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Peaked Density Profiles and High Speed Pellet Injection for the Ignitor Burning Plasma Experiment

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Introduction

A four barrel, two-stage pneumatic pellet injector for the Ignitor experiment is under construction in collaboration between the ENEA Laboratory at Frascati and Oak Ridge National Laboratory. The goal is to reach pellet velocities of about 4 km/s, capable of penetrating near the center of the plasma column when injected from the low field side.

Ignitor is a compact, high magnetic field device (R_0=1.32 m, B_T =13 T) designed to attain ignition in high density, relatively low temperature plasmas ($n_e \cong n_i \cong 10^{21}$ m^{-3}, $T_{e0} \cong T_{i0} \cong 11$ keV) and $n_0/\langle n \rangle > 2$. Previous analyses[1] have shown that ignition can be achieved with ohmic heating only or with small amounts of additional ICRF heating, provided that a sufficient temperature is reached during the initial plasma current rise, so that fusion-generated alpha particles can start contributing to further heat the plasma. In this phase, it is particularly important to tailor the density profile peaking to obtain an optimal rate of ohmic and fusion heating. For this reason, a pellet injector has always been included in the Ignitor project.

The innovative concepts at the basis of the Ignitor Pellet Injector (IPI) design are the proper shaping of the propellant gas pressure front to improve pellet acceleration, and the use of fast valves to considerably reduce the expansion volumes which prevent the propulsion gas from reaching the plasma chamber.

The Ignitor pellet injector.

The IPI consists of four independent injection lines, each including a two-stage pneumatic gun (TSG), a pulse shaping relief valve (PSV)[2,3], a pipe-gun barrel, a propellant gas removal line and related diagnostics, sharing a single cryostat, a common pellet mass probe, and an accelerometer target. Two independent sub-systems have been built by ENEA and ORNL separately.

The ENEA sub-system includes the pneumatic propelling system (4 TSGs and 4 PSVs), the gas removal system (4 independent lines) and related diagnostics as well as its own control and data-acquisition system. The results of extensive tests carried out with this facility have been described in detail in a previous paper,[4] and will not be reported here. The equipment is ready for shipping to ORNL for final joint experiments.


Figure 1. The ORNL facility during preliminary tests

The ORNL sub-system consists of the cryostat and pellet diagnostics. The assembly of most of its components was recently completed (Figure 1), and initial testing with D_2 pellets were carried out. Figure 2 is a close-up view of the inside of the IPI vacuum chamber, showing the freezing zones of the four gun barrels. Upstream and downstream heaters will be added on each barrel (in close proximity to the freezing zone) to provide different thermal gradients for optimized pellet formation. The injector housing design facilitates change-out of gun barrel sets of varying lengths (from 0.7 to 1.1 m). Also, the effective breech length can be varied from 5 to 10 cm. New light gate and microwave cavity mass detector diagnostics have been developed specifically for this application. The light gates make use of only external components (outside the vacuum environment), with a line laser providing the light source and a relatively large detection breadth. A single, toroidally shaped, microwave cavity similar to that used on the Madison Symmetric Torus[5,6] is used to simultaneously monitor all four of the guide tubes. The cavity is equipped with four internal teflon tubes in which the pellets pass through; the tubes are sealed from the cavity such that the injection lines are isolated. This feature is necessary to comply with the ENEA gas removal system. A target chamber will be added at the injector downstream end and will be equipped with a thin aluminum disc and shock accelerometer for determining pellet dispersion and arrival times. Its design allows for target change-outs while the rest of the system remains under vacuum. The ORNL automated control system is based on a personal computer running Lab-


Figure 2. Inside of the IPI cryostat

View and allows the user to setup and control the injector granting highly repeatable results. The pellet firing is controlled with microsecond precision. Data is collected by 8 fast (up to 10 MHz) and 16 slower (up to 333 kHz) digitizer channels. Four 240 frames/s cameras are triggered to capture individual video frames of each pellet in flight. After each shot the pellet pictures and the data collected from different diagnostics are automatically archived and displayed on the users screen along with pellet speeds and masses.

In the initial configuration, the injector has been equipped with four barrels of different bores (2.1, 2.2, 3.0, and 4.6 mm), pellet acceleration lengths of 94 cm, and effective breech lengths of 10 cm. Standard ORNL propellant valves[7] provide the gas to accelerate D_2 pellets to speeds of ≈1 km/s. Cooling is provided by a pulse tube cryo-refrigerator (Cryomech CP980 compressor package and PT810 cold head with a rating of 4 W at 8 K). During preliminary tests, the barrel freezing zones have been cooled down to 10 K in ≈1 hr. An aluminum cold shield surrounding the freezing zones will be added and attached to the first stage of the cold head. The shield and many (≥ 20) layers of super-insulation are considered necessary in order to achieve the minimum temperature (≈8 K or less) for D_2 pellets. Nevertheless, more than 30 pellets have been successfully formed and launched during preliminary tests (without the shield) using the 3 mm bore barrel (see Figure 3). After adding the features discussed above and thorough testing of the injection system with the propellant valves, the ENEA and the ORNL systems will be integrated, and testing at high pellet speeds (up to 4 km/s or higher) will be carried out with a wide range of operating parameters explored. If results from testing at high speeds indicate that even lower pellet temperatures would be useful, the injector is equipped with components to accommodate supplemental cooling from a liquid helium dewar. This would allow pellet operation at temperatures approaching 5 K.

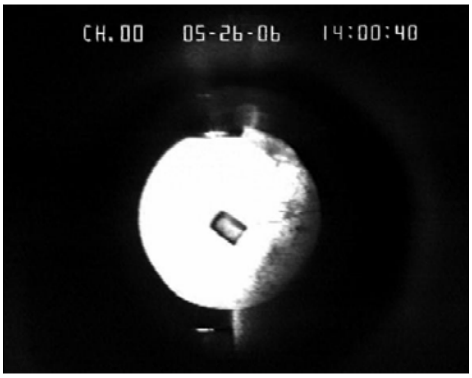

Figure 3. In-flight picture of a 3 mm D_2 pellet, travelling at about 1.2 km/s.

Pellet penetration in Ignitor and JET

An analysis of D_2 pellet penetration for Ignitor was carried out, using the NGS ablation model[8], for the pellet sizes and speeds that the IPI is capable of producing. Plasma temperatures and densities were described by parameterized profiles, with central values ranging from 1 to 13 keV for the temperature, and 0.5 to 12.5 × 10^{20} m^{-3} for the density. Thanks to the compact size of the machine, it was found that pellets of 4 mm at 4 km/s can reach the central part of the plasma column for the typical plasma parameters found at or near ignition conditions. At the lower parameters, smaller and slower pellets can be used.

In order to assess the possibility of testing the new injector on existing experiments, the same model was used to simulate the penetration on JET, for a range of relevant parameters. A more detailed analysis was carried out for a particular case, shot 51976, a 9 keV plasma with an internal barrier[9], for different pellet sizes and speeds. Injection is from the low field side midplane and no mass drift effect is included in the calculation. Fig. 4 shows that a 5 mm pellet at 4 km/s can reach the region inside the ITB, where a higher peak density could produce considerably higher pressures. Such an experiment would be useful also because future burning plasma experiments (e.g., Ignitor and ITER) will operate at a relatively low value of the dimensionless parameter ν* and, for both devices, relatively peaked density profiles are expected to be beneficial from several perspectives; in particular they can provide a stability edge against the so-called ITG modes that enhance the ion thermal transport.

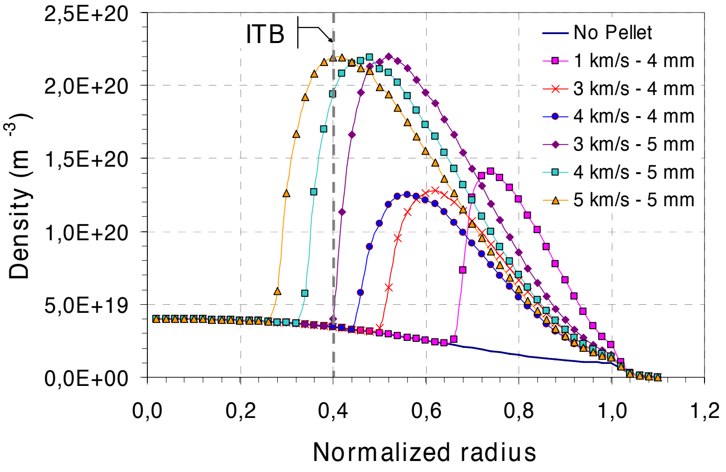

Figure 4. Estimated penetration depth in JET of D_2 pellets (4 to 5 mm size range) injected in the midplane from the LFS

References

[1] B. Coppi et al., *Nucl. Fusion* Vol. 41(9), pp. 1253-1257 (2001).

[2] A. Frattolillo et al. Fusion Technol. 32, 601 (1977)

[3] Italian patent and trademark Office, Rec. No. RM95A000100 issued on Feb. 20, 1995

[4] S. Migliori et al., Proc. of the 21st IEEE/NPSS Symposium on Fusion Engineering, Knoxville (TN), Sept. 26-29, 2005 (to be published)

[5] S. K. Combs et al., Proc. of the 19th IEEE/NPSS Symposium on Fusion Engineering, Atlantic City, NJ, Jan. 22-25, 2002 (IEEE Cat. No. 02CH37231, Piscataway, NJ, 2002) pp. 76-79.

[6] S. K. Combs et al., Fusion Science and Technology, 44 (2), 513-517 (2003).

[7] S. L. Milora et al., *Rev. Sci. Instrum.* 57(9), 2356-2358 (1986).

[8] P. B. Parks, R.J. Turnbull, *Physics of Fluids* 21, 1735 (1978).

[9] R. V.Budny et al., *Plasma Phys. Control. Fusion* 44, 1215 (2002).