EPFL

SWISS PLASMA CENTER

ANNUAL REPORT 2023

Swiss
Plasma
Center

Table of contents

Letter of the Director

This special year for fusion worldwide was also a special year for our Center. We have continued in our growth – in size, diversity and impact, both on research and development, in fusion and other plasma applications, and education.

Greatly impactful results have been achieved across all our research lines. These include new approaches to tokamak magnets that operate with higher currents and integrate low and high-temperature superconductors, how to sterilize objects and environments by eliminating bacteria using atmospheric pressure plasmas, and how to produce uniform high-density plasma for novel acceleration methods for high energy particle physics. We continue to make crucial validations for microwave systems for all major fusion devices in the world, conduct state-of-the-art plasma simulations in both the core and edge of current and future tokamaks and stellarators, bringing new advanced computing and artificial intelligence expertise in, and carry out extended extensive experimental campaigns addressing key tokamak physics questions for core and edge plasmas, and their control, for ITER and DEMO.

Despite the, hopefully temporary, exclusion from Euratom and the European research area, the cooperation agreement between EPFL and Fusion for Energy, generously supported by the SERI, allows us to conduct activities for ITER in a number of crucial areas, including mm-Wave Physics and Technology, Plasma Control System Simulator Platform, Boundary Modelling for ITER, and several other tokamak physics chapters conducted on the TCV Tokamak for the needs of ITER.

Concerning our major experimental asset, the TCV tokamak, we can cite the EUROFusion Facilities Review report: «TCV's value to the EUROfusion and world's fusion programmes is high in proportion to its relatively inexpensive cost of operation. It has important roles in workforce development and international collaboration, where it continues to develop original techniques and configurations that can be further developed at larger facilities ». The importance of TCV contributions to the European program is also testified by the fact that EUROfusion share of TCV operational time has increased to more than 40% for the period ’21-’25.

In 2023, TCV campaigns started in the summer at full speed, after completing a refurbishment operation, mainly to install the new neutron screening, conduct various repairs and the periodic revision of the flywheel generator. The operation of TCV was adapted to limit energy consumption, an important optimization in view of the possible shortage of energy supply, potential consequence of a combination of factors, from the drought in the Alps to the unavailability of French nuclear power stations due to refurbishments, and, naturally, the war in Ukraine.

The neutron screening project was very successfully completed in August 2023. The goal was to be able to operate the device at its full performance, without any limitation of access to the areas where the personnel operate, avoiding that any member of our staff would need to become radiation worker, and adopting the ALARA approach, i.e. As Low As Reasonably Achievable level of radiation. This goal has been reached and even exceeded: all TCV areas are open to the public and safe during operation, even in the worst-case scenario.

The initiative launched in 2022 to further modernize our infrastructure, named Swiss Fusion Hub, has passed several selection steps at national level. The ETH Board has finally decided to allocate the full budget (12.5MCHF) to it, despite having halted other new Joint Initiatives, reduced or delayed some other infrastructure investments. The Swiss Fusion Hub is now fully integrated in the 2025-2028 Swiss Roadmap for Research Infrastructures. The only remaining step before starting the projects is the final approval by the Parliament, to be obtained by the end of 2024.

This initiative includes a series of upgrades to the TCV tokamak, featuring improved diagnostics and real-time control apparatus, a new divertor structure, and additional microwave heating, as well as enhancements to the superconductors’ test facility with the new high-field EDIPO2 coil. These advancements will extend the impact of our research for decades to come.

The education activities of our Center continue to strive, both with highly appreciated ex-cathedra courses at all levels, to the success of which many members of our team contribute, and with laboratory projects, master and PhD theses, and internships. Our participation to the newly launched Summer in the Lab, just to name one initiative, which led to the construction of a very visible plasma demonstration device, was highly appreciated by the whole EPFL community.

Following internal discussions on our everyday life at the Center, a few working groups are evaluating how we can further progress towards a better degree of equity, diversity and inclusion, how to remove implicit biases in our actions, enhance cohesion, increase exchanges, and improve integration, external and internal communication and visibility, and, in general, quality of life and work-life balance. We will soon see the results of this community exercise.

In the fast-evolving international fusion scene, our Center will maintain and even reinforce its central position, as we are prepared to play an important role in the transition of the European program to the ITER operation phase, and to the DEMO developments, via R&D, education & training, and public-private partnerships.

As every year, I underline how our successes and our ever-increasing central position in fusion and plasma science R&D result from the commitment, competence, professionalism and cohesion of our entire staff - to whom I am deeply grateful. I also wish to acknowledge all our stake holders for their support, in particular 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

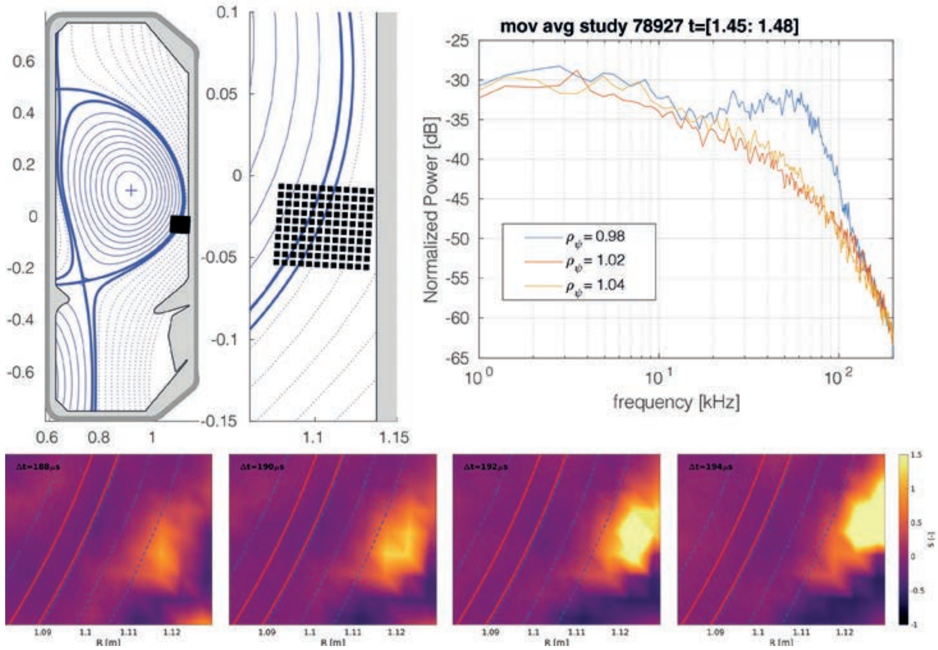
A large fraction of the year 2023 for TCV was devoted to major infrastructure development and large-scale maintenance. Plasma operation occupied the last third of the year, featuring two different sets of baffles, the so-called SILO (short-inner, long-outer) and SISO (short-inner, short-outer) versions. The campaign was shared between the domestic programme and the EUROfusion Work Programme on Tokamak Exploitation (WPTE) as in previous years, with a higher than usual WPTE share of 42%, and was predominantly geared towards exhaust issues (discussed in the TCV Boundary section) while still covering a broad palette of experimental themes. Research is performed in support of ITER as well as looking at alternatives for a fusion power plant, and much of it involves students, both graduate and undergraduate. Highlights are presented below by Dr STEFANO CODA, who supervises TCV operations and science.

TCV underwent a major infrastructure upgrade in 2023, which equipped it with considerable additional neutron and gamma-ray shielding to cope with its increased radiation generation due to the recent increases in neutral beam injection power capability. This was very successful, and the surrounding building now no longer suffers from any radiation-related occupancy limitations (see **highlight 1**). Two major maintenance tasks were undertaken in parallel with this work, which was performed between January and August. The first task addressed the severe degradation observed on a set of polyurethane pads used as shock absorbers on the metal supports of the eight outer poloidal-field coils. These pads were not meant to be replaceable, but the grade of polyurethane chosen at the start was such that it polymerized over time, thus becoming dangerously brittle. A wholesale replacement of all the pads was then performed, involving a near-total disassembly of all diagnostics and heating systems installed on the outer ports of the device. The second task was a planned maintenance of the flywheel motor generator, which required it to be transported to a factory testing site.

Given the short duration of the campaign, concentrated at the end of the year, most of the experimental work performed still requires significant analysis and the results are only preliminary.

The concern about so-called “runaway” electrons (RE) - particles accelerated to the speed of light - which can be a danger to the integrity of a future reactor, has continued to hold our attention. Previous promising results on the so-called “benign termination” strategy, involving recombining the companion plasma in the presence of a RE beam with significant quantities of hydrogen or deuterium gas, and on the ability of injected microwave power to safely expel the RE population, have been followed by more systematic parametric scans, to determine the range of conditions under which these strategies can be effective. A key result of the 2023 experiments was the expulsion of the RE seed population prior to a disruption, resulting in the complete suppression of RE beam formation.

A broad effort is underway to develop “integrated” core-edge scenarios, i.e., discharges featuring good core confinement as well as edge conditions conducive to acceptable first-wall power loads from energy and particle exhaust. Much of the work in 2023 was aimed at establishing the basic scenarios to prepare for further extensive studies in 2024. In the process, the exact



1 Example of measurements of plasma turbulence with the midplane Gas-Puff Imaging system for a QCE plasma. With a 10x12 matrix of measurement points (top left), the 2D plasma turbulence can be tracked both in the confined plasma and also in the SOL (top right).

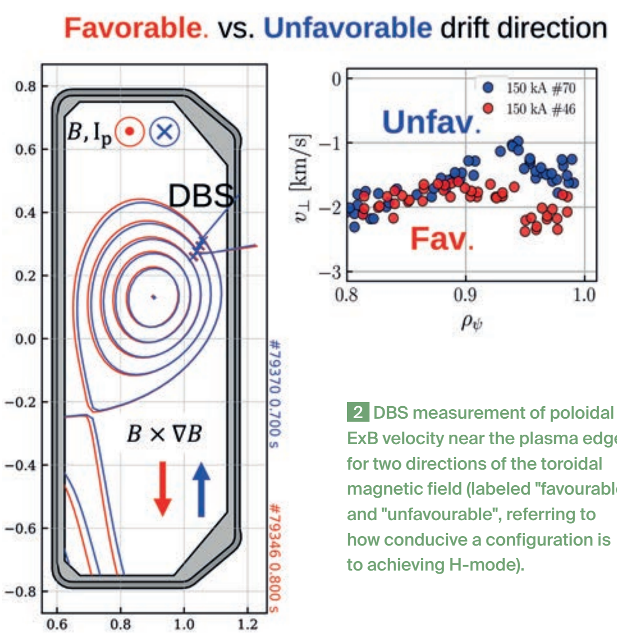
plasma shape expected in ITER has been reached and strategies for H-mode exit during the plasma current ramp-down have been successfully tested, guided by modeling. Development of an H-mode scenario with the second, high-energy (up to 55 keV) neutral-beam injector (NBI) was initiated and will continue in 2024. The crucial lower-density, low-collisionality regime was also obtained reliably with a combination of heating sources involving NBI as well as both 2nd- and 3rd-harmonic electron-cyclotron resonance heating (ECRH), including scans of the gas fueling rate to determine the optimum operational range. Varying the NBI-ECRH mix also resulted in a scan of the ion-to-electron-temperature ratio, while a painstaking tuning of the mix between the two, counter-propagating neutral beams produced a case with vanishing plasma angular momentum which enabled a first-ever measurement of intrinsic torque.

In parallel, the specific concern raised by Edge Localised Modes (ELMs), bursty instabilities that present an extreme danger to ITER's first wall, was addressed through the investigation of regimes that naturally feature small ELMs or no ELMs at all. The former avenue focused on the so-called Quasi-Continuous Exhaust (QCE) scenario, which is now firmly established and has been accompanied by a good set of edge turbulence measurements to help characterize its physics underpinnings. An example of turbulence measurements with gas-puff imaging (GPI) is shown in Figure 1. For the QCE regime, broadband turbulence is measured just inside the LCFS as illustrated by the (blue) spectrum. It is hypothesized that this turbulence is large enough to prevent steep gradients to form in the immediate vicinity of the separatrix such that ELMs cannot be destabilized.

The no-ELM avenue reprised the well-established negative-triangularity, intrinsically L-mode regime with enhanced confinement, with particular emphasis on the exhaust properties and on the dependence of the maximum stable density on the input power. These scenarios are also poised for extensive parameter scans and physics studies in 2024.

A Doppler Back-Scattering (DBS) apparatus was installed temporarily on TCV for this campaign and the next one by collaborators from the Laboratoire de Physique des Plasmas in Palaiseau, France, with the aim of studying plasma flow and turbulence near the plasma boundary. Initial measurements were performed in diverted plasmas, studying in particular the role of the magnetic topology by reversing the magnetic-field direction (see Figure 2) and/or the boundary locations where the poloidal field vanishes (so-called X-points).

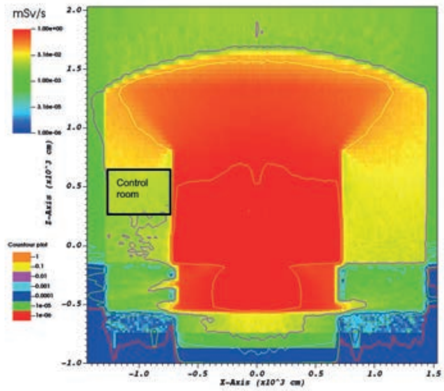
TCV's Short-Pulse Reflectometer was also employed in this and other studies, in particular to study the properties of turbulence, an effort spurred by fundamental analytical and numerical work to quantify the properties and capabilities of this novel diagnostic (highlight 2).

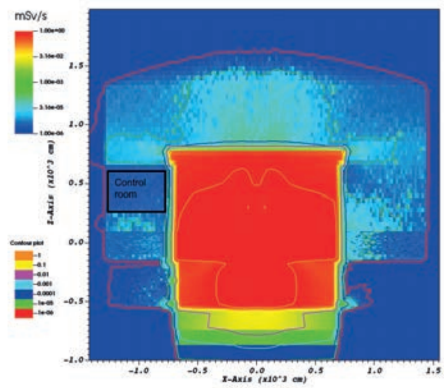


2 DBS measurement of poloidal ExB velocity near the plasma edge for two directions of the toroidal magnetic field (labeled "favourable" and "unfavourable", referring to how conducive a configuration is to achieving H-mode).

The physics of suprathermal ions generated by NBI has been investigated with a growing set of diagnostics, with particular emphasis on the effect of negative triangularity, which indeed appears to improve the confinement of fast ions as well as of the thermal ones. Another intriguing and novel result, this time in standard geometry and H-mode, has been the interplay of coherent modes observed between ELMs with fast-ion dynamics and transport - an interplay that ultimately seems to result in enhanced fast-ion losses.

Finally, improvements in real-time control are constantly sought, and this campaign was no exception, witnessing growing and successful integration of disparate developments such as a generalized shape controller, an optimized vertical-position controller, and a density-profile observer in view of advanced density control.





3 Monte Carlo simulations of neutron dose rate for a source of 4e13n/s, which is the maximum expected neutron rate when both NBH beams are used at full power, on a vertical cut of the TCV building without (**top**) and with (**bottom**) neutron screening, same color scale.

NEW POLYETHYLENE-BASED NEUTRON SCREENING FOR THE TORUS HALL

To study fast ion physics, TCV has been equipped with two-1MW neutral beam heating (NBH) systems that directly heat the plasma ions. Heating the ions enhances the D-D fusion reaction rate and hence increases the neutron production inside the reactor. Following the successful improvement of TCV performance with NBH, it became necessary to take measures to protect personnel from the increased radiation and thus significantly increase the shielding capability around the torus hall, which was carried out in a project led by Dr **PATRICK BLANCHARD**.

Due to weight constraints, concrete could not be used as extra shielding and alternatives were studied with a reliable MCNP (Monte Carlo N-Particle) model of the TCV tokamak and building developed in collaboration with JSI in Slovenia, see **Figure 3**. High Density Polyethylene (PE) was found to be the preferred solution both because of its high content of H atoms that capture the thermal neutrons and its low density of about 1 kg/l. Indeed, 20cm thick PE slab has a moderating power similar to 50cm of concrete for 8.7 times lower weight. Experimental tests were also carried out to better qualify and quantify the neutron attenuation coefficient and the thermomechanical properties of PE. We dimensioned the new screening to be able to perform 30 shots of 2s per day using both NBH injectors at maximum power without reaching the legal daily dose limit for the public.

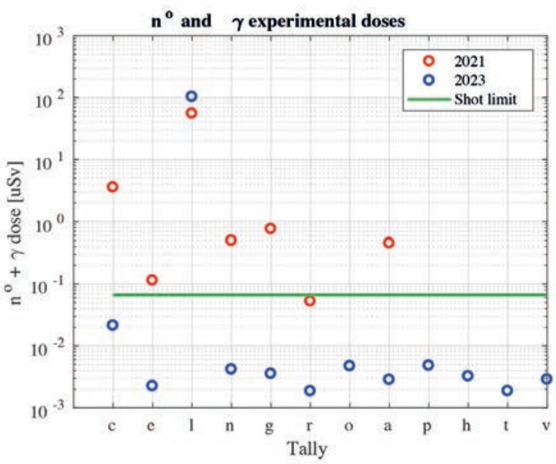
The new shielding installation started early 2023 and was completed within seven months. Technically, the new shielding consists of the following: recycled concrete blocks, 20cm thick PE slabs on the concrete walls, a 35cm thick PE dismountable roof, a concrete belt surrounding the roof and 35cm thick borated PE doors. In total more than 220 tons of PE have been installed. It is the first time that PE has been used for neutron attenuation on such a large scale.

In September 2023, a campaign of radiation dose measurements on 10 reference points within the TCV building has demonstrated that the new screening is a complete success. The experimental measurements are in line with the model predictions within a factor of 2 and neutron attenuation larger than 1000 has been measured in the TCV control room, see Figure H12.

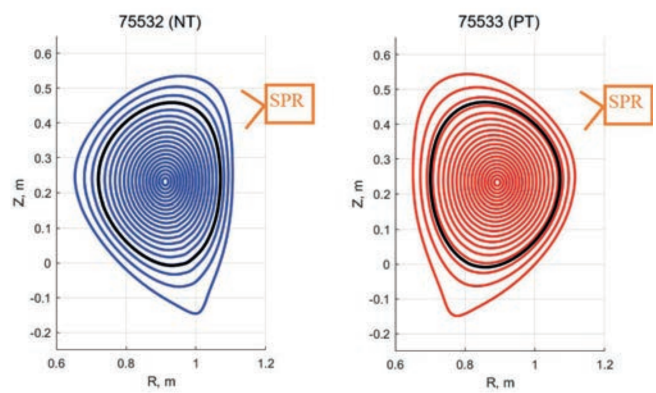
THEORY-EXPERIMENT COMPARISON WITH SYNTHETIC SHORT PULSE REFLECTOMETRY

One of the crucial components of magnetic confinement fusion research is the reconciliation of experimental results with theoretical expectations. This is particularly important when studying anomalous turbulent transport which limits energy confinement in the tokamak. Due to the complexity of the equations governing the plasma dynamics in experimentally relevant conditions, numerical modeling is typically used. Various codes are used to obtain a numerical representation of plasma turbulence, the properties of which are then compared to those inferred from the experimental measurements. However, this inference based on various turbulence diagnostics can itself be a theoretical problem. To make a direct comparison between experimental measurement and theory, the synthetic diagnostic approach can be utilized.

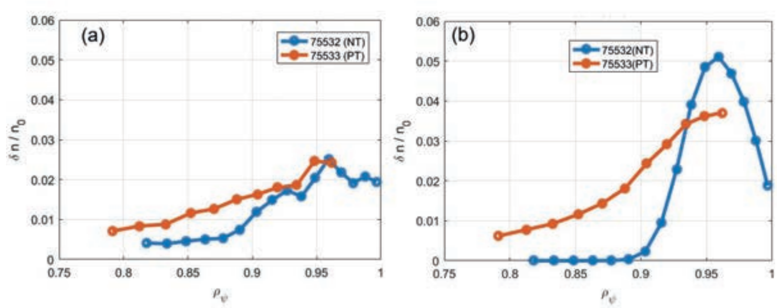
In 2023 such a synthetic diagnostic was developed for and applied to TCV Short Pulse Reflectometry (SPR). Previously, this unique concept offering an alternative to traditional continuous wave reflectometry was used to measure the electron density profile. Recently, under the lead of Dr **OLEG KRUTKIN** the connection between SPR measurements and turbulent electron-density fluctuations was established analytically. The new "fluctuation SPR" method was developed allowing one to obtain the turbulence amplitude and its radial correlation length in addition to the electron density profile. Furthermore, to validate theoretical results the synthetic SPR diagnostic was developed by combining the gyrokinetic plasma turbulence code GENE and the full-wave code CUWA. In addition to validating the fluctuation SPR method, it was utilized to interpret experimental turbulence measurements. In particular, the SPR data was acquired in TCV discharges 75532 and 75533 with shaped plasmas possessing negative (NT) and positive triangularity (PT) as shown in **figure 5**. The measurements suggested lower turbulence amplitude in the NT configuration (**figure 6a**) in agreement with previous research. The synthetic SPR diagnostic confirmed this difference (**figure 6b**) while revealing the complex wave scattering physics affecting the measurement. This result represents a step towards more advanced theoretical analysis in support of the TCV experiments, with further development of the synthetic SPR as well as other core turbulence diagnostics underway.



4 Gamma and neutron experimental doses for a reference shot with 1 MJ NBH1 injection without (red) and with (blue) the new screening at different positions within the TCV building (l = inside the torus hall, a = control room for instance). The green line indicates the project goal.



5 An illustration of magnetic surfaces corresponding to discharges 75532 (left) and 75533 (right) with NT and PT respectively.



6 The relative amplitude of the turbulence measured with SPR in experiment **(a)** and obtained based on the synthetic SPR in combination with experimental measurements **(b)**.

TCV Diagnostics

BASIL DUVAL

Has been involved with TCV diagnostics since operations commenced over 30 years ago and in charge of them for over 25 years. Amazed and heartened by the evolution of these very special systems, he fully expects this amazing progress to continue!

UMAR SHEIKH

Has designed, constructed and operated diagnostics on TCV for nearly 10 years. With a wide range of interests and strong practical skills, from 2024 he has taken up the challenge of corralling and improving TCV's diagnostic set into the future.

2023 remained, mainly, another operational year for TCV diagnostics. Several experimental PhD diagnostic-based projects reached their conclusion with a consequent reduction in diagnostic development leaving a strong emphasis on maintenance and repair. TCV is now planning another major divertor upgrade to start in 2025 where several existing diagnostic systems will be shadowed by larger tile assemblies on the TCV floor. Over recent years, a truly wide range of optical/spectroscopic views have become fundamental in describing TCV's divertor research. Together with fundamental diagnostics, such as Thomson Scattering with its extension into the divertor, all these systems will have to undergo strong modifications to remain pertinent in TCV's future. Legacy diagnostics, such as Thomson Scattering or the Far InfraRed interferometer remain continually solicited and the target of continuing upgrades such as the procuration of a 100Hz pulse repetition or a replacement by a solid-state detection system, respectively.

It is important to highlight that, whereas PhD projects often develop new diagnostics that work when in the hands of their progenitors, these systems often require at least as much effort more to make them reliable and/or automate them to the level where they can be regularly operated with TCV's limited personnel. This reality must then be further extended into diagnostic calibration (or self-calibration where possible) and automation in the data analysis chain following TCV discharges to keep the operational team scientifically informed during experiments.

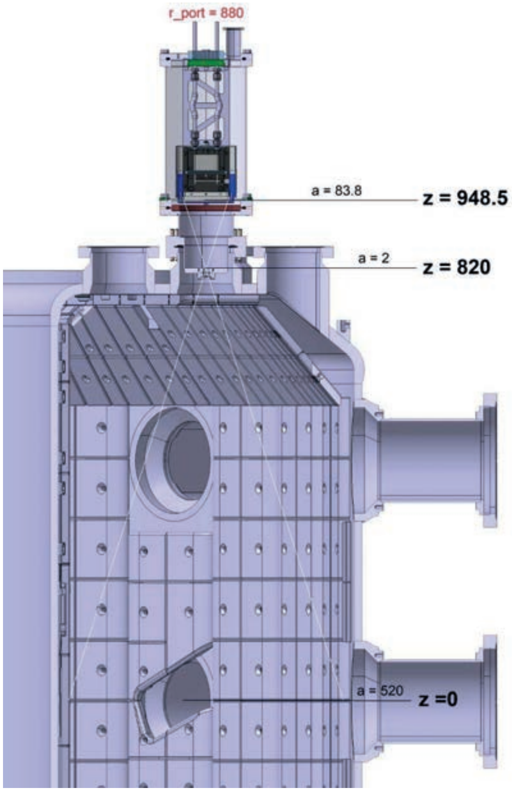
During 2023, several diagnostics have thus been revised. The whole X-ray, core physics, diagnostic array has been revisited following the successful installation of the multi-energy multi-chord Soft-X ray Pilatus camera (**Figure 1**). The Multi-Wire soft-X ray camera was rebuilt and re-installed on TCV (a legacy diagnostic much used before) and plans developed to build new versions with higher resolution and modern vacuum and electronics components. The Spectroscopic divertor systems have been enhanced with two new counter-tangential views giving access to toroidal rotation measurements across the divertor without requiring an absolute wavelength reference. This will be complemented by the implementation of Coherence Imaging on several of the Multi-Camera MANTIS system to provide 2D toroidal flow measurements across the TCV divertor simultaneously from several different ions of different charge states. Following the success of these MANTIS cameras on TCV, the SPC is planning to construct and deliver similar, optimised, systems to several European Laboratories with a view to extending TCV observations to machines with different ranges of parameters.

Turbulence sensitive diagnostics in the frequency range of ion scale micro-instabilities (both Ion Temperature Gradient and Trapped Electron Modes) continue to advance with great expectations over the coming years to link several reported plasma phenomena to the speculated effects of the core-relevant transport features.

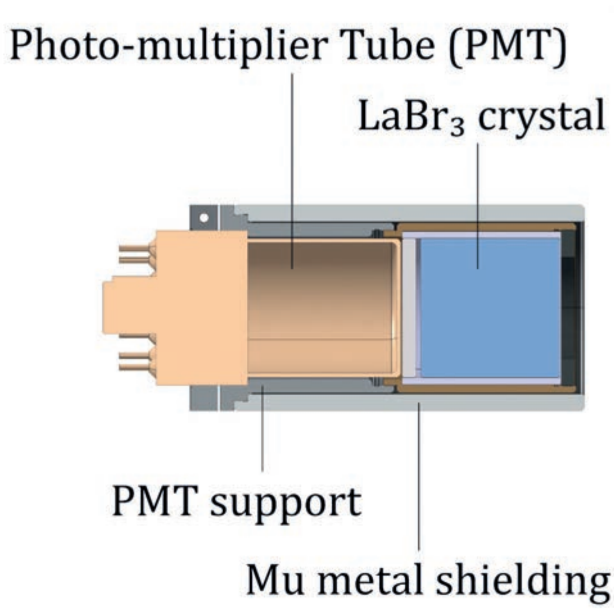
Runaway electrons in Tokamaks, the result of continual electron acceleration in the toroidal electric field with a diminishing toroidal friction with energy, remains a topic of extreme interest for reactor physics where they can form as destructive powerful beams. Runaway-rich scenarios have been developed at TCV and several experimental campaign results published where such beams are manipulated using TCV's control system and/or palliated by combinations of injected working gas (D) and/or heavier elements. Several unusual features of these Runaways have also been detailed and modelled. All these works depend strongly upon knowledge of the energy these Runaways can attain and their energetic distribution. Energies can exceed several 10s of MeV and present a strong diagnostic challenge.

These Runaways generate hard X-ray photons upon interaction with materials, in particular the thick TCV chamber's walls. Since such photon energies are not normally observed, these "hard" X-rays (whose maximum energy can approach that of the incoming Runaway) can be used to diagnose their interaction with TCV. A legacy system (PMTX) simply housed a photomultiplier in a closed soft-iron tube outside the TCV vessel such that only X-rays that traversed the TCV vessel and then interacted with the Photomultiplier generated a signal. This system remains extremely useful, as it is hard to saturate and can exploit the wide amplification gain range from the Photomultiplier arrangement. It can track the "approximate" temporal evolution of the hard X-ray flux but provides little information upon their energy.

To obtain information upon this energy distribution two approaches were implemented. On the hardware side, a Lanthanum Bromide crystal was procured (see **Figure 2**) and configured as an X-ray scintillator with a fast Photomultiplier amplifying the light pulses following hard X-ray interactions, for acquisition. This was accompanied by installing the GEANT4 code that models the interaction of the Runaway electrons and such photons with materials such as the scintillator itself or components of the TCV structure that generate the hard X-rays. Analysis of the resulting pulse-height-spectra immediately provides qualitative information upon the evolution and comparison of such "spectra" between experiments. To simplify the experiment and thus improve the modelling result, X-rays from TCV were collimated through a hole in TCV's 0.5m concrete wall such that the X-ray trajectories were better characterised. Peak photon energies up to several 10s of MeV were deduced from a pulse-height analysis with, probably, the majority of the diagnosed Runaway interactions at considerably lower energies.



1 CAD drawing of TCV with the Pilatus3 detector mounted on the top vertical port.



2 Lanthanum Bromide crystal (shown in blue) set inside an opaque metal housing where X-ray passage generates multiple photons.

TCV Heating

Plasmas in the TCV tokamak, in addition to the Ohmic heating caused by the electric current flowing in it, can be heated by two high power auxiliary heating systems, namely Electron Cyclotron Resonance Heating (ECRH) and Neutral Beam Injection (NBI). Dr JEAN-PHILIPPE HOGGE, Senior Scientist (MER), is the leader of the TCV Heating research line. The main achievements of the year 2023 are exposed below.

NEUTRAL BEAM INJECTION (NBI) SYSTEM

The functional capabilities of the TCV neutral beam heating system (low-energy 28 keV/1.3 MW NBI-1 and high-energy 53 keV/1.2 MW NBI-2) have been improved in 2023. The installation of a radiation shielding around TCV reduces the neutron and gamma doses outside the tokamak hall in the public area to a negligible level and permits up to 30 high performance TCV shots per day with injection of both heating beams at maximal power. Beam ducts in CuCrZr were installed on the two beams and equipped with new thermocouples for monitoring the duct temperature (see **Figure 1**). This allowed us to increase the maximal beam energy delivered in TCV per shot from 1.0/1.3 to 1.7/2.0 MJ without pollution of the plasma with impurities and without disruptions.

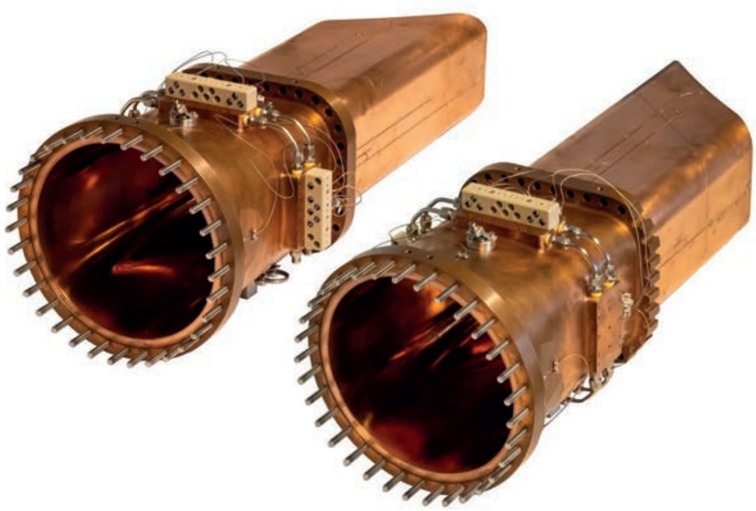
The NBIs integration in the TCV plant control has been updated to add the option for the physics operator ("physicien du jour") to program the NBIs energy and power based on reference traces. The heating beam can now be used in the absence of a dedicated beam operator in the control room, except in case of problem. The NBI operators prepare the system and perform tests on the calorimeter before handing over the control to the scientific team for the experimental sessions.

ELECTRON CYCLOTRON RESONANCE HEATING (ECRH) SYSTEM

The TCV ECRH system is composed of a set of microwave sources, the gyrotrons, transmission lines that bring the radiofrequency power to the entrance of the tokamak, and launchers with steerable mirrors inside the vacuum vessel that allow us to direct the beam power to a precise location in the plasma in a controllable way. The ECRH system is extremely versatile and can be used for a wide range of purposes, from heating to current drive to suppression and control of certain instabilities. In 2023 this range of applications was extended to the prevention of deleterious effects of runaway electrons after a disruption, see below.

The set of microwave sources, depicted in **Figure 2**, include two dual-frequency gyrotrons, G10 and G11 (126/84 GHz, 900 kW, 2s, Thales) that can be operated at both the second and the third harmonic of the electron cyclotron frequency, and two single-frequency gyrotrons, G1 (82.7 GHz, 700 kW, 2s) and G7 (118 GHz, 500 kW, 2s), operating at the second, respectively the third, harmonic.

In 2023, the set of G1, G10 and G11 gyrotrons has been fully available during the experimental campaigns from August to December. The G7 gyrotron was also available but was less demanded since it is connected to a lateral port.



1 Cooled CuCrZr beam ducts equipped with thermocouples.

2 Overview of the gyrotron platform, taken during the installation of the neutron radiation shield. The TCV tokamak hall is beyond the wall to the left.

From January to July, some important modifications of the transmission lines required by the installation of the neutron shielding cage around TCV were implemented. The transmission lines, the loads and the auxiliary systems (pumping systems, control racks, cablings) were dismantled to allow the installation of the shielding panels. The new transmission line routing also necessitated some core drillings on the TCV concrete wall.

The cooling systems were maintained or improved, with the installation of a dedicated cooling substation for G10 and G11 cryo-compressors. Finally, a careful study was performed in anticipation to the installation of a possible third (G12, now confirmed) and hypothetical fourth (G13) dual-frequency gyrotrons.

From the scientific point of view, an ECRH-related achievement that can be highlighted is the usage of central heating to trigger the expulsion of runaway electrons (RE) and prevent the formation of a runaway electron beam after a disruption triggered by a massive gas injection (MGI), through a mechanism that is still under investigation.

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 removing the helium produced by the fusion reactions and avoiding damage to the plasma facing 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 solutions for a reactor. Here are some notable achievements from 2023.

Ideally, one would like to have a cold plasma near the machine walls and reduced plasma-wall contact, thus essentially "detaching" the plasma from any material surfaces, while keeping good fusion core performance. It is unclear whether currently foreseen "conventional" boundary solutions will be adequate for this purpose. New ideas, such as alternative magnetic geometries of the boundary plasma, are therefore being explored.

In 2023, significant progress was achieved in the experimental assessment of the role of various features of divertor magnetic geometry to limit plasma-wall contact. Dedicated parameter scans were conducted and interpreted with reduced analytical models and our recent, 1D detachment code SPLEND1D. This showed that significant plasma flows along the magnetic field in the divertor can critically reduce the beneficial effect of total flux expansion (an effect leveraged in the so-called Super-X divertor). Collection and analysis of an extensive dataset of plasmas with varying divertor length confirmed previously observed benefits of long divertor "legs" for power exhaust. This also revealed, however, rather weak variations of the heat flux width with leg length, at least in attached conditions. More complex divertor geometries with additional X-points have furthermore shown strong wall heat flux reductions and significantly enhanced resilience against divertor re-attachment, a potentially critical property for a future reactor. Interpretive modelling of these plasmas has greatly progressed, **Figure 1**.

These low-power studies have been extended to discharges with 2MW of electron cyclotron heating, in low-collisionality conditions and still remaining in low-confinement mode. This new plasma scenario turned out to be the only one to date on TCV that cannot be detached using nitrogen or neon injection, neither in a conventional nor in an alternative divertor geometry. As such, it constitutes an interesting test case for modelling and for the assessment of tightly-baffled, long-legged divertors as part of the planned next TCV divertor upgrade.

Intense research was also dedicated to improved confinement regimes with naturally suppressed ELM instabilities. The compatibility of negative triangularity plasma shaping, beneficial for confinement, with an adequate boundary solution was explored experimentally and numerically, see the highlight on the next page. Another interesting scenario, the ELM-suppressed X-Point Radiator regime in Snowflake H-mode, was further established as a reliable scenario in 2023. It was achieved with and without baffles and the access conditions for this scenario were assessed and compared to the leading theoretical XPR model.

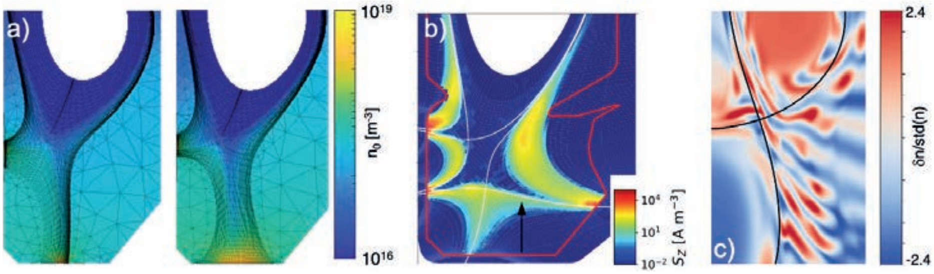
The previous TCV divertor baffle upgrade saw its in-offical completion in 2023 with a plenary talk on the subject at the EPS conference in Bordeaux, presented by Dr Holger Reimerdes. These baffles are now a standard element of TCV. A strongly baffled configuration was used in 2023 to further explore the role and accuracy of available molecular cross-sections by comparing detachment in a deuterium plasma with detachment in hydrogen. Systematic comparisons of the divertor closure are being used to test the new full grid version of the SOLPS-ITER code in collaboration with ITER via an F4E-EPFL agreement.

Significant progress was also achieved in 2023 in terms of turbulence studies. The properties and dynamics of turbulent structures in the boundary plasma and dependencies on plasma parameters and regimes were elucidated, see **Figure 2**. The simulation of such plasmas with the first-principle turbulence code GBS also progressed, scanning plasma current, flux expansion, leg length, and comparing single- vs double-null configurations. To validate these, Gas Puff Imaging turbulence measurements in combination with a sophisticated synthetic diagnostic were employed. This revealed qualitatively good agreement overall and provided critical information for further model improvements in the future.

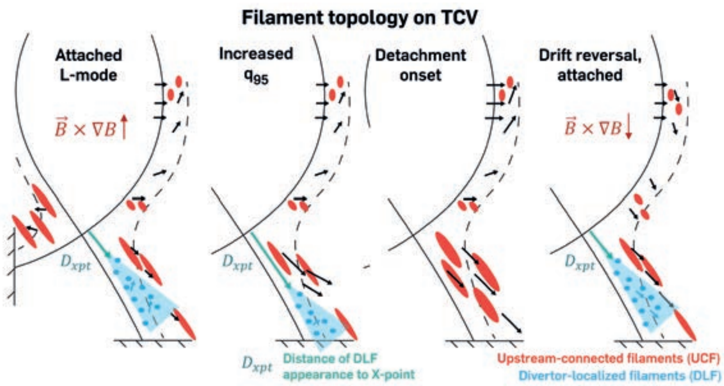
DETACHMENT OF NEGATIVE TRIANGULARITY PLASMAS

Negative triangularity (NT) configurations are a potential candidate for future fusion reactors, as NT plasmas exhibit core confinement that is comparable to Positive Triangularity (PT) H-mode plasmas, while keeping L-mode-like edge profiles and exhaust properties. However, achieving divertor detachment in NT configurations is more challenging than the equivalent in PT, as evidenced in 2022 by core density ramp experiments on TCV.

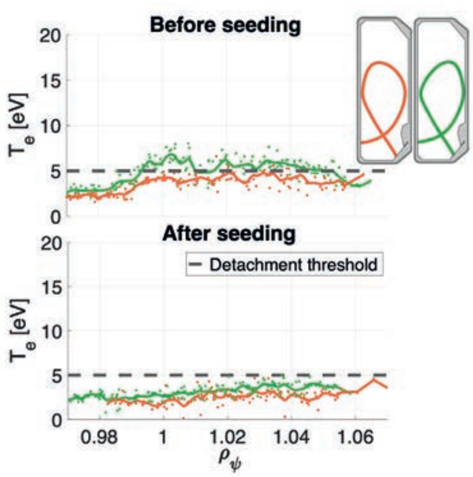
In the framework of her PhD thesis, **GARANCE DURR-LEGOUPIL-NICOUD** further studies the achievement of detachment in NT plasmas. Her experiments on TCV have shown that the previously observed difficulty in reaching detachment can be partly overcome by increasing the divertor closure with the TCV divertor baffles. At high divertor closure, NT plasmas reach an early stage of detachment, as shown by the stronger movement of the C-III emission front in **Figure 3**, a marker of low temperature along the leg of the plasma. Extending NT detachment studies to nitrogen impurity seeding, Garance also showed that detachment is compatible with NT in this more reactor-relevant approach to detachment, with a similar impact on core confinement as for its PT counterpart.

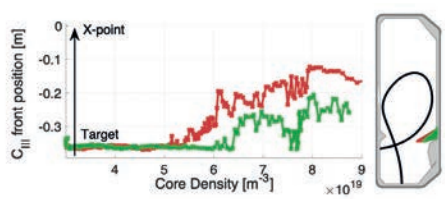


1 Examples showing the significant progress in 2023 in interpretive and predictive modelling of the TCV divertor plasma, with a) a flux expansion scan with SOLPS-ITER, b) an EMC3-EIRENE simulation of a baffled Snowflake, and c) a snapshot of a long-leg configuration with GBS.



2 Cartoon of the nature and dynamics of turbulent structures in the TCV boundary plasma identified with turbulence measurements across parameter scans in plasma current, density, and field direction.





3 Progress in achieving divertor detachment in negative triangularity plasmas with nitrogen impurity seeding (left) and with enhanced divertor closure (right).

Theory and Numerical Simulation

In order to interpret the experimental results from current devices and make predictions for ITER and DEMO, the theory group, led by Prof. **PAOLO RICCI**, advances the first-principle understanding of fusion plasmas. The theory group heavily relies on numerical simulations and makes use of advanced high-performance computing platforms, including Piz-Daint at the Swiss Supercomputing Center (CSCS) and Marconi at CINECA, and it is successful in obtaining computational resources through the most competitive European calls. Within the effort to optimise the performance of simulation codes, the theory group leads one of the EUROfusion Advanced Computing Hubs, that involves the SCITAS (Scientific IT & Application Support) Group, the Laboratory for Experimental Museology (eM+), the Swiss Data Science Center (SDSC), and the Applied Mathematics Group of EPFL.

INTERACTION OF MHD MODES AND FAST PARTICLES

A new kinetic-MHD code, VENUS-KMHD, is being developed for the application of MHD instabilities with energetic particle species that are almost collisionless over the timescales of the instabilities concerned. A novel approach enables the exact capture of wave-particles energy transfer over the full phase space of the energetic ion distributions. Excellent agreement has been obtained with exact analytic solutions for special plasma geometries. This work complements the continuing development of resistive MHD codes, both linear and non-linear, which are being used to investigate the fundamental properties of reconnection in pressure driven tokamak instabilities, and their saturated states, as well as the investigation of heavy ion impurity transport.

STELLARATOR THEORY

We have carried out the first single-stage optimization of stellarator coils to remove islands at finite pressure by combining the SIMSOPT and SPEC codes in an innovative way. This sets the stage for the design of the next-generation stellarators. An example of optimized coils is shown in **Figure 1** and the effect of optimization on the quality of the magnetic field obtained is illustrated in **Figure 2**.

We have also successfully validated the fluid turbulence code GBS against experiments in the TJ-K stellarator in Stuttgart, Germany. The simulations are able to retrieve the correct spectrum of the fluctuations observed in the device.

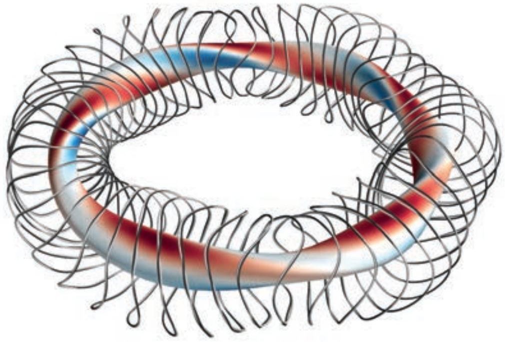
FUNDAMENTAL STUDY OF PLASMA TURBULENCE

In order to enable the numerical simulations of turbulence in situations where the system exhibits strong deviations from the initial state, an adaptive scheme has been developed and implemented into our flagship global gyrokinetic code ORB5. Our results show that this scheme allows for investigations that were previously practically intractable For simulations pertinent to TCV cases, it is shown that even using four times less numerical particles, and hence four times less computational resources, the results obtained have a better quality in long simulations than without the adaptive scheme. An example is illustrated in **Figure 3**, which shows the signal to noise ratio (SNR) as a function of time for a series of flux-driven simulations of turbulence. Only the adaptive scheme is able to cope with large deviations from initial state.

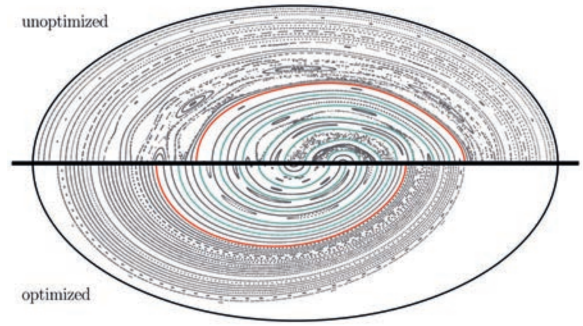
In the last year, a deeper understanding of the formation of internal transport barriers was obtained. If a magnetic field line closes on itself, then long turbulent eddies extending along it will bite their own tails, which was found to significantly reduce the strength of the turbulence. We discovered that the turbulence also gives rise to electric currents that modify the pre-existing magnetic field and increase the number of magnetic field lines that close on themselves.

SHEATH PHYSICS

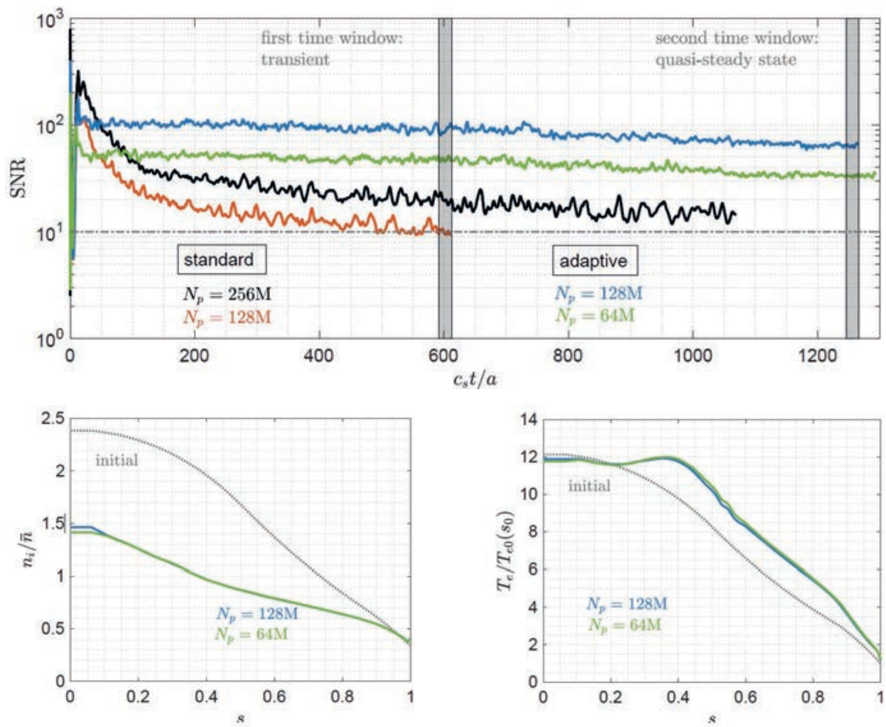
We made progress in the theoretical understanding of magnetized sheaths at the plasma-wall interface under fusion-relevant conditions. First, we derived a generalized kinetic Bohm-Chodura condition (in form of a constraint on the incident ion distribution at the sheath entrance) which accounts for the effect of plasma fluctuations tangential to the wall. In the presence of such fluctuations, we also demonstrated that an additional polarization condition is required to ensure a monotonic decay of the sheath potential asymptotically far from the wall. Second, we obtained a complete unified description of the magnetized plasma sheath accounting for Finite Larmor Radius effects of both ions and electrons.



1 Optimized coils and mod-B contours using the combined SIMSOPT and SPEC codes.



2 Cross-section before (top) and after (bottom) optimization.



3 Signal to noise ratio (SNR) vs time (top) for standard and adaptive schemes, in long flux-driven simulations of turbulence in a TCV configuration. The bottom plots show the initial (dotted line) and final (plain lines) profiles of density (left) and temperature (right).

NEGATIVE TRIANGULARITY

The SPC leads a EUROfusion project assessing the feasibility of a negative triangularity power plant. As part of the mid-term gate review, the results of almost three years of work on the topic were synthesized. We concluded that the benefits of negative triangularity on trapped electron driven turbulence and ion temperature gradient should persist in a conventional tokamak power plant. In contrast, we found that, in spherical tokamaks, negative triangularity can be harmful, for certain types of turbulence. These conclusions have been obtained through a combination of analytic theory and simulation,. This improved understanding allows us to make predictions for how the benefits of negative triangularity should extend to untested parameter regimes. In addition, several independent studies of the scrape-off layer width indicate that it will be wider than in reactor-relevant positive triangularity scenarios, making the problem of extracting the heat from a power plant easier.

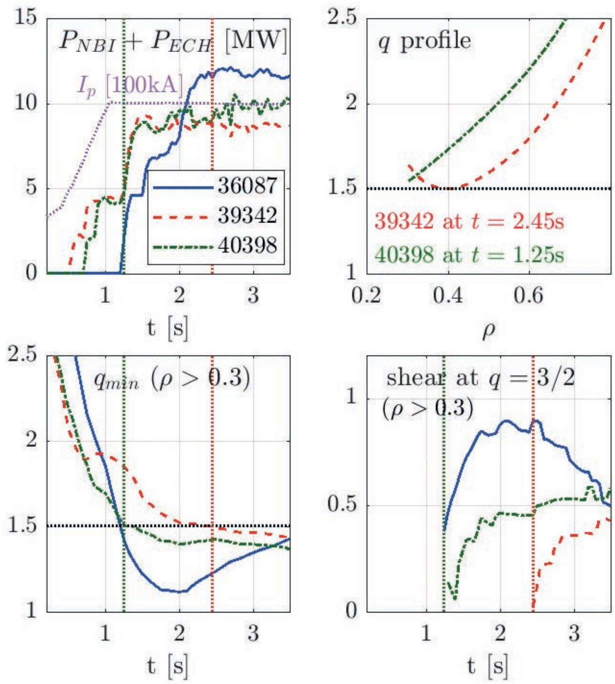
INTEGRATED MODELING AND CONTROL

The suite of codes RAPTOR, MEQ and RAPDENS allow for the design and optimization of new tokamaks and experiments and are now being used worldwide. The same framework, using reduced models, can be used in real-time for physics and data'driven proximity control. Application of this suite include the optimization of advanced scenario and the ramp-up and termination phases in Asdex-Upgrade, and the prediction/optimization of DEMO termination phase.

In addition, the development and maintenance of the MEQ suite of free-boundary equilibrium codes has continued in 2023. This provided an overall speedup of the forward solvers. Ultimately, this work also enabled the development of a novel shape controller for TCV where the control directions are derived from the linearized model and the controller is tuned using either the linearized model or the full non-linear model as a simulator.

DISRUPTION STUDIES

This year has seen the successful start of an exciting project awarded by the Swiss Data Science Center on the use of artificial intelligence and machine learning for predicting tokamak disruptions. In addition to the development of innovative data-driven approaches, the project has so far focused on the construction of a multi-machine disruption database. These activities are closely linked to the development of the EUROfusion Disruption Database, of which the SPC leads, and rely on the unique capabilities of DEFUSE (Disruption and Event analysis framework for FUSion Experiments). DEFUSE is a machine-independent object-oriented framework that implements a fully automated workflow for the analysis of complex events and patterns that characterize different disruption paths. It is the main candidate for the integration into the CFS (Commonwealth Fusion System) control simulation platform and for mapping present machine disruptions data in the ITER IMAS framework



4 Comparison of RAPTOR post-shot simulation for late heating discharge 36087 (blue lines), non-optimized early heating discharge 39342 (red lines) and optimized early heating discharge 40398 (green lines).

SIMULATING THE RAMP-UP AND RAMP-DOWN

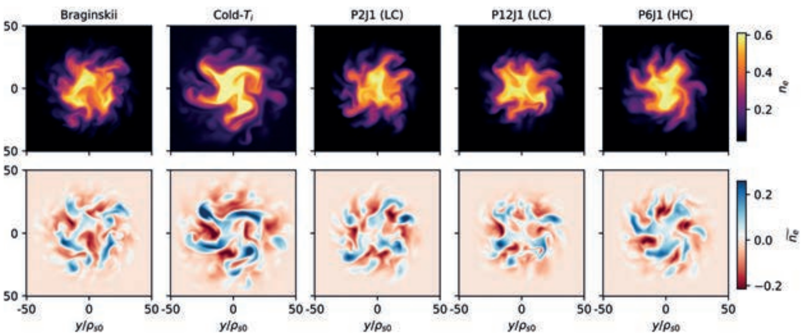
The RAPTOR code is a lightweight plasma simulator, developed at SPC, modelling the coupled dynamics of current diffusion and electron and ion heat and particle transport. Full discharges, from plasma current ramp-up to ramp-down, can be simulated faster than real-time. These fast simulations are used to optimize pulse schedules before the discharge is executed and improve real-time monitoring and control of the plasma. Such a model-based control approach will allow to maintain safe margins to disruptive limits for ITER and DEMO, with limited diagnostic coverage.

In the PhD thesis of **SIMON VAN MULDERS**, the RAPTOR code has been extensively validated for full-discharge simulation and optimization for ASDEX Upgrade (AUG) and has been applied for model-based extrapolations towards ITER and DEMO scenarios. Especially during ramp-up and ramp-down, the dynamics are highly sensitive to the time evolution of heating, current drive, fuelling and shaping actuators, with various stability limits constraining the operating space. Finding the optimum actuator time traces requires a delicate balancing act, benefiting from model-based pre-shot prediction and optimization.

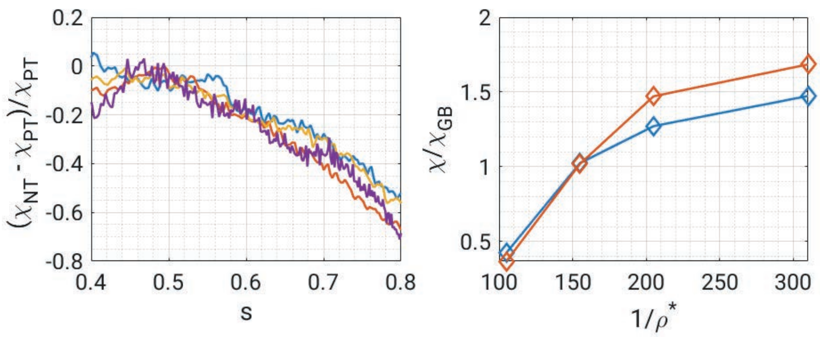
Inter-discharge modelling and optimization has allowed to develop a reliable plasma ramp-up strategy for an advanced scenario on AUG, with an elevated safety factor q profile (qmin~1.35), enabling improved confinement and increased bootstrap current generation. Applying early heating during ramp-up (red traces in **Figure 4**) allows to reach a stationary elevated safety factor profile q early in the discharge in comparison to a late heating strategy (blue traces in **Figure 4**). Fast access to a stationary state is important for ITER and DEMO, with slow current diffusion timescales. Adjusting the heating onset timing and current drive deposition locations, based on predictive simulations before the discharge, deleterious onset of tearing modes could be avoided (green traces in **Figure 5**).

BRIDGING THE GAP BETWEEN FLUID AND GYROKINETICS

Predicting plasma turbulent transport in the boundary region of magnetic confinement devices is crucial for the success of future fusion power plants and remains a highly challenging problem, in particular due to the wide range of plasma collisionality. Towards the core, the plasma is weakly collisional and a kinetic theory is mandatory, whereas towards the edge, the collisionality is orders of magnitude larger and fluid models apply and kinetic simulations are very difficult to implement. In his PhD thesis, **BAPTISTE FREI** has developed a novel analytical and numerical framework valid at arbitrary collisionality, overcoming constraints associated with fluid and kinetic modeling. The new model, referred to as the gyro-moment approach, outperforms traditional fluid models in low collisionality conditions and recovers the predictions of collisionless kinetic theory with reduced computational cost. As a first step in this direction, the thesis also presents the first turbulence simulations of turbulence in the high collisional plasmas of a linear device called LAPD, see **Figure 4**, while incorporating kinetic corrections with minimal computational cost increase. This thesis research paves the way for more comprehensive and efficient simulations of plasma behavior in fusion devices.

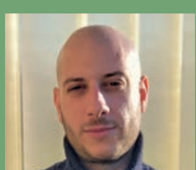


4 Comparison of the normalized electron density **(top)** and fluctuations **(bottom)** between the Braginskii fluid model (leftmost column) and the gyro-moment simulations (with different numbers of gyro-moments and regimes of collisionality).



6 (a) Relative heat transport reduction of negative triangularity (NT) over positive triangularity (PT) versus radius, for various system sizes. The beneficial effect is independent of system size. (b) Scalability of the effective heat diffusivity with increasing machine size for electron and ion heat transport.

NEGATIVE TRIANGULARITY: SIZE MATTERS



When the plasma cross-section shape is flipped from a normal D-shape (positive triangularity) to an inverted D-shape (negative triangularity), energy confinement has shown a substantial improvement in a number of tokamak experiments, the first of which was TCV. In order to assess how this can be attributable to a reduction of turbulent transport, and how this improvement can scale up to future reactors, global gyrokinetic simulations have been performed by Dr **GIOVANNI DI GIANNATALE**, Post-Doctoral researcher at SPC. The simulations, performed with the ORB5 code, confirmed that the beneficial effect of negative triangularity is expected to persist in larger machines (see **Figure 6(a)**). Moreover, these beneficial effects are not confined to the edge, where the geometric differences compared to the classic D-shape (positive triangularity) are significant, but also extend down to the core, where the geometric disparities are minimal (triangularity ~±0.1 at s=0.6). The scaling law of turbulence with machine size (see **Figure 6(b)**) behaves similarly for both positive and negative triangularities, and thus the performance improvement attributed to negative triangularity results to be independent of machine size.

Basic Plasma Physics and Applications

The Basic Plasma Physics and Applications group, led by Prof. IVO FURNO, conducts research on two mid-size basic plasma devices: the TORoidal Plasma Experiment (TORPEX) and the Resonant Antenna Ion Device (RAID). Additionally, the group explores the use of low-temperature plasmas in biology and life sciences in the bio-plasmas laboratory. By integrating advanced experimental techniques with theoretical analysis and numerical modeling, the group deepens the understanding of fundamental plasma phenomena and their practical applications. The main areas of focus are outlined below.

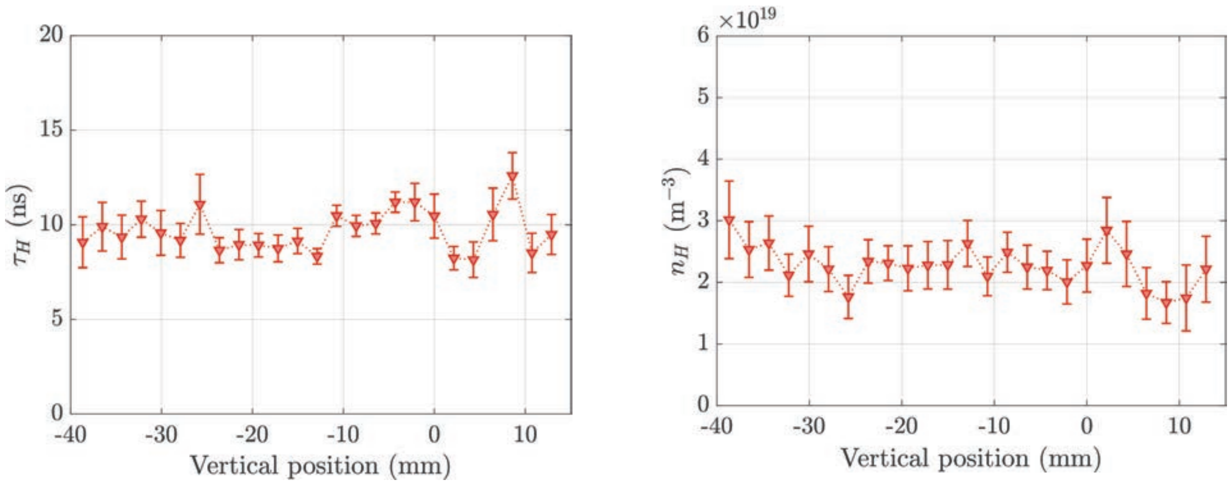
RAID AND TORPEX: UPGRADES AND DIAGNOSTICS DEVELOPMENT

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

On RAID, in 2023, a major upgrade of the Thomson Scattering (TS) diagnostic at RAID was implemented. Utilizing a new laser and a Gated Intensified CCD camera as detector enables us to measure the entire TS spectrum within few minutes, as opposed to few hours in a previous setup that used a single detector. During an extensive campaign, various data, including parameter scans and radial profiles, have been acquired in different gases (argon, helium, hydrogen, deuterium). Special challenges in hydrogen / deuterium operation due to thermal expansion of the vacuum chamber have been partially overcome by adjusted alignment routines. The obtained measurements provide a comprehensive picture of RAID plasma parameters in different operation conditions. Especially, high resolution electron temperature profiles give insight into helicon physics and atomic physics. The data are currently used for validation of helicon theory in conjunction with magnetic field measurements, interpretation of Two-photon Absorption Laser Induced Fluorescence (TALIF) measurements, verification of Langmuir Probe (LP) data, and validation of collisional-radiative (CR) models.

Furthermore, leveraging the lesson learned from the TS on RAID, substantial upgrade to the TS setup was implemented in AWAKE, an accelerator R&D project based at CERN, , which enables the measurement of the plasma parameters along the axis of the Helicon Plasma source (HPS). The main challenge of mitigating the excessive stray light in this changed setup was met by utilization of a second high-performance notch filter. A first axial scan of the plasma parameters was achieved. Extensive measurements are planned in 2024.

The development of our in-house CR model CoRa-He was advanced in 2023 and a first validation of the results was attempted with TS and Optical Emission Spectroscopy (OES) data obtained at RAID. Key features of the model, such as wall recombination and opacity, have been tested against the experiment and set the ground for further improvement of the code. Furthermore, the potential capabilities of laser-induced spectroscopic techniques for the measurement of atomic collision rates and the validation of CR models have been assesed. The concept to use our tuneable picosecond-laser system for the investigation of atomic physics in RAID was well received by the experts and encourages us to pursue along these lines.
Leveraging the installation of a Two-photon Absorption Laser-Induced Fluorescence (TALIF) diagnostic in 2022, we demonstrated for the first time the feasibility of TALIF measurements of atomic H using a picosecond tunable laser in high-power helicon plasmas. This is motivated by the need to broaden our comprehension of hydrogen/deuterium plasma discharges in helicon regimes. First 1D resolved measurements of radial profiles of atomic hydrogen density and decay time were obtained by imaging the fluorescence light, induced by a TALIF scheme, in a section of the RAID plasma column. The results, obtained in a H plasma with $n_e = 10^{18}$ m^{-3} and $T_e \sim 1$ eV on axis, reveal a uniform H density profile, with a mean dissociation degree close to 3%. Exploring wider range of plasma parameters suggests that transport processes and wall interaction play an important role in establishing the H density profile. Furthermore, the picosecond laser system enabled a more accurate measurement of the time evolution of the fluorescence signal compared to standard nanosecond techniques. This has enabled the first measurements of fluorescence decay times in RAID. The measured decay times for H are shown in **Figure 1-left**. The spatial profile is consistent with a uniform decay time across the measured region, for both H and Kr (not shown). In the case of H, the profile has a mean of 9.7ns ± 0.2 ns. This value is significantly lower than the purely optical decay time of the 3d state, 15.5 ns, and is compatible with complete substate mixing of the n = 3 states of H. As shown in **Figure 1-right**, our measurements of the absolute atomic density are consistent with a flat profile of H density across the cylindrical plasma column

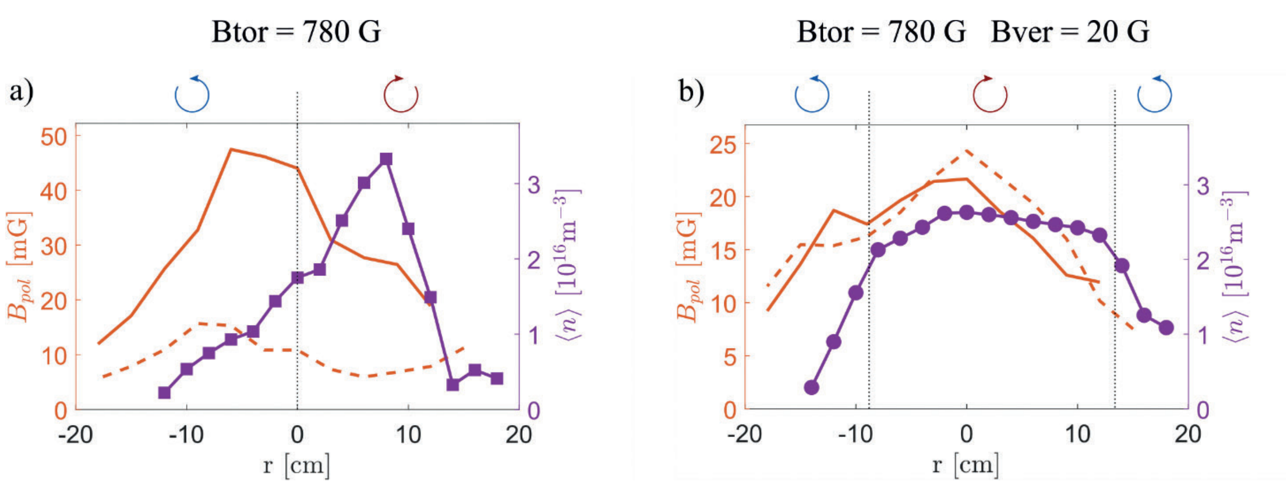


1 **Left:** Fluorescence decay times of hydrogen. **Right:** H density profile across the plasma column in RAID. The error bars do not include the global uncertainty of 50% from Kr absolute calibration.

of RAID, in a region over which ne and T_e show a significant variation. These new results are currently used to improve models of H plasmas in RAID and provide a proof-of-principle for the use of a TALIF diagnostic in fusion experiments, such as TCV, and in linear devices dedicated to the study of divertor physics. Thanks to these results, a grant from EUROFusion Enabling Research was obtained to develop a TALIF system based on a femto-second laser for single-laser-pulse measurement of H/D atomic density, which could possibly be implemented on fusion devices.

On TORPEX, we concluded the characterization of the plasma in the X-point magnetic configuration for several values of the magnetic shear with one further diagnostic, the Slow Langmuir Probe. The main plasma characteristics (modes, turbulence) have been analyzed showing, among others, a sharp reduction in turbulent transport when the magnetic shear is increased. On the hardware side, the HEXTIP array, a set of 95 Langmuir probes, needed a thorough maintenance after the identification of shots circuits between the probes. This diagnostic has been successfully rebuilt, mounted, and tested in TORPEX. Finally, regarding suprathermal ions, several experimental upgrades have been done to prepare future campaigns, such as the building and commissioning of a new toroidal rail.

Following the installation of the helicon resonant antenna in TIORPEX in 2022, we performed the first studies of helicon plasmas in toroidal geometry as a function of the magnetic configuration. We measured radial profiles of the wave magnetic field fluctuations with a three-dimensional magnetic probe, on both sides of the antenna, and varying the confining magnetic field configuration. With only a toroidal field, the wave is strongly damped along its toroidal propagation and reaches the other side of the antenna with a reduced amplitude. When a small vertical component is added to this field, helicon waves are in contrast able to propagate and be sustained across the whole torus of TORPEX, as shown in **Figure 2**.



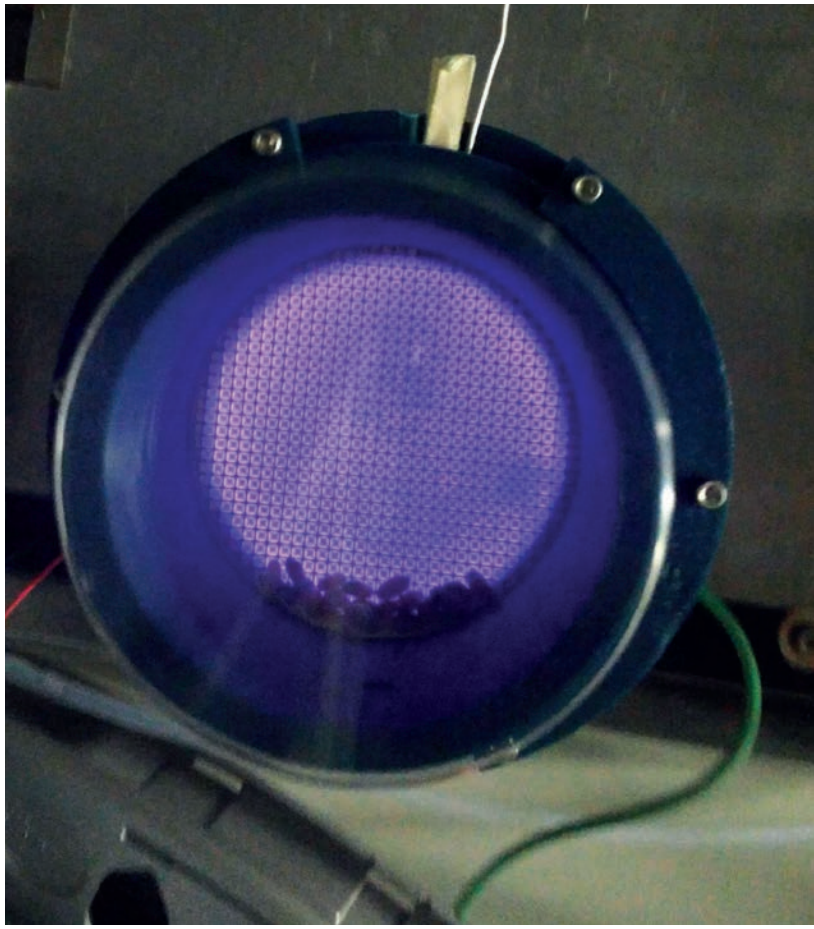
2 Comparison of helicon poloidal amplitude and polarization with the plasma density, in argon for (Magnetron: 600 W / Antenna: 200W), depending on the magnetic configuration.

In addition, we showed that the polarization of the helicon wave does not follow its main amplitude, which is unreported in the literature to our knowledge. Instead, by varying the gas and the magnetic configuration, the wave polarization consistently follows the plasma density profile, with a positive polarization in the plasma bulk, and a negative polarization in the plasma edges.

LOW TEMPERATURE PLASMAS FOR BIOLOGICAL APPLICATIONS

The activities in the field of low-temperature plasmas for biological applications have centered on exploring the use of plasmas and plasma-activated water for sterilization of bacteria and other pathogens and in parallel to deepen our understanding of the fundamental mechanism of interaction between living organisms and plasmas. A few new projects in this field started in 2023, which are briefly reviewed below.

Sterilization of wheat seeds naturally contaminated with Microdochium Nivale (one of the main fungal pathogens in wheat) via Cold Atmospheric Plasmas (CAPs) was investigated. The sterilization efficiency of a Surface Dielectric Barrier Discharge (SDBD) was analyzed by evaluating the fungal pathogen growth on agar medium, as well as the seeds germination, after the plasma treatment. Seeds treated by a SDBD are shown in Figure 3. A proof of principle was obtained according to the industrial standard of sterilization. Preliminary results on the Reactive Oxygen and Nitrogen Species (RONS) produced in the air close to the SDBD have been obtained with a Fourier Transform Infrared Spectroscopy system. The low implementation cost and potential scalability of the implemented setup have paved the way to consider further development and patenting of this technology in the upcoming years.



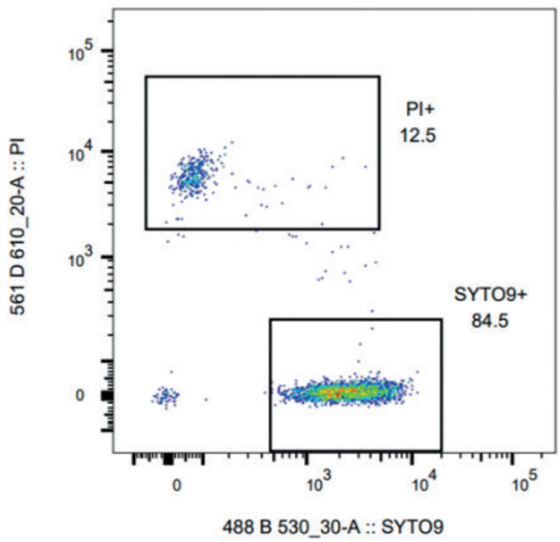
3 SDBS plasma used for the treatment of naturally contaminated seeds.

In the framework of the EPFL Solutions for Sustainability Initiative (S4S), we started the project 'New Plasma-based Sterilization Methods', which aims at reducing the energy consumption and the environmental footprint of sterilization methods presently broadly used in life sciences laboratories and in medical settings worldwide. This project addresses the strategic mission of the S4S initiative, which aims at developing sustainable solutions for reducing energy dependence and carbon footprint by leveraging EPFL's capabilities in R&D. If successful, the novel sterilization devices will be demonstrated by 2024 on campus in the SV-IN and their applicability to broader fields will be analyzed. The success of this proposal would be hugely beneficial to a variety of environments, ranging from industry to hospitals, where the lack of standardization combined with optimization, development of treatment and safety protocols, and ultimately regulatory approval is often a considerable obstacle to expediting new technologies. In 2023, we initiated the first activities by investigating two plasma sources. First tests of surface dielectric barrier discharge (SDBD) on E. coli and M. luteus inactivation were made. Bacteria inactivation in deionized water and in media were compared. The effect of post-treatment incubation to facilitate inactivation was studied. Second, tests of transient spark (TS) discharge on E. coli inactivation were made.

While the effectiveness of plasmas and plasma activated water (PAW) against bacteria is a consolidated fact, the primary obstacle to progress in the field remains the lack of a cohesive understanding as to the modes of action governing the observed effects of treatment. The second aim of the bio-plasmas lab is to address this gap in knowledge. Specifically, this is accomplished by studying the interactions between plasma/PAW and bacteria using a multitude of state-of-the-art diagnostics available at the Swiss Plasma Center involving intricate electrical, laser, and liquid-phase measurements. Among these diagnostics, a novel impedance flow cytometry technique to probe the effect of plasma treatment on bacteria and their membranes has been used in 2023, which was developed in conjunction with the Swiss company Amphasys. The novel application of this diagnostic allows the dielectric spectra of E. coli inactivated by plasma to be recorded and compared to living cells. By analyzing the change in the cellular impedance signal at several frequencies, it is possible to probe the effect of plasma treatment on each sub-cellular layer of E. coli. Along with COMSOL modeling performed in parallel, we believe that this technique can help to identify the mechanisms by which plasmas inactivate bacteria. Doing so is critical for tailoring discharges to specific biomedical applications and obtaining the required regulatory approval before widespread clinical use.

The study of PAW inactivation mechanism on E. coli was also performed using various diagnostic methods. A flow cytometry campaign using the Live/Dead BacLight fluorescence kit confirmed that bacteria treated with PAW were completely inactivated, aligning with the log-reduction results, and ruling out the possibility of viable but nonculturable bacteria. Results are shown in Figure 4.

Gel electrophoresis of proteins extracted from E. coli cells treated with PAW was performed as an initial step to study the interaction between PAW and bacterial proteins. Additionally, the development of a protocol for high-throughput proteomics experiments began, aiming at analyzing the complete mass spectrum of PAW-treated E. coli proteins, with the first experimental run concluding in 2024. The study also explored PAW's inactivation of E. coli in different growth states (exponential and stationary) and at varying bioburden levels (bacterial concentrations) through log-reduction measurements. These results were compared with susceptibility data obtained using the Resistel machine, in collaboration with Professor Kasas' group. The Resistel device, originally developed for antibiotic testing, enabled the study of E. coli sensitivity to PAW by correlating nanoscale vibrations of a bacteria-covered cantilever with the bacteria's susceptibility to the treatment.



4 Example of flow cytometry results: dead cells result positive to PI (gating on the top) and live cells result positive to SYTO9 (gating at the bottom).

Applied Superconductivity

The focus of the Applied Superconductivity Group of SPC remains to be the development and testing of superconductors for fusion magnets and designing of EDIPO 2 test facility. It is lead by Dr KAMIL SEDLAK, Senior Scientist, who exposes below the highlights of 2023 achievements.

A better-than-expected performance was observed on our react-and-wind (RW) Nb3Sn sample designed for 63 kA at 12.3 T for the TF coils of European DEMO. This so-called RW2 sample was tested already three years ago. This year we tried to bend it in steadily decreasing bending radii to mimic the bending during the coil manufacture. Due to the brittleness of Nb3Sn filaments after heat treatment, we expected the maximum allowable bending strain to be around ±0.3%. In the attempt to verify that this value can be achieved safely, we actually reached bending strain of ±0.53% without any degradation of current-sharing temperature, the maximum temperature at which the conductor transfers 63 kA in superconducting state. This gives us an additional margin for the coil design and its manufacture.

Research is not always just successful, and we also had some setbacks. Two newly built high-temperature superconducting (HTS) samples for fusion, ASTRA and non-twisted non-transposed conductors, designed and built for DEMO, did not withstand high electromagnetic-force load during cyclic loading. We believe that the reduced performance can be due to voids in the solder between HTS tapes in the soldered stack of tapes. We will try to improve the soldering process in 2024. Also, the manufacture of the new prototype of Nb_3Sn RW conductor designed for 105 kA (**highlight 1**) took us longer than we expected. Concerning the conductor testing in the SULTAN test facility, our largest "customers" are EUROfusion DEMO, for which the vast majority of the samples comes from SPC, Chinese tokamaks BEST and CFETR, and the Italian DTT. Other samples came from CFS-SPARC, ACT (private company producing "CORC" cables) and still also from ITER.

Concerning the facilities, our operators and technicians renewed cabling in the SULTAN hall, renewed some of the old electronics and upgraded the superconducting transformer. We are designing a subscale coil that shall test the new magnet concept of EDIPO 2, which will be using an accelerator-like

DESIGNING COILS FOR THE FUTURE DEMO REACTOR

FEDERICA DEMATTÈ works on the design of a Nb3Sn-based high-current winding pack (WP) for the toroidal field (TF) coil of the EU DEMO. The operating current I_{op} is roughly 105 kA, which corresponds to a 50% current increase compared to the ITER cables (I_{op} = 66 kA), and allows us to lower the discharge voltage of the coil below 5 kV. This is possible because the inductance of a coil is proportional to N^2, where N is the number of turns, which means that, for a given total TF current $N \cdot I_{op}$, increasing the operating current corresponds to decreasing the number of turns and thus lowering the discharge voltage of the coil. Specifically, an operating current $I_{op} \approx 105 kA$ and a discharge time constant $\tau_d = 35 s$ allow to reduce the terminal-to-terminal discharge voltage to $u_d = 4.23 kV$.

In line with the other TF designs proposed by SPC, also this WP is based on the react-and-wind (RW) technology and features graded layer winding. The RW method foresees a heat-treatment for the Nb_3Sn cable prior jacketing and winding. As shown in **Figure 1**, these cables are typically flat and with a high aspect ratio, and assembled such that the superconductor lies on the neutral bending line. RW4 sample is being manufactured in the SPC workshop in Villigen and will be tested in SULTAN in 2024.

SMART INSULATORS: THE MATERIALS WITH TIME-VARYING PROPERTIES

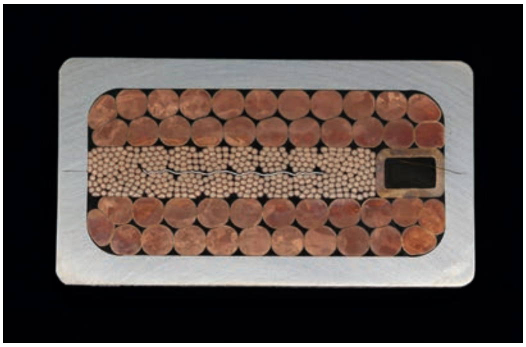
Superconducting magnets, these Sci-Fi looking like machines, are among the best macroscopic demonstrations of (complex!) quantum phenomena. Many layers/turns of superconductors, wires or tapes, are wound to create the final magnet shape, producing fields varying from a few to tens of Tesla. Yet their power does not only come from microscopic sorcery – many classical solutions, e.g. electrical or mechanical, make them work for real. For example, wrapping the superconductors with electrically insulating material (e.g. Kapton, resins, fiber glass) has been the preferred design so far. The main advantage is a fast current (dis)charging, the main consequent drawback being the high voltages during fast current switch offs, e.g. in case of a detected quench. In addition, increasing radiation levels in tokamaks like ITER or DEMO make the insulation extremely fragile.

But what if we remove insulation and allow current to be shared across the coil turns? That idea looks crazy at the first look, because current is no longer forced to follow the coil-turns trajectories. However, if the turns are superconducting, the current will eventually prefer the longer superconducting path to much shorter and much lower-inductance non-superconducting transverse direction. It will just take some time, hours or days. The behavior of such coil, especially the quench behavior, were modelled by Dr **MATTIA ORTINO** in 2023, indicating the benefits of the partially-insulated coils, namely low voltage (1-60 V) during the magnet discharge, leading to a passive magnet safety.

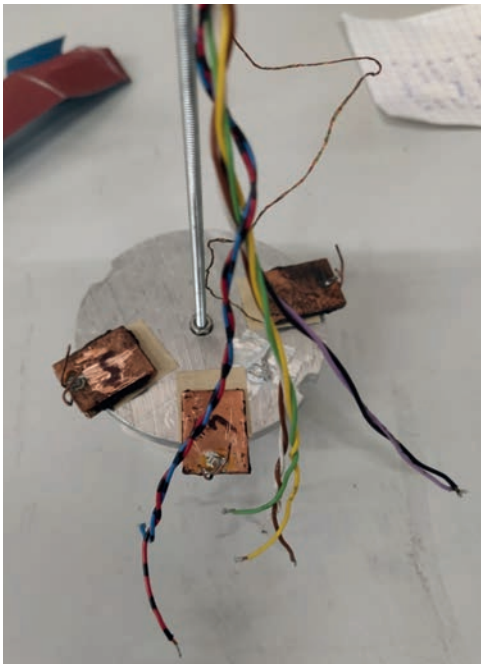
The Smart Insulators like Vanadium Oxide (V_xO_y) are materials with a small, metal-like, resistivity above e.g. 90 K, and a high, ceramic-like, resistivity below. Mattia Ortino and Davide Uglietti investigated this experimentally by preparing different V_2O_3 samples (**Figure 2**) as well as by measuring the electrical and thermal behavior down to 77 K. A magnet built with the smart insulation would inherit the best qualities from both worlds – fast charging like the magnet with insulated turns, yet passively protected in case of quench.

technology of He bath cooled magnets wound of two-stage “Rutherford” cable instead of forced-flow-cooled cable-in-conduit conductors used in EDIPO 1 and in SULTAN.

Apart of the main focus of the group mentioned above, we have several smaller, however very innovative and challenging projects related to fusion superconducting magnets. I would point out quench detection by optical fibers, superconducting switches, stellarator magnets, and partly-insulated magnets (**highlight 2**). We have also launched an industrial-scale laser-welding demonstration of RW conductor production. A 1 km long rectangular steel jacket will be produced by Criotec, Italy.



1 Cross-section of RW4 conductor prototype designed for 105 kA at 12 T. The Nb_3Sn cable is in the center. Other components are: two Rutherford cables (stabilizers) made of Cu, a perforated cooling pipe for the liquid helium and a stainless-steel jacket, which serves both as a mechanical structure and as a vessel to contain the liquid helium.



2 Three samples made of copper plates with V_2O_3 in between. The temperature-dependent resistivity is measured.

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 micro-waves.

UPPER AND EQUATORIAL LAUNCHER EX-VESSEL WAVEGUIDES

During 2023 the Electron Cyclotron (EC) ITER Upper Launchers (UL), including the ex-vessel waveguides that are part of those launchers, is being constructed by the Technical Integrator (TI) who will be responsible to provide the final analysis, documentation, production, and delivery of the launchers. SPC reviews updates of the final design along with Fusion For Energy (F4E).

During 2023 negotiations were finalized between the TI and F4E to perform stray radiation tests of a full-scale model of the beam enclosure of the UL, including uncooled mirrors. SPC will work with the TI to define the thin-walled beam enclosure structure and diagnostic probes, the precise tests to be carried out, the analysis methods and the testing schedule to be followed at FALCON. Infrared measurements of the beam enclosure heating will be compared to novel analyses methods carried out by the TI. These tests should allow the F4E to present reliable and convincing arguments for the viability of the UL to safely fulfil its role for the 20-year lifetime within the ITER machine. Design work is expected in 2024 and testing in 2025.

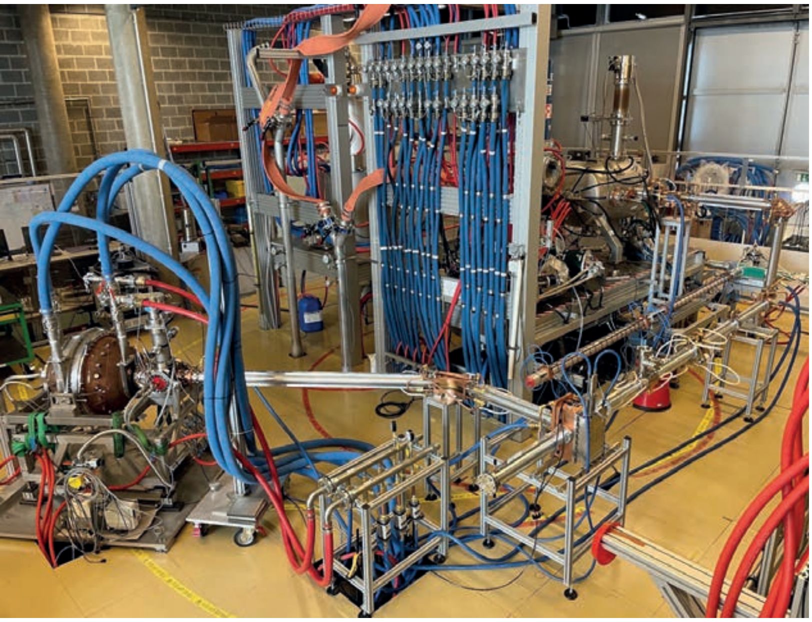
EUROPEAN GYROTRON FOR ITER AND DTT

In 2022, the THALES 1509U gyrotron was selected for procurement by both ITER and the Italian Divertor Test Tokamak (DTT) project. During the first half of the 2023, US-supplied ITER components for the ITER Transmission Line (TL) were tested at full power to permit selection of suppliers and qualify them for series production. This was done in three short campaigns, according to the associated contract and its amendments, after two of the 5 mirrors inside the RFCU were re-designed, manufactured and installed and aligned by SPC to optimally couple the power from the gyrotron to the new TL diameter of 50mm (previously 63.5mm). The EU gyrotron and an EU steady-state calorimetric load (RFL.20) were used to perform the first tests (see **Figure 1**). Similarly, two US supplied high-power, 10s, calorimetric loads were successfully tested with various TL configurations at the end of the 2nd and 4th quarter of 2024 (see **Figures 2 & 3**), the latter using the DTT pre-series gyrotron described below.

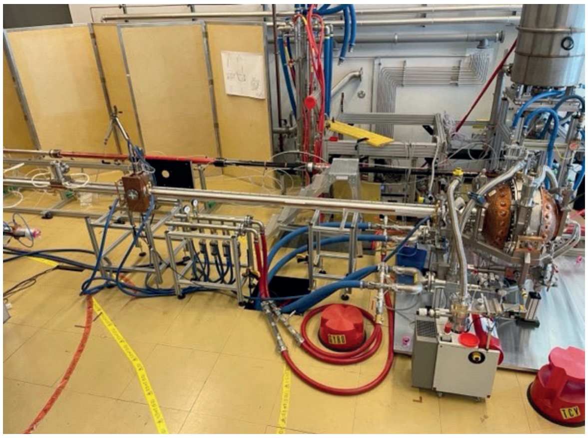
FALCON was reserved by the industrial partner (THALES) of the European Gyrotron Consortium (EGYC), with the requisite accord of F4E, to act as the “factory floor” for testing of the DTT pre-series gyrotron, TH1509UA, in 2023 while their own factory test facility is being finalized. Tests began with the conditioning of the gyrotron using ½ the usual number of vacuum ion pumps. This conditioning was somewhat slower than usual but was possible, allowing simplification of later gyrotrons by the removal of two pumps. Following adjustment of the gyrotron within its magnet to ensure optimal power and mode generation, the output power at very short pulses was measured at atmospheric pressure. This gyrotron has a new beam tunnel and cavity design and showed no parasitic mode oscillations, in contrast to the previous EU gyrotron. The gyrotron mm-wave output beam pattern was then measured and analyzed to provide information required to adjust the mirror orientations in the RFCU to optimally redirect the gyrotron beam into the US ITER TL. A successful pre-alignment of the RFCU was made using a low power source and mm-wave camera. Unlike previous methods, It was not necessary to remove the TL to measure the beam at the output of the RFCU. The power losses in the RFCU and the alignment of the beam in the calorimetric load were equivalent to the previously used method for the TH1509U gyrotron. This result is important for future fusion reactors as it shows that gyrotrons can be removed and replaced at their end-of-life, or for repair, without the need to un-install and re-install sections of the TLs, saving time and expense.

In addition to EU and US ITER testing, a Memorandum of Understanding with Calabasas Creek Research was initiated to test an additional dummy load at FALCON. The first tests resulted in overheating of some parts, requiring a repair. Testing will continue in 2024; once completed, nearly all the major worldwide load designs will have been tested and compared within the same test facility.

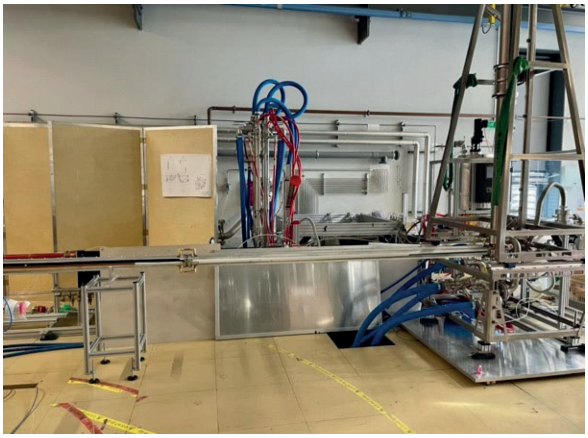
All loads tested show very low reflected power and no measurable effect on the operational behavior of the gyrotron. Nevertheless, heating of the TL can be dominated by load reflections and TL heating rates are different, depending on which



1 The complete test layout for Campaign A. The RFCU is at the upper right and the RFL.20 calorimetric CW load is at the lower left (with blue water tubes for the hemispheres, red water tubes for the load mirror and auxiliaries, and larger red tubes that connect to the water manifolds of the TL connected in parallel to the input-side (north) load hemisphere. A copper high power mm-wave switch diverts the power to the load via a copper 140° miter bend.



2 installation of one 3m WG after the straight through direction of the switch, followed by the first Load.



3 Two 3m WGs, with the switch removed, and the second load. Standardized water connections (blue tubes) are used for both loads.

load terminates the TL. However, even with load reflections all derived TL loss rates measured at FALCON are compliant with ITER specifications.

UPPER LAUNCHER PORT PLUG

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" were mimicked in "piggy-back" tests carried out in the RFCU during gyrotron testing. 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. At FALCON a single spring was installed in the stainless-steel RFCU, which fortuitously has a stray-radiation absorbed power density nearly equivalent to that expected in copper-coated UL. The spring was viewed with an infrared (IR) camera via a sapphire window (for IR transparency) protected by an RF screen similar to that of a microwave oven. The heating rate of the spring was measured with and without a "stray-radiation cap" mock-up. The five-fold reduction in the heating rate was consistent with a simple 1D model and will be compared as a simple benchmark to a 3D model used by the TI for the more complex geometry of the entire UL.

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

DEMO

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. Work was continued in 2023 on detailed designs of the mirror cooling with enhanced contacts and collaborations with other work packages in the DEMO project; in particular, with materials and safety. Initial pre-irradiation testing of material samples were carried out in a Fabry-Perot resonator at DEMO relevant frequencies. Samples were then sent of irradiation and will be retested to assess the effects on the surface resistance of the irradiation, if any.

ITER, EUROPE AND SWITZERLAND

The year 2023 has been historical for fusion. In July, the researchers of the National Ignition Facility at Livermore in the US have managed to inject 2.05MJ of energy from 192 laser beams on a rice-grain-size solid target containing Deuterium and Tritium, and to obtain the release of 3.88MJ of fusion thermal energy. For the first time ever, a fusion experiment, in this case based on inertial confinement, has demonstrated a positive gain of energy from a plasma in a laboratory.

Later in the year, in October, a new world's record of 69MJ for the fusion energy produced in a plasma discharge was obtained on the JET tokamak, the large magnetic confinement experiment located in UK and operated jointly in the context of the EUROfusion Consortium. Such amount of energy was produced by the plasma using 0.2mg of DT fuel, as opposed to the 2-3kg of fossil fuels that would have been necessary for that. The experiments at JET were of particular importance, as they confirmed theoretical predictions used to design next step devices and were obtained in conditions relevant to fusion power plants, namely in terms of the materials of the containing walls.

These successes were complemented by several other results from the most important devices worldwide, and by the ITER project reaching the final stages of the assembly of its infrastructure.

Unfortunately, the past year has also been characterized by several conflicts, in particular the invasion of Ukraine by Russia. The consequences of this tragic event have made society even more eager to develop energy solutions that avoid too large a dependency on single countries.

Many governments have also progressively realized that, despite large investments in renewables, fossil fuels are still covering ~80% of energy usage, and that renewables have large footprints, are intermittent, and imply large-scale storage, which is still expensive and not without environmental impact. They have concluded that baseload electricity plants will continue to be needed.

All these elements together have led to an unprecedented level of interest in fusion, both at the public and political levels, as well as at that of industries and private investors. More than 6 billion euros of private capital have been raised for fusion developments.

The recently installed new ITER management has prepared a new baseline, taking advantage of the project delays to install several systems before the first plasma. This is leading to a realistic and reliable plan, with faster progress towards interesting experiments, namely those with the full fusion fuel mix and full plasma performance, reaching the burning plasma regime.

The project delays, understandable in the context of one of the most complex scientific infrastructures ever constructed worldwide, seem now under control, with the vacuum vessel sectors being under repair and the thermal shields having been shipped to India for reconstruction, to name the two most prominent issues.

At the European level, the Fusion for Energy agency, led by the new director, Marc Lachaise, is under internal restructuring, to improve efficiency for the final ITER developments and its broader range of actions. An increased level of collaboration and coordination with the EUROfusion Consortium is sought.

Fusion for Energy and EUROfusion together coordinate the operation of the JT-60SA tokamak, part of the Broader Approach collaboration between Europe and Japan. JT-60SA has had its first plasmas at the end of the year, a historical coincidence, as at the same time JET ceased its operations, thereby becoming the largest operating tokamak in the word.

Although experimentation on JET has finished, after 40 years of successful campaigns, JET activities and contributions will continue, both to exploit the plethora of invaluable data that has been accumulated over many years, and to document and learn lessons from its decommissioning. The human legacy of JET, which was built over decades of being a central hub for our community, will remain for a long time to come.

At EUROfusion, where I have the honor to chair its highest decisional body, the General Assembly, and which I will manage as Programme Manager from next year, an important strategic activity has been conducted, namely defining a new approach to the European Roadmap to fusion energy.

The present Roadmap contains all elements of a reactor-oriented program, but is based on budget, timing and personnel assumptions that are not valid anymore. In addition, the fusion scene is changing fast, driven by evolving boundary conditions, an increased perception of urgency for clean baseload electricity, and private investments.

To keep European leadership position and increase appeal to younger generations, we are strengthening and accelerating our activities yet maintaining a realistic approach. The DEMO step to commercially feasible fusion power plant is now clearly defined, and, while keeping a central role for ITER, some degree of parallelisation of activities is introduced, together with the need for a strong involvement of fusion industry in the form of Public-Private Partnerships.

The role of EUROfusion itself and of its beneficiaries and associated laboratories, like ours, is further strengthened, also recognizing the strong demand for education and training of fusion experts, and a still significant need for basic research and exploration of new technologies on the way to power plants.

In 2023, EUROfusion also conducted, with the help of an international panel of expert, a facilities review exercise, with the aim of identifying the infrastructures that are needed to carry out R&D in the next two Framework Programme periods. The relevant report highlights that our large facilities are either very important for several areas (TCV) or indispensable for specific areas (Falcon&T-REX, SULTAN&EDIPO), and stresses the vital importance of teaching and education activities for fusion.

Switzerland at present is not associated to the research Framework Programme FP9, hence formally cannot participate to Euratom and ITER. Swiss industry and institutions can participate to bids only as sub-contractors or if they are the unique holders of a technology or know-how worldwide.

However, Switzerland participates to EUROfusion, as EPFL is an associate partner to the Max Planck Institute of Plasma Physics (Germany), to which we are very grateful, and, via the IEA Technology Cooperation Program on tokamaks, to ITPA, ITER Associates and Fellow schemes.

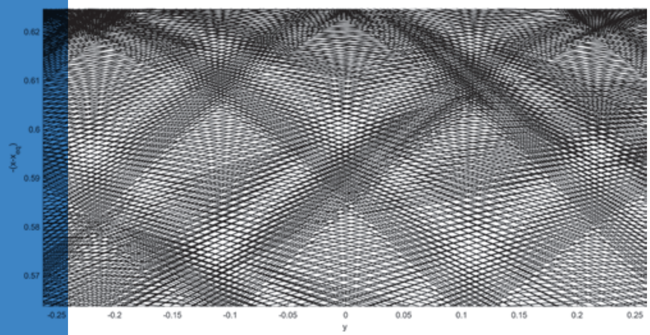
In addition, the cooperation agreement that was signed between EPFL and F4E, generously supported by the Swiss State Secretariat for Research, Education and Innovation, allows us to contribute directly to ITER in crucial areas of physics and technology, even before the re-association of Switzerland to the European research area and EURATOM, to which we all look forward.

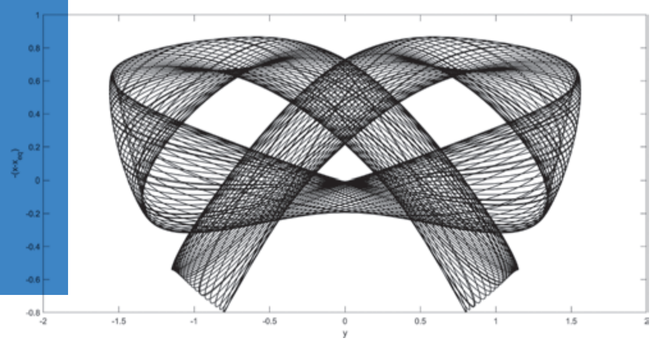
TEACHING

$$\rho = \left(\rho_0^{\gamma-1} - \frac{g(\gamma - 1)}{C\gamma} z\right)^{1/(\gamma-1)}$$

Besides leading world class research, another most important pillar of the missions of the Swiss Plasma Center lies in the education of future generations of plasma physicists. These will bring ITER and other fusion reactors to success, as well as develop innovative new applications of plasmas to various fields. At SPC, we view this as our main contribution to environmental, societal and economic developments.

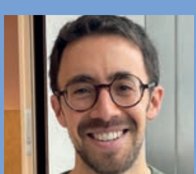
A remarkable feature of SPC in this regard is the fact that it is tightly knit into the academic fabric of EPFL and in particular of its Faculty of Basic Sciences. This is a clear asset for attracting young talents to the field. In 2023 the SPC further expanded its population of PhD students and Post-Docs, besides training a record number of Master students in semester projects and master theses. We are particularly proud of seeing SPC having become a vibrant community of highly motivated, bright and young researchers.





The top-class quality of education provided at SPC is demonstrated, among other things, by a substantial number of awards that have been obtained by PhD students and Post-Doctoral researchers throughout the past years. 2023 was no exception:

MAURIZIO GIACOMIN received the 2023 EPS-PPD PhD Research Award for his thesis “Turbulent transport regimes in the tokamak boundary”. He was also a finalist for the EPFL Doctorate award for which he got the Special Distinction from the selection committee. Maurizio developed a theory-based scaling law of the maximum edge density achievable in tokamaks and successfully validated it against a multi-machine database. This significantly improves our understanding and predictive capability of the density limit and leads to important implications for the design and the operation of future fusion power plants.

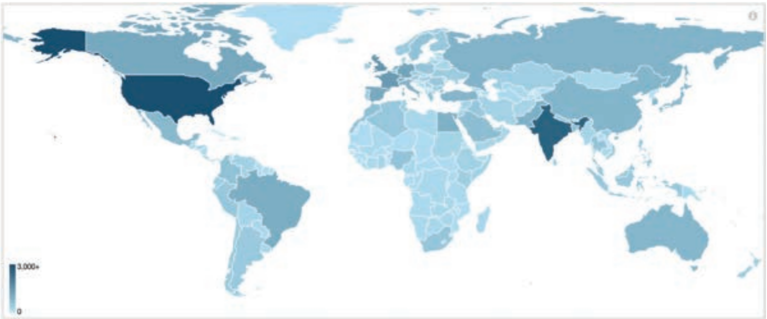


BAPTISTE FREI received the 1st Prize of the 2023 EPFL Physics Doctoral Thesis Award, for his work entitled “A Gyrokinetic Moment Model of the Plasma Boundary in Fusion Devices” which received praise from the jury for its outstanding treatment bridging the gap between fluid and kinetic descriptions. This is crucial in particular for the region of the plasma which is at the boundary of fusion devices, for which a comprehensive theoretical description is highly challenging, because of its wide range of plasma parameters, particularly the plasma collisionality.

At the end of 2023 the SPC had 55 PhD students enrolled in the Doctoral School of EPFL and 33 Post-Doctoral researchers. In 2023, Antoine Baillod, Guillermo Bustos-Ramirez, Jean Cazabonne, Baptiste Frei, Aylwin Iantchenko, Guillaume Le Bars, Mike Machielsen, Lorenzo Martinelli, Arsène Tema Biwole, Simon Van Mulders obtained their PhD in physics for their work carried out at SPC.

The 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 two Massive Open Online Courses (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 18915 subscribed learners in 2023 from around the globe, see **figure**.



Geographical distribution of the registered participants to the MOOC course on plasma physics given by SPC.

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 more than 1000 hours to more than 2000 students.

19	Number of courses given by SPC staff at Bachelor, Master and Doctoral levels
2,180	Number of students in the classes of these courses
115	Average number of students in these courses
1,064	Number of hours taught by SPC staff in these classes
131,166	Number of student-hours taught by SPC staff
18,915	Number of subscribed learners in the MOOCs on Plasma Physics of SPC
52.4	Number of PhD students at SPC (FTE)
32.6	Number of Post-Docs at SPC (FTE)
57	Number of Master students supervised at SPC for semester and thesis projects
30	Number of Visiting PhD students, Master exchange students and Internships

JEAN CAZABONNE was awarded the 2023 Kyushu University Itoh Project Prize for his thesis “Experimental and numerical evidence of electron turbulent transport enhancement by electron-cyclotron waves in tokamaks”. This prize is given in association with the EPS Conference on Plasma Physics. It aims to recognize doctoral students who have performed excellent research on plasma turbulence, transport, confinement, or any related topic.

SOPHIE GORNO received the 2023 PPCF / EPS / IUPAP Student Poster Prize for her work “Experiments and modelling to characterize the effect of connection length on power exhaust in TCV”. At the same EPS 2023 Conference, Alessandro Balestri obtained a special mention for his poster “Role of aspect ratio in confinement enhancement in negative triangularity plasmas”

KYUNGTAK LIM, post-doctoral fellow at SPC, has been awarded a Eurofusion Bernard Bigot Research Grant (ERG) for his project “Investigation of the plasma dynamics in the boundary of double-null (DN) tokamak configurations”, aiming at reducing divertor heat load, which is considered among the most pressing issues to the success of fusion energy. The primary goal of the ERG programme is to enhance the professional development of exceptional post-doctoral researchers.

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 biggest event of 2023 was the 30th anniversary of the TCV tokamak which gathered around 600 participants in the Forum of the EPFL's Rolex Learning Center.

OUTREACH ACTIVITIES

The visits of the Swiss Plasma Center labs continue to be a major outreach activity. In 2023, around 140 visits gave the chance to discover the tokamak and our other facilities to more than 3800 persons, mostly young people between 15 and 22 years. Visitors come mainly from the French speaking part of Switzerland. Many come from the UK, often combining a visit of SPC and the CERN.

In 2023, SPC participated 10 times in the TecDays organized by the Swiss Academy for Research and Technology (SATW), which are aimed at high-school students. SPC staff present the module: “Nuclear fusion - on the way to a sustainable world” in French, German or Italian, depending on the language region of Switzerland. They explain the basics of nuclear fusion and give an insight to the tokamak technology and research. The students can test their knowledge during two quizzes and can win small prizes. The module receives increasingly positive feedback.

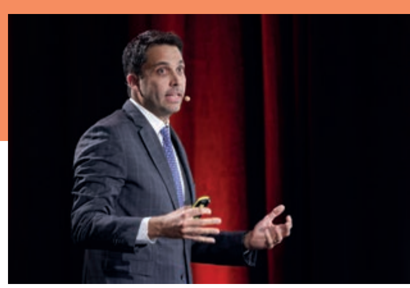
Another extramural event, organized by EPFL, took place in Solothurn, where SPC had a booth and presented plasma and fusion research with the help of Helios, our mobile plasma demonstrator.

And last but not least, SPC participated to the grand open doors event of EPFL which took place during a full week-end in April. More than 2000 people visited TCV, Torpex, RAID and Helios, while hundreds of visitors followed conferences on fusion and education.

TCV TURNS 30

On September 21st the SPC organized the celebration of the 30th anniversary of the TCV tokamak. It brought together major personalities from the scientific and political spheres. Prestigious speakers such as the Federal Councilor Guy Parmelin, the General Director of EUROfusion Tony Donné, the Director of Fusion for Energy (F4E) Marc Lachaise, and the Deputy Director General of ITER Alain Bécoulet testified and praised the broad success of TCV and its significant contribution to the international development of fusion. The equally remarkable speakers of the SPC, Ambrogio Fasoli, Basil Duval, Stefano Coda, Christian Theiler and Sophie Gorno retraced the history of TCV, highlighted some salient results and presented future developments planned for TCV.

The celebration was preceded by guided tours of the tokamak and more than 350 highly interested guests participated. The tours were led by SPC members, especially PhD student and postdocs. The participants had the opportunity to admire the transformation by an artist of old TCV reports in genuine works of art, and, in parallel, to the first viewing of the impressive 3D-visualisation of thousands particles flying in TCV plasmas.



SERVICES AND ADMINISTRATION

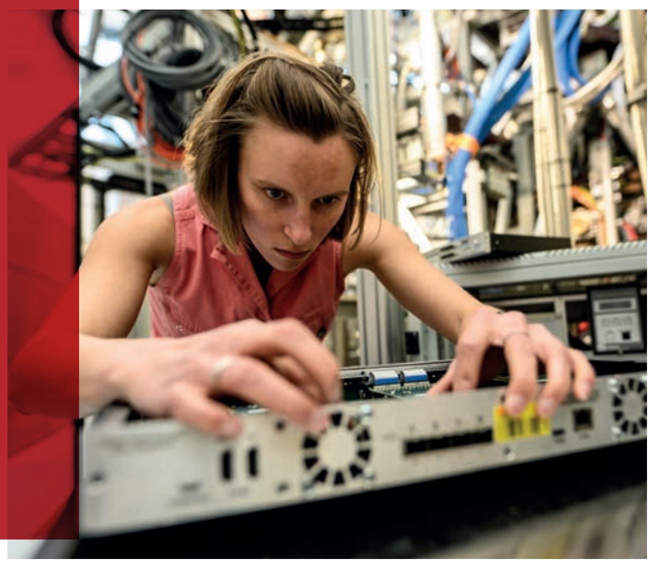
The Swiss Plasma Center could not have reached its objectives without a strong technical and administrative support. All services are continuously solicited to provide the physicists with support of various kinds and are requiring a broad range of competences.

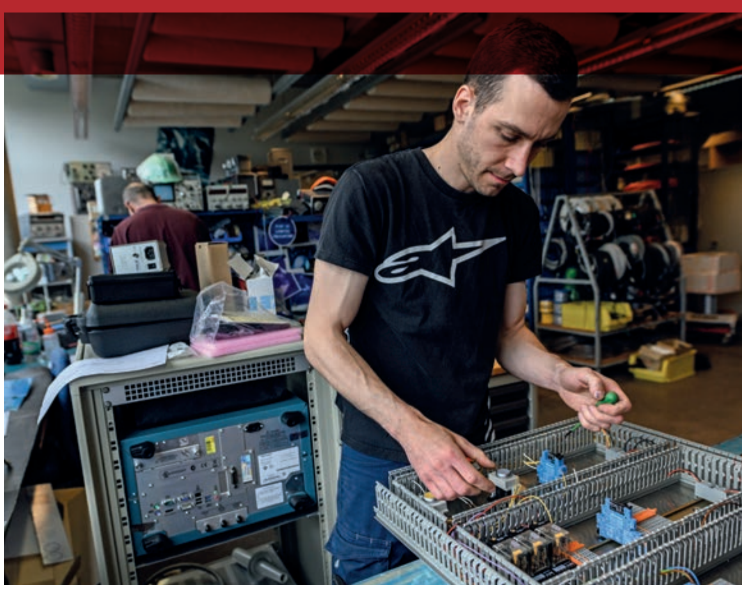
Dr Yves Martin

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

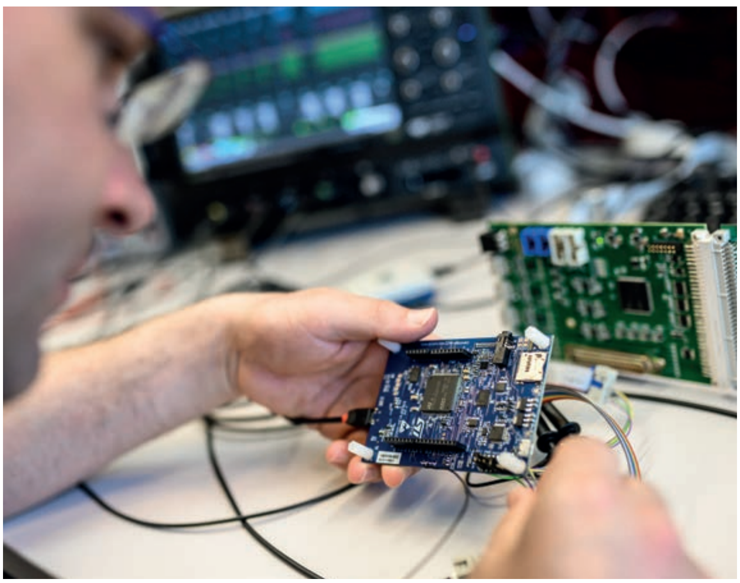
ELECTRONICS

Joan Decker

IT

The shutdowns of the tokamak usually increase the pressure on the services. 2023 was no exception to the rule, with extensive work carried out in and around TCV from January to June. Primarily intended for the installation of walls and a roof to protect against the neutrons, a task subcontracted to external companies, the 2023 shutdown heavily involved our services.

All equipment located against or near the walls had to be removed before the installation of the new walls and replaced afterwards. It included several cabinets containing the control and data acquisition systems for a large variety of systems, such as vacuum, glow discharge cleaning, diagnostics, neutral beams and microwave heating systems. For the latter, one of the two overhead platforms was fully redesigned to accommodate the new path of the waveguides coming from the gyrotrons. All equipment also had to be protected against the dust generated by the work.



We took this opportunity to change all the pads supporting the 8 external plasma shaping coils (PF coils on the low field side). The reason is that these pads became brittle after more than thirty years. But, as these coils are located inside the toroidal field coils in TCV, almost all the heating and diagnostic systems attached to the ports had to be removed to allow access to these pads, and then remounted.

Moreover, a revision of the fly-wheel generator took place during this first semester of 2023. It meant a major commitment of the electrical service to work together with the subcontracting company to remove the rotor for expedition to the testing facility and its reinstatement afterwards.

On the TORPEX side, the design, manufacture and installation of a glass sector with a bird cage antenna around it was a major upgrade, involving all services. The mechanical service for the design, manufacturing and procurement, the vacuum service for its installation, the electronic and electric services for powering and controlling the antenna and the IT service for its inclusion in the TORPEX control system.

PEOPLE, FACTS AND FIGURES

Prof. **AMBROGIO FASOLI** was appointed as the new EUROfusion Programme Manager by the EUROfusion General Assembly on 18 July 2023 following a rigorous selection process. His tenure will officially commence on the 1st of January, 2024.

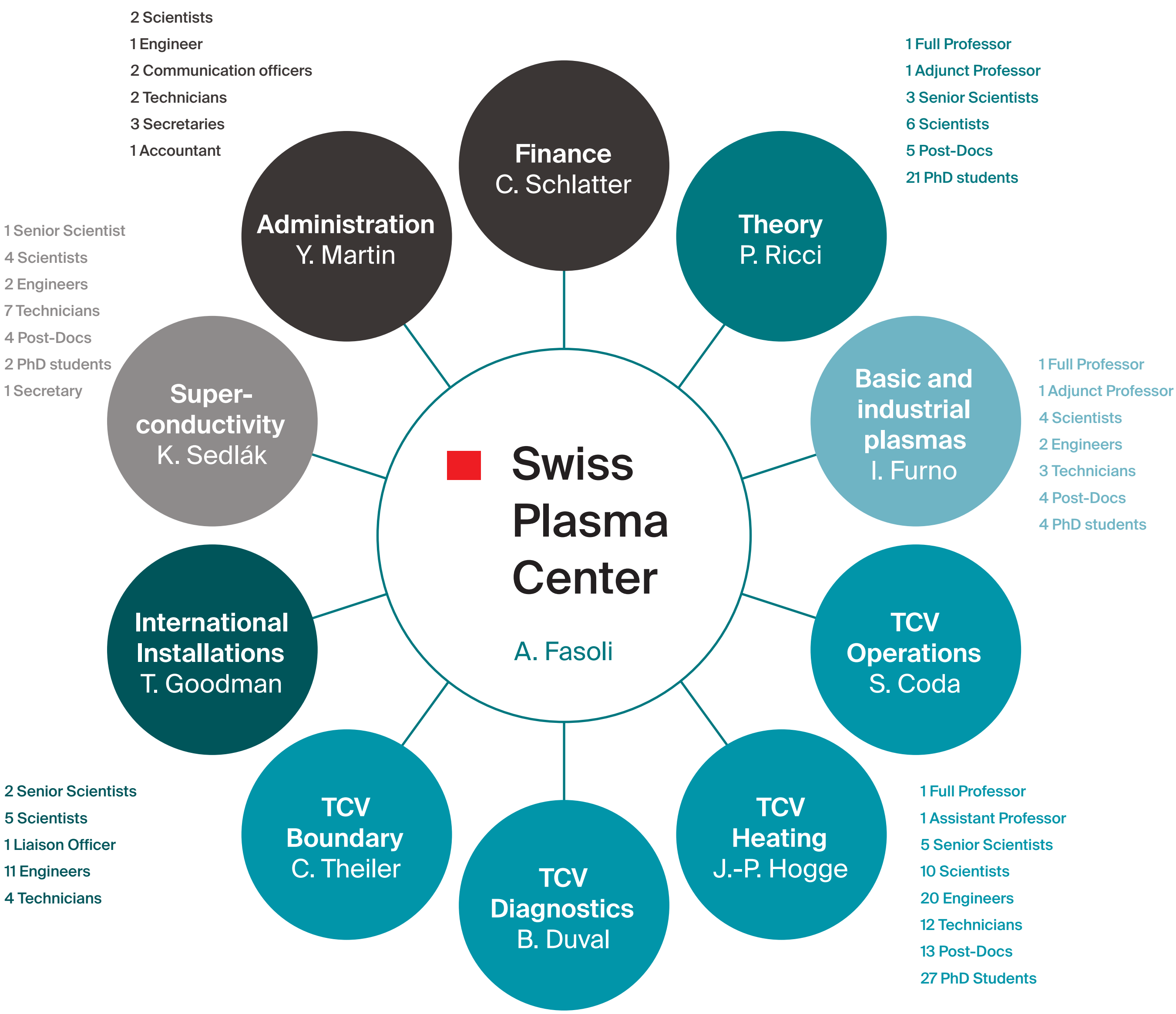
Prof. **PAOLO RICCI** was promoted to Full Professor of Plasma Physics at the School of Basic Sciences (SB), starting from the 1st of October 2023.

Prof. **JONATHAN GRAVES** was appointed as the new Editor-in-Chief of Plasma Physics and Controlled Fusion, a major scientific journal.

HUMAN RESOURCES

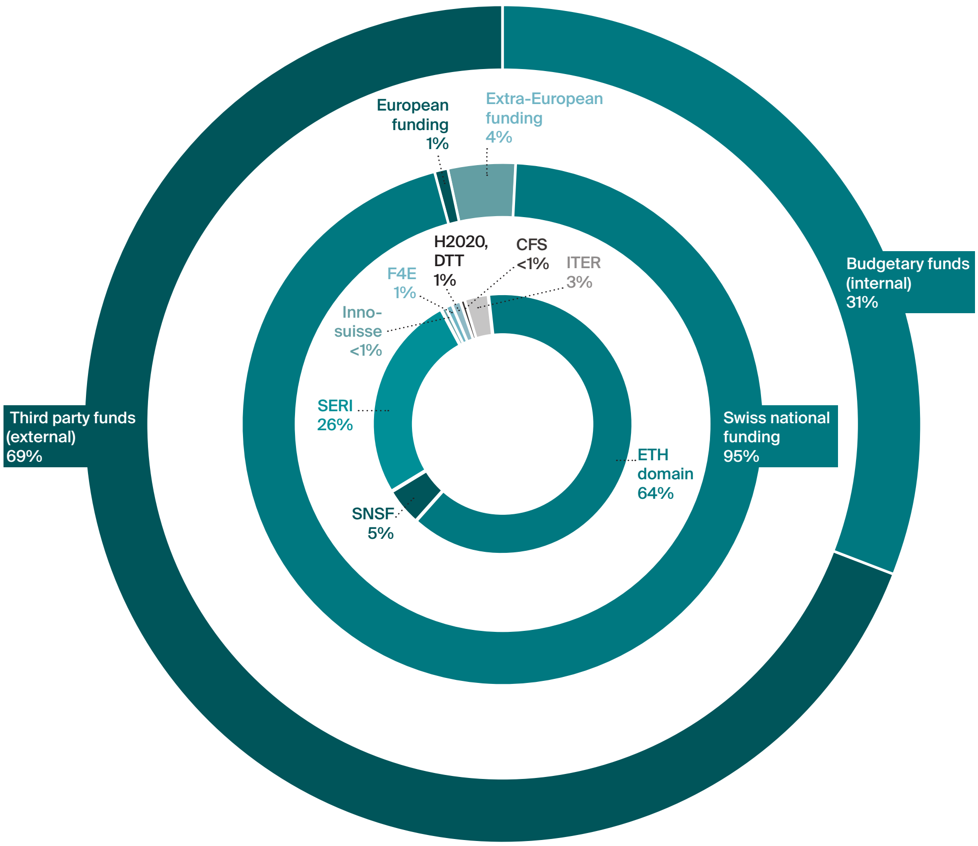
212	Total headcount
180	Full-time Equivalents
52	PhD students (FTE)
33	Post-Docs (FTE)
28	Collaborators joined SPC in 2023
23	Collaborators left SPC in 2023
35	Nationalities represented in SPC staff

STRUCTURE

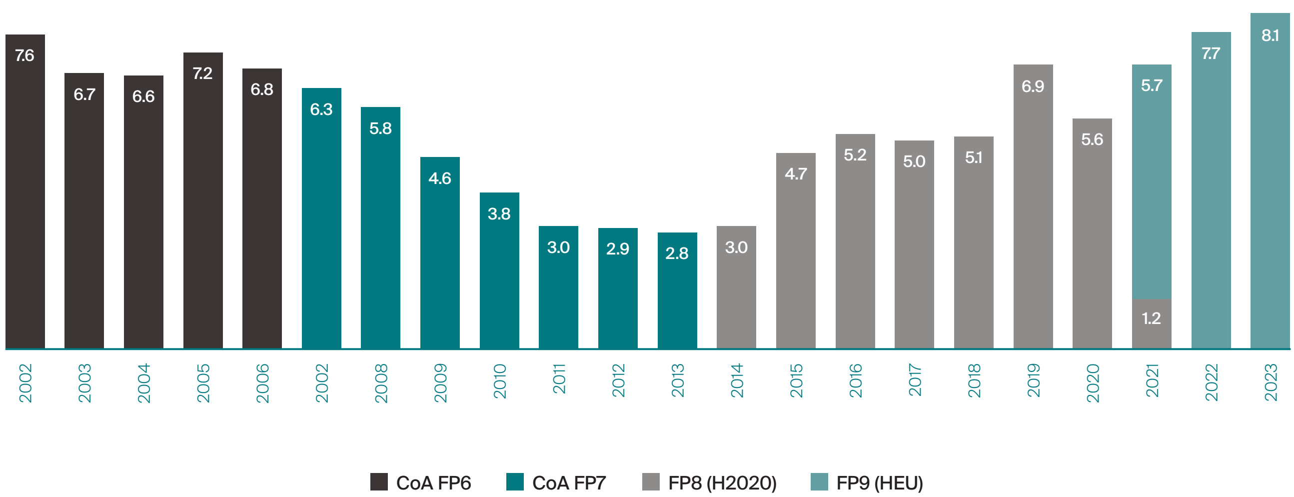


FUNDING 2023

including indirect costs



EURATOM FUSION CONTRIBUTION TO EPFL [MCHF]



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PRINTING EPFL Repro, Switzerland - Certified myclimate

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