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Application of the Laser to Electric Propulsion

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Illumination of a metallic surface with focused light from a ruby laser has been shown to produce very high density ion emission, the ionized particles being emitted with substantial initial velocities. Ion currents of several amperes and electron current of hundreds of amperes have been obtained from a surface disc less than 0.020" in diameter. Ion velocities have been measured to be over 4 kilometers per second as emitted, and changed very slowly with changes in laser energy applied to the emitter. Estimates of emitter temperature and plasma density together with electrical measurements of currents and voltages indicate a highly ionized plasma. Mass spectrometer measurements verified that only singly charged atoms were being formed and that ionization of the emitter was over 99 percent complete.

These findings suggest that the laser excited emission technique should find favorable application to two types of thrustors. In one type the impulse caused by the relatively high initial velocity of the emitted particles would be used directly; in the second, the high density relatively monoenergetic and highly ionized plasma would be used as an ion or plasma source in an accelerator type thrustors thus obtaining higher ejection velocities and consequent higher values of specific impulse. The experimental results show that thrusts of about 25 millipounds were produced with 196 watts per millipound power consumption. The specific impulse in the direct thrustor example cited was about 600 seconds. When used as an ion source, several amperes of ion current can be obtained at ionization efficiencies of 600 ev per ion when only the laser is used. The energy required for ion production was found to be as low as 30 ev/ion when ionization was enhanced by the external circuit. Thrust and specific impulse in this case are controlled by the accelerating potentials selected for a given engine.

The laser excited emission process is inherently free of standby or warmup power requirements; therefore, the cycling of thrustors using this technique could be predicated exclusively on thrust requirements and on the desired precision of control without penalty of added power consumption, or equipment malfunction caused by fast cycling.

Under internal research grant, RM-1863-E a project was established at the Cornell Aeronautical Laboratory to study ion generation by illumination of a metallic surface with focused light from a pulsed laser. One important goal of this project was to explore application of the technique to electric thrustors. The experimental program was divided into two phases: in the first, the quantity and energy of emitted particles over a wide range of conditions was measured; in the second phase, the electrical nature of the emission (charge to mass ratios and percent ionization) was determined. These data are needed to evaluate the applicability of this process to various types of thrustors. This paper describes the results of this internal research study that pertain to thruster application, and then considers possible thruster configurations and performance using this technique.
The experimental apparatus used in the first part of the program to measure the quantity and energy of the emitted ions and electrons is shown in the block diagram in Figure 1.

The light from a pulsed ruby laser was collimated by passing it through a telescope and then focused on the end of an 0.020 inch diameter tungsten wire. A photocell and amplifier detected a small portion of the laser light (scattered from the focusing lens) and provided a signal for the oscilloscope proportional to the amplitude of the laser light. A power supply attached to each half of the split collector made it possible to apply up to 400 volts positive or negative to each half. Viewing resistors were appropriately located so that the wave forms of the current through the collector halves could be observed. In addition, a viewing resistor was placed in series with the emitter. A dual beam oscilloscope was used to observe simultaneously the wave forms of any two of the following: the laser light, the emitter current, or either of the collector currents.

Seven tungsten emitter rods were mounted closely spaced in an OFHC copper block so that the laser light spot could be switched from one emitter to another without opening the vacuum system. A stainless steel split-cylinder collector allowed independent or simultaneous measurement of ion and electron emission. The vacuum chamber in which these electrodes were placed was typically pumped to pressures in the $10^{-9}$ to $10^{-10}$ Torr range.

**Ion and Electron Current Measurements**

Figure 2 contains oscillograms of amplitude of ion and electron current taken under several typical test conditions. A time history of ion current drawn by the collector structure appears in Figure 2a. In this example, -400 volts was applied to both halves of the collector (collecting only ion current) and a moderate laser energy level, about 6.0 joules, was used. In a given configuration the nature of emission does not vary, except in amplitude, as the emitter is illuminated at higher laser intensities up to about 13.0 joules. The trace in Figure 2b shows electron current emitted at 6.0 joules laser input; 50 volts was applied to both collector halves (collecting only electron current). The accompanying (upper) trace shows the fraction of emitted electron current drawn off by the collector cylinder; it is less than the emitted current because the emitted plasma apparently has cosinusoidal velocity distribution about the axis of symmetry, thus about 40% of the plasma does not intercept the open-ended cylindrical collector and not all of the emitted electrons are collected at this point.

With subsequent adjustments in focusing conditions, the average collected ion currents have increased to over 10 amperes. In experiments exploring the properties of the plasma it was found that a collector potential of +20 volts was sufficient to draw off 100 amperes of electron current. To obtain 100 amperes of electron current at a potential of 20 volts in a space charge limited diode with anode and cathode areas of about 3 square inches, the diode spacing, $d$, as computed from the Langmuir-Child law,

$$J = 2.33 \times 10^{-6} \frac{V^{3/2}}{d^2}$$

would be only $1.5 \times 10^{-3}$ in. Since the actual spacing was much larger (approximately 0.6 in.), this data implies that a very dense plasma was formed when the laser light impinged on the tungsten surface and that electrons or ions were
drawn from a very thin sheath at the boundary surface between the collector and the plasma column. This postulation was supported when the current to the collector was examined as a function of the voltage applied to the collector.

Figure 3 shows a plot of current vs. collector voltage for an incident laser energy of 6.0 joules. This curve is similar to that obtained from a Langmuir probe in a plasma. When negative voltages below -5V were applied to the collector, the saturation ion current of about 1 ampere was drawn. This current, or rather the current density at the collector was, of course, simply the product of the drift velocity of the ions multiplied by the charge density of the ions at the collector. Measurements (to be described in a succeeding section) show that the transit time of the ions from the emitter to the collector was independent of the collector voltage. Therefore, the drift velocity of the ions was independent of the collector voltage and the postulated plasma was completely neutral with a potential equal to the ion-source potential.

After the general nature of the plasma had been determined, experiments were performed to investigate parameters affecting the rate of ion generation. First of all, it was found that the rate of ion formation was dependent upon the rate at which the energy impinged on the surface of the tungsten. This, of course, is to be expected and is shown clearly in Figure 4. The energy in the light burst from the laser is the same in Figure 4a and in 4b; however, the duration of the light burst in 4b is roughly 2/3 of that in 4a so that the power in 4b is 3/2 of that in 4a. The resulting ion charge released from the emitter in Figure 4a was only 107 microcoulombs whereas that released in Figure 4b was 289 microcoulombs.

Shown in Figure 5 is a curve of the total charge released from the emitter as a function of the energy in the light burst. The duration of the pulses in Figure 5 was the same as in Figure 4a. Unfortunately, the shorter time duration shown in Figure 4b could not be used at higher laser-output levels because this would have required voltages above the maximum rating of the flash lamp used to pump the ruby. Note that there was a definite threshold which for this specific emitter configuration was just under 5.0 joules. Below this level, no ion generation was observed; however, there was still a considerable amount of electron generation resulting, evidently, from thermionic emission. The curve could not be extended above the 13.0 joule energy level because in the reported experiments this was the maximum output of the laser less the loss in the telescope, focusing lens and vacuum chamber window.

After the ion-charge emission had been maximized to the extent possible by laser and optics adjustments, an attempt was made to achieve additional increases by biasing one of the halves of the split collector positive while the other was held at a negative potential. It was hoped that the large electron currents drawn through the plasma would increase the ionization and also produce higher velocity particles. Although no increase in ionization was observed during the laser pulse, a very interesting and important phenomenon was discovered. As is shown in Figure 6, about 200 ma of ion current was obtained at the negative collector and up to 70 amp of electron current was obtained at the positive collector during the laser pulse (the first millisecond on the time scale). After the cessation of the laser pulse, the ion current increased to about 300 ma while the electron current dropped to about 20 amp. This condition persisted with a slow decay for approximately 2 milliseconds and then both the ion and electron currents decreased exponentially to zero. It is thought that this phenomenon occurred because the electron current being drawn from the emitter was large enough to maintain,
through ohmic heating, a temperature comparable to that caused by the laser thus synthesizing conditions like those of a vacuum arc. No attempt was made during the preliminary experiments to increase the duration or the intensity of this discharge.

**Ion and Electron Energy Measurements**

Measurements were made of the energies of the ions and electrons ejected from the tungsten emitter, primarily so that greater insight into the basic mechanism of the ionization process could be gained. An estimate of the velocities of ions was made by measuring their time of transit from the emitter to the collector. This was done by comparing the time of arrival of a laser spike at the emitter with the time of arrival of the ion burst, caused by the laser spike, at the collector. Shown in Figure 7 are typical oscillograms used for transit time measurements. Figure 7a shows the entire light and ion pulses and Figure 7b shows a selected portion of 7a with the time scale expanded 50 times. Notice that the peaks in the ion current (top trace of 7b) are delayed 3.6 \( \mu \text{sec} \) relative to the laser spikes (bottom trace). Since the average distance from the emitter to the collector was about 1.5 cm, the average ion velocity was about 4 \( \times 10^3 \) m/s. One reason why the ion-current pulses were not as narrow and sharply defined as the laser spikes can be attributed to the diode configuration. Although the average distance from emitter to collector was 1.5 cm, the shortest distance was about 1 cm and the longest distance was about 2 cm. Thus, even when it is assumed that all ions traveled at the same velocity, the broadening (about 2.5 \( \mu \text{sec} \)) of even the narrowest pulse was a large percentage of the average transit time of 3.6 \( \mu \text{sec} \).

Assuming that the tungsten ions were singly charged, and further, that each ion was formed from a single atom, then, based on the velocity of 4 km/s, the average energy of the ions was about 15 ev. This energy was found to remain constant at 15 ev even though the collector voltage was varied from -5v to -400v, which confirms previous indications that no potential drop across the plasma occurred, and further, that the plasma was at the potential of the ion source. It was also found that the average ion energy did not vary even though the energy of the laser light was varied (from 5.0 to 13.0 joules) and the focal position was moved through a considerable range.

**Mass Spectrometer Studies**

Figure 8 shows a block diagram of the configuration used in the series of experiments to determine \( q/m \) and percentage neutrals. To keep the diagram clear of unnecessary detail, electrical connections to measure current and to apply rf and dc voltages have been omitted.

The ion generator shown in these figures is very similar to that described previously except that the focusing lens is installed in the vacuum chamber and the emitter is illuminated at an angle.

The quadrupole mass spectrometer is capable of mass resolution of one part in fifty and with the particular rf generator used can filter up to about mass number 200. If used as a "high pass" filter to measure ions with mass above a stated value, it can detect the quantity of ions with mass numbers above 200 but the composition of this class could not be detailed.
Efficiency of Ionization Process

To be useful as an ion source for thruster application, an ion generator must operate at reasonable ionization efficiency and also must produce an output as free as possible of neutral particles. The data obtained to date and the results derived from it indicate that ionization of the evaporated tungsten was very nearly complete. For example, an estimation was made of the total number of ions collected during a period of about a month when a particular group of experiments were being performed. This estimation was made by going through the oscillograms of the ion data (at least 95 percent of the firings of the laser were recorded on oscillograms) and determining the number of ions generated per firing with a planimeter. The total mass of the ions collected was approximately $220 \times 10^{-6}$ grams and this was compared with the mass of tungsten removed from the emitter of about $490 \times 10^{-6}$ grams as determined by physical measurement of the emitter. This comparison is only approximate but it helps confirm other findings. Computed values of evaporation rate and vapor pressure of tungsten at its boiling point supplied further evidence that ionization was nearly complete. These computations are rather lengthy so they are not included in this paper.

Tests with the quadrupole mass spectrometer gave final and most rigorous demonstration that the tungsten ejected from the emitter was, for all practical purposes, completely ionized. A search was made for emitted neutral tungsten atoms by preventing the emitted electrons from entering the spectrometer and by reducing the number of ions entering to less than 10 percent of the normal value. The ionizer attached to the spectrometer was then activated so that neutral atoms would become ionized, and would be detected at the spectrometer collector cup. No ions were observed which implies, when the ionization cross section of tungsten and when the density and velocity of electrons in the ionizer are considered, that the tungsten plasma was over 99 percent ionized and further no detectable recombination occurred even after the plasma had drifted about 5 cm away from the emitter. In addition to testing for the presence of neutral atoms, the mass spectrometer was used to search for doubly ionized tungsten atoms (near mass number 92) and finally, in a "high mass pass filter" mode, it was used to search for multiple-atom ions. None of these ion species were detected.

Characteristics of Laser Excited Emission Important in Electric Propulsion

Energy Required per Ionization

The lowest energy per ion ratio observed with best possible electrode configuration and focusing adjustment is about 600 ev. Of this amount, no more than 50 ev are required for evaporating a tungsten atom, ionizing it, and accelerating the ion to 15 ev. When ion emission was augmented apparently because of heating by electron current (Figure 6), the energy required for the formation of an ion was found to be as low as 120 ev. With other improvements as low as 30 ev/ion has been achieved in this augmented mode of operation.

Shown in Figure 9 is a plot of over-all engine efficiency as a function of specific impulse in which efficiency is computed for energy/ion ratios of 4000, 600, 129 and 30 ev/ion, values that have been achieved with various test configurations of the laser ion generator. Plotted, for comparison's sake, are curves for a mercury engine and a cesium engine. Observe that with the circuit

augmented emission condition, at 30, and 120 ev/ion relatively high efficiencies should be expected even down to the 1000 second specific-impulse range.

**Mechanical Impulse and Thrust**

Thrust is given by

\[ T = \dot{m}v \]

where \( \dot{m} \) is the mass flow rate, and \( v \) is the final velocity of the particles. From results obtained with the most favorable configuration developed to date, thrust of \( 28.8 \times 10^{-3} \) lbs. is computed. Thrust per unit area is greater than \( 1000 \) lb/in\(^2\). Of course, if the ions were accelerated, then the increase in thrust per unit area would be proportional to the square root of the accelerating potential. The 28.8 mib thrust was obtained with an input power of 5650 watts, or with a power/thrust ratio of 196 watts/millipound. Material consumption in the example cited was \( 0.046 \times 10^{-6} \) lb/second during actual thrusting time. Impulse bits are \( 5.75 \times 10^{-6} \) lb-sec., so that extremely fine control is afforded. Power efficiency, the ratio of exhaust plume kinetic power to input power is a modest 5.82%, suggesting further improvements can be expected; nevertheless, overall system performance computed for a sample task is reasonably good and compares favorably with more complicated accelerator type ion engines.

Although no direct measurement has been made to date of the angular distribution of density of emitted ion about the axis of symmetry, an observation of the density distribution of tungsten deposited on a collector placed in front of an emitter indicated that the distribution was approximately cosinusoidal. That is, most of the ions were emitted normal to the surface and the density fell off approximately as the cosine of the angle to a vector perpendicular to the surface. The relationship between emitted current and current drawn off at the open-ended, cylindrical collector further supports the assumption that the distribution was approximately cosinusoidal. Thus, most of the thrust was normal to the emitter surface.

**Ionization Efficiency**

All of the results presented previously indicate that complete ionization of the tungsten evaporated from the emitter surface should have occurred. This is of great significance in electric propulsion engines where electrostatic acceleration of ions is contemplated. Neutral atoms in a cloud of ions being accelerated by a nonintercepting electrode system can become ionized through charge-exchange processes and can be accelerated directly towards the electrodes. If the kinetic energies attained by the ions are large enough, erosion and subsequent reduction of engine life result. In a thrustor using the initial momentum of emitted particles, the existence of neutrals is irrelevant.

**Propellant Containment and Feed System**

In all propulsion systems, propellant (fuel) must, of course, be fed into the engine at the same rate at which it is expended. In addition, containers must be provided for the propellant. In an electric propulsion engine using the laser ionization processes described in this paper, the propellant being fed into the engine would probably be a solid with a very low vapor pressure at normal temperatures (\( 300^\circ \)K). Propellant containment would, therefore, be accomplished simply by rolling the fuel up on a spool. Feeding the fuel into the engine could be accomplished by unrolling the spool of fuel while directing it into the axis of the laser beam.
Thrustor Application Examples

Attitude Stabilization of a 1500 Lb. Synchronous Satellite

**Design Assumptions**

- Design max. disturbing torque
- Average disturbing torque (3 year average)
- Moment arm
- Max. tolerable error angle

**Operating Conditions, Laser Excited Thrustor**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. thrust</td>
<td>$2.5 \times 10^{-6}$ lbs. continuous</td>
</tr>
<tr>
<td>Average thrust (3 year average)</td>
<td>$1.25 \times 10^{-6}$ lbs.</td>
</tr>
<tr>
<td>Pulse repetition rate (5.75 micro-lb-sec. impulse bits)</td>
<td>1 pulse/2.3 sec. max.</td>
</tr>
<tr>
<td>Error angle accumulated between firings</td>
<td>$.4 \times 10^{-6}$ radians</td>
</tr>
<tr>
<td>Average power from batteries or solar cells (assume 50% efficiency diode laser)</td>
<td>.49 watts/thrustor = 6 watts total (12 thrustors)</td>
</tr>
<tr>
<td>Propellant consumption</td>
<td></td>
</tr>
</tbody>
</table>

**Operating Conditions, Ion Engine**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating thrust</td>
<td>$0.5$ mlb. for 5% duty cycle</td>
</tr>
<tr>
<td>Pulse rep. rate</td>
<td>1 actuation/424 secs.</td>
</tr>
<tr>
<td>Error angle accumulated between firings (404 seconds)</td>
<td>$0.5^\circ = 8.7 \times 10^{-3}$ radians</td>
</tr>
<tr>
<td>Average joules/cycle/axis</td>
<td>10,413</td>
</tr>
<tr>
<td>Average power/axis</td>
<td>24 watts</td>
</tr>
<tr>
<td>Power from batteries or solar cells</td>
<td>103 watts average</td>
</tr>
<tr>
<td>Propellant and tankage weight</td>
<td>$2.5$ lbs/3 years</td>
</tr>
</tbody>
</table>

*Because of the simplicity and low mass of the laser emitter and because no tubing, electrical connections are needed to the thrustor itself, 20 ft. torque arm is considered to be reasonable; published reports suggest a 5 ft. torque arm for the heavier more complicated ion engine.*
Station Keeping of a 1500 lb Synchronous Satellite

Total impulse required 26,500 lb-sec. (3 years)

Operating Conditions Laser Excited Thrustor

Avg. force 0.280 x 10^{-3} lbs.
Avg. force/thrustor (assuming 12 thrustor array) 0.07 x 10^{-3} lbs.
Pulsing frequency 12.5 p.p.s.
Average power 37.5 watts/thrustor
Total power from satellite supply (4 thrustors active) 150 watts
Propellant consumption (I_{sp} = 615 sec.) 43.2 lbs. total

Operating Conditions, Ion Engine

Specific Impulse 4500 sec.
Specific power 200 lbs/mlb.
Duty cycle 20%
Thrust interval approx. 12 minutes each hour
Operating power 375 watts
Avg. power from satellite supply 140 watts
Propellant consumption 5.9 lbs.
Figure 1  BLOCK DIAGRAM - APPARATUS FOR PHASE I EXPERIMENTS OF CAL INTERNAL RESEARCH PROJECT
Figure 2a TYPICAL COLLECTED ION CURRENT

Figure 2b EMITTED AND COLLECTED ELECTRON CURRENT
NOTE SCALE CHANGES IN BOTH COLLECTOR-CURRENT AND COLLECTOR-POTENTIAL SCALES

Figure 3 COLLECTOR CURRENT VS COLLECTOR POTENTIAL FOR LASER EXCITED DIODE (LASER ENERGY = 6.0 JOULES)
Figure 4a  ION EMISSION AT 6 JOULES INPUT TO EMITTER (LONG LASER BURST)

Figure 4b  ION EMISSION AT 6 JOULES INPUT TO EMITTER (SHORT LASER BURST)
Figure 5  ION GENERATION AS FUNCTION OF TOTAL LASER INPUT

Figure 6  ION EMISSION ENCHANTMENT WITH SIMULTANEOUS COLLECTION OF ION AND ELECTRIC CURRENT
Figure 7a  TYPICAL ION CURRENT TRACE SHOWING ENTIRE BURST

Figure 7b  PORTION OF ION CURRENT TRACE EXPANDED 50:1 TO SHOW TRANSIT TIME
Figure 8  BLOCK DIAGRAM - APPARATUS FOR 2nd SERIES OF EXPERIMENTS ON CAL INTERNAL RESEARCH PROJECT
Figure 9  EFFICIENCY VS SPECIFIC IMPULSE FOR TWO EXISTING ENGINES (DASHED CURVES) AND FOR TUNGSTEN BEING IONIZED WITH 30, 120, 600 AND 4000 ev/ION (SOLID CURVES)
Figure 10  TYPICAL EMITTER-OPTICS CONFIGURATIONS SUITABLE FOR THRUSTOR APPLICATIONS