stellarator news

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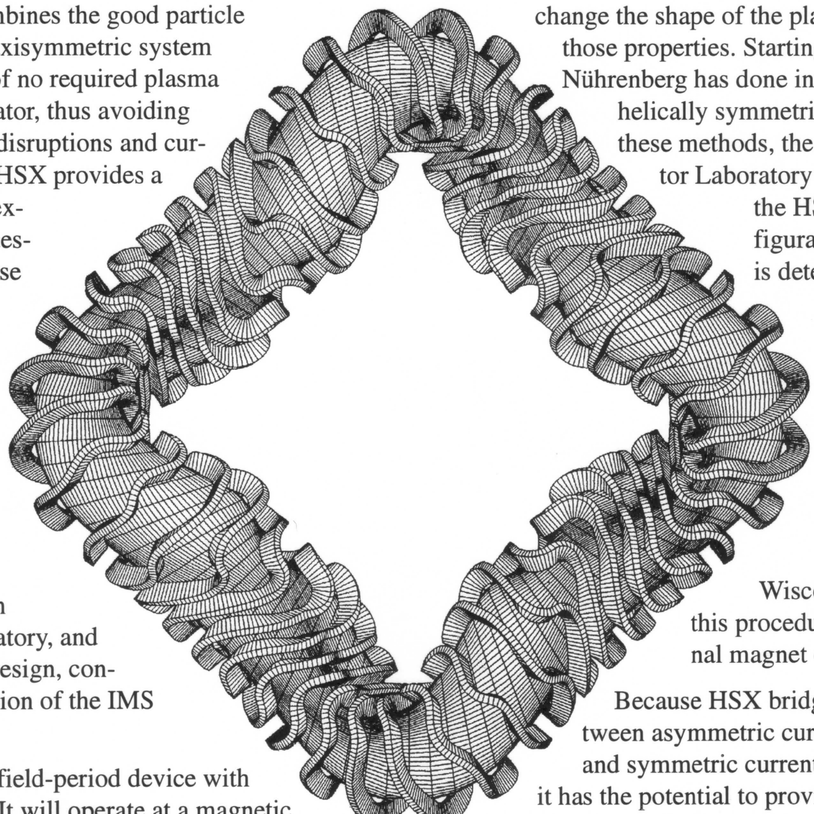
HSX Stellarator to be Built at the University Of Wisconsin



On August 1, 1993, the Department of Energy awarded a grant to the University of Wisconsin's Torsatron/Stellarator Laboratory for the design, construction and initial operation of the HSX stellarator. HSX (Helically Symmetric Experiment) is a new type of stellarator that approximates the magnetic field characteristics of the tokamak. It thus combines the good particle confinement of the axisymmetric system with the advantage of no required plasma current in the stellarator, thus avoiding the difficulties with disruptions and current drive. As such, HSX provides a new opportunity to explore key physics questions common to these two toroidal systems.

The Wisconsin Torsatron/Stellarator Laboratory began operation in 1973 with the acquisition of the Proto-Cleo Stellarator and Proto-Cleo Torsatron from Culham Laboratory, and continued with the design, construction, and operation of the IMS Modular Stellarator.

HSX is to be a four-field-period device with an aspect ratio of 8. It will operate at a magnetic field strength of 1 T in order to take advantage of high-power 28-GHz gyrotrons that can be used to obtain a hot electron plasma in the low collisionality regime. Costs are to be minimized by utilizing equipment furnished by the national laboratories for plasma heating and magnet power.

Design of HSX, whose principal goal is the generation of a quasi-helically symmetric configuration and a test of the predicted improved neoclassical confinement, was made possible with the use of the techniques developed by Nührenberg and Zille at the Max Planck Institute for Plasma Physics at Garching. Until recently, stellarators were designed through a largely empirical process. The German methodology, however, permits researchers to determine desired physical properties and change the shape of the plasma to obtain those properties. Starting from the work Nührenberg has done investigating quasi-helically symmetric systems using these methods, the Torsatron/Stellarator Laboratory team developed the HSX magnetic configuration. The final step is determining whether it is possible to construct the magnet coils to get the desired plasma boundary shape. The methods of Merkel, also at Garching, achieve this goal, and the Wisconsin team utilized this procedure to obtain the final magnet coil design.

Because HSX bridges the gap between asymmetric currentless stellarators and symmetric current-driven tokamaks, it has the potential to provide an opportunity to explore some fundamental physics questions. Among these are the role of the electric field in plasma transport; the effects of symmetry in plasma spin-up, rotation and momentum damping, single particle confinement in the long mean free path regime, and profile differences between tokamak-like and stellarator-like operation.

Neoclassical transport is predicted to be reduced by about two orders of magnitude compared to traditional stellarators, and is expected to be even lower, by a factor of three, than in an equivalent tokamak [a device with the same physical aspect ratio, rotational transform (q), and magnetic field strength].

Key device parameters are major radius (1.2 m), average plasma minor radius (15 cm), and plasma volume (0.44 m^3). Expected plasma parameters with 200-kW 28-GHz electron-cyclotron heating at 1 T central field are power density (0.45 W/cm^3), peak electron density (1×10^{13} cm^{-3}), central electron temperature with LHD scaling, 100 kW absorbed power (700 eV); current flat top (25 s), energy confinement time with LHD scaling (2 ms), and peak beta (0.3 %).

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Around the Labs

Start of the Uragan-2M experiment.

The final assembling of the Uragan-2M (U-2M) torsatron was completed in May 1993, and first experiments on studying the magnetic configuration of this device were performed in June. Fig. 1 shows a view of the U-2M device.

U-2M is a new torsatron concept which employs an additional toroidal field to improve the configuration [1]. The U-2M concept is the result of a search for a torsatron system with a reduced helical ripple but still having a moderate shear and magnetic well.

Main device characteristics are the following:

major radius	$R = 1.7$ m
minor radius of helical winding	$r_h = 0.44$ m
vacuum chamber inner radius	$r_c = 0.34$ m
toroidal field coil number	16
poloidal field coil number	8
toroidal magnetic field	2.4 T
pulse length	2 s

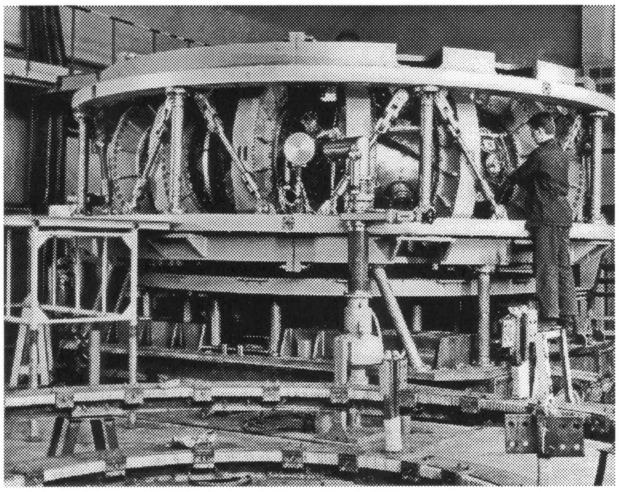

Fig. 1. A view of the U-2M device in Kharkov.

The $l = 2$, $m = 4$ helical winding obeys the law of a toroidal helix with constant pitch angle.

Magnetic configuration parameters:

average radius of LCFS	0.17– 0.22 m
rotational transform	
center:	0.2–0.57
edge:	0.4–0.75
global shear	0.3
edge helical ripple	6%

Magnetic configuration parameters can be adjusted by changing three operational parameters:

- the ratio of currents in helical coil and toroidal field coil set,
- the value of uncompensated vertical magnetic field, and
- the ratio of currents in adjacent pairs of toroidal field coils.

The first parameter changes the center and edge rotational transform and magnetic well values as well as the plasma radius. The second parameter changes the magnetic axis position and magnetic well shape. The third parameter changes the helical ripple at the center.

The magnetic system of U-2M is supplied from an ac-flyweel generator ($P = 250$ MW, $E = 0.8$ GJ) and thyristor rectifiers.

The rf system of U-2M consists of two oscillators ($f =$ 20–65 MHz, $P = 1$–7 MW, pulse duration of 0.3–1.0 s). A currentless plasma will be produced and heated in U-2M using different scenarios of rf wave excitation.

First experiments on rf plasma production will use IBW excitation with a slow-wave antenna, which is shown in

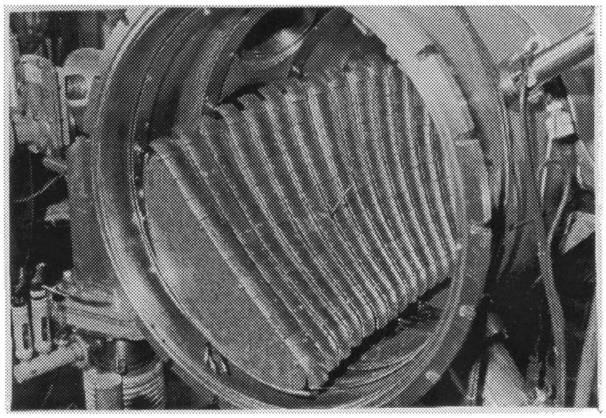

Fig. 2. The slow-wave antenna during the assembly of U2-M.

Fig. 2. This antenna has a large area (1.7 m^2) and is capable of radiating rf power up to 2 MW.

Magnetic configuration studies for U-2M will use two complementary techniques. The stellarator diode will be used for evaluation of the shape and configuration of the confinement region and the luminescent probe technique will be used for the magnetic flux mapping studies.

First measurements with the diode technique showed that there is a rather sharp border of the volume, as shown by the strong emitter current suppression (Fig. 3).

The results of these measurements allowed us to reach the preliminary conclusion that there are no essential errors connected with the design, fabrication, and assembly of the magnetic system of the U-2M torsatron. Final conclusions about the U-2M magnetic configuration quality will be made after the magnetic flux mapping studies are performed using the luminescent probe.

The rf plasma production experiments for U2-M will start this month.

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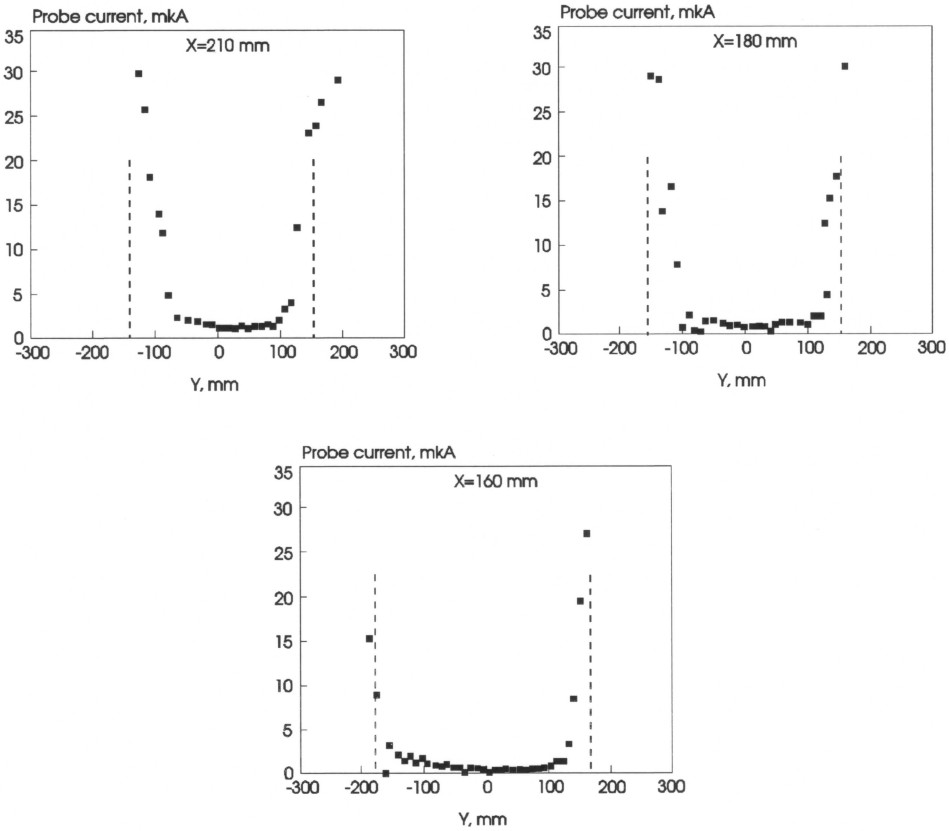

Fig. 3. Initial results from the surface-mapping experiments. Probe current profiles for three vertical scans are shown. Dashed lines show position of calculated last closed magnetic surface. The shape of this border corresponds to the shape of the last closed magnetic surface obtained from magnetic surface calculations.

Atomic hydrogen behavior in the torsatron Uragan-3M

The magnetic system of the torsatron Uragan-3M (U-3M) is located inside the vacuum chamber (volume = 70 m^3), which is filled with hydrogen gas until the working pressure is reached. Accordingly, the constant flux of molecular hydrogen on the confinement-region boundary influences the discharge dynamics and plasma parameters. This fact is especially important for discharges with a low density and a relatively high concentration of the neutral component.

Local measurements of the hydrogen atom density by laser-induced fluorescence have been carried out in the rf-discharge plasma with the electron density $n_e \sim 2 \times 10^{12}$ cm^{-3} at the confining magnetic field 0.46 T [1]. The temperature of electrons and ions was in the range 100–500 eV. The quasi-stationary state of the discharge was maintained for 40 ms. The excitation of the hydrogen atoms on the line H_α was performed by using a pulse dye laser with pumping lamp. The spectral density of the probing radiation power was equal to ~ 2×10^4 W cm^{-2}nm^{-1}. The fluorescence signal was observed from a volume ~ 2 cm^3 near the axis region of the plasma column (r = 4 cm). The absolute calibration was made by means of the Raleigh scattering in nitrogen.

The relatively low linear density of electrons resulted in penetration of the hydrogen atoms and molecules into the central region of the plasma column. As is known, excited atoms are produced not only by electron impact but also by molecular hydrogen dissociation.

In a cylindrical plasma cylinder model, the radial profiles of the excited (levels 2,3) hydrogen atoms were calculated (Fig. 4). The dissociative channel of excitation is sufficient in the examined regimes.

This circumstance created essential changes in the interpretation of the measured fluorescent signals. Considering the results of the calculation, the hydrogen atom density $n_a \sim 8 \times 10^9$ cm^{-3} was nearly a constant during the whole discharge (Fig. 5). The particle lifetime determined from the measurements was $\tau \sim 4$ ms.

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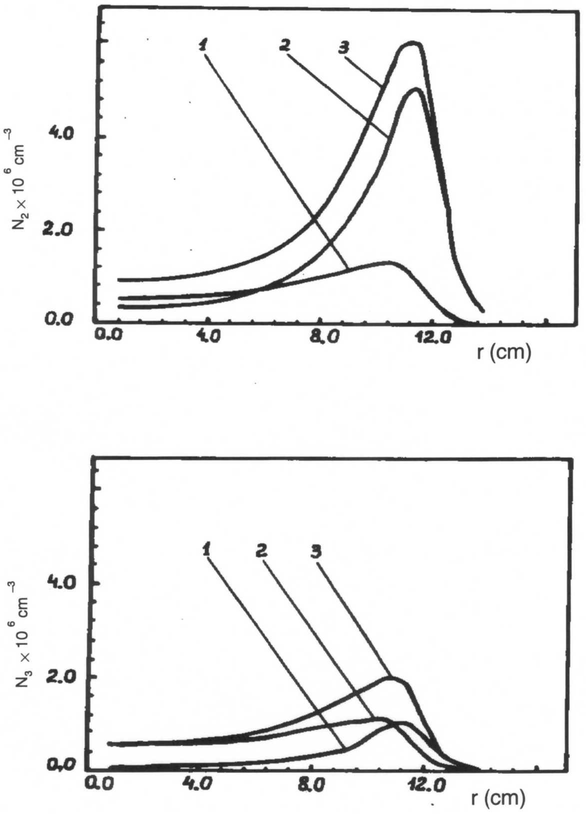

Fig. 4. The radial dependence of the excited state density of the hydrogen atoms (1— from atomic excitation; 2 — from molecular dissociation; 3 — summary).

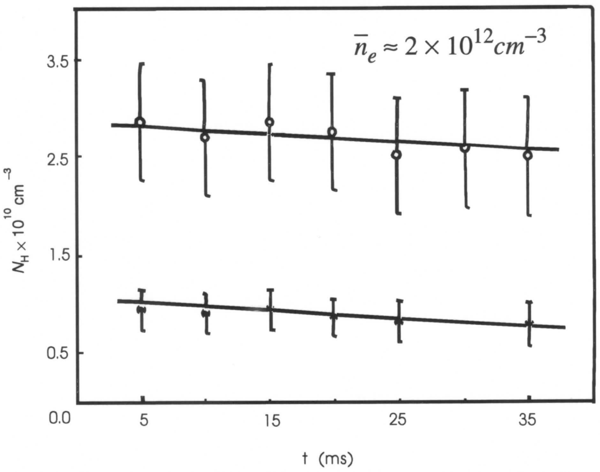

Fig. 5. The time evolution of the hydrogen atom density (white circles — processing with the traditional method; black circles — processing considering molecular dissociation).

Plasma production using a 900-MHz loop antenna for W7-AS

NBI alone cannot produce a plasma in W7-AS, and some form of target plasma is required. This is typically achieved using ECRH. Conventional ICRH antennas [1] have also been used successfully, albeit at a rather low efficiency (140 kW for densities of about 3×10^{18} m^{-3}). A new and simple method of producing a low-density target plasma for NBI has been developed and successfully used on W7-AS, using a small antenna operating at 900 MHz.

The antenna is a rectangular loop of 2-cm-wide stainless steel strip, extending toroidally 8.3 cm and radially 3.5 cm. It is center-fed from a 50-Ohm coaxial transmission line, matched by a double stub tuner. The antenna is inserted through a 10-cm port to about 5 cm outside the last closed magnetic flux surface, and is aligned with the current strap in the toroidal direction. We use a frequency of 900 MHz at 30 kW from an industrial magnetron. Under the plasma conditions achieved by the antenna, the slow wave (lower hybrid [LH] wave [2]) tunnels through a narrow evanescent region near the antenna and propagates into the plasma. The wave is expected to deposit its energy by collisional damping onto the electrons. In order that the LH wave propagates into the plasma and is not refracted back into the edge, an accessibility criterion must be satisfied for the normalized parallel wave number:

$$n_z > \left[1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega^2}\right]^{1/2} + \left[\frac{\omega_{pe}^2}{\omega_{ce}^2}\right]^{1/2}$$

The antenna should couple $n_z = 4$ to the lower hybrid wave. This should allow densities up to the lower hybrid resonance $\omega^2 = \omega_{pi}^2/(1 + \omega_{pe}^2/\omega_{ce}^2)$ to be achieved. Corresponding numerical values are $n_e = 2.5 \times 10^{19}$ m^{-3} for $B = 2.5$ T in hydrogen.

Breakdown could not be achieved by the 900-MHz LH wave alone, and some initial ionization was required. It was found that a short 5-ms NBI pulse produced enough electrons for the antenna to generate a plasma. By using gas puffing during the 900-MHz pulse, a central density of up to 0.8×10^{19} m^{-3} could be reached. Somewhat less than 10 kW was radiated from the antenna, the remainder being lost to mismatching and transmission line losses. Although the antenna spectrum should be toroidally symmetric, a net plasma current of up to 500 A was found to be driven in this low-density plasma, together with a strongly nonthermal electron cyclotron emission (ECE), suggesting the generation of a fast electron tail.

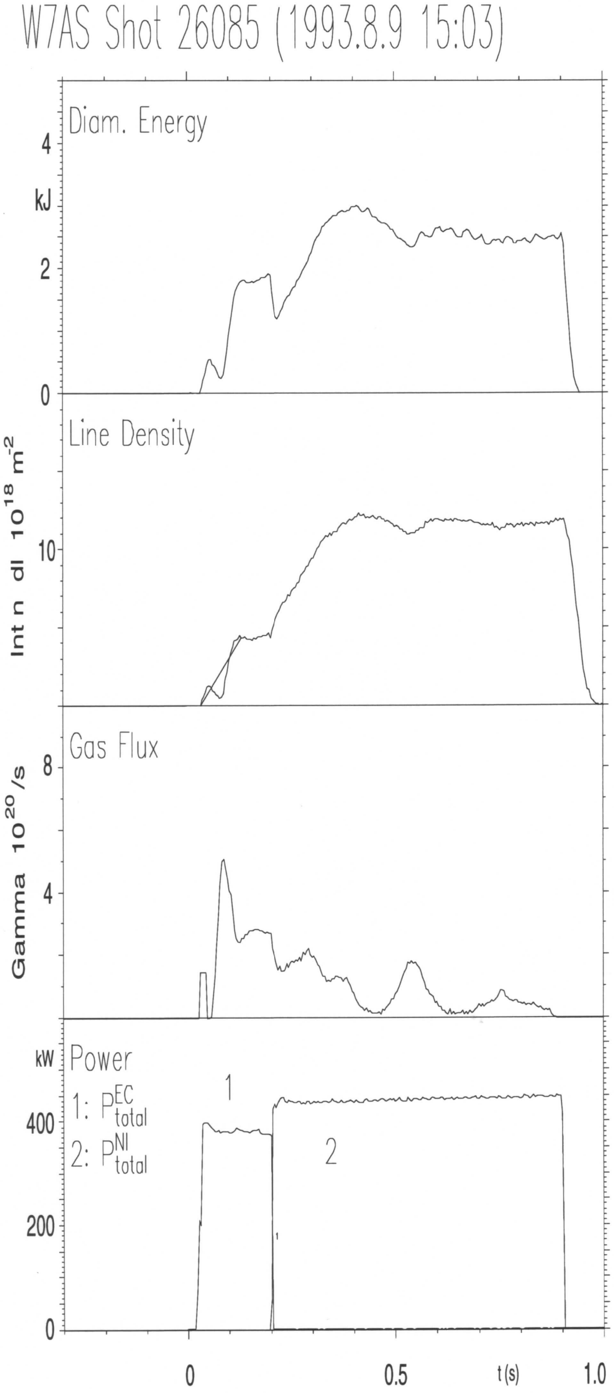

Fig. 6. Shot #26085, using 450 kW of NBI into a conventional target plasma produced by 400 kW of ECRH between 20 and 200 ms.

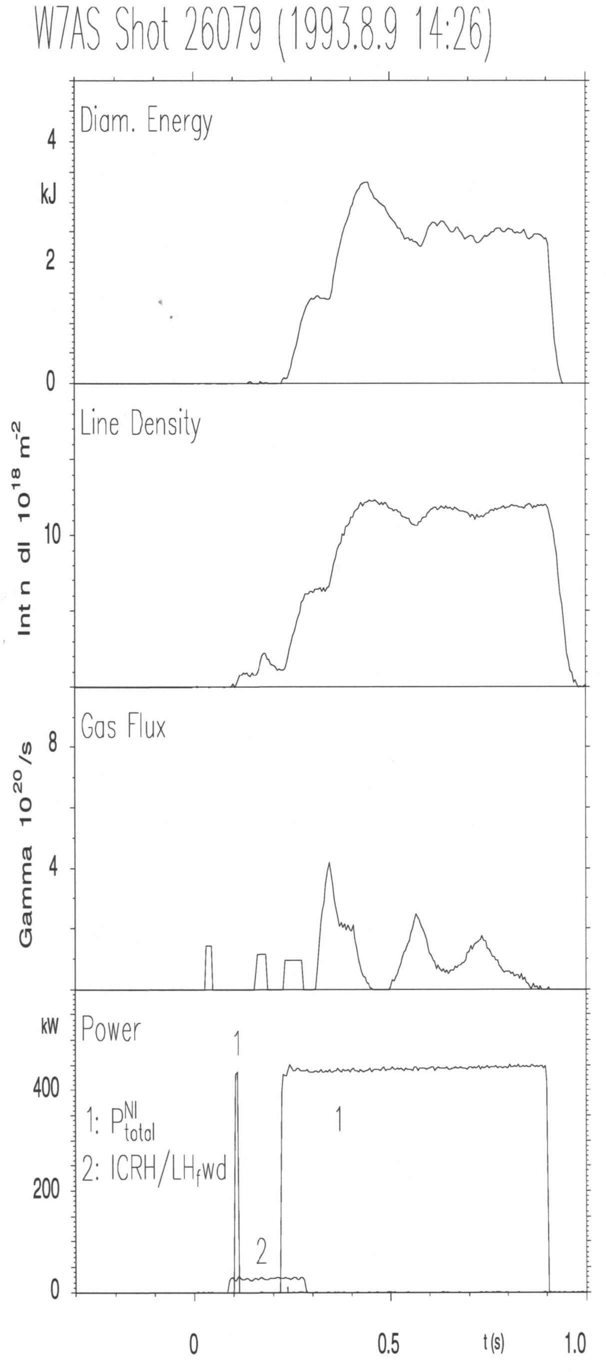

Fig. 7. Shot #26079, using 450 kW of NBI into a target plasma generated by 30 kW to the new 900-MHz antenna between 70 and 280 ms. A short NBI pulse at 100 ms is used for initial breakdown.

This low-density plasma was successfully used as a target plasma for NBI over a range of fields from 0.8 T to 2.5 T, freeing the experimentalists from the restriction of using target plasmas produced by ECRH at fixed magnetic fields of 1.25 or 2.5 T.

The nonthermal ECE and the wave-driven current were found to be suppressed during the high electron density of the NBI pulse. A comparison between neutral beam plasmas that used ECRH as a target plasma and those using the 900-MHz LH antenna is given in Figs 6 and 7. For both discharges the field is 1.27 T and the edge value of $\iota\!\!\!-(a)$ is 0.34 at a plasma radius a = 18 cm set by the limiter. Whereas the plasma conditions differ during the first half-second of the discharge, due to the different start-up, the signals agree during the last 300 ms, apart from a slight difference in the gas flux. Gas fluxes are identical during the last 100 ms of the two shots. Similar impurity levels and time evolutions of other signals are seen.

This increased flexibility has recently been used to conduct magnetic field scans for measuring the dispersion relations of global Alfvén eigenmodes that would otherwise not have been possible, and it should be useful for high-beta plasma experiments at low magnetic field.

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Influence of trapped particles on the electron cyclotron current drive at W7-AS

Electron cyclotron current drive (ECCD) has been systematically investigated at W7-AS. In these experiments both polarization modes — X-mode second harmonic and O-mode first harmonic — have been investigated with on-axis or off-axis launching of the 70-GHz power at variable launch angles. Three different operation scenarios have been applied: experiments without current control, $I_p = I_{boot} \pm I_{ECCD}$; experiments with zero net current, $I_p = 0$, by an appropriate ohmic current; and experiments with modulation of the power of two gyrotrons, in order to change either I_{ECCD} or I_{boot}, depending on the phase of the modulation. These methods and their results have been described in Ref. 1.

Agreement is found between experimental results and theoretical predictions. A typical ECCD efficiency of $\eta_{ECCD} \approx 10$ A/kW results for $T_e \approx 1.5$ keV and $n_e \approx 2 \times 10^{13}$ cm^{-3}. This efficiency scales as $T_e / [\, R_0 (5 + Z_{eff})\, n_e\,]$ for optically thick plasmas. The theoretical predictions are obtained by a 3-D ray-tracing code using the "adjoint approach" in the limit of extreme long mean free path. Neoclassical transport and auxiliary heating are treated as two independent superimposed processes. The effects of the presence of bouncing trapped particles are described through two main parameters: the fraction of trapped particles, f_t (a flux surface averaged quantity), and the fraction of trapped particles at the point where the ECRH power is deposited (a local quantity). Details are given in Refs. 2 and 3.

In this contribution we present some recent results of experiments which focus on the role played by trapped particles in the ECCD mechanism. Two complementary magnetic configurations can be established in W7-AS by a change of the "mirror ratio" [4]. This quantity is defined as the amplitude of the toroidally varying magnetic field strength on axis. It amounts to ±10 % for the two modified configurations with an edge value of $\iota\!\!\!-$ = 0.34. Trapped particle fractions f_t, of 40 to 50 % on axis are estimated, about twice the value of the standard low-iota case of W7-AS. In the first configuration, labeled *R* in the figure, the resonance condition for on-axis ECRH is satisfied close to the maximum value reached by the magnetic field. In this case the power is deposited mainly to passing particles. In the complementary case, labeled *A*, the power is deposited close to B_{min}, where the population of trapped particles is localized. Then the power directly deposited to bouncing trapped particles is not expected to drive any current. The power deposited to barely passing particles, however, can cause their trapping and consequently induce a current of opposite sign with respect to the usual ECCD mecha-

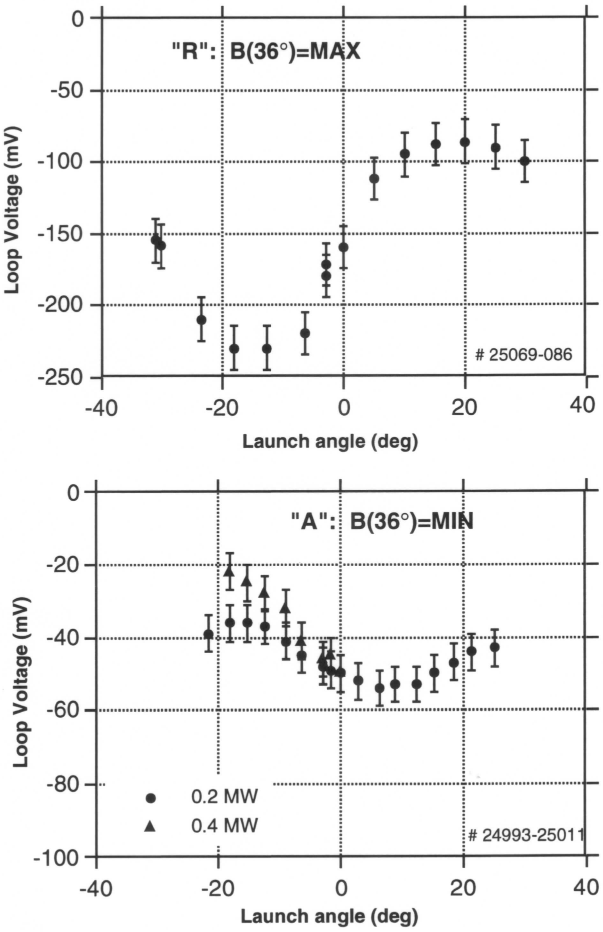

Fig. 8. Experimentally observed loop voltage to achieve net current-free plasmas in W7-AS vs the launch angle of ECRH power. *Top*: configuration *R* with a local maximum of 1.25 T on axis. *Bottom*: complementary configuration *A* with a local minimum of 1.25 T on axis. On-axis ECRH is applied in W7-AS in the 'elliptical plane', ϕ = 36°.
The experimental result agrees with the theoretical predictions: In configuration *A* with heating at B_{min}, ECCD efficiency is strongly reduced, and the driven current is of opposite sign compared to that when heating at B_{max}. For perpendicular ECRH power with launch angle = 0°, the magnitude of η_{ECCD} is zero, and only the bootstrap component has to be controlled. It is considerably smaller in configuration *A* than in *R*, as reflected by the smaller loop voltage.

nism, responsible for ECCD in the case of heating at $B_{\max}$.

The experimental results are shown in the two parts of the figure. The abscissa is the toroidal angle of applied ECRH power; the ordinate is the loop voltage required to keep the net current, I_p, close to zero. The data are time averages over 200 ms, and the error bars represent the change of the loop voltage within this interval. The measured values of density and temperature are similar in the two sets of discharges. The scales differ in the two parts of the figure. In contrast to the experiment in the configuration A, the configuration R requires much larger values of the loop voltage to achieve zero net current. Note that the radial distributions of the current densities are different for ohmic, bootstrap, and ECCD-driven currents, due to the different physics which cause them.

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People

Alejaldre appointed head of fusion research at CIEMAT

On July 1, 1993, Carlos Alejaldre became head of fusion research at the Asociacion EURATOM-CIEMAT in Madrid, Spain. Previously, Dr. Alejaldre was head of Plasma Theory Section. Since 1987 he has been a member of the European Fusion Programme Committee and recently became member of the European Consultative Committee Fusion Programme (CCFP). His main topics of interest had been ECH and MHD theory.

Carlos Alejaldre received the equivalent of a master of physics degree from Licenciado en Ciencias Fisicas-Universidad de Zaragoza, Spain, and a Ph.D. in electrophysics from the Polytechnic Institute of New York.

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