§17. Hydrogen Fuel-Pellet Ablation in LHD Plasma

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Time-resolved emission from fuel or diagnostic pellets injected into magnetic fusion machines provides quantitative data from a unique high-density plasma in a magnetic fusion plasma environment.

Recently pellet injection spectra were taken by M. Goto at the Large Helical Device (LHD) in NIFS [1]. In this case a cryogenic hydrogen "ice pellet" is fired into a magnetically confined plasma at a speed of - 1 km/sec by a pellet injection system [2]. The plasma temperature is about a kilovolt. The pellet material ablates in the plasma during 400 microseconds. Visible-light spectra are taken every 16 microseconds to make a spectral motion picture. The pellet material begins as a dense plasma, so the continuum lowering is strong. During the first 200 microseconds, one can resolve levels up to - $n = 5$ consistent with $n_e \sim 10^{17}/cm^3$, and there is evidence of recombination to the hydrogen negative ion.

The spectra show a mysterious feature: the line-width and continuum lowering increase in time, over some 200 microseconds, as if the electron density were increasing by about a factor two. Since the pellet begins as a cryogenic liquid and is heated by the kilovolt LHD plasma, common sense would argue that the pellet should rapidly expand and its density should rapidly decrease.

Hydrodynamic analysis of the pellet ablation explains why the density seems to rise. The hydrodynamic expansion is driven by heat conduction from the hot plasma and deposition by energetic ions from the neutral-beam heating. Our calculation assumes an initial pellet temperature .05 eV, and assumes external heating approximately equal to the heat flux-limit from a 1 keV plasma environment at $n_e = 10^{14}$ cm^{-3}. As each fluid zone expands, its density drops, and the overall pellet density drops as the pellet ablates. However, the inner part of the pellet is too cold to emit radiation and the outer part is thoroughly ionized. The emission comes from a range of densities on the outer part of the expanding pellet material.

The observed rising electron density near the emitting atoms can be understood as a consequence of heat conduction from the hot exterior during the hydrodynamic expansion of the pellet. Hydrogen in the pellet core is too cold to radiate and the exterior is too hot to emit line radiation. The emission comes from an intermediate region whose density would decrease in time if hydrodynamic flow were dominant, but which increases because the heat conduction is (evidently) more rapid than the hydrodynamic flow.

We concentrate on the region that emits the H_β line. We form an average electron density $< n_e(r,t)>$ weighted by the population of the $n = 4$ excited state $N_4(r,t)$, and find this average electron density does indeed increase with time over the first 200 microseconds of pellet ablation. The 1 - D (planar) calculation does not match the experiment (it predicts higher average densities) but it has the correct qualitative behavior.

Our numerical simulation of the pellet heating includes flux-limited heat conduction and volume heating by high-energy ions from NBI. Hydrogen pressure and energy are obtained from an atomic model including molecules, positive and negative ions and a range of excited states of neutral H. The populations are determined by equilibrium statistical mechanics.

This experiment gives a spectroscopic test of heat conduction in high-density plasma. Since there is a long history of controversy about flux-limited and anomalous heat conduction in comparable laser-produced plasmas, finding a satisfactory numerical model for this relatively well-characterized plasma dynamics has broad scientific interest.

References

[1] private communication.

[2] H. Yamada, R. Sakamoto, Y. Oda, T. Hiramatsu et al., Fusion Engineering and Design 49, 915 (2000); R. Sakamoto, H. Yamada, K. Tanaka, K. Narihara et al., Nuclear Fusion 41, 381 (2001).