The New High Speed Pellet Injector for the Ignitor Experiment

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Density Peaking for Burning Plasmas

- Ignition, the condition where the nuclear plasma heating equals the rate of plasma energy loss, can be attained at relatively low peak temperatures in a high magnetic field experiment, such as Ignitor [1] (R_0=1.32 m, $a \times b$ = 0.47×0.86 m^2, B_T= 13 T, I_p= 11 MA), designed to explore the physics of burning plasmas.

  The most accessible conditions to reach ignition involve relatively peaked density profiles (e.g., $n_0/\langle n \rangle \cong 2$) as they are beneficial for fusion burning plasmas from several perspectives, and in particular can provide a stability edge against the so-called η_i modes that enhance the ion thermal transport.

- [1] B. Coppi, A. Airoldi, F. Bombarda et al, *Nucl. Fusion* **41**, 1253 (2001).

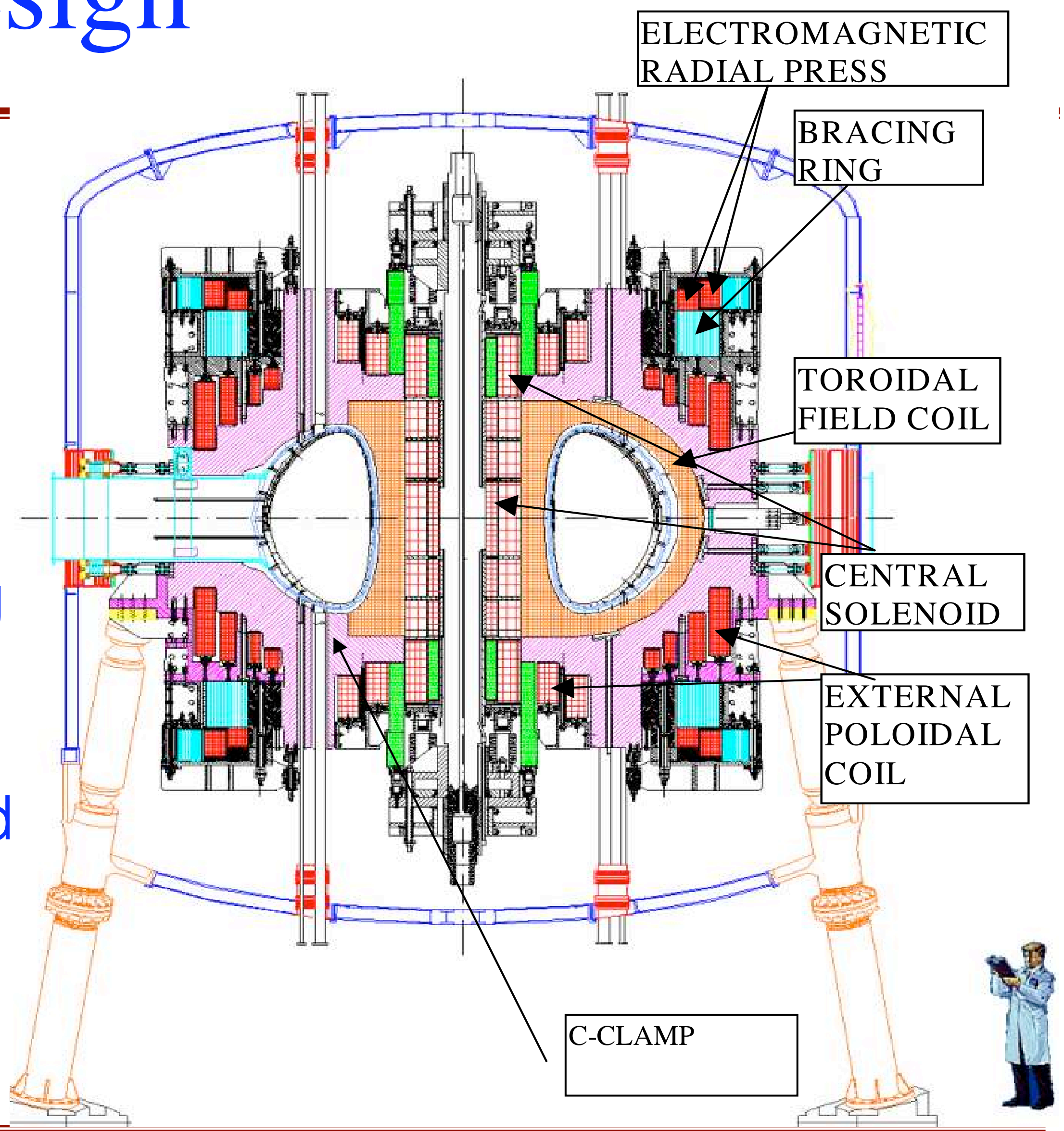
The Fast Pellet Injector Program

- 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 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.
- The purpose is to control the density profile peaking, as well as fueling the discharge and to provide fast control of the thermonuclear instability

Ignitor Design

The machine is characterized by a complete integration among major components.

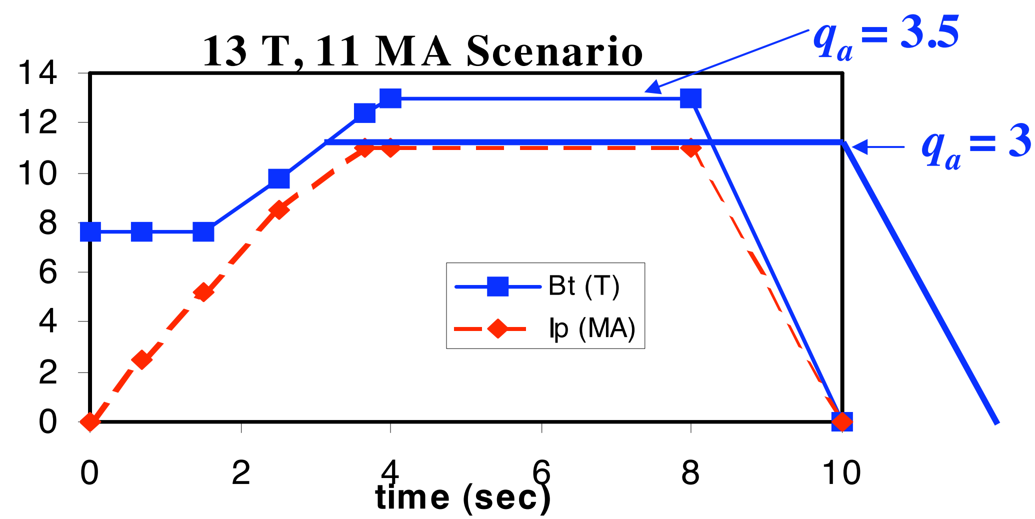
- Bucking and Wedging
- Passive and Active Compression
- No Divertor, optimized for OOP forces
- Cooling to 30 K



Machine Parameters

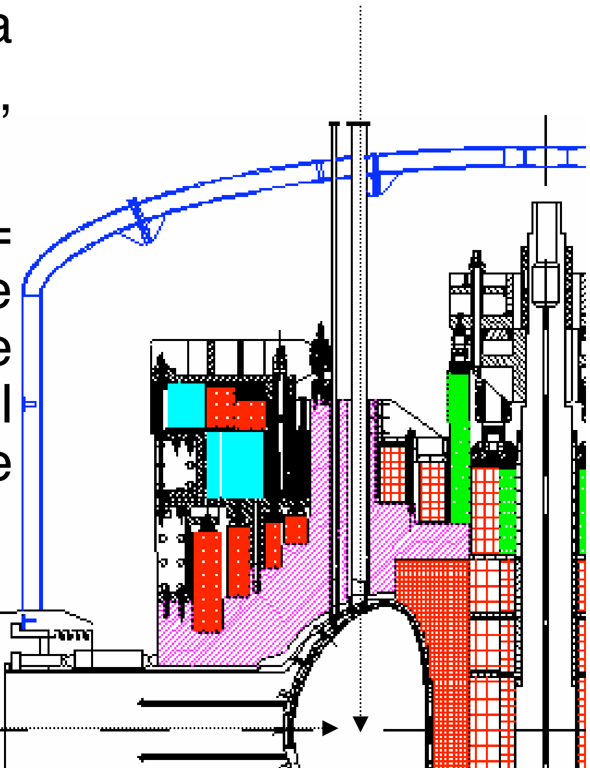
R	1.32 m
A	0.47 m
b	0.86 m
κ	1.83
δ	0.4
V	10 m^3
S	36 m^2
Pulse length	4+4 s

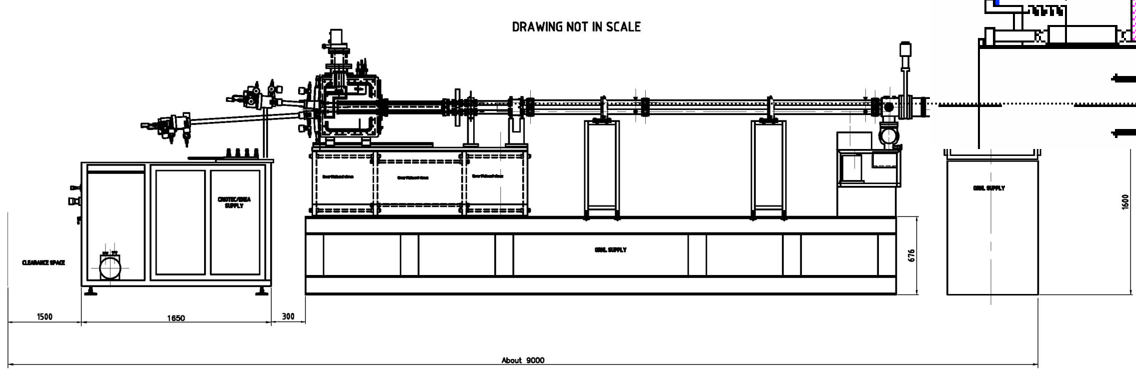
Plasma Current I_P	11 MA
Toroidal Field B_T	13 T
Average Pol. Field $\langle B_p \rangle$	3.5 T
Edge Safety factor q_ψ	3.5
RF Heating P_{icrh}	~9 MW



Pellet Injection for Burning Plasmas

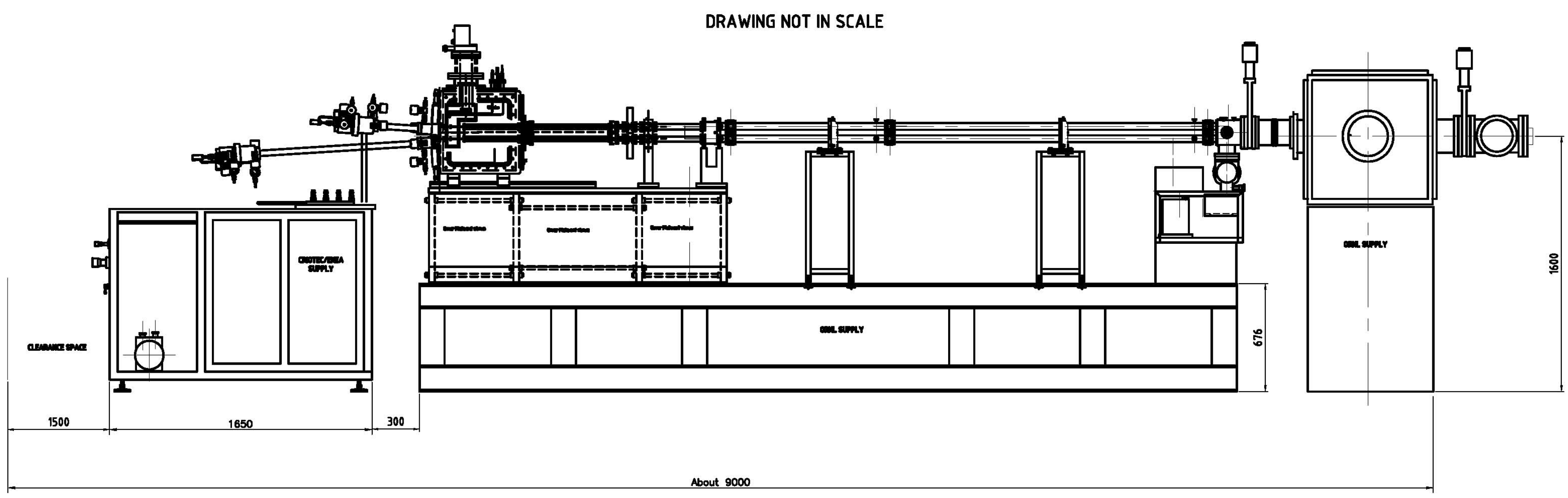
- Both high and low magnetic field experiments have shown that low thermal diffusivities can be produced in the central part of the plasma column as a result of peaked density profiles, such as those resulting from pellet injection.
- The compact design of the Ignitor machine (R_0 = 1.32 m, $a \times b$ = 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 magnetic axis would be beneficial.



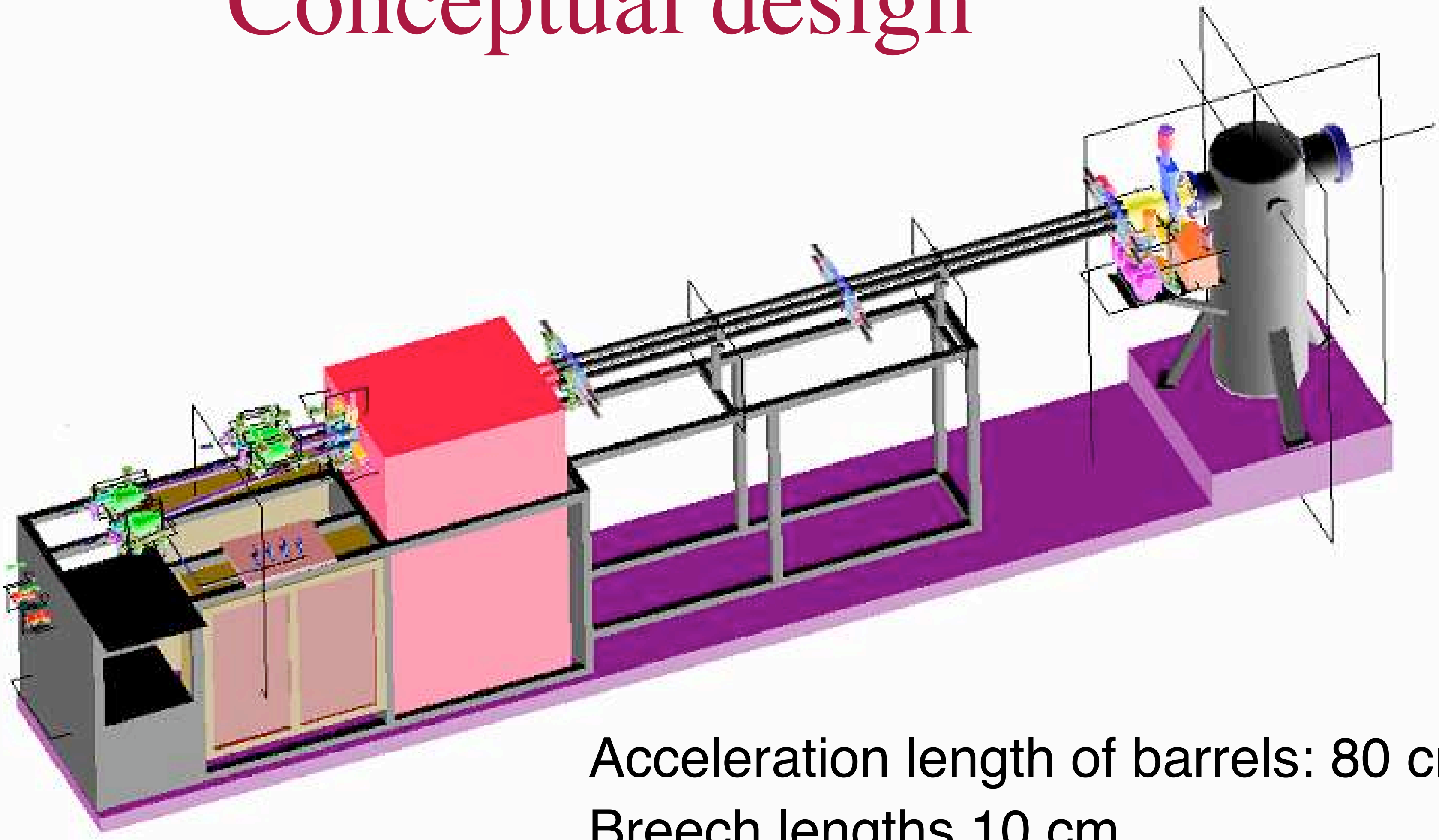


The Fast Pellet Injector Layout

The injector 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.



Conceptual design



Acceleration length of barrels: 80 cm

Breech lengths 10 cm.

The design can accommodate acceleration lengths of 70 to 110 cm and breech lengths of 5 to 10 cm.

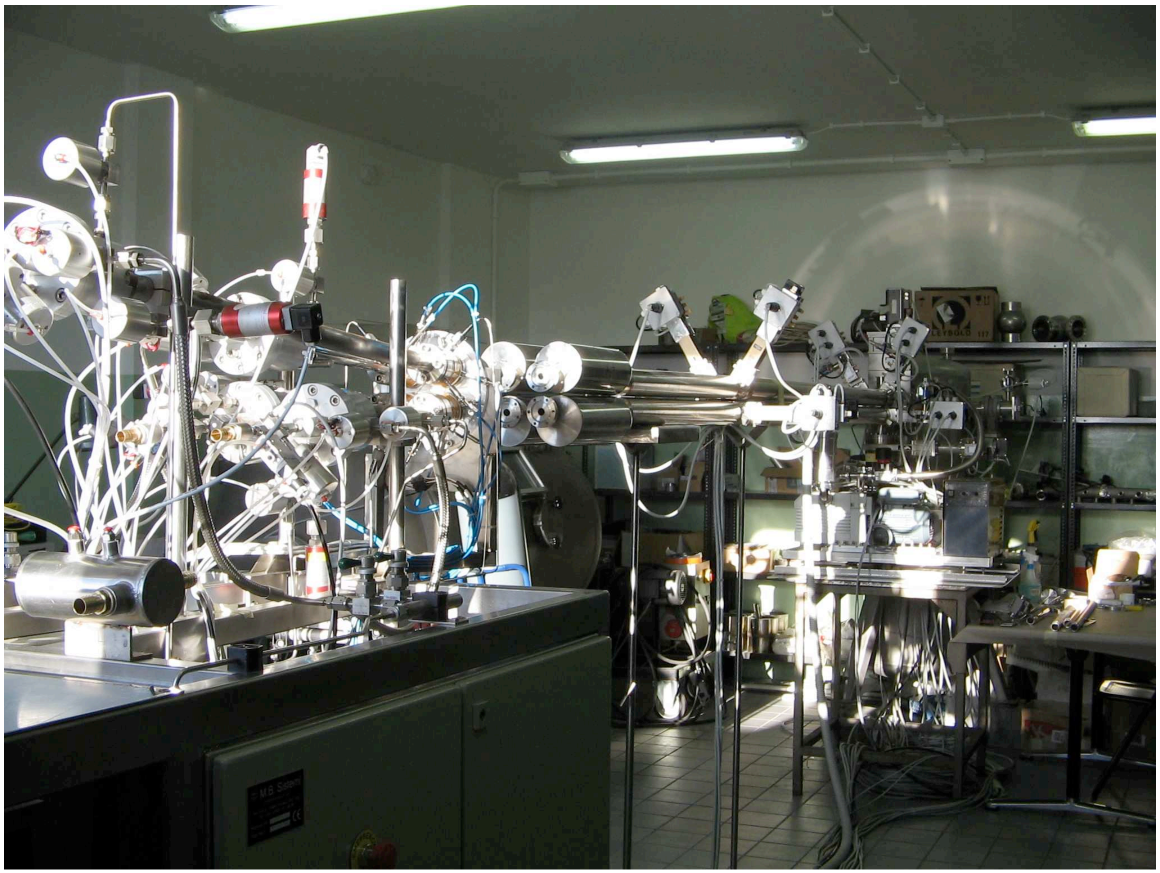
Main design parameters of the injector

No. of pellets	4
Pellet material, sizes	Deuterium, 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 will accommodate barrels of different sizes and lengths; it will also be equipped with a vacuum transfer line to provide additional refrigerating power (if necessary) by liquid helium coolant.
Propulsion	4 independent two-stage pneumatic guns, each equipped with diagnostics. The propelling system includes 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.

Activity Plan

- 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 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 ORNL site. Also the cross-talk protocol of the control systems, independently developed by ENEA and ORNL using LabView, has been defined in detail.

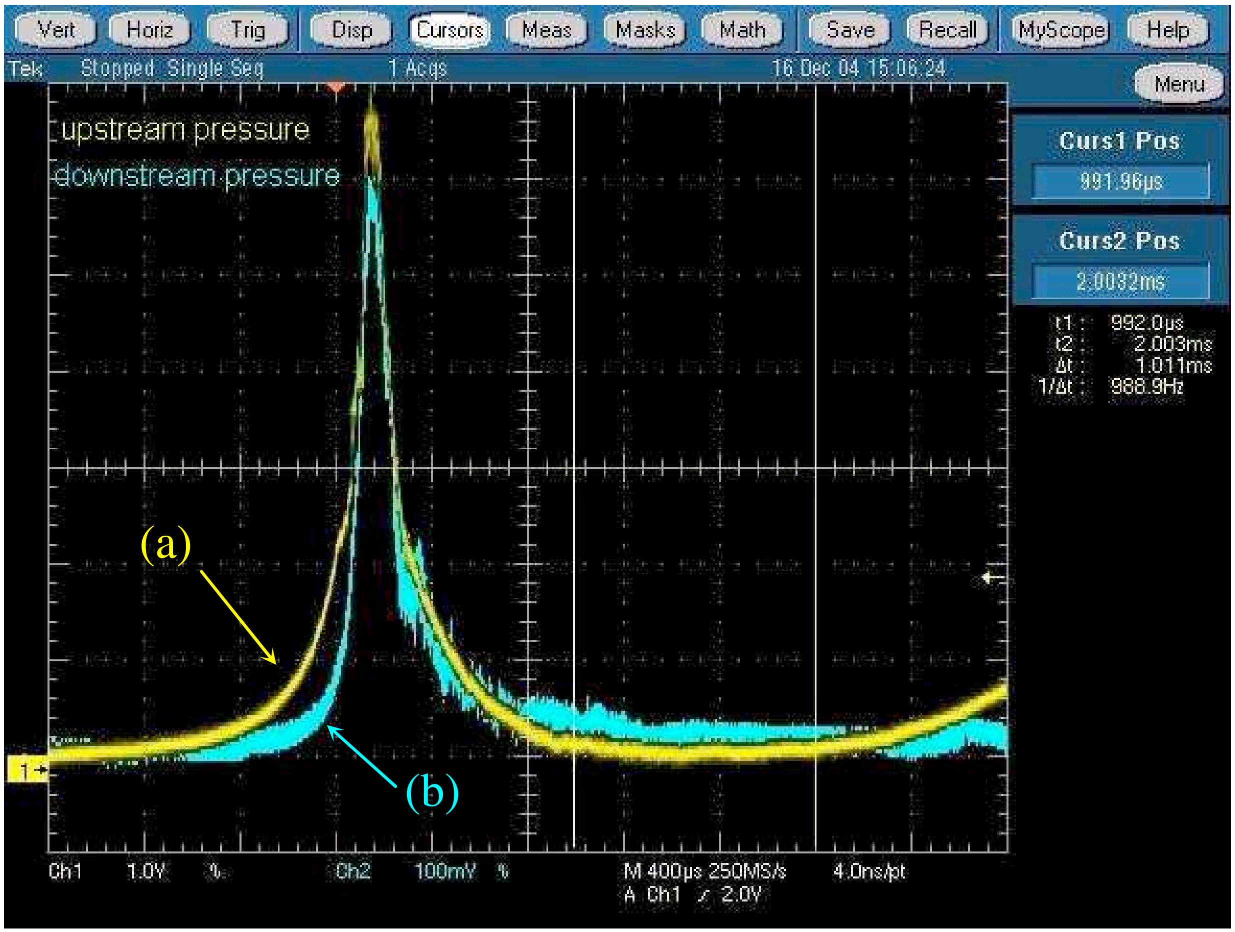
ENEA Propelling sub-system built at Criotec Impianti



Tests on the Propelling System

- A new design of the pulse-shaping valve has been developed, which grants improved reliability with respect to the previous version.
- the separation of the gas removal system into four independent (and identical) systems no longer require the use of large expansion volumes.
- 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.

Pulse-shaping Valve Performance



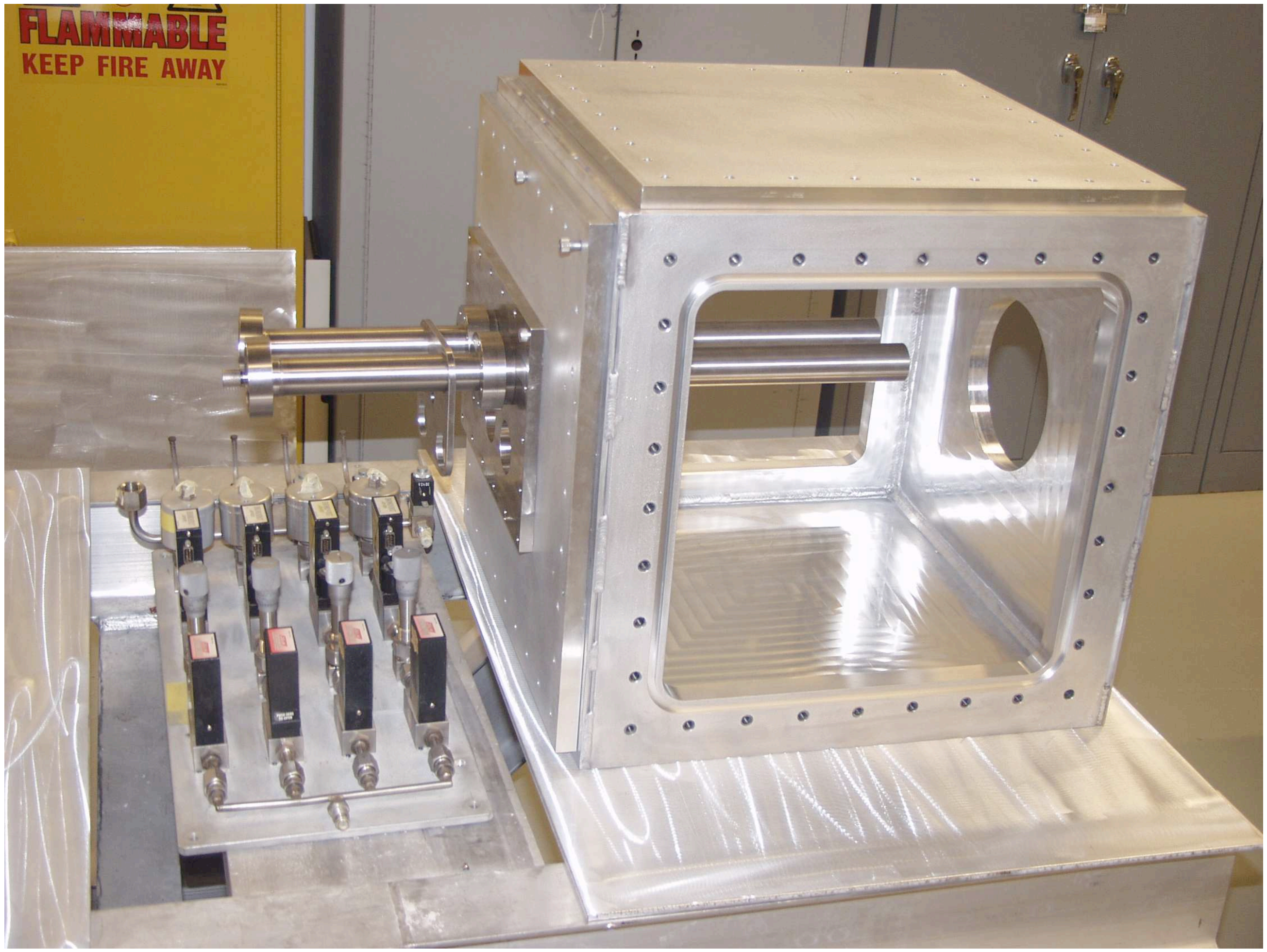
Typical shapes of the pressure pulses upstream (a) and downstream (b) of the relief valve

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%

Cryogenics

- ORNL is responsible for the injector vacuum chamber, cryogenic systems, 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

Pellet Vacuum Chamber



Summary

- The new compact, multiple barrel high speed pellet injector for the Ignitor experiment is being developed jointly by ENEA and ORNL.
- The propelling sub-system is undergoing final testing in Italy before shipping to ORNL for complete integration with the cryogenic system and testing with real pellets.
- In Ignitor good pellet penetration from the low field side can be expected in burning plasma condition
- The injector could soon be ready for try-outs on existing experiments.

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