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HIGH TEMPERATURE FACILITY FOR ATOMIC PHYSICS STUDIES

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TABLE OF CONTENTS

<u>SECTION</u>	<u>PAGE</u>
I INTRODUCTION	1
II MODIFICATION OF THE PLASMA SAMPLE FACILITY FOR HIGH TEMPERATURE OPERATION	2
III OPTIMIZATION AND PRELIMINARY EXPERIMENTS WITH THE HIGH TEMPERATURE PLASMA SAMPLE FACILITY	5
IV CONCLUSIONS AND INDICATION FOR FUTURE WORK	16
REFERENCES	17

LIST OF FIGURES

<u>FIGURE</u>		<u>PAGE</u>
1	Plasma Sample Chamber and Magnet for High Temperature Plasma Sample Facility Using Breakdown Mode Laser Heating.	3
2	Photograph of Beryllium-copper Magnet Sections Before Assembly	4
3	Optical and Vacuum System Layout for High Temperature Plasma Sample Facility Using Breakdown Mode Laser Heating	6
4	Photograph of Assembled High Temperature Plasma Sample Facility, CO ₂ Heating Laser with Unstable Oscillator Optics Installed in the Background	7
5.a.	Calibration of Puff Fill System, Deuterium Filling	9
5.b.	Solenoid Calibration, Field on Axis as a Function of Axial Position.	9
6	Photograph of the High Temperature Plasma Sample Facility with Emission Spectroscopy Diagnostics in Place	12
7	Streak Spectra of Laser Produced Plasmas in High Temperature Plasma Sample Facility.	14
8	Densitometer Scans of Time Integrated Film Spectra in 3434A Region.	15

SECTION I

INTRODUCTION

This report describes the results of a program designed to develop a laser heated plasma sample for atomic physics studies in the 30 to 100 eV range of electron temperature and the $3 \times 10^{17} - 10^{18} \text{ cm}^{-3}$ range in electron density. The approach used was discussed in detail in Mathematical Sciences Northwest, Inc., (MSNW) Proposal 1660, that is, the laser breakdown mode of heating in a slow solenoid. An extensive rework of the plasma sample facility was done in order to use this mode of heating. Specifically, a new solenoid magnet was constructed to allow higher field operation and the plasma chamber was modified to allow the use of puff filling orifices and small bore tube liners. The vacuum system and focussing optics were changed to allow the use of an on-axis Cassagranian system capable of focussing the laser radiation to a nearly diffraction limited spot as is necessary when heating through a small aperture. The 10 liter CO_2 laser optics were changed to an unstable oscillator configuration and additional windows were provided into the optical cavity for alignment purposes.

The plasma sample system was assembled and calibrations of the puff fill and solenoid were performed. The heating wave propagation was studied as a function of fill pressure and laser energy using streak and multi-frame image converter photography. It was found that preionization of the fill gas was necessary to produce a wave speed sufficiently high to reach the observation window during the laser pulse, hence the preionized mode was used in all subsequent experiments.

A series of laser heating experiments was conducted using streak spectroscopy in the visible region and both time resolved and time integrated spectroscopy in the quartz UV region. Spectral lines probably originating from CV and CVI were observed, indicating the presence of electron temperatures in the 60 eV range in the plasma column. Experiments using a fused quartz tube liner showed early wall ablation

commencing within 0.5 μ sec of the start of laser heating. Substitution of an alumina tube liner increased the lifetime of the high temperature plasma, as inferred from the spectroscopic observations.

SECTION II

MODIFICATION OF THE PLASMA SAMPLE FACILITY FOR HIGH TEMPERATURE OPERATION

2.1 Plasma Tube

In order to facilitate proper placement of flow limiting apertures for breakdown mode heating the plasma sample chamber was redesigned according to Figure 1. The plasma tube is now supported from the magnet assembly or polyethylene collars, and the tube liner is supported by the ceramic aperture on one end and by a polyethylene insert on the downstream end. The aperture is located at the axial position where B_z has fallen to 50 percent of maximum, as found to be optimum by the University of Washington researchers.¹ Connection between the plasma sample chamber and the rest of the vacuum system is made using nylon end bells similar to those used in the MSNW Laser Heated Solenoid Program. These end bells also carry the electrical feed through for the z-discharge preionization system. The magnet compression plates made of G-10 plastic were retained, but were modified to accommodate the new magnet sections.

2.2 Magnet

New 7 turn magnet sections were fabricated with a length of 8.8 cm, a bore of 4.0 cm, and 1/2 inch pitch. Beryllium-copper was used for these, in part because of our accumulated experience in fabricating and welding this material, and in part because its high strength would allow an increase of the magnetic field to at least 20 tesla with an adequate power supply and coil support system if desired at a later date. A photograph of the magnet before assembly into the rest of the system is shown in Figure 2.

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Figure 1. Plasma Sample Chamber and Magnet for High Temperature Plasma Sample Facility Using Breakdown Mode Laser Heating.

Figure 2. Photograph of Beryllium-copper Magnet Sections Before Assembly.

2.3 Laser

The 10 liter CO₂ laser optics were modified to allow a new, diffraction coupled, He-Ne alignment system to be used, and the optics were assembled in an unstable oscillator configuration. The sustainer Marx bank was overhauled, with some changes to the triggering system to improve reliability. This, in combination with a complete revision of the e-beam Marx, which had been done on another program, considerably improved the reliability of the CO₂ laser providing much improved energy and intensity reproducibility.

2.4 Assembly

Modifications to the rest of the system are shown in Figure 3. An adjustable mirror mount was fabricated for the Cassagranian diagonal mirror and installed in the turning box. A normal incidence mirror mount was installed in the focussing box, and the vacuum system was assembled with the focus of the laser beam at the entrance aperture. The puff fill system was assembled and arranged to puff gas into the plasma tube through the downstream end bell. Figure 4 shows a photograph of the plasma sample chamber and vacuum system assembled (foreground) with the CO₂ laser and laser diagnostics table in the background.

SECTION III

OPTIMIZATION AND PRELIMINARY EXPERIMENTS WITH THE HIGH TEMPERATURE PLASMA SAMPLE FACILITY

3.1 Preliminary Calibrations Of The Apparatus

After assembly was completed, calibrations of the puff fill system and solenoid magnet were performed. The puff fill system was operated with a pulse of about 20 msec duration applied to the solenoid, which resulted in approximately a 90 msec open time for the solenoid valve. The pressure in the plasma sample chamber was measured using a Kistler piezoelectric pressure transducer, of 113 mV/psi sensitivity mounted in the downstream end bell region. It was found that the pressure

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Figure 3. Optical and Vacuum System Layout for High Temperature Plasma Sample Facility Using Breakdown Mode Laser Heating

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Figure 4. Photograph of Assembled High Temperature Plasma Sample Facility, CO₂ Heating Laser with Unstable Oscillator Optics Installed in the Background.

peaked about 150 msec after application of the solenoid pulse at all reservoir filling pressures. This was taken as the reference filling pressure, and all heating experiments were done at 150 msec after initiation of the puff fill. A calibration of the puff fill system for two different tube liner and aperture combinations is shown in Figure 5a. The 5 mm aperture was used in all the heating experiments discussed later.

A plot of the axial magnetic field produced by the solenoid as a function of axial position was obtained, using a movable search probe of 10 mm² area. The result is shown on Figure 5b. The value of B_z , that is, the maximum value of B_z in the solenoid determined during this calibration was 3.7 tesla at $V_0 = 10$ kV bank charge. This scales to at least 7.5 tesla at the full bank charge of 20 kV, which was used during most of the heating experiments. The solenoid bore has been reduced to 4 cm, requiring an increase in the gap between the magnets to 3.3 cm in order to clear the bulge in the plasma tube and this results in the 90 percent B_z dip shown. Both factors increase the gap to bore field ratio for this magnet, thus actually increasing the dip slightly over that in the previous design. A significant improvement in this could be obtained by redesigning the cross tube so that a gap of perhaps 1.5 cm could be used.

3.2 Preliminary Heating Experiments

Preliminary heating experiments were done to examine the propagation of the heating front from the orifice to the observation area, and to obtain information on radial uniformity of the plasma. Image converter photography in a framing mode was used to obtain information on the axial and radial extent of the plasma. Initial experiments were done with a 3 mm aperture and a 12 mm bore quartz plasma tube. Filling densities (atom) of $2.8 \times 10^{17} \text{ cm}^{-3}$ and $5 \times 10^{17} \text{ cm}^{-3}$ of deuterium were used without preionization. Plasma propagation in the tube was observed to have the form of a narrow pointed channel as has been observed

Figure 5a. Calibration of Puff Fill System, Deutrium Filling.

Figure 5b. Solenoid Calibration, Field on Axis as a Function of Axial Position. At bankcharge of 10 kV, $B_0 = 3.7$ tesla.

earlier¹ in similar experiments. In no case, however, did the heated channel reach the observation region, 10 cm downstream from the aperture during the laser pulse duration. The heating front propagated at a velocity on the order of 5 cm μ sec during the laser pulse.

Two changes were made before further experiments, the aperture size was increased to 5 mm, and preionization was added to the system. An axial preionization discharge was produced in the plasma tube, using a varistor damped system similar to that described in our report MSNW-77-1081-1. An 0.05 μ f capacitor was used with varistor damping to produce a single current pulse of 2 kA peak and 600 nsec duration when charged to 30 kV. This discharge should not produce full ionization nor would it pinch the plasma when operating with filling densities in the 10^{17} range. At the filling aperture, however, the current density is high enough to almost fully ionize the plasma; the idea being to produce a prompt start for this laser-plasma interaction and possibly to modify the front propagation mechanism by adding electron thermal conduction at the front.

Image converter photographs using the preionization, with laser heating started at the end of the preheat pulse showed that the heating front did reach the observation window early in the laser heating pulse. The plasma tube appeared to be uniformly filled with heated plasma. An attempt was made to determine the propagation speed using axial streak photography, but the bright propagating front seen was shown by later spectroscopic experiments to be a wall ablation front, and hence of little interest.

3.3 Heating Experiments with Emission Spectroscopy as a Diagnostic

Since the extent of experimental work done under Task I of this contract was much greater than originally considered, with agreement of the LLL contract monitor, we substituted spectroscopic observation of the plasma for the Thomson scattering measurements intended initially. The apparatus used in these measurements is shown in place in the

photograph (Figure 6). An STL streak spectrometer viewed the whole cross section of the plasma tube in the visible region of the spectrum. Simultaneously the McPherson Model 218 monochrometer viewed 3 mm about the axis of the tube using quartz optics.

The monochrometer was used primarily in an attempt to observe spectral lines in the quartz UV region of the spectrum such as C VI 3434 Å which could be used as temperature indicators.² This instrument was used as a monochrometer with an instrument profile of 1 Å (FWHM) to provide time resolved (photoelectric) intensity information, and as a time integrated (photographic) spectrometer. In the spectrometer mode, detailed information could be obtained in the neighborhood of a line of interest on a single shot. In particular, line profiles could be examined qualitatively, and possible contaminant lines identified.

Using this apparatus, a series of laser heating shots was begun using approximately 100 joules of laser energy to heat preionized fillings of $D_2 + CH_4$ gas at N_{FILL} varying from $1.25 \times 10^{17} \text{ cm}^{-3}$ to $5 \times 10^{17} \text{ cm}^{-3}$. Preliminary experiments showed evidence that plasma temperatures in the 60 eV range were attained. Carbon III, IV and probably CV 4945 Å could be seen in the visible streak spectra, and the monochrometer showed a line to be present with about twice the continuum intensity of 3434 Å.

The streak spectra also showed very early wall ablation, starting about 0.5 μsec after heating at the lowest fill pressure, and even earlier at higher fill pressures. Also, no "burning through" of CIII was observed, indicating that a considerable range of temperatures must exit due to radial gradients.

In an effort to reduce the effect of wall ablation, the quartz tube liner was replaced with an alumina liner of 8 mm ID. Optical access slots approximately 1 mm wide and 5 mm high were cut into both sides of the tube at its midplane. These slots were then imaged on the slits of the spectrometers. A series of laser heating shots was done with this new liner using the same conditions previously used with the quartz liner.

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Figure 6. Photograph of the High Temperature Plasma Sample Facility with Emission Spectroscopy Diagnostics in Place.

Streak spectra for typical heating shots are compared in Figure 7. In the quartz tube shot shown on the upper part of Figure 7, the arrival of the heating front is shown by the appearance of CIII and CV lines while the D line intensity is depressed. After about $0.5 \mu\text{sec}$ SiII lines appear and the D lines increase in intensity, indicating a decrease in temperature (or increase in density). This is labeled t-quench. In the alumina tube shot, the quench event is more difficult to identify, since no SiII is seen, but it appears to occur at about $1.2 \mu\text{sec}$ after the heating front is seen. A number of unidentified lines are present in this experiment which appear immediately on passage of the heating front. They are possibly due to the presence of an air leak in the apparatus which was discovered on disassembly. A crack was found in the outer plasma tube which probably was caused when installing the alumina liner. The resulting leak was not noticed in the base pressure, but due to the flow restriction of the aperture could have caused a significant air concentration in the plasma volume.

Time integrated film spectra were also taken in the region around $3434 \text{ \AA}$ while using the alumina tube. Densitometer scans of the resulting spectra are shown in Figure 8. Results are shown for three different filling pressures, with a result from the DOE Laser Heated Fast Solenoid shown for comparison. A broad line of about $10 \text{ \AA}$ FWHM is seen $3434 \text{ \AA}$ clearly separated from the continuum. This could be the hydrogenic CVI line. The identification in this case is clouded by the fact that the OIII, $3^5\text{D}^0\text{-}3\text{d}^5\text{F}$ multiplet³, the strongest member of which is at $3455 \text{ \AA}$ is also seen in the film spectrum. This probably comes from the air leak discussed earlier. The lithium-like ion OVI has a transition array,³ $6^3\text{G-}7\text{h}^2\text{H}^0$, etc, at $3434 \text{ \AA}$, coincident with the CVI₆₋₇ transition. In fact, the film spectrum taken at the lowest film pressure ($n_{\text{fill}} = 1.25 \times 10^{17} \text{ cm}^{-3}$) probably has discrete lines due to OVI, particularly $6^3\text{F}^0\text{-}7\text{d}^2\text{D}$ at $3438 \text{ \AA}$. It isn't clear at this time whether the broad feature at $3434 \text{ \AA}$ at higher filling pressure is due to CVI or OVI although the lack of clearly defined lines at $3438 \text{ \AA}$, $3433 \text{ \AA}$, and $3426 \text{ \AA}$ suggests that most of this feature is due to CVI.

Figure 7. Streak Spectra of Laser Produced Plasmas in High Temperature Plasma Sample Facility. Both cases were with preionization, $n_{fill} = 1.25 \times 10^{17} \text{ cm}^{-3}$, $D_2 + CH_4$ heated with 100 joules laser energy with a magnetic field of 2.8 tesla at the observation point (15 kV charge). The line just to the left of D_{β} is probably CV 4945.

Figure 8. Densitometer Scans of Time Integrated Film Spectra in 3434 Å Region. Breakdown experiments all with preionization, E laser ~100 joules.

SECTION IV

CONCLUSION AND INDICATION FOR FUTURE WORK

These preliminary results of experiments in the high temperature plasma sample facility indicate that high electron temperatures, on the order of 60 eV are attained in a part of the plasma sample volume. The continued presence of CIII radiation throughout the experiments suggests strongly that low temperature regions of significant extent also exist. More detailed work with this facility will be needed to define the plasma conditions before it will be useful as a calibration source for high temperature diagnostics. Thomson scattering measurements would provide the desired information.

The early wall ablation seen with the quartz tube also suggests that radial heat conduction may be a problem, not only in allowing rapid plasma decay, but in causing formation of a cold radiating boundary layer. The magnetic field strength should be increased to produce better magnetization of the ions than we have achieved so far, and the possibility of using a rapidly increasing B_z to lift the plasma from the wall should be explored. Theoretical models developed in the laser heated solenoid program indicate that nearly isothermal plasma columns may be produced in this way. These techniques are considerably more expensive than those used so far in the high temperature plasma sample facility, but fortunately, we intend to develop these techniques under another atomic physics program.

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