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THE JET MULTIPELLET LAUNCHER AND FUELING OF JET PLASMAS BY MULTIPELLET INJECTION*

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Pellet Injector System Description and Performance

A three-barrel repeating pneumatic pellet launcher developed at ORNL is the principal component of a new plasma fueling system for the Joint European Torus (JET) [1,2]. This versatile device consists of three independent machine-gun-like mechanisms equipped with high-speed extruders to provide solid deuterium to each gun assembly. The injector features nominal pellet sizes of 2.7 mm, 4.0 mm, and 6.0 mm, giving ideal volume-average plasma density increments of $0.82 \times 10^{19}\ m^{-3}$, $2.66 \times 10^{19}\ m^{-3}$, and $8.9 \times 10^{19}\ m^{-3}$, respectively, and has been qualified at repetition rates of 5 Hz, 2.5 Hz, and 1 Hz, respectively. Each gun can operate (individually or simultaneously) at the design repetition rate for 15-s pulses. Pellet speeds in the repeating mode average 1300 m/s; in the single-shot mode, the performance is close to 1500 m/s. Additional components of the ORNL pellet launcher system include: (1) an instrumented propellant and fuel gas feed system; (2) injector diagnostics, including a fiber-optic pellet detection system and optical systems for remote monitoring of solid hydrogen extrusions and high-speed flash photography of pellets; and (3) a data acquisition and remote control system consisting of a programmable logic controller (PLC) and a computer/CAMAC-based operator interface and data acquisition system.

The balance of the installation at JET consists of the following JET-supplied subsystems [3]: (1) a launcher-torus vacuum interface for differential pumping of propellant gas and extrudate fuel featuring a $50\text{-}m^3$ vacuum chamber equipped with an 8×10^6 L/s cryocondensation pump; (2) a liquid helium delivery, storage, and recovery system and fuel and propellant gas distribution systems; (3) a fire control sequencer that provides timed trigger pulses for initiation of the extrusion process and programmable firing of pellets; (4) a microwave cavity-based pellet mass measurement system and an instrumented target array to facilitate aiming of all three guns; and (5) a PLC-based control system and computer operator interface for these subsystems.

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The fueling system became operational on JET in October 1987. To date, plasma fueling experiments have been performed with the 2.7- and 4.0-mm guns operating in the multipellet mode.

Pellet Penetration and Particle Deposition Profiles

Penetration of the 2.7- and 4.0-mm pellets for ohmic plasmas without significant populations of suprathermal electrons agrees with the neutral and plasma shielding model [4], as shown in Fig. 1. Measured penetration is determined from vertical soft x-ray data in all cases. The calculated penetration uses T_e profiles from second harmonic ECE data and n_e profiles from six vertical chords of an FIR interferometer. The 2.7-mm pellets have a pellet-by-pellet mass correction in the calculated penetration using the signal from the microwave cavity. The larger scatter in the 4-mm data may be due to pellet mass variation in the experiment; the calculated penetration is based on an average mass. Earlier JET data from 3.6- and 4.6-mm pellet experiments using the IPP Garching single-pellet injector show similar agreement with the model [5].

The gross particle deposition has been determined by volume integration of the density profiles after pellet injection. This gives, on average, 6.6×10^{20} and 2.3×10^{21} particles for the 2.7- and 4-mm pellets, respectively, which corresponds to ≈70–75% of the pellet inventory as determined by the ideal pellet dimensions. The discrepancy results from a loss of pellet mass by erosion of the pellet diameter in the gun barrels.

Details of the particle deposition in ohmic plasmas are illustrated in Fig. 2 by LIDAR Thomson scattering profiles taken within 20 ms of pellet injection. Figure 2a shows the plasma density profiles after the first and third pellets in a sequence of three 4-mm pellets injected into a 3-MA ohmic discharge at 1 Hz. The profile is strongly inverted after the first pellet (which penetrates to $R = 3.4$ m) but more centrally peaked after the third pellet, which penetrates to the magnetic axis. Central penetration is accomplished as the central electron temperature decreases from 4 keV to 2.5 keV during the fueling pulse. As shown in Fig. 2b, a deeper deposition profile can be achieved by injecting a 2.7-mm pellet a few milliseconds after the 4-mm pellet. This technique was used to produce the highly peaked density profile shown in Fig. 2c. The subsequent evolution of the density profiles in ohmic and auxiliary heated discharges is discussed by Kupschus et al. [6].

Plasma Fueling Experiments

One of the primary objectives of the experimental program on JET is to produce clean, centrally peaked, high-density target plasmas for central and off-axis heating (ICRF and NBI) experiments. To date, the 2.7-mm and 4-mm injectors have been used for this purpose in X-point and limiter plasmas at up to 5 MA of plasma current. Plasma density buildup has been demonstrated in the startup and flattop phases of ohmic limiter and X-point discharges using 2.7-mm pellets for pulse lengths exceeding 2.5 s. Figure 3 illustrates the plasma density evolution from FIR data in response to injection of 2.7-mm pellets at 2.5 Hz starting 1 s into the discharge (at $I_p = 1.5$ MA) and continuing until the start of the current flattop phase of a 3-MA limiter plasma. In this discharge, a centrally peaked density profile is maintained in time as the second and subsequent pellets penetrate to and somewhat beyond the magnetic axis. This was accomplished by adjusting the fueling rate so that the central electron temperature was maintained in the range of 1.2–1.3 keV throughout the fueling pulse. The volume-average density increases linearly during pellet fueling, and 75% of the particle input rate is accounted for in the rate of rise of the plasma particle inventory. Peak to volume-average density ratios in the range of 2–2.5 are maintained during the fueling pulse, compared with 1.3 for gas puffing cases. The

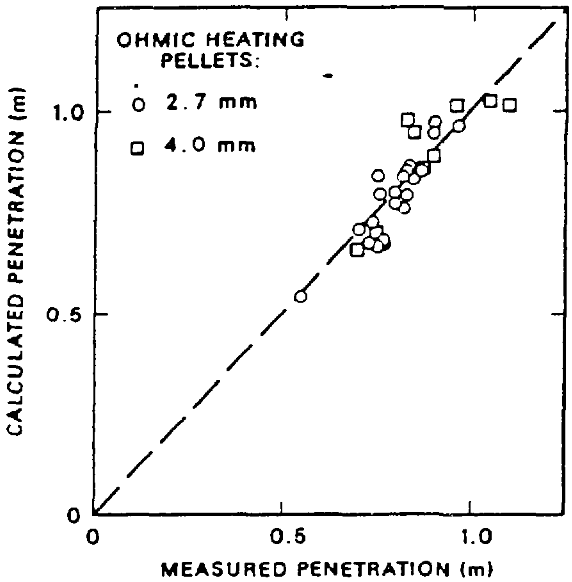

Fig. 1. Measured and calculated penetration for 2.7- and 4.0-mm pellets.

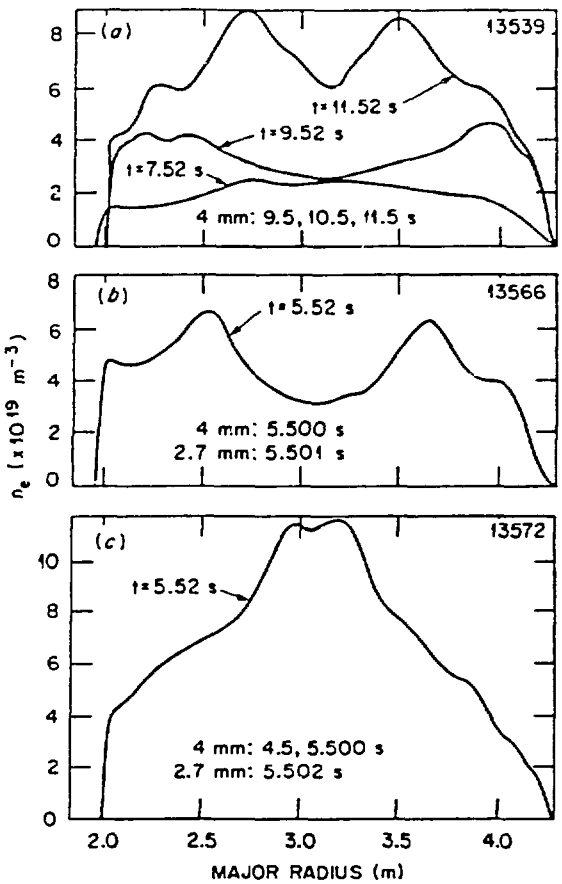

Fig. 2. Density profile shapes after 4-mm and combined 4-mm and 2.7-mm pellets in 3-MA ohmic discharges.

peaking factor is sensitive to pellet penetration, as demonstrated by comparing Fig. 3 (shot 14550) and Fig. 4 (shot 14545). The conditions of Fig. 4 differ from those of Fig. 3 in that the central electron temperature is higher (2–2.2 keV) during the fueling pulse, resulting in reduced pellet penetration (to R = 3.25–3.35 m). The density profiles are consequently broader, giving peaking factors of 1.75 and central densities 50% smaller than the values on shot 14550 . While the volume-average density increments during pellet injection for these two cases are similar, the density decay after pellet injection is somewhat more pronounced on shot 14545, giving a 15% smaller volume-average density at the end of the pellet fueling pulse. The response of these profiles to auxiliary heating, which starts at 3.5 s, is discussed by Kupschus et al. [6] at this conference.

Long-pulse plasma fueling has also been performed in the flattop phases of ohmic discharges using primarily the 2.7-mm gun. In limiter plasmas, the volume-average density can be maintained at 3.5×10^{19} m^{-3} at an injection frequency of only 1 Hz. Preliminary experiments in ohmic X-point discharges indicate that pellet fueling provides better control over the density level than gas puffing but that the fueling efficiency is lower (i.e., the plasma pumpout is faster) than in the high-recycle limiter plasmas. For 2.7-mm pellets that penetrate to R = 3.5–3.6 m (i.e., about halfway to the axis), injection

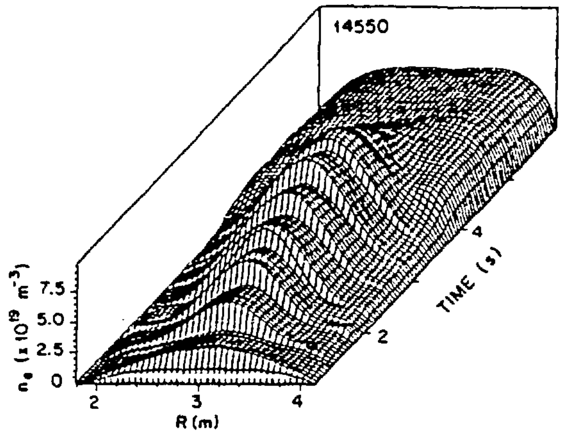

Fig. 3. Plasma startup with centrally penetrating 2.7-mm pellets at 2.5 Hz. Auxiliary heating starts at 3.5 s.

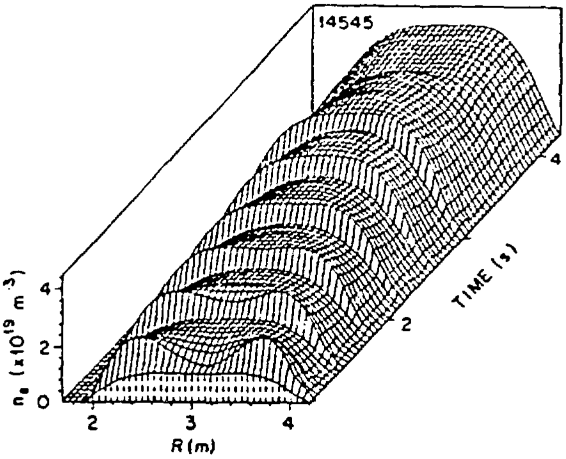

Fig. 4. Plasma startup with noncentral penetration. Auxiliary heating starts at 3.5 s.

frequencies of 2 Hz are required to maintain the volume-average density in the range of 2×10^{19} m^{-3}. A more pronounced effect has been been obtained by injecting a 4-mm pellet (which penetrates to R = 3.15 m) followed by 2.7-mm pellets at 5 Hz. In this case, a central density of 5×10^{19} m^{-3} was sustained with a profile shape similar to that of Fig. 4. For conditions typical of the flattop phases of JET discharges, deep pellet penetration is not achieved with 2.7-mm pellets alone, and to date we have not observed density profile peaking as strong as that observed on ASDEX [7] with partial penetration.

Summary

A new multipellet long-pulse plasma fueling system is in operation on JET. In the initial experimental phase, a variety of plasma density profile shapes have been produced with peak to average values ranging up to 2.5 and peak plasma density up to 1.2×10^{20} m^{-3}.

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