stellarator news

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Editor's Message

The *Stellarator News* is entering its third year of publication. The *Stellarator News* is now an important source of timely information for the international fusion community. I wish to thank all of the contributors to this newsletter and to urge your continued support.

In particular, I would like to single out Bonnie Nestor of Oak Ridge National Laboratory for her help in editing this newsletter. I obtain the articles and do the desktop publishing operations. Bonnie does the difficult job of correcting the English, making meanings clear, and ensuring that the style and tone of the *Stellarator News* are maintained. My secretary, Dorothy Tate, efficiently provides any needed typing and maintains the mailing list.

James A. Rome, Editor

Around the Labs

Fluctuation studies on ATF: Microwave scattering collaboration with the USSR and related experiments

A principal goal of the ATF experiments in 1991 was the study of turbulent fluctuations in long-pulse (1 to 30-s), low-collisionality ECH discharges [$\bar{n}_e \sim (4–7) \times 10^{12}$ cm^{-3}, $T_{e0} \sim 1$ keV]. These plasmas are macroscopically quiet but exhibit anomalous outward transport very much like that seen in tokamaks (gyro-Bohm-like scaling), suggesting that the underlying transport mechanisms in the two types of toroidal plasmas are similar. The flexible magnetic configuration of ATF makes it possible to change properties—rotational transform, magnetic well, shear, trapped particle confinement—that are expected to influence turbulence even within a single shot.

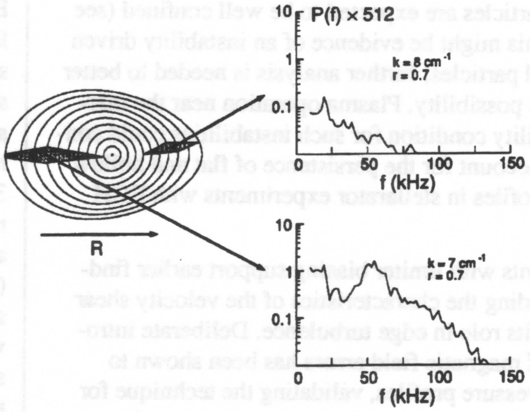

Fig. 1. Density fluctuation spectra in ATF as measured by 2-mm scattering for regions inside and outside the major axis.

Numerous fluctuation diagnostics have been developed and installed on ATF as long-term collaborations with other institutions. These include a heavy-ion beam probe (Rensselaer Polytechnic Institute), a microwave reflectometer (Georgia Institute of Technology and CIEMAT, Madrid), a reciprocating Langmuir probe (CIEMAT, Madrid, and the University of Texas), and, most recently, a 2-mm microwave scattering diagnostic (General Physics Institute, Moscow). Together, these diagnostics make it possible to measure fluctuation amplitudes and other characteristics from the core of the plasma to the edge.

During the 1991 operating period, fluctuation data from the various diagnostics have been combined to yield a picture of the turbulence as a function of radius which can be compared with some theoretical concepts. In the gradient region, $0.7 \le r/a \le 0.9$, the fluctuations most resemble resistive interchange turbulence driven by the unfavorable average magnetic curvature; single-shot

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configuration variations indicate that this region governs the overall energy confinement in ATF. In the plasma core, preliminary examination of the features revealed by the 2-mm scattering measurements suggests the presence of trapped-particle effects like those expected from trapped-electron instabilities. Specifically, the density fluctuation amplitude is larger on the small major radius side of the torus, where the helically trapped particles are expected to be well confined (see Fig. 1). This might be evidence of an instability driven by trapped particles; further analysis is needed to better gauge this possibility. Plasma operation near the marginal stability condition for such instabilities could conceivably account for the persistence of flat and hollow density profiles in stellarator experiments with ECH alone.

Experiments with limiter biasing support earlier findings regarding the characteristics of the velocity shear layer and its role in edge turbulence. Deliberate introduction of magnetic field errors has been shown to steepen pressure profiles, validating the technique for accessing the second-stability regime that was demonstrated in early ATF experiments.

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ATF operations

ATF resumed operation on September 25, 1991, after temporary repair of the helical coil joints damaged in the May flashover. There followed a successful operating period that ended with a scheduled shutdown on November 15. A modest level of effort has begun toward full repair of the coil joints. Significant accomplishments in this operating period include (1) data acquisition for numerous plasma configurations with the 2-mm scattering diagnostic developed and applied in collaboration with the U.S.S.R. (see the accompanying article by J. H. Harris); (2) a proof-of-principle test of the ORNL Physics Division's alpha-particle diagnostic that yielded positive results (see the accompanying article by D. P. Hutchinson et al.); (3) discharge durations of 20.2 s (a new record for ATF) using second harmonic heating with 35-GHz microwave power in collaboration with Japan; and (4) extension of dimensionless scaling experiments, as discussed below.

New experiments in ATF were aimed at gaining a better understanding of the global behavior of the energy confinement time (τ_E*). As in experiments done in DIII-D, JET, and TFTR, we can study specific discharges in which extrinsic variables (density, magnetic field, heating power) are varied together in a way that keeps dimensionless variables of plasma physics (beta, ν*, etc.) fixed. The residual behavior of τ_E* can then shed light on underlying mechanisms for anomalous energy transport. Earlier regression analyses [1] of τ_E* in NBI and ECH plasmas suggested that the gyro-reduced Bohm scaling was followed more closely than the Bohm-like scaling, although discrimination was not strong. The present experiments consisted of two stages, the first with stationary discharges and the second with modulation. The first stage of the experiments utilized second-harmonic ECH with the 53- and 35-GHz gyrotrons. When the magnetic field was reduced from 0.96 T to 0.64 T while keeping the average beta and ν* nearly constant, the stored energy (W_{dia}) changed from 2.04 to 0.84 kJ. The ratio of the stored energies at the two values of B is 2.4 ± 0.1 which compares more favorably with the gyro-Bohm scaling prediction (2.3) than the Bohm scaling prediction (2.0). The second experiment was aimed at sensitive measurement of the residual dependence of τ_E* on beta and ν*. In a single pair of ECH discharges, the plasma density and ECH power were sinusoidally modulated in a specific way such that $\tilde{n}/n = -(2/3)\,\tilde{P}/P$ for one discharge (with fixed beta) and $\tilde{n}/n = (4/9)\tilde{P}/P$ for

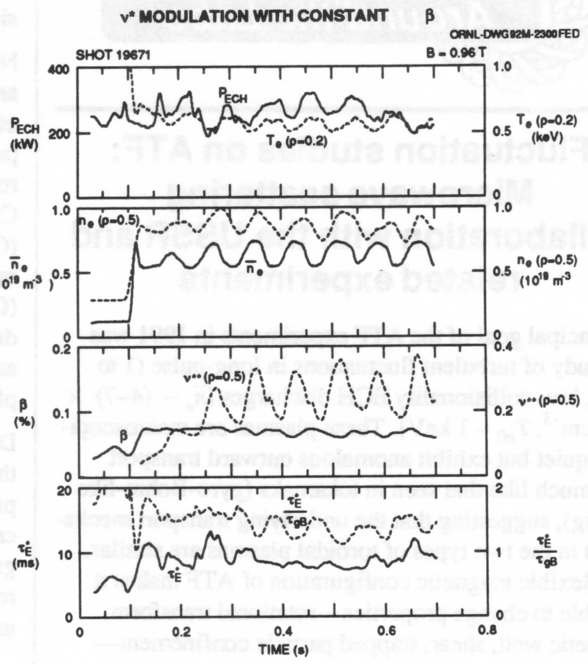

Fig. 1. ATF parameters when ν* is modulated holding beta constant.

the other (with fixed ν*) based on the gyro-Bohm scaling. Figure 1 shows the plasma response in the first case (ν* modulation with constant beta). Fourier analysis with the known modulation frequency (12.5 Hz) yields amplitude and phase relationships among various plasma parameters. The results indicate that the correction to the gyro-Bohm scaling is fairly small ($\tau_E/\tau_{gB} = \nu^{\alpha}\beta^{\gamma}$, where $\alpha \approx -0.2$ and $\gamma \approx 0.3$). By combining these results with the external control of the magnetic configuration (shear, well/hill, etc.),it may be possible to establish the overall dependence of turbulence responsible for anomalous transport.

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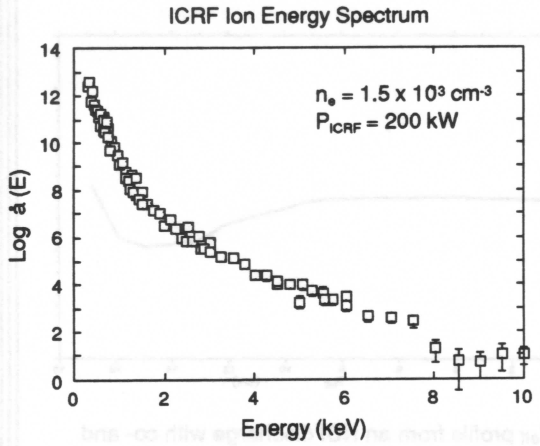
[1]. R. A. Dory et al., Comments Plasma Phys. Controlled Fusion **14**, 237 (1991).

Experiments in CHS

Ion energy spectrum in ICRF heating experiment

The ion energy spectrum was measured for ICRF heating discharges in CHS with the neutral particle energy analyzer (NPA). The heating scheme was fast wave heating with a 10% hydrogen minority in deuterium gas. Because the analyzer is of the electric field deflection type, the two ion species could not be distinguished. The spectrum reveals a two-component Maxwellian shape, as shown in Fig. 1. As the measuring angle is varied, the amount of high-energy component changes significantly, though the equivalent temperature (slope of the spectrum) of the low-energy component does not change much. When we take the product of the equivalent temperature and the density of the high-energy component (total energy of high-energy component), it shows a maximum (40% of low-energy component) at a viewing angle of 70° (the angle between the magnetic axis and the viewing path). This peak value is about four times higher than that obtained for perpendicular measurement. Such a dependence of the amount of high energy component on the viewing angle is consistent with the picture of the adiabatic motion of high-energy ions, which are kicked perpendicularly to the magnetic field at the ICRF resonance region. But the simple model assuming adiabatic motion cannot explain the existence of the high-energy component observed in the perpendicular measurement.



ICRF Ion Energy Spectrum

Neutral beam heating experiment with variable injection angle

CHS is provided with one neutral beam injector whose injection angle can be varied between tangential and perpendicular. Normally, the angle is set for tangential injection. Experiments have recently been done with an oblique angle of injection for the purpose of studying the confinement of high-energy particles in low-aspect-ratio helical systems in conjunction with a magnetic axis shift. The magnetic axis was shifted about 8 cm inward in these experiments. An ECH plasma was used as the target plasma for the injection. With the injection angle defined as the angle between the magnetic axis and the injection path, injection at a 67° angle was successful, but injection at the next setting of 75° was not. In the latter case, the radiation collapse prohibited a normal high-temperature discharge. Because the measured radiation power is more than half of the beam power, it was suggested that the beam power is being absorbed in the bulk plasma and that improved wall conditioning could make possible injection experiments at a larger angle. The spectrum of high-energy beam ions was measured with the NPA. Both the beam ions with oblique pitch angle and beam ions with very narrow pitch angle distribution, near perpendicular to the magnetic field, were measured. These beam particles increase very rapidly when the magnetic axis is shifted inward. Further experiments are planned using a second beam injector to produce a high-density target plasma for the perpendicular injection of the first beam injector.

Second neutral beam injector and upgrade of magnetic field power supply

The second beam injector has been installed. Unlike the first injector, the second is not adjustable. It is set for tangential injection. When the first one is set for tangential injection, the two beams are balanced (co- and

New alpha diagnostic tested

A proof-of-principle demonstration of the pulsed-laser Thomson scattering diagnostic for DT fusion product alpha particles was completed successfully on the Advanced Toroidal Facility (ATF). This diagnostic employs small-angle collective Thomson scattering of a CO_2 laser beam to characterize the density and velocity distribution of these alpha particles in a burning fusion plasma.

The test involved the detection of infrared laser radiation scattered from plasma electrons in ATF. The light scattered from the electrons in this nonburning plasma produces a unique signature similar in intensity to that which would be detected from alpha particles in a burning plasma. This electron feature in the scattered intensity has a resonant signature that occurs at a unique frequency shift for a given electron density. The absolute amplitude and frequency may be calculated from first principles for comparison with our measurements.

Figure 1 contains a summary of the data from the scattering experiments that were performed on ATF beginning Nov. 1 and ending Nov. 14, 1991. The solid curve is a theoretical calculation of the expected scattered signal as a function of electron density for an electron temperature of 500 eV. The dotted curve was calculated for an electron temperature of 300 eV. The scattered signal is shifted 63.23 GHz from line center of the high-power laser and the scattering angle is 0.86°. The actual electron temperature varied from 250 to 500 eV for the tests on ATF. The squares represent data taken on Nov. 1. The triangles represent data from Nov. 13 and the circles represent data from Nov. 14, 1991. The agreement between the experimental data and the theory is seen to be excellent, both in the electron density at which the resonance occurs and in the absolute scattering amplitude. The horizontal error bars represent an estimated maximum absolute uncertainty in the density of 3%, and the vertical error bars were derived from the variation of the background electrical pickup from the pulsed laser. The actual signal-to-noise ratio, neglecting the pickup noise, is better than 10:1.

Critical to the interpretation of these results was an accurate measurement of the electron density profile, which was provided by our multichannel FIR interferometer. Thus, the mean electron density in the scattering volume could be accurately determined at the instant the pulsed laser was fired. This experiment is the first demonstration of a diagnostic technique that will be capable of measurements of confined alpha particles in a burning plasma. The test has proven that high-power light scattering coupled with very sensitive heterodyne detection of the scattered signal is possible at very small scattering angles. These are the conditions needed for an alpha particle measurement on a burning plasma, such as ITER.

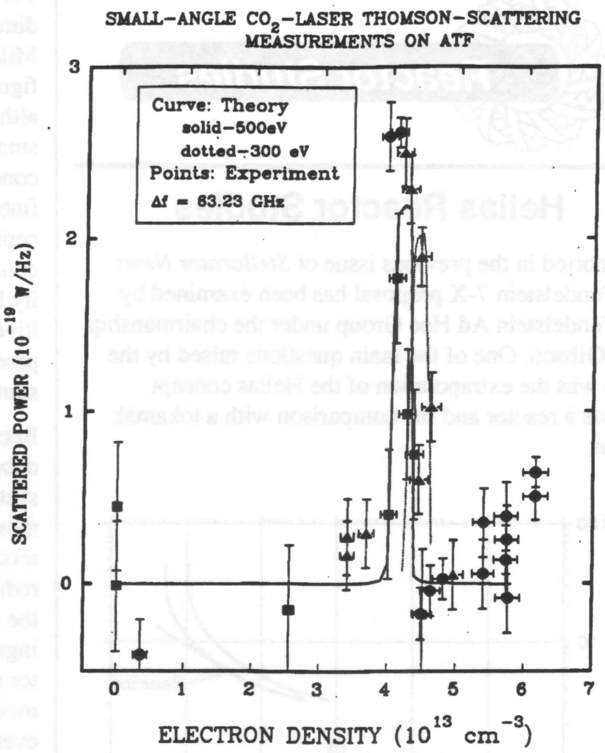


Fig. 1. Comparison of predicted and measured absolute scattered laser power as a function of plasma electron density in ATF.

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Reactor Studies

Helias Reactor Studies

As reported in the previous issue of *Stellarator News* the Wendelstein 7-X proposal has been examined by the Wendelstein Ad Hoc Group under the chairmanship of A. Gibson. One of the main questions raised by the group was the extrapolation of the Helias concept towards a reactor and the comparison with a tokamak reactor.

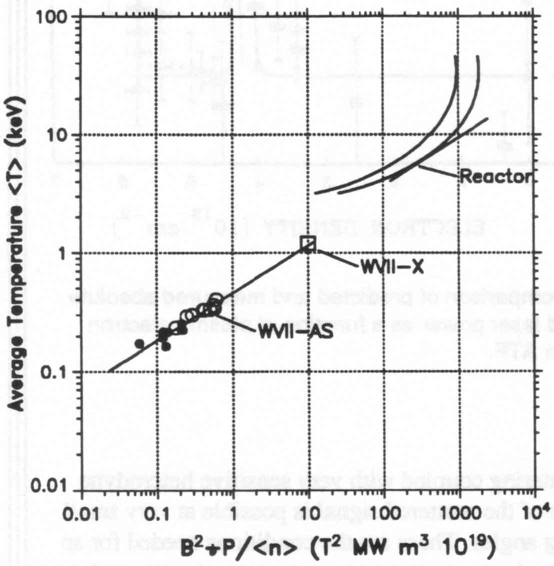

Fig. 1. Extrapolation of advanced stellarators towards a fusion reactor.

The average temperature *T* is the plasma energy divided by the volume-averaged density *n* and the plasma volume. The Lackner-Gottardi scaling (LGS) predicts that *T* is a function of $B^2 + P / n$, where *P* is the external or alpha-heating power.

For the experimental data from W 7-AS, the solid circles are for NBI plasmas; the open circles, ECRH results.

The linear relationship according to the LGS fits well to results of a 1-D transport code used to estimate W 7-X, shown as a square. The extrapolation of LGS towards the reactor is shifted slightly by the isotope ratio $(2.5/1.5)^{1/2}$.

In the two reactor curves a dilution factor of 0.5 is assumed; the average densities are 1.0×10^{20} and 2.0×10^{20} m^{-3}, respectively.

The extrapolation of a modular stellarator to reactor dimensions has been addressed in an early study by R. Miller et al. [1]. In Ref. [2] the Wendelstein 7-AS configuration has been extrapolated towards a reactor, although the beta limits of this configuration were too small for an economical fusion reactor. These studies concentrated mainly on technical issues; limits in confinement and stability were ignored. The Helias concept, however, offers the chance to obtain a self-consistent reactor concept, where plasma losses, stability limits, and alpha particle confinement are not prohibitive to ignition and a 3-GW fusion power can be produced in reasonable reactor dimensions. A short summary of this study is presented here.

Because of the inherent 3-D geometry of stellarators, neoclassical losses are usually larger than in symmetric systems; due to their strong increase with temperature, these losses may prohibit ignition in standard stellarators. The concept of the advanced stellarator with reduced neoclassical losses has removed this threat to the stellarator line. On the technical side, helical windings are the most complicated components of a stellarator or torsatron device; however, the concept of modular coils has opened the path to larger devices, and even in reactor dimensions the modular coils are of reasonable size, which appreciably facilitates manufacturing and handling.

The Helias configuration envisaged for Wendelstein 7-X has an MHD beta limit of 4–5% and an effective helical ripple of 1.5%. A scaleup of this configuration to reactor dimensions is determined by the following conditions and aims:

- Sufficient space for blanket and shield
- Technical limits on the magnetic field
- Sufficient space for divertor components
- Feasible maintenance concept
- Fusion power output approximately 3 GW

In contrast to the experiment Wendelstein 7-X, the reactor HSR has only one coil set; stray fields outside the coil system are rather small. The conditions listed above lead to a system roughly four times larger than the Wendelstein 7-X experiment.

With a magnetic energy of 70 GJ and a total weight of 2.4×10^4 tons HSR is roughly the same size as a typical tokamak reactor. The plasma volume of 1000 m^3 is nearly the same as in the ITER device. The maximum magnetic field on the coils of HSR is rather low; possibly NbTi Superconductor at a temperature of 1.8 K could be used.

Main parameters of a Helias reactor (HSR)

Major radius	20 m
Average plasma radius	1.6 m
Average coil radius	3.9 m
Field periods	5
Number of coils	50
Magnetic energy	70 GJ
Magnetic field on axis	5 T
Maximum magnetic field	10.7 T
Mass of reactor core	2.4×10^4 tons
Maximum plasma density	3×10^{20} m^{-3}
Maximum temperature	20 keV
Average beta	5.1%
Fraction of alpha particles	10%

The plasma performance in HSR is determined by four critical issues: plasma confinement, stability limits, impurity control and alpha-particle confinement. In the transport analysis of the burning plasma, neoclassical ion heat transport and anomalous electron heat transport as found in present stellarator experiments were assumed, with the results showing that the anomalous transport is too large to reach ignition. Extrapolating LHD scaling or gyro-Bohm scaling to HSR shows that a factor of two improvement is necessary. The Lackner-Gottardi scaling [3], which fits the W 7-AS results, predicts ignition without any improvement factor, see Fig. 1. There are also some theoretical arguments which suggest that anomalous transport in the Helias configuration may be smaller than in standard stellarators or tokamaks. Bootstrap currents in HSR are expected to be rather small; the modification of the magnetic field by these currents or by the Shafranov shift is negligible.

For economic reasons (fusion power) the average beta in HSR should be around 5%. Helias configurations with such an MHD stability limit have been found. Although the predicted beta limit in Wendelstein 7-X is 4.3%, there are enough parameters available to raise that limit.

Impurity control in HSR is similar in many ways to that in tokamaks. Outside the last magnetic surfaces the remnants of the $\iota = 1$ magnetic islands yield an X-type structure of the magnetic field lines, which can be utilized for divertor action. However, the divertor target plates must follow the helical path of the islands. If the diffusive broadening of the outflowing plasma is not large enough to avoid hot spots on the target plates, sweep coils can be utilized to overcome this problem. In HSR only small sweep currents ($\Delta I = \pm 40$ kA) are needed to achieve this goal.

Prompt losses of hot alpha-particles are strongly reduced in Helias configurations at finite beta values; therefore, the alpha particle heating rate is only slightly diminished. Accumulation of helium ash is mainly determined by neoclassical losses of thermal helium; since these losses are larger than in axisymmetric configurations, a smaller fraction of thermal alpha particles is expected. Nevertheless, the plasma model for HSR assumes $f_\alpha = 10\%$ for cold helium ions.

In summary, one may conclude that several critical issues of plasma performance in standard stellarators do not arise in a Helias reactor. Impurity accumulation and control remains one of the most critical issues; however, this is a problem common to stellarators and tokamaks. On the technical side, superconducting modular coils of the required size seem to be feasible, possibly with NbTi technology. Although the major radius of HSR is about 20 m, the overall size, weight, and magnetic energy of this reactor are comparable to those of tokamak reactors of equal power output. Given the advantages of steady-state operation, small recycling power, and the absence of current disruption, the Helias reactor is a competitive candidate for a fusion power reactor. Its larger aspect ratio is advantageous with respect to neutron loading at the first wall, as well as to heat deposition at the divertor target plates.

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[3] Lackner, K., Gottardi, N.A.O., Nucl. Fusion **30** (1990) 767.

People

Visitors to ORNL

Drs. Hantao Ji, Shigeyuki Morimoto, Motoyasu Sato, and Hiroshi Yamada from the National Institute for Fusion Science, Nagoya, Japan, visited ORNL and made significant contributions to the ATF program in the last period of operation (September through November 1991). Although the originally intended experiment ("one-hour" ECH discharge) had to be postponed because of the damaged helical coil joints, the microwave components provided by the Japanese group were essential to carry out experiments with the 35-GHz gyrotron. The visitors participated in experiments involving long pulse operation, the dimensionless scaling (see the article by J. H. Harris), multiple ECH resonance (with a simultaneous use of the 35- and 53-GHz gyrotrons), and Ohmic heating using ramped fields (HF or VF). Experimental results are being analyzed.