

# Cryogenic systems for inertial fusion energy

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(RECEIVED 12 February 2008; ACCEPTED 14 July 2008)

## Abstract

The Low Temperatures Laboratory of CEA/Grenoble (France) is involved in the development of cryogenic systems for inertial fusion since a ten of years. A conceptual design for the cryogenic infrastructure of the Laser MegaJoule (LMJ) facility has been proposed. Several prototypes have been designed, built and tested like for example the 1500 bars cryo compressor for the targets filling, the target positioner and the thermal shroud remover.

The HIPER project will necessitate the development of such equipments. The main difference is that this time, the cryogenic targets are direct drive targets. The first phase of HIPER experiments is a single shot period. Based on the experience gained the last years, not only by our laboratory but also by Omega and G.A teams, we could design the new HIPER equipments for this phase.

Some experimental results obtained with the prototypes of the LMJ cryogenic system are given and a first conceptual design for the HIPER single shot cryogenic system is shown.

**Keywords:** Cryogenic system; Laser megajoule; HIPER

## INTRODUCTION

The Laser Megajoule (LMJ) Facility, under construction near Bordeaux in France and the National Ignition Facility (NIF) at Livermore in the United States are being built to study fusion by inertial confinement (Besnard, 2007; Sangster *et al.*, 2007). Both facilities will be equipped with about 200 laser beams that will focus on a 2 mm diameter cryogenic target filled with a deuterium-tritium (DT) mixture. The target will be held by a cold grip situated at the end of a 6 m carbon boom. When inertial fusion is proved at these facilities, it will be necessary to prove that it is possible to shoot on several targets each second to produce the energy of a power plant. For this reason, target technology and delivery techniques are a key issue for the success of inertial fusion energy. Many groups in the world are working on these topics (Baclet *et al.*, 2004; Koresheva *et al.*, 2005; Nobile *et al.*, 2006; Goodin *et al.*, 2005).

For the LMJ, the targets are hollow spheres filled by permeation at ambient temperature then cooled down under the

triple point of the DT mixture (19.79 K). Before the shot, the temperature must be controlled within stability better than  $\pm 2$  mK and the positioning must be performed with a precision better than 5  $\mu\text{m}$ .

The cryogenic targets (Fig. 1) are filled and cooled down in the CEA of Valduc then transported, with their thermal shroud, to Bordeaux (CEA CESTA) in a specific cryostat, which contains six targets at a temperature between 22 and 30 K. Then, they are taken off the cryostat to be transferred with a transfer robot (still with their thermal shroud) to the cryogenic target positioner. After conformation of the solid DT layer, which can last several hours, the cryogenic target positioner drives the target to the center of the 10 m in diameter vacuum vessel. Here, the shroud is slowly disengaged of the target base by the shroud remover situated at the opposite port of the cryogenic target positioner. During this phase, the temperature of the target must not vary more than  $\pm 2$  mK. Then, the accurate alignment of the target is performed and just before the laser shot, the shroud must be removed very quickly (0.5 m in 0.1 s). This concept, proposed by our laboratory 10 years ago, made some technological problems emerged. For this reason, a large program for the development of prototypes was initiated to validate some technical solutions, which is now called the “French concept.”

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Fig. 1. (Color online) A view of the cryogenic target with its thermal shroud.

Thus, the following were developed: a cryo-compressor able to fill the targets, a cryo-target positioner, a cryogenic transfer robot, and recently the thermal shroud remover prototype.

## A REVIEW OF THE PROTOTYPES DEVELOPED

### The Cryo-Compressor

The filling of the LMJ targets is carried out by permeation through the wall of the micro-balloon. To have the required quantity of matter, the pressure in the micro-balloon must lie between 1000 and 1500 bars at the ambient temperature. To prevent that the targets do not break down under the effect of the pressure, the pressure difference between the internal and external walls must be controlled. Our laboratory tested an original idea to solve this problem. DT mixture is liquefied in a small volume in connection with the filling cell maintained at 300 K (Fig. 2). Then this small volume is heated from 20 K to 300 K by controlling the temperature on the wall. This system is able to limit the rise in pressure ( $\Delta P$  on the micro-balloon wall) and it is possible today to ensure a slope from 0 to 2 bars per minute. This cryo-compressor was delivered to the research center of Valduc during the summer 2003 to be installed in a tritium cell. The construction of two compressors working out of tandem was committed at the end of 2005. This system will have to ensure the production of the targets for one period of at least 30 years.

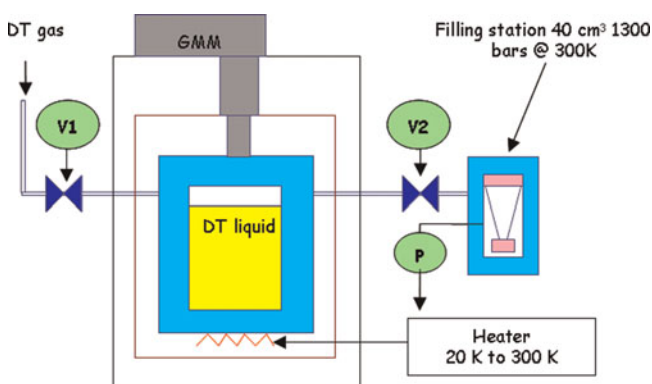


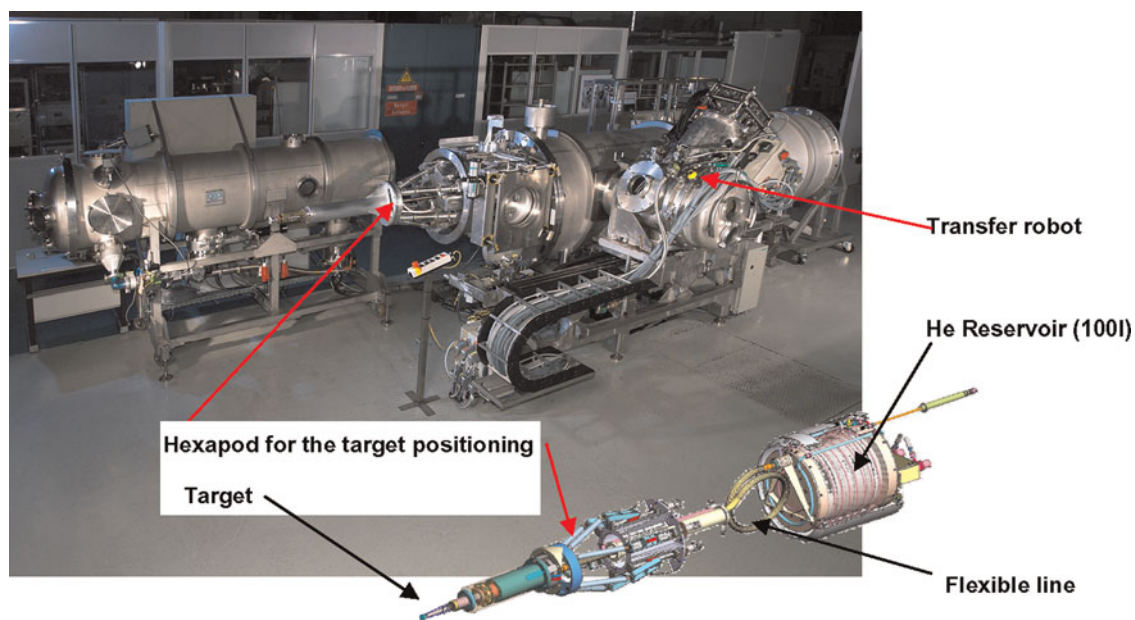
Fig. 2. (Color online) Principle of the thermal cryo-compressor.

### The Target Positioner and Transfer Robot

Once the targets are filled, they are cooled to around 25 K and, in any case, they cannot be heated without being destroyed. It was necessary to develop cryogenic grips, which will be able to handle the targets at a temperature close to 20 K. These grips must provide two important functions: the transfer of heat (power dissipated by T2 and radiation heat load) and the transfer of information. The coating of surfaces was studied in order to obtain thermal resistances of contact between the target and the grip as low as possible. This point is extremely important, because this thermal resistance, being inversely proportional to the temperature, conditions the size of the cold source. Our laboratory undertook a research program to solve the problem of thermal contact resistance and today we are able to carry out thermal contacts of low resistance (1 K/W) at 17 K. During transfers, the temperature of the target must be known, it obliges the grip to ensure reliable electrical contacts and thus free from any trace of pollution, which obliges to ensure the transfers under a very good vacuum. Today procedures of manufacture of the targets are setup to guarantee this criterion of thermal resistance. The cryogenic grip is a key point of the cold chain. Its development required several years and will still require improvements. It is one of the most important technological bolts that it was necessary to solve in priority. Figures 3 and 4 show the cryostats developed to validate the concept of cryogenic transfer, thermal regulation, and target positioning (Paquignon *et al.*, 2005). With these prototypes, we have demonstrated that it is possible to transfer a target from the transfer robot to the target positioner automatically (two cameras drives the hexapod) at a temperature of  $23 \pm 2$  K. After the connection of the target on the target positioner, the thermal regulation of the target base at a temperature of 18 K can be achieved with stability better than 1 mK during several hours. The specific hexapod developed for the target alignment can move the target in a cube of 100 mm with a precision of 50  $\mu\text{m}$ . A rotation of  $\pm 3^\circ$  is possible around the three axes.

### The Thermal Shroud Remover

The thermal shroud of the LMJ target has two functions: it protects the target from the vessel radiations and avoids condensation on the laser entrance hole (LEH). It must be removed 100 ms before the laser shot. As shown in Figure 5, the shroud extraction will be performed with a specific device situated at the opposite port of the cryogenic target positioner. It is composed of a 6 m carbon boom at the end of which is fixed a hexapod. The extraction device is fixed on the mobile part of the hexapod (Fig. 6); it is equipped with a cryogenic grip. The extraction is performed in two steps: the first step consists in disengaging slowly the shroud from the target base; the second step consists in the fast extraction just before the shot. During the first phase, the movement must be very slow because the temperature

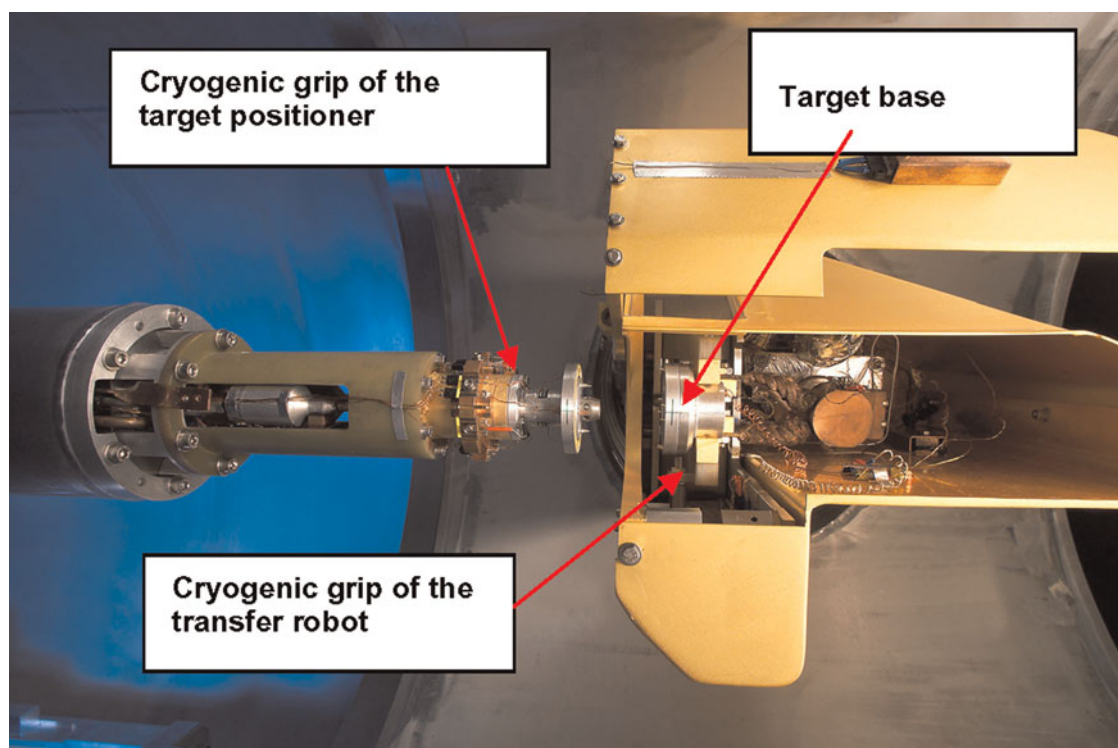


**Fig. 3.** (Color online) A view of the target positioner prototype and the cryogenic transfer robot.

of the target must not vary more than 2 mK. During the second phase, the displacement has to be of 0.5 m within 100 ms. This is achieved with two springs.

Keeping the temperature stability during the gripping and removing phases of the shroud are difficult points. It was decided to build a prototype to test technical solutions. This prototype, shown in Figure 7, operates since the

spring of 2007. Many experiments have already been performed. The temperature stability at  $\pm 2$  mK during the gripping and removing phases of the shroud was obtained by using the following method: (1) Control of the target base temperature at  $18 \text{ K} \pm 1 \text{ mK}$  by adjusting the helium flow rate in the heat exchanger of the target grip (a flow rate of 2300 NL/h is necessary) and by acting on the



**Fig. 4.** (Color online) A zoom of the grip of the target positioner and the grip of the transfer robot.

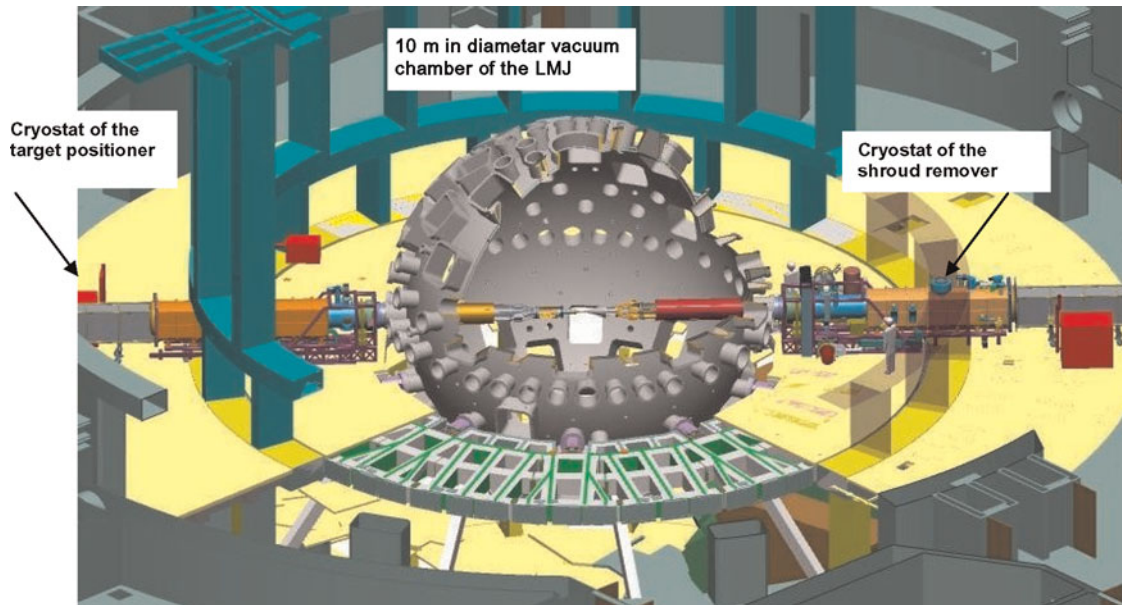


Fig. 5. (Color online) A view of the vacuum chamber and the two cryostats.

heater of the target base. At this time the shroud temperature is about 32 K (about 1.2 W (radiation) falls on the shroud and the thermal contact resistance between the shroud and the target base is about 12 K/W at 20 K); (2) The temperature of the shroud remover grip is stabilized at the same temperature as that of the shroud then the shroud remover is slowly approached; (3) The shroud grip catches the shroud very slowly. This operation lasts about 10 mn. The clamping force is 800 N; (4) The shroud grip temperature is slowly decreased (we should obtain 18 K but for the moment the lowest temperature we could have is 21 K. This will soon be improved); (5) The shroud is removed at a speed of 20  $\mu\text{m/s}$ . Figure 8 shows a typical temperature curve of the target base during the shroud removing.

## HIPER FACILITY

The HIPER facility consists in a 10 m vacuum chamber at the center of which a 2 mm in diameter cryogenic target is

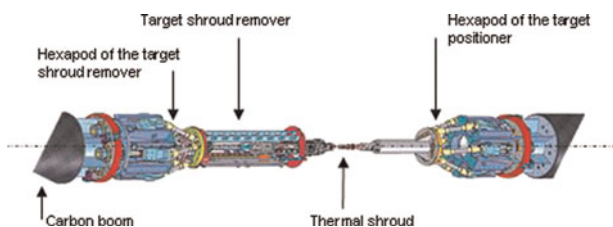


Fig. 6. (Color online) A view of the target shroud remover on the moving part of its hexapod.

irradiated by 40 laser beams (Dunne, 2006). The energy of the laser beams is 200 kJ in 5 ns. The energy of the PW beam line is 70 kJ in 10 ps. The awaited gain is 100.

In a first step, to validate the fast ignition concept, the laser shot will be performed on one direct drive target equipped with a cone as shown in Figure 9. The target is a hollow sphere filled with DT. It is a direct drive target. The dimensions are as follows:

External radius of DT: 1.044 mm

Internal radius of DT: 0.833 mm

Vapor density: 0.1  $\text{mg/cm}^3$  (that means a temperature of 16.3 K)

Solid DT volume: 2.35  $\text{mm}^3$

Solid DT mass: 593  $\mu\text{g}$

$\beta$  heating power: 116  $\mu\text{W}$

## Conceptual Design Proposed for the HIPER Target Single Shot

As shown in Figure 10, we propose to use a direct drive target filled with a capillary. The capillary could be connected to the cone and the cone must be drilled to drive the DT mixture inside the micro-balloon. If we are able to make this assembling, that will simplify enormously the HIPER cryogenic infrastructure. No high pressure filling station and no cryogenic transfer robots will be necessary.

The two proposed concepts proposed in Figure 10 have each advantages and disadvantages which are summarized in the Table 1.

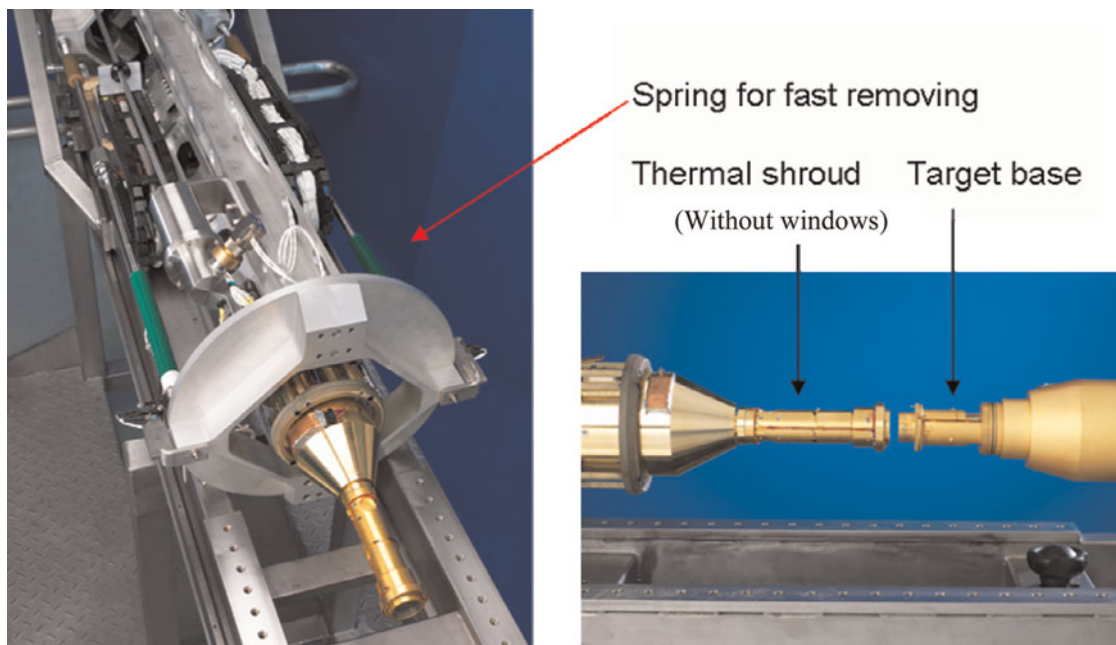


Fig. 7. (Color online) A view of the thermal shroud remover prototype.

The problem of the tightness at 300 K could kill the concept of Figure 10B but a valve (or a membrane which could be pierced at the last moment) could be used between the reservoir and the micro-balloon.

This kind of target can be assembled by hands at ambient temperature on a target positioner which could be similar to the one developed for the LMJ. After the assembling, the cryostat will be pumped to a pressure of  $10^{-6}$  mbar (to avoid the

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### Shroud removing sequence

Standard deviation 0,289mK

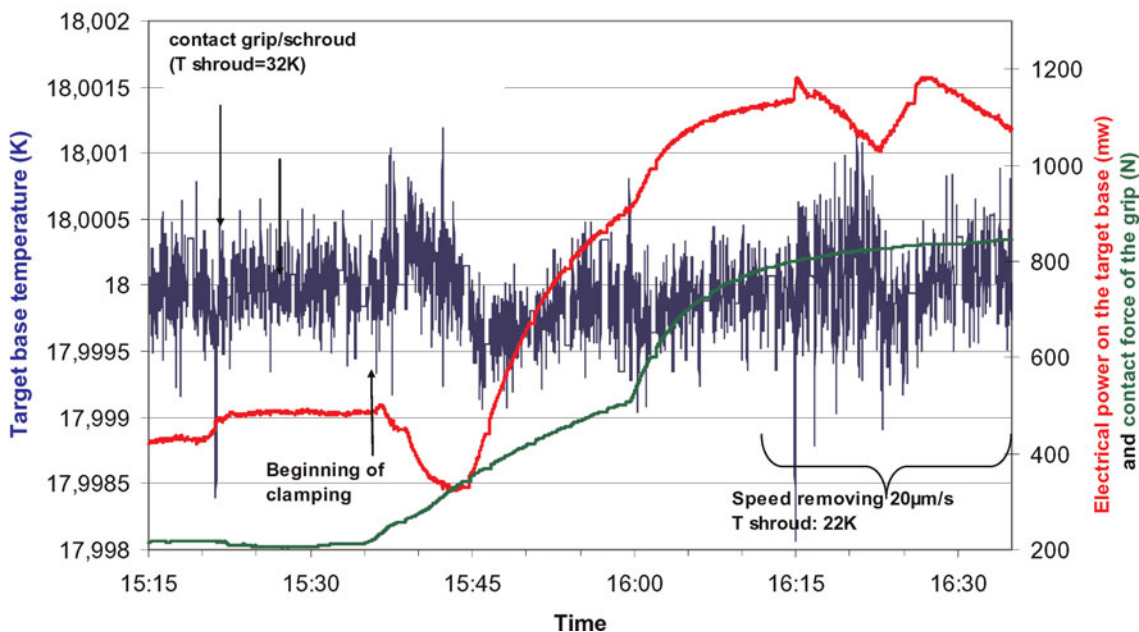


Fig. 8. (Color online) Temperature stability of the target base during the shroud removing.

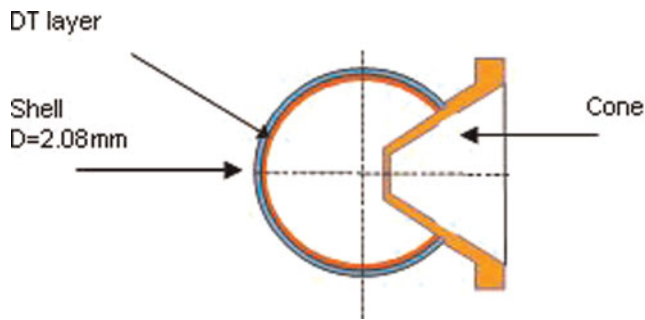


Fig. 9. (Color online) A schematic view of the direct drive target with its cone.

problem of condensation on the target) and then the target will be cooled by the helium cryo-line (or a cryo-cooler).

### Conceptual Design Proposed for the Thermal Shroud of the HIPER Target

The thermal shroud could be similar as the one developed for the OMEGA facility of Rochester but this shroud is very complex and could be simpler for HIPER. As for OMEGA, it must be tight because it contains helium gas which cools down the target. It must be equipped with windows for the laser alignment and for the characterization of the DT layer, and will probably have to be equipped with a layering sphere.

Table 1. Table giving the advantages and disadvantages of the two target concept

	Advantages	Disadvantages
Figure 10A	<ul style="list-style-type: none"> <li>The target is clean before assembling</li> </ul>	<ul style="list-style-type: none"> <li>High DT inventory</li> <li>Target positioner contaminated</li> <li>Double seal between the target base and the grip</li> </ul>
Figure 10B	<ul style="list-style-type: none"> <li>Low DT inventory</li> <li>Single seal between the target base and the grip</li> </ul>	<ul style="list-style-type: none"> <li>Target contaminated before assembling</li> <li>Heater needed in the reservoir</li> <li>Must be tight at 300K</li> </ul>

Figure 11 shows a concept of thermal shroud which could be a solution for the HIPER target. It consists in a thermal shroud (made of golden plated aluminum) connected to the target base at ambient temperature. A polymer membrane between the target base and the shroud will provide the tightness to helium. As for the LMJ, the removing of the shroud will be done in two steps: (1) In the first step (Figs 11A and 11B) the shroud is slowly removed with the cryogenic shroud remover until the disconnection of the target base. At this time, the target can be aligned at the focus point of the

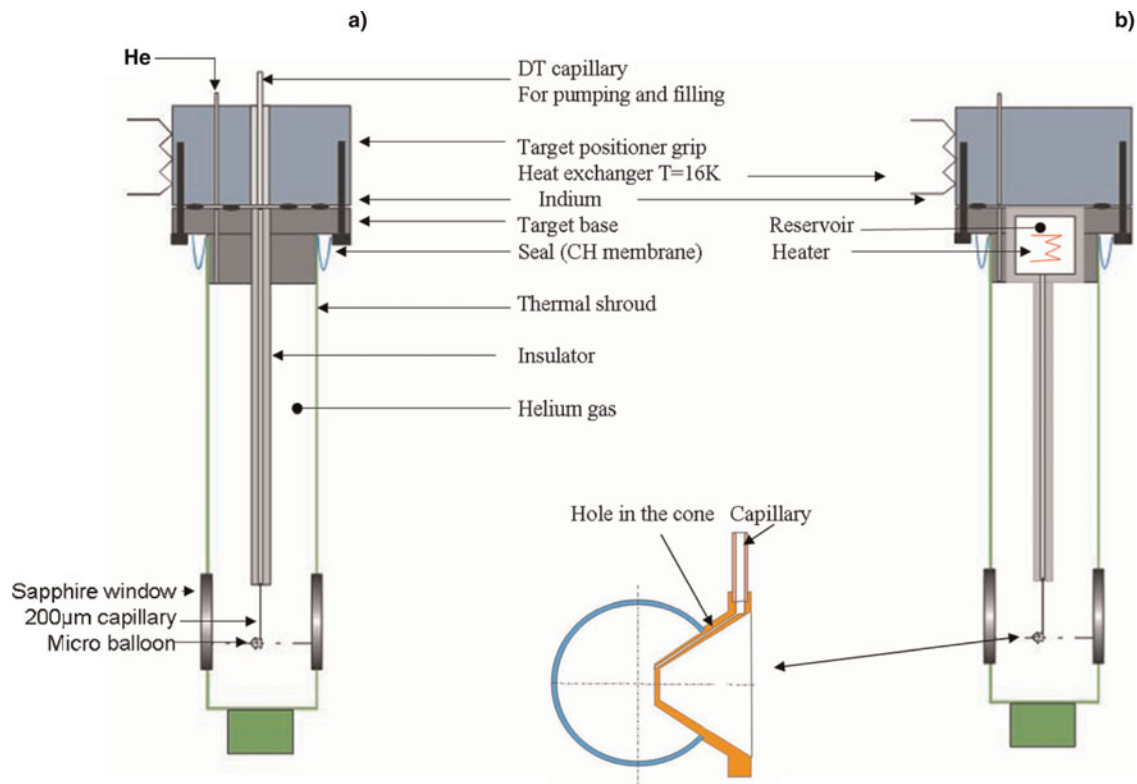
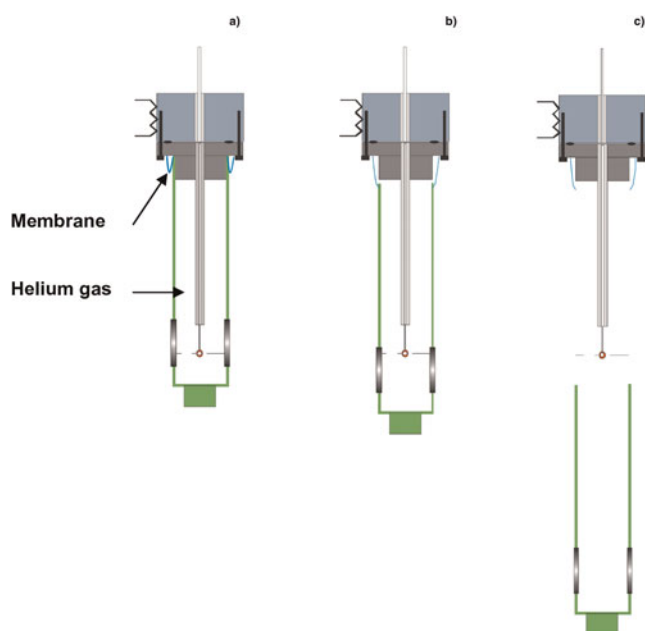


Fig. 10. (Color online) A schematic view of the assembled target. (a) Case of filling by an external tube. (b) Case of filling by using a reservoir.



**Fig. 11.** (Color online) Conceptual design of the proposed HIPER thermal shroud. (a–b): slow disconnection of the thermal shroud before the target alignment. (c): Quick removing before the shot (the membrane is torn).

laser beams with the required accuracy. During the alignment phase, the membrane continues to provide the tightness to helium. (2) In the second step, the shroud is quickly removed by the shroud remover and the membrane is torn (Fig. 11C)

The development of this concept needs to solve some problems, in particular, the problem of the membrane. Some preliminary experiments must show the tightness and the suppleness of such a membrane at low temperature. Some calculations of heat transfer between the shroud and the micro-balloon will soon begin. These calculations must give, versus the geometry, the optimal helium pressure in the shroud to limit the convections effects on the DT layer geometry.

## CONCLUSION

Basing on the experience acquired by our laboratory in the development of cryogenic systems for LMJ, we propose a concept for the HIPER cryogenic system. For the single shot phase, we propose to use targets filled by a thin capillary and cooled down by the target positioner equipped with a hexapod and a helium cryoline similar to the one developed for the LMJ. The thermal shroud of the target will be connected to the target base. A specific membrane must be developed to provide tightness of helium contained in the shroud. The shroud could be removed before the laser shot by a cryogenic shroud remover also similar to the one developed for the LMJ.

## ACKNOWLEDGEMENTS

The authors would like to thank S. Bressieux, M. Charvin, P. Dalban-Moreynas, J. Inigo, T. Jourdan, J. M. Mathonnet, P. Nivelon, and M. Saggioro for their contribution in the development of all the prototypes described in this paper. The development of the prototypes is supported by CEA/DAM Program LMJ.

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