CHARGED PARTICLE RESEARCH LABORATORY REPORT NO. 1-81

INVESTIGATION OF METHODS FOR FABRICATING,
CHARACTERIZING, AND TRANSPORTING CRYOGENIC
INERTIAL-CONFINEMENT-FUSION TARGETS

SCIENTIFIC REPORT

BY

JAMES J. FANNING

AND

KYEKYOON KIM

MASTER

CHARGED PARTICLE RESEARCH LABORATORY
DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS 61801

DISCLAIMER

JANUARY 1981

NOTICE

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-ENG-48.

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ABSTRACT

The objective of this work is to investigate methods for fabricating, characterizing and transporting cryogenic inertial confinement fusion targets on a continuous basis. A microprocessor-based data acquisition system has been built that converts a complete target image to digital data, which are then analyzed by automated software procedures. The low temperatures required to freeze the hydrogen isotopes contained in a target is provided by a cryogenic cold chamber capable of attaining 15 K. A new method for target manipulation and positioning is studied that employs molecular gas beams to levitate a target and an electrostatic quadrupole structure to provide for its lateral containment. Since the electrostatic target-positioning scheme requires that the targets be charged, preliminary investigation has been carried out for a target-charging mechanism based on ion-bombardment.

ACKNOWLEDGMENTS

We would like to thank Harry Rieger and Matt Murphy for their valuable assistance during the course of this work. We would also like to thank Dr. C. D. Hendricks and Dr. T. P. Bernat of Lawrence Livermore National Laboratory (LLNL) for their support and interest in this work.

This work was financially supported by the USDOE through the LLNL Subcontract 8320003.

TABLE OF CONTENTS

	Page
LIST OF FIGURES	iv
LIST OF TABLES	vi
1. INTRODUCTION	1
2. MICROPROCESSOR-CONTROLLED DATA ACQUISITION SYSTEM	5
2.1 Introduction	5
2.2 System Overview	8
2.3 Video Acquisition Circuitry	14
3. THEORETICAL RAY-TRACING AND EXPERIMENTAL ANALYSIS	33
3.1 Introduction	33
3.2 Cryogenic Cooling System	33
3.3 Laser Interferometer	35
3.4 Theoretical Ray-Tracing Procedure and Results	38
3.5 Experimental Results	48
4. TARGET POSITIONING METHODS - QUADRUPOLE AND MOLECULAR BEAM	54
4.1 Introduction	54
4.2 Gas Levitation	58
4.3 Electrostatic Centering	65
4.4 Target Charging	72
5. CONCLUSIONS AND SUGGESTIONS FOR FUTURE EXPERIMENTS	77
REFERENCES	80
APPENDIX I. LAYOUT AND INTEGRATED CIRCUIT DEFINITIONS FOR DATA ACQUISITION BOARD	82

LIST OF FIGURES

Figure	Page
2.1 - Microprocessor-controlled data acquisition system . .	6
2.2 - Microprocessor system functional diagram	7
2.3 - Memory map for data acquisition system	9
2.4 - ROM interfacing circuitry to S-100 bus	11
2.5 - Serial device select circuit	12
2.6 - System hook-up diagram	15
2.7 - Example of data acquisition system output on oscillo- scope displaying line 128 and software selected sample points	16
2.8 - Picture of entire experimental setup	16
2.9 - Standard video format	17
2.10- Video acquisition board block diagram	20
2.11- Variable cutoff low-pass filter circuit and selection guide	22
2.12- Analog-to-digital circuit diagram. Note that IC definitions may be found in Appendix I	23
2.13- Timing diagrams	26
3.1 - Diagram of cryogenic cold chamber	34
3.2 - Layout of laser interferometer and associated optics.	36
3.3 - Typical outputs from laser interferometer	37
3.4 - Ray-tracing model	39
3.5 - Ray-tracing output showing results of changing target glass shell thickness	43
3.6 - Ray-tracing output showing results of changing target room-temperature gas-fill density	43
3.7 - Ray-tracing output showing results of changing target temperature	44

Figure	Page
3.8 - Ray-tracing output showing results of changing DT liquid layer thickness at fixed temperature . . .	44
3.9 - More precise ray-tracing model	47
3.10- Interference micrographs of a target cooling sequence	50
3.11- Data acquisition system's output for interference micrographs shown in Figures 3.10 (a) through (f) . .	51
3.12- Interpreted data from data acquisition system's out- put shown in Figures 3.11 (a) through (c)	52
4.1 - Examples of levitation structures with no lateral visibility	53
4.2 - Example of quadrupole levitation structure showing total lateral visibility. Target shown is 140 micron in diameter	55
4.3 - Cryogenic levitation system	57
4.4 - Types of molecular reflections	60
4.5 - Geometry for calculation of molecular beam levitation	60
4.6 - Quadrupole geometry and drive circuitry	66
4.7 - Quadrupole with additional DC biasing	66
4.8 - Stability diagram for the Mathieu equations	68
4.9 - First (lowest) stability region of Figure 4.8	68
4.10- Reproduction from real-time video tape recording showing centering capabilities of quadrupole	71
4.11- Interferometer output of target on collimated hole structure in quadrupole setup	71
4.12- Theoretical charging limits as a function of dielectric constants	74
I.1 - Integrated circuit layout for data acquisition board	84
I.2 - Schematic diagram for data acquisition board	85

LIST OF TABLES

Table	Page
2.1 - FUNCTIONAL ASSIGNMENTS FOR PORT 3BH	27
2.2 - SAMPLE DIGITIZING PROGRAM	29
2.3 - HARDWARE INITIATED DMA	31
2.4 - SOFTWARE INITIATED DMA	32
4.1 - OPERATIONAL STABILITY CONDITIONS FOR QUADRUPOLE . . .	70
I.1 - INTEGRATED CIRCUIT NUMBER DEFINITIONS AND DESCRIPTIONS	82

1. INTRODUCTION

Nuclear fusion, the basic energy process of the stars, is considered to be a very vital energy source of the future [1]. Controlled fusion offers a potentially inexhaustible energy source in that its fuel will most likely be deuterium, an abundant heavy isotope of hydrogen that is easily separated from seawater. The difficulties in harnessing this energy are two-fold. First, the light nuclei fuel must be heated to the thermonuclear ignition temperature which is between 50 and 100 million degrees Kelvin, depending on the fuel. Second, once the fuel is ignited, the resulting plasma must be contained long enough for a substantial number of nuclei to react. The latter condition must guarantee that more energy is created in the burning process than what was used up in originally igniting the fuel. Only then will the fusion process become a viable candidate for future power production.

The original approach to controlled fusion required magnetic bottles to confine the plasma. An alternative to magnetic confinement is inertial confinement. Inertial confinement fusion (ICF) employs the use of a very high-power laser- or particle-beam to instantaneously ionize a pellet of fuel and contain the plasma by the resulting inward inertia. The future success of the ICF program in terms of its scientific and economic feasibility depends heavily on several factors.

The first is to develop a very high-peak-power laser- or particle-beam source. At this time the theory of scaling these sources to high power and to high repetition rates is fairly well understood [2]. In fact, construction has already begun on a half megajoule laser by Lawrence Livermore Laboratory. This NOVA facility is expected to be in operation by 1985 and should provide the first opportunity for scientific "breakeven." Breakeven

implies that as much thermonuclear energy is given off as was taken to initiate the reaction.

The second factor is production of precision high-gain fuel pellets or targets. The targets fall into two categories [2]. The first type of target developed, known as an "exploding-pusher" target, generally consists of a single glass shell microballoon typically 50 to 300 microns in diameter of shell thickness ranging from 1 to 10 microns. These targets contain high-pressure deuterium-tritium (DT) or simply deuterium gas, the fill pressure at room temperature being anywhere from 50 to 750 atmospheres. The second type of target, known as an "ablative-compression" or "isentropic-compression" target, is usually about the same size as an "exploding pusher" target but has a thicker shell or, in some cases, multiple shells.

In the case of the exploding pusher target, the target is symmetrically illuminated from all sides by a short pulse of energy. The incident energy causes the glass shell to heat rapidly and explode inward and outward. The inward directed mass compresses the DT fuel and raises its temperature to ignition conditions. For optimum burn, these targets must be produced with a high degree of sphericity. In addition, the glass shell thickness must be very uniform in that non-uniformities of over one percent can greatly reduce the burn efficiency.

For increased compression efficiency, it is desirable to liquefy or freeze the DT into a concentric hollow sphere on the inside wall of the glass shell, thereby leading to an isentropic type target. This eliminates the back pressure developed when the target is simply filled with gas. Again the pellet fuel is imploded by the momentum reaction, but, in this case, is more effective in transferring larger amounts of inward momentum to the fuel. Therefore, much higher compressed densities are achieved which lead to greater

burn efficiencies and overall higher target gains. These types of targets, however, complicate the fabrication process further in that the system must have cryogenic capabilities, and the uniformity requirements of the liquid or frozen DT layer are as stringent as those for the glass shell. These requirements of the targets in terms of sphericity and thickness uniformities also suggest a strong need for an accurate diagnostic system.

A third factor important in the progress of the ICF program is development of a reliable automated target handling system capable of delivering the targets to a precise location at the proper moment inside the reactor chamber. Of a more immediate concern, however, is development of a target manipulation scheme that would allow target fabrication, especially cryogenic DT layer formation, and target diagnostics to proceed without having to physically contact the target. Development of this scheme would pave the way later to a target-reactor delivery system. Recent studies [3] have shown that the use of electrically charged targets in conjunction with electrostatic containment structures might offer a practical solution to this problem.

There are many other factors that are important to advancement of the ICF program. However, many of these are too complicated or involve large scale facilities. Therefore, this work will concentrate on the second and third factors previously mentioned. Chapter 2 describes a microprocessor-based data acquisition system capable of digitizing a target image from a standard TV camera and storing this digital information in its memory. In Chapter 3, a cryogenic target fabrication system is described that is capable of providing an isothermally cold environment for the target. For diagnostics, a laser interferometer setup that is interfaced to a video camera is described. In addition, the chapter presents a theoretical analysis of various target configurations and an interpretative procedure for analyzing the digitized

results obtained by the data acquisition system. The next chapter (Chapter 4) describes a new method of target handling that combines a gas levitation technique and an electrostatic positioning system. The final chapter, Chapter 5, contains concluding remarks and suggestions for future work.

2. MICROPROCESSOR-CONTROLLED DATA ACQUISITION SYSTEM

2.1 Introduction

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

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

The system developed is based on the popular Intel 8080A microprocessor and the standard S-100 bus system (see Figure 2.2), which allow system expansion through addition of easily available memory and interface boards at moderate costs. Through standardization, the system also allowed implementation of such "canned" software packages as the Digital Research CP/M operating system [4] and accompanying EBASIC programming language. As a consequence, it was relatively easy to construct new acquisition programs directly in a high level language or machine code.

Figure 2.1 - Microprocessor-controlled data acquisition system.

Figure 2.2 - Microprocessor system functional diagram.

2.2 System Overview

2.2.1 Central processing unit

The heart of the DAS is the Intel 8080A Central Processing Unit (CPU) [5]. The CPU unifies the system as it controls most functions performed by other system components as well as data and address transfers on the two tristate bus lines. Basically, it fetches instructions from memory, decodes their binary contents and executes them. The CPU also responds to several external signals, such as interrupts and direct memory access (DMA) requests. In the latter case, the CPU surrenders bus control activities to the DMA controller unit. The DMA is an important element for high speed video data acquisition - more on this later. The CPU and its supporting hardware are all contained on a single card which plugs into the S-100 master bus system. See Appendix I for card layout and complete circuit diagram.

2.2.2 Memory

Working in conjunction with the CPU is the memory. Three types of memory are used in this system. One type, the Read Only Memory (ROM), is used primarily for permanent program storage. Programs used in power-up initialization (Address locations F000H-F300H) and cold starting of the floppy disk system (E000H-E200H) are found here. The "H" indicates that hexadecimal base was used. The complete memory map is found in Figure 2.3.

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

Figure 2.3 - Memory map for data acquisition system.

scratch-pad purposes for the monitor and disk controller. This is found at address locations FFC0H-FFFFH and E200H-E300H, respectively.

The ROM and RAM, with addition of some simple back-up, hardware can directly be implemented on the S-100 bus. An example of this interfacing with ROM is shown schematically in Figure 2.4. The ROM's in this circuit house the programs used in operating the serial port in TTY format. They also house the data transfer programs used to facilitate the communication between the microprocessor and the main computer.

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

2.2.3 Communication interface

Interfacing to the outside world is accomplished through several devices. The parallel data links are handled through universal input/output ports. They are located at OUTPUT PORTS 4,5,6,7 and INPUT PORTS 4,5,6,7, and are Transistor-Transistor Logic (TTL) compatible signal levels.

The serial links are handled through a Universal Asynchronous Receiver Transmitter (UART) and a serial device select circuit shown in Figure 2.5. PORT 0,1 is wired for a selectable baud rate and free running mode. PORT 0 is

Figure 2.4 - ROM interfacing circuitry to S-100 bus.

Figure 2.5 - Serial device select circuit.

input status only and PORT 1 is the bidirectional data port. This port is usually connected to the solely dedicated CRT terminal and operated at the maximum 9.6K baud rate. PORT 2,3 is wired for only 300 baud and full handshake capabilities. This allows the port to be used for interfacing to the modulator-demodulator (modem) which links the microprocessor into the timesharing system of the main computer. It also allows communication to the on-line plotter and hard copier. PORT 2 is for input status only and PORT 3 is the bidirectional data port. Special drivers are contained in ROM at F800H to F900H to facilitate use of this serial port.

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

2.2.4 Video interface

The video interface portion of the acquisition system is a combination of I/O ports, counters, discrete logic, analog-to-digital conversion circuitry, and a DMA controller. It is by far the most complicated board in the microprocessor system. The following section deals specifically with the operation of this board. Essentially, it accepts software code words via ports 38H through 3BH and sets up a specific digitizing format for the video information. Data destination is then programmed via software into the DMA controller. Upon execution of a port select 3BH, the DMA controller assumes bus control and begins transferring digitized data at the programmed sample rate into the RAM. This process continues until all the data are taken according to the preset format or a DMA terminal count is reached. At termination, the DMA controller surrenders the S-100 bus back to the 8080A CPU and normal programming may continue. Usually the programming after a DMA

involves loading the data into a disk file.

The general hook-up to the microprocessor system is shown in Figure 2.6. With this hook-up the user may observe the complete video image on the TV monitor. In addition, through the use of the line select switches individual video lines may be observed on the oscilloscope. (See Figure 2.7). Also displayed on the scope is the software programmable sample points. Details of these signals are presented in Sections 2.3.1 and 2.3.3, respectively. Communication interface connections (Figure 2.5) are made to the back panel of the microprocessor. The DAS as it appears hooked up to the entire cryogenic system is pictured in Figure 2.8.

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

2.3 Video Acquisition Circuitry

2.3.1 Background

As previously mentioned, the video interface board drastically simplifies the digitizing process and performs its task at a maximum possible speed of 1.25M byte per second. All this speed and convenience, however, were at the cost of the hardware implementation. In the following sections the circuit operation of this board is explained. Before venturing into the board itself, it will be helpful to first look at the standard video format.

A standard black and white television picture is formed through an interlaced scanning procedure (see Figure 2.9(a)). The raster scan begins at position 1 in Figure 2.9(a) and scans slightly downward and across the page. In the case of a television picture, the trace is an electron beam that is amplitude-modulated with picture information. As it strikes a phosphorous surface, the electron beam recreates the picture. For a vidicon tube (camera)

Figure 2.6 - System hook-up diagram.

Figure 2.7 - Example of data acquisition system output on oscilloscope displaying line 129 and software selected sample points.

Figure 2.8 - Picture of entire experimental setup.

Figure 2.9 - Standard video format. (a) Interlaced scanning for standard black and white television picture; (b) Page-detailed composite analog video signal; (c) Line-detailed composite analog video signal.

the trace is a scanning process where local light intensity along the trace is converted into an electrical signal. When the scan reaches the right side of the page, the writing or reading process is blanked out and the scan retraces back to the left side of the screen. This process continues until half way through the 263rd line. At point 2 in Figure 2.9(a) the trace is blanked and repositioned back to the top of the page and the scan lines continued. The next 263 and a half lines, however, lie halfway between the first 263 and a half lines. Thus a 2-to-1 interlace is formed at a maximum of 526 lines of resolution per picture. In the following documentation, lines 0 to 263 1/2 will be referred to as page A and lines 263 1/2 to 526 as page B.

The raster scan is produced electrically through the use of a composite video signal. As shown in Figures 2.9(b) and 2.9(c), the composite video signal essentially contains three distinct signals. Two are used for synchronizing and blanking in the vertical and horizontal positions. The third, of course, is the analog video picture information.

The long 16.7 millisecond vertical sync pulse (Figure 2.9(b)) signals the scanning device to begin at the top of a new page. Subsequent horizontal pulses (approximately 64 microseconds apart) indicate a new line. The voltage variation directly following each horizontal sync pulse is the analog information for that line. From Figure 2.9(c) a voltage of 0.75 volts corresponds to a black level with increasing brightness up to a white level at 2 volts. By counting the number of horizontal sync pulses following a vert sync, it is possible to keep track of the actual line number in the scan. Circuitry can also be set up to detect the half line at 263 and thus differentiate between A and B pages.

The common method of digitizing video pictures is to allow the converter to continually run and effectively digitize the entire composite signal from

one page to the next. This procedure requires very large memory storage and very high sample rates in order to reproduce the sharp transitions found around the sync pulses. This method also suffers from complications in reproducing single line cross sections which will be very important in target fringe pattern analysis. (Typical example shown in Figure 2.7.)

A more conservative way to use the memory and always keep track of the line location is to synchronize the digitizer to the horizontal sync pulse at the beginning of each line. The hardware developed here allows the choice of an initial offset from the horizontal pulse to the first sample point. In addition, selection of the time to the next sample point and the total number of sample points in the line, may also be made. In this way, only areas of interest along the line can be sampled and stored. Additional flexibility is incorporated by allowing the choice of digitizing either a single line (switch programmable), a single page, or the complete interlaced picture.

The board is basically divided up into three sections as shown in Figure 2.10. Section 1 inputs the analog video signal and runs it through a variable cutoff 4-pole active low-pass filter, and then through a sample-and-hold into an eight bit successive-approximation analog-to-digital (A/D) converter. Section 2 accepts the line and page sync signals from the camera and handles formatting the video signal for the digitizer. Its tasks include: counting lines; differentiating between A and B pages; counting the initial offset, increments and total number of samples per line; and finally combining all these with the single line or whole page select to derive a trigger sequence for the digitizer. Section 3 handles interfacing back to the S-100 bus and manages memory access during data acquisition. With exception of the first section the circuitry is software programmable.

Figure 2.10 - Video acquisition board block diagram.

The board has a 20 MHz crystal oscillator to synchronize most of the operations. The A/D unit runs right off the oscillator at the full 20 MHz rate. The video formatter and DMA controller, however, run at a slower 5 MHz rate. The A,B page differentiation is clocked at 250 KHz.

Power to the circuitry is provided by distributed voltage regulators throughout the board, thus minimizing digital cross-talk and other noise problems.

2.3.2 Analog section

The analog section of the board (depicted in block form as Section 1 in Figure 2.10) consists of a variable cutoff four-pole active low-pass filter (shown in Figure 2.11), a sample-and-hold circuit, buffers, and an A/D converter. The latter three elements are shown in Figure 2.12. All integrated circuit references in this section refer to Figures 2.11 and 2.12, and are specified by the letters 'IC' followed by the appropriate number.

The variable filter was necessary in order to ensure flexibility in choosing the sample rate. Nyquist criteria state that in order to faithfully reproduce a signal it must be sampled at a rate at least twice its highest frequency component. Once a sample rate has been chosen, the filter cutoff is selected that assures these criteria are met. The available 3dB cutoffs are shown in Figure 2.11 with the associated switch settings and circuit components. The circuit shown in Figure 2.11 uses two 2-pole Sallen-Key active low-pass filters in cascade form. The first op amp is a first voltage follower used for impedance matching to the filter circuit. After proper filtering the signal is accessible for inspection at a BNC output on the front panel.

The filtered signal is now fed to a shaping circuit on the main board as shown in Figure 2.12. The signal which is AC-coupled throughout the circuitry

Figure 2.11 - Variable cutoff low-pass filter circuit and selection guide.

Figure 2.12 - Analog-to-digital circuit diagram. Note that IC definitions may be found in Appendix I.

is attenuated four-fold (-6dB) and AC-clamped about a -.25 volt DC level. This is necessary for proper ranging in the A/D converter. The signal is then buffered by IC J1, and sampled and held at the selected sample rate by IC J2. Control inputs to the sample-and-hold unit are at Emitter Coupled Logic (ECL) levels and are supplied by a TTL-to-ECL converter, IC J3. Note that the start-to-convert signal is first clock synchronized through two D-latches (IC L1); this allows great freedom in what signals can be used to start the conversion. Any asynchronous logical "1" to logical "0" transition convert pulse will trigger the digitizer properly.

Once the signal is sampled and held, it is buffered by a voltage follower (IC L3) and fed to the A/D converter (IC L4). The eight bit digital conversion is then sent to a data latch IC N4 (see Figure I.2 in Appendix I) where it can be accessed by the internal data bus. The only other support chip of this group is another voltage follower, IC L2, which supplies a voltage reference source for the A/D unit.

2.3.3 Video formatting section

The video formatting section (Section 2, Figure 2.10) handles the programmable circuitry needed to form a complete convert pulse sequence for the digitizer. Line and page sync signals from the camera are needed as inputs. Specific operations and programming are described below. All IC's in this section are referenced to Figure I.2 in Appendix I.

The line counter consists of IC's Z22 and Z1 programmable down counters. They are loaded on a page sync to whatever the line select switches on the front panel are set at. On subsequent line sync pulses, the counters count down and output a pulse at the selected line. This signal is logically "anded" with an A only page signal and used as the scope trigger output. Using the hookup shown in Figure 2.6, it is then possible to view each line

separately by merely changing the line select switches. The D latch (IC Y2) outputs a pulse that is active high (logical "1") during the duration of the chosen line.

The A,B page differentiator circuit consists of IC's M3, X2, V2, and Y3. On a raster scan, line 263 is cut in half by a new vertical sync pulse which moves the trace to the beginning of the interlace page (Figure 2.9(a)). The circuit uses this fact in combination with a gated counter and flip-flop to determine A or B page (see timing diagram in Figure 2.13(a)). At each horizontal sync pulse, a binary counter which is fed by a 250 kHz clock is reset to zero and immediately starts counting up. A D-latch is connected to the most significant bit output of the counter and clocked by the page sync. If the latched bit is a logical "1," it indicates the beginning of page A. An output is also provided that remains high during alternate A,B page sequences (last line in timing diagram, Figure 2.13(a)).

The page or single line format selector consists of IC's X3 and Z2. This is a software programmable option accessed through port 3BH. The code word is latched in port 3BH and used partially by selector IC Z2. The code words and options are listed in Table 2.1.

Use of these software options requires loading the 8080A's accumulator with the correct code word and then executing an OUT 3BH command. For example, loading accumulator with 0FH and doing an OUT 3BH would select a single line in A page for the video format.

The initial offset, increment, and number-of-points-per-line counters are all linked together. They consist of IC's S1, S2, S3, R1, R2, R3, P1, P2, P3, W1, and Y2. These are software programmable options accessed through ports 3SH, 39H, and 3AH. As usual, the code words are latched into the ports upon execution of an OUT instruction. The data are then presented continuously to

Figure 2.13 - Timing diagrams. (a) Timing for A,B page differentiation;
(b) Timing for construction of start-to-convert pulse train.

TABLE 2.1 FUNCTIONAL ASSIGNMENTS FOR PORT 3BH

BIT NUMBER FOR PORT 3BH -- FUNCTIONAL ASSIGNMENT

D7 D6 D5 D4 D3 D2 D1 D0

X	X	X	X	X	X	0	0	-- selects A page for video format
X	X	X	X	X	X	0	1	-- selects B page for video format
X	X	X	X	X	X	1	0	-- selects A,B page for video format
X	X	X	X	X	X	1	1	-- selects D2, port 3BH for video
X	X	X	X	X	0	X	X	-- disables video format s-t-c signal
X	X	X	X	X	1	X	X	-- enables video format s-t-c signal
X	X	X	X	0	X	X	X	-- selects full page format
X	X	X	X	1	X	X	X	-- selects single line format
X	X	0	0	X	X	X	X	-- selects video format for s-t-c
X	X	0	1	X	X	X	X	-- selects port 3FH pulse for s-t-c
X	X	1	0	X	X	X	X	-- selects I/O read signal for s-t-c
-	-	X	X	X	X	X	X	-- unused

X = don't care condition s-t-c = start-to-convert signal

all the programmable down counters. The initial offset and increment counters run off a 5 MHz clock.

The operating sequence shown in Figure 2.13(b) is as follows: The line sync pulse loads the initial offset counter with the latched data. In the example shown, the latched data equal 8. The counter then counts down at a 5MHz rate and generates a borrow signal when zero is reached. The borrow signal then loads both the increment and points-per-line counters, and presets the clock enable latch to the increment counter. In the timing example shown here the increment value is 3. The increment counter then counts down from the preset value and generates its own borrow pulse. The pulse is sent through an edge trigger circuit and fed back to its own load input. The borrow pulse also decrements the points-per-line counters. Of course, the process repeats itself with sample frequency equal to $5/(1+n)$ MHz. For this example, $n=3$ implies a 1.25 MHz sample rate. Eventually, the points-per-line

counters count down from their preset value and send out a borrow pulse. In this example that value was 2. The borrow signal is used to clear the clock enable latch to the increment counter. This action terminates the pulse train for that line.

This whole sequence is again repeated after each horizontal sync signal and blanked out only during the page sync pulse. The pulse train is then combined with the signal that was selected by the single line or page circuitry. This is now a valid start-to-convert signal for the A/D unit.

Additional flexibility was incorporated in this board to handle two digitizing formats other than video processing. Through the use of a start-to-convert signal selector (IC's N5 and V2), it is possible to software program three different sources for the start-to-convert pulse that inevitably triggers the A/D unit. The code word is latched in port 3BH. Options are listed in Table 2.1 and involve only bits D5 and D4.

Normally, the video formatted pulse train is selected. However, for complete software control of slower sample rates, port 3FH is selected as the start-to-convert signal source. Execution of an OUT 3FH then would cause the A/D to convert. The resulting 8 bit conversion could then be read by the IN 3EH instruction. The small program in Table 2.2 which would sample 256 data points and store them in sequential memory locations takes 47 machine cycles per loop. At 1 microsecond per 8080A machine cycle, this corresponds to a 47 microsecond period or a 21.3 KHz sample rate and is the fastest sample rate possible using only software control. Of course, any slower rate is easily achieved.

For the highest possible non-formatted conversion rate, the I/O read pulse is selected. In this mode the DMA controller is used to control data destination and conversion termination. Use of the DMA controller is

TABLE 2.2 SAMPLE DIGITIZING PROGRAM

MACHINE CODE COMMANDS	MACHINE CYCLES
MVI C, FFH	
LP: OUT 3FH	10
IN 3EH	10
MOV M, A	7
INX H	5
DCR C	5
JNZ LP	10
	<hr/> total 47

covered in the next section. With the DMA, conversions can occur every three DMA clock cycles. This corresponds to a 600 nanosecond sample period or a maximum sample rate of 1.67 MHz. Execution of an OUT 25H instruction with 04H in the accumulator will begin this type of conversion.

2.3.4 Timing and interface section

This section (Section 3, Figure 2.10) generally contains much of the house-keeping logic needed on the video board. This logic maintains the internal data bus and access to the S-100 bus, in addition to generating port select pulses and interfacing to the DMA controller.

In order to minimize wiring and unify the system components, the board contains an internal bidirectional data bus line. All the software ports including those in the DMA controller are connected to this bus. This bus is in turn connected to the external S-100 data buses via data buffer IC's R4, P4, and AA2. The first two buffers are used when the board is in slave mode and the 8080A has system control. IC AA2 is used during DMA cycles when the 8080A master is disabled. Data latch, IC T3, is used in DMA cycles to latch the upper 8 address bits from the data bus. Data buffer IC's T4 and S4 allows

bidirectional use of the S-100 bus of the lower eight address lines.

Port select pulses are generated by IC's V3, V4, V5, and T1. In the 8080A system, execution of an IN or OUT instruction causes the port number to appear on the lower eight address lines and the accumulator data on the data bus. Logic on the address lines A4-A7 decodes two chip select pulses, 2XH for the DMA controller and 3XH for port select generation (X stands for "don't care" condition). All the internal registers of the DMA controller therefore can be accessed with the 2XH port numbers.

Using a combination of the 3XH chip select pulse and address lines A0-A3, the additional output port select pulses 38H through 3FH can be generated. Their destination has already been discussed. One additional signal that is generated by this logic enables an input port select pulse 3FH to be used during software controlled conversion routines.

The DMA controller chip is a rather complex device and reference to its specification sheet is recommended [5]. A brief summary will be sufficient here. Basically, the DMA controller has two modes:

Slave mode when it is accessed by the 8080A CPU as a variety of input/output ports. This is essential in initializing and reading the internal registers of the DMA controller.

Master mode when the DMA controller takes charge of the S-100 bus and must generate all necessary memory and I/O read/write signals as well as memory addresses. In this mode the 8080A must be disabled from the system. Logic consisting of IC's X3, W5, N2, and N5 performs this task.

Internally, the DMA controller has 16 bit address registers that can be initially set to any value. These registers increment automatically during

master mode operation. The controller also has 16 bit terminal count registers that can be used to limit the total number of memory transfers. In addition to these, there are several mode registers that format the type of direct memory access the controller is to perform.

The following small program will initialize the DMA controller for a memory transfer starting at location 2000H. The controller will then respond to a hardware request and transfer data until the request ends. Table 2.3 shows the format that is required for video data acquisition.

TABLE 2.3 HARDWARE INITIATED DMA

MACHINE CODE COMMANDS	COMMENTS
OUT 3CH	reset
OUT 3BH	reset
MVI A,00H	load
OUT 20H	starting
MVI A,20H	address
OUT 20H	
OUT 3EH	enable DMA
	request logic

It is possible to begin a direct memory access by a software request and then use the terminal count registers to terminate the action. This is shown in Table 2.4.

The hardware request to initiate a DMA consists of IC's W1, W2, W3, and X1. The logic is first reset by executing an OUT 3DH instruction. The actual DMA request to the controller chip is made when the proper page or line pulse signal occurs. The request is ended by the same line or page pulse. This accounts for the asynchronous nature of the video signal.

During the DMA process, it was necessary to stall the DMA controller if a slow sample rate was chosen. This is done by putting the DMA into a wait

TABLE 2.4 SOFTWARE INITIATED DMA

MACHINE CODE COMMANDS	COMMENTS
OUT 3CH	reset
OUT 3BH	reset
MVI A,00H	load
OUT 20H	starting
MVI A,20H	address
OUT 20H	
MVI A,00H	load
OUT 21H	terminal
MVI A,30H	count
OUT 21H	
MVI A,40H	output a DMA
OUT 23H	request pulse

state sequence until proper A/D conversion has been made. IC M2 is responsible for this action.

3. THEORETICAL RAY-TRACING AND EXPERIMENTAL ANALYSIS

3.1 Introduction

Presently many laser fusion experiments employ hollow glass microballoons (GMB) either filled with high pressure DT gas (exploding-pusher type) or containing a uniform layer of liquid or solid DT (high-gain isentropic type). For an efficient laser fusion reaction to take place, it is very important to employ highly concentric and uniform layers for the glass shell and the liquid or solid DT-condensate [1]. In experimental work, this requires several things. First, in the case of liquid or solid DT layer formation the experimentalist must be equipped with facilities capable of an operating temperature range of 15 K to 30 K. Second, an accurate and convenient method of observation and measurement of the glass shell and/or DT layers must be developed. This is most easily accomplished through the use of laser interferometry. Third, to properly interpret the information produced by the laser interferometer, an accurate theoretical ray tracing program must be developed.

3.2 Cryogenic Cooling System

In order to obtain the cold temperatures necessary for cryogenic target fabrication, a system was developed as shown in Figure 3.1. In the design, liquid helium at 4.2 K is used as the coolant. It enters the copper heat exchanger from the top and flows down through a series of channels filled with copper beads for more efficient heat transfer. This helium is then exhausted through a flow control valve. Adjustments of the exhaust valve will control the steady-state temperature in the heat exchanger. Attached to the top of the heat exchanger is the cold chamber. The cold chamber contains the targets mounted on 10-micron-diameter angel hair fibers. The cold chamber has

HIGH VACUUM SYSTEM

Figure 3.1 - Diagram of cryogenic cold chamber.

provisions to allow evacuation and filling with helium gas. Once filled with gas the chamber will provide an isothermal environment for target cooling. The chamber also has fused quartz windows for target viewing. Temperature measurement is done via a copper-constantan thermocouple which is soldered to the cold chamber.

To minimize heat loss to the external environment, the heat exchanger and cold chamber are gold plated to cut down radiation loss, as well as kept in a high vacuum environment during cryogenic operation.

3.3 Laser Interferometer

Laser interferometry represents one of the most practical methods of target inspection. As shown in Figure 3.2 the current experiment uses a single pass Mach-Zehnder interferometer with a 632.8 nm He-Ne laser source. Also shown in the figure is a high power (500-Watt) pulsed xenon laser used in target heating experiments. The output image of the interferometer is split into two, with one image focused to a video camera for real-time recording on the video tape and for digital storage by the DAS. The other image is focused to a polaroid camera for still shots. The target image is magnified by a microscope objective positioned close to the target along the object beam of the interferometer. An identical objective is placed in the reference beam. Besides magnifying the target image, these objectives convert the incoming parallel phase fronts to spherically expanding fronts. When the two beams are summed together at the final beamsplitter, the resulting interference pattern is, therefore, a circularly symmetric "bull's-eye" pattern. Once the target is placed in the object beam, an additional new interference pattern results.

Typical target interference patterns and accompanying shadow micrographs are shown in Figure 3.3 for two different temperatures. Contained in Figure

Figure 3.2 - Layout of laser interferometer and associated optics.

Figure 3.3 - Typical outputs from laser interferometer. (a) Shadow micrograph of room temperature target; (b) Interference micrograph of the same target in (a); (c) Shadow micrograph of cryogenic target; (d) Interference micrograph of the same target in (c).

3.3 (a) and (b) are examples of a room temperature 200-micron-diameter DT target. Shown in Figures 3.3 (c) and (d) is the same target at approximately 24 K. Note the formation of a liquid layer as shown by the darkening of the target's perimeter in the shadow micrograph and the increase in the number of fringes seen in the interference micrograph. It is obvious that these interference patterns contain information about various parameters of the target.

3.4 Theoretical Ray-Tracing Procedure and Results

3.4.1 Introduction

The ray trace procedure performed here is along the same lines as those performed by Stone, Gregg and Souers [5]. Unlike in this reference, however, a single pass Mach-Zehnder interferometer was used here. This, of course, modifies the phase effects as observed using their two-pass Twyman-Green interferometer.

A computer program was written that would follow a given input light ray through the target assuming the incoming rays are all collimated and parallel to the target's center axis (see Figure 3.4). At each interface (air-to-glass, glass-to-gas, or glass-to-liquid, and so forth) the program would apply the proper Snell's Law criteria and compute the ray's next trajectory. With each medium that the ray goes through, the program would keep track of the overall phase.

Since there is a microscope objective in each arm of the interferometer, the exit rays from the target will appear to have come from some point on the objective's focal plane. To determine the phase difference, the phase of this ray must be compared to its counterpart at the same focal point in the reference arm. For normalization to the central ray, the optical path

(a)

(b)

Figure 3.4 - Ray-tracing model. (a) Model used when only DT gas is present in target; (b) Model used when DT liquid and gas are present in target.

difference calculation must be made on a Huygen's wavefront at a distance equal to the target's radius from its projection on the focal plane. This, of course, assumes that the focus will be in the center of the target. Experimentally this position is also the best for viewing the target.

As seen in Figure 3.4, rays are classified by the number of interfaces encountered within the target. Generally, two things happen to the higher radius entrance rays "types 2 and 3." The most significant effect is the intensity loss due to the high incident angles. This loss in intensity tends to cloud the interference pattern at the target edges. In addition, the ray's long optical path length differences resulting from travelling through more glass weakens its coherence and degrades the interference even more. Fortunately, use of the "type 1" rays is completely sufficient for determining the target parameters.

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

Estimation of the dependence of the index of refraction on gas density, ρ , has been carried out by Briggs, Tsugawa, Hendricks and Souers [7]. Assuming a deuterium gas temperature of 298 K, a wavelength of 546.1 nm, and letting ρ be the density in moles per cubic meter:

$$(N-1) = (3.089 \times 10^{-6})\rho + (1.534 \times 10^{-12})\rho^2 \quad (3.1)$$

where N is the index of refraction. As tabulated by Childs and Diller [8], there is roughly a 0.7% decrease in the value of $(N-1)$ when a 632.8 nm wavelength is used.

In cryogenic temperature range (18.5 K to 36 K) where both liquid and gas DT are present, the parameters of Equation 3.1 change slightly. The index of refraction of both the liquid and the gas may be calculated by

$$(N-1) = (3.076 \times 10^{-6})\rho + (1.857 \times 10^{-12})\rho^2 \quad (3.2)$$

Finding the proper densities of the gas and liquid in this temperature range is more complicated than in the room-temperature gas density case. Since the target represents a closed system, mass is conserved. Once the target reaches liquefaction point, the fill-gas inside the target begins to condensate into liquid. As the target temperature is further lowered, the gas density decreases as the liquid density and volume increase, thereby changing the indices accordingly. Fortunately, tables have been compiled showing the density relationships between the gas and the liquid in the temperature range from 18.5 K to 36 K [9]. Therefore, experimental measurement of the target temperature leads to knowledge of the liquid and gas densities and subsequent indices of refraction.

3.4.2 Theoretical ray-tracing output examples

Figures 3.5 through 3.8 show some typical output curves for various target configurations. For these examples the target radius is assumed to be 70 microns, the laser wavelength to be 632.8 nm, and the index of refraction of the glass to be fixed at 1.5. For easy interpretation, each curve has been normalized to the central ray. The vertical axis, which is the path length difference, D , has been calibrated in half-wavelengths. Interference patterns are made up of a collection of bright and dark fringes where each dark-to-bright or bright-to-dark transition represents a half-wavelength path difference. A visual picture of the fringe pattern for a given curve may be obtained by starting at the center and moving outward. The centers of alternate bright and dark fringes may be located each time the curve moves upward by a half-wavelength interval.

Figure 3.5 shows the path difference variation as a function of change in glass thickness. Here the internal index of refraction is assumed to be 1. The figure indicates that as the glass thickness increases, the number of observed fringes also increases, and they move closer to the center.

In Figure 3.6 the glass thickness is held constant at 5 microns and the gas density inside the target is increased from 0 to 30 mg/cc in increments of 2 mg/cc. The proper index of refraction was calculated by use of Equation 3.1. The equation indicates that an increase in gas density will cause an increase in the index of refraction. This increase in the index will reduce the optical path length differences and give rise to fewer observed fringes. In fact, at a sufficiently high fill-density, the ray-tracing model predicts that there will be no observed fringes.

When adding a liquid layer to the ray-tracing model, several situations may exist. In the event that the layer is uniform, it may be modeled as is shown in Figure 3.4(b). In addition, the layer thickness may be predicted as

Figure 3.5 - Ray-tracing output showing results of changing target glass shell thickness.

Figure 3.6 - Ray-tracing output showing results of changing target room-temperature gas-fill density.

Figure 3.7 - Ray-tracing output showing results of changing target temperature.

Figure 3.8 - Ray-tracing output showing results of changing DT liquid layer thickness at fixed temperature.

a function of temperature if the initial room-temperature fill-density is known. The liquid layer thickness may be calculated by [10]

$$TH = \left[1 - \left(\frac{D1 - D2}{D3 - D2} \right) \right]^{1/3} (r-t) \quad (3.3)$$

where TH is the liquid thickness, r is the radius of the target, t is the glass thickness, and D1, D2 and D3 are, respectively, the mass densities of gas at room temperature, and the mass densities of the liquid and the gas at cryogenic temperatures. This formula was used to calculate the uniform layers at specific temperatures as is shown in Figure 3.7. Room temperature fill-pressure was assumed to be 100 atm or a corresponding density of 16.67 mg/cc. As is seen in the figure, an increase in the thickness of this layer as temperature is decreased will have a similar effect as thicker glass did as shown in Figure 3.5.

In the situation where the liquid layer is nonuniform, the analysis can become very complicated. As a first approximation, however, an extension of the previous method is possible. Again, experimentally knowing the target temperature and room-temperature fill-pressure, the mass densities of liquid and gas may be determined. Knowing the mass densities and applying Equation 3.2, the indices of refraction may be computed. Figure 3.8 shows a family of uniform curves computed by simply incrementing the thickness of a uniform liquid layer at 25 K. For this example, the mass densities are 3.23 mg/cc and 158.98 mg/cc for gas and liquid, respectively. In addition, the computed indices of refraction are 1.0025 for gas and 1.1247 for liquid. Unlike Figure 3.7 in which a constant mass was maintained within the target, Figure 3.8 does not maintain a constant mass.

To derive an approximate nonuniform layer profile, the observed fringe pattern is broken into radial cross-sections propagating out from the middle

of the target. The approximate layer thickness at that radial cross-section is found by locating the first and second extrema (bright-to-dark or dark-to-bright fringe) on the horizontal axis in Figure 3.8. The curve that guarantees a half-wavelength path difference between these two points will be the approximate layer thickness. Combining all the interpreted layer thicknesses at each radial cross-section will provide a rough idea of the liquid layer profile.

3.4.3 Advanced ray-tracing model

Since the approximate method uses a combination of uniform layer ray tracing results, it cannot account for the geometry of the actual liquid layer profile. As the liquid layer becomes more non-uniform, the approximation becomes more inexact. To remedy this problem, a more realistic model must be developed. Shown in Figure 3.9 are two examples of a model that would more closely match the real situation. (The layer profile, however, is not in general expected to be perfectly spherical.)

This model is an extension of that shown in Figure 3.4(b) in that it allows an offset for the internal liquid layer radius. When looking for a match, two approaches are possible. The first, shown in Figure 3.9(a), is to allow the internal radius, r , to vary with a constant offset, d . The parameter R is the radius to the inside of the glass shell. The other approach shown in Figure 3.9(b) uses a constant radius, r , and the offset, d , is allowed to vary. The model benefits from the fact that the enclosed liquid volume may easily be computed knowing R , r , and d . It is possible to find a set of values of (r,d) that all have the same volume. This is important, because experimentally, the liquid volume is usually known for each temperature.

In a special case of this model, when $d+r < R$ the liquid layer is continuous and the volume is only a function of r and R . This case may be

Figure 3.9 - More precise ray-tracing model. (a) Layer defined by varying radius, r , with constant offset, d ; (b) Layer defined by varying offset, d , with a constant radius, r .

used in determining the effects of gravity on continuous liquid layers in terms of the offset variable, d .

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

3.5 Experimental Results

3.5.1 Introduction

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

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

Previously, in Figures 3.5 through 3.9, these points were located on the horizontal axis and a correct curve was found that assured a half-wavelength path length difference between the two points. To obtain higher accuracy and

to further automate the process, a program has been developed that forms tables instead of line plots. The program uses a software look-up procedure for proper "curve" location given the location of the first two extrema. This implies that a complete measurement of DT fuel behavior inside a GMB at any temperature can be accomplished within the period of time it takes the DAS to get the picture and a high speed computer to do the table look-up. In all, a complete target characterization scheme could be worked out for real time monitoring of laser fusion fuel pellet fabrication processes.

3.5.2 Target characterization example

In step one, determination of wall thickness requires having a known index of refraction for the interior of the GMB. This only occurs when all the fuel is frozen solid in a small region of the target (Figure 3.10(f)). The index of refraction of glass is taken to be 1.50 and that of the internal void as 1.00. Figure 3.11(f) shows the data acquired by the DAS. For easier fringe recognition, the data have been inverted so that dark fringes appear higher than the bright ones. After the phase information was processed as previously described, the average glass thickness was found to be 3.04 microns with a standard deviation of 0.16. A simplified drawing is shown in Figure 3.12(f).

With step two, for the gas density measurement, the known glass thickness is entered in the ray-trace program and the gas density is varied until a match occurs. For the present example (Figures 3.10(a), 3.11(a) and 3.12(a)) room-temperature gas density is 16.75 mg/cc or an equivalent pressure of 103 atm.

For step three, two types of interpretation are possible in determining the liquid layer profile. If the layer is uniform, results such as those obtained in Figure 3.7 may be used. If not, the target must be analyzed in

(a)

(b)

(c)

(d)

(e)

(f)

Figure 3.10 - Interference micrographs of a target cooling sequence. (a) Room temperature target; (b) through (e) Increasing deuterium liquid condensation inside target at decreasing temperatures; (f) Frozen deuterium mass inside target.

Figure 3.11 - Data acquisition system's output for interference micrographs shown in Figures 3.10 (a) through (f).

Figure 3.12 - Interpreted data from data acquisition system's output shown in Figures 3.11 (a) through (f).

radial cross-sections with each section interpreted with the type of data found in Figure 3.8. A target-cooling sequence is shown in Figures 3.10(b) to 3.10(e) where the target's temperature is decreased from 25 K to 19 K. Interpretation of the DAS output in Figures 3.11(b) to 3.11(e) by the first approximation method described in Section 3.4.2 leads to liquid layer profiles as shown in Figures 3.12(b) to 3.12(e).

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

4. TARGET POSITIONING METHODS - QUADRUPOLE AND MOLECULAR BEAM

4.1 Introduction

At present, most of the experimental cryogenic work done on GMB's requires the targets be held at a stable, stationary location within a cold target freezing chamber. The analysis done in the previous chapter was performed with the target glued to a 10-micron-diameter glass fiber. Although this setup was satisfactory for those experiments, it presents many disadvantages for future mass production and characterization of cryogenic targets. Ideally, target manipulation must be accomplished without physical contact to the target. In present gold coating processes [11], the target is levitated above a collimated hole structure (CHS) with molecular beams of argon gas. To localize the target to a specific position in the middle of the structure, a centering ring is installed which deflects the beams from the perimeter into the center. This device is called a molecular beam levitator (MBL).

A similar device was constructed out of a 50-micron-diameter tube CHS and operated on helium gas (See Figure 4.1(b)). The MBL worked quite well, however, the structure obscured lateral laser interferometry which is an essential diagnostic in cryogenic target fabrication. Efforts to levitate the target above the structure, while still employing molecular beams to lift and center it, have not been successful. Another type of gas levitator was made by drilling a cylindrical bore into a fritted-glass material as shown in Figure 4.1(a). Although this structure also provided successful target levitation, the viewing angle was even more limited due to the small bore size.

In recent experiments reported by Kim et al. [12], and Kim and Rieger [13], it has been shown that direct wetting of the target with cold He gas is sufficient to form and maintain a liquid DT layer inside the

(a)

(b)

Figure 4.1 - Examples of levitation structures with no lateral visibility.
 (a) Fritted glass structure levitating 200-micron-diameter target;
 (b) Molecular beam levitator with confinement ring levitating 140-micron-diameter target.

Figure 4.2 - Example of quadrupole levitation structure showing total lateral visibility. Target shown is 140 micron in diameter.

target. Therefore, it is advantageous to have the target levitated with gas. However, to circumvent the drawback of the MBL, a new target centering technique must be implemented. The new method uses a quadrupole structure oriented in a vertical fashion with the CHS at its center (see Figure 4.2). An electrostatically charged target can be centered in the alternating fields of the quadrupole while being levitated by collimated molecular beams. This target-positioning scheme gives excellent observability of the target in two directions, therefore allowing the use of laser interferometry for target characterization.

The following sections describe the details of this system and its requirements. The first requirement is to supply a sufficient gas flow to actually lift the target off the CHS and suspend it. The next requirement is to provide a stable centering force for the charged target within the quadrupole structure. And, of course, the success of being able to contain the target depends heavily on properly charging it. The final section describes a promising method which uses a Boxer charger for ionic-charging of high resistivity GMB.

The apparatus shown in Figure 4.3 is a modification of the cold chamber design of Figure 3.1. Cold helium gas is still supplied from the heat exchanger, however, now the top of the cold chamber is opened up to access the target loading mechanism. Long stainless steel bellows are used to thermally insulate the chamber from the rest of the apparatus. Targets are first loaded into the pellet feeder and are manually dropped one at a time into the center of the Boxer charger device. Upon leaving the charger, the target goes through a series of rings, as was first used in a previously published design [3]. The rings then center the target, aligning it for proper entrance into the quadrupole, and decelerate it. The second ring is actually a chamber

Figure 4.3 - Cryogenic levitation system.

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

Once the target enters the quadrupole, it is funneled down into the cold chamber where it is levitated and cooled by cold helium gas. As the target is levitated in the cold chamber, it may then be analyzed through the use of the laser interferometer and the DAS as described in Chapters 2 and 3.

4.2 Gas Levitation

4.2.1 Introduction

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

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

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

The first, known as diffuse reflection, is described in Figure 4.4(a). In diffuse reflection, a molecule hits the surface and is then re-emitted in a random direction. The second type, illustrated in Figure 4.4(b), is specular reflection where the angle of incidence is equal to the angle of reflection. In both cases, the velocity at which the molecule will leave the surface depends on the amount of energy transferred to the surface before the molecule is re-emitted.

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

$$c_m = \sqrt{\frac{2kT}{m}} \quad (4.1)$$

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

For the gas levitation problem considered here, an additional term must be added due to the macroscopic mass velocity of the gas emanating from the CHS. As shown in Figure 4.5, the mass velocity will be defined as u . Exact calculation of u is difficult, however, bounds may be defined through consideration of isentropic flow theory [14]. The gas entering the CHS from

Figure 4.4 - Types of molecular reflections. (a) Diffuse; (b) Specular.

Figure 4.5 - Geometry for calculation of molecular beam levitation.

the bottom will readily achieve sonic velocity, u_{sonic} , defined as:

$$u_{\text{sonic}} = \sqrt{\frac{\gamma kT}{m}} \quad (4.2)$$

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

$$u_{\text{max}} = \sqrt{\frac{2\gamma}{\gamma-1} \left(\frac{kT}{m} \right)} \quad (4.3)$$

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

$$227.8 \text{ m/sec} < u < 394.6 \text{ m/sec} \quad (4.4)$$

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

$$S = \frac{u}{c_p} \quad (4.5)$$

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

$$.912 < S < 1.531 \quad (4.6)$$

4.2.2 Target drag calculations

Exact derivation of the drag force imparted to a sphere in a molecular beam flow is very long and tedious, well beyond the intent of this report. The work, however, has been carried out in great detail by Patterson [15] and results of his calculations are presented here. For the particular geometry shown in Figure 4.5, the total drag force on the target may be written as:

$$\int_0^\pi D \, dA = C_d \left(\frac{1}{2} \rho_m u^2 \pi R^2 \right) \quad (4.7)$$

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

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

$$C_{d,s} = \frac{2}{3} \left[\left(\frac{2s^2-1}{s^2+1} \right) \exp(-s^2) + \left(\frac{4s^4+4s^2-1}{s^2+1} \right) \operatorname{erf}(s) \right] \quad (4.8)$$

and for diffuse reflection:

$$C_{d,d} = C_{d,s} + \frac{2}{3} \left(\frac{T_s}{T_g} \right)^{1/2} \quad (4.9)$$

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

the equilibrium temperature ratio is

$$\left[\frac{T_w}{T_\infty} \right]_{eq} = \frac{(2S^2+5) \exp(-S^2) + [2S^3+6S+(3/2S)] \mp \operatorname{erf}(S)}{4 \exp(-S^2) + 4[S+(1/2S)] \mp \operatorname{erf}(S)} \quad (4.10)$$

Using the limits for the speed ratio, S , as defined in Equation 4.6, it is possible to derive limits for the two drag coefficients, Equations 4.8 and 4.9. For specular reflection the bounds are

$$1.72 \leq C_{d,s} \leq 3.82 \quad (4.11)$$

and for diffuse reflection they are

$$3.99 \leq C_{d,d} \leq 5.41 \quad (4.12)$$

4.2.3 Target levitation requirements

In order that the target be stably levitated by the gas beam, the upward levitation force must be equal to the downward gravitation force. Where M is the mass of the target and g is the acceleration due to gravity, this requirement implies:

$$F_{lev} = F_{grav} = Mg \quad (4.13)$$

or in terms of Equation 4.7:

$$\int_0^\infty \rho \, dx = \rho_0 \int_0^\infty (u^2 - c^2) \, dx = Mg \quad (4.14)$$

In Equation 4.14 the only free parameter is the external gas density, ρ_0 . By applying the limits given for the mass flow, u , (Equation 4.4) and drag coefficients, $C_{d,s}$ and $C_{d,d}$, (Equation 4.11 and 4.12) it is possible to arrive at experimental operating limits for the external gas pressure, P . First, however, the mass of the target must be calculated.

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

$$M = \frac{4}{3} \pi \left([R^3 - (R-t)^3] \rho_{\text{glass}} + (R-t)^3 \rho_{\text{gas}} \right) \quad (4.15)$$

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 fill gas, respectively. For a typical 140-micron-diameter target with a 5 micron wall thickness, a gas fill density of 16.75 mg/cc and a glass density of 2500 mg/cc, the total mass would be:

$$M = 7.35 \times 10^{-7} \text{ g} \quad (4.16)$$

Now, solving Equation 4.14 for the external gas density gives

$$\rho_x = 2Mg/C_d v^2 - R^2 \quad (4.17)$$

It is now possible to find the operating limits assuming the typical target mass shown in Equation 4.16. For specular reflection the gas density range is

$$2.21 \times 10^{-9} \text{ g/cc} < \rho_{x,s} < 4.73 \times 10^{-9} \text{ g/cc} \quad (4.18)$$

and for diffuse reflection

$$1.35 \times 10^{-9} \text{ g/cc} < \rho_{x,d} < 3.33 \times 10^{-9} \text{ g/cc} \quad (4.19)$$

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

$$P = 15571 \rho_x T \quad (4.20)$$

where the pressure, P , is given in Torr. Recalculating Equations 4.18 and 4.19 in terms of pressure, with a gas temperature of 15 K, give operating

ranges of

$$1.10 \text{ mTorr} > P_g > 0.52 \text{ mTorr}, \quad (4.21)$$

for specular reflection, and

$$0.78 \text{ mTorr} > P_g > 0.36 \text{ mTorr}, \quad (4.22)$$

for diffuse reflection.

Generally, molecule-surface interactions are considered to be a combination of diffuse and specular reflections, with diffuse reflection being the dominant contributor [15]. This means that the limits given by Equation 4.22 are probably the most realistic. During operation of the molecular beam levitator at room temperature, the average gas pressure measured above the CHS was 10 mTorr. Adjusting Equation 4.22 for a temperature of 300 K gives operating limits from 7 to 16 mTorr.

4.3 Electrostatic Centering

Lateral containment of the CHS is done through the use of an electrostatic quadrupole structure. Quadrupoles have been in use for some time as mass spectrum analyzers [16]. The quadrupole uses a quasi-static alternating electric field where the value of the field strength is proportional to the distance from the center of the structure. The potential is periodic in time, symmetrical with respect to the center, and depends quadratically on x and y . The device consists of four parallel cylindrical electrodes with a circular cross-section (Figures 4.6 and 4.7). In the general case, a direct voltage $2U$ and an alternating voltage $2V\cos\omega t$ are applied between adjacent pairs of rods. This produces an electric field near the z -axis that can be derived from the

Figure 4.6 - Quadrupole geometry and drive circuitry.

Figure 4.7 - Quadrupole with additional DC biasing.

potential:

$$E(x, y, z) = (U + V \cos \omega t) \frac{x^2 + y^2}{r_0^2} \quad (4.23)$$

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

$$\frac{d^2 x}{dt^2} + \frac{2}{r_0^2} \frac{Q}{M} (U + V \cos \omega t) x = 0 \quad (4.24)$$

$$\frac{d^2 y}{dt^2} - \frac{2}{r_0^2} \frac{Q}{M} (U + V \cos \omega t) y = 0 \quad (4.25)$$

$$\frac{d^2 z}{dt^2} = 0 \quad (4.26)$$

By substituting

$$2\xi = \omega t : a = \frac{8QU}{Mr_0^2 \omega^2} ; q = \frac{4QV}{Mr_0^2 \omega^2} \quad (4.27)$$

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

$$\frac{d^2 x}{d\xi^2} + (a + 2q \cos 2\xi) x = 0 \quad (4.28)$$

$$\frac{d^2 y}{d\xi^2} - (a + 2q \cos 2\xi) y = 0 \quad (4.29)$$

The differential equation has periodic coefficients, i.e., the particle trajectory in the given potential represents an oscillatory motion with a periodically varying restoring force. Solutions to the Mathieu equations [17] are shown in Figure 4.8.

Figure 4.8 - Stability diagram for the Mathieu equations.

Figure 4.9 - First (lowest) stability region of Figure 4.8.

For the present system, there is no need for application of a direct voltage to the rods. The sole presence of the alternating voltage is sufficient to stabilize the target motion in the vicinity of the geometrical center of the quadrupole structure. This position offers the best visibility of the target along the x- and y-axes. (It is possible, however, to use the direct voltage for fine positioning on the $y=x$ or $y=-x$ plane if necessary.) No direct voltage implies $U=C$ and, consequently, $a=0$ in the Mathieu equations. From the stability diagram for the Mathieu functions (Figure 4.8) it can be seen that the system will operate in the lowest stability region as shown in Figure 4.9. The symmetrical stable region in the figure is found by reflecting the stability boundaries about the $a=0$ axis. This gives rise to the characteristic "necktie" stability region where q_{nominal} indicates the position of maximum $|a|$ -variation and q_{max} is the maximum stable value of q when $a=0$. During the operation of this quadrupole, stable paths are obtained for q -values between 0 and 0.908 or, in terms of Equation (4.27):

$$0 < \frac{4QV}{Mr_0^2 \omega^2} < 0.908 \quad (4.30)$$

By adjusting Equation 4.30 to account for the actual operating conditions by letting $r_0=0.635$ cm and $\omega=2\pi f$ the stability bounds become:

$$0 < \frac{Q}{M} \frac{V}{f^2} < 3.613 \times 10^{-4} \quad (4.31)$$

Table 4.1 tabulates some useful operating conditions for given charge-to-mass ratios assuming a stable q -value of 0.5. The equality solved for in the

table is expressed as

$$\frac{V}{f^2} = \frac{2 \times 10^{-4}}{(Q/M)} \quad (4.32)$$

It is obvious, by Equation 4.31, that for a given charge-to-mass ratio an excessive increase in the voltage or decrease in the frequency will tend to make the target unstable.

TABLE 4.1 OPERATIONAL STABILITY CONDITIONS FOR QUADRUPOLE

Q/M (C/kg)	V (volts)	f (Hz)
1×10^{-5}	2000	10
	288000	120
1×10^{-4}	2000	32
	28800	120
5×10^{-4}	2000	71
	5760	120
1×10^{-3}	2000	100
	2880	120

As shown in Figure 4.7 it is possible to superimpose a DC potential in the vertical direction over the previously described fields. This additional electric field which is directed downward will force the positively charged target into the gas levitator. It therefore could be used to maintain the target's position when the gas flow is increased for additional cooling purposes.

Reliable results with the quadrupole confinement structure have been difficult to obtain due to poor target charging. The pictures shown in Figures 4.10(a) and 4.10(b) are taken from a real-time video recording. The target was charged with a very high-voltage tungsten needle which can be seen in the

(a)

(b)

Figure 4.10 - Reproduction from real-time video tape recording showing centering capabilities of quadrupole. (a) Target at rest with no applied voltage to quadrupole and no gas flow; (b) Target oscillating slightly in center of structure while being levitated on collimated gas beams.

(a)

(b)

Figure 4.11 - Interferometer output of target on collimated hole structure in quadrupole setup. (a) Shadow micrograph; (b) Interference micrograph.

center of the pictures. Figure 4.10(a) represents the target at rest with no applied quadrupole potential. In Figure 4.10(b), levitation gas has been introduced as well as a 8000V, 100Hz sinusoidal potential. The target was observed to move into the geometrical center of the quadrupole. With increased gas flow, however, the target would usually go unstable.

Shown in Figures 4.11(a) and 4.11(b) are the laser interferometer outputs of the target for a shadow micrograph and an interference micrograph, respectively. Diffraction effects seen in the figures degrade the interferometer output. The solution to this is to levitate the target higher off the structure. In order to keep the target stable at a higher gas flow, it will be necessary to increase the overall charge on the target as well as the uniformity of the charge distribution.

4.4 Target Charging

4.4.1 Introduction

Success of the electrostatic confinement system described in the previous section depends heavily on a method of consistently and uniformly charging the GMB. Since the glass targets are such excellent insulators, their affinity for acquiring charges is very low. Recent studies by Masuda and Washizu [18] have shown that the use of ion-bombardment may provide a very practical and somewhat efficient method for particle charging. The particle charging device first developed by them, called a "Boxer Charger," charges the particle by bombardment of uni-polar ions within an AC field. Since the field is alternating, the particle or target will undergo only slight oscillations as it passes through the charging unit. Thus the charger may be positioned directly above the quadrupole structure as shown in Figure 4.3. The quadrupole will then electrostatically center the target along its center axis while the target is supported vertically by the gas levitator.

4.4.2 Charging theory

The first estimate for the total charge imparted to an insulating particle by ion bombardment was carried out by Pauthenier [19]. Results show the quantity of charge, Q_p , as a function of time t to be

$$Q_p = Q_\infty \left[\frac{t}{t+\tau} \right] \quad (4.33)$$

With the saturation charge, Q_∞ , given by

$$Q_\infty = 12\pi\epsilon_0\epsilon_s R^2 E / (\epsilon_s + 2) \quad (4.34)$$

and the charging time constant, τ , as

$$\tau = 4\epsilon_s E / J, \quad (4.35)$$

where t is the charging time, ϵ_0 is the dielectric constant of vacuum, ϵ_s is the specific dielectric constant of the particle, E is the field strength and J is the current density.

A more rigorous approach was made by Masuda and Washizu [18] to take into account very high particle resistivities and the situation where the particle does not rotate in the charging field. In general, their results indicate that the saturation charge is considerably smaller than Pauthenier's limit, Q_p , for low dielectric constant materials. The calculations were first done for unidirectional (DC) charging and then for bidirectional (AC) charging. The latter results show a significant improvement over the former, as indicated in Figure 4.12.

Figure 4.12 uses several normalized variables. The vertical axis is the normalized charge in percent of actually acquired charge to Pauthenier's limit, $Q_n = Q/Q_p$. The horizontal axis is the normalized charging time given by $t_n = t/T$,

Figure 4.12 - Theoretical charging limits as a function of dielectric constants.

where $T = \tau = 4\pi\epsilon_0 E/J$. The Boxer charger was assumed to have a normalized frequency of $f_n = \tau T = 10$, f being the frequency of the alternating field. If the target rotates as it passes through the charger unit, the charge density distribution will become more uniform, and its total charge approach that given by Pauthenier's Equation [(4.33)-(4.35)].

4.4.3 Application example

As an application of the above theory, it is possible to arrive at a set of actual operating conditions for the quadrupole. For the calculation of the resultant charge-to-mass ratio the following parameters are assumed:

$$E = 5 \text{ kV/cm} \quad (4.36(a))$$

$$\tau = 6.4 \text{ msec} \quad (4.36(b))$$

$$T = 20 \text{ msec} \quad (4.36(c))$$

For calculating the Pauthenier limit, it is necessary to know how long the target stays in the charging field. Assuming the target is initially at rest and the viscous force of the gas is negligible, the target transit time is given from elementary physics as

$$\tau_{\text{transit}} = (2d/g)^{1/2} \quad (4.37)$$

where d is the length of the charger unit and g is acceleration due to gravity. Letting $d = 5 \text{ cm}$ and $g = 980 \text{ cm/sec}^2$, transit time is found to be 100 msec. The maximum charge assuming target rotation is found from Equations (4.33) and (4.34) to be:

$$Q_p = 461 \times 10^{-15} \text{ C} \quad (4.38)$$

From Figure 4.12, the theoretical charging limit for a target with a specific dielectric constant of 3 and with no target rotation in the charging field is found to be 60 percent of Pauthenier's limit. Therefore, the actual charge on the target may vary between these two values. Assuming a typical

target weight of 735×10^{-9} g, (see Section 4.2.3), a range of charge-to-mass ratio may be computed to be:

$$3.76 \times 10^{-4} \text{ C/kg} < \frac{q}{M} < 6.27 \times 10^{-4} \text{ C/kg} \quad (4.39)$$

Knowing this range, the proper operating voltage and frequency for the quadrupole may be selected from Table 4.1.

5. CONCLUSIONS AND SUGGESTIONS FOR FUTURE EXPERIMENTS

The data acquisition system (DAS) presented in Chapter 2 offers a fast, high-resolution method for acquiring target fringe patterns and storing them digitally in memory for later analysis. The system further benefits through the use of a high-sensitivity video camera. The high-sensitivity camera allows the use of a very low-intensity observation laser for the interferometer that does not appreciably heat the target. Optical heating of the target is quite detrimental to accurate temperature measurements which are based on the assumption that the target temperature is the same as that measured at the wall of the cryogenic cold chamber (for high-fill exchange-gas pressures in the chamber).

The cryogenic cold chamber (Figure 3.4) used in acquiring the data in Section 3.5 lacked an accurate method of temperature measurement. Implementation of a calibrated semiconductor diode sensor with a closed-loop temperature control unit would greatly increase measurement accuracy and repeatability.

Theoretical ray-tracing results, presented in Chapter 2, combined with the automated software look-up tables provide a fast, accurate determination of the glass shell thickness and uniform DT layer thickness. As previously pointed out, however, presence of non-uniform DT liquid layers can greatly complicate the interpretation methods. Fortunately, for inertial confinement fusion, uniformity and concentricity of the cryogenic layers are essential. Therefore, merely detecting any non-uniform thickness condition, which is easily done by the DAS, would result in the rejection of unacceptable targets. The more complicated non-uniform layer determination procedure may prove useful in other experimental work such as investigations of gravitational effects,

surface tension, and liquid-solid interaction forces of the DT liquid contained in a target.

Target positioning and manipulation through the use of a quadrupole structure can be a very valuable tool in cryogenic target fabrication. Success was limited in this work due to inadequate charging methods. The use of a high-voltage needle for charge injection resulted in a very localized charged region on the target which generally led to unstable target behavior. Use of a Boxer charger, described in Section 4.4, should provide for a greater and more uniform charge density on the target.

The molecular beam levitation scheme for the cooling and vertical positioning of the target was hindered by the marginal performance of the quadrupole in laterally confining the target. Due to the diffraction fringes off the CMS (Figure 4.11), it is desirable to levitate the target about 50 microns above the surface. Typically, the target would be lost when the gas flow was increased to accomplish this. Calculations of the operating conditions necessary to provide target levitation were verified for the molecular beam levitator in Figure 4.1(b).

In the future, the success of using an inertial confinement fusion process to generate power on a commercial scale will require an automated method of target fabrication, inspection, and delivery into the fusion reactor chamber. Current studies [1] indicate that a one-gigawatt (million-kilowatt) power plant will require about 100 fusion microexplosions per second. The work presented here has offered several developments that, with further refinement, may help to achieve this goal.

The data acquisition system developed in Chapter 2 can take a complete two-dimensional phase mapping of the target in $1/60$ of a second. Computer software can then determine the location of the first and second extrema

(interference fringes) in the two-dimensional map. Through an automated table-lookup-procedure the extrema data may be converted to actual target parameters such as glass shell thickness, and liquid or solid DT-layer thickness. In addition, criteria in terms of uniformity and concentricity of the target and the cryogenically formed layers may be checked.

Target handling may be accomplished through the use of an electric quadrupole structure, ¹⁴ as follows. The room-temperature targets containing DT-mixture are first charged by a Boxer charger unit (Section 4.3) and funneled into a quadrupole structure. Once in the quadrupole, they may be brought into a cryogenic freezing cell for fabrication and inspection of liquid or solid DT-layers. Defective targets or those not meeting the required specifications are ejected from the quadrupole transporter. Thus, only the uniform and concentric targets are allowed past this point. The targets are then loaded into quadrupole storage racks inside a cryogenic refrigerator. When needed, the targets are guided from the storage compartment into another quadrupole structure that eventually would align and accelerate them into the center of the fusion reactor. To maintain a reasonable inventory in the cryogenic target warehouse and be able to supply 100 targets a second to the reactor, several fabrication stations may be used for each reactor.

All in all, the foundation for the development of an automated cryogenic target fabrication system has been presented in this work. Due to the complexities of this problem, though, the development of a reliable, continuous target fabrication system will only be achieved through a constant effort of refinement and improvement of the ideas presented here.

REFERENCES

1. J. Nuckolls, L. Wood, A. Thiessen, and G. Zimmerman, *Nature* 239, 139 (1972).
2. L. M. Stickle, *Physics Today* 31, 50 (1979).
3. S. Masuda, M. Washizu, and T. Sekiguchi, "Electrostatic Method of Pellet Handling," Proceedings, IEEE-IAS annual meeting, page 1005, Cincinnati, OH, Sept. 1980.
4. An Introduction to CP/M Features and Facilities, 1978, Digital Research, Post Office Box 579, Pacific Grove, CA 93950.
5. MDS-80/85 Family User's Manual, 1979, INTEL CORPORATION, 3065 Bowers Avenue, Santa Clara, CA 95051.
6. R. R. Stone, D. W. Gregg, and P. C. Souers, *J. Appl. Phys.* 46, 2603 (1975).
7. G. H. Briggs, R. T. Tsugawa, C. D. Hendricks, and P. C. Souers, Estimated Refraction Index and Solid Density of DT with Application to Hollow-Microsphere Laser Targets, Lawrence Livermore Laboratory, Report UCRL-51921 (1975).
8. H. E. Childs and R. E. Diller, *Adv. Cry. Eng.* 15, 65 (1969).
9. H. M. Roder, H. E. Childs, R. E. McCarty, and P. E. Angerhofer, Survey of the Properties of the Hydrogen Isotopes Below Their Critical Temperatures, NBS Technical Note 641 (U.S. Government Printing Office, Washington, D.C. 20401, 1973).
10. H. Rieger, Fabrication and Characterization of Cryogenic Targets for Inertial Confinement Fusion, M.S. Thesis, University of Illinois, 1979.
11. T. K. Crane, private communication, 1979, Lawrence Livermore National Laboratory, Livermore CA 94550.
12. S. Kim, S. J. Snot, R. L. Moerner, and C. D. Hendricks, *Appl. Phys. Lett.* 34, 282 (1979).
13. S. Kim and H. Rieger, *Appl. Phys. Lett.* 37, 425 (1980).
14. A. H. Shapiro, The Dynamics and Thermodynamics of Compressible Fluid Flow (The Ronald Press Company, New York, 1953), Vol. 1.
15. G. N. Patterson, Introduction to the Kinetic Theory of Gas Flows (University of Toronto Press, Toronto, 1971).

16. E. Blaith, Dynamic Mass Spectrometers (Elsevier Publishing Company, New York, 1966).
17. E. Jahnke and F. Emde, Tables of Functions (Dover Publications, Inc., New York, 1945).
18. S. Masuda and M. Washizu, J. of Electrostatics 6, 57 (1979).
19. M. M. Pauthenier and M. Moreau-Hanot, J. Physique Radium 3, 590 (1932).

APPENDIX I

LAYOUT AND INTEGRATED CIRCUIT DEFINITIONS FOR DATA ACQUISITION BOARD

TABLE I.1 INTEGRATED CIRCUIT NUMBER DEFINITIONS AND DESCRIPTIONS

IC #	IC type numbers	IC functional description
J1	LM318	high-performance operational amplifier
J2	SHM-HUGC	high-speed sample and hold
J3	10124	TTL to ECL converter
L1	74LS74	dual D-type flip-flops
L2	LM310	unity-gain buffer amplifier
L3	LM210	unity-gain buffer amplifier
L4	TDC-1001J	high speed 8-bit A/D converter
M1	74LS14	hex schmitt-trigger inverters
M2	7474	dual D-type flip-flops
M3	74LS93	4-bit binary counter
M4	CLOCK	20 MHz Crystal oscillator
M5	74LS367	hex bus drivers
N1	74153	dual 4-to-1 data selectors
N2	74LS368	inverted hex bus drivers
N3	74LS373	octal D-type latches
N4	74LS374	octal D-type flip-flops
P1	74193	synchronous dual binary counters
P2	74193	synchronous dual binary counters
P3	74LS373	octal D-type latches
P4	74LS373	octal D-type latches
R1	74193	synchronous dual binary counters
R2	74193	synchronous dual binary counters
R3	74LS373	octal D-type latches
R4	74LS373	octal D-type latches
S1	74193	synchronous dual binary counters
S2	74193	synchronous dual binary counters
S3	74LS373	octal D-type latches
S4	74LS373	octal D-type latches
T1	74LS138	3-to-8 line decoders
T2	HEADER	edge-conditioning circuits
T3	74LS373	octal D-type latches
T4	74LS373	octal D-type latches
V1	74LS04	hex inverters
V2	74LS93	4-bit binary counter
V3	74LS40	dual 4-input NAND gates
V4	74LS04	hex inverters
V5	74LS40	dual 4-input NAND gates
W1	74LS08	quadruple 2-input AND gates
W2	74LS08	quadruple 2-input AND gates
W3	74LS00	quadruple 2-input NAND gates
W4	74LS08	quadruple 2-input AND gates
W5	74LS00	quadruple 2-input NAND gates
X1	74LS74	dual D-type flip-flops
X2	74LS90	decade counter

IC #	IC type numbers	IC functional description
X3	7402	quadruple 2-input NOR gates
X4	74LS08	quadruple 2-input AND gates
X5	74LS04	hex inverters
Y1	8257	A direct memory access controller (DMA)
Y2	74LS74	dual D-type flip-flops
Y3	74LS74	dual D-type flip-flops
Z1	74LS193	synchronous dual binary counters
Z2	74153	dual 4-to-1 data selectors
ZZ1	74LS373	octal D-type latches
ZZ2	74LS193	synchronous dual binary counters
ZZ3	CONNECTOR	LINE SELECT SWITCHES
	7805	5-volt positive voltage regulator
	7812	12-volt positive voltage regulator
	7905	5-volt negative voltage regulator
	7912	12-volt negative voltage regulator

"LS" in type numbers indicates low-power Schottky-clamped series.

Figure 1.1 - Integrated circuit layout for data acquisition board.