Lawrence Livermore Laboratory

Analysis of Long Pulse Physics Experiments at LLL: Late 1977-Early 1979

Mordecai David Rosen

July 18, 1979

MASTER

Prepared for the 1979 Gordon Research Conference on Laser Interaction with Matter,
August 13-17, 1979, Tilton School, Tilton, New Hampshire.

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

Analysis of Laser-Plasma Device Performance at LLNL

Lawrence Livermore Laboratory

Lawrence Livermore Laboratory

University of California
Lawrence Livermore Laboratory
Livermore, California 94550

This paper was prepared for the Conference on Laser
Interaction with Matter, Santa Fe, New Mexico, August 13, 1979.

Work performed under the auspices of the U.S. Department of Energy by
the Lawrence Livermore Laboratory under contract No. W-7405-ENG-48.

NOTICE
This report was prepared as an account of work
specifically for the United States government. Neither the
United States nor the United States Department of
Energy, nor any of their employees, nor any person
contracting with the government, nor the employee, makes
any warranty, express or implied, or assumes any legal
liability or responsibility for the accuracy, completeness,
or usefulness of any information, product, or process
disclosed, or represents that its use would not
infringe privately owned rights.

Fig

In the two years since the last Gordon Conference, we have shifted our interest in laser-plasma interactions to the long pulse (1 ns) regime on the Argus facility. This talk will be divided into a number of parts (Figs. 0a-0c). Gold disks and the dependence of their absorption, scattering, emission, and coronal temperature on intensity will only be briefly discussed since they will be described in great detail in The Physics of Fluids, to be published shortly. A variable Z disk series (at 3×10^{14} W/cm²) has been carried out and the Z dependence of line emission, backscatter, T_h (hot electron temperature) and transport inhibition will be described. A variable thickness Au disk series that studied preheat and shocks will be analyzed. If time permits, a simple theory for why T_h scales as $Z^{1/4}$ will be presented, and a description of an electron transport experiment through layered disk targets will be given if there is any time left after that (highly unlikely!).

I. Au Disks

Since inverse bremsstrahlung absorption scales as $\{Z(Z/A)^{1/2} t_1^{3/5} I^{-2/5}$, in order to maximize this process we shot high-Z disks (Au) at a long pulse (1 ns) at moderate intensities (10^{14} - 10^{15} W/cm²) (Fig. 1a). Figure 1b describes some experimental results and 2-D hydrodynamic modeling with and without transport inhibition (at the 0.03 level). Inhibited transport heats up the corona since the energy is not transported into the overdense material. It is in the dense material where radiative processes are most efficient, so inhibited transport produces less emission. Since the Q factor for

backscatter scales as $1/T_e$, the inhibited model, with higher T_e , predicts less backscatter than the model with classical conduction. Absorptions are lower as well, since $f_{1,3} \propto Z/T$. In general then, the inhibited model tends to reproduce experimental observables whereas classical conduction does not. An x-ray microscope, viewing the disk edge-on (Fig. 1c) sees a narrow emission region, a signature of transport inhibited into the disk. Non-LTE ionization physics plays a crucial role in treating the lines and the coronal region, as is evident from Fig. 1d. In conclusion, inverse bremsstrahlung indeed played a major role in these experiments; the temperature scaled as predicted; stimulated scattering at these long pulses was large; only a few percent of the energy went into a T_h spectrum; and transport seems inhibited. For more details see M. D. Rosen et al., Phys. Fluids, October 1979 (UCRL-82146).

II. Variable Z Disks

The motivation for this series was to assess the feasibility of using a disk target as a source or x-ray backlight an imploding target. Titanium seemed like an appropriate candidate with strong He γ line emission at 4.7 keV. As a bonus we studied backscatter, T_h , and transport inhibition vs Z (Fig. 11a).

Titanium's sub-keV spectrum, with its prominent L lines at 700 eV was a challenging test for the Dante 10 system. As seen in Fig. 11b, it performed very well. From line ratios a Z_{eff} of 16 ± 1 was deduced (by P. Lee). Numerical simulations confirm this result.

Pearlman and Anthes (Appl. Phys. Lett., 27, 581 (1975)) found a threshold for transport inhibition of 1×10^{14} W/cm² for polystyrene ($\bar{Z} \approx 3$). McClellan has asked the question how does this threshold vary with Z? The answer is shown in Fig. IIc. This was derived by looking at the emission from different Z targets. When inhibition sets in, the emission is reduced, as explained in Section I. As the laser pulse rises the intensity rises, so the threshold is crossed at a particular time, as is evident in Fig. IIc. For Be it is almost immediate, for Sn very near the peak of the pulse, and for Au and U the threshold is never crossed. Figure IIe shows gold at two intensities and demonstrates the effect for the higher Z material. If we believe that much of the back reflected light is due to Brillouin scattering then Fig. IIc shows the same effect, since, as explained in Section I, Brillouin is less effective for inhibited transport situations.

Fig. IIg shows high energy x-ray behavior as a function of Z. The level of x-rays rises as $Z^{1.0}$, as expected from classical bremsstrahlung theory. T_h (the slope) is not too well defined since there seems to be a hot portion and a super-hot tail. From the hot portion we see that $T_h \sim Z^{1/4}$, to be explained in Section IV. The super-hot tail may be due to quarter-critical processes, filaments, or hot spots.

In conclusion, titanium may be used in the future to backlight implosions; the inhibition threshold can be written as 10^{14} W/cm² $(1 + (Z/15))$ (for more details see McClellan et al., UCRL-83044); and $T_h \sim Z^{1/4}$ (Fig. IIh).

III. Variable Thickness Gold Disk Series

To study preheat and/or shock propagation in gold disks, we varied the thickness for 2 to 25 μ . Since the energy in suprathermals was about 4 J, with a T_h of about 35 keV (at 3×10^{15} W/cm², 1 ns) we find a range of 0.7 μ (Fig. IIIa). Thus we expect much preheat for 2 μ and very little for 14 and 25 μ .

An optical streak camera measures the temperature at the back of these disks. It finds about 25 eV for 2 μ . This is prompt preheat as confirmed by simulations. For 14 μ it finds about 6 eV (prompt) which is surprisingly high if it were preheat. For 25 μ it finds 5 eV at a 1 ns delay, which if it were preheat, would be downright astounding (Fig. IIIb). In fact simulations predict this behavior, and it is obviously due to shocks (20-25 MB). (A prompt 5 eV signal at the back of the 25 μ slab may be due to local hot spot preheat.)

All of these results may be modeled analytically (Fig. IIIc). Pressure scales as $I^{2/3}$ where caution must be used in applying the correct intensity since reflection, emission losses, and 2-D effects all decrease I . We find $P \approx 25$ MB. From this and the strong shock relation ($P = (2/(1+\gamma))\rho v_s^2$) we find a shock velocity of about 10^6 cm/sec which gives the correct delay time of about 1 ns between a 14 μ and 25 μ sample. Assuming an ideal post-shock gas with four times compressed matter ($\gamma = 5/3$) and with $Z \approx 50$ $T_{keV}^{1/2}$ we find a corresponding temperature of 9 eV, within a factor of two of observation.

To find the preheat (Fig. IIId) we apply the following general formalism. We find T_e (assuming a perfect gas) from the specific

energy λ , which is given by $\lambda = (2/A) dE/dx$ where A is the area of the spot size. The factor of two assumes that the electrons that come through the back are turned around and redeposited.

To find dE/dx we appeal to a $\lambda \sim E^2$ scaling, thus yielding $E(x) = E_0(1-2x/\lambda_0)^{1/2}$. Averaging $E(x)$ over an initial Maxwellian, we can then take dE/dx and evaluate the integral numerically, finding that $dE/dx = 0.4 E_{TOT} \lambda_h^{-1} (L^{\log_{10} L})^{-1}$ for $L = 2x/\lambda_h$ between 1 and 100. Applying this formalism to this series we find (Fig. IIIe) 25 eV preheat for 2 μ , as observed, and less than 1 eV for 14 μ and thicker. Indeed, these are upper limits, since λ scales weaker than E^2 for high energy electrons, which are the ones contributing to the very thick disk preheat. In fact, for 25 μ , suprathermal bremsstrahlung contributes more to the preheat than does direct suprathermal deposition, as crudely estimated in Fig. IIIf. If there were localized hot spots with 1/10 the suprathermal energy in 1/100 the area, the increased range of these hotter suprathermals can produce a prompt 5 eV signal through 25 (Fig. IIIg).

In conclusion, we have observed 2 μ gold to be preheated to 30 eV and have seen a 25 MB shock propagate through gold of thicknesses varying from 14 to 25 μ (Fig. IIIh).

IV. $T_h \sim Z^{1/4}$ Scaling

As shown in Section II, $T_h \sim Z^{1/4}$. This was suspected on the basis of earlier experiments (Fig. IVa). We believe that reheating can account for this effect, since a scattered electron can be reheated as it

makes multiple passes through the critical surface where it interacts with resonant electric fields. The higher the Z , the more the scatter and the reheating (Fig. IVb). Figure IVc quantifies this picture in terms of an energy albedo k and number albedo α . We find T_h scales as $(1-\alpha)-1(1-k)-1$. For Au vs glass we find $T_h \propto Z^{.33}$, close to the observed scaling. Figure IVd shows this scaling theory for all intensities and Z 's. This agreement is quite good. For further details see M. D. Rosen et al., UCRL-82280.

V.

We are in the process of redoing the NRL layered disk targets experiments (CH on Al) to examine electron conduction. Preliminary results seem to reproduce the NRL results. This is a first step in a series designed to study transport inhibition.

In conclusion, Fig. Va, long pulses make lots of plasma, which makes lots of plasma physics, which makes life interesting.

NOTICE

"This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express 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 to a company or product name does not imply approval or recommendation of the product by the University of California or the U. S. Department of Energy to the exclusion of others that may be suitable.

ANALYSIS OF LONG PULSE PHYSICS EXPERIMENTS AT LLL: LATE 1977- EARLY 1979

By

Mordy Rosen

**Gordon Conference on Laser-Matter
Interactions, Tilton, N. H., Aug 13, 1979**

50-90-0779-2146

THIS TALK IS IN 3-5 PARTS

- I Au disks: intensity dependence of absorption, scattering, emission, and T_e**

**[Rosen, Phillion, Rupert, Mead, Kruer, Thomson, Kornblum, Slivinsky, Caporaso, Boyle, and Tirsell
Phys Fluids (Oct 79)]**

- II Variable Z disks: Z dependence of line emission, backscatter, T_h , and transport**

[Attwood, Campbell, Ceglio, Koppel, Lane, Lee, Matthews, Phillion, Pruett, McClellan, Caporaso, and Rosen; (McClellan, Lee, and Caporaso submitted to P.R.L.)]

OUTLINE OF TALK (Cont'd)

- III Preheat and/or shocks in Au disks: T_e (back) vs. thickness (2-25 μ)**
(Rosen, Price, Phillion, Caporaso, and Tirsell)
- IV T_{hot} scaling with Z**
(Lane, Campbell, Pruett, Kornblum, and Slivinsky)
(Rosen, Estabrook, and Albritton)
- V Miscellaneous experiments: Transport inhibition
a la' NRL**

50-90-0779-2148

8/79

Au DISKS: MOTIVATION

Long pulse, Hi Z, moderate intensity to put us into the efficient inverse Bremsstrahlung regime

$$f_{IB} \sim \frac{Z L}{T^{3/2}} \sim Z \left(\frac{Z}{A} \right)^{1/2} \frac{t}{T}$$

$$f_{IB} I \sim T^{3/2} \Rightarrow T \sim \left(I t Z \left(\frac{Z}{A} \right)^{1/2} \right)^{2/5}$$

$$\Rightarrow f_{IB} \sim \left(Z \left(\frac{Z}{A} \right)^{1/2} t \right)^{3/5} I^{-2/5}$$

50-90-0779-2151

AU DISK EXPERIMENTS COMPARISON WITH NUMERICAL SIMULATIONS

Quantity	$3 \times 10^{14} \text{ W/cm}^2$			$3 \times 10^{15} \text{ W/cm}^2$		
	Experiment	SIMULATIONS		Experiment	SIMULATIONS	
		Inhibited Conduction	Classical Conduction		Inhibited Conduction	Classical Conduction
Radiated energy	35 (± 7) %	33%	62%	35 (± 7) %	36%	58%
Absorbed energy						
Coronal T_e (keV)	5 (± 2)	4	1	20 (± 10)	16	4
Brillouin backscatter	13 (± 5) %	14 (± 7) %	40 (± 20) %	20 (± 6) %	20 (± 10) %	40 (± 20) %
Absorption (code corrected for back and side scatter)	50 (± 5) %	55 (± 8) %	70 (± 10) %	36 (± 4) %	36 (± 7) %	54 (± 10) %
Suprathreshold energy incident energy	1 (± 0.5) %	2%	0.1%	3 (± 1) %	3%	1%

50-90-0679-1898

8/79

Fig. 1b

2 keV X-RAY MICROSCOPE IMAGE LOOKING AT A GOLD DISC EDGE ON.
 (1 NS PULSE OF 1.06μ LIGHT, $8 \times 10^{13} \text{ W/cm}^2$). NARROW WIDTH OF
 EMITTING REGION IMPLIES INHIBITED TRANSPORT.

50-02-0878-2715

Fig. 1c

X-RAY SPECTRUM FOR 1 ns 1.06 μ LIGHT ON GOLD DISCS (3×10^{14} W/cm²).
 MODEL WITH NON-LTE AND INHIBITED TRANSPORT (—) MATCHES
 EXPERIMENT NON-INHIBITED (---) AND LTE (---) DO NOT

50-02-0878-2716

8/79

Fig. 1d

CONCLUSIONS FROM Au DISK EXPERIMENTS

- Absorption scaling $\Rightarrow$ inverse Bremsstrahlung as dominant mechanism
- $T_e \sim I^{0.6}$ scaling $\Rightarrow$ ditto $T_{IB} \sim \left(I t Z \left(\frac{Z}{A} \right) \right)^{2/5}$
 $Z \sim T^{1/2} \Rightarrow T_{IB} \sim I^{0.57}$
- Stimulated scattering is at the 30-40% level
- Non-LTE treatment is essential to the modeling
- Only a few % of the energy goes into suprathermals
- Conduction appears to be $\frac{C_s}{V_e} \approx 0.03$ of classical level

VARIABLE Z DISKS:

Motivation: test for x-ray backlighting candidates

Bonus: test backscatter, T_{hot} , and transport inhibition vs Z

Keep intensity fixed at 3×10^{14} W/cm² at 1 ns

50-90-0779-2153

TITANIUM L LINES TEST DIAGNOSTICS AND CODE

Z DEPENDENCE OF LASER INTENSITY THRESHOLD FOR INHIBITED ELECTRON CONDUCTION

20-90-0579-1848

Fig. IIc

Z DEPENDENCE OF THE TIME-RESOLVED SUB-keV X-RAY EMISSION FROM LASER-PRODUCED PLASMAS

Laser

$I = 5 \times 10^{14} \text{ W/cm}^2$

1 ns FWHM

XRD

520 eV channel

190 ps resolution

^4Be [2 V
0

^{22}Ti [20 V
0

^{50}Sn [40 V
0

^{79}Au [80 V
0

^{92}U [200 V
0

0 2 ns

20-50-0679-1864

Fig. 11d

TIME-RESOLVED SUB-keV X-RAY EMISSION FOR Au-DISKS AT DIFFERENT
LASER INTENSITIES (XRD: 940 eV CHANNEL, 170 ps RESOLUTION)

$$I = 5 \times 10^{14} \text{ W/cm}^2$$

$$I = 3.3 \times 10^{15} \text{ W/cm}^2$$

0 2 ns

Laser pulse fiducial

20-50-0679-1865

Fig. 11e

BACK REFLECTED LIGHT SUPPORTS THE THRESHOLD HYPOTHESIS

$$Q_{\text{BBS}} \sim \frac{IL}{T_e} : T_{e\text{INH}} > T_{e\text{CLAS}} > Q_{\text{INH}} \sim Q_{\text{CLAS}}$$

50-90-0779-2154

HIGH ENERGY X-RAY SPECTRA AT 5×10^{14} W/cm² (1 ns PULSE)

CONCLUSIONS FROM VARIABLE Z DISK STUDY

- Titanium is a promising candidate for x-ray backlighting studies
- Threshold for inhibited electron conduction is $I_T \approx 10^{14} \times (1 + Z/15) \text{ W/cm}^2$
- T_h scales as $Z^{1/4}$

50-90-0779-2155

PREHEAT AND/OR SHOCKS IN THICK Au DISKS

Vary thickness 2, 14, and 25 μ and observe T_e (at back of disk) vs time with optical streak camera

All disks shot at 3×10^{15} and 1 ns
 T_{hot} of 35 keV, E_{hot} of about 4 J

$$\lambda_{\text{range}_h} = \frac{2}{5} \mu \left(\frac{\theta_h}{Z_N} \right)^2 \sqrt{Z_N} = 0.7 \mu$$

Intuitively expect large preheat at 2 μ , and very little at 14 and 25 μ

PREHEAT MEASURED ON BACK OF THICK GOLD DISKS

Dante L shows 20 to 30 eV prompt preheat. Simulations agree.

Simulations suggest 0.2 eV preheat plus 5 eV shock near $t = 0$. Dante L shows 15 eV prompt.

Simulations suggest b) 0.02 eV preheat plus 5 eV shock at 1 ns. a) may be due to hot spot preheat. For b) Dante L shows 15 eV at 800 ps delay.

50-90-0779-2150

ALL OF THIS DATA CAN BE MODELED ANALYTICALLY

Shocks:

$$P(\text{MB}) = 10 \left(\frac{A}{2Z} \right)^{1/3} (10^{14} \text{ abs})^{2/3}$$

Include 2-D expansion effects (lowers I) and obtain:

$$P \approx 25 \text{ MB}$$

$$P = \frac{2}{\gamma + 1} \rho_0 V_S^2 \Rightarrow V_S = 1.3 \cdot 10^6 \text{ cm/sec}$$

$$\Rightarrow \Delta t = \frac{\Delta X}{V_S} = \begin{cases} 1.1 \text{ ns } (14 \mu) \Rightarrow \text{a little after peak of pulse} \\ 1.9 \text{ ns } (25 \mu) \Rightarrow \text{a } 1^+ \text{ ns delay} \end{cases}$$

$$P(\text{MB}) = \rho \left(\frac{Z+1}{A} \right) T_{\text{keV}} 10^3; \rho = \frac{\gamma+1}{\gamma-1} \rho_0; Z \approx 50 T_{\text{keV}}^{1/2}$$

$$\Rightarrow T \approx 9 \text{ eV}$$

SUPRATHERMAL PREHEAT: GENERAL FORMALISM

- $T_{eV}(Z+1) \approx 7 \cdot 10^{-5} \epsilon(\text{J/gm}) \quad (Z = 1.6 T_{eV}^{1/2})$

- $\epsilon = \frac{2}{(\text{area}) \rho} \frac{dE}{dX} \quad \text{find } \frac{dE}{dX}$

$$\frac{dE}{dX} = \frac{-E}{\lambda(E)} ; \lambda(E) = \frac{\lambda_h E^2}{\theta_h^2} \Rightarrow E(X) = E_0 \left(1 - \frac{2X}{\lambda(E_0)}\right)^{1/2}$$

$$\langle E(X) \rangle = \int_0^\infty [4\pi V_0^2 f_{\text{mxwl}}(V_0)] \left[\frac{1}{2} m V_0^2 \left(1 - \frac{2X}{\lambda_h} \left(\frac{V_h}{V_0}\right)^4\right) \right]^{1/2} dV_0$$

$$\left\langle \frac{dE}{dX} \right\rangle = -3 \frac{E_{\text{TOT}}}{\lambda_h} \int_{L^{1/4}}^\infty \frac{1/2 y^2 e^{-y} dy}{\sqrt{y^4 - L}} \approx \left(\frac{E_{\text{TOT}}}{\lambda_h} \right) \left(\frac{0.4}{L^{\log_{10} L}} \right)$$

$$L \equiv \frac{2X}{\lambda_h}$$

For $1 \leq L \leq 100$

SUPRATHERMAL PREHEAT: APPLICATION OF FORMALISM

Apply the formalism to $X = 2, 14,$ and 25μ . $\lambda_h \approx 0.7 \mu$.

Use $E_{TOT} = 4 \text{ J}$; area = $2 \cdot 10^{-4}$ (spot size)

Find:

$T_e \text{ (eV)}$	$X(\mu)$
25	2
0.4	14
0.05	25

Note: These are over estimates for the thicker samples.

$\lambda_h \sim E^{1.5}$ $100 \text{ keV} \leq E \leq 1 \text{ MeV}$. Redoing the formalism for this λ_h scaling drops T_e (14μ) to 0.2 eV and T_e (25μ) to 0.002 eV .

SUPRATHERMAL BREMSSTRAHLUNG PREHEAT ESTIMATE

$$\lambda(h\nu)_{\text{mfp}} = \frac{1}{K\rho} \approx 7 \mu \left(\frac{h\nu}{10 \text{ keV}} \right)^3 \approx 300 \mu \text{ for } h\nu = 35 \text{ keV}$$
$$\Rightarrow \frac{\Delta X}{\lambda} \ll 1$$

$$\Rightarrow \frac{dE}{dX} \approx \frac{E_R}{\lambda_{35}} ; \left(E_R \approx \frac{4J}{100} \right)$$

$$\Rightarrow T_e \approx 0.01 \text{ eV} \gg T_e (25 \mu) \approx 0.002 \text{ eV}$$

due to Bremsstrahlung

due to direct
suprathermal deposition

(This result confirmed by simulations)

50-90-0779-2160

WHAT IF THERE ARE HOT SPOTS?

$$\text{Take } E_{hs} = \frac{1}{10} E_{TOT}$$

$$A_{hs} = \frac{1}{100} A_{\text{spot size}}$$

$$\Rightarrow I_{hs} = 10 I_{inc} \Rightarrow \theta_h = 90 \text{ keV}$$

$$\Rightarrow \lambda_R \approx 5 \mu$$

Apply formalism to 25 μ disk ($L_{hs} \approx 10$)

$$\Rightarrow T_e = 5 \text{ eV}$$

Source of prompt preheat?

CONCLUSIONS FROM PREHEAT SERIES

- $2\ \mu$ gold disk preheated to 25 eV
- $14\ \mu$ gold disk preheated to 0.2 eV, but a 5 eV (20 MB) shock arrives shortly after the peak of the laser pulse
- $25\ \mu$ gold disk preheated by suprathermal Bremsstrahlung to 0.02 eV, and the 5 eV shock arrives 1 ns after the peak of the pulse
- Localized hot spots may account for a prompt 5 eV signal through $25\ \mu$ gold disk

θ_H DEPENDS ON INTENSITY AND $\bar{Z}$

75-90-0878-2936

Fig. IVa

ELECTRON REHEATING MECHANISM

50-90-0479-1091

Fig. IVb

ALBEDO APPROACH TO $T_{hot} \sim Z^{0.25 \text{ to } 0.35}$

Define number albedo β , energy albedo K .

50-90-1078-3525

$$\frac{E_f}{E_o} = \sum_{n=0}^{\infty} \beta^n \left(\sum_{m=0}^n K^m \right)$$

$$= \left(\frac{1}{1-\beta} \right) \left(\frac{1}{1-\beta K} \right)$$

$$\sim T_{hot}$$

Example:	Z	β	K	$\left(\frac{1}{1-\beta} \right) \left(\frac{1}{1-\beta K} \right)$
Au	79	0.45	0.6	2.49
SiO ₂	10	0.13	0.45	1.22

$$\frac{2.49}{1.22} = 2.04 = (7.9)^{0.34} \sim Z^{0.34}$$

4/79

Fig. IVc

50-90-1078-3520

Fig. 1Vd

CONCLUSIONS

- Long pulses make lots of plasma ($L \sim C_S t$)
- Lots of plasma makes lots of plasma physics
(Inverse Bremsstrahlung, stimulated scattering, filamentation, resonant absorption)
- Lots of plasma physics makes life interesting
and if that weren't enough . . .
- Not all plasmas are the same (Z effects)