[5]R. Decoste and B. H. Ripin, Phys. Rev. Lett. 40, 34 (1978).
[6]R. L. Morse and C. W. Nielson, Phys. Fluids 16, 909 (1973).
[7]P. M. Campbell, R. R. Johnson, F. J. Mayer, L. V. Powers, and D. C. Slater, Phys. Rev. Lett. 39, 274 (1977).
[8]B. Bezzerides, D. W. Forslund, and E. L. Lindman, Phys. Fluids 21, 2179 (1978).
[9]L. M. Wickens, J. E. Allen, and P. T. Rumsby, Phys. Rev. Lett. 41, 243 (1978).
[10]D. W. Forslund, J. M. Kindel, and K. Lee, Phys. Rev. Lett. 39, 284 (1977); K. Estabrook and W. L. Kruer, Phys. Rev. Lett. 40, 42 (1978).
[11]L. V. Spencer, *Energy Dissipation by Fast Electrons*, National Bureau of Standards Monograph No. 1 (U. S. GPO, Washington, D. C., 1959).
[12]D. Shvarts, C. Yablon, I. B. Bernstein, J. Virmont, and P. Mora, Nucl. Fusion 19, 1457 (1979).
[13]R. J. Mason, Phys. Rev. Lett. 42, 239 (1979).
[14]R. J. Mason, Phys. Rev. Lett. 43, 1795 (1979).
[15]N. A. Ebrahim, C. Joshi, D. M. Villeneuve, N. H. Burnett, and M. C. Richardson, Phys. Rev. Lett. 43, 1995 (1979).

Microinstabilities in the Wendelstein VII A Stellarator Observed by CO_2-Laser–Light Scattering

J. Meyer
Department of Physics, The University of British Columbia, Vancouver, British Columbia, V6T1W5, Canada

and

C. Mahn
Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-8046 Garching, Germany
(Received 30 September 1980)

Homodyne detection of scattered CO_2-laser light demonstrates a close relation between microturbulence level and energy confinement in the Wendelstein VII A stellarator during both Ohmic and neutral-beam heating experiments. With the onset of neutral injection an abrupt order of magnitude decrease in $(\delta n/n)^2$ accompanied by a broadening of the fluctuation spectra is observed, indicating an almost immediate improvement of containment time.

PACS numbers: 52.35.Py, 52.25.Ps, 52.55.Gb

In present day toroidal plasma confinement experiments anomalous energy transport limits efficient confinement to levels well below that expected from calculations based on classical Coulomb scattering. This anomalous transport can be caused if microinstabilities are driven by the free energy in the confined plasma.[1] The nonlinear nature of the theory makes it extremely difficult to calculate quantitative fluctuation spectra and their influence on energy transport; however, in special cases such influence is strongly suggested.[2] It is therefore desirable to investigate these microturbulences and their effect on energy confinement experimentally.[3-6] In this communication experimental results are discussed which were obtained with CO_2-laser–light scattering from the Wendelstein VII A(W VII A) stellarator plasma in Garching, Germany, during the period in which a current-free plasma was achieved as discussed in detail in Ref. 5.

The scattered laser radiation is received in homodyne fashion. 35 W of laser radiation produced by a single-mode cw CO_2 laser is redirected via mirrors over a 10-m path into the W VII A torus into which it is focused by a set of ZnSe lenses to a 3-mm waist. After passing through the torus center the beam is attenuated and reflected from the surface of a BaF_2 plate towards the detector, thus producing 0.1 mW of local oscillator radiation. Scattered radiation after passing through the BaF_2 plate is reflected by a gold-coated surface mirror and is made collinear with the local oscillator beam. The angle and distance between the BaF_2 plate and the gold-coated mirror are chosen such that radiation scattered from 0.5-mm wavelength fluctuations propagating perpendicular to B_0 is detected. Because of the small scattering angle the length of the scattering volume is determined by the plasma diameter. The superimposed beams are then focused onto the HgCdTe detector cooled to 70 °K. Between shots a mirror is placed in the beam path redirecting it into a power meter. The detector signal after passing through a high-pass filter is amplified by a set of two amplifiers. The amplified signal is fed via a 50-Ω cable to the measuring station where it is analyzed with an eight-channel filter set. The rectified filter signals are then recorded on oscilloscopes. For some shots the filter set was replaced by a HP spectrum analyzer.

With the help of the filter set and spectrum analyzer spectra covering the range from 50 kHz to 1 MHz can be recorded. The squared rms voltage at different frequencies is integrated over frequency to produce a value proportional to the square of the fluctuation amplitude δn^2 or the fluctuation parameter $(\delta n/n)^2$ averaged over the plasma diameter.

The first objective of the reported experiment was to investigate the relation between microturbulence and energy confinement. Ideally suited for this is the study of the plasma behavior in the purely Ohmically heated W VII A stellarator ($R = 2.0$ m, $a = 0.1$ m, $B_0 \leq 3.5$ T, helical windings: $l = 2, m = 5$, shearless external transform $= 0.23$). In this mode of operation the energy confinement time can be evaluated accurately via the plasma energy as measured by a diamagnetic coil and the Ohmic power as deduced from loop voltage and plasma current.[5] It has been shown that with increasing line density by puffing in gas as measured by microwave interferometry, the confinement time τ_E increases in the low-density regime with increasing density until a maximum is reached. Beyond this value τ_E decreases rapidly. Figure 1 shows both τ_E and $(\delta n/n)^2$ as a function of line density, demonstrating clearly the relation between both quantities for deuterium and helium plasmas.

It is now interesting to investigate the plasma behavior under the influence of neutral-beam heating and current reduction. It has been shown[5] that a high-density deuterium plasma can be maintained in the W VII A stellator ($B_0 = 3$ T) with two and in a later series with three neutral injectors (27 kV, H_2, $P_N \approx 1$ MW). During the injection phase the plasma current is reduced from initially 17 kA to zero in a time 50 ms while the external rotational transform is kept constant at 0.51. A considerable improvement of confinement has been demonstrated during injection.[6] Figure 2 shows a set of observed parameters during this phase for the case of three neutral injectors. Two interesting observations are made for the fluctuations as indicated by the two signals at

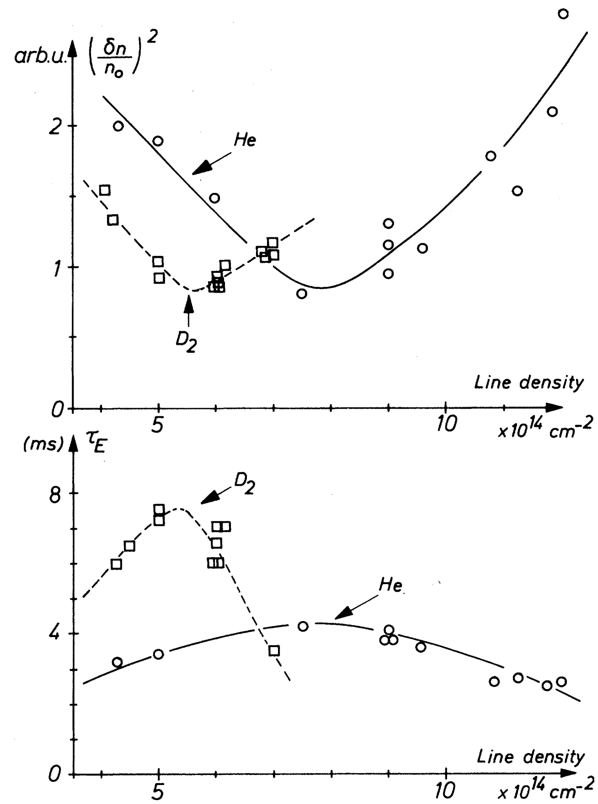

FIG. 1. Fluctuation parameter $(\delta n/n)^2$ and energy confinement τ_E as a function of line density for He and D_2.

70 and 900 kHz. With the onset of injection within a time of 1 or 2 ms, (a) the fluctuation amplitude at lower frequency drops significantly and (b) the spectral composition is changed. Before injection the spectrum is relatively narrow, extending from small frequencies to a slight maximum at 50–100 kHz and then dropping rapidly to small values beyond 200 kHz. During injection the spectrum is much wider, extending out to 1 MHz but of much smaller amplitude at frequencies <200 kHz. The last curve of Fig. 2 shows that the total fluctuation parameter $(\delta n/n)^2$ decreases by a factor of 10 with the onset of injection, and then decreases very slowly until a minimum is reached in the current-free phase. 10 ms after current zero, the fluctuations grow rapidly, coinciding with a rapid increase in radiation losses as observed by the bolometer.[5] Unfortunately, it is impossible to evaluate an accurate energy confinement time during injection because of the uncertainty in absorbed beam power in the plasma.[5]

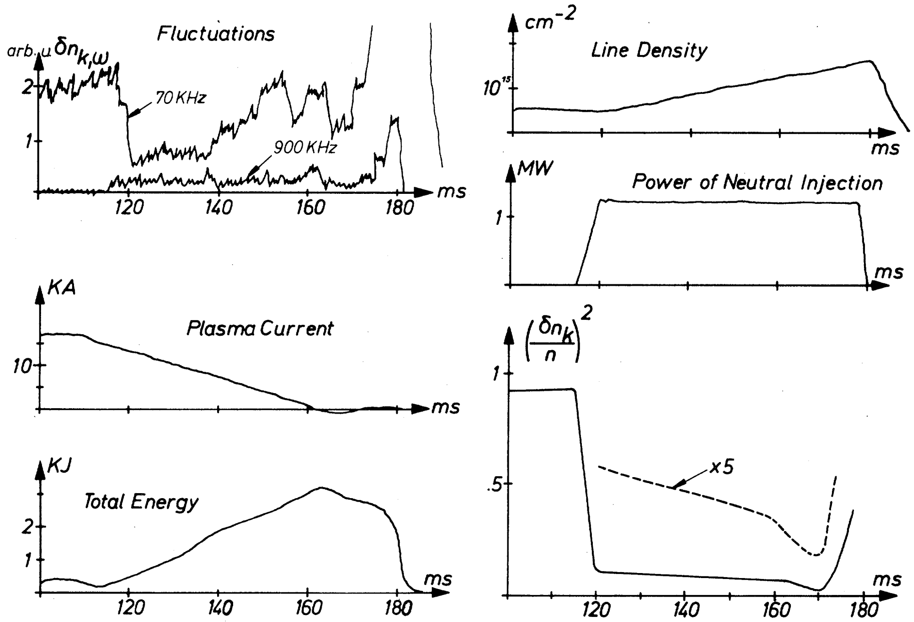

FIG. 2. A set of discharge parameters as a function of time of a deuterium plasma heated by three neutral beams injected during current reduction.

In order to further investigate the relation between confinement and turbulence during injection, a set of discharges was evaluated for which all external parameters were kept the same as in Fig. 2, but for which the plasma energy reached different maximum values. This may be due to different purity levels of the target plasma. For two situations, with two and with three neutral injectors operating, such discharges were observed. The results are indicated in Fig. 3, where the fluctuation parameter $(\delta n/n)^2$ is plotted as a function of the maximum plasma energy. Since the injected power was kept constant (≈ 600 kW in the case of two and ≈ 900 kW in the case of three neutral injectors), the plasma energy is a measure of the energy confinement time. Figure 3 then suggests that with decreasing microinstability level the energy confinement improves drastically. With two injectors the turbulence level can be decreased to the same value as with three injectors, indicating a threshold problem. For the particles this threshold in improved confinement is more evident in Fig. 4. A few current reduction discharges were fired with either one, two, three, or four injectors heating a target plasma of the same initial conditions as in Fig. 2 ($n_e \approx 5 \times 10^{13}$ cm^{-3}). No additional gas was puffed into the torus; however, the density increased in all cases linearly with time during injection.[5] Figure 4 shows the increase in line density over the 60 ms injection period as well as $(dn/n)^2$ evaluated just after the start of injection as a function of beam power. The linear relation for the den-

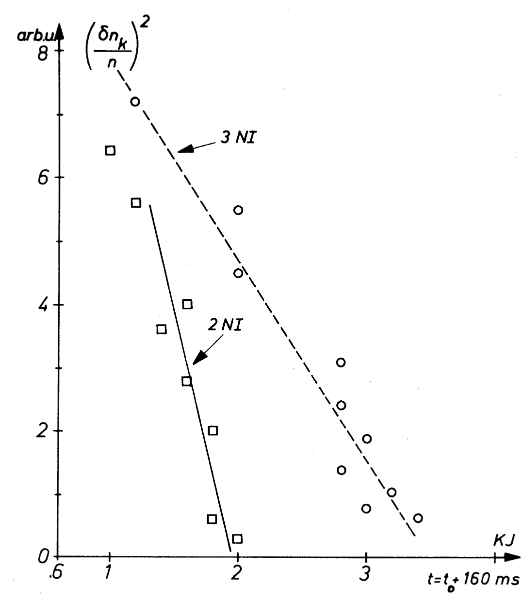

FIG. 3. Fluctuation parameter $(\delta n/n)^2$ as a function of maximum plasma energy reached for the cases of two and three neutral injectors. All global parameters were kept constant in each of the two cases.

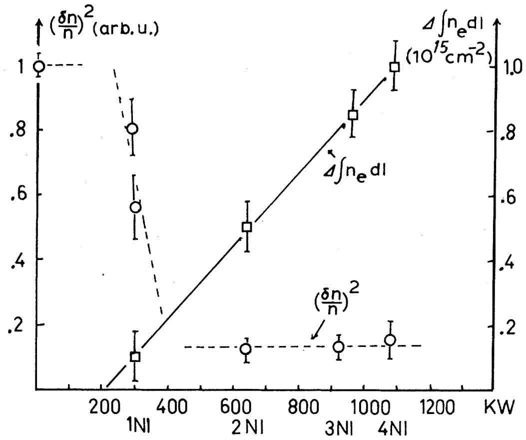

FIG. 4. Fluctuation parameter $(\delta n/n)^2$ and increase in line density $\Delta \int n\, dl$ as a function of neutral injection power for one, two, three, or four neutral injectors.

sity increase intersects the abscissa at around 200 kW, indicating a threshold power below which no density increase occurs. This and the linear temporal density rise could be explained if the particle confinement at threshold is suddenly drastically improved. Making the simplified assumption that at threshold particle losses from the plasma are made up by refueling from the beams leads to an estimate of 0.1 sec particle confinement time, which is an order of magnitude larger than before injection. $(dn/n)^2$ shows the same threshold power beyond which it drops by an order of magnitude, indicating again the close correlation between confinement and turbulence.

The results of Figs. 1, 3, and 4 show that confinement times and microturbulence levels are closely correlated. In the case of neutral-beam heating an improvement of confinement time is observed. Since the fluctuation amplitude drops immediately following the start of neutral injection, before any global plasma parameter has changed, it is reasonable to argue that the microturbulences determine energy and particle transport. It is then interesting to note that in a stellarator neutral beams of sufficient power can improve the confinement properties of the plasma by an order of magnitude within a couple of milliseconds.

We would like to thank the whole W VII A team for their great enthusiasm and excellent research before and during the achievement of a current-free plasma. Without their assistance the reported experiment would not have been possible. We also acknowledge the invaluable technical assistance of Mr. J. Prechtl.

[1]W. M. Tang, Nucl. Fusion 18, 1098 (1978).

[2]K. Molvig, S. P. Hirshman, and J. C. Whitson, Phys. Rev. Lett. 43, 582 (1979).

[3]E. Mazzucato, Phys. Rev. Lett. 36, 792 (1976).

[4]C. M. Surko and R. E. Slusher, Phys. Rev. Lett. 37, 1747 (1976).

[5]W VII A Team, in Proceedings of the Eighth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, Belgium, July 1980 (to be published), International Atomic Energy Agency Report No. CN-38/H-2-1.

[6]W VII A Team, in Proceedings of the Eighth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, Belgium, July 1980 (to be published), International Atomic Energy Agency Report No. CN-38/H-2-2.