**Implementing Agreement for Co-operation on Tokamak Programmes**

**End-of-Term Report
2012-2017**

***Introduction***

**Background**

The Implementing Agreement on Co-operation for Co-operation on Tokamak Facilities, also known as the Technology Collaboration Programme on Tokamak Programmes (CTP TCP), was formed on 15 June 2010 as a merger of activities between two Implementing Agreements.[[1]](#footnote-1)

**Scope**

The scope of the CTP TCP is to advance fusion energy science and technology by carrying out exchanges of information between the Contracting Parties (CPs) 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.

**Relevance**

Fusion research under the CTP TCP is well aligned with the IEA’s goals of energy security, economic growth, environmental protection and engagement worldwide. Fusion energy research under the CTP TCP is also highly relevant to the IEA Medium-Term Strategy for Energy Research and Technology, in particular, to help to accelerate the development and deployment of a broad range of energy technology options and to support continued research and development collaboration efforts and innovation for basic science and frontier or emerging technologies for long-term solutions. The CTP TCP maintains strong links with all the other fusion-related TCPs.

**Contracting Parties**

There are currently seven Contracting Parties (CPs): IEA member countries Japan, Korea, the United States; Partner country India; and three international organisations EURATOM, the ITER International Organisation (ITER IO), and the ITER China Domestic Agency (CNDA).

***Highlights and Key Achievements***

**Overview**

The work conducted under the CTP TCP during 2012-2017 focused on a number of bi-lateral and multi-lateral research collaborations primarily through exchanges of personnel, joint workshops and conferences among the seven CPs. These activities generated 90 articles in respected, peer-reviewed journals including *Physical Review Letters;* *Nuclear Fusion;* *Physics of Plasmas, Plasma Physics & Controlled Fusion;* *Fusion Engineering & Design* and *Fusion Science & Technology*. The results of the activities were presented at international workshops and conferences such as the IAEA Fusion Energy Conference, Annual Meeting of the APS Division of Plasma Physics (APS), European Physical Society Conference on Plasma Physics (EPS) and International Conference on Plasma Surface Interactions in Controlled Fusion Devices (PSI).

During 2012-2017 a number of important developments took place, including upgrades to existing tokamak devices, construction of new facilities, and closure of others. Significant results were obtained in the collaborative experiments. These activities were synthesised into Annual Reports and presentations to the IEA Fusion Power Co-ordinating Committee (FPCC). Details of achievements for each of the devices coordinated through CTP TCP are provided below in alphabetical order.

**ADITYA Tokamak (India)**

**Experiments:** Planned Experiments include confinement scaling experiments in circular and shaped plasmas, plasma shaping experiments and heat load measurements on limiter and divertor plates.

**Equipment:** An upgrade was completed in March 2016 and the components were tested (toroidal field coil assembly, ohmic coil assembly and the vertical coil assembly). First plasma was achieved in December 2016.

**Alcator C-Mod (United States)**

**Experiments:** A new tokamak world record for atmospheric pressure was achieved, an increase of 15% compared to the previous record. Plasma regimes free of edge localised transient events known as Edge localised modes (ELM) were developed and a novel good confinement regime was obtained and extended to high magnetic field demonstrating that higher magnetic fields extends the plasma operating space for this regime.

**Equipment:** After 24 years of producing influential physics results, the Alcator C-Mod facility ceased operations in 2016.

**Axially Symmetric Divertor Experiment (ASDEX Upgrade) (Euratom)**

**Experiments:** Injecting nitrogen into the plasma (“nitrogen seeding”) improved the plasma parameters in ITER-relevant conditions at similar plasma densities. The use of resonant magnetic perturbations for the mitigation of instabilities was transferred to helium plasmas. Tungsten materials were neither modified nor damaged in Helium plasma experiments, and there was no observable net erosion at the divertor, or any nanostructure growth or erosion. In addition, it was found that by varying the relative phase between the upper and lower resonant magnetic perturbations coils, the runaway electron current caused by the abrupt termination of the plasma “Disruptions” was reduced.

**Equipment:** Current upgrades are designed to control ELMs by rotating the magnetic perturbations. Bulk tungsten has been added to the outer divertor target and new power supplies were installed.

**DIII-D[[2]](#footnote-2) (United States)**

**Experiments:** A high-performance hybrid plasma core was achieved with suppression of ELMs.

**Equipment:** During 2016 the 3D-coil power supplies and subsystems provided by the Institute of Plasma Physics (ASIPP), (China) were installed on DIII-D and tested. A modest upper divertor change was completed in 2016 and will allow for tests of a wide range of divertor closures without affecting advanced tokamak operation. These are important explorations along the route to determine optimum exhaust power handling solutions for DEMO reactors beyond ITER and complement related studies ongoing in Europe.

**Experimental Advanced Superconducting Tokamak (EAST) (China)**

**Experiments:** Several discharges of 60-second pulses were achieved under H‑mode. In addition, ELMs were suppressed during a 20‑second pulse, resulting in a small positive effect on plasma performance, and heat fluxes to the divertor were controlled (below 3 Megawatts m‑2).

**Equipment:** In 2014 an actively cooled tungsten divertor, similar to the configuration for ITER, was installed in the upper area of the chamber. Due to hardware issues linked to water leaks, operations on the new divertor were limited. In 2015 the divertor was removed, repaired and reinstalled for the 2016 scientific campaign. In order to achieve long pulse (steady state), high-performance operations, the plasma heating capabilities were upgraded on a number of components.

**Helical tokamak (HL-2M) (China)**

**Equipment:** The HL-2M tokamak is under construction at the South Western Institute for Plasma Physics (SWIP) with machine assembly expected to be completed during 2017. Research goals comprise high‑performance, high­‑beta, and high‑bootstrap current plasmas, advanced divertor configurations (e.g. snowflake) and plasma wall interactions at high heat flux.

**ITER (international)**

**Equipment:** ITER construction advanced significantly during 2012-2017 with the major buildings advancing rapidly. Supported by impressive achievements in fusion technology R&D, manufacturing of major ITER components, such as superconducting magnet systems, vacuum vessel and cryostat, is in full operation. Substantial progress has also been achieved in prototyping and R&D activities in areas such as plasma-facing components (PFC), in-vessel coils, heating and current drive systems, remote handling and power supplies in preparation for manufacturing. A wide-ranging physics R&D programme, covered in many cases by the CTP TCP, is addressing key issues impacting the finalisation of the ITER design and preparations for operation. A new baseline for construction and operation was developed during 2016, featuring a first plasma date in late 2025 and revised operating schedule through to fusion power operation beginning in 2036. A revised Research Plan, consistent with the new schedule, is now being prepared with the support of the fusion physics research community and incorporating new understandings in physics achieved partly thanks to CTP TCP joint activities.

**Japan Torus Super Advanced (JT-60SA) (Japan)**

**Equipment:** Construction of JT-60SA began in 2015 and will continue until 2018, with first plasma expected in 2019. As of January 2017 the project is progressing on schedule. Welding of 94% of the vacuum vessel and installation of the vessel thermal shield was completed in 2016. Installation of the toroidal field coils is underway, with three coils already delivered to the Naka site. Manufacturing of the poloidal field coils was successfully completed with very high accuracy. In March 2016 the JT-60SA Research Plan (Version 3.3), co-authored by 378 experts, was finalised. The installation of a full metal wall in JT60-SA from 2028, in direct support of ITER operation, is being considered.

**Joint European Torus (JET) (Euratom)**

**Experiments:** It was shown that the plasma operating space is narrower with the JET “ITER-like wall (beryllium main chamber and tungsten divertor plasma-facing components), but good confinement was achieved with the divertor strike-points close to the pump duct entrance. Stationary ELMs were developed using gas fuelling to manage tungsten (reducing sources, flushing, central heating to avoid peaking and heat exhaust control for PFC protection). Other experiments demonstrated that the use of nitrogen seeding for divertor heat flux control can also, under some conditions, attain the plasma performance previously achieved with carbon walls.

The development of ITER Baseline operations continued on JET by extending the regimes to higher auxiliary power, plasma current and magnetic field. Similar performance was obtained in baseline and hybrid scenarios through different routes: high current, high confinement and broad profiles (baseline scenario) and moderate current, high confinement and peaked profiles (hybrid scenario). Confinement investigations with hydrogen plasmas across the full range of fuels (hydrogen, hydrogen/deuterium) resulted in a stronger-than-predicted mass scaling.

**Korea Superconducting Tokamak Advanced Research (KSTAR) (Korea)**

**Experiments:** Advances towards steady state operation at higher currents were made. Long-pulse discharges up to 70 seconds were achieved with a plasma current of 0.45 Mega Amps (MA). High‑current discharges were then extended to 1 MA for 20 seconds, with the goal of achieving 2 MA (the KSTAR design value) in the future. A stationary discharge with very good confinement in the core of the plasma was extended to 7 seconds.

**National Spherical Torus Experiment Upgrade (NSTX-U) (United States)**

**Equipment:** NSTX-U underwent a major, multi-year upgrade which was completed in 2015. These upgrades include enhanced research capabilities which are expected to increase the relevance of the reactor to the current state of the art. In 2016 initial operations were promising and progressed rapidly. However, some of the upgraded components subsequently failed. Repairs are underway, with experiments expected to resume during 2017.

**Mega Amp Spherical Tori (MAST) (United Kingdom)**

**Equipment:** MAST is undergoing a major upgrade to install an innovative divertor configuration (Super-X). Operations are expected to begin in 2017.

**Steady-state Spherical Tokamak (QUEST) (Japan)**

**Experiments:** A local electron cyclotron current drive (ECCD) start-up was achieved. A pulse of one- hour 55 minutes was obtained in a limiter configuration using 40 kW of auxiliary power.

**Equipment:** A “hot wall” to control dynamic Helium retention has operated since 2014.

**Steady State Superconducting** **Tokamak (SST-1) (India)**

**Experiments:** Initial experiments are in progress. Plasmas produced with ohmic heating have already been achieved.

**Equipment:** The device is now operational with the integration of various heating systems and first wall components.

**Tore Supra with a tungsten divertor (WEST) (Euratom**

**Experiments:** First scientific campaigns will begin in the Spring of 2017, with the primary focus being the achievement of H-mode. This first phase of operation uses a majority of tungsten coated carbon divertor, with only a few ITER-like actively cooled monoblocks in a single segment of the divertor.

**Equipment:** The new WEST project to access long pulse operation with actively cooled tungsten monoblock components in the Tore Supra Tokamak (France) was completed on schedule and first plasma was achieved in December 2016. Upgrade to a full water cooled divertor will proceed in the coming years.

**Tokamak with Variable Configuration (TCV) (Switzerland)**

**Experiments:** Modelling predictions of radiation trapping of nitrogen-seeded discharges in the snowflake divertor were confirmed by experiments. These results suggest that the nitrogen radiation would be trapped between the primary and secondary cross points.

**Equipment:** The parameter regime has been significantly expanded with the installation of a new heating system. This enables direct ion heating and access to plasmas with ion temperatures greater than the electron temperature as well as access to more reactor-relevant regimes.

**Tokamak Experiment for Technology Oriented Research (TEXTOR) (Germany)**

**Equipment:** After a successful 30-year campaign, the TEXTOR device (Germany) ceased operation in 2013.

**International collaborations**

**Experiments:** Remote operation and execution of experiments on the EAST device (China) were developed and carried out successfully by General Atomics (United States). Staff communication and data transfer from EAST to the United States were very good, without significant impact to the General Atomic staff or added cost from EAST (China) schedule changes. The experiments focused on empirical scaling of error field thresholds for ITER and serve as a model for cross‑continent remote experiment execution, which ITER expects to deploy.

The European fusion roadmap, [*Fusion Electricity: A roadmap to the realisation of fusion energy*](https://www.euro-fusion.org/wpcms/wp-content/uploads/2013/01/JG12.356-web.pdf) (2012) focuses on the support of ITER construction and optimization of ITER operation and risk mitigation for ITER were enhanced by performing joint collaborative supporting research in the existing European devices. The roadmap has improved cooperation within the European fusion programmes (JET, ASDEX Upgrade, TCV, MAST Upgrade, and participation in JT60-SA, Japan). The European tokamak programme is now integrated to address these objectives and the JET and Medium Size Tokamak (MST) Task Force Leaders draft annually a common experimental programme to implement on each device.

***Meetings and Workshops***

During 2012-2017 the CTP TCP held five ExCo meetings at the ITER Headquarters. In addition five joint workshops with the ITPA (ITPA Joint Experiment workshops, or JEX) were held. CTP TCP experts participated in activities of the seven ITPA Topical Groups which led to 61 meetings across all nations of the ITER Members. In addition, three workshops on “[Theory and Simulation of Disruptions](http://tsdw.pppl.gov/)” were organised at Princeton Plasma Physics Laboratory (United States).

***Outreach***

The members of the CTP TCP ExCo have repeatedly expressed their desire to extend activities to other member and non-member countries, where possible. New CPs during 2012-2017 included the ITER IO (2012) and CNDA (2013). Observers from the ITER Russian Domestic Agency attended some of the ExCo meetings during the reporting period. Following a decision of the ExCo meeting Russia was invited to become a member of the CTP TCP in 2015, but the invitation was not taken up. A further attempt will be made in 2017. The Australian Nuclear Science and Technology Organisation recently expressed interest in becoming a CP.

***Communications and dissemination***

The results of research carried out under the CTP TCP are reported widely at international conferences and workshops and in leading journals, including Physical Review Letters, Nuclear Fusion, Physics of Plasmas, Plasma Physics & Controlled Fusion, Fusion Engineering & Design and Fusion Science & Technology. A website has been developed during the period, hosted by EUROfusion (<http://ctp.jet.efda.org/lt/>) which serves as a portal for tokamak facilities of the CPs in the CTP TCP, as well as providing access to TCP documents for the ExCo meetings.

A representative of the CTP TCP attended the meeting led by the IEA Executive Director in September 2015. The CTP TCP has generated articles for inclusion in the IEA biennial publication [*Technology Collaboration Programmes: Highlights and outcomes*](http://www.iea.org/publications/freepublications/publication/technology-collaboration-programmes.html)during the reporting period, which reported on reducing, avoiding and mitigating plasma instabilities. Now that the website is active, the CTP TCP plans to announce developments through the [*OPEN Bulletin*](http://www.iea.org/openbulletin/).

1. The Implementing Agreement on Co-operation on the Large Tokamak Facilities merged activities with the Implementing Agreement on a Co-operative Programme for the Investigation of Toroidal Physics in, and Plasma Technologies of, Tokamaks with Poloidal Field Divertor (ASDEX upgrade) and was renamed as the Implementing Agreement on Co-operation of Tokamak Programmes. The merger grouped tokamak research programmes of all the ITER Members under one Implementing Agreement. [↑](#footnote-ref-1)
2. A non-circular cross-section tokamak in the shape of the letter ‘D’. [↑](#footnote-ref-2)