

Progress with the ENEA-ORNL high-speed four barrels pellet injector

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Introduction.

Pellet injection is a well proven technology representing to date the most efficient method for core fuelling of fusion plasmas. It is believed that, due to favourable drift effects across the plasma column, injection from the inboard torus side via curved guide tubes can provide high fuelling efficiency, in spite of restrictions imposed to the projectiles speed by such a scheme. Extensive tests carried out at ORNL suggest that the speed will need to be limited to a few hundreds of m/s, for reliable delivery of intact pellets^[1]. Simulation codes, however, indicate that the fuelling efficiency increases with the injection speed^[2], while recent tests at Asdex Upgrade demonstrated that D₂ ice pellets can survive at velocities of ~ 1 km/s inside a guiding system, provided this is very carefully designed^[3]. Moreover, when injection from the inboard torus side is impractical due to tight space (as will be for instance the case of Ignitor and JT60-SA), pellets have to be necessarily injected from the outboard side at speeds ≥ 3 km/s, in order to achieve sufficient fuel penetration in spite of the unfavourable drift.

ENEA and ORNL are therefore collaborating on the development of a high-speed four-barrel “pipe gun” injector for the Ignitor experiment (fig. 1), designed to launch D₂ ice pellets (1.9,

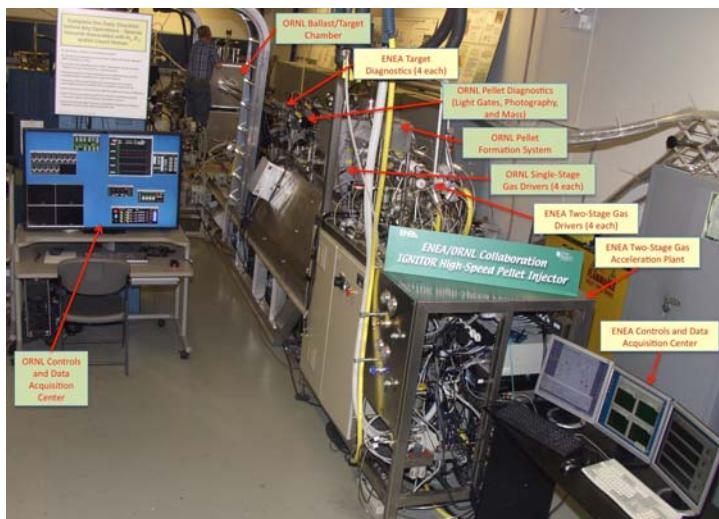


Figure 1. The Ignitor high-speed four barrel pellet injector at ORNL

2.6, 3.2 and 4.4 mm in size) at speeds up to 4 km/s, using two-stage light gas guns^[4].

Innovative features of the ENEA-ORNL injector.

ENEA and ORNL have been collaborating on high-speed pellet injectors since early 90's. A previous joint experimental effort was dedicated to the development

of a high-speed repeating injector, by coupling an existing ORNL piston extruder and an ENEA two-stage gun capable of operating at a repetition rate of 1 Hz. During preliminary tests with this device, the very low break-away pressure of extruded pellets (as compared to that of “in-situ” frozen projectiles) caused them to start moving rather unpredictably, resulting in a wide spread and in a significant reduction of speed performance (≈ 2 km/s). A spring actuated check valve, opening at a well-defined upstream pressure threshold and designed to allow the dynamic transmission of the pressure pulse, was therefore developed by the ENEA team and fitted at the downstream end of the pump tube. This device, capable of suitably tailoring the shape of the rising edge of the pressure pulse, prevented premature movement of the projectiles and improved their acceleration, allowing to launch intact pellets at speeds up to 2.5 km/s, while strongly reducing the spread of experimental data ^{[5], [6]}.

An upgraded (electromagnetically driven) version of this valve has been included in the design of the present “pipe gun” injector, with the aim of investigating whether it may be beneficial from the point of view of speed performance, as well as to improve both reliability and versatility of the whole system. As a matter of fact, this valve prevents the propellant gas, initially admitted at relatively low pressure in front of the piston, from escaping through the gun breech when the cut off valve (separating the gun and the barrel) is opened for firing, thus protecting the piston, which is prevented from hitting the end of the pump tube. Besides strongly reducing the risk of failures of the two-stage gun, this valve allows performing test shots even in the absence of a projectile inside the barrel. Moreover, the new design of the valve, which uses the magnetic field generated by a solenoid to produce the closing force, is much more reliable and versatile as compared to the previous spring loaded prototype, actually getting rid of issues related to the progressive yielding of the spring, while allowing to adjust the force acting on the shutter by simply varying the electric current flowing in the solenoid. The injector accommodates both an ORNL propellant valve and an ENEA two-stage gun on each barrel (fig. 2). A check valve is placed downstream of each propellant valve, preventing flow of hydrogen gas in the backward direction; this ensures that the propellant valves will not be exposed to the hot, high peak pressure pulses generated when

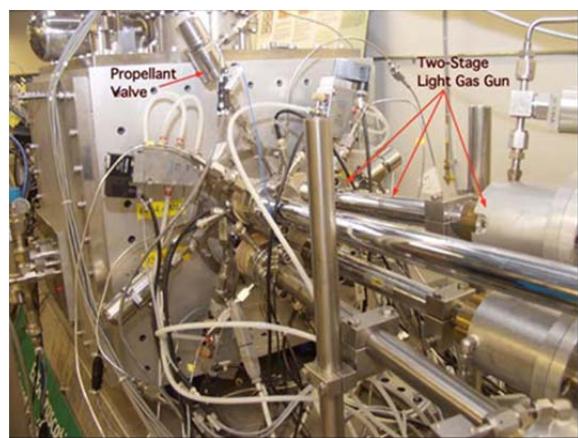


Figure 2. The new arrangement accommodating both a propellant valve and a two-stage gun on each barrel.

firing the two-stage guns. Several hundred shots have been performed, alternating single and two-stage gun operation, without any failure. In the future, this unique feature will provide great flexibility on a fusion experiment since the operator can switch seamlessly and at any time between standard and high-speed pellets, on any or all gun barrels.

Latest improvements.

The injector's cryostat can operate as a cryogen free device. In joint tests carried out up to date at ORNL, it was cooled down using a Cryomech PT810 two-stage pulse tube cryo-generator, already in use at ORNL. With this device, featuring a cooling power of 80 W @ 80K on the first stage and 14 W @ 20K on the second stage, the minimum temperatures reached inside the cryostat were ~100K at the thermal radiation shield, and ~10 K at the pellet freezing zone (nominal 8 K should be available on the second stage with no thermal load). In these conditions launching speeds up to 2.6 km/s have been easily obtained, but pellets were broken above 2 km/s. A more powerful pulse tube cryo-cooler (Cryomech PT415) has been procured by the ENEA team, and replaced the existing unit with the aim of enhancing pellet formation and producing better ice quality. This device, featuring a refrigerating power of 40 W @ 45 K on the first stage and 1.5 W @ 4.2 K on the second (nominal minimum temperature without thermal load is 2.8 K), was chosen also for its design, almost similar to that of the PT810, allowing replacement of the existing unit with minimal mechanical adjustments. Preliminary cooling tests with the PT415 showed a significant reduction of the temperatures achieved at both the shield (~50 K) and the freezing region (~7.5 K).

Remote operation of the injector.

Remote operation capability via Ethernet is a further distinctive feature of this injector. With computer security recently given higher priority than ever at ORNL, getting remote access to local computer has been really challenging. A remote control station has been set up at ENEA Frascati (figure 3), consisting of



Figure 3. The remote control station at ENEA Frascati

several computers that exactly replicate the configuration of the local control system at ORNL. A point to point secure connection enables each ENEA terminal talking with its corresponding local unit. Exceptions to the ORNL firewall had to be raised to allow the static IP addresses assigned to ENEA computers to get through, log into their own paired local unit and share their desktops, using RealVNC® software. Remote operators can thus get full access to the C&DAS of the injector, using the comprehensive LabView software running on local computers. To ensure an adequate level of IT security, access from Frascati to ORNL computers via VNC is protected by a password, but also subject to prior authorization by an operator at ORNL. The full Ethernet bandwidth (1 Gbit) is used to speed up the communication. Additional desktops are also provided for video conferencing, using Blue Jeans platform, and to control and monitor two Ethernet based video surveillance cameras, one installed at ORNL and the other at ENEA, so that visual contact can be maintained throughout each experimental session. Recently, preliminary tests using ORNL propellant valves have been successfully carried out. Solid deuterium pellets have been seamlessly and repeatedly formed and launched at moderate speeds (~ 1 km/s), using up to all four barrels, without coming across any operational issue or failure. Communication via 1 Gbit Ethernet proved fast enough, so that remote operators do not detect any substantial delay as compared to local operation. Actually, remote operation of the injector turns out to be as easy as local operation at ORNL. Experimental data, stored in the hard disk of ORNL computers, are also available to the ENEA team throughout the experimental session, however cloud based solution are being considered to make data accessible to both parties at any time, as well as live streaming of cameras that monitor and record the impact of pellets on the final targets.

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