Energy Confinement of High-Density Pellet-Fueled Plasmas in the Alcator *C* Tokamak

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(Received 15 March 1984)

A series of pellet-fueling experiments has been carried out on the Alcator *C* tokamak. High-speed hydrogen pellets penetrate to within a few centimeters of the magnetic axis, raise the plasma density, and produce peaked density profiles. Energy confinement is observed to increase over similar discharges fueled only by gas puffing. In this manner record values of electron density, plasma pressure, and Lawson number ($n\tau$) have been achieved.

PACS numbers: 52.55.Gb

The standard method of fueling tokamaks is by gas puffing, which supplies particles to the plasma edge in the form of neutral atoms. Since neutrals cannot penetrate far into plasmas with large line-integral densities, the particle source is concentrated at the discharge boundary. Fueling of large high-density plasmas then becomes problematic for the following reasons: First, edge fueling produces relativley broad density profiles which may not be optimal with respect to energy transport. Secondly, the mechanism which carries particles up the density gradient to the center of the plasma is not understood, and thus it is difficult to extrapolate into reactor regimes. Finally, there is the possibility that the mechanism which carries particles into the plasma core is responsible for anomalous energy loss. Some of these problems may be occurring in Alcator *C*, where at high plasma densities energy confinement is considerably worse than what would be expected from the $\tau_E \propto n_e$ scaling observed at lower densities [Fig. (1)].[1]

Injection of high-speed frozen hydrogen pellets has been proposed as an alternative method for fueling fusion devices,[2] and in recent years pellet injectors capable of fueling the current generation of tokamaks have been developed.[3] Experiments on pellet penetration into plasmas have been performed and the effects of pellet fueling on plasma properties are being studied on several devices.[4–7] In this Letter we describe effects of pellet fueling on energy confinement in Alcator *C*.

The pneumatic injector used in the experiments described here was designed at the Oak Ridge National Laboratory and built at Massachusetts Institute of Technology. It fires four independently timed hydrogen pellets with velocities between 8×10^4 and 9×10^4 cm/sec. With appropriate changes in operating procedures it can also fire deuterium pellets at slightly reduced velocities. A beam line with guide tubes and provision for differential pumping prevents the helium propellant

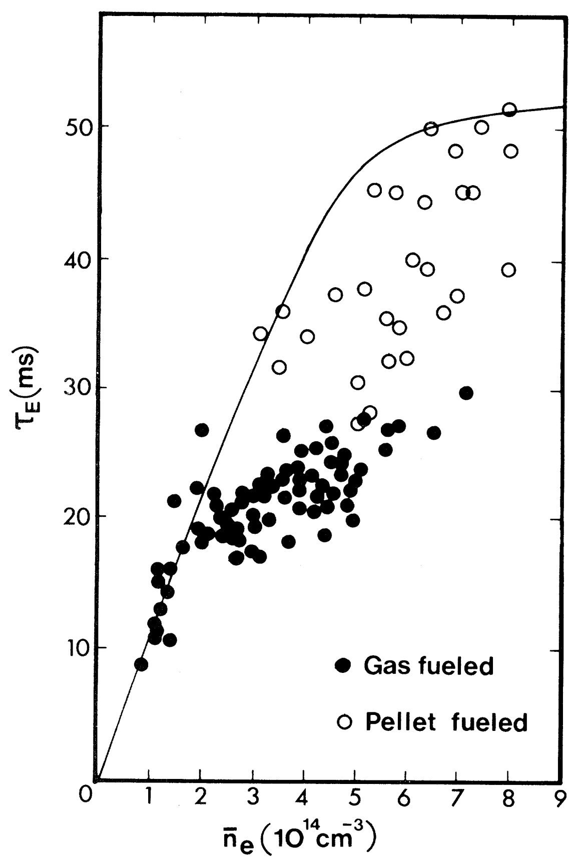

FIG. 1. Energy confinement times. Data from gas-fueled discharges are shown by the solid circles. These points follow the $\tau \propto n_e$ scaling law only below densities of 2×10^{14} cm^{-3}. Data from pellet-fueled discharges are shown by the open circles. These clearly show higher confinement times. The solid curve is the energy confinement time calculated by use of neo-Alactor scaling for the electron heat diffusivity and $1\times$ Chang-Hinton neoclassical ions ($B_T = 10$ T, $I_p = 750$ kA).

from reaching the plasma. Each pellet contains 6×10^{19} particles corresponding to $\langle n_e\rangle=2\times10^{14}$ cm^{-3} in Alcator *C* (16.5 cm minor radius and 64 cm major radius). Standard operation is with a toroidal field between 80 and 120 kG and plasma currents from 400 to 800 kA. Central electron temperatures are from 1400 to 2000 eV. Target plasma densities are in the range $(2-6)\times10^{14}$ cm^{-3}, line averaged.

The pellets last for 100 to 150 μsec under the conditions of temperature and density that prevail inside the Alcator discharge. At the pellet's nominal velocity this corresponds to penetration of 8.5 to 13 cm. The pellets do not reach the magnetic axis but do deposit their fuel deep inside the plasma. Penetration is in rough agreement with the neutral shielding model[8] and 65–90% of the pellet atoms are accounted for in the plasma. Density profiles as measured by Thomson scattering are initially hollow, but become centrally peaked in less than 500 μsec. Scattering measurements and those of a multichord interferometer show profiles with peak to average ratios of about 2. In contrast, profiles without pellet injection are flatter, with peak to average ratios of 1.2 to 1.4. Profiles obtained from the far-infrared interferometer array are shown in Fig. 2(a). By injecting more than one pellet it is possible to double or triple the density without disrupting the discharge. Line-averaged densities up to 1×10^{15} cm^{-3} have been achieved with central densities near 2×10^{15}. Following injection the density falls, returning to the original value in 50 to 150 msec (Fig. 3). The density decay time appears to increase with background density and is longer for deuterium than for hydrogen.

A sharp temperature decrease accompanies the density rise (Fig. 3). This is due to the dilution of hot plasma electrons and ions with cold gas from the evaporating pellet. Electron temperature profiles are determined from electron-cyclotron emission (ECE) measurements, Thomson scattering, and soft-x-ray pulse-height analysis. The ECE instrument, a fast-scanning Fabry-Perot interferometer, shows that temperature profiles regain their Gaussian shape within 250 μsec after injection. In addition, the width of these profiles is unchanged although the magnitude of the temperature drops considerably. Temperature profiles from ECE measurements are shown in Fig. 2(b). The electron temperature recovers to the preinjection level in 15–40 msec. The ion temperature as measured by neutron rate and Doppler broadening of impurity lines shows similar behavior, recovering as quickly as the electrons and overshooting the preinjection temperature by 100–200 eV. This is consistent with

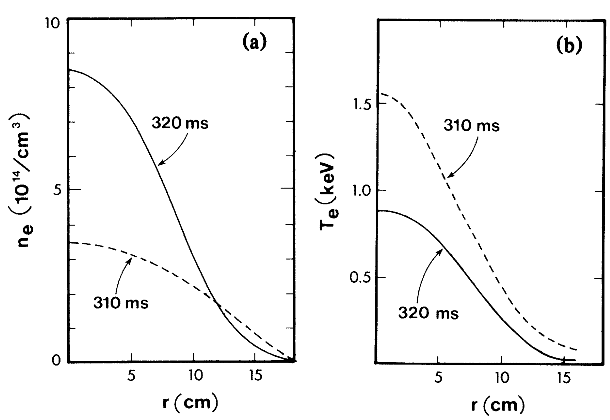

FIG 2. (a) Electron density profiles before and just after pellet injection. The pellet was injected at 315 msec. (b) Temperature profiles before and just after pellet injection. Although the temperature falls because of the influx of cold electrons and ions from the pellet, the shape of the temperature profile is unchanged.

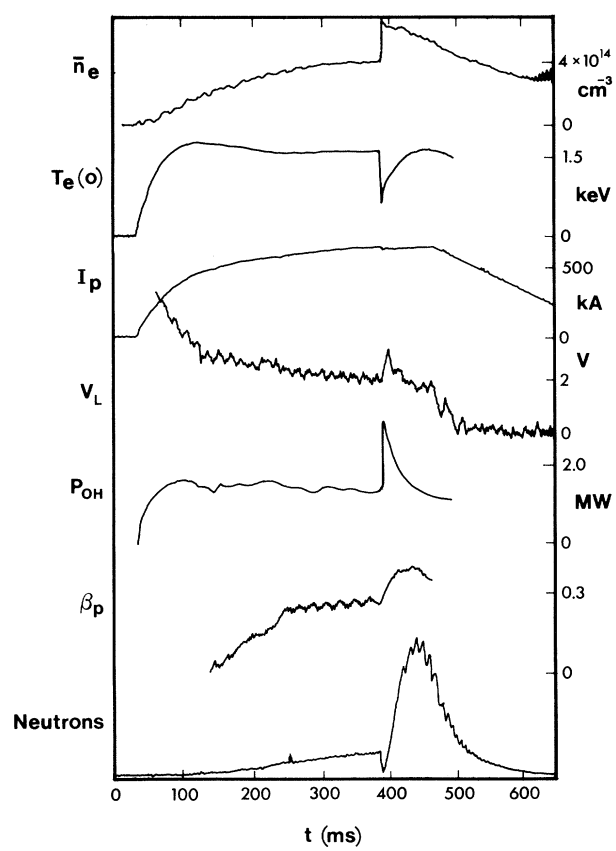

FIG. 3. Typical pellet-fueled discharge. A single deuterium pellet is injected into a deuterium discharge at 390 msec.

the improved electron-ion coupling at higher densities.

Total plasma current is only slightly perturbed by pellet injection, typically falling by a few percent. Because of the long skin time and because there is no change seen in the electron temperature profile, little change is expected in the current profile. The loop voltage increases by about 0.5 V immediately after injection, and then falls to or below its previous values in 15–40 msec. Calculations of field and current diffusion suggest that the electric field perturbation is larger in the interior of the plasma but lasts no longer than that of the surface fields. While this transient lasts, the Ohmic heating power is high and is responsible for the rapid reheating that is observed.

A set of β_θ loops measures $\Lambda = \beta_p + l_i/2$. Measurements of plasma diamagnetism and calculations of magnetic diffusion indicate that most of the change seen after pellet injection is due to changes in β_p, not in $l_i/2$. Figure 3 shows β_p for a pellet-fueled discharge. The values and time histories of β_p obtained this way are in good agreement with calculations of total plasma energy from T_e and n_e profiles. Energy content of pellet-fueled plasmas has been as high as 80 kJ with a corresponding β_p of 0.5 at $I_p = 750$ kA.

Magnetohydrodynamic (MHD) activity is altered by pellet injection. Plasmas usually continue to sawtooth but with increased period and amplitude. Sawtooth periods up to 50 msec have been observed compared to 2–4 msec seen with gas fueling. The large amplitude of sawteeth seen by the soft-x-ray arrays is likely due to peaked density and impurity profiles. At very high densities large $m = 2$ and $m = 3$ MHD oscillations accompany injection. These oscillations are probably related to the density-threshold behavior previously reported.[9]

Figure 1 depicts the behavior of the global energy confinement time, $\tau_E = W/(P_{\text{in}} - dW/dt)$; W is the total plasma kinetic energy and P_{in} the Ohmic input power. Confinement times are calculated by use of standard profile models (which are compared in many cases with measured profiles), with correction of loop voltage for dI/dt and allowance for dW/dt. In all cases the confinement times quoted are determined after the plasma has reheated and these derivatives are small. The major uncertainties arise from the measurement of $T_e(0)$, which is known to 10%, and the temperature profile, which leads to an uncertainty in plasma energy of 14%. The loop voltage and plasma current are measured to within 5%. The line-averaged density is known very accurately, typically to within a few percent. The density profile has substantially more uncertainty but this has very little effect on the calculation of total plasma energy. All of these lead to errors in the quoted confinement time of under 20%. The calculation of plasma energy from measured profile data can be compared with calculations using β_p data. Typically these calculations measurements agree within 15%.

The code TRANSP provides an excellent method for analysis of the time-dependent phenomena.[10,11] Given temperature and density profiles as a function of time along with plasma current and surface voltage, TRANSP solves the magnetic diffusion equations, electron and ion energy balances, particle balances, and neutral transport. It gives as outputs energy and particle confinement times, thermal and particle diffusivities, as well as beta values and neutron rates which can be compared to the experiments. Sufficient data for TRANSP analysis is available for only a handful of shots. In addition, experimental results have been compared with theoretical models by using zero- and one-dimensional time-dependent simulations and by time-slice modeling with code ONETWO.[12]

It is clear that the consistent increase seen in plasma energy at nearly constant input power is the result of improved energy confinement in pellet-fueled discharges. We expect improvement of τ_E with density; even in the saturated regime some increase is seen. The crucial issue is the comparison between gas-fueled and pellet-fueled plasmas. The difference can be seen in Fig. 1 where plasmas which have been fueled by pellet injection are seen to have significantly better confinement. While these discharges show some weak saturation they follow the $\tau_E \propto n_e$ curve to higher densities and the rollover can be explained by ion losses at $1\times$ neoclassical transport[13] (solid curve in Fig. 1).

Improved energy confinement at high densities allowed us to reach record levels of plasma pressure and Lawson number, $n_e(0)\tau_E$ (Fig. 4). Average pressures of 1.6 atm were achieved with peak pressures over 8 atm. $n\tau$ values in the range $(0.6\text{–}0.9)\times 10^{14}$ sec/cm^3 were measured, in excess of the Lawson criterion for thermalized breakeven.[14] These values were reached at ion temperatures near 1500 eV, giving numbers for $n\tau T$ above 10^{17} eV sec/cm^3. Additionally, record levels of thermonuclear neutron production, $(1\text{–}2)\times 10^{13}$/sec, were measured. All of these parameters were achieved simultaneously with 1.6 MW of Ohmic heating power.

In summary, pellet-fueling experiments have produced plasmas with high densities and peaked profiles. Energy confinement is better than in com-

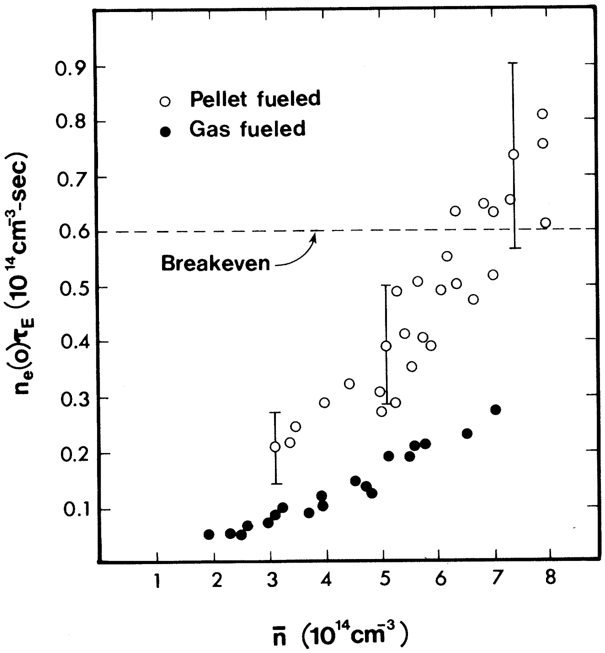

FIG. 4. Values of the Lawson product, $n_e(0)\tau_E$, shown as a function of density for pellet-fueled plasmas.

parable discharges fueled by gas puffing. Very high values of plasma pressure were reached and the Lawson criterion for thermalized breakeven was exceded.

The authors wish to thank Princeton Plasma Physics Laboratory for providing the TRANSP code and assistance; General Atomic for providing ONETWO; P. Politzer for useful discussions; and the entire Alcator technical and support staff. This work is supported by the U.S. Department of Energy under Contract No. DE-AC02-78ET51013.

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