stellarator news

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E-Mail: jar@ornl.gov | Phone: (423) 574-1306 | Fax: (423) 574-0680

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Changed position of the stellarator in the U.S. fusion program

Work on stellarators has again been recognized as a significant element in the U.S. fusion program. On 17 July , the committee that advises the U.S. government on fusion, the Fusion Energy Sciences Advisory Committee (FESAC), made an official recommendation that the United States have "an expanded stellarator program including theoretical studies, concept development, and collaborations on international experiments." The development of a strategy for the United States toward the non-tokamak fusion alternates was the topic of an 18 April meeting of the Scientific Issues Subcommittee of FESAC. Allen Boozer, James Lyon, and Leon Shohet wrote a document with much community input, *Role of stellarators in the U.S. fusion program* (see *Stellarator News* Issue 46), and made an oral presentation at this meeting. The subcommittee released its report on 23 July; the summary findings on the stellarator were as follows.

1. In regard to its development status the stellarator as a concept is in the transition phase between proof-of-principle and proof of performance.
2. The U.S. can play a valuable role in stellarator concept development. An appropriate U.S. focus area is in the effort to reduce the size of stellarator fusion power systems.
3. In view of the planned operation of two large, ongoing proof-of-performance level devices in the world and limited resources available in the U.S., there is little motivation for the U.S. to build proof-of-performance devices similar to LHD and W7-X. Within the world stellarator program, the possibility exists for additional interesting experiments in the proof-of-principle class. Such proposals should be considered as candidate elements of a balanced U.S. concept development program, although the normal course would be to begin at the concept exploration level.
4. In order to maintain beneficial contact with the large stellarator efforts abroad and to gain knowledge from those important experiments, the U.S. should: (1) seek to gain a support role on LHD and W7-X; and (2) seek to provide substantial theory support to LHD and W7-X. This core of theory support could also stimulate domestic initiatives.

Allen H. Boozer
Columbia University
New York, NY 10027, USA
E-Mail: ahb17@columbia.edu

In this issue . . .

Overview of W7-X diagnostics

Engineering aspects of Wendelstein 7-X (W7-X) were discussed in *Stellarator News* Issue 39 (May 1995); details of the W7-X superconductor development program were given in *Stellarator News* Issue 42 (Nov. 1995). This contribution addresses the ongoing development of the diagnostics foreseen for the experiment. W7-X allows ample access for diagnostics, despite its helical geometry and its realization with superconducting coils. Special efforts have been made for diagnostics which are relevant for parameters related to the optimization of the configuration, e.g., very small Shafranov shift, reduced neoclassical transport losses in long mean free path (LMFP) and plateau regimes, small bootstrap current and good confinement of fast particles at high beta.

Figure 1 shows an overall view on the W7-X device. With B = 3 T and heating powers of 10 MW of ECRH, cw, 4.5–18 MW (full performance) of NBI, 10 s, and 4–12 MW of ICRH, 10 s, the following maximum plasma parameters are predicted: $T_e \approx 10$ keV, $T_i \approx 8$ keV, and densities up to 3×10^{20} m^{-3}. The power load on the divertor plates is expected to be less than 10 MW/m^2 .

The confining magnetic field with a helical axis in 5-fold toroidal symmetry is generated by a set of 50 nonplanar superconducting coils, arranged in 5 equal toroidal segments (10 sets of only 5 different types of coils). Separate powering of coils of the same type gives flexibility with regard to the magnetic field topology. An additional set of 20 planar coils (4 per module) allows variations of the axis position and of the rotational transform on axis and at the boundary, $0.75 < ι(0) < 1.01$ and $0.83 < ι(a) < 1.25$, respectively.

The plasma cross section varies from bean-shaped at the position of strongest curvature (Φ = 0°) via drop-like (Φ = 18°) to triangular in the region of smallest curvature (Φ = 36°). Major and average minor radii of W7-X are 5.5 m and 0.53 m, respectively. The strong reduction of the averaged toroidal curvature results in strongly reduced Pfirsch-Schlüter currents, very small Shafranov shift (see Fig. 2) and orbit displacement, good fast particle confinement at high beta, and small bootstrap currents. The magnetic surfaces are smooth and, owing to the low shear, without low-order islands in the confinement region.

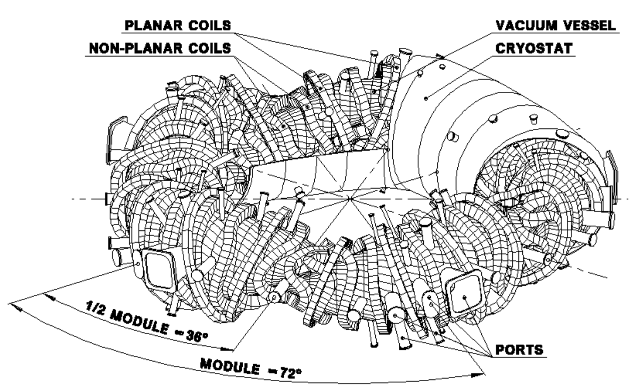


Fig. 1. W7-X with its major components; R = 5.5 m, a = 0.5 m, B = 3 T.

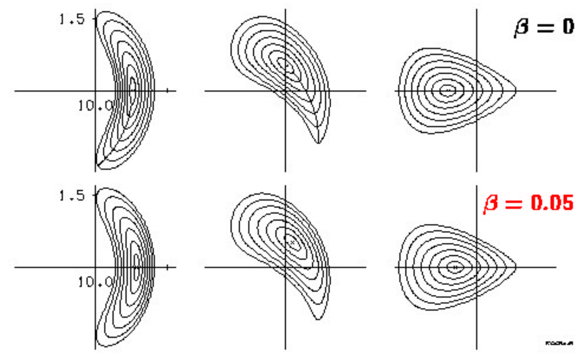


Fig. 2. 3-D plasma surfaces for rotational transform $ι$ = 1. The plasma has a helical axis, and its cross section varies from bean-shaped at Φ = 0° via a drop-like transition to triangular at Φ = 36°. Comparison of poloidal plasma cross sections for beta = 0 (upper line) and beta = 5% (lower line), shows that the effect of finite beta on the flux surfaces is very small.

W7-AS demonstrated the technical feasibility of a nonplanar modular coil system. W7-X will prove the viability of the concept of an Advanced Stellarator with superconducting coils. Particle and energy exhaust under stationary conditions are important in order to develop a suitable divertor system. The objective of W7-X is to prove the relevance of stellarators on the way to the development of a fusion power station [1].

European expertise in high-temperature plasma diagnostics will be used as much as possible. Some associations have already contributed to the diagnostic proposal thatb was part of of the overall approval procedure of W7-X. Several meetings with interested parties have been carried out, and different interests and possibilities have been clarified.

W7-X Diagnostics

The geometrical structure of the superconducting coil system allows us to install a large number of reasonably big ports for heating and diagnostics. Because of the 5-fold symmetry there are 10 times as many ports available as shown in Fig. 3, with some restrictions concerning only the symmetry planes of port A1, Φ = 0°, and the tangential ports, Q1, close to NBI. Becuase of the large aspect

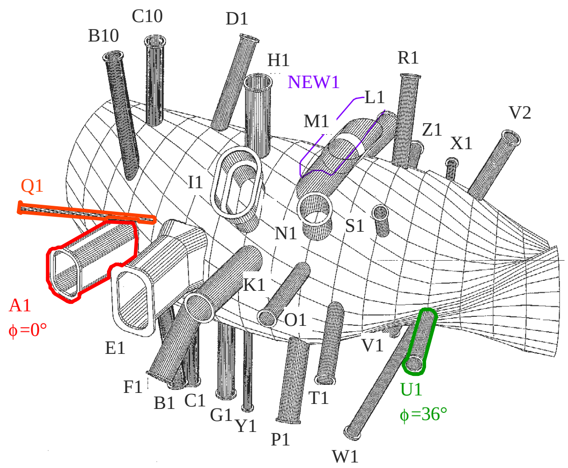


Fig. 3. 3-D plot of about half a torus module (1/10 of entire torus) and ports, $\Phi = 0°$ at the center of port A1, $\Phi = 36°$ at the center of port U1.

ratio there will also be access to ports also on the inboard side of the torus.

The followingl basic fusion plasma diagnostics are compatible with W7-X and are planned to be installed:

- Thomson scattering for $T_e(r)$ and $n_e(r)$
- ECE for $T_e(r)$
- Active charge-exchange (CX) neutral particle analysis (NPA) for $T_i(r)$ and slowing-down spectra of high energetic particles
- CX recombination spectroscopy (CXRS) for $T_i(r)$, $n_{imp}(r)$, v_{pol}/v_{tor}, and $E_{rad}(r)$
- Interferometry and polarimetry for n_e
- Reflectometry and fast lithium beam for $n_{e,edge}$
- Spectroscopy in different wavelength ranges, bolometry, and pulse-height analysis (PHA) for plasma radiation, impurities, and Z_{eff}
- H_α diagnostic for neutral particle fluxes and recycling; soft X ray, magnetic measurements, and probes for T_e fluctuations, MHD instabilities
- Diamagnetic and flux loops for energy content and pressure-driven plasma currents
- Edge probes for n_e , T_e, and potential Φ
- Calorimetry for heat load
- Plasma and infrared video for plasma configuration and survey monitor and heat load.
- Microwave scattering, LENA (low energy neutral particle analysis), collective Thomson scattering (at, e.g., 140 GHz), and neutron measurements, as well as an in situ measurement of the magnetic flux surfaces by an electron beam.

Special attention is being givenb to the choice and quality of diagnostic equipment for the measurement of quantities directly related to the optimization of W7-X, such as stability, equilibrium, confinement and transport, and also

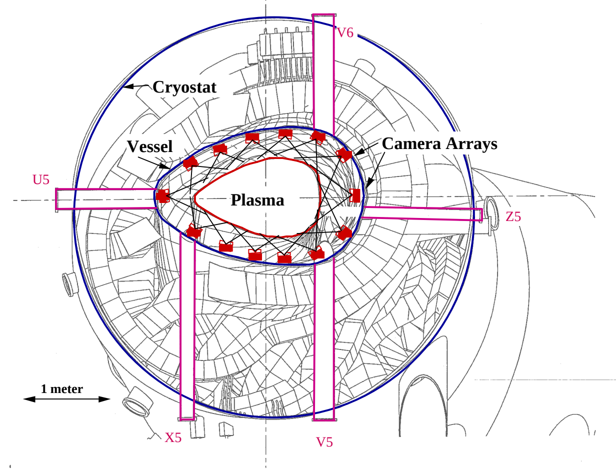


Fig. 4. Mini soft-X-ray camera array, installed inside the vacuum vessel for tomography.

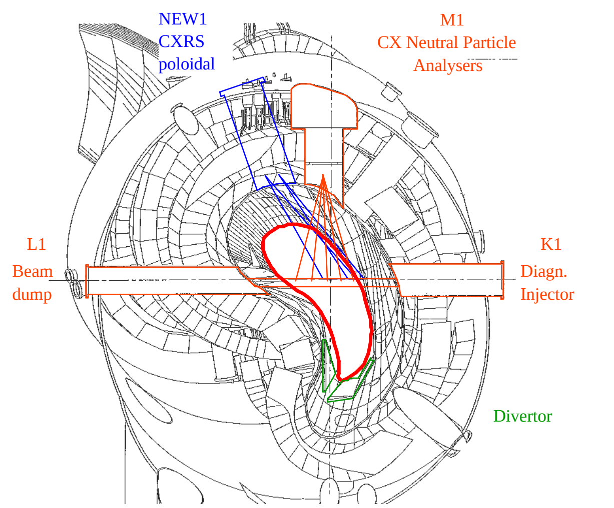


Fig. 5. Layout for active CX with NPA and CXRS. The equivalent geometry will be used for Thomson scattering, laser blowoff, and pellet injection.

with respect to stationary operation. Figsures 4–8 show examples of the geometrical layout for various W7-X diagnostics. Some further details are listed below.

The soft X-ray diagnostic will consist of a system with 3 pinhole cameras (covering plasma and divertor) and a tomographic system with 12–15 compact cameras inside the vessel, see Fig. 4. Probe arrays and video are foreseen for the edge topology. Axis position, plasma radius, and Shafranov shift, the reduction of which is a direct proof of optimization, can thus be measured. MHD activities, the identification of mode structures, possible operational limits due to MHD instabilities, and the comparison of instability thresholds with predictions are aims of these measurements.

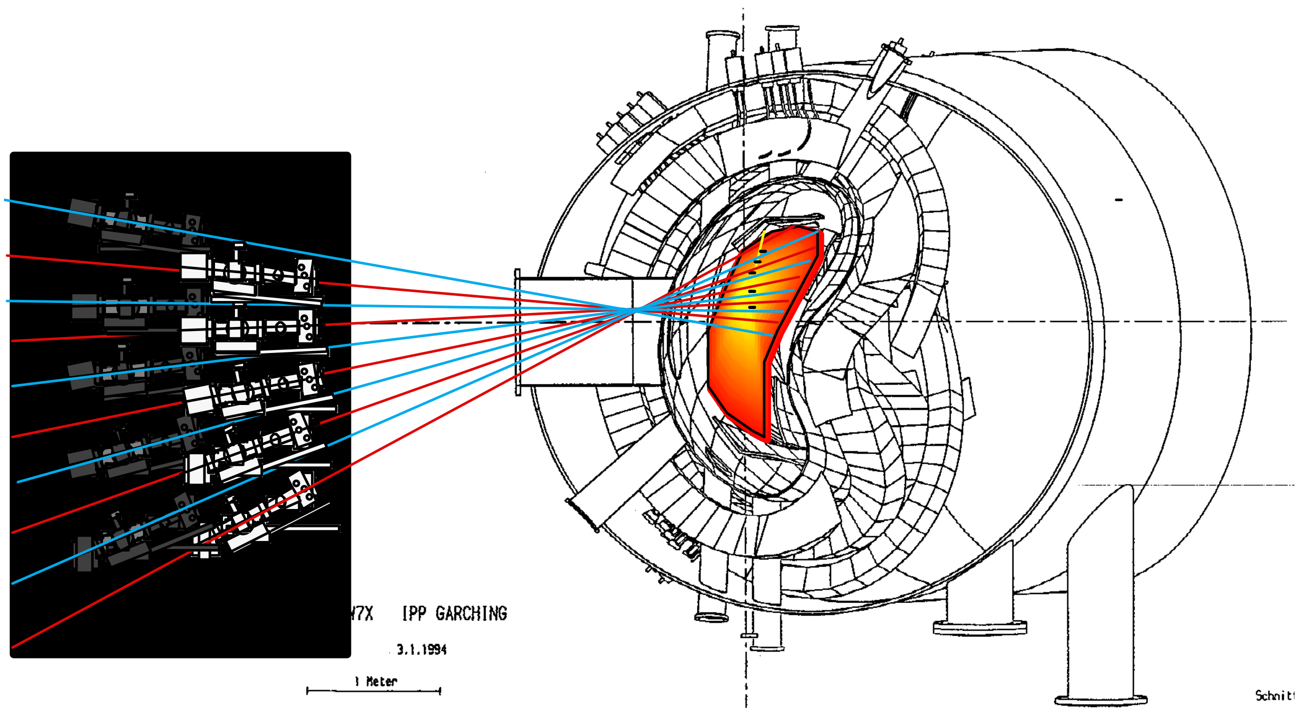


Fig. 6. Array of 10 spectrometers viewing the W7-X plasma from the magnetic axis towards the divertor region, to be used also for tomography.

An improvement of transport by a factor of about 10, in both the plateau and the LMFP region, compared to an axisymmetric configuration is neoclassically predicted for the optimized configuration of W7-X owing to a strong reduction in the average toroidal curvature. In different magnetic configurations, generated for example. by varying the mirror ratio, neoclassical transport properties can be influenced, thus allowing comparisons with theoretical predictions. For local transport analysis, accurate measurements of the T_i, E_{rad}, T_e, and n_e profiles are required. As an example, the geometry of active CX and CXRS is shown in Fig. 5. Thomson scattering, ECE, interferometry/polarimetry, reflectometry, and a fast lithium beam will also be available. A feasibility study for a heavy ion beam probe is now being carried out. Thus, neoclassical transport properties, confinement transitions, changes of the electrical field, the temporal behavior of injected particles, or the distribution of impurities can be investigated, see Fig. 6.

Good fast particle confinement is predicted for W7-X for $\langle\beta\rangle \approx 2\%$, the investigation of which demands the development of new diagnostics. The slowing down of 60-keV deuterons in W7-X corresponds to 3.5-MeV alpha-particles on power station scale (equal ratio of plasma radius and ion Larmor radius, a/r). Supporting calculations of the deposition of fast particles from neutral particle beams (NBI or diagnostic beam) are needed. Comparison can be made with with measurements of, e.g., slowing-down spectra by neutral particle analysis, resonance fluorescence of sputtered impurities or deposition probes.

W7-X Divertor

An open divertor configuration for W7-X will be designed in a first step, Fig. 7. The island divertor concept makes use of the existence of large islands at the boundary in magnetic configurations with moderate shear. Plasma particles passing the island separatrix reach the outer region of the island with typical magnetic connection lengths of 100–300 m. Results of recent calculations with the B2 code were given in *Stellarator News* Issue 45 (May 1996). At finite beta, an ergodization of magnetic field lines at the boundary occurs which can be enlarged at certain values of ι by superimposing stationary magnetic fields. The target plates, intersecting the islands, follow the helical edges and are shaped to decouple the plasma from the vessel wall and to minimize the local wall load ($P_{max} \approx 10$ MW/m^2). They are designed to cover the whole range from $\iota = 5/6$ to $\iota = 5/4$ with different sizes and positions of islands and the ergodic boundary layer. The importance of the knowledge of the edge structure for divertor operation requires exact local measurements in this region. The divertor region will be accessible for diagnostics via special ports parallel to the target plates in the $\Phi = 13.5°$ planes. It will be equipped with Thomson scattering (Fig. 8), laser-induced

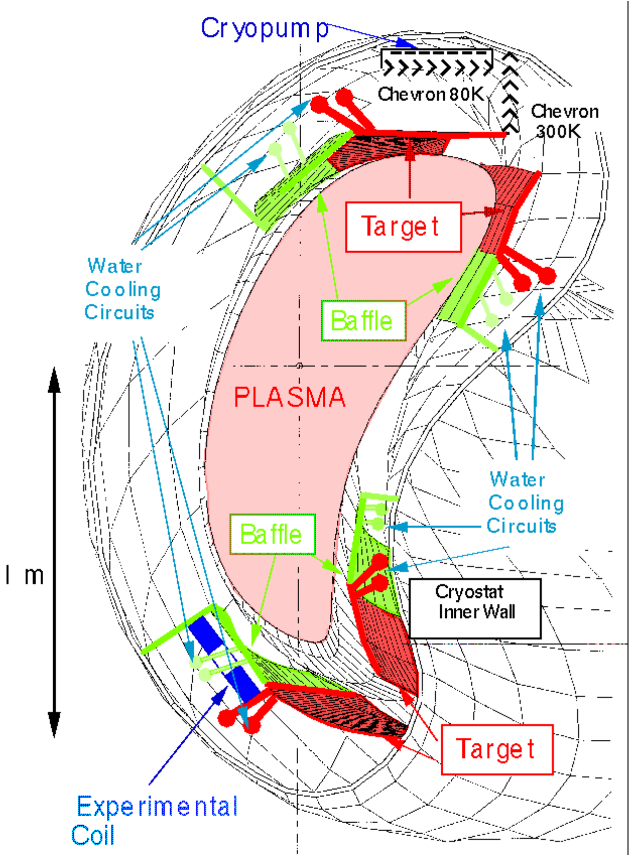


Fig. 7. W7-X divertor shown in poloidal plane, Φ = 9°.

fluorescence, target-integrated retractable Langmuir probe arrays, reciprocating probes, helium beam, a fast lthium beam, microwave diagnostics, video, spectroscopy, and neutral gas diagnostics. Thermography will be installed in a different position, viewing upper and lower divertor plates from different ports.

Several diagnostics now being developed on W7-AS and will likely be installed on W7-X on a larger scale if development is successful. These are the test of the Cotton-Mouton effect for plasma density measurement, correlation scattering for bulk turbulence studies, confinement of energetic particles via combined CX and neutron measurements, perturbation studies for particle transport analysis, and coherent scattering for T_i measurement. European associations are involved in some of these areas.

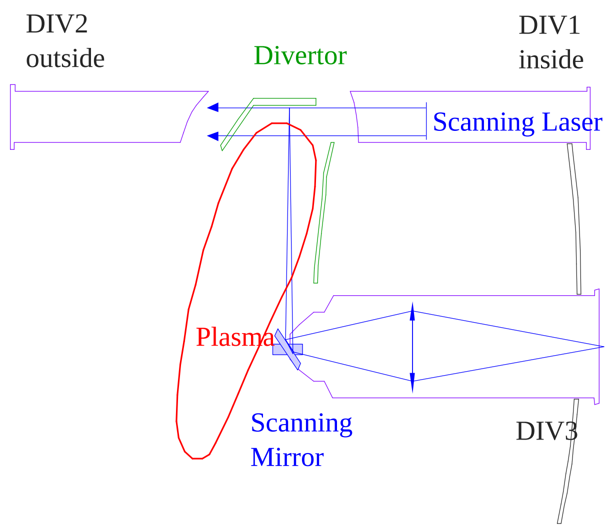


Fig. 8. Divertor Thomson scattering system.

Reference:

[1] . Grieger et al., Physics and engineering studies of W7-X, in Proceedings of 13th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Washington (1990), IAEA,Vienna, 1991, p. 525 ff.

H. J. Hartfuß, J. V. Hofmann, M. Kick, F. Rau, and H. Ringler
for the W7-AS and W7-X Teams
IPP Garching, EURATOM Association
D-85748 Garching, Germany

E-mail : ffr@ipp-garching.mpg.de

Initial operation of a multichannel interferometer at W7-AS

Two interferometer systems for measurement of line-integrated electron density n_e are running at the stellarator experiment W7-AS: a single-chord microwave system using a frequency-modulated klystron and a three-channel HCN laser system. In order to have the possibility of density profile reconstruction, it is necessary to have about ten lines of sight. Microwaves as probing signals show a serious disadvantage — at high densities the microwave interferometer fails owing to refractive effects caused by the density gradient. More useful sources are far-infrared (FIR) lasers (e.g., HCN). The small ports (200 mm in diameter) available at W7-AS do not allow such a large number of probing FIR beams to pass through the plasma. Because of this restriction it was decided to develop a multichannel microwave interferometer. The signals are fed through the ports by waveguides, thus overcoming the access limitation of the W7-AS vacuum vessel.

The new 10-channel microwave interferometer is located at the toroidal plane of $\Phi = 28°$ in the W7-AS plasma. At this plane the W7-AS plasma cross section is approximately elliptical, the longer axis being pitched from the vertical by about 15°. The lines of sight are arranged horizontally. The spatial resolution is 27 mm in the poloidal and toroidal directions. The temporal resolution is 5 ms. Each channel consists of a Gunn oscillator as signal source and a heterodyne receiver, operating on individual frequencies in the range 160–162 GHz ($\lambda \approx 1.8$ mm). The oscillators are coupled in a chain, each one acting simultaneously as a probing signal source and as a local oscillator for the neighboring channel, thus reducing the overall number of oscillators needed. This principle of operation is detailed in Ref. [1].

Eight lines of sight were operated successfully during the first weeks of operation. A code for density profile reconstruction using the maximum entropy method [2] is also running. During the first experiments, it was found that the interferometer fails if the peak density exceeds 7×10^{19} m^{-3}. This value approximately corresponds to 20% of the O-mode cut-off density at $n_e = 3.1 \times 10^{20}$ m^{-3}. Ray tracing calculations support the assumption that refractive effects are the reason for this limit. Interferometer traces of W7-AS shot 35739 are shown in Fig. 1. Characterizing parameters of this deuterium discharge are $B_0 = 2.53$ T, $B_z = 0.07$ mT, rotational transform $\iota = 0.344$. This discharge was heated from 0.03 ms to 800 ms by 450 kW of ECRH power from a single gyrotron at 140 GHz. The reconstructed density profile at $t = 450$ ms is shown in Fig. 2. It is in reasonable agreement with measurements by Thomson scattering.

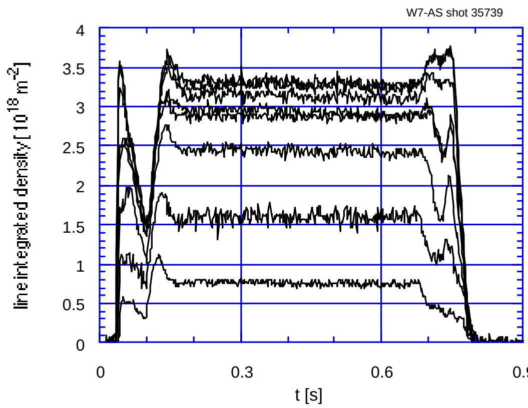


Fig. 1. Line-ntegrated electron density measured with eight interferometer chords during W7-AS shot 35739 ($B_0 = 2.53$ T, $B_z = 0.07$ mT, $\iota(a) = 0.344$, ECRH power, 450 kW).

For W7-AS discharges having a peak density below 7×10^{19} m^{-3}, density profiles are now available as a function of time using eight microwave interferometer chords. The operation of the complete set of ten lines of sight is expected in the next few months.

References:

[1] T. Geist and H.-J. Hartfuß, IEEE Microw. Guided Wave Lett. **6**, 235 (1996).

[2] J. Koponen and O. Dumbrajs, to be published.

T. Geist, E. Würsching, H.-J. Hartfuß and J. Koponen
IPP Garching, EURATOM Assoc., D-85748 Germany
E-mail: geist@wendelstein.ipp-garching.mpg.de

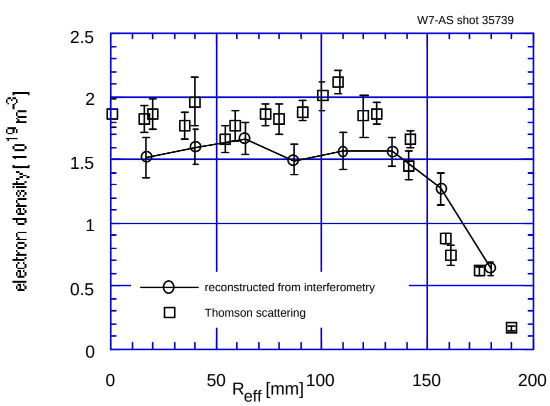


Fig. 2. Density as a function of effective radius for W7-AS discharge 35739 at time $t = 450$ ms as reconstructed from interferometer signals (circles) and measured by Thomson scattering (squares).

HSX Update

Construction is proceeding rapidly on the Helically Symmetric Experiment (HSX) device at the University of Wisconsin (see *Stellarator News* Issue 39). HSX is based on a quasi-helically symmetric configuration which has only a single dominant component in the |**B**| spectrum. While fully toroidal with an aspect ratio of 8, the toroidal curvature term in |**B**| is that of a conventional stellarator with an aspect ratio approaching 300. Neoclassical transport is expected to be nearly two orders of magnitude smaller than in an equivalent conventional stellarator. Device parameters are $R = 1.2$ m, $\langle r \rangle = 0.15$ m, 4 field periods with 12 coils/period, $\iota(0) \sim 1.05$, $\iota(a) \sim 1.14$, well depth ~ 0.6%, and $B_{max} = 1.25$ T. Assuming LHD scaling with 100 kW of electron cyclotron heating (ECH), electron temperatures should approach 1 keV.

Major site modifications have been completed, including machine foundation, service hookups for electrical power and cooling systems, bus to carry magnet current from the motor/generators to the experimental site and installation of bridge crane for assembly. Half of the 16 motor-generator units have been installed, with the remaining 8 to be installed when space currently being used for staging other elements becomes available. The motor drives, obtained from Lawrence Livermore National Laboratories, have been reworked and are operational along with the necessary switchgear. The capacitor bank and modulator system comprising the ECH gyrotron beam power supply have been located on site and are undergoing reassembly, refurbishment, and testing.

The HSX support structure has been fabricated and installed on site. Figure 1 shows the support structure along with accurate models of the coils and coil support rings (for 1/2 period). The coil support rings, which take up the main hoop forces and also provide some lateral support to the coils, have all been cut and machined and are awaiting coil installation. Each ring will have a planar auxiliary coil mounted to one face to change the magnetic

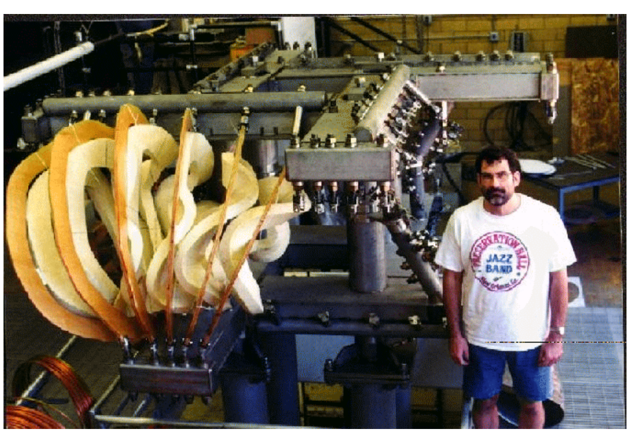


Fig. 1. The HSX support structure and coil/support model.

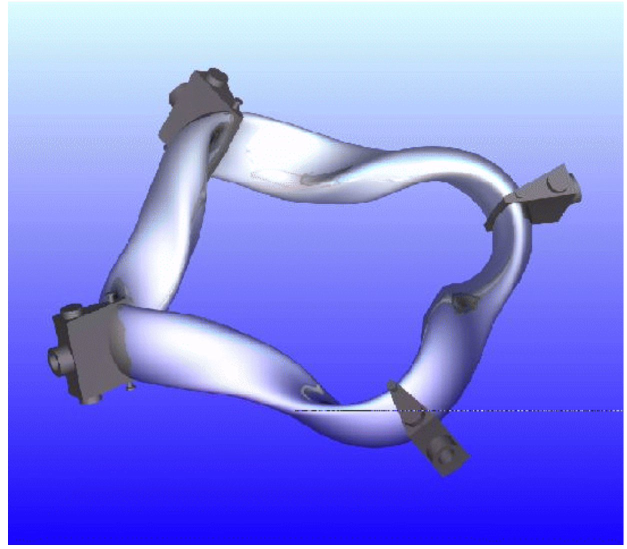


Fig. 2. CAD visualization of the vacuum vessel components.

configuration from a quasi-helically symmetric to one which simulates a conventional stellarator by adding a large toroidal mirror mode to the spectrum. These auxiliary coils have all been fabricated and tested in-house. The support structure can be separated into field period units which retract radially along a set of slides from the operational position. This is necessary for assembly and access to in-torus components. Each period can be positioned independently in all six degrees of freedom for alignment purposes. Also shown in Fig. 1 are the "adjuster struts" used to independently position the coil/ring modules and to support the vacuum vessel.

Figure 2 shows the major components of the vacuum vessel. At the ends of each field period are boxports (flanges on boxports are not to scale) which provide the largest access to the assembled torus. Not shown are four joint flanges, located between the boxports as well as the location and size of diagnostic portings. The joint flanges,

Fig. 3. A section of the formed HSX vacuum vessel.

where the vessel is broken for assembly, have all been fabricated, and the boxports have been fabricated and leak-checked. The main vessel sections are being formed by explosive fabrication. The exterior vessel shape is machined into a segmented mold and high explosives are used to force a 0.25-in. stainless steel plate to conform to this shape. Each half-period (symmetry section) is made from four formed plates. The formed plates are trimmed and welded together. The resulting piece is then solution-annealed to remove residual stresses and temper and remove any permeability induced by the cold working. This product is then reinserted into the mold and final sized with one last explosion. Figure 3 shows a 1/4-period section after final sizing, but before trimming for final assembly and installation of diagnostic ports. Lines where the mold segments come together can be seen to be “coined” into the vessel exterior. Coils can be installed on the vessel with the ports in place. The explosion forming is half complete and should be finished by mid-November.

Coil production has been taken over by the Torsatron/Stellarator Laboratory due to poor performance by the vendor. Two winding lines are now in operation with a third expected to be operational this month. Figure 4 shows a coil of type #3 in fabrication. The conductors (six in hand comprising a coil turn) are overwrapped with Kevlar tape to provide insulation and withstand the forming and clamping forces. After forming and brazing of current connection blocks, the coil is securely clamped and removed from the mandrel for groundwrapping. Figure 5 shows a coil of type #2 receiving its groundwrap application. Measurements of the formed coils, made with a portable coordinate measuring machine, are showing the coil envelopes coming in with a 95% confidence level to within 1.6 mm of the desired location around all coil surfaces. It takes approximately two weeks to wind a coil and turn the mandrel around for the next one. With the advent of the third line, coil winding should be completed by mid-April 1997.

Coils can be assembled into main-coil/ring/trim-coil modules as the main coils are produced. Assembly of these modules into final position can commence with the completion of the vacuum torus, presently expected in April 1997. The device is expected to begin operation in August 1997.

David T. Anderson for the HSX Group
Torsatron/Stellarator Laboratory
University of Wisconsin, Madison
1415 Johnson Drive
Madison, WI 53706, USA

Voice: (608) 262-0172
FAX: (608) 262-1267
E-mail: dtanders@facstaff.wisc.edu

Fig. 4. A coil of type #3 in fabrication.

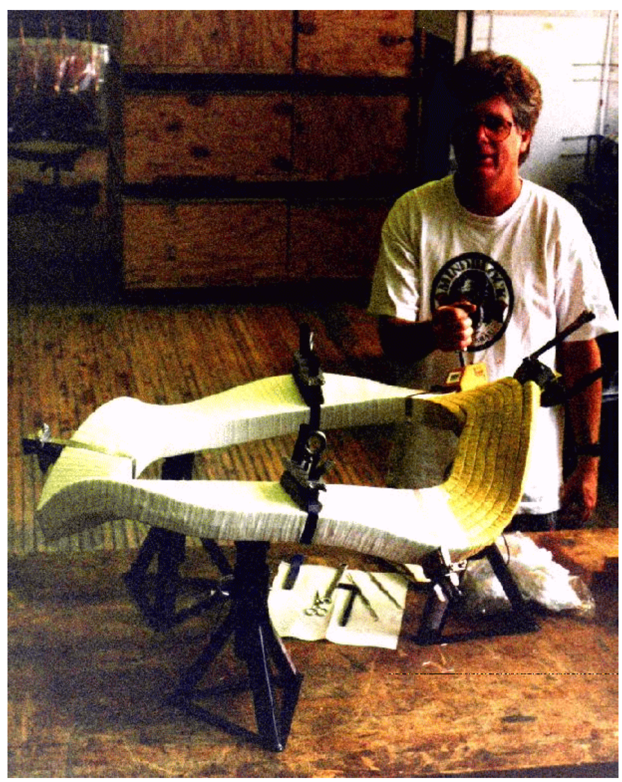
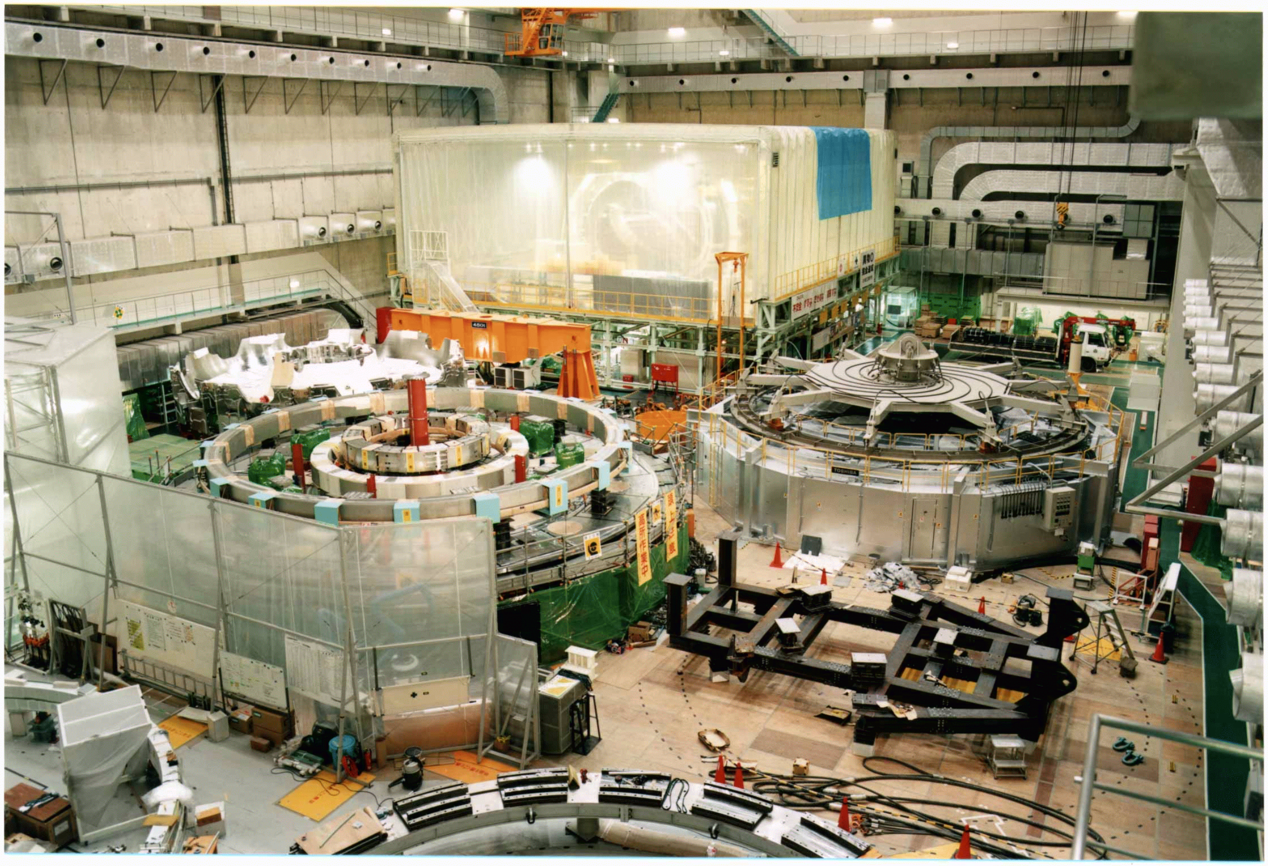
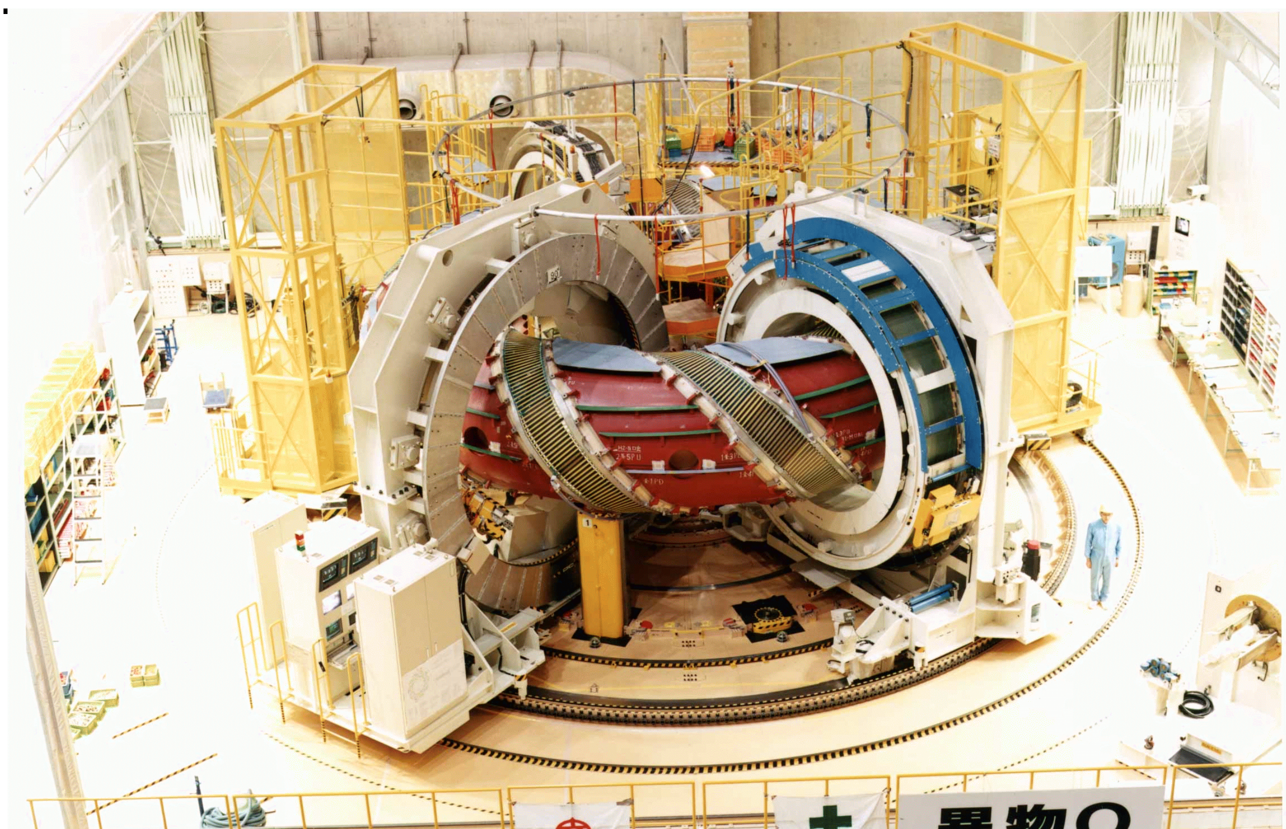


Fig. 5. A coil of type #2 receiving its groundwrap application.

LHD construction photos



Above: View of the LHD machine hall, with the poloidal coils on the left and the machine base on the right.
Below: iThe helical coil in its winding jig.



U.S./Japan workshop focused on stellarators and other helical systems

A U.S./Japan Joint Institute of Fusion Theory workshop will be held at Columbia University in New York City, October 14-17, 1996. The title will be “Advanced Confinement Concepts and Theory” with a focus on stellarators and other helical systems. The organizers are Allen Boozer and Masao Okamoto. Participation by interested persons, experimentalists or theorists, from the world program is encouraged. If you have questions about the scientific organization of the meeting, contact Allen Boozer at ahb17@columbia.edu. Questions about housing arrangements can be directed to Ms. Marlene Arbo, Department of Applied Physics, Columbia University, New York, NY 10027, mja2@columbia.edu.