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ENGINEERING ASPECTS OF CRYOGENIC
LASER-FUSION TARGETS

D. L. Musinski, T. M. Henderson, R. J. Simms and T. R. Pattinson

950 1011

✓ KMS Fusion, Inc., Ann Arbor, Michigan

and

R. B. Jacobs

951 1012

✓ R. B. Jacobs Associates, Inc., Boulder, Colorado

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D. L. Musinski, T. M. Henderson, R. J. Simms and T. R. Pattinson

KMS Fusion, Inc., Ann Arbor, Michigan

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R. B. Jacobs

R. B. Jacobs Associates, Inc., Boulder, Colorado

ABSTRACT

Most current laser-fusion targets consist of hollow spherical glass shells which have been filled with a mixture of gaseous deuterium-tritium fuel. Theoretical considerations suggest that optimum yields can be obtained from these targets if the fuel is condensed as a uniform liquid or solid layer on the inner surface of the glass shell at the time it is irradiated. In principle, this can be accomplished in a straightforward way by cooling the target below the condensation or freezing point of the fuel. In practice, cryogenic targets can appear in routine laser experiments only when the necessary cryogenic technology is reliably integrated into experimental target chambers. Significant progress has been made recently in this field. The authors will discuss the scientific basis and the various engineering features of a system which has allowed the successful irradiation of uniform solid-fuel-layer targets.

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INTRODUCTION

For efficient burn of the deuterium-tritium fuel contained within a hollow, spherical laser fusion target the fuel core must first be driven to a high density and then subsequently be elevated in temperature to initiate the reaction. To achieve high final fuel densities the internal pressure within the target must be overcome during the implosion. A cryogenic target, one in which the fuel is condensed as a liquid or solid layer on the inner surface of the spherical shell, may overcome the mechanisms⁽¹⁾ which can limit the final density. Fuel initially confined to the wall of the target cannot respond quickly enough upon absorption of energy to fill the interior volume of the target before the target implodes. At a given level of laser power, a cryogenic liquid or solid layer target should compress to a higher fuel density and produce a higher yield than a target containing the same mass of fuel in the gaseous state.⁽²⁾

The expected advantage of cryogenic targets can be illustrated by considering the specific example of a target filled with fuel at 100 atmospheres. If irradiated at room temperature, the entire amount of fuel is available to absorb energy and impede the target implosion. However, if irradiated as a liquid-layer target at 21K (approximately 1K above the point where the fuel starts to solidify) only a small fraction of the fuel is in the gaseous state, contained within the inner boundary of the liquid layer. Raoult's law applied to a specific KMSF fuel fill (8.4% HD, 9.3% HT, 19.7% D₂, 46.2% DT and 19.0% T₂)⁽³⁾ indicates that the pressure within the interior volume of this liquid-layer target is 293 torr. At room temperature, the pressure of this amount of gaseous fuel would be 5.5 atmospheres. Thus, only 5.5% of the total amount of fuel is available to absorb energy and impede the implosion if the target is irradiated as a liquid layer target.

If the same target is irradiated at 15K as a solid-fuel-layer target, the pressure within the interior of the target is only 11 torr. This corresponds to less than .02% of the total amount of fuel. Further lowering of the target temperature likewise lowers the vapor pressure and hence lowers the amount of fuel remaining in the gaseous phase. A solid-fuel-layer target irradiated at the minimum temperature attainable should, therefore, yield optimum results. An extensive program has been undertaken at KMSF to test these expectations experimentally. This paper discusses an essential element of the program -- the engineering technology developed to integrate cryogenic systems into actual fusion target chambers.

LIQUID-LAYER AND NON-UNIFORM SOLID LAYER TARGETS

From an engineering point of view, the most direct way to produce a cryogenic target is by use of the technique we refer to as point-contact conduction cooling.⁽⁴⁾ (Illustrated in Figure 1.) The target is bonded to the end of a 17- μ m-diameter copper fiber which is one element of a direct conduction path from the target to a source of refrigeration at liquid-helium temperatures. This technique is chiefly applicable to liquid-layer targets, targets in which the fuel is condensed as a liquid layer that completely covers the inside surface of the containing shell. Once the liquid layer has been established and stabilized by setting and stabilizing the temperature of the cryostat, target manipulation and alignment within the experimental target chamber proceed in the same manner as for a gaseous target at room temperature. Thus, this technique allows cryogenic experiments^(5, 6, 7) to be conducted with minimum disruption of the normal routine of the target chamber.

During the experimental studies on liquid-layer targets it became apparent that absorption of room temperature radiation dominates the dynamics⁽⁸⁾ of the fuel layer. The liquid layer configuration observed is the system's response to the absorbed radiative energy. The most direct engineering way to reduce this energy and its subsequent effect on the fuel is by the use of a radiation shield.

Figure 2 shows in schematic form the integration of a simple cryogenic shield (or shroud) in the experimental chamber. A modular increase in the system's complexity, this shield allows a non-uniform solid fuel layer to be formed within the target. A solid layer of DT fuel that completely covers the inside surface of the target, Figure 3, can be formed by starting with a liquid layer that is protected under the radiation shield⁽⁴⁾ and quickly lowering the temperature of the shell/fiber interface. The thermal gradient, imposed across the interior surface of the liquid layer by this procedure causes evaporation from the surface of the liquid layer. Since the heat of vaporization for the hydrogen isotopes is large compared with the heat of fusion (a factor of 6.6 for D_2), forced boiling of $\sim 15\%$ of the liquid causes the remaining liquid to freeze on the inner surface of the glass shell.

Once frozen, the temperature of the fuel layer is held below the melting point of the fuel by conduction through the copper fiber. As a result, the solid layer of Figure 3 sublimates instead of melting when the radiation shield is retracted and the target is exposed to room-temperature radiation. A fuel layer that must sublime rather than melt

has a substantial lifetime, i.e. time during which solid fuel remains as a continuous layer on the inner wall of the target. The amount of solid fuel remaining on the inner surface of this target at the moment the laser is fired is determined by the duration of the exposure to room-temperature radiation. This exposure time is determined by the retraction speed of the heat shield, Figure 4. This exposure time also sets some bounds on the range of target size and fuel fill that can be used with this system. Figure 5 shows the amount of fuel remaining as a continuous layer on the inner surface of a target as a function of exposure time, for various size targets and fuel fills. The ~ 30 -millisecond exposure time of the retraction device shown in Figure 4 allows a target as small as $70\text{-}\mu\text{m}$ in diameter with a fill pressure of 30 atm to be irradiated with an appreciable amount of fuel remaining as a continuous layer on the inner surface of the target.

Although this technique allows the formation and irradiation of solid-fuel-layer targets, these layers are inherently nonuniform. The liquid ($\sim 15\%$ of the fuel) that vaporizes during formation of the solid layer freezes as a small spheroidal volume localized over the shell/fiber interface. Also, the amount of fuel that sublimates during the exposure time is added to this localized spheroidal mass. Because of this inherent asymmetry these targets are not considered optimal for laser experiments. However, integration of the more complex system into the experimental target chamber afforded the opportunity to clearly identify and specify the problem areas involved with timing an active system (the retracting shield) to the laser firing sequence. The key requirements or problem areas were then addressed when designing the system for uniform solid fuel layer targets.

PRODUCTION OF UNIFORM SOLID-FUEL-LAYER TARGETS

There are two separate aspects of producing a uniform solid fuel layer target for laser irradiation. First, the system and procedure must provide a source of refrigeration to form the fuel layer in a manner that maximizes uniformity. Second, the system must be amenable to integration of the apparatus and procedures with the experimental target chamber. The constraints imposed by existing systems dictate, to a great extent, the options available.

Achieving uniformity in a solid fuel layer requires that two conditions⁽⁸⁾ be satisfied. First, any temperature gradient within the target must be small during the condensation and freezing of the fuel. Any temperature gradient within the target is relieved by a redistribution of fuel, evaporation from the warm region and subsequent condensation at the cold region. This redistribution of fuel mass per unit time becomes negligible only below 10K. Therefore, while the fuel is condensing and freezing (35K to 18K for the nominal 100 atm, 100- μ m-diameter target), temperature gradients are intolerable. The second condition for achieving uniformity requires that the time for condensation and freezing be minimized. Under the influence of gravity the liquid and/or liquid and solid mixture can sag within the target. Minimizing the time minimizes the sag. A condensing and freezing time of 20 milliseconds permits a theoretical nonuniformity of less than 5%. Cooling with gaseous helium can in principle satisfy both of the conditions.

The most practical method of minimizing the condensation and freezing time is to heat the fuel in a previously frozen target, vaporize it and allow it to refreeze rapidly within a cold environment. In a series of

well controlled bench experiments using an isothermal static helium environment, Miller ⁽⁹⁾ has demonstrated the degree of uniformity that is possible with this method. He was able to produce targets that met the criterion of 20% WNU.* In addition, he showed that a CW laser is an efficient means of coupling heat to the target. Subsequently, Woerner ⁽¹⁰⁾ confirmed this result in a similar system. However, integration of a static isothermal environment with the experimental target chamber is a formidable task requiring several levels of complexity. ⁽¹¹⁾ For our current experimental chamber a static isothermal environment is not required.

The primary constraints imposed by our existing experimental chamber are that the main illuminating beams must not be blocked or degraded nor may any of the diagnostic equipment be precluded from operation. These constraints make it unavoidable that the target be exposed to room-temperature radiation for at least a short time prior to the shot. The degradation of the uniformity of the fuel layer when exposed to room-temperature radiation is limited for any particular target by both the amount and the physical properties of the fuel. Figure 6 illustrates the point. It shows the calculated lifetime of the various phases of D₂ in a typical isolated target, initially at 10K, that is exposed to 300K radiation. (The target is assumed to have an absorptivity of one for room-temperature radiation.) After 10 milliseconds, the temperature of the fuel has reached the melting point where the uniformity of the fuel layer degrades as melting commences. Thus, for a uniform solid-fuel-layer target which is thermally isolated, the maximum exposure time is limited to less than 10 milliseconds. To minimize the amount of vaporized fuel an exposure time significantly less than 10 milliseconds is desirable.

* WNU = (Maximum Thickness minus Minimum Thickness)/Minimum Thickness

EQUIPMENT REQUIRED FOR UNIFORM SOLID FUEL LAYERS

The system we have designed and constructed to meet the requirements of uniformity and compatibility with the target chamber uses a gaseous-helium shroud and is shown in schematic form, integrated with the target chamber, in Figure 7. Much like the heat shield, it is lowered from the top of the experimental chamber to envelop the prealigned target and form the fuel layer. Just prior to the target shot the shroud is retracted uncovering the frozen target.

The details of the gaseous-helium shroud are shown schematically in Figure 8. Simplicity of design is achieved by using a commercially available cryostat and allowing the shroud to continually supply gaseous helium at a constant rate through a pinhole orifice to the region around the target. Four windows are provided at the target level, two for observation and two for a heating laser (the CW alignment laser of the target chamber) used to vaporize the fuel in situ prior to the rapid refreeze.⁽⁹⁾

Alignment of the target at the focus of the laser system is critical ($\pm 5\mu\text{m}$ permissible displacement). One must either attempt to prevent any displacement of a prealigned target while the fuel layer is being formed or provide for repositioning afterward. To avoid the complexity of alignment while the target is under the shroud, the system was designed to minimize target displacement during fuel-layer formation. The target is mounted on a copper post which fits into a collet joint in the extension of the lower cryostat. Before target alignment and formation of the fuel layer, the temperature of the lower cryostat is set at a value $< 10\text{K}$ to avoid subsequent thermal displacement of the target under the shroud. Although the target is mounted on a copper post as in previous cryogenic

experiments (Figure 1) with liquid-layer targets, the target itself is thermally isolated from the post by a 200- to 400- μm length of 10- μm -diameter glass fiber. This mounting arrangement prevents target motion due to cooling under the shroud yet assures that the cold gaseous helium is the dominant source of refrigeration for layer formation. Nonuniformities due to asymmetrical cooling by the fiber are thus avoided.

To prevent mechanical displacement of the target, the shroud does not touch the lower cryostat extension. The annular gap between the two acts as a variable impedance to the flow of gaseous helium from the target region inside the shroud to the rest of the target chamber. For maximum fuel-layer uniformity, the pressure near the target needs to be maximized in order to minimize the condensation and freezing time. This pressure is determined by both the throughput of the pinhole and the size of the annular gap. The throughput into the target chamber is set by the size of the pinhole, which must be chosen so that the pressure throughout the target chamber is no higher than ~ 3 millitorr. At higher pressures, the conductivity of the gas in the target chamber is sufficient to overload the cryostats and prevent operation below 10K. For this throughput, the pressure near the target is maximized by decreasing the gap to a minimum. Condensing and freezing of typical targets in this system occurs in ≤ 30 milliseconds.

The physical dimensions of the shroud plus the overlap of shroud and target post are dictated by considerations of shroud retraction. Exposure of the target to room-temperature radiation may be considered to start when the bottom of the shroud reaches the level of the target. From this position the shroud must be lifted clear of the path of the converging laser beams within 10 msec. The acceleration needed to accomplish this can be

minimized by maximizing the shroud overlap, i.e., the distance over which the shroud accelerates before exposing the target. The actual overlap chosen (4 cm) is a compromise between maximizing the overlap and assuring that the clearance (1.6 mm) between the inside of the shroud and the target-post extension can be maintained during both initial alignment of the system and shroud retraction.

The retraction system is shown in schematic form in Figure 9. A primary design consideration (recognized when using the piston retraction system of the radiation shield) is the minimization of target motion due to vibration. Since any impulse applied to the target chamber could displace the target, the retraction system is mounted on the ceiling, not on the target chamber, and the only mechanical coupling between the retraction device to the target chamber is through a 2-inch-diameter bellows, the minimum size that will permit x,y alignment of the shroud through the vacuum seal (see Figure 7).

The force for retraction is provided by two evacuated 5-inch-diameter bellows. This force is initially counterbalanced by flat-faced electromagnets. Retraction is triggered during the laser firing sequence by dumping the current in the magnetic-field coils. Since the holding force of the magnets is very sensitive to gap, free acceleration of the shroud is achieved quickly and the release time is highly reproducible. Figure 10 shows the position of the shroud as a function of time during retraction. Time zero on the figure is the time when the magnet dumping circuit is triggered. The data shown were taken from multiple exposures on high speed polaroid film of an indicator flag attached to the system. The two data points at each time point are the worst-case data for a series of 25 runs

conducted over a two-day interval. Total travel is 10.8 cm and occurs in 60 msec. Laser irradiation of the target is timed to occur at the point indicated on the figure before deceleration (provided by two commercial shock absorbers) begins. This timing precludes target vibration due to deceleration shock. With laser irradiation occurring at this point, the exposure of the target to room-temperature radiation is kept to 4.0 ± 0.35 msec.

EVALUATION OF SOLID FUEL LAYERS

To evaluate the quality of the fuel layers produced with this apparatus the interferometer⁽¹²⁾ shown schematically in Figure 11 was constructed and used in our off-line simulation chamber as well as in our target chamber. The major feature of this interferometer is the shearing cube⁽¹³⁾. With it both high contrast and stability are assured as well as the ability to continuously vary both the background phase and phase gradient. The illuminating lens is adjusted to focus the laser behind the target, producing a diverging beam a few target diameters wide at the plane of the target. The imaging lens is set to focus the crossover of the laser beam on the back side of the shearing cube while focusing an image of the target on the image plane. By limiting the focus point on the shearing cube, extraneous phase shifts due to variations in the surface of the cube are eliminated. Phase shift and shearing are controlled by sliding and rotating one-half of the shearing cube relative to the other.

The quality of targets that this system is capable of producing is shown in Figure 12. Figure 12a is the interferometric image of a DT-filled target when the fuel is in the gas phase. Figure 12b is an interferometric image of the same target with the fuel condensed out in the solid phase.

Using a criterion based on computer modeling for these interferometric images⁽⁹⁾ the target shown in Figure 12b meets the criterion of $\sim 20\%$ WNU.

At the present time the ability repeatedly to obtain acceptable uniformity in a solid layer is not entirely satisfactory. A remelt of the target shown in Figure 12b may produce the target of Figure 12c as often as it reproduces the image of 12b. High speed movie films (500 fps) taken of the vaporize/refreeze cycle clearly show that during condensation, while the fuel is in the liquid state, the fuel layer is very uniform. The nonuniformities observed in the final stable solid layer occur either during or after freezing of the liquid. At present not all the factors responsible for the uniformity or nonuniformities are understood. Further study is required to identify and understand these factors so that uniformity of the fuel layer can be controlled and repeated.

LASER IRRADIATION OF UNIFORM SOLID-FUEL-LAYER TARGETS

The additional operational procedures required for these solid layer targets have been integrated into the normal routine of the experimental program at KMSF. The target is installed in the experimental chamber and aligned with the main laser, following the same sequence as that used in the liquid-layer experiments.⁽⁶⁾ First, the gaseous-helium shroud is lowered over the target to freeze the fuel. Next, the CW alignment laser, which is coaxial with the main laser system, is used to vaporize the fuel within the target. Because of the large angular coverage of the target by our ellipsoidal-mirror illuminating system (see Figure 12) beam reducers are inserted into the path of the alignment laser. These allow the ellipsoidal-mirror illuminating system to focus all the power of the alignment laser onto the target through two of the four windows in the shroud. The power of the alignment laser is increased until the fuel

within the target evaporates. An operator watching the interference pattern of the target regulates the freezing of the fuel by shuttering the CW alignment laser until, in his judgment, the uniformity of the solid fuel layer is satisfactory. The interference pattern is then photographed and the beam reducers are retracted from the path of the main beam. The final preparatory step is to charge the shroud-retraction device by energizing the holding magnets and evacuating the 5-inch-diameter bellows. Triggering of the retraction device is controlled automatically by appropriate timing circuits locked into the normal automated laser-firing sequence.

SUMMARY

Experiments with cryogenic liquid-layer targets, using point-contact conduction cooling, have opened the way to experiments with solid-layer targets. The engineering and integration of successively more complex systems identified the critical design features and procedures needed to achieve uniformity of the fuel layer. The technology has been refined and extended in several iterative steps to eliminate the major causes of nonuniformity and to provide an interferometric viewing system that enables an operator to observe and evaluate the layer formation. The gaseous-helium shroud and retraction system were shown to be capable of producing and presenting to the laser a satisfactorily uniform ($\lesssim 20\%$ WNU) solid-fuel layer target. Successful laser irradiation of such targets demonstrates that this system now offers the opportunity to experimentally study in a systematic way a new class of laser fusion targets -- uniform solid fuel layer targets.

ACKNOWLEDGEMENTS

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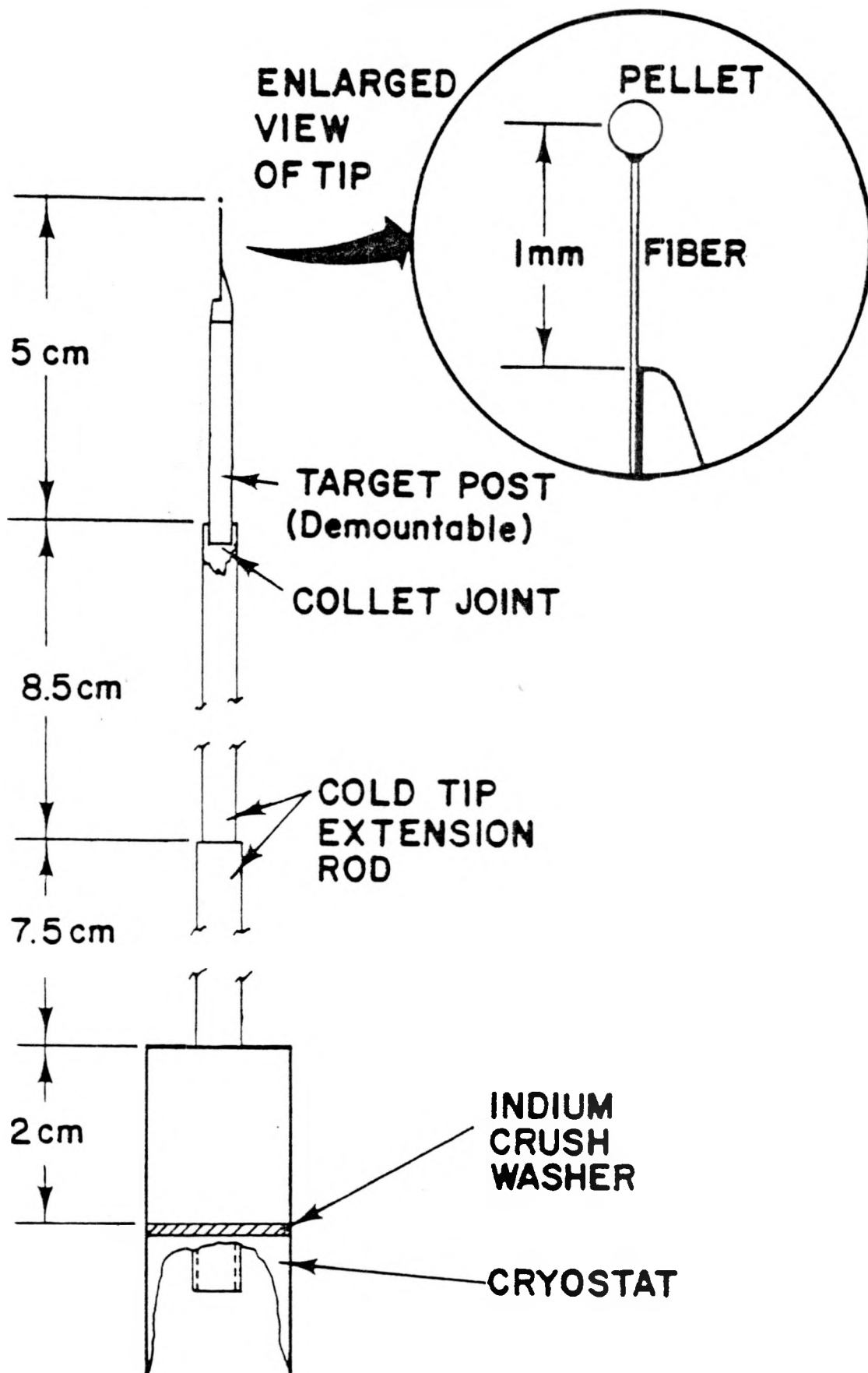
The successes achieved in our cryogenic work are very much a consequence of outstanding teamwork within the Division of Material Sciences at KMS Fusion. We owe particular thanks to D. L. Melmoth whose close attention to details avoided many pitfalls and to E. J. Calabro who, despite a long list of restrictions and constraints, succeeded in converting a few general concepts into a practical, remarkable trouble-free design for the shroud-retraction mechanism. Special thanks must also be extended to R. D. Sigler who suggested the use of the shearing cube interferometer and who guided the authors in its use. J. A. Tarvin contributed both valuable discussions and his laboratory expertise during the final testing stage of the gaseous helium shroud.

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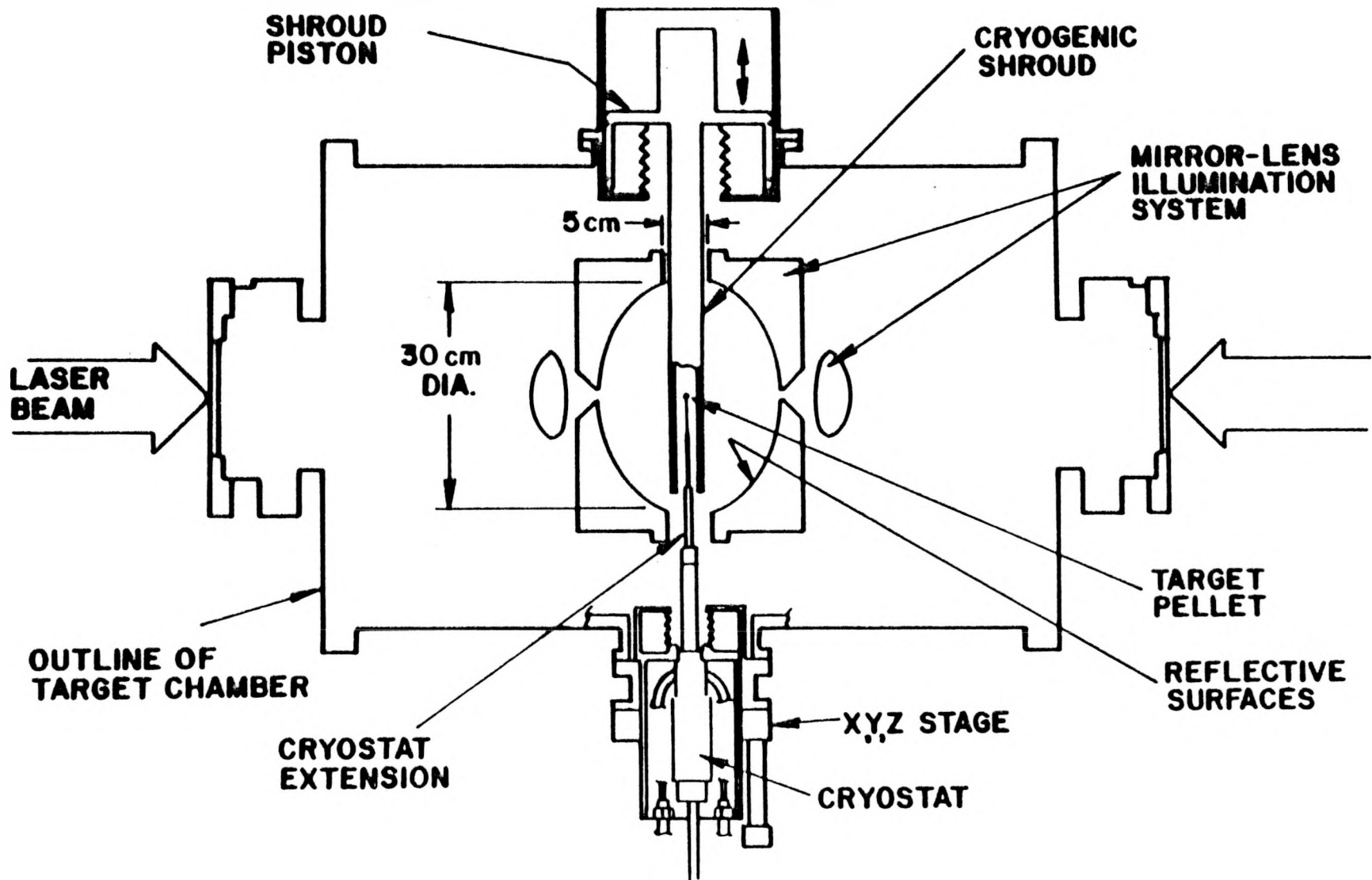
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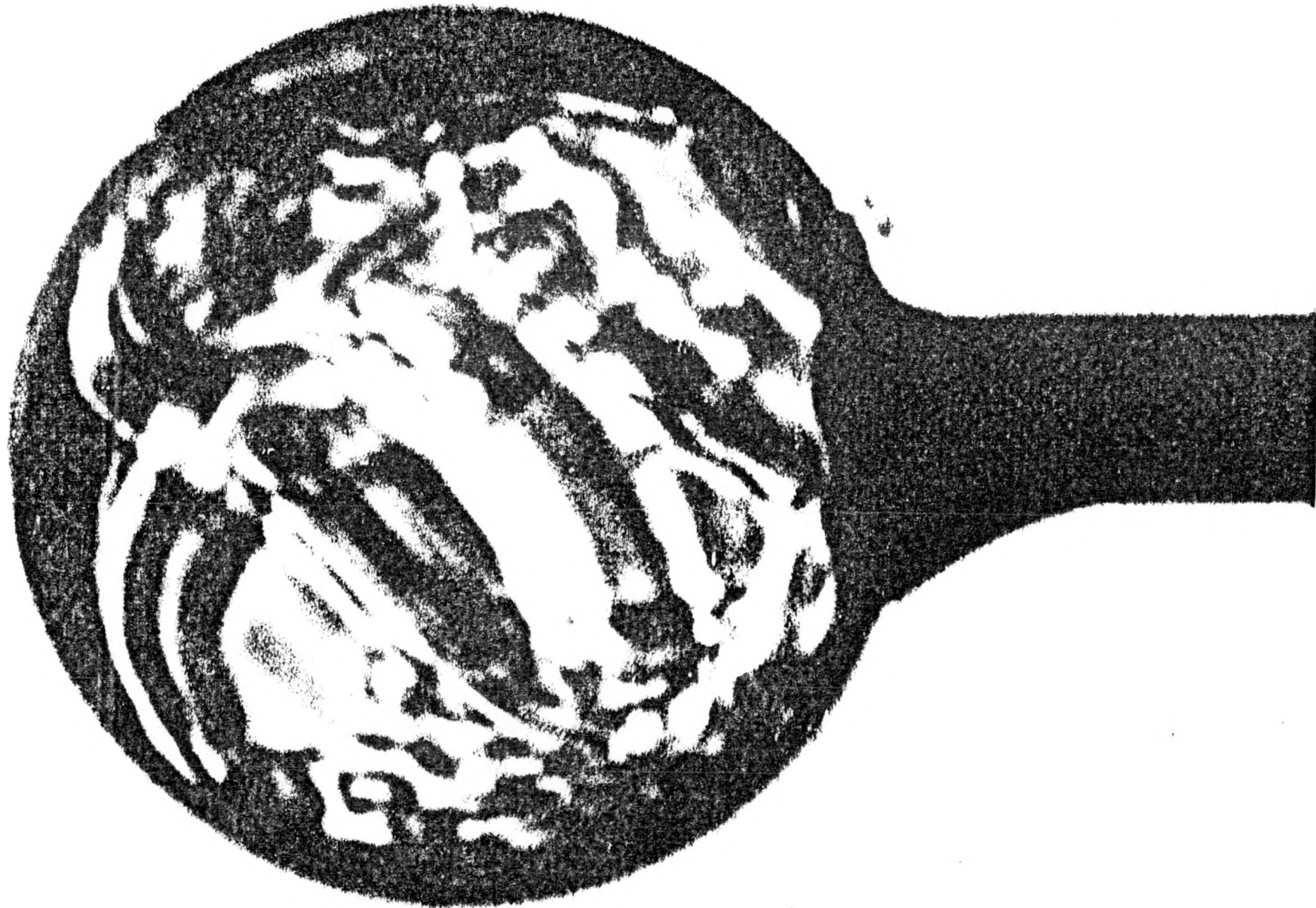
FIGURES

1. Point-Contact Conduction Cooling Cryostat.
2. Integration of a simple cryogenic radiation shield in target chamber.
3. Solid fuel layer on the inside surface of the target.
4. Piston retraction of the radiation shield.
5. Solid fuel layer vs. exposure time.
6. Lifetime of a fuel layer exposed to room temperature radiation.
7. Gaseous Helium Shroud integrated in the target chamber.
8. Schematic of the Gaseous Helium Shroud.
9. Schematic of the Shroud Retraction Device.
10. Retraction of the Gaseous Helium Shroud.
11. Shearing Cube Interferometer System
12. a) Interferometric image of a DT filled target, fuel in gas phase.
b) Interferometric image of a DT filled target, fuel in uniform solid layer.
c) Interferometric image of a DT filled target, fuel in a nonuniform solid layer.
13. Laser heating a shrouded target in the KMSF target chamber.

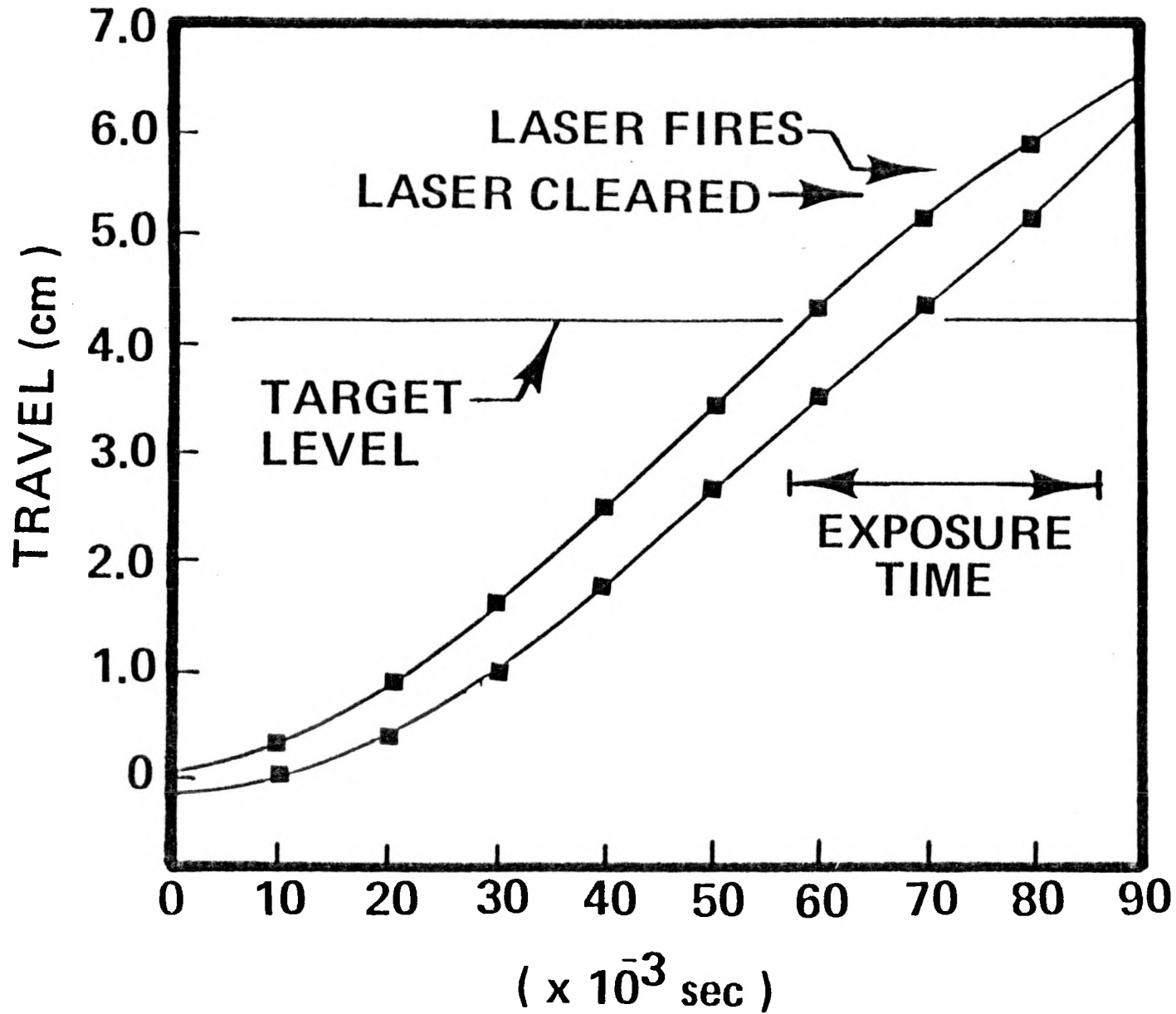


**CONDUCTION COOLING SYSTEM INTEGRATED IN THE
LASER FUSION TARGET CHAMBER**





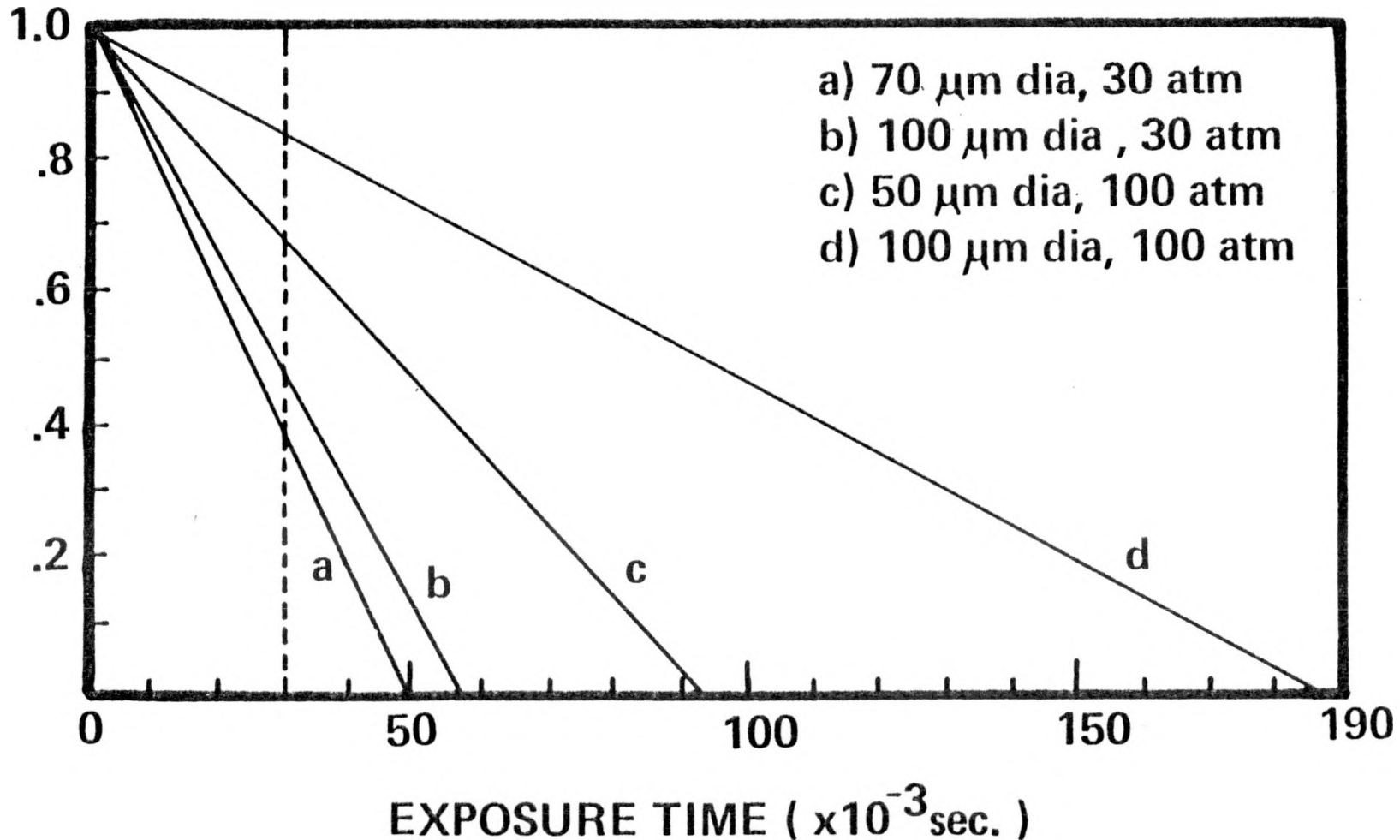
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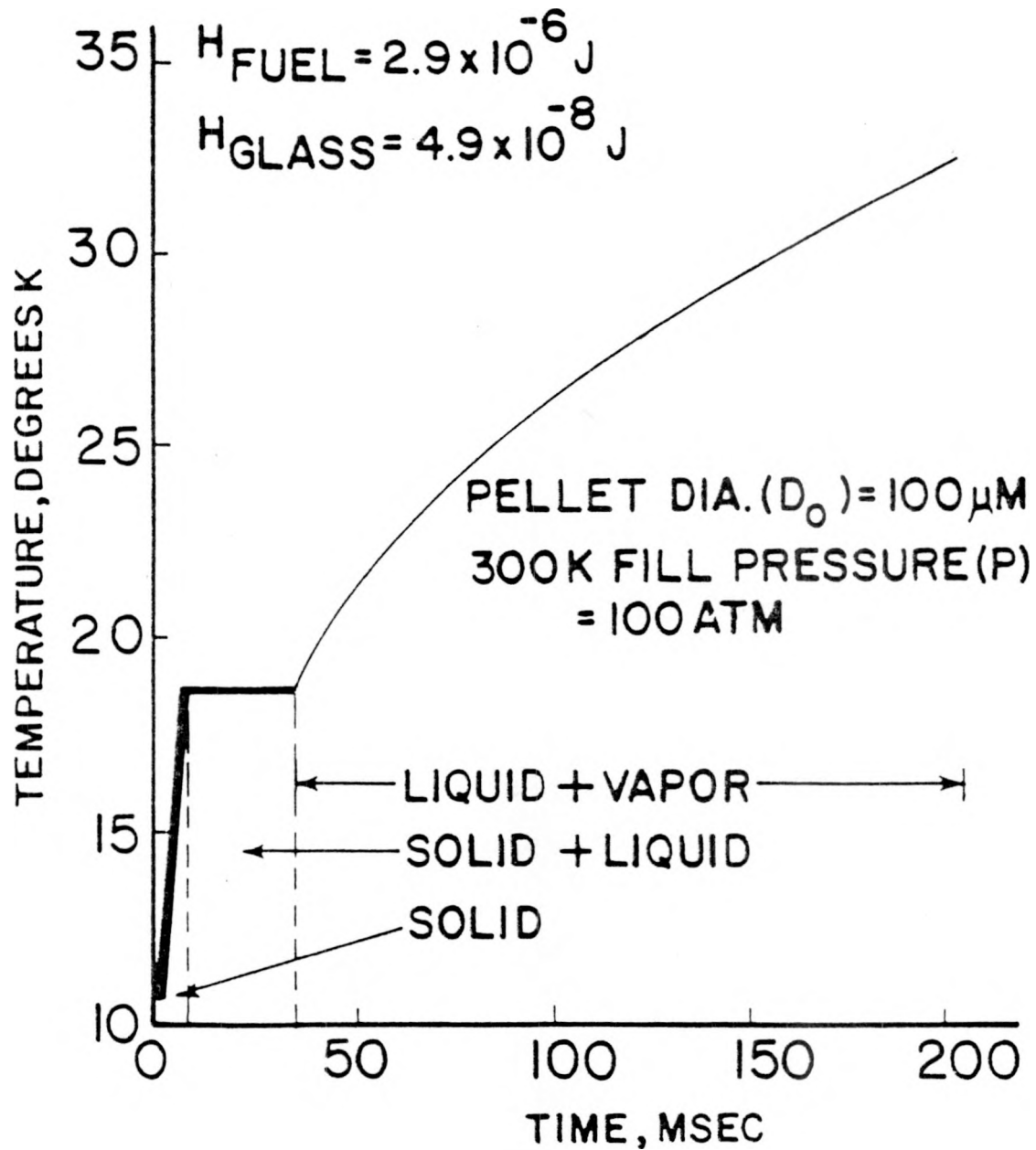
SOLID FUEL REMAINING ON INNER SURFACE OF SHELL

(% / 100)

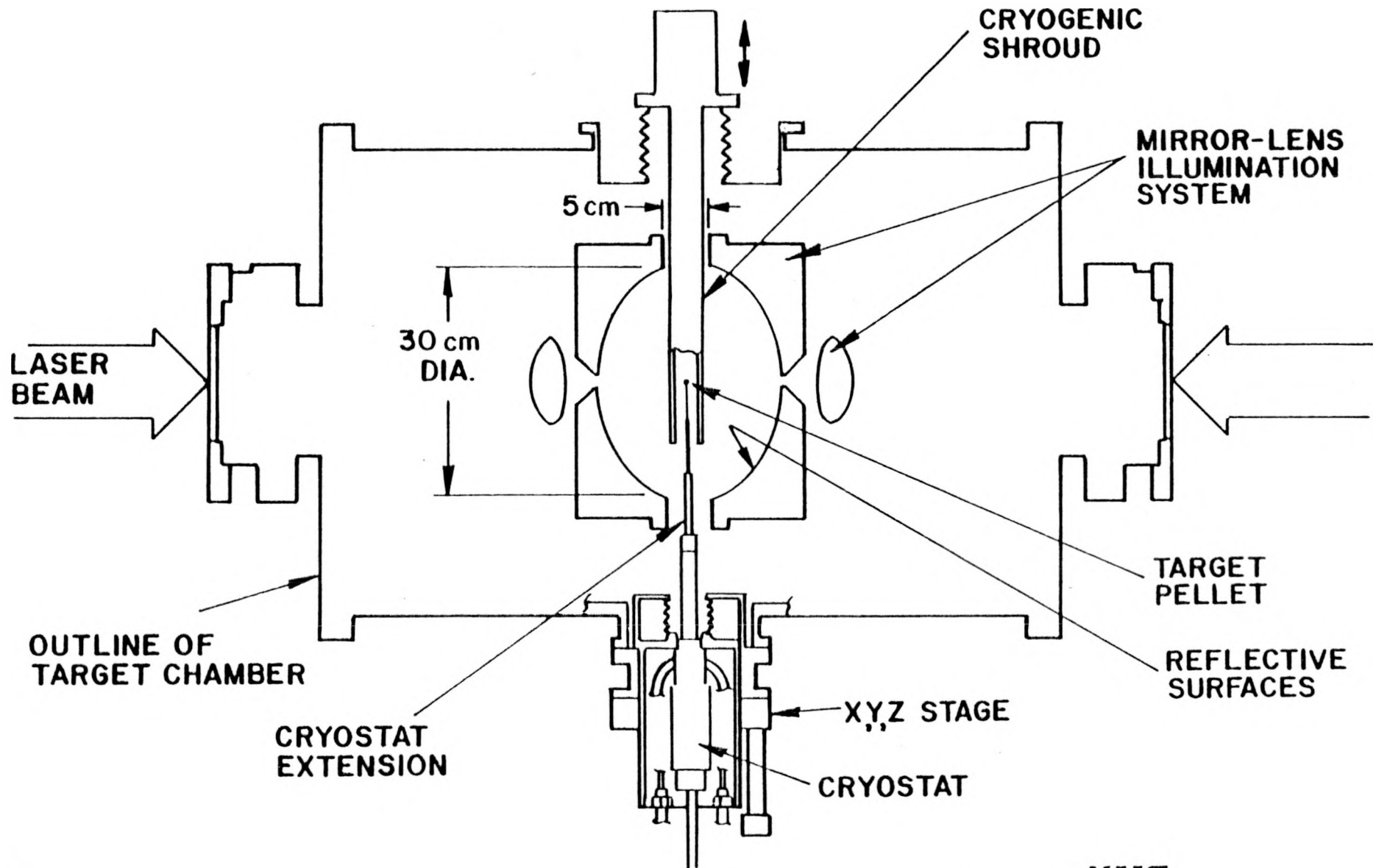
INITIAL FUEL \approx 85 / OF AVAILABLE FUEL



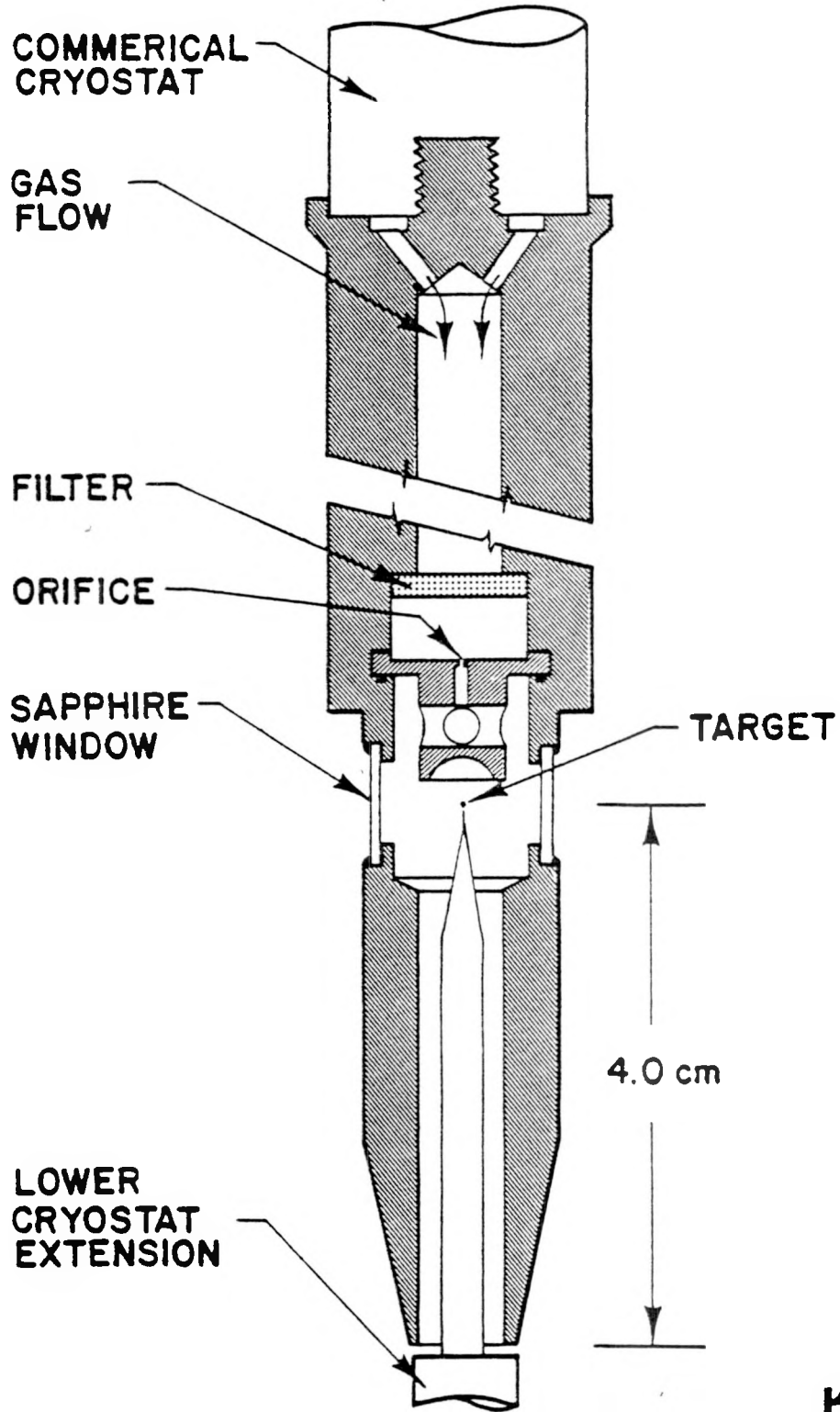
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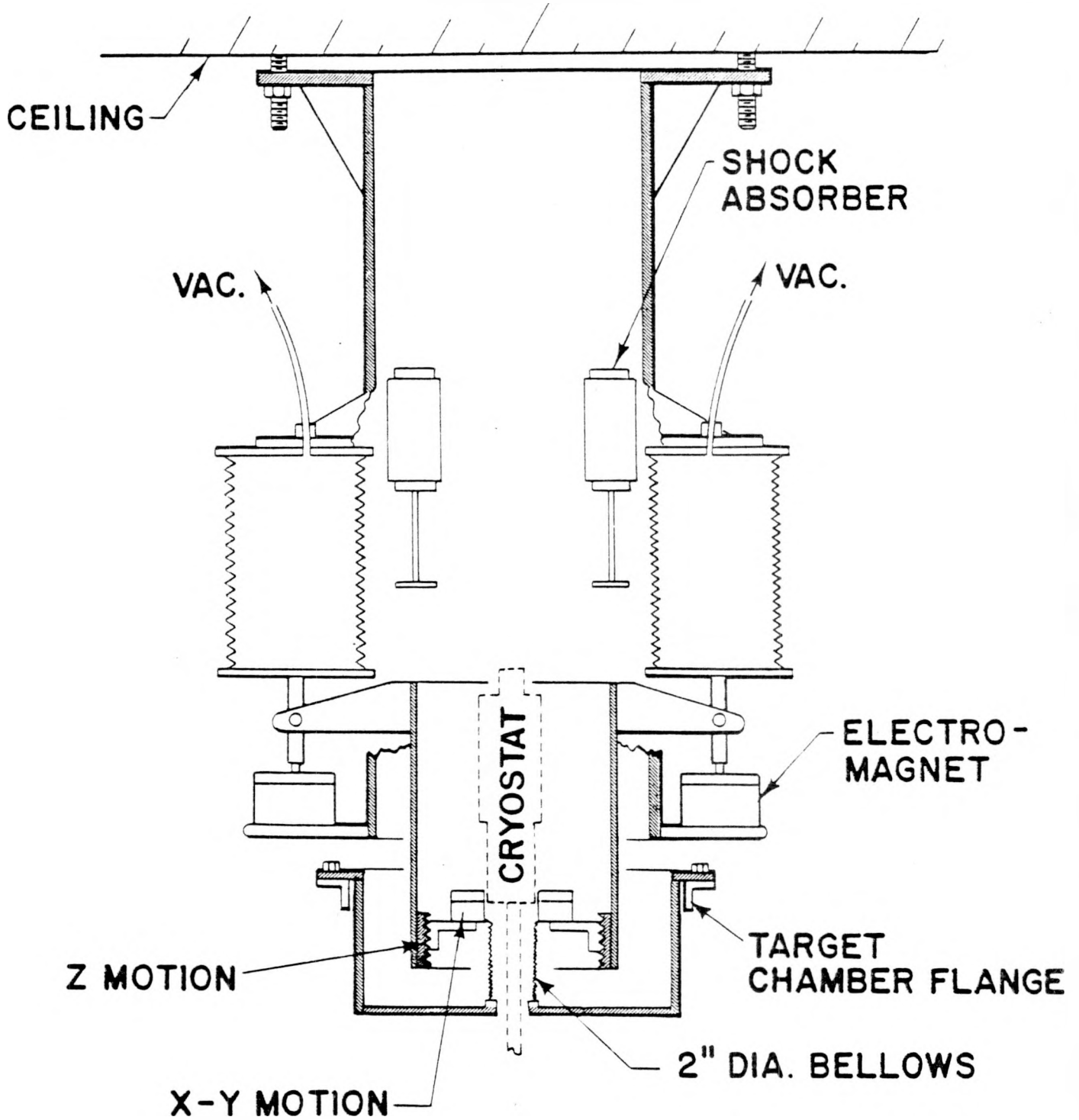
GASEOUS HELIUM SHROUD INTEGRATED IN THE LASER FUSION TARGET CHAMBER



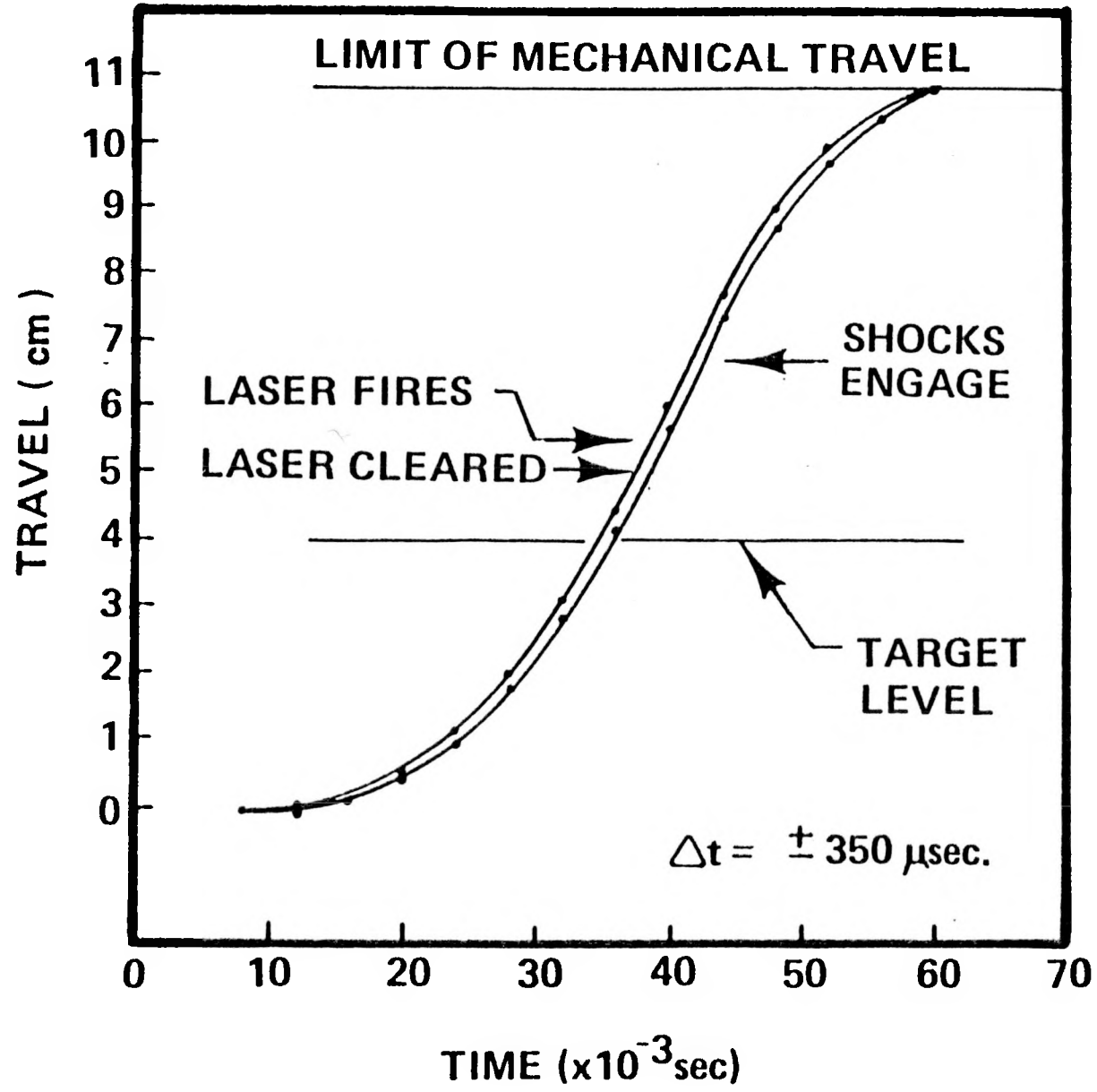
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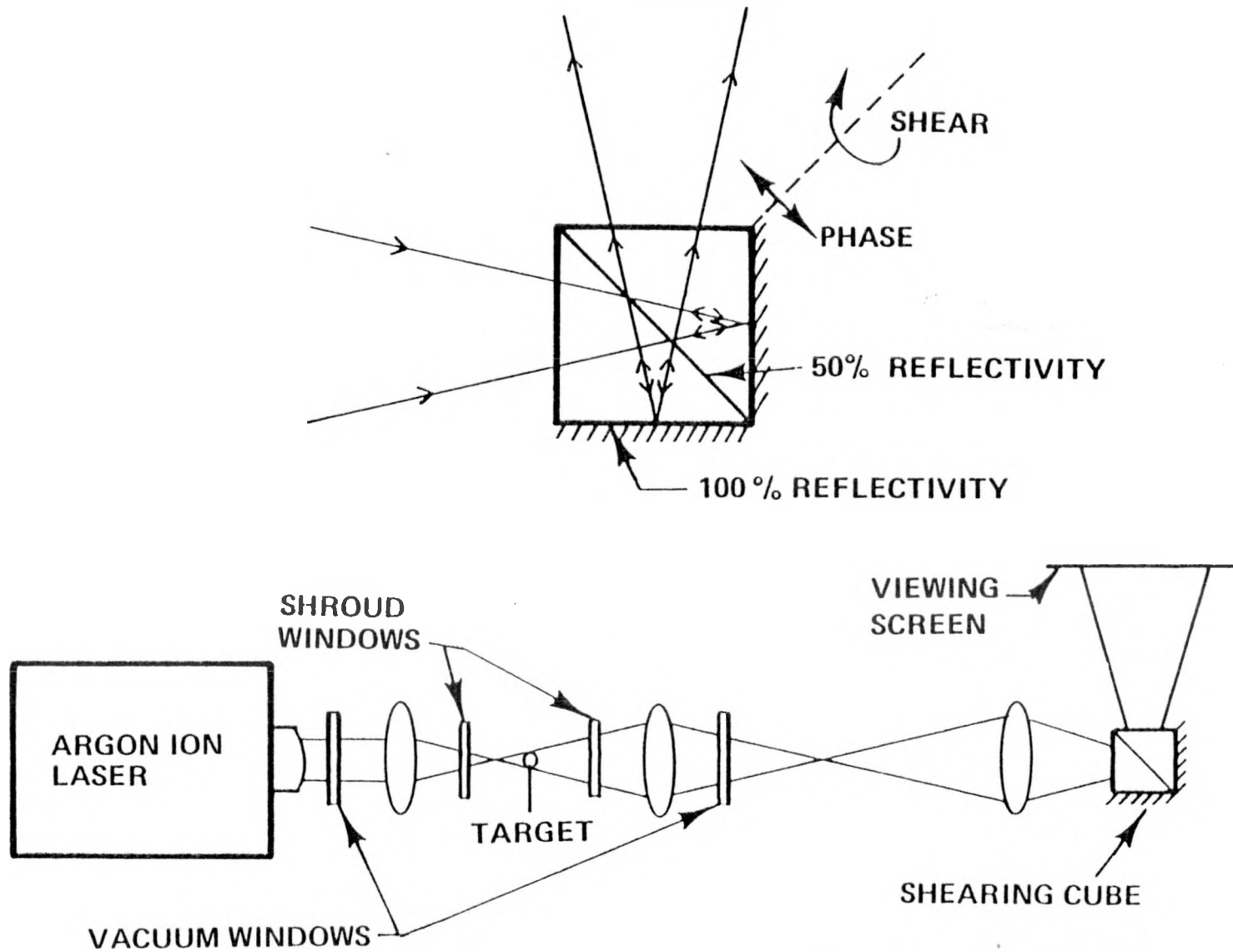
SHROUD RETRACTION DEVICE

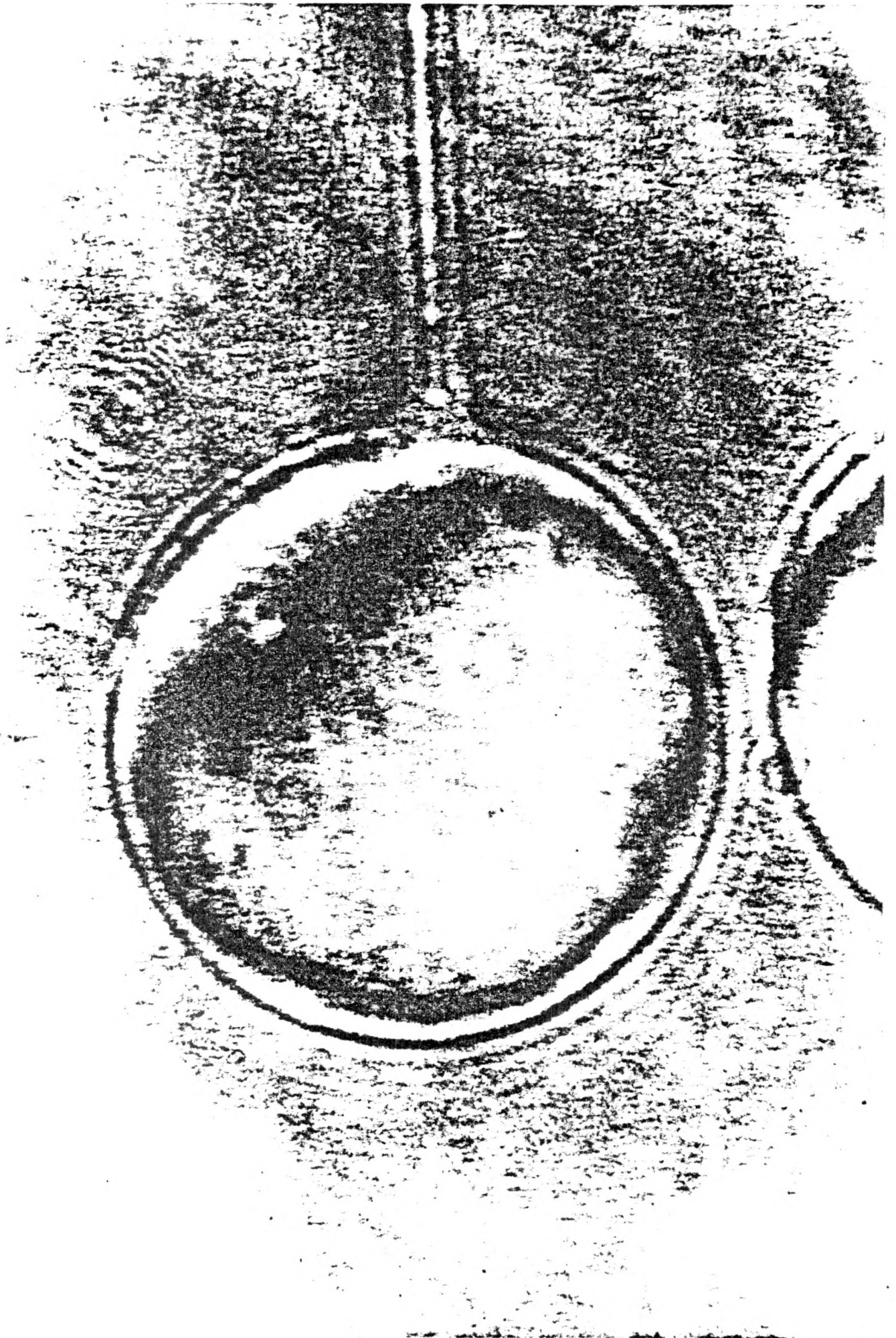


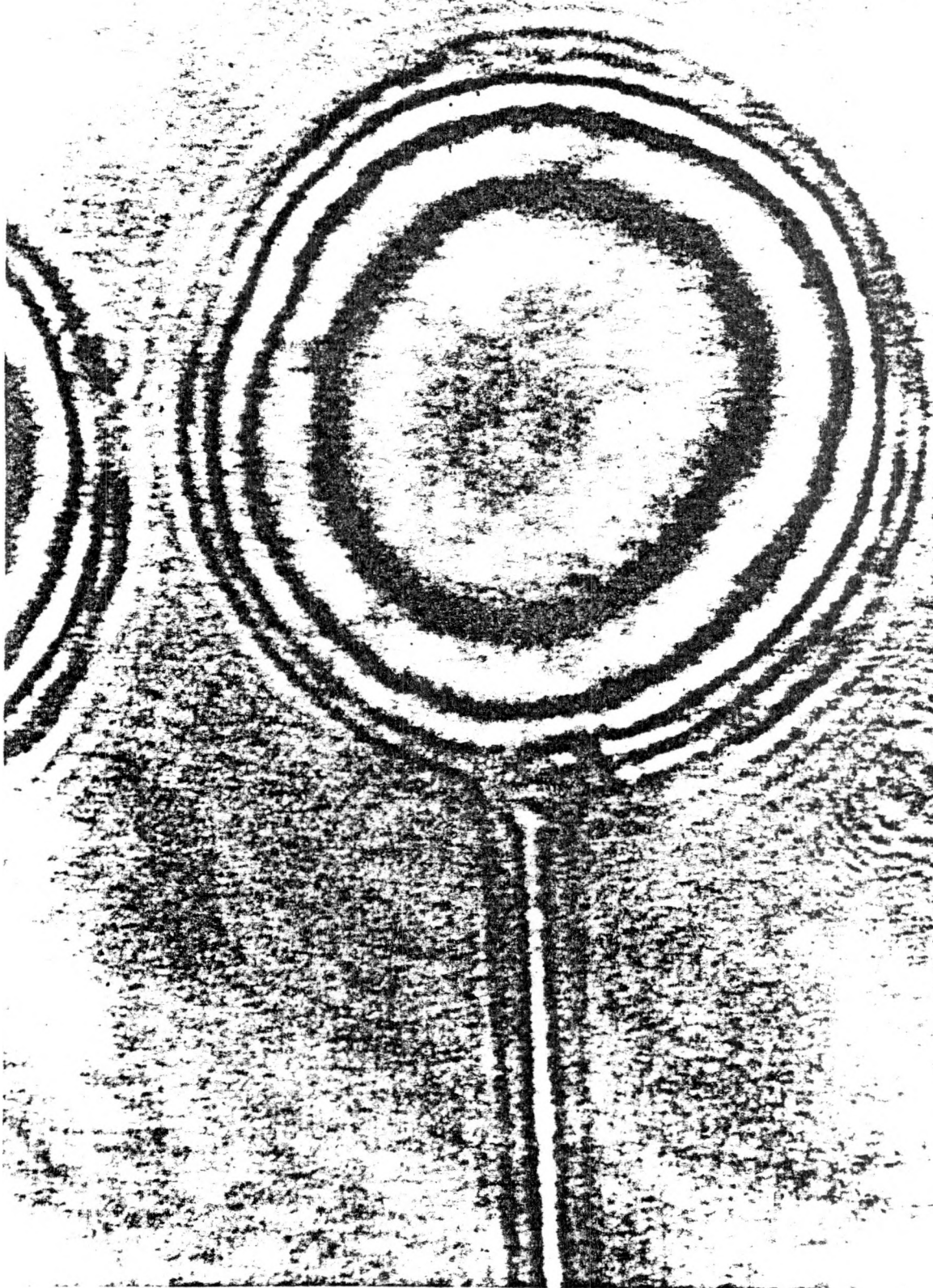
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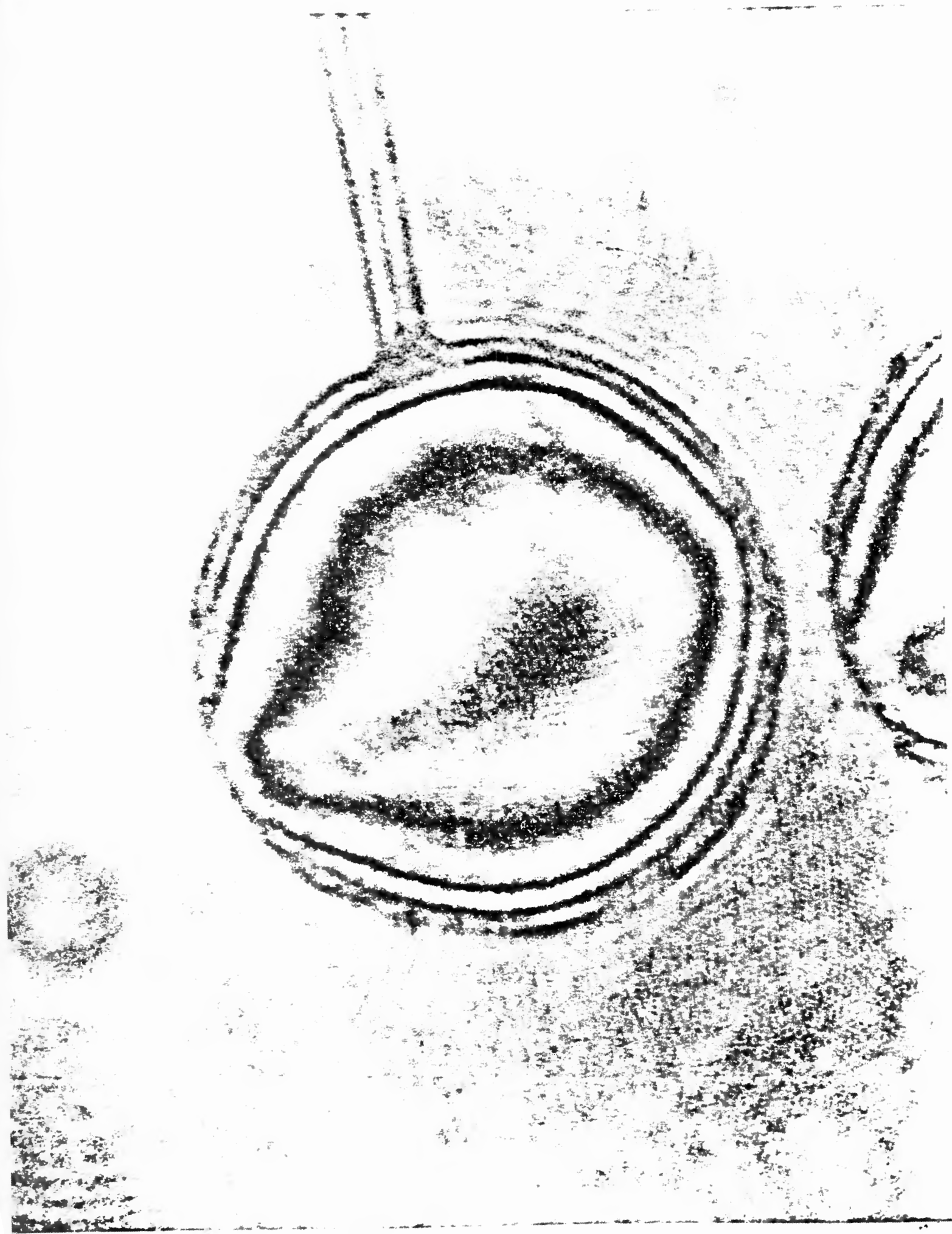


SHEARING CUBE INTERFEROMETER









LASER HEATING SHROUDED TARGET IN TARGET CHAMBER

MIRROR - LENS ILLUMINATION SYSTEM

