stellarator news

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Systems code approach for burning plasma stellarator devices

With ITER now under construction as the first fusion device to study the physics of a burning plasma in detail, an increased focus is being placed on a demonstration power plant (DEMO).

This has been emphasized by the IAEA, which organized the "Second IAEA DEMO Programme Workshop" [1] in Vienna last December. This workshop was organized to facilitate the discussion of current physics and engineering status and issues for a DEMO fusion device. One of the main topics discussed was the fusion systems code approach illustrated in Fig. 1.

Systems codes, also known as design codes, are comprehensive yet simplified models of a complete fusion facility. Since they combine physics, engineering, and economic aspects, they are used to develop conceptual design points and to conduct sensitivity studies.

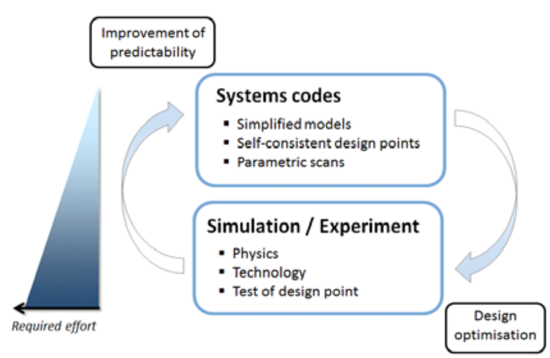

Fig. 1. Concept of systems codes and their interaction with detailed simulations and experiments.

One commonly employed instrument is the systems code PROCESS [2] maintained by the Culham Centre for Fusion Energy (CCFE), which is used in the EU to study and optimize tokamak-based DEMO design concepts. For the heliotron line, the well-developed systems code HELIOSCOPE [3] maintained by the National Institute for Fusion Science (NIFS), is used for purposes such as design window analysis of the force-free helical reactor [4]. Up to now, no such tool was available for the helical advanced stellarator (HELIAS) line. Therefore a HELIAS module has been developed by the Max Planck Institute for Plasma Physics (IPP) and implemented into the framework of PROCESS by CCFE.

The advantage of developing a stellarator module for PROCESS is that common routines for non-device-specific systems such as plant power balance or routines for optimization are already available and have gained maturity through many applications. Moreover, this common framework allows direct comparative studies of tokamak and stellarator design concepts.

In order to incorporate a stellarator module into PROCESS, stellarator-specific models are required that reflect the specific properties of the stellarator. These models include

⇨ a geometry model based on Fourier coefficients that

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can represent the complex three-dimensional (3D) plasma shape,

- ⇨ a basic island divertor model that assumes diffusive cross-field transport and high radiation at the X-point [5],
- ⇨ a coil model which combines scaling aspects based on the Helias 5-B design [6] in combination with analytic inductance and field calculations, and
- ⇨ a transport model that employs a predictive confinement time scaling derived from 1D neoclassical [7] and 3D turbulence [8] simulations.

One requirement of this development is to retain low calculation times without compromising the necessary accuracy and complexity of the 3D stellarator-specific properties.

As an example, in Table 1 results for the coil module are compared to actual values for Wendelstein 7-X (W7-X). Only the mass of the support structure and the mass of the winding pack (WP) differ by a small degree. Since the mass of support structure was not a costing factor for W7-X, it was not optimized in this regard. Also, the winding pack (WP) of W7-X includes additional materials, explaining the higher mass compared to the calculation. If, in contrast, HELIAS burning plasma devices are considered, the structure certainly needs to be optimized, which means that the calculations will be more valid for larger devices.

Device	Coil Module	W7-X
Coil Length [m]	8.5	8.5
Field on Axis [T]	3.0	3.0
Field on Coil [T]	6.6	6.7
Magnetic Energy [MJ]	640	620
Mass of Sup.Struc. [t]	212	~300
Winding Pack [m*m]	0.17x0.18	0.18x0.19
Ampere Turns [MA]	1.74	1.74
Total weight of WP [t]	67	~100
Material	NbTi	NbTi

Table 1. Comparison of the PROCESS stellarator coil model with the actual values from W7-X.

Conclusions

A stellarator module has been developed and implemented in the systems code PROCESS and benchmarked against W7-X, showing good agreement.

With such a tool available, direct comparative studies of tokamak and stellarator reactors can be prepared. Also systems studies of HELIAS burning plasma devices can be carried out to find consistent design points.

This tool can be used not only for reactor-sized facilities but also for an intermediate-step stellarator. A direct step from W7-X to a HELIAS reactor would be substantial and therefore poses certain risks. An intermediate step, an ITER-like stellarator, may thus be desirable to study collective particle behavior in a burning plasma in 3D geometry. The systems code approach will be a valuable tool in designing and optimizing such a device.

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Coordinated Working Group Meeting (CWGM13) for Stellarator-Heliotron Research

The 13th Coordinated Working Group Meeting (CWGM13) was held 26–28 February 2014 at the Uji Campus of Kyoto University. The materials presented at this meeting are available at http://ishcdb.nifs.ac.jp/ and http://fusionwiki.ciemat.es/wiki/Coordinated_Working_Group (→ CWGM13). A brief summary of the meeting is provided here.

Three-dimensional (3D) transport in divertors

In response to a proposal made at the last CWGM (CWGM12 in Padova), recent progress on the experimental identification and physics interpretation of the 3D effects of magnetic field geometry/topology on divertor transport was reviewed. This information has passed the domestic (Japan) selection process for presentation at the 25th IAEA Fusion Energy Conference. Identification of key parameters for 3D effects should open new perspectives on divertor optimization for future reactors. Interactions between the 3D structure of the magnetic field, current in the scrape-off layer (SOL)/stochastic layer, and parallel and perpendicular electric fields should be systematically clarified through diagnostics and modeling for a range of magnetic field configurations. Issues in formulating joint experiments, potential and current measurements, and 2D temperature and density measurements were discussed among the HSX, LHD and TJ-II teams. Comparison with linear devices "without 3D effects" is also recommended to elucidate 3D effects in a comparative manner.

Impurities

Impurity issues have been raised at several CWGM meetings, but unfortunately there had been no impurity sessions. This time, an impurity session was formed to reactivate discussions in the framework of CWGM. Experiments on impurity transport were reported from LHD for both intrinsic and tracer-encapsulated solid pellet (TESPEL)-induced impurities and from TJ-II for a broad range of materials (LiF to W). In TJ-II, TESPEL injection is now under consideration with a newly installed pellet injector. In-surface variation of electrostatic potential caused by ion drift-kinetic dynamics has been proposed as potentially important for radial impurity transport. TJ-II has identified asymmetries in C^{6+} impurity density and floating potential, for which comparisons with the EUTERPE code result have commenced. The importance of the impurity issues calls for coordinated action both in experiments (Heliotron J, LHD, and TJ-II) and simulations (FORTEC-3D, EUTERPE, fluid codes, ...) to assess the existence of in-surface potential variation and its contribution to radial impurity flux. R. Burhenn et al. published a joint paper on impurity issues in 2009 ["On impurity handling in high performance stellarator/heliotron plasmas," Nucl. Fusion **49** (2009) 065005]. Follow-up joint papers (documenting subsequent developments) can be formulated by reactivating joint activities in CWGM.

Highlights in experiments and invitation to joint experiment

Recent experiments in the Heliotron J device were reviewed. Plasma startup; the plasma parallel flow measurement and its comparison with neoclassical prediction; fast-ion driven MHD and related particle flux studies by using several probe systems; the external control of energetic-ion-driven MHD instabilities by ECCD; the fast ion distributions in ICRF experiments; high density operation through high intensity gas puff (HIGP) fueling and supersonic molecular beam injection (SMBI); transition to improved confinement in such a high-density regime; etc. were emphasized to trigger proposal and discussions for joint experiments. From LHD, steady progress in plasma parameters (ion temperature, simultaneous high temperatures, and steady-state operation) was reported. New diagnostics enabling high dynamic-range spectroscopic measurement of the Balmer-□ lines, have facilitated quantitative understandings of the impacts of discharge cleaning on producing high ion temperature plasmas. RMP experiments have fertilized 3D physics, such as magnetic island dynamics (growth/healing), and observation of peaked pressure profiles inside the magnetic island after pellet deposition. A tentative schedule of deuterium experiment was also mentioned, along with planned upgrades of heating and diagnostics capability. MyView (advanced data viewer) and TASK3D-a (integrated transport analysis suite) were introduced, which should facilitate joint experiments. Invitations to the 18th LHD campaign (in 2014) were presented.

Reactor/systems code

After the kick-off session at CWGM10 (2012, Greifswald), interaction between systems codes (HELIOSCOPE and PROCESS) and physics models has been successfully enhanced. Plasma operation control scenario consideration has been progressing for FFHR-d1, in which a transport model based on LHD experiment has been employed. Coupling with TASK3D (an integrated transport analysis suite) is in preparation for consistency checks (time evolution of equilibrium, heating along with plasma profiles). As for PROCESS (see the first article in this issue), modules for plasma geometry, modular coils, and an island divertor have been developed and implemented. An ITG transport model, deduced on the basis of GENE simulation results, will also be included. In this way, common development for these two reactor design activities is in progress to implement further physics models. Benchmarking activities between these developments were proposed. However, it is too difficult at this moment because many modules depend on the individual design. Mutual information exchange and closer links to physics models are anticipated.

Flows and viscosity, transport

Flows and viscosity strongly depend on magnetic configurations, collisionality and radial electric field etc. A variety of magnetic configurations, either within a single device or covering several devices, provide a wide variety of research subjects to be challenged in experiment, theories, and simulations. In terms of neoclassical transport, the neoclassical poloidal viscosity analyses for LHD biasing plasmas, the validation of stellarator optimization via extended neoclassical simulations and dedicated experiment, and parallel flow in Heliotron J NBI plasmas were reported. Benchmarking of a suite of neoclassical transport codes both with (FORTEC-3D) and without nonlocal effects has been progressing through the use of experimental data. Setting a standard case (such as the “Cyclone DIII-D base case” [C.M. Greenfield et al., Nucl. Fusion **37** (1997) 1215]) for this joint activity was proposed, utilizing the International Stellarator-Heliotron (ISH) Profile Database. Uploading the simulation results was also suggested. Joint activities for the evaluation of expected potential variation on a flux surface ($\square_1$) based on EUTERPE and FORTEC-3D are planned in relation to the issue of impurity transport. Neoclassical transport in tokamaks with 3D magnetic perturbations has also been progressing through collaborations among NIFS, PPPL, and the Japan Atomic Energy Agency.

In addition to neoclassical transport, correlations among flow, turbulence, and transport were discussed, stimulated by presentations from HSX (core density turbulence and plasma flows) and LHD (toroidal flows and turbulence, electromagnetic gyrokinetic simulation in finite-beta plasmas). Because such issues have been rapidly evolving among several stellarator-heliotron devices, establishing of a new session or identifying a new key person was proposed to further activate collaborations on this topic.

Plasma startup

In stellarator-heliotron devices, current-free plasmas have been produced by 1st/2nd harmonic ECH or (in LHD) tangential NBI. No successful plasma startup by NBI only has occurred in medium-size devices such as Heliotron J and TJ-II. Successful startup is required in W7-X. Reliable startup at low toroidal electric field is an important issue in superconducting tokamaks. These issues have been programmatically investigated in the ITPA Integration Operation Scenario (IOS) topical group, and Heliotron J and TJ-II have contributed to it. Multi-device experiments and analyses have been made for detailed characterization of plasma startup, yielding better understanding for modeling. As the kick-off of this plasma startup session, (1) issues of plasma startup in stellarator-heliotron plasmas, (2) 2nd harmonic ECH breakdown in Heliotron J, LHD, WEGA, and prediction for W7-X, (3) modeling of NBI startup in LHD and W7-AS and the possibility of plasma startup by NBI in W7-X, and (4) effects of ohmic induced toroidal electric field were reported, as were modeling efforts. A joint paper on ECH breakdown is in preparation.

Energetic particles, Alfvén eigenmodes

Database activity on Alfvén eigenmodes has been developing among H-1NF, Heliotron J, and LHD. The Data mining tool has been upgraded (updated clustering). Effects of ECH/ECCD on Alfvén eigenmodes have been programmatically investigated among Heliotron J, LHD, and TJ-II. In Heliotron J, the global Alfvén eigenmode (GAE) has been targeted for comparison with TJ-II results, and the findings have passed the domestic (Japan) selection process for the 25th IAEA Fusion Energy Conference as a joint paper. Anomalous transport and loss of energetic particles by MHD instabilities are also a leading topic (3 devices mentioned above). The STELLGAP code has been upgraded to consider the coupling between shear Alfvén waves and acoustic waves. Beta-induced Alfvén eigenmodes (BAE) including EGAM (energetic particle-driven GAM), which are observed in many devices, will be examined by STELLGAP from the viewpoints of low-frequency modes in the gap caused by Alfvén and acoustic waves.

3D equilibrium

The programmatic validation and cross-benchmarking initiative for 3D equilibrium calculations (involving 11 codes from 6 institutions) was introduced. Stellarator symmetric tokamak equilibrium with small nonaxisymmetric perturbations (ELM suppression experiments in DIII-D, shot 146058) allows participation of a wide range of equilibrium codes. Calculations have found disagreement between VMEC and linearized tokamak codes, and the source of disagreement has not yet been resolved. A dedicated run day for scanning key plasma parameters and I-coil spectral scans is being planned to widen the database for guiding validation and cross-benchmarking. A joint activity utilizing stellarator-heliotron experiments was recommended. The big impacts of the toroidal current on magnetic topology especially in low magnetic shear configurations were pointed out, and this issue has been systematically investigated in W7-X (VMEC/EXTENDER, HINT2) and TJ-II (HINT2). Some of these investigations will be reported in the plenary talk at the coming EPS

(June 2014 in Berlin) by J. Geiger (IPP-Greifswald). Comparative studies on Heliotron J should be started. The helical core in RFPs and 3D displacement for tokamaks are also emerging as collaborative topics in 3D equilibrium.

International Stellarator-Heliotron Confinement and Profile Database (ISH-CDB, PDB)

The long history of the ISH databases was reviewed, in terms of the evolution of global energy confinement scalings (ISS95, ISS04), and from CDB to PDB with equilibrium database. Reexamination of the iota dependence in ISS04 (~ 0.41) was proposed, exploiting the extended TJ-II data (a wide scan of ι is available) for reducing collinearity of ι with geometrical parameters such as the aspect ratio. Extension of HSX data (recent 1-T operation) was also proposed. Recent TASK3D extension in LHD has enabled sequential production of 0D data in CDB, so that registrations from LHD are foreseen. A. Kus (IPP-Greifswald), who has devotedly contributed to CDB and PDB, will retire this September. He has used the statistical analysis software, JMP. At this occasion, he prepares his scripts to be widely available as a basis for future extension. These will be uploaded in the ISH-DB web page. A trial of the statistical approach for deducing ion and electron heat diffusivities for a wide-range of LHD plasmas (for example the "LHD profile database") was also introduced.

Framework of collaborations

The restructuring of fusion activities in Europe, EUROFUSION, was explained along with the EFDA road map to the realization of fusion energy (http://www.efda.org/wpcms/wp-content/uploads/2013/01/JG12.356-web.pdf). Stellarators are part of this road map, as an alternative approach and to mitigate risks such as steady-state operation and plasma startup. Focus is put on the HELIAS line. Work on other helical concepts (heliotrons, compact stellarators) will continue as a part of international collaborations. In this regard, CWGM is highly relevant to in the EUROFUSION activity. TJ-II experimental plans were introduced to emphasize that they are very much aligned with EUROFUSION work programs. The Steady State Operation Coordination Group (SSOCG) activity was also introduced. This activity has been formulated by coordinating the participation of related International Energy Agency (IEA) Implementing Agreements and national laboratories. Among 7 work packages, there is a "road map to steady-state operation," to which Stellarator-Heliotron efforts should make substantial contributions. It was agreed to hold a brainstorming meeting (video-conference) led by T. Mutoh (NIFS) and A. Dinklage (IPP) along with interested colleagues (such as the steady-state operation theme group at LHD). The outcome from that meeting will be reported at the next CWGM.

Miscellaneous

Setting up a "steering group" for CWGM activity was proposed to facilitate organizational discussions such as the prioritization of topics, session organization, etc.
M. Yokoyama (NIFS) was appointed to initiate discussions on this issue. It was also recommended to report the creation of the steering group to the Executive Committee of the IEA Implementing Agreement on Cooperation in Development of the Stellarator-Heliotron Concept.

At the end of the meeting, A. Dinklage (IPP-Greifswald) proposed to hold the 14th CWGM in Europe. The CWGM activity has been recognized in EUROFUSION (see, "Framework of collaborations") as one of the international collaborative frameworks. It recommends holding two meetings, one abroad and one in Europe, in a year. Based on recent increased interest in the stellarator concept in Hungary and Poland, he will contact these two countries to inquire about their interest in hosting the next CWGM.

Acknowledgements

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