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# Development of The High Speed Pellet Injector For Ignitor

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*Abstract*— ENEA and Oak Ridge National Laboratory (ORNL) are collaborating on the development of a four barrel, two-stage pneumatic injector 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 ( $< 10$  ms) valves to drastically reduce the expansion volumes of the propellant gas removal system. Two independent sub-systems have been built and tested separately by ENEA and ORNL. The ENEA equipment has then been shipped to Oak Ridge, where testing of the two coupled systems have started during the last year. The results of the first two short experimental campaigns, jointly carried out by ENEA and ORNL teams (May 12-16 and December 15-19 2008), as well as the latest advancement of this project will be reported.

**Keywords; Ignitor; pellet injector; two-stage gun**

## I. INTRODUCTION

Ignitor is a compact, high field tokamak ( $R_0 = 1.32$  m,  $B_T = 13$  T) designed to attain ignition in high density, relatively low temperature plasmas ( $n_{e0} \cong n_{i0} \cong 10^{21}$  m<sup>-3</sup>,  $T_{e0} \cong T_{i0} \cong 11$  keV), by ohmic heating (or with small amounts of additional ICRF heating). Control of the density profile during the initial plasma current rise is important to optimize ohmic and fusion

heating rates of Ignitor plasmas. Therefore, a pellet injector has always been included in the Ignitor design. Simulations performed with the NGS ablation model [1], for the reference ignition plasma parameters ( $n_{e0} \cong n_{i0} \cong 10^{21}$  m<sup>-3</sup>,  $T_{e0} \cong T_{i0} \cong 11$  keV), indicate that deuterium pellets of a few mm ( $\leq 4$  mm) in size injected at 3-4 km/s from the low field side should achieve sufficient penetration. ENEA and Oak Ridge National Laboratory (ORNL) are collaborating on the development of a four barrel, two-stage pneumatic injector for the Ignitor experiment. The Ignitor Pellet Injector (IPI) features two innovative concepts: (i) the proper shaping of the propellant pressure pulse to improve pellet acceleration, and (ii) the use of fast closing ( $< 10$  ms) valves to drastically reduce the expansion volumes of the propellant gas removal system. Two independent sub-systems have been built and tested separately by ENEA and ORNL. The ORNL sub-system consists of the four barrel (2.1, 2.2, 3.0 and 4.6 mm bores) pipe-gun cryostat, cooled down by a closed cycle refrigerator, and pellet diagnostics, with related control and data acquisition system (C&DAS). Diagnostics include four light gates and a common microwave mass probe, for measuring speed and mass of the pellets, as well as capability of capturing in-flight pictures of all four pellets and a final impact target equipped with a shock accelerometer. New light gate and microwave cavity mass detector have been developed specifically for this application. A single, toroidally shaped, microwave cavity monitors simultaneously all four of the guide tubes [2]. The ENEA sub-

system, including four independent two-stage guns and pulse shaping valves (PSV's) [3,4], the (patent pending) gas removal system (GRS), associated diagnostics and its own C&DAS, has been thoroughly tested at CRIOTEC, prior to being shipped to ORNL. In particular, it was shown that the pressure rise in the downstream expansion volume could be completely cut-off by reducing at 1.6 ms the delay (relative to the pressure pulse time) with which the valve starts closing [5,6]. This is a safe value, since pellets injected at speeds in excess of 2 km/s will require less than 1.5 ms to travel the 3 m distance separating the fast gate valve from the gun muzzle.

Upon delivery of the ENEA equipment at ORNL, the joint experimental phase was started. During last year, the Italian team joined the American scientists at ORNL, to carry out two short preliminary experimental campaigns (May 12-16 and December 15-19, 2008), mainly aimed at coupling the two sub-systems, prior to starting the final experimental phase including high speed tests.

## II. THE FIRST JOINT EXPERIMENTAL CAMPAIGN

Testing of D<sub>2</sub> pellets formation and launch at speeds of ~ 1 km/s, using ORNL single-stage propellant valves, was carried out with all four barrels. More than 30 shots were carried out,

showing very reliable performance of this system. Unfortunately, at that time, the capability of capturing in-flight pictures of the pellets was limited to only one barrel at a time, because of the inexcusable delay in the delivery of the laser beam expanders, by the manufacturer (Edmund Optics). The only beam expander available was used to test the four photographic stations one by one, which nonetheless demonstrated very satisfactory performance. The ENEA equipment was readily reassembled. The four two stage pneumatic guns assembly was made ready to operate in less than two days (while testing the ORNL equipment). Also the propellant gas removal system was thoroughly reassembled and made available for successive integration in the ORNL facility. A preliminary attempt to combine one of the four ENEA two-stage guns with the ORNL cryostat, using a temporary configuration, was also carried out. A series of 45 shots was performed, with 4.6 mm D<sub>2</sub> pellets consistently launched at progressively increasing velocities, up to ~ 2 km/s, in spite of the unfavorable arrangement featuring a large dead volume at the gun breech [7].

## III. THE SECOND JOINT EXPERIMENTAL CAMPAIGN

In the course of the second campaign, the ENEA two-stage drivers have replaced the ORNL propellant valves (fig. 1).



Figure 1. A picture of the IPI during the second short campaign, showing the ENEA TSG's coupled to the ORNL equipment.

Separate testing of each barrel was first carried out, by forming and launching single pellets, using the corresponding TSG. A number of shot sequences with simultaneous formation of all four D<sub>2</sub> pellets, using all four TSGs, were then performed successfully. These preliminary tests, carried out with the four TSG's fitted to the cryostat in their final configuration, demonstrated that the two systems match properly, while their respective control systems interface correctly. The four photographic stations, completed by the ORNL team prior to starting this campaign, performed very reliably allowing repeatedly capturing frames of all four pellets at each shot (fig. 2). During these tests, however, the pulse shaping valves exhibited some very small leakages. Leak tightness of components interfacing the cryostat is important, since even a very small leakage leads to the accumulation of frozen moisture inside the barrels and results in an unsatisfactory quality of the cryogenic pellets, which may not withstand the very strong acceleration required to achieve speeds in the 3 to 4 km/s range. Therefore, at the end of this second campaign, the valves were returned to Italy to be modified, in order to improve their leak tightness. As a further problem, the analysis of the impact patterns at the final target plate showed that (i) pellets were persistently aiming at the left-upper corner of their respective impact sector, and (ii) most pellets were broken, indicating that they were hitting somewhere along their path to the target. The in-flight pictures as well revealed that pellets were often broken before entering the photographic window (placed less than 0.5 meter downstream of the gun muzzles). This clearly indicated that the cryostat had got somewhat out of the injector axis, maybe while replacing the rear flange or, most likely, during coupling with the TSG stand. To deal with this issue, the ENEA team had built a simple system, consisting of four small adapting flanges which can replace the four TSGs at the cryostat rear flange, and allow feeding the light of small

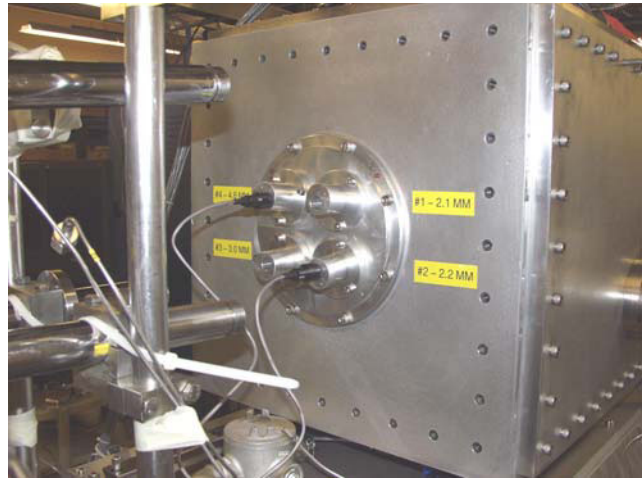


Figure 3. The cryostat rear flange equipped with the four adapters supporting the laser diodes (two are shown on barrels 2 and 4).

laser diodes along the axis of each barrel (figure 3). The collimated laser light passes all the way through the barrels and emerges at the other extremity. By opening the door of the impact target assembly, the laser spots can be easily detected by means of a video-camera facing the injector at the downstream end (figure 4). The position of each laser spot in the plane of the final flange (which is close to that of the impact target) was located by intercepting its light (which then disappears in the image recorded by the camera) by means of a rule, allowed to slide in the plane of the flange.

#### IV. MOST RECENT ADVANCEMENTS

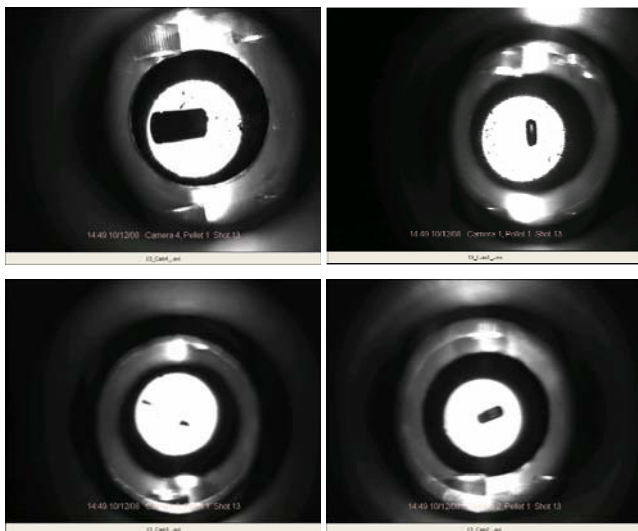


Figure 2. In-flight pictures of all four pellets, as captured in a single firing sequence

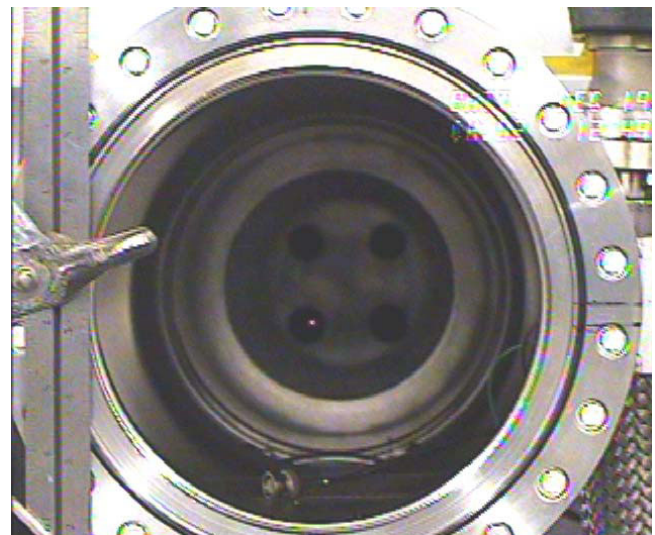


Figure 4. Typical image recorded by the video-camera facing the injector at the downstream end. The laser spot emerging from barrel 2 is clearly visible.



Figure 5. The TSG's facility for testing of components in the laboratory at ENEA Frascati Research Center. From left to right: the stand including the TSG module and the gas distribution manifold, the control system and the PC running the LabView control software.

A specific device is under construction at ENEA Frascati, consisting of a couple of vernier calipers, orthogonal to each other, which can be accommodated on the flange of the impact target port. This particular arrangement will allow carefully identifying the position of each laser spots on the target, by intercepting their light. An automatic facility, equipped with a TSG, has also been built at Criotec, and is presently operating at ENEA Frascati Center (figure 5). The construction of such an item was indeed necessary, after delivery of the four TSG's system to ORNL, in order to have a tool in Frascati for testing components (such as the PSV's), in almost the same conditions they will have to operate on the IPI. The modular design of this equipment, however, allows it to fit different situations. Both the TSG module, including its set of valves, gauges and ballistic transducers, and the gas manifold, are stand-alone units which can be easily removed from the main frame; use of flexible hoses allows easily changing their mutual arrangement. Two long cables (one each) connect these two units to the control system, which is accommodated in a standard 19" rack module, so that it can be easily fitted in any rack. Communication between the control unit and the remote PC, running the LabView control software, is achieved via an Ethernet cable. This test facility, therefore, is ready in principle

for installation on any injector. Capability of performing repeating operation is also being implemented.

The launch of pellets at high speed is planned for this summer, following some more testing of the propellant valves. The integration of the Gas Removal System into the injector system will follow as the last step.

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