ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

SWISS PLASMA CENTER

Annual Report 2015

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1 INTRODUCTION

1.1 Extra-European developments in 2015

ITER construction is in full swing. Significant progress has been achieved in key components, some of which have been delivered to the site, and in major elements of the infrastructure, including the completion of the roof of the tokamak assembly hall, and the poloidal field coil building. Major changes were implemented to the management of the ITER International Organisation by Dr. Bernard Bigot, the new Director General, to improve the efficiency of the project. In 2015, Dr. Bigot also performed a substantial revision of the ITER project planning and budget, which will be translated into a new project baseline plan by mid-2016.

In parallel with the ITER construction, several ITER partners, in addition to EURATOM, are deploying significant efforts towards the realization of a prototype of a commercial fusion reactor, DEMO, in the next decades, which underlines the existence of a broad international consensus on the industrialization of fusion energy in the second half of the 21^{st} century.

1.2 Developments in 2015 at the European level

Since 2014, fusion research in Europe is conducted in the frame of the EUROfusion Consortium, within the 8^{th} EU Framework Program on Research and Innovation, referred to as Horizon 2020. The EUROfusion program follows general guidelines described in the document "EFDA Roadmap to the realization of fusion energy", with the aim of obtaining the first production of electricity by a fusion reactor by 2050. The Roadmap foresees a spectrum of R&D activities including physics studies and technology developments for ITER and DEMO, and also education and training for the ITER and DEMO generations of fusion scientists and engineers. On the basis of a Grant Agreement EUROfusion receives from the Euratom Horizon 2020 program 424 million to manage the European Fusion Program from 2014 to 2018. About the same amount comes from Member States, adding up to an overall budget of 850 million for five years. The Joint European Torus, JET, is operated as a common facility for researchers across Europe. A 283 million euro operation contract signed between the European Commission and the Culham Centre for Fusion Energy (CCFE) in July 2014 secures JET operation until 2018.

The EUROfusion work program is organized into two departments, one focused on ITER physics, the other one on Power Plant Physics and Technology, i.e. on DEMO developments. A key work package in the ITER Physics Department is dedicated to experimentation on the three medium size tokamak (MST) devices that are judged essential for the Fusion Roadmap, Asdex-Upgrade (IPP – Germany), MAST (CCFE – UK), and TCV (EPFL - Switzerland). About 400 European researchers participate in the MST activities. In January 2015, a general planning meeting was held in Lausanne to form the common scientific program on these devices and on JET. In the course of the year, experiments were then run in this international context for the first time on Asdex-Upgrade and on TCV.

The past year was also marked by the first plasma experiments, on December 10, on the world's largest stellarator device, Wendelstein 7-X, in Greifswald (Germany), whose construction took almost two decades. The 16-m-wide Wendelstein 7-X has the crucial goal to assess the potential of the stellarator concept for a future fusion power plant, and verify if the plasma performance in optimized stellarators can reach that of tokamaks of comparable size.

With ITER being the backbone of the European Roadmap to fusion, contributing to the ITER construction continues to be the major priority for the European fusion program. Europe is responsible of the largest share of ITER construction costs and is in charge of the crucial elements of the machine and its infrastructure, including the vacuum vessel and the tokamak buildings. The European participation to ITER is under the responsibility of the European Joint Undertaking for ITER and the Development of Fusion Energy, referred to as Fusion for Energy (F4E), in Barcelona. In 2015, the F4E management was changed and, after a period of interim direction by Dr. Pietro Barabaschi, Mr. Johannes Schwemmer was appointed as the new Executive Director.

1.3 Developments in Switzerland: from the CRPP to the Swiss Plasma Center

In 2015, a historical event marked the life of our institution: the Center for Research in Plasma Physics (CRPP) has become the Swiss Plasma Center (SPC). The change in the name is associated with significant improvements in its facilities and with an enlargement of the scope of its research. The Swiss Plasma Center will use ad hoc investment funds from the Swiss Confederation and new nation wide synergies in academia and industry to reinforce the impact of Switzerland in fusion research for ITER and DEMO, with further significant upgrades to the TCV tokamak systems, but also to expand research activities in space plasmas and and astrophysics, environmental and industrial applications of plasmas. Developments in the TCV infrastructure will be undertaken to increase the DEMO relevance of its research lines. A major component of these upgrade plans is the creation of an in-vessel divertor chamber of variable closure to contribute to the crucial problem of the exhaust in fusion reactors and in particular to closing important gaps in the qualification of alternative divertor concepts for DEMO. The in-vessel chamber will be complemented by a high capacity cryopump and a set of gas valves to enhance particle control, and possibly by additional poloidal field coils (made of high temperature superconductors) to increase the range of accessible divertor configurations and improve the relevant control capabilities. The divertor upgrade will complement a set of major improvements to the TCV infrastructure, which includes the installation of additional plasma heating systems. The heating upgrade is conducted in two steps, one presently under way and another foreseen in 2017-2020. One component of the first step has recently been completed with the installation of a 1MW 15-30keV NBI. The first step also includes acquisition of two 0.75MW gyrotrons for ECH/ECCD at the 2nd harmonic (87GHz), of which one is being commissioned. The second step consists of the installation of a 1MW, ~50 keV beam, for the study of important questions of burning plasmas, plasma rotation and fast ion physics, and two 1MW dual frequency gyrotrons, (83GHz and 126GHz).

On TCV, the year 2015 has marked the first campaigns conducted and financially supported in the international frame of the MST EUROfusion work package, with the participation of 77 scientists from all over Europe and overseas.

Naturally, the Swiss Plasma Center continues to contribute to the other scientific and technological activities of the EUROfusion consortium, as well as the ITER project, through the European domestic agency F4E, at its two sites, EPFL and the PSI. At EPFL, research focuses on the physics of magnetic confinement, with the TCV tokamak, the basic experiment TORPEX, theory and numerical simulation, plasma heating and current drive technology. At PSI, the focus is on superconductivity, in particular to qualify the ITER conductors in the frame of a large contract with the ITER International Organisation, and to develop conductors for DEMO, in the frame of the EUROfusion Power Plant Physics and Technology. The Swiss Plasma Center also participates to the experiments on JET, which to this date remains the largest operating magnetic fusion experiment in the world. Three members of the Swiss Plasma Center act as Project Leaders or Deputy Project Leader of EUROfusion work packages.

Following the foot steps of the CRPP, the Swiss Plasma Center continues to have an important role in education, with about 30 PhD students, and several classes offered at a variety of levels on the physics of plasmas, fusion, and related technologies, at EPFL and in the context of the European wide education initiative Fusenet. In addition, members of the Swiss Plasma Center have launched in 2015 the first Massive Open Online Course on Plasma Physics and Applications, using the US-based EdX platform, to which more than 6’000 students worldwide have enrolled.

2 PROGRESS REPORT

2.1 The TCV tokamak

2.1.1 Tokamak physics

The TCV tokamak facility underwent a lengthy shutdown from November 2013 to September 2015 (except for a short operation period in June 2015), for major modifications to the vacuum vessel in view of the installation of two neutral beam injectors, as well as several upgrades to diagnostics and to the facility infrastructure. The first neutral beam injector was delivered in the summer of 2015. A phased commissioning has taken place since then and is currently nearing completion. A second injector is planned as part of a major upgrade to be effected over the next four-year period.

Initial operation in June and September 2015 was devoted to testing and recommissioning. On 5 October began the first TCV campaign carried out under the auspices of the Medium-Size Tokamak (MST) Task Force within the EUROfusion consortium, in parallel with the internal part of the campaign. The latter, though funded internally, remains entirely open to international collaborations. The all-important Ph.D. thesis work, which in recent years has occupied over 50% of the experimental time of TCV, is primarily scheduled within the internal programme.
Substantial upgrades in the data-acquisition and plant-control hardware and software have reduced the shot cycle substantially. In addition, we have adopted a more flexible mode of operation in which two or more experiments are scheduled for any given day and shots are assigned to them alternately, in the most efficient way possible. As a result, the daily shot count is steadily increasing, and TCV's attractiveness is rising as a device on which to thoroughly test new ideas and theories. In the October-December campaign, the shot count was 587 for MST and 197 for the internal programme.

A vigorous effort has been expended on tackling the most worrying problem for ITER, i.e., disruptions, an understudied issue up to now in TCV. In addition to exploring techniques for disruption mitigation or avoidance (by massive gas injection or ECCD, and with assistance from real-time modeling), the related problems of runaway electron (RE) generation, mitigation, and control were also tackled. The sustainment of a steady RE beam during the discharge flat top has proven easy and robust (at an electric field one order of magnitude larger than the Dreicer field), providing a dataset for the validation of Fokker-Planck modeling. A disruption-generated RE beam can also be obtained by noble gas injection, preferably at low density to benefit from a pre-existing RE population. In cases in which a RE current plateau – initiated by the large loop voltage in the current quench phase – is observed, a new controller was tested successfully to effect a smooth current decay using the Ohmic solenoid. In one remarkable case, the controller sustained a slow decay of an essentially purely RE plasma at nearly zero loop voltage, without any of the MHD instabilities that must indeed be avoided in ITER in this phase. The usual position controller is sufficient for avoiding interaction with the wall.

Investigations of the density disruption limit have continued, in particular to explore its dependence on gas puffing and plasma shape. The broader issue of high-performance operation, with high confinement and tolerable ELMs, in the proximity of the density limit has also been taken on board in this campaign. Disruption prediction efforts are being deployed on many fronts, not least by using the real-time transport code RAPTOR (albeit so far in an offline analysis capacity). In particular, the telltale sawtooth character change before a density-limit disruption (sawteeth often simply disappear) is being used as a trigger to the simulation, which was able to predict the onset of a disruption successfully in several shots.

Neoclassical tearing modes (NTMs), which can also lead to disruption and limit performance, have been studied in their basic physics mechanisms as well as to develop control strategies. In recent TCV discharges the rotation profile was modified by ECRH-induced torque, leading to NTM excitation with no detectable seed islands, a scenario that could be problematic in a reactor, annulling the effect of sawtooth control. A theoretical framework is being advanced to describe this phenomenology.

Edge physics and particularly the search for a solution to the exhaust problem in a prospective fusion power plant is currently an area of intensive experimentation in TCV. Access to divertor detachment has been investigated through density ramps and nitrogen puffing, first revisiting the conventional single-null divertor. then proceeding through the variety of alternative geometrical divertor configurations that TCV can sustain, including the X-divertor (with increased flux expansion), X-point target (with a secondary X-point near the target), and the snowflake “minus” and “plus” (differing by the relative position of the secondary X-point) (Fig. 2.1.1). These studies have been performed thus far only in Ohmically heated L-modes and with “reverse” toroidal magnetic field, resulting in a ∇B drift away from the X-point, which empirically is seen to facilitate detachment. The availability of neutral-beam injection will now permit us to extend this work to high-power heating.

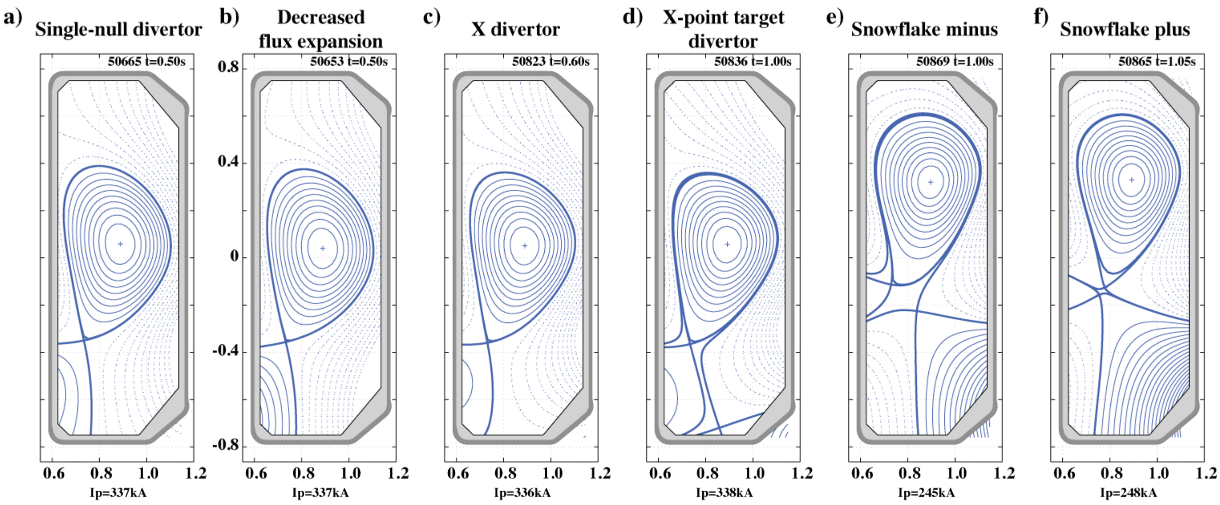


Fig. 2.1.1 *A selection of achieved divertor configurations on TCV: (a) the standard TCV single null divertor (SND), (b) a SND with lower flux expansion, (c) an X divertor, (d) an X-point target divertor, (e) a LFS snowflake minus (SF-) and (f) a snowflake plus configuration.*

As the exhaust problem, and particularly energy release to the plasma-facing wall components, is largely determined by transport in the scrape-off layer, experiments have also been conducted to investigate such transport, and particularly the enhanced convection that leads to profile broadening at high density and that is generally attributed to intermittent filamentary structures. The large range of flux expansion at the outer target that can be explored in TCV has permitted a significant attendant variation in parallel connection length in L-mode plasmas, and detailed probe measurements have been collected for further analysis.

As the transient loads from Edge Localized Modes (ELMs) are ultimately the most dangerous to the wall (aside from disruptions), experiments have also started on ELM mitigation and pacing, using both ECRH and magnetic perturbations. Continuous developments in the TCV plasma control system capabilities are crucial to these efforts. A significant recent achievement is the deployment of a generalized plasma shape and position controller, directly based on real-time, sub-ms equilibrium reconstruction. Initial results have been successful and the controller is set to be tested on increasingly complex geometries, including ones with negative triangularities and advanced divertors. In parallel, work has continued in the quest to improve the reliability of plasma breakdown, through control strategies that are gradually delivering an increased understanding of the relevant parameter space.

2.1.2 TCV heating systems

TCV ECH/ECCD system

The Electron Cyclotron (EC) system on TCV, in the 2015 configuration, is composed of 4 gyrotrons (82.6GHz, 0.5MW/each, 2s pulse duration) used for electron cyclotron heating (ECRH) and current drive (ECCD) at the 2nd electron cyclotron harmonic in the X2-mode, and 3 gyrotrons (118GHz, 0.5MW/each, 2s) used for 3rd harmonic heating in X3-mode. The gyrotrons are connected to the various quasi-optical launchers via low-loss evacuated waveguides. The launcher design allows for the control of 2 degrees of freedom, with one of them controllable in real-time. Specifically for the X2-launchers, the EC-wave polarization is remotely settable between plasma shots.

The Neutral Beam injector installation and commissioning prevented any TCV operation up to the beginning of the MST1 campaign started on October 2015. During the TCV shutdown time, the EC system was not operated.

EC-system activity in 2015

The EC-system has been extensively and successfully used during the above mentioned MST1 campaign. Within this campaign and thanks to the very high level of automatization of the global EC-system, new EC-operators have been trained and became operational on a very short time scale (a few weeks).

As mentioned in last year report, in view of maintaining the X2 power at a level compatible with the TCV scientific mission, two new gyrotron units with enhanced performances (82.7GHz/750kW/2s) have been purchased. The first gyrotron has been delivered and its commissioning is nearly completed. It will be extensively used during the 2016 MST1 campaign starting in April. The second gyrotron will be operational on TCV by October 2016.

For the X3-system, one of the gyrotron superconducting magnets developed a vacuum leak, therefore reducing the X3-power availability to 2 gyrotrons (i.e. 0.9MW). A replacement magnet has been borrowed from CEA-Cadarache and will be operational, together with the gyrotron, by April 2016.

Upgrade of the EC system

X2-X3 upgrade

During 2015, the design activity of the dual-frequency gyrotrons in collaboration with Karlsruhe Institute of Techmology (KIT) and the European Gyrotron Consortium (EGYC) has been intensively pursued. The gyrotron design is practically finalized, and its main design parameters are summarized in Table 2.1.1. It is important to notice that a rf-power in excess of 1MW is predicted by the numerical simulations at both frequencies.

In parallel with the design activity a contract between Thales Electron Devices (TED) and EPFL has been negotiated. This contract has been finalized and signed by the end of 2015 and includes the procurement of two dual-frequency gyrotrons as specified in Table 2.1.1.

Operating cavity mode	$TE_{17,5}$	$TE_{26,7}$
Frequency [GHz]	84 (83.91)	126 (126.16)
RF output power [MW]	1 (1.05)	1 (1.2)
Pulse length [s]	2	2
Cavity wall-loading [kW/cm^2]	2 (1.1)	2 (2.1)
Beam current [A]	40 (40)	40 (40)
Beam energy [keV]	(78)	(78)
Accelerating voltage [kV]	81	81
Mod-anode voltage [kV]	(-38)	(-26)
Pitch angle, α	1.2-1.3(~1.3)	1.2-1.3(~1.3)
Cavity magnetic field, [T]	(3.31)	(4.98)
Electronic efficiency [%]	(35)	(41)
Gaussian content [%]	97 (97.7)	97 (97.6)

Table 2.1.1 *Gyrotron specifications for the TCV Dual-frequency gyrotron. In parenthesis are the present design parameters. The gyrotron will be operated without depressed collector.*

A schematic layout of the transmission line reconfiguration needed for integrating the two dual-frequency gyrotrons is shown in Fig. 2.1.2.

The X2-X3 upgrade updated project time schedule is as following:

a.	Contract Signed	December 2015
b.	Contract enforced	March 2016
c.	First gyrotron commissioning at SPC	Sep-Oct 2017
d.	Second gyrotron commissioning at SPC	March 2019
e.	Completion of X3-upgrade project	Apr-May 2019

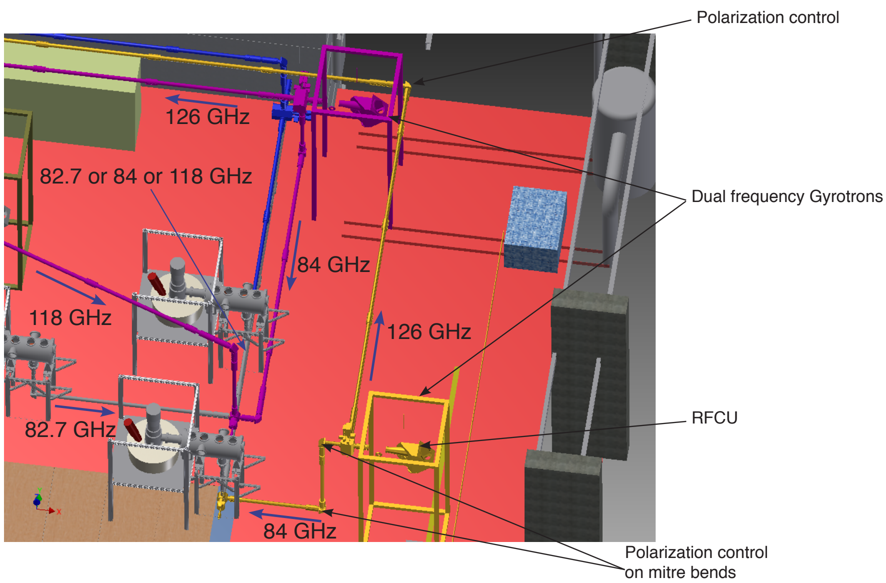


Fig. 2.1.2 *Design of the transmission line reconfiguration for the two dual frequency gyrotrons. Depending on the frequency generated (126 or 84GHz), the mm-wave radiation is directed via high-power switches towards the corresponding existing transmission lines for top-launch (X3 @ 126GHz) or low-field-side launch (X2@82.7/84GHz or X3 @118GHz). The real-time polarization control will be made by polarizers placed in the mitre bends as foreseen in the ITER transmission lines.*

First TCV Neutral Beam Heating Installation

Since the TCV's initial operation in the early 1990's, TCV auxiliary heating has centered around ECH electron systems, as described above. The low electron densities accessible for X2 heating and the higher electron temperatures required for high X3 absorption remains challenging in many plasma configurations of interest. Furthermore, particularly at low plasma densities, ECH heating further decoupled electron and ion populations, resulting in low ion temperatures. Calculations show that with 1MW of Neutral Beam Heating (NBH), all these situations can be remedied. Moreover, it can provide access to new regimes with direct momentum injection affecting plasma rotation, higher ion than electron temperatures, and, with hotter electrons, improved X3 ECH absorption.

In the first stage of this TCV upgrade, a single 1MW neutral beam was installed on TCV in 2015 with a second 1MW system planned during the upcoming TCV upgrades. Although much of the 2013-2015 TCV opening was devoted to the installation of new ports for the new NBH injectors, the initial beam commissioning started towards the end of 2015. Due to the relatively small size of the TCV vessel and surrounding toroidal magnets, physical space and access to the TCV plasma was always going to be problematic. Furthermore, first wall protection in the form of slow thermocouple temperature surveillance and fast surveillance of the surface temperature of TCV's internal surfaces was mandatory before beam injection into the vessel could be permitted.

Thus, most of the work in 2015 was dedicated to terminating the in-vessel modifications, in-vessel NBH related diagnostics and in the installation of the neutral beam itself.

In-vessel monitoring

The goal of the pyrometer inner vessel tile observers is to ensure the tile surface temperatures do not exceed the damage threshold. When the beam is successfully launched into the plasma, it is, hopefully, mostly absorbed by the plasma (resulting in plasma heating). One basic machine protection, also implemented for ECH heating is to provide upper and lower plasma density limits that gate NBH power injection. Direct plasma radiation is problematic for Infra-Red (IR) tile surface temperature measurements. To obtain reliable IR measurements, optical light collection systems were equipped with spectral filters to reduce direct plasma radiation yet retain sufficient sensitivity to thermal IR radiation. Fig. 2.1.3 shows the final calibrated temperature sensitivity of the pyrometer systems that feature a 2-4ms temporal resolution.

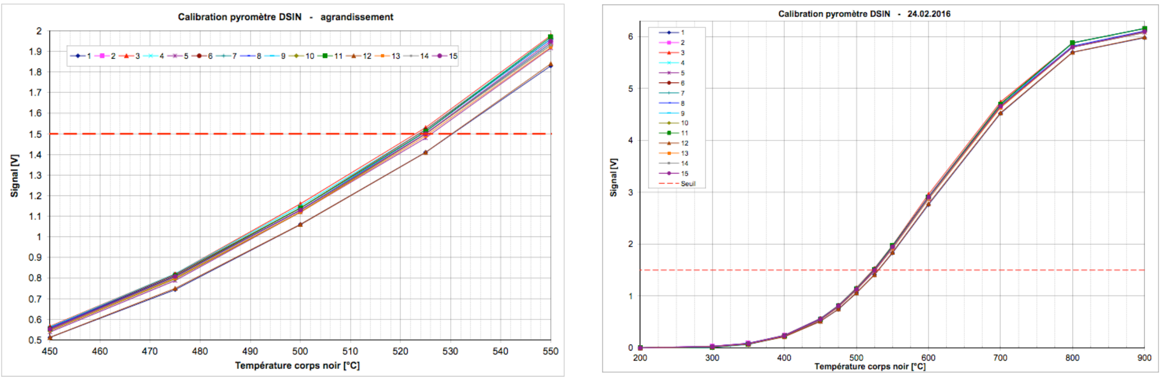


Fig. 2.1.3 *Calibrated pyrometer voltage output as a function of blackbody temperature. Left image shows a zoomed view of the lower temperature response and the horizontal red dashed line indicates the voltage threshold used to interlock NBH power injection.*

Three regions in-vessel were identified as most vulnerable to fast surface overheating, Beam entry into the vessel, the central column tiles on the beam trajectory and the wall opposite beam entry that, in the absence of plasma, would receive most of the beam power.

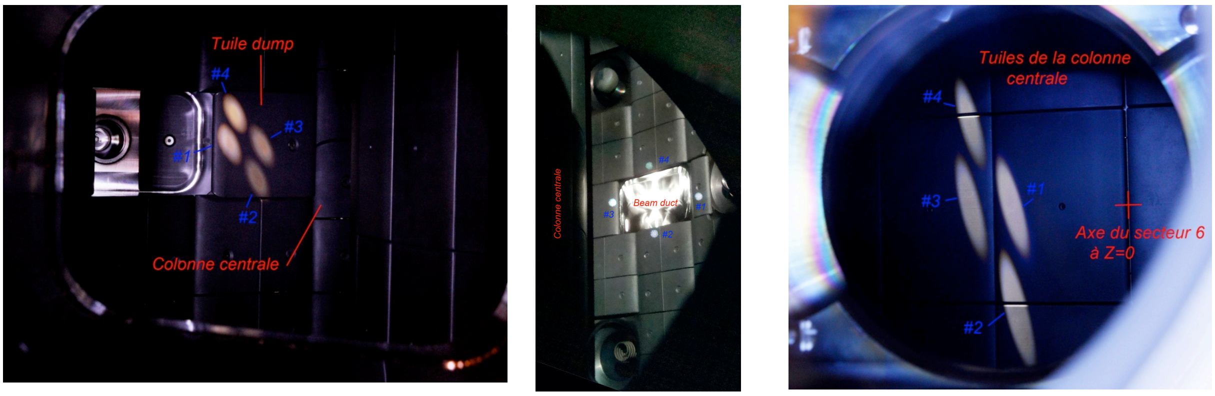


Fig. 2.1.4 *Photographs of, pyrometer measurement locations at beam dump (white circles), beam entry (the 'duct') and the images on the central column.*

By the end of 2015, the NBH and TCV vacuum systems were complete and NBH power was applied to the movable, in-line, calorimeter. Initial operations indicated some relatively minor design problems with the calorimeter and possibly beam divergence that slightly postponed the first beam injection into a TCV plasma to early 2016.

2.1.3 TCV Diagnostics

Most of 2015 remained dedicated to terminating the installation of the first of two 1MW class Neutral Beam Injectors, thus strongly reducing the time available for modifying TCV's diagnostic array. Despite this situation, several major diagnostics continued their planned upgrades and other, smaller, systems were installed and/or developed. TCV's MST campaign, in collaboration with a large number of external scientists, required the installation and/or verification for a large range of diagnostic systems. The diagnostics and interlocks associated directly with the Neutral Heating Beam installation, together with the machine protection system, are described in the heating section so here only the work on plasma diagnostics is described.

Thomson Scattering

The final calibration, installation and commissioning of 24 new spectrometers, part of an upgrade launched in 2013, was completed in 2015 providing a spatial coverage never achieved before on TCV with 47 spectrometers installed as shown in Fig. 2.1.4, left.

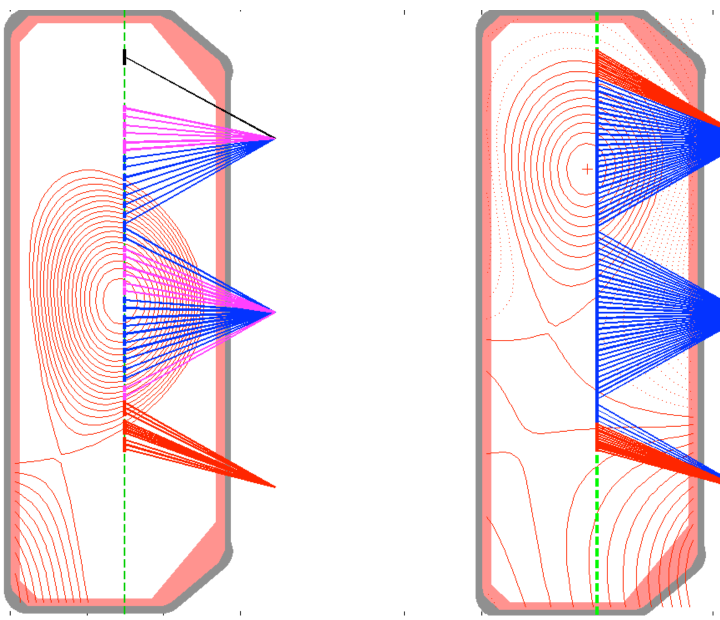


Fig. 2.1.4 *Coverage of the TCV poloidal cross section by Thomson Scattering observation volumes.* ***Left****: during the 2015 MST1 experimental campaign with enhanced resolution obtained with the 6 red lines of sight situated in the middle of the red array at the bottom of the figure.* ***Right****: EUROfusion upgrade proposal*

Following the December 2014 approval of our proposal to the EUROfusion call for participation in ITER Physics Work Package, a comprehensive Project Management Plan describing in details the proposed upgrade of the TCV Thomson Scattering (TS) was sent to EUROfusion for approval. This enhancement main aim is to improve substantially the spatial resolution of TCV TS system in the plasma edge with the primary goal of achieving a spatial resolution of ~1% of the minor radius, i.e. ~2.5 mm, in the outer magnetic midplane of an H-mode pedestal region. EUROfusion will fund the manufacture of up to 40 new spectrometers with a new optical fibre system and the necessary manpower to achieve this upgrade (281kEuros and 1.9ppy for SPC). The proposed spatial coverage is shown on fig. 2.1.4, right.

For this project, new test fibres were procured and installed on TCV providing enhanced spatial resolution in the pedestal region during the 2015 TCV MST1 campaigns as shown in Fig. 2.1.5.

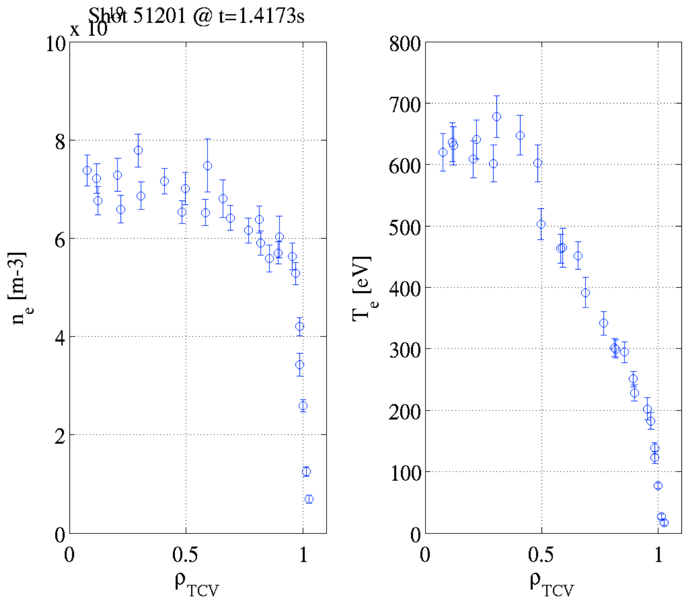


Fig. 2.1.5 *Experimental electron density (left) and temperature (right) as a function of normalised radius for the H-mode configuration in TCV discharge #51201 demonstrating a sufficient resolution for full pedestal characterisation.*

Performance evaluation with these fibres showed promising results and we propose to use similar fibres for the complete upgrade. During the second half of 2015, procurement activities for the new spectrometers were initiated with orders placed for the APD detectors, interference filters and optical components.

Infrared Cameras

The IR imaging diagnostic was upgraded to take advantage of the NBI heating upgrade and improve the heat flux measurements in snowflake and other alternative divertor configurations. It includes the installation of a new horizontal IR system (HIR) with two alternative views and the upgrade of the vertical IR system (VIR) with an expanded set of thermocouples within its field of view. Two IR windows were installed in sector #7 with the midplane port using re-entering flange that allows for the same large field of view as the lower port, Fig. 2.1.6.

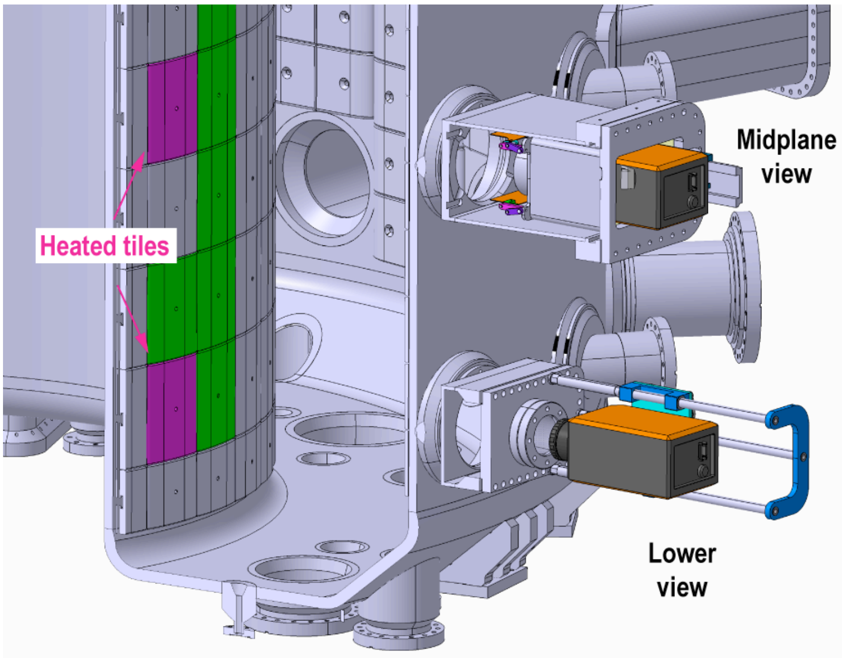


Fig. 2.1.6 *Cut through sector #7 showing the two alternative views of the new HIR diagnostic.*

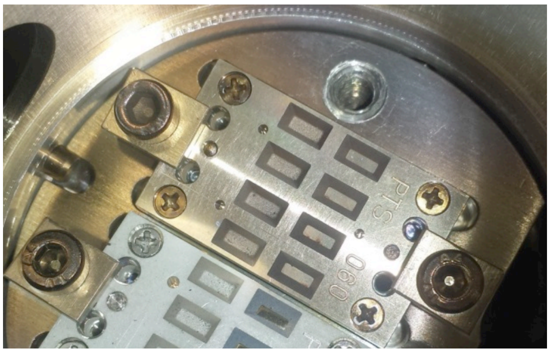
Both horizontal views include a heated tile for in-situ calibrations of the camera. All tiles in both fields of views were equipped with thermocouples (TCs) for a comparison/calibration of the IR thermography heat flux estimates with tile calorimetry.

Similarly, the set of floor tiles in the FOV of the vertical system that are equipped with TCs, was extended to also include the tiles covering the fast coil.

A fast MWIR camera (IRcam Equus 81k) together with a 12.5mm and a 25mm IR lens were purchased for the HIR diagnostic. The upgraded system has been commissioned and is already in use in the on-going TCV campaign

Bolometers

In 2015 a detailed study of gold foil surface reflectance and overall condition was undertaken using the bottom camera of the bolometry array. From visual inspection, it was evident that there was foil damage due to ECRH. A blue laser diode was used to investigate any variation in measured incident power resulting from the damage observed on foils and to provide a relative optical calibration. The relative measured power from the laser was within 7%, which was excellent given the uncertainty in laser position and consequent variation in incident power. From this study it was concluded that the current foil bolometers provide excellent relative measurements and can therefore be reliably used for tomographic inversions Fig. 2.1.6.



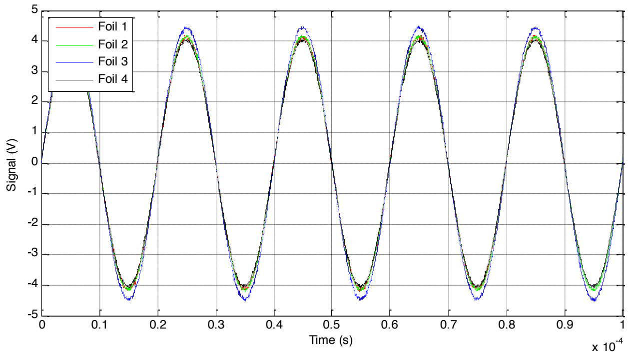
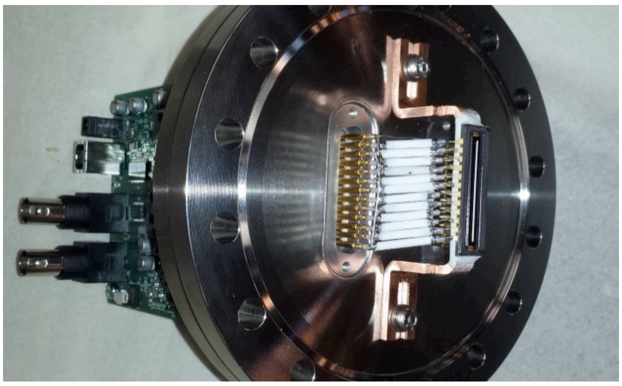


Fig. 2.1.6 *Left - Close up image of the foils with apparent damage on foil 3. Right – Measured incident power by each foil during calibration with a maximum peak to peak variation of 7%.*

SPRED (Survey, Poor Resolution, Extended Domain) UV Spectrometer

During the recommissioning of SPRED UV spectrometer the detector, previously used on the system, was discovered to have become opaque and unresponsive. A detailed investigation into possible alternatives was carried out and a custom CCD detector to be built in-house was selected. This was preferred over the previously used microchannel plate technology as it significantly relaxes high vacuum, high voltage and magnetic field constraints. Furthermore, the new system was designed to significantly improve the spectral and temporal resolution provided by SPRED. Testing revealed that the detector purchased did not perform to the manufacturer's specifications and was not even able to detect vacuum ultraviolet photons. In continuation of the choice of a solid-state detector a commercial CCD camera was physically tested on the SPRED with excellent results. This camera (Fig. 2.1.7) was ordered and is planned for installation on TCV by mid-2016.



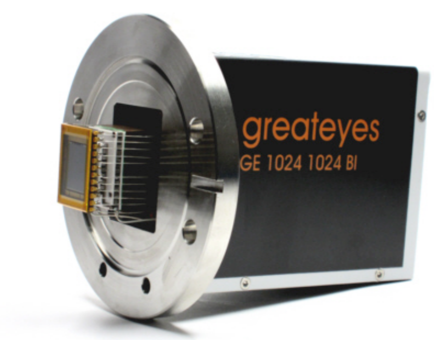


Fig. 2.1.7 *Left – Custom built detector. Right – A variation of the ordered commercial detector.*

Photomultiplier Tube for Hard X-Rays (PMTX)

The PMTX system was repaired and reinstalled during 2015. The repairs addressed issues with the high voltage power supply and electronics driving the photomultiplier tube itself. The PMTX system was crucial in a number of runaway electron experiments carried out over the past year and performed very reliably. The

PMTX is now operating on every TCV discharge with minimal input required from the diagnostics team.

Disruption Mitigation Valve (DMV)

The DMV system went through a major overhaul in 2015. It was redesigned to provide over an order of magnitude higher flow rate and significantly improved control of gas injection times. These improvements were achieved through the removal of the skimmer and turbo pump section, which generated a large volume of trapped particles that slowly entered the tokamak after the programmed gas pulse. The upgraded system is capable of a large range in gas quantity of precise gas puffs through the variation of the supply pressure. This has led to the DMV becoming a critical system for impurity transport and disruption experiments (Fig. 2.1.8).

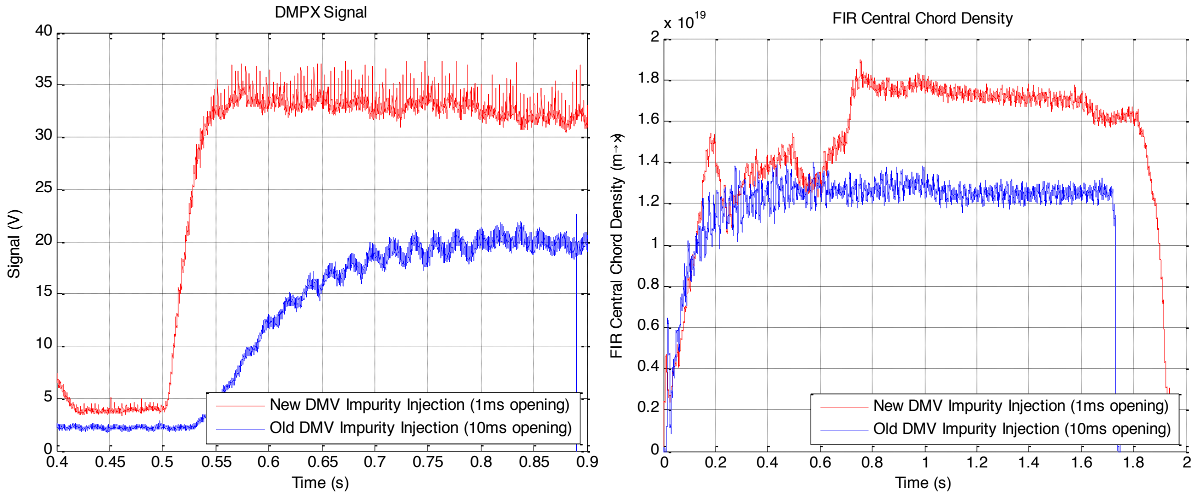


Fig. 2.1.8 *Left – DMPX signal traces during shots with gas injection using the old and new DMV systems. Timescale shifted to normalise valve opening times.*
Right – FIR central chord density showing a significant increase in plasma density using the new system.

Digital Plasma Control System

The activities done on the SCD (Systeme de Controle Distribue) of the TCV tokamak in 2015 can be summarised by Fig. 2.1.9. On the right side the currently valid Simulink model of the SCD is displayed. 2 new nodes were added (node 06 and node 07) and node 05 (already present in the system) was fully integrated. Furthermore a thorough improvement of the overall real-time code structure and its compilation tool-chain was performed. The three strips on the right part of the figure summarize these aspects.

The first strip displays work performed on the code environment and structure and compilation tool-chain. Simulink code and all other necessary tools (among these configurations, build scripts, TDI scripts and SCD TCV operator tools) are now under a single folder under SVN version control, with a repository on the SCD main control machine. Code is automatically committed before every shot and the revision number is recorded in the Real Time Control MDS+ tree. This enables retrieval of an exact copy of the whole code folder for a particular shot. The compilation tool-chain was further improved in two ways: the singular controllers are now built in a fully parallelized way on the SCD main control machine to reduce compilation time and compilation with MATLAB 2015a is now possible for the new nodes 06 and 07 (the old nodes are still compiled and handled with MATLAB 2012b).

The second central strip displays the Simulink model of node #6. This is a computational node interfaced to the rest of the SCD only though the Reflective Memory link. It has a 6-core CPU Intel Haswell i7-5930X 3.5GHz. Presently four of these CPUs are interfaced to the Simulink model and can be exploited to execute 4 separate control algorithms in parallel during the TCV shot. The node has been tested on real shots at 1ms cycle time with the RAPTOR code on 2 cores (observer and simulator) and an advanced density profile reconstruction code on another one with good results. Another possibility offered by this node is off-line hardware-in-the-loop testing of controller algorithms, using one core as a tokamak simulator (for instance with the RAPTOR code used as a profile simulator) and the others as controllers, with their individual loops closed on the simulation CPU. The right side of the central ribbon of Fig. 2.5.9 displays this technique to test a combined beta and iota profile controller on the TCV tokamak before its actual use for TCV shots.

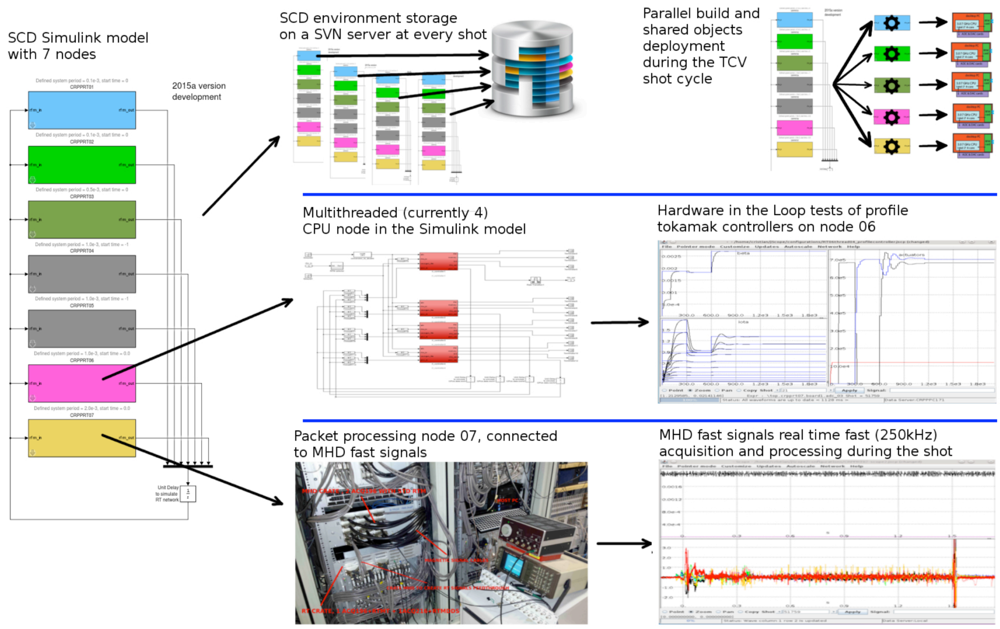


Fig. 2.1.9 *Graphical summary of 2015 SCD activities*

The third strip is related to node #7. This is a real-time diagnostic analysis node, presently interfaced to the magnetic probes. It is capable of acquiring up to 64 channels at 250ksps in packet-processing mode, a modality in which, while the ADCs fill a memory buffer, the previous buffer is delivered to the host CPUs for data processing. This decouples the ADCs sampling frequency from the computation time available to the CPUs enabling fast acquisition and simultaneous and complex real-time analysis on the acquired data. The processing node is an 8-core Intel Haswell i7-5960X 3.0GHz machine able to perform multi-thread processing on the acquired data packets. This system is intended to perform advanced real-time MHD analysis algorithms. As for the other nodes, this node is described by a Simulink model and is interfaced to the rest of the system using the reflective memory network. Acquisition tests have been performed during the TCV shots demonstrating the capability to acquire the magnetic channels and to process them at 2ms cycle time (500 samples per packet). The interface on the reflective memory link is ongoing.

2.1.4 Gyrotron physics

The wave-particle interaction model upon which the nonlinear code such as TWANG-PIC is based has been improved by adding generalized radiation boundary conditions, which are essential for cases where the radiation frequency is not monochromatic and contains well separated spectral lines such as in dynamical After Cavity Instabilities (ACI) and/or non-stationary regimes characterized by a radiation multi-frequency line spectrum (side bands). Extensive benchmarks of TWANG-PIC have been made against experiment and/or other numerical codes based on similar models.

It is important to mention that by the end of 2015, the first results on Dynamic Nuclear Polarization – Nuclear Magnetic Resonance (DNP-NMR) spectroscopy have been obtained using the gyrotron developed at SPC [3]. This important milestone closes a project started in 2008 the results of which, regarding the gyrotron physics, are novel and well beyond expectations.

A very important effort in 2015 has been devoted to the development of a novel linear model based on a spectral approach which has been very successfully benchmarked against experiment using the TWANGlinspec code. To our knowledge this is the most advanced linear model which is suitable for analysing real experimental conditions since it takes into account most of the system parameters inhomogeneities.

Using the different codes of the TWANG-series, the cavity design of the dual-frequency gyrotron (84/126GHz) has been completed. This activity was carried out in collaboration with KIT where the results obtained at SPC have been benchmarked against the ones obtained with the numerical codes developed at KIT.

2.2 Theory

The general objective of the theory group at SPC is to make progress in the understanding of the plasma dynamics in magnetic confinement devices for fusion, in order to provide an interpretation of the experimental results from current fusion experiments and offer suggestions to improve current and future devices. The theory group has very close ties with the TCV group in particular, with a vigorous activity of modeling and interpretation of experimental results.

To get insight into the plasma dynamics state-of-the-art scientific codes are necessary, based on a first-principles approach. The simulations carried out by the group are performed on some of the most powerful computers worldwide and tens of millions of CPU-hours have been allocated to projects led by SPC theory group members; we mention, among the HPC platforms used by the group, the Helios computer at IFERC-CSC and the Piz Daint and Piz Dora computers at CSCS.

Computational expertise of the SPC theory group has been regularly solicited and was used to the benefit of all other research lines of SPC and of other laboratories at the EPFL and worldwide, notably within the European Fusion Programme, through the active participation of one of its staff members to the EuroFusion High Level Support Team (HLST) activities. In the framework of the HLST, a parallel multigrid 2D solver developed for the fluid turbulence code GBS has been improved with the inclusion of the hybrid MPI+OpenMP parallel programming model. In the frame of the PASC project (Platform for Advanced Scientific Computing), we have continued the development of fundamental PIC algorithms for hybrid architectures (CPU+GPU and CPU+MIC). The introduction of sorting, improvement of data locality, and hybrid (MPI+OpenMP or MPI+OpenACC) programming models, resulted in a factor of up to 4 performance improvement for a simplified PIC code. The resulting code demonstrated excellent scalability up to 4096 GPU-equipped compute nodes of the Piz Daint machine of the CSCS, which is currently the highest performing HPC platform in Europe. Finally, in the frame of the collaboration with Lawrence Livermore National Laboratory, CA, USA, the 2+2-dimensional Vlasov code LOKI for laser-plasma interactions was further developed through the implementation of a pitch-angle collision operator. For practical reasons, this operator needed to be restricted to 2-dimensional velocity space. The properties of this operator (compared to full 3-dimensional scattering) were systematically analyzed in the particular case of collisional effects on Landau damping of Electron Plasma Waves. First simulations with the aim of studying collisional effects on the evolution of multi-dimensional, non-linear plasma waves were carried out.

The physics investigations carried out by the theory group are focused on the following main areas of research:

1. First principle based simulations of core plasma turbulence;
2. MHD analysis of tokamak instabilities, 3D magnetic confinement configurations, and interaction with fast particles;
3. Investigations of the plasma dynamics at the edge of fusion devices;
4. Modeling activities in support of experimental activities.

2.2.1 First principles based simulations of core plasma turbulence

- Previous local (flux tube) turbulence simulations were not satisfactorily able to reproduce the experimental observations of improved confinement in negative triangularity discharges, which was seen to extend well inside the plasma to regions of weak local triangularity. The global version of the gyrokinetic code GENE was then used, which takes into account the finite size effects and global profiles. This required high resolution runs, and also an extension of the simulation domain with buffer regions outside the plasma boundary in order to be able to simulate up to the last closed flux surface. The effects of collisions were included, while that of carbon impurities was neglected in order to save CPU resources. Results of a pair of simulations (Fig. 2.2.1) reveal that the heat transport is indeed lower throughout the plasma column for the negative triangularity case than for the positive triangularity. Still, the difference is not as pronounced as in the experiments. The main underlying drive of the turbulence is a Trapped Electron Mode (TEM) driven by the density gradient, which is known to be very sensitive to profile variations: by decreasing only slightly the gradient, within the experimental error bars, one may recover the quantitative transport levels.

- A new field solver valid to all orders in the Larmor radius has been developed and implemented into the global gyrokinetic code ORB5. This development is essential to accurately address shorter wavelength fluctuations. Due to the different time and length scales of ion and electron responses, micro-instabilities and turbulence can exhibit multi-scale features. In particular, the non-adiabatic response of passing electrons in the vicinity of Mode Rational Surfaces (MRS) creates sharp small scales superimposed to the broad scale of underlying microinstabilities such as Ion Temperature Gradient (ITG) and TEMs. The ORB5 and GENE codes have been successfully benchmarked for this behavior. Furthermore, it has been shown that this resonant behaviour has consequences on the turbulent transport as obtained in global simulations: corrugations of the electron temperature gradient appear in the vicinity of MRSs, resulting in a corrugated transport at these positions (Fig. 2.2.2).

- In the TCV tokamak, a coherent mode of oscillation has been observed, at frequencies at or below the Geodesic Acoustic Mode (GAM). A series of global gyrokinetic simulations has been carried out for these parameters and an excellent agreement with the experiment has been achieved. A coherent oscillation over about half the minor radius at the same frequency as measured (within 10%) was found. Another TCV shot was analyzed, in which no such coherent oscillation was observed. The simulations, for these parameters, do not show a coherent mode, again in agreement with experimental data. The main parameter affecting the presence of the coherent oscillation is the value of the edge safety factor.

- A benchmark of local (flux tube) gyrokinetic codes GENE, GKW and GS2 has been carried out in a sequence of ideal MHD equilibria of increasing shape complexity. Excellent agreement has been demonstrated for the frequencies, growth rates and mode structures. In the frame of a EUROfusion Enabling Research project, a benchmark of nonlinear global gyrokinetic codes has been initiated. At this stage, the codes involved are GENE, which is an Eulerian code, and ORB5, which is a Lagrangian, Particle-In-Cell (PIC) code. Good agreement has been obtained so far, even in fully shaped plasmas.

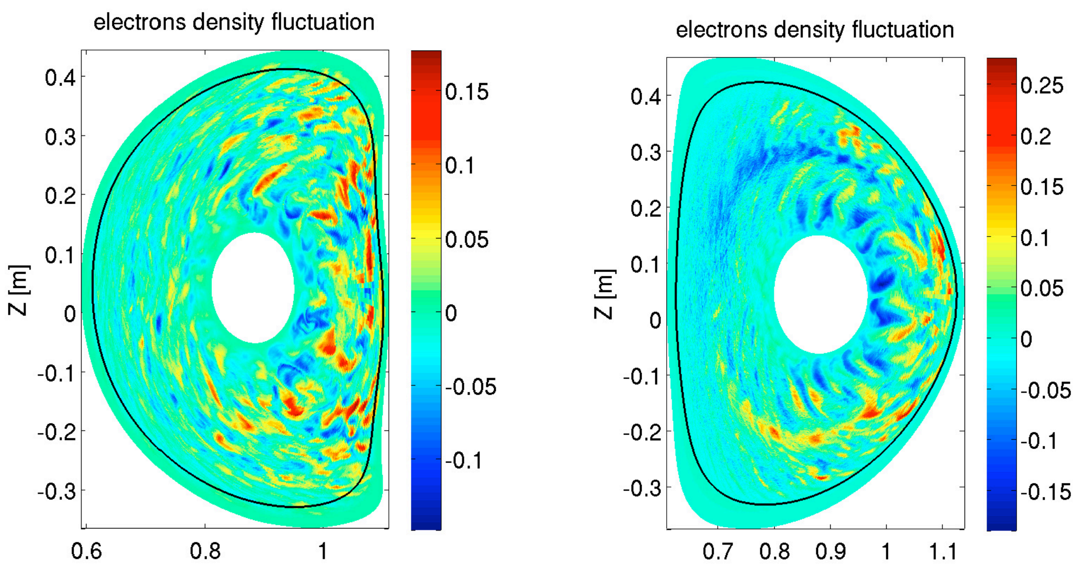


Fig. 2.2.1 *Contours of density fluctuations in positive (right) and negative (left) triangularity TCV discharges computed with the global gyrokinetic code GENE. In qualitative agreement with experiment, heat transport is reduced throughout the plasma cross-section in the negative triangularity discharge*

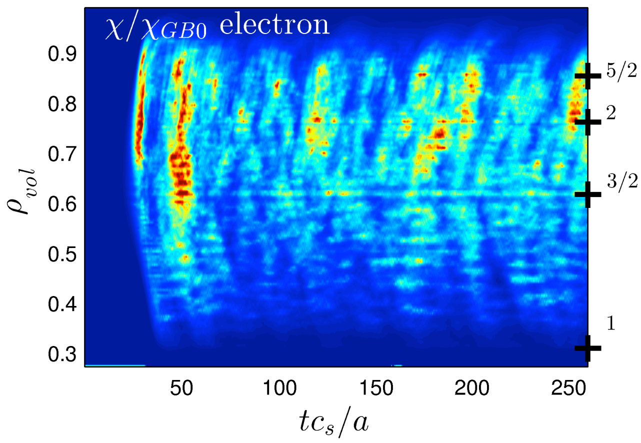


Fig. 2.2.2 *Electron heat diffusivity versus radius and time in a global gyrokinetic multiscale turbulence simulation of a TCV tokamak discharge using the ORB5 code. Superimposed to large scale avalanches and bursts, sharp modulations show up in the vicinity of m/n mode rational surfaces, the positions of the main ones being indicated with the '+" symbols.*

2.2.3 MHD analysis of tokamak instabilities, 3D magnetic confinement configurations, and interaction with fast particles

The optimized stellarator WVII-X began operations this year. Presently the machine does not have Ion Cyclotron Resonance Heating (ICRH), but it is hoped that such a heating system will compensate for expected poor core heating performance of neutral beam injection. The SCENIC code developed here at SPC uniquely provides full 3D modelling capacity for ICRH, and thus has become a key part of the predictive analysis for WVII-X upgrades. Recently, the SCENIC code has been improved to include a localised antenna model, which provides a more realistic wave spectrum in 3D plasmas. New results indicate strong differences between the power coupling for the high and standard mirror configurations, such that for the high mirror cases the resonant layers were localised within the lower magnetic field regions, transferring large amounts of power in the magnetic well regions either side of the antenna localised at a toroidal magnetic field maximum. This work then spurred interest into the loss mechanisms of particles in the WVII-X machine, of which the aim was to understand why fast ion tails do not readily develop. Improvements to tail generation are found to arise from inclusion of the radial electric field arising from ambipolar diffusion of background electrons and ions. The consequential poloidal ExB flow indeed strongly improves confinement for particles with energies around or below 50keV, thus raising the prospect of successful ICRH heating in WVII-X. An example of the improvement to tail generation by ExB flow is shown in the Fig. 2.2.3 for a WVII-X simulation.

Ideal magnetohydrodynamic (MHD) theory has been used to investigate some of the fundamental properties of geodesic acoustic modes (GAMs) in tokamaks, including their global structure, their associated magnetic components both inside and outside the plasma, and effects of a non-circular cross section of the plasma. Some of the electromagnetic characteristics of the ideal MHD GAM agree with experimental data. Further important analysis may examine to what extent the modes agree with global GAM density fluctuations observed in TCV, the extent of agreement with global and fully electromagnetic gyrokinetic simulations, and a derivation of non-axisymmetric zonal flows.

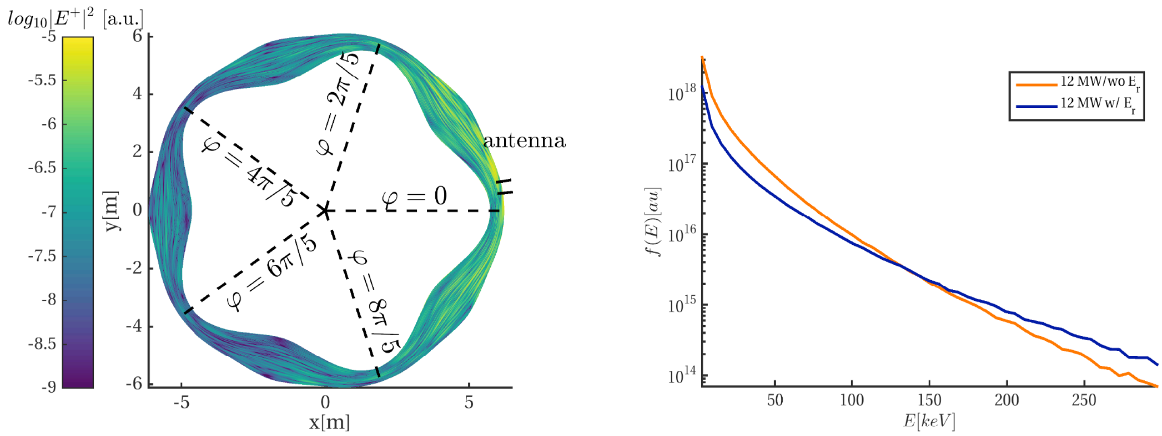


Fig. 2.2.3 *Left: Electric field intensity distribution (log scale) around the midplane [a.u.]. Right: Energy distribution of confined particles in a W7-X plasma heated by ICRH without (red curve) and with (blue curve) radial electric field. The radial electric field assists confinement and the generation of a high energy tail.*

2.2.3 Investigations of the plasma dynamics at the edge of fusion devices

Thanks to significant implementation upgrades, the GBS code can now perform full size simulations of limited Scrape-Off Layer (SOL) of medium size tokamaks. A typical snapshot of plasma turbulence in the SOL of a simulation of the the TCV tokamak is shown in Fig. 2.2.4. We carried out a quantitative comparison between gas-puff imaging (GPI) turbulence measurements in Alcator C-Mod inner-wall limited discharges and GBS simulations. The comparison was carried out for a series of inner-wall limited discharges with varying magnetic field and density. The comparison between GPI data and non-linear simulations yields overall good agreement for several observables, such as the Dα emission levels and intermittency, the radial and poloidal correlation lengths and propagation velocities, and the power and frequency spectral density.

A novel first-principles self-consistent model that couples plasma and neutral atom physics suitable for the simulation of turbulent plasma behavior in the tokamak edge region has been developed and implemented in the GBS code. While the plasma is modeled by the drift-reduced two fluid Braginskii equations, a kinetic model is used for the neutrals, valid in both short and long mean free path scenarios. The model includes ionization, charge-exchange, recombination, and elastic collisional processes. The model was used to study the transition from the sheath to the conduction limited regime by increasing the plasma density in the system. We compared the simulation results with the predictions of an expanded and refined two-point model, estimating the drop of electron and ion temperature along the magnetic field lines in the SOL. The model is now being applied to investigate the impact of neutrals on turbulent edge features, such as the broad shoulder observed in the far SOL at high plasma density.

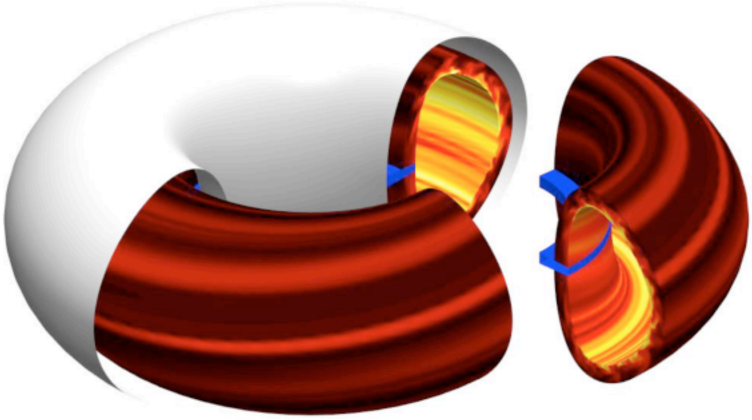


Fig. 2.2.4 *Typical snapshot of SOL turbulence from GBS full size simulations of TCV.*

2.2.4 Modeling activities in support of experimental activities and real time control

A simulation tool has been developed to predict the pedestal height from MHD stability considerations, following an improved Edge PEDestal (EPED) model that includes plasma boundary with X-points and profiles with self-consistent bootstrap current density. This model is being used to predict the effect of negative triangularity on pedestal properties and will be compared with specific experimental results. An automated calculation of the edge stability diagram has also been further developed within the Eurofusion Code Development Work Package. By using a standardized database, the results of this calculation can be easily compared with TCV and ASDEX Upgrade results.

A sawtooth model for real-time control has been included into the RAPTOR code and was used to predict the profile changes present before a disruption occurs. Indeed, both in RFX, where resistive wall modes lead to changes of the sawtooth period before a disruption, and in TCV at high density, it was demonstrated that the comparison between the predicted sawtooth period and the real-time detected sawtooth period can provide accurate information on the fore-coming disruption, or bad behavior of the plasma discharge. Trajectory optimization of tokamak ramp-down phases has also been developed. The first results are very encouraging and have allowed the optimization of the ramp-down phase while maintaining overall stability. Specific experiments have been started to better characterize the transport properties during the ramp-down, and improve the trajectory optimization.

2.3 Basic Plasma Physics

2.3.1 Industrial Plasmas

The activities of the BPPA group continue to be focused on the development of new applications of low temperature plasmas with the goal of bridging the gap between the study of plasma physics in an academic environment and the development of plasma processes in industries. In the period covered by this Report, consolidated projects with previous industrial partners continued, including the development of a large resonant RF network antenna in collaboration with TetraPak, and new activities were started, including a EuroFusion project for plasma source development for negative ion neutral beams. These two projects are reviewed in details below. In parallel, several potential fields for expansion of activities have been identified, such as the development of a high pressure plasma source for powder sterilization for the pharmaceutical industry in collaboration with ETHZ, the use of dielectric barrier discharges for plasma-enhanced combustion for automobile applications, the development of a new concept of a plasma density diagnostic for monitoring processes in industrial reactors.

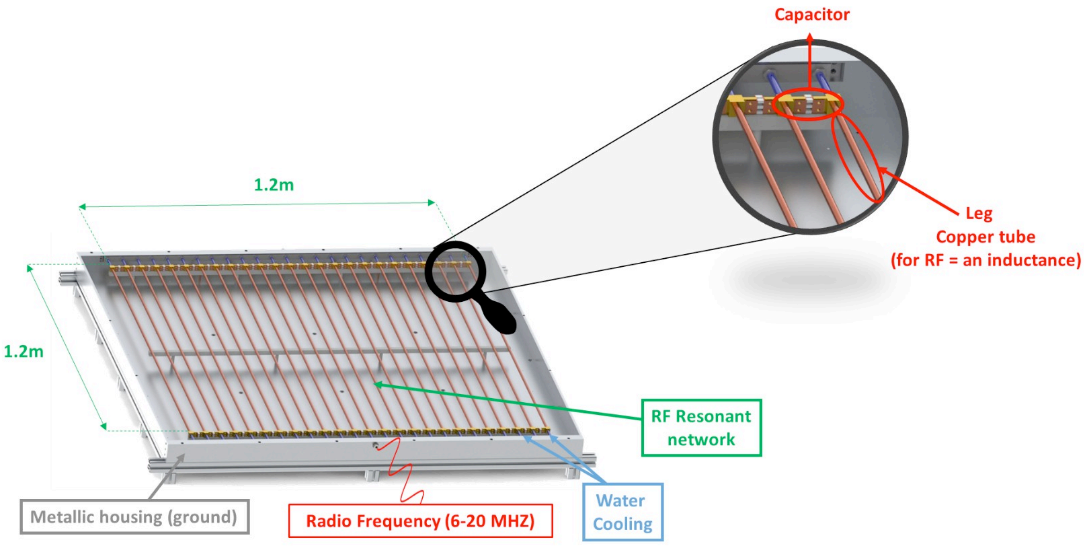


Fig. 2.3.1 *The resonant antenna with its main components for packaging applications.*

Plasma Deposition for Industrial Applications

The development of a large resonant RF network antenna for industrial deposition of barrier coatings on polymers for packaging applications is one of the previously established projects. Its ambition is to construct the first RF resonant network antenna for a full-sized industrial application, to produce gas barrier films for liquid food packaging. Such barrier films are obtained by depositing a thin coating on a plastic film substrate with plasma technology. The antenna, shown in Fig. 2.3.1, designed by Helyssen Sàrl, was mounted into a reactor for plasma deposition by SPC. Films were deposited and analyzed by our industrial partner, Tetra Pak at Romont. Robustness tests of the large antenna (1.2x1.2 m^2) achieved stable plasma up to 15kW RF power using a custom-built matching system by embedding the water-cooled antenna in a homogeneous dielectric. A surface matrix of one hundred multiplexed electrical probes monitored the plasma uniformity, complemented by a lateral scanning magnetic/Langmuir probe for high spatial resolution. These plasma measurements stimulated the development of a new theoretical model for inductively-coupled plasma. Practical solutions were found for challenges such as parasitic plasmas, localized heating, arcing, RF bias electrodes, plasma non-uniformity, automated impedance matching, substrate heating, deposition chemistry, and process and winding parameters. Alternatives were found for prohibitively-expensive components such as polyimide dielectric foam and high-Q, high current RF ceramic capacitors. Rolls of 2000m length, 500mm width, coated with diamond-like carbon (DLC) in an industrial system at Tetra Pak, showed very good barrier layer performance at 100m/min effective speed. Barrier film defects such as pinholes and dust particles could surprisingly be eliminated using a special winding path configuration. Furthermore, the produced barrier films exhibited very good behavior when converted into packaging material and good long term adhesion performances during the required packaging lifetime. An important advantage is that this new antenna process yields good oxygen transmission rate for a wide range of operation parameters, thereby eliminating the constraints of previous technology. The RF bias study concluded that bias can improve the quality of poor barrier layers, but, for plasma parameters which give good quality layers, the improvement is not significant enough to warrant its use in future machines.

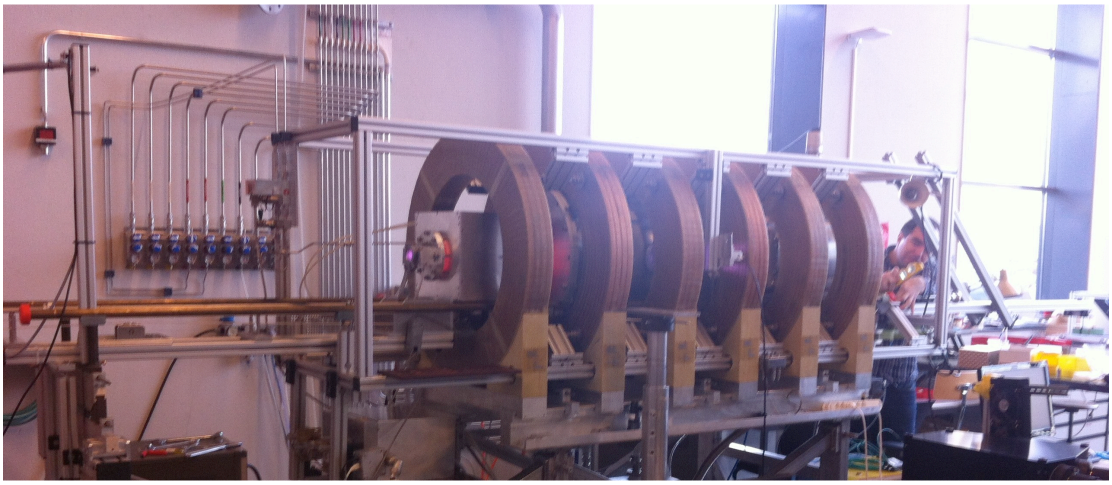


Fig. 2.3.2 *The Resonant Antenna Ion Device (RAID) at SPC with the main elements.*

Helicon Plasma Generator for Negative Ion Source

In the framework of a EUROFusion project and in collaboration with CEA-Cadarache, we have started the development of a 10kW helicon plasma generator, which will be implemented in 2016 on the Cybele negative ion source and compared with the "Inductively Coupled Plasma (ICP) data base". The ability to obtain high plasma density with high ionization rate and a much higher power efficiency than ICP sources make helicon sources an interesting option as plasma source for Cybele. Since first experiments performed by Boswell in the early 1980's, helicon sources have been extensively studied and they are proven to be very efficient for high-density (10^{12}-$10^{13}cm^{-3}$) plasma production with moderate injection power. Recently, they have been considered for nuclear fusion applications and proven to be a very promising candidate as plasma generator for negative hydrogen ion sources for ITER. In this context, helicon sources have the following advantages over traditional ICP generators: 1) reduced required RF power, leading to increased operational domain; 2) stable operation at low pressure (<1Pa), reducing negative ion losses by electron stripping; 3) lower electron temperatures, resulting in higher efficiency of negative ion production; 4) high degree of molecular dissociation in hydrogen plasmas. Although a single 10kW helicon generator will probably not achieve the relevant plasma density required for the ITER NIB source, the 10kW helicon source is an intermediate step towards larger helicon powers, which will allow investigating the main technology and physics issues related to high power helicons.

In the period covered by this report, the construction of the helicon plasma generator was concluded and preliminary tests of its performance were done on the Resonant Antenna Ion Device (RAID) at SPC, shown in Fig. 2.3.2. These include tests with hydrogen and deuterium gas at different pressures, magnetic field and radiofrequency power levels, spectroscopic measurements of the H/D dissociation rate and Langmuir probe measurements of electron density and temperature profiles. Stable operation in both hydrogen and deuterium are obtained for the working nominal conditions required in the Cybele source, namely a pressure of 0.3Pa and a magnetic field of approximately 120 Gauss. First measurements were performed using compensated Langmuir probes and absolutely calibrated emission spectroscopy, indicating the presence of negative hydrogen/deuterium ions and a dissociation degree increasing with injected radiofrequency power. This points towards the resonant helicon antenna as a promising candidate for negative ion sources in future NBI applications.

2.3.2 TORPEX

In the period covered by this report, the Basic Plasma Physics and Applications Group at SPC has contributed to advancing the understanding of turbulence in magnetized plasmas of direct relevance for fusion devices on the TORoidal Plasma EXperiment (TORPEX) device.

TORPEX is a highly flexible basic plasma physics device in which plasmas with densities n_e~10^{15}-$10^{17}m^{-3}$ and temperatures T_e~2-10eV are created and sustained by microwaves at 2.45GHz using different gases. A variety of magnetic configurations of relevance for fusion can be produced in TORPEX, including simple magnetized toroidal (SMT) configurations with a dominant toroidal magnetic field and a small vertical field component, or closed field-line configurations using a current-carrying conductor suspended in the center of the chamber. This produces a poloidal magnetic field with a rotational transform, which, combined with vertical field coils, results in magnetic configurations of increasing complexity and of more direct relevance to confined plasma experiments, including X-point configurations. Thanks to a continuously improving set of diagnostic techniques, of theoretical and modeling tools, together with a rigorous validation methodology, research on TORPEX today allows for detailed quantitative comparisons between theory and experiment.

In 2015, most experiments have been conducted to investigate the interaction between suprathermal ions and intermittent turbulence associated with blobs and to study the propagation of turbulent structures in the presence of X-points. The advances in these two research lines are detailed below.

Supra-thermal ion transport studies

Understanding turbulent transport of supra-thermal (fast) ions, i.e. ions with energies greater than the thermal energy of the background plasma, is of paramount importance for future fusion reactors such as ITER and DEMO, where a good confinement of supra-thermal ions, created by fusion reactions or additional heating, will be necessary to reach burning plasma conditions. On TORPEX, we conduct investigations of supra-thermal ion-turbulence interaction using a miniaturized $Li6^+$ ion source consisting of a thermionic emitter with a two-grid accelerating system, which produces currents up to 10μA with energies in the range 10eV-1keV. In past years, the study of the time-averaged fast ion current profiles and their comparison with fully validated numerical simulations has revealed different regimes for the fast ion transport. Interaction with turbulence results in super-diffusive, diffusive, or sub-diffusive, depending on the fast ion energy and turbulence amplitude.

In 2015, we focused our experiments on time-resolved supra-thermal ion measurements and their statistical properties. Experiments were conducted with 30eV and 70eV ions, which exhibit super- and sub-diffusive transport, respectively. Using time-resolved conditionally averaged sampled (CAS) two-dimensional data (see Fig. 2.3.3), we show that supra-thermal ions in TORPEX plasmas experiencing super-diffusive transport are subject to bursty displacement events, associated with blob propagation resulting in highly intermittent time traces. Supra-thermal ions experiencing sub-diffusive transport do not display such intermittency. This result links observations usually inaccessible in fusion devices, namely energy-resolved three-dimensional time-averaged measurements, with Eulerian time-resolved measurements, which are often the only accessible data.

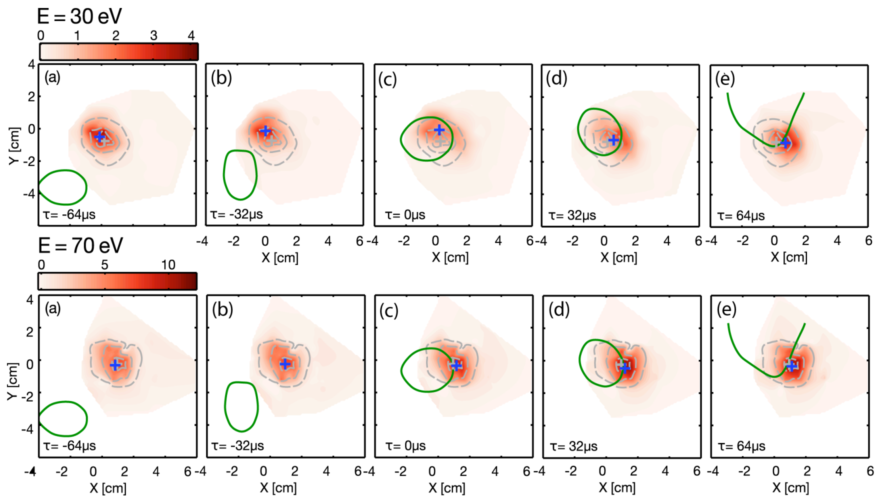


Fig. 2.3.3 *Conditionally averaged dynamics of the supra-thermal ion current density (red contours) for the two energies 30eV (top row) and 70eV (bottom row). Dashed gray contours represent time averaged profiles and the green lines represent the CAS blob ion saturation current iso-contours. The center of mass position of the supra-thermal ion beam is indicated by the blue cross.*

Turbulence studies with closed flux magnetic surfaces and X-point

The toroidal conductor system (see Fig. 2.3.4) opens new avenues for research on TORPEX, allowing the production of magnetic geometries with single and double magnetic null-lines, as well as snowflake divertor configurations. In 2015, we focused our investigations on the study of blob dynamics in the surrounding of a X-point.

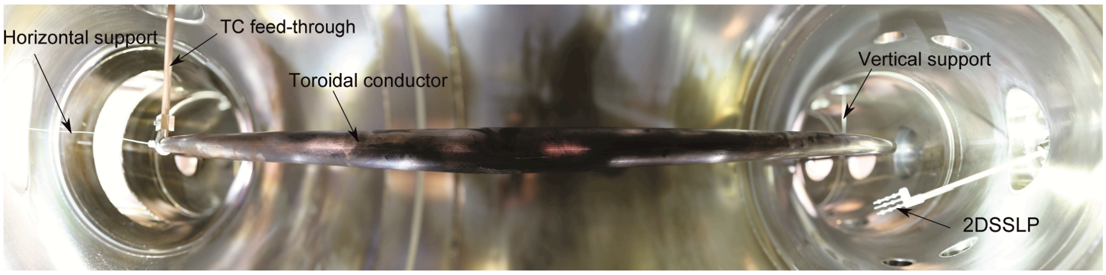


Fig. 2.3.4 *Wide-angle view of the toroidal conductor installed inside TORPEX. Visible are the feed-through together with the vertical and horizontal supports.*

In the present experiments, we position the toroidal conductor at the top of the vessel and drive a current of about 640A to obtain a poloidal magnetic field. This field is superimposed to a quasi-horizontal magnetic component, produced by external vertical field coils. The resulting magnetic configuration includes a first-order X-point on the low-field side (LFS), as depicted in Fig. 2.3.5. Quasi-vertical field lines are obtained on the high-field side (HFS). In this region, highly reproducible hydrogen plasmas are generated outside the last closed flux surface, where blobs originating on the HFS propagate radially outward, exploring the X-point region. The blob motion towards the X-point is tracked and analysed. This shows an acceleration that can be directly linked to the background radial flow and to the blob-induced electric potential dipole. The blob speed can be quantitatively described by an analytical model that includes perpendicular and parallel current contributions. In particular, a crucial role is played by a geometrical parameter, expressing the length of the current path parallel to the magnetic field, along which the blob potential dipole is short-circuited.

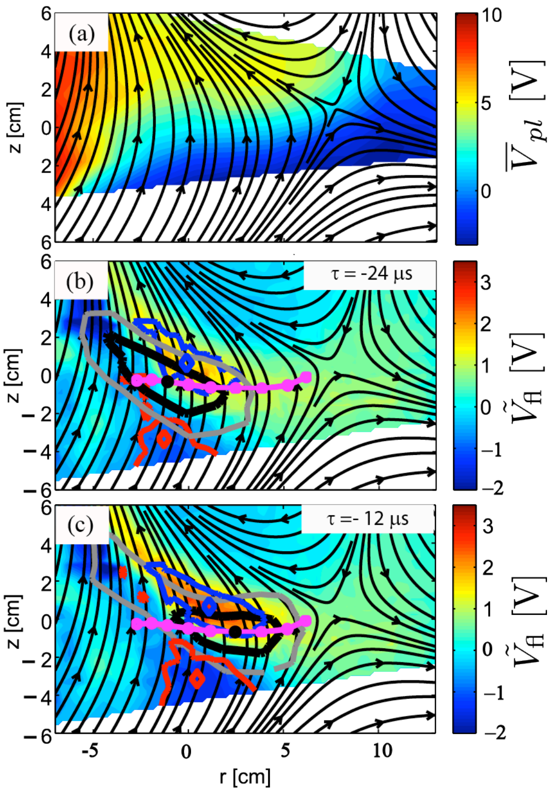


Fig. 2.3.5 *(a) 2D background plasma potential profiles. (b-c) Fluctuating floating potential at two different times from CAS Langmuir probe data. Blue and red contours indicate the floating potential values at 60% of the positive and negative peaks. Gray and black lines correspond to the ion saturation current density contours at 20% and 60% of the maximum. The magenta curve indicates the blob trajectory, with the instantaneous center of mass position (black dot).*

TORPEX will be the ideal validation testbed for the future developments of the GBS code (see Section 2.2.3), which is progressively upgraded in order to be capable of treating complex geometries, such as X-points and snowflakes. Applying the same techniques on numerical and experimental data provides a basis for a benchmark of the numerical simulation, which is necessary to determine the complexity of the numerical model needed for a realistic description

2.4 Superconductivity

2.4.1 Superconducting Magnets for DEMO

In 2015, the main milestones of the DEMO activity have been the tests in EDIPO of the Low Temperature Superconductores (LTS) and High Temperature Superconductors (HTS) high current, high field prototype conductors, assembled in 2014.

The test of the 83kA/13.5T, React&Wind Nb_3Sn conductor has validated the design target (effective use of Nb_3Sn strand properties). No cyclic load degradation was observed. The DC results are fitted by the strand scaling law using a compressive strain, ε=-0.33%, very close to the one assumed in the design one, ε=-0.28%.

The test results at 60kA/12.5T/5K of the HTS prototype conductor, by far the worldwide most advanced large HTS conductor, matched the performance prediction from the single tape, confirming the design approach. The performance degradation upon cyclic load was investigated after disassembling the cable: an improvement of the strand layout with regard to the ability of withstanding a large number of load cycles will be implemented in 2016.

The new reference baseline for DEMO was issued by EUROfusion in summer 2015, with lower field for the TF coils. The SPC conductor and winding pack design (including the supporting electromagnetic and thermal-hydraulic analysis) was updated. Accounting for the feedback from the manufacturing experience of 2014, an updated layout of the React&Wind Nb_3Sn prototype conductor (63kA / 12.5T) is sketched in Fig. 2.4.1 and will be assembled in 2016.

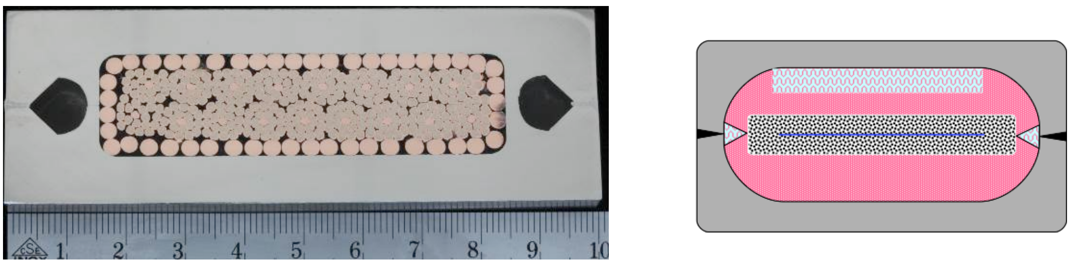


Fig. 2.4.1 *High grade Nb_3Sn conductors for DEMO TF coils: left the 2015 prototype, right the sketch of the updated prototype to be build in 2016 (same scale).*

Design studies for an optimized DEMO Central Solenoid have started in 2015 with the aim of producing the required magnetic flux at the smallest outer radius: the graded winding concept foresees two HTS layers at the inner radius, with operating field 16T and React&Wind Nb_3Sn conductor in the medium grade layers, 14T to 6T. The outermost layers, with operating field <6T are made of NbTi for cost saving.

2.4.2 Development of high field insert coil made of HTS tapes

After completing the trials on small insert coils made by pancakes wound with non-insulated tapes, the activity has focused on the collaboration with the company Bruker. Special attention has been devoted to joint techniques (the commercially available lengths of tapes are not sufficient for a full winding and inter-tape joints are required, with low resistance). The design of a layer wound insert coil, made by insulated tape was finalized and the manufacturing trials have been completed. Upon delivery of the tape, the winding activity and the test are planned in 2016.

2.4.3 EDIPO test facility

With the commissioning of the primary coil of the superconducting transformer in April 2015, the commissioning of the EDIPO test facility is completed. The benchmark test, which compares the performance of the same NbTi sample in SULTAN and EDIPO, was completed in April: within the measurement accuracy, the test results are identical.

The upgrade of the EDIPO sample environment, in order to test HTS samples at elevated temperature, consists of an “adapter” and a counter-flow heat exchanger. The HTS adapter, which is similar to an HTS current lead, connects the HTS sample under test and the NbTi transformer and limits the heat flux between them to less than 20W at a warm end temperature of 50K. Helium of 4.5K and 10 bar supplied by the refrigerator is warmed up to temperatures up to 60K by means of heaters and a counter flow heat exchanger. The heat exchanger ensures that the warm helium leaving the HTS sample can be returned as cold gas with less than 20K to the refrigerator. The HTS adapter was damaged at the first test in June 2015. After repairing, the commissioning of the upgrade of the EDIPO test environment was completed in December 2015.

2.4.4 Non-destructive methods for ITER joints

The development of non-destructive examination (NDE) methods for the ITER TF joints continued in 2015, based on the resistance profile by voltage scanning. The detection of anomalous resistance profiles at room temperature identifies defects in the non-accessible contact between the strand bundle and the copper plates. A scanning head with multiple contacts for current injection and voltage sensing has been prepared together with an instrumentation rack. The scanning head is bolted to the termination to be examined and the resistance profile is obtained. The equipment is commissioned on a number of mock-up terminations prepared with intentional defects. Upon assessment of the diagnostic value of the developed method, the equipment will be used *in situ* at the ITER TF coil manufacturers.

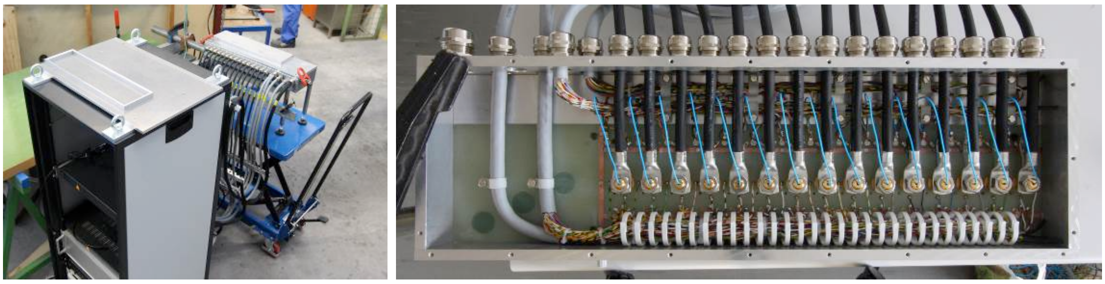


Fig. 2.4.2 The equipment for NDE of the ITER TF joints. Right, detail of the scanning head.

2.4.5 Tests of superconductors for ITER

In 2015, the SULTAN test facility was fully devoted to the test of the ITER conductor and joint samples, in the scope of the ITER framework contract, whose extension till April 2017 was signed early 2015. The samples made of Nb_3Sn conductors were assembled at SPC. The following test campaigns have been carried out in 2015 for 16 samples:

- TFRF7 – RFDA – TF sample from Russian series production – 2 weeks
- PFCN8 – CNDA – PF2-4 conductor sample – 1 week
- PFCN9 – CNDA – PF2-4 conductor sample – 1 week
- PFRF3 – RFDA – PF1 sample from Russian series production – 1 week
- TFEU10 – F4E – TF process qualification sample from EU – 3 weeks
- TFUS6 – USDA - TF process qualification sample from US – 3 weeks
- TFEU12 – F4E – TF sample from European series production – 2 weeks
- PFEU3 – F4E – PF6 sample from European series production – 1 week
- PFCN10 – CNDA – PF2-4 conductor sample – 1 week
- TFCN6 – CNDA – TF sample from Chinese series production – 2 weeks
- CCCNjoint2 – CNDA – Qualification of industrial CC joint sample – 1 week
- CSJA7 – JADA – CS sample from series production – 5+1 weeks
- TFJEU2 – F4E – Qualification of industrial TF joint sample – 1 week
- TFJEU3 – F4E – Qualification of industrial TF joint sample – 1 week
- CSJA8 – JADA – CS sample from series production – 5 weeks
- TFEU13 – F4E – TF sample from European series production – 2 weeks

2.5 International and National activities

2.5.1 Gyrotron development for ITER

The European Gyrotron Consortium (EGYC) activities in 2015 were focused on the development, follow-up of the manufacture, and tests of the 170GHz /1MW gyrotron tubes for ITER, a project that is funded by F4E. F4E's strategy is risk mitigation oriented and is based on the production of 2 gyrotron tubes:

- a modular short pulse (<10ms) prototype with demountable flanges and limited cooling, that is used to validate the RF design of the tube,
- a CW prototype, produced by TED, with the goal a meeting the ITER performance specifications.

The short pulse tube was mostly fabricated by KIT (Karlsruhe Institute of Technology), with the exception of the electron gun that was produced by TED. Extensive tests of this tube were performed at KIT during 2015. It was shown that the tube was able to stably deliver rf power in excess of 1MW, on the right mode, with a high Gaussian content (ca. 98%, compliant with the ITER specifications), an efficiency of the order of 35%, without depressed operation of the collector, and without limitation due to the presence of parasitic oscillation, thus providing a validation of the rf design. The flexible and modular construction of the tube will allow EGYC to make modifications of the non-rf part of the design, making its configuration relevant to operation with a depressed collector, with the goal of reaching the ITER specified efficiency of 50%. These tests are foreseen during the 2^{nd}-3^{rd} quarter of 2016.

A significant fraction of was 2015 was dedicated to the follow-up of the continuous wave (CW) 170GHz/1MW gyrotron prototype manufactured by Thales Electron Devices (TED). It was delivered during the 3^{rd} quarter of 2015, keeping the delay minimal compared to the initial plan. Because of the unavailability of a superconducting magnet at SPC, the delivery took place at KIT, where the pulse length is limited to 180s. The tube was installed and the site acceptance test (SAT) is foreseen beginning of 2016.

Fig. 2.5.1 *CW gyrotron prototype during the factory acceptance test (FAT).*

A procurement contract for a superconducting magnet was signed between F4E and Cryogenic Ltd. in March 2015 for the manufacture of a unit that will be delivered to Lausanne in Sept. 2016. The follow-up of this contract is carried out by SPC.

Other activities have consisted in:

- the support to theoretical activities aiming at securing the design and series production of the gyrotron tubes for ITER,
- support to the preparation of the GT170 test stand in order to host the long pulses tests of the CW prototype (see below),

- support to F4E in the completion of an ITER task order related to the gyrotron building and interfaces.
- support F4E in the follow-up of the procurement contract for the ITER EC power supplies.

The present planning foresees a transport of the CW to Lausanne once the superconducting magnet has been delivered (3rd quarter 2016), and an extension of the pulse length.

In addition, SPC activities also cover the evaluation of the optimal layout for the EC equipment (gyrotrons, HVPS, auxiliaries) inside the ITER RF building, the DC interface between EU gyrotron and EC HVPS, and the grounding proposal for EC equipment in the RF building.

2.5.2 The ITER Upper Launcher for Electron Cyclotron Waves

EC Upper Launcher development for ITER

The European Launcher Consortium (ECHUL) activities continued in 2015 under a new grant. The waveguide components between the port plug and the diamond window are part of the first confinement system (FCS) of the ITER tokamak and are therefore subjected to the most stringent quality, safety, and vacuum requirements. Work in 2015 has concentrated on the 2nd update of the Configuration Management Model for the ITER Enovia database. The models of all FCS components have been re-made to the ITER CAD standards, based on the deviation notices received to date. In addition, extensive work has been done to update and check the Sub-System Requirement Document that gathers all the relevant constraints on the system. Following an investigation of all the millimeter-wave losses associated with the configuration, including stray radiation loading of the in-vessel waveguides, it is clear that cooling of the system must be careful managed. Several designs variants have been investigated.

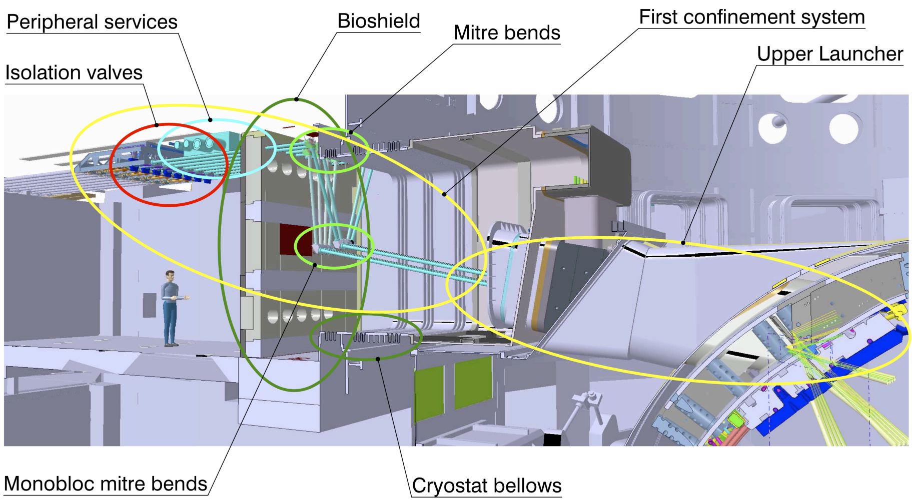


Fig. 2.5.2 *The main parts of the upper launcher system are seen here. The compact Isolation valves, monoblock mitre bends and double-metal-seal evacuated waveguides are unique to the ITER system. All components require carefully designed cooling to handle the 1.5MW, 3600s pulses in each of the 8 transmission lines per port cell. Four port cells house the ITER upper launchers.*

A service contract has been signed with F4E to provide Support to Prototype Procurement & Qualification of EC Isolation Valves). The isolation valve is a critical component between the diamond window and the port plug. This is the first contract for SPC of a Protection Important Class 1 and quality class 1. SPC is responsible for the design of the valve based on a commercially available valve.

It has become clear that high power testing of prototypes will require a test facility in the EU. An European high power gyrotron testing facitlity (called hereafter the EU Gyrotron test stand) was installed at SPC for long-pulse R&D and qualification testing of the EU ITER gyrotron. A call for tender was issued for a service contract by F4E for the Design of the ECT-FALCON Facility (Adaptation of EU Gyrotron Test Stand). A reply to this was call began in December of 2015. This test facility will be provided with a second gyrotron supplied by F4E and acting only as a power source for component testing. The EU GyrotronTest Stand was conceived from its inception to permit the hosting of such a facility and is well placed to carry out the adaptation in 2016.

Finally, preparatory investigations have begun for the manufacturing and testing of low-cost pre-prototype models of other components of the FCS transmission line; which are not readily available commercially. These investigations help to identify critical issues related to tolerances and manufacturing processes for later prototyping programs. For example, SPC provided manufacturing drawings and e-beam welding assistance, from the Paul Scherrer Institute, to other ECHUL partners for manufacturing the coupling of the Diamond Window Unit. Continuation of these and other activities is expected in 2016 and beyond.

2.5.3 ITERIS: Design and first applications of the ITER Integrated Modelling & Analysis Suite (IMAS)

The ITERIS contract has been continued as Task Order Nr 4 until mid 2016, however on a somewhat reduced level. The ideal MHD equilibrium code CHEASE and the versatile cubic spline interpolation/extrapolation with tension tool INTERPOS have been fully integrated into IMAS. The data model has been further extended and is considered for direct use by the WEST and JT-60SA teams.

2.5.4 Work package Heating and Current Drive (WPHCD) in the frame of EUROfusion

In the frame of the EC activities of WP HCD, two tasks were undertaken:

Benchmarking of different free-space measurement methodologies using the VNA and two quasi-optical setpus

Following the preliminary measurements carried out in 2014 with the two quasi-optical setups (Thomas Keating – Optical Bench, OB and the Material Characterisation Kit, MCK), the VDI extension heads and the newly purchased Vector Network Analyser (VNA) (Keysight, PNA-N5224A-401, available since January 2015), detailed measurements methodologies have been compared on different dielectric materials used as loading in gyrotron beam-ducts. An example of such a measurement is shown in Fig. 2.5.3.

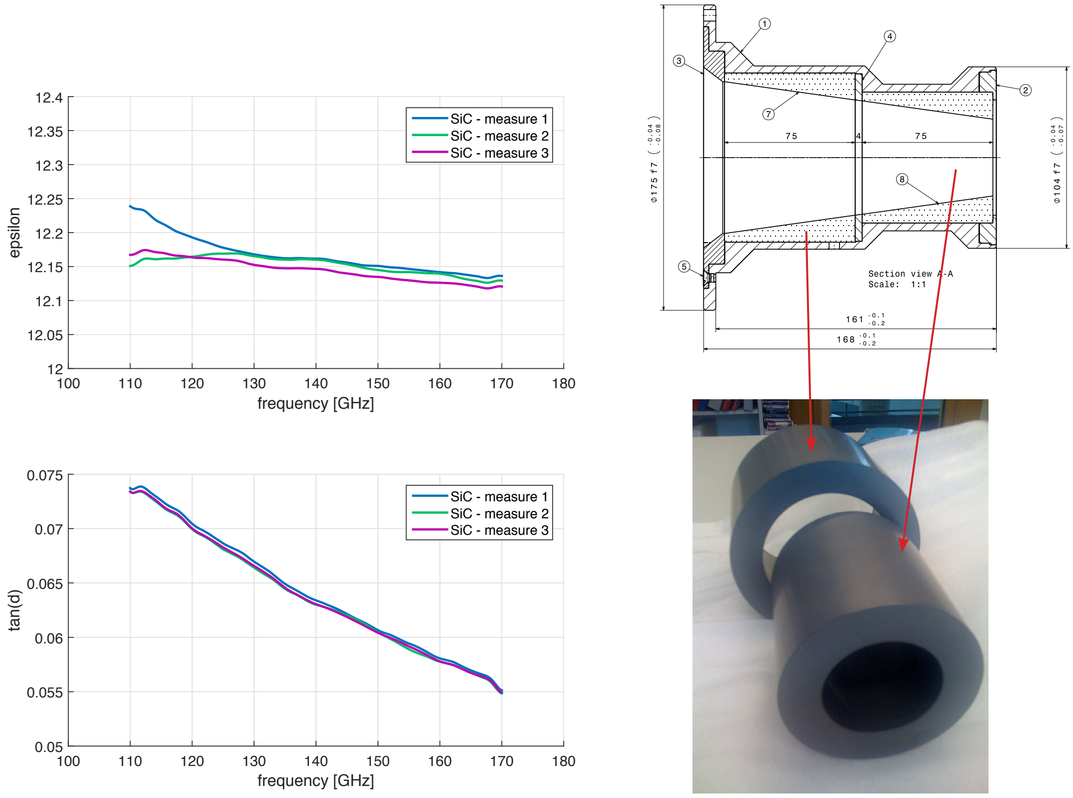


Fig. 2.5.3 *Dielectric property measurements performed with the MCK on a thick (d=12mm) Cerasic-B (SiC) sample. On the left part, ε_r (top) and $\tan\delta$ (bottom) measurements over the WR6.5 frequency band (110-170GHz). On the right part, the geometry and pictures of the Cerasic-B smooth-wall beam duct, which has been used in the 2MW KIT coaxial gyrotron.*

Beam-duct parasitic oscillations studies in smooth dielectric loaded beam-ducts

The code TWANGlinpsec code has been adapted for studying spurious oscillations in metallic or dielectric loaded smooth-wall beam ducts. TWANGlinspec is based on a spectral approach and in its present form is using a finite-difference numerical scheme. In view of studying the excitation of spurious instabilities in smooth-wall beam ducts a more accurate numerical model is required which motivated the development of a finite element numerical scheme considering higher order finite elements for both particle and fields. Application studies using the newly developed code for real gyrotron smooth-wall beam-duct configurations are foreseen in 2016.

2.5 5 *Work package Plant level System Engineering, Design Integration and Physics Integration (WPPMI) in the frame of EUROfusion*

Fast ion confinement in DEMO

Alpha particle losses and consequential heat fluxes on the surface marking the plasma boundary have been calculated in 3D MHD equilibria that model the DEMO coil configuration (Fig. 2.5.4). The work is primarily a physics study that contrasts the losses associated with two models that account for the breaking of axisymmetry due to the finite number of toroidal field coils. By undertaking full-F simulations for the distribution function of the alpha particles, using a full orbit solver VENUS-LEVIS (or the same code in the guiding centre approximation), it is found that the choice of model for the 3D ripple affects the local power flux (locally in toroidal and poloidal angle) on the last closed flux surface, but not the total power given to the edge. In contrast to studies into the effects of resonant magnetic perturbations on fast ion losses, it is found that the plasma response to the ripple associated with the finite number of toroidal field coils is weak, thus ensuring that the plasma response can be neglected. Alpha particle losses due to ripple is weak, with peak losses occurring for particles in the 100-200keV range. This convenient transport process for helium ash is dominated by collisional super banana transport, rather than stochastic ripple transport.

In terms of the overall plan for the studies to be conducted in the area of fast particle physics for DEMO, consensus was obtained on an approach that would focus to the following items:

- assessment of the linear stability of the DEMO reference scenario(s) with respect to fast ion driven modes, using state-of-the-art codes;

- semi-analytical estimates of the linear stability of AEs, including of the path from the beginning of the discharge to the large fusion gain regime;

- investigations of the possibility of utilizing reduced models combining the stability and the nonlinear interactions to describe the effect of fast ion driven modes .

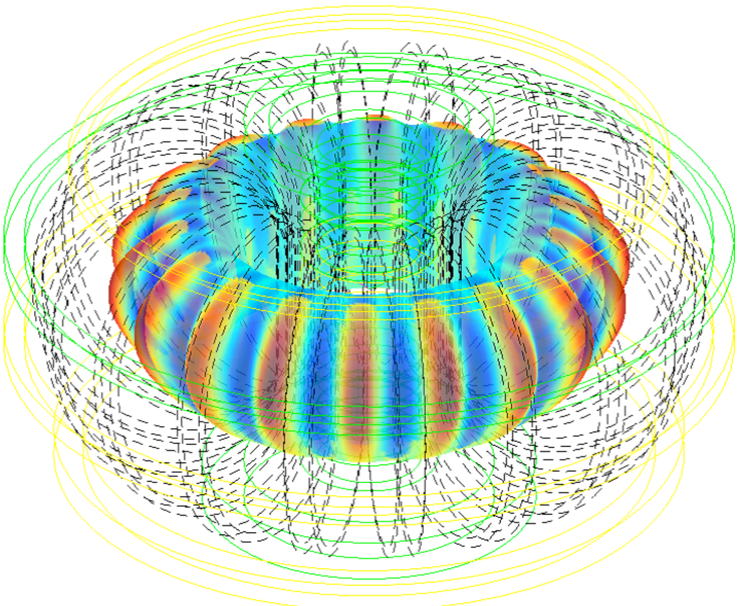


Fig. 2.5.4 *A free boundary calculation of the DEMO equilibrium using VMEC employing the 3D equilibrium approach. Colours show the amplitude of the magnetic field, while the corrugated surface indicates the last closed flux surface (the constant plasma pressure surface would be axisymmetric for the 2D+ripple approach). Note that the 3D ripple has been inflated by a factor of 200 for illustration purposes here.*

2.5.6 Contribution to the scientific exploitation of JET

Impurity control

High performance fusion producing plasma operation requires experimental preparation. Energy confinement and plasma beta must be maximized, while mitigating MHD instabilities, and minimizing heat loads to the all metal wall, especially the divertor. A particular challenge associated with the ITER-like wall which impacts on performance is controlling the influx of high-Z impurities. Experiments have been performed and are continuing in order to address these issues. In particular, experiments dedicated to hybrid scenarios are investigating the variation of the plasma current, in order to maximize energy confinement, and to simultaneously avoid low-n MHD instabilities. High performance also requires a strong pedestal temperature, but unfortunately pedestal gradients are generally associated with significant tungsten sputtering from the divertor surface. The potential impurity accumulation and loss of core plasma temperature by radiation can be mitigated in several ways: cooling the divertor plasma by extrinsic impurity radiation; flushing impurities from the plasma by increasing the frequency of edge localised modes; or mitigating core impurity accumulation by centrally localised heating. The ideal mitigation method for impurity control is central heating using the JET ICRH system and experiments are now underway to assess if this technique is sufficient in the domain of interest for high fusion power or whether a combination of several techniques will be needed. Finally, the JET tungsten divertor cannot tolerate the full available additional heating capability in a static equilibrium. Since high heating power is mandatory for the achievement of high fusion power, two possible techniques for divertor heat load mitigation methods are being tested: neon seeding; and divertor strike-point sweeping. Tests have been carried out with low level neon seeding, which increased the total radiation by ~30%, and 4Hz divertor sweeping, which reduced the divertor surface temperature. But larger reductions in divertor power loads are required for the achievement of high fusion power and further experiments are underway to quantify the relative merits of the two techniques.

Fast ion driven instabilities

Fast ion driven instabilities, such as Alfvén Eigenmodes, Alfvén Cascades and fishbones, could be used as potential markers of the evolution of the plasma equilibrium. For instance, these instabilities provide information on the evolution of the safety factor profile (q), especially on the location of local minima. These data can then be compared with those obtained through the standard equilibrium reconstruction methods based on magnetic measurements at the plasma boundary and, if available, on polarimetry and motional Stark effect measurements. This wider combination of data in turns provides better constraints on the global plasma equilibrium that can be determined using codes such as EFIT. Tearing modes with multiple helicities have also been analysed in the context of equilibrium reconstruction. Since they indicate the presence of nearby magnetic islands, they could help in localizing the flattening of the q-profile, which is seldom captured using standard equilibrium reconstruction codes.

The analysis of ELMs and their possible precursors as function of fuelling location has revealed a wide range of features in the magnetic measurements, indicating that the prevailing understanding of the ELM physics by using only a reduced set of magnetic sensors is not sufficient to generally capture the global behaviour of these instabilities.

Fast-ion instabilities were suspected as being a possible source of the discrepancies observed in the electron temperature profile measurements that are obtained using different diagnostic systems. Preliminary investigations did not show any clear-cut correspondence between these discrepancies and the onset of fast-ion driven modes. This could be attributed to a rather incomplete diagnostic coverage of the fast ion population, which prevents drawing firm conclusions on whether such link may exist or not.

2.5.7. Contribution to the scientific exploitation of Asdex-Upgrade

Convective transport in the SOL

A strong experimental effort is devoted within the EUROfusion program to determine the role of convective filamentary transport in establishing the SOL profiles, in particular concerning the presence of the so called "shoulder" in high density regime. The experiment performed in AUG was devoted to determine if the increase of convective transport in H-Mode is still regulated by the effective collisionality Λ as in the case of L-Mode. The experiment has been carried out by establishing a low-power ECRH heated H-Mode and controlling divertor conditions by adjusting both the level of density and the Nitrogen seeding in order to reach the foreseen condition where the appearance of the density shoulder was supposed to occur. The observed increase of the upstream density in the SOL was weaker than foreseen and additional experiments are planned to check if other elements, like a minimum level of density or neutral pressure, are playing any role in establishing the increase of convective transport in the SOL.

Real-time control of Neoclassical Tearing Modes and Edge Localized Mode behaviour

Several experiments have been performed in parallel on AUG and TCV, in particular those dedicated to the development of a reliable NTM real-time controller and to the operation close to the density limit with tolerable ELMs.The NTM experiments on AUG mainly focused in the development of a scenario that has 2/1 modes triggered with increased NBI power, while avoiding mode locking and disruption. This was successful with real-time control of the NBI, which decreased significantly the beam power as soon as the mode is triggered and detected. Several TCV experiments on the stabilization and pre-emption of the 2/1 mode could be performed. This information will be used in subsequent AUG experiments.

The experiments on small ELMs focused on type II ELMs that can be obtained by moving the AUG plasma shape closer to a double null divertor configuration. This shape was obtained for the first time since the new wall has been installed and nice stationary H-modes with type II (small) ELMs have been obtained. We tried to change the collisionality at the top of the pedestal, with some but little success. The next experiments will focus on type III ELMs, which will also be the focus of the TCV experiments.

Real-time control system

The SVD factorization code of the fast magnetic signals has been implemented on the real-time control system of AUG. It encompassed the reduction of the complexity of the original code developed in 2014 to match the AUG RT constraints in the code's original execution environment.

The first goal of this work was to test whether the functionality of the algorithm is retained after reductions in its complexity. To do so, we developed a parallel version of the off-line code, which writes the results on a parallel AUG diagnostic. In this new version we implemented a reduction of the number of analyzed signals from 28 to 10, the introduction of the signal windowing, the exclusion of the lowpass filters at 2Msps before the downsampling of the signals and the theoretical principal axes retrieval from pre-computed look-up tables. All these cuts were tested running the reduced algorithm on some fiducial shots and comparing the algorithm results w.r.t. the full version. Results were in quite good agreement. As a final step we selected a 10 coils subset among the 28 used by the full algorithm to be used in real-time. Figure 2.5.5 summarizes all these points.

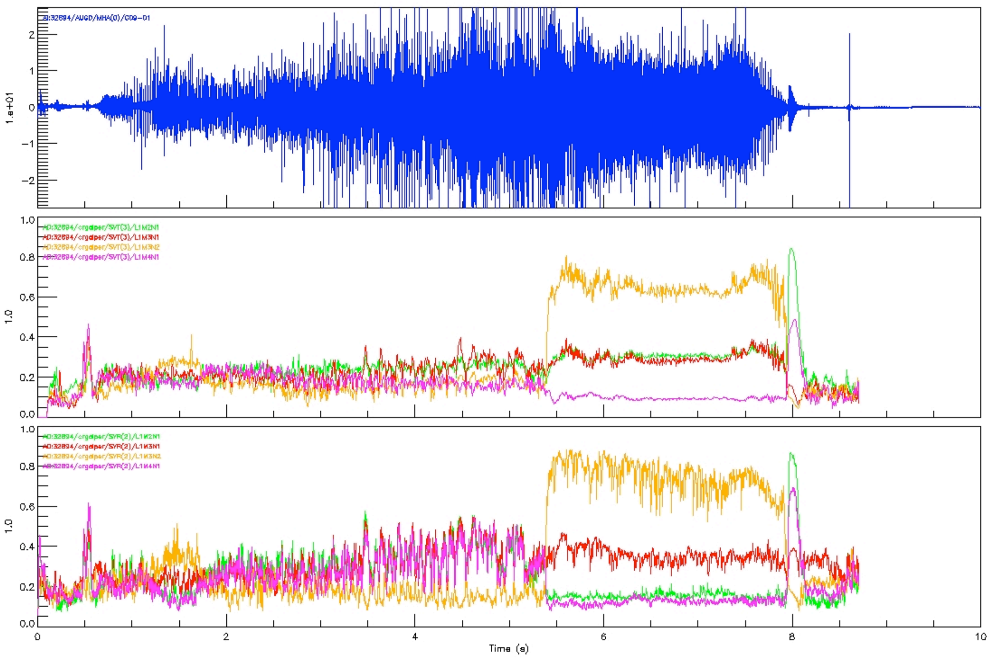


Fig. 2.5.5 *Magnetic coils SVD based analysis algorithm porting to real-time on the Asdex Upgrade Tokamak.*
Plot 1 : raw magnetic signal from 1 fast magnetic sensor.
Plot 2 : off line evaluated mode likelyhoods using the SVD based analysis, showing a dominant (3,2) mode at 5.5 sec (orange track) ending with a (2,1) mode (green track).
Plot 3 : Same analysis preformed with a reduced version of the off-line algorithm for being able to run in real-time on AUG control system as presented in the text, clearly the results are in accordance.

The second part of the work consisted in rewriting the algorithm to let it run on one of AUG real-time analysis machines. This included the study of AUG diagnostic processing system and the DCS (Discharge Control System) system itself. After that the entire code has been re-written in C++ and inserted as an add-on processing tail to the already present MRH real-time diagnostic. Then the diagnostic was renamed MSH and tested either in shot-reprocessing mode and in shot-simulation mode, attached to the real rtLevel0 diagnostic providing data during an off sequence test. Doing so, we were able to measure the computational time, which presently stays below 4ms, so it is foreseen to have online outputs to the upper levels of the DCS at least every 5ms.

Informatics tools were implemented to investigate the plasma pedestal behaviour, in particular with the EPED code. The system was first used for the experiment “Operation close to the density limit with high confinement and tolerable ELMs”.

2.5.8 Divertor Tokamak Test facility

The SPC is sponsoring and leading the EUROfusion WPDTT1 project, which aims at an evaluation of the DEMO compatibility of promising alternative divertor solutions. The result of this assessment should narrow the scope and improve the focus of a dedicated divertor tokamak test facility (DTT) that may be required to develop and qualify an alternative solution before its deployment in DEMO. The project is an integral part of the European Roadmap to the realisation of fusion energy. It comprises contributions from 15 European research laboratories. Considered alternatives include various divertor configurations and liquid metal divertor targets. The strategy of the assessment is based on a comparison of "costs" and "benefits" of the most promising alternatives with the PPPT baseline solution, which foresees a DEMO with a conventional single-null configuration and solid tungsten divertor armour. The most promising alternative configurations include the X divertor (XD), the Super-X divertor (SXD) and the snowflake divertor (SFD). The assessment of liquid metal based solutions focuses on lithium (Li), tin (Sn) and LiSn alloys confined in a capillary porous system (CPS). The physics basis of this subset of alternative solutions has been summarised in a report on the "Development of physics models for particle and power exhaust".

DEMO configurations with the considered alternative divertor configurations have been developed assuming realistic coil current densities and sufficient space for breeding blankets and neutron shielding. Improving the coil position resulted in acceptable forces on the coils. While all alternatives result in higher total coil currents, higher forces and a larger toroidal field coil volume, no show-stoppers were identified. Calculations of the exhaust performance are ongoing. The work on the liquid metal target armour comprises the characterisation of tritium retention and temperature enhanced erosion of the considered metals, the demonstration of liquid metal based solution, mainly in the FTU tokamak and modelling of the liquid metal target as well as its effect on the divertor and core plasma. The project activities identified that a realistic estimate of the power removal potential requires an integrated liquid metal concept including the full liquid metal cycle, a coolant solution and reactor relevant materials, which remains to be developed.

In addition to the above activities, SPC scientists have participated in the EUROfusion WPDTT2 project, which deals with the definition of the scope and the conceptual design of a Divertor Test Tokamak (DTT) facility. Such a facility, which can be either an upgraded existing or a newly built facility, should have the capability to develop an alternative plasma exhaust solution to sufficient maturity for a deployment in a demonstration reactor. This activity is carried out to mitigate the risk that the conventional solution, to be tested in ITER, will not extrapolate to a reactor. As part of this activity SPC scientists helped to formulate the role and objectives of a dedicated DTT facility proposed by Italy to be included in the framework of the European Fund for Strategic Investments (EFSI).

2.5.9 Plasma surface interactions in collaboration with the University of Basel

The aim of this work was to investigate coated first mirrors under very harsh erosion conditions. Mock-up mirrors were exposed to high-flux hydrogen/argon plasma in the linear plasma facility Magnum-PSI. Rhodium (Rh) and molybdenum (Mo) coated mirrors with different thicknesses using or not water cooling exhibit different responses to this loading. Failures of Rh films were demonstrated for a 5 micron thick film, whereas 1 micron film revealed 10% decreased of the specular reflectivity only in the exposed area (Fig. 2.5.6). In comparison water cooled Mo mock-ups show an important diffuse reflectivity in the entire surface leading to more than 50% specular reflectivity losses in visible range. For not cooled Mo samples losses are not exceeding 4% in the whole studied wavelength range of 250-2500 nm.

Three phenomena are proposed to explain these results. First, the mechanical properties of the films as characterized by scratch and hardness measurements as well as residual stress analyses measured by X-ray diffraction of Rh films showed a high compressive stress of -2.5±0.4GPa, leading to a poor adhesion of thick films on stainless steel substrate due to an important available energy per area stored in the unbuckled film i.e. G_0>30J/m^2. This was confirmed by ANSYS simulations: for the Rh coating the von Mises stress was twice as that for Mo due to different mechanical properties. Moreover, the maximum stress for thick Rh film (261MPa) was higher than the critical buckling stress calculated using a buckle clamped Euler column model, thus demonstrating the failure mode of the film. The second phenomenon is a roughening of the mirror surface which is flux and temperature dependent i.e. at low temperatures the surface will roughen randomly without any oriented surface morphology and at higher temperatures the surface diffusion constants dominate the process and smoothen the surface. The third phenomenon was an important oxidation and carbidisation of the Mo surface even on non-exposed areas, as detected by X-ray photoelectron spectroscopy, which lead as well to a decrease of the reflectivity in the entire measured range; these were not observed for Rh film.

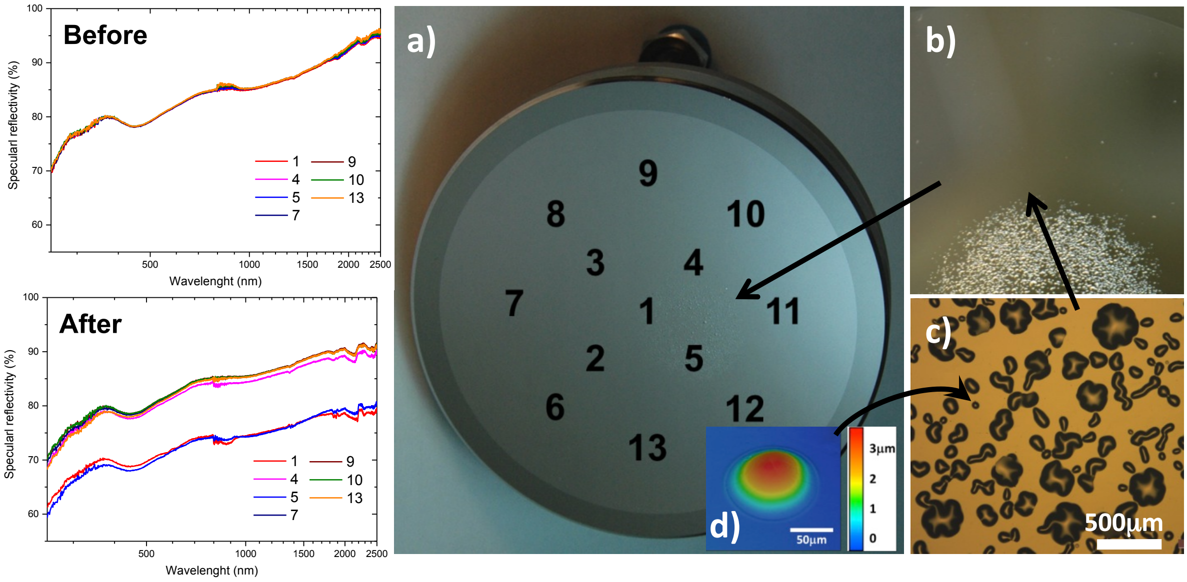


Fig. 2.5.6 *Specular reflectivity of the mock up MI1-01 (1 µm Rh on SS substrate) before and after exposure to a H_2/Ar (10%) plasma for a fluence of 60×10^{24} ions/m^2. The measurement positions are given on the mock up image after exposure. On the right are pictures at higher magnification of the exposed area. For image b) one graduation of the bar scale is 1 mm. Inset image d) is 3D image of blister.*

3 THE EDUCATIONAL ROLE OF THE SPC

The SPC plays a role in the education of undergraduate and postgraduate students, particularly in the Faculté des Sciences de Base (FSB) of the EPFL. Advanced education and training in fusion physics and technology and plasma physics topics is carried out as part of the research activities of the Association. Section 3.1 presents the courses given to physics and engineering undergraduates. In their Master year, physics students spend time with a research group at the EPFL, typically 12 hours per week for the whole year. During this period, they perform experimental or theoretical studies alongside research staff, discovering the differences between formal laboratory experiments and the “real” world of research. After successful completion of the first year of the Master Programme (4th year of studies), they are required to complete a “master project” with a research group, lasting a full semester. This master project is written up and defended in front of external experts. The SPC plays a role in all of these phases of an undergraduate’s education, detailed in Sections 3.2 and 3.3. As an academic institution, the SPC supervises many PhD theses, also in the frame of the Physics Section of the EPFL. Five PhDs were awarded in 2015. At the end of 2015 we had 31 PhD students supervised by SPC members of staff, in Lausanne and at the PSI site in Villigen. Their work is summarised in Section 3.4.

3.1 Bachelor courses given by SPC staff

S. Alberti, Maître d'Enseignement et Recherche – *“Plasma Physics I”*
This course is an introduction to plasma physics aimed at giving an overall view of the essential properties of a plasma and at presenting the approaches commonly used to describe its behaviour. Single particle motion and different fluid models are studied. The relation between plasma physics and developing a thermonuclear reactor is presented and illustrated with examples.

P. Ricci, Assistant Professor – *“General physics II”*
This course is given to the STI Section. It provides an introduction to special relativity and thermodynamics.

A. Fasoli, Professor – *“General Physics II”*
This course, given to the SV Section, completes the introduction to mechanics provided in the first semester with the basic concepts of statics, oscillations and special relativity. It also covers the whole of thermodynamics, from the introduction to heat, temperature and kinetic theory to the first and second principles, including entropy and thermal engines, ending with a treatment of transport and non-equilibrium phenomena in open systems.

M.Q. Tran, Professor - "General Physics II "
This course, given to the Mathematics Section, covers mechanics and thermodynamics.

L. Villard, *Professeur Titulaire – "Computational Physics I-II"*
Full year course given to students in their 2nd year in Physics. The course covers various time and space integration techniques for ordinary and partial differential equations, and is applied to various physics problems ranging from particle

dynamics, hydrodynamical equilibrium, electromagnetism, waves and quantum mechanics. It includes a strong practical work aspect.

A. Fasoli, Professor, **I. Furno**, *Maître d'Enseignement et Recherche (MER),* ***P. Ricci****, Professor,* ***D. Testa****, Research and Teaching Associate* – MOOC on "Plasma Physics and Applications"
The first MOOC to teach the basics of plasma physics and its main applications: fusion energy, astrophysical and space plasmas, societal and industrial applications

A. Fasoli, Professor and **I. Furno**, *Maître d'Enseignement et Recherche (MER) – "Energy for Global Issues"*
Energy involves scientific, technological and societal issues. In this course, all of these aspects are treated in an intertwined way, from the basic concepts to the needs and resources, as well as societal and political implications.
The goal is to provide the students with quantitative tools and to present a global overview of the issue, to form a sufficient background enabling them to discuss in an informed way, and possibly contribute to, various aspects of the energy problem.

S. Brunner, *Maître d'Enseignement et Recherche (MER) and* ***J. Graves****, Maître d'Enseignement et Recherche (MER)* - Mathematical methods for physicists
This course, taught to 4th semester Bachelor Students in Physics, complements the Analysis and Linear Algebra courses in providing further mathematical background required for 3rd year physics courses, in particular electrodynamics and quantum mechanics.
Content: Introduction to Hilbert spaces. Solving linear 2nd order Ordinary Differential Equations (ODEs): Frobenius method, boundary value problems, Sturm-Liouville problems. Fourier analysis: Fourier Series and Fourier Transforms. Special functions. Methods for solving Partial Differential Equations (PDEs).

S. Brunner, *Maître d'Enseignement et Recherche (MER) and* ***J. Graves****, Maître d'Enseignement et Recherche (MER)* - Advanced Theory of Plasmas
This course is given to the Physics Doctoral School
1) MHD equilibrium and stability in Tokamaks
2) Waves and instabilities in Inhomogeneous Plasmas
3) Introduction to Nonlinear Effects in Plasmas

3.2 Master courses and laboratory at the SPC

Master courses given by SPC staff members

A. Fasoli, Professor, **I. Furno**, *Maître d'Enseignement et Recherche (MER),* ***A.A. Howling****, Research and Teaching Associate,* ***D. Testa****, Research and Teaching Associate – "Plasma Physics III"*
An introduction to controlled fusion, presented as a one semester option to 4th year Physics students. The course covers the basics of controlled fusion energy research. Inertial confinement is summarily treated and the course concentrates on magnetic confinement from the earliest linear experiments through to tokamaks and stellarators, leading to the open questions related to future large scale fusion experiments.

A. Fasoli, Professor and **M.Q. Tran**, Professor - *"Nuclear fusion and plasma physics"*
The aim of this course is to provide a basic understanding of plasma physics concepts of fusion energy, and of the basic principles of fusion reactors, including the main technological aspects. This course was given within the frame of the Master in Nuclear Engineering.

P. Ricci, Assistant Professor – *"Plasma physics II"*
One semester option course presented mainly to 4th year Physics students, introducing the theory of hot plasmas via the foundations of kinetic and magnetohydrodynamic theories and using them to describe simple collective phenomena. Coulomb collisions and elementary transport theory are also treated. The students learn to use various theoretical techniques like perturbation theory, complex analysis, integral transforms and solutions of differential equations.

Advanced Physics Laboratory

During the Spring semester of 2015, SPC staff members have supervised 5 students performing their Advanced Physics Laboratory work and 2 ERASMUS students. During the Automn semester of 2015, we had 12 students.

EPFL Master degrees awarded in 2015

Gauthey Chantal: *"Statistical methods for suprathermal ion turbulent transport in magnetized plasmas"*

Hausemman Loïc: *"Development of a Synthetic Diagnostic for Beam Emission Spectroscopy"* (Princeton)

Wuilloud Gaëtan: *"Experimental measurements of plasma current during magnetic reconnection in the experiment VINETA"* (IPP-Garching)

Renevey Silvain: "*Collision Avoidance Maneuver Algorithms for CleanSpace One*" (Space Center, EPFL)

Musil Felix: *"The impact of the Boussinesq approximation on the simulation of scrape-off layer plasma turbulence"*

Ohana Noé: *"Drift-kinetic instabilities in a sheared plasma slab using a particle approach"*

3.3 Doctoral studies

Postgraduate courses given in 2015

S. Brunner, ***J. Graves:*** "Advanced Theory of Plasmas", Doctoral School EPFL
1) MHD equilibrium and stability in Tokamaks
2) Waves and instabilities in Inhomogeneous Plasmas

3) Introduction to Nonlinear Effects in Plasmas

Ch. Hollenstein, P. Bruzzone, S. Alberti, B. Duval, J.-P. Hogge, D. Fasel, Y. Martin, Ph. Spaetig, A. Howling, U. Sheikh, *"Fusion and Industrial Plasma Technologies"*

T.M. Tran, *"MPI, an introduction to parallel programming"*, MPI, SFP Section

3.4 Doctorate degrees awarded during 2015

Fabio AVINO: *"Turbulence at the boundary of toroidal plasmas with open and closed magnetic flux surfaces"* - EPFL Thesis 6734 (2015)
The control and confinement of fusion plasmas are currently limited by a lack of understanding of the physical mechanisms behind the evolution of the turbulent transport experienced by particles and energy. In-situ investigations of plasma turbulence in fusion experiments is strongly hampered by the high temperatures and densities. Basic plasma physics devices represent an alternative solution to perform turbulence studies with the possibility of rigorously validating numerical codes. One of these experiments is TORPEX, in which a comprehensive characterization of plasma turbulence has been conducted in the presence of open helical magnetic field lines in toroidal geometry. These reproduce the main features of the scrape-off layer (SOL), which is the open flux surface region at the edge of magnetically confined fusion plasmas. The SOL has a key role in the balance of the dynamics that determine the overall plasma confinement. The first achievement of this thesis work is a technical upgrade of TORPEX that consists in the installation of a copper toroidal conductor inside the TORPEX vacuum vessel. A poloidal magnetic field is produced by a current flowing inside the conductor, introducing a rotational transform. This allows studying plasma turbulence in magnetic geometries of increasing complexity, starting with the simplest configuration of quasi-concentric flux surfaces. The initial exploration of the main plasma properties, including plasma production mechanisms and particle confinement time, is followed by a detailed spectral characterization of the measured electrostatic quasi-coherent fluctuations. Measurements of the toroidal and poloidal mode numbers reveal field-aligned modes. These present a poloidal localization indicating a clear ballooning feature that is in agreement with the results of a linear fluid code. The first experimental measurements of plasma blobs in the presence of a single-null X-point are performed. Blobs radially propagating outwards across the X-point are conditionally sampled, which allows us to track and analyze in detail the corresponding dynamics. The ExB drifts induced by the background potential gradients and the fluctuating potential dipole are both responsible for the measured blob acceleration in the X-point region. The contribution of the potential dipole is explained on the basis of an analytical model, in which the variation of the magnetic field intensity close to the X-point plays a key role. This results in a blob speed scaling that is in good agreement with the measured values.

Alexandre BOVET: *"Suprathermal ion transport in TORPEX"* – EPFL Thesis 6527(2015)
Suprathermal ions, which have an energy greater than the quasi-Maxwellian background plasma temperature, are present in many laboratory and astrophysical plasmas. In fusion devices, they are generated by the fusion reactions and auxiliary heating. Controlling their transport is essential for the success of future fusion devices that could provide a clean, safe and abundant source of electric power to

our society. In space, suprathermal ions include energetic solar particles and cosmic rays. The understanding of the acceleration and transport mechanisms of these particles is still incomplete. Basic plasma devices allow detailed measurements that are not accessible in astrophysical and fusion plasmas, due to the difficulty to access the former and the high temperatures of the latter. The basic toroidal device TORPEX offers an easy access for diagnostics, well characterized plasma scenarios and validated numerical simulations of its turbulence dynamics, making it the ideal platform for the investigation of suprathermal ion transport. This Thesis presents three-dimensional measurements of a suprathermal ion beam injected in turbulent TORPEX plasmas. The combination of uniquely resolved measurements and first-principle numerical simulations reveals the general non-diffusive nature of the suprathermal ion transport. A precise characterization of their transport regime shows that, depending on their energies, suprathermal ions can experience either a superdiffusive transport or a subdiffusive transport in the same background turbulence. The transport character is determined by the interaction of the suprathermal ion orbits with the turbulent plasma structures, which in turn depends on the ratio between the ion energy and the background plasma temperature. Time-resolved measurements reveal a clear difference in the intermittency of suprathermal ions time-traces depending on the transport regime they experience. Conditionally averaged measurements uncover the influence of field elongated turbulent structures, referred to as blobs, on the suprathermal ion beam. A theoretical model extending the Brownian motion to include non-Gaussian (Lévy) statistics and long-range temporal correlation is developed. This model successfully describes the evolution of the radial particle density from the numerical simulations and provides information on the microscopic processes underlying the non-diffusive transport of suprathermal ions.

Daniele BRUNETTI: *"MHD properties of hybrid tokamak and RFP plasma"* – EPFL Thesis 6636(2015)

It has been observed experimentally that magnetically confined plasmas, characterised by the safety factor q with a small or slightly inverted magnetic shear, have good confinement properties. Such plasmas typically have no internal transport barrier, operate with q_{95} around 4 and are good candidates for long pulse operation at high fusion yield in the reactor ITER. These hybrid scenarios are an intermediate step between the reference standard H-mode (high confinement) scenario with monotonic q and inductive current, and advanced scenarios with strongly reversed magnetic shear in which the entire plasma current is ideally generated non-inductively. This thesis focuses on the study of the dynamics of hybrid plasmas, with weak or almost zero magnetic shear, in tokamak and Reversed Field Pinch (RFP) configurations, when q in the central region assumes values close to one (tokamaks) or to a rational number (tokamaks, RFPs), though the exact resonance is avoided. The first part of this thesis is focused on the study of tokamak and RFP equilibria with slightly reversed shear when an extremum in the safety factor is close to a low order rational. These equilibria are characterised by the possible presence of internal helical cores, although the plasma edge is symmetric in the toroidal direction. Such 3D structures can be understood as the result of the nonlinear saturation of ideal MHD modes. The amplitude of large scale m=1 helical displacements in tokamak and RFP plasmas is investigated using contrasting approaches, namely 3D equilibrium and non-linear stability codes. The non-linear amplitude of such saturated modes obtained with the stability code is compared both with the helical core structure resulting from equilibrium numerical calculations, and with analytic predictions which extend the nonlinear treatment of reversed q plasmas to arbitrary toroidal mode numbers. A preliminary study of the impact of a n=1 RMP on the equilibrium helical distorsion is also presented. The second part of the thesis is devoted to the analytical and numerical study of the stability of an initially axisymetric tokamak configuration when the safety factor is almost flat and very close to a rational value over a macroscopically extended region in the plasma centre. Such conditions typically occur either in hybrid scenarios or following reconnection of a global instability such as a sawtooth. This configuration is characterised by non-negligible coupling between a fundamental mode and its Fourier adjacent modes. A dispersion relation has been derived both for ideal and resistive modes, with additional non-MHD effects such as plasma diamagnetism, viscosity and equilibrium velocity flows. The analytical results show that the resistive sidebands coupled to a core kink-like mode exhibit extremely fast growth, though additional non-MHD effects tend to moderately reduce the extreme growth rate of the resistive modes. The existence of such modes has been confirmed numerically, where the sensitivity of the growth rate to changes in resistivity and two-fluid effects has been demonstrated, and thus in turn provides generally good agreement with the analytical theory developed. A family of modes are obtained, including modes with novel scaling against plasma resistivity, some of which rotate in the electron diamagnetic direction, and others in the ion diamagnetic direction, consistent with experimental observations in e.g. TCV during hybrid-like operation.

Josef KAMLEITNER: *"Suprathermal electron studies in Tokamak plasmas by means of diagnostic measurements and modeling"* EPFL Thesis 6523(2015)

To achieve reactor-relevant conditions in a tokamak plasma, auxiliary heating systems are required and can be realized by waves injected in the plasma that heat ions or electrons under certain conditions. Electron cyclotron resonant heating (ECRH) is a very flexible and robust technique featuring localized power deposition and current drive (CD) capabilities. Its fundamental principles such as damping on the cyclotron resonance are well understood and the application of ECRH is a proven and established tool; electron cyclotron current drive (ECCD) is regularly used to develop advanced scenarios and control magnetohydrodynamics (MHD) instabilities in the plasma by tailoring the current profile. There remain important open questions, such as the phase space dynamics, the observed radial broadening of the suprathermal electron distribution function (e.d.f.) and discrepancies in predicted and experimental CD efficiency. These are addressed in this thesis. One of its main goals is indeed to improve the understanding of wave-particle interaction in plasmas and current drive mechanisms. This was accomplished by combined experimental and numerical studies, strongly based on the conjunction of hard X-ray (HXR) bremsstrahlung measurements and Fokker-Planck modeling, characterizing the suprathermal electron population. The hard X-ray tomographic spectrometer (HXRS) diagnostic was purposely developed to perform these studies, in particular by investigating spatial HXR emission asymmetries in the co- and counter-current directions and within the poloidal plane. The system uses cadmium-telluride (CdTe) detectors and digital acquisition to store the complete time history of incoming photon pulses. An extensive study of digital pulse processing algorithms was performed and its consequent application allows the HXRS to handle high count rates in a noisy tokamak environment. Numerous other numerical tools were developed in the course of this thesis, among others to improve the time resolution by conditional averaging and to obtain local information with the general tomographic inversion (GTI) package.

The interfaces of the comparatively new LUKE code and well-established CQL3D Fokker-Planck (F-P) code to the tokamak à configuration variable (TCV) data were refurbished and a detailed benchmarking of these two codes was performed for the first time. Indeed, the theory-predicted toroidal and poloidal emission asymmetries could be consistently verified by experiment and modeling in many cases, including scans of a variety of plasma and wave parameters. The effects of supra-thermal electron diffusion and radio frequency (RF) wave scattering, both resulting in a radial broadening of the HXR emission, were separated by a poloidal deposition

location angle scan. Furthermore, previous results on anomalous diffusion and CD efficiency were reproduced with increased confidence arising from enhanced diagnostic specifications. The plasma response to electron cyclotron (EC) absorption and the role of quasi-linear effects were investigated using the coherent averaging capabilities of the HXRS.
SeveralMHD instabilities can occur in the plasma center and better understanding of these modes and events is indispensable for their mitigation in order to prevent their negative effects on confinement and stability. Sawtooth crashes are such a major instability and localized at the q=1 surface. They can be described as the evolution of an internal m=1 kink mode leading to magnetic reconnection and consequently enhanced transport; additionally, the crashes can trigger secondary deleterious instabilities. The electron acceleration in the magnetic reconnection process was studied as well as the impact on the suprathermal tail. While acceleration was not specifically observed, the efficient ejection of suprathermal electrons due to sawtooth crashes could be quantified. In low density discharges this rapid transport leads to bursts of energetic HXR thick-target bremsstrahlung from the limiter.
A $m/n = 1/1$ internal kink mode coupled to a $m/n = 2/1$ component and closely related to sawtooth crashes is regularly observed in the presence of ECRH/CD close to the q=1 surface. It occurs in bursts, alternating with phases of one or more sawtooth crashes. The dynamics of this bursty mode, which generally affects confinement, turn out to be connected to suprathermal electrons that are efficiently reheated after the preceding sawtooth crash and then dragged by the mode.
Another mode investigated in this thesis is the electron fishbone instability, another $m/n = 1/1$ internal kink mode excited by resonant interaction with the drift reversal of precessing fast electrons, according to current understanding. There is as yet no complete picture of this instability. Significant differences in the observations on various tokamaks show the importance of a more systematic experimental study to advance the qualitative understanding and quantitative description of the instability. In particular, the presumed roles of barely trapped, barely passing and other specific regions of the e.d.f. in phase space were expected to be clarified by experiments on TCV using the HXRS as the main diagnostic. However, it proved more difficult than expected to destabilize this mode, and only preliminary, though promising results were obtained in the available time.

Doohyun KIM: *"Sawtooth control experiments in KSTAR and AUG"* EPFL Thesis 6539(2015)
The main goal of this thesis is to demonstrate the capability of magneto-hydrodynamic(MHD) instability control, particularly sawteeth and neoclassical tearing modes (NTMs). In order to achieve high performance operation. Experiments and simulations have been carried out to pursue this purpose on different tokamaks: TCV (in Switzerland), KSTAR (in Korea), AUG (in Germany) and ITER (in construction in France). Each tokamak has different features such as machine size, heating systems, operation scenarios and energy confinement time scale, all the tokamaks are equipped or will be equipped with an electron cyclotron heating/current drive (ECH/ECCD) system for plasma heating/current drive and control of MHD instabilities. Therefore, this work focusses on the feasibility of using the localised ECH/ECCD beams to control the instabilities;sawteeth and NTMs.
For the experimental part, sawtooth and NTM control experiments have been carried out. In TCV, novel ways of sawtooth period control - sawtooth pacing and locking – have experimentally been demonstrated using the TCV real-time control system. Based on the successful application of these methods to sawtooth control in TCV, we have next focussed on the extension of these new sawtooth period control methods to other tokamaks: KSTAR and AUG. In the 2013 KSTAR experimental campaign, the applicability of sawtooth locking using EC power

modulation has been tested for sawtooth period control in the presence of fast particles generated by neutral beam injection (NBI). The KSTAR real-time control system was not ready for sawtooth pacing thus only locking has been examined. These preliminary KSTAR experimental results have shown the possibility of sawtooth period control using sawtooth locking, although proper locking was not obtained yet. The locking parameters would still need to be adjusted for single period locking to occur. In order for the investigation of the capability of sawtooth locking on KSTAR tokamak to be complete, more experiments with different locking parameters should becarried out. The sawtooth locking technique has also been applied to AUG plasmas. As in the KSTAR tokamak, the real-time control for sawtooth pacing was not available, thus sawtooth locking has been tested. The AUG plasmas were more complicated compared to TCV and KSTAR cases due to the fast particles effect on the evolution of sawtooth from both NBI and ion cyclotron heating (ICH). Sawteeth did not lock to the EC modulation in AUG experiments, though in some discharges they became somewhat more regular. However, the application of sawtooth locking to the AUG tokamak has been well initiated and more experiments will follow to understand better the behaviour of sawteeth and to determine the sawtooth locking range. In addition, sawtooth control was demonstrated and used in other experiments studying the role of sawteeth on impurity transport.

Concerning the NTM control experiments, we have focussed on the enhancement of the NTM control strategy, which has been achieved in two ways. In previous TCV experiments, NTM stabilisation was obtained as ECH/ECCD deposition was swept in one direction until the mode disappeared. In order to ameliorate the control of NTMs, as a first improvement, a real-time version of the equilibrium reconstruction code Liuqe (RTLiuqe) has been implemented in the TCV real-time control system. Using RT-Liuqe, the safety factor q can be estimated in real-time and from pre-calculated ray-tracing and an assumption on which mode is to be controlled, a target q is converted to a requested EC launcher angle. In this way, the EC launcher can track the location of NTMs in real-time to stabilise the mode or to prevent the onset of the mode. In recent TCV experiments, the capability of NTM stabilisation and pre-emption using RT-Liuqe has been successfully demonstrated. Although the mode location can be estimated by RT-Liuqe, there are still uncertainties; for example an intrinsic offset exists in the estimated q profile. In order to ensure the suppression of NTMs, these difficulties need to be resolved. Therefore, as a second improvement, we have introduced a new simple and robust technique to control NTMs. By adding a sinusoidal variation on the target position estimated by RT-Liuqe, the EC launcher sweeps around the estimated position and can have a higher probability to stabilise the NTMs. In the series of experiments, several discharges have been devoted to demonstrating the capability of this new technique to control NTMs. The application of this technique has been extended to other tokamaks and aims at the projection to ITER.

As with the experiments, simulation works have aimed for a predictive simulation of the control of MHD instabilities, in particular the sawtooth instability. Prior to performing sawtooth simulations, we have introduced a simple transport model to evaluate electron temperature and density profiles during sawtooth cycles (i.e. over a sawtooth period time-scale). Since the aim of this simulation is to estimate reliable profiles within a short calculation time, a simplified ad-hoc model has been developed. It has been developed to rely on a few easy-to-check free parameters, such as the confinement time scaling factor and the profiles' averaged scale-lengths. Due to the simplicity and short calculation time of the model, it is expected that this model can also be applied to real-time transport simulations. We show that it works well for ohmic and EC heated L- and H-modes. In addition, from previous TCV experiments, we have observed that the confinement time is affected by the deposition position of the EC beams. Since this effect has not been considered in the scaling law, as a preliminary test we have introduced a new scaling factor that takes into account the effect of the heating deposition position. These models have been applied to the sawtooth simulation; TCV sawtooth control experiments have been reproduced. For the sawtooth pacing, the calculated delay between EC power off and sawtooth crash agree well with the experimental results. The map of possible locking range has also been well reproduced by the simulation. Based on the TCV sawtooth simulation, we have performed a predictive simulation for the sawtooth control on ITER and with the result of this simulation, the capability of sawtooth control using the present design of ITER EC launcher has been investigated and confirmed.

David PFEFFERLE: *"Fast ion confinement in MHD configurations"* EPFL Thesis 6561(2015)
In the following theoretical and numerically oriented work, a number of findings have been assembled. The newly devised VENUS-LEVIS code, designed to accurately solve the motion of energetic particles in the presence of 3D magnetic fields, relies on a non-canonical general coordinate Lagrangian formulation of the guiding-centre and full-orbit equations of motion. VENUS-LEVIS can switch between guiding-centre and full-orbit equations with minimal discrepancy at first order in Larmor radius by verifying the perpendicular variation of magnetic vector field, not only including gradients and curvature terms but also parallel currents and the shearing of field-lines. By virtue of a Fourier representation of the fields in poloidal and toroidal coordinates and a cubic spline in the radial variable, the order of the Runge-Kutta integrating scheme is preserved and convergence of Hamiltonian properties is obtained. This interpolation scheme is crucial to compute orbits over slowing-down times, as well as to mitigate the singularity of the magnetic axis in toroidal flux coordinate systems. Three-dimensional saturated MHD states are associated with many tokamak phenomena including snakes and LLMs in spherical or more conventional tokamaks, and are inherent to stellarator devices. The VMEC equilibrium code conveniently reproduces such 3D magnetic configurations. Slowing-down simulations of energetic ions from NBI predict off-axis deposition of particles during LLM MHD activity in hybrid-like plasmas of the MAST. Co-passing particles helically align in the opposite side of the plasma deformation, whereas counter-passing and trapped particles are less affected by the presence of a helical core. Qualitative agreement is found against experimental measurements of the neutron emission. Two opposing approaches to include RMPs in fast ion simulations are compared, one where the vacuum field caused by the RMP current coils is added to the axisymmetric MHD equilibrium, the other where the MHD equilibrium includes the plasma response within the 3D deformation of its flux-surfaces. The first model admits large regions of stochastic field-lines that penetrate the plasma without alteration. The second assumes nested flux-surfaces with a single magnetic axis, embedding the RMPs in a 3D saturated ideal MHD state but excluding stochastic field-lines within the last closed flux-surface. Simulations of fast ion populations from NBI are applied to MAST n=3 RMP coil configuration with 4 different activation patterns. At low beam energies, particle losses are dominated by parallel transport due to the stochasticity of the field-lines, whereas at higher energies, losses are accredited to the 3D structure of the perturbed plasma as well as drift resonances.

3.5 Ph.D. Theses supervised by SPC staff at the end of 2015

Himank ANAND: *"Exploration of candidate fusion reactor regimes by real time control of tokamak plasma shape"*
The PhD work was dedicated to the experimental commissioning of the generalized plasma shape and position controller for advanced plasma configurations. The controller was successfully tested for limiter plasma configurations including both positive and negative triangularity plasma shapes. Optimum range of control parameters based on stability and performance were determined. Initial successful experimental results with respect to the divertor plasma configurations were also obtained. Further extension of the generalized plasma position and shape controller to advanced plasma configurations is foreseen in future.

Falk BRAUNMUELLER: *"Nonstationary operating regimes in Gyrotron oscillators"*
Extensive benchmarks of the new code TWANG-PIC against experiment and/or other numerical models have been performed. The TWANG-PIC model together with the results of the benchmark have been published in Physics of Plasmas. The different codes developped throughout the thesis (TWANGlin, TWANG-PIC) have been used for designing the dual-frequency gyrotrons for the X3-Upgrade, the ITER and DEMO gyrotrons. Support for the DNP experiments carried out at LPMN (Prof. J.Ph. Ansermet). The second part of the year has been devoted to the writing of the thesis.

Nikolay BIKOVSKIY: *"HTS high current cable for fusion application"*
Test of 60 kA HTS cable prototypes was successfully performed in the EDIPO test facility including Ic, Tcs, AC loss and electromagnetic cycling measurements. Comparing the assessed and measured DC performance of the cables, the tape transport properties were fully retained in the prototypes. Progressing degradation of the cables performance during the cycling test was fully investigated. This resulted in a further optimization step of the strand design aiming to improve its properties against the transverse mechanical load.

Oulfa CHELLAI: *"Scattering of electron cyclotron waves by the edge turbulence in magnetically confined fusion devices"*
In fusion devices, Radio Frequency (RF) waves at the electron cyclotron frequency (EC) are used to perform localised heating and current drive. My thesis is about understanding the influence of the edge turbulence on the propagation of the EC waves. This year I have achieved progress in understanding the basics of the interactions between blobs and RF waves on TORPEX. I have also installed an X3 transmission diagnostic on TCV.

Dahye CHOI: *"Suprathermal electron physics in TCV"*
Measurements on runaway electron experiments were performed in TCV. The generation of suprathermal electron population during the current quench was analyzed by the hard X-ray spectroscopy and the soft X-ray singular value decomposition analysis.

Julien DOMINSKI: *"Development of an arbitrary wavelength solver in ORB5"*
Implementation, verification, and benchmark of an arbitrary wavelength field solver of the gyrokinetic quasi-neutrality equation. First linear and nonlinear simulations of plasma turbulence and associated transport, in condition relevant to the TCV tokamak, when including the fully kinetic dynamics of particles.

Jonathan FAUSTIN: *"Self-consistent interaction of fast particles and ICRH waves in 3D applications of fusion plasma devices"*
The SCENIC code was used to assess the ICRH fast ion tail formation of a minority ion population in Wendelstein 7-X configuration. Realistic antenna geometry and power were applied and the obtained distribution functions show that the fast ion tail formation is hindered by the high plasma density and substantial particle losses. The loss channels have been identified and were found to be reduced by the inclusion of a neoclassically resolved radial electric field.

Matteo FONTANA: *"Turbulence studies in TCV using Correlation ECE diagnostics"*
The ECE and CECE diagnostics on TCV have been successfully installed and are now able to acquire data in almost all of the designed configurations. Data acquired during the first phases of the MST1 campaign are being analyzed and used to optimize the working conditions of the CECE system. In parallel, the exploration of the potential predictive power of simple, linear gyrokinetic simulations using GENE has begun, with the goal of using them to have a first indication of the expected turbulence regimes in model discharges.

Jérémy GENOUD: *"Advanced models for wave-particle interaction in gyrotrons"*
The development and exploitation of the new linear and spectral code TWANGlinspec, describing the self-consistent wave-particle interaction in the cavity of a gyrotron oscillator, have been pursued. The code has been used mainly to study start-up scenarios, in particular the simulations have been compared to experiments from the 1.5MW, 110GHz MIT-gyrotron. The code has also been adapted to treat spurious instabilities potentially occuring in gyrotron beam ducts and preliminary studies have been made. Moreover, an alternative numerical approach based on a finite element technique is being implemented in the spectral code TWANGlinspec. Furthermore, experiments with the DNP-gyrotron have been performed, both for gyrotron physics and DNP-spectroscopy purposes.

Natalia GLOWA: *"Quench detection and protection of the HTS insert coil"*
Depending on the operating scenarios and the characteristics of the insert coil (insulated and non-insulated), the quench behavior was assessed. Protection schemes were proposed where applicable, and the question of reliable quench detection system was addressed. The final version of the thesis manuscript was finalized and will be submitted in 2016.

Zhouji HUANG: *"Experimental study of plasma turbulence in the TCV tokamak"*
The TPCI experimental data from measurements performed in the TCV 2013 campaign were analyzed and compared with gyro-kinetic modeling in collaboration with the theory group. Turbulence regime transition during density ramp-up in Ohmic plasma was observed and investigated.

Rogério JORGE: *"ISTTOK Scrape-off Layer Turbulent Regimes"*
GBS simulations were successfully ported to a poloidal geometry and validated against the ISTTOK tokamak. It was shown that turbulence is mainly driven by the drift-wave instability in this type of short connection length systems and that the ballooning instability induces a distinction between low- and high-field side dynamics such that the characteristic pressure gradient length has a great poloidal variation. Furthermore, linear studies showed no functional dependence of the growth rate and scrape-off layer width on the safety factor, as confirmed by experimental results.

Andreas KLEINER: *"Non-linear resistive MHD modelling of tokamak stability limits"*
The effect of infernal mode coupling on the non-linear evolution of neoclassical tearing modes has been investigated. The growth of magnetic islands were examined by numerical simulations with the code XTOR-2F, with special attention given to the seeding of neoclassical tearing modes by infernal modes driven unstable in regions of low magnetic shear. Special attention was given to the role of bootstrap current. An analytic non-linear extension to a recently developed analytic linear model of resistive infernal modes was developed and compared favourably with the numerical results.

Mengdi KONG: *"Real-time control of NTMs in TCV"*
Various terms of the modified Rutherford equation (MRE) and corresponding transport theory have been reviewed to help understand the underlying physics of NTMs. The TCV NTM control system has also been reviewed to clarify its working principle, main components and key parameters. More detailed research on the real-time control of NTMs in TCV will be carried out based on this knowledge.

Samuel LANTHALER: *"Higher-order guiding centre motion"*
The particle following code VENUS-LEVIS has been extended to include higher order effects in Larmor radius. This includes in particular the Banos drift parallel to the magnetic field. The particle to guiding-centre switching algorithm has also been improved and includes all first order corrections derived from Lie perturbation theory. An improved correspondence between guiding-centre and full particle motion has been observed.

Emmanuel LANTI: *"Porting of a gyrokinetic PIC code to many- and multi-core platforms and its application to global flux-driven microturbulence transport simulations in tokamaks"*
With the aim of porting the global gyrokinetic PIC code ORB5 to multi- and many-core architectures, a testbed called pic_engine was developed. It is an abstraction of the PIC scheme implemented with a hybrid MPI/OpenMP programming model and retaining only the essential components of the algorithm thus allowing to easily test various optimization approaches. Among them, data structures, particle sorting, and vectorization were tested and showed an improvement of the code performance by at least a factor 2.15 compared to the unoptimized version.

Philip MALLON: *"Development of in-coil joints for NMR devices"*
In the construction of state-of-the-art NMR devices, the maximum producible length of high temperature superconducting (HTS) tape may become a limiting factor. To circumvent this obstacle, a mechanism has been developed to create low-

resistance soldered joints between HTS tapes. Taking into consideration the sensitivity of these tapes to high temperatures and bending strain, a commercially viable system is the end-goal of this work.

Fabian MANKE:
I have been investigating plasma turbulence properties on TORPEX. After assisting the installation of a second Langmuir-probe array, I updated and improved the respective data analysis suite and added new functionalities aiming to discern blob secondary modes and blob-rotation. Currently, my focus is on extending the investigations on the fractional diffusion of fast ions in open to closed field lines in TORPEX.

Claudio MARINI: *"Edge CX plasma rotation diagnostic in TCV"*
The delay in the restart of the TCV Tokamak led to a substantial change in the work done in 2015 with respect to the planning, in particular most of the efforts were spent on the Resonant Antenna Ion Device (RAID), performing passive spectroscopic measurements for the determination of the hydrogen dissociation degree. The analysis was based on the method developed by Lavrov, that requires the intensity ratio of the H_α, H_β and Fulcher α (2,2)Q1 lines and that uses a coronal model. Langmuir probe measurements were performed to characterize the plasma and to check the consistency of the model. The results were presented at the APS conference. A more sophisticated analysis with a collisional-radiative (CR) model, that required the complete Fulcher α Q diagonal spectrum and the determination of the absolute line intensity, is under elaboration. A study of toroidal angular momentum evolution across and after sawteeh in ASDEX Upgrade was carried on in the framework of MST1 campaign. The edge CXRS system (SYS4) was integrated in the TCV plant and is under commissioning, it exploits the active CX signal collected through the newly installed periscope.

Roberto MAURIZIO: *"Infrared measurements of the heat flux spreading under variable divertor geometries in TCV"*
The infrared (IR) system of TCV was recently upgraded to provide coverage of a wider range of divertor configurations and simultaneous measurements at both strike points of a conventional divertor geometry. Using the magnetic shaping flexibility of TCV, multiple divertor configurations ranging from modifications of the classical single null to alternative ones have been tested under attached and detached divertor leg conditions. Infrared measurements of the heat flux distribution on the TCV central column and floor are cross-checked with Langmuir probes and thermocouples. New routines for a more sophisticated analysis of IR data have been developed as well.

Gabriele MERLO: *"Flux-tube and global grid-based gyrokinetic simulations of plasma microturbulence and comparisons with experimental TCV measurements"*
Local and global gyrokinetic simulations have been performed using the GENE code with the aim of investigating some of the experimental observations of microturbulence reported from the TCV tokamak. The beneficial effect of negative triangularity was investigated with global runs, showing a high sensitivity of the transport level with respect to the density gradient profiles. Simulations are able to qualitatively reproduce the TCV transport level only when inputs profiles from a well diagnosed discharge are used.
Simulations investigating Geodesic Acoustic Mode (GAM) dynamics have been made, aiming at reproducing the frequency, wave length and spatial location of the

mode, obtaining a good agreement. The effect of the safety factor profile q on the transition from radially coherent to dispersive GAM was investigated showing that a change of the q profile only is not sufficient to induce this transition.

Pedro MOLINA: *"IR camera measurements of heat loads in plasma-facing components"*
During 2015, a high spatial and temporal resolution reflectometer diagnostic for electron density profile and fluctuations was taken from preliminary to critical design stages. An arbitrary-waveform-generator driven short-pulse reflectometer in U band (covering the TCV H-mode pedestal in O-mode) was proposed. In parallel, work towards implementing a dedicated doppler-backscattering diagnostic (DBS) for TCV was undertaken. Using existing hardware, a heterodyne DBS system was built and tested.

Federico NESPOLI: *"Scrape Off Layer physics in different magnetic configurations in TCV"*
My 2015 work has been focused on designing and performing new experiments in TCV to have a better comprehension of the physics determining the double scale length in limited plasmas. TCV limited plasmas have been modeled using the GBS code and the resulting numerical simulations have been used to study blob dynamics.

Noé OHANA: *"Development of a drift-kinetic PIC code"*
The first months of my PhD were dedicated to the development and optimization of a drift-kinetic PIC code solving for electrostatic instabilities in a sheared slab on new hybrid architectures (in particular GPUs).

Paola PARUTA: *"Advanced numerical algorithm for the simulation of the scrape off layer plasma turbulence"*
This work is aiming at enabing GBS to treat divertor scenarios and magnetic configuration with X-point(s). The work involved an anaytical and a numerical part. The former part consisted of rewriting the differential operators in the drift reduced Braginskii equations (solved in GBS) for an arbitrary magnetic configuration, including equilibria with X-point(s), the latter part consisted of implementing these new expressions for the operators into GBS code with a 4th order finite difference scheme.

Hamish PATTEN: *"Advanced three-dimentional Ion Cyclotron Resonance Heating phenomena"*
With the inclusion of Finite Larmor Radius effects in the code package SCENIC, in addition to collaborating with multiple ICRH and fast ion related experiments ongoing at JET, this project aims to investigate advanced ICRH scenarios. This will involve studying such effects as anisotropy, Finite Orbit Width and RF-pinch effects in two and three dimensional ideal-MHD equilibria. Additionally, if possible then a method will be implemented to extend the flux surfaces in order to follow particles in the vacuum region.

Masuhudan RAGHUNATAN: *"Guiding-centre particle orbits for 3D equilibira with rotation"*
We aimed to calculate the bootstrap current on a MAST-like tokamak for axisymmetric and helical-core VMEC equilibria using a self-consistent iterative procedure. The results were presented in the 597th WEH seminar on stochasticity in plasmas in Bad Honnef, Germany. In addition, the work on implementing toroidal rotation self-consistently between flow-modified VMEC and VENUS-LEVIS was continued, with the NBI module modified to account for toroidal rotation.

Fabio RIVA: *"Verification and Validation of SOL plasma turbulence codes"*
During the last year, a fully-spectral, two-dimensional fluid model has been developed and used to study the effects of uncertainty propagation on simulation results. Moreover, seeded blob simulations have been carried out with five different fluid models, and the results have been compared among each other and with TORPEX experimental measurements, with the target of validating the model equations and investigating the blob dynamics. Finally, an analytical model to express the magnetic field dependence on elongation, triangularity, and Shafranov's shift has been implemented in the GBS code, and it has been used to study the plasma shaping effects on scrape-off layer turbulence dynamics.

Joyeeta SINHA: *"Improvement of the plasma formation and its application for the doublet shaped plasma creation on TCV"*
Merging of two droplet shaped plasma is a promising strategy for the creation of doublet-shaped plasma in TCV, requiring simultaneous breakdown at two locations. Preparations were done to develop the scenario for doublet shaped plasmas. MGAMS was modified to implement the observers for the plasma current, radial and vertical position of the two droplet shaped plasmas. The RZIP2 model was developed to model the plasma response for the position control of the doublet plasma. An estimation of the proportional and derivative gains for the different feedback schemes for the position control of the doublet plasma was obtained.
A new I_P feedback control algorithm based on the I_P threshold along with the bump-less transfer control technique for the I_P feedback control was implemented to improve the present single-axis plasma formation in TCV.

Anna TEPLUKHINA: *"Ramp-down optimization studies"*
An optimization procedure of the ramp-down phase of the plasma discharges has been developed using the RAPTOR code. It provides an optimal time evolution of plasma current and elongation to minimize plasma current as fast as possible and to keep plasmas within common physical limits like Greenwald density limit, low normalized beta and internal inductance values. Numerical study of this problem can help to avoid plasma disruptions during real experiments.

Christoph WERSAL: *"The interaction between neutral atoms and turbulent plasma in the tokamak scrape-off layer"*
In 2015, I finalised the development of a model that describes the interaction of the neutral atoms with plasma turbulence in the tokamak scrape-off layer (SOL). The model is now published in a paper that appeared in the Nuclear Fusion journal. This paper also includes first results about the transition between the convection and conduction limited regimes of the tokamak SOL. Furthermore, I have addressed the plasma equilibrium along a magnetic field line, as it results from its interaction with the neutral atoms, and I compared the simulation results with an

improved version of the two-point model. I have shown that this model can predict the drop in electron and ion temperature along the parallel direction in the SOL.

4 PUBLIC RELATION ACTIVITIES IN 2015

The major event of 2015 was the launching of the new name of the Center that is the Swiss Plasma Center. A series of talks have been given by MM P. Gillet (EPFL), B. Bigot (ITER), Paméla (EUROfusion), Donné (EUROfusion), R. Strohmeier (EU Commission), B. Moor (SEFRI) and A. Fasoli (SPC) in front of a large public. The official ceremony took place at the entrance of the Center, as shown on the cover page. At this occasion, several articles were published in different newspaper in Switzerland and a radio interview of A. Fasoli was broadcast. A new logo has been created.

We also took this opportunity to refurbish the TCV hall with a large TV screen and a rearrangement of the posters. New posters have been produced for the office building and are displayed in the hall to welcome the visitors, together with a large version of the logo. The new logo has also been displayed on the buildings and is now visible from the main road. Four TV screens have been placed in halls and in the cafeteria to display information.

Beside this event, different popular science papers were published, different presentations were given, open doors welcomed about 1200 persons on a Saturday in November and more than 2700 people visited the Center during the year.

5 FUSION & INDUSTRY RELATION

Since 2009 the Swiss industry benefits from the services of an Industry Liaison Officer (ILO) to support procurement opportunities that arise in the course of the construction of the ITER Experimental Fusion Reactor.

In January 2015, the State Secretariat for Education, Research and Innovation (SERI), PSI and EPFL joined forces to extend the ILO services to the seven ground large-scale International Research Organisations of which Switzerland is a member: CERN, ESO, ILL, ESRF, ITER, XFEL and ESS. The creation of the Swiss Industry Liaison Office (www.swissilo.ch) was motivated by the strong synergies existing between the demands arising from these organisations and the available physics-related technology offered in Switzerland. It was decided that the Swiss Plasma Center would host the Swiss ILO due to the paramount importance of the ITER project in the coming years and the new position of the Swiss Plasma Center as a federating laboratory for a number of large-scale applied physics projects in Switzerland.

In 2015, the demand at ITER for specific high-end technology components and world-class engineering solutions has continued to attract Swiss players. Some examples are provided below.

DAES in Petit-Lancy (GE) has won a large engineering service contract for the Ion Heating system "*Framework Contract - ICRH Antenna Global Model Assessment*". DAES performs specific analyses for structures with high power radiation density depositions rates. In addition to the results delivered by standard mechanical stress simulators, DAES provides specific application codes to verify the overall consistency with the French nuclear codes (RCC-MR code).

HEXAGON-LEICA in Unterentfelden (AG) has reported numerous sales successes in 2015 through direct contracts with ITER partners, including ITER IO in Cadarache, by supplying Laser Metrology Systems. As a result, their LEICA 3D tracker systems are becoming the de facto standard over the whole ITER project. For example, the HEXAGO-LEICA metrology system will be used for welding the 9 x 450 tons vacuum segments on a millimeter precision level.

NORDLOCK in Sankt Gallenkappel (SG) is a supplier of *superbolts* and advanced engineering calculation for tensioning systems used for the connection of heavy steel structures. They have been actively pursuing complex business development tasks in 2015 on different subsystems to be delivered by the Far East ITER partners (Korea, Japan and China).

On the marketing side, a major event was organized by the Swiss ILO in Luzern on the 17th June, the *Joint ITER-ESS Swiss Industry information Day*. The procurement activities from ITER and ESS, which in the coming years will be the two international organisations with the most prominent opportunities for Swiss industry, were presented. The speakers were from the scientific and state authorities in Switzerland, from ITER and ESS scientists or procurement managers and from Swiss firms already engaged in contracts. More than 70 representatives of the Swiss industry attended the event.

APPENDICES

APPENDIX A Articles published in Refereed Scientific Reviews during 2015

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APPENDIX B Conferences and Seminars

B.1 Conference and conference Proceedings published in 2015

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Prof. F. Zonca, ENEA C.R. Frascati, I, *"Energetic particle modes: example of autoresonance and superradiance in fusion plasmas"*

D. Choi, Seoul National University, South Korea, *"Analysis of ECH pre-ionization experiment in VEST"*

Prof. C. Forest, Univ. of Wisconsin, Madison, USA, *"Chasing Dynamos with Confined and Unmagnetized Flowing Plasma"*

Dr. A. Bovet, CRPP-EPFL, *"Suprathermal ion transport in turbulent magnetized plasmas"*

Dr. J. Kamleitner, CRPP-EPFL, *"Suprathermal electron studies in Tokamak plasmas by means of diagnostic measurements and modeling"*

Dr. R. Wylde, Thomas Keating Ltd, Station Mills, Billingshurst West Sussex, UK, "*The design and use of THz quasi-optical systems for measurements covering the size range from* 10^{-10} *to* 10^{37} *Metres"*

G. Rossi, Università degli Studi di Roma *"La Sapienza", Italy, "Monte Carlo generated neutron spectra for simulation of inertial fusion diagnostics"*

F. Manke, Imperial College London, UK, *"Modelling diagnostic data from inertial confinement fusion experiments"*

J. Morales, CEA Cadarache, F., *"Rotation of ELM precursors and ejected filaments dynamics"*

Prof. A. Quarteroni, EPFL, SB, "*Modeling and Scientific Computing – MATHICSE-CMCS, "Numerical simulation using reduced order models: algorithms and applications"*

Dr. U. Sheikh, CRPP-EPFL, *"Optical diagnostics for scramjets, planetary entry spacecraft and TCV (The SPRED system)"*

Prof. P. Helander, IPP, Max-Planck-Institut für Plasmaphysik, Teilinstitut Greifswald, D, *"A brief introduction to stellarators and Wendelstein 7-X"*

C. Kanesan, EPFL student, Master, "*Multi-objective optimisation of the 2D Busemann biplane"*

Dr. E. Fable, Max-Planck-Institut für Plasmaphysik, Garching, D, *"ASTRA7: an evolution of the ASTRA transport code"*

Dr. A.D. Turnbull, General Atomics, San Diego, USA), *"The External Kink Mode in Diverted Tokamaks and the Role of q95"*

Dr. A.E. Costley & Dr. A. Sykes, Tokamak Energy Ltd, Culham Science Center, Abingdon, UK, *"Compact Fusion: Two Developments That May Open a Route to Faster, Cheaper Pilot Plants and Reactors"*

M.S. Anastopoulos-Tzanis, Univ. of York, UK, *"Simulation of micro-tearing modes"*

U. Siravo, EPFL-CRPP, *"Les problèmes de compatibilité électromagnétique inhérents aux alimentations électriques de puissance"*

Dr. H. Reimerdes, EPFL-CRPP, for the WPDTT1 EUROfusion project, *"Towards an Assessment of Alternative Divertor Solutions for DEMO"*

D. Pfefferlé, EPFL-CRPP, *"Energetic ion dynamics and confinement in 3D saturated MHD configurations"*

K. Särkimäki, Aalto University, Finland, *"Monte Carlo orbit-following code ASCOT and runaway electron simulations"*

Dr. A. Kazemipour, Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany, *"Quasioptical system for material characterization in millimeter/submillimeter-wave domain"*

Prof. P. Muggli, Group Leader – Future Accelerators Group, Max-Planck-Inst. für Physik, Münich, D, *"Plasma wakefield acceleration driven by charged particle bunches and the AWAKE experiment at CERN"*

Dr. C.J. Ham, CCFE, Culham Science Center, Abingdon, UK, *"Effect of RMPs on tokamak equilibrium and stability"*

Dr. J. Loizu, Max Planck Princeton Center for Plasma Physics, USA, *"Computation of three-dimensional MHD equilibria with current sheets and magnetic islands"*

S. Lanthaler, ETH-Zürich, *"Higher-order guiding-centre motion in VENUS-LEVIS"*

Dr. M. Kikuchi, AAPPS-DPP, Nuclear Fusion BoE JAEA, Japan, *"The negative triangularity tokamak as innovative tokamak concept"*

Prof. M. Koepke, Dept. of Physics and Astronomy, West Virginia University, Morgantown, USA, *"Partnering on grand-challenge opportunities at the fusion-energy-science frontiers"*

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L.M. Milanese (supervisor P. Ricci and F. Riva), *"Application of a full spectral method to the simulation of plasma turbulence"*

Dr. F. Carpanese, Politecnico di Milano, *"Effects of shape changes on ideal stability limit for DIII-D Steady State Hybrid plasmas- Kinetic effects contribution to the RWM growth rate evaluation"*

Prof. C.C. Chaston (with acknowledgement to NASA's Van Allen Probes and THEMIS mission teams), Space Sciences Laboratory University of California, Berkeley, CA 94720, USA and School of Physics, University of Sydney, NSW 2006, Australia, *"Alfvén Eigen-modes, Turbulent Transport and Storms in near-Earth Space"*

E. Nilsson, CEA-Cadarache, F, *"Kinetic modelling of runaway electrons in tokamak plasmas"*

N. Ohana, Etudiant EPFL, *"Drift-kinetics instabilities in a sheared plasma slab using particle approach"*

L. Sorriso-Valvo, Nanotec/CNR, ponte P. Bucci, cubo 31C, I-87036 Rende (CS), I, *"Turbulence and intermittency in solar wind plasma"*

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D. Brunetti, CRPP-EPFL, *"Stability of tokamak and RFP plasmas with an exended region of low magnetic shear"*

R. Maurizio, Max-Planck-Institut für Plasmaphysik, D-85748 Garching bei München, Germany and Università degli Studi di Padova, Via 8 Febbraio 2, I-35122 Padova, Italy, *"Beam property characterization by means of three beam diagnostics at BATMAN"*

J. Uccelli, Faculty of Science, Dept. of Quantum Matter Physics, Univ. Geneva, *"Crystal growth and structural study of superconducting Bi-2212 significantly under-doped"*

Dr. Olaf Grulke, MPI for Plasma Physics, Greifswald, D, *"Dynamics of turbulent structures in the plasma edge"*

F Avino, CRPP-EPFL, *"Turbulence at the boundardy of toroidal plasmas with open and closed magnetic flux surfaces"*

E. Havlickova, Culham Centre for Fusion Energy, UK, *"SOLPS analysis of diverter configurations in MAST Upgrade"*

Dr. Y. Suzuki, NIFS, J, *"Core-density-collapse event in the Large Helical Device"*

Dr. H. Arnichand, CEA-Cadarache, F, *"Identification of trapped electron modes in frequency fluctuation spectra of fusion plasmas"*

C. Bressan, Dept. of Physics, Univ. of Milano Bicocca, I, *"Advanced modelling of JET tokamak scenarios"*

Dr. A. Brizard, Saint Michael's College, Vermont, USA, *"A guided tour of gyrokinetic theory"*

Dr. M. Battaglia, Fachhochschule Nordwestschweiz, Institut für 4D-Technologien, Windisch, Switzerland, *"Solar flares: what can we learn from them about energy release and particle acceleration in magnetized plasmas?"*

R. Agnello, Laboratori Nazionali del Sud (INFN), Catania, I, Dipartimento di Fisica e Astronomia, Università di Catania, Catania, I, *"Experimental characterization of a microwave interferometer for plasma density measurements in ECR ion sources"*

K. Flouris, Inst. of Astronomy, ETH-Zürich, *"Water droplet impingement on aircraft surfaces"*

S. Grieco, Univ. Bologna, I, *"Monte Carlo design space exploration of superconducting wind using MgB2 and YBCO Conductors"*

APPENDIX C External activities of SPC Staff during 2015

C.1 National and international committees and ad-hoc groups

MEMBERSHIP

S. Brunner
Member of the SPS Committee

P. Bruzzone
International Magnet Technology Conference Organizing Committee
Magnet Technology Advisory Board, Chairman (US)
24th Magnet Technology Conference, Programme Committee
EUCAS 2017 Conference, Programme Committee Chairman
Series Connected Hybrid Magnet, Project Review Group
HTS for fusion ad-hoc group

A. Fasoli
Eurofusion General Assembly – Eurofusion Bureau
Swiss expert to the Governing Board of F4E
International Tokamak Physics Activities: Energetic Particles Topical Group
Expert for the Review of projects submitted to the French National Agency for Research (ANR)
Chair of Fusenet Academic Council
Scientific Council of PLAS@PAR, joint plasma initiative across all Universities in Paris, France
Co-chair of Scientific Board of the Helmotz Virtual Institute on Advanced Microwave Diagnostics
Euratom Programme Committee
IAE Fusion Power Coordinating Committee
IEA Fusion Power Coordinating Committee
Scientific Committee of the IAEA Technical Meeting on Energetic Particles
Euratom – India Coordinating Committee
Steering Committee of Swiss Industrial Liaison Office
Project Board of EUROfusion Heating and Current Drive

P. Ricci
Member of the 2016 EPS Plasma Conference Program Committee
Chair of the local organising committee and member of the program committe of the 21st Joint EU-US Transport Task Force Meeting
Member of the EUROfusion HPC allocation committee

O. Sauter
International Tokamak Physics Activities: MHD, Disruption and Control Topical Group

M.Q. Tran
Member of the World Cultural Concil (Interdisciplinary Committee)
Committee of the International Symposium on Fusion Nuclear Technology
President of the Swiss Physical Society
Vice-Chair Commission C16 of the International Union for Pure and Applied Physics

	Committee of the 2015 International Conference on Fusion Reactor Materials Member of the ESFRI SWG on Energy Member of the Committee Physics and Engineering of the Academia Europea
L. Villard	Member, Board of the High Performance Computing for Fusion, Eurofusion Member, Standing Committee of the IFERC CSC Member, Fachbeirat, Max-Planck-Institut für Plasmaphysik Chair, HPC Expert Group, Eurofusion
H. Weisen	Seconded to EFDA-JET CSU, programme department

PARTICIPATION

Y.R. Martin	International Tokamak Physics Activity: "Transport and Confinement Modelling Topical Group" and "Edge and pedestal physics Topical Group"
D. Testa	Expert panel member of PDR got ITER HF system magnetics + Plasma Control working group

C.2 Editorial and society boards

S. Alberti	Editorial Board International Journal Infrared Millimeter and Terahertz Waves
A. Fasoli	Editor in Chief of Nuclear Fusion
J. Graves	Editorial Board of Plasma Physics and Controlled Fusion
Y.R. Martin	Member of the EUROfusion (communication Network FuseCOM) Chairman of the Association Vaudoise des Chercheurs en Physique

C.3 EPFL committees and commissions

A. Fasoli	Commission Stratégique de la Physique, EPFL
J. Graves	Commission du Doctorat de la Section de Physique, FSB-EPFL
J-Ph. Hogge	Commission du Doctorat de la Section de Physique, FSB-EPFL
P. Ricci	Groupe de travail technique HPC (High Performance Computing) – EPFL
M.Q. Tran	Commission du Doctorat de la Section de Physique, FSB-EPFL Membre du Comité de Sélection du Prix de la meilleure thèse EPFL "Core Group" of the Master in Nuclear Engineering Programme

L. Villard — Délégué à la mobilité, Section de physique, FSB-EPFL
Commission d'Ethique, EPFL
Commission d'Enseignement de la Section de Physique, FSB-EPFL
Steering Committee, HPC (High Performance Computing) – EPFL

C.4 EUROfusion Task Force leaders

S. Coda — WPMST1: Medium-Size Tokamak Campaigns, Task force leader deputy

H. Reimerdes — WPDTT1: Assessment of Alternative Divertor Geometries and Liquid Metals PFCs, Project Leader

M.Q. Tran — WPHCD: H&CD systems, Project Leader

H. Weisen — WPJET1: JET Campaigns - Physics and technology for ITER, Deputy Task Force Leader

APPENDIX D The basis of controlled fusion

D.1 Fusion as a sustainable energy source

Research into controlled fusion aims to demonstrate that it is a valid option for generating power in the long term future in an environmentally, politically and economically acceptable way. Controlled fusion is a process in which light nuclei fuse together to form heavier ones: during this process a very large amount of energy is released. For a fusion reactor it is planned to use the two isotopes of hydrogen: deuterium (D) and tritium (T), which fuse together much more readily than any other combination of light nuclei according to the following reaction:

$$D^2 + T^3 \rightarrow He^4 + n + 17.6MeV$$

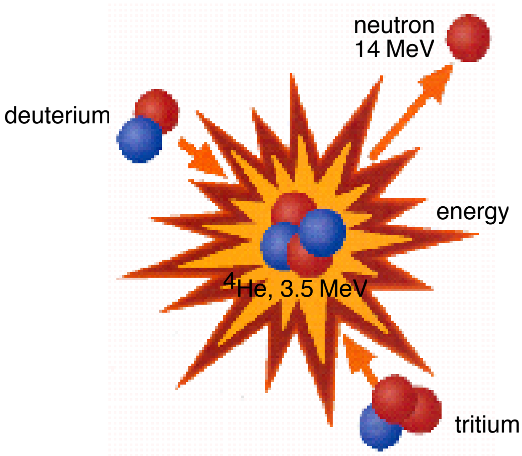

Fig. D.1 *Schematic of a fusion reaction between deuterium and tritium nuclei. The products are 3.5MeV ^{4}He, the common isotope of helium, and a 14MeV free neutron.*

The end products are helium and neutrons (n). The total energy liberated by fusing one gram of a 50:50% mixture of deuterium and tritium is 94000kWh, which is 10 million times more than from the same mass of oil. 80% of this energy is carried by the neutrons with an energy of 14MeV while the remaining 20% is carried by the helium nucleus. Most of this energy eventually becomes heat to be stored or converted by conventional means into electricity.

The temperature at which fusion reactions start to become significant are above a few tens of millions of degrees. For the D-T reaction, the optimal temperature is of the order of 70-200 million degrees. At such temperatures the D-T fuel is in the plasma state.

Deuterium is very abundant on the earth and can be extracted from water (0.034g/l). Tritium does not occur naturally, since its half-life is only 12.3 years, but it can be regenerated from lithium using the neutrons produced by the D-T fusion reactions. The two isotopes of natural lithium contribute to this breeding of tritium according to the reactions:

$$Li^6 + n \rightarrow He^4 + T^3 + 4.8MeV$$

$$Li^7 + n \rightarrow He^4 + T^3 + n - 2.5MeV$$

The relative abundance of the two lithium isotopes Li^6 and Li^7 are 7.4% and 92.6%, respectively. The known geological resources of lithium both in the earth and in the sea water are large enough to provide energy for an unlimited time.

D.2 Attractiveness of fusion as an energy source

The inherent advantages of fusion as an energy source are:

- The fuels are plentiful and their costs are negligible because of the enormous energy yield of the reaction;
- The end product of the reaction is helium, an inert, non-radioactive gas;
- No chain reaction is possible: the neutron emitted by the fusion process does not trigger subsequent reactions;
- Only a very small amount of fuel is present in the core of the reactor: the plasma weights a fraction of gram;
- Any malfunction would cause a quick drop of temperature and all fusion reactions would stop within seconds;
- No after-heat problem can lead to thermal runaway even if the case of a loss of coolant accident;
- None of the materials required by a fusion power plant are subject to the provisions of the non-proliferation treaties.

Its further potential advantages are:

- Radioactivity of the reactor structure, caused by neutrons, can be minimised by careful selection of low-activation materials resulting in a manageable quantity of long lived radioactive waste;
- The release of tritium in normal operation can be kept at a very low level. The inventory of tritium on the site can be sufficiently small so that even the worst possible accident could not lead to a harmful release to the environment requiring evacuation of the nearby population.

APPENDIX E Sources of Financial Support

In 2015, the work carried out at the SPC and presented in this annual report was financed from several sources, either through Research Grants and Subsidies, or Service Contracts. The major financial support is provided by:

Swiss public institutions:

- the Ecole Polytechnique Fédérale de Lausanne (EPFL)
- the Swiss National Science Foundation (SNSF)
- the Board of the Swiss Federal Institutes of Technology (ETH board)
- the Paul Scherrer Institute (PSI), which hosts the Superconductivity science activities
- the Swiss State Secretariat for Education, Research and Innovation (SERI)
- the Swiss Commission for Technology and Innovation (CTI)

International public institutions:

- The eighth (Horizon 2020) and seventh Framework Programme for Research and Technological Development of the European Union, including EURATOM
- ITER
  - ITER Organization (IO), Cadarache, France
  - Domestic Agencies in China, Europe (F4E), Japan, Korea, Russia, USA
- Helmholtz Association of German Research Centres (HGF), Germany
- The Radboud University Nijmegen, The Netherlands
- The Lawrence Livermore National Laboratory (LLNL), USA

Private organisations

- Tetra Pak Suisse SA, Romont
- Bruker BioSpin SA, Fällanden