**Technology Collaboration Programme on Stellarators and Heliotrons (SH TCP)**

End-of-term report 2016-2021

# 1 Objective

The objective of the Technology Collaboration Programme on Stellarators and Heliotrons (SH TCP) is to improve the physics base of the stellarator concept and to enhance the effectiveness and productivity of research and development efforts by strengthening co-operation among member countries. While the main development line in fusion research is the tokamak line, stellarators and heliotrons constitute a promising alternative with advantageous properties, such as steady-state confinement with the prospect of a more economic power plant concept. Stellarators and heliotrons can create the magnetic field without requiring a net toroidal plasma current, which makes auxiliary current drive unnecessary and brings remarkable advantages for plasma stability, in particular the absence of plasma current disruptions. Stellarators have higher limits for the particle density and can thus operate at lower temperatures. Yet, they share many technological aspects with the technically more advanced tokamak lines and can profit from existing solutions from ITER and tokamak research.

However, it has also become evident that the understanding of the more complex three-dimensional confinement properties of stellarators and heliotrons is indispensable for the further development of tokamaks. The promotion of the synergies between tokamaks and stellarators and heliotrons is therefore a central part of the strategic direction of the TCP.

# 2 Scope, Research Goals, and Key Achievement

## 2.1 Scope of Activities

The programme combines the collaborative activities of the worldwide stellarator and heliotron research. The collaboration programme includes jointly planned experiments for comparison and validation, mutual participation in experiments and theory/simulation activities, joint evaluation of results, and information sharing. Exploiting a larger number of devices broadens the basis of experimental results, accelerates progress on physics understanding, and increases the reliability of the results from the various facilities, thus contributing to improving the design of next-step devices and the DEMO reactor towards realization of a fusion power plant.

The joint-programming and research activities are organized via the Coordinated Working Group Meetings (CWGM), interactive workshops to plan joint research actions, experiments and publications and track the progress achieved. The biennial "International Stellarator-Heliotron Workshop" (ISHW) serves as a forum for scientific exchange. An important mechanism to foster synergies with the tokamak community is the participation of an SH TCP representative in each topical group of the International Tokamak Physics Activity (ITPA).

## 2.2 Research Goals

The ultimate goal of the SH TCP as part of the worldwide fusion research is development of the scientific and technical basis of a fusion power plant. Thereby, the SH TCP focuses on the realization of an alternative magnetic confinement concept, which has many fundamental advantages, promising a more economic fusion power plant, but also disadvantages which need to be resolved. Merged under the term stellarator optimization, the research is aimed at finding the optimal magnetic field configuration which best fulfils the requirements of a power plant. This comprises a) the confinement of the high temperature plasma and the fast ions, which are produced by the fusion reaction and are used to heat the burning fusion plasma, b) heating and fuelling methods, required to start the fusion plasma and control it, once the desired plasma parameters have been established, c) operational limits, which determine the accessible range of plasma parameters, and d) plasma and energy exhaust, which is essential for the extraction of the fusion energy. While all these are also essential topics in tokamak research, the SH TCP's focus is on stellarator-specific aspects while building upon synergies between tokamak and stellarator research.

## 2.3 Key Achievements

The last term of the SH TCP saw the achievement of two major milestones, first deuterium plasmas in the Large Helical device (LHD) and first plasma experiments in the optimized stellarator Wendelstein 7-X (W7-X). After many years of preparation making LHD for deuterium plasmas with significant neutron production due to deuterium fusion, experiments gave important insight into the role of the hydrogen isotope on plasma transport and performance. This information is crucial for the extrapolation to a power plant, since fusion power plants are envisaged to use deuterium-tritium plasma for energy production. W7-X is the first stellarator the design of which is based on a comprehensive set of optimization criteria aiming at a device which makes best use of the stellarator-specific advantages by mitigating or even avoiding concept specific disadvantages. The first operational phases already demonstrated the effectiveness of crucial aspects of the confinement optimization, substantiated by a record triple product for stellarators. The two events also attracted public attention and the attention of policy makers and high level politicians. A highlight was the inauguration of W7-X in 2016, which was accompanied by the German Chancellor.

A clear sign of the lively scientific exchange within the SH TCP is the number of joint publications in peer-reviewed scientific journals and exchange visits between the laboratories participating in the TCP. In the years 2016 to 2020 the impressive number of 350 joint papers were published. 120 scientists participated in more than 150 research visits per year during that period. A joint U.S.-German laboratory for divertor research, the Helmholtz International Lab for Optimized Advanced Divertors in Stellarators (HILOADS) received funding for the duration of five years by the German Helmholtz Association.

Finally, the field has been boosted by a major grant from the Simons Foundation in the US for the project "Hidden Symmetries and Fusion Energy", which aims at developing novel mathematical and numerical techniques for optimizing future stellarators. To our knowledge, this is the first term that stellarator research has attracted significant funding (2 million USD per year) from a non-government source.

## 3 Membership

Since December 2020, when the Southwest Jiaotong University of China signed the implementing Agreement, the TCP has seven members: Australia, China, European Commission, Japan, Russia, Ukraine, United States. Costa Rica has been invited to join the TCP and the process of accession is underway.

## 4 Research Highlights by Topic

### 4.1 Divertor and Edge Physics in Stellarators

Helical devices, contrary to tokamaks, need to operate with 3D-divertors in order to accommodate the non-axisymmetric shape of the plasma, which leads to strongly heterogeneous interfaces between plasma and the plasma facing components. In the frame of the activity, 3D-effects and their influence on the plasma exhaust are studied: This includes such effects as plasma edge drifts, migration of material eroded from plasma facing components and interplay between plasma turbulence at the very edge of the plasma, perpendicular anomalous transport and power exhaust.

Both LHD and W7-X were able to reach the state of so-called detachment – where heat and particle fluxes are strongly reduced, which allows for safe operation of a future reactor. Injection of small amounts of impurity species like $N_2$ or Ne, which radiate near the plasma edge, resulted in a significant reduction of divertor loads. The effect was more localized in LHD than in Wendelstein 7-X, which results most likely from different topologies of the exhaust concepts.

The US has pursued experiments aimed at understanding the effects of the controlled introduction of boron based compounds on both W7-X and LHD for both real-time wall conditioning and impurity transport studies. The W7-X experiments used a horizontal powder injection system and LHD used a gravity fed vertical dropper. In both cases tantalizing signs of improved confinement were observed. This work is ongoing with further expansions proposed for W7-X. LHD is currently exploring the use of the Impurity Powder Dropper as a long pulse control tool. Similar research is also being pursued in tokamak collaborations. Moreover, joint studies between Wendelstein 7-X and the HSX stellarator have been conducted to investigate the effect of islands on plasma fuelling, showing changes in particle fuelling and confinement times when island structures were introduced into the ionization region.

### 4.2 Scaling and operation limits

In the past years and decades, stellarators have come much closer to explore reactor-relevant plasma conditions. While a significant gap still remains, the latest experiments in the major stellarator experiments offer a great opportunity to assess the validity of existing scalings by extending the operational space. At the same time, the boundaries of the accessible operational space itself can be examined. These studies are important prerequisites for future experiments and, eventually, stellarator reactor designs.

In the reporting period, the energy confinement time scaling has been re-examined with respect to different isotopes (in particular hydrogen and deuterium) at LHD and the impact of operation limits at W7-X. In LHD experiments, dimensionally similar plasmas are produced for deuterium and hydrogen, respectively. From regression analyses, the global energy confinement time for deuterium and hydrogen plasma is not different. Local heat transport seems to show a more complex behaviour, which has to be studied further. At W7-X it was shown that a radiative density limit exists, which is consistent with observations from other experimental devices. Approaching the critical density, at which a radiative collapse occurs, the energy confinement time is showing a density weaker than the empirical ISS04-scaling. This is an important finding as a reactor will have to operate with a high radiation fraction. Hence, extrapolations from confinement scalings are probably too optimistic. Both the findings of LHD and W7-X show that new joint scalings beyond ISS04 need to consider further parameter dependences and regimes in which they are valid.

Furthermore, since experiments at LHD and W7-X reach higher plasma pressures, the understanding of pressure and reconnection-related instabilities has come into focus. State-of-the-art simulations revealed that observations of severe and abrupt confinement degradations observed in W7-X during current drive are likely related to magnetic reconnection, mediated by electron inertia and ions in the (gyro) kinetic regime. Joint efforts to strengthen the theoretical understanding of beta- or current-related instabilities were discussed and are being strengthened between NIFS and IPP.

### 4.3 Fast Ion Confinement

Experiments, simulations, novel detectors, and new theoretical concepts are being tested and developed for stellarators, providing validated predictive capabilities and optimization strategies for fast ion confinement. In LHD deuterium experiments, the confinement of the triton produced in the deuterium plasma for demonstrating the alpha particle confinement is studied. The ratio between the neutron emission rates from a deuteron-triton and deuteron-deuteron reaction is measured. For an inward shifted configuration, the triton burn-up ratio increased significantly and achieved better triton confinement. The maximum value of the burn-up ratio is comparable to middle-sized tokamaks. It is promising for the alpha particle confinement in stellarator and heliotron devices.

The BEAMS3D, FIDASIM, ASCOT, VENUS-LEVIS, and Serpent codes have been applied to the W7-X stellarator geometry. Code validation and verification efforts are showing good agreement both between models and with experimental data in regards to stellarator fast ions. The Gamma-C metric is being used to design helically symmetric configurations with greatly improved fast ion confinement. Such work is being extended to other configurations. Multi-layer Faraday cup fast ion loss detectors and scintillating fibre neutron detectors are under development and testing to provide data for future experiments. Joint experiments on W7-X and LHD are conducted to investigate the role that radio frequency heating plays in neutral beam heated plasmas with regard to fuelling.

### 4.4 Stellarator Optimization

The success of W7-X has reinvigorated the field of stellarator optimization, resulting in a number of highlights:

The field has been boosted by a major grant from the Simons Foundation in the US for the project "Hidden Symmetries and Fusion Energy", which aims at developing novel mathematical and numerical techniques for optimizing future stellarators. This project involves participants in the US, Europe and Australia. This is, to our knowledge, the first term that stellarator research attracts significant funding (2 million USD per year) from a non-government source.

A major code package, ROSE, has been developed for stellarator optimization and has been employed to design a two-period quasi-axisymmetric stellarator with excellent confinement and stability properties. The older STELLOPT code has also been modernized and extended. Both code packages have been employed to find a quasi-helically symmetric design with similarly excellent properties.

Novel numerical techniques have been developed for finding stellarator coils, resulting in the development of novel codes (REGCOIL and FOCUS) for this purpose as well as a stochastic optimization algorithm, which achieves better results (simpler coils, higher fidelity) than earlier deterministic coil-finding techniques.

A novel concept for designing stellarators with drastically simpler coils has been proposed. The idea is to use permanent magnets in addition to coils. Such magnets cannot create toroidal magnetic flux, but they can be used to shape the plasma and thus to create poloidal flux and rotational transform, thereby easing the requirements on the magnetic-field coils. Several numerical techniques and codes have been constructed to optimize the positioning of the magnets, and funding has been given to PPPL to design and build a proof-of-principle magnet set.

### 4.5 Heating and Fuelling

The standard heating method at W7-X is based on launching centimetre-sized microwave beams into the plasma at a frequency of 140GHz. The input polarization determines the mode purity of the beams and therefore the efficient absorption. The polarization and the resultant power deposition of the microwave beams in W7-X plasmas is calculated by the ray-tracing code TRAVIS. However, TRAVIS is not able to determine possible parasitic mode conversion within the plasma which has to be considered at LHD in general. For this reason, the NIFS' ray tracing code LHDGauss, which is able to incorporate the effects of mode conversion within the plasma, was adapted to W7 X plasmas in 2016. Both codes were crosschecked to each other with the result that mode conversion plays only a minor role for the magnetic field configurations of W7-X. Further investigations of these effects are planned for high beta plasmas achievable in W7-X after 2022.

On the other hand, the output of TRAVIS was successfully used for calculation of the scattering volume for the collective Thomson scattering (CTS) diagnostic at LHD. The resultant CTS diagnostic at 154 GHz which facilitates fast ion measurements in high density plasmas was commissioned with joint Japan-EU efforts. Later, the CTS diagnostic was upgraded for use with a new frequency of 300 GHz, allowing measurements with a very high signal-to-noise ratio. Jointly, a new alignment procedure of 300 GHz transmission line was developed. CTS is sensitive to 1D projection of the fast-ion velocity distribution function. A new machine learning technique was successfully applied to the synthetic measurements in order to reconstruct the complete fast-ion velocity distribution, instead of conventional and slow inversion techniques.

The accumulation of heavy impurities in the plasma core is a problem for fusion reactors. A new mechanism of impurity exhaust in stellarators using specially tailored ion cyclotron heating (ICRH) of impurity ions (so-called three ion scheme) was tested in LHD. The first results are very encouraging; detailed analysis is ongoing.

Another important use case of ICRH is the plasma initiation for configurations where ECRH or neutral beam injection (NBI) can be only applied after a sufficient plasma density and temperature is achieved. For the investigation of the full magnetic configuration space of W7-X, the application of an additional ECRH scenario at the third harmonic of the electron cyclotron frequency is planned. It necessitates the plasma initiation by ICRH with subsequent increase of electron temperature and density by NBI to achieve the necessary target parameters for third harmonic ECRH. The small stellarator Uragan-2M served as a test bed to find the optimum parameters for plasma initiation by a W7-X like ICRH. Further experiments are planned at LHD to validate the results in preparation for the next W7-X campaign starting in 2022.

Additional collaborations on plasma initiation were conducted at Heliotron J where a stochastic acceleration process of relativistic electrons within a 2.45 GHz microwave field is applied to generate a seed plasma for NBI operation. The acceleration process was firstly explained at the small stellarator WEGA in Greifswald, prompting further in depth studies at Heliotron J with a broad characterization of the input parameter dependencies.

Fuelling is a crucial topic not only in the tokamak, but also in stellarators and heliotrons. A cryogenic solid hydrogen isotope pellet injection into the plasma is considered as the most realistic candidate technology for the effective fuelling into the core region of a fusion plasma. During the last five years, cryogenic solid hydrogen pellet injectors were implemented in TJ-II, Heliotron-J and W7-X. The results from those devices and LHD were compared diligently to code calculations of the plasma fuelling by cryogenic pellets. As a result, substantial progress was made in the understanding of physical mechanisms supporting the effective fuelling in stellarator plasmas. In fusion plasmas, the control of a Deuterium-Tritium fuel ratio is a high-priority issue. Charge exchange spectroscopy at LHD revealed that there are two types (mixing and non-mixing) of spatial distribution patterns of hydrogen and deuterium ratios. This finding will contribute to the establishment of an effective and efficient fuelling scheme for fusion plasmas based on the stellarator concept.

### 4.6 Equilibrium

In the last 5 years, the experimental validation of the topological change by the 3D equilibrium response on the edge magnetic field was intensively studied. Up to now, it was expected that the helical divertor configuration of the LHD is robust against the beta effect, because the divertor leg is far from the core plasma. However, the heat load on the divertor clearly changed with increasing beta in the high-beta equilibrium. The edge magnetic topology is studied by the 3D equilibrium code, HINT, and it was found that the connection length of the edge magnetic field is very sensitive to the beta effect. For W7-X, the impact of the equilibrium current on the edge magnetic topology is studied. In the 3D equilibrium calculation, the ECCD current clearly changed the connection length profile of the magnetic island on the divertor, and the IR camera measurements confirmed the change of the heat load on the divertor.

In the LHD experiments, the high-beta plasma production with the low collisional region was studied. In the high-beta plasmas, clear degradation of the confinement was observed. In the LHD, the core MHD is stabilized by the magnetic well, but the plasma edge is still the magnetic hill. In there, the large magnetic and density fluctuations driven by the resistive interchange mode is always observed by the magnetic diagnostics and interferometer. The resistive interchange mode is inversely proportional to the magnetic Reynolds number, and then the decreasing of the magnetic fluctuation in the relatively high magnetic field is confirmed. Also, the high-beta plasma in the LHD is produced and sustained by strong NBI heating. In such a case, the strong pressure anisotropy is expected. In the LHD experiments, the identification of the pressure anisotropy by the magnetic diagnostics was developed and validated by the simulation experiments with parallel and perpendicular NBI heating. This is an important result for the high-beta experiments of W7-X with NBI and ICRF heating.

The 3D equilibrium code is a key tool to understand the high-beta physics. STELLOPT and V3FIT were applied to the equilibrium reconstruction for W7-X, and the well reconstructed equilibrium helped interpretations of the experimental results. Cross-validation of HINT and VMEC/EXTENDER was advanced for W7-X. Also, the new code SPEC bears significant progress for the free-boundary calculation. To consider the strong parallel transport along the stochastic field line, the anisotropic heat transport on the 3D equilibrium is studied by HINT and NIMROD. These comparisons will further understanding of the stochastic transport on the 3D equilibrium.

### 4.7 Transport Turbulence and Impurities

Many exciting advances were achieved in our understanding of stellarator transport during the last five years. The successful deuterium campaign on LHD allowed the effect of hydrogen isotope mass on transport and turbulence to be investigated experimentally in a large stellarator experiment. In LHD deuterium plasmas the highest ion temperature (>10keV) in stellarators were accomplished. A dedicated spectroscopic measurement identified the individual isotope mixing and non-mixing states. The quantitative comparisons with theory and simulations was carried out to clarify the underlying turbulence and zonal flow dynamics. The observation of oscillatory zonal flow relaxation in pellet-induced fast transients by Heavy Ion Beam Probe diagnostics is consistent with GK simulations in TJ-II. These results allow better extrapolation of current experimental performance to stellarator fusion reactors. In addition, studies of turbulent transport in the HSX stellarator show a clear impact on turbulence on the electron heat confinement, and comparisons with linear and non-linear gyrokinetic simulations demonstrate that turbulence saturation mechanisms have to be considered when modelling transport in quasihelically symmetric devices. The operation of W7-X had a major impact on all aspects of energy, particle and impurity transport in an optimized stellarator. The W7-X experiments quickly provided records in terms of energy confinement and triple-product performance. The experimental results were compared with predictions from neoclassical theory, validating neoclassical codes for use in optimized stellarator designs. These experimental results in conjunction with gyrokinetic simulations (GENE) led to improved understanding of the role of turbulent transport, and in particular of the suppressions of microinstabilities such ITG, TEM, and ETG, and their role in optimized stellarator performance.

Major advancements in the understanding of impurity transport have been driven by theory; in particular the development of a theoretical basis and computational codes (SFINCS, EUTERPE, KNOSOS, FORTEC-3D) for understanding the effect of asymmetries in the plasma potential and its effect on impurity transport. Experimental investigation of these plasma potential effects has been carried out at TJ-II. Impurity transport measurements at W7-X and LHD through impurity pellet (TESPEL) and laser blow-off (LBO) have now become standard experimental techniques, along with analysis through transport codes such as STRAHL. These investigations have widely improved our understanding of impurity transport and its drivers in stellarator plasmas.

### 4.8 International Stellarator-Heliotron Profile Database

The International Stellarator-Heliotron Profile Database (ISHPDB) is a strategic backbone activity of the SH TCP. It creates an evolving, sustainable documentation aiming at a physics basis for future fusion power plants. Covering devices at various sizes, different degrees of optimization and exhaust concepts ultimately make ISHPDB a multi-machine data set that extends findings from single devices to otherwise inaccessible settings.

Continuous re-adjustments of covered topics result in an evolution of the data base. Therefore, this database sub-activity also serves for seeding reactor-relevant objectives that became accessible along the progress of scientific research in the field. Specific recent examples refer to the documentation of plasma terminating events in comparison to tokamaks and considerations for reactor scale devices. The definition of required input for reactor systems codes and engineering aspects (for the operation and maintenance of a future power plant) are examples for presently emerging discussions.