CRPP

Centre de Recherches en Physique des Plasmas
Faculté des Sciences de Base
Association EURATOM - Confédération Suisse

École Polytechnique Fédérale de Lausanne

Annual Report

2013

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Preface

The year of 2013 was a year of transition for the European fusion program. It was the last year of the 7th Framework Programme for Research and Development (FP7) in which the transition to 2020 was organized. The challenge for the Centre for Research in Plasma Physics (CRPP) was to both fulfill its commitments to FP7, and to prepare and actively commit to Horizon 2020. The latter, as should be apparent in this report, is a high priority: CRPP members have contributed significantly to the establishment of the new Euratom-Fusion program (establishment of the consortium of European laboratories called "EUROfusion," organisation of the scientific preparation of European projects for the period 2014-2018, and internal planning of activities at CRPP).
In addition to this effort, 2013 was also marked by the launch of the first upgrade to TCV: a neutral beam injection system which will be operational in 2015. The two main challenges were conducted successfully thanks to the unwavering commitment of all employees of the CRPP. The start of the heating system by neutral beams in 2015 will coincide with the sharing of the TCV scientific exploitation by members of EUROfusion.
All scientific achievements described in this report, and all the administrative work and planning for EUROfusion, were only possible by virtue of the commitment of all colleagues of the CRPP, and the support of many public and private organisations. We would like to take this opportunity to express our sincere thanks.

Prof. A. Fasoli Prof. M.Q. Tran

Préface

L'année 2013 fut une année de transition pour le programme européen de fusion: ce fut la dernière année du 7ème Programme cadre de Recherche et Développement (7e PCRD) durant laquelle la transition vers Horizon 2020 fut organisée. Le défi pour le Centre de Recherches en Physique des Plasmas (CRPP) fut de mener de front ses activités comme envisagées dans le 7ème PCRD ainsi que dans les planifications suisses, et une préparation active de son engagement dans Horizon 2020. Cette dernière, si elle peut ne pas être apparente dans un rapport scientifique, n'en est pas moins importante: les membres du CRPP ont contribué à l'établissement du cadre organisationnel du nouveau programme Euratom-Fusion (établissement du consortium des laboratoires européens appelé "EUROfusion", à la préparation scientifique des projets européens pour la période 2014-2018, et à la planification interne des activités du CRPP).
A côté de cet engagement, 2013 a aussi été marqué par le lancement du premier projet d'amélioration de TCV, l'implémentation du système de chauffage par injection de faisceau de neutres, système qui sera opérationnel en 2015. Ces deux grands défis furent menés avec succès grâce à l'engagement sans faille de tous les collaborateurs du CRPP. La mise en marche du système de chauffage par faisceau de neutres en 2015 coïncidera avec l'utilisation de TCV par les membres d'EUROfusion.
Toutes les réussites scientifiques décrites dans ce rapport, tout le travail administratif et de planifications en vue d'EUROfusion ne furent possibles que grâce à l'engagement de tous les collègues du CRPP et au soutien de nombreux organismes publics et privés. Nous tennons à leur exprimer ici nos remerciements les plus sincères.

Prof. A. Fasoli Prof. M.Q. Tran

Vorwort

Das Jahr 2013 ist ein Übergangsjahr für das Europäische Fusionsprogramm gewesen, in dem, als letztes Jahr des 7. Rahmenprogramms für Forschung und Entwicklung (RP7), der Übergang zu Horizon 2020 organisiert wurde. Die Herausforderung für die Forschungsstelle für Plasmaphysik (CRPP) war, sowohl seine Tätigkeit gemäß RP7 und der Schweizer Planung fortzuführen, als auch das Engagement in Horizon 2020 vorzubereiten. Während diese Vorbereitungsarbeit nicht offensichtlich zu einem wissenschaftlichen Bericht beiträgt, ist sie nicht weniger wichtig: CRPP Mitarbeiter haben an der Erschaffung des organisatorischen Rahmens des neuen Euratom-Fusion Forschungsprogramms mitgewirkt (Gründung des Konsortiums europäischer Forschungsinstitute namens "EUROfusion", wissenschaftliche Vorbereitung europäischer Projekte für den Zeitraum 2014-2018 und interne Planung der CRPP Aktivitäten).
Zusätzlich zum Engagement in Horizon 2020 markiert 2013 auch den Beginn des ersten TCV Erweiterungsprojekts, die Einrichtung einer Neutralteilchenheizung, die 2015 ihren Betrieb aufnehmen wird. Diese beiden wichtigen Herausforderungen wurden dank dem unermüdlichen Einsatz aller Mitarbeiter des CRPP erfolgreich durchgeführt. Mit der Inbetriebnahme der Neutralteilchenheizung im Jahr 2015 wird auch die Nutzung von TCV durch die Mitglieder des EUROfusion Konsortiums beginnen.
Alle in diesem Bericht beschriebenen wissenschaftlichen Ergebnisse und die ganze Verwaltungsarbeit und Planung in Hinsicht auf EUROfusion waren nur dank des Engagements aller Kolleginnen und Kollegen des CRPP und der Unterstützung von vielen öffentlichen und privaten Organisationen möglich. Wir möchten hier unseren aufrichtigen Dank aussprechen.

Prof. A. Fasoli | Prof. M.Q. Tran

Prefazione

L'anno 2013 è stato caratterizzato da una transizione nel programma europeo di fusione. Si è trattato dell'ultimo anno del settimo Programma Quadro di Ricerca e Sviluppo, durante il quale è stata preparata la fase successiva, denominata Orizzonte 2020. La sfida per il Centro di Ricerche in Fisica dei Plasmi (CRPP) è consistita appunto nel continuare a condurre le attività di ricerca previste nel settimo Programma Quadro e nella pianificazione a livello nazionale, ed al tempo stesso nel predisporre il suo impegno in Orizzonte 2020. Questo lavoro di posizionamento è poco apparente in un rapporto scientifico, ma è stato di grande importanza. Membri del CRPP hanno contribuito alla definizione del nuovo programma di fusione dell'Euratom, sia dal punto di vista organizzativo che da quello scientifico e strategico, in particolare per il periodo 2014-2018.

In parallelo con questi cambiamenti strutturali, il 2013 ha visto il lancio del primo progetto di 'upgrade' del tokamak TCV, che consiste nell'installazione di un sistema di un fascio di neutri per il riscaldamento degli ioni del plasma. Tale sistema sarà operativo nella seconda parte del 2015, periodo in cui TCV sarà per la prima volta operato come esperimento internazionale nell'ambito del consorzio Eurofusion.

Il successo conseguito in queste sfide organizzative e tecniche, e gli importanti risultati scientifici riportati in questo rapporto sono stati ottenuti grazie all'impegno indefesso e alla grande professionalità di tutti i collaboratori del CRPP, ed al supporto continuo di numerosi organismi pubblici e privati, ai quali va tutta la nostra gratitudine.

Prof. A. Fasoli   Prof. M.Q. Tran

1 INTRODUCTION

1.1 The international frame and its relation to the Swiss Programme

The Euratom framework and ITER are the two most important elements that have a direct impact on the Swiss Programme. 2013 is the last year of the 7th Euratom Framework Programme for Research and Development. The following EU Framework Programme, called Horizon 2020, which also includes Euratom fusion, was finalised and approved in 2013 bringing profound changes. The workplan for the period 2014-2020 will be based on the European Fusion Roadmap ("EFDA Roadmap to the realisation of fusion energy"), which was discussed in depth within the European community in 2012. The Roadmap aims towards the realisation of a demonstration fusion power plant, DEMO, by 2050. To achieve this goal, a set of physics and technology missions were identified and translated into goal-oriented work packages. The Roadmap also recognizes the importance of a vibrant fusion programme to maintain a strong enabling research and an active programme in support of education and training.

A novel structure will be formed to implement the Roadmap. The Research Units of the Member States and Associated State (Switzerland) will cooperate to the implementation of the activities in the frame of the Roadmap under the umbrella of a consortium named "EUROfusion". Euratom will then sign a multi-annual Grant Agreement with EUROfusion. Both the multi-annual workplan 2014-2018, the 2014 workprogamme and the general structure of the consortium EUROfusion were discussed in details in 2013, thus allowing the submission to Euratom of the proposal for the Horizon 2020 Fusion activities. It is foreseen that the formal signature of the Grant Agreement and the EUROfusion Consortium Agreement will take place in 2014.

In parallel with the scientific activities which will be described in the following Annual Report, the CRPP staff was heavily engaged in the preparation of scientific and managerial matters related to the establishment of EUROfusion. Let us mention the discussion on the rules of the consortium, the preparation of proposals for the scientific programmes for 2014, the submission of applications for key leading positions. Globally speaking, the proposals from the CRPP were very positively evaluated. Three staff members of the laboratory were selected, two as Project Leaders and one as Deputy Project Leader. One post-doctoral researcher of the CRPP was also awarded a EUROfusion fellowship. In brief the scientific excellence of the CRPP continues to be recognized and highly prized by the fusion community.

ITER continues to be the second focal point of the activities of the CRPP as it is described in the Annual Report. On the level of the project itself, management of ITER continued to be the main issue. The ITER Parties have requested ITER Organisation to prepare a realistic planning, which will be submitted in 2015.

1.2 Introduction to the Annual Report 2013

As compared to previous years, we have drastically changed the format of the Annual Report, rendering it easier to read while maintaining the quality of the presentation of the scientific contents. The scope of activities were the same as in the past, except in the field of Material Science and Technology where we had to terminate our research activities in 2013 for financial reasons.

Looking towards the future, in 2013 we have started the first phase of the upgrades of the TCV tokamak by launching the procurement of the 1MW neutral beam heating system and the necessary modifications of the TCV vacuum chamber. This important upgrade will be ready in 2015, in time for the scientific exploitation of TCV in the frame of EUROfusion. The second phase of the upgrade (2MW of electron cyclotron wave) will be launched in 2015.

2 PROGRESS REPORT

2.1 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.

Improving understanding and control capabilities of burning plasmas is a major scientific challenge of the experimental program 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 Electron Cyclotron Heating (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 (2014), and will continue with the development and installation of two additional 1MW-2s microwave heating EC systems reaching the 3rd harmonic frequency range (~120GHz) (2015-2017). The NBH and X3-upgrade are planned to be operational by mid 2015 and end of 2018, respectively.

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.

2.1.1 TCV – Tokamak operation and scientific highlights

The TCV tokamak was operated very intensively during 2013, in view of an extended shutdown in 2014 for the modification of the vessel to accommodate neutral beam heating, the first phase of our auxiliary heating upgrades. In particular, we increased the operation hours by 40% for the six final weeks, with a large number of parallel experiments.

A new high-confinement mode, dubbed IN-mode, was discovered, featuring L-mode-like temperature profiles but large edge density gradients. A global H-mode-like confinement is thus obtained without deleterious transient MHD events and potentially leading to high reactivity in a reactor (Fig. 2.1.1). A measurement campaign was carried out on this and a variety of other regimes, targeting specifically the outermost 10% of the kinetic profiles with high spatial resolution. The gradients in this region are found to be regime-dependent and not “stiff”, and appear to govern the scaling of global confinement with a number of variables, including current and power. This may potentially explain the confinement enhancement observed in negative-triangularity plasmas. The modification of plasma confinement in the proximity of the density limit was also investigated. In this study, density limits close to the Greenwald value were reached by sawtooth regularization with ECH, accompanied however by a reduction in confinement.

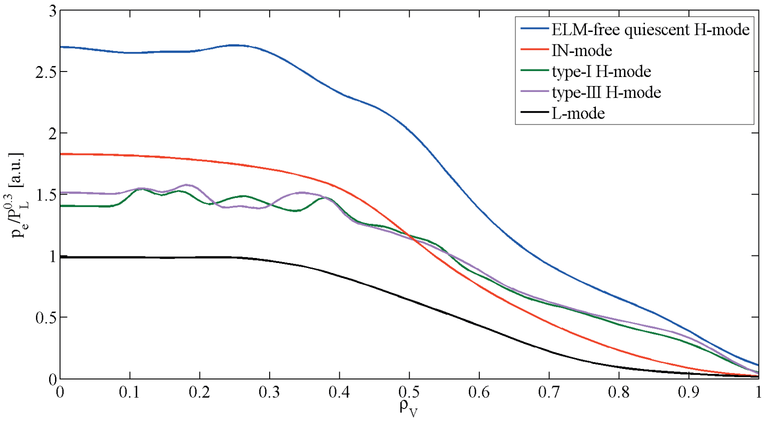

Fig. 2.1.1 *Electron pressure profiles for the IN-mode and several reference regimes, normalized to the input power with an exponent that accounts for the L-mode power scaling of the confinement time (τ_E~$P^{-0.7}$), to illustrate the intrinsic confinement quality.*

An indirect method to measure the poloidal flow velocity of impurities with enhanced accuracy through spatially resolved toroidal velocity measurements, which relies on fluid incompressibility, was tested recently for the first time on TCV. More extensive measurements were carried out in the 2013 campaign in a range of scenarios to compare systematically the measured flow with neoclassical predictions. Poloidal asymmetries in the impurity density were also revealed and are currently being analyzed and compared to theory. The shaping flexibility of TCV was exploited to perform a timely test of a new theoretical prediction of a toroidal rotation component at the plasma edge driven by inhomogeneous transport and geodesic curvature. Initial results appear to vindicate the theory’s prediction of a rotation sign reversal for an X-point shift towards the low-field side.

In a demonstration of how control techniques developed initially for performance enhancement can be applied to diagnostic goals, the effect of sawtooth oscillations on momentum transport was studied with greater effective time resolution than ever before, using coherent averaging over a large number of sawteeth whose period was locked to modulated ECH deposited near the q=1 surface.

A number of studies have addressed questions related to the power requirements for reaching H-mode in varying plasma conditions. The dependence on the main species is particularly relevant to the initial phase of ITER. Measurements in TCV indicate that the L-H transition threshold power is approximately 15-20% higher in both H and He than in D. A strong increasing dependence of the power threshold on the length of the outer separatrix was also evinced. No appreciable effect was observed, by contrast, of the current ramp rate; this study will however be repeated in more reactor-relevant conditions once auxiliary ion-heating power will be available.

Advanced-tokamak regimes have continued to garner our attention. Electron internal transport barriers were revisited to exploit the availability of high-quality charge-exchange recombination measurements of ion properties. In these low-density scenarios with negligible ion heating, no significant barrier is seen in the ion temperature profile. A thorough documentation of the radial electric field behaviour during the barrier formation has now been assembled, showing that ExB shearing is not responsible for the eITB. We have also revisited our steady-state scenarios without current injection, in which the current is driven entirely by the bootstrap effect. As an additional demonstration of the robustness of the effect, we were able to steadily recharge the transformer by requesting a slightly lower plasma current.

A vigorous campaign was conducted in the pursuit of documenting the properties of micro-turbulence and associated instabilities in the core of TCV, making use of phase contrast imaging (PCI), correlation ECE (CECE), and Doppler backscattering (DBS) diagnostics. The long-standing question of the cause of confinement enhancement with negative triangularity was addressed by dedicated shape scans. A strong reduction in turbulence amplitude, in the trapped-electron-mode (TEM) dominated regime, is detected by both PCI and CECE at negative edge triangularity deep into the core (inside the mid-radius), even though the *local* triangularity is in all cases close to zero there. This remains to be understood. Plans are afoot to model these scenarios with global nonlinear girokinetic codes. The multi-diagnostic study of geodesic-acoustic modes (GAM) performed earlier was extended this year. We succeeded in observing the transition between a single global eigenmode and a dispersive continuum by performing a current scan in a single discharge.

With a 4.5MW ECH system at its disposal, the TCV team remains also engaged in fundamental studies of wave-particle interaction. The development of a tomographic hard X-ray (HXR) spectrometer came to fruition this year with 3 out of 4 eventual cameras installed. The first HXR tomographic images from a noncircular tokamak were produced. Theoretically predicted poloidal asymmetries in the emission were confirmed experimentally, and extensive studies of fast electron dynamics in the presence of ECH (as well as internal MHD instabilities) were performed. Studies aimed at quantifying and verifying the quasilinear effects in ECH absorption were conducted by arranging conditions such that only incomplete ECH absorption is expected in a Maxwellian plasma, and by varying parameters to modify the high-energy tail of the electron distribution function. The resulting variations in absorption are currently being analyzed and compared with simulations.

Edge physics in both conventional and advanced-shape configurations is an important and expanding chapter of our program. The heat flux profile decay length and heat load profile on the first wall were documented as functions of plasma shape in limited plasmas, in an effort to provide information for the ITER ramp-up and ramp-down phases. In the snowflake-divertor configuration, featuring four instead of two strike points and with the potential of keeping heat loads on walls within safe limits, we have now documented the heat flux profiles on all four strike-points. The first realistic simulations with the 3D EMC3-Eirene code including the physics of the secondary separatrix in the so-called snowflake-plus topology underestimate the flux to the secondary strike points. A leading candidate for explaining the excess transport is a poloidal-beta-driven convective flux predicted through the null region. In a fusion-power plant such as the planned DEMO prototype, it will be imperative for a high proportion of the plasma energy losses to be channelled into radiation to alleviate the wall loads. In this perspective, Neon injection was used to increase the radiated power fraction in a snowflake scenario and in similarly shaped conventional diverted plasmas for comparison. The former radiates approximately 15% more than the latter, consistent with its larger radiating volume.

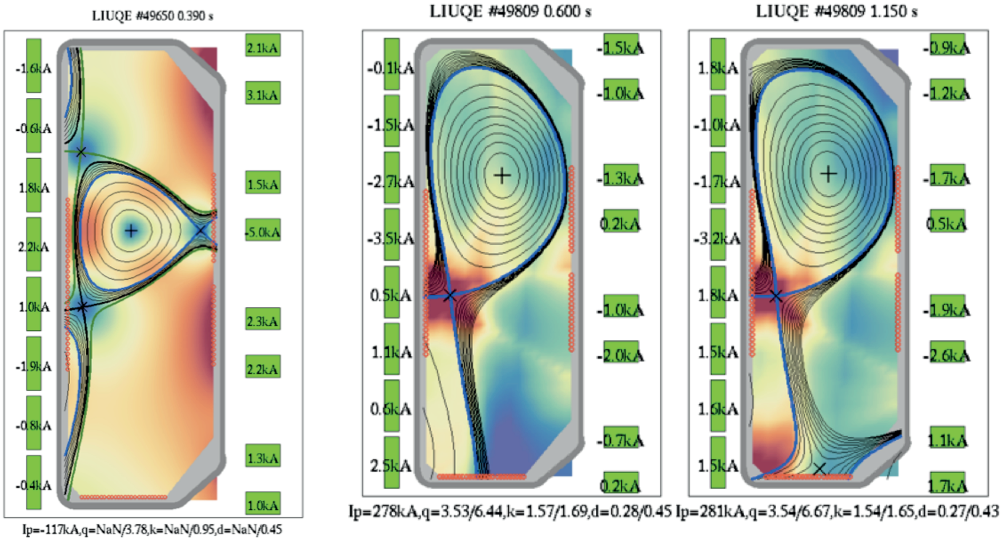

Fig. 2.1.2 *(Left) Triple-X configuration. (Middle) Conventional lower single-null evolving to (right) an X-divertor configuration.*

Even more exotic configurations were attempted and achieved, at least transiently, at the end of the campaign: the triple-X (3 regularly spaced X-points around the plasma boundary) and the so-called X-divertor, a conventional single-null shape with an exceptionally high flux expansion (Fig. 2.1.2). This provides a basis for exploring the potentially favorable properties of these novel topologies.

Recent CRPP theoretical work has predicted the possibility of long-lived non-axisymmetric (helical) equilibria in tokamak plasmas with axisymmetric last closed flux surfaces, in the presence of very flat or slightly hollow safety-factor profiles. This possibility was explored in TCV in the last campaign, with promising results currently under analysis.

Real-time control is the single fastest-growing section of our program and appears now in virtually every scientific theme. A stripped-down, real-time version of our in-house Grad-Shafranov equilibrium reconstruction code LIUQE has been successfully deployed in the last campaign, with a cycle time below 1ms. This has been employed in particular in NTM control by ECH, building on past experience but now benefiting from precise knowledge of the location of the rational q surfaces. Robust control has been achieved against time variations by adding a sinusoidal oscillation to the power deposition location tracking. Real-time LIUQE was applied also to the successful demonstration of a prototype generalized shape controller. An alternative observer set for shape control, the detection of visible light from the plasma boundary, also underwent initial prototyping in a simple vertical position control test, which met expectations. Stability against the fast axisymmetric instability (vertical displacements) was somewhat improved by the application of a tailored bang-bang controller.

The RAPTOR simulation package, including poloidal flux and electron temperature transport equations, was tested successfully in real-time with a 5ms cycle, and used for proof-of-principle current density profile control experiments. RAPTOR calculates the neoclassical conductivity and bootstrap current density to act on the power of EC beams aimed on and off-axis.

Breakdown control is an eventual goal for TCV to increase our success rate over our current empirical strategy. This work was prepared in this campaign by performing systematic scans of the main breakdown parameters.

In a related development, a proof-of-principle of iterative learning control was obtained by adjusting the plasma current reference trace between discharges to approach a desired internal inductance trajectory, with satisfactory convergence.

2.1.2 TCV heating systems

EC systems

The Electron Cyclotron (EC) system on TCV is composed in its original configuration by 6 gyrotrons (82.6GHz, 0.5MW/each, 2s pulse duration) used for electron cyclotron heating (ECH) and current drive (ECCD) at the 2nd electron cyclotron harmonic in the X2-mode, and 3 gyrotrons (118GHz, 0.5MW/each, 2s) used for 3rd harmonic heating in X3-mode.

The long maintenance of TCV during 2012 has allowed remedial work on the ECH system so to have a very successful 2013 experimental campaign. Both systems, X2 and X3 have been very intensively used, in particular during the last 6 weeks of the campaign, up to beginning of November 2013, which were characterized by a two-shift operation (7-14h/14h-21h). Similarly to the preceding two decades, the X2 system has been the work-horse of the 2013 experimental campaign. The 6 launching antennas of the X2 system provide the great flexibility that is a unique feature of TCV: power can be directed into the plasma from above and below the plasma mid-plane in a staggered way using the independent launchers and power supplies.

At the start of the 2013 campaign five X2 gyrotrons were available, but three gyrotrons failed during the campaign, bringing the number of gyrotrons functioning at full power to two and one gyrotrons operating at reduced power. Maintaining the desired launching flexibility required removal of broken tubes, relocation of working tubes and recalibration of subsystems. The presently functioning gyrotrons are of a similar age as those that failed during the previous campaign. According to the gyrotron manufacturer, Gycom (Russia), the broken gyrotrons can no longer be repaired since they have already undergone the maximum number of repairs (2-3) and/or have already exceeded their lifetime (10-15 years). As the present number of functioning X2 gyrotrons is well below the minimum value necessary to carry out the future TCV scientific programme, replacements must be procured. It is planned to purchase two new gyrotrons with higher output power (82.7GHz, 0.75MW/each, 2s). In order to minimize cost and down time, these new gyrotrons will be manufactured again by Gycom. This will also guarantee their compatibility with the existing superconducting magnets. It is planned that the first new gyrotron will be operational by beginning of 2016 and the second one nine months later.

The complete X3 system was operational for the entire 2013 campaign. One gyrotron suffered from partial damage due to the malfunctioning of an electronic interface with the gyrotron superconducting magnet and presently operates at 2/3 of the nominal power.

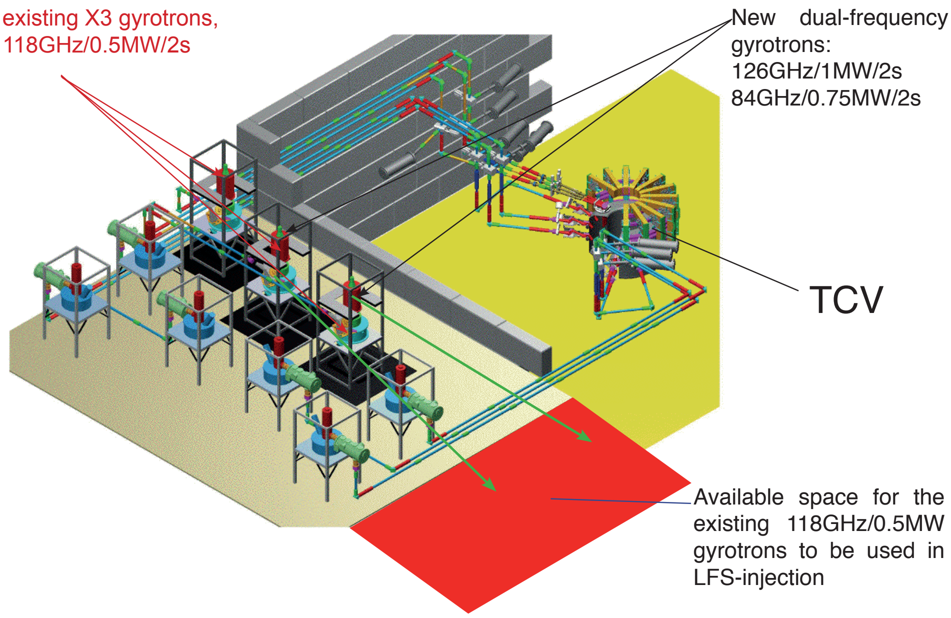

Fig. 2.1.3 *X3-upgrade gyrotron system*

The redesigned X3 launching antenna (top-launch) was operational with some calibration issues related to the precise knowledge of the launching angle. This did not prevent us from using the X3 system, but rendered experiments using the system more complicated and less efficient. Further detailed investigations of the mechanical launcher mechanism will be carried out during 2014, while it is removed from the tokamak, and additional measurement capabilities will be added if needed.

The new EC protection system, using the systematic detection of stray power levels near all diagnostics to stop the gyrotron operation if such levels exceed a threshold value, is now fully integrated in the TCV plant. The integrity of the TCV apparatus was indeed fully preserved. However, this system led to the frequent shutdown of the X3 system due to the calibration issue with the X3 mirror. For future campaigns, we are investigating the possibility of relocating some diagnostics to better allow the full exploitation of the X2 and X3 EC heating systems.

The X3 upgrade project consists in adding two dual-frequency gyrotrons (126GHz/84GHz) with a total power at 126GHz (X3) of 2MW in a top launch injection (or 1.5MW for X2 heating at 84GHz from the low field side). The same transmission lines and power supply presently used for top-injection of the existing 118GHz X3 gyrotrons will be used. Two 118GHz gyrotrons will be moved from their present location to allow for the installation of the new ones. The displaced 118GHz gyrotrons will be relocated so that the three gyrotrons operating at 118GHz can be injected from the low field side (LFS) using the existing X2 transmission lines and launchers. Similarly, the same high voltage power supply will be used for either X2 or X3 LFS launch as required for the experimental program. The reconfigured layout is shown in Fig. 2.1.3. The design of the new dual frequency gyrotron

(126GHz/84GHz) will be carried out at CRPP with contributions from the European Gyrotron Consortium (EGYC), in which CRPP is a leading member. The preliminary design of the gyrotron is being carried out at CRPP with its completion expected by end of March 2014. It is based on the gyrotron (140GHz/1MW/CW) manufactured by the French company, Thales Electron Devices, for the EC-system presently being completed for the W7-X stellarator at Greifswald, Germany. CRPP strongly contributed to the design and industrialization of this gyrotron, nine of which have been built for W7-X. The foreseen project time schedule is as follows:

a.	Preliminary design review completion:	March 2014
b.	Contract signature with THALES:	December 2014
c.	Detailed gyrotron Design	June 2015
d.	First gyrotron commissioning at CRPP	June 2017
e.	Second gyrotron commissioning at CRPP	June 2018
f.	Completion of X3-upgrade project	September 2018

Neutral beam heating system

Numerical simulations of the TCV scenarios of relevance for neutral beam heating scenarios have been undertaken using the ASTRA code. The injection of 1 MW 30 keV deuterium would allow us to access ion to electron temperaure ratios above unity ($T_i/T_e>1$) and higher plasma pressure (β) in both L- and H-mode high density plasmas ($>4\times10^{19}$m^{-3}) compatible with third harmonic (X3) EC heating. The lower power (0.3-0.5MW) 15-25keV deuterium NBH at intermediate (1-3×10^{19}m^{-3}) plasma densities is suitable for experiments at lower plasma current (100-250kA) with X2 ECH and ECCD. The tangential double path NBH alignment is considered to decrease the shine-through losses and avoid strong first-orbit losses, especially at low plasma current. The possibility to gradually vary the injected into tokamak power (in the range of 30-100%) during the plasma discharge is essential for the TCV.

The design choices for the NBH installation on TCV were based on considerations of beam access (for which significant modifications of the vacuum vessel are needed), shine through and orbit losses. Detailed studies confirmed the feasibility of tangentially injecting a 1MW beam through a port with an aperture of somewhat larger dimensions than the existing ports. The modification of the TCV vacuum vessel for the installation of two such ports suitable for NBI has been started in November 2013; the commercial contract for the in situ modifications of the TCV vacuum vessel has been signed with the De Pretto Industrie S.r.l., Schio, Italy (manufacturer of the original vessel).

The design of the neutral beam with an energy range of 20-35keV, tunable power up to 1MW, and 2s duration is based on a development of the NBH for plasma heating at Budker INP. To focus the beam inside the TCV port, the geometry of the grid elementary cell was optimized to minimize the beam angular divergence. The beam emitter has intrinsically anisotropic angular divergence along and across slits (8x18mrad). The beam is geometrically focused at 3.6m from the emitter. The grid diameter of 200mm has been chosen for NBI-TCV. Both beam energy and current are varied during a pulse in order to keep the beam angular divergence minimal angular divergence. The final design of the injector has been launched in the frame of a contract with "BINP-Plasma" LLC (Novosibirsk, Russia) on the design, manufacturing, installation and commissioning of the NB injector. The installation of the heating beam on the TCV is scheduled for the first part of 2015.

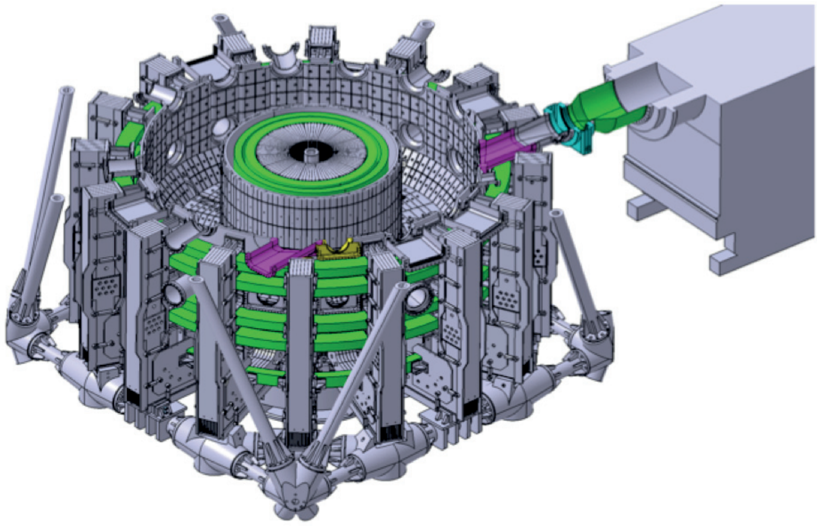

Fig. 2.1.4 *Schematic view of the TCV vessel modifications and NBH injector*

2.1.3 TCV Diagnostics

2013 was mainly a year for diagnostic exploitation on TCV. Diagnostics introduced in previous years and upgrades, such as the renewal of the Thomson Scattering spectrometer suite, were developed and tested on the machine in preparation for the 2013-2014 long vacuum opening for modification of the TCV vacuum vessel. Following this, only some of the major changes to the diagnostics are reported herein.

Thomson Scattering

As part of an upgrade of the TCV Thomson scattering diagnostic, 24 new polychromators are being built. The mechanical design is based on a development by CCFE-Culham and each polychromator is equipped with 5 interference filters to obtain an equal number of spectral channels. Figure 2.1.5 shows a top view into the spectrometer body with a scheme of the beam propagation from one channel to the next. The optical system is designed to form an image of the input aperture (end of a fiber bundle) at the position of each filter. In each spectral channel the radiation is detected by sensitive Si avalanche photodiodes with fast response. They are mounted in adjustable cells that also contain the focusing optics (see Fig. 2.1.6). The workshop of CRPP produced the large majority of the mechanical components and the electronic workshop was responsible for the design and integration of the electronic circuits. A prototype polychromator was assembled in October 2013 and was integrated into the Thomson scattering system on TCV. A series of tests were carried out under representative operating conditions. They confirmed the expected performance of the system and provided valuable information for the implementation of 20 to 24 units. With a larger number of spatial channels and a more sensitive detection system for measurements near the plasma edge, a noticeable gain in performance of the Thomson scattering system is expected.

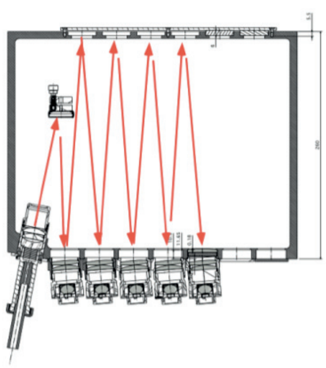

Fig. 2.1.5 *Top view into 5-channel filter polychromator with input via fibre optics entering bottom-left. Arrows show cascading of beam from filter 1 to 5. Detector cells with focusing optics behind each filter.*

Fig. 2.1.6 *Adjustable detector cells (with focusing optics) on front wall, four mirrors for beam cascading on rear wall*

TPCI

The tangential phase contrast imaging (TPCI) system has been improved by eliminating severe optical aberrations, caused by a faulty design of in-vessel mirror supports. The improved system was successfully operated on TCV during the 2013 campaign. However, a mechanical vibration problem persists, limiting the performance of the diagnostic, despite attempted corrective hardware modifications. The second and third of four hard X-ray (HXR) cameras, composing the HXR tomographic spectrometer for suprathermal electron studies, was completed. Each camera comprises 24 CdTe detectors observing the plasma through individual collimators, with energy resolution of ~7keV in the 10-300keV range. These developments have permitted us to generate the first-ever tomographic HXR reconstructions in a non-circular tokamak plasma. A host of data were collected in 2013 on suprathermal and runaway electrons and their relation with ECRH and with MHD instabilities, and are currently under analysis. Simultaneously, the tangential X-ray detector array, a current-mode HXR diagnostic used for extreme tangential viewing of bremsstrahlung emitted by suprathermal electrons during MHD phenomena, was upgraded with a new amplifier set built in-house. A 40GHz homodyne Doppler backscattering system on loan from Forschungszentrum Jülich (Germany) has been put into operation alongside two similar systems at higher frequencies (50-78GHz) that were already in operation, sharing the same antenna. The 40GHz module has broadened our parameter range to lower densities.

IR systems

The calibration of the IR thermography of the centre column was greatly improved by adding a heated tile in the field of view of the horizontal IR system (HIR), Fig. 2.1.7(a). In addition, the heated tile and the vertically adjacent tiles were equipped with thermocouples. The tile can be heated up to a temperature of ~300°C and yields an in-situ calibration of the IR camera over the entire range of tile temperatures typically encountered in TCV discharges. The surface temperature measurements are converted into a heat flux into the tile using the THEODOR code, Fig. 2.1.7(b). Integrating the inferred heat flux over the duration of the discharge yields a stored energy, which can be compared with tile calorimetry using the temperature measurements obtained from the thermocouples. Both measurements of the stored energy are generally found in good agreement.

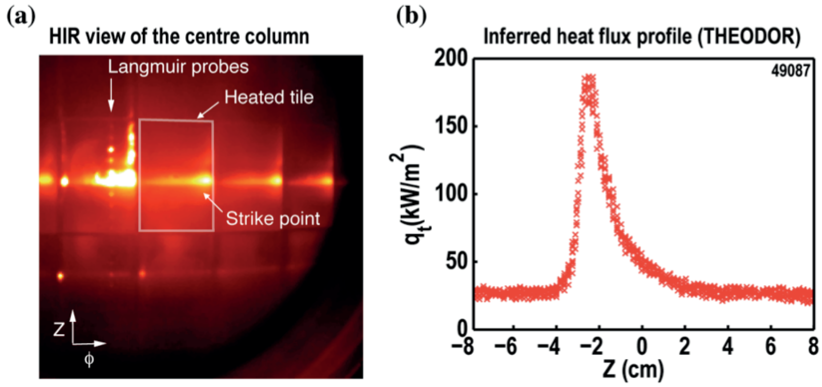

Fig. 2.1.7 *(a) The IR image of the centre column, here with the main high field side strike point on the heated tile, yields the tile surface temperature, which (b) the THEODOR code inverts into a heat flux profile.*

Correlation ECE and 1mm Interferometer

The upgrading of the correlation electron cyclotron emission (CECE) diagnostic continued in 2013 with the purchase of a new set of RF mixers and their associated local oscillators, image reject filters and power supplies. The RF front end is now under construction and will be ready for use for the TCV restart in 2014. All RF components for the new 1mm interferometer have been purchased and tested. A quasi-optical diplexer was procured and during 2014 a set of corrugated waveguides, designed in-house, will be manufactured. The ensemble will be tested and prepared for installation during 2014.

CXRS Visible Spectrometers

Following the development of high throughput imaging visible spectrometers designed for multi-fibre optical view of a plasma at IPP-Garching, a new spectrometer was designed at the CRPP for Charge Exchange spectroscopy and passive edge spectroscopy. Using legacy, large, low F-number lenses and large gratings, the classic “Czerny-Turner” reflective system is replaced with an almost “cartoon-like” system where a lens illuminates a grating with near-parallel light and a second lens focuses diffracted light onto an extremely sensitive state-of-the-art EM-CCD diode detector camera. These cameras can achieve near photon counting sensitivity yet have the speed to record up to 20 simultaneous spectra every ~1.7ms during the ~2-4sec TCV plasma discharge. Using lens optics, system F-numbers up to 2 were achieved (compared to ~F8 of the legacy spectrometers). To further increase the available light, relay optics may be employed to focus directly light from the plasma on the spectrometer entrance. During 2013, a direct spectroscopic view of the plasma edge was obtained using relay optics through a vertical TCV-chamber window and a test spectrometer constructed using Nikon F2-200m “sports” lenses and a large, 140x120mm, blazed grating.

2.1.4 Gyrotron physics

The development of the gyrotron simulation code TWANG has been intensively pursued. Based on the gyro-averaged non-linear time-dependent self-consistent code TWANG, two companion codes have been developed: 1) TWANGlin which is a self-consistent linearized version of TWANG based on a moment approach and 2) TWANGpic in which a particle-in-cell numerical scheme allows to address a limitation of TWANG associated to the underlying assumption on the time scale separation between the electron time of flight in the interaction region and the evolution of the rf-field envelope.

The development of these new codes not only benefits the effort in the domain of R&D of gyrotron for fusion applications, but also the development of advanced gyrotron concepts for Dynamic Nuclear Polarization in the field of NMR spectroscopy, as well as fundamental research studies of strongly non-linear wave-particle dynamical systems.

The novel operational regimes predicted by TWANG and experimentally demonstrated on a THz gyrotron for DNP/NMR spectroscopy had an important echo in the scientific community with, in 2013, three invited papers at international conferences and the publication of a paper in Physical Review Letter where a nanosecond pulsed regime is interpreted as the consequence of a self-consistent Q-switch effect in which the diffraction quality factor is dynamically modulated by driving the gyrotron in a strongly nonlinear regime with phase-locked sidebands. Further explorations of the large variety of dynamical regimes accessible with this gyrotron have allowed us, for the first time, to experimentally observe the route to chaos via a « period-doubling cascade ».

Based on a SNSF R'Equip grant, awarded to CRPP in 2013 for procuring state-of-the-art MMW/THz components for use with a Vector Network Analyzer, advanced research will be carried out in multiple areas of electron cyclotron wave (ECW) and plasma physics including studies of gyrotron oscillators, ECW component characterization, and electron cyclotron emission, radiometry, and reflectometry, as well as a number of other research topics.

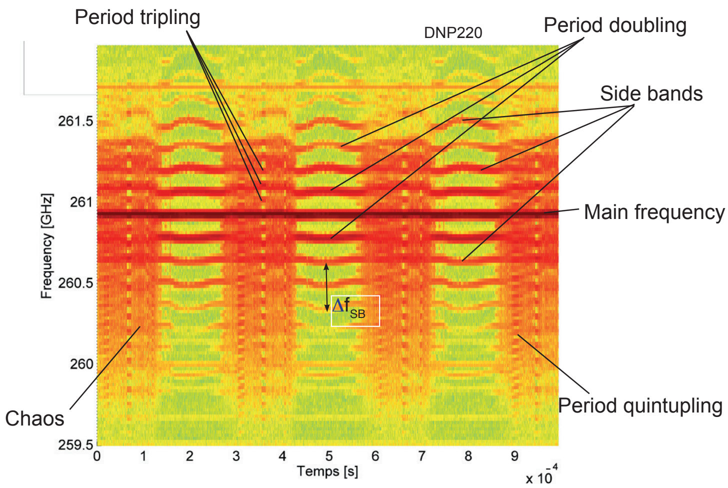

Fig. 2.1.8 *Spectrogram of experimentally measured route to chaos via a " period doubling cascade" scheme. The quantity Δf_{SB} indicates the frequency separation of the side-bands.*

2.2 Theory

The theory group at CRPP is focused on a first-principle approach to the understanding of fusion devices. 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. Understanding and simulating plasma behavior is extremely challenging. To get insight into the plasma dynamics advanced analytic theories are necessary, together with state-of-the-art scientific codes developed at our center or within international collaborations, e.g., in the framework of the EFDA Integrated Tokamak Modeling task force to which the CRPP theory group contributes. The simulations carried out by the group are performed on some of the most powerful computers worldwide. In fact, the CRPP theory group has gained access to HPC platforms such as Helios at IFERC-CSC, Rosa at CSCS, BG/Q at EPFL. Tens of millions of cpu-hours have been allocated to projects led by CRPP theory group members.

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 EFDA High Level Support Team activities.

Theoretical and numerical activities at CRPP cover the following main areas of research:

1. First principles 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

The theory group maintains 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.

2.2.1 Simulations of core plasma turbulence

Geodesic Acoustic Modes (GAMs) in TCV plasmas observed by several diagnostics (Toroidal Phase Contrast Imaging (TPCI), Electron Cyclotron Emission, magnetic probes) have been simulated using the global gyrokinetic code ORB5. Excellent agreement with the measurements on the frequency and radial structure has been obtained. Computations show that GAMs are excited by Trapped Electron Mode (TEM) turbulence.

The effect of the non-adiabatic response of passing electrons in the vicinity of mode-rational surfaces on turbulence and zonal flows was investigated with nonlinear flux tube simulations and results compared with the simplified trapped electron model.

First global gyrokinetic simulations of ITER-shaped plasmas using the trapped electron model have been achieved for situations dominated by ITG modes, with scans in temperature gradient and finite size, showing reduced ion and electron heat transport as compared to circular cross-section plasmas.

Inspired by experimental evidence on TCV of profile stiffness in the plasma core and non-stiffness at the plasma edge, relevant flux-tube simulation scans over density and electron temperature gradient have been carried out. In particular, the improved electron confinement observed with negative plasma triangularity has been investigated.

Momentum conservation laws were verified in global gyrokinetic simulations up to an unprecedented level of accuracy.

A new treatment of the quasi-neutrality equation valid to all orders in the Larmor radius was derived and first tests passed in simplified geometry.

A new geometrical multigrid field solver for massively parallel applications was successfully tested on a 2D curvilinear coordinate system using finite elements.

2.2.2 MHD and fast particle studies

Recently the theoretical study of MHD at CRPP has concentrated on 3D effects which primarily originated from resonant magnetic perturbations and from strong saturated MHD instabilities in the tokamak core. These two affects have been combined in the ANIMEC equilibrium code using a free boundary to also include the discrete toroidal and poloidal field coils. Modelling of MAST and TCV in particular has helped to interpret experimental results.

A novel recent development has been the inclusion of toroidal rotation into the ANIMEC code. This being the first such attempt in a 3D equilibrium code, we are now capable of examining the screening of the RMP coils on the penetration of perturbed 3D magnetic perturbations by the response of a toroidally rotating plasma.

In addition to the equilibrium code approach, another means of calculating saturated structures due to core instabilities is to use a non-linear initial value code. The conditions under which these contrasting but widely employed approaches agree are determined in the ideal limit, with important implications for the way in which equilibrium codes in particular should be used to model helical states. For conditions where the magnetic shear is allowed to become small over an extended region, as appropriate for hybrid scenarios, extremely fast growing multiple resistive instabilities couple to a core kink mode. The sensitivity of these modes to two-fluid effects, shear flow and viscosity is developed analytically and numerically, and comparisons made with experimental observations.

The inclusion of very strong flows introduces new instabilities, which we have classified as Kelvin-Helmholtz like. By assuming very low magnetic shear, we have for the first time been able to reproduce the linear instability in a tokamak plasma analytically, and show favourable comparisons with an MHD code that accounts self-consistently for the strong flow.

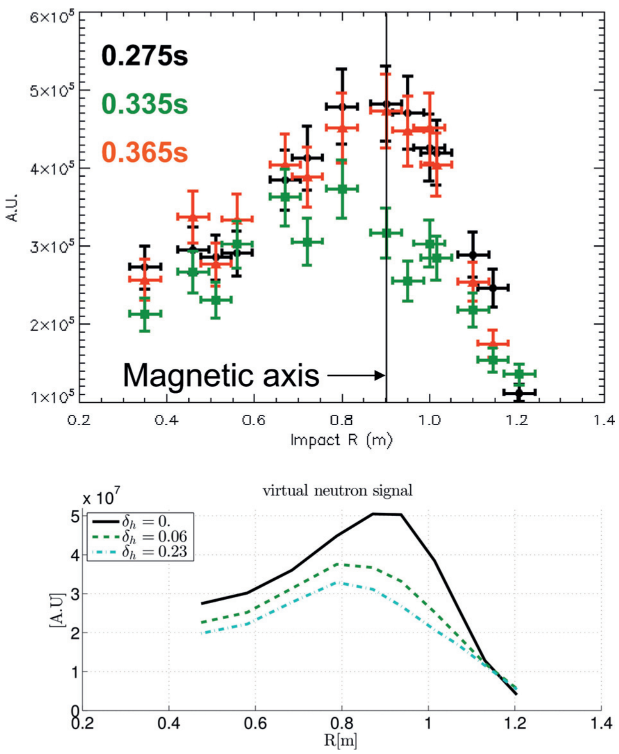

Fig. 2.2.1 *Simulation of fast ion deposition profile which is shifted off axes due to a saturated internal kink core displacement, and comparison with measurement in the MAST tokamak*

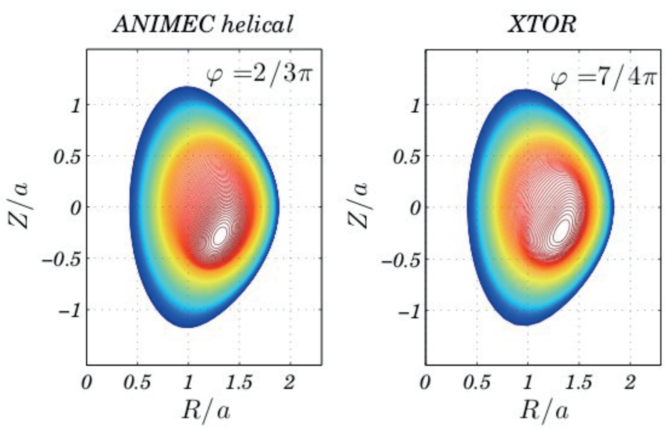

Fig. 2.2.2 *Comparison of a long lived mode helical core in MAST using contrasting calculation techniques of a 3D equilibrium solver (ANIMEC) and an initial value non-linear stability solver (XTOR)*

In Fig. 2.2.1 and Fig. 2.2.2 the result of new fast ion orbit solver are presented. This solver has been developed for realistic tracking of fast ion populations during large scale MHD activity such as modes that occur during hybrid and reverse shear scenarios. The resulting exotic orbits and displaced ionisation position of the injected particles gives rise to off-axis peaked depositions that agree well with fast ion measurements during long lived mode activity in MAST. This work is now being extended to model ICRH ions, which we are using to model sawtooth control, and fast ion loss experiments at JET.

2.2.3 Investigations of plasma dynamics at the edge of tokamak devices

Analytic estimates of the SOL turbulence saturation level, perpendicular transport, plasma profile scale-lengths, and other quantities that are in reasonable agreement with the nonlinear 3D simulations over a wide range of parameters have been obtained. Successful qualitative comparisons have been performed with measurements taken in the TCV tokamak, Alcator C-Mod, JET, Compass, and Tore Supra.

We have provided a framework through which, given the SOL operational parameters (safety factor, magnetic shear, and plasma resistivity), the nature of the instabilities that drive the SOL turbulent transport can be determined: the resistive, inertial and ideal branches of the ballooning modes, and the resistive and inertial branches of the drift wave instabilities.

While the research effort has mostly focused on core and edge rotation, there is strong experimental evidence for the role of SOL flows in determining core rotation profiles. We have used 3D turbulent simulations to understand the mechanisms leading to SOL intrinsic rotation, pointing out that rotation results from the interplay of the sheath dynamics, poloidal asymmetries of the pressure profile, and momentum transport.

We have investigated finite beta effects on SOL turbulence. At low beta, the non-linear simulations confirm the results of the linear analysis, which indicates a competition of drift waves and resistive ballooning modes. As the plasma beta is increased, we observe a flattening of the pressure profile and a transition to long wavelength global modes, leading to large transport, which occurs due to a coupling between electrostatic and ideal ballooning modes. This effect takes place because electromagnetic induction terms act as an effective impedance that increases the drive for electrostatic modes, below the ideal MHD threshold.

2.3 Basic Plasma Physics

2.3.1 Industrial Plasmas

2013 marked the last year before retirement of Christoph Hollenstein, the group leader and co-founder (in 1989) of the plasma applications group. During this year, two doctoral students successfully completed their thesis projects with their respective industrial partners. In one of the thesis, numerical simulations and experiments were carried out of breakdown in satellite solar power transmission assemblies with RUAG Space which resulted in a testbench for the qualification of satellite components. In the other thesis, a novel grid concept of Oerlikon Solar (now TEL Solar) was constructed and tested for RF plasma processing reactors, used for deposition of thin-film solar cells with minimum damage from ion bombardment.

Two new CTI projects were launched in 2013, both applying a new concept in inductive plasma processing using resonant planar network antennas as patented by Philippe Guittienne of Helyssen SA. With Tetra Pak, a large area antenna (1.2m x

1.2m) is being developed for plasma deposition of barrier layers on packaging films. With TEL Solar, a high temperature antenna module is being constructed to investigate its potential for replacing capacitively-coupled plasma sources for deposition of device quality microcrystalline silicon. Basic research into resonant antennas for plasma sources was also performed and published, including the generation of whistler-wave heated discharges.

The group continues as "Basic Plasma Physics and Applications (BPPA)" and several potential contacts for expansion of activities have already been established, including a successful EuroFusion application for plasma source development for negative ion neutral beams.

2.3.2 Torpex

In magnetically confined plasmas for fusion, turbulence causes large particle and energy transport, reducing the effectiveness of the plasma confinement system, hence that of fusion reactors. The Basic Plasma Physics Group at CRPP contributes to advancing the understanding of turbulence in magnetized plasmas of direct relevance for fusion devices.

The experiments are performed in the TORPEX device, where plasmas of different gases are created by microwaves at 2.45GHz and are characterized by low densities (n_e~10^{16}-$10^{17}m^{-3}$) and temperatures (T_e~5-20eV). In the simple magnetized torus (SMT) configurations, plasmas are confined by a toroidal magnetic field up to B_T=0.1T, and a smaller vertical component, B_z≤50mT. The SMT incorporates the main ingredients for drift and interchange instabilities and turbulence, namely pressure gradients, magnetic field line curvature and open filed lines, thus mimicking the Scrape-Off-Layer region of magnetically confined plasmas for fusion. To better mimic the SOL-edge magnetic geometry in tokamak, we have recently developed a new internal toroidal conductor (TC) system that allows creating twisted field lines with rotational transform, in addition to the SMT configurations. Such new system increases the relevance to magnetic fusion devices, by creating a region of closed field lines and magnetic surfaces (as in the tokamak configuration).
In 2013, significant progress was achieved along several research avenues, from the study of the interaction between supra-thermal ions and interchange waves and turbulence to the first characterization of TORPEX plasmas in closed field line configurations. Such progress is detailed in the paragraphs here below.

Supra-thermal ion transport studies

In burning plasmas, supra-thermal ions will be generated by ion cyclotron resonance heating (ICRH), neutral beam injection (NBI) and fusion reactions. As they will be responsible for a significant fraction of plasma heating and, in some scenarios, non-inductive current drive, understanding their transport across the magnetic field is of fundamental importance. In previous years, we started theoretical and experimental investigations of supra-thermal ion-turbulence interaction on TORPEX.
In 2013, we significantly advanced the understanding of supra-thermal ion transport by using extensive sets of three-dimensional (3D) data, together with numerical simulations of supra-thermal ion tracers in fluid turbulent fields. A miniaturized lithium 6+ ion source injects in TORPEX plasmas fast ions with energies up to 1KeV and a double-gridded energy analyzer is used as a detector.

The source is mounted on a toroidally movable system and the detector can be moved in the poloidal cross-section, allowing one to reconstruct 3D fast ion current profiles. Radial transport of the fast ions, associated with plasma turbulence, is measured and compared with experimental results with numerical simulations of the fast ion transport in a global fluid simulation of the TORPEX plasma.

The study of the time-averaged fast ion current profiles and their comparison with numerical simulations has revealed different regimes of the fast ion transport. The measurements have validated the numerical results, using a synthetic diagnostic technique. These results confirm the role of gyroaveraging as an effective mechanism to reduce transport. On a theoretical side, the use of fractional diffusion equations has been investigated to model the transport of fast ions. Fractional Lévy motion has been used to model temporal correlations and non-Gaussian statistics. A good agreement was found between this model and the numerical simulations.

Turbulence studies in closed field line configurations

Year 2013 was devoted to the first characterization of the main plasma features in the presence of quasi circular-shaped flux surfaces. These are produced using the new internal toroidal conductor (TC) system in combination with the vertical external coils. An example of the magnetic field geometry is shown in Fig. 2.3.1. The background plasma parameters were first investigated comparing time windows of TC current flat-top with the no-TC current phase. The same order of magnitude of plasma density, temperature and electrostatic potential is measured in the two cases for the explored experimental parameters. During the current flat-top the

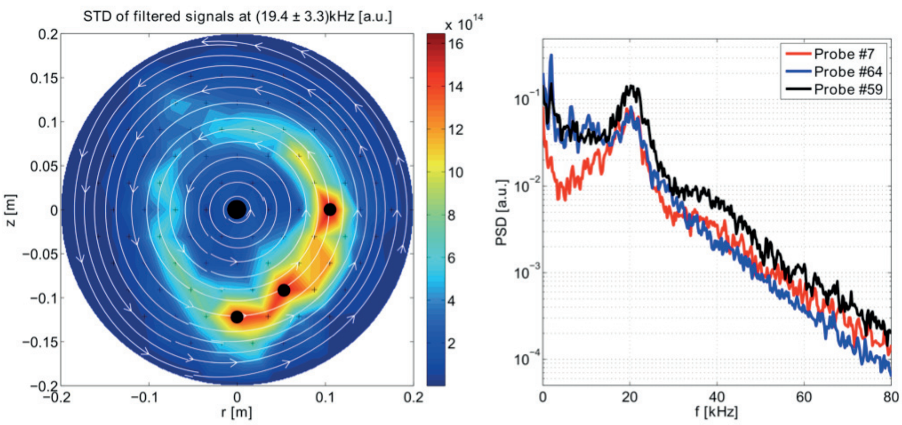

Fig. 2.3.1 *HEXTIP data (HEXagonal Turbulent Imaging Probe) during TC flat-top. Left: profile of the standard deviation of the probe filtered signals in the frequency band between 16.1 and 22.7 kHz. Right: spectra of ion saturation signals from three probes located around the circular region of strong mode activity, associated with strong pressure gradients. The black circles denote, in addition to the TC, the three probes providing the spectra plotted on the right.*

plasma shape changes, peaking in the region of higher poloidal magnetic field close to the TC, forming flux surfaces of almost constant density. Dedicated experiments were carried out to study coherent plasma fluctuations, which clearly feature a ballooning character showing larger amplitudes in the region of unfavorable curvature (Low Field Side). Quasi-coherent modes between 15-30kHz were identified for TC current values in the range 460-770A (example in Fig. 2.3.1). The first characterization of their spectral properties was performed in terms of toroidal and poloidal wave numbers. Further studies are foreseen to compare the experimental measurements with the simulation results of the CRPP theory group to assess the main driving mechanism of the observed modes.

2.4 Superconductivity

2.4.1 Superconducting Magnets for DEMO

Both low and high temperature superconductors (HTS) are investigated in the EFDA WP13-DAS01-MAG. CRPP also participates to the study about the integration of the DEMO TF coils with the vacuum vessel upper port, EFDA WP13-SYS03-T02.

A HTS high current conductor based on soldered, twisted stacks of coated conductor tapes has been developed at CRPP. Short lengths of twisted stacks have been soldered into shaped copper profiles and characterized at 77K for tolerance to bending and torsion strain, Fig. 2.4.1. A 4K, 12T test was carried out at KIT. Based on the excellent performance of the soldered stack, a flat cable made of 20 soldered stacks is being assembled as the first prototype of a 50 kA class HTS forced flow conductor for DEMO. Test of the prototype will be made in 2014.

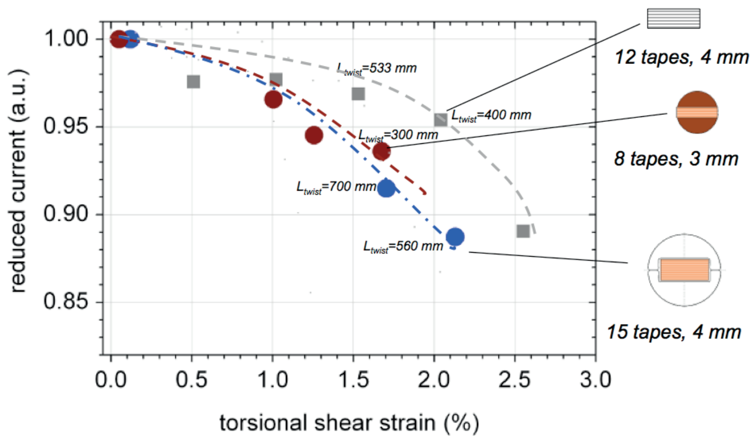

Fig. 2.4.1 *Relative performance degradation of twisted-soldered stack conductors vs. torsional strain*

The effect of transverse loads on the performance of Roebel cables made of coated conductors tape has been investigated. Degradation is observed for loads >400MPa.

In order to test HTS cables in SULTAN/EDIPO at variable temperature, the heat flux between the NbTi flux pump, operated at 4.5K, and the HTS conductor sample must be reduced by a non-stabilized, conduction cooled short bus made of HTS material. The design of the bus is completed and the parts are procured. The assembly of the bus started in December 2013.

To test the HTS cable samples at 20K and above, a counter flow heat exchanger is required. The commissioning of the adapter, together with the counter-flow heat exchanger is planned in 2014 in EDIPO.

As the baseline option for the DEMO TF coils, a 85kA, force flow Nb_3Sn react&wind conductor is proposed. The layout of the graded winding pack and conductors was iterated in 2013 taking as inputs the outcome of the WP12 analysis results, the updated reference for DEMO1 and the constrain of the vertical upper port (reducing the toroidal width of the TC coils). Quotations have been obtained from the industry for the manufacture of a short length prototype conductor in collaboration with ENEA.

In collaboration with ENEA and CIEMAT, the feasibility of the upper ports with respect to the electro-magnetic loads in the TF coils has been investigated. Large inter-coil structures marginally affect the high stress in the thin TF casing between the vertical ports, which is a reason of concern for the feasibility.

2.4.2 Completion of the EDIPO test facility (TW5-TMS-EDFAC)

The first cool-down of EDIPO (only main coils) was completed after seven weeks in December 2012. The commissioning of the EDIPO coils was successfully completed in March 2013. *The nominal current of 17.2kA was achieved on March 26th*. The operating temperature was increased at full current up to about 5.5K without quench. Flux jumps at low field trigger the quench detection system. In coil1, the conductor close to the low field terminal is likely damaged with R 50n . The field in the test well and its homogeneity was measured by calibrated Hall sensors, see Fig. 2.4.2.

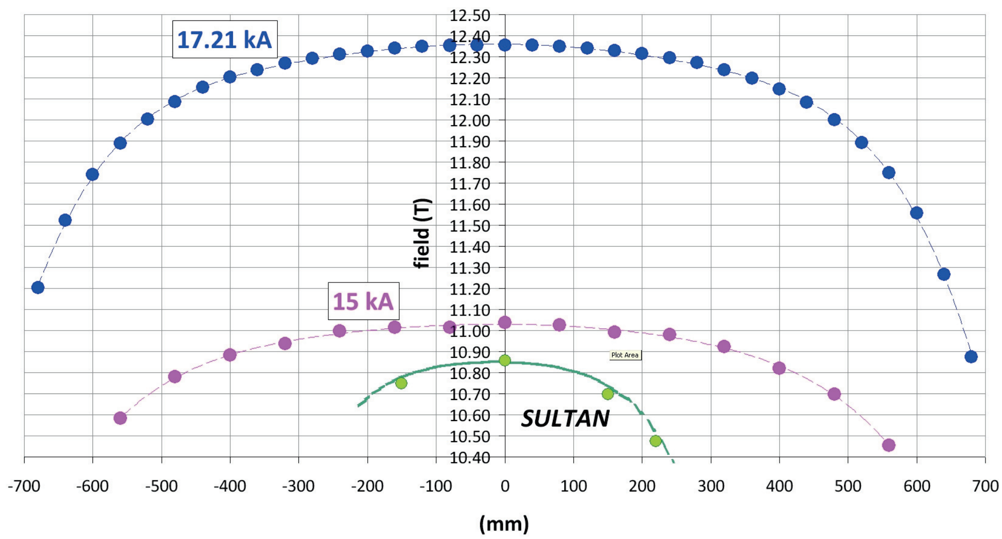

Fig. 2.4.2 *The field profile in the test well of EDIPO at full current, compared to SULTAN.*

In July 2013, the commissioning of the superconducting transformer and sample holder could not be completed because of the partial failure of the primary winding of the transformer, due to insufficient cooling. The transformer was then disassembled and extensively tested in August-October 2013. A modification of the cooling layout was planned in November. The re-assembly of the transformer and the final commissioning will be completed in March 2014.

*2.4.3 Tests of superconductors for ITER**

The test in SULTAN of the ITER conductor samples continued in 2013 in the scope of the ITER-CRPP framework contract. The only breaks of the ITER tests happened in March and July 2013 for the commissioning of the EDIPO coils and in August for the yearly maintenance of the cryo-plant. The following test campaigns have been carried out in 2013:

- TFCS2 – F4E – JT60 TF sample – 1 week
- CSJA5 – JADA – CS conductor with short twist pitch – 5 weeks
- TFKO5 – KODA – TF sample from Korean series production – 2 weeks
- MBCN2 – CNDA – Main Busbar sample – 1 week (test interrupted, sample back to China)
- TFEU9 – F4E – TF process qualification sample – 2 weeks
- CBCN2 – CNDA – Correction coil Busbar – 2 weeks
- PFCN3 – CNDA – PF5 conductor sample – 2 weeks
- TFRF5 – RFDA - TF sample from Russian series production – 2 weeks
- EUTFjoint – F4E – Qualification of industrial TF joint sample – 1+1 weeks
- TFJA9 – JADA - TF sample from Japanese series production – 2 weeks
- PFCN4 – CNDA – PF5 conductor sample – 2 weeks
- MBCN3 – CNDA - Main Busbar sample, assemble in China with U-bend – 1 week
- TFKO6 – KODA – TF sample from Korean series production – 2 weeks
- CCCN4 – CNDA – correction coil conductor, series production – 1 weeks
- TFJA7 – JADA - TF sample from Japanese series production – 2 weeks
- TFRF6 – RFDA - TF sample from Russian series production – 2 weeks
- MBCN4 – CNDA – Main Busbar sample, assembled at CRPP with bottom joint – 2 weeks

2.5 International and national activities

2.5.1 Gyrotron development for ITER

Following the failure of the refurbished 2MW coaxial gyrotron, F4E decided to switch to the development of a conventional 1MW/CW/170GHz tube, which will benefit from the 1MW/CW/140GHz W7-X experience.

Grant-432 was signed on Dec. 19th 2012. It is coordinated by CRPP and is covering the EGYC activities aiming at the production and tests of a 1MW/CW/170GHz prototype tube:

- Support to theoretical development activities,

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* Not part of the Association's Workprogramme. For information only.

- Design of a short pulse prototype to validate the scientific design of the CW tube
- Follow-up of the F4E contracts to produce the 1MW/CW prototype (signed in January 2014), the procurement of a new LHe-free superconducting magnet, as well as the ECPS design.
- Upgrades of the CRPP and KIT test stands.

The Grant-432 will extend until June 2014.

The short pulse tube delivery is expected at the KIT by the 3rd quarter of 2014, whereas the delivery of the CW tube is foreseen by mid-2015. Due to absence of acceptable offers, the contract for the delivery of a He-free SCM is delayed and the initial tests of the CW tube will most probably have to be performed at KIT.

The strategy of F4E regarding the procurement of the gyrotrons to ITER is to continue the support to a European development until end of 2015 (end of Phase 1, hold point #2) and make a decision for the continuation of the (European or International Call for Tender) project based on the results obtained with the short pulse and CW tubes.

2.5.2 Upper launcher development for ITER (ITER EC UL)

The CRPP continues to play a leading role in the consortium (ECHUL) responsible for the design of the Upper Launcher of the Electron Cyclotron current drive system for the ITER project; CRPP heads the mm-wave division charged with the design of the optics for beam propagation.

The work is carried out under contract with the European domestic agency: Fusion for Energy (F4E).

In the spring of 2013, F4E received word from the ITER organization (IO) that some components of the EC system, previously expected to be "components off-the-shelf", would not meet their required specifications. F4E, in discussion with ECHUL and IO agreed to take on the design of these components. These components are part of the First Confinement System of the tokamak having the most strict quality, safety and vacuum qualifications. Because of this deviation of the original aims of the contract, modifications to the layout of the ex-vessel waveguides were incorporated to simplify the manufacturing, installation and maintenance of the equipment, while simultaneously reducing the dose rate in the port cell area by eliminating a line-of-sight view from the port cell towards the tokamak.

In the fall of 2013, an amendment to the contract extended the closure date from October 2013 to March 2014, due primarily to the extra work required to resolve the ex-vessel waveguide changes and other modifications to the boundary conditions of the design coming from IO. In addition, a prototyping service contract was signed covering costs associated with testing to ensure that the new components would meet their design specification. In December of 2013 the project decided a change in the vacuum sealing of the port plug that houses the mm-wave optics to the port (interface with the tokamak). This change makes a major impact on the design in progress. The impact of this change is presently being assessed and will certainly require an additional amendment to the running contracts during 2014 and beyond. CRPP experts work closely with other ECHUL members, F4E personnel and with the IO responsible officer to resolving the continual design issues arising within the project while being careful to ensure that the EC upper launcher will successfully fulfill the NTM stabilizing role to which it is assigned within the ITER project.

In addition to designing the wave propagating transmission lines and quasi-optics, CRPP has investigated the functionality of the resulting beams with respect to control of the sawtooth oscillation in ITER. Using one beam from each of the four upper launchers allows perfect overlap of the current profiles in the plasma producing quadruple the current density. When more power is added, it is not possible to have a perfect overlap due to the geometric constraints within the upper launchers (ULs); therefore, the current density profile tends to broaden as well as increase in amplitude. Detailed combinations of beams have been studied to investigate their effect on sawtooth stabilization.

Starting from the Q=10 operational scenario data provided by ITER/F4E and the beam tracing results for the upper launcher, it was shown that the sawtooth period can be both shortened (destabilization) or lengthened (stabilization) as in present day machines. The expected sawtooth period due alpha-particle stabilization of the internal kink instability responsible for the sawtooth is expected to be around 50s. By adjusting various parameters that determine the several threshold levels beyond which a sawtooth crash is triggered, sawtooth periods of 36s and 100s have been obtained to simulate alpha-particle stabilized sawteeth. It is found that the sawtooth period can be shortened by 50% by different combinations of launcher inputs. As this period may not be short enough to prevent the triggering of neoclassical tearing modes (NTM) by the seed islands generated at the sawtooth crash, the ability of the ULs to lengthen the sawtooth period was considered instead. With the given power it is not possible to lengthen the sawtooth period beyond the length of an ITER discharge. However, the sawtooth period can be regulated by both pacing and locking so that the moment of the sawtooth crash becomes predictable. Using these techniques, it has been shown that it will be possible to first regulate the sawtooth period and then inject power at the NTM resonant surface to preempt NTM appearance, using the same launcher beams. This has the advantage of requiring less power to be dedicated to NTM control and eliminates the need for power switching between ex-vessel waveguides. As the EC system must fulfill several competing tasks, this frees more power for other tasks and is therefore advantageous.

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. The new contract will end mid-2014. A major result of 2013's work was the agreement of the first version of the ITER data model with the IO. The IMAS infrastructure is based on a standardized data model that covers experimental and simulated data with the same representation. The standard data model is tokamak-generic and can be used to access data from existing tokamak experiments. Since the data model will progressively cover a large number of areas (plasma, diagnostics, actuators, other tokamak subsystems) and will be developed by many contributors, a set of data model design rules and guidelines has been established to ensure consistency and homogeneity. To access data, a data model-aware Application Programming Interface (API) has been developed for various programming languages. Physics components, once interfaced to the data model, can be coupled into an Integrated Modelling workflow orchestrated by a workflow engine. A first implementation of all these infrastructure elements has been carried out and the integration of the DINA-

CH simulation tool has been performed. The full integration of the DINA-CH code will be one of the main contributions of CRPP to this ITERIS, ITER-Integrated-Simulation, project.

2.5.4 JET – sawtooth control experiments and modelling

Recent CRPP-led experiments at JET with the ITER-like wall show for the first time that low field side resonance ICRH can be used to control sawteeth that have been initially lengthened by fast particles. These results are welcome not least because the ICRH antenna design of ITER does not allow for high field side resonance at full magnetic field. In contrast to previous high field side resonance sawtooth control experiments undertaken at JET, it is found that the sawteeth of L-mode plasmas can be controlled with less accurate alignment between the resonance layer and the sawtooth inversion radius. This advantage, as well as the discovery that sawteeth can be shortened with various antenna phasings, including dipole (see Fig. 2.5.1), indicates that ICRH is a particularly effective and versatile tool that can be used in future fusion machines for controlling sawteeth.

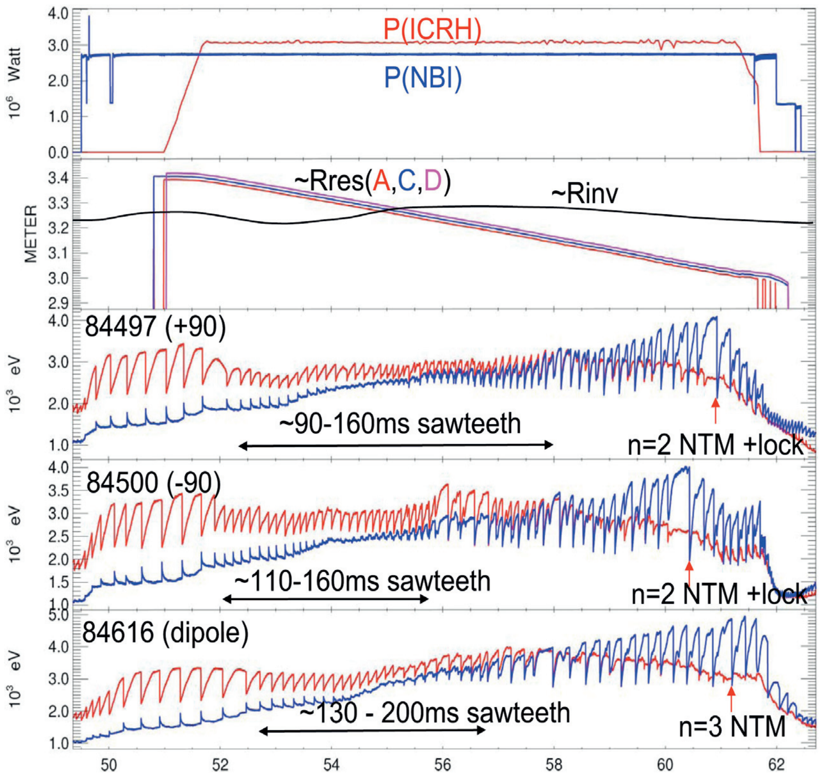

Fig. 2.5.1 *Recent JET L-mode experiments comparing the sawtooth control characteristics for 3 contrasting antenna settings (dipole, +90 phasing, and -90 phasing). Pulses employ ramped toroidal field and current.*

- High power H-mode experiments show the extent to which ICRH can be tuned to control sawteeth and NTMs while simultaneously providing effective electron heating with improved flushing of high Z core impurities.
- By using low field side resonance heating, dipole antenna phasing has been used to control sawteeth for the first time. This antenna phasing has

additional advantages in JET from the point of view of coupling optimization and machine protection.
- Realtime frequency variation has been used in JET L-mode plasmas as an alternative to magnetic field ramping.
- H-mode sawtooth control experiments have been combined with a novel method for controlling the ELM period. The realtime variation of gas puffing enables a constant ELM period, which in turn minimises high-Z impurity accumulation, and avoids disruption from large ELM periods caused by a single large impurity event.
- Continued dedicated ICRH modelling using SELFO, SCENIC and EVE, including wide drift orbit effects, are being used to explain why sawtooth control is effective with arbitrary antenna phasing.
- Kinetic-MHD stability calculations for the internal kink mode, thus modelling the sawtooth triggering conditions, using MISHKA, HAGIS and MARS-K, are being used to unravel the optimal sawtooth control regimes in these ITER relevant plasma conditions.

2.5.5 Participation in the first phase of upgrade for the KC1T diagnostic system on JET.

The first phase of the upgrade for the JET KC1T diagnostic system, originally designed and built by CRPP to drive and detect Alfvén Eigenmodes (AEs) using eight in-vessel antennas, has continued in 2013 with a focus on (a) the development of the new driving system for the in-vessel antennas, and its initial integration with the JET real-time control systems, and (b) on the design and testing of a new set of amplifiers and related power electronics for the in-vessel antennas. This work was carried out in the framework of an international collaboration with the University of Sao Paulo (Brazil), MIT (US) and EFDA-JET, and with the participation of two commercial partners (National Instruments (UK/US) and Politron (BR)). An FPGA-based solution using modules purchased from and developed with National Instruments has been successfully tested, meeting its required target of phase resolution at 1MHz with better than 1ms update time for the control of the eight in-vessel antennas, as shown in Fig. 2.5.2. The prototype amplifier purchased from and developed with Politron was also successfully tested, meeting its required target of gain stability, low VSWR at maximum output current and pulse duration. The first unit has been produced and has been delivered to JET for the initial installation and commissioning tests.

2.5.6 Use of Toroidal Alfvén Eigenmodes to determine the plasma isotopic mass

The measurement of the plasma isotopic composition is necessary in future burning plasma devices such as ITER and DEMO as a tool for optimizing the DT fusion performance. Experiments were performed in JET where Toroidal AEs (TAEs) with different toroidal mode number (N) up to $|N|=12$ were actively driven with a set of in-vessel antennas, and were then used to infer the value of the plasma isotopic composition at different radial positions (see Fig. 2.5.3). A novel and important result with respect to previous work on JET is that by correctly including the effect of plasma impurities in the calculation of the Alfvén frequency it has become possible to distinguish plasmas with different majority ion species but with the same charge-to-mass ratio, notably majority deuterium and helium4 plasmas. Furthermore, and combined with theoretical modelling of JET discharges, these experimental results indicate that a diagnostic system based on the detection of AEs with different toroidal mode numbers and at different frequencies, with these modes being driven by antennas and/or by energetic ions, could in principle provide profile measurements of the plasma isotopic composition in future burning plasma devices such as ITER and DEMO.

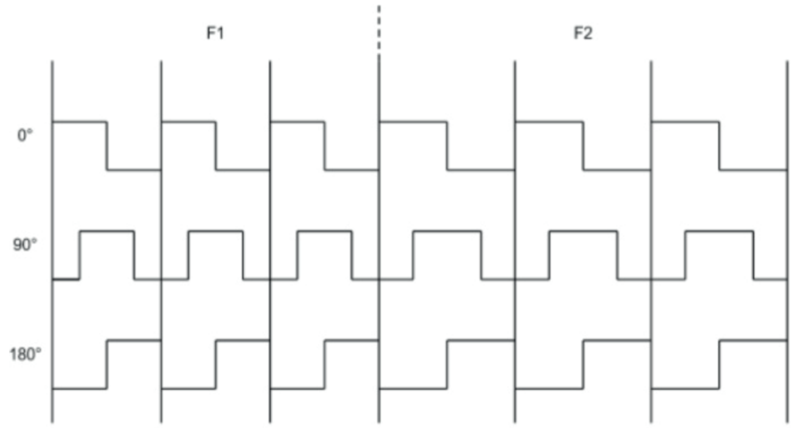

Fig. 2.5.2 The FPGA boards for the upgraded KC1T diagnostic system can *maintain a constant phase relative to the input driving frequency when changing the antenna operating frequency from F1 to F2 for different initial phase offsets.*

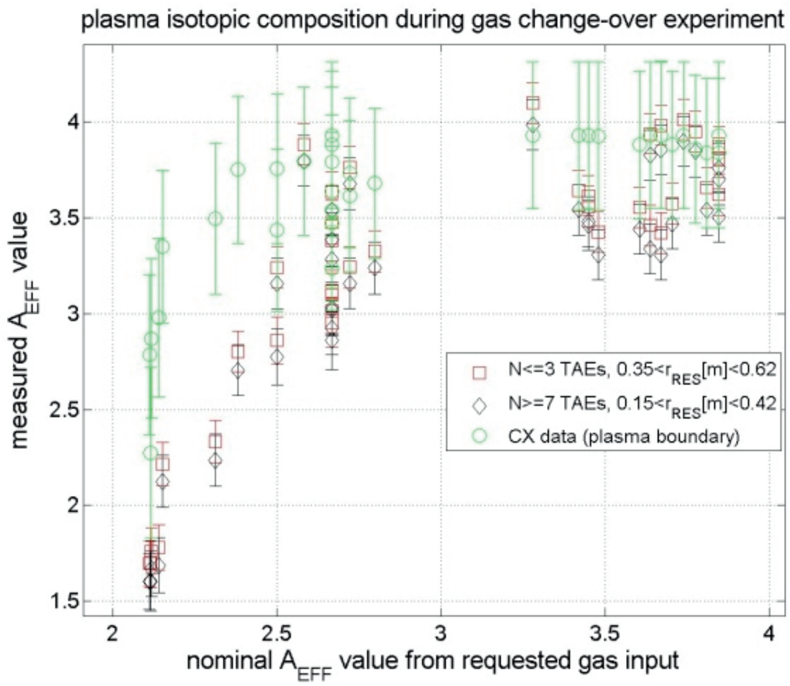

Fig. 2.5.3 *Measurement of the plasma isotopic composition A_{EFF} as function of its nominal value, comparing the results from the charge-exchange diagnostics (CX) with those using TAEs for different toroidal modes numbers N.*

2.5.7 Plasma surface interactions in collaboration with the University of Basel

The effects of low flux, low temperature deuterium plasma (LTP) exposure on nanocrystalline rhodium (Rh) films are investigated. The exposures do not cause any surface damage on the nanoscale and the specific electrical resistivity of the films remains invariant during exposures. However, the spectral reflectivity of Rh decreases during exposure and recovers very slowly during subsequent storage in high vacuum. This drop in the reflectivity can be associated with a formation of a subsurface rhodium deuteride (RhDx, x<2), which has optical constants different to those of Rh. After air storage of the exposed samples, the Rh surface gets depopulated of deuterium adsorbates due to a catalytic reaction taking place between oxygen and deuterium, which results in a diffusion of the incorporated deuterium first to the surface and then into the air.

EFDA Technology Tasks

WP13-IPH-A01-P2-01: Identify phase formation of W with N on samples exposed in tokanak or in TSI 5/2 by XPS
WP13-IPH-A01-P3-02: Deuterium retention of W/N/O films

JET Fusion technology

JW13-FT-3.78: Analysis of mirrors exposed in JET-ILW and procurement of mirrors for exposure in JET 2014 campaigns: First Mirror Test for ITER
JW13-FT-3.79: Plasma cleaning of Be coated mirrors

ITER IO

Amendment N 1 to Service Contract IO/CT/12/4300000557 – Design and Mock-ups for a RF Plasma Sputtering Cleaning System for ITER Diagnostic Fist Mirrors
ITER/CT/13/4300000852: RF Plasma Sputtering Cleaning System for ITER First Mirror Mock-up.

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 6.1 presents the 9 courses given to physics undergraduates and to engineering undergraduates. In their fourth and final 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 (4^{th} 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. 10 PhDs were awarded in 2013. At the end of 2013 we had 24 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 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.

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.

J.B. Lister, *Maître d'Enseignement et Recherche (MER) – "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.

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 2013, CRPP staff members have supervised 5 students performing their Advanced Physics Laboratory work. During the Automn semester of 2013, we had 10 students.

3.3 EPFL Master degrees awarded in 2013

Misev Cyril, *"Fast particles, Confinement, Tokamak, Instabilities"*

Hamel Nils, *"Ion diffusion in scrape-off layer turbulent flows"*

Vuillemin Quentin, *"Développement d'une version du code de simulation pour les gyrotrons basé sur une approche numérique PIC"*

3.4 Postgraduate studies

Postgraduate courses given in 2013

S. Alberti, P. Bruzzone, B.P. Duval, D. Fasel, J.-P. Hogge, Ch. Hollenstein, A. Howling, Y. Martin, Ph. Spaetig *"Fusion and industrial plasma technologies"*, Doctoral School, EPFL

S. Brunner, J. Graves, *"Plasma instabilities",* Doctoral School, EPFL

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

Doctorate degrees awarded during 2013

Karim BESSEGHIR: *"ITER hybrid and steady-state scenario simulations using DINA-CH"* (EPFL Thesis 5808(2013))
The successful operation of ITER advanced scenarios is likely to be a major step forward in the development of controlled fusion as a power production source. ITER advanced scenarios raise specific challenges that are not encountered in presently-operated tokamaks.
In this thesis, it is argued that ITER advanced operation may benefit from optimal control techniques. Optimal control ensures high performance operation while guaranteeing tokamak integrity. The application of optimal control techniques for ITER operation is assessed and it is concluded that robust optimisation is appropriate for ITER operation of advanced scenarios. Real-time optimisation schemes are discussed and it is concluded that the necessary conditions of optimality tracking approach may potentially be appropriate for ITER operation, thus offering a viable closed-loop optimal control approach.
Simulations of ITER advanced operation are necessary in order to assess the present ITER design and uncover the main difficulties that may be encountered during advanced operation. The DINA-CH&CRONOS full tokamak simulator is used to simulate the operation of the ITER hybrid and steady-state scenarios. It is concluded that the present ITER design is appropriate for performing a hybrid scenario pulse lasting more than 1000s, with a flat-top plasma current of 12MA, and a fusion gain of $Q \cong 8$. Similarly, a steady-state scenario without internal transport barrier, with a flat-top plasma current of 10MA, and with a fusion gain of $Q \cong 5$ can be realised using the present ITER design.
The sensitivity of the advanced scenarios with respect to transport models and physical assumption is assessed using CRONOS. It is concluded that the hybrid scenario and the steady-state scenario are highly sensitive to the L-H transition timing, to the value of the confinement enhancement factor, to the heating and current drive scenario during ramp-up, and, to a lesser extent, to the density peaking and pedestal pressure.

Ciro CALZOLAIO: *"Irreversible degradation in Nb_3Sn Cable in Conduit Condcutros"* (EPFL Thesis 5952(2013))
One of the biggest goals for the international thermonuclear experimental reactor (ITER) is the steady state operation. For this reason all its coils will be superconducting and Nb3Sn material is used for both the toroidal field (TF) and the

central solenoid (CS) coils. The primary current carrying unit in a coil is the cable, which contains hundreds of superconducting strands. The ITER coils will be made using a kind of cable called cable in conduit conductor (CICC). Both CS and TF magnets have to withstand several electromagnetic (EM) cycles in their lifetime. This has been discovered to cause a severe reduction of the magnet performances. Nb_3Sn is a brittle material, therefore it is very strain sensitive. The knowledge of the strain state in a CICC allows the explanation of the performances of the cable itself, providing also information regarding the permanent damaging of the Nb_3Sn structure. The measurement of the Nb_3Sn strain state in a CICC is a very challenging task because it is not possible to make it directly. An indirect technique that allows the measurement of the thermal strain through the measurement of the magnetic susceptibility vs. temperature ($\chi(T)$) for a CICC has been developed. A CICC is a complex system and as such it behaves in a way which is not directly predictable studying the single components. The elastic deformation of the superconducting layers produces reversible phenomena which interact with irreversible phenomena due to Nb_3Sn fractures and to plastic deformations of the matrix surrounding the superconducting layers. Reversible and irréversible phenomena occurs together and are deeply shuffled such that it is not straightforward the explanation of the cable performance. The magnetic susceptibility measurements, via an appropriate data analysis, allow to quantify and to separate the thermal strain from the jumble of parameters necessary to describe the cable performance. Several TF and CS samples have been measured with this technique in the SULTAN test facility. Each cable behaves differently from the others but at least it is possible to identify common features. For some samples, the evolution of the performance with the EM cycles is dominated by reversible rearrangements of the strand position in the cable and consequently by the change of the strain distribution during the EM load, for others it is dominated by breakages and irreversible phenomena.

Michael CHESAUX: *"A grid reactor with low ion bombardment energy for large area PECVD of thin film silicon solar cells"* (EPFL Thesis 5686(2013))
This thesis presents the development and study of a plasma processing radio-frequency (RF) reactor design using intense localized plasmas in a grid. The aim is to reduce the ion bombardment energy inherent in RF capacitively-coupled parallel-plate reactors used to deposit large area thin lm silicon solar cells. High ion bombardment energy can cause defects in silicon layers and deteriorate electrical interfaces, therefore, by reducing the ion bombardment energy, lower defect density might be obtained.
The approach followed in this study was to insert a grounded grid inside a symmetric parallel-plate reactor. The reactor and grid were designed to form a uniform array of intense localized plasmas in the grid holes. The grid then divides the symmetric parallel-plate reactor into two connected volumes: a parallel-plate RF plasma source above, and a grounded chamber below. The plasma fills both volumes by conducting the plasma potential via the plasma in the grid holes. In this way, the grounded chamber increases the effective area of the grounded electrode, thereby creating a novel asymmetric-area reactor whilst maintaining a uniform plasma across the substrate. The low ion bombardment energy in this grid reactor is a consequence of the negative DC self-bias caused by this strong electrode asymmetry. In addition to the self-bias, the time evolution of plasma light emission and plasma potential RF waveform are also affected by the grid, thereby further reducing the time-averaged plasma potential and ion bombardment energy.
The analysis of these phenomena was supported by a wide range of complementary plasma diagnostics (i.e. retarding field energy analyser, phase-resolved optical emission spectroscopy, capacitive probe and Langmuir probes). The measurements

were complemented by a numerical fluid simulation which reproduced the observed physics.
In parallel to the plasma diagnostics, silicon thin films were deposited using a semi- industrial version of the grid reactor. The analysis showed that the layer defect densities and the best solar cells obtained with this grid reactor are approaching the quality of the reference cells obtained with other low energy ion bombardment reactors.

Cornelis DE MEIJERE: *" An experimental study of plasma fluctuations in the TCV and TEXTOR tokamaks"* (EPFL Thesis 5610(2013))
The main body of this thesis reports on the commissioning and first measurements with a novel tangential phase-contrast imaging (TPCI) diagnostic, which had previously been installed in the TCV tokamak. The instrument measures fluctuations in line-integrated electron density along 9 parallel chords within a 6 cm diameter CO_2 laser beam.
TPCI measurements reveal the first evidence in TCV of the geodesic acoustic mode (GAM), which is an oscillating zonal flow. Frequency, radial wavelength, radial extent and propagation are all in qualitative agreement with a gyro-kinetic simulation and recent theoretical work. The mode is found to have a modest, but measurable magnetic component, whose spatial structure is characterised for the first time in a toroidal plasma. For some experiments, clear evidence is found of the theoretically expected $m/n = 2/0$ mode structure, although in others the structure appears to be more complex.
Electron energy confinement in X2 heated TCV L-mode plasmas had previously been observed to increase on changing the triangularity (δ) of the poloidal plasma cross-section from $\delta = +0.4$ to $\delta = -0.4$. Measurements with the TPCI diagnostic reveal that this change coincides with a clear decrease in both the absolute level and the decorrelation time of broadband electron density fluctuations. This is in agreement with the conjecture that the increased confinement time is caused by a change in the turbulent state.
The second part of the thesis reports on a fluctuation study in the TEXTOR tokamak. At sufficiently weak toroidal magnetic field, NBI heated, limited TEXTOR plasmas exhibit bursts of beam-ion driven ‘fishbone’ and Alfvén modes, which are characterised using the multi-antenna reflectometer and Mirnov coils. In H-mode the fishbone trig- gers ELMs and in L-mode it triggers previously unobserved bursts of particle recycling, resembling the ELMs. The reflectometer phase shows statistically significant bispectral coherence between the fishbone and the Alfvén modes, indicative of non-linear coupling between them.
Additionally, using conditional averaging techniques, two ELM precursor modes are found that are not related to the beam-ions. The first is a global mode with toroidal mode number $n = -2$, which is also seen with the Mirnov coils. Bispectral analysis of the reflectometer signals shows that this mode modulates the amplitude of broad-band turbulence in the pedestal. The second ELM precursor is a down-chirping mode with a poloidal wavelength of 6cm.

Nazar ILCHUK: *“Characterization and modeling of neutron irradiation, pre-deformation and warm prestressing effects on the fracture behavior of the tempered martensitic steel Eurofer97”* (EPFL Thesis 5867(2013))
The high-chromium reduced activation tempered martensitic steel Eurofer97 has been developed as structural materials for the future thermonuclear fusion reactors. It is being subject of many research activities and characterization to assess its applicability in the aggressive irradiating environment of deuterium-tritium plasma. In this study, the evolution of the Eurofer97 mechanical properties following neutron irradiation and forging at room temperature was investigated. The

focus of this work was put on the plastic flow and fracture properties measured with small and ultra- small, standard and non-standard specimens, for which new evaluation methods were proposed.

Two specimen sets, containing sub-sized pre-cracked compact tension specimens and small flat tensile specimens, were irradiated up to doses of 0.33 and 0.37dpa (displacement per atom) at 150°C and 350°C respectively, in the experimental reactor at AEKI-KFKI in Budapest. The irradiation-hardening (increase of the yield stress) and post-yield behavior were measured with small flat tensile specimens in the temperature range from -120°C to 20°C. Berkovich and Vickers tests micro-hardness were also performed at room temperature on the broken parts of sub-sized irradiated compact tension specimens as well as on the unirradiated Eurofer97. A series of micro-pillars were produced by focused ion beam and tested at room temperature on the unirradiated and irradiated at 150°C Eurofer97. Embrittlement caused by the neutron irradiations was characterized by positive temperature shift of the median fracture toughness-temperature curve *K(T)* describing the fracture toughness behavior in the lower to middle ductile-to-brittle transition region. The approach used was that recommended in the Master Curve method (approved as the ASTM standard E1921) to determine the reference temperature T_0 at which the median toughness is 100MPa√m. The embrittlement was quantified by positive shifts ΔT_0 of the *K(T)* curves. The most significant ΔT_0 shift of 95°C was observed for Eurofer97 irradiated at 150°C, while ΔT_0=52°C was measured for 350°C irradiation.

The tensile and fracture properties of cold-forged Eurofer97 plates, deformed in compression by about 8%, were also determined. This mechanical treatment was applied to increase the yield stress of the material and, at the same time, to decrease the strain-hardening. Thus, the constitutive behavior of the cold-forged material mimics that of the irradiated one, even though the underlying hardening mechanisms are different. Small flat tensile specimens and sub-sized pre-cracked compact tension specimens were employed to characterize the constitutive and fracture behavior of this cold-forged Eurofer97. An increase of the yield stress was found accompanied by a significant decrease of the strain-hardening capacity. A moderate ΔT_0 temperature shift of 18°C of the *K(T)* curve was determined.

Two series of tests on sub-sized pre-cracked compact tension specimens with two different sizes were realized to assess the warm prestressing effects on the effective fracture toughness Eurofer97. Warm prestre sssing effects can be of great importance when temperature-load-unload transients are involved and have to be taken into account in embrittlement evaluation. The specimens were pre-loaded at room temperature before being tested at low temperature in the low transition region. A practically temperature independent increase of fracture toughness was found, at least in the lower shelf region were the tests were conducted. However, the increase was shown to be specimen size dependent and was tentatively attributed to the difference in the residual stress states introduced during the pre-loading sequence between specimens.

Residual stresses, introduced by pre-loading at room temperature around the notch of flat tensile specimens of the tempered martensitic steel F82H-mod, were measured by neutron diffraction using POLDI facility at PSI-Switzerland. This activity was realized in the context of assessing the effects of warm-pressing on the notch and crack toughness of tempered martensitic steels. The specimen geometry was specially designed to avoid a too large residual elastic strain gradient in the vicinity of the notch. The pre-load level was chosen to introduce a sufficiently high residual elastic strain field. Finite element simulations were run to supplement the experimental data. Among the three perpendicular strain components measured, two were found very close the calculated ones, while one exhibits more discrepancy that may be associated a pre-existing residual stress in the as-received F82H-mod steel.

Finite element models were developed for Vickers, Berkovich and axisymmetric indentations, as well as for micro-pillars. From the models of these non-standard small specimen test techniques, ad-hoc methods were proposed to determine theconstitutive behavior represented by a simple power law describing the true stress- strain curves. From the micro-pillar deformation, it was shown that it is possible to reconstruct the true stress-strain curve satisfactorily up to about 5% strain, while the indentation allows assessing the constitutive behavior up to larger strain.
The 1% failure lower bound temperature dependence of the Eurofer97 fracture toughness data in the transition region in all the conditions studied was successfully modeled with a local approach criterion of fast fracture, based upon the attainment of a critical stress σ^* encompassing a critical area A^* to trigger fast fracture. It was shown that the critical stress increases slightly with temperature, while A^* was taken constant. This dependence on σ^* was interpreted as a consequence of the increasing plastic work contribution with temperature in the crack advancement Griffith's criterion. The positive shifts of the reference temperature ΔT_0 of the toughness temperature curve K(T) were well described with the local approach criterion to fracture. Nonetheless, the observed weak dependence of σ^* on the irradiation conditions remains an open issue to be addressed in the future.

Joaquim LOIZU: *"The role of the sheath in magnetized plasma turbulence and flows"*
(EPFL Thesis 5985(2013))
Controlled nuclear fusion could provide our society with a clean, safe, and virtually inexhaustible source of electric power production. The tokamak has proven to be capable of producing large amounts of fusion reactions by confining magnetically the fusion fuel at sufficiently high density and temperature, thus in the plasma state. Because of turbulence, however, high temperature plasma reaches the outermost region of the tokamak, the Scrape-Off Layer (SOL), which features open magnetic field lines that channel particles and heat into a dedicated region of the vacuum vessel. The plasma dynamics in the SOL is crucial in determining the performance of tokamak devices, and constitutes one of the greatest uncertainties in the success of the fusion program. In the last few years, the development of numerical codes based on reduced fluid models has provided a tool to study turbulence in open field line configurations. In particular, the GBS (Global Braginskii Solver) code has been developed at CRPP and is used to perform global, three-dimensional, full-n, flux-driven simulations of plasma turbulence in open field lines. Reaching predictive capabilities is an outstanding challenge that involves a proper treatment of the plasma-wall interactions at the end of the field lines, to well describe the particle and energy losses. This involves the study of plasma sheaths, namely the layers forming at the interface between plasmas and solid surfaces, where the drift and quasineutrality approximations break down. This is an investigation of general interest, as sheaths are present in all laboratory plasmas. This thesis presents progress in the understanding of plasma sheaths and their coupling with the turbulence in the main plasma. A kinetic code is developed to study the magnetized plasma-wall transition region and derive a complete set of analytical boundary conditions that supply the sheath physics to fluid codes. These boundary conditions are implemented in the GBS code and simulations of SOL turbulence are carried out to investigate the importance of the sheath in determining the equilibrium electric fields, intrinsic toroidal rotation, and SOL width, in different limited configurations. For each study carried out in this thesis, simple analytical models are developed to interpret the simulation results and reveal the fundamental mechanisms underlying the system dynamics. The

electrostatic potential appears to be determined by a combined effect of sheath physics and electron adiabaticity. Intrinsic flows are driven by the sheath, while turbulence provides the mechanism for radial momentum transport. The position of the limiter can modify the turbulence properties in the SOL, thus playing an important role in setting the SOL width.

Anna PROKHODTSEVA: *"Modelling oriented investigations of primary radiation damage in ultra high purity Fe and FeCr alloys"* (EPFL Thesis 6008(2013))
In the quest of the structural materials for the future fusion reactor, it has been shown that ferritic/martensitic (F/M) steels are very promising candidates, with a good radiation resistance in terms of damage accumulation in the microstructure relative to for example austenitic steels. However, our ability to predict their response to irradiation in such harsh conditions is still not satisfactory. In this view, there is a critical need for information on the primary damage occuring in this materials class, as input to the multiscale modelling of the irradiation effects, including the impact of He and H. Despite numerous studies in the last 50 years, there is still lack of knowledge in many areas of the irradiation response of the microstructure of ferritic steels. This is due to the complexity of these materials, for they contain numerous alloying elements, grains boundaries and precipitates. The strategy nowadays to identify basic mechanisms of primary damage is to investigate so-called model alloys of those, which allows parametric studies in simplified structures.
In this work ultra high purity Fe and Fe(Cr) model alloys were investigated in a transmission electron microscope (TEM) under ion irradiation in an attempt to better understand the fundamental mechanisms of radiation damage starting from the lowest doses, and the dependence on Cr content. Attention is also paid to the effects of He and H. Radiation-induced dislocation loops and cavities were quantified. This study provides data for validation of the modelling efforts.
Single, dual and triple beam ion irradiations were performed in JANNuS facility located on two sites, in Orsay and in Saclay in France. In Orsay, electron transparent thin foils of UHP Fe, Fe -5, -10 and -14Cr were irradiated in situ in TEM as a single beam experiment with 500keV Fe^+ ions and as a dual beam experiment with 500keV Fe^+ and 10keV He^+ ion beams, to a dose of 1 dpa with and without 1000appm/dpa He at room and liquid nitrogen temperatures in order to observe the very first defects, desirably before their thermal evolution. Effects of dose rate on the produced damage were assessed in UHP Fe. The impact of He and Cr on defect accumulation was scrutinized in terms of the number density, size and Burgers vector of the visible defects. Special care was taken in the analysis of the TEM micrographs, for which new techniques were developed, with a particular one to determine the Burgers vector of a dense dispersion of fine nanometric defects. Emphasis was put on the identification of the loops Burgers vector, which is considered to be either $a_0<100>$ or $^1/_2a_0<111>$ in ferritic materials.
In order to study the effect of the free surfaces of the electron transparent thin specimens on the irradiation induced microstructure, the results obtained for TEM thin foils were compared to bulk samples that were irradiated ex situ in Saclay in single beam experiments with 24MeV Fe^{8+} ions, and dual beam ones with 24 MeV Fe^8 to 1dpa and 2MeV He^+ ions 1000appm/dpa He at RT. To study synergistic effects of He and H a triple beam bulk irradiation with 24 MeV Fe^{8+}, 2MeV He^+ and 0.6MeV H^+ ions, to 1 dpa, 1000appm/dpa He and 4000appm/dpa H at room temperature was performed. From the bulk specimens thin lamellae were extracted by focused ion beam, which allowed the TEM observation of the damage through the whole implanted range of about 3.5μm. In this way, the effect of irradiation with and without He and synergistic effects of simultaneous He and H implantation on the produced defects were assessed. In addition, radiation induced hardening was assessed by nano-indentation and related to the radiation induced microstructure.

The analysis shows that in thin foils of UHP Fe the defect population is dominated by $a_0\langle 100\rangle$ defects, while in presence of He it is dominated by $^1/_2a_0\langle 111\rangle$ loops after irradiation to 1dpa. It indicates that helium stabilizes mobile $^1/_2a_0\langle 111\rangle$ loops, which in thin foils otherwise escape to the free surfaces. Irradiation to the lowest dose of 0.05 dpa resulted in the production of either increased ratio of $^1/_2a_0\langle 111\rangle$ loops, compared to the highest dose, or in the entire population of $^1/_2a_0\langle 111\rangle$ loops in all materials in single and dual beam. In bulk UHP Fe and Fr(Cr) samples after single and dual beam irradiation mainly $^1/_2a_0\langle 111\rangle$ loops and few a xxx loops were observed, but of smaller size than in thin foils, emphasizing the effects of free surfaces on the type of produced loops. It is thus inferred that $^1/_2a_0\langle 111\rangle$ loops dominate the early loop population and visible $a_0\langle 100\rangle$ loops observed in UHP Fe and Fe(Cr) thin foils stem from addition and/or absorption reactions between $^1/_2a_0\langle 111\rangle$ loops. It follows that these reactions are reduced by the presence of He, which may eventually impede the formation of a $a_0\langle 100\rangle$ loops, leaving a loop population dominated by $^1/_2a_0\langle 111\rangle$ loops. The same type of reactions are valid for Fe(Cr) alloys, but the reduction in mobility of $^1/_2a_0\langle 111\rangle$ loops by Cr in the single beam case and the synergistic effects of He and Cr after dual beam irradiation result in a mixed population of $^1/_2a_0\langle 111\rangle$ and $a_0\langle 100\rangle$ type loops. This confirms the idea that the formation of visible $a_0\langle 100\rangle$ loops is promoted by the presence of free surfaces.

Irradiation of UHP Fe thin foil at liquid nitrogen temperature confirmed the assumption of initial $^1/_2a_0\langle 111\rangle$ loops. These then escape to the free surfaces after warming to RT, the more so in the thinnest regions of the sample leaving a loop population dominated by a $a_0\langle 100\rangle$ loops. In single beam irradiated UHP Fe no dependence of the total density of defects or their Burgers vector on the rate of irradiation was observed. However, in the presence of He, only $^1/_2a_0\langle 111\rangle$ loops formed under higher dose/implantation rates, while at the lowest dose rate results were similar to the single beam. This observation is attributed to the local increase of the effective He/defect ratio in the case of the high dose rate due to the increased temporal overlap of displacement cascades.

Regarding mechanical properties, it appears that hardness of the as received materials increases with increasing Cr content. Following irradiation there is a significant hardening, which is not monotonous with Cr content, and which increases for all materials when irradiated together with He, and the more so when irradiated simultaneously with He and H. Hardening relates well to the observed microstructure and is the largest for Fe-5Cr.

Ralf SCHNYDER: *"DC Breakdown in gases for complex geometries from high vacuum to atmospheric pressure"(EPFL Thesis 5962(2013)*

This thesis presents an experimental investigation and a numerical simulation of breakdown in a ring assembly. Previous works are mostly limited to breakdown in simple geometries such as parallel plates or pin-to-plate. Here we discuss the effect of more complex geometries for DC breakdown in gases over a large pressure range from high vacuum to atmospheric pressure. The breakdown voltage versus pressure curves shows a similar shape as Paschen curves but with a wide flat plateau between the low and high pressure thresholds. The low pressure threshold determines the limit between gas and vacuum discharges. Additional optical emission spectroscopy confirms the presence of two different kinds of discharges: Gas and vacuum discharges. Moreover the global shape of the gas breakdown voltage curve in the ring assembly has been fully understood by a complementary numerical simulation. Further current-voltage study showed that voltage only is the most significant factor for breakdown and that current determines the kind of discharge after breakdown. As the breakdown voltages are lower for gas discharges than for vacuum discharges, a numerical simulation model for gas breakdown using a fluid model was developed in order to support the experimental conclusions. Starting as simple as possible with par- allel plates (1mm and 100mm gap width representing approximatively the shortest and longest electric field path length in the ring assembly geometry) and extending to double gap and multi-gap geometries, an understanding of the overall shape of the breakdown voltage versus pressure curve is established: The high (low) pressure thresholds of gas discharge are determined by the shortest (longest) electric field path length in a complex geometry. Moreover, the availability of multiple path lengths leads to a breakdown voltage minimum over a wide range of intermediate pressure because breakdown can occur in the most favorable gap. Finally, the numerical simulation in the ring assembly shows the importance of parameters such as the secondary electron emission coefficient which play a major role in determining the breakdown voltage value.

Thibaud VERNAY: *"Collisions in Global Gyrokinetic Simulations of Tokamak Plasmas using the Delta-f Particle-In-Cell Approach: Neoclassical Physics and Turbulent Transport"* (EPFL Thesis 5638(2013))

The present work takes place within the general context of research related to the development of nuclear fusion energy. More specifically, this thesis is mainly a numerical and physical contribution to the understanding of turbulence and associated transport phenomena occuring in tokamak plasmas, the most advanced and promising form of magnetically confined plasmas. The complexity of tokamak plasma phenomena and related physical models, either fluid or kinetic, requires the development of numerical codes to perform simulations of the plasma behaviour under given conditions defined by the magnetic geometry as well as density and temperature profiles. The studies presented in this work are based on electrostatic kinetic simulations, taking advantage of a reduced kinetic model (the gyrokinetic model) which is particularly suitable for studying turbulent transport in magnetically confined plasmas, in effect solving an approximate form of the Vlasov equation for the distribution function of each species (electrons, ions) along with a reduced form of the Poisson equation providing the self-consistent electric fields.

The main tool of this work, the gyrokinetic ORB5 code making use of numerical particles according to the Particle-In-Cell (PIC) method, has been upgraded during this thesis with different linearized collision operators related to both ions and electrons. The BIRDIE code, enabling to study collisional effects on the evolution of Langmuir waves in an unmagnetized plasma, has been written in order to serve as a test-bed for the collision operators ultimately implemented in ORB5. Some essential algorithms related to collisional simulations have been jointly implemented, such as the two-weight scheme which is extensively described in this work. The collision operators in ORB5 have been further carefully tested through neoclassical simulations and benchmarked against other codes, providing reliable levels of collisional transport. Together with different procedures controlling the numerical noise, the collision operators have then been applied to the study of collisional turbulent transport in two different regimes, the Ion-Temperature-Gradient (ITG) regime and the Trapped-Electron-Mode (TEM) regime requiring a trapped electron kinetic response. Although not dominant in core tokamak plasmas, collisional effects nevertheless lead to interesting modifications in the turbulence behaviour which are not captured by the often considered collisionless gyrokinetic models. The so-called coarse-graining procedure, a noise-control algorithm which is suitable for collisional gyrokinetic simulations with particles, is shown to enable carrying out relevant simulations over many collision times. Consequently, reliable conclusions regarding turbulent transport in the presence of collisions could be drawn in this thesis. Namely, the turbulent transport in the ITG regime is found to be enhanced by ion collisions through interactions with so-called zonal ows associated to axisymmetric modes, while it is reduced by electron collisions in the TEM regime through electron detrapping processes. The zonal flow dynamics in collisionless and collisional ITG turbulence simulations is studied, emphasizing the limitation of the zonal flow level due to Kelvin-Helmoltz-type instabilities. Additionally, some purely collisionless issues related to tokamak physics are discussed, such as the finite plasma size effects in TEM-dominated régime which are found to be important in non-linear simulations but unimportant in linear simulations. The role of zonal flows in temperature-gradient-driven TEM turbulence saturation is confirmed to be weak, in agreement with previous studies. Finally, a realistic global gyrokinetic simulation, accounting for a proper TCV tokamak magnetic equilibrium and related experimental profiles, has been successfully carried out thus demonstrating the relevance of the ORB5 code for predictions related to physics of real tokamaks. A good agreement with GAM experimental measurements is indeed obtained.

David WAGNER: *"Electron and Impurity Transport Studies in TCV Tokamak"* (EPFL Thesis 5720(2013)

In this thesis electron and impurity transport are studied in the Tokamak à Configuration Variable (TCV) located at CRPP-EPFL in Lausanne. Understanding particle transport is primordial for future nuclear fusion power plants. Modeling of experiments in many specific plasma scenarios can help to understand the common elements of the physics at play and to interpret apparently contradictory experiments on the same machine and across different machines.

The first part of this thesis deals with electron transport in TCV high confinement mode plasmas. It was observed that the electron density profile in these plasmas flatten when intense electron heating is applied, in contrast to observations on other machines where the increase of the profile peakedness was reported. It is shown with quasi-linear gyrokinetic simulations that this effect, usually interpreted as collisionality dependence, stems from the combined effect of many plasma parameters. The influence of the collisionality, electron to ion temperature ratio, the ratio of temperature gradients, and the Ware-pinch are studied with detailed parameter scans. It is shown that the complex interdependence of the various plasma parameters is greatly simplified when the simulation results are interpreted as a function of the average frequency of the main modes contributing to radial transport. In this way the model is able to explain the experimental results. It was also shown that the same basic understanding is at play in L-modes, H-modes and electron internal transport barriers.

The second part of the thesis is devoted to impurity transport. A multi-purpose gas injection system is developed, commissioned and calibrated. It is shown that the system is capable of massive gas injections to provoke disruptions and delivering small puffs of gaseous impurities for perturbative transport experiments. This flexible tool is exploited in a series of impurity transport measurements with argon and neon injections. The impurities are observed by detecting their radiation in the soft x-ray range. The effect of varying background plasma parameters on the soft x-ray emissivity temporal and spatial evolution is tested. Argon emissivity displays a rising emissivity signal following the injection with a time constant of about 15ms, and a clear decay phase about ten times slower than the rise time. Neon stays considerably longer in the plasma, much longer than the expected difference in transport properties. It is shown that centrally deposited electron heating enhances impurity transport, whereas increasing plasma current leads to better argon confinement. Varying the plasma position relative to the injector and the background electron density did not result in significant effect on impurity transport. The shape scans varying the plasma elongation, triangularity and comparing limited and diverted configurations, were inconclusive and possible future experiments are proposed. It is shown that their effect are not sufficiently significant to study them separately, therefore a combined experimental campaign accounting for the various couplings is required. The experimental results are interpreted using a diffusive-advective picture. A tool chain is developed and tested providing transport coefficients for the plasma current and electron cyclotron heating experiments. The inverse diffusive-advective transport equation is solved and the obtained transport coefficients reproduce well the experimental soft x-ray emission profile evolution. It is shown, however, that the soft x-ray evolution is somewhat insensitive to variations in the advection velocity profile, that is a strongly positive (outward) or strongly negative (inward) advection result in very similar soft x-ray evolution. This is shown to be due to both the high sensitivity of SXR radiation on T_e and hence of the limited range of relevance ($\rho_\psi \leq 0.4$) and on the sawtooth activity which acts as a large effective diffusion.

Ph.D. Theses supervised by CRPP staff at the end of 2013

Himank ANAND: *"Real time control of plasma shape using poloidal flux measurements"*
A plasma shape control algorithm, using real-time magnetic equilibrium reconstruction, was successfully commissioned and demonstrated during the 2013 TCV campaign. This algorithm, with appropriate improvements and additions, will be employed in the next TCV campaign to assist experiments with advanced plasma shapes.

Fabio AVINO: *"Turbulence at the boundary of toroidal plasmas with open and closed magnetic flux surfaces"*
During this year, we carried out the spectral analysis of the plasma coherent structures in the TORPEX device in magnetic configurations with quasi-circular closed flux surfaces. The toroidal and poloidal mode numbers have been measured, revealing the field-aligned nature of the mode structure. A first comparison with the linear GBS code indicates a dominant ballooning character of the measured modes.

Alexandre BOVET: *"Non-diffusive transport of fast ions in TORPEX"*
The study of the time-averaged fast ion current profiles and their comparison with numerical simulations has revealed different regimes of the fast ion transport.
The measurements have validated the numerical results, thanks to the synthetic diagnostic, and confirmed the role of gyroaveraging as an effective mechanism to reduce transport.
On a theoretical side, the use of fractional diffusion equations has been investigated to model the transport of fast ions. Fractional Lévy motion has been used to model temporal correlations and non-Gaussian statistics. A good agreement was found between this model and the numerical simulations.

Falk BRAUNMUELLER: *"Nonstationary operating regimes in Gyrotron oscillators"*
For comparison with experiment, a large database of simulations of nonstationary oscillations on the gyrotron for DNP-NMR has been produced and the evaluation and analysis of experimental data of nonstationary oscillations has progressed. Much effort was given to developping a simulation code with moment-based linearized gyrotron equations, which was also benchmarked and described in a paper, submitted to Physics of Plasmas.

Danielle BRUNETTI: *"MHD properties of hybrid tokamak an RFP plasma"*
The stability of large scale m = 1 helical displacements of tokamak and reversed field pinch (RFP) plasmas with safety factors which have an extremum close to a low order rational (qmin ≈ 1 in tokamaks, and qmax ≈ 1-7 in RFPs), has been investigated using the 3D equilibrium code VMEC and the non-linear initial value stability code XTOR. The non-linear amplitude of such saturated modes obtained with XTOR is compared both with VMEC calculations and with analytic predictions which extend the nonlinear treatment of reversed q plasmas to arbitrary toroidal mode numbers in tokamaks and RFPs. A study of the impact of an n = 1 RMP coil on the helical equilibrium in MAST plasmas by using free boundary VMEC code, has been carried out.

Nikolay BIKOVSKIY: *"High current HTS cable for fusion"*
Calculative part of my work consisted of parametric analysis of the cable design and its mechanical properties. According to this analysis, optimal cable design was found and its critical mechanical parameters were predicted. Verification measurements were done, and its data are in fine agreement with calculations. 60 kA class cable for fusion with parameters, based on the proposed analytical model and proved by measurements, is in the final preparation stage.

Gustavo CANAL: *"Sawtooth Generated Magnetic Islands and properties of the Snowflake divertor"*
Neoclassical tearing modes (NTMs) are thought to be one of the critical limiting plasma instabilities in ITER. In this work, the seeding of NTMs by sawteeth is investigated in order to improve the development of new strategies for NTM prevention. Another outstanding issue encountered in controlled nuclear fusion research is the handling of the exhaust power in the divertor. In this part of the work, the potential advantages of the snowflake divertor concept for alleviating the heat loads on the plasma facing components are investigated experimentally and through modelling.

Julien DOMINSKI: *"An arbitrary-wavelength solver for the gyrokinetic quasi-neutrality equation"*
The development of a Fortran module able to compute the polarization drift contribution to the gyrokinetic quasi-neutrality equation for arbitrary wavelengths gas been pursued. This module is polymorphic, i.e. able to adapt to different geometries (slab, cylinder, tokamak) and boundary conditions (periodic, Dirichlet, unicity,...). A slab prototype and first results were presented at the PASC conference 2014 in Zurich.

Lucia FEDERSPIEL: *"Rotation and Impurity Studies in the presence of MHD activity and Internal Transport Barriers on TCV"*
During this year extensive work on transport barriers has been performed to better understand the formation and characteristics of eITBs on TCV, using toroidal and poloidal rotation measurements. The poloidal rotation, E_r and the E×B shearing rate have been derived systematically from the asymmetry of the toroidal rotation measurements at the HFS and LFS.
Two scenarios, a central barrier and a strong off-axis eITB, were developed at Z=0cm to facilitate CXRS analysis. 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 was investigated for both targets. The barrier strength increases with cnt-CD applied on axis, higher total power and

negative Ohmic perturbations. A barrier in Te at 7keV and ne with a 23cm barrier width, confinement factor H_{RLW}=5.4 and $|R/L_{Te}|$=45 was achieved. No special dependence was found between the experimental E×B shearing rate and the confinement factor H_{RLW} or the maximum $|R/L_{Te}|$, confirming that on TCV, the barrier improvement is not linked to E×B shearing rate 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 was 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.

Jonathan FAUSTIN: *"Self-consistent interaction of fast particles and ICRH waves in 3D applications of fusion plasma devices"*
The SCENIC package is used to model in a self-consistent manner ICRH minority heating scenarios in fusion plasma devices. The package has been upgraded to now use the ANIMEC version of the VMEC equilibrium solver and the most recent in-house orbit solver VENUS-LEVIS. We have been able to model JET tokamak plasmas in which ICRH was used to control the sawteeth period. The distribution functions generated by these simulations were used to compute the stability of the n=m=1 internal kink mode

Natalia GLOWA: *"Quench detection and protection of the HTS insert coil"*
A model in Matlab that will allow for the simulation of the quench in a non-insulated YBCO insert coil is under development. The main objective is to study the quench behavior of such coils, calculate the heat and current propagation in order to ensure the safe operation of a real coil.

Zhouji HUANG: *"Experimental study of plasma turbulence in the TCV tokamak"*
The majority of the thesis work performed in 2013 consists of measurements and preliminary studies of plasma turbulence and geodesic acoustic modes (GAM) in the TCV 2013 campaign, with the tangential phase-contrast imaging (TPCI) and Doppler backscattering diagnostics. Dedicated measurements were carried out to investigate the dependence of microturbulence on macroscopic plasma parameters; Turbulence in the eITB region was also studied. Additionally, parametric studies of the dependence of the GAM frequency and amplitude on plasma density, temperature, shape and safety factor were performed.

Josef KAMLEITNER: *"Suprathermal electron studies in Tokamak plasmas by means of diagnostic measurements and modeling"*
The main objective of this work is to improve the current understanding and develop new insight into the physics involving electrons at suprathermal energies in tokamak plasmas. This part of the electron distribution is a key element in ECRH/ECCD and connected to MHD instabilities such as sawteeth. The study is performed on TCV using the novel, state-of-the-art hard X-ray tomographic spectrometer (HXRS) diagnostic in conjunction with theory predictions and Fokker-Planck simulations.
In 2013, the HXRS cameras 2 and 3 were installed. Furthermore, several series of dedicated experiments were carried out, providing, among further results, evidence

of poloidal HXR emission asymmetries and new insight in suprathermal electron dynamics.

Doohyun KIM: *"Stabilisation of NTMs using real-time equilibrium reconstruction"*
The control of NTMs has been enhanced using a real-time (RT) version of the equilibrium code LIUQE. With given q profile from RT-LIUQE, the mode location can be tracked and converted to a requested EC launcher angle. EC beams are directed at the NTM and the mode is successfully stabilized or pre-empted. In addition, a new robust control method (adding sine wave form on the target position) has been successfully demonstrated.

Claudio MARINI: *"Impurity density and momentum transport during the sawtooth cycle"*
An experimental determination of Carbon impurity density and toroidal angular momentum evolution across the sawteeth events has been carried out. Conditionally resampling measurements were employed and led to the determination of the properties of a canonical sawtooth. The development of the new poloidal CXRS system is ongoing, the new spectrometer is commissioned and will be tested soon.

David MARTINET: *"Development of industrial gas-metal plasma sources for the deposition of nanostructured GaN semiconductor layers for lighting applications"*
This CTI project (No. 11548.1 PFIW-IW), in collaboration with Sulzer METCO and the Laboratory of Advanced Semiconductors for Photonics and Electronics (LASPE) at the EPFL, will try to modify the existing RF and DC plasma sources in order to grow GaN films on SiC or sapphire substrates, by evaporating Ga in nitrogen plasma.
During the past year, depositions with the DC plasma source were made, as the new effusion cell has been sent. Different conditions were tested in order to obtain controllable nanocolumns density. The magnetic field has been revealed to be a critical plasma parameter for the growth and the uniformity of the growth of nanocolumns. Beside the plasma experiments in the laboratory, the plasma models, based on the reactions occurring in the chamber, have been further developed. The particle balance equations are solved to obtain the different states densities, including the gallium. The different ratios between the states obtained with the models and the experiments showed good agreement. Thus the developed models have identified the main phenomena occurring at low pressure.

Gabriele MERLO: *"Global gyrokinetic simulations of plasma microturbulence and validation against TCV experimental measurements"*
Most of last year work has been devoted to the study of the effect of triangularity experimentally observed on TCV. Several GENE flux tube simulations, with different degrees of realism, have been performed looking at profile stiffness as a function of electron temperature gradient at different radial positions for both positive and negative triangularity plasmas. Signs of a radial dependent stiffness, as well as stiffness reduction in plasmas characterized by negative triangularity are found. However, finite ρ^* effects appear to be crucial in aiming at reproducing the experimentally measured heat fluxes.

Annamaria MOSETTO: *"Linear and non-linear modelling of scrape off layer instabilities"*
During the last year I have finalized my thesis, focused on the study of the scrape-off layer (SOL) turbulent regimes. We developed a methodology that allows the prediction of the SOL turbulent regimes, given the SOL operational parameters. The methodology is based on the gradient removal saturation mechanism for the turbulence. This mechanism states that turbulence saturation occurs when the radial gradient of the background pressure is comparable to the radial gradient of the pressure fluctuations. Our methodology has been tested against SOL non-linear simulations performed with the GBS code, showing good agreement.

Federico NESPOLI: *"Study of the edge plasma physics in TCV"*
During the last year I worked on edge plasma physics and diagnostics. The main task has been the planning, performing and data analysis of an experimental campaign aimed at measuring the heat loads on the limiter for inboard limited L-mode plasmas in TCV, using infrared thermography. Moreover, I took active part part in the integration on TCV of the new reciprocating Langmuir probe. Finally, I took part in snowflake divertor experimental campaign.

David PFEFFERLE: *"Exploitation of a general-coordinate guiding-centre code for the redistribution of fast ions in deformed hybrid Tokamak equilibria"*
The implementation of the spline-Fourier interpolation scheme within VENUS-LEVIS code was finalised. This technique has considerably improved the calculation of fast particle orbits, in particular in the presence of strong 3D helical cores. VENUS-LEVIS was used to simulate the redistribution of NBI fast ions in saturated internal kinks. Numerical results were compared with experimental data from MAST neutron camera with excellent agreement.

Masuhudan RAGHUNATAN: *"Fast ion guiding center orbits in axisymmetric, toroidally rotating plasmas"*
We aimed to study the effects of rotation on formation of equilibria in axisymmetric rotating plasmas using a magnetohydrodynamic (MHD) model. The equilibria were generated using the Variational Moments Equilibrium Code (VMEC), for free boundary conditions. In order to study the orbits of the particles in such equilibria, the orbit-folowing code VENUS-LEVIS was used, with a particle distribution generated assuming a local Maxwellian in the rotating frame. A poster was presented, encompassing a part of the work done, in the 2014 annual meeting of the Swiss Physical Society (SPS) (June 29-July2, Fribourg).

Fabio RIVA: *"Verification and Validation of SOL plasma turbulence codes"*
During the past year, I verified the GBS code. I used the Method of Manufactured Solutions to perform an order-of accuracy convergence test, in order to verify the implementation of the model equations in GBS, and I estimated the numerical error affecting GBS simulation results, by computing the Grid Convergence Index. Moreover, I extended the ODISEE code to the second dimension in configuration space and I optimized its parallelization.

Joyeeta SINHA: *"Improvement of the plasma formation and its application for the doublet shaped plasma creation on TCV"*
The year 2013 was mainly dedicated to conduct experiments on TCV to understand the dynamics and the main problems associated with the inductive plasma

formation. It was concluded from these experiments that the mismatch between the planned and the actual breakdown timing and plasma current evolution were the main causes for the failure of the plasma formation in TCV. The magnetic configuration and the loop voltage have been identified as tools to control the breakdown timing and plasma current evolution. The knowledge gained from these experiments will be used to develop a better breakdown and plasma current control strategy for the inductive plasma formation.

Christoph WERSAL: *"The interaction between neutral particles and turbulent plasma in the tokamak scrape-off layer"*
The first-principle understanding of the processes in the Scrape-Off-Layer (SOL) of a tokamak is crucial for the developement of a thermonuclear reactor. Since the plasma temperature in the SOL is rather low, the plasma is typically not fully ionized, and the neutral atoms play an important role in determining the SOL regimes. A simple kinetic model for neutral atoms in the SOL has been developed and implemented in the GBS code to study the different SOL regimes in self-consistent non-linear simulations of the turbulent plasma in the SOL.

4 PUBLIC RELATION ACTIVITIES IN 2013

CRPP organised a ‘Fusion Day’ on May 17th at the EPFL. Four speakers (Prof. J. Li, Chinese Academy, China; Prof. J. W. Van Dam, Dept. of Energy, USA; Dr F. Romanelli, EFDA Leader, EU; Dr H. Bindslev, Director of Fusion for Energy, EU) presented to a large public the status and prospects of fusion in the world. About 200 persons attended the talks and took the opportunity to visit TCV.

During the ‘Infrastructure Day’, which took place on November 15th at the EPFL, the Directorate of the CRPP invited Ms D. Leuthard, Federal Councillor, to visit the TCV facility.

Several articles were published in different newspaper in Switzerland. More than 2000 people visited the CRPP.

5 FUSION & INDUSTRY RELATION

The Swiss industry benefits from the services of an Industry Liaison Officer to support procurement opportunities that are arising from the construction of the ITER Experimental Fusion Reactor. 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 either directly from ITER Organization, located in Saint-Paul lez Durance, Cadarache, France.

In 2013 emphasis has been placed to support Swiss SMEs in their business development tasks for wining preliminary contracts in the R&D design phase. Several Swiss SMEs are now extremely well positioned to deliver in the next years strategic components to ITER in a widely diversified technological spectrum.

A large part of the ITER contracts for the manufacturing of the magnetic coils has been recently awarded. In this field a few Swiss companies are now involved in extensive subcontracting activities to other European ITER prime contractors. Mostly mechanical engineering & consulting expertise associated with sales of high precision mixing and metering machines are concerned.

A major in kind procurement contract for the design, manufacture, installation and commissioning of the power supply systems of the gyrotrons to be supplied by the EU and RF was awarded in December 2013 to AMPEGON, a Swiss SME based in Turgi, near Baden. The performances of this equipment are critical since a reliable operation of the overall electron cyclotron wave system is crucial for ITER operation.

APPENDICES

APPENDIX A Articles published in Refereed Scientific Reviews during 2013

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

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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 2013

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B.2 Seminars presented at the CRPP in 2013

Prof. A.E. White, Plasma Science and Fusion Center, Alcator C-Mod Team, MIT, Cambridge, USA, *"Reduction of Core Turbulence in I-mode Plasmas in Alcator C-Mod"*

Dr. E. Kolemen, Princeton Plasma Physics Laboratory and General Atomics, San Diego, USA, *"Summary results from DIII-D NTM control and snowflake divertor experiments are presented"*

Dr. N.T. Howard, Plasma Science and Fusion Center, Alcator C-Mod Team, MIT, Cambridge, USA, *"Experimental and Gyrokinetic Studies of Multi-Channel Transport in the Core of Alcator C-Mod Plasmas"*

Alexandre Poyé, Université de Provence, Marseille, F, *"Magnetic island dynamic with current sheet and turbulence"*

Dr. Michael Chesaux, CRPP-EPFL, *"A grid reactor with low ion bombardment energy for large area PECVD of thin film silicon solar cells"*

Dr. Kees de Meijere, CRPP-EPFL, *"Detailed measurements of oscillating zonal flows in the TCV tokamak"*

Ivone Benfatto, ITER Organization - Electrical Engineering Division, Cadarache – France *"The ITER electrical power distribution and the coil power supplies"*

Fabio Riva, Etudiant EPFL, *"Experimental investigation of filamentary current structures associated with blobs in TORPEX plasmas"*

Dr. H. Heumann, Department of Mathematics, Rutgers, New Brunswick, NJ, USA, *"Plasma Shape and Trajectory Optimizationin CEDRES++"*

Dr. F. Courbin, Laboratoire d'Astrophysique, Observatoire de Sauverny, EPFL, Versoix, CH. *"A golden age for observational cosmology"*

E. Fokina, Bauman Moscow State Technical University, Moscow, RU & Max-Planck-Institute für Plasmaphysik, Garching, D, *"Stabilizing an aircraft on a previously calculated trajectory"*

Dr. F. Hariri, IRFM/SCCP - CEA Cadarache, France, *"FENICIA: A New 3D Code for a General Class of Plasma Models using a New Approach to Field-aligned Coordinate Systems"*

K. Besseghir, CRPP-EPFL, *"Free-boundary simulations of ITER advanced scenarios"*

Dr. J. Cary, Tech-X Corp., Boulder, CO 80303, USA, *"Advances in electromagnetics modeling and application to hybrid photonic-metallic cavities"*

Dr. G. Arnoux, Plasma Boundary Group, JET Diagnostics Unit, Culham Science Centre, Abingdon, UK, *"Power handling of the JET ITER-like wall (limiter and divertor)"*

Yangyang Zhang, University of Gent, B, *"Deuterium Retention and Plasma Characterization"*

Baran Eren, Physics Department, Univ. Basel, CH, *"Effect of Hydrogen Plasma Treatment on the Electronic, Optical, Mechanical and Chemical Properties of Mo, Rh, Au, HOPG and Graphene"*

Dr. J. Anderson, Earth and Space Sciences, Chalmers University of Technology, Göteborg, S, *"Statistical features of drift wave plasma turbulence"*

Dr. Y. Idomura - Japan Atomic Energy Agency, Kashiwa, Chiba 277-8587, Japan, *"Full-f gyrokinetic simulation over a confinement time"*

M. Nakata - Japan Atomic Energy Agency, Rokkasho, Aomori 039-3212, Japan & **Y. Idomura** - Japan Atomic Energy Agency, Kashiwa, Chiba 277-8587, Japan, *"Comparisons on plasma size and collisionality dependence of ITG turbulent transport among fixed-flux, fixed-gradient, and fluxtube models"*

Dr. M. Wischmeier, Max-Planck-Inst. für Plasmaphysik, Garching, D, *"Power Exhaust in Fusion Devices"*

Cyril Misev, EPFL *"Implementation models of RMP fields in single particle simulations and their impact on fast ions"*

Dr. J.V. Minervini, MIT, Boston, USA, *"Research on Superconductor Applications at the MIT Plasma Science and Fusion Center for Energy, Medical, and Security Systems"*

Prof. I.H. Hutchinson, MIT, Boston, USA, *"Computational Studies of Probes and Dust in Flow Plasma"*

Prof. H. Wilson, University of York, York, UK, *"Nonlinear ideal MHD simulations of plasma eruptions: towards a prédictive model for ELM size"*

Joaquim Loizu, CRPP-EPFL, *"The role of the sheath in magnetized plasma turbulence and flows"*

Maria Schillaci, National Institute of Nuclear Physics INFN, Laboratori Nazionali del Sud LNS, Catania, Italy, *"My contribution to the project "ADS system: beam transport and neutron yield measurement of the converters"*

Mahmoud Jafargholi, Etudiant EPFL, *"Real-time Solution of Network Optimization Problems"*

Dr. A.A. Howling, CRPP-EPFL, *"Industrial plasmas at CRPP from 1989 to 2013 - an overview"*

Dr. O. Sauter, CRPP-EPFL, *"On the non-stiffness of edge transport in L-modes"*

APPENDIX C External activities of CRPP Staff during 2013

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

MEMBERSHIP

P. Bruzzone	International Magnet Technology Conference Organizing Committee European Magnet Expert Group 23rd Magnet Technology Conference, Programme Committee EUCAS 2013 Conference, Program Committee Series Connected Hybrid Magnet, Project Review Group
A. Fasoli	EFDA Steering Committee Eurofusion working group International Tokamak Physics Activities: Energetic Particles Topical Group Scientific Committee, IAEA Technical Meeting on Energetic Particles in Magnetic Confinement Systems, 2013 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 Fusenet 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 Helmotz Virtual Institute on Advanced Microwave Diagnostics Review Panel for US Department of Energy "Scientific Discovery through Advanced Computing Initiative"
Ivo Furno	Member of the SPS Committee
Ch. Hollenstein	Editorial Board Plasma Chemistry and Plasma Processing Kluwer Academic/Plenum Publisher Member of the IUVSTA Plasma Division
J.B. Lister	Member of the European Physical Society Executive Committee
A. Pochelon	Member of the Committee of the SWISS NUCLEAR FORUM Secretary of the Swiss Physical Society
O. Sauter	International Tokamak Physics Activities: MHD, Disruption and Control Topical Group
M.Q. Tran	Consultative Committee for the Euratom Specific Research and Training Programme in the field of Nuclear Energy, Fusion (CCE-FU) 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 Vice-Chair and Swiss delegate at the Fusion Power Coordinating Committee Member of the Power Plant Physics and Technology Board

L. Villard	Member, Board of the High Performance Computing for Fusion, EFDA Special working group 1 of the IFERC-CSC Member, Standing Committee of the IFERC CSC Member, Fachbeirat, Max-Planck-Institut für Plasmaphysik
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 Editorial Board IEEE Transaction on THz Science and Technology (Topical editor: THz plasma science and instruments)
S. Coda	Editorial Board of Plasma Physics and Controlled Fusion
A. Fasoli	Associate Editor of the Journal of Plasma Physics
J.B. Lister	Member of the International Advisory Board of Plasma Physics and Controlled Fusion
Y.R. Martin	Member of the EFDA Public Information Network (PIN) Chairman of the Association Vaudoise des Chercheurs en Physique

C.3 EPFL committees and commissions

A. Fasoli	Président de la 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	Director of the Inst. of Physics of Energy and Particle, EPFL Commission du Doctorat de la Section de Physique, FSB-EPFL Commission stratégique de la Section de Physique, EPFL Membre du Comité de Sélection du Prix de la meilleure thèse EPFL "Core Group" of the Master in Nuclear Engineering Programme
T.M. Tran	Groupe de travail technique du Comité de Pilotage HPC/MPC, EPFL
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

Groupe de travail technique HPC (High Performance Computing) – 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:

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

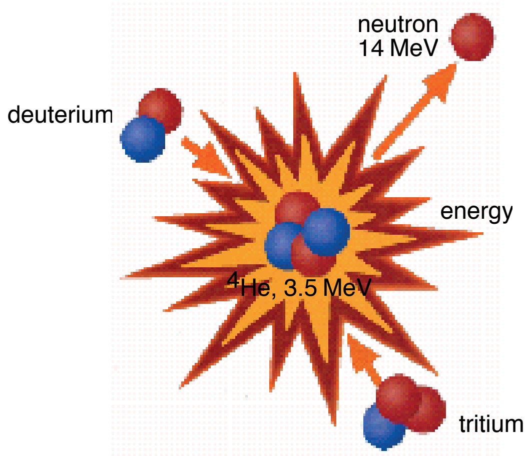

Fig. D.1 *Schematic of a fusion reaction between deuterium and tritium nuclei. The products are 3.5MeV ^{4}He, the common isotope of helium, and a 14MeV free neutron.*

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

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

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

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

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

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

D.2 Attractiveness of fusion as an energy source

The inherent advantages of fusion as an energy source are:

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

Its further potential advantages are:

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

APPENDIX E Sources of Financial Support

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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 Swiss University Conference (SUC)
- the Paul Scherrer Institute (PSI), which hosts the Superconductivity and the Materials 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
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- ITER
- ITER Organization (IO), Cadarache, France
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- 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

- ATELA SA, Neuchâtel
- RUAG Space, Nyon
- Sulzer Metco AG, Wohlen (division acquired by Oerlikon in 2014)
- TEL Solar, Trübbach, subsidiary of Tokyo Electron Ltd., formerly Oerlikon Solar
- Tetra Pak Suisse SA, Romont
- WEKA AG, Bäretswil

APPENDIX F Members of the Steering committee

Members of the Steering Committee of the Association Euratom – Confédération Suisse are:

Present for the Associate:
Members: B. Deveaud, A. Fasoli, M.Q. Tran (Chair), X. Reymond

Present for the EU Commission:
Members: M. Cosyns, G. Sonnino

Experts: D. Borba, P. Bruzzone, Y. Martin, K. Mieusset, P. Ricci, C.Schlatter, L. Villard

Apologies: S. Webster (E.U. Commission)