HIGH POWER LASER TRANSPORT SYSTEM FOR LASER COOLING TO COUNTERACT BACK-BOMBARDMENT HEATING IN MICROWAVE THERMIONIC ELECTRON GUNS*

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Abstract

Heat from a high power, short pulse laser deposited on the surface of a thermionic electron gun cathode will diffuse into the bulk producing a surface cooling effect that counteracts the electron back-bombardment (BB) heating intrinsic to the gun. The resulting constant temperature stabilizes the current allowing extension of the gun's peak current and duty cycle. To enable this laser cooling, high power laser pulses must be transported to the high radiation zone of the electron gun, and their transverse profile must be converted from Gaussian to top-hat to uniformly cool the cathode. A fiber optic transport system is simple, inexpensive, and will convert a Gaussian to a top-hat profile. Coupling into the fiber efficiently and without damage is difficult as tight focusing is required at the input and, if coupled in air, the high fluence will cause breakdown of the air resulting in lost energy. We have devised a vacuum fiber coupler (VFC) that allows the focus to occur in vacuum, avoiding the breakdown of air, and have successfully transported 10 ns long, 85 mJ pulses from a 1064 nm Nd:YAG laser through 20 m of 1 mm diameter fiber enabling testing of the laser cooling concept.

INTRODUCTION

A method to counteract back-bombardment (BB) heating in microwave thermionic electron guns [1, 2] is being tested at the University of Hawaii. A fiber optic transport system has been developed to deliver the high energy laser pulses required for laser cooling from the optics lab where the laser and its radiation sensitive electronics reside to the high radiation zone of the electron gun. The fiber is a very simple, flexible, and cost effective means of laser transport and has the additional advantage of converting the quasi-Gaussian input from the Nd:YAG laser used into a near top-hat beam. Most of the system consists of off-the-shelf parts (mirrors, lenses, fiber optic cable), but a special vacuum fiber coupler (VFC) [3] was necessary to couple the high power laser into the fiber without damage. Previous authors have shown that a 50 mm lens system in air with a 'mode scrambler' or a fiber-to-fiber injection method has the ability to transport over 100 mJ, 13.5 ns pulses [4]. These two methods have the effect of more evenly distributing power over the supported optical modes in the fiber to prevent damage; necessary since the input beam's divergence angle is much less than the numerical aperture (NA) of the fiber. Our method employs an short focal length lens focusing the beam in a small vacuum chamber that couples light to the fiber. This has the advantage of utilizing nearly the entire NA of the fiber so the input beam is much less likely to damage the fiber.

DESIGN AND EXPERIMENT

A schematic of the VFC appears in Figure 1 and illustrates the concept. The laser is focused in vacuum to avoid breakdown of the air witnessed at any pulse energies over a couple millijoule. The vacuum level is 65 mTorr and is provided by a rotary vane pump. The vacuum seals for the lens and fiber are made with buna o-rings coated with a thin layer of vacuum grease. The focal plane is initially placed slightly back from input face of the fiber to decrease the laser fluence at the entrance. The input beam to the VFC is a fundamental Nd:YAG at 1064 nm with a quasi-Gaussian TEM_{00} transverse profile with width w =2.15 mm and z_R =13.7 m at the VFC. The shortest focal length lens tested, 8 mm, at the input to the VFC provides a divergence (half) angle $\theta \approx 15^{\circ}$ which fills the majority of acceptance (half) angle of 23° of the NA=0.39, 1 mm diameter fiber (Thorlabs part number FT1000EMT). The fabricated VFC is shown in Figure 2.

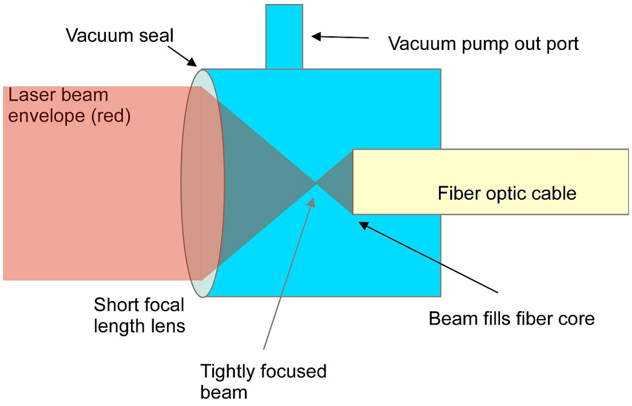

Figure 1: Schematic of the VFC. The laser beam (red) is focused with a short focal length lens sealed to the front of an aluminum (blue) vacuum chamber with ports for vacuum pumping and a vacuum seal to the input fiber optic cable. The input face of the cable is placed such that the beam expands to fill the fiber diameter.

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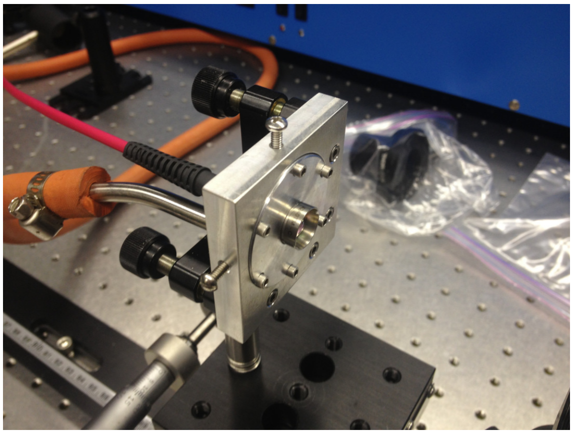

Figure 2: Image of the VFC which couples the laser into the fiber optic cable. A short focal length lens (8 mm in this photo) in the center of the aluminum cylinder focuses the light in vacuum into the fiber optic cable protruding from the back of the cylinder. Vacuum is provided by a rotary vane pump through the rubber hose and pump out port visible in the back of the VFC adjacent to the fiber optic cable. Alignment of the angle and position of the VFC relative to the laser is done with the micrometer stages shown.

To enable movement of the focal plane near the fiber input face, a telescope was placed between the laser and VFC consisting of a -100 mm focal length diverging lens, a variable distance, a 75 mm focal length converging lens, and a 75 mm distance to the VFC input lens. This enabled movement of the focal plane from 0.2 mm to over 3 mm from the fiber input face by adjustment of the distance between the diverging and converging lenses. Note that this also slightly changes the beam size at the input lens of the VFC and consequently the divergence angle of the beam at the fiber input face, though the change is at most 2 degrees across the distances tested.

In order to maximize the transmitted power, we aligned the system at low power (about 1 mJ) and placed the focus at the optimal location as follows. First the height and transverse position of the VFC relative to the beam was slowly changed to maximize the transmitted energy, E_{trans}, as measured by a Molectron J-25 optical pyrometer. The input energy was monitored with a CaF_2 plate providing a 1% energy pick-off and a Molectron J-4 optical pyrometer. Next the angle of the VFC relative to laser was adjusted to maximize E_{trans} and the process of height/transverse position and angular adjustment was iterated until no change in E_{trans} was seen.

To find the maximum transitted energy, the distance between the two telescope lenses was varied to produce the fiber face to focal plane distances (calculated with standard ray-matrix analysis for Gaussian beams) shown on the x axis of Figure 3. In theory, the coupling efficiency should follow the trend

$$\frac{P_{\text{out}}}{P_{\text{in}}} = 100\left[1 - e^{-2r^2/w(z)^2}\right] \qquad (1)$$

with $w(z)$ being the typical Gaussian beam radius [5]. In figure 3 equation 1 is multiplied by the transmission of the two telescope lenses since the pick-off to measure P_{in} is before the telescope. The optimal operation point is to have the focus approximately 1.25 mm from the fiber face as this would allow for the lowest fluence at the fiber face while still capturing nearly all of the laser light.

After the optimal focal plane location was found the power was increased in steps of 2 mJ until an abrupt drop in coupling efficiency was encountered. To test the theory that damage threshold increases with increasing divergence angle [6] the process of alignment, optimal focal plane location, and testing was repeated for 5 different focal length lenses at the VFC input (100, 35, 25, 20, and 8 mm) yielding 5 different diverging angles and the maximum transmitted power was recorded for each.

RESULTS AND DISCUSSION

To date a minimal number of tests have been done, but nevertheless they follow the expected trends and we now have in hand 30 additional cables with which to build a more extensive data set with more reliable damage probability predictions.

Figure 3 shows two data sets (one before improvements to the precision of the alignment kinematics, one after) of coupling efficiency measurements taken at 1064 nm compared to theory. While the trend is roughly correct, the overall efficiency is lower than expected, most likely due to additional losses due to the finite size of the telescope and VFC input lenses and an offset (discussed below) in the actual position compared to these calculated positions. Despite these additional losses, the coupling efficiency is still high (up to 89% in the best case) and the technique of moving the focal plane using a telescope has enabled us to find the optimal operating point at the 'shoulder' of the efficiency curve where the efficiency is still near its maximum value since most of the light is captured by the fiber, but the fluence is lower as the beam has more distance to diverge after the focus.

Figure 4 shows the pulse energies that caused damage to the fiber for different divergence angles. Indeed, the damage threshold increased with increasing divergence angle. At the smallest divergence angle of just over one degree, the damage to the fiber always occurred at the core/cladding interface in a longitudinal stripe within the first 1-2 cm of the fiber as noted by Allison [6]. At the three intermediate angles, a mixture of core/cladding and input face damage occurred most likely due to inconsistencies in our end face preparation technique that caused the surface damage. At the highest energies, with consistent end face preparation, we saw again only core/cladding damage. However on inspection of the fibers damaged at the highest diverging angles and powers, we noticed a halo

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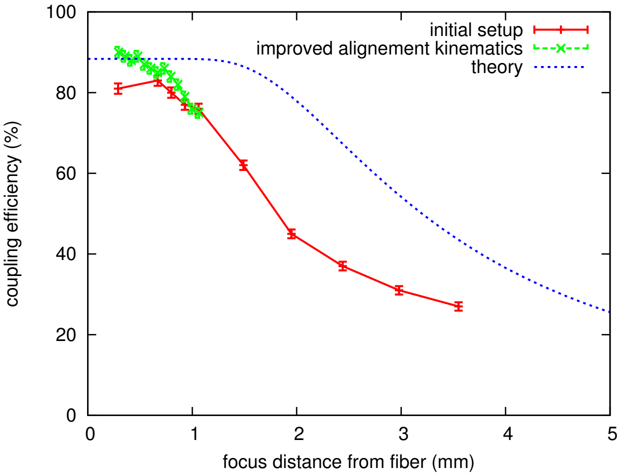

Figure 3: Coupling efficiency as a function of laser focus location at 1064 nm wavelength. Each point represents the average of 10 measurements. High coupling efficiency (80-90%) has been obtained with the focus near the fiber face with a low energy input of 1 mJ. As the focus moves away, the efficiency decreases due to the beam cross section being larger than the fiber cross section. The error bars represent the precision of the readout electronics.

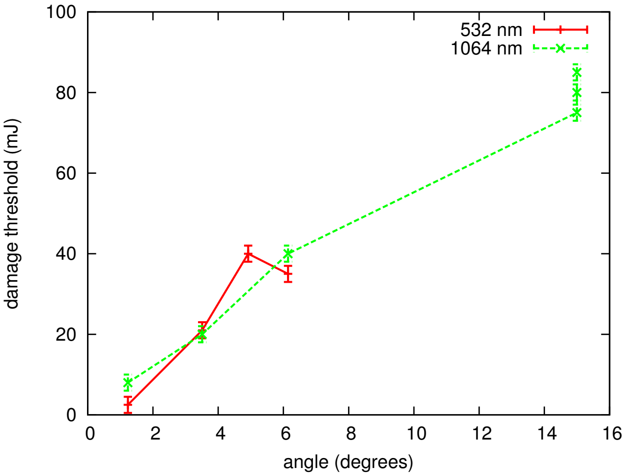

Figure 4: Damage threshold of fiber as a function of divergence (half) angle of the incident beam. Both 532nm and 1064nm light show the same trend of larger diverging angle yielding a much higher damage threshold. Each data point represents a single fiber that was ultimately damaged after a schedule of alignment at 1 mJ and then single shots with 2 mJ increments up to the damage threshold.

of laser induced damage in the epoxy around the fiber input face. This indicates that there was considerable energy outside of the fiber diameter which would have also coupled directly into the cladding which authors have noted causes damage to the cable far below its realizable damage threshold [4]. It appears as if our choice of focal plane location of approximately 1 mm from the fiber face was too great and should be decreased and/or the actual distance is greater than we have calculated. Preliminary burn-paper measurements of the focused beam indicate that the distance is indeed greater than calculated. The increased distance would shift the experimental curves to the right in Figure 3 which would bring the experimental and theoretical curves into better agreement. Setchell has shown that energies over 100 mJ can be transmitted with 400 micron diameter fibers [4] so we are optimistic that our system can exceed those results and tolerate the increased fluence from moving the focus closer to the fiber face to prevent core/cladding damage.

As we discussed in these proceedings, laser pulse energy in the range of 300 mJ will be necessary to eliminate the temperature rise due to BB over 23 µs [2] and the maximum energy continually transported has been 85 mJ per pulse with our transport system. However the 300 mJ pulse duration was 7 µs and the 85 mJ pulses tested were only 10 ns long as the need for a longer pulse laser has only recently been realized. Using the scaling rule of thumb for laser induced damage threshold ($LIDT$) [7, 8],

$$LIDT_{\text{adjusted}} = LIDT\sqrt{\frac{\text{adjusted pulse length}}{LIDT\text{ pulse length}}}, \qquad (2)$$

the $LIDT_{\text{adjusted}} = 80\text{ mJ}\sqrt{\frac{7\ \mu\text{s}}{10\text{ ns}}} = 2012$ mJ: more than sufficient to meet the required 300 mJ.

CONCLUSION

It has been demonstrated that a vacuum fiber coupler can enable transmission of 10 ns, 85 mJ 1064 nm laser pulses through 1 mm diameter multi-mode fiber and that high efficiencies of nearly 90% can be obtained. Transmission of higher energies appears to be possible with slight modification of our of our setup to enable smaller focal plane to fiber input face distances. Even with the current energy transportation ability, scaling rules of thumb indicate that the current damage thresholds are sufficiently high to enable testing of the laser cooling technique up to its full potential.

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