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STUDIES OF LASER-DRIVEN FLYER ACCELERATION USING OPTICAL FIBER COUPLING*

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ABSTRACT

An optically recording velocity interferometer system has been used to measure acceleration histories and maximum velocities for laser-driven aluminum foil targets launched from the output face of optical fibers. Peak flyer velocities have been determined as a function of various parameters, including driving laser fluence, laser pulse duration and target thickness. The results at high fluences are consistent with a nearly constant efficiency of coupling optical energy into flyer kinetic energy and a small ablated mass fraction; however, the coupling efficiency falls off rapidly at fluences < 15 J-cm^{-2}. Measurements of the time delay between laser pulse arrival at the target and the onset of flyer motion have also been performed. Significant delays are observed at low fluences, arising from the increased time required for plasma formation at the fiber/foil interface under these conditions.

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1. INTRODUCTION

Commercially available step-index, multimode optical fibers can reliably transmit Nd:Glass (λ = 1.06 μm) laser pulses of high irradiance (>3.5 GW-cm^{-2}) without bulk or surface damage.[1] Coupling this high optical power onto thin foils placed on the fiber ends is an efficient method for producing high-velocity thin flyers which, in turn, can be used for well-controlled, short-pulse compressive loading of a second material.[2,3] In addition to providing a flexible and relatively safe delivery system for such applications, optical fibers offer two important advantages in fundamental studies of flyer generation. First, the spot size of the optical driver is essentially defined by the fiber core diameter. This aspect of fiber coupling permits facile variation and control of the illumination area on target. Second, multiple internal reflections tend to distribute the laser energy uniformly in the waveguiding volume of a fiber. As a result, a nearly ideal "top hat" intensity distribution in the output beam may be obtained. Uniform deposition on target promotes a geometrically simple, well-conditioned driving process that can be studied in detail.

In this paper, we discuss recent measurements of optically-driven flyer performance (using fiber coupling) as a function of various parameters, including laser fluence, laser pulse duration and target thickness. One area of emphasis has been the effect of pulse duration, particularly in the low-fluence (<15 J-cm^{-2}) regime. The results of this work help to define the practical operating range for laser-driven flyer generation and also provide useful data for validation and calibration of developing theoretical treatments of the process.[4,5] To assist in analysis of laser/material interaction phenomena occurring at the fiber/target interface, we have measured the time delay between laser pulse arrival at the foil and the onset of flyer motion. In addition, we have examined the temporal properties of laser light reflected from the interface as a function of incident fluence. These data constitute a useful probe into the interesting and complex "threshold" regime of laser-induced plasma formation that applies to flyer generation at lower fluences.

2. EXPERIMENTAL

Many details of the experimental design have been described previously.[1,2] As before, a laser-based optically recording velocity interferometer system (ORVIS)[6] was used to determine acceleration histories and maximum velocities for aluminum flyers launched from the output face of optical fibers. The interferometer fringe displacement (linearly proportional to flyer velocity) was viewed by an electronic image-converter streak camera, recorded on high-speed film and analyzed using digital image processing techniques.[7,8] The primary driving laser used in this work was an actively Q-switched Nd:Glass oscillator (Lasermetrics Model 9380). The pulse duration of this laser can be varied over the range 16-50 ns (FWHM) by simple adjustment of the flashlamp bank voltage.

Newer elements in the experimental arrangement are illustrated in Fig. 1. The additional features include: (1) a high-speed electro-optic modulator ("pulse slicer") for generation of short pulse durations, (2) a "reference fiber" used for temporal correlation of driving laser pulses with flyer velocity records, and (3) a fast photodetector to measure the temporal profile of laser light reflected from the fiber/foil interface.

We were able to generate pulses as short as 3 ns (FWHM) using the high-speed electro-optic modulator; however, it was difficult to limit the "shot-to-shot" variation in pulse duration to less than 1 ns due to timing "jitter" in the various components. The sliced pulses exhibited very fast rise and fall times (~1-2 ns) with a small amount of afterpulsing. With pulses of 4-5 ns (FWHM) duration, output energies as high as 80 mJ were obtained.

For measurements of the time delay between laser pulse arrival at the foil and the onset of flyer motion, a small portion of light from the driving laser was coupled into a 0.4-mm-diameter fiber and transmitted to the slit of the streak camera for simultaneous recording with the interferometer fringe motion. It was possible to relate the recorded delay between the fiducial pulse and the onset of fringe motion to the <u>actual</u> delay at the target plane by careful measurement of light propagation times in (1) the optical train coupling the laser pulse to the foil, (2) the "reference fiber" leg and (3) the ORVIS optics. The uncertainty in this temporal correlation was estimated to be ~1 ns.

In addition to channeling the incident laser pulse to the target foil, the coupling fiber efficiently collects 1.06 μm light reflected and backscattered from the fiber/foil interface. This property was utilized in tests comparing the temporal profiles of the two signals. A portion of the backreflected light was viewed by an appropriately filtered fast photodetector (time constant < 0.4 ns) identical to that used to monitor the incident pulse (cf. Fig. 1). Comparison of the observed temporal profiles at low laser fluences (<1 J-cm^{-2}, resulting in high reflectance from the foil) confirmed that the frequency responses of the two detectors were very nearly equal.

3. RESULTS AND DISCUSSION

Peak flyer velocities have been determined as a function of laser fluence, foil thickness, fiber core diameter, and laser pulse duration. Fig. 2 illustrates the effect of driving fluence for three different foil thicknesses. The observed trends are the same in all three cases. Above 10-15 J-cm^{-2}, peak flyer velocity appears to scale with the square root of fluence. This behavior suggests a simple kinetic-energy relationship assuming a small ablated mass fraction and a nearly constant efficiency of coupling optical energy into flyer kinetic energy. In other words, flyer velocity, v_f, is proportional to $(kE_1/m_f)^{1/2}$, where E_1 is the optical energy reaching the target, m_f is the flyer mass and k is a constant. For a given fiber core area, $(kE_1/m_f)^{1/2}$ is essentially equivalent to $(kF_1/\rho x_f)^{1/2}$, where F_1 is the fluence at the output end of the fiber, ρ is the foil material density and x_f is the foil thickness. In the low-fluence regime, however, the coupling efficiency falls off rapidly and, for the experimental conditions represented in Fig. 2, flyer acceleration does not occur at fluences below 3 J-cm^{-2}.

Under conditions of negligible mass ablation and constant coupling efficiency, v_f should scale as $m_f^{-1/2}$. Correspondingly simple relationships should hold for v_f as a function of foil thickness and fiber core diameter (assuming the flyer diameter is large enough that a one-dimensional description of the system is reasonably accurate). For $F_1 > 15$ J-cm^{-2}, the data in Fig. 2 are consistent with the predicted flyer-thickness scaling; i.e., v_f is proportional to $x_f^{-1/2}$. Flyers accelerated from fibers of different core diameter ($\geq$0.2 mm) also follow the expected kinetic-energy relationship.[2,4]

The effects of laser pulse duration are strongly coupled to the input fluence. At F_1 well above the threshold for flyer motion, the maximum flyer velocity is only mildly dependent on the pulse duration. Figure 3 shows velocity-time records for 0.0127-mm-thick Al foils launched from 0.4-mm-diameter fibers using optical pulses ranging from 4 ns to 48 ns (FWHM) in duration. The foils driven by shorter pulses displayed much more rapid acceleration but the changes in peak velocity were fairly modest. By assuming that the flyer mass is approximately equal to that contained in the full foil thickness (i.e., negligible mass ablation) over an area corresponding to that of the fiber core, coupling efficiencies can be estimated from these data. The observed range in maximum velocities indicates that the coupling efficiency increases from 21% for the 48-ns pulse to near 40% for the shorter pulses. It is interesting that the velocity-time records for the 4-ns and 8-ns pulses are very similar in terms of both rate of acceleration and apparent maximum velocity. These results suggest that important limitations exist in the rate at which optical energy can be coupled into foil kinetic energy in the intensity regime appropriate for fiber-coupled flyer generation.

In the low-fluence regime, pulse duration plays a dominant role in determining the coupling efficiency. In Fig. 4, peak flyer velocities are plotted vs. incident fluence for driving pulses of three different durations. As already shown in Fig. 2, flyer velocity increases rapidly as a function of fluence for $F_1 < 10$ J-cm^{-2}. Appreciable "scatter" in the data is seen under these conditions (probably due to small shot-to-shot variations in the mechanical coupling between the fiber and foil); however, it is clear that shorter pulses result in a substantially reduced threshold for flyer motion. In a system in which thermal diffusion controls the energy deposition process, the threshold fluence should scale with the square root of pulse duration.[4] The data in Fig. 4 are roughly consistent with this trend.

The experimental data relating peak flyer velocities and acceleration histories to various optical parameters and foil thickness are being used to calibrate and validate models of flyer generation and performance. Since the late-time recoil momentum of a flyer is relatively insensitive to details of the radiation/material interaction processes, most of the salient features of optically-driven flyer production can be modeled using a simple "effective properties" approach[4,9] employing conservation of energy and momentum, in the framework of the well-known Gurney theory[10] for high-explosive-driven plates. A comprehensive, time-dependent numerical approach treating both the radiation interaction processes and the ensuing hydrodynamic motion is also under development.[5] Measurements of the time delay between laser pulse arrival at the fiber/foil interface and the onset of flyer motion (detected at the opposite face of the foil) provide useful input to these calculations. Complementary information is contained in the observed temporal profiles of light reflected from the interface.

The delay between the leading edge of the optical pulse and the initial acceleration of the foil correlates directly with the magnitude of input fluence. While this relationship is evident in data acquired using a short-pulse (4-5 ns) driver, delayed flyer motion is even more obvious in experiments using the "unsliced" laser pulse at modest fluences. The temporal correlation of an 18-ns (FWHM) input pulse and the corresponding flyer velocity-time record is illustrated in Fig. 5. Also shown is the recorded pulse of 1.06 μm light reflected and backscattered from the fiber/foil interface (adjusted in time and normalized in intensity so that the leading edges of the incident and reflected pulses are aligned). Clearly, the onset of flyer motion coincides with the dramatic drop in the intensity of reflected light near the middle of the input pulse. This event undoubtedly corresponds to initiation of strong inverse bremsstrahlung absorption at the interface. In varying the input conditions, we have seen that both efficient absorption of the incident energy and flyer motion occur progressively later in the pulse as the fluence is lowered. Near threshold, it is apparent that most of the optical energy is expended before substantial ionization takes place at the interface and a strongly absorbing, driving plasma can be formed. Consequently, only the tail of the pulse effectively contributes to sustaining the plasma and "pushing" the flyer.

For the experimental conditions represented in Fig. 5, the drop in reflected light intensity occurs fairly rapidly; however, the "fall" time (~5 ns) is significant compared to the laser pulse duration. Preliminary results of other tests suggest that this time may vary with foil thickness as well as optical intensity. Since initiation of a strongly absorbing plasma is apparently not an "instantaneous" process under irradiation conditions appropriate for flyer generation, the efficiency of flyer acceleration using optical pulses shorter than 5 ns may be limited by dynamic phenomena in both plasma formation and expansion.

4. SUMMARY

We have examined the effects of incident laser fluence, laser pulse duration and foil thickness on the efficiency of launching aluminum foil flyers from the output face of optical fibers. Relatively simple scaling laws for maximum flyer velocity apply over a wide range of conditions. In order to define the practical operating range for optically-driven flyer generation, threshold fluences have been determined for pulse durations in the range 4-32 ns. The time delay between laser pulse arrival and the onset of flyer motion varies with input fluence. The significant delays observed at low fluences arise from the increased time required for plasma formation at the fiber/foil interface under these conditions. Dynamic elements in the plasma formation and expansion processes appear to limit the efficiency of flyer production using short-pulse (i.e., <5-ns) irradiation.

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FIGURE CAPTIONS

Figure 1	Schematic diagram of experimental arrangement for optically-driven flyer studies
Figure 2	Peak flyer velocities vs. incident fluence for indicated foil thicknesses and laser pulse durations. Al targets were coupled to 0.4-mm-diameter fibers.
Figure 3	ORVIS velocity-time records for 0.0127-mm-thick Al foils coupled to 0.4-mm-diameter fibers at pulse durations shown. Input fluence was near 25 J-cm^{-2} in all cases. Records for the 4-ns and 8-ns pulses are shorter because a faster sweep speed was used on the streak camera.
Figure 4	Peak flyer velocities vs. incident fluence for 0.0127-mm-thick Al foils coupled to 0.4-mm-diameter fibers at pulse durations shown.
Figure 5	Temporal correlation of incident optical pulse, reflected light pulse and flyer velocity-time record for experimental conditions shown. Al target was coupled to 0.4-mm-diameter fiber. Signal in early (time < -10 ns) part of reflected light record was due to stray reflection of incident pulse.

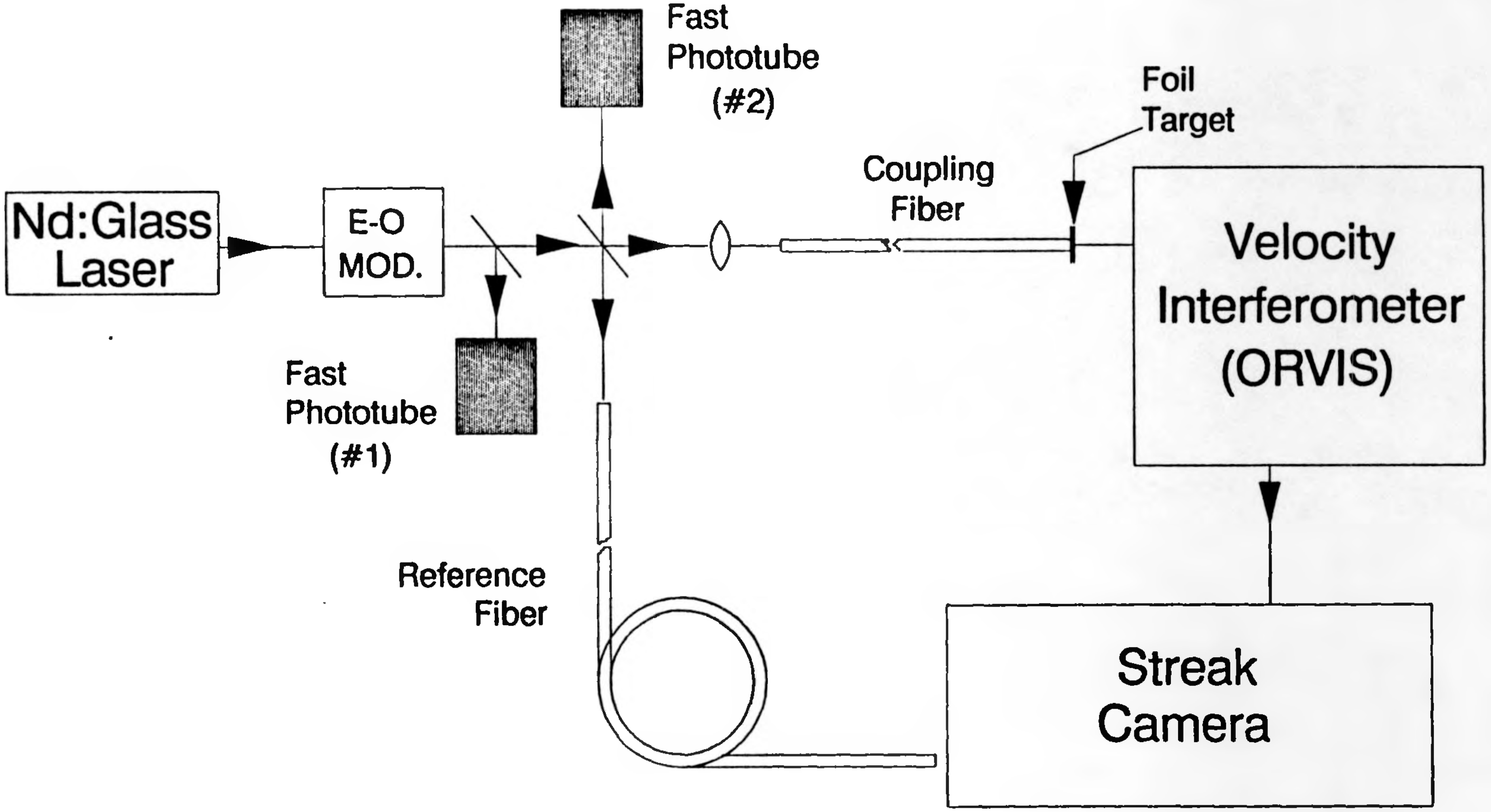

Nd:Glass Laser
E-O MOD.
Fast Phototube (#1)
Fast Phototube (#2)
Coupling Fiber
Foil Target
Velocity Interferometer (ORVIS)
Reference Fiber
Streak Camera

Fig. 1

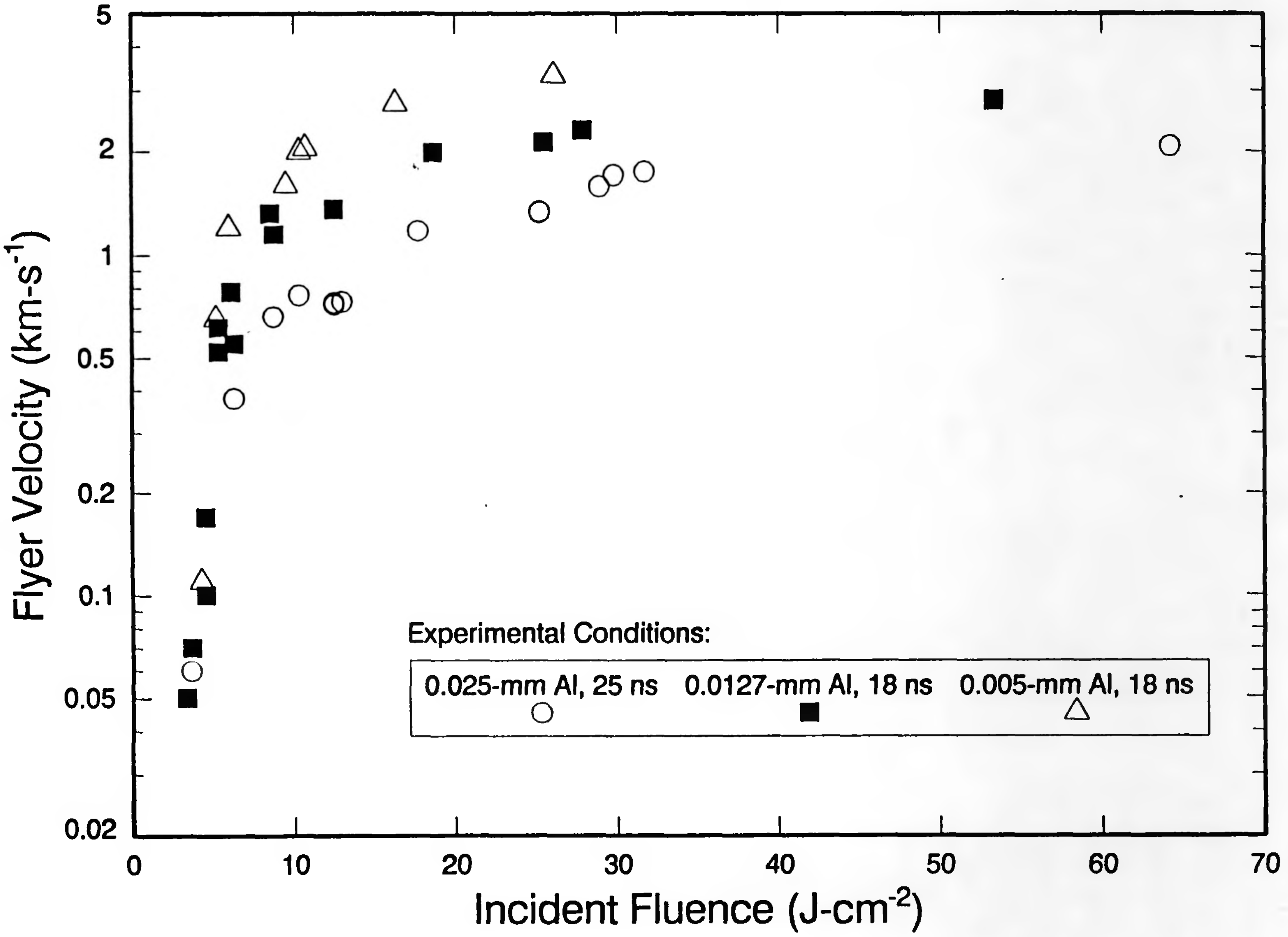

5
2
1
0.5
0.2
0.1
0.05
0.02
Flyer Velocity (km-s^{-1})
0
10
20
30
40
50
60
70
Incident Fluence (J-cm^{-2})
Experimental Conditions:
0.025-mm Al, 25 ns ○
0.0127-mm Al, 18 ns ■
0.005-mm Al, 18 ns △

Fig. 2

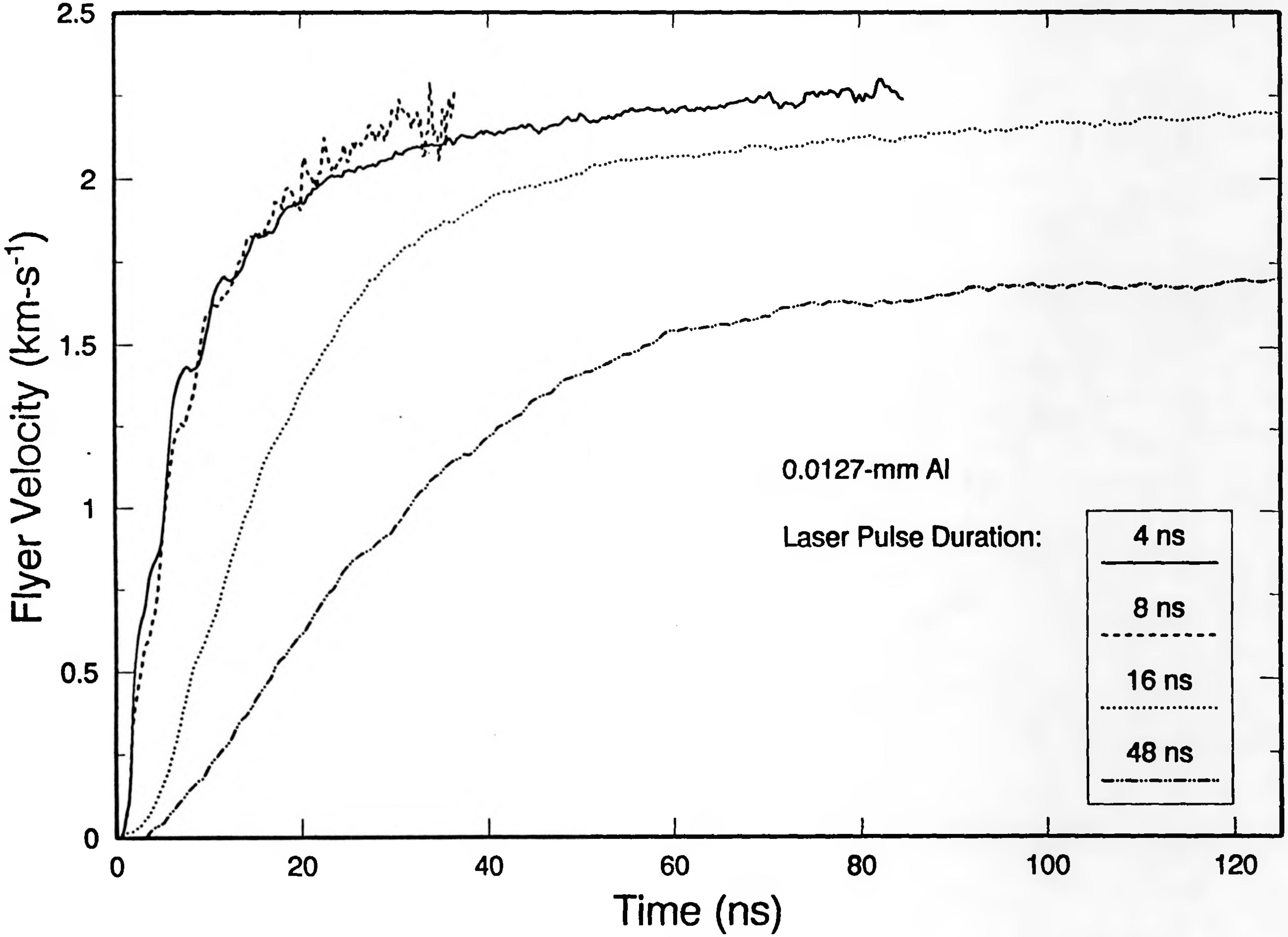
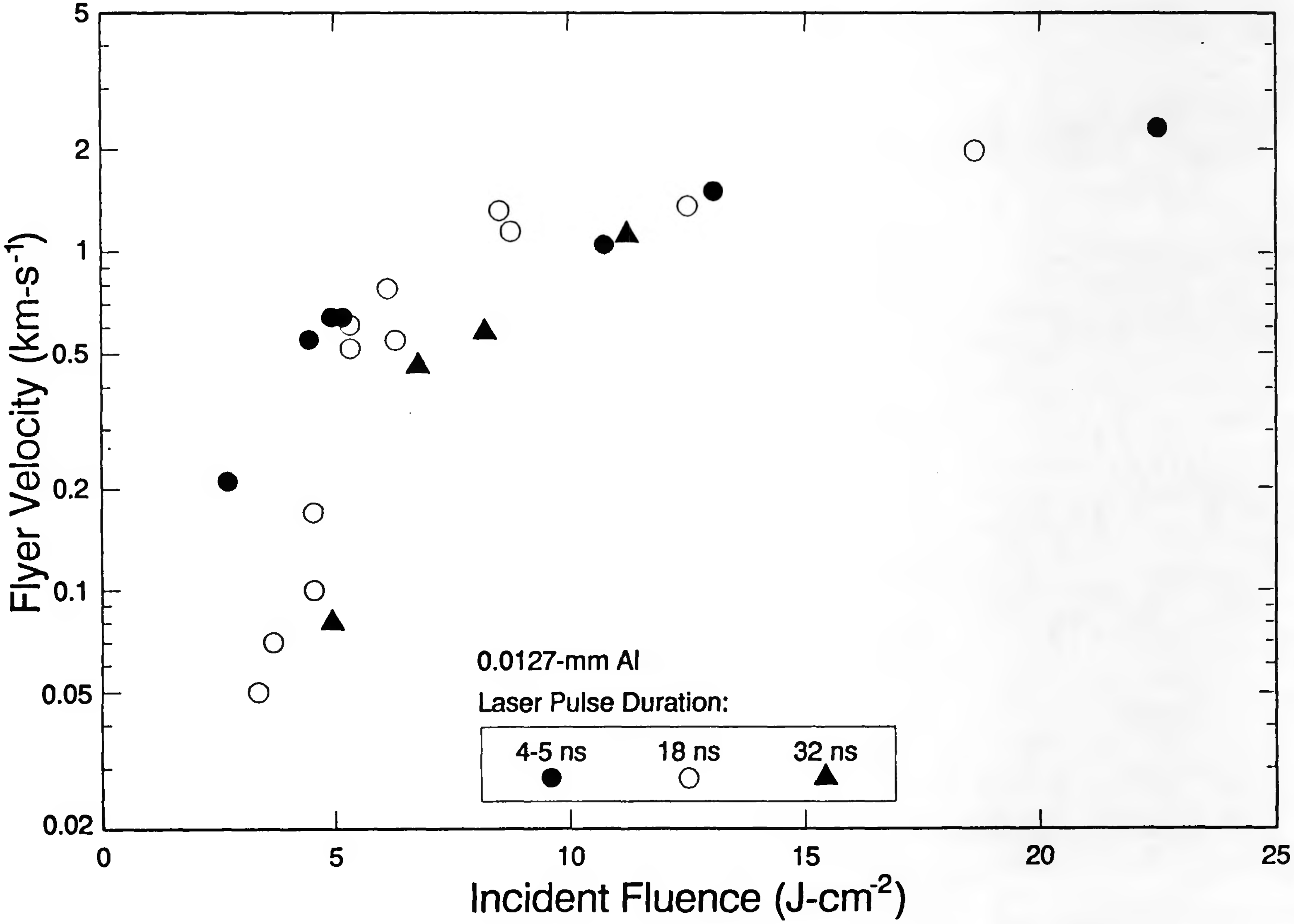

Flyer Velocity (km-s^{-1})
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
120
Time (ns)
0.0127-mm Al
Laser Pulse Duration:
4 ns
8 ns
16 ns
48 ns

Fig. 3



5
2
1
0.5
0.2
0.1
0.05
0.02
Flyer Velocity (km-s^{-1})
0
5
10
15
20
25
Incident Fluence (J-cm^{-2})
0.0127-mm Al
Laser Pulse Duration:
4-5 ns ●
18 ns ○
32 ns ▲

Fig. 4

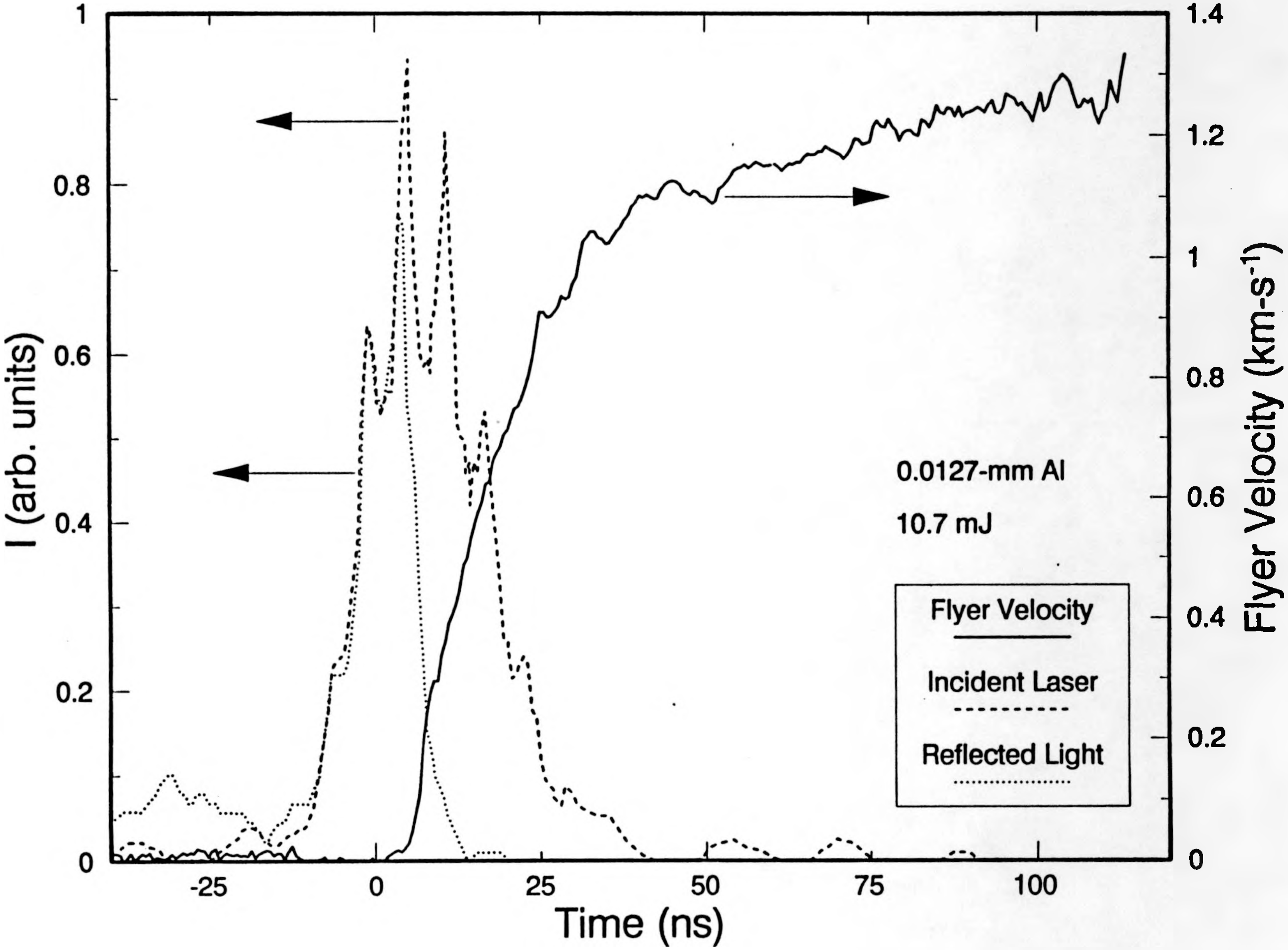

I (arb. units)
0
0.2
0.4
0.6
0.8
1
Time (ns)
-25
0
25
50
75
100
Flyer Velocity (km-s^{-1})
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0.0127-mm Al
10.7 mJ
Flyer Velocity
Incident Laser
Reflected Light

Fig. 5