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Cryogenic hydrogen targets for proton beam generation with ultra-intense lasers.

A. Girard[1], D. Margarone[2], P. Bonnay[1], S. Michaux[1], N. Luchier[1], D. Chatain[1]

[1]Univ. Grenoble Alpes, CEA INAC-SBT, F-38000 Grenoble, France
[2] ELI Beamlines, Institute of Physics, CAS, Na Slovance 2, 182 21 Prague 8, Czech Republic

Corresponding author: alain.girard@cea.fr

Abstract. The recent emergence of commercial, high repetition rate, intense lasers opens up new prospects for applications. Of particular interest is the production of energetic proton beams through the interaction of an intense laser with a hydrogen target: this beam can then be used e.g. for proton therapy (cancer treatment), or for neutron production through interaction of the proton or deuteron beam with a secondary target. If physical processes involved in the production of protons have started to receive satisfactory explanations, the reliable production of protons at high repetition rate without any debris is still an issue. In this context, SBT has developed different cryostats to generate thin ribbons of hydrogen through extrusion of solid hydrogen, and optimize and predict the conditions for extrusion. In this article, we show, how thin hydrogen ribbons are produced, and high energy proton beams are generated. A few results are given, and future plans are discussed

1. Introduction

Over the past years the technology of high power lasers experienced huge progresses. Petawatt (PW: 10^{15} W) lasers become more and more available (in the UK at RAL, in Spain at CLPU, at the ELI projects in eastern Europe, in France (Petal, soon Apollon)). Moreover, these lasers have often a high repetition rate (up to 10 Hz), which is to compare to the repetition rate so far (1 shot per hour typically). This puts a severe challenge on the targets which these lasers impact on: indeed, the targets (destroyed after every shot) must be supplied at the same repetition rate as the laser pulse, without debris which might damage optics [1]. This requires high progress in the field of target engineering.

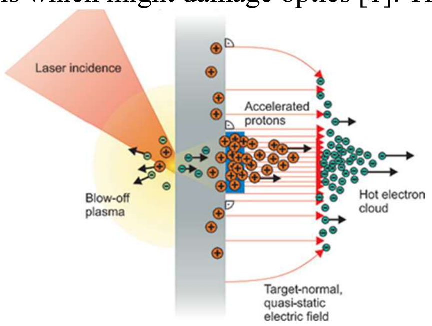

Figure 1: TNSA mechanism

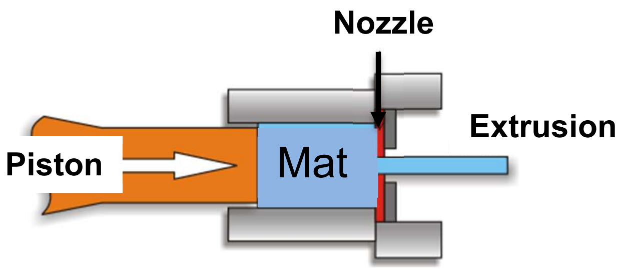

Figure 2: principle of extrusion of material Mat

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The production of proton beams is a topic of increasing interest, in particular due to its potential applications (eg proton therapy) [2]. In order to fulfil these new requirements, CEA/SBT has developed a cryostat dedicated to the production of proton beams via laser/solid hydrogen interaction [3]. In this paper we describe the recent advances in this development, major achievements, and future projects.

2. Hydrogen extrusion and the ELISE cryostat.

2.1. Principle

In order to produce a high density plasma, we decided to design a solid hydrogen (instead of gaseous) target, which requires cryogenics. The thickness of the target should be in the micron or tens of micron range, with a continuous production in order to be compatible with the high repetition rate. As a consequence, we decided to produce a thin ribbon of solid hydrogen via extrusion. Extrusion (figure 2) is a process through which a material (here solid hydrogen) is pushed through a nozzle by means of a high pressure applied to the material, thus leading to the continuous generation of a ribbon with a shape defined by the nozzle. An innovative process was patented [4] to produce the high pressure without any mobile part. Figure 3 presents the principle of this process: hydrogen gas is fed to the cell through a valve V1, while the extrusion nozzle is cooled below the triple point (fig 3-A, temperature T1): this allows the freezing of hydrogen and subsequent closure of the tank. The cell can be then be filled by hydrogen (B), which is frozen by cooling down the upper heat exchanger (B-C, temperature T2). Once the cell is full, V1 is closed (D). In step E, T2 is increased, leading to phase change close to the heater, which results in a pressure increase thanks to the thermodynamic properties of hydrogen.

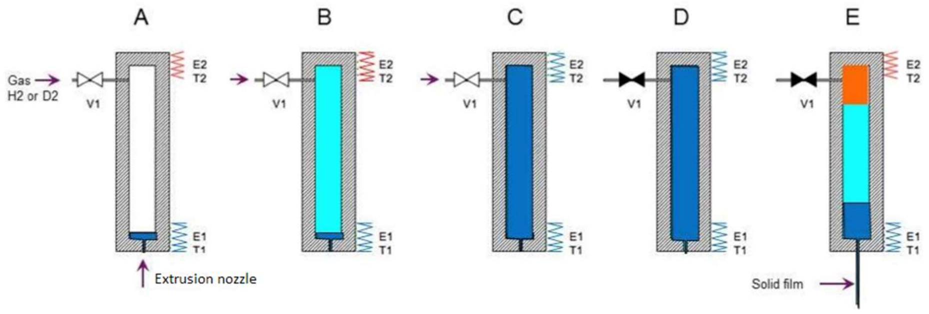

Figure 3: principle of operation of the extrusion process

This principle is applied in the SOPHIE cryostat, whose schematic drawing is shown in figure 4, where the two heat exchangers for the control of temperatures T1 and T2 are shown.

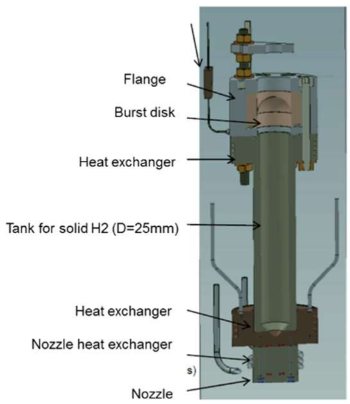

Figure 4 Schematic drawing of the cell of the SOPHIE Cryostat

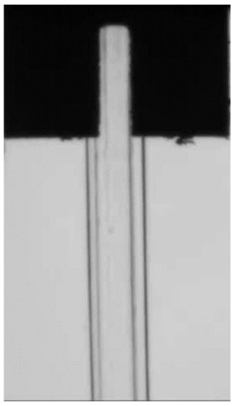

Figure 5: hydrogen ribbon produced, slit of 100 µm

Thanks to this technique, we are able to produce a thin (between 20 and 200 µm) ribbon of solid hydrogen. Such a ribbon is shown on Figure 5. The speed of the ribbon can be adjusted by the control of the temperature T1, and also of the extrusion pressure through the control of the temperature T2. Figure 6 shows, how T1 affects the velocity of the ribbon.

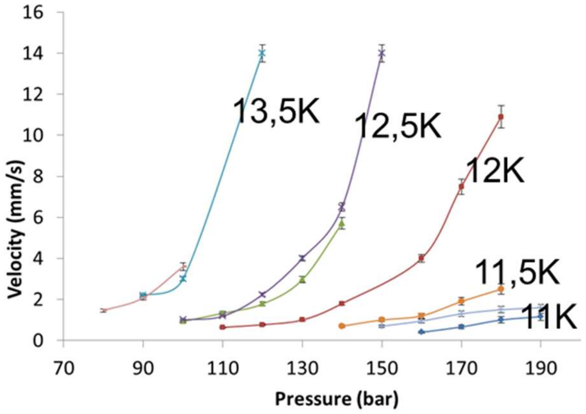

Figure 6: speed of the ribbon versus pressure for different temperatures at the nozzle

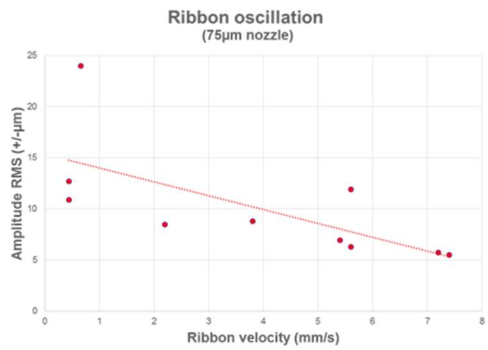

Figure 7: spatial stability of the hydrogen ribbon

For laser operation, it is important that the position of the ribbon be stable with respect to the focal point. Figure 7 shows the rms amplitude of fluctuations of the ribbon with respect to its mean position. A ten µm stability is usually sufficient for efficient laser/target interaction, but higher values might lead to a loss of laser peak intensity in the interaction with the target.

2.2. Adaptation to laser facilities

The SOPHIE cryostat needed modifications for adaptation to laser interaction chambers. The ELISE cryostat was then developed (figure 8) based on the SOPHIE design. The vertical position of the nozzle could be adapted during the experiments within a range of a few cm. This cryostat was installed first at PALS [5], then at ELFIE [6], and later at VULCAN at RAL [7].

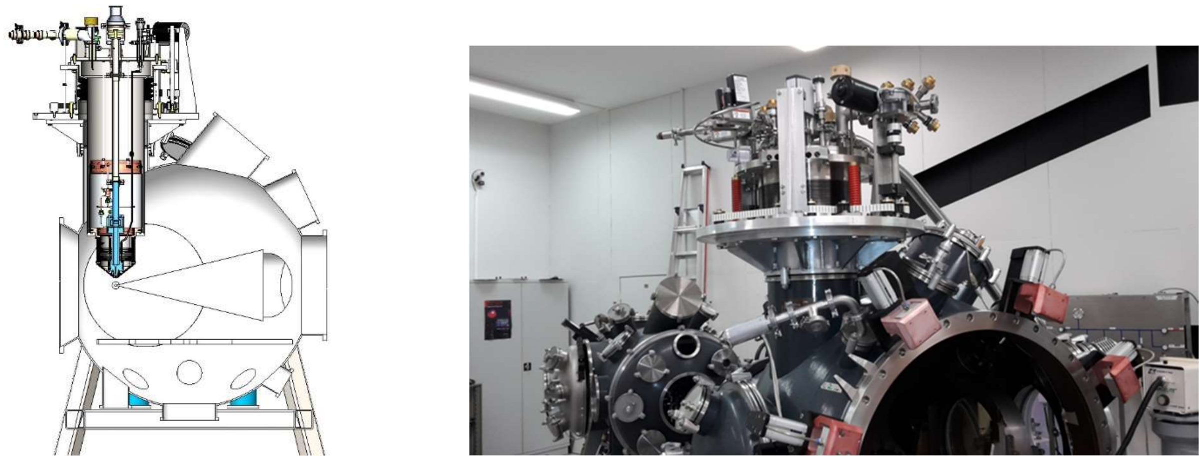

Figure 8: schematic drawing of the ELISE cryostat (left) and installation at PALS (right)

3. Experiments with lasers

3.1. Typical measurements

The experiments performed at the three above laboratories were all successful: after a necessary period of adaptation of the cryostat to the laser interaction chamber, experiments could be performed and energetic protons were produced at each facility, in spite of their very different characteristics in terms of intensity and pulse duration. The diagnostics of the laser/target interaction are usually similar at each facility, in particular Thomson parabolas were always used. The experimental setup at PALS is

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shown in Figure 9: ion collectors (IC or ICR), silicon-carbide (SiC) detectors, and diamond detectors (DD), as well as small Faraday cups (FC), placed at various distances and directions, are used to characterize the accelerated proton beams. At Elfie and RAL the energy spectra of the protons emitted at the target rear surface were also recorded using Radio-Chromic Film stacks (RCF) placed behind the target.

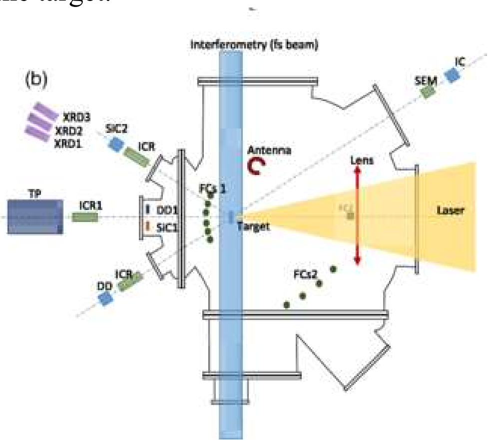

Figure 9: experimental set up at PALS

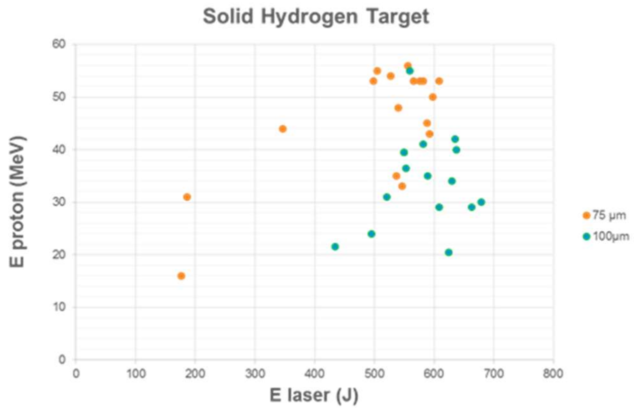

Figure 10 maximum energy of the protons produced at RAL versus laser energy

3.2. Proton energy

Depending on the characteristics of the laser pulse, and on the thickness of the target, proton beams of different energies are generated. At PALS, where the intensity is modest (in spite of high energy, the pulse duration is in the ns range), pure protons beams of energies up to 1 MeV with high efficiency were produced with 62 µm thick targets. At ELFIE, where the intensity is higher (smaller pulse energy, but much shorter pulse duration: typically 350 fs), proton beams up to 14 MeV were produced for 62 µm thick targets. With 100 µm targets, the energy of the protons was slightly reduced. At RAL, where the energy of the laser is as high as at PALS, with pulse durations comparable to Elfie's, the energy of the protons could reach 55 MeV (Figure 10, [7]) at maximum intensity.

These results are very promising: indeed, within nearly 150 laser shots, the ELISE system demonstrated that it could be used to generate with high efficiency intense beams of protons. However, a few improvements are still needed.

4. Further improvements and prospects

The main problem we had to face at high laser energy was the following: after each intense (> 7 J) pulse, hydrogen in the cell was liquefied, thus leading to the emptying of the cell. This effect needs still some further understanding, but we suspect that a current flows through the nozzle and through the cell to the ground, thus heating by Joule effect the hydrogen, leading to the emptying of the cell. This phenomenon must be solved for high repetition rate operation with modern lasers. By directing the flow of this current through metallic wires away from the tank, we expect to solve this issue.

Moreover, the stability of the ribbon need still to be improved. Indeed, the dispersion of energies (see figure 10) might be due to an excessive instability of the ribbon. This issue is also of major concern for a reliable and reproducible production of proton beams. This problem is under analysis and different solutions will be tested in a near future.

The thickness of the target needs also to be reduced: indeed, experiments at ELFIE showed that the thinner the ribbon, the higher the energy of the protons. This task is also under development, and is linked to the stability of the ribbon, since thinner ribbons need to be better stabilized in the present status.

In the ELISE cryostat, the cold source is provided by cold helium gas fed by liquid helium tanks. If this is not an issue in large laboratories, this may raise some problems in laboratories of smaller size, where cryogenics is not available. Therefore, we have developed a new cryostat, called ELISE II (figure 11), where the cold source is provided by a low frequency pulse tube. This is expected to make the operation of cryogenic targets easier and more widespread in the community of laser physicists.

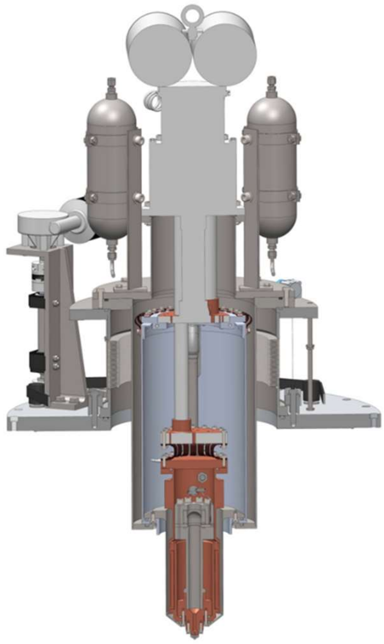

Figure 11: the ELISE II cryostat

As a conclusion, the ELISE cryostats are expected to bring major results in the field of high repetition rate target production. Intense energetic beams of protons have already been produced, demonstrating the high potential of the extrusion technique for target generation. ELISE and ELISE II will be improved in the coming months to provide thinner, more stable ribbons of hydrogen. More experiments are needed to test these devices at different intensities and pulse durations, with high repetition rates. Eventually, new applications of such cryogenic ribbons will be tested in the near future, in particular for neutron production.

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