Technology Collaboration Programme on Stellarators and Heliotrons
(SH TCP)

Annual Briefing 2021

1 Preface

1.1 Objective

The SH TCP's objective is to improve the physics base of the Stellarator concept and to enhance the effectiveness and productivity of research by strengthening co-operation among member countries. All collaborative activities of the worldwide stellarator and heliotron research are combined under the umbrella of this programme, which promotes the exchange of information among the partners, the assignment of specialists to facilities and research groups of the contracting parties, joint planning and coordination of experimental programmes in selected areas, joint experiments, workshops, seminars and symposia, joint theoretical and design and system studies, and the exchange of computer codes.

1.2 Organization

The joint-programming and research activities are organized via the Coordinated Working Group Meetings (CWGM), an interactive workshop to facilitate agreements on joint research actions, experiments and publications under the auspices of the SH-TCP. The bi-annual "International Stellarator-Heliotron Workshop" (ISHW) serves as a forum for scientific exchange.

2 Chair's Report

2.1 Membership

After the accession of China in Dec. 2022, the SH TCP has seven members: Australia, China, the European Union, Japan, Russia, Ukraine, and the United States of America

The membership invitation to Costa Rica is still pending.

2.2 Amendment of the Implementing Agreement

In close cooperation between the IEA office of legal counsel and the ExCo, the legal text of the Stellarator-Heliotron implementing agreement was revised to implement the new TCP framework. Via written procedure of Oct. 13 - Nov. 4, 2021, the ExCo unanimously voted to adopt the proposed amendments. Since the SH TCP was the first fusion TCP to incorporate the new framework, the European Commission made their vote conditional on a subsequent commission decision, which is envisaged for April 2022.

2.3 Meetings

2.3.1 23rd International Stellarator and Heliotron Workshop (ISHW)

Due to the ongoing Covid19-pandmic, the 23rd international Stellarator and Heliotron Workshop was postponed from October 2021 to June 20-24, 2022. It will take place in Warsaw, Poland and will be organized by the Institute of Plasma Physics and Laser Microfusion (Conference website: https://www.ifpilm.pl/ishw2022).

2.3.2 19th Coordinated Working Group Meeting (CWGM)

The coordinated working group meeting activity has been pursued despite the difficulties due to the COVID pandemic. The 21st CWGM was held as a virtual meeting on Nov. 22 -24, 2021. The meeting had its focus on the perspectives for stellarators as a fusion reactor. About 130 people registered for three consecutive days in one-hour video conferences to allow attendance from different time zones. In order to facilitate the scientific discussion further, the meeting sessions were recorded. Additionally, the presentation slides and notes in an electronic documentation system running the INDICO software (https://event.ipp-hgw.mpg.de/event/67/). The material is available for registered participants working in laboratories being members of the IEA TCP.

Each of the three sessions had introductory presentations addressing "Open questions for a fast track to stellarator reactors" (Allen Boozer, Columbia University, USA), "What can we learn for the first W7-X campaigns for a HELIAS reactor?" (Robert Wolf, IPP Greifswald, Germany) and "Multi-ion physics and isotope effects in helical devices" (Hiroshi Yamada, Tokyo University, Japan). Essential outcome of the sessions was ensured by structured discussions guided by expert Chairpersons (Arturo Alonso (CIEMAT), Felix Warmer (IPP) and Friedrich Wagner (IPP).

2.3.3 49th SH TCP executive committee meeting

The annual ExCo meeting took place via Zoom on Nov. 10, 2021.

3 Milestones achieved

3.1 Wendelstein 7-X Completion

Wendelstein 7-X has concluded its completion phase towards high-power steady-state capability. All in vessel components have been installed – most notably the actively cooled high-heat-flux (HHF) divertor for heat fluxes of up to 10 MW/m^2 with its cooling water supply and the helium connections of the cryo pumps. The NBI system has been extended to four sources, and the new ICRH system has been installed.

3.2 Deuterium Operation of LHD

During the 2020/2021 deuterium campaign, experiments on LHD have further advanced for the understanding of the isotope effect to explorer the stellarator fusion reactor. An important finding is the transition between isotope-mixing and non-mixing states in hydrogen-deuterium mixture plasmas. In the non-mixing state, the isotope density ratio profile is non-uniform when the beam fuelling isotope species differs from the recycling isotope species and the profile varies significantly depending on the ratio of the recycling isotope species, although the electron density profile shape is unchanged.

3.3 Model Validation and Diagnostic Development in TJ-II

Reinforced capability in theory and modelling has allowed comparison and validation activities on neoclassical and turbulence mechanisms including: *Asymmetries:* Validation of a variation of the radial electric field on the flux surface has been accomplished and its dependence with the magnetic configuration and plasma scenario investigated. *Fuelling physics and impurities*: Research on the physics and modelling of plasma fuelling with pellet and TESPEL injection has shown that, although post-injection particle radial redistributions can be understood qualitatively from neoclassical mechanisms, turbulence and fluctuations are strongly affected during the ablation process. *Edge – SOL coupling*. Edge radial electric field is capable of reducing the propagation of turbulence from the edge into the Scrape Off Layer (SOL). *Fast particle physics*: Developments of control strategies of fast particle driven instabilities using Electron Cyclotron Resonance Heating and current drive.

3.4 Liquid Metals in TJ-II

TJ-II keeps an active programme for the assessment of novel solutions for plasma facing components using liquid metals (LM). The OLMAT (Optimization of Liquid Metal Targets) facility, aimed at testing LM prototypes under DEMO-relevant heat loads was constructed, installed and commissioned. It is based on the use of the Neutral Beams (NBI) of the TJ-II stellarator for the irradiation of LM targets and at DEMO-relevant powers.

3.5 Continues Pellet Fuelling System for W7-X in final testing stage

The US International Collaboration on Superconducting Stellarators has several major activities on W7-X and LHD. The largest system currently being constructed is a steady state pellet injector being prepared for installation W7-X. The Continuous Pellet Fuelling System is currently undergoing testing at ORNL and is a multi-party collaboration between NIFS, IPP-Greifswald, PPPL, and ORNL. It is expected that it will be shipped to IPP soon and be installed in time for the upcoming OP2.1 run.

3.6 Observation of a reduced-turbulence regime with boron powder injection in LHD

Another major activity is utilization of an Impurity Powder Dropper (IPD) that was installed at LHD by PPPL. The IPD was installed on LHD in 2019 and was commissioned for use in 2010-2020. In the following year the IPD was used in high performance discharges and a new operating regime with suppressed turbulence and increased ion temperature was observed. This improved performance regime was recently report in Nature Physics. https://www.nature.com/articles/s41567-021-01460-4

3.7 Configuration dependence of energy confinement in Heliotron J

The magnetic configuration has been scanned by changing the bumpiness (toroidal mirror ratio) and the rotational transform to study the dependence of energy confinement in Heliotron J. The experiments have shown that the stored energy measured is the highest at the standard configuration where the neoclassical transport is reduced. The rotational transform scan has shown that the global energy confinement degrades with an increase in rotational transform, which contradicts with ISS04 scaling. The ne and Te profiles at mid-radius are affected when the magnetic island chain is formed around the LCFS. The plasma discharge is unstable with fluctuations induced around the rational number 4/8.

3.8 JSPS Advanced Core-to-Core Network for High-Temperature Plasma Dynamics and Structure Formation Based on Magnetic Field Diversity

The Institute of Advanced Energy (IAE), Kyoto University won the Core-to-Core Program implemented by the Japan Society for the Promotion of Science (JSPS) in 2019. The program was approved for five years (Apr. 2019 – Mar. 2024) with an interim evaluation. The program is named "PLADyS", Advanced Core-to-Core Network for High-Temperature PLAsma Dynamics and Structure Formation Based on Magnetic Field Diversity. This program designs to create a top world-class research center with Max-Planck Institute for Plasma Physics (Germany), University of Wisconsin-Madison (USA), and Southwest Jiaotong University (SWJTU, China). One of the scientific goals is to elucidate the trigger and the dynamical evolutions of the structural formation. The program includes developing a research program of multi-scale structure formation human resource development, personnel exchange for young researchers and students, remote international collaboration experiments, international and domestic seminars, summer school, and lectures.

3.9 ICRH plasma production scenario

The Uragan-2M team has developed a plasma production scenario in ion cyclotron range of frequencies which could be used in conditions where the use of electron-cyclotron heating is not possible. Within this scenario plasma has been successfully created in the Large Helical Device in Japan with the participation of Ukrainian scientists. This experiment opens up opportunities to study new modes of operation in LHD, Wendelstein 7-X (Germany) and Uragan-2M.

3.10 Construction of the CFQS stellarator

By collaboration with NIFS in Japan, SWJTU in China keeps on promoting the construction of the CFQS stellarator. The 16 modular coils and the vacuum chamber are being fabricated in the Keye company, China. By now, more than half of the modular coils have been manufactured and tested in high quality. The vacuum vessel and the supporting system are also under construction. It is envisaged that all the components will be finished and assembled in SWJTU by the end of 2022. Meanwhile, in the campus of SWJTU, a 600 m^2 experimental hall has been built for testing facilities of the CFQS device.

4 Future plans

4.1 Operation Phase 2 of Wendelstein 7-X

After the final closure of the plasma vessel in January 2022, Wendelstein 7-X will undergo commissioning for its next operation phase OP2.1. The commissioning process will last until fall 2022 since it includes the filling and hydraulic balancing of the significantly extended system of cooling water circuits (with more than 5000 sub circuits). Plasma operation is planned to start in September 2022 and the scientific campaign will last until the end of March 2023. Wendelstein 7-X will approach 30 minutes plasmas with 10 MW of heating power in three major steps until 2025, accompanied by the successive adaptation of heating systems (ECRH power upgrade), diagnostics (improvement of cooling capabilities), and data acquisition and control schemes capable of collecting, handling and processing the increasing amount of data. The major scientific objective of this phase of experiments is the development of an integrated high-power, high-performance plasma scenario, validating and demonstrating the effectiveness of stellarator optimization. Another major area of research is the investigation of the possibilities to equip Wendelstein 7-X with all-metal plasma facing components.

4.2 Last campaign of LHD deuterium operation

After the last LHD deuterium campaign, the LDH team will promote scientific research on various plasmas through international cooperation, including phase-space turbulence, instabilities, sudden events, and particle-wave interactions. Its aim is to enhance the academic value and universality of plasma research through collaboration with researchers in the nuclear fusion field and researchers in a wide range of plasma fields by making the LHD data public.

4.3 TJ-II and OLMAT

Using its unique advanced plasma diagnostics and reinforced capability in theory and modelling, the TJ-II programme will support the development of plasma scenarios in W7-X and contribute to the understanding of critical challenges in fusion plasmas. The OLMAT facility will address testing prototypes under DEMO-relevant heat loads. Its design guarantees its compatibility with TJ-II plasma operation.

4.4 Uragan-2M for Wendelstein 7-X

The Ukrainian research unit in EUROfusion headed by KIPT will pursue experiments in Uragan-2M helical device which are aimed at plasma production and wall conditioning scenarios development in support of the Wendelstein7-X research programme.

4.5 CFQS operation

During the stage of assembling the CFQS device, the ECRH and related diagnostics provided by NIFS (Japan) will be transported to SWJTU, China. Then, after commissioning, CFQS will start its first plasma with 0.1 T magnetic field strength in the spring of 2023. The next task is to check the quasi-axisymmetric (QA) magnetic configuration by mapping the magnetic topology, and meanwhile scientifically prove the major advantage of a QA stellarator in confining plasmas with reduced magnetic ripple, and hence, neoclassical transport in comparison with previous conventional stellarators. After that, we will start experimental studies with various scientific topics.

4.6 Relocation of H1 in University of South China (USC)

University of South China (USC) continues its effort to relocate the H1 stellarator to China from Australian National University in 2021. After relocation, USC will try to restore the operation and experimental capability of H1, followed with related physical studies.

4.7 Configuration study in Heliotron J

The configuration study will be performed by using the flexible magnetic field control in Heliotron J. Non-resonant plasma production using 2.45GHz microwaves will be focused to investigate the stochastic acceleration of energetic electrons. New diagnostic systems are under preparation such as multi-channel interferometer, edge beam emission spectroscopy, Doppler reflectometer, and upgraded Langmuir probes. A laser blow-off system for the impurity transport measurement and a multi-path Thomson scattering system for the high-reliability measurement will be also available soon.

Annex

Report from the 21st Coordinated Working Group Meeting (CWGM)

1 Open Questions for a Fast Track to Stellarator Reactors

Professor Allen Boozer presented arguments backing a fast track to develop a demonstration fusion power plant. Estimates of the cost of the available solutions to stop the use of CO2-producing fuels are in the 4 trillion USD/year. This is to be put in perspective of a proposed investment of a few billion USD/year for a fusion plant development program. Prof. Boozer appealed to the stellarator community to instill a sense of thrill and opportunity of bringing the stellarator fusion reactor to contribute to a medium-term solution for the great environmental challenges that lie ahead of us in the XXI century.

2 What can we learn for the first W7-X campaigns for a HELIAS reactor?

Professor Robert Wolf summarized the status of experimental findings from W7-X in terms of stellarator optimization. In support to Prof. Boozers argument about potentials for computational design improvements, W7-X is a proof of concept as the first magnetic device derived from comprehensive optimization procedures based on physics criteria.

Substantial milestones have been attained in the first campaigns of W7-X, the planned extensions in heating power and exhaust capabilities provide opportunities to explore high-beta plasmas and fast ion physics in optimized magnetic configurations.

A lack of theoretical investigations of 3D turbulent particle transport was pointed out. It was agreed that a clear understanding of impurity transport is necessary for a reactor scenarios: a balance of improved thermal transport by suppression of turbulence may be required to avoid impurity accumulation.

With respect to heat and particle exhaust, very reproducible, reliable, and stable detachment was achieved but needed to be qualified for longer discharges. At the end of this path, demonstration of integrated core/divertor scenarios needs to combine good plasma performance in the core with feasible heat and particle exhaust with detached divertor plasmas. This litmus test is considered to be one of the most important qualification milestones for future reactor proposals. Moreover, the effect of metallic plasma facing components in stellarator geometry appears to be largely unknown and needs broader assessments building on experience gained with tokamak operation. How exactly an integrated reactor scenario in existing devices looks like and expected insights and limitations concluded the discussion.

3 Multi-ion physics and isotope effects in helical devices

Professor Hiroshi Yamada addressed two related topics highly relevant to burning helical plasmas: the isotope effect on confinement and the observation plasmas with different ion density profiles, so-called *non-mixing plasmas*. Evidence is provided by recent experiments conducted on the Large Helical Device. The discussion revealed the importance of the topic since the expected particle sources in multi-ion plasmas at low collisionality as expected in the nuclear phase of ITER are also affected by anomalous inward pinches but are expected to be different in stellarators.

While all discussions focused on open questions that appear to be addressable in future research, no show-stopper was identified. Specific emphasis is needed to maintain and pursue strong theory support to get the largest benefit from the attained physics understanding and to provide tools for reactor design. The current pace of stellarator research is set by the availability of resources, but long-term programs (EUROfusion) foresee assessment points in the nuclear phase of ITER to consider stellarators as an alternative line to the tokamak for fusion electricity.