stellarator news

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E-Mail: jar@ornl.gov Phone: (615) 574-1306

H-1 Highlights, July 1995

The H-1 heliac resumed operation in February 1995 after an extended vacuum break to add 17 diagnostic/heating ports, including an 8-port toroidal array, several RF/ECRH ports, and provision for limited tangential access. Extra ports will facilitate installation of the second phase of the multi-view interferometer in July. The ports will allow three views each of as many as 15 beams,

Gas puffing

In hydrogen and helium, higher densities and temperatures as well as lower ionization outside the plasma volume have been achieved by a high throughput (> 300 Torr-l/s), directed gas puffing system. For example, a 10-ms, 80 Torr-l/s pulse in helium provides a peaked profile $n_e \sim 10^{12}$ cm^{-3}, T_e ~20–30 eV at $B_0 = 0.13$ T, for which conditions a lower puff rate or static fill produces a flat or hollow profile of lower density.

Confinement studies

In quasicontinuous mode (continuous $B_0 > 2$ T, pulsed plasma), Langmuir probes can be used under some conditions. A hydraulically driven, 3-mm diameter ceramic-sheathed single probe is the least perturbing, and a probe array with 24 tips has been installed for fast profile acquisition (Fig. 1), at the expense of a greater plasma perturbation. The decay time of the ion saturation current is proving to be a useful indicator of local and global energy decay times, and indirectly of confinement times. Preparation of the support structure, intensified spectrometer, and laser for a scanning Thomson scattering system is complete.

Finite beta studies

Magnetic data are collected from three fixed diamagnetic loops and two scanning Rogowski diamagnetic loops. Perpendicular energy increases with *B* until limited by rf power. For 60 kW rf power ~ 0.1% beta has been achieved in helium. Higher values have been achieved in argon. Measurements of plasma internal cur-

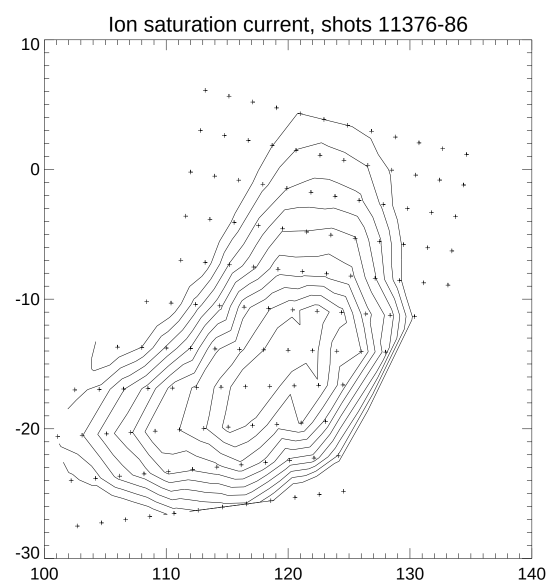

Fig. 1. Bean-shaped density profile in H-1 obtained using new 24-tip Langmuir probe. Data from 11 channels are shown.

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rents are qualitatively consistent with VMEC calculations of pressure-driven currents; some uncertainty in baseline is caused by a net toroidal current which appears under certain conditions.

Correlation spectroscopy

A new technique for monitoring spatial correlations in fluctuations, sensitive to both temperature and density, has been developed and applied to H-1 in a proof-of-principle experiment. Initial results are encouraging, but interpretation can be complicated by the presence of long scale-length coherent oscillations. This is described in more detail in a separate article by M. Shats.

Spectroscopic flow imaging

The installation of fiber-optic/lens arrays mounted on a rotatable carrier is planned to allow tomographic reconstruction of ion flow fields from line-integrated spectroscopic measurements. It can be shown that the first moment (the Doppler shift) is proportional to the emission-weighted component of the ion velocity in the direction of, and integrated over, the line-of-sight. From a sufficient number of measurements it is possible, using principles of vector tomography, to recover the 2-D structure of the solenoidal component of the flow velocity.

Plasma theory group

Theoretical work ranges from the development of a robust coordinate system for use in magnetic geometries with islands to large-scale numerical optimization of reactor configurations. The HINT code is being used to study the evolution of magnetic islands with plasma pressure using the flexibility of the heliac design to find theoretically interesting cases, such as resonances at points where the global magnetic shear changes sign, which are also interesting in vacuum fields.

The effect of the sign of the shear on drift wave stability is also of interest [1]. Ideal and drift wave stability is being studied in the ballooning representation using both the cold-ion and gyrokinetic models. Visualization of global and local stability criteria is being developed into a valuable tool for searching for and identifying instabilities, both in the experiment and in numerical simulations. Use of a WKB formalism allows ballooning calculations to treat global modes [2].

A Monte Carlo transport code using VMEC equilibrium information is being written to iteratively determine self-consistent electric fields and transport in the H-1 plasma. In a separate study [3], optimization of high equilibria, transport, and bootstrap current has led to an economical compact reactor configuration, the three-field period modular helias-like heliac. The effect of rf and fluctuations on transport and current drive is also being investigated.

Future

Pulsed operation at higher fields (0.5-1T) will commence this year in preparation for electron cyclotron heating. Several means of upgrading the machine to national facility status are being explored. Demonstrated international collaboration is an important factor in the advocacy of these applications and will be enhanced by their success.

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Boyd Blackwell
Plasma Research Lab
RSPhysSE
Australian National University
Canberra ACT 0200/AUSTRALIA

E-mail: Boyd.Blackwell@anu.edu.au

Phone: +61 6 249 2482
FAX: Boyd Blackwell, PRL +61 6 249 2575

WWW page:
http://online.anu.edu.au/rsphyse/prl/PRL.html

Degradation of energy confinement or degradation of plasma heating — what is the main definite process for plasma transport in stellarator?

The analysis of plasma energy balance in stellarators and tokamaks depends on the different assumptions made and may give different and even contradictory results.

When full power absorption by thermal plasmas is assumed, paradoxical results can be obtained; degradation of the energy confinement time with heating power as well as degradation of plasma thermal conductivity in very short times ($t \ll \tau_E$) during power modulation experiments is deduced. On the other hand, assuming that plasma transport characteristics do not change while main plasma parameters (density and temperature, their gradients, etc.) are kept constant leads to the conclusion that heating efficiency is not unity and that it depends on both, plasma parameters and heating power. In this case, no contradiction is found when plasma energy balances are analyzed.

This article presents the results of electron cyclotron resonant heating (ECRH) experiments on L-2M. The aim of the experiments was to try to answer this important question.

Analyses of the fast processes occurring during the switch-off phase of the ECR heating, modulation of the heating power, and specific plasma decay phase have led to the conclusion that it is correct to assume that plasma transport characteristics remain unchanged during fast variations of the heating power.

Experimental results and discussion

Determining the plasma energy balance in closed magnetic traps is one of the most important problems. Analyses are based on main equations of particle and energy balances and include the different transport coefficients for diffusion and thermal conductivity.

The investigation of the energy balance is mainly directed to determine magnitudes such as the energy confinement time or the thermal conductivity and their dependencies on plasma parameters (n_e, T_e, their profiles), magnetic configuration, and heating methods (ECRH, ion cyclotron resonance heating (ICRH), neutral beam injection (NBI), etc.). Experimentally, both stationary and time-dependent methods are applied for this purpose: transition from the stationary plasma to the free energy decay phase, heating power modulations, and single pulse launching to study heat wave propagation.

Main equations for the energy balance are:

$$\frac{3}{2}\frac{d}{dt}[(T_e + T_i)n_e] = -\frac{1}{r}\frac{d}{dr}[r(F_e + F_i)] - P_{rad} - P_{cx} + P_{ab} \quad (1)$$

$$\frac{dW}{dt} = -P_c - P_{rad} - P_{cx} + P_{ab}\,, \quad (2)$$

$$S_i + S_e = 0\,, \quad (3)$$

where T_e, T_i, n_e, and W are particle temperatures and density and total energy, respectively; $P_c = 4\pi\, Ra(F_e + F_i) = -W/\tau_E$, conduction, $P_{rad} = \int p_{rad}(r)dV$, radiation and $P_{cx} = \int p_{cx}(r)dV$, charge-exchange losses; $P_{ab} = \int p_{ab}(r)dV$, the absorbed power, and F_e and F_i, the thermal fluxes. The condition (3) expresses plasma neutrality.

Plasma thermal conductivity can be determined from the local plasma energy equation as

$$\chi_e(r) = \frac{P_{ab}(r) - \frac{dW(r)}{dt} - P_{ei}(r) - P_{rad}(r) - P_{cx}(r)}{r n_e(r)\frac{dT_e(r)}{dr}}\,. \quad (4)$$

Therefore, to calculate thermal transport parameters, it is necessary to know total and local plasma parameters and the profiles of P_{rad} and P_{cx}. At the same time, the radial profile and the total value of the heating power which is absorbed by the thermal plasma, must be determined. In this study, we have paid attention mainly to the question of determining the real absorbed power (P_{ab}), because of its importance in the plasma energy balance.

To perform the global energy balance in L-2M stellarator plasma (ECRH, $2\omega_{ce}$, 75 GHz, P_0 = 100–400 kW), we have always used the value of absorbed power estimated from diamagnetic measurements. At the switch-off time (t_{off}) of the heating power (P_0), from Eq. (2), we have the following:

$$P_{ab} = \frac{dW(t < t_{off})}{dt} - \frac{dW(t > t_{off})}{dt}\,.$$

The system used for diamagnetic measurements has good time resolution (dt = 20 μs, $dt \ll \tau_E$), and during this short time the losses do not change. For the present experiments, the estimated heating efficiency, $\eta = P_{ab}/P_0$ [1], varies from 0.3 to 0.5 and, in general, is always less than 1.0. As displayed in Fig. 1a and Fig. 1b,

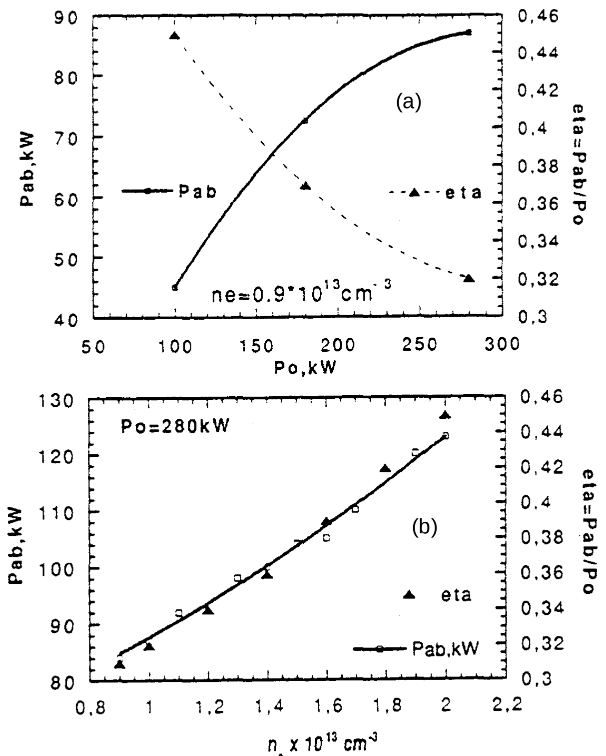

Fig. 1. *W* and η (eta) dependencies on (a) input heating power and (b) plasma density.

the efficiency decreases when P_0 increases and shows a favorable dependence on plasma density. We do not find any paradoxical result in L-2M plasma energy balances in comparison with neoclassical transport theory. In our analysis, we have included the heating power degradation, and although the definite reason for this degradation is still open, we have some indications of its possible link with the presence of trapped particles in the plasma.

The local energy balance on W7-AS (ECRH, $2\omega_{ce}$, 70 GHz, P_0 = 200, 600 kW) was analyzed on the assumption the efficiency, η, equals 1 [2]. In our opinion, this assumption leads to paradoxical results. In Fig. 2, the electron temperature (T_e) and transport coefficient for stationary heating (one or three gyrotrons) and for transient phases (from one to three and back) are represented. In the opinion of the authors [2] and our own, the results are surprising: only 1 ms after changing the input power the transport coefficient had already changed its value to that corresponding to the steady state of the new power level. Becauses this event took place in a time much shorter than the energy confinement time, the T_e and n_e profiles did not change. But if for this analysis the real absorbed power, which can be determined from Δ(d*W*/dt), were taken into account, this transport paradox should disappear.

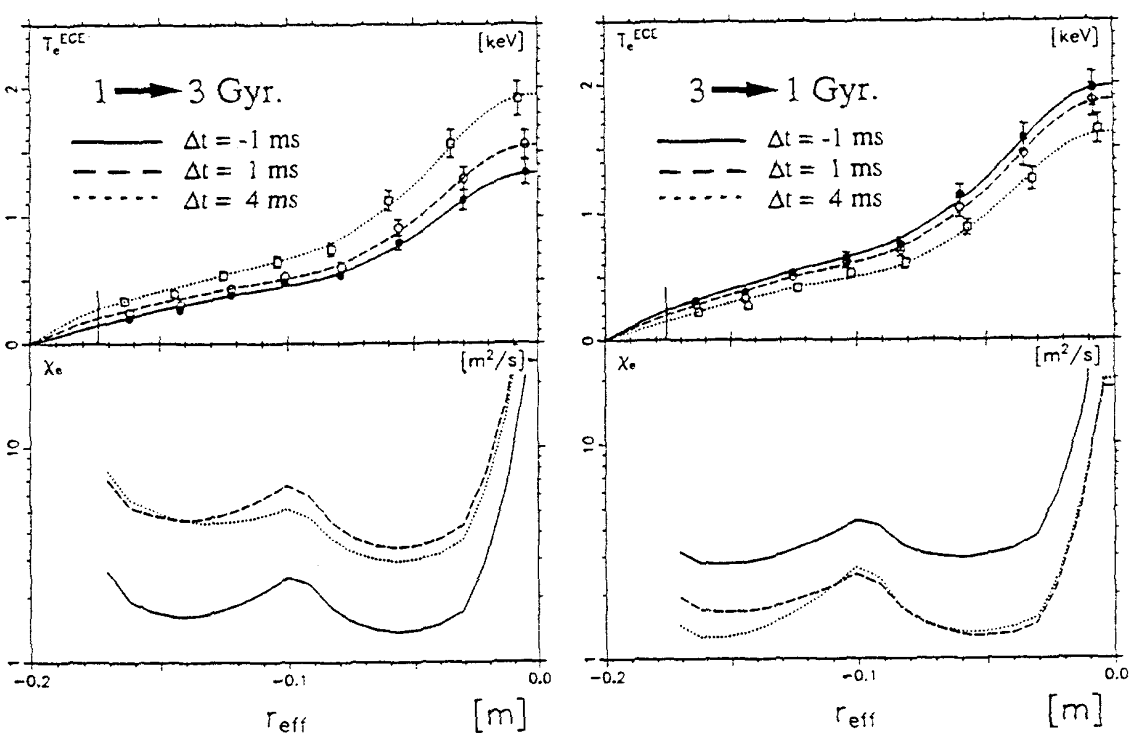

Fig. 2. T_e and transport coefficient profiles before and after (1 and 4 ms) the gyrotrons are switched on (left) and switched off (right).

The only weak point in our above-mentioned method to determine the heating power efficiency is the assumption of the constancy of the energy confinement time during the short time ($dt << \tau_E$) considered in the free phase decay. The strong electromagnetic heat waves can induce high-frequency instabilities and generate high-energy electrons. Both phenomena can increase the transport processes during the heating phase. After the input power switches off, fast dissipation of energy due to plasma turbulence and to the decrease of the electric field can modify the energy transport. This means that our assumption about τ_E needs further investigation.

The heating source (ECRH power) heats the central part of the plasma ($r < 0.2a$), and from there a thermal flux goes to the rest of the plasma column establishing the corresponding density and temperature profiles. Some part of this heating flux to the plasma periphery is lost by radiation. In the L-2M stellarator, the second main channel of thermal losses is radiation. The most common impurities are oxygen and carbon, and they radiate mostly from the outermost region of the plasma ($r > 0.7a$).

From the point of view of increasing confinement after the heating power is switched off, it would mean that the central flux from the main plasma volume will be decreased, and radiation flux should react to this process. The full analysis of this phenomenon is very complicated, and for the correct calculation many data about the profiles of T_e, n_e, n_z (for C and O) are needed, but the accuracy of these data is not enough to answer this question. However, it is possible to do this in another way—by experimental modeling of the property radiation layer (P_{rad} layer) for L-2M conditions.

During the quasistationary phase of ECRH [1], the heating power was modulated: for 1 ms the power decreased by 15 to 20%. The time evolutions of W, dW/dt, and P_{rad} are shown in Fig. 3. It can be seen that the value of the energy changes only about 5% and that $P_{rad}(t)$ shows that the thermal flux reaching the radiative layer has also diminished. It must be emphasized that the high sensitivity in the time correlation found between dW/dt and P_{rad} was not expected (see Fig. 3c).

The next experiment was dedicated to the study of • the free plasma decay. For high heating power ($P_0 > 350$ kW) and plasma densities $< 1.5 \times 10^{13} \text{cm}^{-3}$, a particular behavior was found in plasma decay. The energy decay showed two steps: within the first 500 μs, dW/dt decreased by a factor of two, but only 10% of the total energy was lost; then a slow plasma decay was observed (see Fig. 4). The nature of this phenomenon will be described elsewhere in terms of particle overheating during the active phase. Here we want to emphasize that

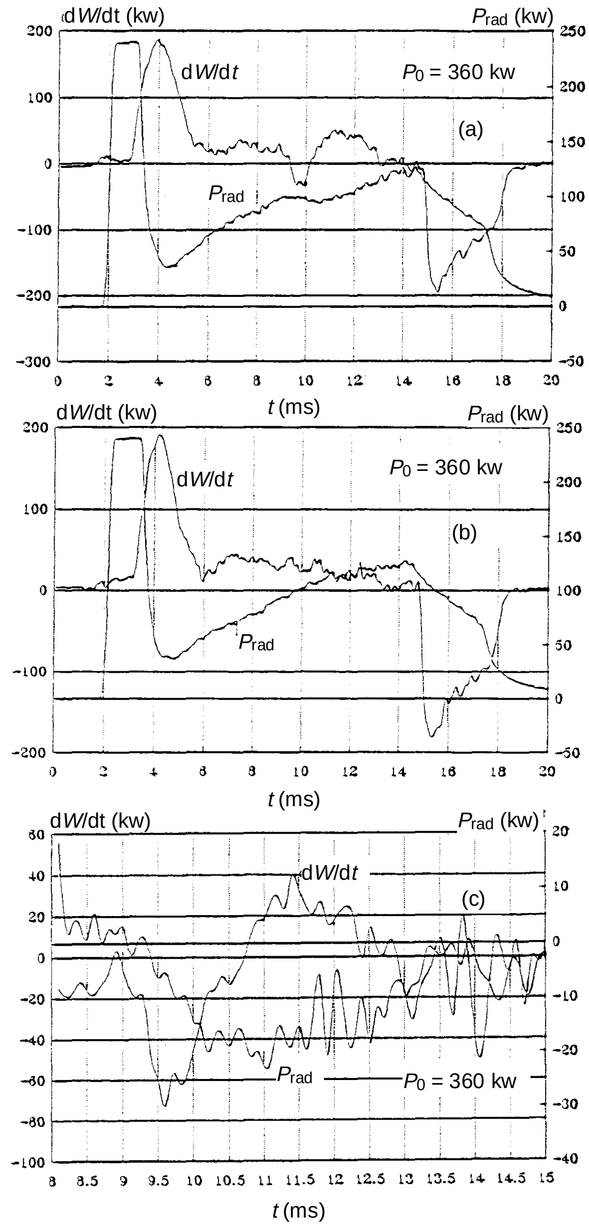

Fig. 3. Time behavior of dW/dt and P_{rad}, (a) with ECRH power modulation; (b) without modulation; (c) the effect of the power modulation on $\Delta(dW/dt)$ and $\Delta(P_{rad})$.

the time evolution of P_{rad} shows clearly this kind of plasma decay and is a good monitor of the time evolution of the thermal flux. Up to now and during the switch-off phase of ECRH, we had never seen any particularity for P_{rad}. $P_{rad}(t)$ has a quite good correlation with $dW(t)/dt$, but for relative high values of plasma density on L-2M ($n_e = 3 \times 10^{13} \text{cm}^{-3}$) radiation losses are directly proportional to the energy losses: $P_{rad}(t) = \propto dW(t)/dt$, as can be seen in Fig. 5.

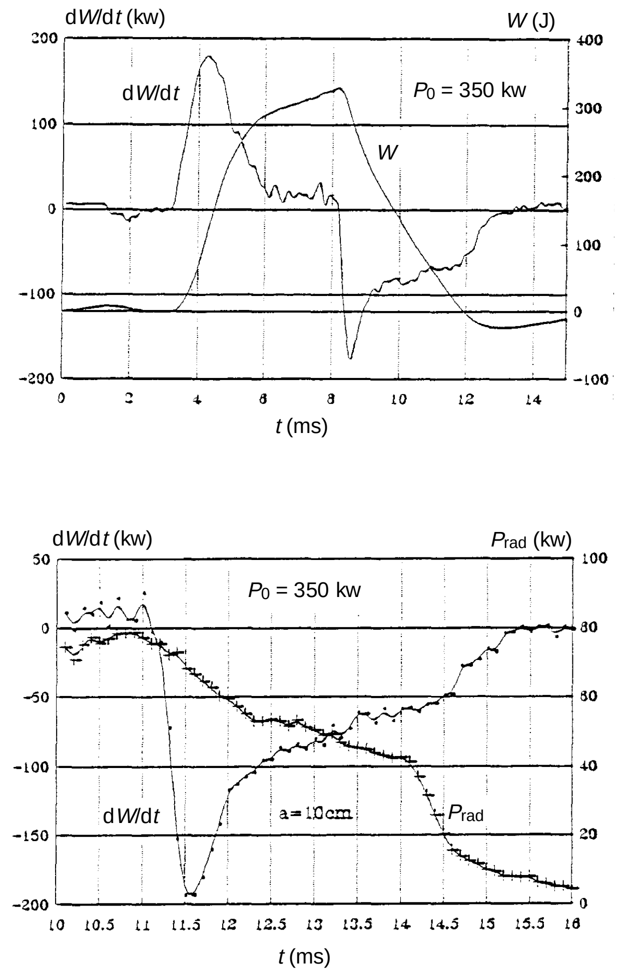

Fig. 4. Time behavior of W, dW/dt and P_{rad} for two-step plasma decay.

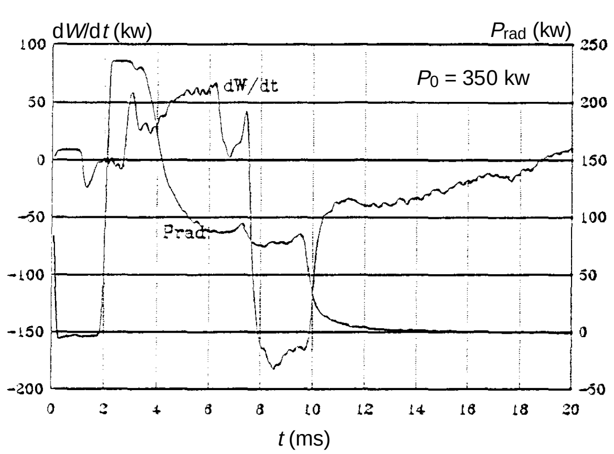

Fig. 5. Time behavior of dW/dt and P_{rad} for a quasiradiation type of an ECRH discharge.

Conclusions

Experimental investigation of the behavior of the plasma radiative layer has provided the necessary evidence to affirm that the energy confinement time does not change during the transition from the ECR heated to the free plasma decay phases.

This conclusion is of extreme importance because it would lead to reconsideration of most energy confinement analyses and may definitively solve the problem of energy confinement time degradation with increasing input power.

Acknowledgments

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O. I. Fedyanin, E. D. Andryukhina
General Physics Institute of the Russian Academy of Science
Moscow, Russia

Summary of the Japanese talks presented at the Madrid Stellarator Workshop

Eight papers were presented in the oral sessions, and ten papers were presented in the poster sessions covering Japanese helical research activities. The experimental results were reported from three helical systems : CHS, Heliotron-E, and TU-Heliac.

CHS

In CHS the results of the optimization of magnetic field configuration were reported. The key parameter was the magnetic axis position, which determines two contradicting optima: the magnetic well and the trapped particle confinement. The optimum solution was found experimentally to be an 8-cm inward-shifted magnetic axis position. It produced both the best confinement and the highest beta.

By applying various heating schemes, CHS has been producing experimental results that increased the understanding of general confinement and transport processes in helical systems. The confinement of trapped particles in low aspect ratio helical systems was studied in experiments using variable injection angle neutral beam injection (NBI) and ion cyclotron radio frequency (ICRF) heating. The plasma rotation measurements for different heating schemes revealed many types of electric field structures. These were basically understood from the neoclassical point of view, but the quantitative calculation of individual currents of ions and electrons was not consistent with the measurements for many cases.

An intensive study of magnetic fluctuations was reported for high beta plasmas. Observed fluctuation structures could be understood with magnetohydrodynamic (MHD) models that included the effect of toroidal currents. TAE-like modes have been observed in discharges with intensive NBI heating. Also, in the low shear configuration, nonresonant modes were observed which can be GAE modes driven by fast ions.

Heliotron-E

Heliotron-E introduced a new boronization technique using 2.45-GHz electron cyclotron heating (ECH) discharges with 0.045-T magnetic field. The boronization reduced light impurities and titanium. Density control was also improved with the boronization which enabled experiments with low-density and high-T_i discharges. $T_i(0)$ measured by the TV charge-exchange spectroscopy was 0.8 keV with the density 2.3×10^{19} cm^{-3}. The ion temperature profile was more peaked than in normal discharges. In these discharges the ion collisionality was in $1/\nu_e{}^{**}$ regime. The observed $\chi_{i\text{-exp}}$ deviated from the neoclassical value in the outer region. The overlapping of the ECH power on low-density NBI plasmas caused an increase of both electron and ion temperatures. E_r modification caused by the ECH can be one of the reasons for such an increase in the temperatures.

The edge turbulence was studied with Langmuir probes. The observed turbulence was very different for the inside and outside of the last closed magnetic surface, which is expected to reflect the connection length of the field lines. The limiter discharges gave the similar structure of the turbulence in the boundary plasmas. The detailed structure of stochastic magnetic field lines was studied with the two-dimensional stellarator diode method. The neoclassical effect in the diffusion of weakly ionized plasma was considered in comparisons of the experimental results and the field calculations.

TU-Heliac

TU-Heliac in Tohoku University reported the analysis of particle confinement time based on the measurement of breakdown time of ECH plasmas. Longer confinement was obtained when there was a magnetic well. The researchers also presented one analytical method of calculating heliac equilibrium.

LHD

The construction of LHD is now in its sixth year of an eight-year program. Each construction procedure is making steady progress. The first experiment is scheduled in 1997. The ECH system (168 GHz, 5–10 MW for second harmonic ECH at 3 T) is now under construction. Construction of one NBI (180 keV, 7 MW, 10 s) has also been started. The control system of LHD has been designed on the basis of the operational scenarios of various experiments. It includes 1-hour discharges, which require interactive control of the machine and the plasma.

Theoretical calculations for LHD continue. Optional configurations with different pitch parameters are obtained by using a part of conductor currents of the multilayer helical coils. MHD stability and transport were studied for these configurations. The calculations of high-beta equilibria and configurations with large bootstrap currents were made to allow more reliable planning of experiments. The detailed modeling of divertor plasmas in LHD is also under way.

Theory

The physical mechanism of the high-*n* ballooning modes in heliotron/torsatron configurations was clarified in terms of the local magnetic shear and the local magnetic curvature. In particular, the change of the local shear due to the Shafranov shift was explained by using the stellarator expansion. The possibility of the destabilization was pointed out in the basic MHD model. Judging from the properties of the high-*n* ballooning modes, the finite Larmor radius effects are very significant in their stabilization.

A new helical system called "Modular Heliotron" was proposed. It has modular coils that are compatible with an efficient closed helical divertor. This magnetic configuration concept is based on the physical design of the LHD machine and the confinement results from present heliotron devices with continuous-winding helical coils. Configuration optimization has been studied (keeping the basic properties of heliotron field with its natural helical divertor) as a function of the gap between adjacent modular coils. Ignition conditions of D-T burning plasmas in Modular Heliotron Reactors (MHRs) were also reported.

Errata

In the last issue of *Stellarator News*, the editor used the wrong name for the HSX device at the University of Wisconsin. The correct expansion of the acronym was in the article, and it is Helically Symmetric Experiment.