stellarator news

An international journal of news from the stellarator community

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Report from the 19th Coordinated Working Group Meeting

March 12–14, 2019,
Helmholtz Society, Berlin, Germany

Overview

Worldwide stellarator research has gained substantial momentum: On Wendelstein 7-X (W7-X, Greifswald, Germany), first campaigns with an uncooled divertor have demonstrated the highest-ever fusion performance normalized to the plasma volume and at the same time, the longest pulse lengths. Deuterium experiments in the Large Helical Device (LHD, Toki, Japan) showed confinement at higher performance than gyro-Bohm scaling—differences in terms of engineering parameters are less clear. Smaller devices are enabling experimental insights for physical understanding, such as 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 (CFQS, Chengdu, China) complement the larger experiments, creating new opportunities to assess 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 [e.g., integrated systems for overload detection (EU consortium), x-ray detectors (Princeton Plasma Physics Laboratory), superfast surveillance cameras (EU around WIGNER Research Centre for Physics, Hungary) and phase-contrast imaging (MIT)] to the stellarator programs with obvious mutual synergies: the pace of experiments is accelerated by employing these unprecedented measuring capabilities.

More and more benefits for tokamaks are materializing: experience gained in long-pulse stellarator experiments contributes to large-scale devices such as JT-60SA and ITER. A select example is the steady-state fueling pellet injector from Oak Ridge National Laboratory (ORNL) that is being brought to W7-X with additional support from EUROfusion and NIFS, Japan, and which implements technology planned for use on ITER.

The scientific community is excited by early theoretical ideas to explain the latest results from stellarator experiments. Worldwide groups, concentrated in research centers as well as in universities, are increasingly applying their expertise in the understanding of ground-breaking physics questions, such as turbulence in three-dimensional (3D) fields, impurity transport, fast-ion confinement, and plasma flows and currents.

The above-mentioned aspects were the essence of a three-day meeting held at the headquarters of the Helmholtz Society, the funding agency of the German fusion programme (see Fig. 1). The meeting was organized and sponsored by the Max Planck Institute for Plasma Physics. Roughly forty on-site and ten remote participants provided reports on collaborations, grouped into seven topics. In an informal workshop format, the participants discussed proposals for joint action and experiments, taking advantage of comparative studies in different devices. The CWGM is not a scientific conference, but rather a interactive work-

In this issue . . .

Report from the 19th Coordinated Working Group Meeting (CWGM)
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Fig. 1. Participants of the 19th CWGM in Berlin (March 12–14, 2019).

shop wherein agreements on joint publications under the auspices of the IEA Technology Collaboration Program on Stellarators/Heliotrons are promoted to become the measurable outcome of the CWGM. A session on the program plans of the main contributors served to enable the exchange of information, and the community was invited to provide feedback to programmatic considerations. China's quickly developing stellarator program, with a sound balance of sustainable build-up of know-how and scientifically interesting new concepts, namely the outline of a quasiaxially symmetric device, attracted great interest.

The sessions were led by colleagues serving as coordinators. The remainder of this report gives brief summaries of each session.

Divertor and Edge Physics in Stellarators (M. Jakubowski)

Two major experimental campaigns were recently conducted that 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 hydrogen (H) and deuterium (D) plasmas in terms of divertor physics. The asymmetries in divertor particle fluxes, that 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 about 50%, while the radiated power was doubled compared with neon seeding.

At W7-X, a high-density campaign with an island divertor was conducted. As reported by Marcin Jakubowski, this led to the first achievement in stellarators of a high recycling regime, where downstream densities are significantly higher than upstream densities. This allowed reaching stable detachment of the plasma with plasma duration of up to 30 s. It is possible to reduce divertor power loads with the help of impurity seeding. Florian Effenberg showed that with neon as the seed, global reduction of divertor loads by a factor of 4 could be achieved at W7-X. Seeding with N_2 leads to more subtle influence on power loads. Nitrogen seeding results in lower recycling and requires a long puff duration in order to establish a significant enhancement of radiated power. Nitrogen is therefore a promising candidate for radiated power control using a feedback system.

As is the case in LHD, edge transport is observed to be affected by drift effects in W7-X, e.g., **E**×**B** drifts. Ken Hammond presented results from experiments with positive and negative directions of the main magnetic field. Victoria Winters discussed experiments on the 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 for modeling of W7-X limiter plasmas with a new code FINDIFF. It solves fluid equations for main ions and neutrals in curvilinear coordinates. The code is still not in good enough shape to be able to reproduce experimental data; nevertheless, significant progress has been made in the last year.

Several areas in which joint research could be performed at LHD and W7-X were identified. They include the investigation of stable detachment, the 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 the course of 2019.

Scaling and operation limits (G. Fuchert)

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

Concerning the energy confinement time scaling, Yamada presented experimental data on isotope effects in LHD. In plasmas heated using neutral beam injection (NBI), no obvious difference in the global energy confinement time is observed. It was stressed, however, that the lack of degradation in deuterium violates gyro-Bohm scaling and is in that sense an isotope effect. Participants discussed how the isotope dependence is reflected in the current International Stellarator-Heliotron Database. The extension of available data led to a 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 to provide more data points.

Fuchert presented operational limits found in W7-X plasmas heated by electron cyclotron resonance heating (ECRH) so far and showed experimental data indicating 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 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. An instability observed in W7-X is likely caused by magnetic reconnection, mediated by electron inertia with ions in the (gyro) kinetic regime. Important questions are: How general are these observations, and which magnetic field properties are needed to prevent such Instabilities?

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 agreed to 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.

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 not only to generate neutrons but also to sustain the plasma parameters necessary for the reaction by heating the plasma with the fusion-produced alpha particles While to date no deuterium-tritium stellarator experiments have been performed, a wide range of devices spanning 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 LHD was reported by Ogawa and Nuga. Äkäslompolo reported on first experiments with NBI in W7-X. Cappa reported on the interplay between ECRH and fast ions in TJ-II experiments. These reports indicate that there is an outstanding task to place this data in the context of fusion alphas. Doing so will allow the identification of future experiments to clarify the important fast-particle physics for a burning plasma reactor. Scaling to alpha particles will also clarify the role ITER plays in development of a stellarator reactor. Goncharov presented work highlighting the role that non-thermonuclear fast ion populations can play in D-D and D-T neutron production. An outcome of this work was the conclusion 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 of 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

Fueling Pellets and Impurity injection (N. Tamura)

The injection of hydrogen-isotope pellets and impurities is a highly important technique 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 may 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 or ions. K. J. McCarthy (CIEMAT) reported plans and progress for a tracer-encapsulated solid pellet (TESPEL) preparation laboratory at CIEMAT. The integrity of TESPELs made at CIEMAT will be checked in the TJ-II experiments. A first TESPEL batch is expected around 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 electrons on the plasmoid drift was considered to explain a higher fueling efficiency. For W7-X, new simulation results for 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 allowed performance of a detailed study of impurity transport in W7-X. Transient effects (e.g., increment of electron temperature) of TESPEL injection on W7-X plasmas were also observed.

T. Wegner (IPP) reported recent results from laser blowoff (LBO) experiments in W7-X. In OP1.2b, 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 on the 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 for an impurity power dropper (IPD). The IPD showed many beneficial effects (e.g., ELM mitigation, power exhaust) in 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 time for comparative studies of pellet fueling and the impact of impurity injection in stellarators.

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

- ⇨ A benchmark activity for the 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 through a comparison of penetration depth in tokamaks and stellarators in the reactor-relevant regime.
- ⇨ 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.
- ⇨ 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 modeling among 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 a fusion reactor, but has not been developed in stellarators.
- ⇨ Z-dependence studies of impurity transport using multi-impurities-embedded TESPELs. The optimization of the impurities embedded in the TESPEL is included in this activity. The application of TEPSELs to tokamak experiments was also discussed.

Equilibrium (Y. Suzuki)

In the Equilibrium Session Six contributions were reported. Those contributions can be categorized into three areas: (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 in equilibrium reconstruction using V3FIT and STELLOPT. Both codes well work to reconstruct equilibria of the W7-X experiment. From these results, two joint actions were planned:

- ⇨ Cross-checking of codes using specific targeting shots or synthetic data.
- ⇨ Application of V3FIT and STELLOPT to LHD and comparisons of reconstruction codes and predictive modeling.

In category (ii), Suzuki (NIFS) reported recent progress on 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.

Responsible persons were assigned to each joint action, and progress will be reported in the next CWGM.

In category (iii), Loizu (EPFL) and Landreman (U. Maryland) reported progresses of new theoretical and modeling work. SPEC was applied to model the saturated tearing mode, and analytical theory is developing to construct a quasisymmetric configuration directly. A possible idea for future collaboration is under consideration: extension of analytical models to include higher order terms (triangularity and plasma beta) and integration with stellarator optimization. Discussion of these ideas will continue. Finally, Moiseenko (KIPT) reported on ultra-short repetitive pulse wall conditioning discharges. This technique was considered as a possible area for future collaboration, but applicability of ultra-short pulses to other devices should be considered carefully.

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 microinstability 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 E_r and E_r-shear on turbulence and zonal flows, i.e., electron- to ion-root transition, intrinsic coupling of neoclassical and turbulence dynamics, and turbulence suppression/spreading in the edge-SOL region.
- ⇨ Validation and extension of gyrokinetic (GK) turbulence simulations, i.e., full-f global model development, validations with flux tube 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, zonal flows (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 and saturation mechanisms in multiple devices.
- ⇨ Continued joint activity on constructing the "stellarator base case" for verification platform.

A collaboration framework for these topics will be organized.

Impurity Transport (N. Pablant)

A comprehensive range of topics was covered as part of the impurity transport session through nine 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 the 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 discussed was the impact of pressure anisotropy on impurity transport, which was presented by I. Calvo (CIEMAT). Calvo showed a theoretical presentation of how anisotropy can affect impurity transport, along with an 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 by M. Nunami (NIFS) and J. Alcusón (IPP). These presentations discussed the state of the art in using GK 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 was focused on experimental results from HSX, presented by S. Kumar (Wisconsin) and from W7-X presented by M. Kubkowska (IPPLM) and A. Langenberg (IPP). The presentation on 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 the fact 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 IPD 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 IPD 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 holes.
- 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.

Conclusion

Ongoing collaborations on plasma terminating events and electron root confinement studies were reported and agreed to be continued.

Given the broadness of the aforementioned topics, the CWGM effectively tracked progress in the most active fields aiming at collaborative studies. Initiated in the 2018 Princeton edition of the CWGM, coordinated working group actions (CWGA) serve as a basis to follow up joint actions and will be followed up in forthcoming meetings.

Information on forthcoming CWGMs will be provided to subscribers of the mailing list. Sign up at:

cwgm@ipp.mpg.de

The next CWGM activity will be a brief meeting—the 22nd International Stellarator and Heliotron Workshop 2019 in Madison, Wisconsin (September 23–27, 2019).

Acknowledgements

The authors are indebted to Ms. Maria Radau for her excellent support in organizing the meeting. The participants and organizers are grateful for support by Max-Planck-Institut für Plasmaphysik and EUROfusion.

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