The Compact, Multiple Barrel High Speed Pellet Injector for the Ignitor Experiment

S. Migliori[a], A. Frattolillo[a], S.K. Combs[b], L.R. Baylor[b], G. Roveta[c], F. Bombarda[a, d], R. Foust[b], D. T. Fehling[b], J. M. McGill[b], J.B.O. Caughman[b], J.C. Thomas[d]
a ENEA – CR Frascati, Frascati, Italy
b Oak Ridge National Laboratory, Oak Ridge, TN
c CRIOTEC IMPIANTI, Chivasso, Italy
d Massachusetts Institute of Technology, Cambridge, MA

***Abstract*—A four barrel, double stage pellet injector for the Ignitor experiment is under construction in collaboration between the ENEA Laboratory at Frascati and the Oak Ridge National Laboratory. The goal is to reach pellet velocities up to 4 km/s. Innovative concepts at the basis of the injector design considerably reduce the requirements on the expansion volumes necessary to prevent the propulsion gas to reach the plasma chamber. The full four barrels, double stage gun and gas removal system have been built and tested, while the design and construction of the pellet injector vacuum chamber, cryogenic system, gun barrels and pellet diagnostics is underway at ORNL, where the final assembly and testing of the complete system will be carried out.**

Keywords: Ignitor, pellet injector, high speed pellet injector

I. INTRODUCTION

As shown in previous analyses [1], Ignitor can reach ignition shortly after the end of the current ramp (╬ 4 s) when Ohmic heating only is present, with central density n_0 ╬ 10^{21} m^{-3}, peak temperature T_{e0} ╬ T_{i0} ╬ 11 keV, B_T ╬13 T and I_p ╬ 11 MA.

Although the line average density for the highest performance plasmas is comfortably below the empirical limit, it is conceivable that such a high value may not be reached sufficiently fast if the plasma is fueled simply by gas puffing or if the net particle loss is higher than expected. The pellet injector has however been included in the machine design also to control the density profile, especially during the crucial phase of the initial current rise. Relatively peaked density profiles (e.g., $n_0/\langle n\rangle$ ╬ 2) are beneficial for fusion burning plasmas from several perspectives; in particular they can provide a stability edge against the so-called η_i modes that enhance the ion thermal transport. The injection of pellets is also envisaged as a possible method to provide fast control of the thermonuclear instability during the ignited phase.

Based on the above issues, a combined arrangement of pipe gun injectors, featuring a limited number of projectiles at high-speed, and repeating injectors (capable of launching a large number of pellets at speeds up to about 2.5 km/s) has been considered. The high-speed injector was given a higher priority among these two options, therefore the main effort has been devoted, in this preliminary phase of the Ignitor project, to the design, construction and testing of a four-barrel pipe gun injector featuring four two-stage pneumatic propellers, and equipped with the necessary diagnostics and propellant gas removal systems. The injector 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 3-4 km/s, capable of penetrating near the center of the plasma column when injected from the low field side, even at or near the ignition temperature, as the compact design of the Ignitor machine (R_0 = 1.32 m, $a \times b$ = 0.47 × 0.86 m^2) makes the injection of pellets from the high field side unpractical, while it is unclear that a vertical injection on the

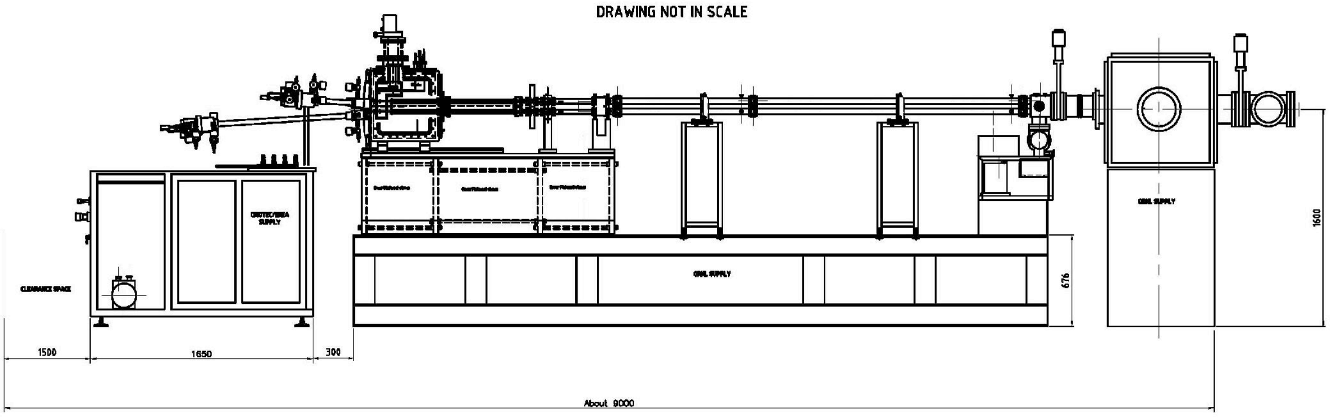

Figure 1. Schematic drawing of the high-speed multi-pellet injector for Ignitor

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magnetic axis would be beneficial.

Since Ignitor will produce plasmas covering a wide range of parameters, a modular, flexible design for the pellet injector is envisaged, allowing for variable pellet sizes and speeds. It draws on the previous joint experimental efforts aimed at the development of a repeating two-stage gun coupled with an ORNL extruder [2]. The pellet dimensions and optimal speeds for Ignitor have been evaluated by means of the PELLET code [3], using the NGS (Neutral Gas Shielding) model [4], both for the reference ignition scenario and a range of other plasma parameters. In a similar fashion, the accessibility of these pellets on other machines presently in operation has been estimated, as possible candidates to host the injector.

In the following sections the main design characteristics of the pellet injector are described and the results of the tests performed so far are shown, together with the plan of the work to be carried out at ORNL to complete the construction and testing.

II. THE MULTIPLE PELLET INJECTOR

In the early nineties, the ENEA team built and tested a similar injector for the Frascati Tokamak Upgrade (FTU), which was capable of launching small deuterium pellets (in the 1.2 to 1.6 mm range) at speeds up to about 3 km/s [5]. The design of this earlier device was strongly influenced by some severe constraints related to the shape of an inner duct inside the access port of FTU, which compelled the Frascati team to develop a number of "*ad hoc*" solutions. Fortunately, similar constraints need not to be met in the case of Ignitor, thus allowing for a simpler design; nevertheless, some of the techniques used in that previous case turn out to be suitable also in the case of the present injector. It has also been demonstrated [6] that, in spite of their heavier mass, bigger pellets (up to 6 mm) are more easily accelerated than smaller ones, mainly due to the larger bore of the launching barrel, which actually enhances the propagation of the propellant gas front along the barrel and may improve the efficiency of energy transfer to the projectile, resulting in higher launching speeds. Optimum performance can be achieved by properly selecting the lengths of the pump tube and of the launching barrel, as well as by an appropriate design of the gun breech. The introduction of relief valves, similar to those used to improve the performance of the repeating two-stage pellet injector jointly developed by ENEA and ORNL [2,7] may also be beneficial to enhance speed performance, as well as to prevent the piston from hitting the end of the pump tube [6] and to reduce the amount of propellant gas to be removed downstream.

A schematic drawing of the facility, presently undergoing its final stage of development, is shown in Fig. 1, while Table I summarizes the main design parameters.

The injector mainly consists of four independent injection lines (each including a two-stage pneumatic gun (TSG), a pulse shaping valve, 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 are under construction, to be preliminarily tested by ENEA and ORNL separately:

- ENEA provides the pneumatic propelling system (4 TSG's and 4 pulse shaping relief valves), the gas removal system (4 independent lines) and related diagnostics, as well as its own control and data acquisition system (C&DAS).
- ORNL provides a 4-barrel pipe-gun cryostat cooled down by a cryocooler (but also equipped with a liquid helium line to provide additional refrigerating power if needed), pellet diagnostics (including mass and speed measurements, in flight pictures, and accelerometer target) as well as related C&DAS.

The interfaces have been carefully agreed by the two teams in a closely coordinated manner, in order to prevent any trouble when coupling the two subsystems for final joint testing, which will be carried out at the ORNL site. Also the cross-talk protocol of the control systems, independently developed by ENEA and ORNL using LabView, has been defined in detail.

TABLE I. MAIN DESIGN PARAMETERS OF THE IGNITOR HIGH-SPEED, MULTIPLE PELLET INJECTOR

No. of pellets:	4
Pellet material:	Deuterium
Pellet sizes:	in the range relevant to IGNITOR and presently existing tokamaks (2 – 4.5 mm nominal diameter)
Pellet speed:	3.5 – 4 km/s (or higher if possible)
Type of cryostat:	Pipe gun, cooled by a cryocooler. The cryostat design will allow for easily accommodating barrels of different sizes and lengths; it will also be equipped with a vacuum transfer line allowing for providing additional refrigerating power (if necessary) by liquid helium coolant.
Propulsion:	4 independent two-stage pneumatic guns, each equipped with diagnostics. The propelling system will include 4 independent relief valves, capable of suitably shaping the rising edge of the pressure pulse to improve pellet acceleration.
Diagnostics:	Pressure pulses (piezoelectric ballistic transducers), pellet speed (light gates) and mass (microwave cavity), in flight picture (laser strobe and camera), accelerometer impact target.
Gas removal system:	A particular effort will be made to reduce the overall size of this system, trying to avoid the use of large expansion volumes.

III. THE PROPELLING SUB-SYSTEM

The pneumatic propelling sub-system built by ENEA at Criotec Impianti (Chivasso, Turin) is shown in Fig. 2. Both the hardware and the software are almost completed, and final testing of this part of the plant is scheduled to start early on next October. The whole sub-system should be ready for shipment to Oak Ridge by the end of this year.

A new design of the pulse-shaping valve has been developed, which grants improved reliability with respect to the previous version. Moreover, the absence in the present project of the severe constraints encountered in the case of FTU, allowed the separation of the gas removal system into four independent (and identical) systems, which no longer need

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to use large expansion chambers. Details about these two topics will not be given here, since both the new design of the pressure-tailoring valve and that of the innovative gas removal system are patent pending.

Extensive preliminary tests have been already carried out using only one injection line, in order to optimize the design and the performance of these new concepts. The pulse shaping valve has been tested first, using a short (about 10 cm) stainless steel tube placed downstream of the valve and closed at its end, to simulate the conditions actually met in the real experiment, where the pellet "plugs" the barrel at roughly such a distance from the gun breech.

Figure 3 shows the typical shapes of the pressure pulses upstream (a) and downstream (b) of the relief valve, as measured by means of two identical ballistic pressure monitors. The valve actually suppresses the pressure pulse downstream until the upstream pressure overcomes the relief threshold, thus sharpening the rising edge of the pulse at the gun breech. Roughly speaking, this effect corresponds to an increase of the pellet breakaway pressure, resulting ultimately in an enhanced speed performance.

During preliminary tests of the gas removal system, an 80 cm long stainless steel barrel took the place of the cryostat, thus connecting the TSG and the gas removal line. The presence of the pulse-shaping valve at the end of the pneumatic gun allowed avoiding the use of surrogate pellets. Actually, should the valve be removed, the TSG could not operate without a pellet "plugging" the barrel, since in this case the propellant gas would escape the pump tube, thus resulting in the piston hitting the end of the tube. As a matter of facts, the relief valve prevents such an occurrence, allowing the tests to be carried out in a much easier way. It must be clear, however, that the absence of a pellet causes the propellant gas to cross the barrel by far more quickly, thus resulting during these tests in a reduced efficacy of the gas removal scheme, with respect to real operating conditions.

Two different bores were investigated, using 6 and 4 mm I.D. barrels. This is, once again, an unfavorable condition, since the gas throughput increases very quickly with the barrel diameter; however it was of great interest to test the performance of this system in the worst operating condition, in order to settle the limits of this technology.

The performance of this innovative concept has been estimated by monitoring the pressure rise inside a 300 liter tank placed downstream of the gas removal line and simulating, in a certain sense, the tokamak vacuum chamber. The tank is evacuated (with an ultimate vacuum in the 10^{-3} Pa range) by means of a turbo molecular pump; a CF100 gate valve allows isolating the tank from both the injection line and the pump.

Let the maximum acceptable amount n_{max} of propellant gas escaping the gas removal line be a given fraction α of the pellet content n_p (moles); typically, $\alpha \leq 5\%$ is considered as a reasonable value. Assuming that frozen projectiles have the shape of small equilateral cylinders (i.e. with length l equal to their diameter d), we have:

$$n_{\max} = \alpha \pi d^3 \rho / 4$$

where ρ ($\approx$ 0.05 mole/cm^3) is the density of solid deuterium. The corresponding pressure rise P_{max} in the 300 liter tank is therefore expected to be:

$$P_{\max} = \frac{n_{\max} RT}{V}$$

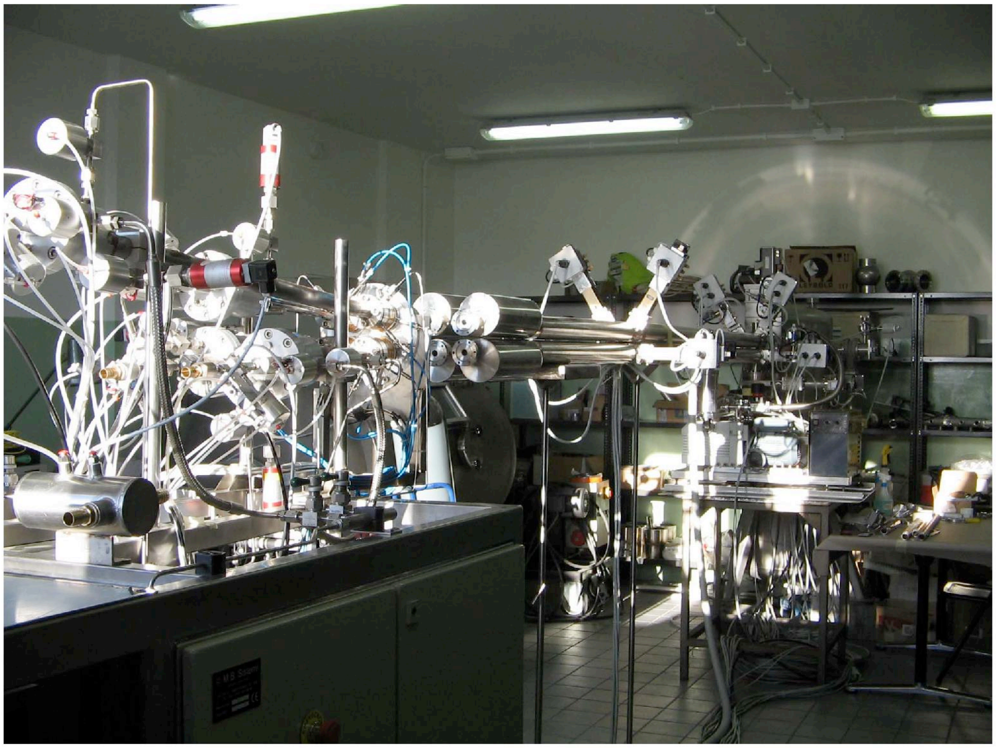

Figure 2. The ENEA sub-system under construction at Criotec Impianti

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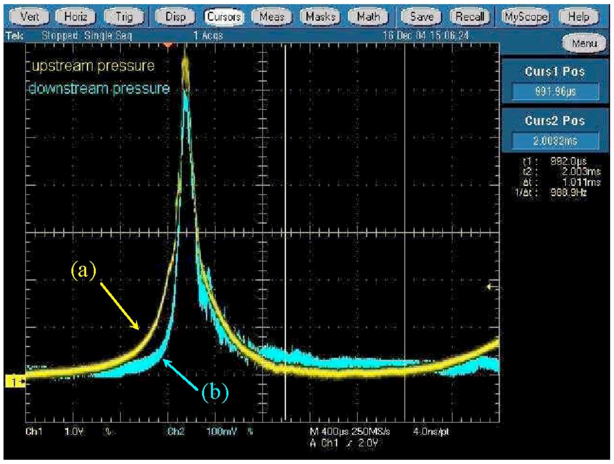

Figure 3. Typical shapes of the pressure pulses upstream (a) and downstream (b) of the relief valve

where R (= 8.314 J/mole K) is the molar gas constant, T (≈ 300 K) is the ambient temperature and V (≈ 0.3 m^3) is the volume of the tank. Satisfactory performance is achieved, provided that the recorded pressure rise P is less than P_{max}.

Many somewhat different configurations (of the same concept) have been tested, resulting in a progressive improvement of the performance, until satisfactory operation has been finally achieved. Preliminary assessments have been carried out using nitrogen as a first approach; then hydrogen propellant has been introduced for latest refinements, after an almost optimized arrangement had been found out. The results achieved with the ultimate configuration, using the 4 mm I.D. barrel and hydrogen propellant, are summarized in Table II, showing that the measured propellant gas load is below 1%.

TABLE II. PERFORMANCE OF THE GAS REMOVAL SYSTEM

Barrel I.D., d (cm)	0.4
Corresponding pellet mass, n_p (moles)	2.45×10^{-3}
Maximum acceptable gas load, α	5 %
Maximum acceptable gas load, n_{max} (moles)	1.23×10^{-4}
Maximum acceptable pressure rise, P_{max} (Pa)	1.02
Measured pressure rise, P (Pa)	2×10^{-1}
Measured propellant gas load	0.98%

IV. CRYOGENICS AND FUTURE ACTIVITIES

ORNL is responsible for the design, construction, and testing of the pellet injector vacuum chamber, the cryogenic systems, the gun barrels, and pellet diagnostics (including light gates/photography stations, microwave cavity mass detector, and a target plate). The injector housing incorporates a new telescopic feature that facilitates change-out of gun barrel sets of varying lengths in the range of 0.7 to 1.1 m. New light gate and microwave cavity mass detector diagnostics have been developed at ORNL 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. The new microwave cavity is equipped with four internal polyimide tubes in which the pellets pass through; the tubes are sealed from the cavity such that the injections lines are isolated. This feature is particularly important for the experimental studies of the gas removal system

In initial testing at ORNL, four barrels with diameters in the range of 1.8 to 4.4 mm will be extensively tested with ORNL single-stage propellant valves and D_2 pellets at speeds of ~1 km/s. In the second phase, the ENEA two-stage drivers and support systems will replace the ORNL propellant valves, and integrated testing at high pellet speeds (>3 km/s) will be carried out with a wide range of operating parameters explored. These activities are expected to start at the beginning of 2006.

V. SIMULATION OF PELLET PENETRATION IN IGNITOR AND OTHER DEVICES.

Using the NGS ablation model [4], an analysis of deuterium pellet penetration in Ignitor was conducted for various pellet sizes and speeds in order to assess the range of operational scenarios in which a high speed pellet can reach significant penetration when launched from the low field side midplane. The plasma characteristics were described by parameterized profiles for temperature and density, and penetrations were calculated for a broad range of pellet velocities and diameters, and of central plasma temperatures. The influence of other parameters, such as profile peaking factors and plasma density has also been considered. Thanks to the compact size of the machine, it was found that pellets of 3.5 mm at 4 km/s can reach within the inner 30% of the plasma column for temperatures up to 10 keV, or higher with pellets of larger diameter, for the typical profile shapes found at or near ignition conditions.

In order to assess the possibility of testing the new injector on existing experiments, the same model was also used to simulate the penetration in JET, DIII-D, Alcator C-Mod, and FTU, for a range of plasma parameters accessible to each of these devices. Not surprisingly, a possible window of operation exists on every one, given the flexibility of the injector in terms of pellet dimensions and speeds. On the smaller devices like Alcator C-Mod and FTU, however, the high speed capabilities of the injector would probably not be fully exploited.

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