stellarator news

Published by Fusion Energy Division, Oak Ridge National Laboratory
Building 5700 P.O. Box 2008 Oak Ridge, TN 37831-6169, USA

Editor: James A. Rome Issue 129 December 2010
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On the Web at http://www.ornl.gov/sci/fed/stelnews

An overview of LHD results

Recently, the journal *Fusion Science and Technology*, published a special issue (Vol. 58, No.1) on results from the Large Helical Device (LHD). The issue comprises 13 chapters with 60 papers and covers not only the progress of experimental studies for past 12 years, but also work on diagnostics, heating devices, theory including three-dimensional (3D) effects, and engineering related to superconductivity. Several key experimental results are discussed here.

LHD experiments started in 1998. Since then, studies to understand the intrinsic physics of net current-free plasmas have successfully proceeded. The LHD operational regime has been extended by increasing the heating capability to 23 MW of neutral beam injection (NBI), 3 MW of ion cyclotron resonance frequency (ICRF) heating, and 2.5 MW of electron cyclotron resonance heating (ECH). In addition, a new 5 MW perpendicular neutral beam injection system and a new ICRF antenna were added in FY 2010. Significant physical achievements include high beta (5.1%), high density (1.2×10^{21} m^{-3}), and steady-state operation (3200 s with 490 kW), supported by a reliable cryogenic system that has safely operated for >56,000 hours.

Global energy confinement obtained with a configuration optimized according to neoclassical theory, has proved comparable to that of tokamaks running in ELMy H-mode, exhibiting a gyro-Bohm-like property as seen in the International Stellarator Scaling (ISS95). Significant collisionality dependence (predicted by neoclassical theory) has not been observed (Fig. 1). The optimization according to neoclassical transport theory successfully demonstrated that anomalous transport is reduced simultaneously.

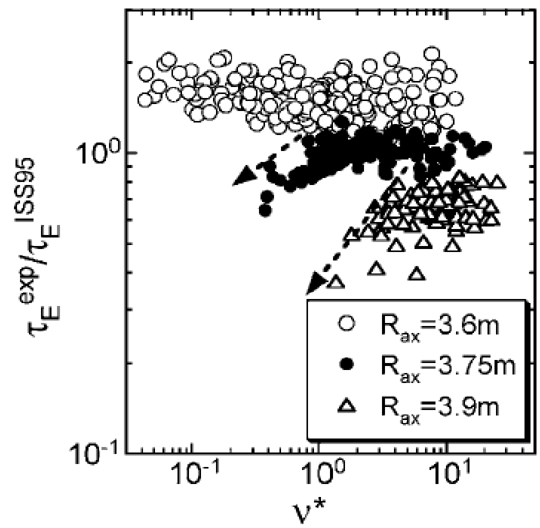

Fig. 1. Dependence of the ratio of confinement enhancement factor to the ISS95 scaling on collisionality. Three cases with different magnetic axes are plotted [1].

In this issue . . .

An improved electron energy confinement mode, found in several helical devices, has been characterized by a highly peaked electron temperature profile in the core region, and appears when the centrally focused ECRH power exceeds a certain threshold value. The threshold power has been determined to be related to the transition of the radial electric field from the ion root to the electron root, based on the bifurcated nature of the radial electric field due to the ambipolarity condition of neoclassical transport fluxes.

In ion heating experiments with high-Z_{eff} conditions, a central ion temperature of 13.5 kV was achieved in an argon-seeded plasma, strongly suggesting the capability of the helical configuration to confine high-performance plasmas. In low-Z_{eff} experiments, ion heat transport improved in core plasmas heated by high-power NBI. The ion temperature has a peaked profile with a steep gradient in the core region (ion internal transport barrier). Transport analysis indicates that anomalous transport is reduced in the core region, where a negative radial electric field is predicted by neoclassical ambipolarity. Improvement of ion heat transport with positive radial electric field was also successfully demonstrated utilizing strongly focused ECRH, suggesting further improvement of ion heat transport in reactor-relevant plasmas.

Spontaneous toroidal flow driven by the ion temperature gradient and an extreme hollow profile of carbon impurities ("impurity hole") is observed associated with the increase in ion temperature gradient (Fig. 2).

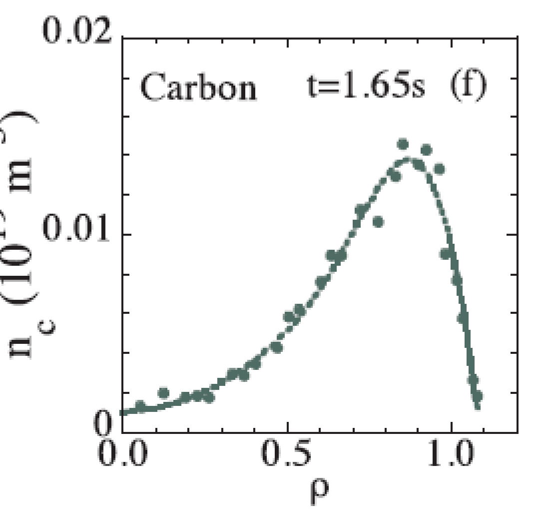

Fig. 2. An "impurity hole" carbon density profile [2].

The positive radial electric field drives spontaneous flow in the counter-direction at the plasma edge and in the co-direction near the magnetic axis. The component of the spontaneous toroidal flow driven by the ion temperature gradient is clearly observed and expected to be one of the dominant components of toroidal flows in high-ion-temperature discharges in LHD. Transport analysis of the carbon impurity in discharges with an impurity hole reveals a low diffusion coefficient and an outward convection velocity, whereas inward convection is predicted by neoclassical theory at half the minor radius.

An interesting high-density operational regime with an internal diffusion barrier (IDB) has been observed. Typical profiles are shown in Fig. 3. The IDB is characterized by a steep density gradient in the core plasma, and the attainable central density approaches 1.2×10^{21} m^{-3} while a relatively low-density mantle plasma continues to surround the core. The maximum central pressure reaches 150 kPa for an optimized magnetic configuration. Such a high central pressure causes a very large Shafranov shift, more than half the radius. Core fueling is absolutely essential for the IDB formation, and the IDB is reproducibly obtained using intensive multiple-pellet injections. The attainable density is restricted by limited heat deposition in the core plasma due to the strong attenuation of the neutral beam in the high-density plasma.

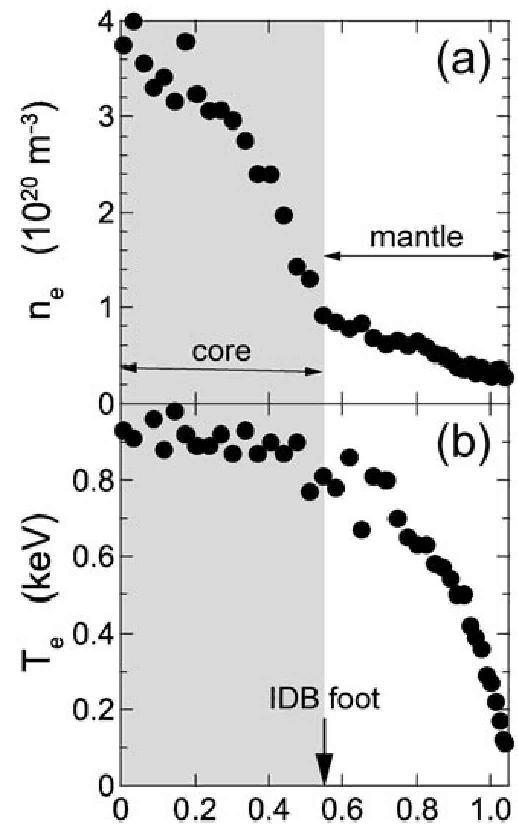

Fig. 3. Electron density and temperature profiles in an IDB plasma. [1]

Easy access to the high-density regime without fatal disruptive phenomena is one of the attractive characteristics of helical devices (Fig. 4). The operational density is considerably higher than the Greenwald density limit that applies to tokamak plasmas. In LHD, the density limit is reached when the edge density at the last closed flux surface exceeds a value approximately equivalent to the Sudo density limit, which increases with the square root of the heating power. IDB plasmas with a peaked density profile can be maintained as long as the edge density does not exceed the Sudo limit.

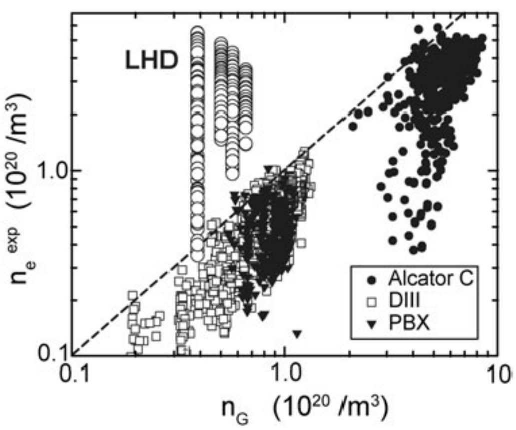

Fig. 4. Comparison of experimental electron density with the Greenwald density limit (dashed line) [1].

High-beta (>5%) plasmas have been successfully obtained without major disruption by suppressing the Shafranov shift that would reduce the heating efficiency of NBI and increase the amount of helical ripple.

The dominant MHD instabilities have been observed in the peripheral region with a magnetic hill. The amplitudes of the modes clearly depend on the magnetic Reynolds number, and the dependence is almost the same as that of the linear growth rate of the resistive interchange mode. Near the ideal stability boundary, a strong MHD mode appears and deforms the pressure profile near the resonant surface.

Spontaneous change in MHD equilibrium is a key issue for high-beta plasma production. Theory predicts that the magnetic field structure in the periphery becomes disordered due to finite-beta effects, whereas experiments show that significant pressure is maintained in the edge region in the high-beta regime. The relationship between the predicted magnetic field structure and collisionality, mean free path of particles, and other factors has been investigated. Also, an understanding of the spontaneous dynamics of magnetic islands, self-healing, and growth is important for maintaining high-beta equilibria. Experiments using a resonant magnetic perturbation indicate that self-healing occurs in the higher-beta and lower-collisionality plasmas, while a magnetic island grows in the lower-beta and higher-collisionality region. Magnetic configuration effects on island dynamics also have been investigated.

Energetic ion-driven MHD instabilities such as Alfvén eigenmodes and energetic particle modes (EPMs) and their impacts on energetic ion confinement are being studied. Two types of toroidicity-induced Alfvén eigenmodes (TAEs) are typically observed in LHD plasmas that are heated by tangential NBI. One is localized in the plasma core region near a central TAE gap, and the other is a global TAE having a radially extended eigenfunction. Core-localized TAEs with even and odd radial mode parities are often observed. The global TAE is usually observed in medium- to high-beta plasmas with broad regions of low magnetic shear. Helicity-induced Alfvén eigenmodes (HAEs), which exist in gaps, are unique to three-dimensional plasmas that have both toroidal and poloidal mode couplings and were detected for the first time. Recently, reversed magnetic shear Alfvén eigenmodes (RSAEs) having characteristic frequency sweeping were discovered in reversed magnetic shear plasmas produced by intense counter-neutral beam current drive. In the reversed-shear plasma, the geodesic acoustic mode (GAM) excited by energetic ions was also detected for the first time in a helical plasma.

Many other important results are included in this special issue of *Fusion Science and Technology*. Please visit the American Nuclear Society site
http://epubs.ans.org/?p=fst
to obtain the whole issue.

References

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Engineering for installation of W7X superconducting coil leads

For the past year, a U.S. team led by J. H. Harris (ORNL) and G. H. Neilson (PPPL) has been working with the Wendelstein 7-X (W7X) stellarator assembly team headed by L. Wegener [Max Planck Institut für Plasmaphysik (IPP), Greifswald] to design tooling and techniques for the precision assembly of the high-current (17 kA) leads connecting the W7X stellarator coil set to the cables from the W7X power supply. This activity is part of a larger joint PPPL-ORNL-LANL project to prepare for a long-term U.S. partnership on W7X that has received initial funding of $7.5M for FY 2011–13 from the U.S. Department of Energy Office of Fusion Energy Sciences.

The first task of this project was to develop a scheme to lift and support the heavy (~500 kg) lead assemblies and align and hold them securely in position so that the leads could be welded to the coil current feeds in five positions around the torus. The temporary supports must then be lowered and the loads shifted precisely to the permanent support structure without disturbing the joint itself. The working space in and near the lead fixing boxes is barely large enough for a technician's arms, with millimeter-scale tolerances for placement of the leads. The design work therefore has had to be carried out using 3D computer techniques supported by real-world checks at ORNL and IPP using mock-ups of the relevant parts of the W7X device.

The overall approach was developed by M. J. Cole (ORNL), P. J. Fogarty (ORNL), and T. J. Brown (PPPL). It features a custom-built, movable lead installation cart with precision hydraulic positioners for the current feeds (Fig. 1), which can be used in a variety of configurations to translate, raise, position, support, and remove the lead assemblies, as illustrated in Fig. 2.

Detailed design of the cart, its fixtures, and the procedures to be followed required the preparation of 122 engineering drawings at ORNL by M. J. Cole, K. Logan, and G. McGinnis and supporting engineering analysis by A. Lumsdaine of ORNL, working with the IPP engineering team.

Nearly all of the work was carried out with the teams working at their home institutions and communicating in weekly three-way teleconferences (IPP-PPPL-ORNL) and via e-mail and computer file exchange. P. J. Fogarty visited IPP-Greifswald for a week in 2009 to start work on the concept, and M. J. Cole and A. Lumsdaine visited IPP for two weeks in mid-2010 to verify key aspects of the design in discussions and mock-up trials with the IPP team.

Final versions of the drawings were completed at ORNL and posted for download by IPP on 10 September 2010. IPP conducted final checks before sending out a tender for fabrication of the cart and associated fixtures by industry during the week of 20 September; delivery of these items

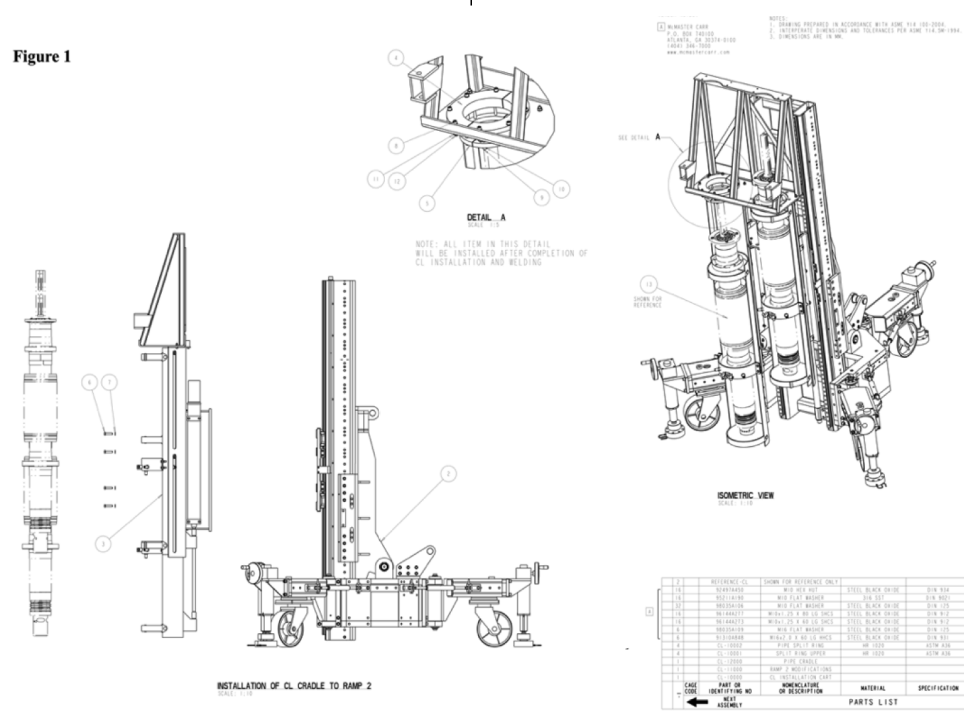

Fig. 1. The lead assembly cart.

is expected in early 2011. In this time frame, IPP will also verify the lead assembly process using its on-site mock-up. IPP is now preparing for coil lead installation on the W7X machine, which will begin in the Summer of 2011.

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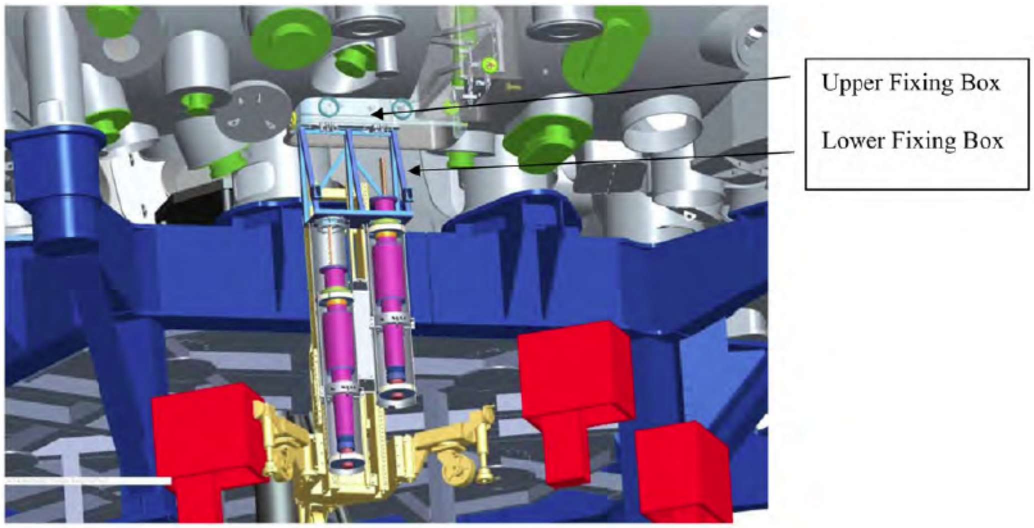

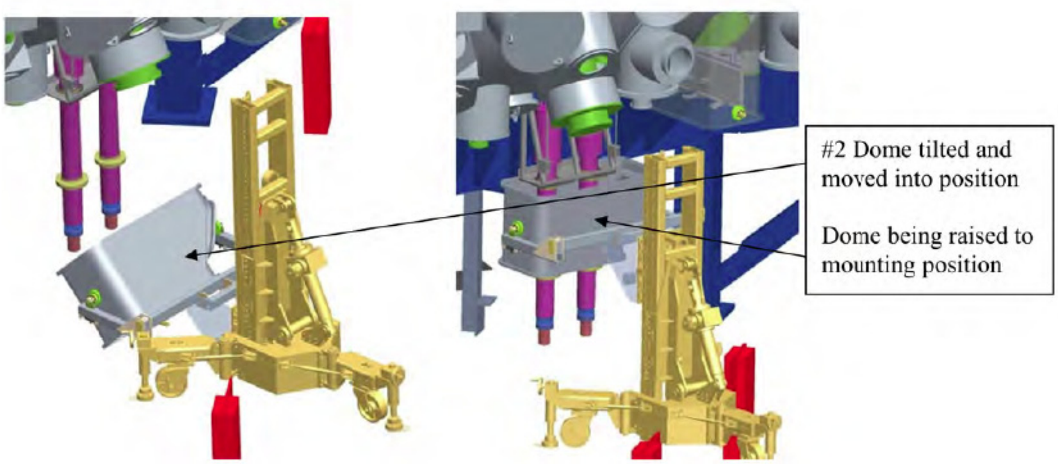

Fig. 2. The assembly cart in action.

Public Day at IPP: Stellarators are attractive

More than 2600 visitors took the opportunity to see Wendelstein 7-X at its construction site during the Public Day at IPP Greifswald. It was a unique chance to see the interior of the five modules of the superconducting stellarator in different states of assembly, like in a textbook—top view and poloidal cut—before they are finally hidden in the vacuum vessel. Guided tours were given in groups of 15 to 20 persons to facilitate explanations despite the reverberant torus hall acoustics. At the entrance of the experiment building, queuing was unavoidable and patiently accepted. For those waiting and those who wanted to learn more, presentations were given in the also well-filled lecture hall—on W7-X physics, the design and engineering activities, the cryo-technics applied, and particular assembly issues. A real highlight was the 3D movie contributed by the IPP theory department showing the device interior, its complexity, but also its symmetry properties, for example, from the viewpoint of a drifting particle. Finally, the main corridor hall of IPP Greifswald was used both for an arts exhibition—the so called magistrale, and for children's activities and some do-it-yourself experiments, providing IPP members with the opportunity to attract a new generation of fusion scientists.

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Fig. 1. A view of the visitor's platform in the torus hall. (Photo: IPP, Anja Richter-Ullmann)