stellarator news

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Impact of lithium-coated walls on plasma performance in the TJ-II stellarator

1. Introduction

Plasma-wall interaction issues are paramount in achieving fusion plasmas with high purity, controlled density and high confinement. Even when plasma-facing components (PFCs), such as limiter and divertor target materials, are selected on the basis of their ability to withstand the very high particle and power fluxes characteristic of present fusion plasmas, interactions between the first wall and charge-exchange neutrals, photons, and some more or less tenuous plasma are considered to contribute to the plasma impurity content as much as the PFCs do. Therefore, concern has been growing for many years about proper conditioning of the total inner wall of the fusion device. Compared to tokamaks, stellarator plasmas show distinct features in their interaction with the surrounding materials. On the positive side, the lack of disruptions and type I ELMs makes them more reliable for reactor operation. The absence of an MHD-driven density limit is another positive factor. However, due to their significantly higher aspect ratio, stellarators offer a less favorable area-to-volume ratio and also worse screening of recycled neutrals. This last parameter has obvious implications for divertor design and, in general, for density control by external sources.

Although some specific divertor concepts developed for stellarators have yielded reasonable success in impurity and particle control, no specific coating strategies for the first wall exist. However, application of concepts with good performance in tokamaks, such as boronization or Ti gettering, has also improved machine operation in the stellarator community. Due to the systematically higher complexity in the vacuum vessel topography of stellarators, homogeneous coatings are harder to produce, in particular if line-of-sight deposition (i.e., Ti gettering) is sought. In the present work, the implementation of a system for fully coating of the inner walls of a stellarator (the TJ-II Heliac) with lithium is described for the first time. Compared to other low-Z coating elements such as Be, C, and B, Li is a very attractive element due to its very low radiation power, strong H retention (leading to the formation of the very stable hydride, LiH), and strong O getter activity, and excellent results have been achieved recently in tokamaks [1].

2. Wall conditioning of the TJ-II stellarator

The TJ-II stellarator at CIEMAT in Madrid, Spain, has been operated under diverse first wall conditions since its beginning [2]. Under electron cyclotron resonance (ECR) plasma generation and heating, density control is ham-

In this issue . . .

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Lithium coating, tested for the first time in a stellarator, has proven a very effective method for particle control in the TJ-II stellarator. Changes in the shot-by-shot fueling characteristics as well as in the total particle inventory compatible with good density control have been recorded after the Li deposition. The fueling rate at constant density was a factor of 4 higher than with B-coated walls, and an even higher value was estimated for the allowed H inventory in puffing-controlled ECRH discharges. These changes were also mirrored in the radiation and edge radial profiles, with increased electron temperatures. Record values of plasma energy content were measured at densities up to 4.5×10^{13} cm^{-3} under Li-coated wall conditions. Important changes in the radial profiles of total radiation were also recorded in NBI plasmas, implying a different, more benign, mechanism for plasma collapse at high densities. 1

Report on the 17th International Toki Conference and the 16th International Stellarator/ Heliotron Workshop
A summary of the joint meeting that was held in Toki (Japan) October 15–19 2007 and was organized by the National Institute for Fusion Sciences (NIFS) is presented. 6

pered by the combination of a low cut-off density and the large surface/volume ratio of the vacuum vessel with respect to the plasma. However, different origins of the problem were identified depending on wall conditioning and plasma-facing materials.

For the initial scenario, a full metal machine, the principal issue was desorption of high-recycling He from the walls, which was implanted during overnight glow-discharge (GD) conditioning, either by the plasma, or by direct interaction with the microwave beams. The systematic use of a short Ar GD period led to a significant improvement in control. With boronized walls and graphite limiters (low-Z scenario), the improvement in plasma purity and the low recycling conditions at the beginning of the operation (shortly after the depletion of H from the film by He GD) provided a higher tolerance of the plasma to external fueling. Two complications, however, were found using boronized walls. First, the gradual loading of the C/B film by H degrades the good recycling characteristics in a relatively short period. After a total implantation dose corresponding to the maximum uptake of the film ~1 × 10^{17} cm^{-2}, was achieved, a spontaneous density rise drove the discharge to the cut-off density, even with no external puffing. The application of a few dry discharges was required for recovery, but this was only transiently obtained. A second factor in play was the presence of the Enhanced Particle Confinement (EPC) mode, characterized by a sudden increase of particle confinement at a critical density on the order of 0.6×10^{13} cm^{-3} [3]. This mode, whose presence seems correlated with edge collisionality and the development of a velocity shear layer at the edge [4], was found to strongly depend on the fueling pulse shape and amplitude [5], and its development can be eventually suppressed by proper tailoring of the gas puffing.

In the 2007 campaign, a low recycling, low-Z wall was tested. For that purpose, an in situ lithium coating technique was developed. It is based on evaporation under vacuum from four ovens, symmetrically spaced and oriented tangentially to the plane of the corresponding flanges in the equatorial plane of the vacuum vessel, filled with 1g of metallic Li each. A set of metallic resistances (Thermocoax) and thermocouples (K-type, two per oven) are operated at pre-programmed temperatures of 500–600ºC by a central, PID-based power supply. Effusion from the ovens creates an atomic beam aimed at the remote region opposed to the corresponding flange. Under high-vacuum operation, the mean free path of the Li atoms is long enough to produce a thin layer on the vessel walls located midway between adjacent ovens. The deposition pattern, directly visible in the groove protecting the central coils, matches the line of sight flight of the Li atoms.

Alternatively, effusion under a He atmosphere was tried to enhance lateral diffusion of the beam, hence providing a more homogeneous coating of the walls in areas closer to the ovens. A pressure of 10^{-5} mbar was chosen, based on the experimentally determined mean free path for the He-Li system at this pressure, $l \sim 70$ cm and the characteristic length of the vacuum vessel, $V/S \sim 20$ cm (assuming pure cylindrical geometry). In order to extend the lifetime of the Li coating, and due to the very high reactivity of this species with background gases (water, O_2, N_2, CO, …) a ~50-nm boron layer was deposited prior to the evaporation by conventional GD of an orto-carborane/He mixture. A pure He GD depleted the B coating of H after its deposition. Also, He GD was applied every day on the Li layer in order to remove H from the areas not fully covered by the coating. A total of 12 g of Li was evaporated for the ~650 discharges performed in this period.

3. Particle control on Li walls

Compared to operation on boronized walls, the control of plasma density by external puffing was very much upgraded upon lithiumization of TJ-II. Not only were the required puffing levels significantly higher for the same density, but also no sign of saturation was observed after a full day of ECRH operation. Of particular relevance for machine performance is the recovery of pumping wall characteristics after shots with densities above cut-off. Typically, one or two purges (dry discharges) were required in B scenarios. However, no such a need was found upon lithiumization, the wall memory effect being basically washed out. In order to quantitatively understand this effect, the particle balance on a shot-to-shot basis was evaluated from the injected hydrogen and the desorbed hydrogen after the plasmas, the latter being measured by an absolutely calibrated mass spectrometer. In Fig. 1 results for a typical operation day under both types of wall conditions are displayed. Two main differences between B and Li walls are clearly seen from the figure. First, the required particle injection for a given density is systematically higher in the Li case. Second, while the B wall shows saturation at a total retained inventory of H < 5×10^{20} (which, for the nominal saturation level of B films, implies an effective interaction area of less than 1 m^2), no sign of such saturation is seen for values up to 4 times higher in the Li case.

The dynamic behavior of plasma particles during the discharge is shown in Fig. 2 for a characteristic shot. First, gas puffing is injected for density build-up. Then it is abruptly interrupted and the evolution of cord density and H_α emission are recorded. For pure H plasmas, a simple equation of the form

$$\frac{dN_e}{dt} = fQ_{in} - \frac{N_e}{\tau_p/(1-R)} \tag{1}$$

can be applied. Here, Q_{in} is the puffing rate (e^-/s), τ_p is the particle confinement time, f is the fueling efficiency, and R is the recycling coefficient.

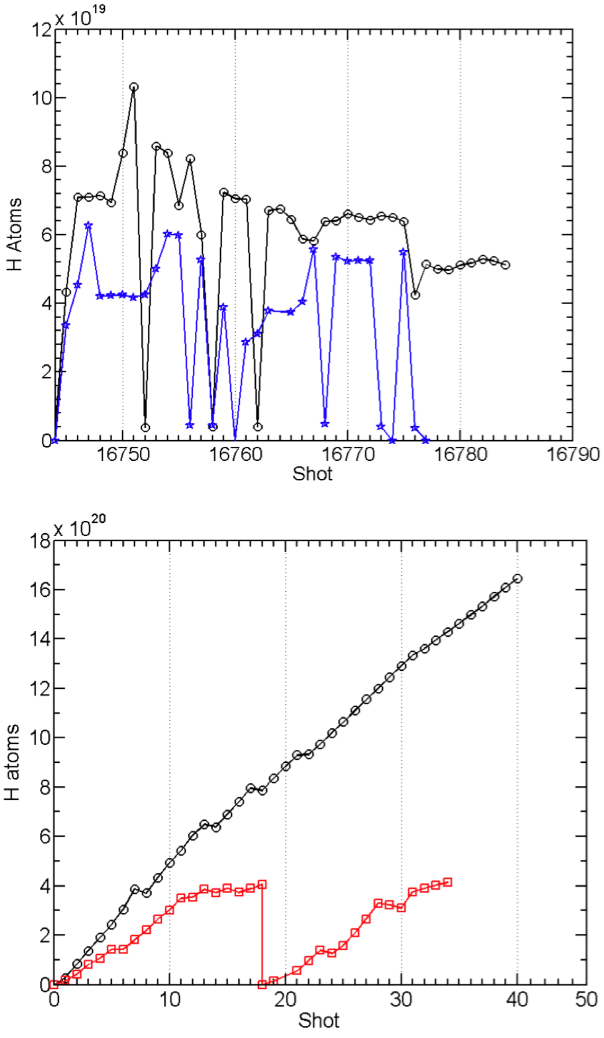

Fig.1. Particle balance under B and Li wall conditions. Top: Integrated particles injected per pulse. Bottom: Cumulative retention of H in the walls. Black, Li. Blue and red, B.

Application of Eq. (1) to the data of Fig. 2 yields a f value near unity and an effective confinement time, $\tau_p/(1-R)$, of ~30 ms. Assuming no major changes in particle confinement with respect to the boron and metal cases (see below), a value of ~0.65 is obtained for R. This value, although lower than that deduced for boronized walls, is significantly higher than expected for a fully absorbing wall and may reflect the limited extent of the wall coverage by the Li coating.

Another important factor contributing to density control by external puffing is the absence of discontinuities in the confinement characteristics, such as that introduced by the transition to the EPC mode. In Fig. 3, the dependence of line-average density on particle flow to the wall (H_α signal) is shown for Li wall operation. The location of the EPC transition for the B and metal cases is also shown. For constant recycling conditions and negligible contribution of impurities to N_e, the linearity displayed in the figure obviously implies that no change in the particle confinement characteristics of the plasma is taking place during the scan. This is also confirmed through the ion energy confinement analysis shown in Sec. 5.

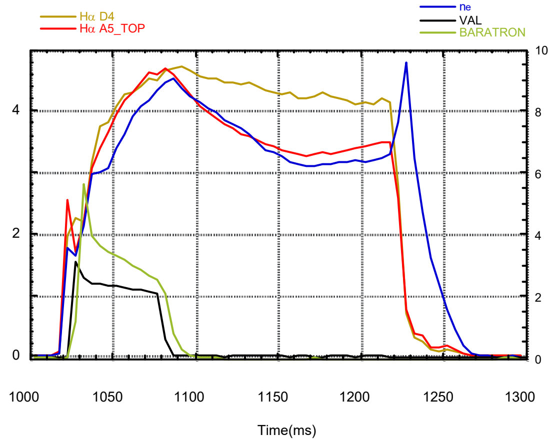

Fig. 2. Time response of electron density (blue) and fluxes to the wall (H_α, red and gold) to a gas pulse (black and green) with Li walls.

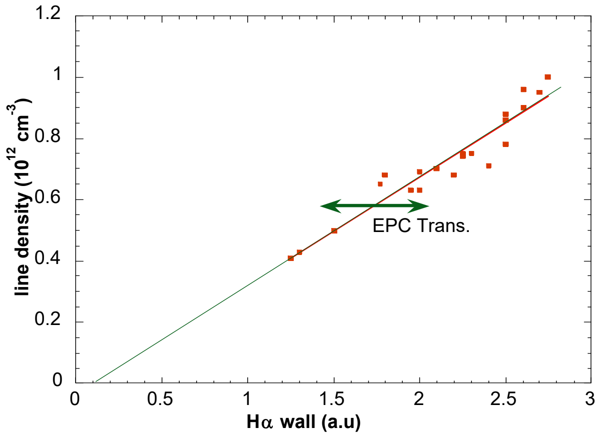

Fig. 3. Line-average density vs flux to the walls for Li wall conditions. The line is a linear regression fit to the data

4. Impurity behavior and plasma parameters

Clean plasmas are routinely obtained in TJ-II using ECR heating under low-Z scenarios, largely due to the strong oxygen gettering effect of the B coatings and the use of graphite limiters [6]. Although the Li coatings were not aimed at improving this situation, a significant effect was observed in the last campaign. Carbon emission was seen to decrease during the operation day. Figure 4 shows the evolution of some relevant signals, normalized to the line-average density. After an initial spike in all impurity monitors, associated with the very first shots after Li deposition, a systematic decrease takes place upon plasma operation. Of special relevance is the strong decay of the bolometer signal, closely related to the suppression of carbon impurities from the plasma. The strong reduction of the C source in the presence of Li is a well-documented effect that is associated with a decrease of the physical and chemical sputtering of carbon due to its coating with Li [7]. The second day of operation is preceded by 30 min of He GD.

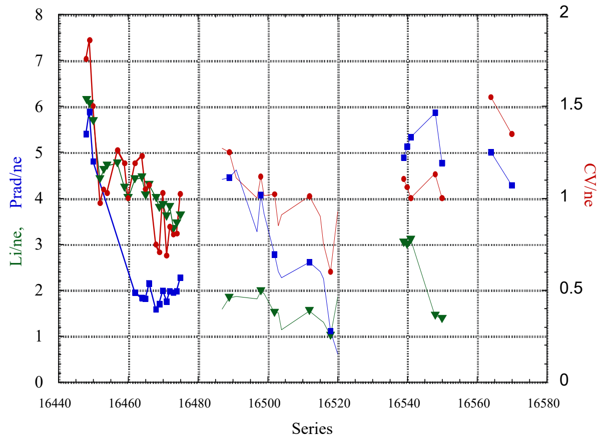

Fig. 4. Shot-to-shot evolution of some impurity signals, normalized to the line density. Circles: C V (right axis), triangles: Li I, squares: Bolometer.

The impurity levels at the start of the second day are seen to rise initially, but they soon recover to their low levels, the Li signal reaching a level up to seven times lower than before. Since its measurement is local, the erosion of the initial layer at the observation window, with subsequent spreading over other areas of the vessel, could account for this effect. This would also account for the concomitant decrease in impurity radiation, which would not be expected if simple removal of the beneficial effect was taking place. After discharge 16540, systematic higher contamination of the plasma is seen. This is associated with the insertion of the graphite limiters 1 cm into the separatrix during several shots. The interaction of the limiters with the plasmas was seen to be stronger for Li walls than in the B case, as monitored through the increase in total radiation and the C V signal upon their insertion up to 2 cm. This is an apparent contradiction with the effect just described, and it was ascribed to the higher edge temperature in Li-wall plasmas. A profile of edge parameters, as deduced from the supersonic He beam diagnostic, is displayed in Fig. 5.

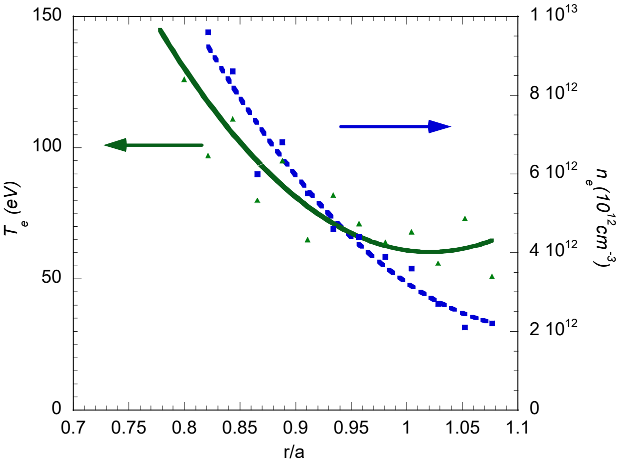

Fig. 5. Characteristic edge profiles under Li wall conditions.

Although electron densities are similar to those found with boronized walls, electron temperatures are higher by a factor between 1.5 and 2, tentatively ascribed to changes in dominant impurity and edge power balance rather than to changes in confinement. Since physical sputtering of carbon has been proposed as the main contamination mechanism in TJ-II ECRH plasmas [8], these changes are in line with the observed increase.

Impurity radiation profiles are also seen to evolve upon changing the wall material. Even when total radiation levels are somewhat lower in the Li case (clean discharges), analysis of soft x-ray (SXR) emission profiles suggests higher central values of Z_{eff} for the Li case. The important issue of impurity accumulation in centrally heated plasmas, however, deserves a more rigorous analysis of the observed changes, and it is out of the scope of this work. Although no major changes in density profiles are seen by the Thomson scattering diagnostic, it is worth mentioning that cut-off line densities are 10% higher than in the B counterpart, and a more detailed characterization of these profiles is presently under way. Ion energy balance and confinement have been analyzed through a simple zero-dimensional model for the metal and boron cases in previous campaigns [9]. In its volume-average notation, for an ECRH plasma, it can be expressed in the form

$$\nu_{ei}(T_e - T_i)n_e - \left[\frac{T_i}{\tau_i} + K_{cx} n_0 T_i\right] n_i = 0 \qquad (2)$$

where electron-ion collision frequency, ion energy confinement time, and charge-exchange (CX) losses are integrated in the steady-state balance. Volume-average electron temperatures are used for T_e. Previous estimates of CX losses allow for neglecting this channel in Eq. (2) under the ECRH conditions in TJ-II, which allows for the evaluation of the characteristic τ_i value by simply plotting the terms of the equation, as displayed in Fig. 6. Two important remarks must be made about the behavior displayed in the figure. First, a very similar slope, directly giving a first-order estimate for τ_i of ~5 ms, in agreement with particle confinement times mentioned above, is found in the three cases. Second, the discontinuity observed at collisional frequencies of 10 s^{-1}, corresponding to the transition to the EPC mode, is missing in the Li case, thus confirming the results found through the fueling analysis of Fig. 3. Thus, although central electron temperatures were found to be higher with Li walls, which can be initially ascribed to the higher performance of the ECRH system in the last campaign, no changes in the ion channel are observed as the wall material is changed, at least when the electron-ion collisionalities are high enough to disregard CX losses.

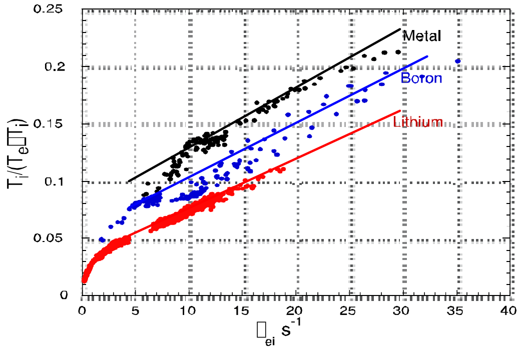

Fig. 6. Ion energy balance analysis for three wall scenarios.

5. NBI plasmas

High-beta operation is one of the major goals of the TJ-II program. Therefore, extensive neutral beam injection (NBI) heating must be coupled to the plasma, and efforts in this direction have been made in the last few years. It was soon found, however, that proper density control was extremely challenging under additional heating, partly due to the extra fueling term introduced by the beams and their interaction with the vessel walls. In the absence of divertor configurations, a low-recycling wall can be of great help in preventing plasma collapse resulting from excess density under finite heating power. Although at present the discharge duration under NBI heating is still dominated by this problem, important changes have been detected in the evolution of the NBI plasma parameters. In Fig. 7, a comparison of these parameters for boron and lithium walls is shown. Central electron temperature, edge and central radiation and line-average densities are shown in both cases. A squared pulse shows the time of injection. Although central emissivities are similar at the collapse, a higher line density (4.6 vs 3.4) is reached in the Li case. Interestingly, edge emissivities are significantly lower in the Li case. Furthermore, the central to edge radiation behaves in a significantly different way in the two cases. According to the ratio of the running models for radiation at the edge, the results presented here suggest the presence of radiative instability as candidate cause for collapse in stellarators [10] and the different shapes of the cooling rates for the dominant impurities for the B case, while a pure thermal collapse would limit the plasma density in the lithium wall scenario, with obvious implications for future upgrading of the NBI power in TJ-II.

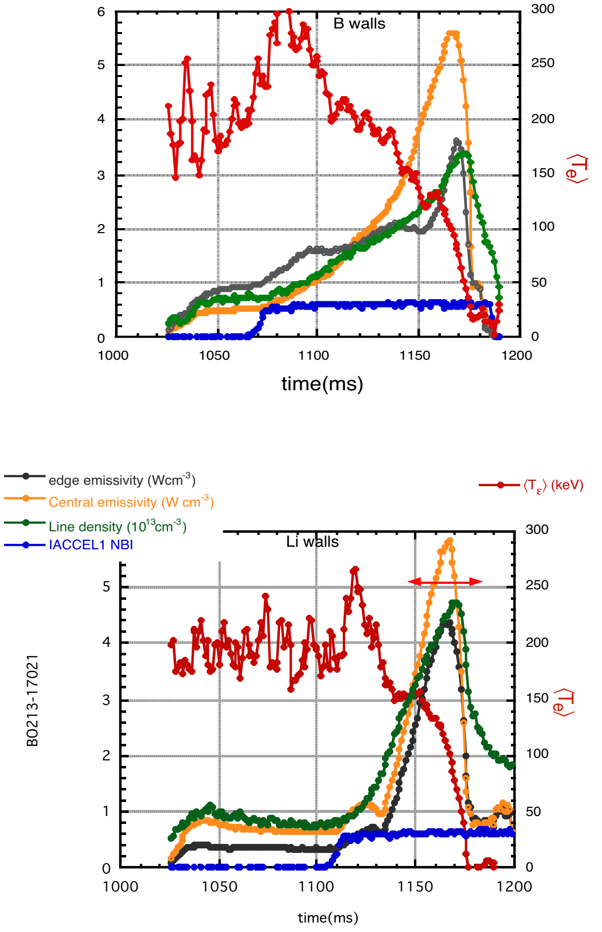

Fig. 7. Plasma emissivity (W · cm^{-3}, central and edge lines), line density (10^{13} cm^{-3}), and volume-averaged electron temperature (green). A 500-kW neutral beam was injected during the time indicated by the bottom pulse in each plot.

6. Conclusions

TJ-II has been operated under lithiated wall conditions, the first time that this technique has ever been applied to a stellarator. Very encouraging results in terms of density control and impurity level have been obtained, even when only partial coverage was achieved. The strong improvement in density control is due not only to lower recycling from the walls but also to the inhibition of the transition to the EPC mode by the higher puffing levels required. NBI heating has been possible for record densities of 4.5×10^{13} cm^{-3}, its limit, possibly due to a pure thermal collapse under the limited NBI power available at present. New techniques for improvement of film homogeneity and careful control of limiter conditions are foreseen in order to improve the results.

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Report on the 17th International Toki Conference and the 16th International Stellarator/ Heliotron Workshop

The Joint Conference of the 16th International Stellarator/ Heliotron Workshop (ISHW) and the 17th International Toki Conference (ITC) was held in Toki (Japan) October 15–19, 2007, and was organized by the National Institute for Fusion Sciences (NIFS). More than 200 experts in stellarator/heliotron research from Australia, Austria, Belgium, Germany, Japan, Russia, Serbia, Spain, Ukraine, and the United States of America gathered at the conference. The International Advisory committee, chaired by O. Motojima, the International Program Committee (IPC), chaired by C. Hidalgo, and the Local Organizing Committee (LOC) chaired by H. Yamada, developed the scientific program of the joint conference. This series of stellarator workshops is organized biennially in the framework of the International Energy Agency (IEA) Implementing Agreement on the Stellarator Concept. NIFS has organized the ITC as an annual meeting for fusion-related sciences since its establishment in 1989. The IPC arranged 2 plenary talks, 1 review talk, 2 tutorial talks, and 23 invited talks in addition to 202 contributed presentations.

The driving force behind magnetically confined fusion research is the design of magnetic traps to confine high-temperature plasmas of deuterium and tritium in reactor-relevant conditions (i.e., to produce self-sustaining fusion reactions and release useful energy). Although the next step in magnetic confinement devices, such as ITER, will be based on the tokamak idea, it is not clear that a unique magnetic configuration will be the answer to the various possible applications of fusion energy, and hence other magnetic confinement concepts should be explored. The stellarator is an alternative magnetic confinement concept, with the specific advantages of an intrinsically steady-state magnetic field and disruption-free operation. The three-dimensional (3D) magnetic field geometry in stellarators needs an elaborate optimization to guarantee confinement properties that meet the basic requirements of a fusion reactor plasma. Development of stellarators as an alternative fusion reactor concept is a key issue confronting the stellarator community. This issue was addressed in the meeting by including special sessions on topics which are particularly relevant to the stellarator line as reactor concepts (e.g., divertor physics).

From the perspective of the basic understanding of systems far from thermal equilibrium, fusion plasma studies are a fully multidisciplinary area of research. The joint ISHW/ITC conference has emphasized the topical area of

"Flows and Turbulence," which are seen widely in nature and are also becoming a high-priority research area in magnetically confined plasmas.

Stellarators and tokamaks are complementary magnetic confinement concepts, but nevertheless share many common aspects. Thus, we should exploit synergies with the tokamak wherever meaningful. The ISHW benefited greatly from the presence of invited talks from the tokamak community, as in previous stellarator workshops.

The development of stellarator/heliotron working groups, including the confinement database and profile database working groups, has been very successful as a means of promoting productive international collaboration. Invited talks reporting on these key activities in the stellarator community were included in the program. In addition, the workshop has been an excellent forum to trigger discussion on possible additional stellarator/heliotron working groups. This discussion has been fully welcomed and stimulated by the IEA Stellarator Executive Committee. Considering that a fusion reactor stellarator should operate at high beta with control of particle and energy exhaust, it was agreed to promote the development of a new stellarator/heliotron working group for further development of helical divertor concepts.

Slides of some oral presentations as well as the proceedings are available at http://itc.nifs.ac.jp/. Extended papers of major contributions will be also published in a special issue of Plasma and Fusion Research (http://www.jspf.or.jp/PFR/).

The 17th International Stellarator Workshop will be held in Princeton, USA, in 2009 and will be hosted by the Princeton Plasma Physics Laboratory.

Carlos Hidalgo
CIEMAT, Madrid, Spain
Chairperson of International Program Committee

Hiroshi Yamada
National Institute for Fusion Science, Toki, Japan
Chairperson of Local Organizing Committee

Attendees at the Joint Conference of the 16th International Stellarator/Heliotron Workshop and the 17th International Toki Conference.