Technology Collaboration Programme on Stellarators and Heliotrons
(SH TCP)

Annual Briefing 2022

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

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 and term extension

On Nov. 4, 2021, the ExCo unanimously voted to adopt the proposed amendments, conditional on a subsequent decision of the European Commission. The approval by the European Commission was given on Oct. 25, 2022, removing the conditionality of the amendment. Therefore, the term extension of the SH TCP until June 30, 2026 has become effective.

2.3 Meetings

2.3.1 23rd International Stellarator and Heliotron Workshop (ISHW)

The 23rd international Stellarator and Heliotron Workshop took place from June 20-24, 2022 in Warsaw, Poland. It was organized by the Institute of Plasma Physics and Laser Microfusion (Conference website: https://www.ifpilm.pl/ishw2022). 130 Participants attended the workshop, which was comprised of 15 oral sessions and two poster sessions. A special issue of the Journal of Plasma Physics will soon be available under https://www.cambridge.org/core/journals/journal-of-plasma-physics/collections/the-23rd-international-stellarator-heliotron-workshop-ishw. The 24th ISHW is planned to take place in Japan in 2024.

2.3.2 22nd Coordinated Working Group Meeting (CWGM)

The 22nd CWGM was held on June 24, 2022 as an in-person satellite meeting to the ISHW in Warsaw. Roughly 40 participants joined the meeting to explore to what level international collaborations can be implemented considering the risks from the COVID pandemic still existing at the time the meeting was held.

A dedicated call for joint experiments on LHD, W7-X, Heliotron-J and TJ-II was backed by presentations summarizing the device statuses and the focus topics of forthcoming campaigns.

A dedicated discussion to exploit the synergies from the collaborative actions was related to the META-stellarator concept – basically a joint experiment employing different machines obeying basic scaling invariances to assess similarity properties of magnetic geometries. The first experiment was a proposal for LHD and Heliotron-J.

Discussions focused on the urgent need to extend the stellarator physics basis to derive updated scaling laws for scoping studies, e.g. from HSX, incorporating new data at yet undocumented regimes from W7-X and LHD in the last versions of the stellarator databases. A community-driven committee was established to iterate the specific requirements and to prepare the next CWGM in summer 2023 in Kyoto, Japan.

2.3.3 51stth SH TCP executive committee meeting

The annual ExCo meeting met in the frame of the 23rd ISHW in Warsaw on June 20, 2022 – on-site and via web conference.

3 Milestones achieved

3.1 Wendelstein 7-X Operation

The commissioning of Wendelstein 7-X took 9 months including the new procedures on leak testing, filling and hydraulic balancing of the 580 water cooling circuits crossing the vacuum barrier. No serious issues were found. The plasma operation started in autumn last year and the campaign program, based on more than 500 submitted proposals, is conducted under the guidance of three topical task forces. Key elements of the program are the extension to 1 GJ energy throughput, which becomes now possible with the fully water-cooled in-vessel component system, and simultaneous increase of the plasma performance in terms of ion temperature and density. Controlled turbulence suppression, e.g. with continuous pellet injection, combined with additional heating capabilities is the approach to bring Wendelstein 7-X to high-performance, very long pulse operation. First long discharges have achieved 350 kJ energy throughput with stable divertor detachment and full radiation and density control. The experimental campaign is continued until end of March 2023, followed by a maintenance and enhancement phase until end of 2023.

3.2 New US diagnostics on W7-X

Several new diagnostics provided by the US have been installed in preparation for OP2 and are now routinely providing diagnostic measurements. These include the Gas Puff Imaging (led by MIT), Infrared Imaging Bolometer (led by LANL), and the Impurity Charge Exchange diagnostics (led by UW Madison). Many other US provided diagnostics have additionally completed substantial upgrades enabling improved performance and full integration with the W7-X control and acquisition system (this includes for example the X-Ray Imaging Crystal Spectrometer, Phase Contrast Imaging, and Penning Gauge systems among others).

3.3 Continuous Pellet Fuelling System installed at W7-X

The Continuous Pellet Fuelling System (CPFS) has been installed in the W7-X experimental hall. The CPFS has been developed as a multi-party collaboration between NIFS, IPP-Greifswald, PPPL, and ORNL and is one of the key investments from the US stellarator program to the W7-X experiment. Final integration of the injector with the W7-X safety and fast control and acquisition system (CoDaC) is now underway. It is expected that first pellet injection into W7-X plasmas will be possible during the current experimental campaign (OP2.1).

3.4 Collisionless energy transfer from energetic particle to bulk ions in LHD

The energy transfer from the alpha particle (energetic Helium ion) to the fuel ion (deuterium or tritium) through wave-particle interaction is one of the crucial issues in fusion plasmas. The ion heating scenario through equipartition is inefficient because the ion thermal confinement is degraded at the electron temperature ratio to ion temperature below unity. Therefore, direct ion heating is indispensable to maintaining a high ion temperature enough for a fusion reaction. Mass-dependent collisionless energy transfer via Landau and transit-time damping were observed to be associated with the collapse of tongue-shaped deformation in LHD [K.Ida et al, Comm. Physics 5 (2022) 228]. The collisionless energy transfer efficiency is higher for the impurity ions where the ion thermal velocity is close to the resonance velocity. This result strongly supports the realization of the alpha-channeling technique and demonstrates that collisionless energy transfer efficiency depends on isotope species with different ion masses.

3.5 Reduction of heat load on divertor plate by turbulence spreading in LHD

The high heat flux to the divertor plate is also a severe problem in burning plasma because replacing the divertor plate requires remote handling in the burning plasma, and frequent maintenance is unrealistic in the fusion reactor. Therefore, reduction of the peak heat load at the divertor plate is indispensable to extending the lifetime of the divertor plate. There are various approaches to increasing the fall-off length of power. One of the practical techniques is utilizing turbulence spreading. Turbulence spreading into an edge stochastic magnetic layer induced by magnetic fluctuations and its impact on divertor heat load were clearly observed in LHD [*M. Kobayashi et al., Phys. Rev. Lett.* ***128****, 125001 (2022)*]. The peak divertor heat load is found to be reduced by the enhancement of turbulence spreading.

3.6 Boron and Lithium powder injection in LHD

The US supplied Impurity Powder Dropper installed on LHD has continued to play an important role in the last LHD campaign. Experiments using the IPD have been conducted by researchers from Japan (NIFS), the US (PPPL) and Europe (IPP), with close collaboration between the teams. These experiments have followed from the previous important results showing the ability to improve wall conditions in real time and the ability to access improved confinement regimes though the injection of boron powder. New results have led to improvement of performance in high-T_i plasmas, with increased ion and electron temperatures available. Recent experiments have also used the IPD to successfully inject lithium into LHD. The results from these recent Lithium injection experiments are currently being analysed and will be reported soon.

3.7 ICRH and RF plasma production scenarios at LHD

The scenario of plasma production in ion cyclotron range of frequencies developed by the Uragan-2M team had been studied at LHD in two experimental sessions. The target helium-hydrogen plasma is obtained with the density up to 10^{19} m^{-3}. In the last session the full ionization had been achieved and the electrons had been heated to the temperature higher than 2 keV by ICRH only. These experiments open up opportunities to employ low magnetic field (1.7 T) operation mode at Wendelstein 7-X.

The scenario of RF plasma production in low magnetic fields (0.5 and 0.4 T) had been tried at LHD employing its ICRH heating equipment. The target helium is successfully produced with the density higher than 10^{19} m^{-3}. Such discharges, with further NBI, could be used for high-beta confinement studies. Another area of their usage is the wall conditioning in the hydrogen atmosphere. The studies were done in the frame of the international collaboration within EUROfusion with participation of scientist from VR (Sweden), KIPT (Ukraine) and other research units.

3.8 Model Validation and Diagnostic Development in TJ-II

The National Fusion Laboratory - CIEMAT keeps an active programme in neoclassical and turbulence model validation including:

Turbulent transport and density profiles hollowness. In Wendelstein 7-X flat or weakly peaked density profiles are generally measured, indicating that neoclassical theory is not sufficient and that an inward contribution to the particle flux is missing in the core. It has been shown that the turbulent contribution to the particle flux explains the difference between experimental measurements and neoclassical predictions. The results also prove that theoretical and numerical tools are approaching the level of maturity needed for the prediction of equilibrium density profiles in stellarator plasmas, which is a fundamental requirement for the design of operation scenarios of present devices.

Validation of pellet deposition physics by simulation/experiment comparisons on helical devices. Systematic comparison of experimental observations of cryogenic pellet injection (PI) in non-axisymmetric devices of markedly different magnetic geometry and plasma profiles, namely W7-X, LHD, TJ-II and Heliotron J, has been carried out. Results show anomalies in drifts near rational surfaces that would imply differences in particle deposition and fuelling efficiencies between magnetic configurations.

The challenge of cross-phase validation. A novel high speed spectrally resolved imaging system has been in operation in TJ-II during 2022. It allows simultaneous 2-D electron temperature and density edge plasma measurements down to the 100 kHz frequency range. First results have shown its strength to characterize the cross-phase between density and temperature fluctuations; this is a fully unexplored area of research that is crucial for understanding the decoupling between particle and energy transport in fusion devices.

3.9 Plasma-wall studies in TJ-II

OLMAT (Optimization of Liquid Metal Advanced Targets) is a new High Heat Flux (HHF) Facility for testing solid and liquid metallic targets at DEMO-relevant power densities that has been operated at the National Fusion Laboratory in Madrid in 2022. A TJ-II Neutral Beam Injector (NBI) is used as a high- power source providing 100 ms pulses at maximum repetition rate of 1p/30s and delivering power densities at the target above 50 MW/m^2. Targets consisting of Mo (TZM), W and liquid tin supported in a CPS structure have been investigated to date. Remarkably, experiments in Sn wetted 3D printed W structure show no damage up to 58 MW/m^2.

3.10 Configuration dependence of energy confinement in Heliotron J

The high configuration flexibility of the Heliotron J provides us with the physics study on the role of magnetic configuration on plasma performance. The rotational transform has been scanned to study the dependence of energy confinement and heat transport. The experiments have shown that the edge magnetic island chain around LCFS improves core heat transport. T_e at middle range radius is higher when the rotational transform is 0.48, close to 4/8. The heat transport is sensitive to the island position, and the E_r shear is formed at the inner side of the magnetic island. Non-resonant plasma production using 2.45GHz microwaves has also been studied to investigate the stochastic acceleration of energetic electrons.

3.11 Construction of the CFQS stellarator

The construction of the CFQS device moved forward in 2022 by collaboration with NIFS, Japan. But the original schedule is slightly delayed due to the influence of the corona virus pandemic. The modular coils, vacuum chamber and supporting system are being manufactured in the Keye Company, China. Till now, the 16 modular coils have almost been finished and tested. The vacuum vessel and the supporting system are still under construction. It is foreseen that all the components will be finished and assembled in SWJTU in autumn of 2023.

Meanwhile, the stellarator research activities in SWJTU got increasing support in China. In 2022, both of Ministry of Science and Technology and National Natural Science foundation of China have approved new projects for stellarator studies in SWJTU. Very recently, the local governments of Sichuan province and Chengdu city approved another Major Science and Technology Infrastructure Project (250 million CNY) for SWJTU, by which a new Plasma Physics Laboratory for stellarator research will be established.

3.12 Multiple region relaxed MHD model: stability and fast-particle orbits

The ANU fusion plasma theory and modelling group advanced development of the multiple region relaxed MHD (MRxMHD) model, contributing strongly to the *Simons Hidden Symmetries and Fusion Energy Collaboration*. The MRxMHD model is a generalised of Taylor relaxation principle to multiple toroidal volumes, enabling toroidal volumes with nested flux regions, magnetic islands and stochastic regions. The volumes are separated by ideal MHD interfaces. In 2022 the SPEC code was further developed to determine MRXMHD stability in toroidal geometry, by relating the second variation of the MRxMHD energy functional to the Hessian matrix, enabling the prediction of magnetohydrodynamic (MHD) linear instabilities [Plasma Phys. Control. Fusion 64 (2022) 065001]. Results were benchmarked to the ideal MHD stability code packages MISHKA-1 (tokamak geometry), and CAS3D (stellarator geometry). The MRxMHD model was further advanced by constructing a new formulation: relaxed MHD with ideal Ohm's law constraint. In this model an augmented Lagrangian method borrowed from optimisation theory is used to bridge the relaxed and ideal MHD models. [*J. Plasma Phys.* (2022), v*ol*. 88, 835880101].

3.13 Status of Uragan-2M stellarator

The Uragan-2M experimental hall and Uragan-2M itself was damaged during the artillery and air attacks. Cosmetic repairs were made for the hall to protect it from the atmospheric deposits. The scale of Uragan-2M damages is yet been assessed. Meanwhile, measures were taken to protect it from the negative temperatures' impact during the winter.

4 Future plans

4.1 Operation Phase 2 of Wendelstein 7-X

The years to come for Wendelstein 7-X are dominated by the sequence of routine device commissioning, plasma operation and maintenance. It is planned to achieve 18 GJ energy throughput at good plasma performance until the end of 2027. Until 2030, upgrading the heating systems to a total of 30 MW is foreseen, where the power increase of gyrotrons to 1.5 MW or even 2 MW each is of particular importance. From 2025 onwards deuterium operation is planned. In parallel, the development of design and technologies for a full-metal tungsten device is running.

4.2 US contributions to W7-X

The Continuous Pellet Fuelling System (CPFS) is expected to be fully operational for the upcoming OP2.2 campaign schedule for the beginning of 2024. This system, along with gas and neutral beam injection, is expected provide greatly enhanced control of the steady-state density profile in W7-X. This enhanced control is in turn expected to lead to a better understanding of density gradient driven turbulence and the requirement for access to the high-performance regime. A new real-time Thomson scattering diagnostic is now under development by the US (PPPL) which can be used for profile feedback and will further enhance this understanding.

A new Beam Emission Spectroscopy is also being developed by the US (U. Wisconsin) for installation on W7-X; this diagnostic will provide detailed turbulence measurements based on emission from the neutral beams and further enhance the fluctuation diagnostics set on W7-X.

Another US led diagnostics project, the Scintillating Fast-Ion Loss Detector sFILD, is being developed for W7-X as a collaboration between PPPL, University of Seville and IPP-Greifswald. The diagnostic is now undergoing final design review and is expected to be installed in W7-X for upcoming campaigns.

4.3 Last campaign of LHD deuterium operation

The LHD deuterium campaign finished at the end of 2022. The LHD 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.

4.4 TJ-II and OLMAT

Using its unique advanced plasma diagnostics and reinforced capability in theory and modelling, the TJ-II programme will continue its support to the development of plasma scenarios in W7-X and contribute to the understanding of critical challenges in fusion plasmas focussed on the physics of density profiles, decoupling between particle and energy transport and fast ion driven transport mechanisms. The OLMAT facility will address testing prototypes under DEMO-relevant heat loads including optimization of CPS geometry for Liquid Metals (Sn) and ITER relevant first wall materials (W).

4.5 CFQS operation

During the assembling phase of the CFQS device, the heating facility and 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. 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) has transported components of the H1 stellarator to China from Australian National University at the end of 2022. In year 2023, USC will reassemble the device and restore the operation and experimental capability of H1, followed with related physical studies.

4.7 Heliotron J

Physics experiments such as the configuration study, turbulence transport, electron internal transport barrier, stabilization of energetic-particle-driven MHD instabilities by ECH/ECCD, stochastic acceleration by using the flexible magnetic field control will be carried out in Heliotron J. New diagnostic systems are under preparation such as multi-channel interferometer, multi-pass Thomson scattering system, edge beam emission spectroscopy, multi-channel Doppler reflectometer, and upgraded Langmuir probes.

4.8 Uragan-2M

Uragan-2M is not accessible now and the future plans for it depend on the termination of the war on the Ukrainian territory. The Uragan-2M team may keep its workability participating in experiments at other stellarator machines.