Technology Collaboration Programme on Stellarators and Heliotrons
(S-H TCP)

Annual Briefing 2019

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

Worldwide stellarator research has significantly gained momentum: on Wendelstein 7-X, first campaigns with an uncooled divertor have demonstrated highest fusion performance (expressed in form of the triple-product which is a figure of merit for fusion performance)or special plasma exhaust conditions which allowed long pulses despite having only un-cooled targets (so-called plasma detachment). Deuterium experiments in the large helical device (Toki, Japan) showed confinement at higher performance than gyro-Bohm scaling. Smaller devices allow the detailing of insights for physical understanding, like turbulence studies in TJ-II (Madrid, Spain) , fueling studies in Heliotron-J (Kyoto, Japan) and the examination of flows in HSX (Wisconsin, USA). Progress in the refurbishment of Uragan 2-M (Kharkiv, Ukraine) and new concept devices (CFQA Chengdu, China) complement the larger experiments, giving new opportunities to assess concepts for aspects relevant to reactor-like operation and stellarator optimization.

Equally important, stellarators benefit from the latest cutting-edge developments in diagnostics, heating, and plasma fueling. Coordinated programs in the EU, the US and Japan link innovative developments to the stellarator programs, e.g., integrated systems for overload detection (EU consortium), x-ray detectors (Princeton Plasma Physics laboratory), super-fast surveillance cameras (EU around WIGNER, Hungary), and phase-contrast imaging (MIT). The mutual synergy is the acceleration of the pace of experiments by technical improvements of measuring capabilities.

More and more benefits for tokamak research are materializing: Experience gained in long-pulse stellarator experiments contributes to large scale devices like JT-60SA and ITER. A selected example is the steady-state fueling pellet injector developed by the Oak Ridge National Laboratory that is being brought to W7-X with additional support from EUROfusion and NIFS. This implements a technology planned for use on ITER.

The scientific community is excited by first theoretical ideas to explain the latest results from stellarator experiments. Worldwide-distributed groups, in research centers as well as in universities, are increasingly bringing their expertise in the understanding of fundamental physics questions, like turbulence in 3D fields, impurity transport, fast-ion confinement, and plasma flows and currents.

2.1 Meetings

2.1.1 22nd International Stellarator and Heliotron Workshop (ISHW)

The 22nd International Stellarator and Heliotron Workshop ISHW2019 was held in at the University of Wisconsin - Madison, Wisconsin, USA from September 23-27, 2019. It was attended by 156 participants from ten countries. The workshop covered key stellarator topics from confinement and equilibrium, to plasma edge and divertor physics, reactor concepts, energetic particle confinement and new numerical and computational methods for stellarator optimization.

Main highlights included results from the first Island Divertor campaign at Wendelstein 7-X and from the deuterium campaign at the Large Helical Device (LHD). Wendelstein 7-X has demonstrated high performance plasmas with up to 1 MJ confined energy at 8 keV electron and 3 keV ion temperature during pellet-fuelled high density plasmas. Also, full detachment of the island divertor for up to 30 s has been demonstrated. In LHD, the effects of isotope ratios (H vs. D) were investigated in detail, including diagnostic innovations to quantify the effects of isotope mixtures. Results from a variety of international conceptual design studies for next step stellarators were shown and advances in numerical methods to optimize these new experimental devices were discussed.

2.1.2 19th Coordinated Working Group Meeting (CWGM)

The 19th CWGM was held in Berlin, Germany from March 12-14, 2018. On-site and remotely, fifty participants provided reports on collaborations, grouped into seven topics. In an informal workshop format, the participants discussed proposals for joint actions and experiments, taking advantage of comparative studies in different devices. The CWGM effectively tracked the progress in the most active research fields and initiated a series of new Coordinated Working Group Actions (CWGA) for joint activities. A session on the program planning of the main contributors served to enable the exchange of information and the community was invited to provide feed-back to programmatic considerations. China's rapidly developing stellarator program has a sound balance of sustainable build-up of know-how and scientifically interesting new concepts. In particular the outline of a quasi-axially symmetric device attracted great interest.

2.1.3 48th S-H TCP executive committee meeting

The 48th ExCo meeting of the S-H TCP took place on Sept. 24, 2019 on the venue of the 22nd International Stellarator and Heliotron Workshop. The meeting was attended by representatives from all six contracting parties and observers from Costa Rica and China.

2.2 Milestones achieved

2.2.1 Model Validation and Diagnostic Development in TJ-II

Using its advanced plasma diagnostics, TJ-II stellarator is contributing to model validation in fusion plasmas, including simulations of electrostatic potential variations on flux surfaces, pellet-particle redistribution mechanisms, role of edge radial electric fields on edge-SOL coupling, relation between zonal structures and Alfvén Eigenmodes (AE) and the development of AE control strategies using ECRH and ECCD.

2.2.2 Liquid Metals in TJ-II

TJ-II keeps an active programme for the assessment of novel solutions for plasma facing components using liquid metals. Solid and liquid samples of Li/LiSn/Sn, in a Capillary Porous System (CPS) arrangement, have been exposed to the edge plasma.

2.2.3 Deuterium Operation of LHD

During the 2018/2019 deuterium campaign, experiments on LHD have further advanced in the fusion-relevant temperature regime. In several discharges it was possible to produce plasmas with high ion temperatures T_i in the internal transport barrier range of 10 keV and significantly improved electron temperatures T_e.

2.2.4 New Diagnostics on LHD

An Impurity Powder Dropper and fast Thomson scattering system have been installed by PPPL and UW-Madison, respectively, in the framework of a DOE funded bilateral collaboration. Both diagnostics are now operational on LHD.

2.2.5 Steady State Pellet Injector for Wendelstein 7-X

The prototype extruder for the Continuous Pellet Fuelling System, which is being developed for W7-X as a joint activity between ORNL, PPPL, NIFS and IPP, has been successfully tested at ORNL. Prototype nozzles and controls are being tested.

2.2.6 Wendelstein 7-X Completion

Wendelstein 7-X is still in its final completion phase towards high-power steady-state capability. This completion phase two (CP 2) consists of the installation of several major components, notably the actively cooled high-heat-flux (HHF) divertor, cooling water supply, and extensive measures to protect the in-vessel components against high heat loads. The NBI and ICR heating systems will be extended and the set of diagnostics will be expanded. The development of long-pulse gyrotrons aiming at an output power of 1.5 MW is envisaged for mid 2021.

While the installation of in-vessel components is currently slower than expected, mainly due to the extremely demanding conditions in the assembly space of components combined with high quality requirements for in-vessel water cooling circuits and low assembly tolerances, the project is still within the general schedule. The start of commissioning is expected for July 2021, with first experiments planned to take place around the end of that year.

2.2.7 Simons Collaboration on Hidden Symmetries and Fusion Energy

For the further development of computational methods for stellarator optimization, the Simons Foundation (NY, USA) has awarded a grant to a collaboration of scientists from the United States, Australia, Germany, Switzerland and the UK on the topic of *Hidden Symmetries and Fusion Energy.* While tokamaks have continuous circular symmetry for good confinement, the stellarator relies on symmetry breaking to realize the magnetic field needed to confine particles. However, stellarator fields may have hidden symmetries (like the quasi-helically symmetric stellarator HSX) that can have the same virtues as tokamaks while overcoming some of the inherent drawbacks of the latter. The project's primary purpose is to create and exploit an effective mathematical and computational framework for the design of stellarators with such hidden symmetries. The multidisciplinary collaboration will receive an annual two million USD over for years.

2.3 Future Plans

2.3.1 Towards long-pulse high power operation in Wendelstein 7-X

After the completion of the actively cooled plasma facing components, including a high-heat flux divertor capable of dissipating heat fluxes of up to 10 MW/m^2 in steady-state, 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. The Wendelstein 7-X strategy is also reflected in the planning of the European fusion programme for the next European framework programme "Horizon Europe", implemented by the EUROfusion consortium,

2.3.2 Tungsten Divertor for the Large Helical Device

A proposal to enhance the Large Helical Device (LHD) with a full tungsten Divertor was presented to the Japanese Government. The project is aimed at improving LHD's steady state capabilities and to allow the investigation of the effect of Tungsten on the core plasma. The project has a total duration of six years and foresees the installation of the new tungsten divertor in 2024, which would precede the tungsten phases of ITER and JT60-SA. After initial short pulse experiments under hydrogen, it is intended to perform long pulse deuterium experiments with higher heating powers of 2-3 MW, densities of $n_e > 3 \cdot 10^{19} m^{-3}$ and plasma temperatures of $T_e = T_i = 2\text{-}3$ keV until the end of the year 2028.

2.3.3 HILOADS

After a successful grant application to the German Helmholtz Association, the "Helmholtz International Lab for Optimized Advanced Divertors in Stellarators" will start in early 2020 as a collaboration project between IPP Greifswald and the University of Wisconsin, Madison (UWM) as lead partners. HILOADS will focus on the integrated stellarator optimization loop between divertor, plasma facing materials and the plasma confinement. While W7-X with its island divertor will be the main experimental facility, the Wisconsin based lab will also use smaller experiments like HSX (at UWM) and CTH (at Auburn University) for concept exploration. The work program consists of three tasks: 1) Stellarator divertor optimization with focus on the plasma wall interaction domain (divertor) for the U.S. mid-scale stellarator concept conceptualized at UWM, 2) optimization of the plasma edge and island divertor conditions at W7-X, and 3) targeted developments and verification activities to inform the conceptualization phase of a U.S mid-scale stellarator.

2.4 Participation

In response to the ExCo invitation to join the SH-TCP, the Costa Rica Institute of Technology (TEC) has signed a letter of acceptance. The designation by the government of Costa Rica and the signing of the legal text is still pending.

Following a written ExCo procedure, a letter of invitation was sent to the Institute of Fusion Science at Southwest Jiaotong University, Chengdu. Approval by MOST is pending.

2.5 TCP Name Change

The ExCo unanimously decided in its 48th committee meeting to change the TCP title from *TCP on the Stellarator-Heliotron Concept* to *TCP on Stellarators and Heliotrons.*

Annex

Report from the topical sessions of the 19th Coordinated Working Group Meeting

1 Divertor and Edge Physics in Stellarators (M. Jakubowski)

Two major experimental campaigns were recently conducted, which aimed at investigating important aspects of divertor physics in helical devices. At LHD, results of the first deuterium campaigns were reported by Suguru Masuzaki. There is no clear difference between H & D deuterium plasmas in terms of divertor physics. The asymmetries in divertor particle fluxes, which arise due to edge drifts, look identical in both plasmas. The same is true for divertor load patterns. Additional non-evaporative getter pumps installed under the dome structure of the helical divertor allowed for increasing of the pump speed by about 25%. Stable detachment was achieved using superimposed seeding of krypton and neon in low density discharges. In the seeding experiments, the edge electron temperature decreased to about the half while the radiated power was doubled compared with neon seeding.

At W7-X high density campaign with an island divertor was performed. It allowed to achieve for the first time in stellarators, as reported by Marcin Jakubowski, high recycling regime, where downstream densities are significantly higher than upstream densities. This allowed reaching stable detachment with plasma duration of up to 30 s. It is possible to reduce divertor power loads with help of impurity seeding. Florian Effenberg showed that with Ne global reduction of divertor loads by a factor of 4 could be achieved at W7-X. Seeding N2 leads to more subtle influence on power loads. Nitrogen-seeding results in lower recycling and requires long puff duration in order to establish a significant enhancement of radiated power. Nitrogen is therefore a promising candidate for radiated power control with a feedback system.

Similar to LHD, edge transport is also observed to be affected by drift effects in W7-X, e.g. ExB drifts. Ken Hammond presented results from experiments with positive and negative direction of main magnetic field. Victoria Winters discussed experiments on influence of carbon impurities on radiation patterns. During methane puffs, the percentage increase of C-VI radiation is the same at different density levels, which probably means that transport processes are similar. Grzegorz Pełka presented first results of W7-X limiter plasmas with a new code FINDIFF. It solves fluid equations for main ions and neutrals in curvilinear coordinates. Code is still not in the shape to be able to reproduce experimental data, nevertheless significant progress has been made in last year.

Several areas were identified were common research could be performed between LHD and W7-X. This includes investigation of stable detachment, role of plasma drifts at the edge, changes in divertor structures due to plasma dynamics and 3D migration patterns in helical devices. More specific actions will be defined in a course of 2019.

2 Scaling and operation limits (G. Fuchert)

Knowledge about operation limits and scalings of global confinement parameters is crucial for efficient scenario development in stellarators. In this session, three main topics have been discussed: The scaling of the energy confinement time, MHD and reconnection instabilities and the radiative density limit.

Concerning the energy confinement time scaling, experimental data has been shown by Yamada concerning the isotope effect in LHD. In NBI heated plasmas, no obvious difference in the global energy confinement time is observed. It was stressed, however, that the lack of a degradation in deuterium violates a gyro-Bohm scaling and is in that sense an isotope effect. It has been discussed how the isotope dependence is reflected in the current International Stellarator-Heliotron Database. The extension of available data led to the proposal for a new version of the empirical energy confinement time scaling in stellarators. However, no deuterium data will be available from W7-X in the near future.

Fuchert presented operational limits found in ECRH plasmas in W7-X so far and showed experimental data that the global energy confinement time may be affected close to those limits. This should also be taken into account for future scaling efforts, since many fusion relevant scenarios are in fact close to operational limits.

Suzuki and Zocco reported about the latest progress in the theoretical and numerical description of MHD and reconnection-related instabilities in LHD and W7-X. Such instabilities can lead to severe confinement degradations or plasma termination. In W7-X, an instability has been observed which is likely caused by magnetic reconnection, mediated by electron inertia with ions in the (gyro) kinetic regime. An important question is how general these observations are and which magnetic field properties are needed to prevent those.

Furthermore, Gates presented a brief comparison of the density limit in stellarators and tokamaks and introduced fundamental differences and similarities. It was stressed that there was seemingly no interest in the tokamak community to tackle this issue at the moment and it was proposed that the stellarator community should lead an effort to verify the presented models experimentally.

Joint actions that have been agreed on in this session are:

- A comparison of operational limits for different stellarators including, but not limited to, the three largest ones: LHD, TJ-II and W7-X.
- An investigation on whether identified instabilities are generic to stellarators or depend on the specific details of a particular magnetic configuration.
- An assessment of the density limit with special focus on a comparison with tokamaks.

3 3D Fast Ion Physics (S. Lazerson)

The study of fast ions in stellarators speaks to a fundamental issue of nuclear fusion, specifically the nuclear fusion reaction of hydrogen isotopes to not only generate neutrons but to sustain the plasma parameters necessary for the reaction. While to date no deuterium-tritium stellarator experiments have been performed, a wide range of devices scanning both device size and plasma parameters use heating mechanisms which produce particles with energies significantly above those of the background plasma species.

The status of energetic particle confinement in the Large Helical Device was reported on by Ogawa and Nuga. Äkäslompolo reported on first experiments with neutral beam injection in Wendelstein 7-X. Cappa reported on the interplay between electron cyclotron resonance heating and fast ions in TJ-II experiments. These reports indicate there is an outstanding task to place this data in the context of fusion alphas. Doing so will allow the identification of future experiments which can be performed to clarify the important fast-particle physics for a burning plasma reactor. It was also identified that scaling to alpha particles will clarify the role ITER plays in development of a stellarator reactor. Goncharov presented work highlighting the role non-thermonuclear fast ion populations can have on D-D and D-T neutron production. An outcome of this work was to identify that auxiliary heating systems which drive such populations can result in neutrons with energies higher than 14.1 MeV. This observation has important implications for first wall materials. Bader reported on optimization and design work focused on improving stellarator energetic particle confinement through tailoring of magnetic fields. These collisionless simulations show that it is possible to use magnetic field shaping to improve the confinement of fusion alphas in a collisionless sense. Placing this work in the context of collisional simulations and mode activity is an open task.

Joint actions were agreed to be conducted on

- Identification a set of dimensionless parameters relevant to energetic particle physics in stellarators
- Determination of reactor relevant values for said parameters to better place experimental results in the context of a reactor

4 Fuelling Pellets and Impurity injection (N. Tamura)

The injection of hydrogen-isotope pellets and impurities are highly important techniques in magnetic fusion research for both the tokamak and the stellarator concept. Pellet injection is still a principal tool for fueling steady-state fusion reactors and ITER. Impurities must also be injected as actuators for plasma performance and diagnostics.

G. Motojima (NIFS) reported hydrogen pellet experiments in plasmas with NBI and NBI+ECH in Heliotron J. A deeper pellet penetration was observed in the NBI+ECH plasma, which might be explained by the effect of fast electrons/ions. K.J. McCarthy (Ciemat) reported plan and progress for a TESPEL preparation laboratory at Ciemat. The integrity of TESPEL made at Ciemat will be checked in the TJ-II experiments. A first TESPEL batch is expected around by the end of 2020, before the OP2 of W7-X. N. Panadero (Ciemat) reported recent results of pellet ablation analysis. For TJ-II, the effect of fast electron on the plasmoid drift was considered to explain a higher fueling efficiency. For W7-X, new simulation results for the W7-X campaign OP1.2b suggest that the predicted fueling efficiencies are close to the experimental results. N. Tamura (NIFS) reported first TESPEL injection experiments on W7-X. In the OP1.2b of W7-X, the latest TESPELs (e.g. multi-tracers) were injected, which allow us to perform a detailed study of impurity transport in W7-X. And transient effects (e.g. increment of electron temperature) of the TESPEL injection on W7-X plasmas were also observed. T. Wegner (IPP) reported recent results from LBO experiments in W7-X. In the OP1.2b of W7-X, a variety of impurities was injected by LBO, which contributes to the Z-dependence study of impurity transport. The impurity amount scan experiment by LBO shows that the LBO can be also a plasma killer. L. Baylor (ORNL) reported a current status of the continuous pellet injector for W7-X. The injector was designed based on twin-screw extruder (TSE) and gas gun technology. Now a prototype TSE is under fabrication. E. Gilson (PPPL) reported recent results and plans of an impurity power dropper (IPD). The IPD already showed many beneficial effects (e.g. ELM mitigation, power exhaust) in the previous tokamak experiments. In stellarators, a probe-mounted powder injector (PMPI) was successfully deployed in the OP1.2b of W7-X and the IPD will be commissioned in the JFY2019 campaign. These reports clearly suggested that it is almost prepared for comparative studies about pellet fuelling and the impact of impurity injection in stellarators.

As joint actions/experiments, the following topics were discussed:

- a benchmark activity of HPI2 code, especially in terms of magnetic configuration. This action can be performed on LHD, W7-X, TJ-II and Heliotron J, and can be one of the bridges between CWGM and ITPA by a comparison of penetration depth between tokamak and stellarator in the reactor-relevant regime.
- an optimization of the fueling scheme to achieve the highest density beyond the Sudo limit, and to realize the peaked density profile during on-axis ECRH heating. This activity can be pursued on LHD, W7-X, TJ-II and Heliotron J.
- a development of the accurate TESPEL ablation model can be performed with LHD, TJ-II and W7-X. This activity will be beneficial to the comparative studies regarding impurity transport modelling between those devices using the STRAHL code (this is related to the joint task in the impurity transport session).
- a reactor-oriented mixed-species particle control. This is a demanding task in fusion reactor, but has not been developed in stellarators.
- a Z-dependence studies of impurity transport using multi-impurities-embedded TESPEL. The optimization of the impurities embedded in the TESPEL is included in this activity. The application of TEPSEL to the tokamak experiments was also discussed.

5 Equilibrium (Y. Suzuki)

In the Equilibrium Session 6 contributions were reported. Those contributions can be categorized in 3 categroeis, (i) equilibrium reconstruction, (ii) full field model to the fast ion and edge transport simulations, and (iii) developments of new theory and modeling. In category (i), Schmitt (Auburn) and Lazerson (PPPL) reported recent progress of the equilibrium reconstruction by V3FIT and STELLOPT. Both codes well work to reconstruct equilibrium of W7-X experiment. From these results, two joint actions were planned;

- cross checking of codes using specific targeting shot or synthetic data.
- application of V3FIT and STELLOPT to LHD and comparisons of reconstruction codes and forward model.

In category (ii), Suzuki (NIFS) reported recent progress of full field calculation including net toroidal current. To interpret experimental observation of IR camera measurements. Here, two more joint actions were discussed

- validation of full field models by fast ion and edge transport simulations. (Suzuki, Lazerson)
- validation and verification of codes by cross benchmarking.

We assigned responsible persons to each joint action and then progress will be reported in the next CWGM. In category (iii), Loizu (EPFL) and Landreman (U. Maryland) reported progresses of new theoretical and modeling works. SPEC was applied to model the saturated tearing mode and analytical theory is developing to construct quasi-symmetric configuration directly. We are considering a possible idea for future collaboration: extension of analytical models to include higher order terms (triangularity and plasma beta) and integration with stellarator optimization. We will continue to discuss these ideas going forward. Finally, Moiseenko (KIPT) reported Ultra-short repetitive pulse wall conditioning discharges. We realized a possible idea for future collaboration but applicability of ultra-short pulse to other devices should be considered carefully.

6 3D Turbulence (M. Nakata)

The 3D turbulence session was the largest session covering a full day of the CWGM. There were many contributions (14 talks) from experimental and theoretical aspects, where the main outcomes are summarized as follows:

- Identification of micro instability and turbulent fluctuations, i.e., TEM and ITG characteristics including the surface-global effects, the isotope effects, the geometric dependence, and the verification of stellarator optimizations.
- Impact of Er and Er-shear on turbulence and zonal flows, i.e., electron- to ion-root transition, intrinsic coupling of neoclassical and turbulence dynamics, and the turbulence suppression/spreading in edge-SOL region.
- Validation and extension of GK turbulence simulations, i.e., full-f global model development, validations with fluxtube simulations, and the stability map for electromagnetic turbulence observations.

Based on the above results, several research targets for joint experiments and/or cooperative simulation studies have been specified:

- Validation activity on fluctuations, ZFs, and E_r, in addition to transport levels. This can be addressed by joint experiments and cooperative simulation studies with local and/or global GK codes and neoclassical codes.
- Joint studies on nonlinear energy transfer & saturation mechanism in multiple devices.
- Continued joint activity on constructing “Stellarator base case” for verification platform.

The collaboration framework along the above topic will be organized.

7 Impurity Transport (N. Pablant)

A comprehensive range of topics was covered as part of the impurity transport session through 9 presentations. Significant progress has been made on all of the Impurity Transport Joint Tasks, and this activity has led to a number of joint papers in 2018/2019.

Updates on research related to effect of potential asymmetries (φ_1) on impurity transport were discussed by S. Buller (Chalmers) and Regaña (CIEMAT). Bueller presented updates on theoretical advances in understanding the effect of fast-ions, along with a discussion on optimization of φ_1 to achieve desired impurity transport properties. Regaña showed simulations from EUTERPE, SFINCS and KNOSOS of impurity fluxes in the mixed-collisionality regime with φ_1, along with simulations of expected D and V profiles in W7-X with and without the consideration of φ_1. Related to these discussions, S. Kumar (U. Wisc) presented theoretical modeling of impurity transport in mixed collisionality regimes for HSX like plasmas. This set of talks led to an extended discussion on how to develop joint experiments that could be used for validation of these theoretical findings.

The next topic to be discussed was the impact of pressure anisotropy on impurity transport, which was presented by I. Calvo (CIEMAT). In the presentation Calvo showed a theoretical presentation of how anisotropy can affect impurity transport, along with expression for when this consideration is important. A new code is being developed to study the effect of anisotropy in realistic geometries, which can then be compared with other codes and experimental results.

The effect of turbulence on impurity transport was discussed during the next two presentations by M. Nunami (NIFS) and J. Alcusón (IPP). These presentations discussed the state of the art in using gyro-kinetic simulations to study turbulent transport of impurities. Nunami showed GK simulations of LHD impurity hole plasmas which indicate that turbulent transport cannot account for the observed impurity fluxes; however, a study of the effect of externally applied torque on the neoclassical fluxes may provide a possible explanation.

The next set of talks were focused on experimental results from HSX by S. Kumar (Wisc) and W7-X by M. Kubkowska (IPPLM) and A. Langenberg (IPP). A presentation on capabilities of HSX showed some initial first results from a recently installed LBO system. The W7-X talks by Kubkowska and Langenberg highlighted a wide range of experimental results, including topics of Z-dependence, 1D transport modeling, the effect of turbulent transport, and observed scaling laws. These talks highlight that impurity transport experiments from W7-X are now sufficiently mature to start cross-machine comparisons and advanced theoretical validation exercises.

The final presentation in this session was on the use of an impurity power dropper for impurity injection by E. Gilson (PPPL). Gilson presented capabilities of this system on W7-X and LHD and showed some first W7-X results. An extended discussion on the possible use of the powder dropper for high-Z impurity injections studies followed the presentation.

Several additional topics related to impurity transport were discussed in the dedicated session on fueling pellets and impurity injection, as summarized by N. Tamura.

At the conclusion of the session it was decided that the five Joint Tasks in impurity transport identified in the prior CWGM are still representative of the major open research questions and are serving well to organize collaborative research around these topics. The Impurity Transport Joint Tasks are:

- Z dependence of impurity transport and impurity accumulation.
- Investigation of impurity hole.
- Investigation of potential asymmetries (φ_1) on impurity transport.
- Development of general-purpose 3D stellarator impurity deposition/ionization/transport tools.
- Turbulent modeling for impurity transport.