

Development of the High Speed Pellet Injector for Ignitor

A. Frattolillo¹, F. Bombarda^{1,3}, S. Migliori¹, S. Podda¹, M. Capobianchi¹, G. Ronci¹, L. R. Baylor², S. K. Combs², S. Meitner², C. Foust², D. Fehling², J. McGill², B. Coppi³, G. Roveta⁴

¹ENEA - C.R. Frascati, Frascati, Italy

²Oak Ridge National Laboratory, Oak Ridge, TN (USA)

³Massachusetts Institute of Technology, Cambridge, MA (USA)

⁴Criotec Impianti, Chivasso, Italy

Introduction.

For Ignitor plasmas, control of the density profile during the initial plasma current rise is important to optimize ohmic and fusion heating rates. For this reason, a pellet injector has always been included in the Ignitor design. Simulations performed with the NGS ablation model¹, for the reference ignition plasma parameters ($n_{e0} \cong n_{i0} \cong 10^{21} \text{ m}^{-3}$, $T_{e0} \cong T_{i0} \cong 11 \text{ keV}$), indicate that deuterium pellets of a few mm in size ($\leq 4 \text{ mm}$) injected at 3-4 km/s from the low field side should achieve sufficient penetration.

ENEA and ORNL are collaborating on the construction of a four barrel, two-stage pneumatic injector^{2,3,4,5} for the Ignitor experiment, featuring two innovative concepts: (i) the proper shaping of the propellant pressure pulse to improve pellet acceleration, and (ii) the use of fast closing ($< 10 \text{ ms}$) valves to drastically reduce the expansion volumes of the propellant gas removal system. The Ignitor Pellet Injector (IPI) consists of four independent injection lines, each including a two-stage pneumatic gun (TSG), a pulse shaping relief valve (PSV)^{6,7}, 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 ORNL sub-system consists of the cryostat and pellet diagnostics, with related control and data acquisition system. New light gates, microwave cavity mass detector and control software have been developed specifically for this application. The ENEA sub-system, including four independent two-stage guns (TSGs) and pulse shaping valves (PSVs), the (patent pending) gas removal system (GRS), and the associated controls and diagnostics, has been thoroughly characterized at CRIOTEC. In particular it was shown that the pressure rise in the downstream expansion volume could be completely cut-off by reducing to 1.6 ms the delay (relative to the pressure pulse time) with which the fast gate valve starts to close. Such a delay allows pellets traveling at speeds of 2

km/s or more to safely cross the gate, which is placed about 3 m downstream of the gun muzzle. The ENEA sub-system has been finally shipped to Oak Ridge, to be coupled with the ORNL facility for joint experiments.

Upon delivery of the ENEA equipment, the Italian team spent one week (on May 12-16, 2008) visiting ORNL, to jointly carry out a preliminary short experimental campaign aimed at: (i) completing testing of D₂ pellet formation and launch with all four barrels, using ORNL single-stage propellant valves, (ii) inspecting the ENEA equipment against damages possibly suffered during the travel from Italy to USA, (iii) reassembling the whole ENEA equipment and (iv) trying to separately operate the TSGs. A preliminary attempt to couple the two sub-systems, with the aim of testing their information exchange protocol (i.e. of checking that they correctly talk to each other), was regarded as a secondary issue, in case the main program would have been completed ahead of schedule. The excellent results achieved in this preliminary joint experimental campaign are reported.

Experimental results.

Testing of D₂ pellets formation and launch at speeds of ~ 1 km/s, using ORNL single-stage propellant valves, have been successfully carried out with all four barrels. The addition of the cold thermal radiation shield inside the cryostat resulted in a lower ultimate temperature (~8 K) of the freezing zones, as compared to that (~10 K) measured without the shield. Wrapping the shield with several (≥ 20) layers of super-insulation should grant some further improvement. Moreover, if necessary, the cryostat is equipped with components for providing supplemental cooling by a liquid helium dewar, using a special flexible transfer tube built by ENEA, which allows only cold helium vapors to circulate in the cryostat (this indeed prevents the onset of thermal oscillations at low temperatures)⁸. The ORNL automated control system, based on a personal computer running LabView, allows the user to setup and control the injector, granting highly repeatable results. After some initial trials, aimed at adjusting the main pellet formation parameters (temperature of the freezing zone, D₂ pressure and flow, and so on), several shots were performed, in which all four pellets were successfully launched.

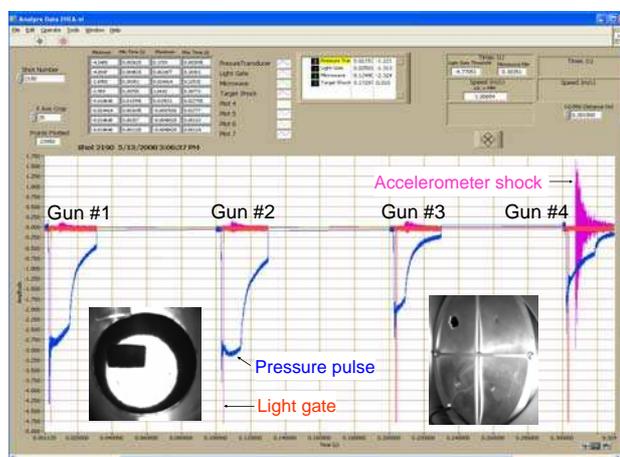


Figure 1. Record of a typical shot with all four guns.

The data acquisition system demonstrated very high reliability, allowing regularly capturing records of each shot. Figure 1 shows a typical record of a shot sequence with all four pellets. In this case, guns 1 to 4 were firing, in the order, at 100 ms from each other. The insets show the in-flight picture of the 4.6 mm pellet (left) and the brass target with the impact pattern of four intact pellets (right). The four expanded windows in figure 2 show details of pressure pulse, light gate, microwave cavity mass detector and shock accelerometer for each pellet, referred to the same shot of figure 1; as expected, the amplitude of the mass detector signal is proportional to pellet size.

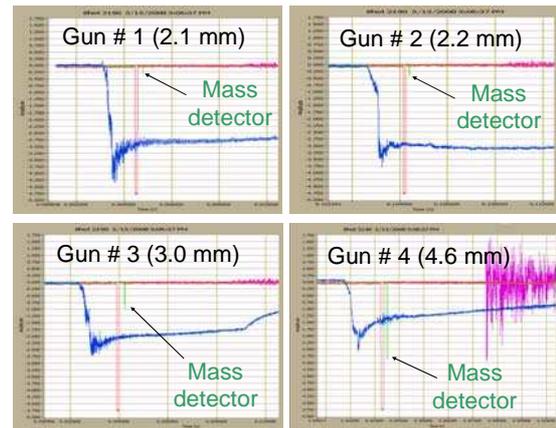


Figure 2. Expanded view of data recorded for each gun, in the same shot of figure 1.

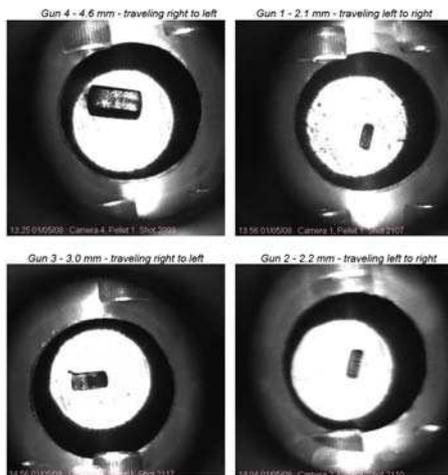


Figure 3. In flight pictures of D2 pellets of different sizes, accelerated at speeds of about 1 km/s, using standard ORNL propellant valves.

Unfortunately, only one of the four photographic stations was complete and fully operational, because of the deplorable delay in the delivery of the laser beam expanders by the manufacturer (Edmund Optics).

In-flight pictures of pellets from different guns (figure 3) had therefore to be taken individually, in different shots, by relocating the laser light each time.

The ENEA equipment was unpackaged, inspected and thoroughly reassembled. In less than two days, the TSGs were operational, and a few separate shots were performed, just in order to check that everything was working properly. Also the GRS was completely

reassembled, and made ready for successive integration in the ORNL facility (figure 4). On the last two days, a preliminary attempt to couple the two sub-systems was carried out. In the final configuration of the IPI, the four TSGs will be directly connected to the rear flange of the cryostat, in order to minimize dead volumes at the gun breeches. This demands the existing ORNL rear flange (which accommodates the four propellant valves), to be replaced by the ENEA flange



Figure 4. The assembled ENEA GRS at ORNL

(supporting the four TSGs), as schematically shown in figure 5. However, in this phase, opening the cryostat vacuum enclosure to replace

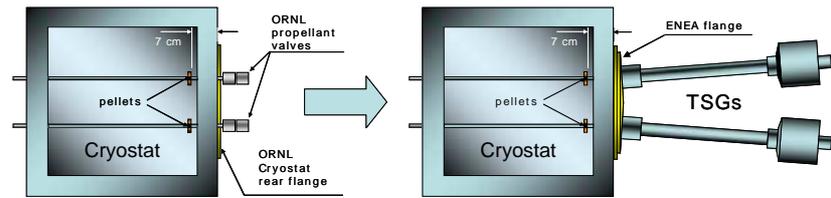


Figure 5. Schematics of transition from present to final IPI configuration

the flange would have required too much time. Preliminary tests have been therefore carried out using only gun #4 (4.6 mm bore) in a quick-fix coupling configuration. The corresponding ORNL propellant valve

was removed and a piece (about 30 cm long) of 4 mm i.d. stainless steel tube

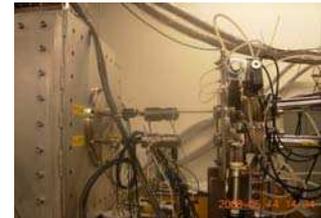
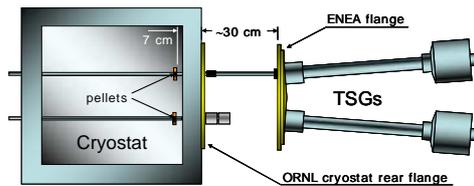


Figure 6. The quick-fix configuration used in preliminary joint tests.

TSG head and the gun breech, as shown in Figure 6. In spite of such an unfavorable configuration, which adds a huge dead volume to the gun breech, intact pellets were easily accelerated at velocities progressively increasing from ~ 1.2 up to ~ 2 km/s (figure 7). This result is very promising from the point of view of the final injector speed performance. During this summer, the ORNL team will incorporate the ENEA GRS in their equipment, and will prepare the cryostat in order to accommodate the four two-stage drivers, which will replace the ORNL propellant valves.

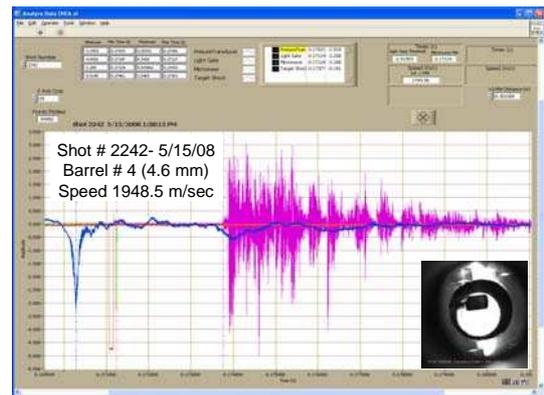


Figure 7. Record of a shot at ~ 2 km/s

Joint testing of the injector in its final configuration will start on next September.

References

- [1] P. B. Parks and R. J. Turnbull, *Physics of Fluids* 21(10), pp. 1735-1741 (1978).
- [2] A. Frattolillo et al. Proc. of the 45th Annual Meeting of the Division of Plasma Physics (DPP03), Albuquerque (NM), U.S.A., Oct. 27-31 2003
- [3] S. Migliori et al. Proc. of the 21st SOFE, Knoxville (TN), USA, Sept. 26-29 2005
- [4] A. Frattolillo et al. Proc. of the 33rd EPS Conference on Plasma Phys. Rome, Italy, 19 - 23 June 2006, ECA Vol. 301, P-4.185 (2006)
- [5] A. Frattolillo et al. Proc. of the 22nd IEEE/NPSS Symposium on Fusion Engineering (SOFE07), Albuquerque (NM), U.S.A., June 17-21 2007
- [6] A. Frattolillo et al., *Fusion Technol.* 32, 601 (1977)
- [7] Italian patent and trademark Office, Rec. No. RM95A000100 issued on Feb. 20, 1995
- [8] L. Martinis et al. Proc. of the 13th SOFE, Knoxville (TN), USA, Oct. 2-6, 1989