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The Ignitor High Speed Pellet Injector* F. BOMBARDA, S. MIGLIORI, A. FRATTOLILLO, ENEA, Italy, L.R. BAYLOR, J.B.O. CAUGHMAN, S.K. COMBS, D. FEHLING, C. FOUST, J.M. MCJILL, ORNL, G. ROVETA, CRIOTEC Impianti, Italy — A joint ENEA-Frascati and ORNL program for the development of a four barrel, two-stage pellet injector for the Ignitor experiment is in progress. The pellets will reach velocities up to 4 km/s, in order to penetrate close to the center of the plasma column when injected from the low field side at the temperatures expected at ignition. Recent activities carried out at ORNL include improvements to the cryostat, the addition of miniature adjustable heaters in the the freezing zone, and of four close-coupled valves for rapid evacuation of gas after a shot. The LabView application software was successfully used to control the simultaneous formation of D_2 pellets, from 2.1 to 4.6 mm in diameter, that were launched at low speed. ORNL developed, specifically for this application, the light gate and microwave cavity mass detector diagnostics that provide in-flight measurements of the pellet mass and speed, together with its picture. The ENEA two-stage pneumatic propelling system, now ready for shipping to ORNL, makes use of special pulse shaping valves, while fast valves in the independent gas removal lines prevent the propulsion gas from reaching the plasma chamber. Novel experiments, e.g. to create high pressure plasmas in existing devices using this innovative facility, have been envisioned and are being simulated.

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The Ignitor High Speed Pellet Injector

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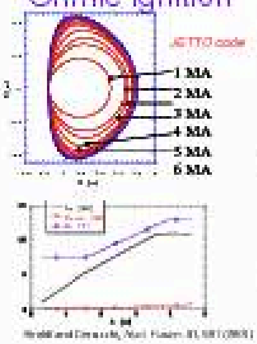
The Ignitor Experiment

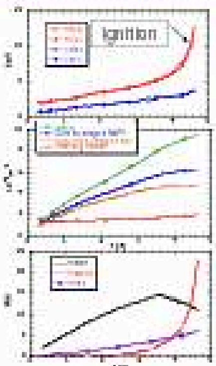
Ignitor can reach ignition shortly after the end of the current ramp (~4 sec) when ohmic heating only is present, with central density $n_0 \sim 10^{21}$ m^{-3}, peak temperature $T_0 \sim T_{e0} \sim T_{i0} \sim 11$ keV, $B_T = 13$ T and $I_p = 11$ MA.

During the current rise, it is particularly important to tailor the density profile peaking, to obtain an optimal rate of ohmic and fusion heating.

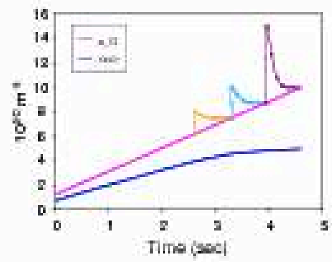
In Ignitor, pellet injection can be more effectively done from the Low Field Side. To yield significant effects, injected pellets must penetrate near the center of the plasma column.

Ohmic ignition





Pellet Injection Scenario



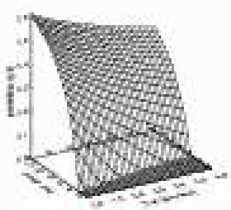
Pellet Penetration

An analysis of deuterium pellet penetration for Ignitor was carried out, using the NGS ablation model[1], for the pellet sizes that the IPI is capable of producing. 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.

1 P.B. Parks, R.J. Turnbull, *Physics of Fluids* 21, 1735 (1978).

Penetration of 4 mm pellets in Ignitor



$T_e = (T_{e0} - T_s)(1-r^2)^2 + T_s$

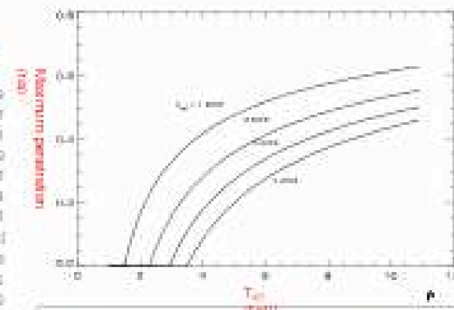
$n_e = (n_{e0} - T_s)(1-r^2)^2 + n_s$

$n_0 = 0.5 \div 12.5 \times 10^{20}$ m^{-3}

a = 0.47 m

Ablation Depth of D_2 pellets into LHD

A similar analysis has been applied to plasmas produced by the Large Helical Device. 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 ($n_{e0} \sim 5 \times 10^{21}$ 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 in LHD for a 3 mm pellet (~1.3 x 10^{21} D ions) is shown as a function of increasing electron temperature, for a fixed peak density $n_{e0} = 5 \times 10^{20}$ m^{-3} and different velocities. 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.



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.

O.Motojima

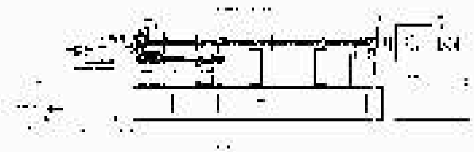
Proceed. 21[st] IAEA FEC, Chengdu, China (october 2006) Paper OV_2-1

A four barrel, two-stage pneumatic pellet injector for the Ignitor experiment 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 4 km/s, capable of penetrating near the center of the plasma column when injected from the low field side.

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.

Main design parameters of the high-speed Ignitor Pellet Injector (IPI)

No. of pellets:	4
Pellet material:	Deuterium
Pellet sizes:	2.1, 2.2, 3, and 4.6 mm (in the initial testing configuration)
Pellet speeds:	3.5 - 4 km/s (or higher if possible)
Cryostat design:	Pipe gun, cooled by a pulse-tube cryo-refrigerator (4 W at 8 K). The injector housing design facilitates change-out of gun barrel sets of different bores and lengths (from 0.7 to 1.1 m). Also the effective breech length can be varied from 5 to 10 cm.
Propulsion:	4 independent pneumatic TSGs, each equipped with its own diagnostics and a new electromagnetic pulse shaping relief valves, capable of suitably shaping the rising edge of the pressure pulse for improved pellet acceleration.
Diagnostics:	Pressure pulses upstream and downstream of the PSVs (8 piezoelectric ballistic transducers), pellet speed (4 light gates) and mass detector (1 toroidally shaped microwave cavity), in flight pictures (1 laser strobe and 4 CCD cameras), and an accelerometer impact target.
Propellant gas removal:	4 identical independent lines equipped with fast closing gate valves, allowing to avoid the use of large expansion volumes.



The IPI consists of four independent injection lines, each including a two-stage pneumatic gun (TSG), a pulse shaping relief valve (PSV)[1,2], 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.

[1] A. Frattolillo et al. Fusion Technol. 32, 601 (1997)

[2] Italian patent and trademark Office, Rec. No. RM95A000100, issued on Feb. 20, 1995

Two independent sub-systems have been built by ENEA and ORNL separately.

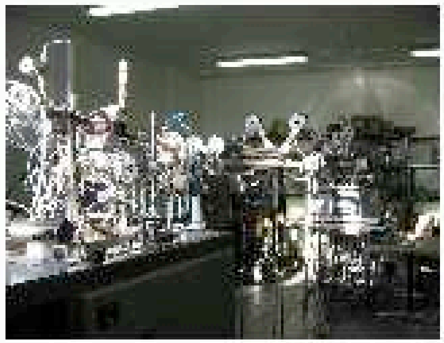
The ENEA sub-system

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).

The C&DAS has been improved to allow control and data acquisition on two distinct computers, and to provide easier and more immediate access to mimics and data.

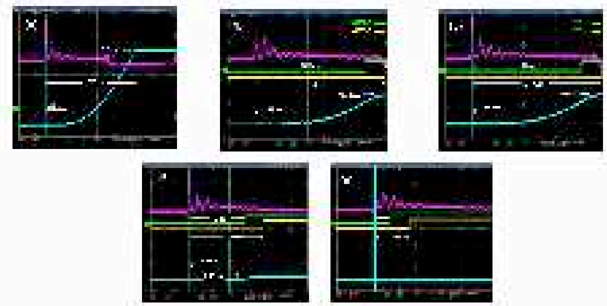
An additional cut-off (pneumatically actuated) ball valve has been integrated in the valve body to separate the pneumatic guns from the launching barrels. This allows to disassemble each TSG from the cryostat without breaking the vacuum in the launching barrel and to ignore possible small leakages through the PSV.

Further tests have been carried out to characterize the gas removal system.



The ENEA Frascati sub-system during testing at Criotec Impiant in Chivasso (Turin, Italy)

The new pulse shaping valves with integrated cut-off ball valves



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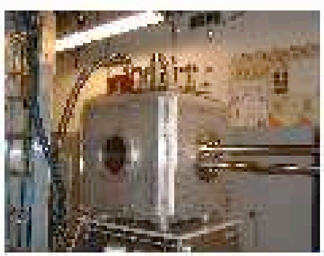
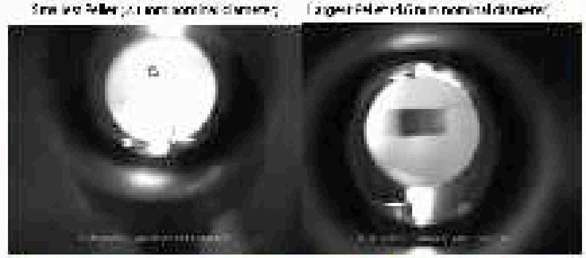
The ORNL sub-system

The ORNL sub-system consists of the cryostat and pellet diagnostics, as well as of its own C&DAS. The assembly of most of its components was recently completed, and testing with D_2 pellets was started, using standard ORNL propellant valves.





A cold thermal radiation shield has been added to the cryostat. Temperatures of less than 10K were achieved after adding such shield. Upstream and downstream heaters have been added on each barrel (in close proximity of the freezing zone).

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. The cavity is equipped with four internal teflon tubes (in which the pellets pass through), which are sealed from the cavity such that the injection lines are isolated.

An automated control system, based on a personal computer running LabView, allows the user to set-up and control the injector granting highly repeatable results, as well as to collect and archive data after each shot.

Members of the IPI group in front of the LabView control system console during a recent visit at ORNL.

The ENEA and the ORNL systems are ready to be integrated for testing the complete system at high pellet speeds. A wide range of operating parameters will be explored.