Implementing Agreement for Co-operation on Tokamak Programmes
(CTP-TCP)
End-of-Term Report 2017-2022

1 Objective

The objective of the Technology Collaboration Programme on Tokamak Programmes (CTP TCP) is to advance fusion energy science and technology by carrying out exchanges of information between the Contracting Parties in the areas relevant for fusion research. These include exchanges related to the experimental programmes of the tokamak facilities; design and planning of experiments on tokamaks contributing to the database for the next-generation devices including, but not limited to, support of joint activities identified by the International Tokamak Physics Activities (ITPA) under ITER; experimental, theoretical and technical studies in the areas of plasma equilibrium and stability, energy and particle transport, plasma heating, plasma-wall interaction, plasma current drive, plasma fuelling and plasma diagnostics. The CTP TCP is one of the main agreements for the implementation of the ITPA, which coordinates activities among the domestic programmes of the signatories to the ITER Agreement.

2 Scope, Research Goals, and Key Achievement

2.1 Scope of Activities

The CTP TCP provides a forum for tokamak programmes of the ITER Members to work closely together in coordinating their tokamak research by carrying out scientific and technological exchanges and holding workshops and meetings for the purpose of advancing the tokamak concept towards fusion energy and support ITER physics and technology needs. The focus of the CTP TCP are the ITER research priority areas, addressing the avoidance, control and mitigation of the key plasma instabilities, protection of the plasma facing components and access to good confinement plasma regimes in ITER.

2.2 Research Goals

The main research goals of the CTP TCP are to support the development of fusion energy by contributing to the scientific exploitation of ITER and the development of a demonstration power plant (DEMO) design. This research is carried out by tokamak experiments operating or under construction around the world, together with the accompanying theory and modelling programmes. The CTP TCP promotes scientific exchanges among all tokamaks operating within the ITER Members' research programmes enhancing the planning of such experiments and efficient implementation of scientific exchanges. These collaborative experiments are carried out under the coordination of the ITPA by the Joint Experiments (JEX) programme supported by ITER. This Programme substantially enhances the understanding of the complex fusion science and engineering issues.

2.3 Key Achievements

2.3.1 Experimental Results

As part of co-ordinated experiments involving Shattered Pellet Injection on Doublet III D-shaped Tokamak (DIII-D), Axisymmetric Divertor Experiment (ASDEX) Upgrade , Superconducting Tokamak Advanced Research (KSTAR) and Joint European Torus (JET); a framework agreement has been put in place between ITER, EURATOM, the United States Department of Energy, the Oak Ridge National Laboratory and the United Kingdom Atomic Energy Authority (UKAEA) to design, construct, install and operate ITER relevant Shattered Pellet Injection hardware on the Joint European Torus (JET). The Shattered Pellet Injection experiments were successfully completed; performing disruption mitigation at high energy and providing unique data for ITER; emphasising the evidence that high-Z injection is not sufficient and deuterium pellets found to be efficient in mitigating Runaway Electrons.

2.3.2 Equipment Upgrades

HL-2M tokamak assembly has been completed with the mission to develop the physics basis for advanced plasma scenarios with flexible divertors; to address burning plasma physics issues and advanced tokamak scenarios in support of future machines. Mega-Amp Spherical Tori (MAST) Upgrade achieved first plasma and conducted first physics experiments with over of 3MW NBI power injected. The manufacturing of the ITER-grade divertor components of the Tungsten (W) Environment in Steady-state Tokamak (WEST) has been completed. Doublet III D-shaped Tokamak (DIII-D) completed the helicon antenna commissioning and started to conduct experiments. The upgrade of Experimental Advanced Superconducting Tokamak (EAST) included a new lower tungsten divertor with new geometry, improvement of the capability of heating systems, position rearrangement of heating and diagnostics.

3 Membership

There are currently seven Contracting Parties (CPs): IEA member countries Japan, Korea, the United States, Australia; Partner country India; and three international organisations

EURATOM, the ITER International Organisation (ITER IO), and the ITER China Domestic Agency (CNDA).

4 Research Highlights by Topic

4.1 Transport and confinement physics

The updated ITPA H-mode confinement database including the new data from Joint European Torus ITER-like Wall and Axisymmetric Divertor Experiment (ASDEX) Upgrade W-wall concluded that the confinement dependence on density and power degradation is weaker in metallic devices with weaker dependence on density, major radius, and stronger dependence on the plasma current with a projection to ITER predicting a 22% reduction in the energy confinement time with respect to the previous scaling. In Doublet III D-shaped Tokamak (DIII-D) stable zero-torque operation using balanced Neutral Beam injection was obtained by modifying the initial current profile, slowing the current ramp and delaying the H-mode transition. Joint European Torus (JET) Deuterium-Tritium experiments sustained high performance plasmas compatible with the ITER-like wall and fusion power consistent with predictions, with a record fusion energy of 59 MJ.

4.2 Divertor/sol physics

A coordinated multi-experiment and simulation effort was initiated via the International Tokamak Physics Activity (ITPA) and through ITER contracts, aimed at improving the physics basis supporting a Mono Block shaping decision from the point of view both of edge power loading and melt dynamics, with experiments on the Joint European Torus (JET), Doublet III D-shaped Tokamak (DIII-D), Superconducting Tokamak Advanced Research (KSTAR), Compact Assembly Tokamak (COMPASS), Pilot-Plasma Surface Interaction (Pilot-PSI), Magnum-Pilot-Plasma Surface Interaction (Magnum-PSI) and Axisymmetric Divertor Experiment (ASDEX) Upgrade. It was concluded that Mono Block top surface shaping is recommended to shadow poloidal gap edges in the high heat flux areas of the ITER divertor targets “R. Pitts et al Nuclear Materials and Energy 12 (2017) 60–74”.

4.3 Integrated operating scenarios

The access to high q_{min} >2 high beta scenarios has been expanded in the Korean Superconducting Tokamak Advanced Research (KSTAR), by early shaping, early heating and H-mode transition controlled by power injection to avoid instabilities. This strategy allows maintaining high q_{min} showing strong dependency of confinement on q_{min} and improved confinement with broader current profiles. Long pulses have been sustained for 30 seconds in hybrid scenarios, however, the performance gradually degraded mainly due to a drop in density and ion temperature. High ion temperature discharges in diverted L-mode edge with Upper Single null was sustained for 20 seconds with stable Internal Transport Barrier.

Experimental Advanced Superconducting Tokamak (EAST) long pulse high beta poloidal plasma operation in support of the Chinese Fusion Engineering Testing Reactor (CFETR) 1GW scenario was obtained with 3.5 MW of radio frequency Heating and Current Drive in the tungsten upper divertor configuration, with improved energy confinement time by increasing the density peaking factor. Divertor detachment studies compatible with the grassy ELM regime considered in the Chinese Fusion Engineering Testing Reactor (CFETR) design were performed providing a robust solution to achieve long-pulse high-performance H-mode operation with high heating power in a metal wall environment with several feedback control schemes, but without the use of Resonant Magnetic Perturbations as these are not foreseen for Chinese Fusion Engineering Testing Reactor (CFETR). Fully non-inductive operation, steady-state scenarios using pure Radio Frequency heating have been developed.

A study has been carried out on data from existing tokamaks to improve our understanding of the dynamics and control of ITER terminations. The aim of this joint analysis is to compare the assumptions for ITER terminations with the present experience basis. The study examined the parameter ranges in which present day devices operated during their terminations, as well as the dynamics of these parameters "P. de Vries et al Nucl. Fusion 58 (2018) 026019".

4.4 Pedestal physics

Promising small ELM regimes for ITER and DEMO were found on Tokamak à Configuration Variable (TCV) and Axisymmetric Divertor Experiment (ASDEX) Upgrade with good core performance, with high fuelling and reduced magnetic shear at the plasma edge.

Experimental Advanced Superconducting Tokamak (EAST) has demonstrated ELM suppression by applying 3-D resonant magnetic fields with toroidal symmetry of $n = 4$ with minimal effect on energy and particle confinement providing first evidence of the viability of such approach to achieve ELM control while ensuring the confinement requirements for ITER $Q = 10$ operation.

Supersonic molecular beam injection (SMBI) technique is envisaged to be an advanced fueling method in magnetic fusion devices, based on which the impurity mixture SMBI has been successfully used in strong ELM mitigation on HuanLiu-2A (HL-2A) tokamak.

4.5 Stability and Control

Major progress in disruption mitigation has taken place thanks to the activities implemented under this TCP. This includes the reduction of radiation asymmetries by torodally distributed injection of shattered pellets in KSTAR, and the demonstration of optimized disruption mitigation by sequential injection of shattered pellets at DIII-D and JET to maximize radiative losses and avoid the generation of runaways. Of particular importance are the results of joint DIII-D/JET experiments, which have identified a novel approach to runaway electron mitigation by injection of deuterium shattered pellets into a fully formed runaway beam leading to negligible localized losses on plasma facing components.

4.6 Energetic particles

Regarding the destabilization of Alfvén eigenmodes and energetic particles driven modes, measurements of damping rates of Alfvén waves have been further developed in the Joint European Torus (JET) and the experimental results agreed well with theory. The control method of Alfvén waves by integrated model has been applied in the Doublet III D-shaped Tokamak (DIII-D); and the control of Alfven waves by Electron Cyclotron Heating and Magnetic Perturbations have been explored. Regarding the interaction of fast ions with background MHD, interaction between neoclassical tearing modes (NTMs) with energetic ions has been observed in Doublet III D-shaped Tokamak (DIII-D) and HuanLiu-2A (HL-2A) tokamak, where frequency chirping of NTMs occurs within a few milliseconds. Recent theoretical and experimental studies have bolstered the case that fast ions might play an important role in NTMs. The interaction between turbulence and energetic ions have been studied and the results agreed well with experimental results in Axisymmetric Divertor Experiment (ASDEX) Upgrade. Ion Cyclotron Heating has been applied in the Joint European Torus (JET) with the generation of energetic Deuterium ions, together with Neutral Beam Injection in mixed Hydrogen and Deuterium plasmas to improve understanding of fast ion losses and Neutral Beam Injection effects on current-drive. Experimental achievements on HuanLiu-2A (HL-2A) tokamak include the experimental identification of Beta induced Alfven eigenmodes driven by energetic electrons, Alfvénic ion temperature gradient modes and geodesic acoustic modes induced by energetic particles, which will not only contribute to better understanding of energetic particles physics, but also provide technology bases for active control of Alfvénic modes on ITER and in the Chinese Fusion Engineering Testing Reactor (CFETR).

4.7 Diagnostics

A series of studies have been conducted to identify and address the key diagnostics required for plasma control and physics studies of ITER and its difficulties, and to further develop the key diagnostics required for ITER to achieve high fusion gain and for future DEMO design. The joint research activities are to optimize life-time of plasma facing mirrors used in optical systems, to assess impact of microwaves on diagnostic systems, to assess Plasma Control System measurement requirements, and to develop diagnostic, calibration techniques and strategies compatible with the burning plasma environment. A joint working group has been established to develop self-consistent data validation procedures for key ITER measurement parameters such as the density, ion and electron temperature, current and q-profile, Zeff , wall condition. The determination of the runaway electron distribution function by spectral bremsstrahlung measurements in the gamma-ray energy range has been studied on the Axisymmetric Divertor Experiment (ASDEX) Upgrade , D-shaped Tokamak (DIII-D) and Experimental Advanced Superconducting Tokamak (EAST). The final analyses of results of the Mirror Station exposure and evaluation of feasibility of future mirror experiments have been conducted on Experimental Advanced Superconducting Tokamak (EAST), as well the new studies on diagnostic mirror cleaning in support of future experiments, together with investigations of single crystal molybdenum and rhodium mirrors in plasma-sputtering environment in the linear Plasma Surface Interaction (PSI-2) device. Analyses of multi-machine exposures of duct mirror systems have been executed on the Mirror Stations in Tokamak Experiment for Technology Oriented Research (TEXTOR), Doublet III D-shaped Tokamak (DIII-D), Axisymmetric Divertor Experiment (ASDEX) and Experimental Advanced Superconducting Tokamak (EAST), in Superconducting Tokamak Advanced Research (KSTAR) and in the baffled cassette in the Joint European Torus (JET). Infra-red Reflections Benchmarking in the Tungsten (W) Environment in Steady-state Tokamak (WEST) and Axisymmetric Divertor Experiment (ASDEX) Upgrade coupled with laboratory experiments are on-going.