Abstract. Laser propulsion is an innovative concept of accessing the space easier and cheaper where the propulsive energy is beamed to the aerospace vehicle in flight from ground- or even satellite-based high-power laser sources. In order to be realistic about laser propulsion, the Institute for Advanced Studies of the Brazilian Air Force in cooperation with the United States Air Force and the Rensselaer Polytechnic Institute are seriously investigating its basic physics mechanisms and engineering aspects at the Henry T. Hamamatsu Laboratory of Hypersonic and Aerothermodynamics in São José dos Campos, Brazil. This paper describes in details the existing facilities and measuring systems such as high-power laser devices, pulsed-hypersonic wind tunnels and high-speed flow visualization system currently utilized in the laboratory for experimentation on laser propulsion.

Keywords: High-power laser, laser propulsion, hypersonic wind tunnel, instrumentation

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INTRODUCTION

The concept of propelling a spacecraft by means of high-power laser beams was suggested for the first time in the seventies by Kantrowitz [1]. Almost two decades later an aerospace vehicle was successfully propelled by a 10-kW pulsed laser in a series of outdoor free-flights performed by Myrabo at White Sands Missile Range, New Mexico [2]. A remarkable altitude of 72 meters was reached during these pioneering launches. Currently, various researches around the World have seriously investigated in laboratory the fundamental mechanisms and technologies of laser propulsion (see bibliography on Ref. 3). Since 2007 scientists and engineers from the Prof. Henry Nagamatsu Laboratory of Aerothermodynamics and Hypersonics of the Institute for Advanced Studies (IEAv) in São José dos Campos, Brazil are performing experimental research on laser propulsion. After years of experimentation with laser-supported directed-energy air spike (DEAS) for aerodynamic drag and heating attenuation purposes in hypersonic flow [4,5], the IEAv team in cooperation with the Rensselaer Polytechnic Institute (RPI) and the United States Air Force (USAF) is now...
turned its attention to laser-sustained detonation wave or LSD wave for aerospace propulsion purposes [3]. In order to performed hypersonic wind tunnel experiments on laser propulsion concept, it is crucial to synchronize high-power laser beams, high-speed air flow and measuring systems all together. This paper describes in details the existing facilities and measuring systems such as high-power laser devices, pulsed-hypersonic wind tunnels and high-speed flow visualization system currently utilized in the laboratory for experimentation on laser propulsion.

**FIGURE 1.** (a) and (b) First ever demonstrations of laser-supported DEAS in hypersonic flow and (c) First ever experiment on laser propulsion concept in hypersonic flow.

**HIGH-POWER PULSED LASER SYSTEM**

**Operating Characteristics**

Two CO₂ TEA lasers manufacture by Lumonics Inc. are utilized as sources of very energetic pulsed infrared radiation in the laser propulsion research at IEAv as shown in Fig. 2. Each laser operates near atmospheric pressure and employs the technique of transverse excitation along with a method of preionization by ultra-violet radiation (UV). In this way, sufficiently large volumes of lasing medium containing 25 % of CO₂, 12.5 % of N₂ and 62.5 % of He all at 10 psi can be ionized through UV-photoionization prior to formation of a uniform glow discharge with the use of much lower pulse voltages for lasing. The output laser beam of each CO₂ TEA has pulse duration of the order of 1 µs, laser energy per pulse up to 200 J as measured during the laser shots and an annular ring pattern (see next subsections). The CO₂ TEA laser system is a single-shot laser source with charging time of around 1 min. As of October of 2008, the laser system has been fired about a thousand times at output energy of around 200 J per pulse.
An electrical diagram of the pulsed CO$_2$ TEA laser is shown in Fig. 3. There are two capacitor discharge systems associated to the pulsed CO$_2$ TEA laser: The UV preionizer capacitor and the main discharge Marx generator. The electrical characteristics of each are summarized in Tables 1 and 2, respectively. The UV preionizer is formed from a flashboard and its driver. The flashboard consists basically of ten identical rows of stainless steel which sparks when energized. The flashboard driver is formed from an energy stored capacitor C11, a spark gap (regulated via air pressure) and a DC power supply of 32 kV. A plasma of laser mixture or glow discharge is then generated via UV ionization when the flashboard is fired (see Fig. 4).
FIGURE 3. Electrical diagram of the pulsed CO₂ TEA laser.

TABLE 1. Electrical characteristics of UV preionizer.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charging voltage</td>
<td>32 kV</td>
</tr>
<tr>
<td>Capacitance</td>
<td>150 nF</td>
</tr>
<tr>
<td>Stored energy</td>
<td>77 J</td>
</tr>
<tr>
<td>Discharge time</td>
<td>Up to 1 µs</td>
</tr>
<tr>
<td>Configuration</td>
<td>10 sparking rows</td>
</tr>
</tbody>
</table>

TABLE 2. Electrical characteristics of the Marx generator.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor per stage</td>
<td>2</td>
</tr>
<tr>
<td>Number of stages</td>
<td>4</td>
</tr>
<tr>
<td>Trigger gap per stage (regulated via air pressure)</td>
<td>1</td>
</tr>
<tr>
<td>Capacitance</td>
<td>150 nF (each)</td>
</tr>
<tr>
<td>Charging voltage per stage</td>
<td>Up to 100 kV</td>
</tr>
<tr>
<td>Stored energy</td>
<td>77 J</td>
</tr>
<tr>
<td>Discharge time</td>
<td>Up to 1 µs</td>
</tr>
</tbody>
</table>

FIGURE 4. Uniform glow discharge in between the electrodes showing the flashboard sparking behind the grounded anode (without optics).

The Marx generator is a four stage generator with energy storage capacitors (C1 to C8) arranged as shown in Fig. 3. In a Marx generator, obviously, the capacitors are charged in parallel and discharged in series. A DC power supply is utilized to charge them up to 100 kV which means that around 1.5 kJ is stored in each stage generator. In this manner, when the Marx generator is fired the resulting 400 kV is fed to the cathode (charged electrode) which rapidly deposits it in the ionized laser mixture. The geometry of the cathode and anode, the formation of a glow discharge and the microsecond deposition of almost 6 kJ into the ionized laser medium all together help to mitigate the occurrence of undesirable electrical arcs.

Laser Cavity

The entire laser consists of an unstable resonator with two active mediums sharing the same laser cavity as can be noted in Fig. 2. The unstable laser cavity setup is
illustrated in Fig. 5. Its configuration suits well large round-trip gain with has the advantage of producing a collimated output beam (low divergence) with good far-field pattern. The total length of the cavity is 3750 mm, of which 2740 mm is round-trip length or active length.

**TABLE 3.** Characteristics of unstable cavity mirrors

<table>
<thead>
<tr>
<th>Mirror</th>
<th>Material</th>
<th>Curvature radius [m]</th>
<th>Diameter [mm]</th>
<th>Reflectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concave</td>
<td>Al</td>
<td>15</td>
<td>254</td>
<td>99 %</td>
</tr>
<tr>
<td>Convex</td>
<td>Al</td>
<td>7.5</td>
<td>120</td>
<td>99 %</td>
</tr>
</tbody>
</table>

The laser cavity is terminated by a concave back mirror and a convex output mirror whose characteristics are shown in Table 3. The “spider” technique is employed to mount the convex output mirror while the concave back mirror lies in a cell on an optic mount. Rubber bellows are employed to join both heads and the reflectors to the end of each head given flexibility to align them and sealing laser mixture from atmosphere environment. A salt window is setup at the output end (behind the convex mirror) to seal the laser mixture while allowing infrared transmission across it. Concerning the alignment of laser cavity, several adjustments of the back and output optics with the help of an alignment laser should be done until a beam pattern such as the one in insert of Fig. 6 comes up. Realignment of the laser cavity is eventually needed after each BEP run.
FIGURE 6. (a) Alignment of the concave back mirror and (b) Measured annular ring pattern.

Laser Instrumentation and Optics

Laser energy and pulse duration are performed to characterize the beam delivered to the lightcraft model. A power meter and a photon drag are utilized simultaneously to diagnose the output laser beam prior to power the lightcraft. Figure 7 shows a scope image of the waveform of the output laser beam.

FIGURE 7. (a) Scope image of the output laser beam waveform and (b) Scope image of timing between preionization and Marx generator trigger signals.

Also, voltage measurements concerning the power system of each TEA laser are carried out in a regular base for sake of integrity (see Fig. 7). All the optical components of the TEA lasers such as salt windows, mirrors and lenses should be handled with care, periodically cleaned up against microdusters, protected against humidity (mainly NaCl windows) and inspected by looking at any induced damages by laser beams (see Fig. 8). Such a caution with optics is needed when operating very energetic lasers devices.
FIGURE 8. (a) Lens damaged due to repetitive laser beam incidence and (b) Dehumidificator for housing salt windows when not in operation.

Also, safety must be paramount for the sake of experimentalist in lab because of the very energetic laser radiation handling. For this reason people in lab must wear ir glass and the use of a beam guide line is mandatory during BEP runs (see Fig. 9).

FIGURE 9. (a) Beam guide line for BEP runs at IEA, (b) Laser measurement station and (c) Salt window setup at the T3 sting entrance (beam gate).

At the end of the beam guide line there is a laser measurement station to diagnose the laser beam before delivering it to the lightcraft model as shown in Fig. 9. At the T3
sting entrance there is a beam gate which contains a salt window at 45 degree serving as a beam splitter reflecting around 7% of the actual incident laser energy to the laser measurement station while seals the vacuum into the test chamber.

**IEAV HYPERSONIC TEST FACILITY**

Currently, there is only one hypersonic test facility in existence in Brazil. The 0.6-m Diameter Hypersonic High Enthalpy Real Gas Pulsed Reflected Shock Tunnel (T3) installed at the Laboratory of Aerothermodynamics and Hypersonics of the Institute for Advanced Studies (IEAv) and under the Brazilian Air Force administration is the only national asset capable of simulating the high enthalpy that would be experienced by vehicles during hypersonic flight [8]. The T3 (see Fig. 10) can generate free-stream Mach numbers ranging from 6 to 25 and stagnation pressures and temperatures of 200 atm and 5500 K, respectively with run times ranging 2 and 10 milliseconds making BEP and aerodynamic experiments possible.

![Figure 10](image)

**FIGURE 10.** Hypersonic wind tunnel of Brazilian Air Force showing the driver, buffer and driven section, reservoir, nozzle and test chamber.

**Driver Section**

The driver section (see Fig. 10) is sized as follows: Wall thickness of 60 mm, hydraulic volume of 114 liters, inner diameter of 190 mm and length of 4 m. The driver section is very heavy (2 ton) and is capable of operating at 35 MPa or 5000 psi. The driver tube length relative to the driven one is such that the reflected expansion waves from the end of the driver reaches the nozzle throat at the same time as the driver gas interface which means that the useful test time is in fact determined by the drainage of the driven gas.

**Double-Diaphragm Section**

The T3 wind tunnel employs a double-diaphragm section (DDS) in order to control the exact moment of the beginning of the experiment. The DDS separates the driver from the driven section by means of a pair of diaphragms or buffer region as shown in
Figs. 11 and 12. The buffer region is filled to a pressure between the driver \( P_4 \) and driven pressure \( P_1 \). The pressure load \( P_4/P_1 \) is therefore distributed over both diaphragms. The first diaphragm is burst by rapidly purging the buffer gas via solenoid valves. In consequence, the second diaphragm will rupture as the pressure in the buffer region rises resulting in compression waves which will propagates downstream into the driven section. The contracted DDS is a way of increasing the speed of the compression waves which will build up the incident shock wave. The DDS technique has three advantages. First, the pressure load on both diaphragms can be reduced, thus enabling the use of thinner diaphragms which decreases the diaphragm’s opening time and increases the incident shock strength. Second, the pressure ratio \( P_4/P_1 \) can be set to a desirable value independently from the variation of the burst pressure of the first diaphragm, thereby leading to no erratic runs. Third, with DDS there is no need to move the heavy driver section during the replacement of the ruptured DDS diaphragms because of a sliding sleeve system (see Fig. 11). BEP runs take advantage of DDS technique because of no erratic runs, controllability of run conditions and convenient setup of T3 wind tunnel.

**FIGURE 11.** Scheme of DDS section showing the sliding sleeve system containing both diaphragms which limits the buffer region.
Driven Section

The driven section (see Fig. 10) is sized as follows: three carbon steel tubes with inner diameter of 127 mm and length of 3.5 m each and a heavy section at the end (reservoir) whose length is 1.5 m. The heavy section withstands pressures of 40 MPa and is well instrumented with various static pressure sensors to determine the stagnation conditions. The driven tube length is optimized in terms of useful test time.

Reflected Shock Wave Heating Technique

The gas temperature after the incident shock wave can be further increased by reflecting the shock wave at the end of the tube as shown schematically in Fig. 13. After the reflected shock wave, the gas temperature and pressure are increased by large amount and the gas is brought to rest, thereby increasing the stagnation temperature and pressure (reservoir conditions). Such a heating technique is utilized in T3 operation by simply arranging a second diaphragm at the end of the shock tube. Thus, the second diaphragm or nozzle diaphragm separates the shock tube end from the nozzle entrance. There is a sliding sleeve system which makes the replacement of the rupture nozzle diaphragm very easy (see Fig. 13).
Conical T3 Nozzle Section

The nozzle is an important component of the test facility, because it directly influences the flow quality delivered to the test chamber. The T3 nozzle is a conical nozzle with 15 degree half-angle, and interchangeable throats inserts. Thus, the area ratio can be conveniently changed, thereby freestream Mach number in the test chamber. Such a geometry is the simpler to design, but diverges the flow a bit at the nozzle exit. The conical T3 nozzle consists of four pieces made of carbon steel alloy and aluminum as shown in Fig. 14. The sliding sleeve system mentioned before makes the replacement of throat inserts very easy too. During BEP runs, the T3 nozzle was arranged to yield freestream Mach numbers ranging within 6 and 10.
MEASUREMENT TECHNIQUES

Classical

Figure 15 shows the lightcraft compression ramp, shroud and afterboby equipped with a Pitot pressure probe and several static pressure sensors. The freestream Mach number of the existing hypersonic can be estimated because it relates to Pitot pressure and freestream static pressure.
Static pressure probes fitted on the lightcraft model gives an estimative of compression ratio, LSD wave strength and coupling coefficient in hypersonic flow. A cross-shaped rake equipped with Pitot pressure probes are under way to measure wheatear the flow is uniform or whether no-uniform during the expansion.

Schlieren Imagery and High-Speed Video

The schlieren visualization technique [9] in combination with an ultra-high speed Cordin 550-32 digital camera was integrated to the laboratory facilities to record the temporal behavior of the BEP phenomena such as LSD waves. Schlieren imagery is a non-intrusive optical technique whose alignment is not so difficult yielding images with a lot of details about the BEP phenomena. The Cordin 550-32 is a rotating mirror digital camera capable of capturing 32 color frames (32 CCDs, 1000 x 1000 pixels/frame with 10 bit of resolution) and operating at a maximum rate of 2000 frames per second (fps). When the TEA laser is fired, it generates inherently an electromagnetic noise because of the operation of the Marx generator. Such a noise interferes in the main trigger of the Cordin camera resulting in a loss of synchronism between the electronics of the rotating mirror position sensor and the CCDs trigger in a manner that only “black” frames are gotten. Fortunately, the Cordin camera has a pre-trigger mode through which it is possible to record some images preceding the trigger itself. This mode is used to resolve the problem of noise. In this case, the camera is triggered 120 µs after firing the TEA laser and it is setting to record from 8 to 16 images of the pre-trigger. The schematic of the “z-type” (for astigmatic compensation) schlieren optical layout is shown in Fig. 16.

FIGURE 16. Schematic of the schlieren setup: Pulsed flash lamp (PFL), slit (SLT), focal lens (FL), flat mirror (FM), parabolic mirror (PBM) and knife edge (KE).
The main components of the schlieren technique are the two f/8 on-axis parabolic mirror PBM1 and PBM2 (12 in dia. and 71 in focal length manufactured by SORL-Space Optics Research Labs, USA), the knife edge (KE, razor blade) and the light source (PFL, xenon flash lamp). The others optical components are used in the assembly as auxiliary optics to compensate the limited space around the T3 test chamber. In this way, the flat mirrors FM1 and FM2 (16 in dia. by SORL) are used to redirect the collimated light and the focal lens FL (2 in dia. and 10-cm focal length) along with the FM3 to position the light source at focus of the parabolic mirror PBM1. The T3 test chamber has two 12 inch diameter fused silica windows (FSW) with 250 mm effective vision area. The photo in Fig. 17 shows the schlieren light beam path and the arrangement of the Cordin camera with respect to the T3 test chamber.

FIGURE 17. T3 test chamber showing the schlieren setup and the light path.

OPERATION FOR BEP RUNS

BEP runs are conducted by means of T3 shock tunnel integrated with both TEA lasers. Synchronization is vital to successful runs. More than a hundred runs without erratic runs were performed through the methodology discussed as follows. The T3 shock tunnel is setup while both TEA lasers are putting into action. T3 setup time takes around one hour. Usually, the TEA lasers are ready to go around fifteen minutes before the pressure ratio P4/P1 reaches the diaphragm brakeage “zone”. However, in the case of anything goes wrong with the TEA lasers the pressure ratio can be held for a while by means of the DDS section. When both facilities are ready to go T3 is then shouted and instantaneously after P5 signal comes up and triggers the Cordin camera and both TEA lasers. The Cordin camera begins to take pictures at 1.6 ms after P5 signal while the laser beam is delivered to the fully-developed hypersonic flow exactly 0.2 ms ahead. Figure 18 shows the first ever schlieren images of the ignition chamber of the lightcraft during hypersonic flight powered by energetic laser beams.
CONCLUSIONS

Beamed-energy-propulsion is a technology in maturation and will be available within the next two decades. Under the Brazil-USA BEP cooperation, T3 hypersonic wind tunnel is now integrated with two energetic CO$_2$ TEA laser devices and equipped with schlieren high-speed flow visualization for experimentation on laser propulsion at IEAv in São José dos Campos, Brazil. These experiments are already leading to scientific findings and new approaches that overcome the challenges of laser propulsion concept.
REFERENCES