

# Air-breathing mode laser propulsion with a long-pulse TE CO<sub>2</sub> laser

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Air-breathing mode laser propulsion experiment with a long-pulse transversely excited (TE) CO<sub>2</sub> laser is carried out, and its ignition problem is solved with the ignition needle of lightcraft. Owing to the ignition needle, an order of magnitude reduction in the ignition threshold is demonstrated. The result is compared with previous study. The momentum coupling coefficient is also measured in the experiment and its dependence upon laser pulse energy (6–14 J) and pulse width (20, 32, and 40 μs) is discussed.

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Air-breathing mode is one of the main operation modes of laser propulsion. Because it uses air as propellant and has no mass dissipation, this propulsion mode has attracted a number of researchers since it was proposed<sup>[1–3]</sup>. The laser used in air-breathing mode propulsion is supposed to be a high power and high beam quality pulsed laser. When the focused laser pulse initiates air-breakdown in the lightcraft, laser plasma ignition is formed; the plasma absorbs laser energy and expands to drive a detonation wave which propels the lightcraft to move. Compared with many other pulsed lasers, transversely excited atmospheric (TEA) CO<sub>2</sub> laser is one of the most popular choices at present to be used as the high power source in laser propulsion<sup>[4,5]</sup>.

The typical pulse profile of TEA CO<sub>2</sub> laser includes a sharp peak and a following long tail, as shown in Fig. 1. The sharp peak part contributes the most to air-breakdown. However, if a laser that has much longer pulse duration than a TEA CO<sub>2</sub> laser is used, its power intensity falls beneath the ignition threshold which is about 10<sup>7</sup> W/cm<sup>2</sup> for 10.6-μm laser radiation<sup>[6]</sup>, so that the ignition cannot be generated and effective propulsion cannot happen.

Long-pulse transversely excited (TE) CO<sub>2</sub> laser, with adjustable pulse width, is such a potential high-energy source for laser propulsion, the pulse of which is one order of magnitude longer than that of TEA CO<sub>2</sub> laser<sup>[7,8]</sup>. An attempt to use long-pulse TE CO<sub>2</sub> laser to propel parabolic lightcraft was made once, but the laser pulse failed to initiate air-breakdown since its power intensity was not high enough. In order to induce air-breakdown, an ignition needle was utilized, the needle was fixed on the top of the lightcraft along the symmetry axis and its needlepoint was located at the focus of the paraboloid. With this ignition needle, the laser initiated air-breakdown easily and completed the propulsion successfully. German researchers studied the employment of ignition needle to lower ignition threshold<sup>[9]</sup>. Their laser source was an electron-beam sustained pulsed CO<sub>2</sub> laser with the pulse width several times shorter than long-pulse TE CO<sub>2</sub> laser, and their needle also served as the fixture for solid propellants besides the function of ignition. In this letter, the needle aims to help re-

alize air-breathing mode propulsion and is made much thinner so that the influence of ablation can be ignored. In Refs. [9,10], the ignition threshold was decreased to 10 J/cm<sup>2</sup> with the pulse width of 12 μs, which was about 10<sup>6</sup> W/cm<sup>2</sup>. In our experiment, the ignition threshold is decreased by one order of magnitude, which is also around 10<sup>6</sup> W/cm<sup>2</sup>.

To evaluate the propulsion performance, momentum coupling coefficient as an important figure of merit was measured, and its dependences on pulse width and pulse energy were also studied in the experiment. The experimental setup is shown in Fig. 2. A horizontal linear air track was utilized and the lightcraft was fixed on a slider to move on the track. The output beam was sampled by a beam splitter, and the sample signals were detected by a laser energy meter for monitoring. Meanwhile, the main part of the beam was shot into the lightcraft and propelled the lightcraft to slide on the track. The moving process was captured by a high speed charge-coupled device (CCD) camera and stored in a computer.

Neglecting the air resistance and the friction, the imparted instantaneous velocity  $\Delta v$  of the lightcraft can be calculated from the recorded time and displacement data; thereby the momentum coupling coefficient  $C_m$  can be derived from

$$C_m = \frac{p}{E} = \frac{m\Delta v}{E}, \quad (1)$$

where  $p$  is the imparted momentum,  $E$  is laser pulse energy, and  $m$  is the total mass including mass of the

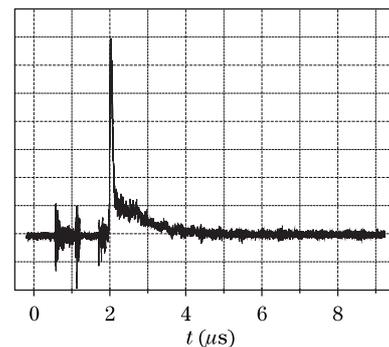


Fig. 1. Pulse profile of TEA CO<sub>2</sub> laser.

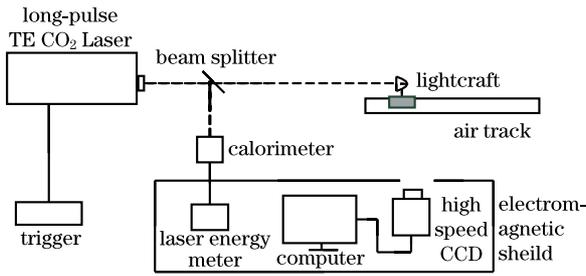


Fig. 2. Schematic of the experimental setup.

lightcraft and the slider.

The beam spot of the long-pulse TE CO<sub>2</sub> laser near the output exit is shown in Fig. 3(a), and the typical pulse profile is shown in Fig. 3(b). The full-width at half-maximum (FWHM) of the pulse is about dozens of microseconds and can be altered with the adjustment of the discharge network. Three typical pulse widths (20, 32, and 40 μs) were involved in the experiment.

The lightcraft used in the experiment was an aluminum parabolic lightcraft with a steel ignition needle. The model is shown in Fig. 4(a). The reflectivity of the polished inner surface was about 90%, the focal length was 5 mm, the diameter of the exit was 50 mm, and the total mass was 68.7 g. Close-up of the needle with the diameter of 0.6 mm is shown in Fig. 4(b).

Three groups of coupling coefficient data are shown in Fig. 5, each corresponding to one typical pulse width. The results show that for the same incident energy, the coupling coefficient decreases with increasing pulse width. The data difference between pulse widths of 20 and 32 μs is obviously smaller than that between 32 and 40 μs, so the dependence of the coupling coefficient on the pulse width is nonlinear, of which more details need further study and more experiment data. Figure 5 also indicates that for the same pulse width, the coupling coefficient increases with the increase of incident energy, the changing tendency is similar to that of a TEA CO<sub>2</sub> laser<sup>[11]</sup>. The value of the coupling coefficient varies from 65 to 203 N/MW. Limited by the pulse energy, more characteristics of the coupling coefficient are not

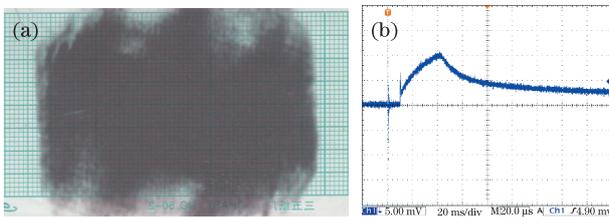


Fig. 3. (a) Beam spot and (b) pulse profile of long-pulse TE CO<sub>2</sub> laser.

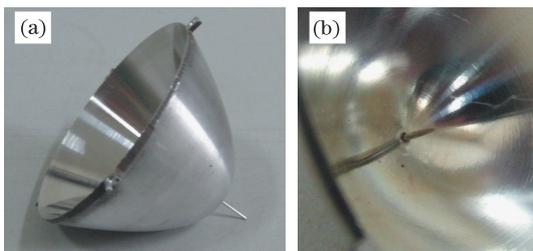


Fig. 4. (a) Photo of the parabolic lightcraft with (b) ignition needle.

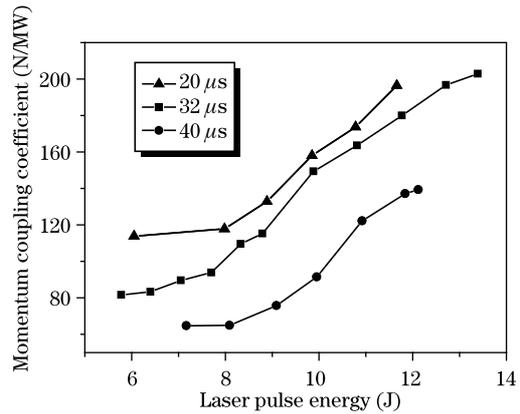


Fig. 5. Momentum coupling coefficient of long-pulse TE CO<sub>2</sub> laser.

clear. The upward trend will probably reach saturation if the pulse energy keeps on increasing.

Ablation of the metal needlepoint was also observed in the experiment. The losing mass was 0.39 mg after 600 laser pulses, corresponding to  $6.5 \times 10^{-4}$  mg per pulse. It was found in the experiment that air-breakdown would happen as long as the needlepoint was in the focal area. Since the laser focal spot is much larger than the needlepoint, ablation cannot cause obvious deviation from the focal area and its influence can be ignored.

In conclusion, the air-breathing mode propulsion experiment of long-pulse TE CO<sub>2</sub> laser is completed successfully utilizing the lightcraft with ignition needle. Through the instrumentality of such an ignition device, the ignition threshold can be reduced to  $10^6$  W/cm<sup>2</sup>. The momentum coupling coefficient is also measured, and the results show that the coupling coefficient increases with increasing pulse energy from 6 to 14 J and decreases with increasing pulse width from 20 to 40 μs.

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