Pellet Injector for Inertial Fusion

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Abstract

An Inertial fusion power plant is intended to produce electric power by use of inertial confinement fusion techniques on an industrial scale. This type of power plant is still in a research phase. One of the key technical issues is the target injection at a frequency in the range of 5-10 Hz with an accuracy of positioning of few microns.
These targets are hollow sphere (2 mm diameter) with an inner solid fuel layer (Tritium-Deuterium mixture) of 200 microns at a temperature of 16 K approximately. These targets have to be injected in an experimental vessel (5 m diameter) with a speed of 1000 ms^{-1}. This speed is required to reduce the radiation heat load coming from the chamber wall. The scattering angle has to be less than 10^{-6}. The mechanical strains of the target due to the launching acceleration have to be less than a maximum value beyond which the modes of deformation introduce hydrodynamic instabilities.
In this paper we describe some path of research and techniques which are promising as target acceleration with a gas gun or laser ablation. The goal is also to give the environment limit in terms of mechanical stresses, heat load, pressure vessels and to find a compromise with these all items to be sure that the target will survive till they reach the implosion point.

1. Introduction

To day researchers imagine that a possible way for an inertial fusion reactor is the “shock ignition” For this solution, the temperature of the target will be in the range of 16K and the implosion technique will be a “direct dive attack”. For HiPER or a reactor the temperature of the walls will be room temperature or 600K. In This case the time life of the target will be an issue. The main problems we have to solve are the mass production, the injection and the positioning in the chamber.
A reactor working at a repetition of 10 Hz needs approximately 1 million targets per day. To maintain an high availability of the injection, a redundancy is necessary. This redundancy will have two impacts: it increase the reliability of each injector and reduce the frequency repetitive rate which reduce the constraints on the equipments.
The goal is to reach a velocity in the range of 500-1000 m/s and a positioning of few microns at the centre of the experimental chamber. To day no technology exists for such requirement, but coupling different techniques and using the best of each, some progress can be made. The target is very brittle, for this reason it is embedded inside a “sabot” which protect it against the mechanical stresses due to acceleration and from the thermal load induced by the acceleration process. But before the free fly in the chamber, the target must be separated from the sabot very smoothly to prevent any shock which could affect the trajectory.

2. Acceleration techniques

This speed should be produced in a 50 m long acceleration tube which can generate an acceleration which does not exceed a value of 10 000 $m.s^{-2}$ that would certainly destroy the thin layer of solid DT mixture.
The launcher is divided in two sections. In the first section of 40 meters long, the target is moved by a gas wave produced by a high pressure discharge of gas. The target is accelerated until a 800$m.s^{-1}$ speed. In the second section, long of 10 meters, a laser beam, focused on the

back side of projectile, will produce a quick evaporation of a solid fused matter; the projectile and the spherical shell containing the DT mixture will be propelled by rocket effect until a $1000 m.s^{-1}$ speed before being inserted into the vacuum vessel. The fly-way tube of the launcher is schematically illustrated in the following figures 1 and 2. In the figure 1 a complete scheme is shown with the loading section, the cryogenic system, the separator

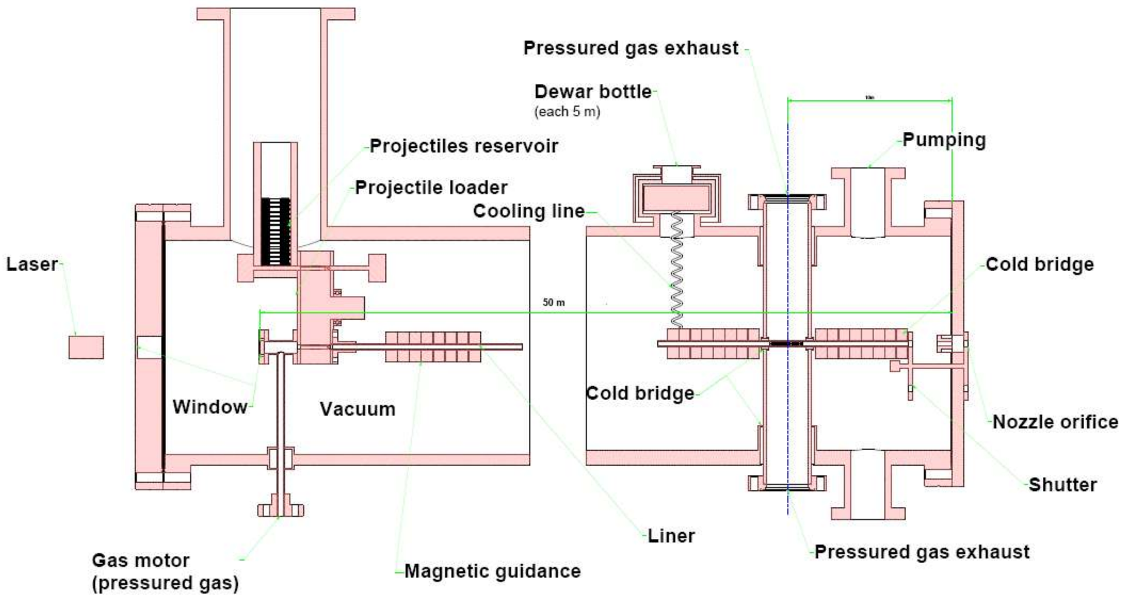

Figure 1 - General view of the injector

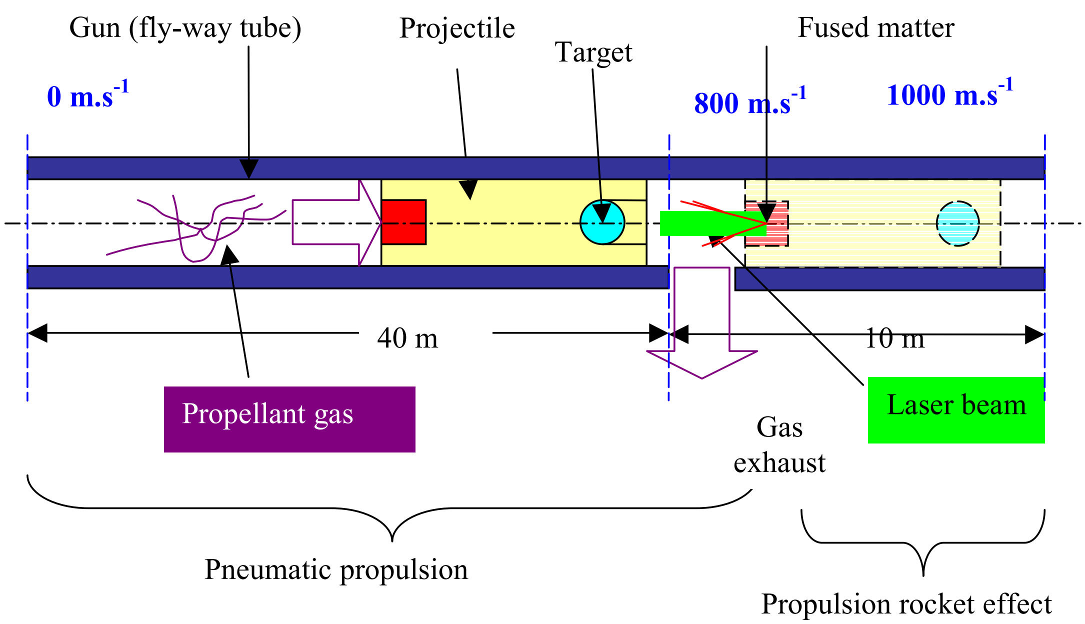

Figure 2. - Acceleration sections of the injector

3. Gas gun injector

For a repetitive rate in the rage of 5-10 Hz, a close loop is required for the management of the propellant gas. The figure 3 describes such a loop where components as vacuum pumps with high speed are needed, a high pressure compressor. Such a loop is compatible with the nuclear safety management due to the fact no propellant gas is rejected outside. Indeed during the acceleration process the propellant can be in contact with target which contains 200µg of Tritium.

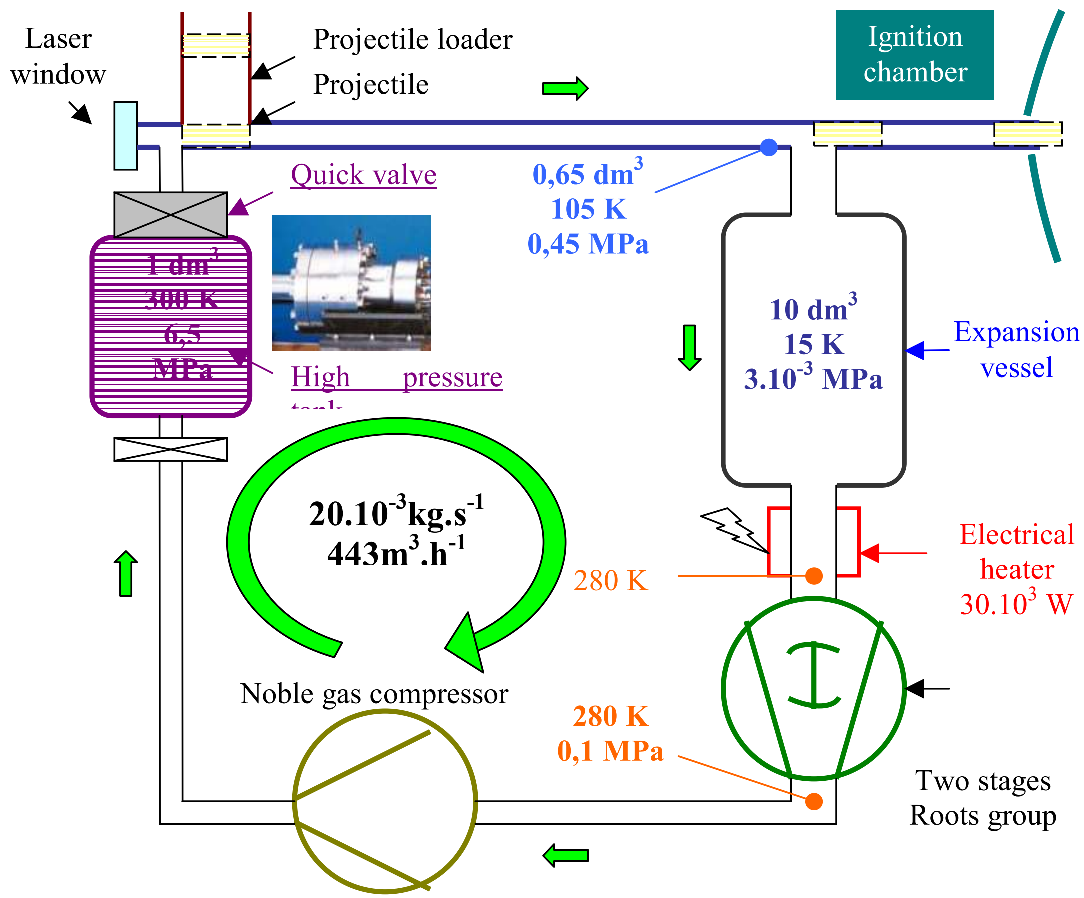

Figure 3 - layout of a pneumatic injector

4. Laser acceleration

In the ablative laser propulsion (ALP) the material of the target is removed from a solid surface at high velocities by directly converting it into plasma. The exhaust velocity of this laser-produced plasma depends on the intensity the laser produces on the target, but for intensities between 10^{11} and 10^{13} W/cm^2 the velocity is typically ~10^7 cm/s (i.e. 10^5 m/s).

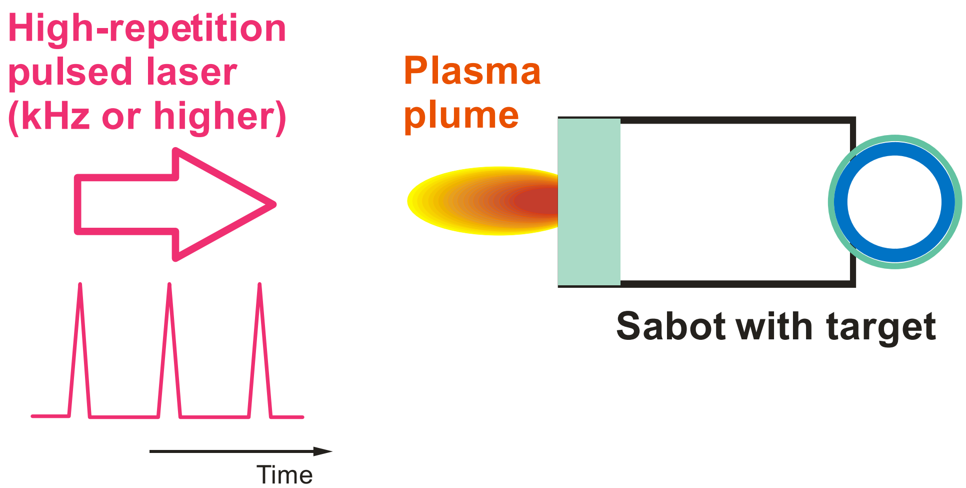

Figure 4 - Principle of an ablation laser accelerator

For focused intensities between about 10^{11} and 10^{13} W/cm^2 the material of the sabot is converted into plasma with a typical mass ablation rate of ~2x10^5 g/cm^{2}s. Assuming size of the laser “focus” of 1 mm, for laser pulses lasting 1 ns the ablated mass is 2 μg, for 10 ns it is 20 μg.

The efficiency of the incident laser energy into the kinetic energy of the expanding plasma depends of the material of the ablator material. For low or medium atomic-number of the target material (Z smaller than ~30) and for intensities between 10^{12} and 10^{13} W/cm^2 about 40 to 60% of the energy of the incident laser is converted into the kinetic energy of the expanding plasma.

Assuming energy of 2 J provided by the laser head one laser shot (see below), focused to a spot of 1 mm in diameter, the focused intensity is 10^{12} W/cm^2 for pulses 1 ns long and 10^{11} W/cm^2 for pulses 10 ns long.

We propose to use as the ablator material cryogenic Ne, Ar or Kr – the obvious advantage is that the resulting plasma/gas does will simply be exhausted from the injector and will not produce any contamination.

Advantage of the suggested ALP

A sequence of short (nanosecond) pulses used for the ablative laser propulsion offers two key advantages:

- Acceleration is perfectly axial and is totally decoupled from the guiding of the target (i.e. acceleration does not compromise the precision of the guiding mechanism)
- Application of a selected number of pulses offers a remote “instantaneous” and “on-line” precise control of the final speed of the sabot - no modification of other injector parameters is needed

4.1. Energetic balance

Let us assume a high-repetition rate laser operating at 1 kHz and providing in one shot 2 J of energy. These lasers are currently developed in the Max-Planck Institute for Quantum Optics in Garching near Munich; they are based on the compact thin-disk technology (the lasers are table-top size).

Over 100 ms (=1/10 s), i.e. within the time interval between two consecutive HiPER shots (assuming operation at 10 Hz), the 2 J/1 kHz laser delivers 100 shots, i.e. energy of 100x2 J =200 J. Assuming that 50% of energy of the laser is converted into the kinetic energy of the plasma (see above), the 2 J/1 kHz laser unit will impart kinetic energy of 100 J to the sabot over the 100 ms time interval.

The kinetic energy of the sabot (2 g) accelerated to 1000 m/s is 1000 J. In order to accelerate the sabot from 0 to the full speed of 1000 m/s, 10 units of the 2 J/1 kHz laser from the Max-Planck Institute would be needed (ideally they would be time-multiplexed to provide effectively 10 kHz rep-rate). Alternatively, only part of the acceleration would be accomplished by one or two laser unit(s).

4.2. Kinetic momentum balance

The 2 g sabot at 1000 m/s speed represents kinetic momentum of 2 kgm/s. By assuming 20 µg of matter ablated in one laser shot (see above), with exhaust speed of 10^5 m/s, 1000 shots would be needed to produce total kinetic momentum of 2 kgm/s by the expanding plasma. This represents the same conclusion as that made above – either 10 laser units (2 J / 1 kHz) would be needed to accelerate the sabot from 0 to the full speed of 1000 m/s, or only part of the acceleration would be accomplished by one or two laser unit(s).

4.3. Beam size considerations

For the 4th harmonics of the laser (1030 nm / 4 = 257.5 nm) it is possible to keep the diameter of the laser within the 4-mm aperture of the accelerator over a distance of about 24 m (see below figure).

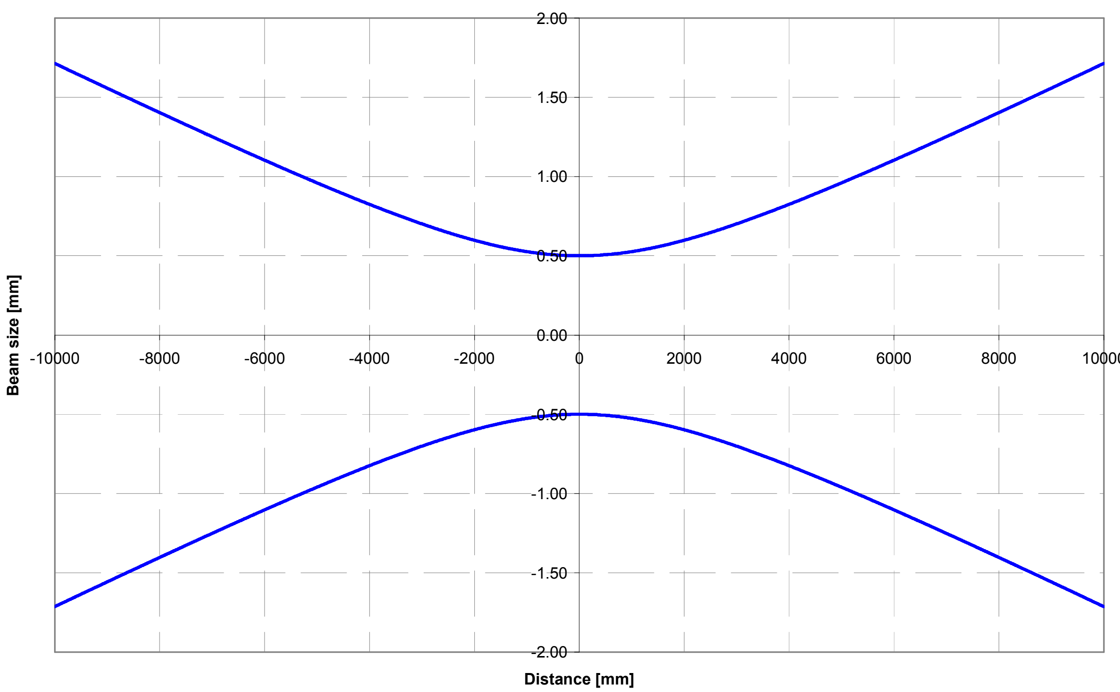

Figure 5 - Divergence of the 4th harmonic

For the 3rd harmonics of the laser (1030 nm / 3 = 343.3 nm) the laser can be kept within the 4-mm aperture of the accelerator over a distance of about 18 m, for the 2nd harmonics of the laser (1030 nm / 2 = 515 nm) this distance is about 12 m.

The converging laser beam can be inserted into the injector either axially from one end, or can be inserted at a desired distance by a simple 45-degree mirror (with a hole on the axis for the sabot) with a diameter of ~25 mm.

Where $\dot{m}$ is the mass flow, q is the volume deposition ($W*m^{-3}$), e the slab thickness, L1 the slab length, Cp the heat capacity, ΔT axial the thermal gradient in gas.

5. Guiding

For having the best trajectory with the smallest angle of scattering (10^{-6} rad), a possible technique is available. This later is based on the electro-magnetic levitation. The configuration of permanents magnets is describes in the figure 6. This configuration creates a magnetic field in the acceleration tube which can stabilize the projectile in a plan perpendicular to the the movement. Using a long sabot with a ratio aspect (length/diameter of 5) and two wiring in front and rear Electromagnetic forces appear which prevent title and spinning movements.

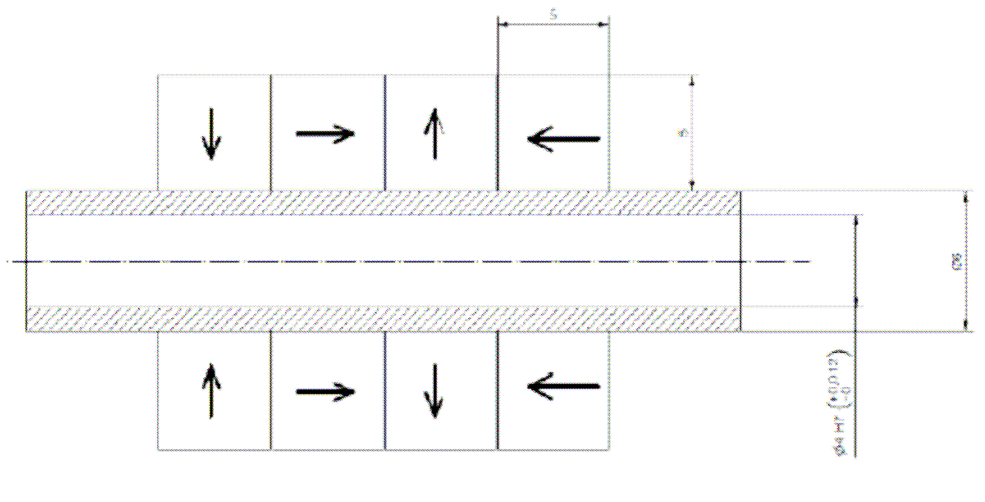

Figure 6 - Halbach magnetic configuration

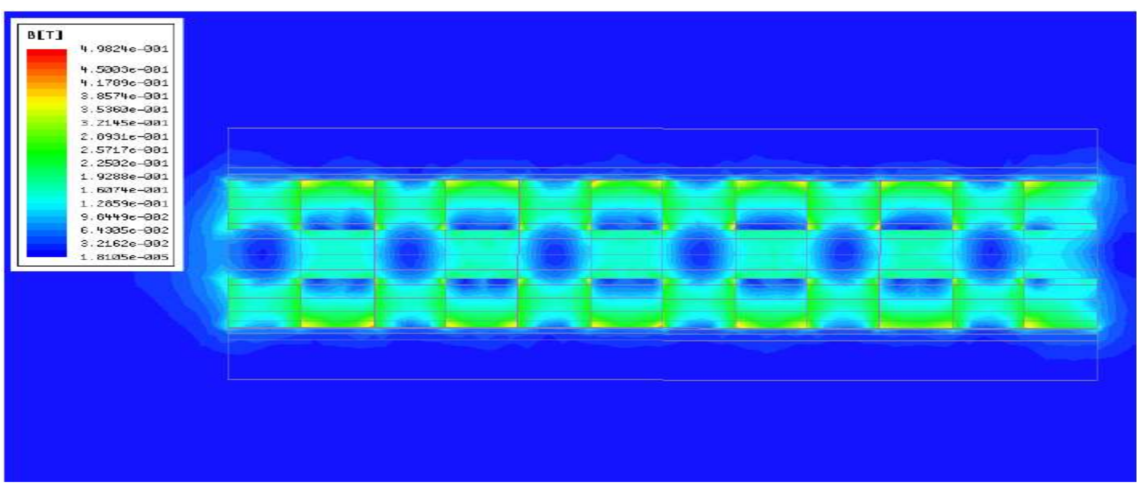

Figure 7 – magnetic configuration along the acceleration

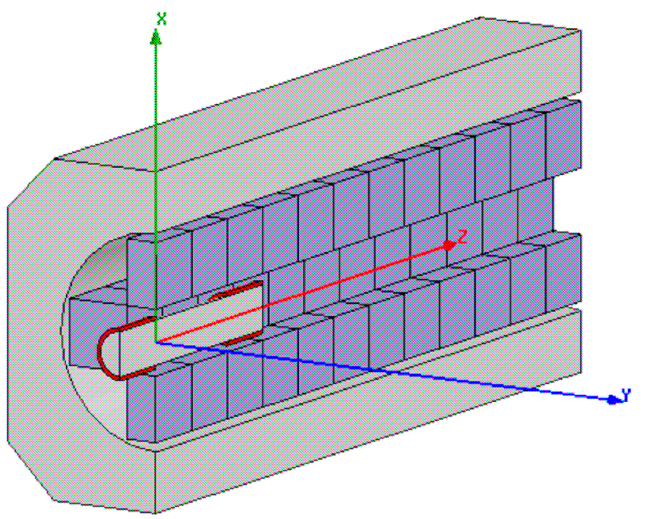

Figure 8 - Section of a guiding section

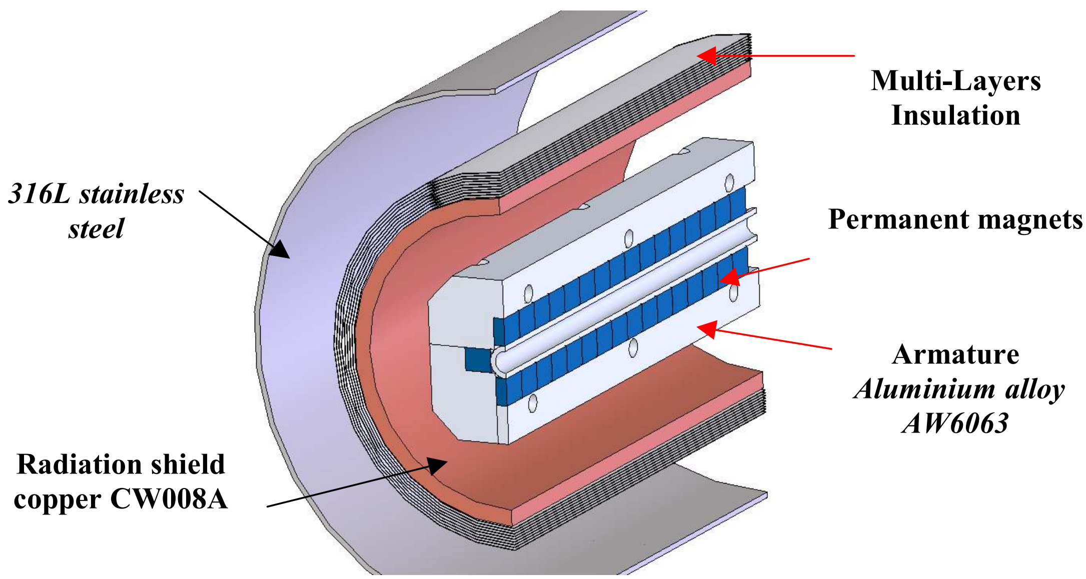

Figure 9 – Cut of a section of a guiding section with mechanical structure and thermal insulation

6. Braking

To separate the pellet from the sabot last meters of the guiding tube are made with a conducting material, the eddy current generated in this later create an opposite current in the sabot wiring which brakes this one. This phenomenon is very smooth and so the target and the sabot can be separated

7. Conclusions

To day some technologies are available and they are promising. The targets can be accelerated at a speed of 500 to 1000 m/s within a time of 100ms without an excessive heat load or to high mechanical stresses. But other issues have to be solved in the future in particular two issues have to be studied: the impact of the debris generated in the chamber during the implosion with the targets and the free fly in the chamber if a gas is used to manage the nuclear aspect of the working cycle.

8. References

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