Work in progress with the high speed pellet injector for Ignitor

A. Frattolillo[1], F. Bombarda[1], S. Migliori[1], S. Podda[1], M. Capobianchi[1], G. Ronci[1], L. R. Baylor[2], S. K. Combs[2], C. R. Foust[2], S. Meitner[2], D. Fehling[2], B. Coppi[3], G. Roveta[4]

[1] *ENEA C.R. Frascati, Frascati, Italy*

[2] *Oak Ridge National Laboratory, Oak Ridge (TN), U.S.A.*

[3] *Massachusetts Institute of Technology, Cambridge (MA),U.S.A.*

[4]*Criotec Impianti, Chivasso, Italy*

Introduction.

Ignitor is a compact, high field tokamak designed to achieve ignition in plasmas with Ohmic heating only (or with modest amounts of additional ICRH heating but no NBI), at high density ($n_0 \simeq 10^{21}$ m^{-3}) and relatively low temperatures ($T_e \simeq T_i \simeq 11$ keV).[1] In this experiment, the optimization of Ohmic and fusion heating rates during the initial current rise phase of the plasma discharge is a critical issue, which requires adequate control of the density profile. Gas puffing alone may not be sufficient for this purpose, because of the poor penetration of neutrals, due to the high temperature and density at the plasma edge. Therefore a pellet injector has always been included in the Ignitor design. Pellet injection from the high filed side is unpractical in the case of Ignitor, however, simulations carried out using the NGS ablation model[2], for the reference ignition plasma parameters, indicate that deuterium pellets of a few mm (≤ 4 mm) in size injected at 3-4 km/s from the low field side achieve the needed penetration into the fusion burning region. A fast pellet injector has been therefore developed for this experiment, in collaboration between ENEA Frascati and Oak Ridge National Laboratory (ORNL). The Ignitor Pellet Injector (IPI) consists of two independent subsystems, separately built and preliminary tested by ORNL and ENEA. The ORNL apparatus includes the four barrel cryostat, actively cooled by a closed cycle refrigerator and also equipped to accommodate supplemental cooling from a liquid helium dewar, pellet diagnostics (light gate, photographic station, microwave cavity mass detector, and target/shock accelerometer station) with its own Control and Data Acquisition System (C&DAS). The ENEA subsystem consists of four independent two-stage pneumatic guns (each equipped with innovative magnetic propellant pulse shaping valves), a novel gas removal system making use of fast closing (< 10 ms) gate valves that avoid the need for large expansion volumes, and related C&DAS. The two subsystems have been coupled and preliminary tested in the course of two previous experimental campaigns carried out by the two tams jointly working at ORNL, demonstrating that the equipments match properly, while their respective control systems interface correctly. The injector performed outstandingly well, showing very good repeatability. However, it was more difficult than expected to accelerate pellets to over 2 km/s and observe intact projectiles throughout the pellet diagnostics.[3,4] This indicates that the trajectories of pellets launched at speed over 2 km/s exhibit a too wide dispersion, resulting in most of the pellets breaking (and perhaps slowing down) along their path to the final target. One possible explanation might be due to the oscillation of the thin walled barrels, as a consequence of the propellant shockwave propagating along the tube. As a matter of fact, thin walled stainless steel barrels were used to minimize thermal conduction, however they were not guided tightly enough to prevent such oscillation, for fear of possibly damaging them. This practice, on the other hand, is necessary to ensure precise stability and alignment. Therefore the barrels 1 to 4 have been replaced with ones featuring slightly thicker walls, and having internal diameters of 1.9, 2.6, 3.2, and 4.4 mm, respectively.

Latest experimental results

On last April, two weeks of joint campaign have been carried out at ORNL, to test this new configuration. The dispersion of pellet trajectories was significantly reduced after replacing the barrels, as shown by the impact patterns on the final target. However, the overall alignment of the injector still needs some minor adjustment, as the impact patterns are actually centered slightly on the left of their expected locations (figure 1)

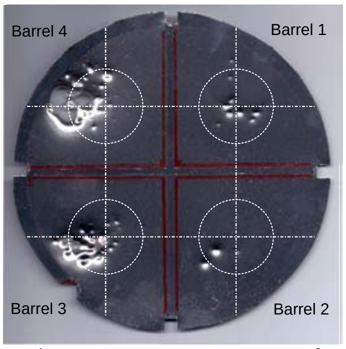

Figure 1. Impact patterns of pellets on the final target

Prior to this campaign, the ENEA team had also developed a new arrangement to accommodate both an ENEA two-stage gun and a standard ORNL propellant valve on each barrel (figure 2). A check valve is placed between each propellant valve and two-stage gun, which allows flow only in the direction from the propellant valve to the pellet; this ensures that the propellant valve will not be exposed to the hot, high peak pressure (easily up to 500 bar) gas pulses generated when firing the two-stage guns. About 200 shots have been fired, alternating single- and two-stage gun operation, without any

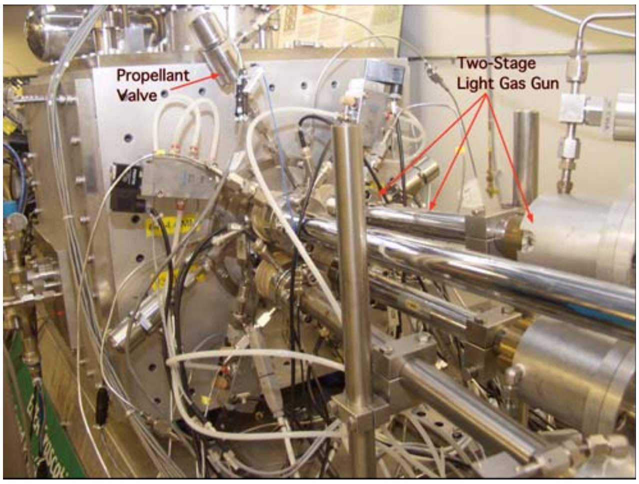

Figure 2. The new arrangement accommodating both single- and two-stage guns on each barrel.

failure. In the future, this configuration will provide great flexibility on a fusion experiment since the operator can switch seamlessly between standard and high-speed pellets on any or all gun barrels.

In addition, the ball valves placed at the gun breech to separate the TSGs and the cryostat, have been equipped each with a couple of limit switches, in order to optimize their timing during the firing sequence. These valves, indeed, must be kept always closed, except when firing; it is important, however, that they open as near as possible to the pressure pulse, to avoid warming up and softening (or even partially melting) the cryogenic pellet by the propellant gas. Preliminary tests, carried out in Frascati prior to shipping the valves to ORNL, showed outstanding performance and excellent repeatability of valve operation; typically, the valves are fully open about 30 ms after energizing their coil. Adjusting the programmable delay of the firing control, relative to that of the ball valve, we are able to get the valve fully open just ~ 5 ms before the pressure pulse starts to rise up, which is a safe but short enough time.

Most of the remaining tests during the two weeks concentrated on optimizing pellet formation parameters (temperature, pressure, upstream and downstream heaters' power) for high speed performance, with the aid of supplemental cooling by the liquid helium dewar. Attempts to push for higher pellet speeds were finally performed. As a first approach, a special transfer tube was used, which was designed by ENEA to allow only cold helium vapor to flow through the cryostat, in order to prevent the temperature oscillations usually observed with liquid.[5,6] This attempt, however, resulted in a poor additional cooling, due to the excessive impedance of the small bore (1/8") tube, allowing vapor circulation inside the cryostat. Such a small tube is perhaps more suitable to ensure adequate thermal exchange by liquid flow. As a matter of fact, better results have been achieved using a standard helium transfer line, allowing liquid helium flow. A suitable procedure was outlined with this configuration. An automatic cut-off valve placed inside the cryostat, allows to start and stop the helium flow. Opening this valve during the warm-up phase (which is necessary to adequately clean-up the system before starting the formation of new pellets) helps rising the temperature of the system, due to the relatively high temperature of the helium vapor initially flowing. As soon as liquid helium reaches the heat exchanger, the temperature begins to fall down; a PID loop then controls the temperature at a desired constant value during pellets formation. Upon completing this phase, the PID heater is switched off, allowing the system to further cool down before firing the pellets. The cut-off valve is finally closed soon after shooting, thus stopping the helium flow, and the warm up phase starts again. This method allows achieving a minimum temperature as low as about 7.5 K, as compared to the 11 K typically attained with the cryocooler only. Such results could be further improved by creating, downstream of the main heat exchanger, a thermal link to the radiation shield, whose temperature is presently limited to a minimum value of about 110 K, typically achieved after several hours of operation.

As for pellet speeds, previous results were consolidated. Figures 3 compares the performance of barrels 3 and 4 achieved during the latest campaign, with those of earlier operation of the

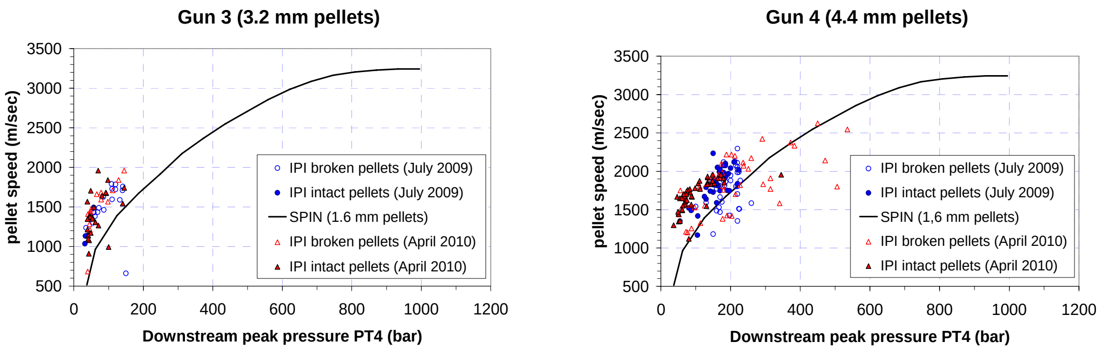

Figure 3. State of the art performance of the IPI. Launching speeds achieved with barrels 3 (left) and 4 (right) are plotted vs the peak value of the pressure pulse produced by the corresponding two-stage guns. Previous results of the SPIN are reported (black line) for comparison.

IPI, as well as with the performance of the FTU Single Pellet Injector (SPIN).[7] Launching speeds as high as ~ 2.6 km/s were achieved. However it was still more difficult than expected to preserve pellet integrity at velocities above 2 km/s. This could be due to the very narrow channel (i.d. ~ 9 mm) guiding the pellets through the photographic station and the mass probe. As the launching speed approaches 2 km/s, the pellets are often observed to rotate, so that they may hit against the side wall of this channel and break. The diameter of this conduit will be enlarged as much as possible prior to the next joint campaign, scheduled by October 2010.

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