

CRPP

CENTRE DE RECHERCHES EN PHYSIQUE DES PLASMAS
FACULTÉ DES SCIENCES DE BASE
ASSOCIATION EURATOM - CONFÉDÉRATION SUISSE



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1 INTRODUCTION

1.1 *Developments in 2014 at the European level*

EUROfusion, the new European fusion research programme

At the European level, 2014 was the first year of the 8th EU Framework Programme on Research and Innovation, called Horizon 2020, to which the European fusion research programme is attached. As compared to the 7th Framework Programme, the fusion part of Horizon 2020 presents some novelties. Its work plan is based on the document “EFDA Roadmap to the realization of fusion energy”. The goal of this Roadmap is the realization of a demonstration reactor, DEMO, by 2050, achieving fusion for extended times and injecting electrical power to the grid. To this aim, the Roadmap work plan includes physics studies, R&D activities for the technology necessary for DEMO, as well as an important component dedicated to the education of future generations of scientists and engineers. The Roadmap also prepares European fusion scientists for a fruitful exploitation of ITER.

In December 2014, the agreement signed in 1978 between Switzerland and EURATOM was replaced by an agreement between Switzerland and European Union in the frame of the negotiations for the partial association of Switzerland with Horizon 2020. According to the terms of this agreement, Switzerland shall participate to the EURATOM programme and the ITER project at least up to 31st December, 2016. A continuation of Switzerland’s participation is conditioned to the evolution of political relations between Switzerland and European Union in the domain of free movement of persons beyond 2016.

The Research Units of EURATOM member states and Switzerland participate to the execution of the Roadmap in the frame of the EUROfusion consortium, which started its activities in 2014. The EPFL has signed a Consortium Agreement in July 2014 in order to become a member, whereas University of Basel is affiliated as Linked Third Party. In total, 29 research institutes in Europe are members of EUROfusion, and more than 40 participate to its activities.

European participation to the ITER construction

Participating to the ITER construction represents the other major focus of European fusion activities. As a matter of fact, Europe is responsible of the largest share of ITER construction costs and is in charge of the construction of strategic elements such as the building housing the machine. The European participation is under the responsibility of Fusion for Energy (F4E), a joint venture based in Barcelona.

1.2 *Extra-European developments in 2014*

Several ITER partners, in addition to EURATOM, are also aiming at the realization of DEMO in the next decades. Both China and India are even considering the construction of intermediate devices between ITER and DEMO. This shows that a

broad international consensus exists on the industrialization of fusion energy in the second half of the 21st century.

The ITER construction is in full swing, with first large components of the tokamak delivered in 2014. An in depth review of ITER management was conducted in 2014, and a number of measures to improve the efficiency of the project are being implemented, including a rapid change of personnel at the head of ITER. A new Director-General has been appointed, who took up his duty in February 2015: Bernard Bigot, who was until then General Administrator of the Commissariat à l'Energie Atomique at aux Energies Alternatives (CEA), in France. Under his leadership, a substantial revision of the ITER project planning and budget is foreseen for the end of 2015.

1.3 Developments in 2014 at CRPP

In 2014, the CRPP took part to the scientific and technological activities of the EUROfusion consortium, as well as the ITER project, in particular through the European domestic agency F4E. Research in controlled fusion is performed at two sites: at EPFL, activities are dealing with the physics of magnetic confinement, with the TCV tokamak, the basic experiment TORPEX, theory and numerical simulation, plasma heating and current drive technology based on microwaves. At PSI, activities are dealing with superconductivity. Moreover, CRPP participates to the experiments on the Joint European Torus (JET), which to this date remains the largest operating magnetic fusion experiment in the world. Three members of the CRPP are Project Leaders or Deputy Project Leader of EUROfusion Workpackages and launched the corresponding European works. The CRPP research activities have led to about one hundred papers in peer-reviewed scientific literature and about as many in international conferences, many of which as invited papers.

In 2014, the first step of a series of major upgrades to the TCV tokamak was undertaken, with the modification of the vacuum vessel to accommodate a 1MW (2s, 30keV) tangential neutral beam for core ion heating. The beam is being procured at present and will be operational by the end of 2015. Subsequent steps will include the replacement of two of the 0.5MW gyrotrons to heat electrons at the second harmonic of the cyclotron frequency, and the procurement of two dual frequency 1MW gyrotrons that can be operated at the second or at the third harmonic.

Scientific excellence is also reflected in education: the CRPP has about 30 PhD students, many of whom have obtained their degree in 2014. In addition, the CRPP maintains its duties in basic teaching and its numerous public relation activities aiming at presenting plasma physics and controlled fusion to non-specialists.

On 1st September 2014, Prof. A. Fasoli was nominated as Director of the CRPP in replacement of Prof. M. Q. Tran, who stepped down on 31st of August 2014.

2 PROGRESS REPORT

2.1 *The TCV tokamak*

Experimentation on the TCV tokamak represents the main effort of the CRPP teams. TCV has been operational since 1992 and is characterized by the most extreme plasma shaping capability worldwide, the highest microwave Electron Cyclotron (EC) power concentration in the plasma, and a large degree of flexibility in its heating and control schemes. The main mission of TCV is to contribute to the physics basis for a more efficient ITER exploitation, and for the optimization of the tokamak concept, plasma scenarios, heating and control techniques, in view of the step following ITER, referred to as DEMO. While ITER will demonstrate the scientific and technological feasibility of fusion, the DEMO activities will pave the way to the deployment of commercial fusion power plants. To continue to play a significant role, upgrades of the TCV tokamak are presently under way, in particular to enhance the plasma heating capabilities, by installing a Neutral Beam Heating (NBH) system and additional microwave power.

The European fusion community has recently agreed on a Roadmap, focused on the objective of providing fusion power on the grid by 2050, by optimizing all steps from the present machines through ITER and DEMO. The upgraded TCV tokamak is one of the three national facilities in Europe that are retained as essential for the implementation of the European fusion Roadmap towards the realization of fusion energy by 2050. Within the newly established EUROfusion consortium, starting from mid-2015, participation in the TCV experiments for parts of its campaign is therefore open to all Euratom members or partners.

The TCV tokamak facility was shut down during the whole of 2014. The primary reason for the shutdown was the modification of the vessel to accommodate neutral beam heating, the first phase of our auxiliary heating upgrades. This is discussed in more details in Section 2.1.2. In parallel with this we undertook several diagnostics modifications and upgrades, and significant maintenance and replacement tasks related to the most aging components of the infrastructure. The latter work included refurbishing the entire water-cooling network and compressed-air network, replacing several ailing vacuum pumps, and inspecting and repairing failing thermocouples within the torus baking system. As the vessel wall had to be stripped of all its plasma-facing graphite tiles, to protect them during the vessel modifications, we took the opportunity to sandblast them in their entirety, a cleaning technique already used a few times in the past few years to cleanse the tile surface of accumulated deposits.

Scientific progress during 2014 relied on analysis of past data and on the associated modelling efforts. Part of this work was carried out for the first time under the auspices of the Medium-Size Tokamak (MST) Task Force within the newly created EUROfusion consortium. This structure will fund and manage part of the TCV experimental activities throughout the 2014-2020 period.

2.1.1 Scientific highlights in 2014

An analysis and modelling task was performed in particular on studies of advanced-divertor configurations in TCV in the last campaign. The X-divertor configuration, achieved in 2013, was shown to feature substantial heat flux reduction at the outer target, as expected, with additional indications of a possibly facilitated access to detachment. Radiation experiments in snowflake configurations were analysed, yielding the result that the snowflake divertor radiates more (by 10-15%) than a conventional single-null divertor with neon seeding, whereas the opposite is true at high density with intrinsic carbon impurities. The difference is attributed to the different radiation loss parameter of C and Ne, which radiates at higher temperature, favouring the hotter null region over the outer scrape-off layer (SOL) and thus benefiting from the local flux expansion near the null.

The ongoing puzzle of the anomalously high particle flux across the separatrix in a snowflake-plus configuration has approached a possible explanation with the discovery of the significant role of ExB flows, which remain to be included in the leading numerical SOL models. The possibility that more favourable heat reduction can be achieved in a snowflake-minus than in a snowflake-plus configuration is suggested by experimental data and has also been investigated with EMC3-Eirene simulations. The BOUT++ code was used to study filament dynamics in varying diverted configurations. The increased magnetic shear in the null region of the snowflake configuration was seen to distort the filaments, as expected, and this distortion was observed to propagate very efficiently to the plasma midplane. The maximum growth rate of SOL instabilities was calculated to decrease in the snowflake configuration, again as a result of the larger shear. However, a more-than-linear concomitant increase in the mode wavelength results in an effective overall increase of the upstream diffusion coefficient.

Progress was made in the analysis of integrated control experiments from the 2011-2013 TCV campaigns, particularly in view of developing algorithms and control scenarios for the upcoming TCV campaigns. These include improvements in fast vertical stabilization and the development of a position control algorithm through optical imaging, as well as refinements in breakdown, density and shape control. Technical work was also performed to streamline the recall and compilation of control algorithms in the SIMULINK environment.

Work begun in 2013 on optimizing the control of snowflake configurations using the CREATE-L and CREATE-NL codes was continued in 2014, with the specific aims of minimizing the poloidal field coil currents and forces, of improving the vertical stability properties and of maximizing the plasma volume.

The field of suprathermal electron dynamics was recently boosted significantly by the commissioning of the first tomographic hard X-ray spectrometer. In particular, past results on the importance of cross-field electron transport in the efficiency of current drive were confirmed under much more controlled conditions, excluding in particular possible spurious effects from runaway electrons. ECRH-accelerated electrons were found to be significantly transported by the sawtooth instability, in contrast with the case of lower-hybrid heating.

The nonlinear phase of type-I ELMs was recently studied using a complete set of magnetic measurements. The rigidity of the observed toroidal mode structure leads to the conclusion that the collected data pertained exclusively to the nonlinear phase, implying that the linear phase was too rapid to be accessible to

measurements. Furthermore, a dominant $n=1$ toroidal mode number is found, while the peeling-ballooning modes believed to be responsible for ELMs are predicted to possess higher periodicity. This suggests a spatial cascade mechanism in the nonlinear evolution. The more global nature of the nonlinearly-generated low- n modes may help explain the large energy losses of type-I ELMs.

Results obtained in the past few years on the geodesic acoustic mode (GAM) were further analysed. In particular, the nonlinear interaction of the GAM with the background turbulence was studied through bicoherence analysis. The bicoherence level between the GAM and the entire turbulence spectrum is significant, corroborating the expected generalised nonlinear drive of the GAM by the turbulence. Insight into the damping mechanism was gleaned by performing a density ramp. As density increases, the broadband turbulence increases as well, whereas the GAM amplitude remains approximately constant. This suggests that the increased drive may be compensated by the increase in collisional damping – indicating that the latter is dominant over the collisionless Landau damping mechanism in the conditions under study.

2.1.2 TCV heating systems

Improving understanding and control capabilities of burning plasmas is a major scientific challenge of the experimental programme of the TCV tokamak. This requires access to plasma regimes and configurations with high normalized plasma pressure, a wide range of temperature ratios, including $T_e/T_i \sim 1$, significant populations of fast ions and relatively low collisionality. These conditions will be reached by an upgraded TCV heating system: installing a neutral beam for direct ion heating and increasing the ECH power injected in X-mode at the third harmonic. These upgrades, which will allow TCV to attain parameter ranges that are more directly relevant for a fusion power plant, are starting with the installation of a first 1MW-2s Neutral Beam Heating (NBH) system, and will continue with the development and installation of two additional 1MW-2s microwave heating EC systems reaching the 3rd harmonic frequency range ($\sim 120\text{GHz}$).

EC systems

The Electron Cyclotron (EC) system on TCV, in its original configuration, is composed by 6 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. An evacuated rf transmission line system (63.5mm diameter waveguide, HE_{11} mode) connects the gyrotrons to the various launchers allowing the quasi-optical injection in TCV of the rf-wave from the low-field side (X2-mode) or from the top (X3-mode).

For the EC-system, after more than a decade of operation some X2 gyrotrons failed and cannot be refurbished anymore. As mentioned in last year report, in view of maintaining the X2 power at a level compatible with the TCV scientific mission, which is now embedded in the Eurofusion programme via the Medium Size Tokamak (MST1) activity, two new gyrotron units with enhanced performances (82.7GHz/750kW/2s) have been purchased. The first gyrotron will be delivered in December 2015 and its commissioning completed by February 2016. The second gyrotron will be operational on TCV by October 2016.

The scientific programme carried out on TCV relies on the full functionality of the existing X2 and X3 systems as well as on the ongoing upgrades.

EC-system activity in 2014

Due to the activity carried out on the TCV vessel during 2014 in relation to the NBH upgrade, the EC system has not been operated, however, remedial work has been carried out. In preparation of the arrival of the new X2 gyrotrons, the old, still functional, gyrotrons have been relocated.

For the X3 gyrotrons, characterized by a triode electron gun, the power supply controlling the modulation anode voltage has been fundamentally modified. The tests carried out on a X3 gyrotron show that the noise level, the fluctuations as well as the overshooting during the gyrotron rf startup have been significantly reduced. This will eventually allow us to drive the gyrotron in operating points with higher rf-power. With the success of this development the anode power supplies connected to the two other X3 gyrotrons will be modified in the same fashion during 2015.

X2-X3 upgrade

Compared to the initial project outlined in last year report and consisting of adding two dual-frequency gyrotrons (126/84GHz) with an rf power of 1/0.75MW, respectively, a significant design effort, using gyrotron simulation codes developed at CRPP, has been carried out in 2014. The results of these studies show that by a minor modification of the gyrotron cavity it is possible to reach an rf-power well in excess of 1MW at both frequencies. These results have been confirmed by simulations performed within the European Gyrotron Consortium (EGYC) in which CRPP is one of the main actors. Moreover, within EGYC and with contribution by F4E, advanced design concepts have been used and implemented in the final design. At present the final design of the dual-frequency gyrotron for TCV is nearly completed and includes novel concepts that will be eventually implemented in the ITER-gyrotron R&D programme carried out by EGYC and F4E.

A detailed design of the reconfiguration of all the rf transmission lines from the gyrotrons to the launchers, together with the rf-auxiliary equipment (matching optics units, rf-switches, rf loads, etc) of the entire upgraded system (including two dual-frequency gyrotrons), has been performed in 2014.

A schematic layout of the upgraded EC system is shown in Fig. 2.1.1.

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

a. Detailed design review:	June 2015
b. Contract signature with THALES:	June 2015
c. First gyrotron commissioning at CRPP	June 2017
d. Second gyrotron commissioning at CRPP	June 2018
e. Completion of X3-upgrade project	September 2018

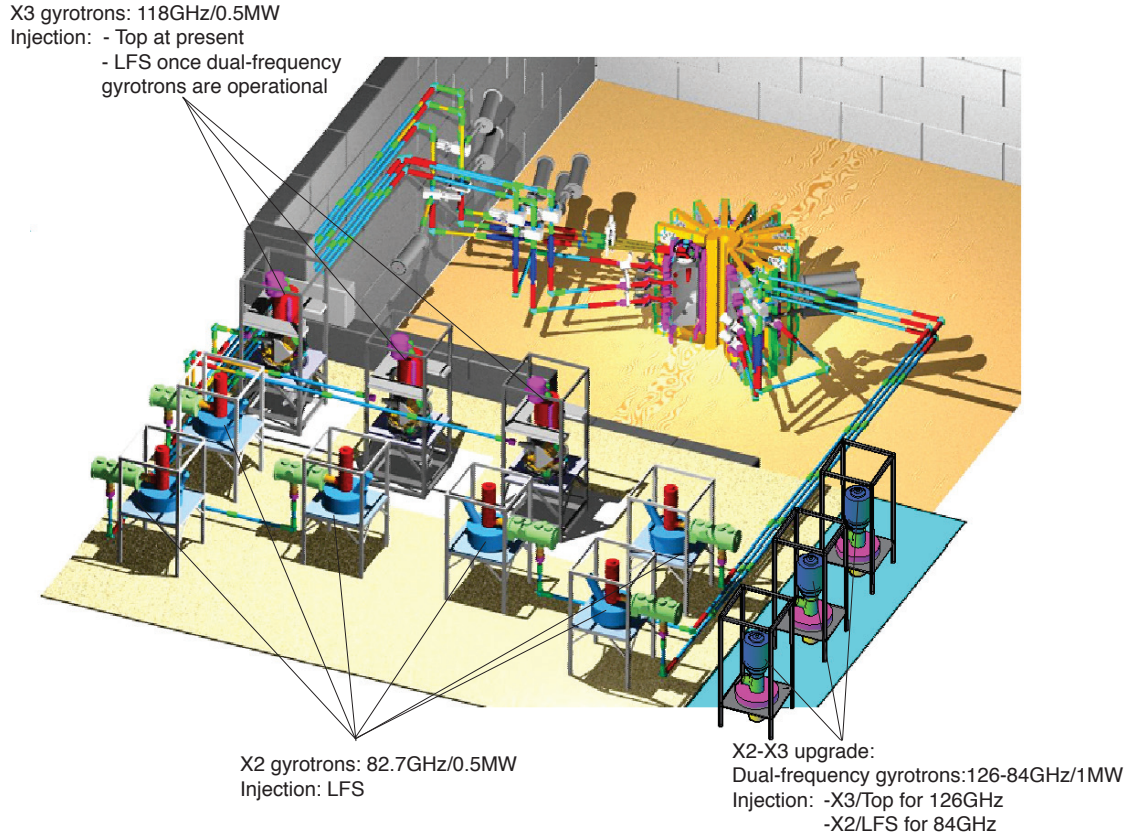


Fig. 2.1.1 *Layout of the upgraded EC X2-X3 system on TCV. The X2 gyrotron system as well as all the rf-transmission lines shown in the figure correspond to the original system. Due to failure of some X2 gyrotrons, two new X2 gyrotrons with enhanced performances 750kW/2s will be installed in 2016 in replacement of broken ones. For the X2-X3 upgrade with dual frequency gyrotrons, only two gyrotrons are foreseen up to the end of 2018. The third one shown in the figure can possibly be installed in the context of a future further upgrade. In this figure the rf-line reconfiguration compatible with the operation of dual frequency gyrotrons is not shown.*

Neutral beam heating system

The neutral beam is under construction at BINP-Plasma LLC (Russia), with energies of 18-35keV and power up to 1MW for 2s. The injection of 1MW 30keV deuterium beam will allow access to regimes with $T_i/T_e > 1$ and $\beta_N \sim 2.8$ in H-mode, at high density ($> 4 \times 10^{19} \text{m}^{-3}$), compatible with X3 EC heating. A lower energy and power (18-20keV, 0.3-0.5MW) deuterium NB is on the other hand suitable for experiments at intermediate densities ($1-3 \times 10^{19} \text{m}^{-3}$) and lower plasma current (120-250kA) with second harmonic X2 EC heating and current drive. Further constraints for the TCV NB system design stemmed from the issues of beam access, shine through and orbit losses, which all favoured a tangential injection. The TCV vacuum vessel has been modified to allow for the beam tangential injection.

In-situ modification of the TCV vacuum vessel

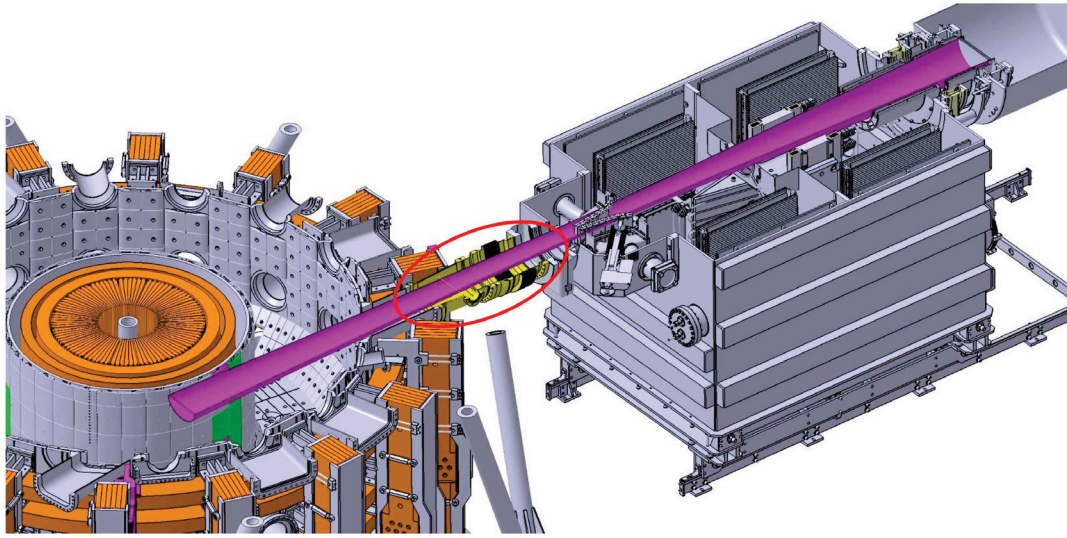


Fig. 2.1.2 Schematic view of the TCV and NB injector

Substantial modifications to the TCV vacuum vessel were required for installing two ports, providing the possibility of adding a second beam in the future, each with an aperture of $170 \times 220 \text{ mm}^2$, through which 1 MW of power can be injected (see Fig. 2.1.2). Such modifications were performed in situ by the De Pretto Industrie S.r.l., Schio, Italy (manufacturer of the original vessel) in 2014, with a substantial fraction of the machining and welding done from inside the vacuum vessel (see Fig. 2.1.3). Prior to the intervention, finite element analysis of the relevant mechanical stresses proved that the addition of the two new openings would have no significant impact on the structural properties of the vacuum vessel. The internal configuration of the graphite first wall has been changed to fit with the two new apertures, and tiles with special geometry and high heat load capability have been added to protect the beam facing elements in the area of beam-wall interaction. The beam dump uses graphite tiles that are tolerant to a full duration (1 sec) full power beam injected into a vertically centred plasma with on axis electron density higher than $2.0 \times 10^{19} \text{ m}^{-3}$. According to finite elements simulations, the surface temperature would only reach $\sim 1200 \text{ K}$.

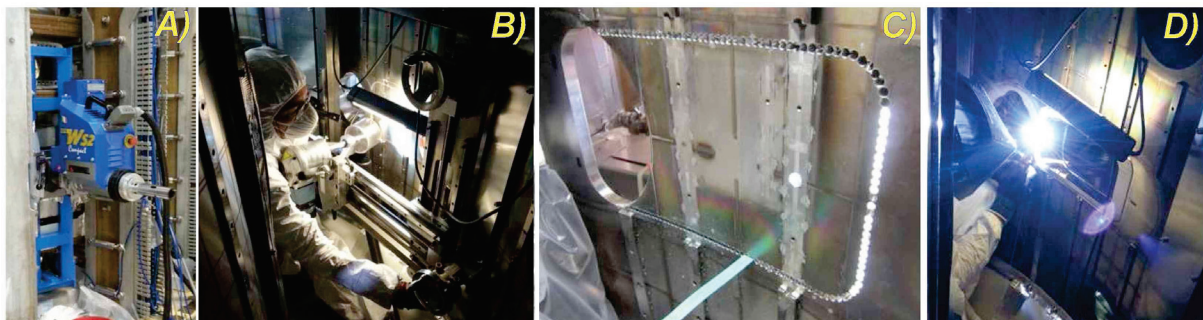


Fig. 2.1.3 In situ modification of the TCV vacuum vessel:
A) Boring machine mounted outside the tokamak VV;
B) Drilling machine with XY structure, inside the VV;
C) Series of holes and manual sawing of the port aperture;
D) Welding from inside of the VV.

Neutral beam injector for TCV

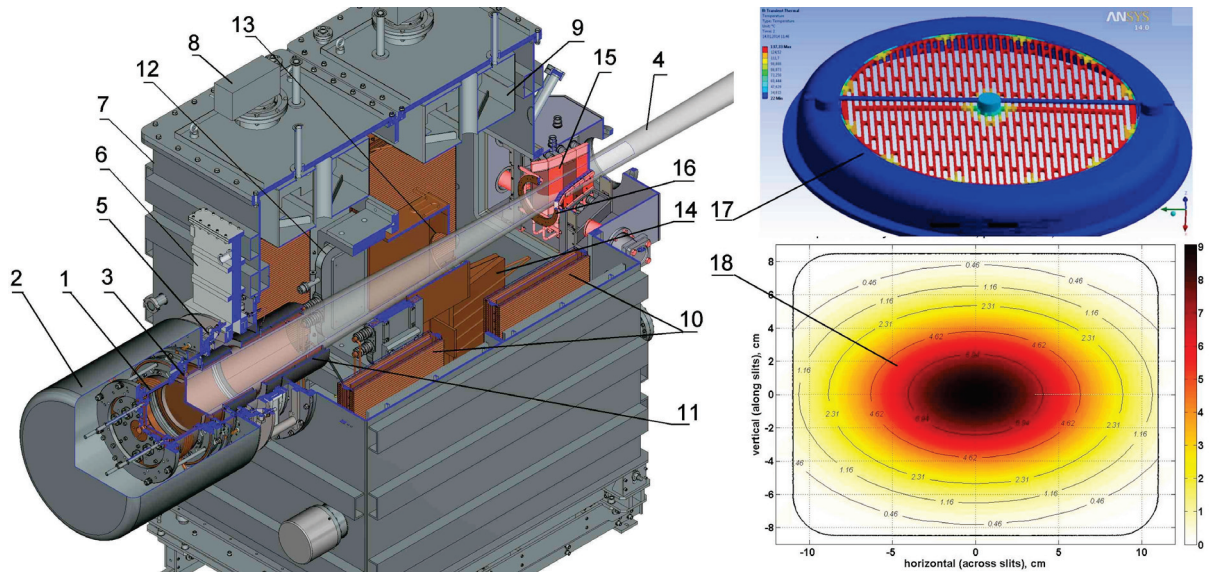


Fig. 2.1.4 Main elements of the TCV NBI: 1 – RF plasma source, 2 – magnetic screen, 3 – ion-optical system, 4 – neutral beam; 5 – alignment unit; 6 – ions source gate-valve; 7 – vacuum tank; 8 – cryopump cold head; 9 – liquid nitrogen volume; 10 – cryo-panels, 11 – neutralizer, 12 – bending magnet, 13 – diaphragm, 14 – ion dump for positive ions, 15 – calorimeter, 16 – aiming device. 17 – Temperature field of the plasma grid exposed by 2s beam. Deposited power 12kW, maximal temperature 137°C; 18 – NB power density (max. 92.5MW/m²) on the exit from the port in the TCV, 1MW transmitted.

The design of the injector has been completed in 2014 in the frame of the contract with "BINP-Plasma" LLC (Novosibirsk, Russia) on design, manufacturing, installation and commissioning of the NB injector. The injector cover an energy range of 18-35keV, with tunable power up to 1MW, and 2s duration. The injector design incorporates a standard positive ion source with an average nominal current density of 3kA/m². The plasma emitter is formed in a plasma box with up to 40 kW of inductively coupled RF power at ~4 MHz, with 15 kV at the multi turn RF coil. To focus the beam inside the TCV port at ~3.6 m from the ion source, the grids are formed in spherical segments. The radius of the plasma electrode is 4m, and 3m for accelerator and ground grids. The geometry of the grid elementary cell was optimized to minimize the beam's angular divergence and power losses in the beam duct especially in the TCV port. A slit geometry of the elementary grid cell was chosen; slits are placed inside the 250mm diameter area. The beam emitter has intrinsically anisotropic angular divergence along and across slits (8×18mrad for the individual slits, and overall 12×20mrad). The main elements of the TCV NB system, plasma grid geometry and NB power density distribution at the entrance in the tokamak are shown in Fig. 2.1.4.

NB injector reference scenario	
NB power injected in TCV	1 MW
Nominal beam energy	30 keV
Max. NB pulse duration	2 sec
Beam full energy fraction in power	≥ 65 %
NB operation domain	
Beam power range	30...100 %
Beam energy range	15...35 keV
Beam main species	D ⁰ & H ⁰
Power sweep during TCV shot	30...100 %
Power sweep response (P/(dP/dt))	0.3 ms
Full power modulation on-time	10 ms...2 sec
Minimal modulation off-time	5 ms
Modulation rise/fall time	0.5 ms
Fast modulation at reduced power	100...300 Hz

TABLE 2.1.1: Main characteristics of the NB system for TCV.

The basic characteristics of the NB system for TCV are summarised in Table 2.1.1. The upper limit for the beam energy of 35keV is compatible with the orbit losses in plasma with currents up to $I_p=400$ kA. The tunability in power 0.3...1.0MW within the same discharge is required to investigate the plasma response to various levels of ion heating in otherwise identical discharge conditions. The first NB operations on TCV are scheduled for mid-2015.

Electrical supply of NBI

The upgrade of the infrastructure required to integrate the NBI in the TCV. NBI electrical supply system is shared into:

- the high power part, delivering the energy to the beam through a high voltage power supply (HVPS), connected to the medium voltage (MV) power sources available at CRPP;
- the low power part, supplied through the domestic grid (400 V, 50 Hz), where particular supplies, like the RF source, the suppression grids, etc. are connected.

Two power sources are available at CRPP to supply high power equipment:

- The CW power source, connected to the 20kV/50Hz distribution network, delivering 1.9MVA in CW or up to 7MVA on limited pulse length and duty cycle (2sec/5min). This source will be dedicated to the injector commissioning, the acceptance tests on-site, as to the regular injector conditioning before the TCV operation, or between plasma pulses.
- The pulsed power source, available exclusively during plasma shots, made of a Motor-Generator (MG) delivering a peak power of 220MVA at 120Hz, for which the stored energy is of 200 MJ for a frequency decrease of 20%. The NBI will be connected to this source for operation during the tokamak plasma discharge.

The commutation system has been designed and it will allow selecting the desired power source and will be able to protect the installation against short-circuits which could arise at the secondary of the transformers. For faults occurring at the

primary side of the transformers, only the main breaker at the output of the motor generator can interrupt the estimated peak short-circuit current ($\sim 35\text{kA}$). The beam high voltage acceleration system is supplied through a HVPS (see Table 2.1.2) based on the PSM principle. The main components of this HVPS, like the power modules, the multi-secondary transformer and the control, will be procured from Ampegon AG (Turgi, Switzerland). The HVPS DC output is connected to the injector ion source through a coaxial cable ~ 30 meters long. The DC stage is formed of 40 modules connected in series, each one being powered through an individual secondary.

AC voltage	10kV/50Hz or 120Hz
DC voltage	0...40 kV
DC current	0...50A
Voltage accuracy & ripple	$< \pm 1\%$
Voltage slew rate	200kV/msec
Shutdown time	$< 10\mu\text{sec}$
Pulse length/duty cycle	3msec...2sec/1%

TABLE 2.1.2: Main parameters of the HVPS.

Auxiliary PSs required for the NBI operation will be powered from the domestic grid (400 V/50 Hz) distributed in the TCV building. As presented below, this grid will support the impact of pulsed load equivalent to $\sim 100\text{kW}/2$ sec.

The RF generator for the NBI plasma source consists of:

- 16 RF modules based on power transistors modulated at 4MHz in a push-pull configuration. Each module is delivering 2.2kW of RF power.
- Module outputs are combined by pair through transformers, cabled with coaxial cable and adapted on 50 Ohm impedance.
- The power drawn from a DC power supply rated at 300VDC. Four inverters in series, clocked at 20kHz, are supplied from the mains to deliver a pulsed DC power of 80kW/2sec.
- Finally the RF power is applied to the antenna through a decoupling transformer made of RF-ferrite core, and isolated at 45kV.

The potential of -400V to -800V is applied to suppression grid with ramp-up/down time of 200 μsec . The equivalent peak current drawn from the power supplies is lower than 15A. The deflecting magnetic field of ~ 0.07 T is produced by two coils comprising the bending magnet. Coils are supplied from a low DC voltage PS: 30 VDC/500A. All auxiliaries PS, including their control, will be installed in 4 19" frames.

Cooling system

The NBI water cooling system must integrate continuous as well as pulsed flow, and part of the circuits must be cooled down with demineralized water. Around 50% of the electrical power consumed by the NBI (650kW/2sec) will be dissipated in the water.

The industrial water, available in the TCV building, is used at the primary side of two heat exchangers.

The demineralized water circuit will cool down NBI elements at the HV potential, in order to minimize the leakage currents. The water resistivity in this circuit must be

maintained higher than $0.1\text{M}\Omega/\text{cm}$ using adapted resins. The plasma box and grids are cooled in parallel. The total power to be evacuated during the pulse is $<100\text{kW}/2\text{sec}$, mainly in the plasma box ($\sim 60\text{kW}/2\text{sec}$). A pump will ensure a pressure of $4\text{ bars}@2\text{m}^3/\text{h}$ at the input of all circuits.

Several clean water circuits are supplied from the storage tank:

- The first circuit ($5.7\text{ bars}@4.5\text{m}^3/\text{h}$), is shared between several sub-circuits cooling down internal components of the injector: neutralizer, ion dumps and magnet, $550\text{ kW}/2\text{ sec}$ are evacuated.
- The second circuit is exclusively dedicated to the cool down of retractable calorimeter. The neutral beam energy (1MW , 2sec) is dissipated on it during injector tests, calibration and conditioning. The hypervapotron principle is used to cool down the calorimeters surface, requiring a high flow rate from a pump rated at $4.3\text{ bars}@50\text{m}^3/\text{h}$.
- An individual circuit is used for cooling down the four compressors for four cold heads of cryo-pumps located in the NBI vacuum vessel. This circuit is running continuously, even when the injector is not operated, since the cryo temperature must be maintained continuously.

Each cooling water circuit is equipped with a local monitoring of the flow rate and the temperature.

NBI Control and operation

The neutral beam operation is controlled by an instrumental computer (LCS) with commercial PCIe National Instruments cards, controlled via LabView (see Fig. 2.1.5) and by electronic control modules integrated into the TCV plant control system. Such a system, already used to control the TCV diagnostic neutral beam, is capable of handling a large variety of low-voltage analog and digital input/output signals. The NBI can operate either under the supervision of the TCV central control system, or independently, in Local-mode, for testing and commissioning. A number of protections and interlocks are implemented at the hardware level together with some status monitors and controls. All functions necessary for safe NBI operation are included in the LCS that is designed to protect itself from externally generated dangerous situations and commands.

The NBI shot design code realized in Matlab has been created to setup and/or modify the desired neutral beam power vs time waveform ($P_0(t)$). Then, logical beam ON/OFF, beam energy, neutral and ion currents time traces are calculated taking into account their dependencies on $P_0(t)$ in order to keep the beam perveance optimal for minimal angular divergence. Later on digital and analog control waveforms with 0.1 ms discretisation are pre-calculated, transmitted in the LabView LCS programme and uploaded in the FPGA memory of PCIe cards. After receiving the trigger the beam pulse control sequence is executed, analog and digital control waveforms are transmitted to NBI power supplies electronics.

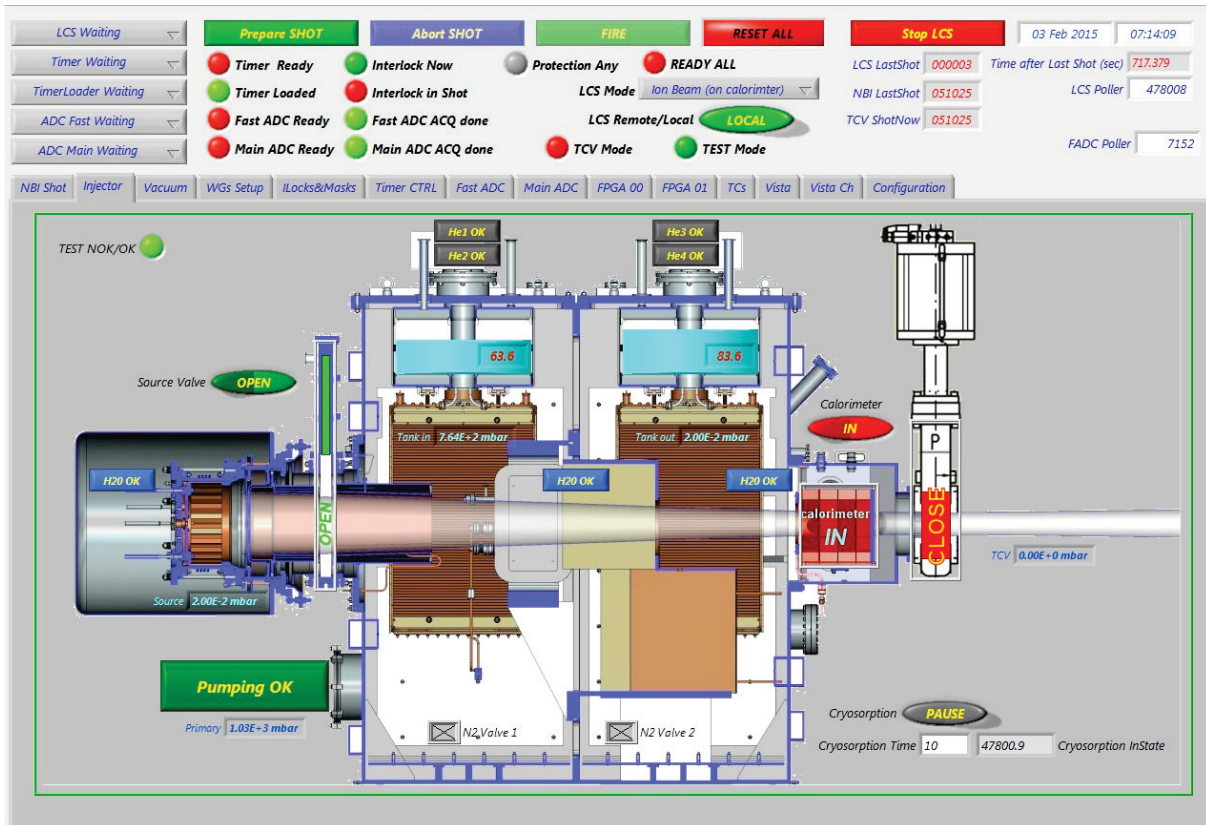


Fig. 2.1.5 Front panel of the NBI local control system.

The beam dump protection system is implemented on TCV to protect against overheating of beam facing elements in the area of beam-wall interaction. To estimate the power density distribution of the NBI and the beam losses and heat load on different elements along beam path, the complete beam propagation was modelled. The geometry of the beam dump was optimized using the COMSOL Multiphysics® modelling. The selected beam dump design uses graphite tiles that are tolerant to a full duration (2s) full power beam injected into vertically centred plasma with on axis electron density higher than $1.7\text{--}2.0 \times 10^{19} \text{ m}^{-3}$. The surface temperature would only reach $\sim 1200\text{K}$.

The combined RT processing beam inhibit signal generated by plasma disruption detector, by a plasma density interferometer measurement and direct pyrometric measurement of beam dump surface temperature is available to the NBI control system. Thermocouples embedded in the beam dump check the bulk tile temperature between pulses to calculate the power absorbed on the dump. A software inhibit from shot design (predicted line integrated density in the TCV plasma) is integrated into the shot preparation codes.

2.1.3 TCV Diagnostics

With no TCV operations in 2014, the main achievements were orientated around repairing, upgrading and in developing new diagnostic systems. Many of the details of these diagnostic systems are now routinely described in great detail on the CRPP's Wiki pages [<https://crpplocal.epfl.ch/wiki>] that are also, in part due to these upgrades, covering legacy systems. As before, some of these upgrades,

notably to the Thomson Scattering, ECE and Charge Exchange Spectroscopy are aimed at improving TCV's basic plasma profile parameter measurements. An increasingly pronounced tendency is to ensure that modifications are compatible with making physics data available during the TCV discharge pulse and thus integrated into TCV's continually augmented Real-Time digital control system.

New physics goals, in particular an increased interest in the behaviour of plasma divertor configurations, entail enhancements and the implementation of new diagnostic systems. The installation of a high power (1MW) Neutral Heating Beam for 2015 entails both the development and installation of plasma and vessel diagnostics designed to monitor the beam injection performance and to ensure rapid beam injection termination to protect the internal vessel components. Many plasma parameters that will be affected by the additional auxiliary heating are well covered by existing diagnostic but new systems, for instance to track the behaviour of fast ions or monitor the beam-plasma interactions are under review.

The rest of this short report provides a flavour of these, sometimes conflicting requirements and their present status. Throughout 2014, many of the CRPP's resources were dedicated to the machine vessel changes that must be successfully terminated for TCV to again become operational. In this respect, the progress of many projects, including many diagnostic systems, not absolutely necessary to this goal, has been limited and will be more strongly developed in 2015.

Upgrades

As in the previous year's report, the main diagnostic upgrade is to TCV's 20 year old Thomson Scattering system. 25 new 5-channel spectrometers were completed and a further 25 more are planned within an EuroFusion MST grant in 2015. The spectrometers are equipped with fast, yet naturally stable, preamplifiers and self-resetting integrators such that the Thomson scattered signal is acquired by a simple, relatively slow speed (500kHz) ADC. Using TCV's standard 96 channel ADC boards, up to 19 spectrometers are acquired with Real-Time compatible hardware. The new spectrometers are housed in an optimised rack next to TCV together with the acquisition hardware. Finally, to increase the available spatial resolution, the observation fibre bundles are being subdivided and the laser power optimised to obtain a sufficient signal from more chords.

TCV's ECE system has been plagued by the reliability and stability of the mixer and detector systems. In 2014, the system was completely stripped and mechanically rebuilt retaining as many of the legacy filters and mixers as possible but only when considered reliable. New high bandwidth amplifiers were designed and mounted in proximity to the detectors. The ECE view lines were also revised and the microwave laboratory was equipped with a high speed oscilloscope and a microwave network analyser that will be employed to sort out residual problems and perform a stable calibration. It is expected that the HFS, LFS and in the future the vertical ECE systems will become an "every-shot" temperature profile diagnostic with a future option of making it Real-Time compatible.

Charge Exchange spectroscopy of the Diagnostic Neutral Beam has to date been based on classic Czerny-Turner spectrometers. A lens spectrometer design was adapted from that recently implemented on the AUG machine in Germany that uses photographic lenses to collimate and focus the spectral image. Commercial F2 200mm lenses were acquired, at very modest cost from EBAY, and the grating and fibre assemblies from an existing CXRS poloidal view converted. This system promises a large optical efficiency improvement whilst retaining sufficient

wavelength dispersion and a tight instrument focal. If these translate into improved temperature and rotation measurements, the toroidal viewing spectrometers will be transmuted into lens spectrometers during 2015 operations.

The number of Langmuir probe heads was increased in 2013 to cover the range of new positions on the TCV machine wall exercised by TCV's research into advanced divertor regimes such as the Snowflake configuration. The attack angles of the divertor legs to some of the probes have led to a fear that the flush mounted tile probes are suffering from partial shadowing and/or subtle effects of the plasma sheath. To investigate this further to validate the legacy measurements or help indicate possible changes in the probe tip design to improve the reliability of plasma parameters for these divertor configurations will be a large area of research on TCV in the coming years. Furthermore, the legacy Langmuir probe amplifiers that proved vulnerable to large currents and used out-of-date and expensive components, were redesigned using relatively cheap and widely available high power transistor components.

New systems

A reciprocating probe, on loan from UCSD, was exported to the CRPP and is undergoing a complete revision for installation on TCV. The high aspect ratio TCV vessel and the requirement to diagnose plasmas at all vertical positions resulted in a design where the probe can be mounted at three heights on the TCV vessel (necessitating, however, a vacuum opening). The probe head, equipped with a wide range of probe tip configurations, can perform up to 3 reciprocations, that can reach up to mid vessel radius, during a single discharge, and requires a considerable number of interlocks and power supplies to operate safely. Systems integration and initial operations are expected during the 2015 campaigns.

To monitor the plasma parameters along the divertor leg, in particular for divertor detachment studies, a multi-chord high and low spectral dispersion spectroscopic system has been purchased together with a high performance CCD detector. The system should provide upwards of 25 spatial chords through the divertor leg with down to 2-3ms temporal resolution in the initial configuration. The first goal is to compare the relative intensity of the Balmer series radiation from Hydrogen/Deuterium that monitors the transition to recombination dominated atomic physics, prevalent during divertor leg detachment. By changing the grating and spectrometer setting, the same system can monitor impurity density changes as a function of divertor leg position providing, at the least, a signature of the proximity to detachment together with spatially resolved information for use in modelling the physics processes involved. The diagnostic's use will be extensively enhanced with the addition of the edge (Langmuir) probe and Infrared observation systems described in this text.

TCV has already gone through two Infrared (IR) camera technology updates. The present system, consisting of a single camera monitoring temperature changes of the TCV vessel floor was supplemented during 2013 operations by the loan of a short wavelength IR camera. This IR camera is reaching its end of life and a grant was obtained through EuroFusion for 2014 which will be extended in 2015 to purchase two modern IR cameras so TCV can routinely monitor the strike points on the vessel floor and the central column. In combination with the Langmuir probe data and bolometer arrays, this information is used to track the power distribution between the divertor legs of a single null divertor system and more complex configurations such as the Snowflake divertor. Fast scan modes, albeit over a restricted pixel range, will also be used to examine the power deposition profile of

rapid events such as ELM instabilities. Both systems will become increasingly important with the addition of high power NBH and the planned power upgrades to the ECH heating systems.

NBH heating with TCV's relatively small size provides several challenges. The limited deposition length and restricted LFS vessel access could result in the beam either having difficulty entering the plasma or over heating the wall facing the injection (beam shine through). To monitor these possibilities spectroscopic and thermocouple systems are being installed from across the beam duct that couples the injector to TCV and on the far wall from the beam entry. Fast temperature changes of the tiles at the beam dump are insufficient to protect the machine against a sudden change in plasma transparency. Several two-colour pyrometric observation chords with a spatial resolution of a few cm will be installed on TCV to monitor the tile temperatures both at the beam deposition centre and in the surrounding regions. This system is to be considered as a last interlock to stop beam injection in the case of excessive tile temperatures and obligatory for secure TCV operation.

Finally in this section, the routine tangential camera observation of the plasma light emission was replaced in 2014. The new system is fully digital and features 500x500 pixel images with over a 1000Hz frame rate. Initially, they will be used in pure acquisition and playback mode. For a PhD thesis project completed in 2014, the digital frame grabbers used for these cameras featured high power FPGA based on-board calculation that was used to measure the plasma's position from its light emission with only a 2-3ms latency. Although operating these cameras in a high magnetic field can be challenging, this upgrade has increased the frame rate of routine visible light monitoring of the TCV plasma by over an order of magnitude.

Computing Acquisition and Control systems

The main goal of 2014 was to remove the final components of the legacy VMS-based TCV control system for a complete UNIX (Linux) based system. The VMS computers are over a decade old and were impeding both TCV repetition rate and extension possibilities. In short, the main issue is that over 20 years of effort were invested in this system that was sufficiently bug-free to completely run the TCV plant, acquisition and analysis software. Many of the legacy commercial components are available on Linux and the choice was made to perform this upgrade in transferring the components, in so far as possible, from VMS with minimal changes.

During 2014, the complete plant control software and hardware were reconfigured under Linux and only some Physics control software remains to be translated from archaic versions of Matlab and IDL to present day versions. The delay in the remaining transfer is mainly due to a lack of manpower and because of the wish to use this translation to clean up 20 years of partially redundant software code. The transfer of the whole acquisition system, that had already been mostly updated to a Linux platform was completed. This is presently being complemented by the transfer of data storage to Linux with the provision for executing the post discharge primary and secondary data analyses automatically following discharge completion. The goal of these procedures will be to have an up-to-date and highly performant informatics system that should provide complete data acquisition within 2 minutes of shot termination together with the majority of the automatic data analysis chain within another 2 minutes. Finally, a revision of TCV's data backup system will be completed in 2015 using commercial Tivoli software that will mark the complete revision of TCV's legacy hardware and software.

For physics operations, the Real-Time control system is being continually upgraded to accommodate further diagnostics and software codes. In 2013, the first Real-Time version of TCV's home-built plasma configuration reconstruction routine, LIUQE, was demonstrated during operations. This was further refined in 2014 and promises to provide reliable magnetic based data for many plasma control tasks including shape control. The inclusion of new diagnostics, such as the Thomson Scattering data described in the diagnostics section, will be used to improve these reconstructions and to provide necessary information to TCV's real-time plasma tracking code RAPTOR. More Real-Time acquisition nodes are being implemented to further increase the raw and processed diagnostic information available to the control systems. With the development of increasing complicated plasma control and an increase in the number of available actuators (more Neutral Beam Heating, multiple gas valve injection, spectroscopy etc.) TCV is dedicating considerable effort in examining the possibilities of multiple-input and multiple-output (MIMO) control to facilitate and extend physics operations.

2.1.4 Gyrotron physics

The development of advanced wave-particle interaction models for gyrotrons, accompanied with experimental validations on low-power and high-power gyrotrons has been actively pursued. The results obtained with the reduced-PIC code TWANGpic together with experiments carried out with the Dynamic Nuclear Polarisation (DNP)-gyrotron have clearly demonstrated that in presence of complex dynamics, characterized by a multi-frequency spectra, only using the PIC approach an agreement is found between theory and experiment.

In the frame of a master thesis, a novel linear gyrotron interaction model based on a spectral approach has been developed. Using this wave-particle interaction model a deeper physical insight is gained on the spectrum (eigenvalues) of the possible linearly stable and unstable oscillating modes existing in a spatially inhomogeneous system such as it occurs in a gyrotron cavity-mode coupled to a magnetized mildly-relativistic electron beam. This work is presently continued in the context of a PhD thesis in which the associated numerical code, TWANGlinspec, is being benchmarked against experimental results and will be used for studying the conditions of excitation of spurious instabilities in gyrotron beam-ducts and/or in gyrotron launchers. Further explorations of the large variety of dynamical regimes accessible with the DNP-gyrotron will be intensively pursued both on theory and experiment within a PhD project started at the end of 2014.

At the beginning of 2014, the complete gyrotron-DNP system developed at CRPP has been fully commissioned in view of being used for DNP/Nuclear Magnetic Resonance (NMR) spectroscopy experiments carried out at the Laboratoire de Physique des Matériaux Nanostructurés (LPMN). The gyrotron control system developed at CRPP, in collaboration with LPMN, allows non-gyrotron experts to operate the system in a user-friendly manner. Indeed, since February 2014, this system is being continuously and very reliably operated by LPMN PhD's students for DNP/NMR experiments.

Within the project of upgrading the Electron Cyclotron system on TCV, using the different codes of the TWANG-series, the cavity design of the dual-frequency gyrotron (84/126GHz) has been performed. It has been shown that by imposing slight modifications of the cavity geometry of the existing gyrotron developed for the W7-X stellarator, it is possible to obtain RF powers well in excess of 1MW for both frequencies of interest for TCV. This activity was carried out in collaboration with

the Karlsruhe Institute of Technology (KIT) where the results obtained at CRPP have been successfully benchmarked against the ones obtained with the numerical codes developed at KIT.

The THz scientific equipment founded by a SNSF R'Equip grant has been fully procured by the end of 2014. Moreover, a state-of-the-art Vector Network Analyser (VNA) has been purchased in December 2014. The THz hardware together with the VNA is being organized in a state-of-the-art low-power THz-lab which will be the backbone of a variety of research project to be carried out in the coming years. In 2014, two students could already take advantage of this equipment for their master projects carried out at CRPP in the field of gyrotron R&D as well as two PhD students who have just started their projects in the domain of plasma diagnostics based on EC-waves spectroscopy.

2.2 *Theory*

By using a first-principle approach, the goal of the theory group at CRPP is to make progress in the understanding of the plasma dynamics in magnetic confinement devices for fusion. This is essential 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, with a vigorous activity of modeling and interpretation of experimental results. The investigations of plasma turbulence in the TORPEX device constitute another important asset for the group.

To get insight into the plasma dynamics state-of-the-art scientific codes are necessary. 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 CRPP theory group members; we mention, among the HPC platforms used by the group, the Helios computer at IFERC-CSC and the Rosa and the Pitz Daint computers at CSCS.

Computational expertise of the CRPP theory group has been regularly solicited and was used to the benefit of all other research lines of CRPP and of some other laboratory at the EPFL, as well as within the European Fusion Programme, notably through the active participation of one of its staff members to the EuroFusion High Level Support Team (HLST) activities. In particular, in the framework of the HLST, a parallel multigrid 2D solver has been developed for the fluid turbulence code GBS. With the new multigrid solver, GBS runs 5 and 10 times faster, respectively for electrostatic and electromagnetic simulations than the previous version that was making use of the direct MUMPS solver. In the frame of the PASC (Platform for Advanced Scientific Computing) project, we have started the development of fundamental PIC algorithms for hybrid architectures (CPU+GPU). A 3D+3D simplified code has been written and several algorithms have been implemented and tested. The best result so far is a factor 3.4 times faster on 1 GPU than on 8 CPU cores.

The physics investigations carried out by the theory group cover 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

1. *Study of the improved electron heat confinement observed on the TCV tokamak when going from plasmas with positive to negative triangularity.* Local (flux tube) simulations carried out with the GENE code were completed for analyzing the radial variation of profile stiffness in TCV-relevant plasmas, in particular the dependence of stiffness on plasma triangularity. Comparison of results obtained with both a “reduced” and “full physics” model, pointed out the importance of accounting for realistic electron-ion mass ratio, impurities, collisional and electromagnetic effects. Electron heat fluxes from these local simulations remain however significantly larger than the experimentally measured ones. Corresponding global simulations, which account for so-called finite ρ^* effects (in particular profile shearing stabilization), have thus been initiated. The issue of carrying out simulations up to the Last Closed Flux Surface (LCFS), with an “ad-hoc” radial extension of the magnetic geometry to accommodate the outer radial edge buffer region required by the global version of GENE, has been addressed.
2. *ORB5 electrostatic field solver, valid to all orders in the Larmor radius.* A new field solver valid to all orders in the Larmor radius is being developed and shall replace the current ORB5 solver only valid to second order. This development is essential to accurately address shorter wavelength fluctuations. The solver has been verified in simplified geometry (slab and cylindrical).
3. *Core and edge profile stiffness, zonal flows and avalanches.* Global gyrokinetic ITG turbulence simulations using the ORB5 code have been carried out considering temperature profiles with constant logarithmic gradient in the core and constant linear gradient in the pedestal. Spatially non-local transport has been evidenced. Avalanche-like events mediated by zonal flows are observed propagating over a radial zone extending from the pedestal to the core regions (Fig. 2.2.1). The frequency and radial extent of these events is in good agreement with experimental observations on the TCV tokamak. In qualitative agreement with general experimental observations, global simulation results show that with increased input power the logarithmic gradient in the core is only slightly increased whereas the linear gradient in the pedestal is substantially enhanced.

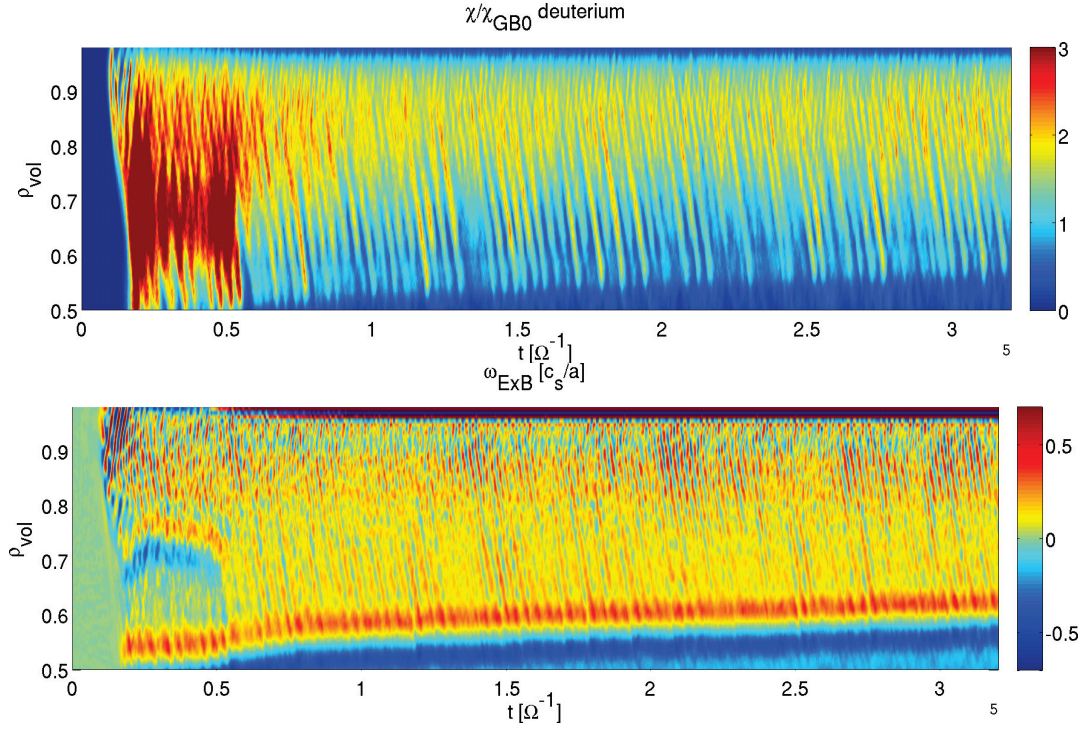


Fig. 2.2.1 Contours of ion heat diffusivity (top) and zonal ExB flow shearing rate (bottom) versus radius and time. Repetitive avalanche-like events propagate over almost half the plasma radius and are responsible for non-local transport features. Global gyrokinetic simulation using the ORB5 code.

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

1. *Fast ion orbits in 3D rotating equilibria.* We aimed to study particle orbits, especially those of fast-particles, for a MAST-like tokamak plasma which exhibits strong toroidal flow and a helical kink 3D deformation of the equilibrium. A significant part of this work required the inclusion of the higher-order electric field and the lower-order quasi-neutrality restoring electric field into the orbit-following code VENUS-LEVIS.
2. *Orbit Motion in Curvilinear Magnetic Coordinates.* To identify under what conditions guiding-centre or full-orbit tracing should be used, an estimation of the spatial variation of the magnetic field was proposed, not only taking into account gradient and curvature terms but also the local shear of the field-lines. The criterion is derived for general 3D magnetic equilibria including stellarator plasmas.
3. *Contrasting models for fast ion transport in tokamaks with resonant magnetic perturbations.* Two opposing approaches to include resonant magnetic perturbations (RMPs) in fast ion simulations were 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, which excludes stochastic field-lines, and embeds the RMPs within a 3D saturated ideal MHD state.

4. *General Kinetic-MHD problem using the MINERVA-VENUS-LEVIS packages to study the non-adiabatic contribution to the MHD pressure tensor from supra-thermal populations.* The orbit code VENUS-LEVIS is employed to evolve an ensemble of weighted markers in the rotating magnetic equilibria produced by the MHD stability code MINERVA. Moments of the perturbed distribution are sequenced to yield the hot ion kinetic response. The Laplace transform of the perturbed parallel and perpendicular pressure is calculated at the resonance as a function of the radial position and the poloidal and toroidal mode number. The resulting profiles are fed back into MINERVA as an additional source term in the MHD force balance equation.
5. *Non-linear resistive MHD instability of extended low shear plasmas.* This study showed that under particular conditions, due to mode coupling, fast growing resistive modes could develop leading to the formation of sizable magnetic islands within a brief time much faster than the standard tearing mode timescale. The growth rate of the linear theory of such instabilities, obtained from the dispersion relation which includes non-MHD effects such as bi-fluid effects and equilibrium toroidal sheared flows, has been successfully compared with numerical simulations performed with the XTOR-2F code.
6. *Applications of the LEMan code to minority ICRH scenarios in Wendelstein 7-X.* A typical Wendelstein 7-X (W7X) magnetic equilibrium was computed using the 3D equilibrium code ANIMEC. This equilibrium was used by the 3D full wave code LEMan to compute the propagation of ICRF waves in He4 with H minority plasma. A scan in frequency with a simplified antenna model exciting only one mode, showed that frequencies around 33.8 MHz allow for an optimal power deposition in the centre of the plasma while limiting the absorption at the edge (see Fig. 2.2.2).

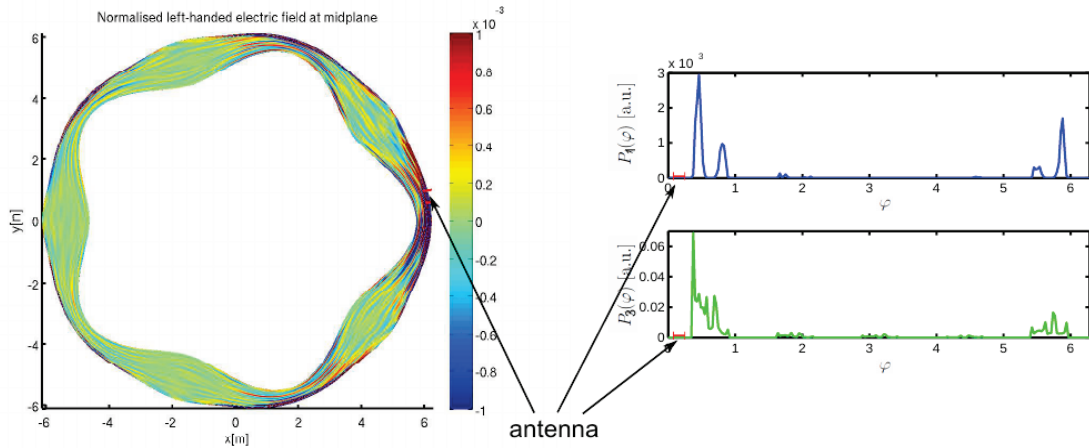


Fig. 2.2.2 Normalised electric field at the W7X midplane computed by LEMan as well as power deposition at the centre (blue curve) and edge (green curve) domains of plasma. The position of the localised antenna is shown.

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

1. *Progress in the theoretical understanding of SOL plasma turbulence.* The mechanism leading to the plasma intrinsic toroidal rotation in the SOL have been clarified, pinpointing that pressure poloidal asymmetry, as well as the boundary conditions at the magnetic presheath entrance, act as an effective source of plasma momentum. The impact of the limiter position on SOL turbulence has been pointed out, demonstrating that the experimentally observed difference between the low-field and high-field side limited discharges are due to the different nature of the instability driving turbulence. The impact of the ion temperature on SOL turbulence has also been identified. It has been shown that ion-temperature gradient modes do not play a significant role in the SOL, and that the ballooning character of plasma turbulence is enhanced with the increase the ratio of ion to electron temperature. We have also explored the effect of the plasma elongation and triangularity on SOL turbulence, focusing on limited plasmas.
2. *Comparison of SOL plasma turbulence with experimental results.* Along with the development of the theoretical understanding of the SOL plasma dynamics, a detailed comparison with the turbulence in the SOL has been carried with experimental measurements. The results of this validation project have greatly enhanced the confidence in our simulation results, as they have shown that our model recovers the main features of the experimental results. Among the validation exercises performed, we would like to mention the comparison of our simulation results with the gas puff imaging diagnostics of Alcator C-Mod.

2.2.4 *Modeling activities in support of experimental activities*

1. *MHD modes and transport.* Effects of MHD modes on transport simulations, in particular on the time evolution of density and temperature profiles are being analyzed for TCV, for the ASDEX Upgrade experiments that have been performed during the 2014 medium size tokamak campaign, and for the JET data within the WP-CD project. In particular, the sawtooth and NTM modules have been developed, as well as the edge stability calculations and the comparison with the EPED model. Recent developments and their impacts on the NTM stabilization on ITER have also been analyzed.
2. *Development of models for real-time control.* The RAPTOR code is being developed for both offline and real-time simulations, focusing on the sawtooth and NTM modules that have been validated with ASDEX Upgrade results. A new simple transport model is being developed, based on expected inverse scale lengths of the profiles and on the core stiffness properties of tokamak plasmas. It has the potential to provide rapid, accurate, and reliable kinetic profiles for both predictive and interpretative simulations, thus applicable to real-time transport simulations.

2.3 *Basic Plasma Physics*

2.3.1 *Industrial Plasmas*

Following the retirement of the former Industrial Plasmas group leader, Christoph Hollensten, the activities have been pursued in the newly formed Basic Plasma Physics and Applications group. The ongoing projects concern the development of plasma sources for high rate deposition processes and for packaging applications, as well as the development of a new helicon source for NBI for the next generation of fusion reactors. These important topics are investigated in the frame of CTI projects in close collaboration with industrial partners, TEL, TetraPak and Helyssen Sarl, and also in the framework of a EUROfusion project in collaboration with CEA Cadarache. The achievements in 2014 are briefly reviewed below.

High rate deposition of microcrystalline silicon for solar cell applications by means of a resonant network RF antenna

A change from the traditional capacitively-coupled plasma reactors to inductively-coupled plasma (ICP) devices has the potential to improve thin film solar cells because ICP operates in new regimes of low pressure (5-10Pa) and low ion energy bombardment (20eV). In this project, a resonant RF antenna reactor was constructed to investigate photovoltaic related material in these new conditions. The project was aimed towards the concept of a novel plasma-enhanced chemical vapour deposition (PECVD) production reactor. The antenna, designed by Helyssen Sarl, was built into a reactor for plasma deposition investigations at the CRPP. The deposited film properties were measured by the industrial partner, TEL Solar at Truebbach.

The 47x57cm² antenna, made of 23 copper bars interconnected with ceramic capacitors, was designed to resonate at the industrial standard frequency of 13.56MHz, with mode number $m=8$ for optimum plasma uniformity. The assembly was protected from the plasma by dielectric foam and ceramic plates. First depositions of silicon using hydrogen-diluted silane showed a high deposition rate, up to 2.5nm/s, of microcrystalline silicon with the milestone Raman crystallinity fraction of 50 - 60%, corresponding to transition material optimal for integration into solar cells. However, film porosity was evidenced by the strong incorporation of oxygen into the film as shown by infrared absorption spectroscopy. It was deduced that the low ion bombardment energy associated with inductively-coupled plasmas was too low to densify the growing film. Consequently, a partial-area RF bias electrode was installed below the glass substrate to control the ion impact energy on the film surface. Comparison of the films deposited inside and outside the bias area clearly showed that RF bias effectively reduces the porosity and post-oxidation.

The deposition rate and crystallinity fraction surpassed expectations for the project, but the film defect density was worse than specifications despite improvement using RF bias. A second reactor project would be necessary to reduce oxygen contamination, with a systematic study of defect density as a function of deposition parameters. More versatile than the conventional planar spiral design, the resonant antenna itself showed great potential as a large area inductively-coupled plasma source for this and other applications.

Large resonant RF network antenna for industrial deposition of barrier coatings on polymers for packaging applications

Robustness tests of a large antenna ($1.2 \times 1.2 \text{ m}^2$) at CRPP for packaging applications in collaboration with TetraPak and Helyssen were successfully accomplished and stable plasma at 15 kW maximum power was achieved by careful attention to the antenna construction. The plasma is enclosed by solid reactor walls with broad ground planes to the RF stripline and vacuum chamber to eliminate spurious plasmoids and corona, even for argon plasma. However, heat load of reactor walls will be an issue for continuous high power operation.

Plasma impedance measurements as a function of frequency, or at 13.56MHz fixed frequency, were limited to 2kW and 10kW, respectively, by the specifications of commercial equipment. Progress continues on a custom-built tandem match coupler and automatic matching box to remove these limitations. A surface matrix of one hundred multiplexed electrical probes to monitor the plasma uniformity was complemented by a scanning axial probe for high spatial resolution. The plasma is uniform parallel to the antenna legs, and this will determine the antenna orientation for uniform process in a roll-to-roll reactor. However, the plasma profile is hollow perpendicular to the legs in the presence of a top screen; this may be attributed to transmission-line effects peculiar to the large reactor and will be investigated further. Overall, these plasma measurements have stimulated the development of a new theoretical model for inductively-coupled plasmas.

Development of a resonant antenna based helicon plasma source for NBI for DEMO

The ability to obtain high plasma density with high ionisation rate and much higher power efficiency than inductively-coupled plasma (ICP) sources make helicon sources an interesting option as plasma sources for Neutral Beam Injectors (NBIs) for the next generation of nuclear fusion reactors. In this context, they have the following advantages over traditional ICPs: 1) reduced RF power, leading to increased operational domain; 2) stable operation at low pressure; 3) lower electron temperatures; 4) high degree of molecular dissociation in hydrogen plasmas. In the framework of a EUROfusion project and in collaboration with CEA Cadarache, we have started the development of a 10kW helicon generator to be implemented on the Cybele source at Cadarache. The design is based on a “birdcage” resonant antenna, which was previously shown to be very efficient in terms of helicon wave excitation.

In 2014, a birdcage resonator capable of withstanding 10kW was designed and constructed. An antenna with 13cm diameter was chosen to fit on the Cybele source. A Cad drawing of the antenna is shown in Fig. 2.3.1. The antenna arrangement is composed of 15cm long water cooled copper tubing, which are connected in parallel by high quality factor mica capacitors. The birdcage antenna will be mounted axially on one end of a test stand vacuum chamber, as shown in Fig. 2.3.2. The discharge tube is made of alumina (internal diameter: 11cm, length: 38cm). The cooling of the RF antenna is ensured by water circulation. Two semi-cylindrical metallic screens are disposed around the coil. The adjustment of the screen positions allows the antenna resonant frequency to be finely tuned with 2MHz accuracy. The system is designed to resonate at 13.56MHz which, being an industry standard, corresponds to the largest availability of hardware at CRPP. In a first phase, the antenna will be tested at CRPP on a test stand, which was also

developed in 2014. This first test period will focus on important issues in the application of the generator as a source for next generation of NBIs.

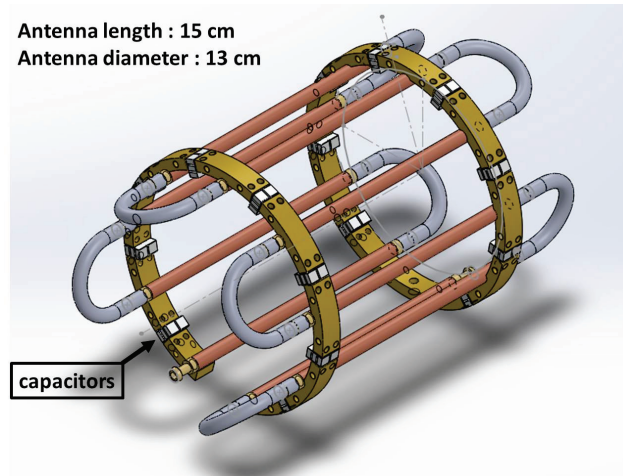


Fig. 2.3.1 *Nine-leg cylindrical resonant network used for helicon excitation. The capacitors value is 3840pF to bring the $m=1$ resonance close to 13.56MHz (with the screens). With regards to the closed configuration, the chosen open configuration enables a better control of the RF field polarization.*

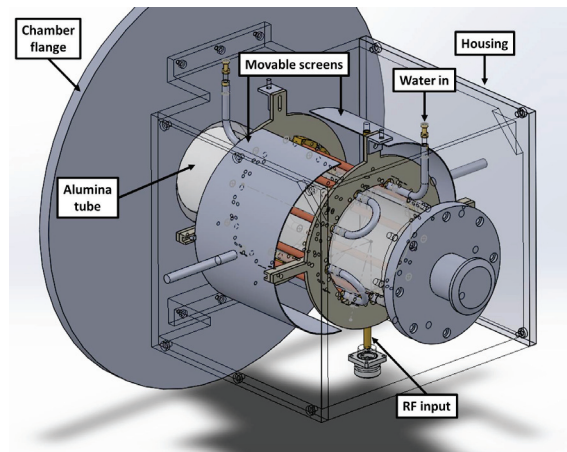


Fig. 2.3.2 *General view of the helicon source. The discharge tube is made of alumina (internal diameter: 11cm, length: 38cm). The cooling of the RF antenna is insured by water circulation. Two semi-cylindrical metallic screens are disposed around the coil. The adjustment of the screens position allows the antenna resonant frequency to be tuned over 0.2MHz.*

2.3.2 Torpex

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

In TORPEX, plasmas are created by microwaves at 2.45GHz with different gases and are characterized by low densities ($n_e \sim 10^{16}-10^{17} \text{m}^{-3}$) and temperatures ($T_e \sim 5-20 \text{eV}$). In the simple magnetized torus (SMT) configurations, plasmas are confined by a toroidal magnetic field up to $B_T=0.1\text{T}$, and a smaller vertical component, $B_z \leq 50 \text{mT}$. The SMT incorporates the main ingredients for drift and interchange instabilities and turbulence, namely pressure gradients, magnetic field line curvature and open field lines. In addition to SMT configurations, the new internal toroidal conductor (TC) system allows creating twisted field lines with rotational transform, thus creating a region of closed field lines and magnetic surfaces (as in the tokamak configuration) and increasing the relevance to magnetic fusion devices.

In 2014, significant progress was achieved along several research avenues, from the study of the interaction between supra-thermal ions and intermittent blobs, to the first experiments in the presence of an X-point in the device. Such progress is detailed in the paragraphs here below.

Supra-thermal ion transport studies

Understanding turbulent transport of suprathermal ions, i.e., ions with energies greater than the quasi-Maxwellian background plasma, is of paramount importance for a variety of laboratory and natural systems. In future fusion reactors such as ITER and DEMO, a good confinement of suprathermal ions, created by fusion reactions or additional heating, is necessary to reach and control burning plasma conditions. On TORPEX in previous years, we conducted investigations of suprathermal ion-turbulence interaction using a miniaturized suprathermal (10eV-1keV) Li^{6+} ion source and a detector system. A picture of the system is shown in Fig. 2.3.3. 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 depending on the ion energy. After a brief ballistic phase, in which the fast ions do not interact significantly with the turbulence, a turbulence interaction phase follows, which shows the entire spectrum of fast ion spreading: super-diffusive ($\gamma_R > 1$), diffusive ($\gamma_R = 1$), or sub-diffusive ($\gamma_R < 1$), depending on particle energy and turbulence amplitude.

In 2014, we focused our experiments on time-resolved suprathermal ion measurements and their statistical properties. The existence of different non-diffusive transport regimes should naturally be accompanied by different signatures in the time traces of the detected suprathermal ions, which could be the sole method to reveal different transport regime less easily diagnosed in fusion-grade plasmas. Initial results on TORPEX indicate a clear transition in the intermittency properties from the case corresponding to sub-diffusion to that characterized by super-diffusion. Experiments were conducted with 30eV and 70eV ions. For the 30eV case, Fig. 2.3.4 displays the time-evolution of the detector signals with the detector located at the position of maximum time-averaged ion current. Due to the low signal-to-noise level, the suprathermal ion source was modulated at 30Hz to detect differences in the statistical features of the signals. During the on-phase, the signal is clearly intermittent, and is characterized by a positively skewed probability distribution function, which is suggestive of a process associated with intermittent blobs.

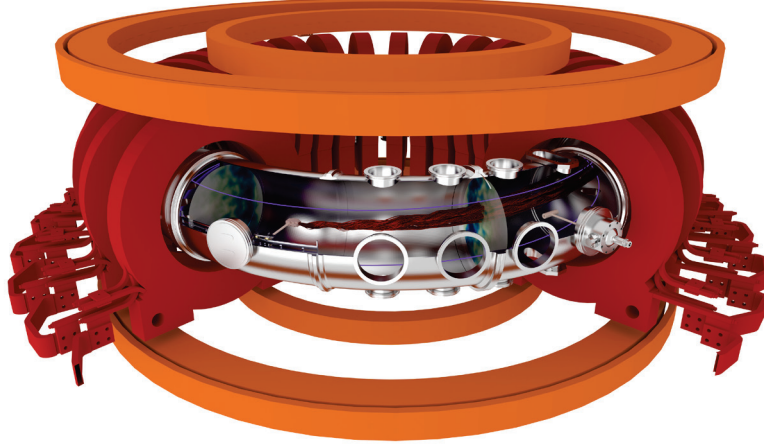


Fig. 2.3.3 View of the TORPEX device with the main elements (vacuum vessel, toroidal and poloidal coils) together with the suprathermal ion source and one suprathermal ion detector. A helical magnetic field line of a SMT configuration is shown in violet. The suprathermal ion source is mounted on the toroidal moving system. Examples of simulated suprathermal ion trajectories computed for 30eV ions are shown in red. Simulated plasma potential profiles at two toroidal positions are shown. These are obtained from numerical simulations using the GBS code.

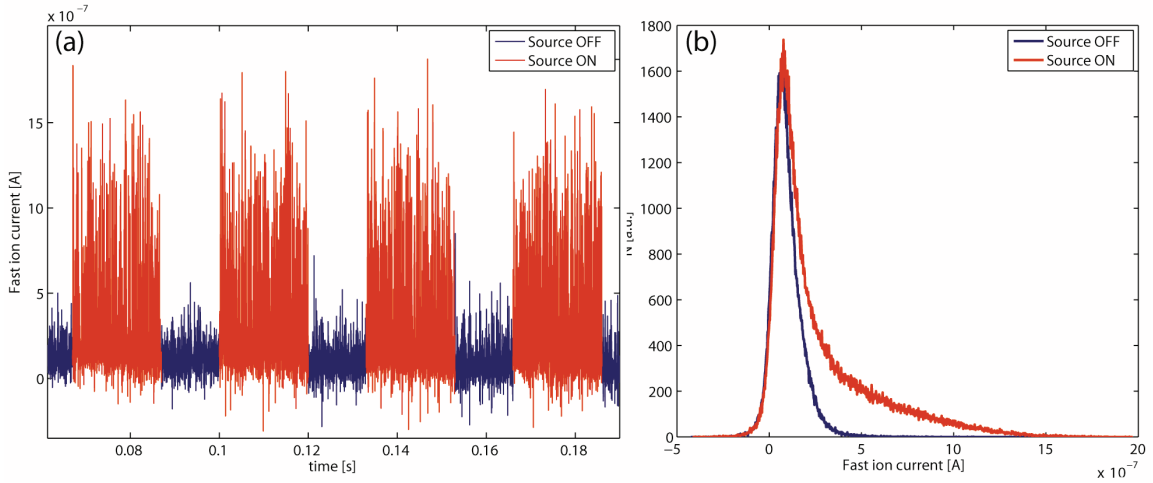


Fig. 2.3.4 (a) Time evolution of the detector signal and (b) its probability distribution function during periods in which the suprathermal ion source is switched on and off.

Figure 2.3.5 shows the poloidal profile of the skewness for the two energies. While the skewness profile for the 70eV ion beam is flat, Fig. 2.3.5(b), the profile for the 30eV ions reveals a region of high skewness around the peak of the time-average current. This indicates that the broadening of the 30eV suprathermal ion beam is due to intermittent bursts perturbing the gyromotion of the ions. This pattern is not visible on the skewness profile for 70eV ions. This implies that, in the surrounding of the profile, where the time traces have a low time-averaged current compared to the center of the profile, the intermittency is more important. Using conditionally-averaged measurements, we have shown that the observed intermittency is caused

by the interaction of the suprathermal ions with blobs. Conditionally-averaged measurements prove that the intermittency in the superdiffusive ions is due to their higher sensitivity to intermittent blobs, which move the ions through their electrical field both inwards and outwards, depending on the their relative location.

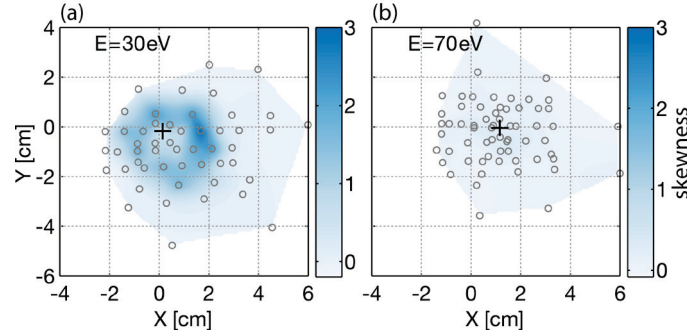


Fig. 2.3.5 *The skewness profile for the 30eV ions (a) reveals an annular region of high skewness around the peak of the time-averaged profile. This suggests that the broadening of beam is due to intermittent blobs perturbing the ion gyromotion. This pattern is not visible for 70eV ions (b). Gray circles show the positions of measurements and the black cross the positions corresponding to the time traces.*

Turbulence studies with closed flux magnetic surfaces and X-point.

In 2014, plasma fluctuations in the presence of closed-field lines of direct relevance to magnetic fusion devices were fully characterized. Quasi circular-shaped flux surfaces are produced using the new internal toroidal conductor (TC) system in combination with the vertical external coils, Fig. 2.3.6.

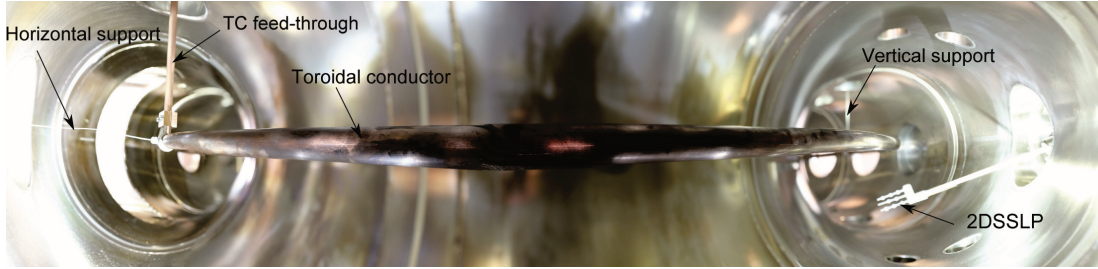


Fig. 2.3.6 *Wide-angle view of the toroidal conductor installed inside TORPEX. Visible are the feed-through together with the vertical and horizontal supports.*

Plasma fluctuations feature a clear ballooning character with the presence of quasi-coherent modes between 15-30kHz. The first characterization of the mode spectral properties was performed in terms of toroidal and poloidal wave numbers. A dominant toroidal mode number $n \sim 1$ is found together with a poloidal mode numbers m that are related to safety factor by the relation $q = m/n$. This indicates that the modes are field-aligned as expected for interchange-driven instabilities.

The toroidal conductor system opens new avenues for research, enabling the production of magnetic geometries with single and double magnetic null-lines, as well as snowflake divertor configurations. An example of a single-null X-point

configuration is shown in Fig. 2.3.7. The presence of fluctuations around the X-point is revealed, as well as the generation of intermittent blobs, which propagate towards the low field side. More complex geometries with multiple fully 3D X-points and/or magnetic ergodic/chaotic surfaces could also be generated by additional ad-hoc coils installed inside the TORPEX vessel.

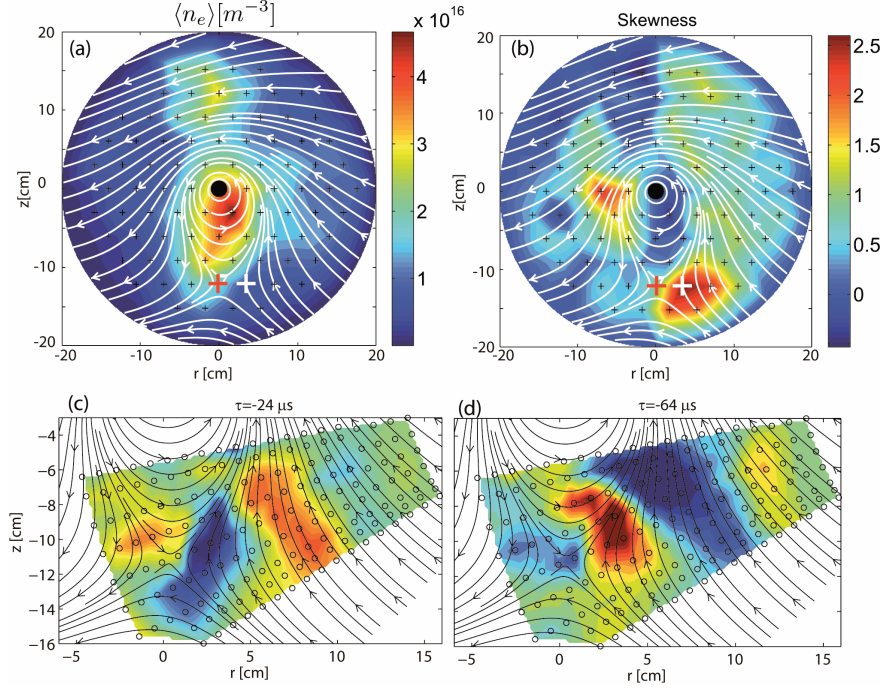


Fig. 2.3.7 *X-point geometry: (a) time-averaged electron density and (b) skewness profiles. (c, d) Conditionally sampled data showing the blob generation and propagation around the X-point.*

On the theory side, starting from the simulations of the TORPEX device, the GBS code has been recently upgraded and the physics of the tokamak SOL in the limited configuration has been the subject of a number of detailed investigations. Future development include the implementation of a flexible numerical algorithm to describe more complex geometries, in particular the presence of an X-point, and of a kinetic solver for the neutral atoms.

TORPEX will continue to provide an ideal validation testbed for the future developments of GBS. Applying the same techniques on numerical and experimental data allows testing the accuracy of these techniques, and 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 not only of TORPEX data but especially for fusion devices.

2.4 Superconductivity

2.4.1 Superconducting Magnets for DEMO

The development of advanced, high current, high field superconductors for DEMO made good progress in 2014. A short length prototype of the 83kA/13.5T,

React&Wind Nb₃Sn conductor designed in the past years was manufactured. Two hundreds kg of the 1.5mm strand was procured at WST (China) and 13m of the novel flat cable layout was realized at Tratos (Italy) in collaboration with ENEA. The assembly of a SULTAN sample is on going. The larger merit of the innovative conductor layout is to exploit without degradation the performance of the Nb₃Sn strands and simplify the coil manufacturing process, leading to substantial cost reduction compared to the Wind&React, Cable-in-conduit approach of ITER.

A HTS high current conductor based on soldered, twisted stacks of coated conductor tapes is developed at CRPP. Based on the successful R&D of 2013, a cable made of 20 soldered stacks is assembled in 2014 as the first prototype of a 60kA / 13T HTS forced flow conductor for DEMO. The cost of the HTS tapes is today one order of magnitude higher compared to the LTS conductors and the availability in km length not yet established. Nonetheless, the feasibility demonstration of a prototype conductor is a major milestone in the field.

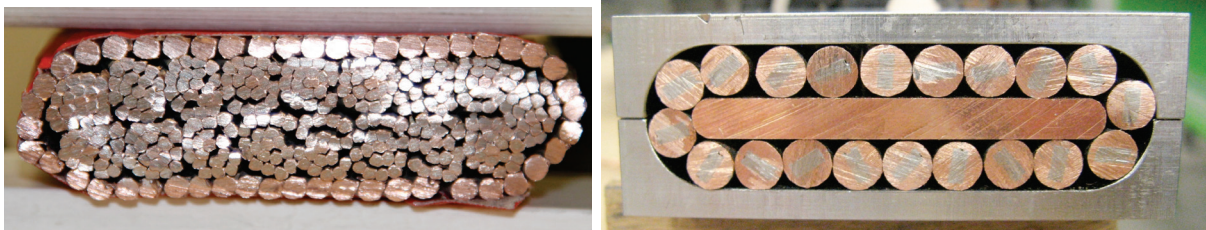


Fig. 2.4.1 *The Nb₃Sn W&R cable, 68mm x 18mm, left and the HTS conductor 72mm x 26mm, right.*

The development of both prototype conductors is supported by electro-magnetic, thermal-hydraulic and mechanical analysis. The test at relevant operating conditions in the CRPP facilities is planned in early 2015.

2.4.2 *Development of high field insert coil made of HTS tapes*

The option of using insert coils made by HTS tapes is considered in the last few years by laboratories and companies to enhance the field of commercial superconducting solenoids, limited to about 18T-20T. A prototype insert coil has been assembled and tested at CRPP using commercial 4mm wide tape: it consists of a stack of 26 pancakes, made of 275m of tape. The design field is 4T in the background of 12T produced by a commercial lab solenoid. Extensive analyses are carried out about the quench behaviour of insert coils of HTS, to identify the simplest and safest approach to quench protection. The innovative feature of the insert coils is the absence of electrical insulation on the tape, providing self-protection in case of local quench.

In collaboration with the company Bruker, other technology aspects of the insert coils are investigated, including winding layout, joining techniques and passive protection, with the aim to offer commercial solenoids up to 25T, where the added field by the insert is 6T.

2.4.3 Conductor test for high field hybrid coils

In support of the 45T high field hybrid coil project at the Radbaud University (Nijmegen), the Nb₃Sn 18kA conductor for the superconducting outsert was tested at the SULTAN test facility. The cable was produced at ICAS (Italy) with two options for the twist pitches of the multistage cable. The assembly of the sample was done at CRPP. The test results confirmed the suitability of the conductor layout. The relative performance of the two pitch sequence are experimentally assessed in terms of DC test and AC loss.

2.4.4 Completion of the EDIPO test facility

The commissioning of the main coils of EDIPO was satisfactory completed in 2013. On the other hand, the primary coil of the superconducting transformer did underperform due to insufficient cooling. The demanding modification of the cooling scheme was completed in March 2014, but the transformer commissioning failed because of the poor centering of the primary and secondary coils. A new primary coil was manufactured and eventually tested in October 2014, but failed again due to the poor impregnation of the winding. The former primary coil is now refurbished with the aim of completing commissioning in spring 2015.

2.4.5 Non-destructive methods for ITER joints

Non-destructive examination (NDE) performed at room temperature, has the potential to identify TF joints with a high resistance, prior to cold commissioning in the machine. The ITER TF joints are of a twin-box design and the critical parameters of the overall resistance is the pressure contact between the Nb₃Sn strand-bundle and the copper plate inside the termination. The applicability of several methods has been verified on an ITER TF joint sample. More extensive investigations are carried out on a demountable mock-up.

A resistance profile method, obtained by a scanning head with multiple sliding contacts, was shown to have some potential and was developed further. Resistance profile NDE was performed on the upper and lower terminations of the joint sample. In agreement with ITER, the method will be applied in the coming year to artificially caused defects, whose impact on the low temperature performance will be assessed by dedicated tests of joint samples in SULTAN.

2.4.6 Tests of superconductors for ITER

In 2014 a total of 35 weeks of test operation in SULTAN were devoted to the qualification and acceptance tests of the ITER conductors and joints, in the scope of the ITER framework contract, whose extension into 2017 has been recently agreed. Out of 17 samples, only one joint sample did not fulfil the specification. The samples made of Nb₃Sn conductors were assembled at CRPP. Following test campaigns have been carried out in 2014:

- CSJA6 – JADA – CS conductor with short twist pitch – 5+3 weeks
- TFKO7 – KODA – TF sample from Korean series production – 2 weeks
- PFCN5 – CNDA – PF5 conductor sample – 1+1 weeks
- TFCN5 – CNDA – TF sample from Chinese series production – 2 weeks
- TFEU11 – F4E – TF process qualification sample – 2 weeks
- CBCN3 – CNDA – Correction coil Busbar from production – 1 weeks
- CCCN5 – CNDA – Correction coil conductor sample from production – 1 weeks
- PFCN6 – CNDA – PF2-4 conductor sample – 1 weeks
- CCCNjoint – CNDA – Qualification of industrial CC joint sample – 1 weeks
- PFEU2 – F4E – PF6 process qualification sample – 2 weeks
- TFEUjoint – F4E – Qualification of industrial TF joint sample – 1+1+1 weeks
- PFCN7 – CNDA – PF5 conductor sample – 1 weeks
- MBCN5 – CNDA – Main Busbar sample, assembled at CRPP – 1 week
- TFKO8 – KODA – TF sample from Korean series production – 2 weeks
- TFJA10 – JADA – TF sample from Japanese series production – 2 weeks
- TFUS5 – USDA – TF process qualification sample from US – 3 weeks
- PFRF2 – RFDA – PF1 sample from Russian series production – 1 weeks

2.5 *International and National activities*

2.5.1 *Gyrotron development for ITER*

The CRPP is member of an European Consortium, EGYC, which is responsible for the development of the ITER gyrotron, to be delivered in kind by EURATOM. The EGYC activities in 2014 were focused on the development of the 170GHz/1MW/CW gyrotron tube for ITER, a project that is managed by F4E. The Grant GRT-432 was terminated normally in June and was followed by the entry in force of GRT-553, coordinated by CRPP as for RT-432.

The F4E strategy is articulated around the production of 2 gyrotron tubes:

- a modular short pulse 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 purpose of GRT-553 is

- to support theoretical activities aiming at securing the design of gyrotron tubes
- to finalize the design of the short pulse and CW tubes
- to support F4E in the follow-up of the CW tube (OPE-447), the new He-free Superconducting magnet to be installed at CRPP, and the procurement contract (OPE-454) for the ITER EC power supplies.
- to complete the tests with the short pulse tube carried out at KIT,
- to complete the initial tests with the CW tube, also foreseen at KIT because of the unavailability of a magnet at CRPP,
- to perform further upgrades of the gyrotron test stand I view of the future CW tests,
- to support F4E in the completion of an ITER task order related to the gyrotron building and interfaces.

The short pulse tube (Fig. 2.5.1) has been delivered in the 3rd quarter of 2014 and tests have begun early in December at KIT. The tube has shown its ability to reach 1MW of output power without any parasitical oscillation, with a stray radiation level of a few percent in agreement with the simulations. The output beam is centered at the window and the Gaussian content is higher than 95%. As a conclusion, the RF design of the tube is considered as validated.

The final design review of the CW tube was carried out in 2 phases and the fabrication is progressing according to the plans, with a delivery foreseen at KIT by the end of summer 2015.



Fig. 2.5.1 *Picture of the short pulse gyrotron before its installation in the superconducting magnet.*

2.5.2 *The ITER Upper Launcher for Electron Cyclotron Waves*

The ITER EC Upper Launcher Consortium (ECHUL)

Grants and contracts from F4E for work on the ITER electron cyclotron (EC) upper launcher (UL) are undertaken by a consortium of associates possessing between them the requisite manpower and expertise to cover the scope of the work. Specific members receive contracts directly, outside of the consortium, when appropriate; the consortium is kept up-to-date on the developments or results related to such contracts at biannual face-to-face meetings, or during monthly video conferences.

Development of the ITER Upper launcher (F4E-GRT-161)

The first grant for the finalization of the ITER UL has been signed with ECHUL-CA on 1st November 2011. Since then, three amendments have been made to the contract resulting in the extension of the contract until 30 November 2014. The work is concentrated on the first confinement system (FCS) but required an update of the quasi-optical portions of the launcher system as well, taking into account the various modifications to the ITER vessel and issues raised by the expert panel. since the time of the preliminary design review (PDR) in November 2009.

Several significant changes have been made to the grant scope, arising from changes to the ITER machine and buildings as the overall ITER design and construction progresses. In particular, the space available for waveguide passages into the machine was reduced. This precludes the use of waveguide bellows in the design and led to the need for ECHUL, CRPP in particular, to design new waveguide couplings and other components that were originally meant to be “components off-the-shelf” (COTS). A further grant amendment (and a change in Grant number (F4E-GRT-615) has been signed to carry the work from December 2014 through 2018.

Prototype testing of component double metal seal couplings for the ITER EC Upper Launcher

Scoping tests of the waveguide/component coupling designs were carried out under an additional contract from F4E; F4E-OPE-528 and its amendment resulting from a change in waveguide diameter (one of the F4E-GRT-161 amendments). This change results in a system design that is more mechanically compliant. The coupling design results from F4E-GRT-161 and test component waveguides were purchased from Swiss manufacturers under F4E-OPE-528. A 50mm displacement occurs at the level of the ITER Upper Launchers when the ITER vacuum vessel is baked. The ex-vessel transmission lines must take up this displacement since the lines are rigidly fixed to the ceiling of ITER building in the port cell. This fixation mechanically isolates the rest of the transmission line – most importantly the gate valves and diamond windows – from the torus; thereby protecting these two main confinement barriers from excessive stresses. The couplings provide vacuum tightness and tritium confinement as part of the first confinement system (FCS), but must also ensure precise alignment of the waveguide axes to avoid millimeter-wave power losses through mode conversion. They are subject to high forces and moments. The scoping tests these various functionalities. Figure 2.5.2 shows the CRPP waveguide couplings, instrumentation and the Test rig. Figure 2.5.3 is a photo of the manufactured couplings under test. The couplings were confirmed to maintain vacuum leak tightness with alignment even when subjected to larger-than-worst-case forces and moments. A further contract is expected in 2015 to continue testing of other FCS components.

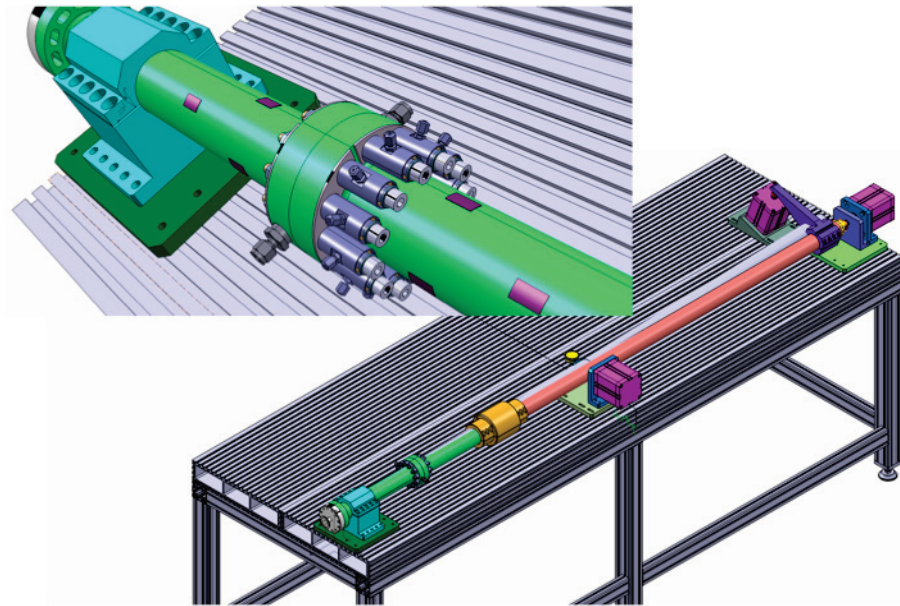


Fig. 2.5.2 Test rig on a table bench, for simulating mechanical loads on a waveguide coupling assembly, using pneumatic cylinders. The detail of the coupled short waveguide assembly is represented with the force sensors measuring the tightening force of the bolts. The patches indicate locations for applied strain gages to measure waveguide deformation near the flange.

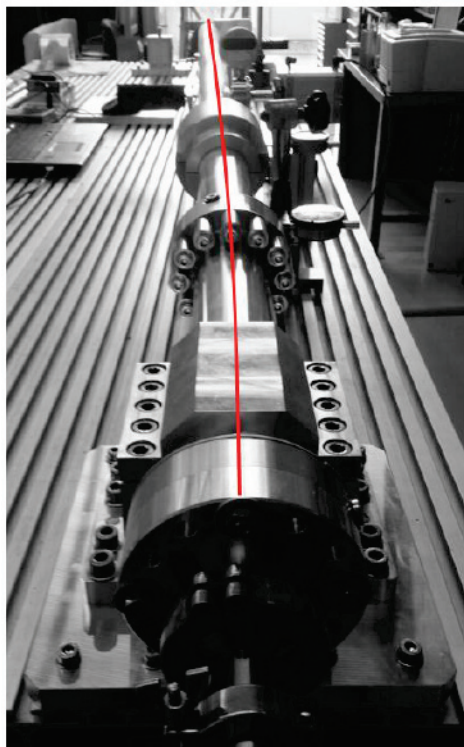


Fig. 2.5.3 The test rig with the manufactured couplings under vacuum and subject to large deflection testing conditions (1529Nm required, 2161Nm applied). No leaking nor plastic deformation occurred.

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

CRPP has continued its contribution to the design of the IMAS-ITER project, finalizing the contract TO3 for the end of 2014. The data model has been extended and discussed extensively with the IO. A major agreement has been obtained including more systematically arrays of structures. The life cycle of the data model and of the infrastructure has been well defined and adopted. This will enable a stable yet evolving environment for ITER collaborators. The design of the architecture for physics data access, based on our rapid prototype, has been finalized as well. The full integration of the DINA-CH code into the IMASv2 infrastructure has been realized. The results of this whole contract have been well accepted by the ITER Modelling Expert Group meeting at the end of 2014.

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

In view of the challenging requirements of the heating and current drive system for DEMO, within the EUROfusion Roadmap, a specific workpackage named WPHCD (Workpackage Heating and Current Drive) was established. The involvement of the CRPP encompass:

- the overall WPHCD leadership, with one staff member of CRPP being Project Leader at 50% of his time;
- activities in the field of electron wave system;
- activities in the development of an advanced negative neutral beam source.

Project leader of WPHCD

WPHCD includes the development of three main H+CD systems, the electron cyclotron (EC) one, the ion cyclotron (IC) one and the (negative) neutral beam (NB). One of the main guidelines for the R&D is to benefit as much as possible from the one performed for ITER. However, there are specifications of the DEMO machine, which render necessary to develop "advanced technologies" (for EC the development of a high frequency (240 GHz) gyrotron at high efficiency, and for NB a better concept of neutralization of the negative ion beam).

2014 was the first year European laboratories have been working together to meet the objectives of WPHCD. Viewed from the programme management, it implies the establishment of a workprogramme for the whole duration of Euratom-Horizon 2020 (2014-2018) and a workplan for 2014, which was discussed with all the participating laboratories.

The Work Breakdown Structure (WBS) for the workpackage Heating and Current Drive includes:

- System engineering for EC, IC and NB;
- R&D, conceptual design and Advanced Technologies for EC and NB;
- IC conceptual design.

According to the WBS, the technical specifications for 2014 activities were established. In the course of the year, all the necessary management activities were performed with the help of the EUROfusion Programme Management and the Project Leadership. The final annual report was prepared for submission to EUROfusion.

EC activities in the frame of WPHCD

The CRPP was involved in two main fields of WPHCD:

- a) the benchmarking of the codes TWANG and TWANG-PIC using experimental data of a high-power gyrotron tested at KIT;
- b) the commissioning of an optical bench covering the frequencies 110-170GHz and 220-330GHz.

a) Benchmarking of codes

We have used two codes developed at CRPP, TWANG and its particle in cell version TWANG-PIC, to analyze the experimental data obtained with the coaxial gyrotron under test at KIT. The simulation based on the experimental parameters gave the same level of discrepancy between theory and experiment as also found by KIT with two other codes EURIDICE and SELFT. In order to understand the reason of this discrepancy, a first set of parametric studies have been carried out by varying the gyrotron magnetic field, electron beam energy, pitch angle, velocity and guiding centre spreads. The reasons of the discrepancy seems to be associated to the high uncertainty of the system parameters such as the electron beam pitch angle and the electron guiding centre average position and spread. Both KIT and the CRPP are continuing the comparative study.

Using the same codes, we also cross-checked the simulations made by KIT in the frame of the design of the DEMO 240GHz 2MW coaxial gyrotron. In these studies, the electron beam is assumed to have no energy spread but a spread in pitch angle. It was found that 2MW power level could be achieved, however, in the "hard excitation region": i.e. through a modification of external parameters such as the magnetic field or the beam energy. In the "soft excitation region" only 1.25MW could be achieved. The power is also degraded ($\Delta P/P > 5\%$) in the presence of a perpendicular velocity spread (\geq resp. 7.5%).

b) Commissioning of an optical bench in the frequency ranges 110-170GHz and 220-330GHz

The development of a gyrotron requires the knowledge of complex dielectric constant $\epsilon(\omega) = \epsilon_r(\omega) + i\epsilon_i(\omega)$ if dielectric. An optical bench was set up (Fig. 2.5.4) using a vector network analyser with the appropriate measurement heads. Measurement of the complex dielectric in the frequency ranges 110-170GHz (170GHz being the frequency of the electron cyclotron system of ITER) and 220-330GHz (240GHz being the frequency of the DEMO gyrotron) could thus be performed both for high loss material (large by $\tan\delta = \epsilon_i/\epsilon_r$) and low loss material such as CVD diamond used as RF window for the gyrotron or at the wave launcher near to the torus.

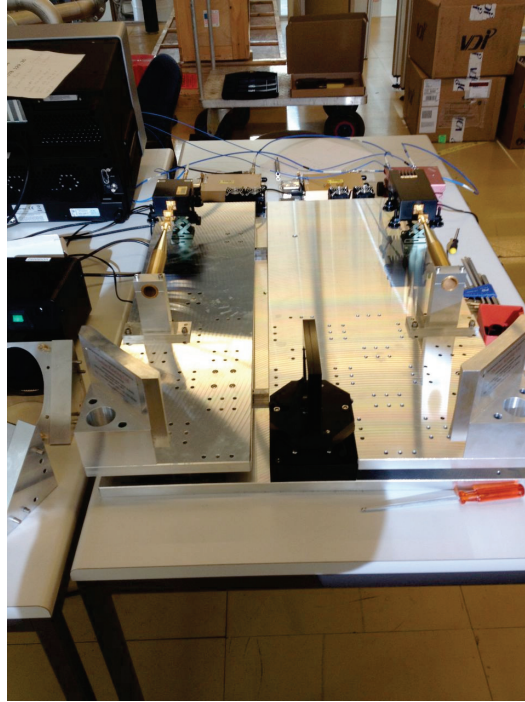


Fig. 2.5.4 *The test bench configured for dielectric properties measurements in the WR6.5 band (110-170GHz).*

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

In the frame of the EUROfusion WPPMI project, a task specifically focused on the issue of energetic particles in DEMO was started in 2014. While ITER will be the first plasma to enter the burning regime, with the self-heating from the fusion generated alpha (α) particles taking over the external heating, in DEMO alphas will be providing by far the dominating component of the plasma heating mix. Understanding and controlling fast ions, to reach and sustain the burning plasma conditions, to assure the stability of the self-heating process and the optimisation of the burn, will therefore be even more important than in ITER.

All fast particle issues that are presently under scrutiny for ITER are of relevance for DEMO. These include the fast ion contribution to the bootstrap current, the fast ion losses induced by three-dimensional structures on the magnetic field, the fast ion interaction with large scale MHD modes (stabilisation of internal kink modes, i.e. sawteeth, and Resistive Wall Modes).

Significant differences are nevertheless expected between ITER and DEMO. As the fast ion beta β will be significantly larger in DEMO than in ITER, becoming a significant fraction of the total, the question of the effect of β_{fast} on the β limit arises. With a much higher fusion gain than ITER, DEMO will be well into the burning regime: the different profiles will be more strongly coupled by the α 's themselves and isolating the individual building blocks will be even harder. The β_{fast} profile will in fact be determined by the redistribution, local and/or global, caused by the same modes that the fast ions will resonantly drive.

The first part of this work conducted in 2014 was to provide a global assessment of the fast particle issues in DEMO, on the basis of a global vision of the field, past experience with experiments in weakly self-heated plasmas and with pre-existing runs of state-of-the-art numerical simulation codes. The next step will need to involve dedicated runs of the most advanced numerical codes available in the community.

2.5.6 Contribution to the scientific exploitation of JET

CRPP scientists led 7 sessions dedicated to sawtooth control in H-mode plasmas. These experiments showed, for the first time in JET, that sawteeth can be controlled using low field side ICRH fundamental resonance of H minority in a D-plasma. In low power pulses it has been shown that the resonance does not have to be very precisely located in order to control sawteeth. Resonance position accuracy of about five centimetres on either side of the $q=1$ surface would provide the desired sawtooth control effect, which contrasts with previous experiments with resonance on the high field side where a tolerance of about 1 centimetre would be required. However, in high performance discharges, it was found that the position of the resonance should be precisely located just inside the $q=1$ surface in order to maintain small sawteeth. Impurity flushing from the core was also found to function very effectively with the resonance position just inside the $q=1$ surface. This resonance position creates a strong temperature gradient near the $q=1$ surface, which lessens the influx of impurities to the core. Any impurities that do enter the core are repeatedly flushed out by sawteeth. In summary, it is found that sawteeth, impurities and temperature peaking can be controlled simultaneously by ICRH. Finally, the experiments showed that sawteeth are controlled with all ICRH antenna phasings, in contrast to high field side resonance experiments where only -90° phasing on the $q=1$ surface can control sawteeth. This result is particularly useful for H-mode ELMy operation in JET, which is optimised for dipole phasing.

The VENUS-LEVIS and SCENIC codes have been used to help to devise experiments, and then to interpret experimental data. SCENIC ICRH simulations helped to predict which ICRH scenarios would be able to control sawteeth. Dedicated SCENIC simulations were undertaken after experiments in order to compare modelling with experimental data. The results showed agreement with the recent experiments. In particular, it was shown that when the resonance is placed on the low field side of the device near $q=1$, all antenna phasings provide a fast ion destabilisation effect on the internal kink mode. This is in contrast to earlier modelling results which assumed high field side resonance, where again, in agreement with the experiments, only -90° phasing provides sawtooth control. Finally, the VENUS code has been used to support experiments into fast ion confinement in 3D JET plasmas. Particular attention has been given to NBI ion confinement during deployment of error field correction coils.

2.5.7 Plasma surface interactions in collaboration with the University of Basel

Investigations of the lifetime of potential mirror materials in linear plasma facility were carried out. Coated mirrors were exposed to H_2/Ar (10%) plasma in the Magnum-PSI linear plasma device. To summarize these experiments, it was shown that Mo mock ups of coated mirrors exposed in Magnum-PSI show a high diffuse

reflectivity after H₂, Ar plasma inducing an important decrease of the specular reflectivity. In case of thick Rh films, the exposure of the water cooled mock up to high flux of plasma beam ($3 \times 10^{23} \text{ m}^{-2} \text{ s}^{-1}$) generates a high stress in the film leading to a delamination. 1 μm Rh film mock-up show a decrease of the reflectivity only where the plasma beam heats the surface.

We also studied the possibility of in-situ cleaning of first mirrors in ITER by plasma technique by developing and testing a method in our laboratory and by assessing the feasibility of such technique for ITER at JET. Cleaning of Be, Be/D₂, BeO and Be/W deposited by magnetron sputtering, by Thermionic vacuum arc (TVA) and in PISCES-B with RF plasma using He or Ar (300-600eV) were performed successfully. Cleaning of JET-ILW mirrors (Rh and Mo) deposited with Be, W and Inconel elements with RF plasma using He or Ar (300-600eV) were performed successfully. Mo mirrors are oxidized after cleaning like before JET installation and after exposure. In contrast, Rh mirrors are not oxidized after cleaning. These results shows a promising efficiency of cleaning Be coated mirrors and a really step forward for ITER.

The effect of helium on the tungsten microstructure was investigated first by exposure to a radio frequency driven helium plasma with fluxes of the order of $1 \times 10^{19} \text{ m}^{-2} \text{ s}^{-1}$ and second by helium incorporation via magnetron sputtering. Roughening of the surface and the creation of pinholes were observed when exposing poly- and nano-crystalline tungsten samples to low-flux plasma. A coating process using an excess of helium besides argon in the process gas mixture leads to a porous thin film and a granular surface structure whereas gas mixture ratios of up to 50% He/Ar (in terms of their partial pressures) lead to a dense structure. The presence of helium in the deposited film was confirmed with glow-discharge optical emission spectroscopy and thermal desorption measurements. The latter revealed that the highest fraction of the embedded helium atoms desorb at approximately 1500K. Identical plasma treatments at various temperatures showed strongest modifications of the surface at 1500K, which is attributed to the massive activation of helium singly bond to a single vacancy inside the film.

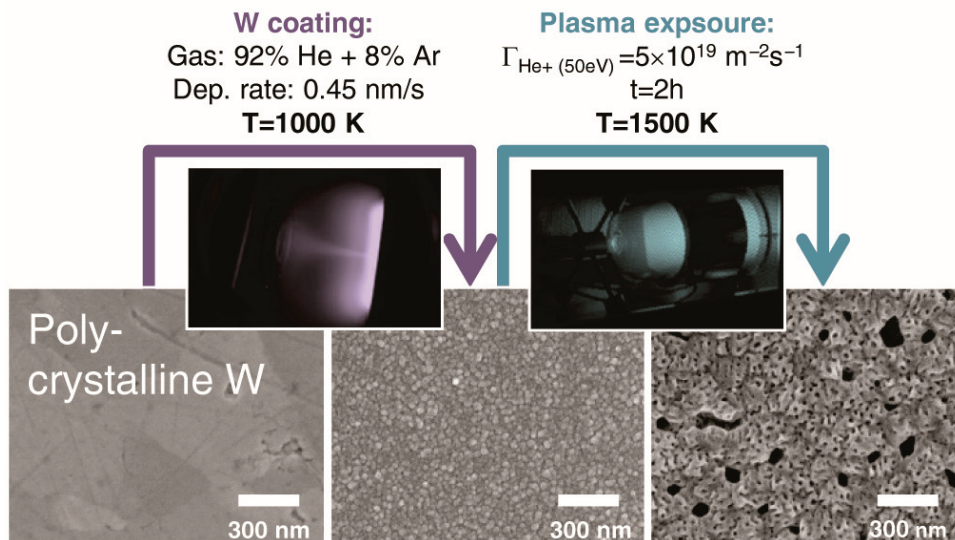


Fig. 2.5.5 Poly-crystalline W coated by W in an Ar/He gas mixture and after exposed to a He plasma at 1500K.

3 THE EDUCATIONAL ROLE OF THE CRPP

The CRPP 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 undergraduates 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), physics students 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 CRPP 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 CRPP supervises many PhD theses, also in the frame of the Physics Section of the EPFL. 4 PhDs were awarded in 2014. At the end of 2014 we had 28 PhD students supervised by CRPP members of staff, in Lausanne and at the PSI site in Villigen. Their work is summarised in Section 3.4.

3.1 *Undergraduate courses given by CRPP 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, fluid description and kinetic models are studied. The relation between plasma physics and developing a thermonuclear reactor is presented and illustrated with examples.

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.

P. Ricci, Assistant Professor – “*General physics II*”

This course is given to the STI Section. It provides an introduction to Lagrangian mechanics, 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.

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.

A. Fasoli, Professor and **I. Furno**, *Maître d'Enseignement et Recherche (MER)* and **A.A. Howling**, *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 **I. Furno**, *Maître d'Enseignement et Recherche (MER)* – *"Energy for Global Issues"*

M.Q. Tran, Professor - *"General Physics II and III"*

This course, given to the Mathematics Section, covers mechanics and thermodynamics (General Physics II) and hydrostatic, hydrodynamics waves and electromagnetism (General Physics III).

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.

3.2 Undergraduate work performed at the CRPP

EPFL Master students (4th year)

During the Spring semester of 2014, CRPP staff members have supervised 5 students performing their Advanced Physics Laboratory work and 4 ERASMUS students. During the Autumn semester of 2014, we had 6 students and 3 ERASMUS students.

3.3 EPFL Master degrees awarded in 2014

Genoud Jérémy, *"Self-consistent linear analysis of a gyrotron oscillator: spectral approach"*

Lanti Emmanuel, *"Shaping effects on tokamak scrape-off layer turbulence"*

Kleiner Andreas, *"Finite Toroidal Mode Number Ideal MHD Instabilities in Tokamak Plasmas with Externally Applied Magnetic Perturbations"*, ERASMUS Student

Manuel Cabete De Jesus Jorge Rogério "*Simulation of Plasma Blobs in Realistic Tokamak Geometry*", ERASMUS Student

3.4 *Postgraduate studies*

Postgraduate courses given in 2014

I. Furno, H. Reimerdes, B. Labit: "*Plasma diagnostics in basic plasma physics devices and tokamaks: from principles to practice*", Doctoral School, EPFL

H. Weisen, P. Blanchard, S. Coda, I. Furno: "*Plasma diagnostics*", Doctoral School, EPFL

W.A. Cooper, A. Fasoli, J.-M. Moret, P. Ricci, O. Sauter, D. Testa, M.Q. Tran, W. Vijvers: "*Magnetic confinement*", Doctoral School, EPFL

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

Doctorate degrees awarded during 2014

Gustavo CANAL: "*Sawtooth Generated Magnetic Islands and properties of the Snowflake divertor*" (EPFL Thesis Nr. 6272(2014))

The potential of nuclear fusion to provide a practically inexhaustible source of energy has motivated scientists to work towards developing nuclear fusion power plants. In this thesis, two outstanding issues encountered on the road to nuclear fusion power plants are addressed: triggering of neoclassical tearing modes (NTMs) by sawteeth (ST) and handling of the exhaust power in the divertor.

The experiments presented in this thesis were performed on the Tokamak à Configuration Variable (TCV), which is a medium sized tokamak that has been operational since 1992 at the CRPP/EPFL in Lausanne, Switzerland. TCV was designed to study the effects of plasma shape on the plasma behavior and, for this reason, features a highly elongated rectangular vacuum vessel and a full set of independently powered shaping coils. Another unique feature of TCV is a high power and current drive capability provided by a flexible electron cyclotron waves system, designed to access a wide range of plasma shapes. Furthermore, with its high degree of operational flexibility, TCV recently became one of the few machines able to test new divertor configurations without hardware modifications, e.g. the snowflake (SF) and the x-divertor.

The first issue addressed in this thesis is the seeding of NTMs by ST crashes. Many tokamaks observed that ST, of sufficient duration, may trigger NTMs that can lead to plasma performance degradation and/or disruptions depending on the plasma conditions. From constraints imposed on the plasma performance, the onset of NTMs poses a threat to the main goal of ITER, which is to demonstrate sustained burning plasma operation with a fusion power gain factor $Q \geq 10$. TCV's ability to accurately control the period of individual ST was exploited to examine the seeding mechanism of NTMs by ST for the purpose of finding routes to safer operation at higher plasma pressures. The electron cyclotron resonance heating and current drive (ECH and ECCD) system of TCV was used to trigger NTMs under controllable conditions and provided an excellent environment for the study of the NTM triggering by ST crashes. Results show evidence for an extremely fast formation of

seed islands with poloidal/toroidal mode numbers $m/n=3/2$ and $2/1$ within a few microseconds after a ST crash. ST with a longer period, were observed to generate larger seed islands but also increase the plasma stability to conventional tearing modes. These effects compete in TCV but the ST generated seed islands were sufficiently large to overcome the increased critical island width leading to an overall more NTM-susceptible plasma to higher period ST crashes. The ST generated seed island width was shown to be reduced and, thereby, the plasma stability improved, by increasing the value of the edge safety factor (q_{95}). Alternatively, the plasma stability to NTMs can be increased by applying preemptive ECH at the resonant surface of the NTM. Preemptive ECH is found to enlarge the plasma operational domain by improving the conventional tearing stability and by reducing the coupling between the driving ($m/n=1/1$ or $2/2$) and the driven modes ($m/n=2/1$ or $3/2$), resulting in smaller ST generated seed islands. This two-fold beneficial effect increases with ECH pulse duration and is more efficient when the pulse is closer to, but before, the ST crash. Since seed islands can be observed in the plasma with finite size within only a few tens of microseconds, strategies for NTM prevention in ITER cannot assume a slow rise of the mode amplitude. The results given in this thesis can be used for the development of new strategies for avoiding ST NTM triggering in ITER.

The second issue addressed in this thesis is the handling of the exhaust power in the divertor. In DEMO and future fusion power plants, the severity of the power handling in the divertor is substantially larger than that foreseen for ITER. Technological constraints on the exhaust properties of a conventional divertor configuration, require research and development of new divertor concepts for a successful fusion power plant based on the tokamak configuration. The SF is one of several magnetic divertor configurations that have emerged to solve this problem. In this work, some of its exhaust properties were investigated experimentally, where the properties of the SF are compared with those of a conventional divertor configuration, and the results interpreted using modeling. An analysis of the geometrical properties of the SF configuration shows that the TCV scrape-off layer (SOL) is not suited to demonstrate the exhaust performance of a reactor. However, it is an excellent device to investigate the underlying physics that determines the exhaust performance of a reactor with a SF divertor. Measurements of the power distribution among the four strike points (SPs) show that the SF- configuration forks one side of the SOL towards two divertor legs with the power largely following the magnetic field lines. Experiments with increased plasma density show that the conventional divertor configuration radiates about 10% more power than the SF, which is consistent with a slightly larger SOL volume of the conventional divertor compared with TCV's SF configuration. A comparison between measurements with simulations of particle, momentum and energy transport in the SOL using the EMC3-Eirene code shows that the observed fraction of the power distributed to secondary SPs in a SF+ configuration cannot be explained by changes in the field line geometry with constant transport coefficients, suggesting an additional cross-field transport channel in the null-point region. Additionally, diffusive cross-field transport is found to be insufficient to explain the observed double-peaked heat flux profiles. An analysis of the discrepancies between measurements and simulations reveals that neglecting $\vec{E} \times \vec{B}$ drift is a possible explanation. The influence of the $\vec{E} \times \vec{B}$ drift on the edge plasma transport in the SF was confirmed in experiments using a reversed toroidal magnetic field.

Lucia FEDERSPIEL: *"Rotation and Impurity Studies in the presence of MHD activity and Internal Transport Barriers on TCV" " (EPFL Thesis Nr. 6050(2014))*

This thesis focuses on measurements of toroidal rotation and impurity profiles in improved plasma scenarios and in the presence of MHD activity. These experiments were performed on TCV, the Tokamak à Configuration Variable in Lausanne. In TCV, plasma rotation is measured by the charge exchange recombination spectroscopy diagnostic (CXRS). The CXRS is associated with a low power diagnostic neutral beam injector (DNBI) that provides CX emission from the hot plasma core, without perturbing the plasma with additional torque. The beam is observed transversally by the CXRS diagnostic so that local ion temperature, density and intrinsic velocity measurements are obtained.

During this work, a pre-existing CXRS diagnostic was improved and automated. The three systems composing the present day CXRS2013 diagnostic cover the entire TCV radial midplane with up to 80 measurement locations separated by around 7mm with a time resolution ranging from 2-30ms. The main upgrades concerned the installation of new sensitive cameras, the overhaul of the toroidal HFS system, the extended-chord configuration and the automation of the acquisition and analysis processes. These new CXRS capabilities permitted the investigation of more complex scenarios featuring low intensity and/or fast events, like the low density electron internal transport barriers (eITBs) and the sawtooth (ST) instability discussed in this work.

For the first time, a comparison between rotation profiles measured over several sawtooth events and across a “canonical” sawtooth cycle has been undertaken in limited L-mode plasmas in this thesis, in order to identify the effect of the various ST phases on the rotation profile, and thus momentum transport. It is shown that the main ST effect on momentum is not simply a rotation profile flattening, as might be conjectured from their effect on electron temperature and density (consistent with a ST reconnection model), but results appear more complicated. The averaged rotation profiles obtained with the upgraded CXRS diagnostic show that ST restrict the maximum attainable $|v_{\phi, \max}|$ and that, in the plasma core, inside the $q=1$ surface, the rotation profiles are flattened and almost always display a small co-current contribution. It is this effect that results in the $1/I_p$ scaling observed in TCV limited L-mode plasmas. The co-current core contribution is identified to be related to the ST crash, whilst, during the quiescent ramp of the sawtooth period, a plasma recoil outside the mixing radius is observed. A high degree of momentum conservation, up to 80-90%, is measured, suggesting that a supplementary torque accompanying the ST crash is not required to explain the experimental observations. This study demonstrates the importance of including fast perturbing effects such as MHD modes in momentum transport models to build a complete picture, since they are likely to generate strong and rapid fluxes inside the plasma.

Extensive work on transport barriers has been performed to better understand the formation and characteristics of eITBs on TCV, using, for the first time, toroidal and poloidal rotation measurements. During this work, the poloidal rotation, E_r and the $E \times B$ shearing rate have been derived systematically from the asymmetry of the toroidal rotation measurements at the HFS and LFS. Since the position of the CXRS diagnostic view is at $Z=0\text{cm}$, two scenarios, a central barrier and a strong off-axis eITB, similar to previous targets investigated at $Z=21\text{cm}$, were developed to facilitate CXRS analysis during this thesis. The effect on the barrier strength and on the rotation profiles of several parameters, such as the central and total power, Ohmic current perturbations and MHD activity is investigated for both targets. The barrier strength increases with cnt-CD applied on axis, higher total power and negative Ohmic perturbations. Indeed, for the strong co-CD off-axis eITB, a barrier in T_e at 7keV and n_e with a 23cm barrier width, confinement factor $H_{\text{RLW}}= 5.4$ and $|R/L_{Te}|=45$ was achieved. No special dependence is found between the experimental $|\omega_{E \times B}| \propto 10^4 \text{s}^{-1}$ and the confinement factor H_{RLW} or the maximum $|R/L_{Te}|$, confirming that on TCV, the barrier improvement is not linked to $|\omega'_{E \times B}|$

values. The experimental E B shearing rates were compared with the growth rate of the most unstable mode for these discharges (TEM) obtained with the GENE code. The growth rate is found always one order of magnitude larger than the measured E B shearing rates, confirming that the E B shearing rate is not the cause of the formation of eITBs on TCV. This result supports previous theoretical studies concluding that the reversed shear profile is mainly responsible for the eITB formation. The comparison between the experimental ion temperature profiles and the results obtained with a quasi-linear model applied to TCV eITBs has shown some discrepancies. The $|R/L_{Ti}|/|R/L_{Te}|$ ratios measured at the barrier position are much lower than expected from the model, and no ion barrier is observed in these discharges. The installation of a new NB heating in 2015 will allow direct heating of the ion channel and may elucidate these discrepancies.

David MARTINET: *"Characterisation and modelling of nitrogen plasmas for the deposition of nanostructured GaN using different plasma sources" " (EPFL Thesis Nr. 6202(2014))*

This thesis presents an experimental investigation of RF and DC arc plasma sources used at low gas pressure (10^{-4} - 10^{-2} mbar), for the deposition of structured GaN layers directly on silicon wafer, in order to increase the growth rate and lower the costs. The aim is to characterise the nitrogen plasmas from both plasma sources, exhibiting different electron energy distribution functions (EEDF), and their influence on the plasma composition to increase the growth rate. Numerical simulations were developed to understand the underlying physics in such low pressure plasmas, and the predictions are compared to the experimental plasma parameters and composition.

Langmuir probe measurements were used to determine the EEDF in both plasma sources: a Maxwell distribution in the RF plasma source, and a Maxwell with an electron beam superposed in the DC plasma source, due to the accelerating voltage. The plasma composition, determined by means of optical emission spectroscopy, was found to be similar with the different plasma sources in the various configurations tested. The variation of the external parameters caused slight changes in the ratio of excited state densities, but no fundamental modifications were observed. Nevertheless the plasma density is sensitive to these changes and can vary from 10^{15} - 10^{17} m^{-3} . The admixture of Ga vapour in such plasmas does not affect the nitrogen composition and plasma density, as the fraction of Ga is very low, below 1%. The uniformity of the plasma is better than 5% with the RF plasma source, but worse than 10% with the DC plasma source. This is due to the electron beam penetrating into the chamber and being only slightly affected by the collisions. The current in the DC arc discharge and the use of magnetic field are the principal parameters which lead to a non-uniformity of the plasma which is directly linked to the deposition profile. The developed collisional-radiative model showed good agreement with the experiment in the electron temperature determination as well as in the plasma composition. The dominant reactions occurring in plasmas at low gas pressures have thus been identified.

In parallel to the plasma diagnostics, GaN layers were deposited and their morphology, uniformity and growth rates were correlated to the plasma parameters. The structure can be either 2D bulk layer or 3D nanocolumns with both plasma sources, depending on the density ratio of the N and Ga. The growth rates are dependent on the plasma density, which determines the density of atomic nitrogen. The typical growth rate using the RF plasma source is $1.5 \mu\text{m/h}$. The maximal growth rate reached with the DC plasma source is $6.9 \mu\text{m/h}$ showing a nanocolumnar shaped deposition, higher than with the typical MOCVD deposition technique ($\sim 4 \mu\text{m/h}$) or MBE systems ($\sim 2 \mu\text{m/h}$)

Annamaria MOSETTO: *"Turbulent regimes in the tokamak scrape-off layer"* (EPFL Thesis Nr. 6197(2014))

The tokamak scrape-off layer (SOL) is the plasma region characterized by open field lines that start and end on the vessel walls. The plasma dynamics in the SOL plays a crucial role in determining the overall performance of a tokamak, since it controls the plasma-wall interactions, being responsible of exhausting the tokamak power, it regulates the overall plasma confinement, and it governs the plasma refueling and the removal of fusion ashes. Scrape-off layer physics is intrinsically non-linear and characterized by phenomena that occur on a wide range of spatio-temporal scales. Free energy sources drive a number of unstable modes that develop into turbulence and lead to transport of particles and heat across the magnetic field lines. Depending on the driving instability, different SOL turbulent regimes can be identified. As the SOL turbulent regimes determine the plasma confinement properties and the SOL width (and, consequently, the power flux on the vessel wall, for example), it is of crucial importance to understand which turbulent regimes are active in the SOL, under which conditions they develop, and which are the main properties of the associated turbulent transport. In the present thesis we define the SOL turbulent regimes, and we provide a framework to identify them, given the operational SOL parameters. Our study is based on the drift-reduced Braginskii equations and it is focused on a limited tokamak SOL configuration. We first describe the main SOL linear instabilities, such as the inertial and resistive branches of the drift waves, the resistive, inertial and ideal branches of the ballooning modes, and the ion temperature gradient mode. Then, we find the SOL turbulent regimes depending on the instability driving turbulent transport, assuming that turbulence saturates when the radial gradient associated to the pressure fluctuations is comparable to the equilibrium one. Our methodology for the turbulent regime identification is supported by the analysis of non-linear turbulence simulations performed with the GBS code, a flux-driven, 3D code that solves the drift-reduced Braginskii equations without separation between background and fluctuations. We find that drift waves drive transport at low resistivity and negative magnetic shear, while ballooning modes dominate at high resistivity and positive magnetic shear. The ion temperature gradient instability plays a negligible role in the SOL dynamics, since the ion temperature gradient is generally below the threshold necessary for the development of this instability

Ph.D. Theses supervised by CRPP staff at the end of 2014

Himank ANAND: *"Exploration of candidate fusion reactor regimes by real time control of tokamak plasma shape"*

The majority of the work was devoted to the refinement, generalization and completion of the plasma shape control algorithm. A generalized position plus shape control algorithm was developed for advanced plasma configurations using the linearized plasma model RZIP.

Fabio AVINO: *"Turbulence at the boundary of toroidal plasmas with open and closed magnetic flux surfaces"*

Investigations of plasma fluctuations in advanced magnetic field geometries have been performed on the TORPEX device for the first time. In particular, the dynamics of quasi-coherent structures and isolated blobs have been explored in the presence of a single null X-point. Further studies with a magnetic snowflake are foreseen.

Alexandre BOVET: *"Suprathermal ion transport in TORPEX"*

We performed time-resolved measurements of the cross-field suprathermal ion transport in a toroidal magnetized turbulent plasma. Measurements in the superdiffusive regime are characterized by a higher intermittency than in the subdiffusive regime. Using conditional averaging, we show that, when the transport is superdiffusive, suprathermal ions are transported by intermittent field-elongated turbulent structures that are radially propagating

Falk BRAUNMUELLER: *"Nonstationary operating regimes in Gyrotron oscillators"*

The year 2014 was mainly dedicated for developing and benchmarking of a Particle-In-Cell version of the gyrotron code TWANG. This extension removes an important constraint of the model and is necessary for the simulation of non-stationary oscillation. It has been applied to study the effect of dynamic After-Cavity Interaction (ACI) and is being used for simulating non-stationary oscillation in the gyrotron for DNP-NMR spectroscopy. Furthermore, simulations for the development and analysis of several high-power gyrotrons (TCV upgrade, DEMO, 170GHz/1MW coaxial) have been performed.

Daniele BRUNETTI: *"MHD properties of hybrid tokamak and RFP plasma"*

This study showed that under particular conditions, due to mode coupling, fast growing resistive modes could develop leading to the formation, within a much faster time than the standard tearing mode timescale, of sizable magnetic islands. The growth rate of the linear theory of such instabilities, obtained from the dispersion relation which includes non-MHD effects such as bi-fluid effects and equilibrium toroidal sheared flows, has been successfully compared with numerical simulations, which qualitatively agree with theoretical predictions, performed with the XTOR-2F code (ideal and resistive), with the inclusion of plasma diamagnetism but with neoclassical effects switched off.

Nikolay BIKOVSKIY: *"HTS high current cable for fusion application"*

Fabrication of the first full-size prototype of the High Temperature Superconductivity (HTS) cable for fusion was successfully completed. During that process around 1.5 km of HTS tapes were used in order to realize the proposed design of the cable. All the intermediate validations of the process were carried out, which allows us to predict the cable performance for the coming low temperature-high magnetic field characterization step of the project.

Julien DOMINSKI: *"Development of an arbitrary wavelength solver in ORB5"*

The development of a new electrostatic field solver valid at arbitrary wavelength has been carried out, in order to replace the current solver only valid in the long wavelength approximation. The upgrade concerns the linear polarization drift contribution to the perturbed density.

Jonathan FAUSTIN: *"Self-consistent interaction of fast particles and ICRH waves in 3D applications of fusion plasma devices"*

A new antenna model was developed in the 3D full-wave code LEMan that allows the calculations of wave propagation generated by straps antennae used experimentally, e.g. in JET. In association with CADMOS, the SCENIC code was successfully run on a hybrid HPC architecture comprising both a high shared memory computer and a massively parallelized cluster. Preliminary ICRH

simulations with 3D Wendelstein 7-X equilibrium were performed and showed promising results.

Matteo FONTANA: *"ECE diagnostics for the study of high frequency broadband turbulence"*

Search for possible causes of high frequency Electron Cyclotron Emission (ECE) signals in low field plasmas characterized by long sawtooth modes and Electron Cyclotron Current Drive. Working on upgrade of High Field Side ECE radiometer.

Jérémy GENOUD: *"Advanced models for wave-particle interaction in gyrotrons"*

With the goal of getting a better understanding of new operational regimes in gyrotrons, a new model was developed. This model is based on a spectral approach to solve the linearized system of equations describing the self-consistent wave-particle interaction in the cavity of a gyrotron. Based on this model, a new code has been written. In addition, some experiments have been carried out with the DNP-gyrotron for comparing the theoretical prediction with the experiment.

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. The protection schemes were proposed where applicable, and the question of reliable quench detection system was addressed.

Zhouji HUANG: *"Experimental study of plasma turbulence in the TCV tokamak"*

The Tangential Phase Contrast Imaging (TPCI) experimental data from measurements performed in the TCV 2013 campaign were analyzed. Studies are focused on two specific areas: one is the dependence of broadband plasma density fluctuations on plasma shape, especially triangularity, radial position, and effective collisionality; the other is a further study of the GAMs on TCV, focusing in particular on the Geodesic Acoustic Modes (GAM) regime transition from dispersive mode to global eigenmode, and the turbulence drive and collisional damping of the GAM during density ramp-up.

Josef KAMLEITNER: *"Suprathermal electron studies in Tokamak plasmas by means of diagnostic measurements and modeling"*

After the publication of a comparative analysis of digital pulse processing methods at high count rates the focus was put on the Fokker-Planck codes LUKE and CQL3D. In comparison to experimental data from TCV original results on ECRH/CD physics including HXR emission asymmetries, RF wave scattering and anomalous suprathermal electron diffusion as well as on interaction of suprathermal electrons with MHD instabilities were obtained and summarized in the PhD thesis.

Doohyun KIM: *"Sawtooth control experiments in KSTAR and AUG"*

The sawtooth pacing and locking are a promising way to control sawtooth periods and the capability has been experimentally demonstrated in TCV plasmas. In KSTAR (2013) and AUG (2014) operation campaigns, we have tested the applicability of sawtooth locking for sawtooth period control. Full locking has not been demonstrated, however significant sawtooth control has been demonstrated and used in other experiments.

Andreas KLEINER: *"Non-linear and three dimensional modelling of pressure driven modes in tokamaks"*

A new infinite- n Ballooning mode solver is being developed for 3D equilibrium configurations. In addition, strong $m=1$ modes that can occur in the low shear regions of tokamaks and reverse field pinches have been obtained with the ANIMEC equilibrium code and the XTOR initial value stability code. This benchmarking has cleared the path for non-linear pressure driven instabilities to be modelled, including various non-MHD effects, and compared against experimental measurements.

Philip MALLON: *"Development of in-coil joints for NMR devices"*

Joints between high-temperature superconductor (HTS) tapes are often required during the winding of a layer-wound solenoid coil. Developing a low-resistance soldered bridge joint with advantageously oriented tapes is key to the performance of the solenoid. It has also been found that HTS tapes are sensitive to the temperatures experienced during joint soldering. Research in this area, and in the area of coil impregnation materials, has been initiated toward the goal of improving commercial scale manufacturing techniques.

Claudio MARINI: *"Poloidal passive CX plasma rotation diagnostic in TCV"*

The analysis of the Carbon transport across sawtooth events in TCV was refined and completed, and the results presented at the EPS 2014 and SPS conferences. The new diagnostics system (SYS4) for passive CX measurements is ready to be mounted on TCV and the software for the data analysis is under development.

Gabriele MERLO: *"Global gyrokinetic simulations of plasma microturbulence and validation against TCV experimental measurements"*

The hypothesis of a radially and shape dependent profile stiffness as a possible explanation of the enhanced confinement in TCV discharges with negative triangularity has been further investigated studying profile stiffness with respect to a variation of density gradient. For such study, nonlinear fluxtube gyrokinetic simulations using the GENE code have been carried out. First global GENE simulations have been performed as well, with the aim of reproducing the measured transport level in plasmas with both positive and negative triangularity. A significant transport reduction (because of finite machine size stabilization) compared to flux-tube results is found. An effort to model TCV discharge #45353, and reproduce the experimental GAM measurements, has been initiated.

Pedro MOLINA: *"IR camera measurements of heat loads in plasma-facing components"*

A review of the current IR systems at TCV was performed. MATLAB data analysis routines for processing IR imagery was reviewed, commented, and put in the SVN network. Research was performed in the future optics options available for the HIR system using CAD drawings of TCV in combination with the ray-tracing software WinLens.

Federico NESPOLI: *"Scrape Off Layer physics in different magnetic configurations in TCV"*

The work has been focused on the analysis of experimental data of TCV limited L-mode plasmas. The heat flux on the limiter is determined using infrared thermography. The resulting heat flux profiles exhibit a double scale length in the SOL. Langmuir probe data analysis and numerical simulations with the GBS code have been undertaken to have a better comprehension of the physics determining the double scale length.

Paola PARUTA: *"Advanced numerical algorithm for the simulation of the scrape off layer plasma turbulence"*

With the ultimate aim of studying scrape-off layer plasma turbulence in diverted configurations, we are investigating coordinates system not singular at the X point. This system of coordinates will be used to rewrite the drift-reduced Braginskii equations that are implemented in the GBS code.

Hamish PATTEN: *"Advanced modelling of Ion Cyclotron Resonance Heating in three dimensional configurations"*

Preparations are being made to extend the VENUS-LEVIS code to include particle trajectories that can cross last closed flux surfaces. Within the frame of this thesis project, it is hoped that the extension will enable more accurate modelling of ion cyclotron resonance heating where fast ion tails can occur near the edge of a fusion device.

David PFEFFERLE: *"Fast ion confinement in MHD configurations"*

An estimation of the spatial variation of the magnetic field was proposed, not only taking into account gradient and curvature terms but also the local shearing field-lines and parallel currents. This measure triggers the switching between guiding-centre and full-orbit equations in the orbit code VENUS-LEVIS. Two opposing approaches to include resonant magnetic perturbations (RMPs) in fast ion simulations were 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 interface between the MHD stability code MINERVA and VENUS-LEVIS was implemented in order to compute, via a delta-f PIC scheme, the non-adiabatic contribution to the MHD pressure tensor from supra-thermal populations. The mode structure, the frequency and the growth rate of the perturbations are modified due to resonances with the hot particles' bounce/transit motion and their toroidal precession drift.

Masuhudan RAGHUNATAN: *"Guiding-centre particle orbits for 3D equilibria with rotation"*

We aimed to study particle orbits, especially those of fast-particles, for a MAST-like tokamak plasma with strong toroidal flow. A significant part of this work required the inclusion of the higher-order electric field and the lower-order quasi-neutrality restoring electric field. The orbits were studied using VENUS-LEVIS, the orbit-following code. A particular focus was given on the study of orbit behaviour for a MAST-like equilibrium with a helical core, with and without toroidal flow.

Fabio RIVA: *"Verification and Validation of SOL plasma turbulence codes"*

A considerable effort has been made in the past years by the plasma physics community to increase the understanding of the plasma dynamics in the Scrape-Off-Layer (SOL), with a particular focus on developing numerical codes able to perform fully turbulence simulations of this region. In order to increase the reliability of the results obtained from these codes, several seeded blob simulations have been done with different codes, and the numerical results have been validated against experimental data provided from the TORPEX device. Moreover, a 2D PIC code has been optimized, in order to provide a powerful tool useful for the study of the plasma dynamics in the proximity of a biased wall.

Joyeeta SINHA: *"Improvement of the plasma formation and its application for the doublet shaped plasma creation on TCV"*

Mismatch in I_p ramp rate leading to strong oscillations in I_p was identified as the main reason for failures during the plasma formation in TCV. A 'bump-less transfer' control technique for the I_p feedback control was proposed to reduce the resulting controller oscillations in I_p whilst maintaining a higher proportional gain. The bump-less transfer control technique was numerically shown to reduce the amplitude of the I_p oscillations.

From the modelling of the plasma evolution during the plasma burn-through and plasma current ramp-up phases, it has been concluded that it is necessary to include the ionization states of the impurities in the model to understand the physics associated with all the breakdown phases.

Anna TEPLUKHINA: *"The RAPTOR code development"*

The RAPTOR transport model has been extended to include time-varying terms, in particular including a time derivative of the magnetic field. Reconstruction of the RAPTOR intrinsic functions responsible for the processing of the equilibrium data allows now to take into account a time evolution of the plasma shape and other parameters necessary for equilibrium reconstruction. Comparisons with ASTRA results have been used to validate the modifications.

Christoph WERSAL: *"The interaction between neutral particles and turbulent plasma in the tokamak scrape-off layer"*

During the last year, the development of the neutral model that is coupled to the drift reduced Braginskii equations to simulate the interaction of the neutrals with scrape-off layer plasma turbulence has been finalized. The model has been implemented in the GBS code. In particular, advanced boundary conditions for the neutral particles, i.e. a mixture of reflected and absorbed particles at the boundaries, have been developed. By performing parameter scans, the transition between different scrape-off layer regimes has been found. Simulations have shown the typical signature of the conduction limited regime, e.g. significant parallel temperature gradients, which will be investigated further in the coming year.

4 PUBLIC RELATION ACTIVITIES IN 2014

A projection space equipped with a large 3D screen was created in the TCV building to present slide shows and movies to the public.

A 9-page popularization paper was published in the Bulletin 'Electro-Suisse'.

Two days of 'Open Doors' were organised at TCV in the frame of the FIFEL (Festival International du Film de l'Energie de Lausanne).

CRPP participated in the 'Nuit de la Science' a large science festival that took place in Geneva.

Several articles were published in different newspaper in Switzerland.

A few radio interviews were broadcast.

More than 2500 people visited the CRPP.

5 FUSION & INDUSTRY RELATION

The Swiss industry benefits from the services of an Industry Liaison Officer to facilitate procurement opportunities that are arising from the construction of the ITER Experimental Fusion Reactor. The official submissions to which the Swiss industry is invited to apply are issued either from the European Domestic Agency (Fusion for Energy, in short F4E) seated in Barcelona, or directly from the ITER Organization in France.

The major achievement for the Swiss Industry in 2014 was the award to VAT Vakuumventile AG in Haag (SG) of the “*Framework Contract – Standardised All Metal Vacuum Valves*”. This contract implies that each metallic valve to be integrated in an ITER system must be purchased from VAT. VAT has also been awarded in 2014 the contract to design and produce the largest ever manufactured metallic valve with a nominal bore dimension of 1600mm (approximately five times bigger than the existing products). This so-called Absolute Valve will ensure tightness between the Tokamak vacuum chamber and the Neutral Beam Injectors, one of the main ITER heating systems.

Another important achievement was that of SMARTEC in Manno (TI), which won – after several years of R&D study contracts, the final contract for the production of hundreds of sensor devices measuring the dimensional stability of the superconductor magnets in Helium cooled cryogenic environment.

On the side of international marketing actions, the main focus was given to the Swiss Industry promotion booth during the SOFT (Symposium On Fusion Technologies) Conference in San Sebastian, Spain, in September 2014, in order to increase the visibility of the ITER tender activity for Swiss participants and to raise awareness among ITER senior engineering managers of the specific technological competences of Switzerland with regard to the ITER project.

APPENDICES

APPENDIX A Articles published in Refereed Scientific Reviews during 2014

(see CRPP archives at <http://crppwww.epfl.ch/archives>)

M.J. Aliaga, A. Prokhodtseva, R. Schaeublin, M.J. Caturla, *Molecular Dynamics Simulations of Irradiation of Alpha-Fe Thin Films with Energetic Fe Ions under Channeling Conditions*, Journal of Nuclear Materials **452**, 453-456 (2014).

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APPENDIX B Conferences and Seminars

(see CRPP archives at <http://crppwww.epfl.ch/archives>)

B.1 Conference and conference Proceedings published in 2014

H. Anand, J.M. Moret, F. Felici, S. Coda, H. Le, *First Experimental Results of Plasma Shape Control Using Real Time Equilibrium Reconstruction in TCV*, 41st European Physical Society Conference on Plasma Physics, Berlin, 23-27 June 2014, Proceedings 41st EPS Conference on Plasma Physics, Berlin, Germany, 23-27 June 2014, P5.069 (2014).

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T.M. Tran, N. Aiba, *An Approximate Single Fluid 3-Dimensional Magnetohydrodynamic Equilibrium Model with Toroidal Flow*, Plasma Physics and Controlled Fusion 56 (9), 094004 (2014).

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S.Y. Medvedev, A.A. Ivanov, A.A. Martynov, Y.Y. Poshekhonov, M. Kikuchi, A. Pochelon, H. Reimerdes, O. Sauter, L. Villard, *Stability Limits for Tokamak Plasma with Negative Triangularity*, 41st EPS Conference on Plasma Physics, Berlin, June 23-27, 2014, Europhysics Conference Abstracts **38F**, P4.039 (2014).

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P. Spaetig, Y. Yamamoto, G.R. Odette, N. Ilchuk, *Assessing Some Effects of Irradiation on the Yield and Post-Yield Constitutive Properties of Structural Alloys for Nuclear Energy Applications (Key Note Lecture)*, Symposium International Plasticity 2014, Bahamas, January 3-8, 2014 (2014).

B. Tal, B. Labit, D. Nagy, B. Duval, G. Veres, TCV Team, *Plasma Radiation Dynamics with the Upgrade Axuv Tomographical System in the TCV Tokamak*, 41st European Physical Society Conference on Plasma Physics, Berlin, Germany, 23-27 June, 2014, Europhysics Conference Abstracts **38**, P5.058 (2014).

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C. Wahlberg, J.P. Graves, *Global Structure and Magnetic Components of Geodesic Acoustic Modes in Shaped Tokamak Plasmas*, 41st European Physical Society Conference on Plasma Physics, Berlin, 23-27 June 2014, Proceedings 41st EPS Conference on Plasma Physics, P2.047 (2014).

B.2 Seminars presented at the CRPP in 2014

Dr. G. Zimbardo, Università della Calabria, Dipartimento di Fisica, Ponte P. Bucci, Cubo 31C 87036 Rende CS, I, *"Superdiffusive transport in space and laboratory plasmas"*

S. Pasquier, Bibliothécaire de liaison en Physique/Astrophysique, Bibliothèque EPFL, *"The EPFL library resources"*

Dr. J.-P. Hogge, CRPP-EPFL, *"Gyrotron development for ITER: status, scientific and technological challenges "*

Dr. E. Serre, Université Aix-Marseille, Marseille, F *"A simulation effort of turbulent transport in the edge and SOL plasma of tokamaks"*

A. Dupré, EPFL, *"Personal experience in simulation of neutronic transport with state-of-the-art MCNPX code"*

Dr. B. Lipschultz, University of York, UK, *"The divertor exhaust problem and potential solutions"*

Dr. P. Geelen, Eindhoven University of Technology, NL, *"Improving the predictions of a control-oriented tokamak profile evolution model"*

M. Cutforth, Univ. of Cambridge; Corpus Christi College, Cambridge, UK, *"Fixed-Grid Interface Tracking Methods in Computational Fluid Dynamics"*

Prof. P. Beyer, Université d'Aix Marseille, France, *"3D turbulence simulations of edge transport barrier dynamics and resonant magnetic perturbations"*

Prof. P. Sonato, Consorzio RFX, Univ. Padova, I, *"The Neutral Beam Injectors from present experiments to ITER and the step forward to DEMO"*

Dr. N. Loureiro, Instituto Superior Técnico Lisbon, Portugal, *"Magnetic reconnection via stochastic plasmoid chains"*

Dr. A. Adelman & Dr L. Stingelin, Paul Scherrer Institut - Villigen, CH, *"Multipacting and Plasma Disturbance Effects in the PSI High Intensity Ringcyclotron"*

Prof. J.P. Allain, University of Illinois at Urbana-Champaign Urbana, IL, *"Challenges and innovation for tungsten-based plasma-facing materials in future burning plasma tokamak environments"*

Prof F. Skiff, University of Iowa, *"Measurement of the linear response of fast electrons to Alfvén waves using whistler-mode absorption"*

Dr A. Diallo, Princeton Plasma Physics Laboratory, *"Relationship Between the Pedestal Recovery and Edge Fluctuations"*

Dr. A.W. Leonard, General Atomics San Diego, US, *"Edge Localized Modes (ELMs) in Tokamaks"*

Dr. L. Delgado-Aparicio, Princeton Plasma Physics Laboratory, *"Destabilization of Internal Kink by Suprathermal Electron Pressure"*

Dr. A. Pflug, Fraunhofer Institute for Surface Engineering and Thin Films Braunschweig, Germany, *"Simulation of particle transport and plasma discharges under rarefied flow conditions"*

A. Malygin, KIT- Institute for Pulsed Power and Microwave Technology, Eggenstein-Leopoldshafen, Germany, *"Some aspects of experimental and theoretical investigations of a 400kV/150A/30GHz pulsed relativistic gyrokystron and a 20kW/28GHz CW 2nd harmonic gyrotron"*

Dr. A. Mariani, Universita degli Studi di Milano, I, *"Wave energy flux and absorption of Electron Cyclotron Gaussian beams in tokamak plasmas"*

Prof. V. Naulin, Plasma Physics and Fusion Energy, Technical University of Denmark, Lyngby, DK, *"How structures help to win or lose the battle for fusion energy"*

M. Fontana, Politecnico di Milano, I, *"Propagation of visible light in hierarchical nanostructured materials for advanced photovoltaic applications"*

G. Canal, CRPP-EPFL, *"Sawtooth generated magnetic islands and the properties of the snowflake divertor"*

A. Masetto, EPFL-CRPP), *"Turbulent regimes in the tokamak scrape-off layer"*

J. Genoud, Etudiant EPFL, *"Self-consistent linear analysis of a gyrotron oscillator: spectral approach"*

O. Chellai, SUPELEC, Gif-sur-Yvette, F, *"RF scattering by turbulent structures in the TORPEX Plasma"*

M. Griener, Ulm University, Germany, *"Optical transport and evaporation to a degenerate Fermi gas"*

Dr. T. Nicolas, National Institute for Fusion Science, Japan, *"Two-fluid effects on MHD instabilities in tokamak and heliotron plasmas"*

M. Tatari, EPFL-STI-IGM-RRL, *"Automotive Body Concept Modelling Method for the NVH Performance Optimization"*

Dr. T. Donné – EUROfusion Programme Manager, **Dr. X. Litaudon** – Head of the ITER Physics Department, **Dr. L. Horton** - JET Exploitation Manager: *"JET Science Meeting on EUROfusion Consortium and Organisation"* (Videoconference)

H. Patten, University of York, UK, *"The Coupling of Neoclassical Tearing Modes with Resistive Wall Modes in Rotating Tokamak Plasma's"*

S. Cristofaro, University of Padua, Padova, Italy, *"Characterisation of the BATMAN beam properties by H-Doppler shift spectroscopy and mini-STRIKE calorimeter"*

A. Kleiner, Technische Universität Darmstadt, D, *"Finite Toroidal Mode Number Ideal MHD Instabilities in Tokamak Plasmas with Externally Applied Magnetic Perturbations"*

Dr. N. Aiba, Japan Atomic Energy Agency, J, *"Excitation of flow-stabilized resistive wall mode in rotating tokamak plasmas"*

Dr. B. Teaca, Coventry University, UK, *"The impact of the magnetic geometry on the energetic coupling of scales in gyrokinetic turbulence"*

Dr. N. Vianello, Consorzio RFX, C.so Stati Uniti 4, Padova, Italy, *"Turbulence and its interaction with magnetic topology"*

Dr. C. Tsui, EPFL-CRPP, visiting from UCSD, San Diego, USA, *"Measuring the inboard side scrape-off layer of DIII-D plasmas using Swing-Probes, Accounting for Sheath Expansion in Langmuir Probe Analyses without a 4th Parameter, and the DIII-D Inner-Wall-Limiter Heat Flux Experiment"*

Th. Richard, ISAE-Supaero, Toulouse, F, *"Numerical analysis of simplified kinetic model for ozone production in surface dielectric barrier discharge plasma actuators"*

E. Lanti, Etudiant EPFL, *"Shaping Effects on the Tokamak Scrape-off Layer Turbulence"*

R. Jorge, IPFN – IST, Lisboa, Portugal, *"Simulation of SOL turbulence in the ISTTOK tokamak"*

Prof. F. Romanelli, EFDA Leader and EFDA Associate Leader for JET, UK, *"The Fusion Roadmap and the challenges of the ITER era" (videoconference)*

Th. Blanken, TU Eindhoven/DIFFER, NL, *"Model-based reconstruction and feedback control of the density profile in a tokamak"*

I. Arapoglou, CIEMAT, Spain, *"A hydrogen pellet injector for the TJ-II stellarator: Testing, modelling and first experiments"*

M. Messmer, Technische Universität Dresden, D, *"Laser guiding through Capillary Discharge Plasma Channels"*

Dr. H. Weisen, JET, UK (permanent address: CRPP-EPFL), *"The 'neutron deficit' in JET"*

APPENDIX C External activities of CRPP Staff during 2014

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 International Tokamak Physics Activities: Energetic Particles Topical Group Expert for the Review of projects submitted to the French National Agency for Research (ANR) International Scientific Committee for the French Laboratory of Excellence in Plasma Science Chair of Fusernet Academic Council French National Research Agency review Scientific Council of PLAS@PAR, joint plasma initiative across all Universities in Paris, France Scientific Board of the Helmutz Virtual Institute on Advanced Microwave Diagnostics Euratom Programme Committee IAE Fusion Power Coordinating Committee Swiss expert to the Governing Board of F4E
O. Sauter	International Tokamak Physics Activities: MHD, Disruption and Control Topical Group Co-chair Varenna-Lausanne International Theory Conference
M.Q. Tran	Swiss expert to the Governing Board of F4E Member of the Core Commission for nomination of Max-Planck for Plasma Physics 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
L. Villard	Member, Board of the High Performance Computing for Fusion, Eurofusion Special working group 1 of the IFERC-CSC 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
S. Coda	Editorial Board of Plasma Physics and Controlled Fusion
A. Fasoli	Associate Editor of the Journal of Plasma Physics Editor in Chief of Nuclear 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 Direction de la Faculté FSB Comité de Coordination Joint Doctoral Initiative EPFL-IST Lisbon
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

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:

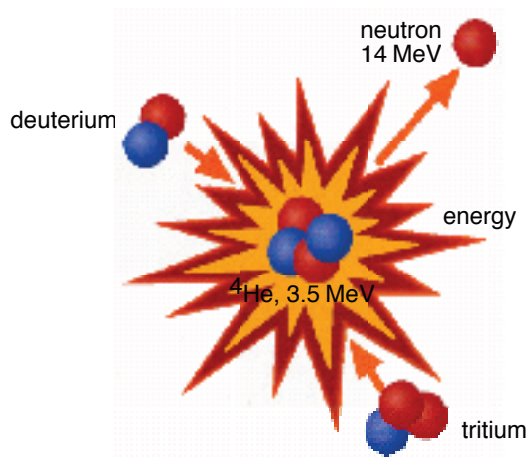
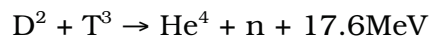
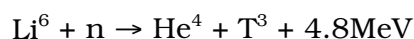


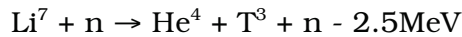
Fig. D.1 *Schematic of a fusion reaction between deuterium and tritium nuclei. The products are 3.5MeV ^4He , the common isotope of helium, and a 14MeV free neutron.*

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:





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 2014, the work carried out at the CRPP 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 Federal Department of Home Affairs (FDHA) in the frame of the Broader Approach activities in the field of fusion energy research
- 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-Zentrum Berlin (HZB), Germany
- Helmholtz Association of German Research Centres (HGF), Germany
- The Lawrence Livermore National Laboratory (LLNL), USA
- The European Space Agency (ESA), Paris, France

Private organisations

- RUAG Space, Nyon
- Oerlikon Metco AG, Wohlen
- TEL Solar, Trübbach, subsidiary of Tokyo Electron Ltd.
- Tetra Pak Suisse SA, Romont