



# stellarator news

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## Editorial: The U.S. Stellarator Program: A Time for Renewal

There is growing recognition in the U.S., and elsewhere, that the conventional tokamak does not extrapolate to a commercially competitive energy source except with very high field coils ( $> 20$  T) or large size ( $> 1000$  GWe). This conclusion is the result of recent comprehensive tokamak reactor studies (ARIES) and an increased appreciation of the difficulty of simultaneously satisfying conflicting tokamak requirements for efficient current drive, high bootstrap-current fraction, complete avoidance of disruptions, adequate beta limits, and edge-plasma properties compatible with improved (H-mode) confinement and acceptable erosion of divertor plates. In the U.S., the result has been an intensive effort to design an experiment, the steady-state advanced tokamak (SSAT), that could explore solutions for these difficulties. In parallel, there is an ongoing re-examination of the role of alternate concepts in the U.S. fusion program.

We applaud these efforts in concept improvement. However, in addition to efforts to explore ways of improving the tokamak, U.S. program leaders should consider the need to devote adequate resources to the only concept that has performance comparable to that achieved in tokamaks without the plasma-current-related limitations listed above. The rest of the world is following this approach; vigorous stellarator programs are being pursued in Japan, Germany, Spain, Russia, Ukraine, and Australia. The LHD under construction in Japan and the W VII-X proposed by Germany are in the same class as the SSAT being considered in the U.S. Together, they should give definitive guidance in the next decade as to the best route to an attractive toroidal reactor concept.

The smaller concept improvement experiments at the University of Wisconsin [the Interchangeable Module Stellarator (IMS) and the Proto-Cleo stellarator and torsatron] and at Auburn University [the Compact Auburn Torsatron (CAT)] are an important, integrated part of the U.S. stellarator program. But the Advanced Toroidal Facility (ATF) at Oak Ridge National Laboratory, the focal point of the U.S. stellarator program, and the largest and most flexible stellarator in the world, is not being used. These experiments were purposely designed not to duplicate other experiments in the U.S. and abroad; they complement other stellarators in providing the basis for stellarator concept optimization.

ATF was designed to explore confinement improvement and higher-beta operation in the second-stability regime and to test steady-state operation under all these conditions. It complements the tests of confinement improvement due to reduction of the Pfirsch-Schlüter current (Wendelstein VII-AS) in Germany, lower aspect ratio (CHS) and higher transform and higher shear (Heliotron E) in Japan, reduced effective helical ripple (Uragan-2M) in the Ukraine, and the helical-axis "heliac" concept (H-1 in Australia and TJ-II in Spain). The flexible IMS and Proto-Cleo experiments were focused on improving our understanding of stellarator divertors, and CAT is studying the repair of broken magnetic surfaces in stellarators.

Together, this set of stellarators was pursuing a coordinated effort of stellarator concept optimization. The absence of the leading U.S. component has left a major gap in this effort. Repairing this gap does not require construction of major new facilities, only making use of existing facilities. We suggest that U.S. program leaders take advantage of this cost-effective opportunity.

James A. Rome  
Editor

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## Around the Labs

### Radial potential profile measurements in ATF

A heavy ion beam probe (HIBP) has been used to measure radial potential. Potential profiles have been obtained under a variety of conditions during ECH discharges. In Fig. 1, typical radial profiles obtained in these discharges for two different values of the volume-averaged density are shown, along with predictions of a model for the potential. The potential is measured relative to the ATF vacuum vessel. The high-density case corresponds to a line-averaged density of  $1.0 \times 10^{13} \text{ cm}^{-3}$ , while the low-density case corresponds to a line averaged density of  $5.0 \times 10^{12} \text{ cm}^{-3}$ . The trend of the measured profiles can be described as follows. At low volume-averaged densities, the potential is peaked in the center with a value of approximately 250 to 300 V above the potential at the last closed flux surface. As the density is increased, the central potential begins to drop, both in absolute magnitude and in relation to the edge potential. Finally, during the high-density ECH discharges, a small potential well begins to form.

With the experimentally measured electron density and temperature profiles, a comparison has been made to the predictions of neoclassical theory. The model used

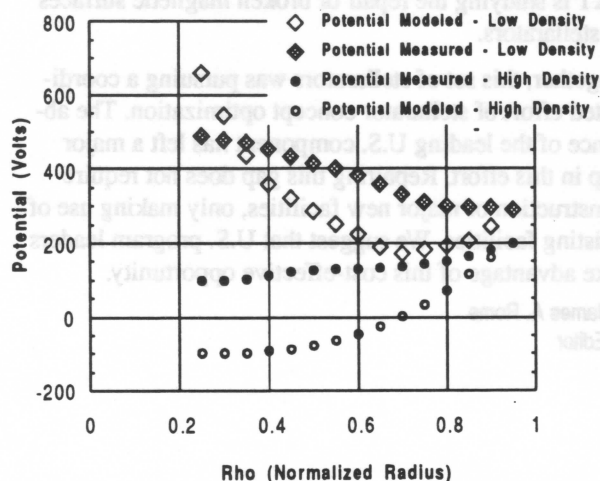


Fig. 1. Comparison of the potential profile measured by the HIBP with model predictions. The modelled profiles are normalized to the measured profiles at  $\rho = 0.95$ .

is based on that of Hastings et al. [1], where a self-consistent field is determined using an ambipolarity constraint on the nonambipolar particle fluxes. The results shown are those obtained using a three-species model in which one species is an oxygen-like impurity ion. The ion temperature and density profiles, which are also needed to perform the analysis, are obtained from the PROCTR-MOD code [2], with the central ion temperature determined from neutral particle analysis. Two features deserve emphasis. The first is that the overall trends of the measured and predicted potential profiles are in agreement, in that at low density both have a central potential higher than the edge potential, while at high density, both have a central potential less than the edge potential. However, the magnitude of the measured and predicted values can differ by a factor of two or more. This difference is well above that of the estimated uncertainty in the potential measurement of  $\pm 60 \text{ V}$ . An investigation of the sensitivity of the model predictions to uncertainties in the temperature and density (and their gradients) of each species is under way.

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### Biased limiter studies in ATF

Biasing experiments on tokamaks have been very successful in improving the global confinement parameters (H-mode-like) resulting from the setup of a radial electric field at the edge. These experiments have been extended to the current-free ATF torsatron to study and characterize effects of electric field on the plasma confinement.

The results of positive limiter biasing indicate a significant increase in the particle confinement with no improvement in the energy confinement. Experiments have been carried out in 1-T plasmas with about 400 kW of electron cyclotron heating (ECH). Two rail limiters, one at the top and one the bottom of the device, are biased at positive and negative potentials with respect to the vacuum vessel. The limiters are inserted slightly inside the internal separatrix,  $\rho = r/a \approx 1$ , where the

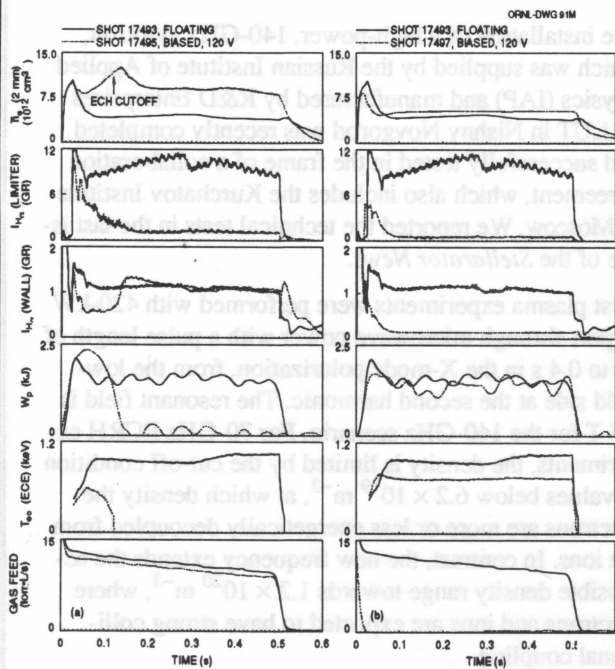


Fig. 1. The effects of biased limiters in ATF.

safety factor  $q$  is unity, compared to  $q \sim 3$  at the plasma center. Here, the limiters are considered to be electrodes for biasing because they cover only about 15% of the the last closed flux surface (LCFS), owing to their small physical size and the low  $q$  value at the LCFS. The limiters do not affect the plasma potential profile when they are floating. The plasma cross section is almost elliptical at the location of the limiters. When the limiters are positively biased at up to 300 V, the plasma density increases sharply, by about a factor of three, to the ECH cutoff density as shown in Fig. 1(a). At the same time, the  $H_{\alpha}$  radiation drops, indicating that the particle confinement improves. When the plasma density is controlled with a reduced gas feed, the  $H_{\alpha}$  radiation is further reduced, Fig. 1(b), and there is almost no change in the plasma stored energy. Under these conditions, the density profile becomes peaked, the velocity shear layer moves in radially, from  $\rho \approx 1.1$  to  $\rho \approx 1.0$ , and the electric field becomes outward-pointing outside the LCFS and more negative inside the LCFS.

The edge fluctuation levels and the resulting fluctuation-induced particle flux are reduced. One explanation for this process is that the decorrelation of the turbulence mechanism around the shear layer results in suppression of fluctuation-induced transport.

In contrast, negative biasing yields some reduction of the density and stored energy at constant gas feed. Simultaneous measurements of the plasma potential profile indicate almost no significant change with negative biasing of the limiters. Biasing causes almost no increase in the iron impurity signal from the plasma center or in the oxygen impurity signal from the edge.

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## Study of electron density fluctuations in Heliotron E by the laser-phase-contrast method

In order to investigate the relation between plasma confinement and the electron density fluctuations, a  $CO_2$  laser-phase-contrast (LPC) system [1] for measuring the density fluctuations was installed on Heliotron E.

This method has several advantages compared to the conventional scattering method based on Bragg diffraction: 1) the maximum accessible wavelength of density fluctuations is determined only by the size of the beam waist in the plasma and is independent of the wavelength of the probe beam; 2) it is simple to obtain fluctuation intensities; and 3) the dispersion relations, including the propagation direction, can be measured despite the fact that the technique is in the family of homodyne detection.

The LPC system in Heliotron E consists of a 5-W  $CO_2$  laser, transmission optics with mirrors and lenses, and detection and data acquisition instruments. A part of the optical arrangement of the LPC system near the plasma

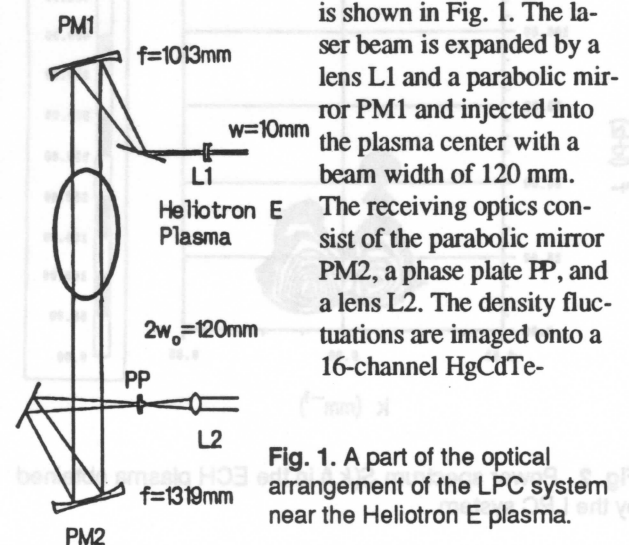


Fig. 1. A part of the optical arrangement of the LPC system near the Heliotron E plasma.

detector array cooled at 77 K. The optical system is designed to measure the density fluctuations with wave numbers of  $0.05 \leq k \text{ (mm}^{-1}\text{)} \leq 1.5$  in the plasma column  $-0.5 \leq r/a \leq 0.5$  ( $a$  is the shorter minor radius). The sensitivity and the wavelength resolution of the system were calibrated by using an ultrasonic wave, which simulated the electron density fluctuations.

Figure 2 shows an example of the power spectrum  $S(k, f)$  in the ECH plasma. The average electron density was  $1.2 \times 10^{13} \text{ cm}^{-3}$ . The spectral intensity is represented by contour lines, where fluctuations propagating toward the outboard of the torus appear in the positive- $k$  region, and those propagating to the inboard appear in the negative- $k$  region. Thus, the measured density fluctuations propagate in both directions. The frequency and the wave number are distributed from 10 kHz to 60 kHz and from  $\pm 0.05 \text{ mm}^{-1}$  to  $0.45 \text{ mm}^{-1}$ , respectively. The power spectrum  $S(k, f)$  has its maximum at  $f \approx 30 \text{ kHz}$  and  $k \approx \pm 0.19 \text{ mm}^{-1}$ . In future experiments, the probe beam width will be expanded to 200 mm in the plasma center and density fluctuations with a much longer wavelength in the edge region will be measured. This system will provide useful information for understanding plasma confinement.

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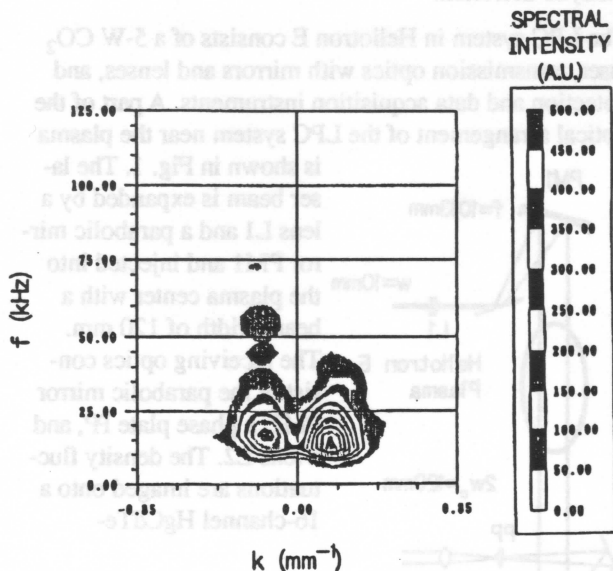


Fig. 2. Power spectrum  $S(k, f)$  in the ECH plasma obtained by the LPC system.

## First experiments with high-power, 140-GHz ECRH at W7-AS

The installation of a high-power, 140-GHz gyrotron, which was supplied by the Russian Institute of Applied Physics (IAP) and manufactured by R&D Enterprises SALUT in Nishny Novgorod was recently completed and successfully tested in the frame of a collaboration agreement, which also includes the Kurchatov Institute in Moscow. We reported the technical tests in the last issue of the *Stellarator News*.

First plasma experiments were performed with 420-kW of port-through microwave power with a pulse length of up to 0.4 s in the X-mode polarization, from the low-field side at the second harmonic. The resonant field is 2.5 T for the 140-GHz scenario. For 70-GHz ECRH experiments, the density is limited by the cut-off condition to values below  $6.2 \times 10^{19} \text{ m}^{-3}$ , at which density the electrons are more or less energetically decoupled from the ions. In contrast, the new frequency extends the accessible density range towards  $1.2 \times 10^{20} \text{ m}^{-3}$ , where electrons and ions are expected to have strong collisional coupling.

This extended parameter range is of particular interest for stellarator operation because of the favorable density scaling of the energy confinement derived from the existing W7-AS data base. Furthermore, it would allow combined heating with ECRH and NBI, which unavoidably runs at high density. Therefore, the experiments aimed at demonstrating high-density operation as close as possible to the cut-off density. Stationary discharges were maintained with a line-averaged density of  $0.9 \times 10^{20} \text{ m}^{-3}$ , indicating a broad density profile when compared to the central density of  $1.1 \times 10^{20} \text{ m}^{-3}$  measured by Thomson scattering. The observed electron and ion temperatures in the plasma center were 860 and 440 eV, respectively. For discharges with a reduced density, around  $0.5 \times 10^{20} \text{ m}^{-3}$ , the central electron temperature was 2.0 keV. Heat wave experiments with  $\pm 25$ -kW square-wave modulation of the incident microwave power were performed. The time delay and the amplitude decay across the plasma radius were measured by ECE diagnostics. A detailed analysis of the heat wave propagation is under way.

Future experiments will address electron cyclotron current drive in the extended parameter regime and combined heating with neutral beam injection.

Volker Erckmann for the W7-AS Team, IPP-Garching, and the collaborating Russian Institute of Applied Physics R&D Enterprises SALUT, Nishny Novgorod, and the Kurchatov Institute, Moscow

## LHD Construction Status

Fiscal year 1992 is the third year of LHD project. We report the present status of the construction of LHD apparatus. Our major activities are concentrated on the engineering design, research and development (R&D), and practical construction. The construction is on schedule and progressing satisfactorily.

We have almost completed the final engineering design. At the same time, we are trying to complete the necessary R&D items, especially for the superconducting coils. We have initiated fabrication of several parts of the major components. The construction of the main experimental building has also begun. Here we briefly describe the present status of each item.

### 1. Design of LHD

LHD construction is at the final stage of the engineering design phase. The LHD Design Group (LOB Group) of NIFS is responsible for R&D and engineering design based on R&D data. To start the construction of the lower part of the inner vertical field coil, the engineering design has been completed treating the coil as a stand-alone component (no interface). Construction of the winding machine for the helical coil has begun. Engineering design of the major parts (helical coils, supporting structure, etc.) is still progressing. However, it is nearing completion. Therefore, arrangements for material acquisition have begun for the necessary components. The figure shows the configuration of the structural shell for the stress analysis during engineering design.

### 2. R&D program

R&D activities on superconductors, vacuum components, power supplies, control systems, etc., are being pursued. Construction of superconducting material and a test coil has been completed, and the final liquid helium cooling tests are being performed on various test components. The Low Temperature Experiment Building was completed by the end of 1990, and the research staff is moving gradually to the new site. A test facility for developing vacuum components has been completed in the Low Temperature Experiment Building, and is in full operation. The main purposes of the R&D program are the development of advanced technology based on new ideas and positive confirmation of performance. A great deal of technical knowledge has been obtained, as expected. Significant contributions have been made, especially in the field of superconductor research where highlights include (1) development of stable large current conductor, (2) development of large magnets, (3) development of refrigeration technology, (3) clarifica-

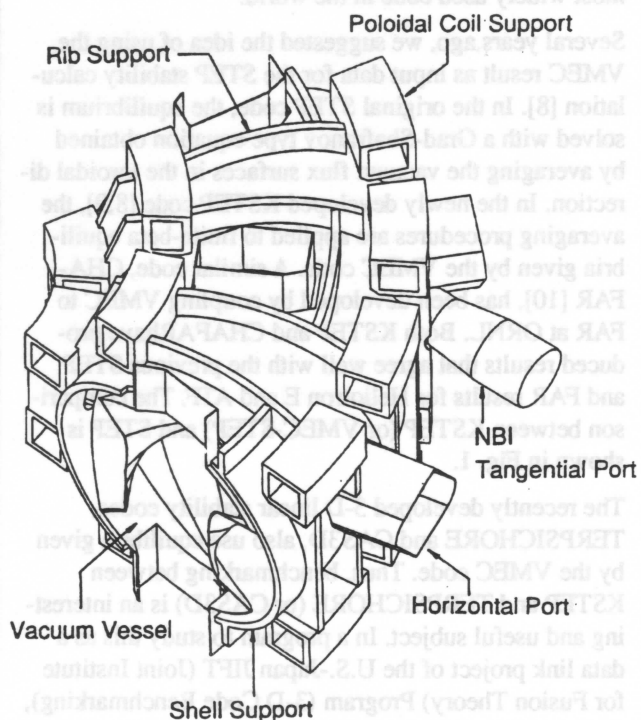
tion of superconductor characteristics, and (4) accumulation of coil control technology.

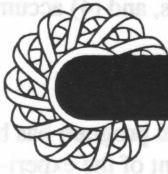
### 3. Planning of experimental program

Detailed planning of the experimental program has begun, providing for the commencement of the experiments in April 1997. The major objectives of this activity are incorporate the advanced physics understanding, improve the accuracy of predicting plasma parameters, and establishment of concrete operational scenarios. The major subjects are transport, MHD (high beta), heat and particle exhaust with divertors, confinement improvement, steady-state operation, and D-D experiments. One more important objective is to establish analysis methods for experimental data. The arrangements for the necessary components of the experiment (e.g., plasma production and control, fueling, heating, diagnostics) have begun.

Fabrication has been started on some components (PF coil, winding machine, and lower cryostat). Orders for other components (e.g., other PF coils, He liquefier, coil power supplies, cooling system) will be placed shortly. On-site fabrication and assembly are scheduled to start in April 1994.

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## Theory

### Comparison of KSTEP and TERPSICHORE codes for low- $n$ mode stability analysis of a heliotron/torsatron system

In the past ten years, many MHD numerical codes have been developed and used extensively to study the stability properties of heliotron/torsatron systems with respect to global modes. In order to survey a wide parameter space of stellarator configurations, an approach based on the stellarator expansion or the stellarator approximation has been demonstrated to be workable. Established codes include STEP [1], FAR [2], and H-ERATO [3]. More rigorous three-dimensional MHD stability analyses have been pursued, and there are several codes such as BETA [4] and the recently developed TERPSICHORE [5] and CAS3D [6] codes.

For equilibrium, three-dimensional (3-D) MHD codes are more useful than averaged equilibrium solvers for study of stellarator plasmas. Of these, VMEC [7] is the most widely used code in the world.

Several years ago, we suggested the idea of using the VMEC result as input data for the STEP stability calculation [8]. In the original STEP code, the equilibrium is solved with a Grad-Shafranov type equation obtained by averaging the vacuum flux surfaces in the toroidal direction. In the newly developed KSTEP code [8,9], the averaging procedures are applied to finite-beta equilibria given by the VMEC code. A similar code, CHAFAR [10], has been developed by coupling VMEC to FAR at ORNL. Both KSTEP and CHAFAR have produced results that agree well with the previous STEP and FAR results for Heliotron E and ATF. The comparison between KSTEP (or VMEC-STEP) and STEP is shown in Fig. 1.

The recently developed 3-D linear stability codes, TERPSICHORE and CAS3D, also use equilibria given by the VMEC code. Thus, benchmarking between KSTEP and TERPSICHORE (or CAS3D) is an interesting and useful subject. In a program to study this as a data link project of the U.S.-Japan JIFT (Joint Institute for Fusion Theory) Program (3-D Code Benchmarking), John Johnson (PPPL) visited the Plasma Physics Labo-

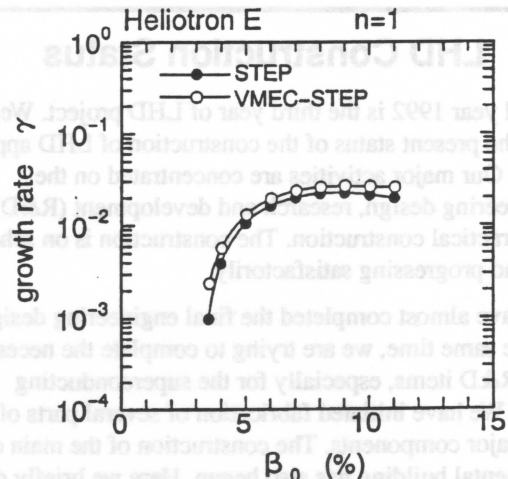


Fig. 1. The comparison between the 3-D MHD codes KSTEP (or VMEC-STEP) and STEP.

ratory, Kyoto University, in March 1992. The TERPSICHORE results are being calculated by David Anderson of NERSC, LLNL. We think that the comparison will provide validation for the codes and will clarify the role of 3-D effects on low- $n$  mode stability in heliotron/torsatrons. We would like to extend the benchmarking study to other codes (H-ERATO, CAS3D, CHAFAR, the Russian MHD Stability codes at Kurchatov Institute, etc.). We invite anyone interested in collaborating on this project to contact one of the authors.

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## Neoclassical Current and MHD Stability with Net Toroidal Current

The construction of the Large Helical Device (LHD) has been started and extensive physics calculations have been done to explore the confinement characteristics of the LHD plasma. Recent theory activities concerning the LHD and helical systems in the National Institute for Fusion Science (NIFS) are as follows:

- ➔ Neoclassical theories for the parallel flow, current, and rotation have been extended to a multispecies plasma in general toroidal systems to investigate the bootstrap current, poloidal and toroidal plasma rotations, and the effect of the external momentum source in a heliotron/torsatron.
- ➔ Data analyses have been carried out for the radial electric field structure and the rotations observed in the Compact Helical System (CHS).
- ➔ Ripple diffusion in the LHD plasma has been calculated by the DKES code [1], and the transport code has been used to predict the plasma parameters for the LHD.
- ➔ Three dimensional equilibria have been solved by the VMEC code [2] by consistently taking into account the neoclassical current to estimate the bootstrap current in the LHD plasma.
- ➔ Computer codes for the MHD equilibrium and stability, H-APOLLO, H-ERATO, KSTEP, and RESORM, have been further developed. The effect of the net toroidal current on the ideal MHD stability has been investigated.
- ➔ In connection with the toroidal Alfvén eigen mode (TAE) in tokamaks, high- $n$ , helicity-induced shear Alfvén eigenmodes (HAE) have been considered both analytically and numerically for a low-beta straight helical system.
- ➔ A sophisticated 3-D MHD equilibrium code, HINT has yielded useful results for breaking of magnetic surfaces and island formation.
- ➔ Nonlinear behavior and transport properties of the resistive interchange mode have been investigated.
- ➔ A  $K$ - $\epsilon$  transport model has been proposed for the resistive interchange mode turbulence, in which the turbulent transport is determined not locally but globally.
- ➔ The effect of transport on the resistive interchange mode and the resultant beta limit have been studied.
- ➔ Monte Carlo simulation codes have been developed for NBI and ICRF heating to examine heat deposition and heating efficiency.

- ➔ The field structure of the scrape-off layer and divertor region in the LHD has been clarified. It has now been shown that all the energetic particles escaping out of the outermost flux surface reach the divertor region in the LHD configuration, in contrast to the tokamak case.

From among these recent activities, we report some results from the studies for the neoclassical current and the local ideal MHD stability with net toroidal current.

Neoclassical theories for parallel flow have been extended to a multispecies plasma in general toroidal systems, in which each species can lie in a different collisionality regime [3]. As a result, for a simple plasma consisting of electrons and a single ion species, the bootstrap current is given by

$$\langle BJ_{\parallel} \rangle = L_{11} \langle G_{BS} \rangle_e \left( \frac{dP_e}{d\psi} + n_e E_{\psi} \right) + L_{11} \langle G_{BS} \rangle_i \left( \frac{dP_i}{d\psi} + n_e E_{\psi} \right) - L_{12} \langle G_{BS} \rangle_e n_e \frac{dT_e}{d\psi}$$

where  $\langle G_{BS} \rangle_{e,i}$  and  $E_{\psi}$  are the geometric factor and the radial electric field, respectively. In axisymmetric systems the geometric factor is independent of the collisionality ( $\langle G_{BS} \rangle_e = \langle G_{BS} \rangle_i$ ) and the current proportional to  $E_{\psi}$  vanishes. This is the direct result from symmetry, the momentum conservation of friction forces, and charge neutrality. On the other hand, in non-axisymmetric systems, because the geometric factor depends on the collisionality the current directly generated by  $E_{\psi}$  exists if  $v_e^* \neq v_i^*$  ( $\langle G_{BS} \rangle_e \neq \langle G_{BS} \rangle_i$ ).

This newly found current can be comparable with the pressure-driven current since  $e\phi \gtrsim T$  ( $E_{\psi} = -d\phi/d\psi$ ). In the region where  $|\langle G_{BS} \rangle_{e,i}|$  increases as  $v_{e,i}^*$  decreases, if  $v_e^* < v_i^*$ , then  $|\langle G_{BS} \rangle_e| > |\langle G_{BS} \rangle_i|$  and  $E_{\psi} > 0$  would be realized according to the neoclassical theory. In this situation, the first term with  $\langle G_{BS} \rangle_e$  dominates and the current proportional to  $E_{\psi}$  tends to cancel the conventional pressure-driven current. In the opposite case of  $v_e^* > v_i^*$ , where  $|\langle G_{BS} \rangle_e| < |\langle G_{BS} \rangle_i|$  and  $E_{\psi} < 0$ , the resultant current would also be reduced. If  $|E_{\psi}|$  is large enough we can even expect an inverted bootstrap current in a heliotron/torsatron. Careful estimation of the bootstrap current in LHD is under investigation taking into account the 3-D equilibrium self-consistently.

The extended neoclassical theory has been applied to the poloidal and toroidal rotation in a plasma consisting of electrons, ions, and impurity ions in the Pfirsch-Schlüter regime [4]. It has been found that the differences between bulk ions and impurities come from the different diamagnetic flows and the ion temperature gra-

dient in the  $1/\nu$  regime, but depend strongly on the field structure in the heliotron/torsatron. For the experimental parameters of CHS the differences are small and on the order of the bulk ion diamagnetic flow.

The currentless condition is often violated by a net toroidal current such as the bootstrap current. We have considered the effects of a net toroidal current on the Mercier criterion by systematically using the 3-D VMEC equilibrium code [5]. As an example, we take the standard configuration of LHD, where  $R = 3.9$  m,  $B = 3$  T,  $\gamma_c = 1.25$  ( $\gamma_c$  is the pitch parameter of the helical coils),  $\alpha = 0.1$  ( $\alpha$  is the pitch modulation parameter),  $\Delta_{\text{axis}} = -15$  cm ( $\Delta_{\text{axis}}$  is the magnetic axis shift in the vacuum field), and the toroidally averaged magnetic surfaces are nearly circular. We have found second stability for the currentless equilibrium with a pressure profile of  $P = P_0(1 - \Phi_T)^2$ , where  $\Phi_T$  is the toroidal flux. The unstable region is so small that the growth rates of low- $n$  interchange modes are expected to be very small.

The additive current, which increases the central rotational transform  $\bar{i}_0^y$  and makes the magnetic well shallow in the vacuum field, is unfavorable to the MHD stability. On the other hand, the subtractive current decreasing  $\bar{i}_0^y$  allows the large Shafranov shift to extend the well region and makes the shear strong near the edge as  $\beta$  increases. Thus the subtractive current improves the MHD stability against interchange modes. For the same pressure profile as in the above currentless case the additive current of 50 kA [the current density is  $J = J_0(1 - \Phi_T)^2$ ] extends the unstable Mercier region, but second stability persists for  $\beta \geq 3\%$ . The subtractive current of 50 kA can stabilize the plasma completely against Mercier instabilities; hence, the configuration is stable to ideal low- $n$  interchange modes. Analyses of ballooning modes and current-driven modes are under investigation.

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## Neoclassical Current and MHD Stability with Net Toroidal Current

The construction of the Large Helical Device (LHD) has been started and extensive physics calculations have been done to explore the confinement characteristics of the LHD plasma. Recent theory activities concerning the LHD and helical systems in the National Institute for Fusion Science (NIFS) are as follows:

- Neoclassical theories for the parallel flow, current, and rotation have been extended to a multipeaked plasma in general toroidal systems to investigate the bootstrap current, poloidal and toroidal plasma rotations, and the effect of the external momentum source in a heliotron/torsatron.
- Data analyses have been carried out for the radial electric field structure and the rotation observed in the Compact Helical System (CHS).
- Ripple diffusion in the LHD plasma has been calculated by the DKES code [1] and the transport code has been used to predict the plasma parameters for the LHD.
- Three-dimensional equilibria have been solved by the VMEC code [2] by consistently taking into account the neoclassical current to estimate the bootstrap current in the LHD plasma.
- Computer codes for the MHD equilibrium and stability, H-APOLLO, H-ERATO, K-STER, and H-ER-SORM, have been further developed. The effect of the net toroidal current on the ideal MHD stability has been investigated.
- In connection with the toroidal Alfvén eigenmode (TAE) in tokamak, high- $n$  helicity-induced shear Alfvén eigenmodes (HAEL) have been considered both analytically and numerically for a low-beta straight helical system.
- A sophisticated 3-D MHD equilibrium code, HINT, has yielded useful results for the study of magnetic surfaces and island formation.
- Nonlinear behavior and transport properties of the resistive interchange mode have been investigated.
- A  $K$ -transport model has been proposed for the resistive interchange mode turbulence, in which the turbulent transport is determined not locally but globally.
- The effect of transport on the resistive interchange mode and the resultant beta limit have been studied.
- Monte Carlo simulation codes have been developed for NBI and ICRF heating to examine heat deposition and heating efficiency.