The Compact, Four Barrel High Speed Pellet Injector For The Ignitor Experiment

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Abstract*— 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^{-3}, $T_{e0} \cong T_{i0} \cong$ 11 keV), by ohmic heating (or with small amounts of additional ICRF heating). Tailoring of the density profile peaking during the initial plasma current rise is important to optimize ohmic and fusion heating rates. Therefore, a pellet injector has always been included in the Ignitor design. Simulations performed with the NGS ablation model, for the reference ignition plasma parameters in Ignitor, indicate that deuterium pellet of a few mm sizes (≤ 4 mm) injected at 3-4 Km/s from the low field side should achieve sufficient penetration, particularly during the current ramp up. A four barrel, two-stage pneumatic injector for the Ignitor experiment has been built in collaboration between ENEA and Oak Ridge National Laboratory, 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. The ENEA sub-system, including four independent two-stage guns and pulse-shaping valves, the gas removal system, and the associated controls and diagnostics, has been extensively tested at CRIOTEC. The ORNL sub-system consists of the cryostat and pellet diagnostics, with related control and data acquisition system. Initial testing with D_2 pellets at speeds of ~1 km/s, using ORNL single-stage propellant valves, are scheduled to be completed by June 2007. The ENEA two-stage drivers will then replace the ORNL propellant valves, and integrated testing at high speeds (>3 km/s) will be finally carried out. The NGS model was also used to assess the maximum ablation depth of D_2 pellets, of the sizes and speeds produced by the Ignitor Pellet Injector, inside JET plasmas. A similar analysis is now extended to the Large Helical Device (LHD), which has recently obtained high density plasma discharges (up to 5×10^{20} m^{-3}). Deep pellet penetrations can be achieved over a wide range of plasma parameters in LHD, even at its highest temperature, thanks to the high speed of the IPI pellets.

Keywords-component; Ignitor, high-speed pellet injector. deuterium

I. INTRODUCTION

Previous analyses [1] have shown that 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. A pellet injector has therefore been included in the machine design 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. Pellet injection is also envisaged as a possible method to provide fast control of the thermonuclear instability during the ignited phase.

The compact design of the Ignitor machine (R_0 = 1.32 m, $a \times b = 0.47 \times 0.86$ m^2) makes the injection of pellets from the high field side unpractical, while it is unclear that a vertical injection on the magnetic axis would be beneficial. An analysis of penetration of D_2 pellets, injected from the low-field side, was therefore carried out for Ignitor, using the neutral gas shielding (NGS) ablation model [2], for different pellet sizes and speeds. 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. Based on the above issues, a high-speed four barrel pipe gun injector, featuring four independent two-stage pneumatic guns, has been considered as part of the pellet fuelling system. The injector has been constructed in collaboration between the ENEA Laboratory at Frascati and Oak Ridge National Laboratory. In the following sections the main design characteristics of the pellet injector are described and the results of the more recent tests performed are shown, together with the plan of the work to be carried out at ORNL to complete the testing.

II. THE IGNITOR PELLET INJECTOR

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.

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The IPI consists of four independent injection lines, each including a two-stage pneumatic gun (TSG), a pulse shaping relief valve (PSV) [3,4], 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 (figure 1) consists of a 4-barrel pipe-gun cryostat, cooled down by a pulse-tube cryo-refrigerator (but also equipped with components to provide supplemental cooling from a liquid helium dewar if necessary), pellet diagnostics (including mass and speed measurements, in flight pictures, and accelerometer target) as well as related C&DAS. In the initial configuration, the cryostat has been equipped with 94 cm long barrels having different bores (2.1, 2.2, 3.0, and 4.6 mm). A detailed description of this facility, featuring a very flexible design, has been given in a previous paper, together with the results of preliminary tests carried out with the system partially assembled, using only one launching barrel [5]. The assembly has been recently completed, and tests with all four barrels are scheduled soon after this conference, using ORNL propellant valves.

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 (C&DAS). This facility has been extensively tested at Criotec Impianti in Chivasso (Turin), showing very satisfactory performance [6]. Before shipping it to ORNL, some refinements have been recently made. The C&DAS has been improved, with the addition of a second computer and two supplemental monitors (figure 2). This allows control and data acquisition to be performed independently on two distinct computers, and provides an easier and more immediate access to both mimics and plots of collected data, which can be shown simultaneously on different monitors. The design of the pulse shaping valves has been also upgraded, by integrating in the valve body an additional cut-off (pneumatically actuated) ball valve, which allows separating the pneumatic guns from the launching barrels inside the cryostat (figure 3). The commands of these additional valves have been integrated in the control software. Thanks to this feature, it is possible to disassemble each TSG from the cryostat (e.g. for maintenance purposes) without breaking the vacuum inside the launching barrel; moreover, possible small leakages through the PSV, when filling the pump tube with H_2 propellant, can be totally neglected.

Figure 1. The ORNL facility during preliminary tests of last year

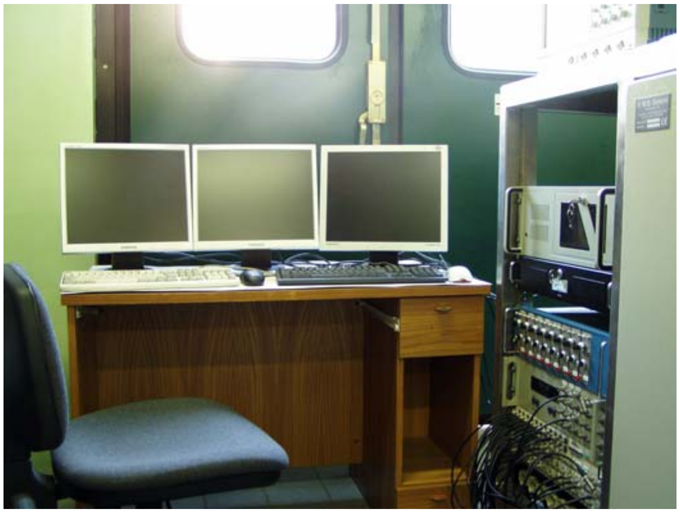


Figure 2. The new consolle of the ENEA sub-system

Further tests have also been finally carried out in order to complete the characterization of the (patent pending) gas removal system. Figures 4 and 5 show the progressive attenuation of the pressure rise recorded in an expansion volume placed downstream of the gas removal system, as a result of the gradual reduction of the delay (referred to the

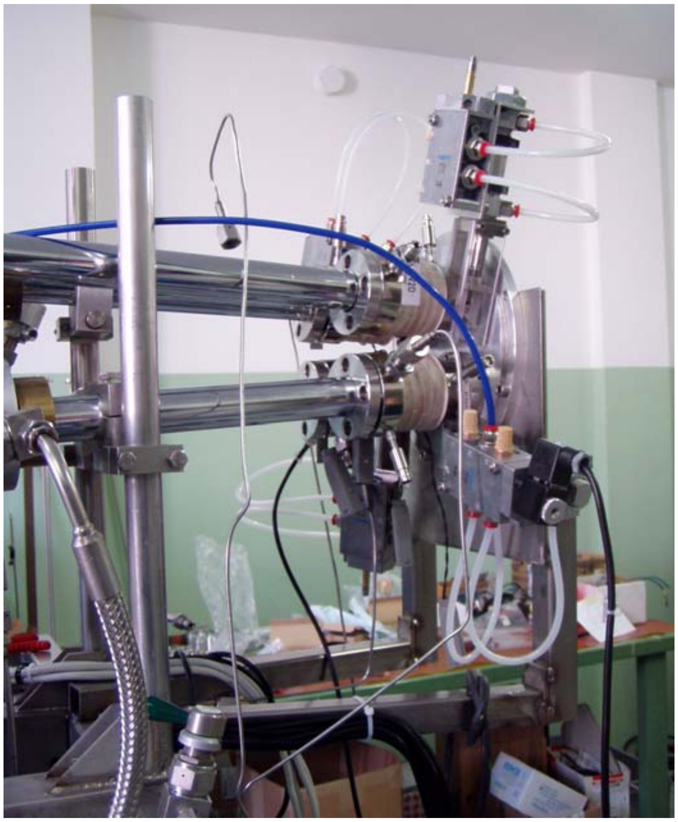


Figure 3. The new pulse shaping valves with integrated cut-off ball valves

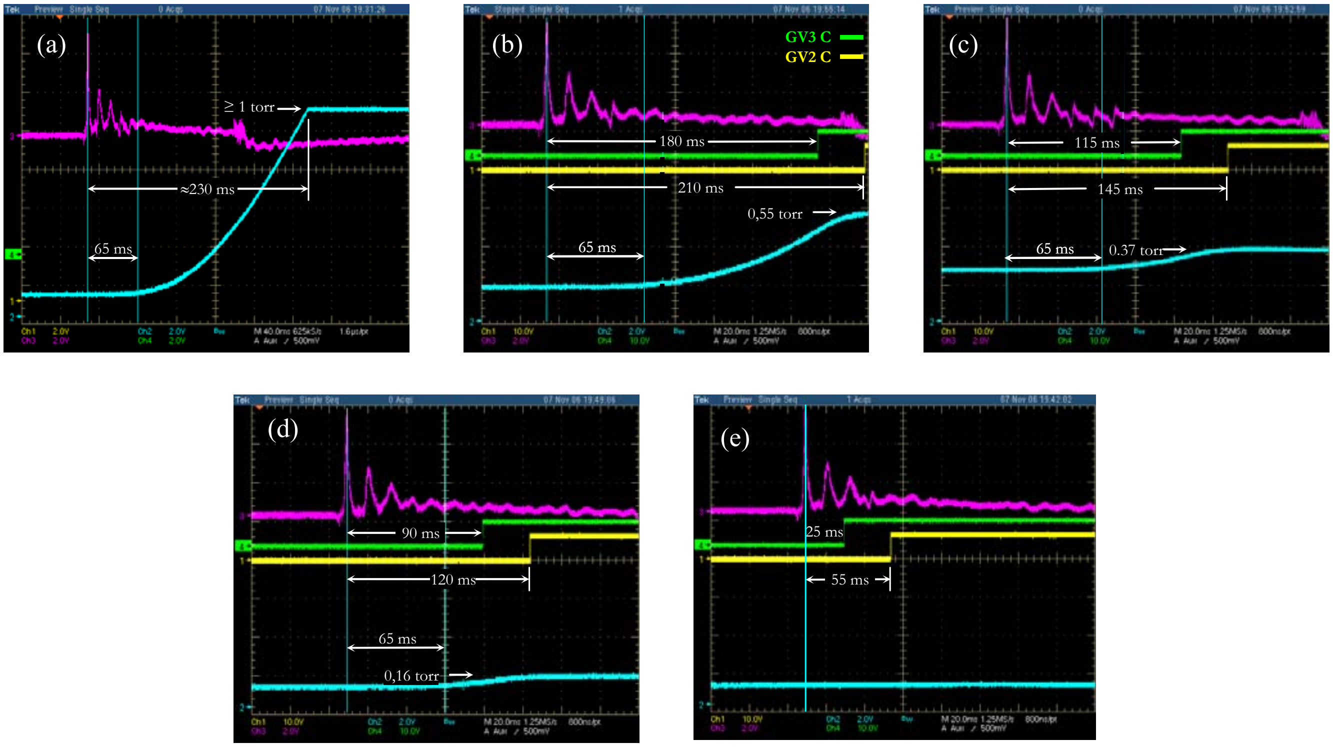
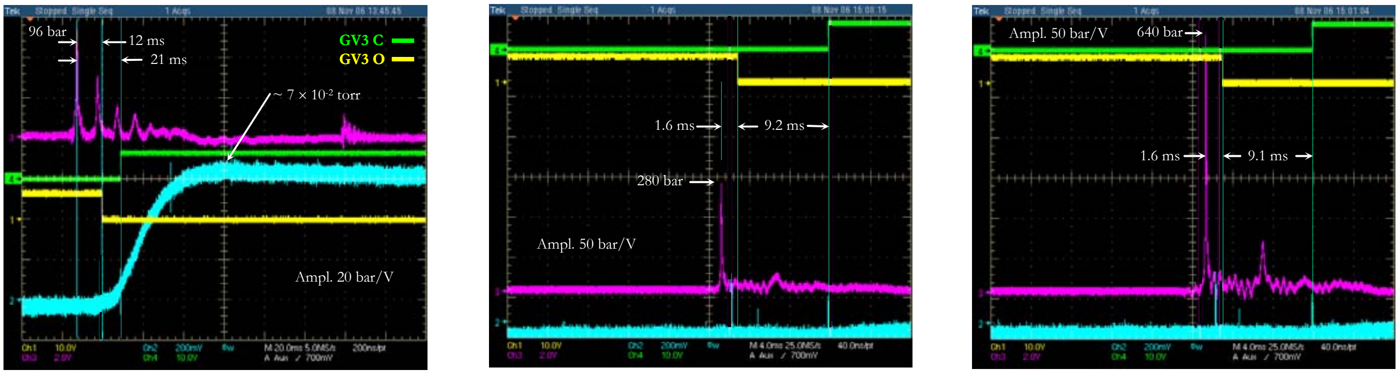


Figure 4. Progressive attenuation of the nitrogen pressure rise recorded in the final expansion volume (downstream of the gas removal system) as a result of the gradual reduction of the time delay (referred to the pressure pulse occurrence) with which the fast valves GV2 (2 m apart) and GV3 (3 m apart) closes. (a) The gate valves are excluded and the pressure rises above the full scale range (1 tor) of the capacitive gauge head. (b) Closing the gate GV3 at about 180 ms results in a consistent reduction of the amount of gas passing over the removal system. Further reducing the delay of the gate valve, as in (c) and (d), turns out in a progressive improvement of performance, until, at a delay of 25 ms, no pressure rise is detected in the downstream volume.



(a) (b) (c)

Figure 5. Progressive attenuation of the hydrogen pressure rise recorded in the final expansion volume (downstream of the gas removal system) as a result of the gradual reduction of the time delay (referred to the pressure pulse occurrence) with which the fast valve GV3 (placed 3 m apart) closes. For pressure peaks above 280 bar (figures (b) and (c)), an effective cut-off of the downstream hydrogen pressure is achieved by starting to close the fast valve 1.6 ms after the pressure peak (the gate closes completely within about 9 ms).

pressure pulse time) with which the fast valve closes. Figures 5 (b) and (c), in particular, demonstrate that, for pressure peaks above 280 bar, an effective cut-off of the downstream hydrogen pressure is achieved by starting to close the fast valve 1.6 ms after the pressure peak (the gate closes completely within about 9 ms). At speeds above 2 km/s, the pellet travels the distance up to the gate (placed about 3 m downstream) in less than 1.5 ms, thus crossing the gate safely.

A special transfer line, purposely designed to decant cold helium vapors only from a liquid helium dewar [7,8], has also been constructed at Criotec. Previous experience have indeed demonstrated that the onset of thermal oscillations at the pellet freezing zone, usually observed when liquid helium is used to cool down the cryostat, can be prevented by allowing only cold vapor to flow through the heat exchanger. This decant line will be shipped to ORNL, to provide additional cooling of the cryostat if necessary.

The ENEA equipment will be shipped to ORNL, where the two systems will be matched for final joint testing, by the end of this year. The goal is to reach pellet velocities of about 3-4 km/s. A first experimental campaign is scheduled soon after delivery of the equipment at ORNL.

III. ABLATION DEPTH OF D_2 PELLETS INTO THE LARGE HELICAL DEVICE

At velocities of about 4 km/s, pellets of the sizes which the IPI is able of producing, are capable of penetrating near the centre of the plasma column when injected from the low field side, in Ignitor as well as in JET [9]. A similar analysis, based on the well known NGS ablation model [10], has been applied to plasmas produced by the Large Helical Device (LHD) [11]. This is a superconducting, large aspect ratio (plasma major radius R = 3.9 m, minor radius a = 0.6 m), net current-free heliotron machine, where remarkably high densities ($n_{e0} \sim 6 \times 10^{20}$ m^{-3}) plasmas have been obtained with pellet injection in the presence of a Local Island Divertor (LID). These dense, well confined, but relatively cold (< 1 keV) plasma regimes have the potential of leading to new ignition scenarios provided that higher temperatures (of the order of 10 keV) are achieved. The estimated maximum penetration depth for a 3 mm pellet (~1.3 x 10^{21} D ions) is shown in Fig. 6 as a function of increasing electron temperature, for a fixed peak density $n_{e0} = 5 \times 10^{20}$ m^{-3}. At the highest speed, the pellet can penetrate inside the Internal Diffusion Barrier (approximately located at $\rho \sim 0.5$) even at the highest temperatures, possibly raising the density by 2 x 10^{20} part/m^3.

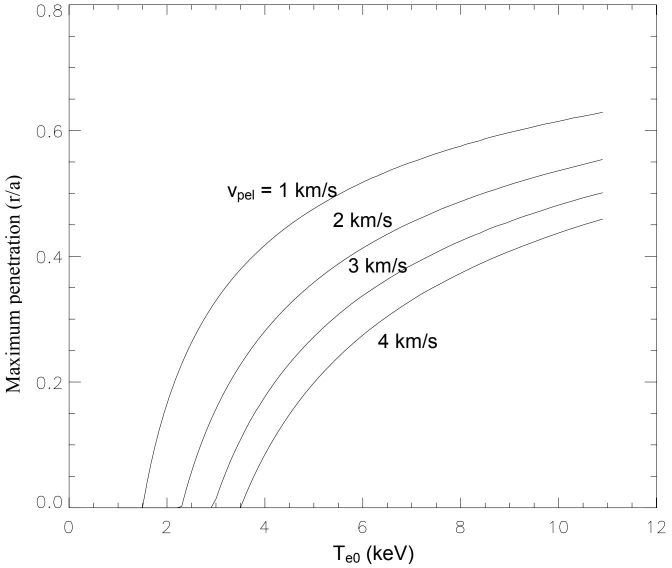


Figure 6. Penetration depths achievable by a 3 mm pellet launched at speeds between 1 and 4 km/s into plasmas of the typical size of LHD (0.6 m) and peak density $n_e = 5 \times 10^{20}$ m^{-3} . The density and temperature profiles are assumed to be parabolic and parabolic square respectively.

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