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Testing of the High Speed Pellet Injector for Ignitor*

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Introduction

A general concern for future burning plasma experiments is that it may prove difficult to fuel the discharge with gas puffing alone, in consideration of the poor penetration of neutrals due to higher densities at the plasma edge. Even in large volume devices, neutral beam injection (NBI) is not expected to give a significant contribution to the discharge particle inventory, and wall recycling should not play an important role. However, it would be preferable to keep the gas injection, in particular the Tritium inventory to a minimum. Therefore, pellet injection is going to play an important role for any size machine aiming at producing plasmas that are significant for fusion.

Ignitor is a compact, high field machine designed to reach ignition in Ohmically heated plasmas (or with modest amounts of additional ICRH heating but no NBI), at high density ($n_0 \cong 10^{21}$ m^{-3}) and relatively low temperatures ($T_e \cong T_i \cong 11$ keV) [1]. It will operate well below the beta and density limits. The relevance of high density plasma regimes for the development of energy producing fusion reactors is analyzed in a separate paper [2]. Time dependent simulations of Ignitor plasmas at full parameters (11 MA, 13 T) by means of the JETTO transport code, indicate that ignition is most readily achieved when adequately peaked density profiles are established ($n_0/\langle n\rangle \cong 2$), as good confinement properties are usually associated with them. A pellet injector has always been included in the Ignitor design, because control of the density profile during the initial plasma current rise is especially important to optimize the Ohmic and fusion heating rates, and it can also be envisaged for a fast quench of the thermonuclear instability.

Simulations performed with the NGS ablation model, for the reference ignition plasma parameters indicate that deuterium pellets of a few mm in size (≤ 4 mm) injected at 3-4 km/s from the low field side achieve the needed penetration into the fusion burning region. In fact, the considered scenario is one where several pellets of increasing size and speed are injected into the discharge during the initial plasma density and current rise. Experiments performed on the Frascati tokamak FTU [3] are the latest to show that pellets delivered into the core plasma in a slow sequence during the discharge can produce higher density and more peaked profiles, corresponding to an overall improved confinement, up to 30% longer than the non-pellet energy confinement time. These considerations have led to the choice, for Ignitor, of a multiple barrel, high speed injector, rather than a repetitive one, which would achieve lower speeds. Injection from the high field side was also ruled out, because the much lower pellet speed due to sharply curved guide tubes seemed to offset any possible benefit deriving from the favorable grad**B** drift.

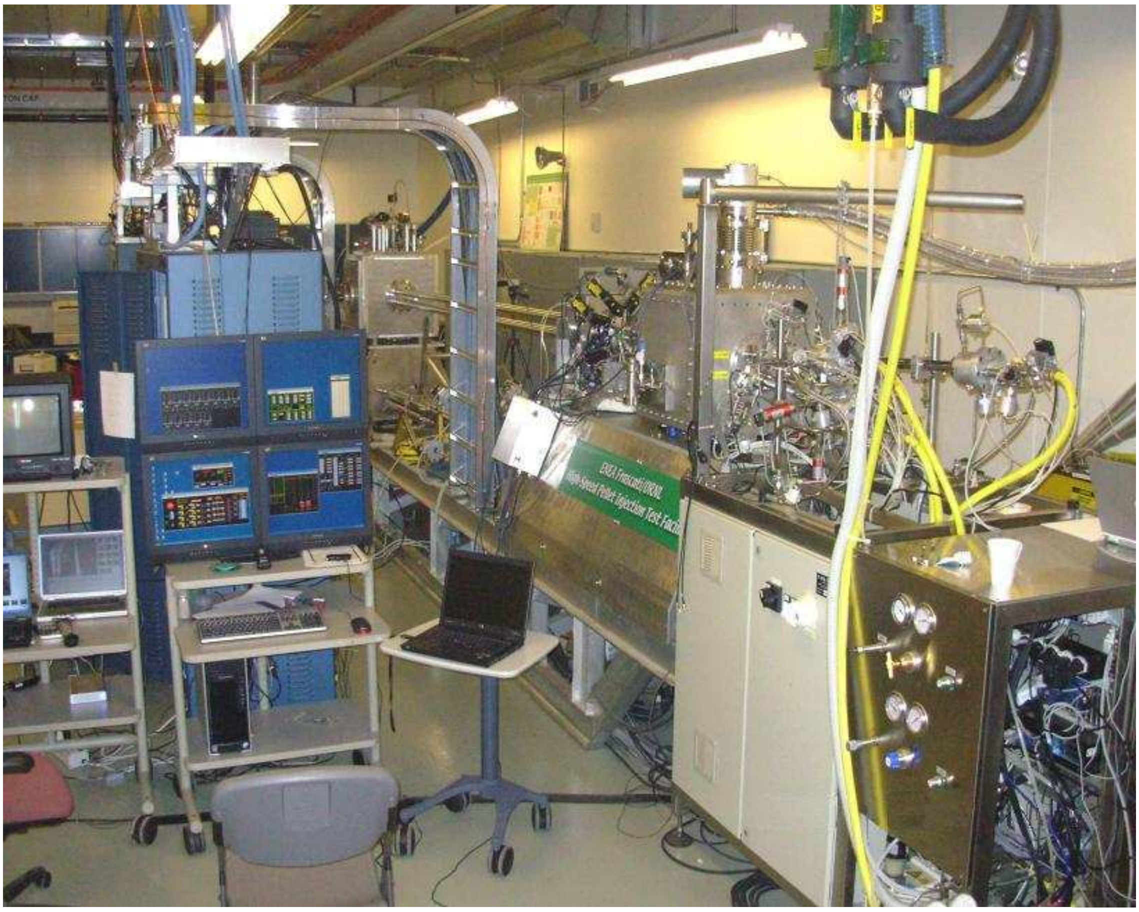

Fig. 1 A picture of the IPI, showing the ENEA TSG's coupled to the ORNL equipment.

The Ignitor Pellet Injector

The Ignitor Pellet Injector (IPI) is developed in collaboration between ENEA and Oak Ridge National Laboratory [4]. The four barrel, two-stage pneumatic injector (Fig. 1) 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 being capable 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 [5]. The ENEA sub-system, including four independent two-stage guns and pulse shaping valves (PSV's), 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 [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.

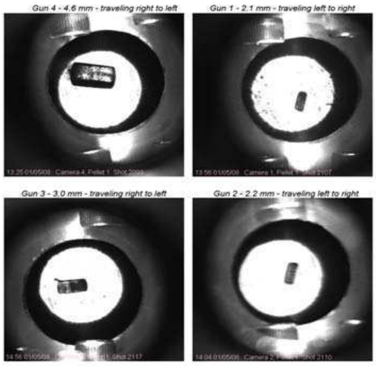

Fig. 2 In-flight pictures of all four pellets, as captured in a single firing sequence.

Two joint experimental campaigns were carried out at ORNL, mainly aimed at coupling the two sub-systems, and at starting high speed tests, after D_2 pellets formation and launch at speeds of ~ 1 km/s, using ORNL single-stage propellant valves, had been successfully demonstrated with all four barrels, showing very reliable performance of the system (Fig. 2). In the first tests with one of the ENEA two-stage guns, a series of shots was performed, with 4.6 mm D_2 pellets consistently launched at progressively increasing velocities, up to ~ 2 km/s, on a single line. All four ENEA two-stage drivers have replaced the ORNL propellant valves, and preliminary tests have been carried out, demonstrating that the two systems match properly and their respective control systems interface correctly. However, some small leakage in the pulse shaping valves and a misalignment of the cryostat and/or the barrels relative to the injector axis, probably occurred during the mechanical coupling, has limited both speed and quality of the resulting pellets. This problem has been dealt with by inserting four small adapting flanges to allow feeding the light of small laser diodes along the axis of each barrel, and by building a specific device for the alignment. A facility was also built by CRIOTEC to allow testing of components, in particular the PSV's, in conditions similar to those they will have to operate on the IPI (Fig. 3). The modular design of the equipment, moreover, allows it to fit different experimental lay-outs and could be used, in principle, for installation on any injector [7]. Such device has allowed to try different solutions to the valve problems, which now perform as desired (i.e., downstream pressure pulse rise time < 200 μs) and soon a new set of PSV valves will be ready for shipping to ORNL. A third experimental campaign is planned to take place before the end of the summer; the integration of the GRS will follow as the last step.

Fig. 3. The automatic TSG facility for testing of valve components

The IPI for other experiments

Pellet injection is performed, more or less routinely, on most present day fusion devices. With the exception of the early experiments on the FTU machine, however, pellet speeds are generally limited to less than 1.5 km/s, and down to about 250 m/s for high field side injection. Not every pellet injection experiment results in improved performance, but deep penetration seems to be a necessary, if not sufficient, condition for the onset of some form of transport barrier. For example, the JET experiment seems to be one that could possibly benefit from a faster injector. We have simulated the injection of pellets up to 5 mm in size and 4 km/s in speed into a high performance JET discharge [5] and the results show that the IPI pellets could indeed reach the plasma core in high performance discharges. Of course there is no way of predicting if the higher pressure gradients could be sustained, on the other hand a wide range of other target plasma can be considered. Even more interesting would be the utilization of the IPI on the LHD experiment, where super dense, but cold, plasmas have been obtained by means of multiple pellet injection [8]. These results are in fact pointing to a fusion reactor based on the helical magnetic configuration with plasma parameters similar to those expected to be achieved in Ignitor. As the heating power on this device is upgraded, a faster injector will be necessary to fuel the discharge and promote the formation of the particle transport barrier. We estimated that the pellet size and speed of the IPI could cover a wide range of plasma parameters produced on the LHD machine.

Conclusions

A pellet injector has always been considered as integral part of the Ignitor machine design to perform a number of tasks, such as (fast) core fueling, density profile control, active burn control, to promote the formation of ITB's, etc. The four barrel, high speed injector developed in collaboration between ENEA and Oak Ridge National Laboratory is a prototype that will soon be available for installation on existing experiments. Of particular interest is the LHD machine in Japan, where exciting high density regimes were discovered that could lead to attractive concepts of fusion reactors.

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