Laser Damage to Optical Windows in the Laser Wire Apparatus

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1. Introduction

In the laser wire technique for beam profile measurements, a collimated laser beam intercepts the H- beam, neutralizing a small fraction of the ions. Changes in the properties of the ion beam provide information about the ion density in the portion of the beam that interacts with the laser light. If the laser beam is small enough, then it can be used to "sample" the ion beam, thus providing profile information. Resolution increases as the size of the laser beam is decreased, although a beam that is too small will neutralize too few ions to detect. A compromise between resolution and signal to noise yields an optimal size for the laser beam of approximately 25% of the size of the ion beam[1].

One of the more serious limitations in the trial at Brookhaven is the poor signal-to-noise ratio. One way to improve the signal, of course, is to increase the number of photons interacting with the ion beam. As long as the ion beam is not depleted, a greater number of photons equates to a larger signal. As the laser power is increased, however, care must be taken to avoid damage to the optics. This is especially important for optical windows on the vacuum chamber, since a catastrophic failure of the window could spread catastrophe throughout the system. Two methods for dealing with this problem are presented below. In Section 2, we study the effect of changing the pulse duration. Although the amount of energy that an optic can safely transmit grows as the pulse increases in duration, we find (somewhat surprisingly) that shorter pulses provide more optical energy for the interaction with the ion pulses. In Section 3, we investigate the possibility of minimizing laser damage by moving the windows farther from the interaction region.

2. Effects of Pulse Duration

Theoretical studies of optical damage in dielectric materials predict that the damage threshold fluence (energy per unit area) should vary as the square root of the pulse duration τ_L [2]:

$$E_{damage} = \gamma\sqrt{\tau_L}\,. \tag{1}$$

Thus, if the pulse energy is near the damage threshold for a particular pulse duration, then it is safe to double the energy only if the pulse duration is increased by a factor of four (for a constant beam size). This scaling has been found to be in fairly good agreement with experimental results down to pulse durations of 10-20 ps[3]. For shorter pulses, the observed damage fluence is generally higher than would be predicted by this rule, so the $\tau_L^{1/2}$ scaling represents a "safe" limit.

From this relationship, it would seem that longer pulses provide a means of safely increasing the optical energy in the laser wire technique. Because the ion pulses are only 20 ps long, however, the *total* pulse energy is not the quantity of interest. Rather, it is the amount of optical energy delivered in that 20-ps time window that is important. [Here, we consider the neutralization fraction in a single ion pulse, since this would determine, say, the notch depth observed on an oscilloscope screen. While it is true that laser pulses overlapping several ion pulses may provide more *total* energy for the interactions, the observed effect still depends on the amount of energy that can be deposited in a *single* ion pulse.] For optical pulses longer than the ion pulse duration τ_I, the amount of optical energy available for the interaction is approximately

$$E_{\text{int}} = E_L \frac{\tau_I}{\tau_L}, \tag{2}$$

where E_L is the energy in the laser pulse. That is, only a fraction of the optical energy is available—the longer the pulse, the smaller the fraction. For a 200-mJ, 8-ns optical pulse, for example, only 0.5 mJ is available for a 20-ps ion pulse.

It is useful at this point to calculate the maximum amount of optical energy available for the interaction as permitted by the damage threshold of the windows. If the pulse energy reaches the damage threshold energy, then the energy in the ion pulse time window becomes

$$\left(E_{\text{int}}\right)_{\max} = \gamma \frac{\tau_I}{\sqrt{\tau_L}}. \tag{3}$$

Although the damage threshold decreases for shorter pulses, it is actually possible to provide *more* energy for the interaction since a greater fraction of the pulse energy arrives within the ion pulse window.

Consider the following example: CVI offers laser windows with a damage threshold of 10 J/cm^2 for a pulse duration of 8 ns. If we assume a spot size of 0.004 cm^2 at the window, then we have $\gamma = 14.14\ \text{mJ}/\sqrt{\text{ns}}$. The following table shows the maximum permitted pulse energies and the maximum amount of energy in a 20-ps time window for various pulse durations.

Pulse Duration	Maximum Pulse Energy (mJ)	Maximum Energy in 20 ps (mJ)
20 ps	2.00	2.00
50 ps	3.16	1.26
100ps	4.47	0.894
200 ps	6.32	0.632
500 ps	10.0	0.400
1 ns	14.1	0.283
2 ns	20.0	0.200
5 ns	31.6	0.126
10 ns	44.7	0.0894

The values in this table are particular to this example. Different glasses will have different damage thresholds (although this figure will not vary significantly from glass to glass).

3. Effects of Window Position

In addition to the effects of pulse duration discussed above, the amount of energy that can pass through a window safely depends critically upon the spot size: a spot that is twice as large may carry twice as much energy. One way to increase the spot size at the windows is to move them farther from the point of focus. When light is confined to a limited spatial region, it diffracts as it propagates: the greater the confinement, i.e., the smaller the beam at its focus, the greater the diffraction. A laser beam with a Gaussian transverse profile propagates in free space with an intensity described in cylindrical coordinates by[4]

$$I = A_0^2 \left[\frac{w_0}{w(z)}\right]^2 e^{-2\left[\frac{r}{w(z)}\right]^2}, \tag{4}$$

where z is the direction of propagation and r is the distance from the axis of propagation. The 1/e width of the field reaches a minimum value of w_0 at the beam waist which, for the sake of convenience, is located at z=0. The size of the beam increases with distance from the waist according to the formula

$$w(z) = w_0\sqrt{1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2}\ . \tag{5}$$

This function is plotted in Fig. 1 for $w_0 = 0.25\ \mathrm{mm}$ (beam diameter is 0.5 mm at the center of the ion beam). Unfortunately, the spot size at the focus is large enough that the spreading is not significant. Even at a distance of 25 cm from the ion beam, the laser beam diameter is still less than 1 mm. The situation may be improved by adopting a tighter focus. This will increase the spot size at the windows, but may reduce the

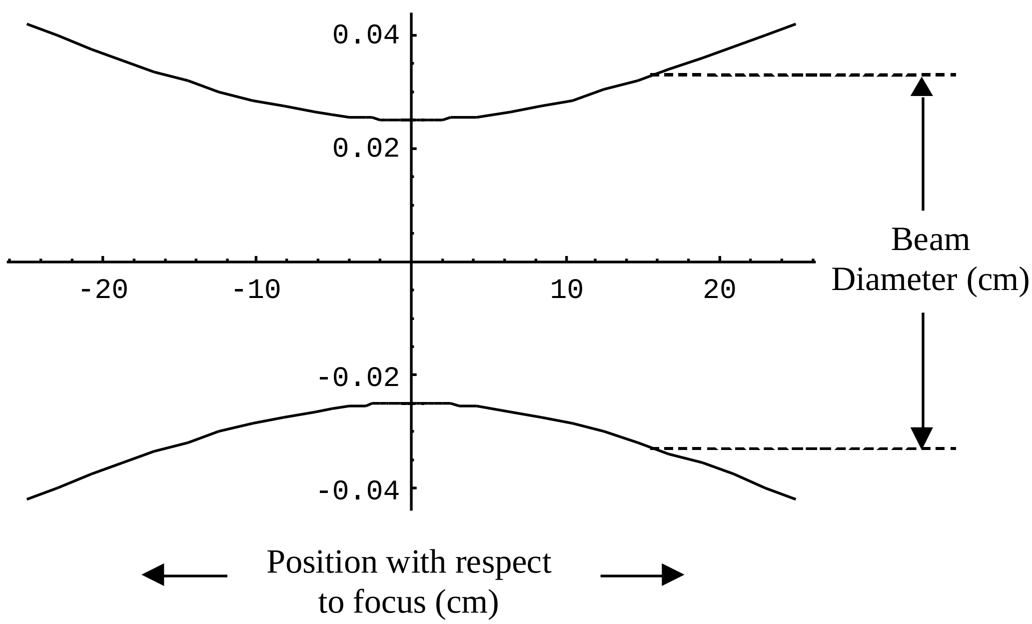

Fig. 1. Gaussian beam propagation.

resolution of the measurement.

An alternate solution has been adopted by the Brookhaven group, where cylindrical optics have been employed to spread the beam in the direction parallel to the ion beam. This works quite well for longer pulses, but timing of the different portions of the laser pulse become important when the pulse duration is closer to the ion pulse duration.

4. Summary

In order to ensure that the energetic pulses employed in the laser wire do not cause damage to the vacuum chamber windows, it may be necessary to modify the spatial and/or temporal profiles of the laser pulse. Self-diffraction of the laser beam results in an increasing spot size as the distance from the focus is increased. For the proposed laser beam parameters, this results in only a modest increase in spot size for reasonable window positions. It is possible, however, to increase the spot size in the dimension parallel to the ion beam. For all but the shortest pulses, this technique brings no penalty in signal or resolution.

The analysis of the effect of the pulse duration brought about the result that more energy can be brought to the ion pulse when the optical pulse is short. It seems then, that whatever the geometric scheme, shorter pulses offer an even greater “cushion” against laser damage.

References

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