stellarator news

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Greifswald Branch of IPP moves into new building

In early April, about 120 employees of the Max-Planck-Institut für Plasmaphysik (IPP), Greifswald Branch, moved into their new building on the outskirts of the old university town. Up to this time the staff of the Stellarator Theory, Wendelstein 7-X Construction, and Experimental Plasma Physics divisions as well as Administration, Technical Services, and the Computer Center had worked in rented offices at two different locations. Now everybody works under one roof — a roof in the shape of a wave (see Fig. 1), symbolizing the waves on the Baltic Sea.

About 300 persons will work in this new branch institute by the start of the Wendelstein 7-X (W7-X) experiment, scheduled for 2006. This experiment is the successor to the W7-AS stellarator in Garching, with a goal of demonstrating that the advanced stellarator concept, developed at IPP, is suitable as a fusion reactor. Even before W7-X has its first plasma, a smaller, classical stellarator will run in Greifswald. The WEGA device will be reactivated at IPP Greifswald to train the students of the Ernst Moritz Arndt University in Greifswald from the next term on.

Fig. 1. The new IPP Greifswald building with its distinctive roof in the shape of a wave is one of the first sights of Greifswald when arriving from the south by train.

Fig. 2. After unpacking their boxes, the staff of IPP Greifswald gathered on the galleries above the institute's "main road" for an informal opening ceremony on 3 April 2000.

In this issue . . .

The official opening of the institute will take place on 7 July 2000 in the presence of many guests from Germany and all over Europe.

About one month earlier, on 5 June 2000, one of the more than 700 Worldwide Projects of the World Exposition EXPO 2000 will officially start at IPP Greifswald. Under the motto "Vision Fusion—Competence for energy in Greifswald-Lubmin area," the new building, the construction of the device, the technology, and the workshops of the institute will be shown to the public. Visitors will be able to get information on fusion research in general and on the importance of the energy question for the future by walking through our Fusion Exhibition with its numerous information boards and mock-ups. Guided tours of the Institute are planned on Tuesdays at 10 a.m. and on Thursdays at 2 p.m. Welcome to our new site!

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The proposed Compact Toroidal Hybrid experiment

A new stellarator experiment, the Compact Toroidal Hybrid (CTH), has recently been proposed to the U.S. Department of Energy as an innovative confinement concept. The new device is a highly flexible, low-aspect-ratio stellarator in which a substantial fraction of the rotational transform will be provided by Ohmic plasma current. The primary goal of this work is to develop a better understanding of current-driven instabilities and the potential for disruptions in current-carrying stellarator plasmas.

Interest in current-driven MHD instabilities in stellarators has grown in recent years because it is recognized that high-performance, finite-beta stellarators are generally not current-free because of pressure-driven currents. For example, the Large Helical Device (LHD) has been predicted to be unstable to bootstrap current–driven kinks near $\langle\beta\rangle = 2\%$ [1]. Although these currents can be minimized in configurations such as that of W7-X, the bootstrap and Pfirsch-Schlüter currents generally cannot be reduced to negligible levels in low-aspect-ratio stellarators with optimized confinement. In particular, the bootstrap current in quasi-axisymmetric stellarators such as the National Compact Stellarator Experiment (NCSX) [2] under development at PPPL is predicted to be comparable to that in an equivalent tokamak configuration. On the positive side, the bootstrap current can be used to good advantage because, depending on the Boozer spectrum of the magnetic configuration, it can produce a significant fraction of the required rotational transform, thus allowing compact stellarators to be designed with simpler coil configurations. Since coil complexity and high aspect ratio are considered by many to be drawbacks to the stellarator, their reduction represents a substantial improvement to the stellarator concept. Furthermore, the non-axisymmetric vacuum helical field of the stellarator provides a measure of control over current-driven MHD instabilities through external control of the rotational transform profile and the local magnetic curvature of the plasma, and it may also alleviate the effect of current disruptions in toroidal plasmas. Nevertheless, the presence of pressure-driven or externally driven current in a stellarator could, if the device is not properly designed and operated, lead to fatal current-driven instabilities and disruptions, as in any toroidal device.

Experience with current-driven instabilities in stellarator plasmas dates from the Model C stellarator [3]. Current-driven disruptions were observed in the shearless JIPP T-2 [4] and W7-A [5] stellarators, but major disruptions could be suppressed in these devices when the vacuum rotational transform ι_0 was raised above 0.14. The addition of the helical stellarator field was found to convey a measure of gross stability to the current-carrying plasma column. In more recent stellarator experiments, small amounts of Ohmic current (on the order of 10 kA) are introduced to globally cancel the bootstrap current in plasmas with average beta in the range 1–2% and restore a good equilibrium for optimal confinement. With Ohmic currents above this level, new experiments on W7-AS have shown that, depending on the ramp rate of the plasma current, major disruptions associated with internal tearing modes can occur with as little as 40% of the total rotational transform provided by the plasma current [6]. These studies provide a strong motivation for this proposal as they clearly demonstrate that stellarator disruptions are possible even at high fractions of external field.

This new experimental study is planned for a new stellarator to be built in the existing Compact Auburn Torsatron (CAT) [7] laboratory located at Auburn University. On the new CTH device, we will perform the following program:

- Investigate the MHD stability of Ohmic currents in a compact stellarator plasma over a wide range of magnetic field configurations.
- Measure the stability of both peaked and transiently hollow, bootstrap-like current profiles.
- Measure the onset and growth of current-driven tearing, kink, and vertical instabilities as a function of plasma current, vacuum rotational transform, and plasma elongation in low-beta plasmas.
- Measure the rotational transform profiles using a

Table 1. Parameters of the CAT experiment and the expected parameters of CTH.

Parameter	CAT	CTH
Major radius (m)	0.53	0.75
Vessel minor radius (m)	0.18	0.30
Average plasma radius (m)	0.10	0.19
Magnetic field (T)	0.1	0.5
Density (m^{-3})	7×10^{15}	$(0.5–1) \times 10^{19}$
Avg. electron temp. (eV)	10	325
Ion temperature (eV)	0.5	≤50
Plasma current (kA)	0	0–60
Input power (kW)	2 (ECH)	100 (OH); 200–250 (ICRF)
Pulse duration (s)	120	0.4 (magnets); 0.1 with OH
Edge transform	0.15–0.7	0.15–0.5 (vac); + 0–0.5 (OH)
Plasma beta (%)	~0	≤0.5

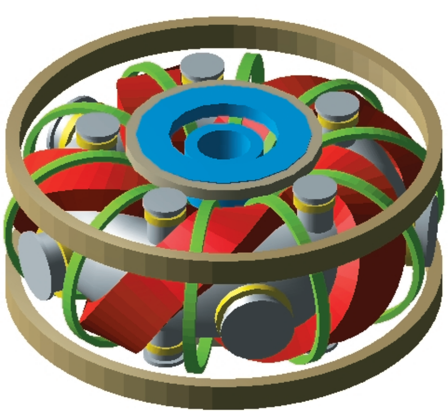
novel application of the motional Stark effect (MSE) that makes use of laser-induced fluorescence (LIF). This diagnostic will enable a definitive comparison of experimental results and three-dimensional (3-D) stability theory evaluated with the TERPSICHORE code.

➠ Determine the conditions for stellarator disruptions and assess their severity—to what extent can a disrupted discharge recover?

These studies will be carried out using Ohmically-driven current in a flexible but relatively simple concept exploration level stellarator. The CTH stellarator design has been developed from Auburn's low-aspect-ratio ($A_p = 5$) CAT stellarator. To obtain greater flexibility in the variety of current profiles to be used in the stability studies, the CTH plasma has a minimum aspect ratio of $A_p = 4$. As in CAT, the vacuum rotational transform of the CTH plasma can be varied by a factor of two or more. Stability studies will be carried out with centrally peaked current profiles and with transiently hollow bootstrap-current-like profiles that are particularly relevant to high-beta stellarator operation. Broad and/or hollow profiles will be created by ramping the Ohmic current into an existing plasma, taking advantage of the finite penetration time of the current, and by rapidly reversing the Ohmic current. The investigations will make use of a novel MSE diagnostic under development by Levinton [8] to measure the rotational transform profile in low magnetic field discharges using LIF.

This project was first explored with the idea that the existing CAT device could be upgraded for higher field and Ohmic operation because the flexibility and moderate shear of the rotational transform of the CAT configuration are well suited for this study. However, an analysis by members of the Princeton Plasma Physics Laboratory (PPPL) staff revealed a number of engineering and physics constraints that appear to make the use of the CAT platform infeasible.

Accordingly, we will construct a new core that will keep the inherent flexibility and simplicity of CAT. The parameters of the new device are compared with those of CAT in Table 1. As in CAT, the main helical field is produced by a helical coil with a poloidal periodicity $\ell = 2$ and a toroidal



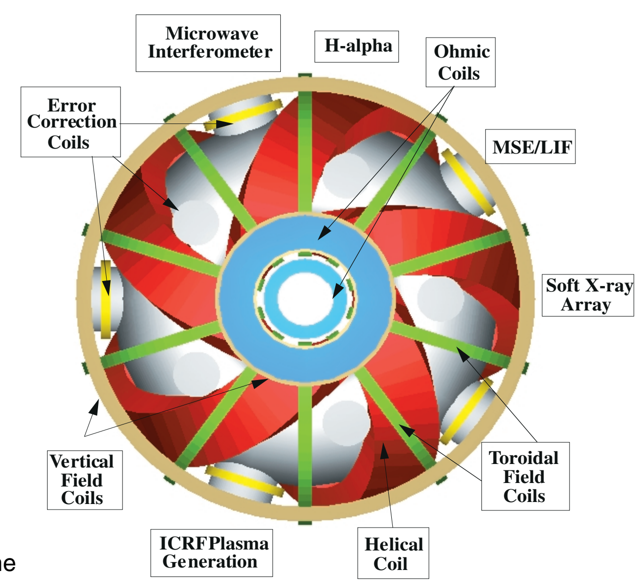


Fig. 1. The Compact Toroidal Hybrid device. At left is an isometric view of CTH. The diagram on the right shows the main coil systems and diagnostics.

Fig. 2. Exploded view of the support structure for the $\ell = 2$ coil.

periodicity $M = 5$. The CTH device is shown in Fig. 1, and its key features are summarized in Table 1.

1. The CTH plasma will have a minimum aspect ratio A_p of 4 and a major radius of 0.75 m, increasing the average minor radius of CAT by 70%. The one-piece CTH vacuum vessel will have a circular cross section and standard circular metal-gasket ports, which makes the design and construction relatively simple and inexpensive for a stellarator.
2. The $\ell = 2$ helical coil of CTH will be wound into cast aluminum helical troughs. A preliminary design of the troughs has been developed by the PPPL engineering staff and is illustrated in Fig. 2. Using cast supports (1) allows for greater winding accuracy than was achieved on CAT and (2) provides sufficient structural support for the coils that the vacuum vessel need not be used as a support or winding guide. The five-fold increase in magnetic field capability of CTH is provided by ten 1-MJ flywheel motor generators recently transferred from the Massachusetts Institute of Technology and the University of Wisconsin.
3. A capacitor bank–driven, double-swung Ohmic heating transformer will provide the plasma current. In addition to the vertical field coils needed for plasma equilibrium, a set of quadrupole field coils will be used to vary plasma elongation and central rotational transform. A set of ten simple toroidal field coils will be used to adjust the global rotational transform.
4. Plasma breakdown and heating will be performed with nonresonant ion cyclotron resonant frequency (ICRF) making use of a 250-kW, 5 to 10-MHz amplifier recently constructed on site, powered by high-voltage supplies and capacitors transferred from Lawrence Livermore National Laboratory. Because the plasma will be generated with ICRF, there is no need of an electric break for rapid Ohmic heating flux penetration to break down the plasma.
5. On CTH, we expect that islands $m/n = 3/2, 2/1, 3/1$, and 4/1 may play a role in stability based on the rotational transform profiles that will be achieved both with and without plasma current. Accordingly, we plan to install a set of at least 15 small circular correction coils to control the size of the magnetic island as needed.

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Book announcement

Half of Vol. 21 of *Reviews of Plasma Physics* is a review of the MHD theory of plasma equilibrium in stellarators by Vladimir D. Pustovitov. Information about the book can be found at
http://www.wkap.nl./book.htm/0-306-11064-4

Energetic beam ion transport in LHD

The behavior of trapped particles in heliotrons is complicated by the relatively large orbit size in the radial direction. Radial motion of trapped particles can enhance the radial transport of energetic ions because of (neoclassical) diffusion and also because of the direct convective transport by ∇B drift of ripple-trapped particles. In thermal plasmas, the diffusive effects dominate. Thus, ripple-induced transport is an important issue for the confinement of energetic ions in heliotrons.

In order to study the energetic ion behavior experimentally, fast neutral particle analysis using a natural diamond detector (NDD) [1] has been applied to measure the distributions of energetic beam ions generated by neutral beam injection (NBI) heating in the Large Helical Device (LHD). Figure 1 shows a schematic view of the tangential NDD device configured to measure counter-injected beam ions. The NDD device has the advantage of a nearly continuous energy spectrum, which makes it easier to compare the experiment with simulation results. We set the NDD line angle so that it is almost parallel to the magnetic field line at the plasma center and up to 40° at the plasma edge.

Figure 2 shows the count number measured by the NDD for two different time periods during a discharge in LHD (the standard configuration; R_{ax} = 3.75 m). In this discharge the plasma density increases to 1.5×10^{19} m^{-3} and then decreases to 0.7×10^{19} m^{-3}. The beam (E_b = 100 keV) was tangentially injected and slows down to the thermal energy. We can see a nearly linear increase of count number as the energy decreases in the higher density case. On the other hand, saturation of the count number is found as energy decreases in the lower density case. The dashed lines show the prediction of a two-dimensional (2-D) Fokker-Planck simulation, where no radial transport effect on beam ions is taken into account. We can see large differences between the experimental and the 2-D simulation results below about 40 keV.

Several explanations for the difference in count number can be considered; these include anomalous transport, strong charge-exchange effects, etc. Among them, radial transport due to the helically-trapped particles is a plausible cause. To clarify this point we study the ripple-induced transport of energetic ions using the GNET code [2], where the drift kinetic equation in 5-D phase space is solved in the LHD plasma with the initial condition $f(\boldsymbol{x}, v_{\parallel}, v_{\perp}; t = 0) = 0$ as

$$\frac{\partial f}{\partial t} + (\boldsymbol{v}_d + \boldsymbol{v}_{\parallel}) \cdot \frac{\partial f}{\partial \boldsymbol{x}} + \dot{\boldsymbol{v}} \cdot \frac{\partial f}{\partial \boldsymbol{v}} - C^{\text{coll}}(f) = S^{\text{NBI}}(\boldsymbol{x}, v_{\parallel}, v_{\perp}),$$

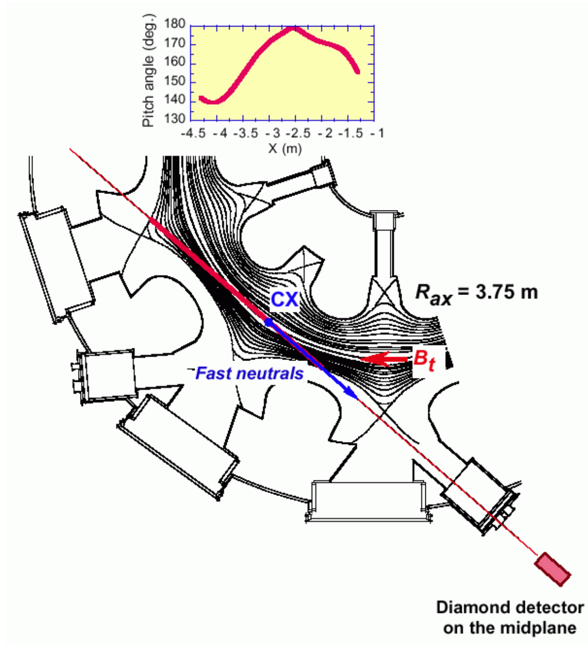

Fig. 1. Schematic view of the NDD tangential device and the line of sight.

where $\boldsymbol{v}_d$ is the drift velocity and $\boldsymbol{v}_{\parallel}$ (= $v_{\parallel}\hat{\boldsymbol{b}}$) is the parallel velocity. The acceleration term $\dot{\boldsymbol{v}} = (\dot{v}_{\parallel}, \dot{v}_{\perp})$ is given by the conservation of magnetic moment and total energy, and C^{coll} and S^{NBI} are the collision operator and the heating source term for NBI heating, which are evaluated by the HFREYA code [3] assuming a beam energy of 100 keV.

Figure 3 shows the steady-state slowing-down distribution with the NBI beam source obtained by the GNET code in the3-D space (r/a, v, θ_p), where r/a, v, and θ_p are the average minor radius, the total velocity and the pitch angle, respectively. The density, n is $n(r) = n_0[1 - (r/a)^8]$ with n_0 = 1.0×10^{19} m^{-3}, and the ion and electron temperatures are $T_e(r) = T_i(r) = T_{e0}[1 - (r/a)^2]$ with T_{e0} = 1.6 keV. The magnetic field strength is set to 1.5 T. The NBI heating and plasma parameters are assumed based on the parameters of the lower density case in Fig. 1. The beam ions slow down on electrons in the high-velocity region ($v \sim 11v_{th0}$) and slow down to the thermal velocity. When the beam ion reaches the critical velocity (about 5 times thermal velocity), pitch-angle scattering takes place via collisions with background ions, and the beam ion distribution spreads toward the higher pitch angle region (upper side). We can see the decrease of the distribution due to ripple-induced diffusion at the radial region, $r/a > 0.6$, where the fraction of helically trapped particles becomes large. We can also see the deficit in the distribution in the trapped particle region ($\theta_p \sim \pi/2$) near the edge region caused by the direct convective transport of helically trapped particles to the outside of the plasma. Because of lower collisionality, the decrease in the distribution is clearer in the

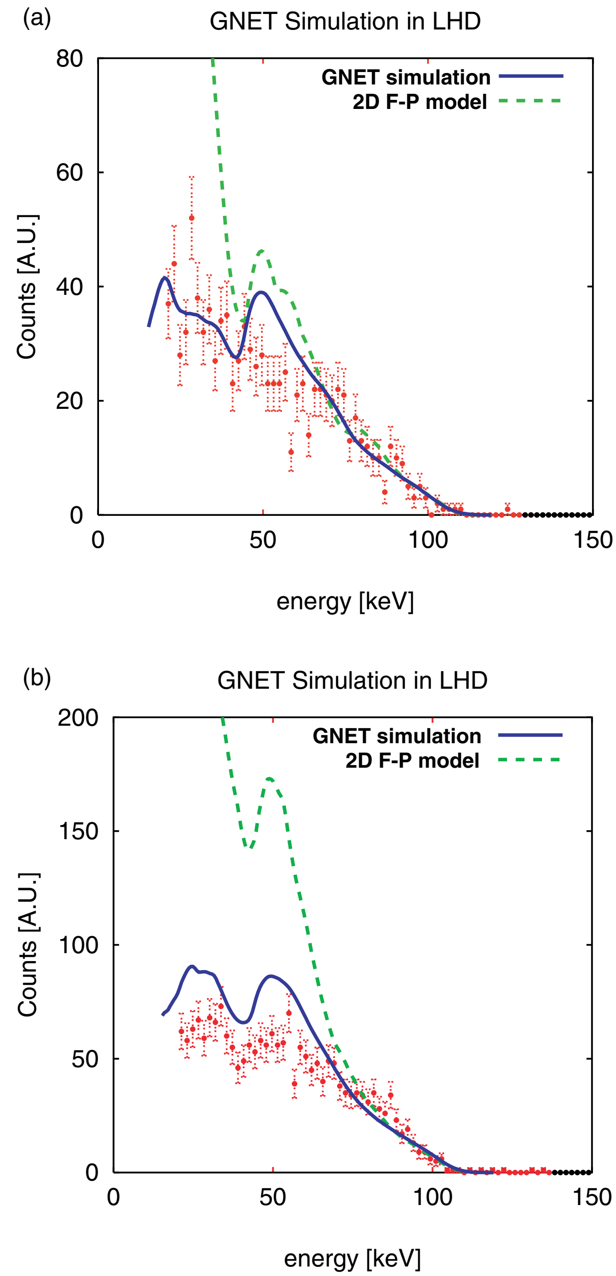

Fig. 2. Plots of the NDD count number with error bars for two different densities in LHD: (a) 1.5 $\times 10^{19}$ m^{-3} and (b) 0.7 $\times 10^{19}$ m^{-3}. The dashed (green) and solid (blue) lines show the predictions of a 2-D Fokker-Planck calculation and the simulated NDD count number using the GNET results, respectively.

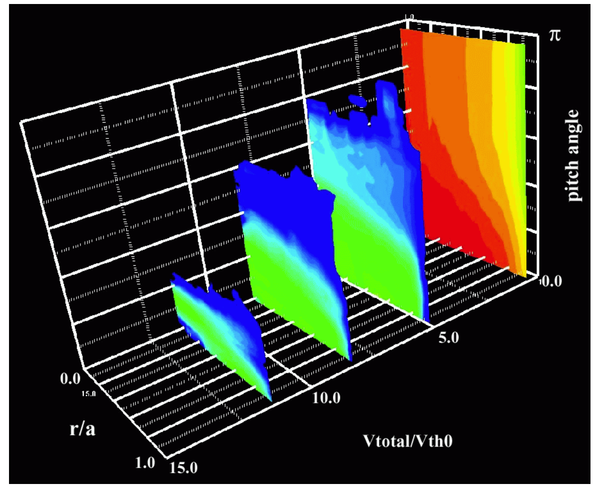

Fig. 3. Contour plots of the energetic ion distribution in (r/a, v, θ_p) coordinates in the LHD plasma (lower density case).

lower density case than in the higher density case. These results indicate the significant role of ripple-induced transport in the energetic ion confinement in LHD.

Using the distribution obtained by the GNET code we have evaluated the number of neutral particles detected by the NDD (Fig. 2). We can see a clear decrease of count number due to the ripple-induced transport from the 2-D Fokker-Planck results in both density cases. A similar saturation due to the larger ripple-induced transport is found in the lower density case. Consequently, we obtain relatively good agreement in both density cases, and this indicates the important role of ripple-induced transport in the radial transport process in the LHD.

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