TCV also features spontaneous toroidal rotation in the absence of external torque, which can undergo a sign reversal in certain conditions. This has often been heuristically linked with the so-called Local-to-Saturated Ohmic Confinement (LOC-SOC) transition, but recent work with both hydrogen and deuterium plasmas has conclusively shown that there is no such correlation: the reversal in fact is associated with the SOC regime alone.

There is significant concern that runaway electrons (REs) could damage the first wall in a reactor. TCV has proven to be an excellent device in which to study RE dynamics, thanks to the attainability of very low densities and negligible danger to the wall. In the most recent work, benign termination of a RE discharge with deuterium or hydrogen flushing has been established, with exhaustive scans of the gas quantity and of the RE characteristics (controlled by a primary injection of a noble gas). Decreasing the density of the plasma that accompanies the RE beam, through recombination, leads to the RE beam carrying the entirety of the current and thus to benign termination, as seen in the heat flux at the final collapse (**Figure 2**). Suppression of REs by ECRH and ECCD has also been achieved and documented. In parallel, first measurements have emerged of rf waves driven by the RE population.

The real-time control architecture of TCV evolves continually, in particular with the goal of maximum integration, to render disparate control schemes available in parallel under an overall supervisory management entity. Handling of off-normal events and control of the proximity to an instability boundary are examples of complex tools cohabiting with direct control of quantities such as edge density and more basic and standard plasma parameters. Efforts have been devoted specifically to the optimization of the discharge initiation (breakdown and ramp-up), with and without ECRH assistance, using shot-to-shot learning techniques and real-time control tools. A very successful foray into Deep Learning techniques is described in **highlight 2**.



2 Infrared thermography images of the central column of TCV. Increasing density at time of compression from left (benign termination) to right (unmitigated impact) led to reduced wetted area and higher surface temperatures.

MACHINE-LEARNING-BASED CONTROLLERS TESTED ON THE TCV TOKAMAK

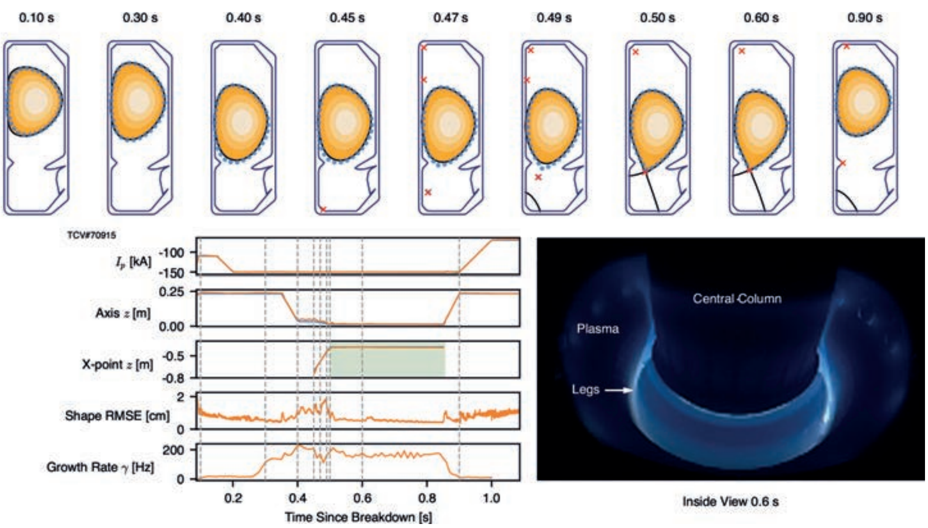
In tokamaks, feedback control is used for various purposes: to stabilize the plasma position and give it the desired shape, to reach the desired pressure and density via external heating and fueling, and to suppress undesired instabilities. Recently, a technique for solving decision-making problems called reinforcement learning, developed in the machine learning community, has been shown to be capable of solving large and complex control problems. This technique relies on trial-and-error exploration of the to-be-controlled system's dynamics, e.g. using a simulation model and is able to naturally deal with complex nonlinear behaviour of the system.

Scientists from the Swiss Plasma Center, led by **FEDERICO FELICI**, teamed up with scientists from DeepMind, based in London, to apply reinforcement learning to control the magnetic equilibrium in TCV. By coupling SPC's in-house simulator for the magnetic equilibrium evolution to a state-of-the art reinforcement learning algorithm developed by DeepMind, it was possible to train controllers that use real-time measurements and manipulate the voltages in TCV's flexible set of poloidal field coils to generate a wide variety of plasma shapes, see **Figure 3**. This included the sustainment, for the first time, of two plasmas in the chamber simultaneously in a so-called 'droplet' configuration. This work represents the first time reinforcement learning was applied to control an engineering system of this complexity in the real world, as well as showing a path towards designing more advanced controllers for tokamaks in the future.

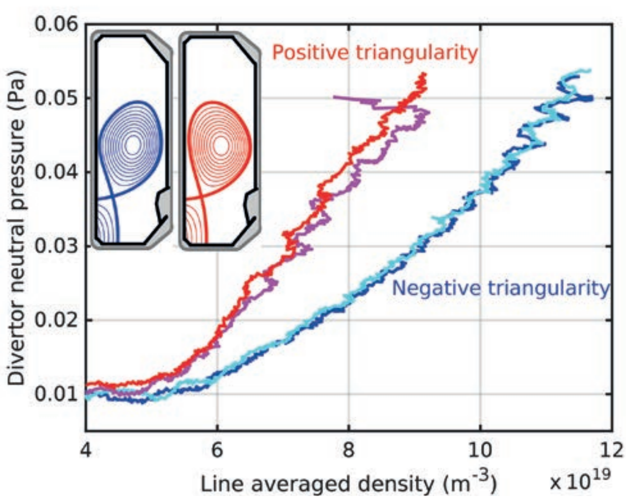
DETACHMENT IN FLIPPED-D SHAPES

Power exhaust is a crucial issue for future fusion reactors, where large heat fluxes will reach divertor targets. When operating in High-confinement mode (H-mode), large intermittent bursts of heat called Edge Localized Modes (ELMs) also reach the targets, exacerbating the problem. The most promising way to protect the divertor targets from these high heat fluxes is to operate in the detached divertor regime, where the targets are protected by a pocket of neutral gas. Neutral interaction and volumetric radiation cool the plasma down before it reaches the target, but the ELMs are often powerful enough to 'burn through' the neutral gas to reach the target. Therefore, it is necessary to find regimes where ELMs can either be mitigated or are naturally small or entirely absent. One such regimes is negative triangularity (NT).

Experimental observations have shown that NT discharges, in which the standard D-shape of the plasma is flipped compared to its positive triangularity (PT) counterpart, can exhibit H-mode grade confinement whilst staying in Low-confinement mode (L-mode), hence side-stepping the difficulties caused by ELMs. Dr. **OLIVIER FEVRIER** has recently made progress in understanding how divertor detachment behaves in NT configurations. Experiments performed in TCV show that detachment is generally more difficult to achieve in NT, where significant detachment only occurs with impurity seeding at concentrations high enough to degrade core confinement. This seems to be related to a lower divertor neutral pressure in NT discharges (**Figure 4**), an effect that is still being studied, but that could be overcome in the future with the help of divertor baffles, as will be studied in the next TCV campaigns.



3 Example of plasma shapes obtained in TCV by controlling the operation using a state-of-the-art reinforcement learning algorithm developed by DeepMind.



4 Evolution of the divertor neutral pressure as a function of the line-averaged density for positive (red, magenta) and negative (blue, cyan) triangularity discharges.

TCV Diagnostics

2022 was, mainly, an operational year for the TCV Diagnostics group, led by Dr **BASIL DUVAL**, Senior Scientist (MER). As the year progressed and more bugs were ironed out of working diagnostic systems, several new diagnostic and upgrades to existing systems were developed strongly. Since TCV operations were due to pause for 6 months at the start of 2023 for the installation of Neutron and Gamma human safety shielding systems, (following the success in implementing the second high energy neutral heating beam), exploitation of existing diagnostic systems was favoured over their development that would then accompany the 2023 pause in operations.

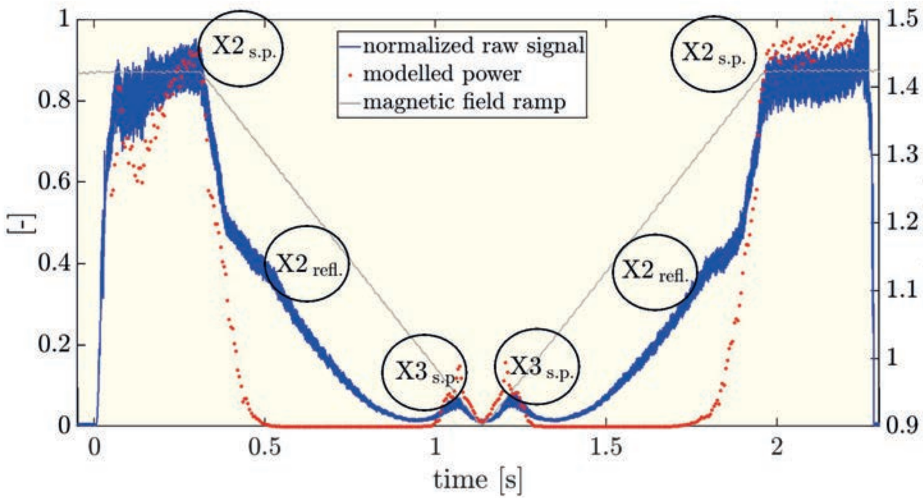
Several long-term diagnostic systems were perfected or, for the first time, operated in better unison to provide a fuller physical view of the research plasma discharge. In the TCV divertor, in particular, a simultaneous and co-ordinated operation of all edge plasma diagnostics during a set of "standard" edge exhaust relevant configurations that were operated for a range of TCV in-vessel baffles. Together, these systems are providing unrivalled divertor diagnosis, particularly for Divertor Detachment experiments. Diagnostics, mentioned in previous reports, (MANTIS- multi camera imaging, FILD cameras and 128-channel detector, Edge Spectroscopy, Electron Cyclotron Emission, Charge Exchange Spectroscopy and others) gained in performance, albeit with the continual repairs associated with these special devices. This data set enhances the numerical divertor plasma models for physics interpretation.

Continuing the upgrade of TCV's legacy diagnostic systems, the whole soft X-ray diagnostic array, from the X-ray tomographic camera, previously described, to include XTe (electron temperature from graded filtered diode), Xmodes (X ray diodes distributed toroidally and poloidally around the machine) was reviewed. With the ever-increasing use of Neutral Beam heating that enters the plasma vessel through metal ducts, there is a heightened risk that TCV plasmas become polluted by metal sputtering from the duct walls as the Neutral Beam transits. An energy sensitive imaging X-ray camera was prepared for installation on TCV in 2023 to monitor a poloidal X-ray image of the plasma. This camera features a user-selected X-ray energy threshold that can be used to separate the lighter of such impurities (Aluminium) from elements associated with the beam duct or the machine vessel structure (Copper and Stainless Steel, respectively).

In 50 years of ECE, calibration of the diagnostic systems has, in general, been considered as experimentally challenging. Classic approaches either use external sources to irradiate the antenna or exploit cross-calibration upon other diagnostics measuring the same plasma properties. The first approach is experimentally cumbersome and the second is, at best, indirect. A novel technique using plasma radiation has been developed on TCV that is applicable to arbitrary lines of sight and does not require ECE-optically thick plasma conditions. It uses a calculation of the X3 radiation intensity for low plasma optical thickness employing a plasma blackbody emission approximation that depends solely on the electron temperature.

An ECE synthetic diagnostic, exploiting well-established ECE emission, computes the radiation intensity leaving the plasma to the Vertical ECE radiometer. We observed an operational window in the Vertical ECE frequency response where the thermal background remained well below instrumental noise. A reliable calibration was achieved by fitting the high frequency (X3) and full-field X2 (single-pass) signal (see **figure 1**).

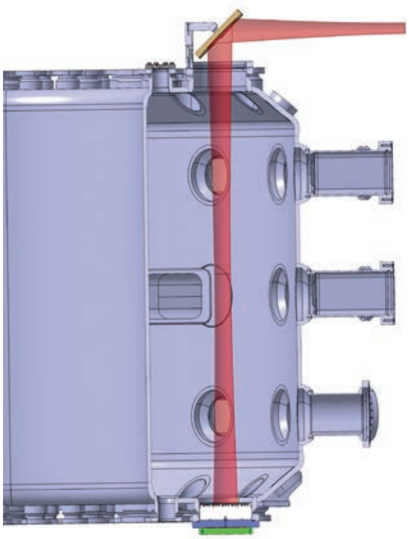
The technique was demonstrated on a vertical viewing ECE has validity for arbitrary line of sight. For vertical ECE, this novel calibration now allows a reliable electron distribution analysis. For the ECE community, more generally, the new calibration approach represents a new, stable and modern, technique available to the fusion physics community.



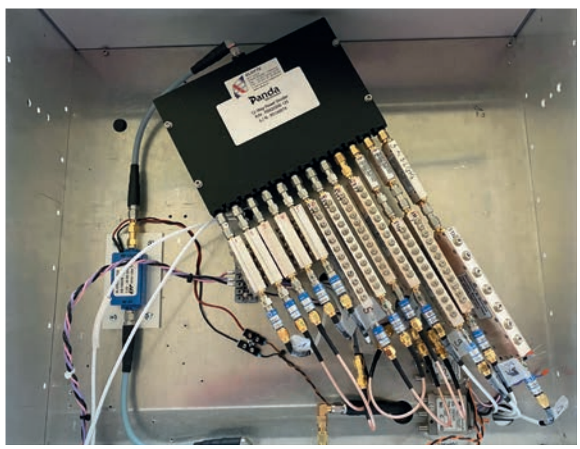
1 One ECE-chord signal: During a TCV discharge, the toroidal field is scanned and a calibration of the raw power was achieved by selecting two resonance regions not dominated by reflected X2, second order cyclotron emission (X3-single pass: red and blue curves ~1.2s on plot). This, together with agreement at full field (at 0.2s and 2.1s) for single pass X2, provides a clean calibration that can then be applied to all the ECE channels over a range of major radii.as the front moves up the divertor leg across plasma floor detachment.

LISTENING TO ELECTRONS TO MEASURE THEIR ENERGY

For a range of specific experiments, the electron population can deviate substantially from local thermodynamic equilibrium, for example in current drive or runaway scenarios, which produce high-energy tails. During his PhD thesis, **ARSENE TEMA-BIWOLE**, improved and applied a technique called Electron Cyclotron Emission using vertical RF beams in order to measure the energy spectrum of electrons. Electron Cyclotron emission comes from the natural movement of free electrons around the magnetic field lines that confine the Tokamak plasma. A vertical observing ECE diagnostic (see **Figure 2**) collects ECE radiation from the plasma where, after a 12-way power splitter (**Figure 3**) is analysed by an array of Radio-Frequency filters. Although the collected beam line terminates on a "beam dump" (**Figure 2**) to avoid reflections and other perturbative signals, this "vertical ECE" signal is often hard to interpret. By scanning the magnetic field strength in the observed plasma, effectively scanning the observed ECE radiation colour, regions of the spectrum were found to be free from contamination allowing that radiation to be modelled (**Figure 1**) and plasma parameters obtained where, now, clean spectral regions are well distinguished. It is therefore with a calibrated diagnostic system, and a relaxed window of operation, that it was possible to measure the radiation from non-thermal electrons at very high temporal resolution, in the order of ~10μs.



2 Cross-section of the TCV tokamak with the vertical ECE beam (red) and the beam dump in the bottom.



3 Power splitter and array of Radio-Frequency filters.

TCV Heating

Dr **STEFANO ALBERTI,** Senior Scientist (MER), is the leader of the TCV Heating research line and exposes below the main achievements in 2022.

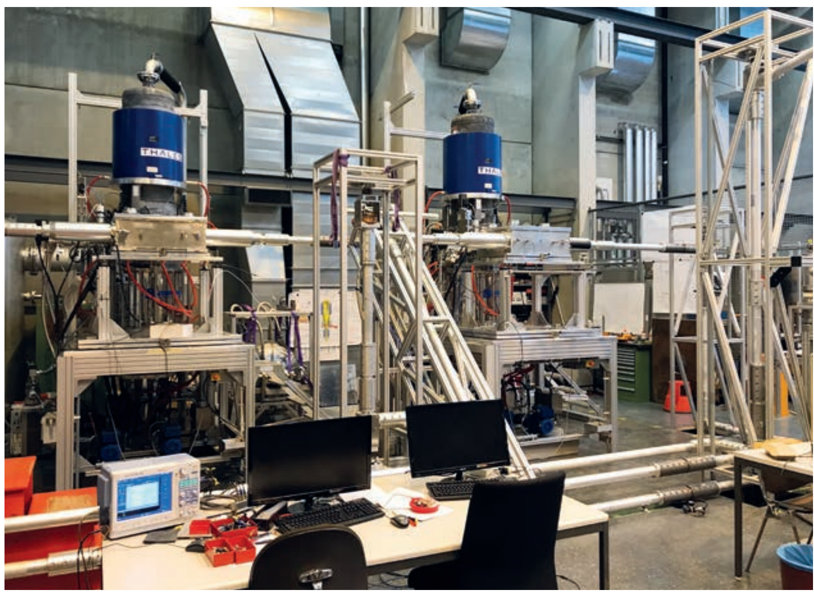
In 2022, the upgraded auxiliary heating system on TCV, including Electron Cyclotron Heating (ECH) and Neutral Beam Heating (NBH), has been essentially completed and fully exploited in the TCV experimental campaigns. The MW-class dual frequency gyrotrons and the MW-level neutral beam injectors have become essential actuators for interacting with the plasma electron and ion populations, respectively. These two actuators are compatible and exploitable with the extreme flexibility in plasma scenarios offered by TCV. The "Swiss Fusion Hub" proposal, which includes a further extension of the ECRH system with a third dual-frequency gyrotron, has been accepted by the ETH board. The realization of this project will be fundamental for TCV to make crucial and unique contributions in support to ITER operation and DEMO design.

For the ECRH system, the G2 gyrotron (82.4GHz/700kW/2s) has suffered of a major failure which would require the gyrotron to be sent back to the manufacturer in Russia for repair. This gyrotron is still under warranty, but with the present geopolitical situation it is not possible to organize such a repair. As a mitigation action for this loss, the possibility of replacing the faulty gyrotron with a dual-frequency gyrotron (in addition to the one part of the "Swiss Fusion Hub" proposal) is under discussion.

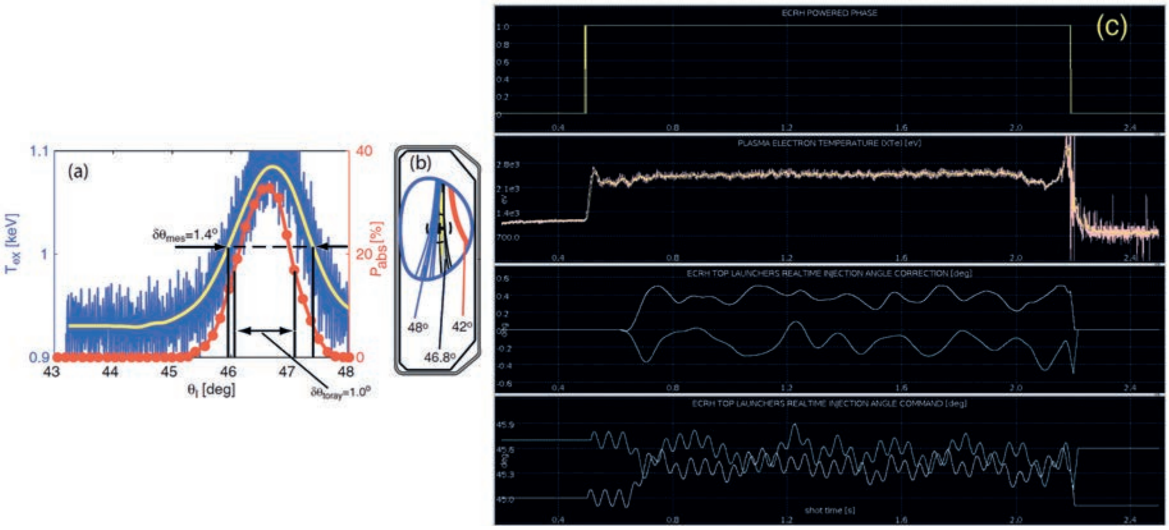
The G10 dual-frequency gyrotron, has been successfully commissioned after repair. Throughout the 2022 scientific campaigns the ECRH system offered the following capabilities:

G10 (126/84GHz, 900kW, 2s), G11 (126/84GHz, 900kW, 2s), G1(82.7GHz, 700kW, 2s).

Figure 1 shows the two dual-frequency gyrotrons integrated in the ECRH system, with G11 connected to a new launcher for top-launch injection of the X3-wave at 126GHz. In top-launch configuration, the angular injection-angle range for which there is a good single-pass absorption of the X3-wave is extremely narrow, typically < 1.5° FWHM as shown in **Figure 2 (a)**. This narrow range, together with the fact that plasma properties evolve during the 2s plasma, demands a real-time control of the injection angle with a precision better than 0.1°. With two independent launchers and a single observable (the electron temperature measured with the T_{ex} diagnostic), the independent real-time control of the two launchers has been achieved by a "lock-in like" technique in which the two mirrors angles were modulated in quadrature at 20Hz. The successful implementation of this technique is illustrated in **Figure 2 (c)**.



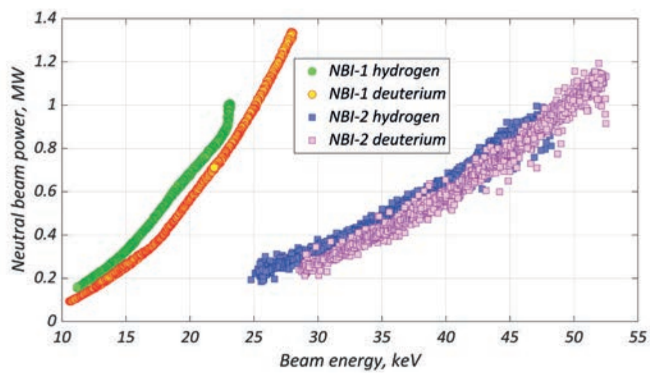
1 The two dual-frequency gyrotron (84/126GHz, 1MW-each, 2s) connected to the versatile transmission line system directing the rf-power to the EC-launchers mounted on TCV.



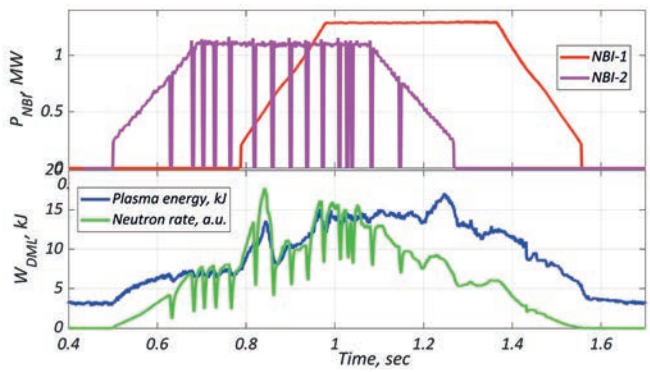
2 X3 top-launch heating experiment using the two top-launchers with an idependent real-time control of the injection angle on each launcher. **(a)** Blue curve, example of angular sensitivity of the absorption measured with the TeX diagnostic with in red, the predicted single-pass absorption calculated with the TORAY ray-tracing code. **(b)** Ray tracing for different injection angles. **(c)** Real-time control of two independent launchers, ensuring maximum absorption, based on a quadrature modulation at 20Hz of the two launchers.

The capability of the TCV neutral beam heating system has been extended with the second beam (NBI-2) intensively commissioned in 2022. Most major technical issues with NBI-2 have been solved, in particular, the installation of a CuCrZr alloy beam-duct without B4C coating allows to inject 1 MW, 2 sec beam into TCV without plasma disruptions and pollution of plasma with impurities. The new beam duct is equipped with a spectroscopy diagnostic for monitoring the possible beam-blocking events.

Both neutral beams: 1.3 MW/28 keV low-energy heating neutral beam (NBI-1) and 1.1 MW/53 keV (high-energy, NBI-2) have been optimized for operation with deuterium and hydrogen (**Figure 3**). NBI-1 and NBI-2 have been intensively and reliably used for ion heating and fast ion studies. NBI-1/NBI-2 used in 1334/333 TCV shots (870/55 in 2021). The NBI-2 energy injected in TCV increased from 300 kJ to 1.1 MJ with upgrade of the beam duct and optimization of beam parameters. Example of the TCV shot with simultaneous injection of both beams (max. 2.4 MW) is illustrated in **Figure 4**.



3 Operational range of TCV neutral beams.



4 TCV shot 77383 with two neutral beams.

TCV Boundary

Successful operation of a fusion reactor depends crucially upon the boundary plasma. Adequate confinement of the extremely hot, 100 million °C plasma core must be ensured whilst avoiding damage to the plasma surrounding wall structures. By leveraging TCV's unique magnetic shaping capabilities, operational flexibility and excellent diagnostic accessibility, the Boundary Group, led by Prof. **CHRISTIAN THEILER**, works on advancing the fundamental understanding of the complex, turbulent boundary plasma and developing improved solutions compatible with a reactor. Here are some notable achievements from 2022.

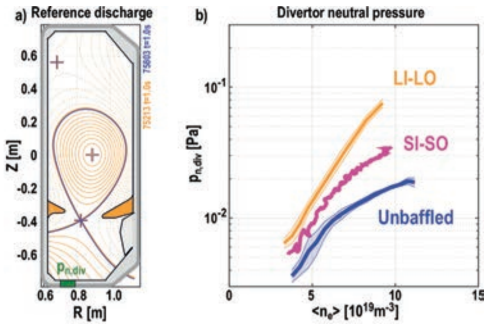
Ideally, one would like to have a cold plasma near the machine walls and reduced plasma-wall contact, thus essentially "detaching" the plasma from any material surfaces. Despite substantial progress in our understanding of the boundary plasma, quantitative predictions for future reactors are still accompanied by uncertainties. It is unclear whether currently foreseen "conventional" boundary solutions will be adequate for a reactor. New ideas, such as alternative magnetic geometries of the boundary plasma, are therefore being explored.

In 2022, we further studied the role of neutral particles in the divertor region, controlled by TCV's flexible divertor neutral baffling structures installed as part of the EUROfusion multi-device plasma exhaust (PEX) strategy. For the first time, all three foreseen sets of baffles have been tested and compared to the un-baffled TCV, demonstrating successful decoupling of divertor neutral pressure and core density, **Figure 1**. Increasing baffle closure was shown to enhance divertor neutral pressure by up to a factor 5, resulting in enhanced power exhaust mitigation and a detachment onset at up to 30% lower plasma density. Testing of models used to predict exhaust performance of future, high power devices such as ITER and DEMO in these flexible, well-diagnosed TCV plasmas was further constrained by new divertor ion temperature measurements, inferred from Doppler-broadening of C-III emission, experiments in both magnetic field directions, and a more accurate numerical treatment of molecular processes.

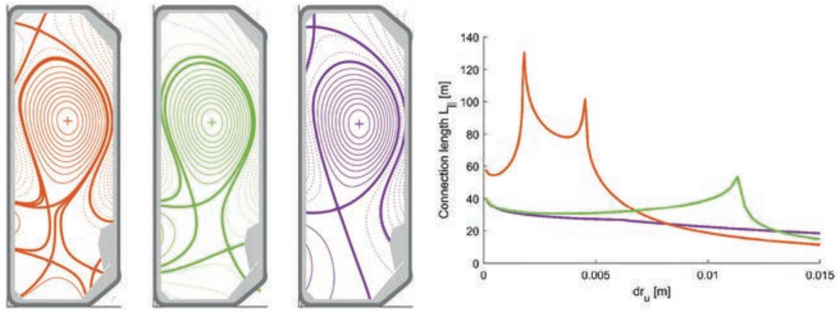
The X-Point Radiator (XPR) regime, which promises well-controlled power exhaust and good core performance, see **highlight**. Significant progress was also achieved in two other, promising reactor regimes, the Quasicontinuous Exhaust (QCE) scenario and Negative Triangularity (NT) plasmas. In the former, a significant widening of the heat flux width was demonstrated. In NT plasmas, the possibility to operate with a detached divertor was demonstrated for the first time.

Considerable progress was also achieved in 2022 in the assessment of alternative divertor magnetic geometries for optimal plasma exhaust. Detailed geometry scans, compatible with the baffles and optimized for subsequent modeling, were performed. First highlights of these studies include the reproduction of the key experimental findings in the Super-X divertor on TCV using SOLEDGE2D-modelling.. In the baffled Snowflake geometry, significant reductions in peak wall heat fluxes were further demonstrated. To further study the role of magnetic field-line length in the boundary plasma on volumetric power losses, a new, extreme geometry dubbed "Jelly-Fish" has been developed in TCV, **Figure 2**. Overall, our studies point towards the concept of a divertor with a relatively long divertor leg and very strong baffling as a promising future exhaust solution. We have proposed to test such a concept on TCV as part of a major upgrade of the SPC experimental facilities, in response to a call by the ETH Board. This proposal has been accepted in full in December 2022 for implementation and scientific exploration in 2025-2028.

Another topic that has received more and more attention is the real-time control of divertor detachment. Progress includes emission front control using deuterium fueling and nitrogen seeding and the real-time assessment of volumetric loss processes in the divertor by applying machine-learning techniques used in medical imaging to accelerate the tomographic inversion process in data analysis. Additionally, deep-learning neural networks were used to approximate the inverse mapping between those volumetric losses and the measured emission over 30 000 times faster than classical methods.



1 **left:** TCV reference discharge with the longest set of baffles (LI-LO) in yellow, separating the main chamber from the divertor region. **Right:** Divertor neutral pressure vs plasma density, shown to increase substantially with increasing baffling.

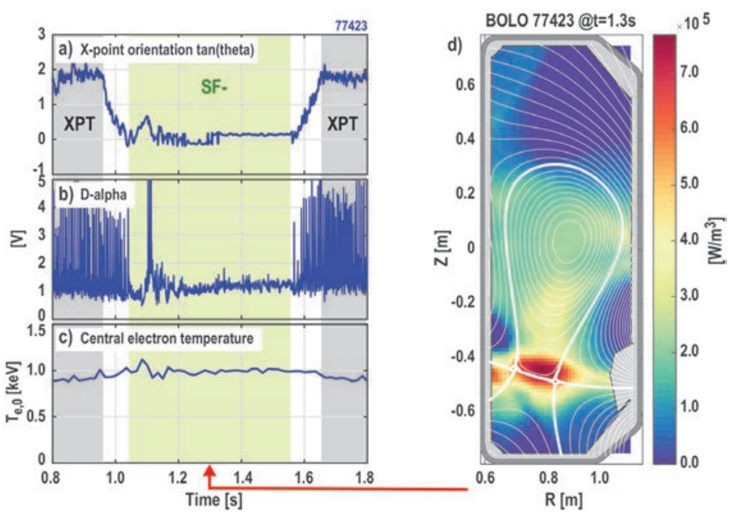


2 Newly developed, extreme magnetic field-line lengths plasma shape dubbed "Jelly-Fish" (orange), compared to the more traditional Snowflake (green) and Singe-null shape (purple). The right plot shows radial profiles of the magnetic field-line length ("connection-length") in these three shapes.

X-POINT RADIATORS AND SNOWFLAKES

Recent experiments led by Dr. **HOLGER REIMERDES**, Senior Scientist (MER) at the SPC and member of the TCV boundary group, aimed at broadening the operating regime with X-point radiators (XPR) in TCV. XPRs, which were discovered on ASDEX Upgrade, have several properties that could make them a very attractive power exhaust solution for future fusion reactors. They convert most of the exhaust power into radiation, which is benignly spread over a large surface area. They have also been seen to modify the H-mode density and temperature pedestal in such a way that edge localised modes (ELMs), which generate intense and potentially destructive bursts of energy towards the divertor targets, are completely suppressed.

TCV had previously accessed this interesting regime only with difficulties, as predicted for plasmas where radiative losses are dominated by carbon impurities, ubiquitous in TCV. The recent works used TCV's configurational versatility to demonstrate that access to the XPR regime can be facilitated by means of magnetic geometry. Guided by a theoretical model of the XPR, the length of magnetic field lines connecting the region just inside the X-point with the hot core plasma was increased by introducing a second X-point in the vicinity of the separatrix, **Figure 3 (d)**. Transitioning to this configuration, which is a particular snowflake-minus configuration, in a high-power H-mode led to a shift of the radiating region from the diverter across the separatrix to a volume just above the X-point, characteristic for an XPR. This shift of the radiating region went along with a disappearance of ELMs while maintaining H-mode confinement, **Figure 3 (a-c)**. Detailed measurements of the plasma kinetic parameters inside and outside of the separatrix now challenge the models for access and stability of the XPR and models for ELMs alike.



3 Discharge with **(a)** a configurational change from the X-point target (XPT) to snowflake-minus (SF-) configuration and back, where the SF-phase (green shading) leads to **(b)** ELM suppression, while maintaining **(c)** high core electron temperature. **(d)** The tomographic inversion of the plasma radiation shows strong radiation from an extended region just above the two X-points.

Theory and Numerical Simulation

Led by Prof. **PAOLO RICCI** and fully embedded in the EUROFusion program through the participation to E-TASC, Enabling Research and code development projects, the SPC theory group goal is to advance the first-principles understanding of fusion plasmas. This is necessary to provide an interpretation of the results from current experiments, and to make predictions for future fusion devices while leading their development.

Since the equations governing the plasma dynamics are generally too complex to solve analytically, the theory group heavily relies on numerical simulations and makes use of some of the most advanced High-Performance Computers worldwide, including the Piz-Daint at Swiss Supercomputing Center (CSCS) and Marconi at Cineca. At the same time, with the goal of optimizing the European advanced simulation codes used for plasma simulations, the theory group coordinates one of the five EUROfusion Advanced Computing Hub, which joins the SCITAS (Scientific IT & Application Support) group, the MATHICSE (Mathematics in Computational Science and Engineering) group, the Laboratory of Experimental Museology (eM+) and the Swiss Data Science Center (SDSC).

GLOBAL PLASMA STABILITY

A EUROfusion enabling research project is supporting the development of a new hybrid kinetic-MHD code, VENUS-KMHD. This new code, which is undergoing initial benchmarking against known analytic results, will handle corrections to MHD associated with the long mean free path of particles in a hot reactor plasma.

We have also progressed in our understanding of the fundamental properties of pressure-driven ideal and resistive instabilities in tokamak plasmas, especially with extended regions of low magnetic shear. This allows for the investigation of 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.

CORE TURBULENCE

The self-interaction of turbulent eddies with themselves when magnetic field lines bite their own tails after a small number of circuits of a tokamak was studied. Gyrokinetic simulations in a novel way were used to isolate the effect of changing the field line topology. It was found that very small changes in the safety factor (i.e. the pitch angle of the magnetic field lines) can dramatically alter the turbulent transport.

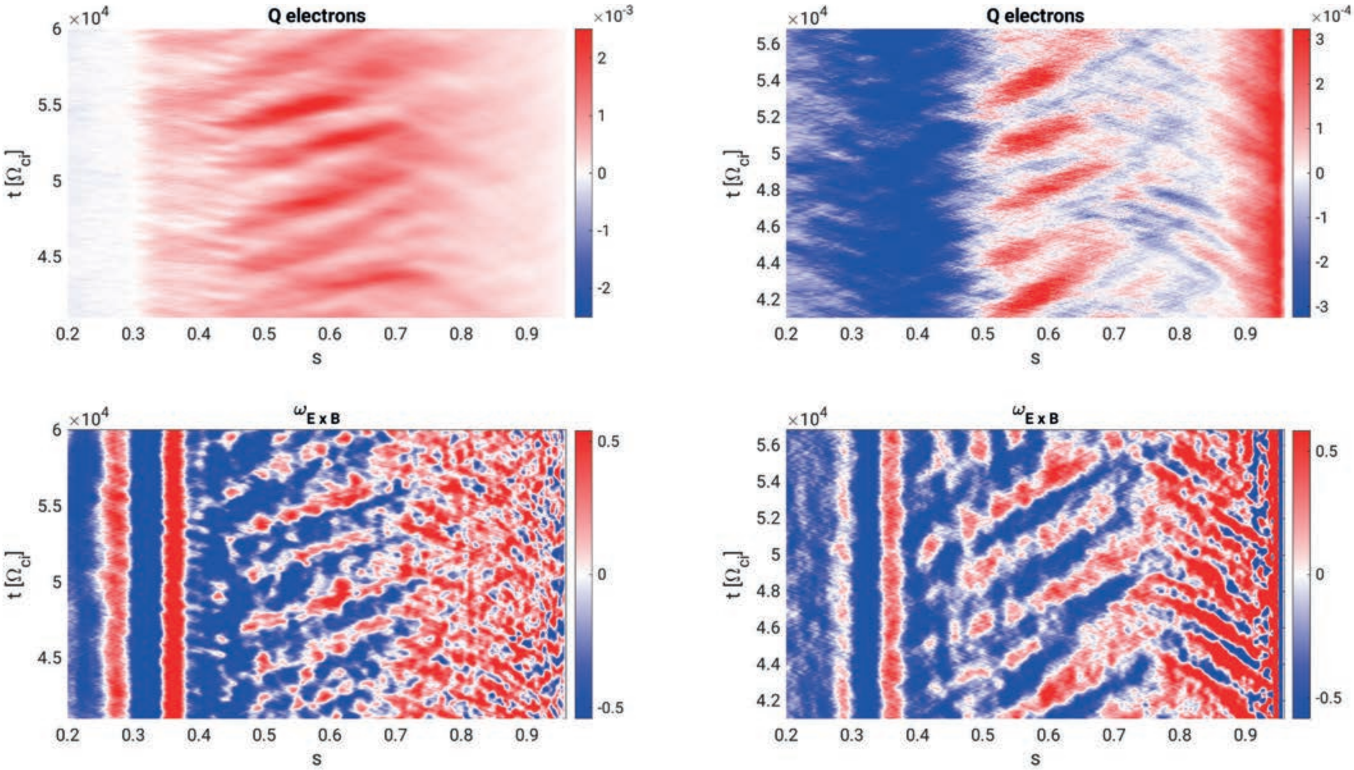
Progress has also been made in the development of gyrokinetic particle-based codes. In fact, obtaining a relevant and reliable prediction of the consistent evolution of plasma profiles and turbulent transport requires long simulations, in which the temperature and density profiles can strongly evolve from their initial specification, in particular near the edge regions. We have implemented and applied an adaptive control variates scheme to a global gyrokinetic code in simplified geometry as a proof-of-principle test bed. Our tests show a massive improvement of the signal to noise ratio, paving the way of its application to long, flux-driven simulations. This technique is now being implemented into the ORB5 code.

BOUNDARY TURBULENCE

We have implemented and tested simplified model for the plasma beyond the last closed flux surface (LCFS) in limiter configurations in the ORB5 code. The model, initially developed in the GYSELA code in the limit of adiabatic electrons, was implemented and tested in the ORB5 code and extended to trapped kinetic electrons. Studies focused on the non-local effects in both positive and negative triangularity TCV configurations. The presence of a limiter is found to have an influence on the behaviour of avalanches, which can be seen on the electron heat flux and on the zonal flows (see **Figure 1**).

The approach to the gyrokinetic model based on the evolution of the moment of the distribution function was pursued. By studying the development of linear instabilities and through the first nonlinear results, it was found that this model is particularly efficient to simulate plasmas in edge conditions.

Fully supported by EUROFusion, we have investigated the physics of the plasma sheath that forms at the interface with the vessel walls. A semi-analytic sheath model, valid for small angles of incidence of the magnetic field, was generalised to include multiple ion species. In addition, analytical calculations were performed towards understanding the effect of turbulent gradients on sheath boundary conditions. He has already obtained first preliminary results of 2-dimensional spatial profiles of electrostatic potential and density in the magnetized sheath with small-amplitude fluctuations.



1 Contours of the electron heat flux **(top)** and of the zonal flow shearing rate **(bottom)** versus radius (horizontal axis) and time (vertical axis). Simulations using the global ORB5 code without **(left)** and with **(right)** a limiter, in a TCV configuration with negative triangularity.

NEGATIVE TRIANGULARITY

The SPC theory group leads the EUROfusion activities targeted to the development of negative triangularity scenarios. TCV experiments to study negative triangularity plasma shaping were compared with gyrokinetic simulations to understand his experimental results. Interestingly, it was found that, in single-null discharges, the triangularity at the X-point has a very different effect on plasma performance than the triangularity on the side opposite to the X-point.

In addition, gyrokinetic computer simulations were performed aimed at testing how the turbulence reduction caused by negative triangularity extrapolates to larger devices such as a power plant. In order to enable these simulations, a novel method to include finite machine size effects in the standard local simulation domain was devised. In contrast to a past studies, it was found that the confinement in negative triangularity scales similarly to conventional plasma shaping, which suggests that power plant-sized devices will still benefit from negative triangularity.

TOKAMAK CONTROL AND DISCHARGE OPTIMISATION

The development and maintenance of the suite of free-boundary equilibrium codes continued in 2022 with the inclusion of a rigid displacement model allowing faster study of the plasma vertical stability compared to the full free-boundary equilibrium model. It is now possible to implement feedback controllers for the plasma position, current and individual coil currents in the free-boundary evolutive simulations, this enables considerably faster iterations between the design and testing of the controllers.

RAPTOR simulations and optimization of the ramp-down phase of tokamak discharges has been extended and has inspired specific experiments on AUG and TCV with the ITER baseline scenario. These have confirmed the predictive simulations, providing further confidence in the prediction for DEMO ramp-down optimization, which now includes also the effect of radiated power from impurities according to the time evolution of the temperature.

Simulations of disruptions in TCV were conducted to assess dominant runaway generation mechanisms, cooling time scales and the role played by runaway electron collisional heat transfer. A tool for the study of runaway electrons during tokamak startup was also developed and applied to selected TCV discharges.

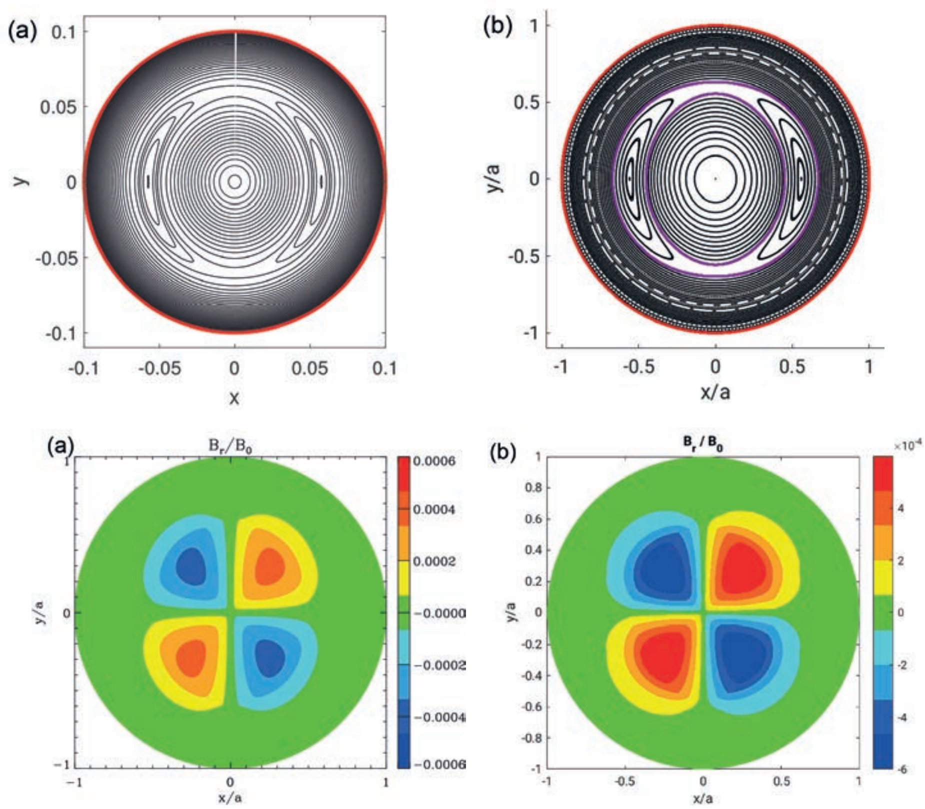
STELLARATOR

The Stepped-Pressure Equilibrium Code (SPEC), combined with novel numerical measures of magnetic field-line integrability, has been used to investigate stellarator pressure limits by quantifying the emergence of chaos and the associated enhancement of heat transport, taking into account the effect of the self-generated (bootstrap) current. Furthermore, an analytical nonlinear theory has been derived that explains these pressure-limits.

The SCENIC ICRH code has been upgraded to include hot plasma effects and also a new collision operator for thermalized particles. These developments will permit modelling of advanced heating regimes in W-7X such as multi-harmonic and synergistic RF-NBI.

The Global Braginskii solver (GBS) has been used to perform the first validation of stellarator fluid turbulence simulations against measurements from the TJ-K stellarator in Stuttgart, Germany. Some striking differences with respect to tokamak boundary turbulence are starting to come to light, and these simulations are allowing to gain basic understanding on their origin.

We investigated a novel approach to predict the nonlinear saturation of a tearing mode in a cylindrical tokamak with no pressure. Instead of solving the time-dependent, resistive MHD equations until saturation, we used the code SPEC to find this saturated state as a lower-energy 3D MHD equilibrium. The two approaches produce a very similar result, see **Figure 2**, but the SPEC approach is orders of magnitude faster.



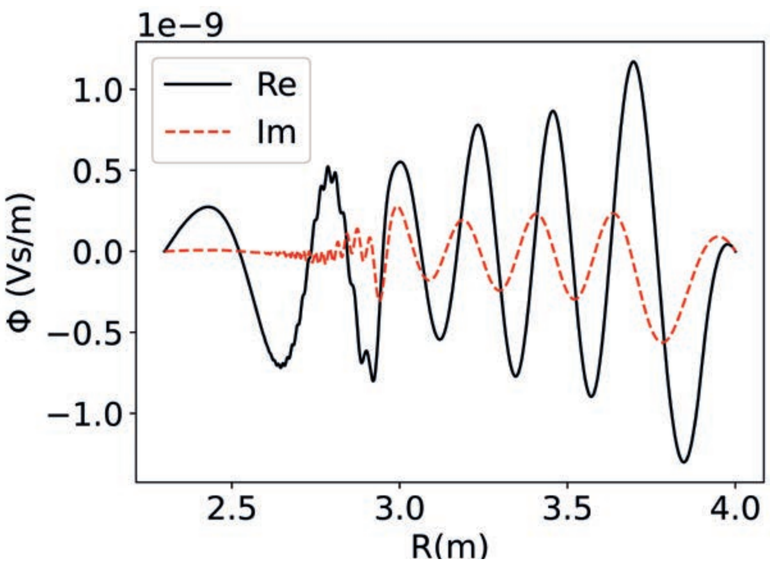
2 Nonlinearly saturated tearing mode in a cylindrical tokamak as predicted from **(a)** initial-value resistive MHD simulations carried out with the SpeCyl code, and **(b)** 3D MHD equilibrium calculations with the SPEC code, which can describe the formation of islands. **Top**: Poincaré plots of the magnetic field. **Bottom:** radial component of the magnetic field.

LINEAR MODE CONVERSION

Electromagnetic waves in the radio and microwave frequency ranges play a key role in the heating of many of the world's fusion experiments. The frequency of these waves is carefully chosen to exploit a specific resonance in the plasma. In resolving any wave resonance there always exists some amount of linear mode conversion (the process in which energy is transferred between different types of waves).

This phenomenon is usually studied in Fourier space (wavenumber space), however, it may be more advantageous to use configuration space instead. This provides certain numerical advantages, enabled by today's high performance computing platforms. **MIKE MACHIELSEN**, a PhD student at the lab, explored this modelling approach. To this end, a constitutive relation in configuration space had to be derived for the plasma, which is anisotropic and non-local.

However, in certain special cases this can be derived analytically. It has then been applied to study wave propagation and mode conversion of ion cyclotron resonance heating in a tokamak in 1D, see **Figure 3**. Although simplified in its geometry, it provides a proof of concept of the newly derived expressions, which can later be implemented in 2D or 3D.



3 Scalar potential vs major radius of the tokamak. The wave is launched from the outboard side (right), and moves to the left, where it is damped by the plasma. At R<3 m, the excitation of short-wavelength waves is visible.

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 AND TORPEX: UPGRADES AND DIAGNOSTICS DEVELOPMENT

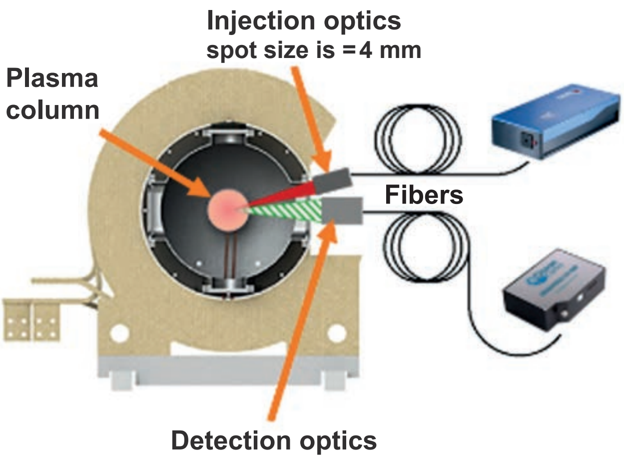
The activities on RAID and TORPEX were devoted to upgrade the devices as well as the set of available diagnostics and, in parallel, to continue the basic physics investigations of previous years.

On RAID, in 2022, we finalized a significant upgrade. The device is now operating with two plasma sources located on the extremities of the RAID chamber and an additional magnetic coil symmetrizes the axial DC magnetic field. The new systems have been integrated in a LabVIEW interface to automatize the plasma generation and to proceed to more reliable and sophisticated measurements. Effort has been put into expanding the set of diagnostics. A new probe holder has been installed, which can be equipped with Langmuir Probe, Double Langmuir Probe or B-dot Probe and allows 2D scans of the plasma parameters. A double Langmuir probe for 2D mapping of plasma columns was developed. The main challenge was to build probes that can withstand the harsh environment of high-power helicon regimes. The probe data are analyzed according to a newly developed theory allowing the determination of electron temperature and density as well as ion temperature. Mappings of plasma parameters has been performed for various conditions of RF power, magnetic field, pressure, and gas.

The installation of a Two-photon Absorption Laser-Induced Fluorescence (TALIF) diagnostic, started on RAID in 2021, was completed in 2022, and first measurements were taken. The diagnostic is capable of measuring 1D resolved lifetimes and densities of atomic H, in conditions relevant to the scrape-off layer and the divertor in tokamaks. The optical path guiding a 205nm UV laser beam from the Biolab to RAID was assembled, including the mounting and alignment of the mirrors and lenses used to focus the beam to the RAID plasma column. The fluorescence signal is detected by an ICCD camera, which was mounted and aligned on a lateral window of RAID. A preliminary version of the data analysis routines was developed, which extract the TALIF signal from the pictures taken by the camera and perform the calculations needed to determine the decay time of the fluorescence signal and the density of atomic H.

We continued investigating Helium plasmas using laser induced fluorescence (LIF). This very well-established technique has been used in RAID to determine the behavior of Ar II ions in Argon plasmas as well as in studies of He I neutrals in Helium plasmas. In the case of He I, we use a tunable CW diode laser near 668 nm to pump electrons from the 21P to the 31D states. The electrons then undergo collisional excitation transfer to the nearby 31P state, from which they can decay to the 21S by emitting 501 nm photons. This emission signal has allowed us in the past to recover temperatures, and through a collisional-radiative model (CRM), approximate densities of He I in Helium plasmas. Collisions can also transfer excited electrons to other nearby states. In 2022, we performed observations of these additional decay photons using a wide-range spectrometer and dedicated experiments. **Figure 1** shows the experimental setup on RAID. Through comparisons with CRMs, this so-called laser-collisional induced fluorescence (LCIF) approach can be used to determine localized plasma quantities in a way that can be shown to be robust to many typical hurdles encountered in plasma models, such as line-integration of emission data, opacity, laser power, etc. Further studies and experiments are currently underway to further develop this technique and, together with future Thomson Scattering measurements, explore possible applications in CRM parameter estimations.

On TORPEX in 2022, we prepared the device and diagnostics for future fast ion studies in new magnetic configurations. This restart has required some maintenance and upgrades of the experimental setup. As an example, new data acquisition systems and new patch panels have been set up, a new control computer has been installed, the fast ion source and its detector have been tested and reinstalled, etc. The first magnetic configuration of interest consists in a poloidal field with a single-null point (or X-point). It has been implemented and validated



1 LCIF experimental setup on RAID. Fluorescence stemming from excitation by the injected laser beam is detected via a wide wavelength range spectroscope.

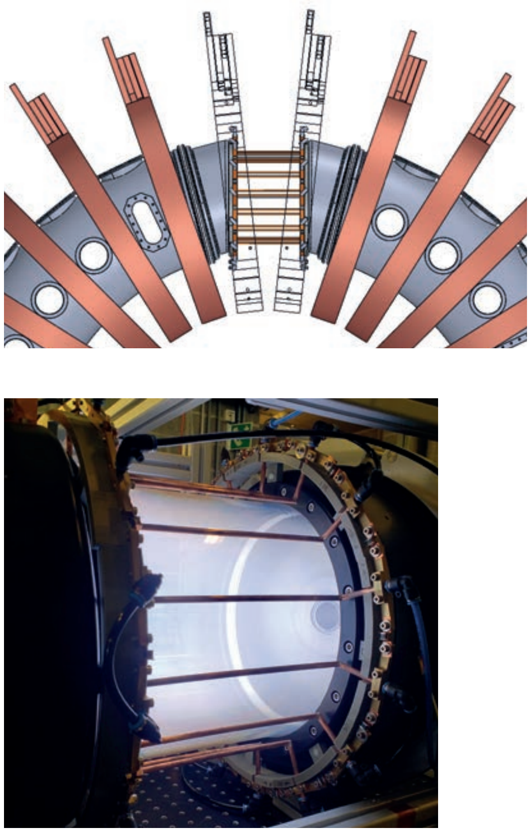
owing to a new diagnostic: a Hall probe (measuring the magnetic field by using the Hall effect). TORPEX plasmas with an X-point have been thoroughly studied by varying the magnetic shear and by using a large set of Langmuir probes, to choose the scenario of interest for fast ions studies. Interesting features of the plasmas have been observed and a more detailed analysis of these results will be conducted in 2023. In parallel, a new moving system has been developed for the fast ions: the source itself can be moved toroidally inside the vessel, along a rail of ~ 52 cm length. This will allow for 3D reconstruction of the fast ion beam profiles.

A major upgrade of the TORPEX device has been undertaken in 2022. A helicon antenna has been designed to be mounted on TORPEX (see **Figure 2**). The design of the antenna and the choice of its components has been determined from numerical simulations. The antenna has been assembled on a testbench and was successfully operated, up to a power of 1 kW and in the range of TORPEX operating pressures. The final mounting of the antenna on TORPEX will be achieved in 2023. This antenna will constitute a major upgrade of TORPEX: plasmas of higher density should be achieved, and the magnetic field will become an independent control parameter (contrary to the current magnetron plasma generation).

LOW TEMPERATURE PLASMAS FOR BIOLOGICAL APPLICATIONS

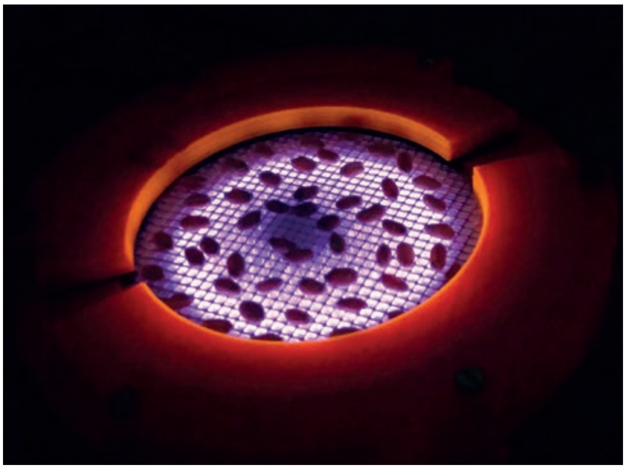
The activities in the field of low temperature plasmas for biological applications focused on the characterization of dielectric barrier discharge (DBD) plasmas, their use for sterilization of seeds and surfaces as well as the investigation of plasma-activated water and its effects on bacteria.

A new DBD plasma source for biological applications in high-humid environment was designed and tested. Insights on the mechanism inhibiting the breakdown in the presence of high humidity were obtained, both experimentally and with numerical simulations (COMSOL). A new project on seeds sterilization started, aiming at reducing the percentage of specific fungi on wheat seeds as an alternative method to current industrial-grade solutions, such as steam treatments (see **Figure 3**).



2 **Top:** A toroidal sector of Torpex with the new helicon resonant antenna. **Bottom:** first plasma with the helicon antenna on a test bench.

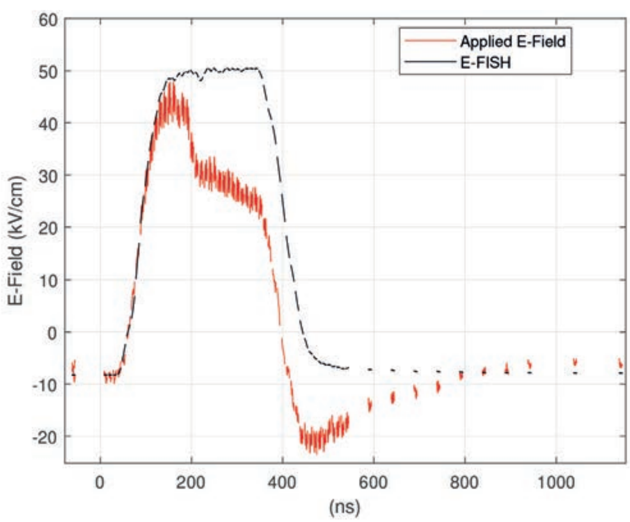
LIF measurements of NO produced by a finger electrode configuration Surface-DBD (SDBD) plasma, powered by a nanosecond pulsed high voltage power supply, by measuring the NO concentration during the plasma discharge. The results show strong spikes of NO in proximity of the plasma discharge and more precise measurements should show the clear relation of this spikes with the plasma discharge. NO concentration was also measured in correlation to some relevant plasma parameters, like frequency, voltage, and humidity. FTIR measurements were performed on the same setup used for LIF, showing trace of HNO_3, NO_2, N_2O and O_3. This setup was studied owing to its effectiveness in bacteria inactivation. Moreover, in collaboration with the CNR of BARI, we performed first measurements of Electric-Field Induced Second Harmonic (EFISH) generation inside a nanosecond pulsed VDBD plasma in humid air. The measurements were successful, and we were able to follow the time evolution of the electric field during the nanosecond pulsed plasma discharge. For the first time, a clear e-field inversion and a strong residual charge after the plasma discharge was observed (see **Figure 4**). The results gave us first insights on the ions and electrons dynamics during the ionization wave in humid air at atmospheric pressure. The setup is currently under development at SPC, to replicate the same, and more, measurements, with the picosecond laser we have at the Biolab at SPC, as opposed to the nanosecond laser used in Bari.



3 **A DBD plasma used to treat wheat seeds.**

The plasma-activated water (PAW) studies continued in 2022. A new design of a PAW reactor was developed in the framework of R. Agus Ph.D. project. The final reactor allows sustaining the discharge at high humidity, in very close proximity to the water level, for long water treatment times (tested up to 60 min of plasma on with duty cycle approx 80%), and high temperatures of the DBD (backplate T >120 C when plasma is on), without any problem of backplate oxidation for long periods of time (up to now, 11 months of use). Different water samples produced with the reactor were characterized photometrically through colorimetry methods to measure the concentration of NO_{2-}, NO_{3-}, H_2O_2, and in terms of pH, electrical conductivity and oxidation reduction potential. The effect of different PAW samples, produced with and without a water flow, was tested on nonpathogenic E.coli proving different efficacies as a function of the sample characteristics and the treatment times. Single cell microfluidic experiments were finally set up in the biolab solving all issues related to microchip, instrument (Nikon Eclipse Ti2 inverted microscope) and software compatibility, and first time-lapses were recorded observing that cells are not able to duplicate, and they shrink after the PAW treatment. Effect of PAW has been tested also on B.subtilis with a visiting master student. B.subtilis growth protocol in liquid culture has been developed and PAW effect was tested, proving its efficacy also for this microrganisms. Two bachelor projects have been supervised helping on the quantification of PAW effect of static PAW and NO_{2-} and NO_{3-} single effect on E.coli.

Ozone measurements and theoretical quantification have been performed in PAW samples proving that there is not ozone left in PAW after the plasma exposure (half-life time of the order of millisecond). Flow cytometry experiment have been performed on E.coli samples proving that cells follow an apoptotic-like death pathway and keep their cellular membrane intact after PAW treatment. PAW characteristics for different water flows and discharge power where measured during a semester project.



4 **Electric field measurements in a Volume DBD using the E_FISH technique.**

TACKLING THE HIGH-VOLTAGE NEEDS OF NEXT-GENENERATION SATELLITES

During the last decade, the possibility of increasing the current satellite operating voltages of 30-100 V up to 300-600 V has been one of the hot topics under investigation by the aerospace community. This upgrade mostly aims at reducing the power-to-mass ratio, and therefore the cost, for the next generation of satellites equipped with ion and Hall high-power thrusters. However, one of the main risks associated with new range of voltage is the electrical breakdown in the slip ring assembly (SRA), which is the key element in the power transmission line of a satellite allowing for the current transfer from the rotating solar panels to the main body of the satellite. To face this challenge, the SPC has performed dedicated investigations in close collaboration with Beyond Gravity (before RUAG space) since 2010, when the RETS (Robust Electrical Transfer Systems) project started and continued in 2016 within the HV-EPSA (High Voltage Electrical & Power System Architecture) project. This joint effort, lead on the SPC side by Dr. **FABIO AVINO**, has successfully culminated in 2022 with the last milestone of the APRIOM project (Advanced sliP Ring for hIgh vOltage Mechanism), during which a new SRA prototype has been designed, developed, and tested at the Beyond Gravity facility in Nyon. The new design has been proved to be robust against breakdown for 25000 turns (11000 turns of a geo-satellite), function within 400-500 Volts (and 8 A) from very low pressures (10-5mbar) to the most critical pressure values (~1 mbar), with a resulting transferred power of up to 40 kW. This result paves the way to produce SRA for the next generation of high-power thrusted satellites.

Tackling the high-voltage needs of next-gen satellites

Applied Superconductivity

Located in the premises of the Paul Scherrer Institute (PSI) at Villigen and led by Dr **KAMIL SEDLAK**, the group is focused on the development and testing of large superconducting cables for fusion magnets.

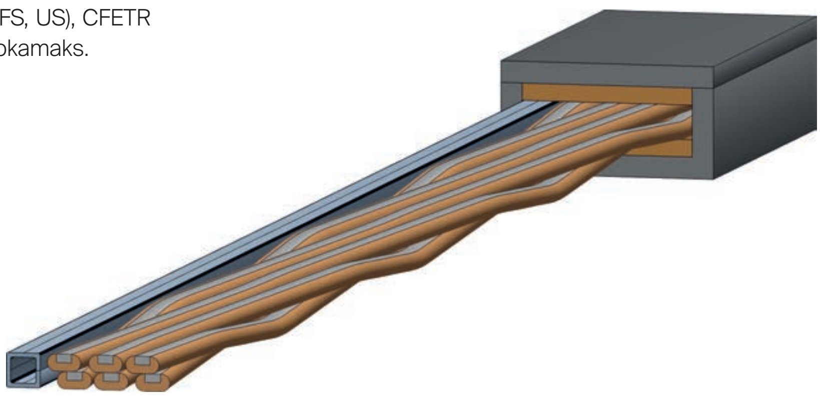
Likely, a big milestone in the development of fusion magnets was the manufacture and test of the toroidal field (TF) coil prototype made of high-temperature superconductors (HTS) by the Commonwealth Fusion Systems (CFS). The uniqueness of the coil was the usage of an unprecedented amount of HTS material, as well as its non-insulated winding pack, which means that during the coil charging or discharging, electric current can flow not only along the superconducting coil winding, but also transversely through the steel jackets of coil turns and layers. In a steady state situation, the transverse paths are inconvenient (they are resistive) and current flows along the superconducting winding. In case of a local quench, current can bypass the quenched region, and the coil does not need active quench protection. Despite the first TF CFS prototype coil has not validated the concept of the passive protection yet, it triggered a big attention of the community and confirmed the trend of going towards HTS conductors for fusion magnets. In our SULTAN test facility, we observe a steadily increasing demand to test HTS conductor samples, e.g. for the SPARC (CFS, US), CFETR (China), BEST (China), and EUROfusion DEMO tokamaks.

The HTS conductors for fusion machines are designed for magnetic fields in the coil up to 20 T (corresponding to ~11 T on plasma axis), unavailable in nowadays test facilities. SULTAN, the most powerful test station for fusion-magnet conductors, can reach “only” 10.9 T. For this reason, we wish to repair and upgrade the other existing test facility, EDIPO, where our goal is to reach 15 T. We continued optimizing the EDIPO coil design and purchased a Nb3Sn strand for producing a test cable, which will be later used for a sub-size test coil.

Our group is also developing the HTS fusion-magnet conductors and related technologies. In 2022, we manufactured the fifth sub-scale, 15 kA HTS conductor and tested its quench behaviour. We are finalizing the manufacture of the second SPC full-size HTS prototype for EU DEMO (**Figures 1-2**). It will be tested in 2023. A quench detection system based on optical fibers is being developed that is specifically suited for the HTS conductors. See **the highlights** for other projects.

We also continued R&D on LTS conductors for EU DEMO, with the so-called RW3 (react-and-wind, prototype no. 3) set of samples, whose performance did not reach our expectations, and we are trying to understand why. We further investigated new design options for TF, PF and CS coils, and proceeded with the design of the feeders, which connect the cryogenic environment around the magnets with the outside world.

Within an Innoswiss project, the development of small magnets made of Bi2212 HTS strands was done in collaboration with Bruker BioSpin. The project formally finished at the end of 2022, however a few test coils will be built also in 2023 to demonstrate the technological maturity of this technology, which Bruker BioSpin intends to use for constructing very high-field NMR magnets.



1 Sketch of HTS prototype conductor for DEMO developed at SPC.

TESTING OF CONDUCTORS OF THE COMMONWEALTH FUSION SYSTEMS (CFS)

The CFS company based their ambitious plans to build fusion reactors on high-temperature superconductors (HTS). An HTS conductor cooled to very low temperatures (4-20 K) can operate at twice-higher magnetic field (~20 T) compared to the more traditional low-temperature superconductor (LTS) used in ITER (~12 T). In the field of fusion magnets, it would be more appropriate to call those conductors "high-field superconductors" rather than "high-temperature superconductors". Though the first full-size HTS fusion conductor prototype in the world was manufactured and tested in 2015 by SPC, presently the rapid and most advanced R&D program is carried out by CFS. For testing their conductors named VIPER, CFS chose SULTAN test facility. Four conductor samples were tested in 2019, the fifth one was tested by **HUGO BAJAS** in 2022, and the sixth shall be tested in 2023. The test results are very promising – the VIPER conductor reached the expected performance and (unlike the first SPC prototype from 2016) almost did not degrade during cyclic loading.

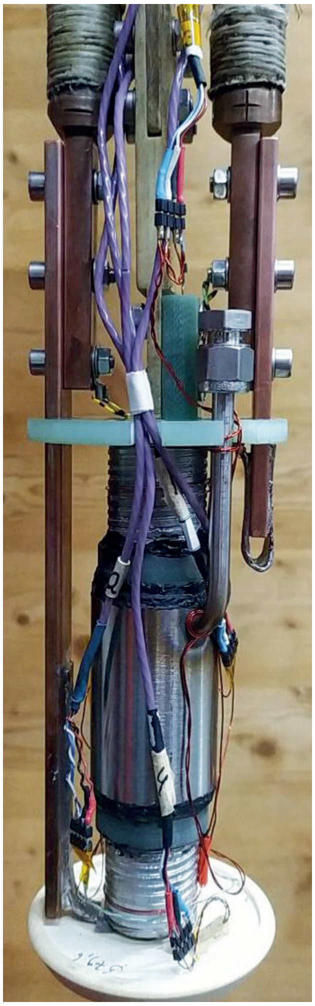
2 HTS prototype conductor for DEMO manufactured at SPC, to be tested in 2023.

SUPERCONDUCTING HIGH-CURRENT SWITCHES

As **NIKOLAY BYKOVSKIY** explains, the magnetic energy stored in fusion magnets operated at nominal conditions is extremely high, reaching 40 GJ in ITER TF and 150 GJ in DEMO TF, or about 5 and 20 times the kinetic energy of an Airbus-330 at the cruise speed. In case of a fault in the magnet operation, one has to face the challenge of releasing this energy in a safe manner. Conventional protection methods are based on using a sufficient amount of stabilizing copper in the conductor and energy release through external dump resistors. The latter one is achieved by a set of switching components, including mechanical, vacuum and pyro breakers, operated at room environment and triggering up to 10 kV discharge voltages in the system. The complexity of the fast discharge units and the risk of arcing call for alternative solutions.

The promising option is based on using superconducting high-current switches connected in series with the TF coil modules, which should not only address the key protection issues but also allow substantial saving in the cryogenic power consumption (a factor 2 to 3) by avoiding the flow of operating current back and forth from room to cold environment. Given that the switching is achieved by triggering superconductor into the normal state, thus maintaining the circuit continuity in contrast to the mechanical switches, the arcing problems are also simplified.

Aiming at the experimental demonstrations, Nb-Ti wires in a highly resistive Cu-Ni matrix were procured both as a single strand and in a 6-around-1 cabling configuration. An Ayrton–Perry winding, essentially layer-wound co-axial solenoids with reversed winding directions, is proposed for this application and implemented in the first 1 kA/2 Ohm thermally-activated switch demonstrator using the two single strands (**Figure 1**). The next demonstrations are planned using the 6-around-1 cables, rated up to 10 kA and 30 kA operation.



3 Sub-size Nb-Ti/Cu-Ni switch demonstrator in a test stand.

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

During 2022 the final design of the Electron Cyclotron (EC) ITER Upper Launchers (UL), including the ex-vessel waveguides that are part of those launchers, has been passed to the Technical Integrator (TI) who will be responsible to provide the final analysis, documentation, production, and delivery of the launchers. SPC has been contracted by Fusion For Energy (F4E) to assist and advise them during the running of the contract with the TI and to provide punctual additional analyses, if required. This allows F4E to retain the expertise from plug to plasma that is embedded in SPC. That includes the possibility to provide prototype testing for resolution of open questions identified by the TI.

The engineering team now leverages the expertise gained from ITER to pivot to more intensive work on the DEMO project, while maintaining a strong commitment to the success of ITER.

EUROPEAN GYROTRON

Testing and development of the European gyrotron for ITER continued in 2022. In 2021, the longest pulses possible was 256s, limited by heating in the transmission line waveguides that attach the gyrotron to the dummy load. Using a simple cooled waveguide design developed by SCP the maximum pulse length of 1000s was achieved with good temperature stability of the transmission system, bring the gytoron to its full specifications. Following this achievement, the THALES 1509U gyrotron was selected for procurement by both ITER and the Italian Divertor Test Tokamak (DTT) project.

By the end of the year, a Contract was signed with the US DA to test US-supplied ITER components at full power to permit selection of suppliers and qualify them for series production. The EU gyrotron will be used to perform these tests (see **Figure 1**).

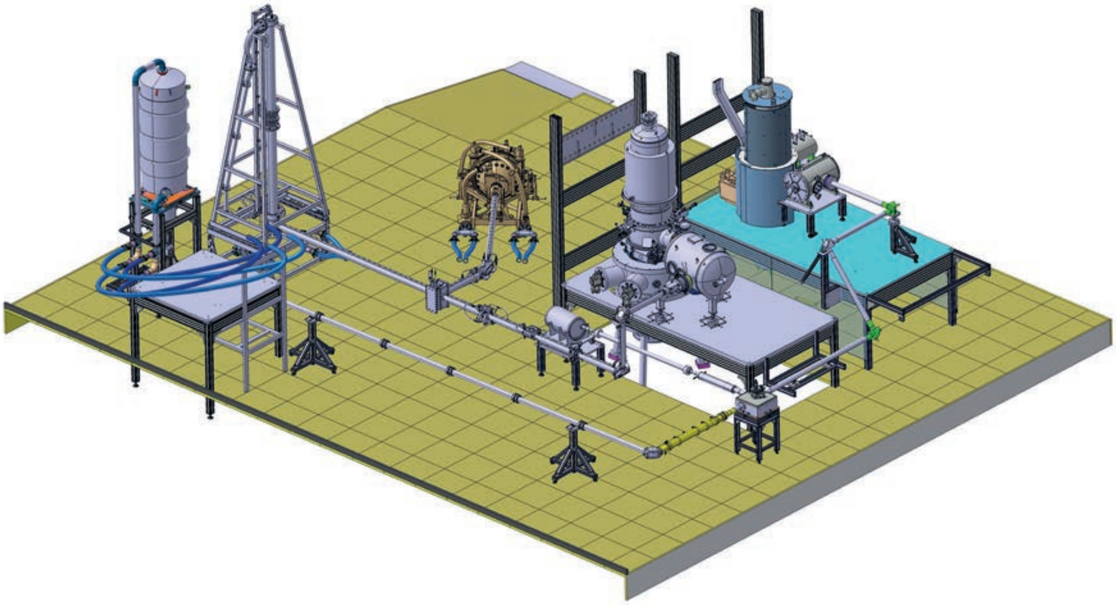
Additionally, following discussions begun during the *21st Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating* held at the ITER headquarters from June 20th to 24th, a Memorandum of Understanding was signed with Calabasas Creek Research to test an additional dummy load at FALCON. This brings the total number of different load designs tested at the facility to five. By the end of US-DA testing that number will be six and include nearly all the major worldwide load designs, providing a comparison/validation of all loads within the same test facility.

UPPER LAUNCHER

The transmission line components between the tokamak and the diamond window unit are part of the ITER nuclear first confinement system and have the most stringent quality, vacuum, and safety class. Tests at the FALCON facility show that the heat flux from the ohmic losses in the Miter Bend mirror is not a pure HE11 distribution (perfectly-centered J0 Bessel field profile). This situation is expected at the ITER site, as well. For this reason, the Miter Bend mirror cooling design has been modified to a three-channel spiral-shaped configuration, with non-central inlet and outlet location (see **Figure 2**); this design is able to better cope with possible beam offsets due to higher order modes in the transmission line. Thermo-hydraulic and thermo-mechanical analysis were performed to validate this concept. Thermal simulations were also carried out to the assess the performance of the different waveguide insert concepts for the ECH Isolation Valve and to provide design options for transmission line baking for good vacuum cleanliness.

Work on the in-vessel components of the wave launching system concentrated on detailed design and thermomechanical analysis of the structure that protects the springs, bellows and flexure pivots of the steering mirror actuator of the ITER upper launchers – the so-called “stray-radiation caps”. The caps are meant to create a thermal environment that ensures the functionality of the key components of the moveable steering mirror. The flexibility of the ITER EC heating system is largely based on this mirror motion.

All designs and analysis were delivered to F4E and passed on to the TI for incorporation and implementation into their final design.

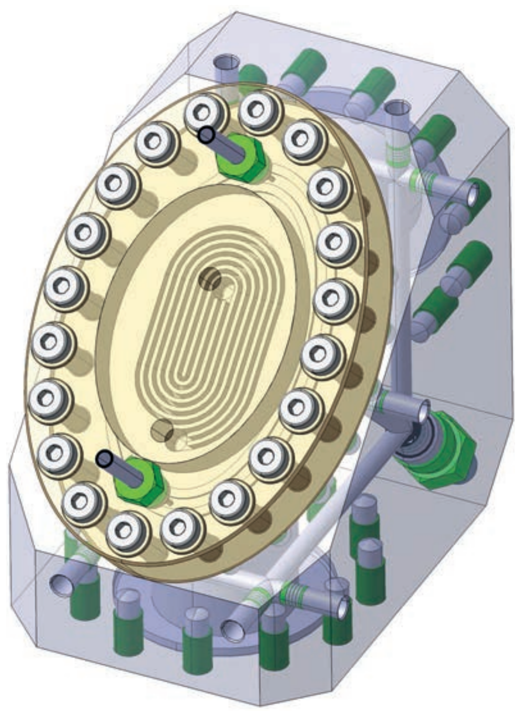


1 CAD view of the agreed testing installation of the US DA test equipment attached to the EU gyrotron. (The GYCOM gyrotron is also seen at the right connected to the F4E test line.)

DTT & DEMO

FALCON has been reserved, with the requisite accord of F4E, to act as the "factory floor" for testing of the DTT pre-series gyrotron in 2023 while their own factory test facility is being finalized. These works have been negotiated and organized in collaboration with THALES, the DTT team and F4E to ensure a timely validation of the TH1509U for series production for DTT. These tests will be the first using the actual ITER/DTT matching optics unit (MOU). Subsequently, DTT plans to train its EC team at the facility with the pre-series gyrotron to ensure rapid future deployment of the series gyrotrons when they will be delivered to the DTT facility. SPC has assisted all parties with preparations of the tests and provided the design of the matching optics (quadratic mirror surfaces to optimally couple power from the gyrotron to the transmission lines) for both the DTT and ITER gyrotron.

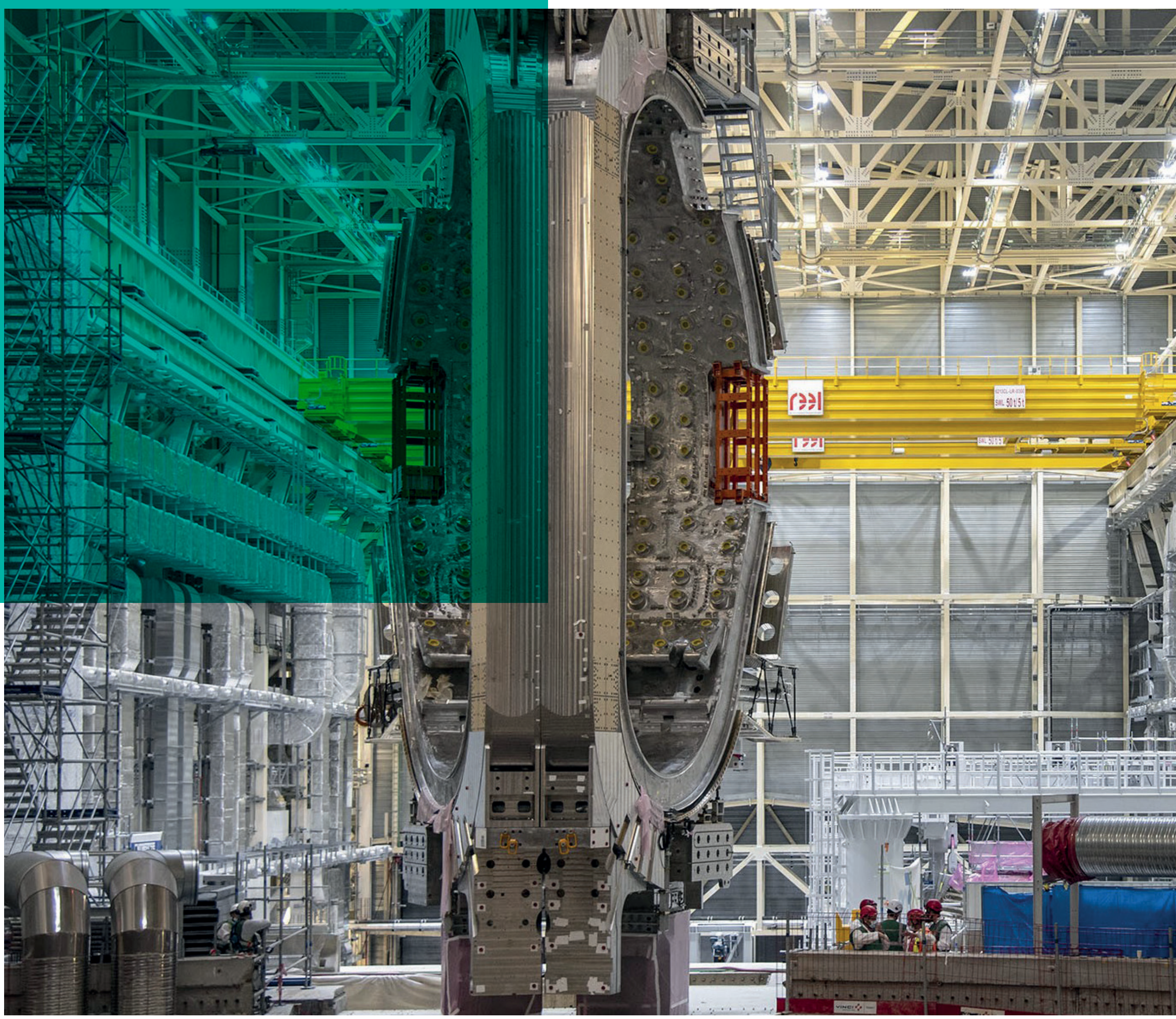
SPC holds the Project Lead and Project Lead Support of the Heating and Current Drive for DEMO. In addition, design and analysis of the EC launcher in-vessel waveguide, fixed and mobile mirrors and remote-handleable ex-vessel waveguides has been executed for the pre-conceptual phase of the project. The increased fusion plasma pulse length and significantly higher displacement per atom (dpa) in the materials used in DEMO, with respect to ITER or fission reactors, requires a change in the design with respect to the materials used, structures, and integration of components to permit fully robotic handling for maintenance; the latter will significantly affect the designs in the next design phases.



2 CAD view of the ITER 90° mitre bend to connect adjacent waveguides. The triple spiral mirror cooling is designed to be insensitive to non-ideal beams that may be off-set from the center of the mirror.

ITER, EUROPE AND SWITZERLAND

Just like our Center and EPFL, the international fusion community was eager after two years of pandemic to resume meeting in person, and has appreciated the possibility to participate in international conferences and workshops, giving rise to exchanges that are even more intense than before the pandemic.



This year, the full spectrum of the experimental results of the JET DT campaign was announced, representing important milestones on the way to ITER exploitation, including world record fusion energy production. A positive plasma energy balance was obtained in inertial fusion at NIF, marking a scientific breakthrough and a technological prowess. A stable plasma was maintained for up to 1000s in the Chinese tokamak EAST, and a plasma energy turnover exceeding 1GJ was achieved in the W7X stellarator.

The assembly of the ITER tokamak is on the way of being completed, although delays due to difficulties with a number of elements, including the vacuum vessel, the buildings and the concrete radiological shielding motivate the establishment of a new baseline for the operations, aimed at reaching as directly as possible the ultimate, high-performance, D-T fuel experiments that will demonstrate a high fusion power gain.

Thanks to all of these recent achievements, interest in fusion has increased enormously, industries and private investors have become part of the fusion effort. At the same time, the perception of urgency for clean baseload electricity has grown, driven by the realization of the urgency to fight climate change, and by evolving social and economic conditions, including the dramatic war in Ukraine, which has made society eager to develop energy solutions that avoid too large a dependency on too few countries.

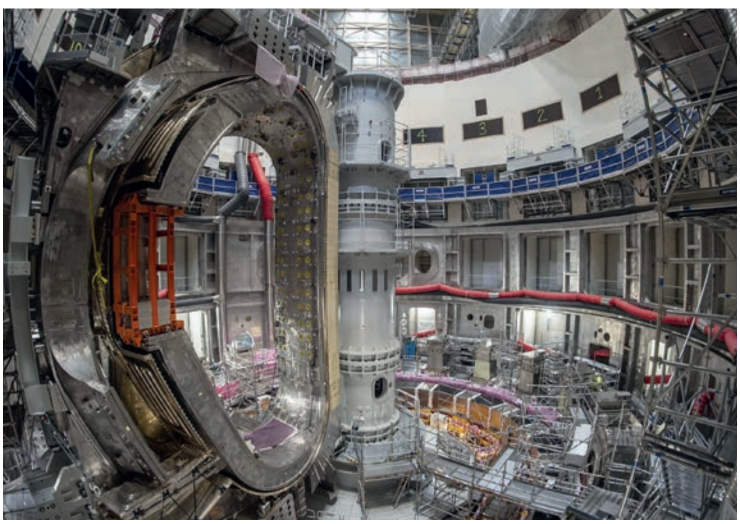
Sadly, 2022 was also marked by the passing of Bernard Bigot, Director General of ITER, who played a crucial role in advancing the construction of ITER, and was a true global beacon of fusion research, unanimously recognized by all the individuals and institutions involved in the quest for fusion energy across the planet. Our best wishes go to his successor, the new ITER Director General Pietro Barabaschi, whose engineering vision, wide knowledge and pragmatism will ensure a successful progress of the project.

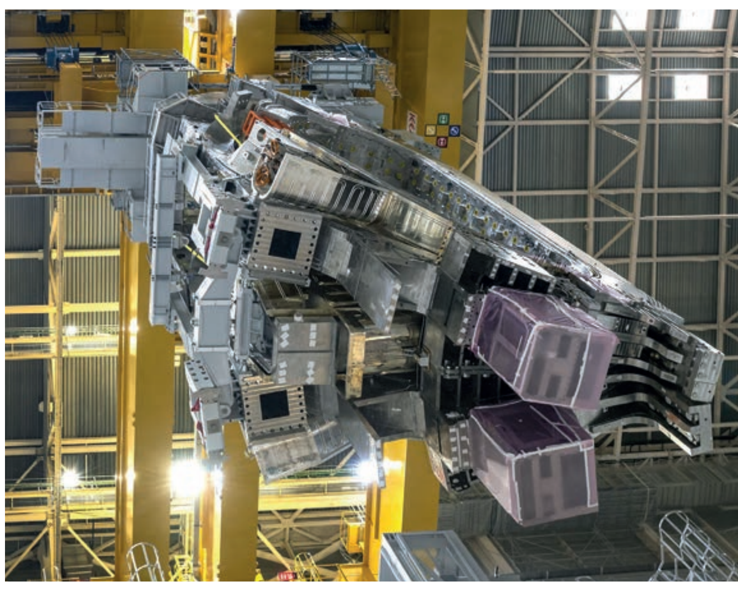
In 2022, the European fusion community realised that a new approach to the fusion Roadmap should be developed. In order to maintain its leadership position and technological competitiveness and to ensure that fusion energy becomes a reality, in spite of ITER delays, the current European fusion effort should be strengthened. The present Roadmap is being revised, as, while containing the main elements of a reactor-oriented program and the links between them, it is based on a sequential approach from the JET generation of experiments to ITER and then the demonstration power plant, and on assumptions that are no longer valid.

Recognizing the need to proceed as rapidly as possible to the demonstration of commercial feasibility of fusion energy, the revised approach aims at accelerating the development of DEMO, the demonstration fusion plant. In addition to strengthening and focusing the whole program, the involvement of industries in Public-Private Partnerships is introduced, allowing for a more targeted and effective design and construction phase for DEMO, and the parallelisation of a number of activities between ITER and DEMO.

The role of EUROfusion will remain crucial, as a coordinating body of the European fusion program. In particular, basic research and exploration of new technologies on the way to fusion power plants, still crucially needed, will best be delivered by the research organizations, and the need for education and training of fusion experts will only increase.

Before the re-association of Switzerland to the European Research Framework Programs which hopefully will become possible in the near future, our Center continues to participate to EUROfusion as an associate partner of the German Max Planck Institute of Plasma Physics, whose openness we highly appreciate. Our Center can also contribute to the ITER activities via a cooperation agreement between EPFL and the European undertaking Fusion for Energy, which was signed in 2022, and which is generously supported by the Swiss State Secretariat for Research, Education and Innovation.

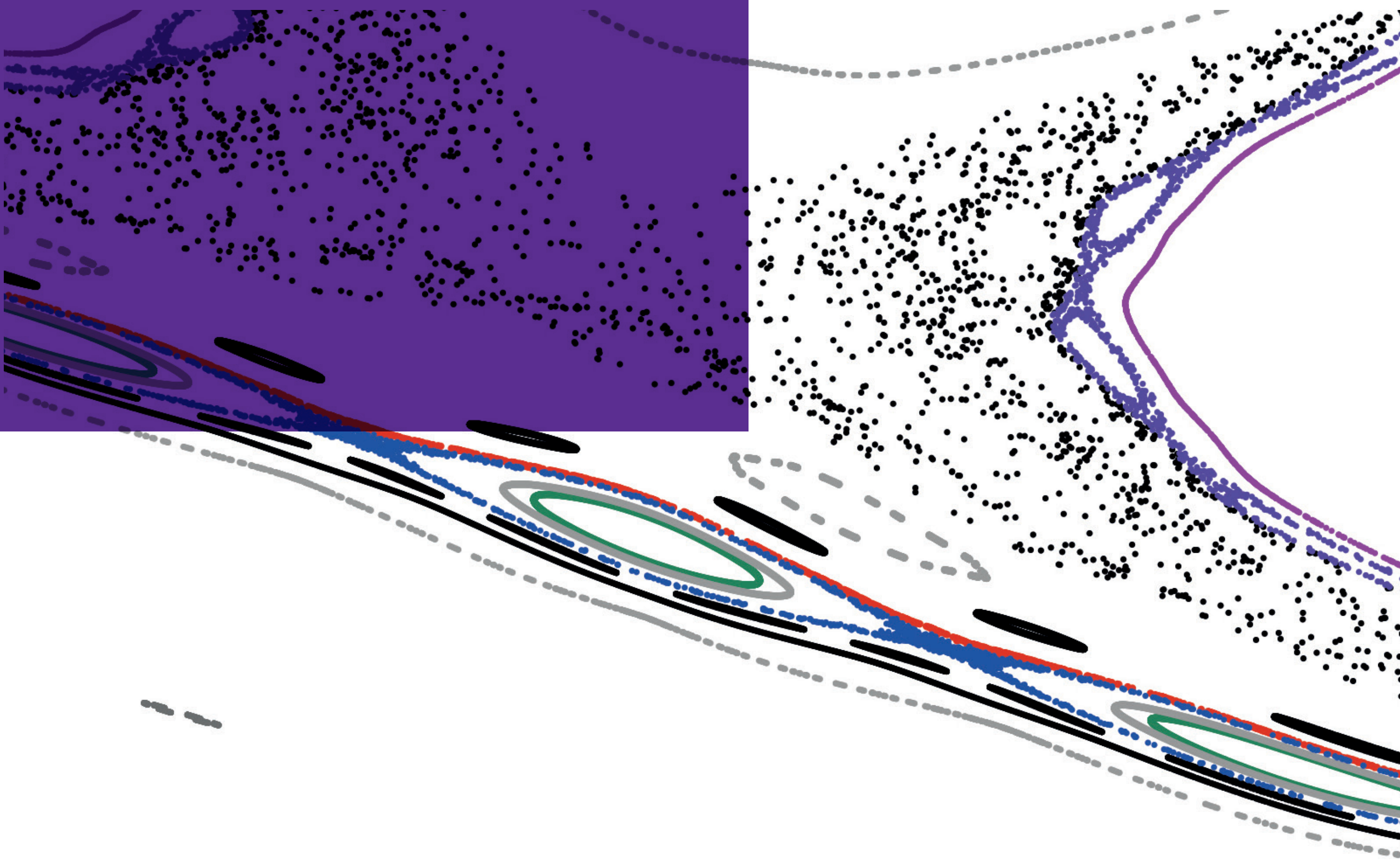




TEACHING

One of the most important missions of the Swiss Plasma Center consists in the education of future generations of plasma physicists in the fields of fusion science and various industrial applications. In the coming years they are the ones who will bring ITER to operation, design, build and operate DEMO, and ultimately bring fusion power to the grid, as well as developing cutting edge new applications of plasmas to various domains. All of these have the potential to contribute substantially to societal, environmental and economic developments.

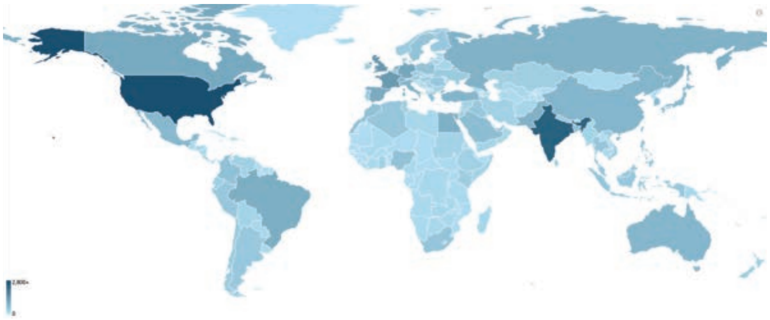
The SPC is fully embedded in the Faculty of Basic Sciences of the EPFL, which includes the Institute of Physics for its Research leg and the Section of Physics for its teaching leg, as well as the Doctoral School of Physics. This anchoring in the academic fabric is an essential and hugely beneficial factor for the fulfilment of SPC role in education.



At the end of 2022 the SPC had 52 PhD students enrolled in the Doctoral School of EPFL and 31 Post-Doctoral researchers. In 2022, Filippo Bagnato, Vincenzo D'Auria, Ortensia Dicuonzo, Maurizio Giacomin, Eduardo Lascas Neto and Alexandra Waskow obtained their PhD for their work carried out at SPC.

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

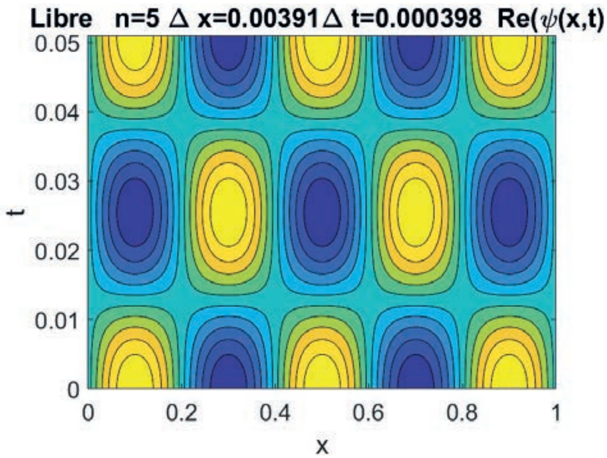
The SPC is giving a Massive Open Online Course (MOOC) on Plasma Physics Introduction and Applications. This course also includes lectures on plasma medicine, superconductivity for fusion and laser-plasma interaction, together with experts from Sorbonne University in Paris and Ecole Polytechnique in Palaiseau. The SPC MOOC on plasma physics is highly successful, with 15,564 subscribed learners in 2022 from around the globe, see **figure**.

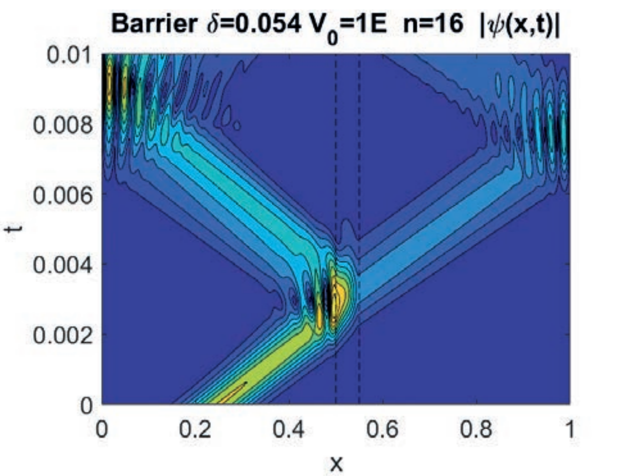


In addition to plasma physics courses, SPC staff is teaching several classes in general physics, advanced physics, computational physics and mathematical methods for physics. In total, but excluding the MOOC, SPC staff taught a total of more than 1000 hours to an average number of students per class above 100.

The high quality of the teaching by SPC staff is regularly appreciated and acknowledged: after the "Polysphère d'Or" awarded in 2021 to Prof. Paolo Ricci, in 2022 it was the turn of Prof. **LAURENT VILLARD** to be awarded the "Craie d'Or", as the Best Teacher of Physics at EPFL.

17	Number of courses given by SPC staff at Bachelor, Master and Doctoral levels in 2022
131	Average number of students in the classes of these courses
1,078	Number of hours taught by SPC staff in these classes in 2022
140,714	Number of student-hours taught by SPC staff in these classes in 2022
15,564	Number of subscribed learners in the MOOCs on Plasma Physics of SPC
52	Number of PhD students at SPC by the end of 2022
31	Number of Post-Docs at SPC by the end of 2022
54	Number of Master students supervised at SPC for semester and thesis projects in 2022

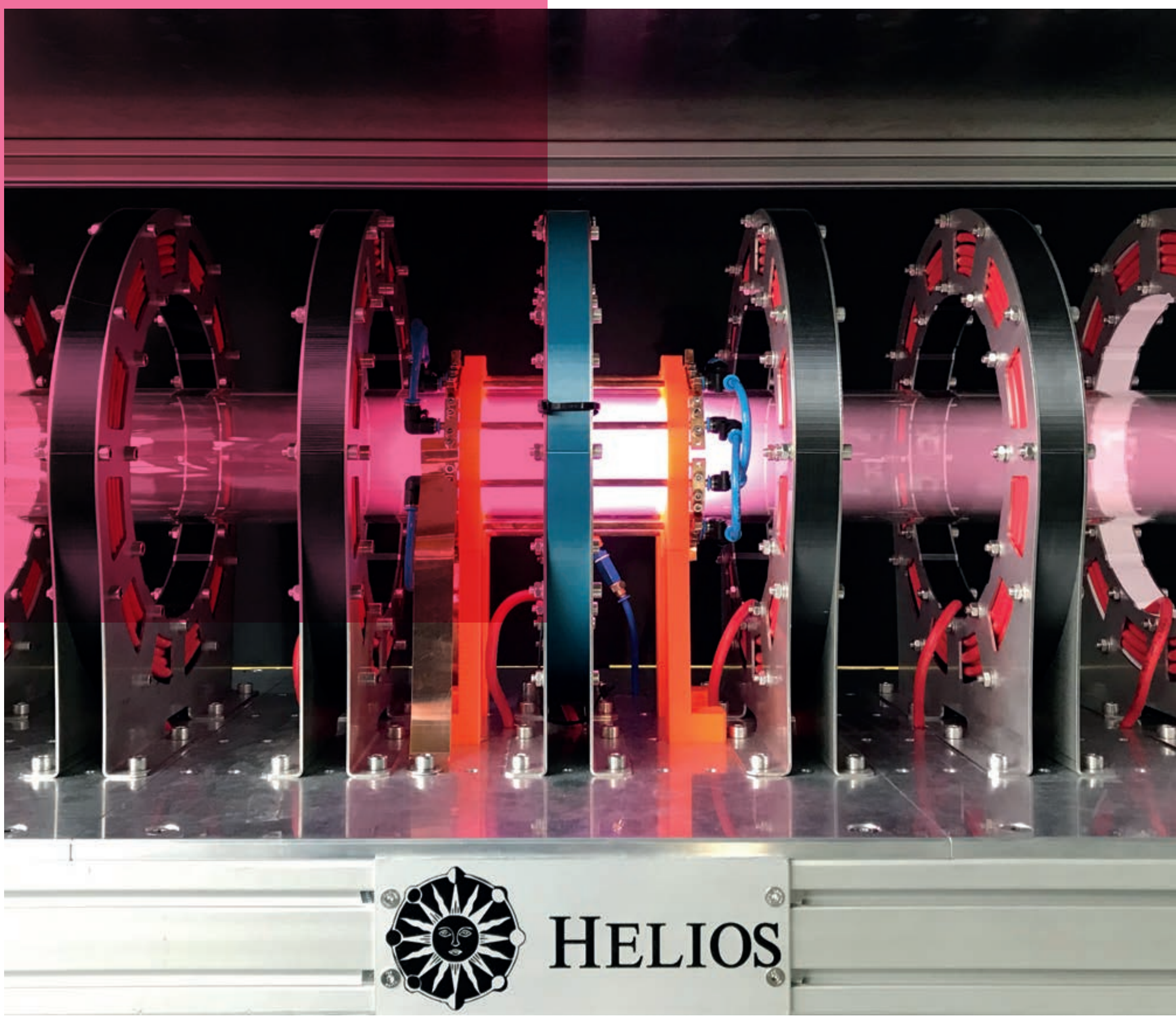




OUTREACH

The Swiss Plasma Center recognizes the importance of outreach activities and conducts a variety of initiatives, encompassing visits of the Center, contributions to a wide range of media, conferences given on-site or outside, as well as the publication of printed or electronic documents for the general public. The salient point of 2022 was the construction, by Bachelor students, of a plasma demonstrator called Helios, which is now currently used in our outreach activities.

Helios, the new plasma demonstrator.

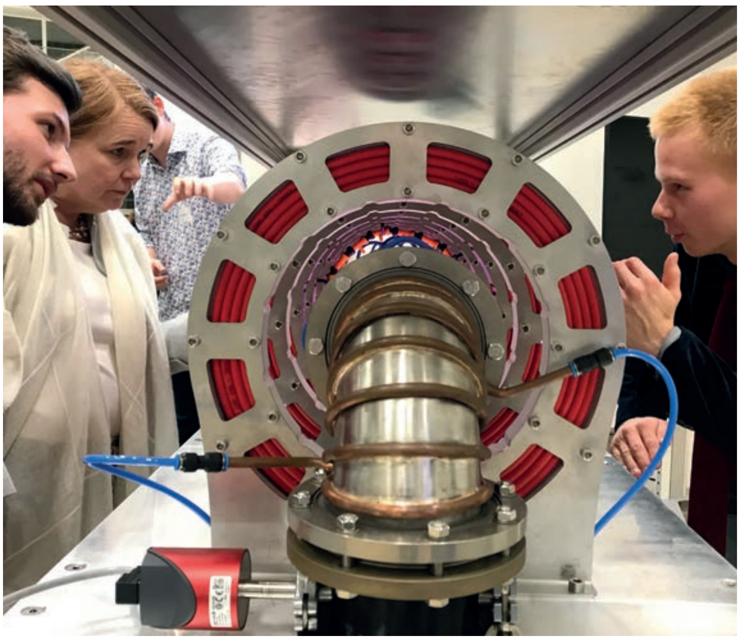


Our main outreach activity continues to be the visits of the SPC. After being prohibited during the first two months of 2022, the visits restarted slowly, at first with groups of EPFL students led by SPC teachers, then followed by small local groups. It only returned back to normal in May when groups from foreign countries, such as High-Schools from UK, came again. Therefore, the total number of visitors, 2360, is still lower than the pre-pandemic value.

Visits are enhanced a by a plasma demonstrator called Helios. The device consists in a linear evacuated glass tube, surrounded by magnetic coils. It is equipped with a microleak valve to establish a small Neon gas flow in the tube. A Helicon wave antenna located at the middle of the device generates a plasma in the tube, mainly at the antenna position. The switching on of the longitudinal magnetic field makes the plasma expanding along the tube.

Helios was also presented during the Scientastic festival, which took place in November and was all about the light. To coincide even more closely to the theme, Helios was equipped with a second gas injection line, which made possible to change from Neon to Argon and vice-versa without plasma interruption. It was a great success with the public.

In addition, large touchscreens were set up to improve the public experience. They offered visitors the opportunity to discover the fusion, to visit virtually the different experimental halls of the SPC, to visit the web sites of other fusion labs, and a few other activities.



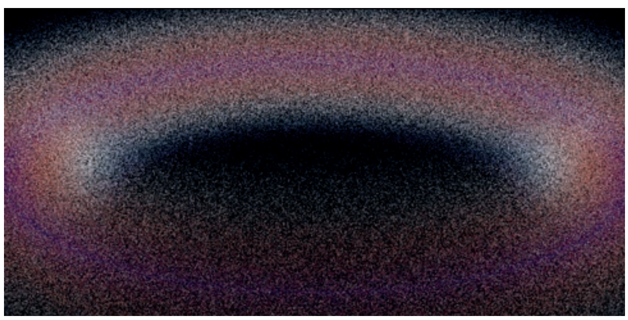
Inauguration of Helios at the closing ceremony of 'Summer-in-the-lab'.

Year 2022 was also marked by the presence at the SPC of an artist, David Simon, for an artist-in-residence internship of a duration of three months. He discovered the activities of the TCV physicists and learned how the TCV multiple plasma shapes can be programmed, produced and reconstructed from raw magnetic data. He then created images and videos art work essentially featuring 3D views of particles or turbulence evolving in toroidal plasmas.

The announcement, in December, of the record-breaking results obtained at NIF triggered a huge media interest in fusion energy. TV and radio journalists asked SPC directorate members to come and explain the importance of these results. Several newspapers reporters also called to cover the event.

Eventually, SPC hosted the annual meeting of the European Network of communicators in Fusion, FuseCom. On the fusion conference front, it's worth mentioning the TED talk given by Ambrogio Fasoli and the EPFL Curiosity video featuring Yves Martin, in addition to several presentations performed in the frame of TecDays, Fusenet Teacher Day, Forum Horizon, etc. And about fifteen High School students dedicated their *Travail de Maturité* (an in-depth work) to fusion and included interviews of SPC physicists.

Artist David Simon discussing next to TCV.



A representation of a TCV plasma by David Simon.

SERVICES AND ADMINISTRATION

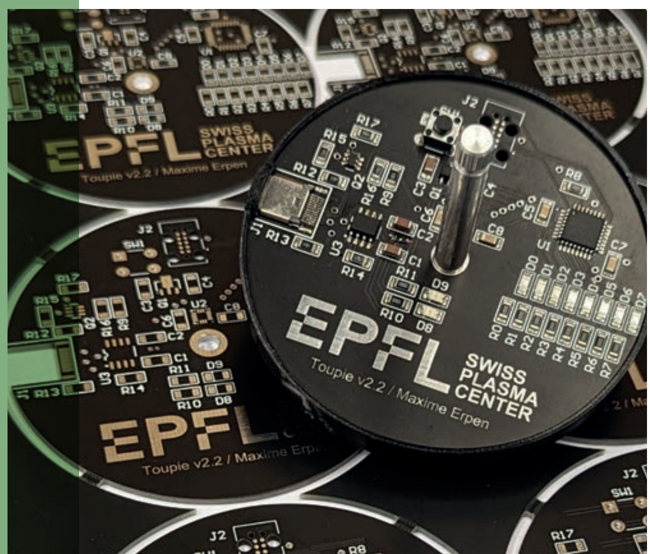
The Swiss Plasma Center could not have reached its objectives without a strong technical and administrative support. All services are continuously solicited to provide the physicists with support of various kinds and are requiring a broad range of competences.

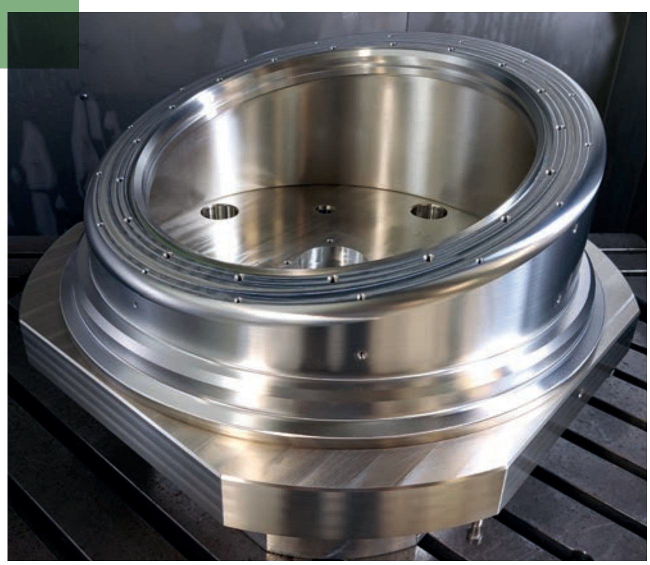
Dr Yves Martin

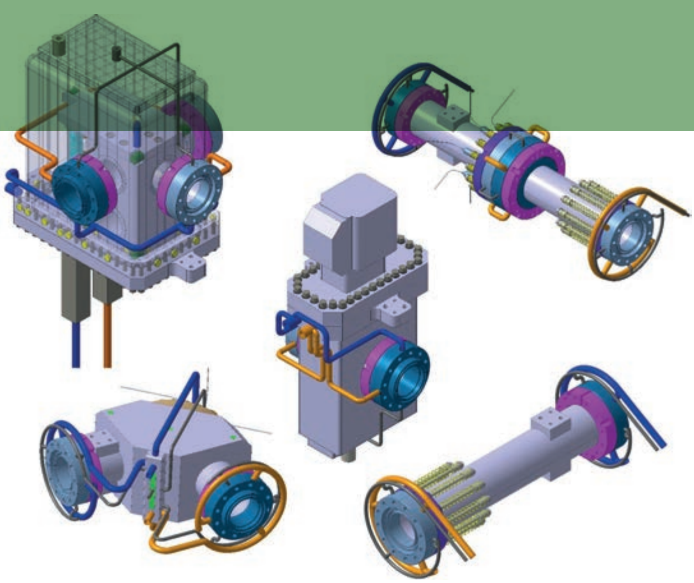
CAO COMM' & HEAD OF SERVICES

Dr Christian Schlatter

CFO







Matthieu Toussaint

MECHANICS CONSTRUCTION OFFICE AND WORKSHOP

Frédéric Dolizy

VACUUM TECHNICS

Damien Fasel

ELECTRICAL HIGH POWER INSTALLATIONS

Pascal Lutz

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.

A large fraction of the services activities is devoted to the TCV tokamak and, to a lesser extent, to the basic plasma experiments and gyrotron test stand. TCV was open twice in 2022, first to install the sets of long baffles in June and second to remove them in August. The openings also gave us the opportunity to work in the NBH beam ducts, on the ECH launchers and on several diagnostics such as Langmuir probes, Gas Puff Imaging and Fast Ion Loss Detector. In parallel, some preparatory work for the installation of an improved neutron protection wall and for the revision of the motor generator was performed.

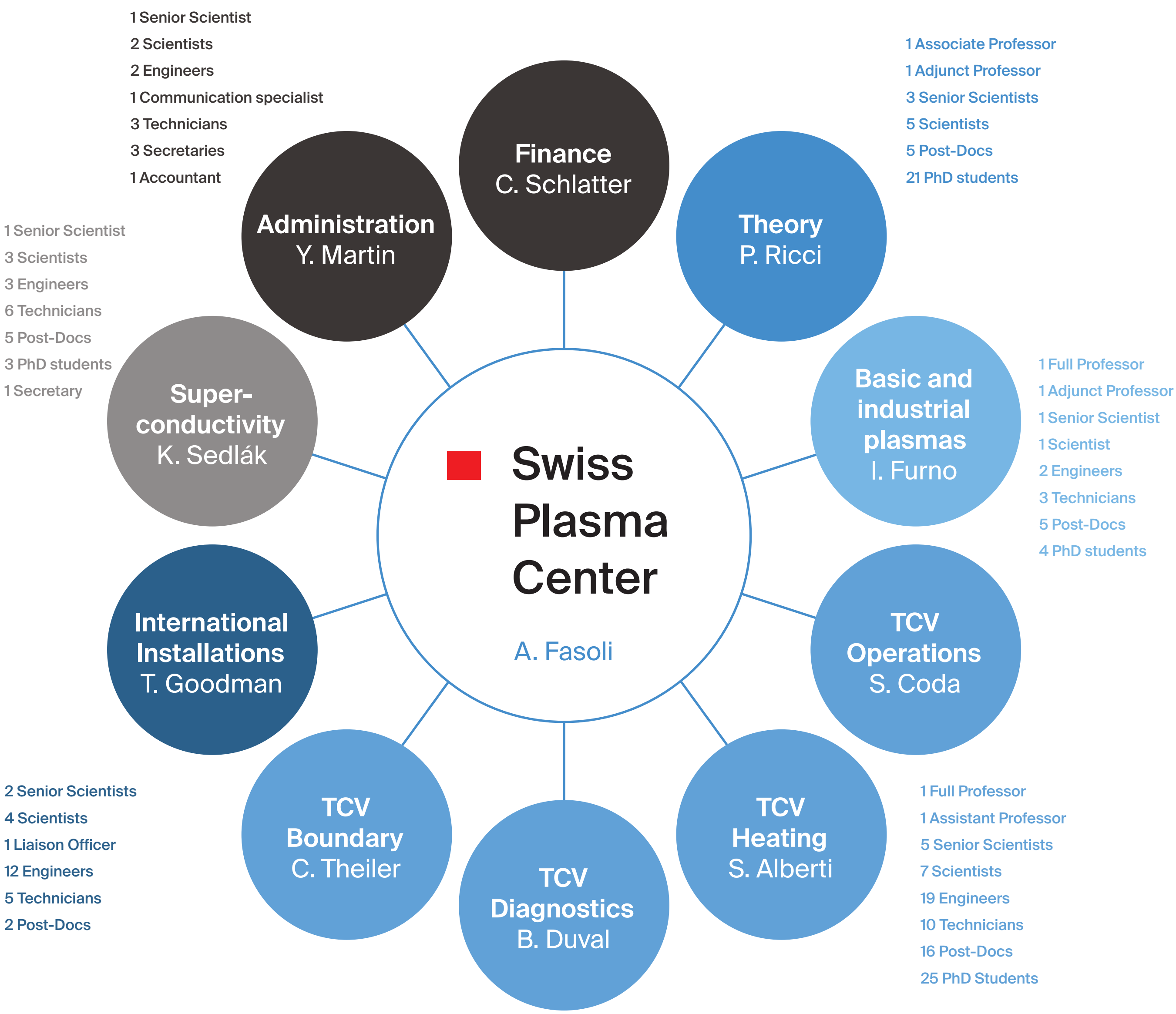
Services also contributed to the basic plasma physics experiments TORPEX and RAID. They manufactured, prepared and installed plasma sources and diagnostics on these devices. In particular, they strongly committed to the construction of Helios, the plasma demonstrator for outreach and scientific purposes and, in this context, closely coached the bachelor students involved in the project, in a very fruitful collaboration with the senior scientists.

PEOPLE, FACTS AND FIGURES

HUMAN RESOURCES

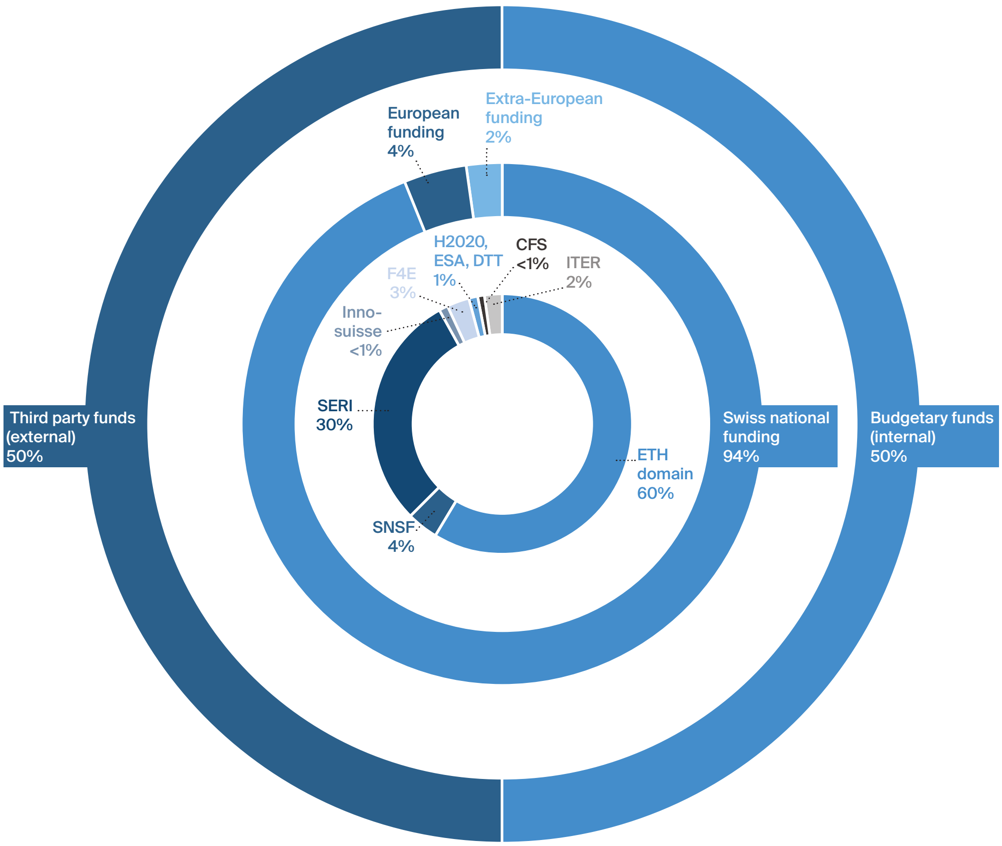
184	Total headcount
180	Full-time Equivalents
53	PhD students (FTE)
31	Post-Docs (FTE)
39	Collaborators joined SPC in 2022
17	Collaborators left SPC in 2022

STRUCTURE

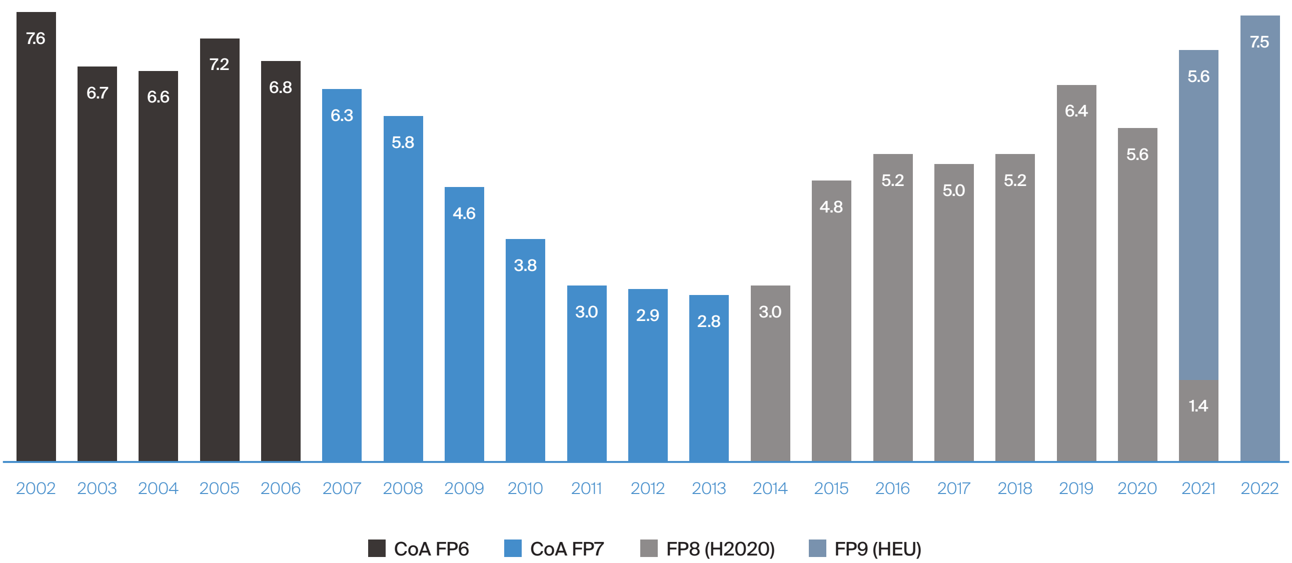


FUNDING 2022

including indirect costs



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



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