CHARGED PARTICLE RESEARCH LABORATORY REPORT NO. 2-81

MASTER

INVESTIGATION ON NON-GLASS LASER FUSION TARGETS--
THEIR FABRICATION, CHARACTERIZATION, AND TRANSPORT

PROGRESS REPORT

June 1, 1980 -- January 31, 1981

by

Kyekyoon Kim
Department of Electrical Engineering
University of Illinois
Urbana, Illinois 61801

Prepared for
Lawrence Livermore National Laboratory
Under Subcontract # 8320003

TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
Chapter 1. BEHAVIOR OF LIQUID HYDROGEN INSIDE A SPHERICAL TARGET	2
1.1 <u>Theoretical Work</u>	7
1.2 <u>Comparison Between Theory and Experiment</u>	8
Chapter 2. DEVELOPMENT OF AUTOMATED TARGET CHARACTERIZATION SCHEME	10
2.1 <u>Microprocessor-Controlled Data Acquisition System</u>	10
2.1.1 Central processing unit	13
2.1.2 Memory	13
2.1.3 Communication interface	15
2.1.4 Video interface	16
2.2 <u>Theoretical Ray-Tracing and Results</u>	18
2.2.1 Introduction	18
2.2.2 Theoretical ray-tracing output examples	25
2.2.3 Advanced ray-tracing model	30
2.3 <u>Experimental Results</u>	32
2.3.1 Introduction	32
2.3.2 Target characterization example	33
Chapter 3. CRYOGENIC TARGET FABRICATION SYSTEM UTILIZING COLD-GAS-LEVITATION AND ELECTRIC FIELD POSITIONING	38
3.1 <u>Introduction</u>	38
3.2 <u>Gas Levitation</u>	42
3.2.1 Introduction	42
3.2.2 Target drag calculations	45
3.2.3 Target levitation requirements	47

Table of Contents (continued)

	<u>Page</u>
3.3 <u>Electrostatic Centering</u>	49
Chapter 4. CRYOGENIC TARGET FABRICATION SYSTEM BASED ON TARGET FREE-FALL CONCEPT	57
4.1 <u>Overall System Description</u>	57
4.2 <u>Preliminary Test</u>	62
Chapter 5. HYDROGEN POWDER GENERATION SYSTEM BASED ON ELECTRO- HYDRODYNAMIC SPRAYING	64
Chapter 6. STUDY OF TARGET-CHARGING TECHNIQUES FOR APPLICATION TO CONTACTLESS CRYOGENIC TARGET FABRICATION SYSTEM . .	70
6.1 <u>D.C. Operation</u>	73
6.2 <u>Target Charging Experiment</u>	75
Chapter 7. TECHNIQUES FOR PRODUCING HOLLOW METAL SPHERES	78

INTRODUCTION

A summary is presented of the research progress made under LLNL Subcontract 8320003 for the period of June 1, 1980 through January 31, 1981. The main theme of the research has continued to be the development of techniques for fabricating, characterizing, and transporting laser fusion targets on a continuous basis. The target fabrication techniques are intended mainly for non-glass spherical shell targets, both cryogenic and non-cryogenic. Specifically, progress has been made in each of the following categories.

1. Investigation of liquid hydrogen behavior inside a spherical laser fusion target.
2. Development of automated target characterization scheme.
3. Study of cryogenic target fabrication scheme utilizing cold-gas-levitation and electric field positioning.
4. Development of a cryogenic target fabrication system based on target free-fall method.
5. Generation of hydrogen powder using electro-hydrodynamic spraying.
6. Study of target-charging techniques for application to contactless cryogenic target fabrication.
7. Development of hollow metal sphere production technique.

A brief summary of the research progress made in each category is presented.

1. BEHAVIOR OF LIQUID HYDROGEN INSIDE A SPHERICAL TARGET

Preliminary calculations were presented in the previous progress report (for the period of December 1, 1979 through May 31, 1980) which are intended to describe the behavior of liquid hydrogen inside a spherical target. These calculations had been motivated by a series of target cooling experiments performed earlier by us at the University of Illinois. The experiments indicated that the configuration of liquid hydrogen inside a spherical glass shell is highly temperature-dependent, ranging from a compact spheroid near the triple point to a fairly uniform spherical layer completely covering the interior of the glass shell at higher temperatures. In a transition region, the liquid forms an incomplete layer existing over only a portion of the shell interior. This rather interesting liquid hydrogen behavior, clearly distinguishable from that of a sessile drop sitting on a flat plane, manifests itself mainly due to the sphericity of the wetting surface leading to formation of a continuous liquid layer at and above a certain temperature.

Since an in-depth study of this phenomenon can help one to assess the feasibility of fabricating inertial confinement fusion (ICF) targets containing a uniform layer of DT-condensate, we have proceeded to extend the preliminary calculations so that the theory may include all the important fundamental forces, such as the gravitational force, the interfacial surface tension forces, and the van der Waals force. This theoretical attempt appears to carry more significance than ever before in light of the recent target cooling experiments performed by T. P. Bernat, et al. at LLNL.[1]

1/ T. P. Bernat, private communication (1981).

Their observation indicates that the wetting angles of liquid hydrogen with the glass shell are of such small values that the liquid forms a continuous layer (thus wetting the entire target interior) at all temperatures of liquid phase. Noting that this liquid hydrogen behavior observation is not in total agreement with that of our own (described at the beginning of this chapter), there clearly exists a need for a similar, more extensive experimentation.

1.1 Theoretical Work

The theory presented here is an extension of the simple theory described in the previous report. The simple theory, although formulated using the method of calculus of variations and, therefore, different from the derivation of Bashforth and Adams, has led to an equation essentially identical to the so-called Bashforth-Adams equation for a sessile drop. More specifically, in the coordinate system defined by Figures 1.1 and 1.2, the simple equation governing the behavior of a liquid inside a spherical shell target of inner radius R_i is obtained as

$$\frac{x'''}{[1 + (x')^2]^{3/2}} - \frac{1}{x[1 + (x')^2]^{1/2}} = -\alpha - \beta y \quad (1.1)$$

$$\text{where } x = \tilde{x}/R_i, \quad y = \tilde{y}/R_i, \quad \alpha = \frac{\lambda R_i}{\gamma_{LV}},$$

$$\beta = \frac{\rho g R_i^2}{\gamma_{LV}} \quad \text{and } \lambda = \text{Lagrange multiplier.}$$

The Lagrange Multiplier λ is a constant subject to the volume of liquid contained in the target at a given temperature.

Figure 1.1 Cylindrical coordinate system employed for the description of a spherical target.

Figure 1.2 The cylindrical system shown in Figure 1.1 redefined in dimensionless units.

Two end point conditions needed to close this equation are .

$$1. \quad \left[\frac{dx}{dy} \right] = \infty \text{ at } x = 0$$

$$2. \quad [x(y)] = [1 - (y_2 - 1)^2]^{1/2} \text{ at } y = y_2$$

The first condition simply states that the liquid profile is symmetric about the y-axis. The second condition is the so-called "transversality condition." Namely, at $y = y_2$, the profile of the liquid must match that of the target's inner surface. At the point of contact between the liquid, gas and target wall, the following equation must be satisfied:

$$x + \frac{\gamma_{LS} - \gamma_{SV}}{\gamma_{LV}} \left[1 + \left(\frac{dx}{dy} \right)^2 \right]^{1/2} - (y-1) \frac{dx}{dy} = 0$$

It is easy to verify that this equation is identical to the usual Young's equation for contact angle, i.e.,

$$\cos (\theta_1 - \theta_2) = \frac{\gamma_{SV} - \gamma_{LS}}{\gamma_{LV}} \quad (1.2)$$

Numerical solutions of the liquid profile equation (Eq. (1.1)) for deuterium contained in a spherical glass target are shown in Figure 1.3. In this example, the target diameter is 140 μm , wall thickness is 3 μm , deuterium fill pressure at room temperature is 110 atm, and target temperature is 24 K. The corresponding contact angle is shown with each profile.

Figure 1.3 Profiles of liquid deuterium contained in a spherical glass shell as obtained by solving Eq. (1.1). The deuterium fill pressure at room temperature is 110 atm and the target temperature is 24K. The contact angles are used as a boundary condition in the numerical calculations.

The simple theory described thus far does not contain a term resulting from the van der Waals forces between the liquid and the target wall. As a consequence, it should become increasingly less accurate as the liquid layer becomes thinner and covers more target wall surface. This effect should then be most felt when the liquid wets the entire target inner surface and forms a continuous layer.

Van der Waals forces $\left(\sim \frac{1}{r^6}\right)$ are added to the simple theory not as a surface force but as a body force, resulting in an equation similar to the Bashforth-Adams equation but more relevant to the present problem.

$$\frac{x''}{[1 + (x')^2]^{3/2}} - \frac{1}{x [1 + (x')^2]^{1/2}} = -\alpha - \beta y - D(x, y) \quad (1.3)$$

$$\text{where } D(x, y) = A \left[\frac{R^3}{(R^2 - r^2)^3} - \frac{1}{(1 - r^2)^3} \right],$$

$$A = \frac{4\pi n_L n_S C_{LS}}{3\gamma_{LV} R_i^2},$$

$$R = \frac{R_0}{R_i},$$

$$r = \frac{1}{R_i} \left[x^2 + (y - R_i)^2 \right]^{1/2} = \left[x^2 + (y-1)^2 \right]^{1/2}$$

With this equation, it is straightforward to show that, without the gravitational force, a continuous liquid layer must have uniform thickness.

1.2 Comparison Between Theory and Experiment

In order to solve the theory represented by Eq.(1.3), one needs information on various physical quantities: the equation of state of hydrogen for determination of liquid volume; the interfacial surface tensions, γ_{LV} , γ_{SL} and γ_{SV} ; and the London constant C_{LS} characterizing the van der Waals forces between the hydrogen and glass molecules. All of these quantities are temperature-dependent except C_{LS} . With these quantities known, the Lagrange multiplier λ may then be determined in a self-consistent manner for each temperature by requiring that the volume calculated from the resulting liquid configuration be equal to that predicated by the equation of state. In other words, a complete determination of the liquid profile is possible for each temperature (except to note that, in actuality, information on γ_{SL} and γ_{SV} is not readily available).

Since γ_{LV} , the equation of state, and the London constant are all known for hydrogen, and γ_{SL} and γ_{SV} do not play a role when the liquid layer completely wets the entire glass shell (thus forming a continuous liquid layer), solving Eq.(1.3) for the continuous liquid layer case is possible. This solution, which is relevant to temperatures near the liquefaction point, can then be compared easily with the data. Adjustment of the London constant to produce the best fit to the data can also lead to prediction of an accurate London constant value.

Once the predictions of Eq.(1.3) have been checked for the continuous liquid layer case, one can then extend the comparison to the lower-temperature region where the liquid layer exists in a non-continuous configuration. Contact angles can be measured, and by utilizing Young's equation, Eq.(1.2),

$(\gamma_{SL} - \gamma_{LS})$ can, for example, be determined for different temperatures since γ_{LV} is already known. For theoretical calculations, the experimentally measured contact angles and the coordinates of the contact points (between solid, liquid and gas) provide a useful set of boundary conditions in checking the accuracy of the theory.

We are currently in the process of solving Eq.(1.3) for D_2 -filled glass shell targets possessing different parameters. A new target freezing cell is also being built, which is designed to provide an isothermal environment around a target and which is equipped with accurate temperature sensors to monitor its temperature at various locations.

2. DEVELOPMENT OF AUTOMATED TARGET CHARACTERIZATION SCHEME

2.1 Microprocessor-Controlled Data Acquisition System

The purpose of the microprocessor-controlled data acquisition system (DAS) is to place a specified length of video information, either full page or single lines, in memory and then process it with regard to the fuel density and the overall uniformity and concentricity of the fabricated laser target. The target image may also be permanently stored on magnetic floppy discs for later retrieval and analysis. The microprocessor system shown in Figure 2.1 also offers the flexibility of plotting the target phase map information in two dimensions. In addition, the system can format the data and load them into a main computer (CDC Cyber 175) via a telephone link.

Once this is accomplished, the user may manipulate the data with more sophisticated higher-speed programming. This opens the door to such things as two-dimensional Fourier analysis, fringe matching to theoretical calculations, and advanced concentricity mean-error calculations.

The system developed is based on the popular Intel 8080A microprocessor and the standard S-100 bus system (see Figure 2.2), which allow system expansion through addition of easily available memory and interface boards at moderate costs. Through standardization, the system also allowed implementation of such "canned" software packages as the Digital Research CP/M operating system [2] and accompanying EBASIC programming language. As a consequence, it was relatively easy to construct new acquisition programs directly in a high level language or machine code.

The key elements of the data acquisition system are the central processing

2/ An Introduction to CP/M Features and Facilities, 1978, Digital Research, Post Office Box 579, Pacific Grove, CA 93950.

Figure 2.1 ~ Microprocessor-controlled data acquisition system.

Figure 2.2 - Microprocessor system functional diagram.

unit, the memory, the communication interface, and the video interface. In the sections to follow, these four components are briefly described. A more detailed description is included in a separate report [3].

2.1.1 Central processing unit

The heart of the DAS is the Intel 8080A Central Processing Unit (CPU) [4]. The CPU unifies the system as it controls most functions performed by other system components as well as data and address transfers on the two tristate bus lines. Basically, it fetches instructions from memory, decodes their binary contents and executes them. The CPU also responds to several external signals, such as interrupts and direct memory access (DMA) requests. In the latter case, the CPU surrenders bus control activities to the DMA controller unit. The DMA is an important element for high speed video data acquisition--more on this later. The CPU and its supporting hardware are all contained on a single card which plugs into the S-100 master bus system.

2.1.2 Memory

Working in conjunction with the CPU is the memory. Three types of memory are used in this system. One type, the Read Only Memory (ROM), is used primarily for permanent program storage. Programs used in power-up initialization (Address locations F000H-FB00H) and cold starting of the floppy disk system (E000H-E200H) are found here. The "H" indicates that a hexadecimal base was used. The complete memory map is found in Figure 2.3.

3/ J. Fanning and K. Kim, "Investigation of methods for fabricating, characterizing, and transporting cryogenic ICF targets," CPRL Report No. 1-81, University of Illinois (1981).

4/ MCS-80/85 Family User's Manual, 1979, INTEL CORPORATION, 3065 Bowers Avenue, Santa Clara, CA 95051.

Figure 2.3 - Memory map for data acquisition system.

Another type of memory used is a volatile one and is erased when power is removed. It is called Random Access Memory (RAM) and, unlike ROM, it can have information written into it. In the current system, the RAM has access times of less than 250 nanoseconds and is used primarily for temporary program storage and high-speed data storage. The main RAM is memory-mapped from 0000H to C000H with a total capacity of 48K bytes. Some additional RAM is used for scratch-pad purposes for the monitor and disk controller. This is found at address locations F000H-FFFFH and E200H-E300H, respectively.

The ROM and RAM, with addition of some simple backup hardware, can directly be implemented on the S-100 bus. The ROM's in this circuit house the programs used in operating the serial port in TTY format. They also house the data transfer programs used to facilitate the communication between the microprocessor and the main computer.

The final type of memory is a magnetic floppy disk. Although this type of memory is relatively slow with access times averaging 260 milliseconds, its high density of 256K byte/disk makes it very versatile. The floppy disk machine requires its own special S-100 bus interface. The disk operating system is contained in the software on the diskette. All development programs are written, assembled and run with the aid of the CP/M floppy disk system. When running the computer for video data acquisition, the data are first jammed into the high speed memory and then slowly loaded onto a floppy disk for later retrieval and manipulation. Depending on formatting, the video picture information may occupy up to 24K byte for a single video frame. This works out to about 10 frames worth of storage per diskette.

2.1.3 Communication interface

Interfacing to the outside world is accomplished through several devices.

The parallel data links are handled through universal input/output ports. They are located at OUTPUT PORTS 4, 5, 6, 7 and INPUT PORTS 4, 5, 6, 7, and are Transister-Transister Logic (TTL) compatible signal levels.

The serial links are handled through a Universal Asynchronous Receiver Transmitter (UART) and a serial device select circuit shown in Figure 2.4. PORT 0, 1 is wired for a selectable baud rate and free running mode. PORT 0 is input status only and PORT 1 is the bidirectional data port. This port is usually connected to the solely dedicated CRT terminal and operated at the maximum 9.6K baud rate. PORT 2,3 is wired for only 300 baud and full hand-shake capabilities. This allows the port to be used for interfacing to the modulator-demodulator (modem) which links the microprocessor to the timesharing system of the main computer. It also allows communication to the on-line plotter and hard copier. PORT 2 is for input status only and PORT 3 is the bidirectional data port. Special drivers are contained in ROM at F800H to F900H to facilitate use of this serial port.

The purpose of the device select circuit is to allow either the CRT terminal or the main computer (via a telephone line and modem) to "talk" to the microprocessor system. In addition, it may allow the CRT terminal to "talk" directly with the main computer.

2.1.4 Video interface

The video interface portion of the acquisition system is a combination of I/O ports, counters, discrete logic, analog-to-digital conversion circuitry, and a DMA controller. It is by far the most complicated board in the microprocessor system. Essentially, it accepts software code words and sets up a specific digitizing format for the video information. Data destination is

Figure 2.4 - Serial device select circuit.

then programmed via software into the DMA controller. Upon execution of a port select, the DMA controller assumes bus control and begins transferring digitized data at the programmed sample rate into the RAM. This process continues until all the data are taken according to the preset format or a DMA terminal count is reached. At termination, the DMA controller surrenders the S-100 bus back to the 8080A CPU and normal programming may continue. Usually, the programming after a DMA involves loading the data into a disk file.

The general hookup to the microprocessor system is shown in Figure 2.5. With this hookup, the user may observe the complete video image on the TV monitor. In addition, through the use of the line select switches individual video lines may be observed on the oscilloscope. (See Figure 2.6). Also displayed on the scope is the software programmable sample points. Communication interface connections (Figure 2.4) are made to the back panel of the microprocessor. The DAS as it appears hooked up to the entire cryogenic system is pictured in Figure 2.7.

This concludes the system overview. Software programs were written to operate the video system and to provide various output formats.

2.2 Theoretical Ray-Tracing and Results

2.2.1 Introduction

Experimentally, an accurate and convenient method of observation and measurement of a glass shell target and/or a solid-DT-layer inside of it is the use of laser interferometry. To properly interpret the information produced by an interferometer, however, requires an accurate ray-tracing model.

The ray trace procedure developed here is along the same lines as those

Figure 2.5 - System hookup diagram.

Figure 2.6 - Example of data acquisition system output on oscilloscope displaying line 128 and software selected sample points.

Figure 2.7 - Picture of entire experimental setup.

performed by Stone, Gregg and Souers [5]. Unlike in this reference, however, a single pass Mach-Zehnder interferometer was used in the present case (See Fig. 2.8). This, of course, modifies the phase effects as observed using their two-pass Twyman-Green interferometer.

A computer program was written that would follow a given input light ray through the target assuming the incoming rays are all collimated and parallel to the target's center axis (see Fig. 2.9). At each interface (air to glass, glass to gas, or glass to liquid, and so forth), the program would apply the proper Snell's Law criteria and compute the ray's next trajectory. With each medium that the ray goes through, the program would keep track of the overall phase.

Since there is a microscope objective in each arm of the interferometer, the exit rays from the target will appear to have come from some point on the objective's focal plane. To determine the phase difference, the phase of this ray must be compared to its counterpart at the same focal point in the reference arm. For normalization to the central ray, the optical path difference calculation must be made on a Huygen's wavefront at a distance equal to the target's radius from its projection on the focal plane. This, of course, assumes that the focus will be in the center of the target. Experimentally this position is also the best for viewing the target.

As seen in Fig. 2.9, rays are classified by the number of interfaces encountered within the target. Generally, two things happen to the higher radius entrance rays "types 2 and 3." The most significant effect is the intensity loss due to the high incident angles. This loss in intensity tends to cloud the interference pattern at the target edges. In addition, the ray's long optical path length differences resulting from travelling through more

5/ R. R. Stone, D.W. Gregg, and P. C. Souers, J. Appl. Phys. 46, 2693 (1975).

Figure 2.8 - Layout of laser interferometer and associated optics.

(a)

(b)

Figure 2.9 - Ray-tracing model. (a) Model used when only DT gas is present in target; (b) Model used when DT liquid and gas are present in target.

glass weakens its coherence and degrades the interference even more.

Fortunately, use of the "type 1" rays is completely sufficient for determining the target parameters.

In the ray-tracing procedure, the resulting calculated interference of the ray depends on its refractions at each interface and subsequent phase delays as it travels through each medium. Both of these effects are dependent on the index of refraction. For the glass shell, the index may be fixed at 1.5, but for deuterium gas and liquid, the index varies with density. This dependence provides for a convenient method of measurement when analyzing the target's parameters. For example, in a room-temperature target with a known glass shell thickness, varying the internal gas-fill-density will vary the index of refraction. As the index changes, the refraction angles at each interface and the overall phase delay change. These changes, in turn, modify the resulting observed interference pattern. By matching the actually observed fringe pattern to that calculated by the ray-tracing program, it is possible to predict the gas-fill density. When a liquid layer is present, the same procedure may be carried out; however, the geometry of the problem becomes a little more complicated.

Estimation of the dependence of the index of refraction on gas density has been carried out by Briggs, et al. [6]. Assuming a deuterium gas temperature of 298 K, a wavelength of 546.1 nm, and letting ρ be the density in moles per cubic meter:

$$(N-1) = (3.089 \times 10^{-6})\rho + (1.534 \times 10^{-12})\rho^2 \quad (2.1)$$

where N is the index of refraction. As tabulated by Childs and Diller [7],

6/ C. K. Briggs, R. T. Tsugawa, C. D. Hendricks, and P. C. Souers, Lawrence Livermore National Laboratory, Report UCRL-51921 (1975).

7/ G. E. Childs and D. E. Diller, Adv. Cry. Eng. 15, 65 (1969)

there is roughly a 0.7% decrease in the value of $(N-1)$ when a 632.8 nm wavelength is used.

In the cryogenic temperature range (18.6 K to 36 K) where both liquid and gas are present, the parameters of Eq. (2.1) change slightly. The index of refraction of both the liquid and the gas may be calculated by

$$(N-1) = (3.076 \times 10^{-6}) \rho + (1.857 \times 10^{-12}) \rho^2 \quad (2.2)$$

Finding the proper densities of the gas and liquid in this temperature range is more complicated than in the room-temperature gas density case. Since the target represents a closed system, mass is conserved. Once the target reaches the liquefaction point, the fill-gas inside the target begins to condensate into liquid. As the target temperature is further lowered, the gas density decreases as the liquid density and volume increase, thereby changing the indices accordingly. Fortunately, tables have been compiled showing the density relationships between the gas and the liquid in the temperature range from 18.6 K to 36 K [8]. Therefore, experimental measurement of the target temperature leads to knowledge of the liquid and gas densities and subsequent indices of refraction.

2.2.2 Theoretical ray-tracing output examples

Figures 2.10 through 2.13 show some typical output curves for various target configurations. For these examples, the target radius is assumed to be 70 microns, the laser wavelength to be 632.8 nm, and the index of refraction of the glass to be fixed at 1.5. For easy interpretation, each curve has been normalized to the central ray. The vertical axis, which is the path length difference, D , has been calibrated in half-wavelengths. Interference

Figure 2.10- Ray-tracing output showing results of changing target glass shell thickness.

Figure 2.11- Ray-tracing output showing results of changing target room-temperature gas-fill density.

Figure 2.12- Ray-tracing output showing results of changing target temperature.

Figure 2.13- Ray-tracing output showing results of changing DT liquid layer thickness at fixed temperature.

patterns are made up of a collection of bright and dark fringes where each dark-to-bright or bright-to-dark transition represents a half-wavelength path difference. A visual picture of the fringe pattern for a given curve may be obtained by starting at the center and moving outward. The centers of alternately bright and dark fringes may be located each time the curve moves upward by a half-wavelength interval.

Figure 2.10 shows the path difference variation as a function of change in glass thickness. Here the internal index of refraction is assumed to be 1. The figure indicates that as the glass thickness increases, the number of observed fringes also increases, and they move closer to the center.

In Fig. 2.11 the glass thickness is held constant at 5 microns and the gas density inside the target is increased from 0 to 30 mg/cc in increments of 2 mg/cc. The proper index of refraction was calculated by use of Eq. (2.1). The equation indicates that an increase in gas density will cause an increase in the index of refraction. This increase in the index will reduce the optical path length differences and give rise to fewer observed fringes. In fact, at a sufficiently high fill-density, the ray-tracing model predicts that there will be no observed fringes.

When adding a liquid layer to the ray-tracing model, several situations may exist. In the event that the layer is uniform, it may be modeled as shown in Fig. 2.9(b). In addition, the layer thickness may be predicted as a function of temperature if the initial room-temperature fill-density is known. The liquid layer thickness may be calculated by

$$TH = \left[1 - \left(\frac{D1 - D2}{D3 - D2} \right) \right]^{1/3} (r-t) \quad (2.3)$$

where TH is the liquid thickness, r is the radius of the target, t is the

glass thickness, and D_1 , D_2 and D_3 are, respectively, the mass densities of gas at room temperature, and the mass densities of the liquid and the gas at cryogenic temperatures [9]. This formula was used to calculate the uniform layers at specific temperatures as shown in Fig. 2.12. Room temperature fill-pressure was assumed to be 100 atm or a corresponding density of 16.67 mg/cc. As seen in the figure, an increase in the thickness of this layer as temperature is decreased will have a similar effect as thicker glass did, as shown in Fig. 2.10.

In the situation where the liquid layer is nonuniform, the analysis can become very complicated. As a first approximation, however, an extension of the previous method is possible. Again, experimentally knowing the target temperature and room-temperature fill-pressure, the mass densities of liquid and gas may be determined. Knowing the mass densities and applying Eq. (2.2), the indices of refraction may be computed. Figure 2.13 shows a family of uniform curves computed by simply incrementing the thickness of a uniform liquid layer at 25 K. For this example, the mass densities are 3.23 mg/cc and 158.98 mg/cc for gas and liquid, respectively. In addition, the computed indices of refraction are 1.0025 for gas and 1.1247 for liquid. Unlike Fig. 2.12 in which a constant mass was maintained within the target, Fig. 2.13 does not maintain a constant mass.

To derive an approximate nonuniform layer profile, the observed fringe pattern is broken into radial cross-sections propagating out from the middle of the target. The approximate layer thickness at that radial cross-section is found by locating the first and second extrema (bright-to-dark or dark-to-bright fringe) on the horizontal axis in Fig. 2.13. The curve that guarantees

a half-wavelength path difference between these two points will be the approximate layer thickness. Combining all the interpreted layer thicknesses at each radial cross-section will provide a rough idea of the liquid layer profile.

2.2.3 Advanced ray-tracing model

Since the approximate method uses a combination of uniform layer ray tracing results, it cannot account for the geometry of the actual liquid layer profile. As the liquid layer becomes more nonuniform, the approximation becomes more inexact. To remedy this problem, a more realistic model must be developed. Shown in Fig. 2.14 are two examples of a model that would more closely match the real situation. (The layer profile, however, is not in general expected to be perfectly spherical.)

This model is an extension of that shown in Fig. 2.9(b), in that it allows an offset for the internal liquid layer radius. When looking for a match, two approaches are possible. The first, shown in Fig. 2.14(a), is to allow the internal radius, r , to vary with a constant offset, d . The variable R is the radius to the inside of the glass shell. The other approach shown in Fig. 2.14(b) uses a constant radius, r , and the offset, d , is allowed to vary. The model benefits from the fact that the enclosed liquid volume may easily be computed knowing R , r , and d . It is possible to find a set of values of (r, d) that all have the same volume. This is important, because experimentally, the liquid volume is usually known for each temperature.

In a special case of this model, when $d+r < R$ the liquid layer is continuous and the volume is only a function of r and R . This case may be used in determining the effects of gravity on continuous liquid layers in terms of the offset variable, d .

Figure 2.14- More precise ray-tracing model. (a) Layer defined by varying radius, r , with constant offset, d ; (b) Layer defined by varying offset, d , with a constant radius, r .

Modifications to the ray tracing program are still being made. Complete results, therefore, have not yet been obtained.

2.3 Experimental Results

2.3.1 Introduction

The procedure used in characterizing a target is basically a four-step process. Wall thickness is first obtained from the target fringe pattern when all of the hydrogen isotopes inside a GMB are frozen into a solid in a single clump. Then the gas density is determined with the target at room temperature. Knowing the density, the equilibrium conditions of the liquid and the vapor pressure can be computed for temperatures between 18 K and 36 K. This leads to a thickness measurement of the liquid layer as previously discussed. The last step is estimation of the solid layer, which can be done knowing the gas density or mass. This last step, however, is not analyzed in this report.

Common to all these steps is the interpretation procedure used to translate the DAS output cross sections (target fringe patterns) into the target parameters, such as glass shell thickness, etc. Due to interferometer instabilities, the center spot of the target interference pattern is not always pure bright or dark. A more consistent comparison can, therefore, be obtained by measuring the spatial difference between the first and second set of extrema.

Previously, in Figs. 2.10 through 2.13, these points were located on the horizontal axis and a correct curve was found that assured a half-wavelength path-length difference between the two points. To obtain higher accuracy and to further automate the process, a program has been developed that forms tables instead of line plots. The program uses a software look-up procedure for proper "curve" location given the location of the first two extrema. This

implies that a complete measurement of DT fuel behavior inside a GMB at any temperature can be accomplished within the period of time it takes the DAS to get the picture and a high speed computer to do the table look-up. In all, a complete target characterization scheme could be worked out for real-time monitoring of laser fusion fuel pellet fabrication processes.

2.3.2 Target characterization example

In step one, determination of wall thickness requires having a known index of refraction for the interior of the GMB. This only occurs when all the fuel is frozen solid in a small region of the target (Fig. 2.15(f)). The index of refraction of glass is taken to be 1.50 and that of the internal void as 1.00. Figure 2.16(f) shows the data acquired by the DAS. For easier fringe recognition, the data have been inverted so that dark fringes appear higher than the bright ones. After the phase information was processed as previously described, the average glass thickness was found to be 3.04 microns with a standard deviation of 0.16. A simplified drawing is shown in Fig. 2.17(f).

Step two, for the gas density measurement, the known glass thickness is entered in the ray-trace program and the gas density is varied until a match occurs. For the present example (Figs. 2.15(a), 2.16(a) and 2.17(a)), room-temperature gas density is 16.75 mg/cc or an equivalent pressure of 103 atm.

For step three, two types of interpretation are possible in determining the liquid layer profile. If the layer is uniform, results such as those obtained in Fig. 2.12 may be used. If not, the target must be analyzed in radial cross-sections with each section interpreted with the type of data found in 2.13. A target-cooling sequence is shown in Figs. 2.15(b) to 2.15(e) where the target's temperature is decreased from 25 K to 19 K. Interpretation

(a)

(b)

(c)

(d)

(e)

(f)

Figure 2.15 - Interface micrographs of a target cooling sequence.
(a) Room temperature target; (b) through (e) Increasing deuterium
liquid condensation inside target at decreasing temperatures;
(f) Frozen deuterium mass inside target.

Figure 2.16 - Data acquisition system's output for interference micrographs shown in Figure 2.15 (a) through (f).

Figure 2.17- Interpreted data from data acquisition system's output shown in Figure 2.16 (a) through (f).

of the DAS output in Figs. 2.16(b) to 2.16(e) by the first approximation method described in Section 2.3.2 leads to liquid layer profiles as shown in Figs. 2.17(b) to 2.17(e).

The final step, of course, is to produce and analyze a solid deuterium layer. Formation of a uniform solid layer requires a laser pulse of a substantially high power to induce rapid fuel evaporation inside the target without heating the surrounding environment. Consequently, refreezing of fuel occurs in a very short time span, resulting in a uniform solid layer. Since no laser of such power was available, data could not be taken for this step.

3. CRYOGENIC TARGET FABRICATION SYSTEM UTILIZING COLD-GAS-LEVITATION AND ELECTRIC FIELD POSITIONING

3.1 Introduction

At present, most of the experimental cryogenic work done on GMB's requires the targets be held at a stable, stationary location within a cold target freezing chamber. The analysis done in the previous chapter was performed with the target glued to a 10-micron-diameter glass fiber. Although this setup was satisfactory for those experiments, it presents many disadvantages for future mass production and characterization of cryogenic targets. Ideally, target manipulation must be accomplished without physical contact to the target. In present gold coating processes [10], the target is levitated above a collimated hole structure (CHS) with molecular beams of argon gas. To localize the target to a specific position in the middle of the structure, a centering ring is installed which deflects the beams from the perimeter into the center. This device is called a molecular beam levitator (MBL).

A similar device was constructed out of a 50- μ m-diameter tube CHS and operated on helium gas (See Fig. 3.1(b)). The MGL worked quite well; however, the structure obscured lateral laser interferometry which is an essential diagnostic in cryogenic target fabrication. Efforts to levitate the target above the structure, while still employing molecular beams to lift and center it, have not been successful. Another type of gas levitator was made by drilling a cylindrical bore into a fritted-glass material, as shown in Fig. 2.1(a). Although this structure also provided successful target levitation, the viewing angle was even more limited due to the small bore size.

In previous experiments, including Kim, et al. [11], and Kim and Rieger [12],

10/ J. K. Crane, Private Communication, LLNL (1979)

11/ K. Kim, B. J. Smoot, R. L. Woerner, and C. D. Hendricks, Appl. Phys. Lett. 34, 282 (1979)

12/ K. Kim and H. Rieger, Appl. Phys. Lett. 37, 425 (1980)

(a)

(b)

Figure 3.1 - Examples of levitation structures with no lateral visibility.
(a) Fritted glass structure levitating 200-micron-diameter target;
(b) Molecular beam levitator with confinement ring levitating 140-micron-diameter target.

Figure 3.2 - Example of quadrupole levitation structure showing total lateral visibility. Target shown is 140 micron in diameter.

it has been shown that direct wetting of the target with cold He gas is sufficient to form and maintain a liquid DT layer inside the target. Therefore, it is advantageous to have the target levitated with gas. However, to circumvent the drawback of the MBL, a new target centering technique must be implemented. The new method uses a quadrupole structure oriented in a vertical fashion with the CHS at its center (see Fig. 3.2). An electrostatically charged target can be centered in the alternating fields of the quadrupole while being levitated by collimated molecular beams. This target-positioning scheme gives excellent observability of the target in two directions, therefore, allowing the use of laser interferometry for target characterization.

The following sections describe the details of this system and its requirements. The first requirement is to supply a sufficient gas flow to actually lift the target off the CHS and suspend it. The next requirement is to provide a stable centering force for the charged target within the quadrupole structure.

A schematic of the apparatus is shown in Fig. 3.3. Cold helium gas is supplied from the heat exchanger. The top of the cold chamber is opened up to access the target loading mechanism. Long stainless steel bellows are used to thermally insulate the chamber from the rest of the apparatus. Targets are first loaded into the pellet feeder and are manually dropped one at a time into the center of the Boxer charger device. Upon leaving the charger, the target goes through a series of rings, as was first used in a previously published design [13]. The rings then center the target, align it for proper entrance into the quadrupole, and decelerate it. The second ring is actually a chamber separation plate allowing a pressure differential

13/ S. Masuda, M. Washizu, and T. Sekiguchi, Proceedings, IEEE-IAS Annual Meeting, p 1005 (Cincinnati, OH, 1980)

Figure 3.3 - Cryogenic levitation system.

to exist between the upper and lower chambers and therefore reducing the pumping load of each chamber. For good corona discharge in the Boxer charger, the upper chamber must be operated at a fairly high pressure. The lower chamber, on the other hand, must be operated below 50 mTorr for proper molecular beam levitation.

Once the target enters the quadrupole, it is funneled down into the cold chamber where it is levitated by the cold helium gas. As the target is levitated in the cold chamber, it may then be analyzed through the use of the laser interferometer and the DAS as described in Chap. 2.

3.2 Gas Levitation

3.2.1 Introduction

Levitation of the target in the vertical direction is done through the use of a CHS. This structure consists of an array of closely-packed 50- μ m-diameter glass tubes 0.204 cm long. The CHS is secured to the top of a glass tube and positioned at the center of the quadrupole. Since the tube and CHS are both made of glass, they do not interfere with the electric fields produced in the quadrupole.

As gas flows through the CHS, the molecules are collimated and exit the top of the structure in a rather coherent beam. Since the targets are typically 140 μ m in diameter, they will be supported by approximately 5 to 7 beams. In order to compute the force on the target, the molecular beam-target surface-interaction must be specified. Generally, most target surfaces are rough compared to the size of the molecules impinging on it. This implies that the molecules will hit the surface, bounce around in the gaps between the surface molecules or atoms, and then leave the surface some time later. This reflection process, which will determine the amount of momentum that

is transferred to the surface, may be categorized into two types.

The first, known as diffuse reflection, is shown in Fig. 3.4(a).

In diffuse reflection, a molecule hits the surface and is then re-emitted in a random direction. The second type, illustrated in Fig. 3.4(b), is specular reflection where the angle of incidence is equal to the angle of reflection. In both cases, the velocity at which the molecule will leave the surface depends on the amount of energy transferred to the surface before the molecule is re-emitted.

When computing the force exerted on the surface, in addition to knowing the molecule-surface-interaction process, it is also important to know the velocities of the impinging gas molecules. Kinetic theory states that velocities of molecules in equilibrium can be specified by the Maxwellian velocity distribution function. Within the Maxwellian distribution there exists a most probable random speed, c_m , of the molecules defined as:

$$c_m = \sqrt{\frac{2kT}{m}} \quad (3.1)$$

where k is the Boltzmann constant, T is the temperature, and m is the mass of the molecule.

For the gas levitation problem considered here, an additional term must be added due to the macroscopic mass velocity and will be defined as u . Exact calculation of u is difficult; however, bounds may be defined through consideration of the isentropic flow theory [14]. The gas entering the CHS from the bottom will readily achieve sonic velocity, u_{sonic} , defined as:

$$u_{\text{sonic}} = \sqrt{\frac{\gamma kT}{m}} \quad (3.2)$$

14/ A. H. Shapiro, The Dynamics and Thermodynamics of Compressible Fluid Flow (The Ronald Press Company, New York, 1953), Vol. 1

Figure 3.4 - Types of molecular reflections. (a) Diffuse; (b) Specular.

Figure 3.5 - Geometry for calculation of molecular beam levitation.

where γ is the ratio of specific heats. Since the pressure at the top of the CHS is lower than at the bottom, the emanating gas will undergo an increase in velocity. The maximum attainable velocity, $u_{\max}$, can be written as:

$$u_{\max} = \sqrt{\frac{2\gamma}{\gamma-1} \left(\frac{kT}{m} \right)} \quad (3.3)$$

The expected mass velocity, u , therefore, will lie somewhere between the two limits. Assuming helium gas is used ($\gamma=1.667$ and $m=6.647 \times 10^{-24}$ g) at 15 K, numerical limits for the mass flow, u , are

$$227.8 \text{ m/sec} < u < 394.6 \text{ m/sec} \quad (3.4)$$

A convenient dimensionless quantity often used in gas flow mechanics is known as the speed ratio, S . The speed ratio, defined as the ratio of the magnitude of the mass velocity, u , to the most probable random speed, c_m , may be written as:

$$S = \frac{u}{c_m} \quad (3.5)$$

This ratio is used throughout the drag calculations for the targets. In terms of the limits placed on the mass velocity, u , and assuming helium gas is used, the limits may be written in terms of the speed ratio, S , as

$$.912 < S < 1.581 \quad (3.6)$$

3.2.2 Target drag calculations

Exact derivation of the drag force imparted to a sphere in a molecular beam flow is very long and tedious, well beyond the intent of this report.

The work, however, has been carried out in great detail by Patterson [15], and

15/ G. N. Patterson, Introduction to the Kinetic Theory of Gas Flows (University of Toronto Press, Toronto, 1971)

results of his calculations are presented here. For the particular geometry shown in Fig. 3.5, the total drag force on the target may be written as

$$\int_0^\pi D \, dA = C_d \left(\frac{1}{2} \rho_\infty u^2 \pi R^2 \right) \quad (3.7)$$

where D is the drag force per unit area, dA is the incremental area, ρ_∞ is the mass density of the external gas, u is the mass flow of the levitation gas, R is the radius of the target, and C_d is the drag coefficient.

Two types of drag coefficients are possible depending on the type of reflection. For specular reflection:

$$C_{d,s} = \frac{2}{S^2} \left[\frac{2S^2+1}{2\pi} \exp(-S^2) + \left(\frac{4S^4+4S^2-1}{4S} \right) \operatorname{erf}(S) \right] \quad (3.8)$$

and for diffuse reflection:

$$C_{d,d} = C_{d,s} + \frac{2\pi}{3S} \left(\frac{T_w}{T_\infty} \right)^{1/2} \quad (3.9)$$

where T_w is the temperature of the target surface and T_∞ is the temperature of the external gas. The ratio of target surface temperature to external gas temperature may be calculated for the ideal case when the front and back surfaces of the target are in perfect thermal contact. For helium gas, then, the equilibrium temperature ratio is

$$\left(\frac{T_w}{T_\infty} \right)_{\text{eq}} = \frac{(2S^2+5) \exp(-S^2) + [2S^3+6S+(3/2S)] \pi \operatorname{erf}(S)}{4 \exp(-S^2) + 4[S+1/(2S)] \pi \operatorname{erf}(S)} \quad (3.10)$$

Using the limits for the speed ratio, S , as defined in Eq. (3.6), it is possible to derive limits for the two drag coefficients, Eqs. (3.8) and (3.9). For specular reflection, the bounds are

$$3.82 > C_{d,s} > 2.72 \quad (3.11)$$

and for diffuse reflection they are

$$5.41 > C_{d,d} > 3.88 \quad (3.12)$$

3.2.3. Target levitation requirements

In order that the target be stably levitated by the gas beams, the upward levitation force must be equal to the downward gravitation force. This requirement implies:

$$F_{lev} = F_{grav} = Mg \quad (3.13)$$

or in terms of Eq. (3.7)

$$\int_0^\pi D \, dA = C_d \left(\frac{1}{2} \rho_\infty u^2 \pi R^2 \right) = Mg \quad (3.14)$$

where M is the mass of the target and g is the acceleration due to gravity. In Eq. (3.14) the only free parameter is the external gas density, ρ_∞ . By applying the limits given for the mass flow, u , (Eq. (3.4)) and drag coefficients, $C_{d,s}$ and $C_{d,d}$, (Eqs. (3.11) and (3.12)), it is possible to arrive at experimental operating limits for the external gas pressure, P . First, however, the mass of the target must be calculated.

It can easily be shown that the mass of a target is given by

$$M = \frac{4}{3}\pi \left([R^3 - (R-t)^3] \rho_{glass} + (R-t)^3 \rho_{gas} \right) \quad (3.15)$$

where R is the target radius, t is the thickness of the glass, ρ_{glass} and ρ_{gas} are the mass densities of the glass and fill gas, respectively. For a typical 140- μ m-diameter target with a 5- μ m wall thickness, a gas fill density of 16.75

mg/cc, and a glass density of 2500 mg/cc, the total mass would be:

$$M = 7.35 \times 10^{-7} \text{ g} \quad (3.16)$$

Now, solving Eq. (3.14) for the external gas density gives

$$\rho_{\infty} = 2Mg/C_d u^2 \pi R^2 \quad (3.17)$$

It is now possible to find the operating limits assuming the typical target mass shown in Eq. (3.16). For specular reflection the gas density range is

$$4.72 \times 10^{-9} \text{ g/cc} > \rho_{\infty, s} > 2.21 \times 10^{-9} \text{ g/cc} \quad (3.18)$$

and for diffuse reflection:

$$3.33 \times 10^{-9} \text{ g/cc} > \rho_{\infty, d} > 1.55 \times 10^{-9} \text{ g/cc} \quad (3.19)$$

Through application of the ideal gas law, mass density may be related to absolute pressure for a given temperature. It can easily be shown that

$$P = 15571 \rho_{\infty} T \quad (3.20)$$

where the pressure, P , is given in torrs. Recalculating Eqs. (3.18) and (3.19) in terms of pressure, with a gas temperature of 15 K, gives operating ranges of

$$1.10 \text{ MTorr} > P_s > 0.52 \text{ mTorr}, \quad (3.21)$$

for specular reflection, and

$$0.78 \text{ mTorr} > P_d > 0.36 \text{ mTorr}, \quad (3.22)$$

for diffuse reflection.

Generally, molecule-surface interactions are considered to be a combination of diffuse and specular reflections, with diffuse reflection being the dominant contributor [15]. This means the limits given by Eq. (3.22) are probably the most realistic. During operation of the molecular beam levitator at room temperature, the average gas pressure measured above the CHS was 10 mTorr. Adjusting Eq. (3.22) for a temperature of 300 K gives operating limits from 7 to 16 mTorr.

3.3 Electrostatic Centering

Lateral containment of the GMB is done through the use of a electrostatic quadrupole structure. Quadrupoles have been in use for some time as mass spectrum analyzers [16]. The quadrupole uses a quasistatic alternating electric field where the value of the field strength is proportional to the distance from the center of the structure. The potential is periodic in time, symmetrical with respect to the center, and quadratically dependent on x and y . The device consists of four parallel cylindrical electrodes with a circular cross-section (Figs. 3.6 and 3.7). In the general case, a direct voltage $2U$ and an alternating voltage $2V\cos\omega t$ are applied between adjacent pairs of rods. This produces an electric field near the z -axis that can be derived from the potential:

$$E(x, y, t) = (U + V\cos\omega t) \frac{x^2 - y^2}{r_0^2} \quad (3.23)$$

The distances between the rods is $2r_0$. For particles of a given charge-to-mass ratio, e/M , the particle paths may be described near the z -axis by the following equations of motion:

$$\frac{d^2x}{dt^2} + \frac{2}{2} \frac{e}{M} (U + V\cos\omega t)x = 0 \quad (3.24)$$

Figure 3.6 - Quadrupole geometry and drive circuitry.

Figure 3.7 - Quadrupole with additional DC biasing.

$$\frac{d^2 y}{dt^2} - \frac{2}{r_0^2} \frac{e}{M} (U + V \cos \omega t) y = 0 \quad (3.25)$$

$$\frac{d^2 z}{dt^2} = 0 \quad (3.26)$$

By substituting

$$2\zeta = \omega t; \quad a = \frac{8eU}{Mr_0^2 \omega^2}; \quad \text{and } q = \frac{4eV}{Mr_0^2 \omega^2}, \quad (3.27)$$

it is possible to obtain the well-known Mathieu differential equations for the particle positions x and y :

$$\frac{d^2 x}{d\zeta^2} + (a + 2q \cos 2\zeta)x = 0 \quad (3.28)$$

$$\frac{d^2 y}{d\zeta^2} - (a + 2q \cos 2\zeta)y = 0 \quad (3.29)$$

The differential equations have periodic coefficients, i.e., the particle trajectory in the given potential represents an oscillatory motion with a periodically varying restoring force. Solutions to the Mathieu equations [17] are shown in Fig. 3.8.

For the present system, there is no need for application of a direct voltage to the rods. The sole presence of the alternating voltage is sufficient to stabilize the target motion in the vicinity of the geometrical center of the quadrupole structure. This position offers the best visibility of the target along the x - and y -axes. (It is possible, however, to use the direct

17/ E. Jahnke and F. Emde, Tables of Functions (Dover Publications, Inc., New York, 1945)

Figure 3.8 - Stability diagram for the Mathieu equations.

Figure 3.9 - First (lowest) stability region of Figure 3.8.

voltage for fine positioning on the $y=x$ or $y=-x$ plane if necessary.) No direct voltage implies $U=0$ and, consequently, $a=0$ in the Mathieu equations. From the stability diagram for the Mathieu functions (Fig. 3.8), it can be seen that the system will operate in the lowest stability region as shown in Fig. 3.9. The symmetrical stable region in the figure is found by reflecting the stability boundaries about the $a=0$ axis. This gives rise to the characteristic "necktie" stability region where q_{nominal} indicates the position of maximum a -variation and q_{max} is the maximum stable value of q when $a=0$. During the operation of this quadrupole, stable paths are obtained for q -values between 0 and 0.908 or, in terms of Eq. (3.27),

$$0 < \frac{4eV}{Mr_0^2 \omega^2} < 0.908 \quad (3.30)$$

By adjusting Eq. (3.30) to account for the actual operating conditions by letting $r_0=0.635$ cm and $\omega=2\pi f$, the stability bounds become:

$$0 < \frac{e}{M} \frac{V}{f^2} < 3.613 \times 10^{-4} \quad (3.31)$$

Table 3.1 tabulates some useful operating conditions for given charge-to-mass ratios assuming a stable q -value of 0.5. The equality solved for in the table is expressed as

$$\frac{V}{f^2} = \frac{2 \times 10^{-4}}{(e/M)} \quad (3.32)$$

It is clear from Eq. (3.31) that, for a given charge-to-mass ratio, excessive increase in the voltage or decrease in the frequency will tend to make the target unstable.

TABLE 3.1 OPERATIONAL STABILITY CONDITIONS FOR QUADRUPOLE

e/M (C/kg)	V (Volts)	f (Hz)
1×10^{-5}	2000	10
	288000	120
1×10^{-4}	2000	32
	288000	120
5×10^{-4}	2000	71
	5760	120
1×10^{-3}	2000	100
	2880	120

As shown in Fig. 3.7 it is possible to superimpose a DC potential in the vertical direction over the previously described fields. This additional electric field which is directed downward will force the positively charged target into the gas levitator. It therefore could be used to maintain the target's position when the gas flow is increased for additional cooling purposes.

Reliable results with the quadrupole confinement structure have been difficult due to poor target charging. The pictures shown in Figs. 3.10(a) and 3.10(b) are taken from a real-time video recording. The target was charged with a very high-voltage tungsten needle which can be seen in the center of the pictures. Figure 3.10(a) represents the target at rest with no applied quadrupole potential. In Fig. 3.10(b), levitation gas has been introduced as well as a 8000V, 100Hz sinusoidal potential. The target was observed to move into the geometrical center of the quadrupole. With increased gas flow, however, the target would usually go unstable.

Shown in Figs. 3.11(a) and 3.11(b) are the laser interferometer outputs

(a)

(b)

Figure 3.10 - Reproduction from real-time video tape recording showing centering capabilities of quadrupole. (a) Target at rest with no applied voltage to quadrupole and no gas flow; (b) Target oscillating slightly in center of structure while being levitated on collimated gas beams.

(a)

(b)

Figure 3.11 - Interferometer output of target on collimated hole structure in quadrupole setup. (a) Shadow micrograph; (b) Interference micrograph.

of the target for a shadow micrograph and an interference micrograph, respectively. Diffraction effects seen in the figures degrade the interferometer output. The solution to this is to levitate the target higher off the structure. In order to keep the target stable at a higher gas flow, it will be necessary to increase the overall charge on the target as well as the uniformity of the charge distribution.

4. CRYOGENIC TARGET FABRICATION SYSTEM BASED ON TARGET FREE-FALL CONCEPT

4.1 Overall System Description

Since the last progress report, work has continued toward developing a target fabrication system which is capable of fabricating a uniform layer of solid DT inside a target while the target is in active free fall through a cold helium gas column. This developmental work has simultaneously involved three different tasks: first, to develop a reliable target loading-and-launching mechanism which is capable of repetitive target launching and is compatible with the target fabrication system vacuum requirements; second, to develop a target detection scheme which not only can detect the passage of a target but also measure its speed; and third, to design a target cooling chamber which can instantaneously deliver sufficient cooling power to a target free-falling through it and which can provide observational capabilities for detailed inspection of the moving target.

A system designed to achieve these tasks is schematically shown in Fig. 4.1. A target to be cooled containing high-pressure DT gas is injected at the top into a glass microtube using a target injector device. The target injector device, shown in more detail in Fig. 4.2, can store a number of targets and unload them into the glass microtube one at a time for the target freezing experiment. These targets are carefully characterized before they are loaded into the injector. The glass microtube, through which the target free falls, is maintained at a low temperature by the liquid helium continuously flowing from the reservoir. Once inside this cold glass microtube, the target quickly cools down to a temperature below the freezing point of DT, resulting in a nonuniform DT-condensate layer inside of it.

Figure 4.1 Schematic of a cryogenic target fabrication system based on target free-fall concept

Figure 4.2 Target injector schematic

This cold target containing a frozen DT-layer, while in transit, is viewed by an optical diagnostic consisting of an LED-phototransistor combination, denoted as the "room-temperature detection system" in Fig. 4.1. A more detailed drawing of this viewing device is in Fig. 4.3. The viewing system is also interfaced to a computer, which, by using a preprogrammed software package, calculates the speed of the target and records its entrance and exit times in the detection region. While passing through this detection region, the target also experiences a sudden increase in the temperature, which gives rise to fast evaporation of the DT-condensate contained in it.

Upon departure from this detection-and-heating region, the free-falling target enters a cryogenic chamber maintained at a temperature well below the freezing point of DT, resulting in a uniform layer of refrozen DT inside of it. Inspection of the uniformity of this DT-layer is made farther downstream through the two windows using a homemade dual AC interference microscope system (see the previous Progress Report for a detailed description of this system). The AC interferometer at the first window, combined with the motion of the target across it, can make a scan of the entire target fringe pattern. By interfacing this optical signal from the interferometer, after appropriate optical signal processing, to the data acquisition system described in Chap. 2, it is therefore possible to construct a complete 2-dimensional phase map of the target's fringe pattern. This can then be compared with the information on the room-temperature target already obtained and stored in memory. The purpose of the second AC interferometer at the bottom window is not just for more analysis, but to screen out the possible noises, both optical and electronic, which are common to the two interferometer units. If deemed necessary, the laser beam used in this dual interferometer system can also be utilized to heat the target.

Figure 4.3 LED-phototransistor-combination target-viewing diagnostic

4.2 Preliminary Test

The target fabrication system described in Section 4.1 has been constructed and is currently being tested. The room-temperature target launching and detection systems have worked well. The target speeds were accurately measured to within $\pm .5\text{cm/sec}$. The launch system dynamics and the detection traces were consistent for every set of launches. A typical target trace is shown in Fig. 4.4. A target of $190\text{-}\mu\text{m}$ diameter was injected into a glass microtube $320\text{ }\mu\text{m}$ in diameter. From the trace, since the aperture of the target detection port is $660\text{ }\mu\text{m}$, the speed of the target is calculated to be 1.06 m/sec .

The parts of the target fabrication system to be maintained at cryogenic temperatures have been tested with liquid nitrogen. This test showed that both the launch precool and final cryogenic chambers, respectively, at the top and bottom of Fig. 4.1 were maintained at the liquid nitrogen temperature with no major problems. It is expected that the entire system will be tested with liquid helium in the near future and that actual target freezing experiments will be performed with D_2 -filled glass microballoons.

Figure 4.4 Typical trace of a moving target obtained by the diagnostic shown in Fig. 4.3.

5. HYDROGEN POWDER GENERATION SYSTEM BASED ON ELECTROHYDRODYNAMIC SPRAYING

In the last progress report, we described a hydrogen pellet generator developed by us which is capable of producing uniform hydrogen spheres of variable sizes. Although the performance of this machine was satisfactory, it had limited flexibility for varying pellet sizes and production rates. Another limiting feature of this machine was that pellet production had to be on a continuous basis rather than being ready-on-demand only.

Since our desire is to be able to produce hydrogen spheres only when needed, vary their size and production rate with ease, and, in particular, control their trajectories in a predictable manner, work has been initiated to achieve all these goals using an electrohydrodynamic (EHD) spraying technique. The idea is to inject charges into liquid hydrogen and let the resulting electrical forces at the charged surface disrupt the liquid. By placing a sharp needle inside the liquid and varying the high voltage connected to it, we demonstrated earlier with liquid freon [18] that the disruption of the charged surface mentioned above could in fact be brought about in a controlled manner resulting in production of uniform charged droplets of controlled size and charge. This technique, known as EHD spraying, has recently been tested on liquid hydrogen, producing satisfactory preliminary results.[19, 20] Based on these preliminary experiments, a hydrogen

18/ K. Kim and R. J. Turnbull, J. Appl. Phys. 47, 1964 (1976).

19/ J. P. Woosley, K. Kim, and R. J. Turnbull, J. Electrostatics 5, 381 (1978).

20/ J. P. Woosley, R. J. Turnbull, and K. Kim, Proc. IEEE-IAS 1980 Annual Meeting, 2, 964 (1980).

droplet production system has been designed and is under construction. An important unique feature characteristic of this system is that the charging needle is driven by a high-voltage pulse generator capable of delivering pulses of variable repetition rates and durations. Since droplet production is closely dictated by the charge injection at the needle electrode, by tailoring the high-voltage pulses driving the needle, not only the size but also the production rate of the charged hydrogen droplets being produced will be controlled. Having charged droplets is also an advantage over the neutral ones since their trajectory is easily controllable using electric fields. The main objective of the present investigation is to determine the limitations of the pulsed EHD spraying technique for controlling droplet size and production rate. Charge-to-mass ratio of the droplets will also be measured to determine the strength of electric fields required for the droplets' trajectory control.

A schematic of the liquid hydrogen EHD spraying system is shown in Figure 5.1. The liquid hydrogen is produced by a liquefier which is enclosed in a vacuum jacket. The liquefier consists of a coaxial tube counterflow heat exchanger, which terminates in a small reservoir where the liquid hydrogen is collected. The coolant is liquid helium which is introduced into the heat exchanger through a transfer tube and exhausted as warm gas into the atmosphere. The temperature of the hydrogen reservoir is measured with a copper-constantan thermocouple. The liquid hydrogen exits the liquefier through a double-walled transfer tube similar to the one used for the incoming liquid helium. The coaxial tube heat exchanger was chosen in preference to the copper-block heat exchanger used previously by us [21] because the former consumes less

21/ C. A. Foster, K. Kim, R. J. Turnbull, and C. D. Hendricks, Rev. Sci. Instrum. 48, 625 (1977).

Figure 5.1 Schematic of the liquid hydrogen EHD spraying system

liquid helium to liquefy a given amount of hydrogen.

The EHD spraying of liquid hydrogen, as indicated by the schematic of Figure 5.2, is effected by a sharp tungsten needle immersed in the liquid which is raised to high voltage for charge injection (either through field ionization or field emission). The needle electrode is driven by a high-voltage pulse generator which can provide pulse voltages of up to 10 kV. The repetition rate and duration of the pulses are adjustable, with the first ranging from 0.1 to 100 Hz and the last from 10 μ s to 2 ms.

The tungsten needle is inserted into a glass capillary tube providing a fairly tight fit. The bottom end of this tube is then immersed in the liquid hydrogen in the reservoir, resulting in formation of a stationary liquid hydrogen meniscus at the top of the tube through capillary action. The needle position is adjusted such that its sharp end at the top which protrudes the glass tube is completely inside the meniscus. In this way, one can always maintain a stable EHD spraying configuration immune to possible liquid surface disturbances in the reservoir due to, for example, local boiling.

The reservoir for the liquid hydrogen to be sprayed is a copper cup in which the tungsten needle is mounted. This reservoir is suspended in the spraying chamber by the electrical connection of a high-voltage vacuum feed-through and does not touch the chamber. The liquid hydrogen drips into this cup from a tube above connected to the exit end of the hydrogen liquefier, which is far enough away to avoid electrical breakdown.

The spraying chamber is provided with a connection port for pressure measurement and an exhaust tube for evacuation of the hydrogen gas. This

Figure 5.2 Schematic of the pulsed hydrogen droplet production scheme

will allow us to study the EHD spraying at different ambient pressures. Two indium-sealed windows are installed on the inner chamber to observe the spraying processes. The liquid droplets are illuminated by a xenon flashlamp which is triggered by the high-voltage pulse generator.

6. STUDY OF TARGET-CHARGING TECHNIQUES FOR APPLICATION TO CONTACTLESS CRYOGENIC TARGET FABRICATION SYSTEM

Success of the electrostatic confinement system described in Chapter 3 depends heavily on a method of consistently and uniformly charging the glass microballoon (GMB). Since the glass targets are such excellent insulators, their affinity for acquiring charges is very low. Recent studies by Masuda and Washizu [22] have shown that the use of ion-bombardment may provide a very practical and somewhat efficient method for particle charging.

The target-charging technique under investigation uses an electron beam extracted from a hollow cathode discharge (HCD). [23] The device constructed for the investigation is shown schematically in Figure 6.1. This device consists of three major regions: (1) the plasma generation region where the beam electrons are created by the HCD; (2) the extraction and control regions in which the electrons are extracted from the HCD plasma through the grid anode G_1 and their energy is controlled by the control grid G_2 ; and (3) the acceleration region in which the electrons move toward the accelerating anode without colliding with the gas molecules or ions. The target to be charged is placed in this acceleration region.

The plasma generation region is the volume surrounded by the hollow-cylinder cathode and the grid anode G_1 . An important feature of this HCD system is that the surface area of the cathode surrounding the plasma is much larger than that of the anode. Since the HCD is sustained by the secondary electrons resulting from ion bombardment of the cathode surface, a large cathode-to-anode surface area ratio means that most ions leaving the discharge region are accelerated through the cathode sheath and utilized

22/ S. Masuda and M. Washizu, J. of Electrostatics 6, 57 (1979).

23/ R. C. Knechtli, et al., Technical Reports Nos. 1-6, Nov. 1972-June 1975, Hughes Research Labs.

Figure 6.1 Hollow-cathode-discharge target charging system

very efficiently in the production of secondary electrons. The large surface area ratio is also responsible for increasing the number of reflections the secondary electrons go through inside the hollow cylinder structure. This, in turn, increases the number of ionizing collisions and leads to creation of more electrons. Helium gas was used for the HCD because of the relatively low sputtering yield of the He^+ -ions which prolongs the device life.

The electrons from the HCD are extracted through the grid anode G_1 . The control grid G_2 serves the purpose of varying the energy of these extracted beam electrons.

The acceleration region, in which the target-charging is done, is in between the grid G_2 and the accelerating anode AA. The length of the region is chosen such that Paschen breakdown does not occur. For helium gas at the pressure of 60 mTorr, this corresponds to a maximum allowed length of 4 cm at an applied voltage of 10 kV. The minimum length of the acceleration region, which is dictated by the vacuum breakdown, is of no practical concern because vacuum breakdown is not possible at such low voltages ($<10\text{kV}$).

An important element of the HCD system not mentioned thus far is the igniter wire with a sharp tip. This is introduced to permit the initiation of the hollow cathode discharge without the application of excessively high voltages between the cathode and the anode. The igniter initiates a glow discharge by the breakdown of gas which results from the strong electric field existing around the tip. The electrons from this discharge go through ionizing collisions with the gas molecules which in turn give rise to a breakdown of the entire gas contained in the hollow cathode cylinder.

One thing to note regarding the operation of the present charging

device is that the operating pressures in the target-charging (or acceleration) region are in the same range as those for the cryogenic target fabrication system and the target chambers of the projected power reactors. In this sense, the HCD target-charging device is compatible with other components of the target fabrication and delivery system.

6.1 D.C. Operation

In the D.C. operation of the HCD, the high voltage is applied to the cathode through a 15 k Ω resistor. Another 15 k Ω resistor is used to supply a voltage to the accelerating anode (AA). The anode guide (G_1) voltage, on the other hand, is applied through a 100-k Ω resistor. As a result, most of the electron current extracted from the HCD is directed toward the accelerating anode without getting collected by the anode grid.

A plot of the extracted current (I_{AA}) vs. the cathode voltage ($V_{cathode}$) is given in Figure 6.2. In these measurements, the grid anode G_1 was grounded, the control grid G_2 was open, and the accelerating anode AA was kept at 250 V. To create a pressure gradient in the device such that the pressure inside the HCD cylinder is higher than that in the acceleration region, the helium gas was puffed into the HCD cylinder using an electrically operated fast valve. This allowed a higher pressure operation of the HCD resulting in more electrons to be extracted, yet, because of the lower pressure in the acceleration region, Paschen breakdown did not occur. As is clear from Figure 6.2, the extracted electron current reached a point of saturation at the cathode voltage of about -650 V, at which point the current value was about 10 mA. To ensure high repeatability, a cathode voltage slightly lower than -650 V was used during the preliminary target-charging experiment. Section 6.2 is devoted

Figure 6.2 Plot of extracted current (I_{AA}) vs. cathode voltage (V_{cathode})

to the description of this charging experiment.

6.2 Target Charging Experiment

A target-charging experiment was performed using a simulated laser fusion target--a spherical polystyrene target 500 μm in radius. One side of the target was first bombarded with the electron beam extraced from the HCD. The target was then rotated about its vertical axis by 180° , and the charging process was repeated.

In order to achieve maximum charge on a target using bombardment with an electron beam [24], the self-induced field resulting from the charge being imparted to the target must distribute itself uniformly on the target surface. In the case of a highly resistive particle such as a glass or a polystyrene particle, the electrons bombarding one side of the particle cannot readily redistribute themselves uniformly over the entire surface. As a result, only the side of the target exposed to the electron beam is charged. The unexposed side remains essentially uncharged. This is so unless the target is immersed in the electron beam for a period of time longer than the charge relaxation time which is characteristic of the target material. For polystyrene and silicon glass, this time is on the order of 10^5 sec.!

For a preliminary charging experiment, the polystyrene sphere was mounted on a sharpened tip of a tungsten wire and positioned in the acceleration region as shown in Figure 6.1. A voltage of -400V was applied to the cathode, the grid anode (G_1) was grounded, the control

24/ M. M. Pauthenier and M. Moreau-Hanot, La charge des particules sphériques dans un champ ionisé, J. Physique Radium 3, 590 (1932).

grid (G_2) was open, and the accelerating anode (AA) was set at 950V. The spacing between G_1 and AA was 3.2 cm. The igniter wire was set at 800V above the cathode voltage. With all these provisions, a pulse of helium gas was introduced into the hollow cathode structure through a hole on the left-hand side using an electronic valve. This resulted in the initiation of the hollow cathode discharge and, subsequently, an electron beam bombarding the target in the acceleration region. The pressure outside of the cathode cylinder, measured by a thermocouple, was less than 40 mTorr.

The pulsing of helium gas was repeated ten times. After this, one end of the tungsten wire which is not glued to the polystyrene target was connected to ground so that the charge on the tungsten wire could be eliminated. The target was then lowered into a Faraday cage for charge measurement, producing a charge of 5.2×10^{-12} C. Using the same target, but after rotating it by 180° about its vertical axis, the charging procedures were repeated in an identical manner as before, resulting in a charge on the target of 9.9×10^{-12} C. This result is consistent with the theory developed by Masuda and Washizu for ion bombardment charging [22].

On the other hand, according to Pauthenier's charging theory, the maximum charge on a target, known as "Pauthenier's limit," is

$$Q_{\text{p}} = 4\pi\epsilon_0 \frac{\epsilon_s^3}{\epsilon_s + 2} R^2 E$$

where ϵ_0 is the free-space permittivity, ϵ_s and R are, respectively, the dielectric constant and radius of the target, and E is the external D.C. field. Since $\epsilon_s = 2.5$ and $R = 500 \mu\text{m}$ for the polystyrene sphere, and E in the acceleration region is of the order of 4.22×10^4 v/m, the Pauthenier's

limit for the present case is

$$Q_{ap} = 1.95 \times 10^{-13} \text{ C.}$$

In light of this, we can only conclude that the preliminary target-charging results reported in the foregoing did not correctly reflect the amount of charge exclusively on the target. The measured charge, although repeatable, apparently corresponded to the total charge, not only on the target but also on the glue joint between the tungsten wire target mount and the target, and on the impurities on the tungsten wire.

Based on this observation, the following experiments are being planned for the near-term investigation.

(1) An extensive target-charging study using D.C. operation of the HCD device as before, but this time with a mechanism to break loose the target off the mounting device after it is charged. This will allow measurement of the charge only on the target.

(2) Target-charging experiment using pulsed-operation of the HCD device. In this pulsed-operation, after a pulse of discharge gas is injected into the hollow cathode cylinder, a high-voltage pulse is applied to the cathode, grid anode, and accelerating anode with a predetermined variable time delay. The performance of the HCD device under this pulsed-mode operation has recently been tested in our laboratory, and shows that an electron beam current pulse as high as 60 A is possible with a pulse duration of 25 μ sec. Target-charging experiments will be performed with metallic targets. Since these targets have very small charge relaxation times, uniform charging will be possible with the unidirectional charging.

7. TECHNIQUES FOR PRODUCING HOLLOW METAL SPHERES

Investigations intended to develop techniques for fabricating uniform hollow metal sphere targets have been initiated during the current research period. The techniques being developed are essentially an attempt to synthesize and refine the earlier techniques [25, 26] for application to liquid metals (i.e. high-temperature liquids).

More specifically, the implementation of the investigation is directed in the following manner:

1. Establish the basic hollow sphere production methodology by employing low-melting alloys such as the mixtures of bismuth, lead, tin, cadmium, and indium. Many of the bismuth alloys, for example, are liquid at temperatures below the boiling point of water and would therefore provide ease and flexibility for experimentation.
2. Define the critical parameters (both physical and geometrical) affecting the metal sphere production and determine their optimal ranges. Some of the parameters to be studied are:
 - a. Spray nozzle configurations.
 - b. Variations in the gas species with which the hollow metal spheres are to be filled and the effects of their thermodynamic parameters (mainly temperature and pressure) in the hollow sphere formation.

25/ R. J. Calliger, R. J. Turnbull, and C. D. Hendricks, Rev. Sci. Instrum. 48, 846 (1977)

26/ K. Kim and R. J. Turnbull, J. Appl. Phys. 47, 1964 (1976).

- c. Effects of charging on the uniformity of metal spheres.
 - d. Effects of metal sphere cooling time (i.e., ∇T -variation inside the cooling tower).
 - e. Effects of liquid metal viscosity and surface tension (if necessary, doping will be done to reduce liquid metal surface tension).
 - f. Effects of liquid metal superheating.
3. Extend the investigation into high-melting liquid metals, both pure and alloyed.

Shown in Figure 7.1 is a schematic of the hollow metal sphere production system designed and constructed for low-temperature applications. Some of the distinct features and the operational principles of this system are as follows:

First, the system has two coaxial nozzles: the outer one for the flow of liquid metal and the inner one for the flow of inert gas.

Second, the outer nozzle has a sharp tip connected to a high voltage, which will be used principally to effect the EHD spraying of the liquid metal. As a result of this, a uniform jet of liquid metal will be produced, with its size readily controllable by externally adjusting the injection current into the liquid metal.

Third, the inner gas nozzle is excited by a piezoelectric transducer giving rise to the breakup of the gas jet as well as the liquid metal jet outside of it into a stream of uniform hollow liquid metal droplets.

Fourth, the design consideration of the dual-nozzle system is such that

Figure 7.1. Schematic of the hollow-metal-sphere laser target fabrication system, designed for low-temperature applications.

the orientation as well as the position of the inner nozzle relative to the outer one can easily be varied externally during the experiment. This flexible feature will prove to be particularly useful since the relative configurations of the two coaxial nozzles will play an important role in determining the aspect ratios, stability, etc. of the hollow liquid metal droplets being produced.

Employing the system of Figure 7.1, a preliminary experiment has been performed with Wood's metal, a low-melting Bi alloy (50 Bi-25Pb-12.5Cd-12.5Sn; Melting Point=68°C). The observations made during this experiment indicate that the metal spheres produced were charged and likely to be hollow. The effects of the charge injection into the liquid metal were clearly visible to the extent that the liquid metal droplets being sprayed reduced their size as the injection current was raised. Promising as they might appear, these preliminary results must be looked at with caution for the following reasons:

First, although the metal droplets being produced increased their size as the fill gas was introduced through the inner nozzle, since the droplets could not be completely cooled in the drop tower, they collapsed as they hit the collection cup. As a result, no direct measurement could be made to determine the hollowness of the metal spheres.

Second, for the same reason, the surface uniformity of the metal spheres could not be determined. This, as we know, will have to be studied in conjunction with an accurate measurement of the liquid metal temperature at the spray nozzle exit and the temperature profile inside the drop tower.

Third, an accurate flowrate control, both for the fill gas and the liquid metal, is an essential element for the controlled EHD spraying,

which was not available at the time of the preliminary experimentation.

All these deficiencies are currently being corrected and are to be implemented with the reported system in the near future. A system applicable to high-melting metals (such as silver and gold) has also been designed and is currently under construction.