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Report from the 21st Coordinated Working Group Meeting (Virtual Meeting Organized by IPP Greifswald, Nov. 22–24, 2021)

Where do we stand with stellarators as a reactor concept? About 130 people registered to attend a virtual workshop focusing on the prospects for stellarator reactors. The meeting was conducted within the framework of the Coordinated Working Group Meeting (CWGM) under auspices of the IEA Technology Collaboration Programme (IEA TCP) on Stellarators and Heliotrons.

As with the 20th CWGM, the pandemic did not allow for an in-person meeting originally planned to be held in Kyoto. Instead, the attendees met on three consecutive days in one-hour video conferences but because of the many time zones involved, some attendees had to join in the late evening or early morning. This compromise, however, allowed the stellarator/heliotron community to take part as much as possible from its world-wide distributed locations. In order to further facilitate the scientific discussion, the meeting sessions were recorded. Additionally, presentation slides and notes were archived in an electronic documentation system running the INDICO software (https://event.ipp-hgw.mpg.de/event/67/). The material is available for registered participants working in laboratories that are members of the IEA TCP.

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

Open Questions for a Fast Track to Stellarator Reactors

Professor Allen Boozer presented arguments backing a fast track to develop a demonstration fusion power plant [1–3]. Estimates of the cost of the available solutions to stop the use of CO$_2$-producing fuels are in the 4 trillion USD/year range. This is to be put in perspective of a proposed investment of a few billion USD/year for a fusion plant development program.

The stellarator concept is best placed for a fast development with minimum risk. Compared to the more popular tokamak line, a stellarator power plant would benefit from much lesser requirements for active plasma control—the failure of which could have serious consequences in a tokamak reactor. Reliable computational design reduces the number of generations of experiments needed to develop a stellarator power plant. The design of the magnetic configuration and coil set, Prof. Boozer argued, should incorporate fundamental efficiency and “plasma quality” properties of field distributions in an otherwise high-dimensional search space.

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Stellarator reactors could operate in the 10 keV temperature range, where the requirement of confinement improvement over gyro-Bohm is smallest. A gyro-Bohm scaling of the energy confinement time in stellarators forecasts viable reactor design points. A number of technological developments could help in realizing the promise of a stellarator power plant. Coil technologies that are allowed to have joints; improved, thinner blankets with higher breeding ratios; and liquid-metal-based wall protection layers were mentioned.

Prof. Boozer appealed to the stellarator community to instill a sense of thrill and opportunity by bringing a stellarator fusion reactor to contribute to a medium-term solution for the great environmental challenges that lie ahead of us in the 21st century.

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

Professor Robert Wolf summarized the status of experimental findings from Wendelstein 7-X (W7-X) in terms of stellarator optimization. Demonstrating Prof. Boozer's argument about the potential of computational design improvements, W7-X is a proof of concept as the first magnetic device derived from comprehensive optimization procedures based on physics criteria.

Substantial milestones have been attained in the first campaigns of W7-X: even without full cooling of plasma-facing components and without the full envisaged heating, fueling, and exhaust capabilities, W7-X could demonstrate that a magnetic field with very small, noncritical field errors could be created with superconducting coils [4]. Small and controllable plasma currents were demonstrated [5], supporting the HELIAS concept goal: to avoid difficulties for exhaust and plasma stability. Experiments with core pellet fueling and peaked density profiles have already demonstrated reduced neoclassical energy transport [6]. Expectations for higher plasma beta, however, were not yet attainable: MHD stability and equilibrium as well as the impact on fast-ion confinement will need a successive increase of heating power that is now underway. Furthermore, an integration of highest plasma performance with feasible divertor operation [7] needs wider exploration and requires demonstration in discharges much longer than the maximum pulse durations achieved thus far. The successful reduction of neoclassical transport in stellarators, draws attention to the understanding of turbulence in helical geometries.

For an assessment of reactor prospects, the discussion revealed the necessity for confirmation of neoclassical optimization at high plasma beta. Swiftly attaining beta values up to $\langle\beta\rangle \sim 4\%$ would add beneficial support for the development of the stellarator line. MHD stability, equilibrium stiffness, fast particle confinement, and electromagnetic effects in plasma transport, e.g., turbulence stemming from kinetic ballooning modes, were confirmed as high-priority topics. Achievable high-beta operation is apparently restricted by heating power and plasma confinement; uncertainties in performance predictions need to be overcome to define required heating power levels. On a short time scale, two options appear to offer ways forward: a considerable improvement in confinement (H-mode, potentially related to a power threshold that can be beneficially affected by deuterium operation), and low-field operation (1.7 T using the full available ECRH power but in X3-mode).

Findings from the W7-X campaigns underlined the roles of both particle transport and impurity transport. The observed flat or even peaked density profiles in W7-X cannot be understood by neoclassical theory. Signatures for an inward (turbulent) particle pinch effect were suggested as a research focus. The discussion brought up the question of wether it would make sense to aggressively pursue the development of a high-velocity pellet injector (low investment, high reward).

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

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

Multi-ion physics and isotope effects in helical devices

Professor Hiroshi Yamada addressed two related topics highly relevant to burning helical plasmas: the isotope effect on confinement and the observation of plasmas with different ion density profiles, so-called nonmixing plasmas. Evidence is provided by recent experiments conducted on the Large Helical Device (LHD).

The isotope effect manifests in tokamaks as an increase of the energy confinement time τ_E with the ion mass *M*. A full understanding is lacking but a positive M-scaling does match, e.g., with gyro-Bohm scaling of confinement ($\tau_E\Omega_i \sim \rho^{*-3}$). Gyro-Bohm behavior is also found in helical devices [8]. For tokamaks, the isotope effect is ubiquitous and can control energy, particle, impurity, and momentum transport. A critical aspect for ITER operation is the power threshold for transitions to H-mode ($P_{\text{thr}} \sim M^{-1}$). The isotopic effect is favorable for reaching the D-T fusion reactor targets.

It appears to be self-evident that any isotope effect is also relevant to helical systems. In consequence, readiness for deuterium operation in large stellarators is crucial to develop plasma scenarios with enhanced confinement (e.g., H-mode confinement with edge pedestals) or discharges with self-induced density profile peaking.

While LHD could make substantial progress once it has been commissioned for deuterium and mixed plasma operation, smaller devices contribute as well. W7-AS, TJ-II, Heliotron-E, and CHS did not show any noteworthy M scaling. LHD confirms this finding with its own isotope scaling for the confinement time $\tau_E \sim M^{-0.07}$. On the other hand, similar energy confinement times for hydrogen and deuterium imply an improvement with M with respect to the gyro-Bohm expectation [9]. Excellently matched, dimensionally similar plasmas in LHD show a gyro-Bohm like turbulence level and spectrum but nevertheless also a distinct isotope effect as $\tau_E\Omega_i \sim M^{0.94}\rho^{*-3.02}$. It is concluded that helical systems are also governed by an isotopic energy confinement dependence, possibly smaller than that in tokamaks.

The control of isotope ratios is important for the efficacy of fusion in burning plasmas. Deviations of the individual isotopic shapes of ion density profiles with respect to the electron density profile appear to be possible for multi-ion plasmas so long as the ambipolarity condition is maintained. New diagnostic capabilities recently allowed the study of ion density profiles from different isotopes on LHD. Studies of the evolution of H^+ and D^+ density profiles in mixed plasmas showed two different states. An enthralling observation was plasmas with *nonmixing states*, in contrast to *mixing states* for which all density profiles have the same shape. *Nonmixing states* were found at low densities ($\sim 3 \times 10^{-1\ 9}\text{m}^{-3}$) and transiently in fueling experiments [10]. Evidence was found that the density source location is decisive where shape deviations occur. Linear gyro-kinetic calculations and turbulence measurements provide indications that the destabilization of trapped-electron modes favors nonmixing deviations whereas ion-temperature gradient (ITG) mode turbulence ends up in isotope mixing.

The particle sources in multi-ion plasmas at low collisionality that are expected in the nuclear phase of ITER are also affected by anomalous inward pinches. In contrast, hollow profiles in stellarators may occur due to a neoclassical temperature-gradient-driven outward flow.

The discussion revealed the importance of the topic. Action needs to be taken for a better understanding of isotope-dependent particle transport. The forthcoming experimental campaign on LHD will make it possible to address some of resulting open questions. Systematic differences in the Alfvenic turbulence between H^+ and D^+ due to differences in fast-ion velocity and Alfvenic speed have not yet been studied but will be investigated in the future. The possible effect of beta on multi-ion transport physics in the interplay of trapped electron mode (TEM) and ITG (when interchange modes become relevant) has not yet been studied, but it may not be possible to explore this question with sufficient quality on LHD. The transition to H-mode in LHD does not lead to a strong increase in temperature but rather to an increase in density. There is only a small increase in confinement and no distinct pedestal is formed. In order to study He transport, He-NBI injection has been started at LHD. The strong recycling of He did not yet allow conclusive results, and a He pump is needed. Helium transport will be an important topic for multi-species plasmas in LHD.

The interesting question of whether the physics of reversed shear tokamak configurations, which are known to not show an isotopic confinement effect, could play a role in stellarators could not yet be answered.

The pioneering studies with deuterium operation in LHD provided important new insights, and thus the study of isotopic effects in W7-X was deemed to be of highest interest. In the discussion, the better understanding of the role of TEM and other turbulence mechanisms on mixed ion species discharges in optimized configurations was identified as a need for reactor predictions. In this context, the role of theory and modeling was underlined. Specific points were the question of the impact of neoclassical transport on the global confinement time and its isotopic effect. Moreover, modeling of electromagnetic turbulence is limited by the lack of precise simulation codes. The topic is flagged as a priority for theory developments.

Conclusion

Recent LHD and W7-X experiments have delivered substantial scientific progress highly important to a stellarator reactor concept. Developments in stellarator theory and increasing maturity of computational tools for optimized stellarator designs open the door for rapid concept developments. The meeting identified open questions and provided ways to address them. No showstopper for a stellarator reactor has been revealed. It is concluded that the time scale for scientific progress is dominantly set by the progress and available resources in the experimental programs, lead times for critical technologies (e.g., metallic divertor targets), and decision-making periods, which are not within the control of scientific planners. The documented progress in the scientific exploitation of the facilities allows one to define specifically required steps for an assessment of the stellarator line as a reactor concept. Smaller devices that can focus more flexibly on dedicated objectives (e.g., qualification of techniques like wall conditioning or turbulence studies) play a vital role in this process. Open questions for helical reactors are identified and deliver specific objectives for forthcoming experiments, such as operation at high plasma beta and its impact on stability, neoclassical, and turbulent transport. Particle transport, fueling, and exhaust define the development path to exploit the paramount advantage of stellarators for steady-state operation. First glimpses into multi-ion plasma reveal how much isotopic effects may affect the operation at reactor relevant conditions. A comparative discussion with upcoming JET results and the perspective of fusion plasmas in ITER give rise to the anticipation that multi-ion plasmas in 3D will get more and more into the focus of stellarator research. It appears to be of utmost interest to study multi-ion plasmas also in optimized plasmas as in W7-X—a potential benefit could be a lower threshold for improved confinement regimes.

The next CWGM is planned to be in 2022 in Japan. This virtual meeting indicated strong interest and enthusiasm in the community, providing strong motivation to keep the CWGM as accessible as in the 21st edition. The stellarator community is invited to subscribe to the CWGM mailing list by sending an e-mail to cwgm-subscribe@ipp.mpg.de.

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On behalf of the 21st CWGM

References

[1] Boozer, AH, Why carbon dioxide makes stellarators so important, Nucl. Fusion **60**, 65001 (2020).

[2] Boozer, AH, Stellarators as a fast path to fusion, Nucl. Fusion **61**, 096024 (2021)

[3] Boozer, AH, Carbon dioxide, fusion, and stellarators, *Stellarator News* issue 176, https://arxiv.org/pdf/2111.04213.pdf (2021).

[4] Sunn Pedersen, T, et al., Confirmation of the topology of the Wendelstein 7-X magnetic field to better than 1:100,000, Nature Comm. **7**, 13493 (2016).

[5] Dinklage, A, et al., Magnetic configuration effects on the Wendelstein 7-X stellarator, Nature Phys. **14**, 855 (2018).

[6] Beidler, CD, et al., Demonstration of reduced neoclassical energy transport in Wendelstein 7-X, Nature **596**, 221 (2021).

[7] Jakubowski, , et al., Overview of the results from divertor experiments with attached and detached plasmas at Wendelstein 7-X and their implications for steady-state operation, Nucl. Fusion **61**, 106003 (2021).

[8] Yamada, H, et al, Characterization of energy confinement in net-current free plasmas using the extended International Stellarator Database, Nucl. Fusion **45**, 1684 (2005).

[9] Yamada, H, et al., Isotope Effect on Energy Confinement Time and Thermal Transport in Neutral-Beam-Heated Stellarator-Heliotron Plasmas, Phys. Rev. Lett. **123**, 185001 (2019).

[10] Ida, K,et al., Transition between Isotope-Mixing and Nonmixing States in Hydrogen-Deuterium Mixture Plasmas, Phys. Rev. Lett. **124**, 025002 (2020).