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CHARGED-PARTICLE RESEARCH LABORATORY REPORT NO. 2-82

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FABRICATION OF CRYOGENIC INERTIAL-CONFINEMENT-FUSION TARGETS
USING TARGET FREE-FALL TECHNIQUE

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Scientific Report Prepared for
Lawrence Livermore National Laboratory

by

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April 1982

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ABSTRACT

Techniques for fabricating cryogenic inertial confinement fusion targets (i.e., spherical shells containing a uniform layer of DT ice) are investigated using target free-fall concept. Detection and characterization of the moving targets are effected by optoelectronic means, of which the principal is an RF ac-interferometer. This interferometer system demonstrates, for the first time, the speed capabilities of the phase-modulation ac-interferometry. New techniques developed for handling, holding, launching, and transporting targets are also described. Results obtained at both room and cryogenic temperatures are presented.

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1. INTRODUCTION

The use of energy, in one form or another, is a basic need for all people. The economic and political implications of energy consumption place a heavy burden on modern society. The reliance on non-renewable carbon-based fuels, such as coal and oil, has two direct consequences. First, the price of energy will rise as supplies are depleted or held back from consuming parties. Second, the by-products resulting from burning these fuels will increase the levels of air pollution which affect the earth's energy, ecological, and human balances. The harnessing of new and better energy sources is, therefore, essential to the well-being and continued growth of the society.

The energy released by the sun is one of the earth's most vital energy sources. Thermonuclear fusion reaction supplies all stars (i.e., the sun) with a tremendous amount of energy lasting over billions of years. The fuel required for fusion is hydrogen and its isotopes, deuterium (D_2) and tritium (T_2). Hydrogen and deuterium are the most abundant elements in the universe, and on earth, the oceans contain an endless supply of both (note that tritium is not found in nature, and that it, therefore, must be bred). However, taking the hydrogen and successfully fusing it requires the conditions found only in stars. Matching these conditions on earth is extremely difficult to do. Although the density and temperature of a star are hard to attain by conventional methods, two ways are being actively studied: magnetic confinement and inertial confinement.

The basic principle of energy production behind the thermonuclear fusion reaction is the transfer of the mass difference into energy ($E=mc^2$) resulting from the reaction. Two nuclei are made to collide with such forces that they overcome the repulsive part of the nuclear forces and fuse into one. The products of the fusion reaction are given the released energy in the form of

kinetic energy usually expressed in terms of mega electron volts (1 Mev = 1.602×10^{-13} joules). These fusion products will vary with the fuel used and are not radioactive, except for tritium which beta-decays with a half life of 12.26 years. Here are the major fusion reactions and their products with their kinetic energy expressed in megaelectron volts:

The kinetic energy (or temperature) of the fusion fuel ions is usually expressed in terms of kilo electron volts, kev ($1 \text{ kev} = 1.605 \times 10^7 \text{ K}$). The values needed for fusion are dependent on the fuel. The D-T reaction is the most probable reaction at the lowest energy, which is 10 kev. The probability that the fuel will fuse is dependent on its density and how long it is held in that dense state.

Lawson's criterion is a well-known criterion for the possibilities of fusion reaction. It uses the density of the plasma, in nuclei per cm^3 , and the confinement time needed at that density, τ , to estimate the conditions required to start the reaction (see [1]).

$$n\tau = 10^{16} \text{ (sec/cm}^3\text{) for D - D} \quad (1.5)$$

$$n\tau = 10^{14} \text{ (sec/cm}^3\text{) for D - T} \quad (1.6)$$

The input energies needed to hold these high temperature plasmas in a dense state till they react are immense. The magnetic confinement approach is to hold the ionized fuel in magnetic bottles that do not allow the ions to escape. The inertial confinement approach uses symmetric energy concentration on a spherical target containing the isotopes of hydrogen. The use of both laser and charged beams is presently employed to achieve target implosion. The laser driver is in an advanced stage; at the Lawrence Livermore National Laboratory laser facility, they are nearing "scientific breakeven" for input powers up to 200 tera(10^{12}) watts. The cost of both the magnetic bottles (mirrors or tokamaks) and large lasers is enormous. The cost and complexity of the confinement devices are the major obstacles for the realization of efficient use of fusion energy.

One of the important laser implosion targets requires an extremely symmetric hollow glass microballoon (GMB) filled with high pressure fuel gas. The gas pressure of a GMB ranges from 50 to 750 atmospheres. The glass walls confining the gas are from 1 to 10 microns thick (1 micron = 1×10^{-6} meter). The GMBs are usually 100-500 microns in diameter. The laser beam illuminates the GMB, heating and ionizing the glass shell. The shell explodes both inwardly and outwardly. The inwardly directed fuel eventually undergoes fusion reaction, depending on its density and temperature. This type of GMB is known as an "ablative-compression" target.

The compression of the fuel is hindered by the gas at the center of the target which exerts its own outward pressure. This creates the need for a higher laser driver input power. In order to reduce the laser power requirements and increase target implosion gain, one can liquefy or solidify the gaseous fuel inside the GMB. This increase in the density of the fuel and decrease in the back pressure result in a better fuel burn, with subsequent higher target gain.

The techniques for fabricating these highly symmetric cryogenic (10 K - 30 K) targets have been studied by Rieger [2], Fanning [3], and others [4]. These techniques generally fall into two categories. The first category is stationary fabrication. The GMB is glued onto a thin stalk, which is then subjected to a cryogenic environment. The methods used to cool the deuterium gas inside the stationary target range from a cold helium gas heat transfer to conduction through the holding fiber. This stationary method of target mounting and manipulation is the most common in present implosion experiments.

The second category of cryogenic target is non-contact fabrication. One non-contact method employs either cold gas levitation, or cold gas levitation with additional electric quadrupole confinement structure. This latter method necessitates charging the GMB sufficiently enough to be retained by the quadrupole (see [3]).

The symmetry of the liquid or solid layer inside the GMB needs to be analyzed in detail. The method most often used is the laser interferometry. This method provides for a three-dimensional view of the layer. In a stationary target fabrication scheme, the target fringe pattern can be recorded by a video recorder or photographed. For cryogenic levitation, the target is held stationary by a molecular beam of cold gas, or a combination of gaseous and electric forces. For these techniques, the GMB can be analyzed with a video camera, provided the GMB is above the diffraction line of the levitator device.

The stationary fabrication serves the present research well, where the requirement for GMB implosion is on the order of a few events per day. When the requirement for higher implosion rates arises, the methods of cryogenic GMB fabrication will need to be modified to deliver many targets per second. The work presented here details a method capable of fabricating cryogenic targets on a continuous basis.

The method is a non-contact free-fall cryogenic technique equipped with the diagnostic instrumentation necessary to completely analyze the GMB's behavior and symmetry. Chapter 2 describes first the GMB handling method used in the GMB preanalysis at room temperature, and the target loading, holding, and launching procedures. The analysis of a free-falling GMB target at both room and cryogenic temperatures is presented next.

The requirements of the cryogenic system pose many difficult problems. The diagnostic instrumentation must take data without affecting the cryogenic GMB environment. Chapter 3 first details the constraints involved in accessing into the free-fall cryogenic environment. Next, the design of a detection system integrating both the cryogenic system and the interferometer is described. The results from the free-fall detection system are also presented and compared with the theory. Finally, representative data showing the form of the collected data are presented to complete the detection system description.

Due to the speed of the free-falling target, the interferometric analysis of the target cannot use a video camera and recorder. The moving GMB will never be "seen" by the video camera. This means that another method of analyzing the GMB interference patterns will be needed. Chapter 4 presents an RF ac-interferometer which is capable of measuring the GMB phase as the GMB falls past the interferometer. This chapter demonstrates the speed capabilities of the RF ac-interferometric measurements. In Chapter 5 the cryogenic target fabrication system is described along with the discussion of its setup and operating techniques. The results of the cryogenic experiments are also presented and analyzed. These include cryogenic detection and interferometric data. Chapter 6 contains conclusions and suggestions for future work.

2. TARGET PREANALYSIS, HANDLING, AND TRANSPORT

2.1 Introduction

Since the beginning of the inertial confinement fusion effort, the importance of the fabrication, analysis, and handling of the GMBs has been clearly established. The need for extreme symmetry in the glass shell meant that new techniques for fabricating this type of target needed to be developed. Once these techniques were developed, the target still needed thorough analysis to insure the symmetry of the glass shell. The requirements for the glass shell were met; however, it required analyzing many targets before a suitable target was found.

The requirements for cryogenic GMB fabrication are identical to those for room-temperature GMB used for target implosion studies. The time-consuming task of searching for a symmetric GMB needs to be done for the GMB which will undergo the cryogenic fuel layer formation. This search is done in our work by an interference microscope. It provides an interference picture of the GMB at room temperature from which we can judge the GMB in terms of symmetry, diameter, and thickness of the glass shell. This picture also provides a reference for later comparison to the cryogenic GMB.

The methods of GMB handling developed for room-temperature implosion studies can be used to handle and position a cryogenic GMB inside a reactor. However, when the demand for many cryogenic GMBs per second (up to 10/s) arrives, the techniques of GMB handling will have to advance beyond the presently available methods.

Laser implosions are presently being done to test the feasibility of inertial confinement fusion. The emphasis is on scientific data for

understanding the fusion physics, not on producing power. Mounting the target, at room-temperature or at cryogenic temperatures, simplifies the difficult task of focusing and timing as many as 20 laser beams.

The mounting is done by gluing the GMB onto a thin 10 micron glass fiber. Figure 2.1 shows two cryogenic GMBs mounted in this fashion. This method has many advantages. The most obvious is the ease of positioning. By attaching the fiber to an x-y-z translater, the GMB can be positioned anywhere desired. The layer analysis is simplified, so that still photography or the use of a video data acquisition system can be implemented directly. The work done by Rieger [2] and Fanning [3] shows that this method is well-established.

The use of a mounting fiber does, however, have disadvantages. The mounting fiber creates a non-uniform cryogenic environment. This causes the formation of a non-uniform layer inside the GMB. This can be overcome using a fast freeze-vaporization-freeze cycle, which allows the use of this method for an implosion experiment, provided that the cryogenic layer is maintained until the laser illumination. The major obstacle this method cannot overcome is the rapid delivery of many cryogenic targets.

A proposed method which might overcome this obstacle is molecular beam levitation. This is a non-contact method which uses cold helium gas to lift the GMB and freeze the fuel inside of it into a symmetric layer. The most pressing problem in this method is confining the GMB in the levitation and cooling regions. The use of an electric quadrupole to hold the GMB in this region necessitates charging of the GMB. Fanning [3] presents a system for charging, confining, levitating, and freezing a GMB. This method has proven to be very difficult to implement, but it does present an attractive solution to non-contact cryogenic GMB fabrication.

(a)

(b)

(c)

(d)

Figure 2.1 -- Stationary cryogenic GMB targets. (a) shadow micrograph of 300 μ m diameter GMB with solid D_2 at bottom; (b) interference micrograph of (a); (c) shadow micrograph of 140 μ m diameter GMB with solid D_2 at the bottom; (d) interference micrograph of (c).

This chapter will describe a new method for non-contact cryogenic GMB fabrication which employs "target free-fall" concept. This system is somewhat simpler to implement than the levitation quadrupole system, but it still poses many problems in target (GMB) handling and transport.

Covered first in the following is the laser interferometer target preanalysis station. Next, the GMB handling techniques are discussed in three parts: construction of a GMB holder, loading the GMB holder, and launching the GMB inside the cryogenic chamber. Last, a brief analysis of the free-fall phenomenon is presented.

2.2 Target Preanalysis

The first analysis of the GMB is done outside of the cryogenic chamber. The apparatus used is a Mach-Zehnder interference microscope. Figure 2.2 shows the general setup for analysis. The camera is positioned at one output of the interferometer. The other output can be used for video analysis if available.

The output from a 1 mW He-Ne laser is divided into two equal beams by a 50-50 beamsplitter. One of the beams passes through the GMB being analyzed, and the other is used as a reference beam. The image of the target is magnified using a microscope objective. The other beam (reference beam) is also magnified by the same amount. Upon recombining, the beams add or subtract, depending on their relative phase difference (a detailed analysis is provided in Chapter 5). The output is a fringe pattern of the GMB. Figure 2.3 shows two targets with and without the reference beam. The dark splotch is dirt on one of the GMB. This fringe pattern would show a concentric bull's-eye pattern if the GMB were perfectly symmetric. The nonconcentricity

Figure 2.2 -- Preanalysis Mach-Zehnder interference microscope.

(a)

(b)

(c)

(d)

Figure 2.3 -- Two GMB targets in the pre-analysis station.
(a) and (b) are a shadow/micrograph of a $160\mu\text{m}$ GMB target; (c) and (d) are shadow/interference micrograph of another $160\mu\text{m}$ GMB target (note dirt splotch).

of the bull's-eye pattern gives the degree of asymmetry of that GMB glass shell since at room temperature the hydrogen is a uniform high-pressure gas. This fringe pattern photograph can be used for comparison when the cryogenic target is analyzed in free fall. The initial analysis helps to weed out the overly dirty, broken, or non-symmetric GMBs before loading. This involves many hours of tedious work but insures that only symmetric GMBs containing hydrogen are used.

2.3 Target Handling

GMB handling is inherently complicated. The small size of the target requires the use of a high-power microscope during any attempt to see or manipulate the GMB. Extreme precision in the instruments needed to manipulate and hold the targets is also required for placement of the target to within a fraction of the GMB diameter, ± 1 micron. The simpler methods of handling are the most attractive because of these requirements. In this experiment the GMBs are held inside a holding microtube before launching them into the free-fall system. Figure 2.4 shows the steps needed to analyze the GMB, load the holder, insert it into the chamber, and launch the GMB into free fall. These steps are repeated for every target free-fall experiment, whether or not the chamber is cooled down.

Since there are no commercially available GMB holders, we need to fabricate one to the specifications. Fabrication of the holder proved to be a difficult task. The holder microtube must perform several tasks. It must hold the targets stationary in the order in which they were loaded. When launching the GMB, the holder must provide some means of pushing the GMB out of the microtube. The holder must allow only one GMB to be launched at a time. The final design satisfied all of these requirements.

Figure 2.4 -- General scheme for preanalysis, loading, and launching.

The construction of the holder system is shown in Figures 2.5 and 2.6. Figure 2.5 shows the construction of the vacuum outlet and the means of sealing the holder in the high vacuum jacket. The bellows provide the flexibility needed for a "pushing" tungsten wire. The end of the bellows is fixed inside the launch chamber. When the micrometer is rotated inward, the bellows compress. The 125 micron pusher tungsten wire is fixed to the micrometer side of the bellows. As the bellows contract, the wire is pushed outward. This pushing action will move the GMB toward the mouth of the holder microtube.

Figure 2.6 shows the steps required in the construction of the holder microtube. The microtube is originally drawn from a 7 mm pyrex tube. The inside diameter of the microtube is controlled by the length that the tube is drawn down. The inside diameter needs to be larger than the largest GMB diameter. Typically, the inside diameter of the drawn microtube is 180 microns.

The first step in the construction is to glue the 180 micron diameter glass microtube onto the end of the bellows (Figure 2.6(a)). The pusher tungsten wire is inserted inside of the microtube. The wire provides for the pushing action previously described. The mouth of the microtube is critical in the target loading, holding, and launching sequences. It has to be formed by pulling the end shown in Figure 2.6(b) into a shape like that in Figure 2.6(e). This pulling is accomplished by contacting the mouth of the microtube with a red-hot heater wire (Figure 2.6(c)). As the microtube contacts the wire, the end melts, and as the tube is pulled away from the wire as shown in Figure 2.6(d), the melted glass is pulled outward and upward into the shape shown in Figure 2.6(e). The process may have to be repeated many times before the appropriate mouth shape is obtained.

Figure 2.5 -- Holder microtube system.

Figure 2.6 -- Construction of holder microtube.

After the microtube mouth is prepared, a 25 micron tungsten wire is threaded into a sleeve microtube placed over the holder microtube (Figure 2.6(f)). This sleeve is a glass microtube drawn slightly larger than the holder microtube. The wire forms a spring obstacle to the GMB entry and exit from the holder tube. The sleeve is then glued onto the holder microtube to fix the wire's position over the microtube's mouth (Figure 2.6(g)). A closeup is shown of the final mouth in Figure 2.6(h).

The GMBs are originally kept in an ethanol-filled test tube. A hypodermic syringe with an I.D. of 100 micron is used to suck a GMB onto the end of the needle. The GMB is then transferred to the preanalysis interferometer. Figure 2.7 shows the integration of the GMB holder system with the interferometer. The GMB is put on a glass slide, inspected, and photographed. If it satisfies the symmetry requirements, the GMB is loaded into the holder microtube; if it does not meet the requirements, it is discarded.

The GMB is first pressed onto the end of the holder microtube where the wire holds it. Figure 2.8(a) shows a GMB ready to be pushed into the holder microtube. The GMB is then pushed into the holder microtube where it stays until launching. This procedure is repeated until the holder has approximately 10 to 20 GMBs inside of it (Figure 2.8(b)).

The entire holder microtube assembly is then inserted into the launch chamber. As carefully as possible, the holder is inserted into the transport microtube. The holder and transport microtubes are made of glass, so care is needed to prevent breaking or shattering these tubes. Figure 2.8(c) shows a loaded holder microtube inserted vertically into the transport microtube. The GMBs are then ready for launching.

(a)

(b)

Figure 2.7 -- Holder microtube system integrated with pre-analysis interferometer station, (a) total system view; (b) close-up view.

(a)

(b)

(c)

Figure 2.8 -- Loading and launching the holder microtube.
(a) a target ready to be loaded into the holder microtube; (b) a fully loaded holder microtube; (c) holder inserted into transport microtube.

2.4 Target Launching

The launching procedure is a reversal of the loading procedure. The end of the bellows is fixed, so that when the micrometer is moved, the pusher wire inside the holder will push the GMB down into the mouth. There the wire clip holds them until the downward force pushes the clip upward. This allows the bottommost GMB to be pushed out. When the GMB reaches the halfway point, the clip will slip down the backside of the GMB. This spring action launches the target off the holder and into the transport microtube. The mouth of the holder plays an important role here. The symmetry of the launching push determines what direction the GMB initially will take. In this case, a downward direction is preferred since any contact with the wall of the transport tube will decelerate the GMB and otherwise change the GMB path. For this reason, the holder mouth needs to be able to produce this initial direction. After the launch, the next GMB in the holder is ready for launch. Again, it should be pointed out that the launching procedure needs a high-power microscope to insure that only one target is launched at a time.

2.5 Target Transport System

Since the requirements for cryogenic GMB fabrication are imposing and the constraints difficult to change, the need for simplicity is great. Ideally, the best method for non-contact GMB fabrication is the use of electrostatic forces. However, use of a quadrupole confinement structure in a cryogenic regime is a complex and difficult task. For this reason, a free-fall system using a transport microtube was designed to simplify the task of confining the free-falling GMB in a cryogenic environment. The transport microtube obviously needs to be larger than the diameter of the GMB. The transport

microtube used is not constant in diameter. At the launching point at the mouth of the transport microtube, the I.D. must be large enough to insert the holder microtube inside it. This insures that the GMB will enter the transport tube after it is pushed out of the holder. The exit point of the transport microtube is in the interferometer. The I.D. here needs to be small enough to position the free-falling GMB onto the detection mechanism. The form of the transport microtube is, then, that of a tapered microtube, large at the mouth, 800 microns, and small at the end, 300 microns. The use of glass allows for the construction of any size tube with any desired taper. The transport microtube needs to be transparent to enable detection of the moving GMB (discussed further in Chapter 3).

The transport microtube is held in place inside the cryogenic chambers. Once the GMB has entered the transport microtube, it falls downward through the three zones of the fabrication system. During the free fall, the GMB is detected by solid state optical sensors which can obtain the parameters characterizing the GMB behavior in a non-contact fashion.

2.6 Target Free-Fall Analysis

The GMB in free fall will ultimately reach a terminal velocity. The value of this terminal velocity is dependent on several parameters. The GMB size and average density along with the inside diameter of the transport microtube and the density and viscosity of the transfer gas will determine the GMB terminal velocity. Assuming that the GMB is in free-fall in an infinite media, we will first calculate the terminal velocity. Then using a velocity correction factor to take into account the wall effects of the transport microtube, we will arrive at a value for the terminal velocity inside the transport microtube.

For a free-falling rigid sphere with diameter d , the value of the terminal velocity can be obtained using Stoke's Law (see Clift [5]). The terminal velocity of the falling sphere, assuming that the medium is at rest, is given by

$$V_{\text{term}} = \frac{g d^2 \Delta \rho}{18 \nu} \quad (2.1)$$

where g is the gravitational acceleration, d is the sphere diameter, $\Delta \rho$ is the density difference between the sphere and the media, and ν is the kinematic viscosity of the media. Since the density of helium is on the order of 2×10^{-4} g/cm, we can neglect it and use the dominating term of the average density of the free-falling GMB. The average density of the GMB can be calculated in a straightforward manner:

$$\rho_{\text{av}} = \frac{(r^3 - (r-t)^3) \rho_{\text{glass}} + (r-t)^3 \rho_{\text{gas}}}{r^3} \quad (2.2)$$

where r is the target radius, t is the glass thickness, and ρ_{glass} and ρ_{gas} are the mass densities of the glass and fuel gas, respectively. For an average 150 micron diameter target with a 10 micron wall thickness, a gas fill density of 16.75 mg/cc, and a glass density of 2.5 g/cc, the average density would be:

$$\rho_{\text{av}} = 0.883 \text{ g/cc} \quad (2.3)$$

The kinematic viscosity of helium gas at 20 C is equal to 1.94×10^{-4} g/cm-s, and g is equal to 980 cm/s^2 . The only temperature sensitive parameter in this formulation is the kinematic viscosity of helium; the value of ν at -263 C (10 K) is 5 times less than at 20 C. Using these values, we arrive at a terminal velocity of

$$V_{\text{term}} = 55.78 \text{ cm/s at } 20 \text{ C} \quad (2.4)$$

$$V_{\text{term}} = 278.9 \text{ cm/s at } -263 \text{ C} \quad (2.5)$$

Now that we know the velocity in an unbounded medium, we need to find what effects the transport microtube will have on the GMB terminal velocity. The physical situation is shown in Figure 2.9. The GMB diameter is again d , the tube diameter is D . Assume the helium gas inside the transport microtube is at rest. It is convenient to define a diameter ratio:

$$\lambda = \frac{d}{D} \quad (2.6)$$

Most work done on bounded media is related to the unbounded case. There is defined a velocity ratio, K , based on constant particle dimensions.

$$K = \frac{V_{\text{term}^0}}{V_{\text{term}}} \quad (2.7)$$

To find the terminal velocity in the bounded case, we need to evaluate the velocity ratio in terms of the diameter ratio, λ . Several authors have done this evaluation (Faxen [6], Haherman and Sayre [7], and Francis [8]). Using the formulation of Faxen, the velocity factor is approximately 5.5 for a λ of 0.5. This gives the terminal velocity of a 150 micron GMB, with a 10 micron wall thickness, inside a 300 micron transport microtube as:

$$V_{\text{term}} = 10.14 \text{ cm/s} \quad \text{at } 20 \text{ C} \quad (2.8)$$

$$V_{\text{term}} = 50.70 \text{ cm/s} \quad \text{at } -263 \text{ C} \quad (2.9)$$

Since the transport microtube is really tapered and not uniformly cylindrical, the actual velocity of the GMB will be higher than that calculated. Also, variation in the GMB diameter (they are not all of the same diameter) will cause the diameter ratio to change from the assumed value of 0.5. This will change the velocity ratio. Another factor is the thickness of the GMB glass shell. A thicker shell will increase the terminal velocity and a thinner shell will decrease the terminal velocity. The shell thickness

Figure 2.9 -- Free-falling target inside the transport microtube.

determines the GMB average density. Table 2.1 shows the ranges of GMB diameter and shell thickness with their average density, ρ_{av} , terminal velocity, V_{term} , and velocity ratio K . Also included are velocity ratios for different diameter ratios. This proves the need for a preanalysis to determine the GMB diameter and shell thickness before launching the GMB into the system.

TABLE 2.1 -- FREE-FALL VELOCITIES AND VELOCITY RATIOS FOR DIFFERENT GMBs

SHELL THICKNESS IN μm		AVERAGE DENSITY IN $\frac{\text{g}}{\text{cm}^3}$	TERMINAL ∞ VELOCITY $\frac{\text{cm}}{\text{sec}}$ AT 0°C ; IN $\frac{\text{cm}}{\text{sec}}$	TERMINAL ∞ VELOCITY $\frac{\text{cm}}{\text{sec}}$ AT -269°C ; IN $\frac{\text{cm}}{\text{sec}}$	VELOCITY RATIO INSIDE A 450 μm TUBE	VELOCITY RATIO INSIDE A 300 μm TUBE
GMB OUTSIDE DIAMETER IN μm 120	1	.138	5.60	28.0	2.08	3.54
	2	.256	10.37	51.8		
	5	.587	23.72	118.6		
	10	1.060	42.95	214.5		
140	1	.122	6.67	33.4	2.45	4.75
	2	.223	12.27	61.3		
	5	.511	28.18	140.9		
	10	.936	51.49	257.5		
150	1	.114	7.22	36.1	2.65	5.57
	2	.209	13.24	66.2		
	5	.481	30.35	151.5		
	10	.883	55.78	278.9		
160	1	.108	7.78	38.9	2.87	6.40
	2	.198	14.23	71.2		
	5	.454	32.59	162.9		
	10	.836	60.08	300.0		
180	1	.098	8.93	44.6	3.54	8.68
	2	.178	16.21	81.0		
	5	.407	37.07	185.4		
	10	.755	68.72	343.6		

3. DETECTION SYSTEM

3.1 Introduction

During the free-fall target-freezing experiment, the behavior of the free-falling GMB must be monitored. Knowledge of the GMB position and speed is needed for determining the temporal change of the GMB temperature and in the timing of the data acquisition. The detection mechanism for these measurements must also be compatible with the cryogenic requirements of the target freezing system and the high vacuum required for thermal insulation. The use of an optical detection system provides a flexible method to meet all these requirements. This chapter describes a detection system that uses optical techniques to achieve the measurements while coping with the various constraints imposed by the cryogenic environment.

3.2 Detection System Parameters and Constraints

The parameters that are to be measured by the detection system are of two types. The first is verification that the target has entered the transport system and to find its relative position in the system. The second parameter is the speed of the free-falling target.

A two point detector system was used because accessing the target throughout the system is impossible. Placement of two detectors in the target freezing and interferometric analysis zones will detect when the target is entering these zones. These two detection positions can accurately measure the target speed in these critical zones. The time interval between the two detection signals gives the average speed of the target through the transport

system. Comparison of the target's instantaneous speeds at the two detection positions along with the average speed can be used to determine the forces acting on the target while in the transport system.

The two measurement points and how they can be implemented are determined largely by the constraints of the experiment. In the present case, the entire experiment must be performed surrounded completely by cryogenic walls to provide the low temperatures needed to freeze hydrogen inside the GMB. To maintain these temperatures (10 K-30 K), the cryogenic chamber must be isolated from the 300 K walls by an insulating high-vacuum jacket. The jacket and the cryogenic chamber, combined with a free-fall environment, specify the use of optical detection. Optical detection can access through the walls of both the high-vacuum jacket and the cryogenic chamber without disturbing the free-falling target. The variety of optical sources and detectors available does allow for some flexibility in how the detection positions are implemented.

3.3 Optical Methods for Target Detection

The first detection mechanism consists of a matched infrared (940 nm) LED-phototransistor-combination, (TIL 31 and TIL 81). Figure 3.1 shows a schematic of the physical setup. The LED and the phototransistor are soldered, facing each other, into a hollow cylinder. A 660 micron aperture separates the pair from each other. This aperture increases the detection pulse signal-to-noise ratio which helps to insure target detection. A 660 micron hole is drilled perpendicularly intersecting the aperture. The target transport microtube is inserted through this intersecting hole, and the aperture transmits light through the transport microtube. The microtube will

Figure 3.1 -- Room temperature detection system.

attenuate some of the infrared light, but a portion of the light will be transmitted. This transmitted light is available for object detection. The GMB will be free falling inside the transport microtube, and as it falls through the aperture, the light inside the aperture is decreased due to reflection and absorption by the target. The phototransistor detects this decrease of light. After the GMB has left the aperture, the light will return to the normal dc bias level. The speed of the GMB is determined by the GMB diameter, the aperture length in the direction of the GMB travel, and the duration of the detection pulse. The speed is given by

$$v = \frac{d + a}{t} \quad (3.1)$$

where d is the GMB diameter, a is the aperture length, and t is the length of the detection pulse. The speed measurement at this detector can be considered nearly instantaneous since the measurement is taken in nearly four GMB diameters.

The placement of this detector helps to solve a few problems. The cryogenic chamber, to be described in Chapter 5, has three zones, one cryogenic and two at room temperature. Although the launch chamber is designed for cryogenic temperatures, in the present system it is operated at room temperature (300 K). The LED-phototransistor pair will not operate at the cryogenic temperatures of liquid-solid hydrogen. By placing the LED-phototransistor pair in the room-temperature zone, we can access the GMB without putting windows in either the high vacuum jacket or the inner experimental chamber (note that the word, "room-temperature," in this case is used to indicate that the temperature of this zone is much higher than the liquid hydrogen temperatures). The ability to directly solder the pair into the inner chamber close to the GMB transport microtube assures a detection

pulse and a reliable vacuum. The detection pulse indicates to the operator that the target is in the microtube and falling past the room-temperature detection zone into the bottom cryogenic chamber. The use of this pulse for any timing or reset pulse relieves the operator of having to "watch" for a GMB entering into the system.

The second detector is integrated with the RF ac-interferometer. (This ac-interferometer is described in Chapter 4.) The placement of the detector is shown in a simplified interferometer schematic, Figure 3.2. The transport microtube is in the diagnostic arm of the interferometer. The detector (TIL 81) is placed behind the imaging microscope objective, but in front of the reflecting mirror. The transport microtube is imaged behind the microscope objective. The top portion of the image is placed onto the detector, and the image of the exit opening of the microtube is reflected into the interferometer aperture where it recombines with the reference arm. As the target falls through the upper portion of the microtube, the laser light transmitted through the microtube will decrease, as in the other detector, and this decrease in intensity is detected by the phototransistor. Because of the magnification provided by the microscope objective, the detection aperture at the second detector is a fraction of the transport microtube's I.D.. The size of the detector pad must, therefore, be normalized to account for the magnification of the target. At the photodetector, the magnification is approximately 11.1 times. The detector pad size is 0.86 mm. Normalizing this by the magnification of the transport microtube gives an aperture height of 77.4 microns. The microscope objective also causes the transport microtube to act as a cylindrical lens. The self-focusing caused by this lens effect focuses the laser light illuminating the microtube. The microtube's focal region is a line rather than a round spot, and the second detector is placed

Figure 3.2 -- Second detector integrated with RF ac-interferometer.

in this focal line. The detection aperture formed by the objectives is a rectangle, with a 300 micron width (the microtube's I.D.), and a 77.4 micron height (the value that was just calculated). This aperture height is important in the following calculations.

The instantaneous speeds at the second detector are calculated using the same method applied at the first detector. Adding the GMB diameter to the aperture length and dividing by the pulse duration gives the instantaneous speed at the second detector. The equivalent aperture length, in this case, is the dimension in the direction of the target's free fall. The value of the second detector's aperture height is 77.4 microns. Detecting the exit of the cryogenic target from the transport microtube is a significant event because the target then falls into the interferometer. The second detector's pulse is also used for triggering the interferometric data collection electronics.

The placement of the second detector helps to simplify the cryogenic chamber design. The use of the microscope objective, already needed for the interferometer, provides a small detection aperture which will improve the signal-to-noise ratio and insure target detection. The windows for accessing the end of the transport microtube are needed for the interferometric target symmetry analysis. The integration of the second detector with the interferometer simplifies the cryogenic system design in that no additional optical access ports are needed.

Using the two detection pulses to stop and start a digital counter will provide the average speed between the two detectors. The average speed of the GMB between the first and second detectors is given by

$$v_{av} = \frac{L}{t} \quad (3.2)$$

where L is the distance between the two detectors and t is the time between the detection pulses.

3.4 Description of the Experimental Procedures and Detection Electronics

The experimental detection pulses need to be collected and recorded. Figure 3.3 shows the general scheme of the data acquisition. The optical detectors are biased via a front-panel coaxial cable arrangement which reduces clutter and eliminates external vibrations on the high vacuum jacket. The pulses from the two phototransistors are displayed on the oscilloscope using an alternate display mode. These pulses are amplified and are used as trigger pulses for an HP-5262A digital counter. The first detection pulse starts the counter and the second detection pulse stops it. The time a GMB spends in each aperture can be read directly off the oscilloscope, and the time spent between the detectors is displayed on the digital counter. These time values are used to calculate the instantaneous target speed at each detector and the average target speed between the detectors.

The detection procedure happens in three distinct events. The first event is the launch of the GMB target. The launch is initiated by the operator looking through the microscope to insure that only one target is launched at a time. The second event is the detection of the target at the room-temperature detector half-way between the launch chamber and the bottom cryogenic chamber. This pulse is recorded on the oscilloscope and is amplified to start the digital counter. The third event is the appearance of the target in the interferometer aperture. As the target falls out of the transport microtube, the second detector detects its passage. This pulse is recorded on the oscilloscope. The second pulse is also amplified and used to stop the digital counter. This pulse also triggers a delayed-sweep for the RF ac-interferometer (see Chapter 4), or a fast movie camera for the interferometric analysis. The appearance of the GMB into the interferometer aperture, outside of the transport microtube, gives the first unobstructed

Figure 3.3 -- Scheme for detection data acquisition.

view of the GMB since its launching.

The electronics used to bias the detectors is shown in Figure 3.4. The coaxial cables carry the negative bias voltage to the emitter of both phototransistors and the anode of the LED. Negative polarity biasing voltage is used for both phototransistors and the LED due to the physical setup being used. In the TIL 31, the cathode is connected internally to the case, and in the TIL 81, the collector is connected internally to the case. Soldering the LED and the phototransistor into the room-temperature detector grounds the cathode and the collector of the two devices. Biasing must be done, therefore, via the anode and emitter of the LED and phototransistor using a negative voltage source.

The current through the LED produces 940 nm infrared light, and its intensity is adjusted by a potentiometer. The LED current is measured with a digital voltmeter (DVM). This voltmeter can also monitor the bias level (V_{ce}) of both phototransistors. This bias level is important in the proper operation of the phototransistors. The operating levels of V_{ce} for both transistors and the LED current used in the present system are given in Figure 3.4.

3.5 Results of Detection System

The detection system output data contain the temporal record of the target free fall. After launching, the GMB target free falls down the transport microtube past the first detector and then the second detector, and finally into the interferometer for symmetry analysis. The pulses are recorded on an oscilloscope. The top trace is the first detection pulse at the room-temperature zone, and the bottom trace is the second detection pulse

OPERATING CONDITIONS

$$V_{CET_1} = 9.0 \text{ V}$$

$$V_{CET_2} = 5.0 \text{ V}$$

$$I_{LED} = 150 \text{ mA}$$

Figure 3.4 -- Electronics for detection system.

at the end of the transport microtube. A third detection occurs outside the transport microtube in the RF ac-interferometer and is described in Chapter 4.

Figure 3.5 shows two oscillograms. Each oscillogram is an actual recording of the two detection pulses for a single free-falling room-temperature GMB. Figure 3.5(a) is for a 150 micron diameter target having a shell thickness of 10 microns. Figure 3.5(b) contains data for a 160 micron diameter target with a shell thickness of 10 microns. The top trace in each oscillogram shows the time spent in the room-temperature detection aperture. Adding the aperture (660 microns) and the GMB diameter, and then dividing the sum by the pulse duration, we can arrive at the instantaneous GMB speed of each target in the room-temperature detector. The 150 micron GMB had a speed of 21.3 cm/s, and the 160 micron GMB had a speed of 21.5 cm/s.

The second detection pulse, the bottom trace, gives the time spent in the second detection aperture. The instantaneous speed is the aperture (77.4 micron) plus the GMB diameter divided by the pulse time. The pulse times are 3.2 ms for Figure 3.5(a) and 3.8 ms for Figure 3.5(b). This gives an instantaneous speed at the second detector of 7.1 cm/s for 3.5(a) and 6.25 cm/s for 3.5(b).

The second detection pulse also stops the digital counter started by the first pulse. The measured times between the first and second detection pulses are 447.21 ms for 3.5(a) and 572.21 ms for 3.5(b). The distance between the two detectors is 7.0 cm. Dividing this distance by the digital counter time measurement gives the average speed of the GMB between the first and second detectors. The average speeds for Figures 3.5(a) and 3.5(b) are 15.6 cm/s and 12.2 cm/s, respectively.

Before comparing each target's speed throughout the transport system, we must investigate any system detail that will affect the speed of the GMB. The

(a)

(b)

Figure 3.5 -- Detection system output pulses. The top trace in each oscillogram is the room-temperature detection pulse. The bottom trace is the second detection pulse. (a) is a 150 μm GMB; (b) is a 160 μm GMB.

most important consideration is the GMB launching procedure. In order to free the GMB from the holder microtube, the 25 micron tungsten wire "spring" holding the GMB inside the holder must "spring" or "eject" the GMB. The initial velocity given to the GMB will depend on the amount of wire deflection as it is pushed out of the holder microtube mouth. Whatever the initial velocity, once the GMB has left the holder microtube, it is in free fall, because any force that accelerates the GMB will be acting uniformly on the GMB. In most cases this initial "ejection" speed is greater than the free-fall terminal velocity. This means that the GMB must be decelerated by the viscous drag force of the exchange gas. The GMB will decelerate continuously until it reaches terminal velocity. At this point in the system, the only forces acting on the GMB are the gravity and the drag force due to the wall effects described in Chapter 2. The point in the system where the target reaches terminal velocity depends on the magnitude of the viscous drag force and the initial GMB velocity.

A second consideration, already mentioned in Chapter 2, is that the transport microtube has a tapered funnel shape, so the velocity ratio calculated for a single transport microtube diameter ratio will not completely describe the wall effects throughout the transport system. At the first detector, the transport microtube has an I.D. of 450 microns. The exit opening has an I.D. of 300 microns. The increase in the calculated velocity ratio, K , from the first detector to the second detector is approximately a factor of 2.1. Velocity correction factors for various diameter ratios, λ , are in Table 2.1.

The theoretical free-fall speed of a target having a diameter of 150 microns and a shell thickness of 10 microns is 55.78 cm/s. Inside a cylindrical tube with an I.D. of 450 microns results in a velocity ratio of

2.65. The theoretical free-fall speed of this target is calculated to be 21.0 cm/s. The theoretical free-fall speed of a 160 micron diameter target having a shell thickness of 10 microns is 60.08 cm/s. The velocity ratio of this target inside a 450 micron tube is 2.87. This results in a calculated free-fall speed of 20.9 cm/s. The experimental target speeds are very close to the calculated theoretical free-fall speeds. The targets have, therefore, reached their terminal velocities by the time they are inside the first detection aperture. The difference in each target's speed at the two detectors shows the expected deceleration for both 3.5(a) and 3.5(b). The target speed at the second detector is approximately 3 times slower than the target speed at the first detector. The theoretical speed deceleration calculated using the wall effects at each detection aperture predicts a deceleration of 2.1 times. The experimental results, therefore, show a slightly larger deceleration than the theory predicts. It should be noted, however, that the position of the target may not be centered inside the transport microtube. The calculated theoretical deceleration assumes that the target is centered, and any deviation from the center of the transport microtube would increase the target's deceleration. Since the absolute position of the target inside the transport microtube is not readily observable, we must assume that the experimental deceleration is greater than that predicted by theory due to the off-center positioning of the target.

The shape of the detection pulses is determined primarily by each detector setup. The first detector provides a smooth, almost Gaussian pulse. This shape represents the amount of light transmitted through the aperture as it changes with time. Since there are no lenses in the first detector, there is no magnification or focusing of the microtube or the GMB. The relative length of the aperture compared to the GMB diameter will determine the

internal details of a GMB that can be seen. In the first detector, the aperture is 4 times larger than the GMB diameter. This pulse will not reveal any of the internal details of the GMB. The light stopped in the aperture, therefore, is the attenuation caused by the entire GMB.

The second detection pulse has an interesting humped shape. This is due primarily to the use of a microscope objective to form an image of the transport microtube. The microtube's image is magnified by the microscope objective. The cylindrical self-focusing mentioned above will occur, and placing this focused line on the second detector will cause the second aperture to have a width of 300 microns. Note that this focusing will happen only in the region before the image focal plane of the microscope objective. A GMB inside the microtube will also be magnified and display self-focusing in the region before the image focal plane.

Magnification of the GMB image also causes more internal detail of the GMB to show up in the second detection trace. This magnification reduces the detection aperture relative to the GMB diameter, making the aperture a fraction of the GMB diameter. Therefore, as the leading edge of the GMB appears to the second detector, the amount of light decreases. As the center of the target reaches the detector, the amount of light increases due to the thinner glass of the target and the self-focusing at the center of the GMB. As the target leaves the detector, the focal point of the target moves downward, and the detector "sees" the thicker glass at the trailing edge of the target, which attenuates the light intensity as the leading edge had done. The shape of the detection humps is due to the fact that the detection aperture is one half the size of the GMB diameter, and so reveals the leading and trailing halves of the falling GMB. The alignment of the second detector with the focused laser light will affect the symmetry of the leading and trailing halves.

By comparing the optical dc bias to the amount of light transmitted through the target, we can determine the fraction of light stopped by a GMB. The light in the first detector's aperture biases the phototransistor. The dc light intensity corresponds to a collector current, I_c , of 0.6 mA. The 10 kilohm load resistor establishes a V_{ce} of 9 volts (the power supply is 15 volts). The dc light intensity, then, corresponds to a 6 volt drop across the load resistor. The height of the GMB detection pulse is typically 150 mV at the peak. By dividing the total amount of dc light (in volts) into the peak pulse value, we determine that 2.5% of the infrared light in the aperture is stopped by the GMB. In this detector, the peak pulse value is the maximum total amount of light that the target can stop, because the target fits entirely onto the detector pad.

The fraction of light stopped at the second detector is calculated using the same method used for the first detector. The dc light intensity at the second detector results in a dc bias collector current, I_c , of 12.5 mA. The bias voltage established, V_{ce} , with a load resistance of 820 ohms, is equal to 5 volts. Therefore, the dc light intensity corresponds to a 10 volt drop across the load resistor. The second detection pulse peak value is typically 2.25 volts. Note that this peak value is the light stopped by only the leading half of the GMB. This is due to the small size of the detection aperture compared to the GMB diameter. The pulse peak value gives the fraction of light stopped by the leading half of the GMB at this detector as 22.5%, and the fraction stopped by an entire GMB as 2 times the light stopped by the leading half of the GMB, which is 45%. This value is 20 times that calculated for the first detector.

As mentioned briefly before, the reason for the increase in the fraction of light stopped at the second detector over the first detector is that the

detectors sample different length apertures. The first detector has an aperture diameter of 660 microns. If the diameter of the GMB is 150 microns, then the target can occupy, at most, 5.1% of the first detection aperture. In the second detector, the magnification provided by the microscope objective allows for a smaller detection aperture area. The second detector has an equivalent aperture length of 77.4 microns. The percent of the second detection aperture occupied by the GMB will be 100% since the GMB image is larger than the detection aperture. The increase from 5.1% to 100% in the percent of the aperture occupied by the GMB accounts for the increase of 20 times in the amount of light stopped.

A major difficulty in the free-fall detection system operation is the target no-drop condition. The primary cause of the no-drop condition is the initial direction the GMB takes after launching. When the GMB is directed toward the transport tube wall, it hits the wall, slows down, and bounces off toward the other side of the microtube. After bouncing off the wall, the GMB can either continue rattling down the transport tube until it becomes stuck onto the wall, or it can fall through the system. In most cases, if the GMB hits the wall more than once, it becomes stuck, and a no-drop condition results. The critical factor in the determination of the initial GMB launch direction, as mentioned in Chapter 2, is the symmetry of the holder microtube. The construction of the holder microtube is extremely tedious, and can only be judged initially by sight. The only way to test the launch procedure of the holder microtube is to place it inside the transport tube and launch targets. If the targets do not fall through the system, the mouth shape must be modified. This testing and modification procedure must be repeated until a proper shape is found which allows successful target free-fall drops. The importance of the detection system in this procedure is obvious.

Another important experimental variable that has to be carefully monitored is the optical dc biasing of the second detector. This biasing is done by the laser light transmitted through the transport microtube. As mentioned above, the cylindrical shape of the microtube causes focusing of the laser light. The resulting line of laser light, which will eventually form a focused image of the microtube, is very sensitive to the placement of the microtube. If during the experiment, the microtube shifts to one side, the focused line moves also, which decreases the amount of light focused onto the detector. If the microtube moves far enough, the second detector will not detect the GMB as it falls past the detector. This microtube movement is especially noticeable during the system cooldown. This can be remedied by watching the dc bias on the second detector with the DVM and adjusting the microtube image placement.

The free-fall detection system works well in the free-fall regime of operation. Another regime of interest is the very fast freeze-vaporize-refreeze cycle (discussed in detail in Chapter 5). For this type of operation, the speed of the GMB is much higher than for free fall. The dynamics of the GMB behavior is no longer determined by that of free fall, but by the turbulent flow. The transport system can force the GMB up to velocities as high as 2 m/s. Even at these high speeds, the detection system can provide the instantaneous and average speeds. Since this work is primarily concerned with studying the effects of free-falling targets, the high GMB velocities merely demonstrate the range of speed attainable and detectable using the present detection system.

3.6 Conclusion

The detection system gathers the parameters needed to analyze the target behavior inside the transport system. The data presented in this chapter confirm that the targets are free-falling objects. The measured target speeds show that the GMB, once launched into the transport system, will slow down to a terminal velocity. The terminal velocity then decreases as the wall effects increase, due to the narrowing of the transport microtube diameter. This decrease in target velocity is predicted by the theory of free-falling objects inside restraining walls. The fraction of light stopped by the GMB at both detectors is shown consistent after compensating for the different size detection apertures. The attenuation of the light intensity caused by the GMB can be expected to increase when the GMB has a cryogenic layer. This will provide a crude method of evaluating the GMB temperature, and the fuel's state, in each detection aperture.

The reliability of the detection system is excellent. When a target is launched, the detection system always provides the measurements needed, except when the target is stuck inside the transport microtube. The system then tells the operator of a no-drop condition. The operator can then clear the transport microtube by pressurizing the launch chamber. The detection system tells the operator when the microtube is cleared by detecting this rapidly moving purged GMB.

The use of the soldered construction for the first detector and integration of the second detector with the interferometer provide a convenient and reliable detection of a falling GMB in a high-vacuum and cryogenic environment. The results presented here are only for room-temperature GMB free-fall drops.

4. RF AC-INTERFEROMETER

4.1 Introduction

The use of laser interferometry to measure transparent objects, reflecting surfaces, and propagation paths provides an accurate, nondestructive measurement. Efforts have been made recently to utilize the interferometer's abilities while minimizing the problems. Improving the phase resolution (e.g., $\pm 1/100$), reliability, and data acquisition has led many researchers to incorporate automatic signal processing to provide accurate real-time measurements. Automatic fringe counting utilizes phase modulation, since it has been concluded to be one of the best techniques for fringe counting. Several authors [9] - [11] have used some type of phase modulation with a wide range of experimental setups. The flexibility of application is a benefit of laser interferometry. The basic concept of the Radio-Frequency (RF) ac-interference microscope is similar to that of other phase-modulation systems. The optical spatial resolution is determined by the microscope objectives used, along with the detector pad size.

Conventional techniques, such as photographing the interference pattern and then using a microdensitometer to study it, require time-consuming analysis. When fast phase events are encountered, the use of ac-interferometry enables accurate phase measurements in real time. The speed of data acquisition depends on the several parameters. The frequency of the phase modulation, the post-detection filtering, and the type of ac-interferometry used are crucial in determining the useful data acquisition rate.

The effect of phase-modulation on the fringe pattern can be visualized as an optical derivative. The intensity at any point in the fringe pattern is a function of the optical phase, $I \propto \cos(\delta)$. The derivative of $\cos(\delta)$ is $-\sin(\delta)$. Therefore, the intensity modulation caused by the phase modulation is proportional to the slope of the fringe pattern, i.e., at a maximum, $\cos(0)=+1$, or at a minimum, $\cos(\pi)=-1$, the intensity modulation is zero, and where the intensity slope is greatest, $\cos(\frac{\pi}{2})=0$, the intensity modulation is at a maximum. The intensity-modulation output can also give the direction (+) of the fringe slope movement. This feature enables relative fringe counting required to determine the total phase shifts for multiple 2π phase shifts.

The main advantage of the use of an RF ac-interference microscope over other techniques is the data channel bandwidth. The average data bandwidth is 500 Hz for systems using lock-in amplifiers. The use of RF phase modulation enables us to increase the data channel bandwidth up to 100 times the bandwidth available in the previous systems. This increased bandwidth improves the time resolution, allowing detection and measurement of interference fringes as small as 4 microns in size moving at a speed as fast as 20 cm/s.

The RF ac-interference microscope has some other attractive features. Since phase modulation produces intensity modulation only when the two beams are interfering, the intensity modulation will be present only if the interferometer is properly aligned. This insures that only interference data are gathered. Another advantage is that the RF ac-interferometer can use lower cost $\lambda/4$ optics instead of the usual expensive $\lambda/20$ optics employed for conventional interferometers. This is made possible by making a measurement of the phase fringe pattern before the sample is put in the interferometer.

In the present application, we measure only one point in the fringe pattern. This means that we can observe the static phase of this point (δ_0 plus vibration) in real time. The temporal phase of the sample will add directly to this static phase ($\delta = \delta_0 + \delta(t)$). In x-y scan operation, the static phase at all points can be recorded and used to subtract from any sample measurement taken thereafter. The most important advantage of the ac-interferometer over other techniques is that the ac-interferometer measures the phase directly. Microdensitometry, for instance, measures only the photographic film intensity transmission which is affected by speckle, dirt, and grain.

Presented first in what follows is the theoretical basis for the RF ac-interferometry. The signal processing procedure will be included in this analysis. A brief discussion of noise in the system, the actual physical system, including the electronics, the results, and the conclusion will then follow.

4.2 Theory of Operation

A schematic of the Mach-Zehnder interferometer is shown in Figure 4.1. The intensity of the two interfering beams is proportional to $1 + \cos \delta$, where δ is the phase difference in the two beams:

$$\delta = \frac{4\pi L v_0}{c} \quad (4.1)$$

L is the optical path difference, v_0 is the frequency of light, and c is the speed of light.

Phase modulation implies adding a controllable phase shift or optical path difference in one of the two arms of the interferometer. There are several ways to accomplish phase modulation. These methods are explained in

Figure 4.1 -- Basic Mach-Zehnder Interferometer.

Eselun [9]. RF ac-interferometry uses the simplest method to accomplish phase-modulation. A piezoelectric crystal vibrates a mirror causing a change in the optical path length. The phase shift is given by

$$\delta = \frac{4\pi v \lambda}{c} \quad (4.2)$$

where λ is the maximum change in the optical path length. If the crystal is driven at the resonance, the phase shift as a function of time will be:

$$\delta_m = \phi \sin \omega_m t \quad (4.3)$$

where ω_m is the crystal resonance frequency.

In general, the intensity field can be expressed:

$$I = I_{dc} + I_{ac} \cos \delta \quad (4.4)$$

with fringe visibility β defined as I_{ac}/I_{dc} .

$$I = I_{dc} (1 + \beta \cos \delta) \quad (4.5)$$

Ignoring the dc term for now, the output of a photodiode-preamp will give an output voltage:

$$V = V_0 \cos \delta \quad (4.6)$$

δ has two components: δ_0 the dc static phase and $\delta(t)$ the phase as a function of time.

If phase modulation is introduced in one arm of the interferometer, Eq. (4.6) becomes:

$$V = V_0 \cos (\delta + \phi \sin \omega_m t) \quad (4.7)$$

When Eq. (4.7) is written in terms of Bessel functions of the first kind,

$$V = V_o J_o(\phi) \cos \delta + 2V_o \sum_{n=1}^{\infty} [J_{2n}(\phi) \cos \delta \cos 2n \omega_m t - J_{2n-1}(\phi) \sin \delta \sin (2n-1) \omega_m t] \quad (4.8)$$

Equation 4.8 contains quadrature signals $\cos \delta$ and $-\sin \delta$. The $\sin \delta$ term, however, is heterodyned up to a higher frequency due to the $\sin(2n-1)\omega_m t$ term. The other terms are heterodyned to multiples ($n > 1$) of the original modulation frequency ω_m . Since ω_m is in the RF range (680 kHz), these higher frequencies can be filtered out. The original $\sin \omega_m t$ is available to synchronously demodulate the $-2V_o J_1(\phi) \sin \delta \sin \omega_m t$ signal. Multiplying in phase the $\sin \omega_m t$ and the heterodyned $-2V_o J_1(\phi) \sin \delta \sin \omega_m t$ term will give us the baseband $2V_o J_1(\phi) \sin \delta$ signal. The two waveforms are now:

$$V_x = V_o J_o(\phi) \cos \delta \quad (4.9)$$

$$V_y = -2V_o J_1(\phi) \sin \delta \quad (4.10)$$

The amount of phase-modulation, ϕ , controls the signal amplitudes. Assuming small values of ϕ , $J_o(\phi) = 1$ and $J_1(\phi) = \phi/2$, the result is the original signal with its first derivative.

$$V_x = V_o \cos \delta \quad (4.11)$$

$$V_y = -\phi V_o \sin \delta \quad (4.12)$$

V_y can be normalized by multiplying by $1/\phi$.

The signal processing system does several things. Its main function is to retrieve the phase difference δ . It should be able to do this independently of I_{dc} . The system should also be able to count fringes along the direction of the fringe movement.

To automatically compensate for I_{dc} , it needs to be measured. Fortunately, this is easily accomplished with a Mach-Zehnder interferometer which provides two interference patterns, each out of phase with the other by π . A second detector measures fringes I' which will be out of phase with I by π .

$$I' = I'_{dc} (1 - \beta \cos \delta) \quad (4.13)$$

Converting I' and I into voltages, V' and V , variable gains G' and G are available. Equations (4.5) and (4.13) become:

$$V = GI_{dc} (1 + \beta \cos \delta) \quad (4.14)$$

$$V' = G'I'_{dc} (1 - \beta \cos \delta) \quad (4.15)$$

These voltages are subtracted and the gains adjusted so that $GI_{dc} = G'I'_{dc}$.

$$V - V' = 2GI_{ac} \cos \delta \quad (4.16)$$

This signal is now independent of the value of I_{dc} .

I_{dc} can be compensated for, I_{ac} , however, it poses a larger problem. The exact equation for I_{ac} is

$$I_{ac} = \sqrt{I_1 I_2} \quad (4.17)$$

where I_1 and I_2 are two beams of the interferometer. When the target falls past the detectors, the transmitted light at the edge of the target is attenuated by over 100 times relative to the center of the target. Since the intensity changes so drastically from edge-to-middle-to-edge, the output signal magnitude is also drastically affected due to the dependence of I_{ac} on I_1 and I_2 . The capabilities of automatic gain control (AGC) can remove the magnitude changes that are of a low frequency nature. However, rapid

fluctuations in magnitude will be detected and will amplitude-modulate the system output as the target moves past the detector. The transmittance information can be used in determining the transmission symmetry of the targets since it creates an envelope on the phase information.

Once the quadrature signals (i.e., V_x and V_y) are available, a rectangular-to-polar conversion can be performed which will give the phase and magnitude of the detected optical signal. Fringe counting can be accomplished by putting the V_x and V_y signals into an up/down counter which will then give us a relative fringe number.

Discussion of noise sources can be categorized into two types. Amplitude noise in the laser output beam has to be considered. The laser in use has a RMS noise specification of 0.5%. The amplitude noise is present in both arms of the interferometer, and can be considered to be a fluctuation of I_{ac} . This does not allow for the use of the measuring and subtraction methods discussed earlier. The phase noise due to vibration and air currents will always be present since the interferometer is built to measure such very small phase displacements. An advantage of having a large output bandwidth is that filtering over a specific band will allow the measurement of fast phase events, if their bandwidth is known, while filtering out the slower phase events, such as vibrations and air currents.

One last consideration is the fringe spacing relative to the physical size of the detector. It makes sense that if the fringe (bright to dark) can fit onto the detector pad, the phase modulation will not be detected since the intensity incident on the pad does not change with time. Therefore, tilt fringes should be eliminated so that the remaining fringes will have the largest possible spacing. As a rule of thumb, the fringe spacing should be at least 1.5 times the detector pad size to receive the phase modulation.

4.3 Apparatus

The RF ac-interference microscope is a modified Mach-Zehnder interferometer. Figure 4.2 shows a schematic of the RF ac-interference microscope. As with any microscope, the resolution of the magnified objects is controlled by the numerical aperture of the objectives. In this particular system, the objectives have a numerical aperture of 0.65 giving a lateral resolution of 2.32 line-pairs/micron. The spatial resolution of the output system is controlled by the detector pad size in relation to the image magnification. The currently used magnification is 84 times and the detector has a pad diameter of 250 microns. This results in a resolution of 4.5 microns. The laser source is a 20 mW He-Ne laser, where $\lambda = 632.8$ nm.

The phase-modulator shown consists of a piezoelectric transducer tube which has resonances at 680 kHz and above. At these RF frequencies, the mirror mounted on the tube must have a very small inertia. The mirror being used presently has a 0.75 inch diameter with a thickness of 175 microns. The amount of phase modulation decreases with an increase in frequency, above the first resonance at 680 kHz. The phase modulation is approximately $\lambda/10$. This is consistent with the assumption of $\phi \ll 1$.

The usual arrangement for a Mach-Zehnder interferometer calls for equal arm lengths. The reason it is not set up this way with the current system is because the microscope objectives must image objects, in this case, moving laser fusion targets. The image distance must remain the same for both objectives which insures that the image will remain in focus at the same magnification on the photodiodes. This arrangement does not affect the fringe visibility due to the long coherence length of the He-Ne laser.

Figure 4.2 -- Schematic of the RF ac-interferometer.

The optics used are all $\lambda/10$ optics or better. The phase-modulator mirror is a thin quartz plate with a nichrome-gold, (10 nm-100 nm), evaporated coating. The surface quality of this modulator mirror will determine the quality of the output fringes, especially since it was not bought commercially. Observation of the fringe pattern using this mirror leads us to believe that the surface quality is at least $\lambda/10$ quality.

At present, the system is capable of measuring one point in the image plane. The static phase at this point is a constant dc, and any ac signal will be the phase as a function of time at that one point. Vibration, or any other phase event like a moving GMB target, will be detected.

The system can be modified to provide for two-dimensional scans. In this case, the output signal will be the image plane's phase as a function of position (x,y), plus the vibration, which is a function of time and position (x,y,t), plus the interferometer's image plane dc phase, which is a function of position. The image plane position on the photodiode is controlled by the scanning system. The allowable scanning rate is limited by the data bandwidth and the desired resolution in scan lines per target diameter. The scanning can provide both x- and y-scans yielding two-dimensional phase maps. The scanning is not presently being done since we are interested in high speed GMB targets. The available bandwidth allows for a single scan across a free-falling GMB.

4.4 Signal Processing Electronics

The signal processing system is shown in Figure 4.3. The system consists of a front end, a precision adder, a demodulator, and an output low-pass Filter. Also shown is an analog rectangular-to-polar conversion. In the

Figure 4.3 -- Signal processing system.

present system this conversion is done by an oscilloscope CRT, using the vertical and horizontal amplifiers as the x-y axis.

The front end converts the optical signal into an electrical signal. The optical detector is a TIED 83 avalanche photodiode. This photodiode provides a signal gain of approximately 200. This photodiode is followed by a fast, low-noise preamplifier. There are two front ends used for the I and I' outputs of the interferometer. As in most electronic systems, the signal-to-noise ratio is determined by the front end. The front end used in this detection system has an NEP (noise equivalent power) of 2×10^{-13} W.

The signal of the I' front end is inverted. The inverter also provides the variable gain necessary to compensate for I_{dc} as mentioned earlier. The two front end signals, I and I', are then added using a precision adder. This precision adder utilizes an RCA 3140 FET op-amp.

Following the adder, the two frequency band components of the added signal are divided up. The low frequency cosine term is low-pass filtered to provide the cosine signal. The high-frequency modulated sine signal is high-pass filtered, amplified, and then synchronously demodulated. The high-pass filter is a Sallen-and-Key 2-pole configuration. The amplifier is an LM318 with a gain of 10 dB. The demodulator used is an MC1496 4-quadrant multiplier. Since the RF phase-modulating signal is available, a buffer attenuates the RF modulating signal to a proper level for the multiplication circuit (60 mV rms). This attenuated signal is in phase with the detected RF modulated sine signal. Multiplying synchronously the RF modulated sine signal by the attenuated original RF signal demodulates the modulated sine signal into a baseband sine signal. This baseband sine signal is then low-pass filtered to give the output sine signal. Both of the low-pass filters used for the output cosine and sine signals are 4-pole Sallen-and-Key filters with a measured -3 dB cutoff at 56 kHz.

The output cosine and sine signals are displayed on an oscilloscope. The output signals, since they are random events dependent on the GMB speed, are displayed using a time-delayed sweep on the oscilloscope. The trigger for this delayed sweep is provided by the detection system.

4.5 Results

The results presented here are broken into two categories. The first category is represented by the free-fall GMB drops that are detected in the RF ac-interferometer. The second category is the detection of a mounted GMB rotating at high speed. The high-speed GMB results are presented to show the high data bandwidth capabilities of the RF ac-interferometer.

The output of the RF ac-interferometer electronics can be dealt with in two ways. First, the cosine and sine signals can be displayed independently, or second, a phase-magnitude signal can be displayed on the oscilloscope by inputting the cosine signal to the horizontal amplifier and the sine signal to the vertical amplifier. The symmetry of the peaks in both the cosine and sine signals can be readily observed when the two signals are displayed independently. However, the phase-magnitude oscillogram will overwrite itself as the phase progresses through multiple 360 degree (2π) phase shifts. In the present system, the independently displayed signals give a better measure of the GMB multiple π phase-shift symmetry.

The results for free-fall drops are shown in Figure 4.4. This figure shows two oscillograms. The top trace in each oscillogram is the cosine of the GMB phase as the GMB falls past the detector. This signal is derived directly from the GMB fringe pattern. The bottom trace in both oscillograms is the sine of the GMB phase. This sine signal comes directly from the output filter of the demodulation circuit.

(a)

(b)

Figure 4.4 -- GMB free-fall fringe pattern at room temperature.
 (a) top trace is the cosine of the GMB phase and the bottom is the sine of phase; (b) same as (a), except the GMB is moving slower.

The traces in Figure 4.4 show the cosine and sine outputs of a free-falling GMB. The initial offset off the trace axis is due to the attenuation of the laser beam by the GMB. The amount of offset depends on the intensity at the detector at the time the GMB enters the interferometer. If the detector is on a bright fringe, the resulting offset is negative. If the detector is on a dark fringe, the offset will be positive. Note that the phase of the cosine trace is 90 degrees behind that of the sine trace. We can say, then, that the output is the cosine of the phase with its first derivative, i.e., the sine of the phase.

A high-speed GMB interferometric measurement is shown in Figure 4.5. This shows a stalk-mounted GMB, which is rotated at high speed. In Figure 4.5(a) the microscope objective is clearly visible behind the stalk. Figure 4.5(b) is a photograph of the GMB used in this demonstration. Figure 4.5(c) is the unfiltered output of the demodulator. The rotational velocity of the GMB is 1.5 m/s. The sine output signal shows the ability of the RF ac-interferometer to demodulate fast phase events. In this case of the fast rotating GMB, the smallest fringe frequency is above 50 kHz.

The intensity envelope seen in both the free-falling and rotating GMB fringe patterns is due to the attenuation of the laser light at the edges of the GMB. This corresponds to a change in I_{ac} and cannot be compensated for. However, since the edges of the GMB hold the least amount of information, it does not cause a lot of concern. As long as the center of the GMB gives us the symmetry information, we can evaluate the GMB, and any layer inside it. The envelope can also be used to evaluate the transmittance symmetry of the GMB, but usually this information is secondary to the phase information found in the fringe pattern.

(a)

(b)

(c)

Figure 4.5 -- High speed rotating GMB at room temperature.
(a) stalk mounted on rotating mirror; (b) GMB
mounted on glass stalk; (c) output of demodulation
circuit ($\sin \delta$),

The uniformity of these room temperature GMBs is not as great as that required by implosion experiments, but it correlates well with the preanalysis photograph taken before the launch.

The phase resolution of the RF ac-interferometer is approximately $\lambda/50$. The major causes of noise in the system are external vibrations, air currents, shot noise in the detector, and intensity noise in the laser beam. Fortunately, the phase events being analyzed in this application are faster than the slower phase noise events. We can filter out these slow phase events and improve the phase resolution to $\lambda/100$. The vibration cannot be completely eliminated, but it can be monitored. This is not done in the present system, but by using two other detectors and an identical demodulation circuit, we can get the phase of the vibrational noise in time. If the interferometer is designed well, the vibration at one point will be the same in the entire output fringe pattern. By subtracting this phase noise from the GMB fringe pattern output, we can obtain a vibration-insensitive measurement system. The shot noise also cannot be eliminated. The best way to compensate for this is the design of a low-noise preamp, and to provide as much gain as possible in the avalanche photodiode, TIED 83. Intensity ripple on the laser beam is usually specified in the laser specs.

The laser being used presently has a ripple of 0.5%. This ripple can be eliminated using an optical negative feedback technique. This technique places a phase modulator in the laser beam followed by a polarizer. One can sense the ripple using a photodetector, and by using this as a negative feedback signal, amplitude-modulate the laser beam with the phase modulator. This arrangement is extremely expensive, but produces a very low-noise "clean" laser beam.

The major difficulty in the free-fall data acquisition is GMB placement. As the GMB exits the transport tube, there is a degree of freedom as to where the GMB will exit. The exit opening is 300 microns in diameter and a typical GMB diameter is 150 microns. Another difficulty is GMB rotation. One way to tell if the GMB is rotating is to observe the fringe pattern output signals. Another method for determining both the GMB placement and rotation is to use high-speed photography. This method can be implemented easily using the signals provided by the detection system.

It should be noted that the speed of the GMB can be read off the oscillogram knowing the GMB diameter. This provides an instantaneous velocity measurement of the GMB during the interferometric measurement. This value of velocity can correlate the measurements of the detection system.

The interferometer system, therefore, works extremely well for targets in free-fall. By restricting the band pass, the output noise could be reduced further. In this experiment, the GMB speed is not constant for every drop, as shown in Chapter 2. As a consequence, the output band-pass filter allows broad-band output to insure detection and recording of the free-falling GMB, despite variations in the GMB speed.

The results shown here are the first to show the broad-band capabilities of the RF ac-interferometer. Most other people use very restricted low-pass output due to a lower phase-modulation frequency and to increase the signal-to-noise ratio. Typical phase objects that have been dealt with in past techniques are slow-phase phenomena, or slowly scanned stationary phase objects. In contrast, the current experiment deals with a phase object that is moving rapidly, and this in turn necessitates the use of both RF phase modulation and broad-band output filtering. With the proper changes, the system could easily achieve a fast scan of stationary phase objects. The high

data bandwidth is very attractive for this type of application. As shown by the results, the RF ac-interferometer can detect and record fast phase objects in real time.

4.6 Conclusions

The present system has room for further improvement. The use of higher modulation frequencies can enable the analysis of even faster phase objects. This can be accomplished by using a solid state phase modulator (KD*P crystal) which can modulate up to 50 MHz. Another technique is to frequency-modulate the laser cavity. This method is attractive because the cavity frequency modulation depends on the mirror velocity, not its frequency. For a 12.5 kHz resonant mirror, the laser output is frequency-modulated at 1 MHz (see [9] for details).

Another improvement would be to interface the system with a computer data acquisition system. This would allow for more flexibility, accurate filtering, extracting of the phase, and plotting the phase data. The phase information would not be available in real time but the added flexibility would compensate for this.

This chapter has shown an RF ac-interferometer which has a high data bandwidth. This bandwidth enables the detection and measurement of fast-phase events, such as a moving GMB. The application of this technique can be implemented onto most types of interferometers. Further improvements to this system can be implemented using a higher power laser, a "cleaner" laser beam with no ripple, and compensation for external vibration and other phase noise sources.

5. CRYOGENIC SYSTEM

5.1 Introduction

The fabrication of uniform cryogenic GMB targets has, until recently, concentrated on techniques capable of interfacing with present implosion experiments. These techniques have produced cryogenic GMBs for implosion. The work being presented is of a cryogenic target fabrication system which achieves the major requirements for future laser fusion power reactors, namely, the ability to fabricate, analyze, and deliver cryogenic targets on a continuous basis.

The freezing method being used in this particular experiment has several advantages over the earlier techniques, [12]-[14]. The most important is that condensing layers inside a free-falling target are not affected by gravitational forces if the target is being accelerated. Another advantage is that the surroundings of the GMB can be tailored to provide any desired temperature. The GMB moves through the system, so each temperature zone can be designed specifically for either cooling or heating. This allows for more efficient chamber design since the chambers do not need to provide both cooling and heating power.

Presented first is a general discussion of the cryogenic fusion fuel layer formation theory and the work that has been done for stationary target implosion experiments. The free-fall method being presented is analyzed in comparison with those stationary methods already developed by others, [12]-[14]. Next, a detailed description is presented of the free-fall cryogenic target fabrication system, including the construction of its different chambers and the total system operation. Presented last are the

results of cryogenic GMB free-fall experiments. This includes the operational conditions of the cryogenic system, such as the temperature and liquid helium flow rates used to produce the cryogenic free-falling targets. The detection and interferometric data are also included to show the characteristics of cryogenic GMB drops in relation to room-temperature results shown earlier.

5.2 Cryogenic Fuel Layer Formation

It is generally recognized that the formation of a uniform cryogenic fuel layer inside a laser fusion target will increase the achievable maximum fuel density during target implosion [15]. Considerable effort has gone into the understanding of the physics of cryogenic layer formation, and has led to several techniques aimed at producing uniform solid and liquid cryogenic layers inside stationary mounted targets [12]-[14]. These techniques have one thing in common; they are all designed to overcome the effects of gravity.

Gravity is the major obstacle to any attempt to condense a uniform fuel layer inside a stationary mounted target. The gravitational force pulls any liquid layer downward, and this force must be negated in some fashion. Since the target is stationary, it does not feel the gravitational acceleration. The liquid in the target is affected by gravity and will flow to the bottom of the target. This deforms the uniformity of any layer condensed unless the target is also freely accelerated by gravity.

Uniform solid layers can be formed using a scheme that has many different experimental approaches. The scheme, usually known as fast isothermal freezing (FIF), forces uniform condensation of the gas inside the GMB and freezes it rapidly before gravity can deform the liquid layer. One of the methods utilizes cold exchange gas to provide an isothermal cooling. Then by

pulse heating the GMB, the frozen fuel inside the GMB will quickly vaporize. The gas will rapidly recondense and freeze before gravitational effects can deform the uniformly condensed layer. The heating methods used are varied and include heater wire [13], laser pulses [14], and a few others. The first successful implosion of a cryogenic target was achieved using the FIF technique [16].

The only way to form a uniform liquid layer inside a stationary GMB is to cool the GMB in a non-uniform fashion. A good example of this type of technique is that of Kim and Rieger [12]. This technique uses a cold gas jet to maintain a non-uniform cooling of the target which dynamically balances the effects of the gravitational force.

After a uniform fuel layer is formed, it must be maintained until the implosion. Since exposure of the cryogenic target to 300 K chamber walls will completely vaporize the fuel layer in only 20 ms [17], one must either thermal-shield the target within the cryogenic chamber, or provide continuous cooling to the target until laser illumination. The technique being implemented at Lawrence Livermore National Laboratory utilizes a retractable shroud which maintains the cryogenic fuel layer. This shroud is retracted at a high speed just before the arrival of the implosion laser pulse.

In any dynamic system the free energy will tend to minimize itself. In a free-fall regime, the absence of the gravitational force leaves only the free surface energy of the liquid for consideration. Minimization of this free surface energy will result in a uniform liquid layer. This allows for the use of a slower target-freezing scheme because the liquid will not migrate, provided the GMB is in an isothermal environment.

The aim of the present free-fall cryogenic system is to manipulate the fusion fuel through its different states (gaseous, liquid, and solid), as the

GMB falls through the free-fall system. The free-fall cryogenic system provides three zones with different functions. The first zone is the launch chamber. This chamber is able to operate at cryogenic temperatures but is presently operated at room temperature. This first zone is where the targets are launched into free fall. The second zone is the room-temperature detection zone, which is the heating source in this free-fall experiment provided that the launch chamber is operated at cryogenic temperatures. The second zone provides the detection capability, discussed in Chapter 3, needed to diagnose the free-falling target. The third zone is the cryogenic freezing chamber. The freezing chamber provides the cooling necessary to quickly freeze the fuel inside the free-falling target. The analysis of the frozen fuel layer occurs in this chamber using the RF ac-interferometer, discussed in Chapter 4.

The layer formed inside the GMB by the cryogenic free-fall system is dependent on the operational techniques and relative temperatures of the three zones. The fusion fuel can be in either a gaseous or cryogenic state prior to launching. Operating the launch chamber at room temperature means that the fusion fuel is in a gaseous state at launching. Regardless of the state of the fuel prior to launching, when the GMB is launched, it is accelerated briefly by the holder microtube's spring. This force will not affect a room-temperature target, but a cryogenic target with a liquid layer will be affected. However, after leaving the holder microtube's mouth, the target and the liquid inside the target will be uniformly accelerated by gravity. The liquid will minimize the available free surface energy and assume a uniformly distributed liquid layer covering the inside surface of the GMB. If the target is launched with a solid layer inside, the solid fuel will remain in that state until the target is heated in the room-temperature zone. It should

be noted that this solid layer will be nonuniform since it was formed under the influence of gravity. The free-falling target, with either a gaseous or condensed layer, will fall out of the launch chamber into the room-temperature detection zone. Upon reaching the room-temperature zone, a cryogenic fuel layer will liquefy or vaporize depending upon the amount of time the target spends in the room-temperature detection zone. A room-temperature target will not be affected. When the falling target leaves the room-temperature detection zone, it immediately encounters the cryogenic freezing chamber. The chamber is cooled using cold high-pressure helium gas. The temperature inside the freezing chamber is maintained below the freezing temperature of the fuel inside the falling GMB. In this case, the fuel is deuterium, so the chamber is maintained at 17 K. The fusion fuel, which leaves the room-temperature zone in the gaseous state, will rapidly condense on the inside surface of the GMB. After condensation, the fuel freezes immediately into a solid layer. The speed of the GMB should not affect the uniform distribution of the condensing liquid inside the GMB unless the GMB is decelerated by aerodynamic forces during its flight. In this case, the rate of cooling will determine the layer uniformity. If the rate is great enough, it should produce an FIF layer with some degree of uniformity. This free-fall system, therefore, can implement both the FIF method and the zero-gravity method for uniform layer formation.

5.3 Cryogenic System Description

5.3.1 Introduction

The system presently being used is shown in Figure 5.1. The system is

Figure 5.1 -- Cryogenic free-fall fabrication system.

divided into three regions: the launch chamber, the room-temperature detection zone, and the cryogenic freezing chamber. These zones provide the temperature gradient needed to freeze the deuterium layer inside of the GMB while it travels downward in the transport microtube.

5.3.2 Launch chamber

The launch chamber serves several purposes. One important task is to provide visual access to the target holder microtube during its insertion into the transport microtube. The entrance of the transport microtube is centered in the launch chamber window. While inserting the GMB holder system, or actually launching a GMB, a high-power microscope is needed to observe the procedures. Since the launch chamber was designed to operate at both cryogenic and room-temperatures, the windows are vacuum-sealed using indium wire between the chamber and the window. The indium provides a flexible seal which is needed if the chamber is operated at cryogenic temperatures.

When operated at cryogenic temperatures, the launch chamber will freeze the fusion fuel in the GMB into a nonuniform layer before launching. The liquid helium, or cold helium gas, is transferred into the chamber via an input line. The input line is at the top of the launch chamber because the bottom of the launch chamber is at room temperature. The quick-disconnect used to vacuum seal the chamber is isolated from the cryogenic chamber by a stainless steel bellows. The input line then travels down into the bottom of a small heat exchanger. This heat exchanger consists of two coaxial tubes. The inner tube is made of OFHC, and the outer tube is made of cupro-nickel. The input helium is forced up into the region between the tubes. The inner copper tube is cooled, and the zone between the tubes serves as a holding reservoir for the cold helium when target launches are made.

The copper tube holds the target transport microtube. The transport microtube is glued into a coaxial position at the bottom opening of the copper tube. This is the only position where the transport microtube is attached. The top opening of the inner copper tube stops just at the start of the launch chamber window. The transport tube continues up into the chamber window aperture, which allows for visual access to the loading and launching procedures.

The flow of liquid helium coolant comes up the input line and down into the heat exchanger. It then goes up the heat exchanger length into the launch chamber. The exhaust helium gas is vented through the exhaust line on the side of the launch chamber. Since the heat exchanger will be cryogenic, a high-vacuum thermal jacket surrounds the input line and cryogenic heat exchanger. The opening to the high-vacuum jacket is shown in the upper right-hand corner near the bottom of the launch chamber window. This jacket insures that the heat exchanger will not warm up due to gaseous conduction.

The entire launch chamber is easily removed out of the vacuum jacket. This helps enormously in the chamber leak-checking and testing. The input line is soft-soldered, so that by unsoldering the input line and loosening the quick-disconnect, the entire launch chamber can be lifted out of the vacuum jacket. The quick-disconnect at the bottom of the bellows is loosened by turning the retainment ring. Removal of the launch chamber must be done with extreme care since the transport microtube is held only at the bottom of the heat exchanger and extends beyond the heat exchanger. As the launch chamber is removed upwards, the transport microtube is extracted out of the cryogenic target-freezing chamber zone and then out of the room-temperature detection zone.

One reverses these steps when inserting the launch chamber. The room-temperature detector aperture has a flared funnel top. This simplifies the insertion of the transport microtube into the bottom half of the system. Carefully, the transport microtube is inserted into the funnel which directs the transport microtube through the detector aperture. The microtube is somewhat flexible but any amount of force on the microtube during insertion will shatter it and necessitate replacing it.

In the present experiment, the launch chamber is operated at room-temperatures (300 K). Future experiments can be done utilizing the cryogenic capabilities of the launch chamber. To completely describe the cryogenic system operation of the two other chambers, we will include discussion of how these chambers function at both of the possible operational temperatures of the launch chamber.

5.3.3 Room-temperature detection chamber

When the launch chamber is operated at cryogenic temperatures, the detection chamber acts both as a heat source and as a target detector. The room-temperature zone utilizes gaseous heat conduction and radiative heating through the transport microtube to heat the GMB glass shell. The heat will conduct inwardly and heat the cryogenic fuel. The transport microtube is held by the liquid-helium-cooled heat exchanger after which the microtube goes into the room-temperature zone. A temperature gradient is established inside the transport microtube. This will cause heat conduction up into the heat exchanger. However, since the transport microtube is so thin (10 micron walls, 300 micron diameter), and since glass is a good insulator, the heat conduction up into the heat exchanger is negligible.

The positioning of the room-temperature zone between the two cryogenic zones has advantages other than providing for a thermal gradient. Since the solid state LED and phototransistor will operate only at the temperatures between -55 C to 125 C, this detection zone has to be near room temperature for the solid state devices to work. The ability to remove the launch chamber easily is a benefit of using a quick-disconnect for vacuum sealing. This quick-disconnect will, however, provide vacuum seal only near room temperature. The placement of the room-temperature zone, therefore, provides for a thermal gradient, detection capability, and simplified vacuum seal and launch chamber removal.

After the transport microtube exits the room-temperature zone, it enters the cryogenic target-freezing chamber. It is in this zone that the fuel layer will be formed inside a GMB target.

When the launch chamber is operated at room-temperature, the detection chamber will provide the detection capability needed for measuring the target speed and position. The temperature gradient between the detection chamber and the freezing chamber is the same regardless of the launch chamber temperature.

5.3.4 Cryogenic target-freezing chamber

This chamber provides the thermal gradient required for GMB freezing or refreezing depending on the launch chamber temperature. It is constructed of OFHC for good thermal conduction. The chamber is isolated from the room-temperature zone and the vacuum jacket by stainless steel bellows. Inside of the bellows isolating the freezing chamber from the room-temperature zone is an OFHC precool cylinder. This is a cold finger connected to the

freezing chamber. The finger cools, via gaseous and contact conduction, the transport microtube section immediately following the room-temperature zone. This provides the high-temperature gradient needed to quickly freeze the fusion fuel (e.g., deuterium) inside the GMB.

The liquid helium goes into the upper left-hand side of the freezing chamber and flows into the two side channels inside the chamber. The middle channel is the target free-fall channel. This is where the target exits from the transport microtube into the interferometer aperture. These three channels are recombined at the bottom of the chamber, and the helium is exhausted through either the bottom exhaust or a side exhaust. Presently, the side exhaust is not being used. The channels provide for even cooling of the entire freezing chamber. The coolant flow rate is controlled by the exhaust flow rate at the bottom outlet.

Access into the chamber is provided by windows mounted on the chamber. The windows are mounted on specially designed stainless steel inserts which are silver-soldered into the freezing chamber. The windows are mounted on these inserts with indium wire as mentioned above. There are two sets of windows, one set for the reference beam of the interferometer and the other set for the diagnostic beam of the interferometer.

The removal and insertion of the target-freezing chamber are similar to that for the launch chamber. Several tasks must be done before the chamber can be removed. The micrometer translators, which position the target-freezing chamber inside the vacuum jacket, must be backed out of their mounts on the chamber. The input liquid helium line can be easily disconnected due to the use of a specially modified quick-disconnect. The modified quick-disconnect utilizes an indium O-ring which maintains a vacuum seal at cryogenic temperatures. The bottom exhaust line uses a

quick-disconnect to seal the high-vacuum jacket, and simply loosening the retainment ring will allow for the removal of the target-freezing chamber, provided that the other tasks are already done. The entire cryogenic system can then be completely removed in two pieces: the cryogenic launch chamber with the transport microtube, and the freezing chamber with the room-temperature detection zone.

The temperature measurement of the cryogenic chambers can be accomplished in two ways. The easiest involves mounting a silicon thermistor onto the chamber. This thermistor, when used with a temperature measurement and controller system, like the Lake Shore Cryogenics Inc. model DRC 80C, can measure and control the temperature of the chamber to ± 0.1 K. The second method employs thermocouple junctions soldered onto the chamber. This only measures the temperature of the chamber and does not provide any feedback control. Both methods can be employed, but the first is obviously preferred due to the controlling ability.

5.4 Cryogenic System Operation

The temperature gradient in time experienced by the GMB is determined by the speed of the GMB through the different zones. The speed is affected by the relative pressure difference at the two ends of the transport microtube, plus the size of the GMB, and other factors discussed in Chapter 2. The system can be operated in two different modes, which allow different target speeds in the cryogenic transport system. The first is the free-fall mode. The free-fall mode is defined as any target uniformly accelerated by gravity. This can happen at any target speed. The other mode uses aerodynamic acceleration to move the target rapidly through the system. This mode is

characterized by uniform aerodynamic acceleration of the target. The liquid inside the target, however, is not accelerated at the same acceleration, and so deforms.

The steps for operating the system in a free-fall mode are straightforward. If the target needs to be cryogenic prior to launching, the liquid helium is flowed through both the launch and freezing chambers. Once the chambers have attained the proper temperature range, 10 K for formation of a solid fuel layer and 20 K-30 K for a liquid layer, the system is ready for the target injection. One GMB is launched into the transport microtube. As the GMB nears the coldest part of the launch chamber, the end of the heat exchanger, the gas (or liquid, or solid) in the GMB (deuterium for the current experiment) freezes or liquefies depending on its temperature. The GMB then exits the heat exchanger and travels into the room-temperature zone. The detector system will detect the GMB as it falls through this zone. The deuterium condensate will vaporize. The GMB then enters the freezing chamber zone where the temperature gradient refreezes the deuterium.

Operation of the system with the launch chamber at room temperature will eliminate the heating action of the detection chamber. The target temperature just before entering the freezing chamber will be at 300 K. When the target enters the freezing chamber, the target will cool rapidly causing condensation and then solidification of the gaseous fusion fuel.

The aerodynamic forces acting on the falling target, along with the temperature gradient, determine the symmetry of the layer formed. The cryogenic system operation mode will establish the forces that will be present during the experiment. The force of gravity is always present. In the free-fall operation mode, discussed above, gravity can be neglected in the condensation process, provided the target has not reached terminal velocity.

When the GMB reaches terminal velocity, it is no longer accelerating. At terminal velocity, the target can not be considered to be in a zero-gravity environment. Any cryogenic layer formed while the target is at terminal velocity will be nonuniform. This is because the condensing fuel is accelerated by gravity while the target is moving at a constant speed. The GMB experiences aerodynamic forces if there is a pressure differential between the launch and freezing chambers. Then the target will be accelerated until it reaches a terminal velocity. As before, when the target reaches terminal velocity, whether in a gas flow or not, the condensation process is affected by gravity. If the target is aerodynamically accelerating, which means it does not reach terminal velocity, then there is a constant force acting in the same direction as gravity. It is in this regime that the temperature gradient in time becomes important. In the aerodynamic acceleration mode, the temperature gradient in time increases, due to the fact that the GMB is moving rapidly from one zone to the next. This provides a faster refreezing cycle which helps the formation of a more uniform layer, despite the presence of accelerating aerodynamic forces. This is directly analogous to the FIF fabrication method, except that in the present system the accelerating force which can deform the condensing liquid is not gravity, but aerodynamic forces. The major difference is that the aerodynamic forces can aid the formation of a uniform layer by increasing the refreezing rate, which gravity might not do.

After the GMB has been analyzed by the diagnostics, either the RF ac-interferometer or high-speed photography, the cryogenic transport system is ready for another launch. The launching procedure is then repeated until all of the GMB's inside the holder microtube are injected into the system. Choosing one of the two possible operating modes gives the operator flexibility to compensate for other experimental problems. Pressurizing the

launch chamber relative to the target-freezing chamber helps to alleviate the no-drop condition (i.e., the GMB getting stuck inside the transport microtube) Which sometimes occurs after the target launching.

5.5 Results

The cryogenic system design gives the operator many choices of how the experiment can be run. In order to prevent the no-drop condition, the cryogenic system is presently operated in a gas flow free-fall mode. The launch chamber is pressurized using ultra-pure helium gas which is cold-trapped before entering the launch chamber. The cold trap insures that the transport microtube will not freeze impurities at the point where the microtube enters the cryogenic freezing chamber. The gas pressure in the launch chamber is maintained above the exhaust pressure of the freezing chamber. This establishes a gas flow through the transport microtube. This gas flow cools rapidly as it enters the freezing chamber and as the gas cools its density will increase. The increased gas density will slow the target down and in some cases it will cause a no-drop condition. To prevent a no-drop condition, the gas flow must be fast enough to aid the target's free fall. This will result in a higher target free-fall speed, when compared to the room-temperature free-fall drops, but the prevention of the no-drop condition is more important than the relative target free-fall speed.

The results presented in Figures 5.2 and 5.3 are the detection and interferometric data gathered for two cryogenic free-fall drops. The two targets are identical 160 micron diameter GMBs with 10 micron glass shells. For both of the target drops, the freezing chamber was maintained at 17 K.

(a)

(b)

Figure 5.2 -- Cryogenic free-falling GMB detection and interference output. (a) detection system output; (b) RF ac-interferometer output.

(a)

(b)

Figure 5.3 -- Cryogenic free-falling GMB detection and interference output. (a) detection system output; (b) RF ac-interferometer output.

Figure 5.2(a) and Figure 5.3(a) are the output pulses of the detection system. The smaller amplitude trace in both oscillograms is the first detection pulse at the room-temperature detection aperture. This first detection pulse shows no changes when compared to the room-temperature free-fall drops presented in Chapter 3. The time duration of the pulse is decreased due to the gas flow inside the transport microtube. The target in Figure 5.2(a) had a speed of 2.27 cm/s at the first detection aperture. The target in Figure 5.3(a) had a speed of 3.41 cm/s.

The time the target spends inside the cryogenic freezing chamber is given by the time the target spends between the two detectors. This time is displayed on the digital counter, mentioned in Chapter 3, which gives the average speed of the target in between the two detectors. The target in Figure 5.2 was inside the freezing chamber for 130.0 ms, and the target in Figure 5.3 was inside the freezing chamber for 99.8 ms. This results in an average speed of 53.8 cm/s for Figure 5.2 and 70.1 cm/s for Figure 5.3. The amount of time the target spends inside the freezing chamber is significant in determining whether the fuel inside the target is in a cryogenic state (liquid or solid). Previous work [17] has shown that the cooling of the glass shell is the slowest process in terms of thermal time response. Once the glass shell has reached cryogenic temperatures, the fuel inside the target condenses rapidly (in less than 1.0 ms). The times spent in the freezing chamber for the targets in Figures 5.2 and 5.3 are more than sufficient to condense a layer inside the free-falling targets. This evaluation is confirmed by the second detection pulse.

The large amplitude traces in Figures 5.2 and 5.3 represent the second detection pulse. The pulse shows the amount of time each target spends in the second detection aperture. The pulse shape is significantly different from

the pulse obtained in the room-temperature free-fall drops shown in Chapter 3. The self-focusing of the GMB is no longer present. This means that the GMB optical transmission is less at cryogenic temperatures than it is at room temperature. The only reasonable explanation for the decrease in optical transmission is the presence of a cryogenic layer inside the GMB. The second detector does, therefore, provide a quick evaluation of the GMB temperature just before the target moves into the RF ac-interferometer aperture.

The speed of each GMB in Figures 5.2 and 5.3, measured at the second detector, is 48.9 cm/s for Figure 5.2 and 65.0 cm/s for Figure 5.3. Comparison of each target's speed at the two detectors shows the targets slowing down. This deceleration is due to the combined effects of the decreasing transport microtube diameter and the increasing gas density. Both targets slow down approximately 5.0 times when traveling from the first detector to the second detector.

The interferometric analysis of both free-falling targets are shown in Figures 5.2(b) and 5.3(b). The oscillograms are the output of the fringe pattern intensity (top trace- $\cos\delta$) and the filtered output of the demodulation circuit (bottom trace- $\sin\delta$). Due to the higher speeds of the cryogenic GMB free-fall drops, the output filter of the demodulation circuit attenuates the higher frequencies of the fringe pattern. The intensity ($\cos\delta$) output does have sufficient bandwidth to allow some analysis of the free-falling cryogenic GMB. However, the uncertainty of the target's position as it exits the transport microtube makes detailed analysis of the cryogenic layer difficult. In both oscillograms, the liquid has formed at the bottom of the GMB (the leading edge). This shows up as many fringes on the leading edge with the nonuniformity showing on the trailing edge where the fringe pattern becomes irregular. The interferometric asymmetry observed does show that the layer

was formed while the target was at terminal velocity. At terminal velocity, the target can not accelerate since the viscous drag force negates the gravitational force. As mentioned earlier, when the target is at terminal velocity, the condensate inside the GMB is deformed by the gravitational acceleration. Therefore, the interferometric data show the expected nonuniform layer which was condensed while the target was at terminal velocity.

6. CONCLUSIONS AND SUGGESTIONS FOR FUTURE EXPERIMENTS

The work presented in Chapters 2 through 5 shows significant advances in all of the critical aspects required for continuous, non-contact fabrication of cryogenic targets. The work also establishes a basis for future work in the field, showing the need for flexibility and integration to reduce the overall system complexity.

The combined difficulties of GMB target handling, transport, and free-fall cryogenic fabrication are tremendous. The extremely small size of the GMB targets and tendency to collect contamination (dirt) make target handling a tedious and meticulous task. The useable forces that can confine and transport GMB targets are threefold: electrostatic, aerodynamic, and gravitational.

The forces used in this work to confine and transport GMB targets are aerodynamic and gravitational. Cooling the moving target rapidly to 17 K requires a tremendous temperature gradient. The requirements of cryogenic experimentation specify a high vacuum environment for insulation. Accurately measuring cryogenic layers inside a GMB can be realized in only one way, laser interferometry. Laser interferometry requires ultra-stable tables, precise alignment, and in this case, microscopic optics. When all these difficulties are present at one time, the system must be integrated enough so that satisfying the experimental requirements does not make the system difficult to operate.

Chapter 2 introduces new target handling, holding, launching, and transporting techniques needed to fabricate free-falling cryogenic targets. Specifically, the target holder system enables the experimenter to choose individual targets to undergo free-fall cryogenic fabrication, and hold them until each target is launched into the confining transport microtube. This

holder system is the first system capable of holding and then launching 160 micron GMB targets into free fall on a continuous basis.

Also presented in Chapter 2 is a successful cryogenic transport system, needed for guiding and confining a free-falling target. The aerodynamic force and wall effects are dominant in dictating the target's motion. The use of a transparent glass transport microtube enables the transportation of the target through different temperature chambers, each of which can be designed for a specific purpose (launching, detecting, and freezing). This feature is particularly useful since it simplifies chamber design and operation.

Chapter 3 presents a detection system which reliably and simply measures the speed of a free-falling target in a completely non-contact fashion. Taking advantage of the transparent transport microtube, the optical detectors sense the moving target through the microtube. The detection system interfaces with the requirements of a cryogenic, high-vacuum environment. This system is capable of measuring any attainable target speed, and will notify the experimenter in the event of a no-drop condition (when the target gets stuck in the transport microtube). The detection system also provides the triggering for the interferometric analysis system.

Chapter 4 presents the RF ac-interferometry. This technique measures the symmetry of free-falling cryogenic targets in real time. The results presented show an increase in the data bandwidth of over 50 times when compared to previous systems. The RF ac-interferometer also represents a significant simplification over previous systems. The phase resolution is not as sensitive as other phase-measuring systems, but the increase in data bandwidth is critical in measuring moving 160 micron GMB targets.

Chapter 5 presents the cryogenic system used to fabricate free-falling cryogenic targets. Although the cryogenic fuel layers inside the targets were

not uniform, this system shows the ability to fabricate cryogenic targets on a continuous basis. Producing free-falling cryogenic targets demonstrates, for the first time, the ability to confine and produce cryogenic targets in a non-contact fashion. The cryogenic system is smaller and easier to remove and modify than any of the previous heat exchanger designs. The smaller size increases the temperature response time, while using less liquid helium to attain and maintain the cryogenic temperatures.

Improvements in the RF ac-interferometer could improve the system's performance to the state-of-the-art in phase resolution, besides offering the advantages of real-time analysis, video bandwidths, and the monitoring of the system phase noise (vibration, air currents). This would permit precise measurements in high-vibration environments. The use of UHF phase-modulation frequencies would allow for two-dimensional maps of moving laser fusion targets. The application of this technique is not restrained to measuring fusion targets but can measure any transparent or reflective microscopic objects.

Future experiments will concentrate on production of uniform cryogenic layers. The present system has the capability to produce a uniform layer inside the target. Freezing the targets prior to launching, utilizing the room-temperature detector as a heat source, and quickly refreezing the GMB will produce uniform layers. By controlling the target's free-fall speed through the system, the freeze-vaporize-refreeze cycle time can be optimized for rapid uniform condensation and solidification.

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