BOOK OF ABSTRACTS
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High-Power Laser Propulsion
Keynote I

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Abstract: The practical use of high-power laser propulsion is limited by such physical and technical problems as generation of laser radiation and control of the laser beam, pointing of the beam to a vehicle with a laser propulsion engine as well as optimization of interaction of the laser radiation with propellants, and so on. Moreover, some specific technical questions have to be considered such as putting the radiation power into a jet nozzle without losses, and thermal and dynamic loads onto the engine device. Radiance and thermal loads onto optical elements of the engine are increased under the high-power laser radiation, too. A special issue concerns the determination of optimal composition of a propellant for laser propulsion at space conditions. It is clear that the option of the propellant components will determine efficiency of using the laser power that is the efficiency of the engine. All listed questions from laser physics and optics through gasdynamics, plasma chemistry, and strength of materials are considered in the book as applied to the development of laser propulsion engines, laser propulsion correction devices, and laser launch sites.

Airbreathing Pulsed Laser Propulsion Experiments with Terawatt Pharos III 1 µm Laser

Keynote II

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Abstract: Unique airbreathing pulsed laser propulsion experiments were performed at the Naval Research Laboratory (NRL) with the 1 µm Pharos III laser, delivering 23 to 376 joules with pulse durations of 5 to 30 ns. The research objective was to investigate the impulse generated by laser supported detonation waves under ambient atmospheric conditions. The experiments employed a 3.5-cm line focus bounded with parallel endplates to restrict the resultant blast wave expansion into a two-dimensional geometry against an instrumented impact plate. Laser-induced impulse was measured in two ways: by integrating pressure transducer data from the impact plate, and from ballistic pendulum deflections.

Data acquired from these experiments, along with predictions from the EQUINT code, are used to estimate air plasma properties behind laser-induced blast waves. The basic research results shed insight into methods for increasing impulse coupling, efficiency, and thrust performance of future airbreathing pulsed laser detonation engines.

Super long conductive canal for energy delivery from space

Keynote III

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Abstract: The objective of the project is to accomplish a circle of experimental, engineering and technological works on creation of super long conductive canals for energy delivery. A high repetition rate pulse-periodic CO_2 laser system and the most important components for the project realization will be presented. An optical system for long range energy delivery will be discussed, as well. Some new applications of long range energy delivery system will be highlighted. Relying on a wide cooperation of different branches of science and industry organizations, it is very possible to use the accumulated potential for the orbital scale experiment performance.

Power Beamed Photon Sails: New Capabilities Resulting from Recent Maturation of Key Solar Sail and High Power Laser Technologies

Keynote IV

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Abstract: This paper revisits some content in the First ISBEP in 2002 related to the concept of propellantless in-space propulsion utilizing an external high energy laser to provide momentum to an ultralightweight (gossamer) spacecraft. The design and construction of the NanoSail-D ssoal sail demonstration spacecraft has demonstrated in space flight hardware the concept of small, very light, yet capable spacecraft. The results of the Joint High Power Solid State Laser (JHPSSL) have also increased the effectiveness and reduced the cost of an entry level laser source. This paper identifies the improvement in overall system parameters made possible and also surveys new mission applications made possible.

Session 2: Lightcraft I

Australian Airbreathing Propulsion Research for Hypersonic, Beamed Energy-Propelled Vehicles

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Abstract: A 3-year laser-propelled vehicle analysis and design investigation was begun in June, 2009 at the University of Adelaide under the sponsorship of the Asian Office of Aerospace Research and Development (AOARD). Major objectives of this investigation are: (a) development of hypersonic airbreathing "lightcraft" with innovative air inlets that enable acceptable air-flow capture and combustion and acceptable cowl-lip heating rates during hot, high-speed, high angle-of-attack, hypersonic flight; (b) test a promising lightcraft-air inlet design in the laser shock tunnel facility at CTO Instituto in Brasil; and (c) plan a series of laser guided and propelled vehicle flights that achieve supersonic or higher speed at the Woomera Test Facility WTF) in South Australia – using the existing WTF launching and tracking facilities and sponsor-provided laser pointing and tracking, and illumination systems.

Investigation on altitude characteristics for air-breathing laser propulsion

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Abstract: Altitude characteristics are the basic characteristics needed to be explained when an air-breathing pulsed laser thruster works in the dense atmosphere condition of 0~30km altitude. The experimental findings over the world show the similar relations between the momentum coupling coefficient and the altitude. Based on the intense explosion theory and ideal hydromechanics model, dimensionless factor which indicates the law of energy similarity is presented, and the formula of impulse coupling coefficient is deduced. Then theoretical investigation of the altitude characteristics is carried on and the mechanism of altitude characteristics is further explained. The results indicate that: there always exists a maximum value of C_m if the dimensionless factor ¯ equals to 0.41 in the theory, whether the phenomena of maximum appears depends on the range of the dimensionless factor related with the altitude. As to the conical nozzle with the fixed length of 120mm, coupling relation between the sonic velocity and the dimensionless factor cause the maximum phenomenon at the altitude of about 12.5km, and the similar law of maximum C_m is also found in the experimental investigations of altitude characteristics.

Energy Law of Similitude for Laser Propulsion Powered by Single Laser Pulse

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Abstract: Energy law of similitude for laser propulsion refers to the law that there is an optimum nozzle configuration for constant laser energy, making impulse coupling coefficient remaining largest. A dimensionless factor combined with incident laser energy, nozzle configuration parameters, and working gas parameters was introduced. Energy law of similitude was established by means of theoretical analysis, experimental study and numerical simulation of radiation gas-dynamics. Since the qualitative results obtained from 3 ways accorded with one another, energy law of similitude was authentic. Furthermore, physics meaning and engineering application of dimensionless factor and energy law of similitude were analyzed. Results indicate: 1) impulse coupling coefficient has a maximum with dimensionless factor equaling to about 0.4; 2) impulse coupling coefficient is independent of incident laser energy when dimensionless factor is constant.

Experimental Investigation into Beam-Riding Physics of Lightcraft Engines

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Abstract: The twin Lumonics K922M pulsed TEA CO_2 laser system at RPI was employed to experimentally measure the beam-riding behavior of Type #200 lightcraft engine family, using a lightweight ballistic pendulum and the Angular Impulse Measurement Device (AIMD). Beam-riding forces and moments were examined along with the thrust-vectoring behavior as a function of: a) laser beam angular and lateral offset from the vehicle axis of symmetry; b) laser pulse energy (12 to 36 joules); c) pulse duration (100 ns and 1 μs); and d) engine size (97.7 mm to 161.2 mm). The beam-riding performance of the Type #200 engine was contrasted with that of #150 and #250 geometries, as well as with bell engines. This study, which included historical data from both US and German investigations, provides insight into the influence of engine geometry upon beam-riding behavior.

Subsonic Aerodynamics of Spinning and Non-Spinning Type 200 Lightcraft

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Abstract: A combined experimental and numerical investigation of subsonic aerodynamics for Type 200 laser lightcraft was carried out for both spinning and non-spinning cases. A 12.2cm diameter aluminum model with a "closed" annular airbreathing inlet was fitted to a sting balance in RPI's 61 cm by 61 cm subsonic wind tunnel. Aerodynamic forces and moments were measured first for the non-spinning case vs. angle of attack, at several freestream flow velocities (e.g., 30, 45, and 60 m/s) to assess Reynolds number effects. The CFD analysis was performed for 0-180^o angles of attack for a fixed coordinate system (i.e., non-spinning Type 200 model), and predictions compared favorably with the experimental data. For the spinning case, a brushless electric motor was employed to rotate the wind tunnel model at 3000 to 13,000 RPM; Magnus force effects upon the coefficients (C_d, C_l, and C_m) revealed interesting departures from the non-spinning database.

Inlet Aerodynamics and Ram Drag of Laser-Propelled Lightcraft Vehicles

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Abstract: Numerical simulations are used to study the aerodynamic inlet properties of three axisymmetric configurations of laser-propelled Lightcraft vehicles operating at subsonic, transonic and supersonic speeds up to Mach 5. The 60 cm vehicles were sized for launching 0.1-1.0 kg nanosatellites with combined-cycle airbreathing/rocket engines, transitioning between propulsion modes at roughly Mach 5-6. Results provide the pressure, temperature, density, and velocity flowfields around and through the three representative vehicle/engine configurations, as well as giving the resulting ram drag and total drag coefficients—all as a function of flight Mach number. Simulations with rotating boundaries were also carried out, since for stability reasons, Lightcraft are normally spun up before lift-off. Given the three alternatives, it is demonstrated that the optimal geometry for minimum drag is the configuration with a power-law nose; hence, these inlet flow conditions are being applied in "direct connect" 2D laser propulsion experiments in a small transonic flow facility.

Analysis of the Laser Launch and Beam Module Concept

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Abstract: The main purpose of this paper is to define characteristics of power and aperture size for possible beam modules using laser technology. For a launch system, the range limit may be set by the vehicle getting too close to the laser's horizon, or (for a ground-based laser), resulting in the beam being absorbed in the atmosphere. The main interest for this is that the laser beam divergence will cause the beam to grow with distance, eventually becoming larger than the beam-collecting surface so that the transmission efficiency from the laser to the vehicle falls off, as $1/R^2$. The useful range of the laser system depends on the beam divergence and of vehicle dimensions, or, conversely, a range requirement can be used to define the beam divergence, and therefore the laser and optical system requirements.

In this work is calculated a maximum mass versus range by ignoring gravity and drag effects, and considering simple free-space acceleration with a thruster exhaust power. Two possible limiting cases are considered: conventional constant-specific impulse operation with constant exhaust velocity, and matched-velocity operation where the exhaust velocity equals a fixed multiple of the vehicle velocity.

Experimental Analysis of a 2-D LightCraft Model in Hypersonic Flow

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Abstract: A 25 cm wide, 2D LightCraft model was tested in the T3 Hypersonic Shock Tunnel at the Henry T. Nagamatsu Laboratory for Aerothermodynamics and Hypersonics. The 200 J laser pulses were supplied by a Lumonics CO_2 TEA 620 laser system operating in the unstable resonator cavity mode. Experiments were performed at a nominal Mach=9.2, as well in static mode (no flow). The high speed digital Schlieren visualization movie camera captured both the cold hypersonic flowfield structure (laser off) and the time-dependent flowfield structure (laser-on), following laser induced breakdown inside the absorption chamber. The 2D model was fitted with piezoelectric pressure transducers and surface junction thermocouples, in an attempt to measure transient pressure and heat transfer distributions across internal engine surfaces. The 2D model's modular design permitted flexibility of geometrical features that direct the expansion of laser induced blast waves. Finally the future evolution of 2D experiments currently being pursued is addressed.

Session 3: Lightcraft II

High speed Analysis of Free Flights with a Parabolic Thruster

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Abstract: A laser-based range finder with high temporal resolution, synchronized with the laser burst, is employed for fast on-site analysis of pulsed free flights. Additional high speed recordings from two different angles of view allow for full 3D-reconstruction of the trajectory and adjustment of the range finder data. This reveals the whole dynamics of the flyer including the lateral and angular impulse coupling components as well as information on the detonation process. The employment of an ignition pin enhances the reproducibility of the momentum coupling due to a more reliable plasma ignition during the flight. The impact of initial lateral offset is studied and shows beam-riding properties of the parabolic craft within a small range. Back-driving forces are derived and compared with the theoretical model. The flight stability is evaluated with respect to the minimization and compensation of the lateral and angular momentum in a hovering experiment. Stable laser acceleration ranges up to 3 m altitude, giving ballistic free flights close to the laboratory ceiling at 7.8 m are reported.

Remotely controlled Steering Gear for a Laser-driven Rocket with a Parabolic Thruster

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Abstract: A new steering concept for laser driven parabolic thrusters is presented. As an alternative to the well-tried spin-stabilization our concept provides rocket stabilization and trajectory control and is suitable for the injection of a laser-driven launcher into a planetary orbit: Angular and lateral momentum components are systematically applied to the rocket by specific variation of the ignition configuration inside the parabolic thruster. The impact of the tilting angle of the steering gear against the axis of symmetry on momentum coupling is examined as well as the influence of pulse energy and ignition geometry. Based on the experimental results an off-axis detonation is modeled with respect to the fluence distribution at the ignition area and the resulting force components. A demonstrator model of a laser-driven rocket with a parabolic thruster has been constructed including a remotely controlled steering gear and a separate payload fraction. Test flights employing a high energy CO_2 laser have been performed successfully.

Excimer Laser Annealing of Silicate Glass with Ion-Synthesized Silver Nanoparticles

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Abstract: The effect of KrF excimer laser radiation on a composite layer consisting of sodium–lime silicate glass with silver nanoparticles is studied as a function of the number of laser nanosecond pulses. The silver nanoparticles are synthesized by ion implantation. The measured optical absorption of the composite layer demonstrates that the silver nanoparticle size decreases monotonically as the number of laser pulses increases. Rutherford backscattering shows that laser annealing is accompanied by silver diffusion into the bulk of the glass and partial metal evaporation from the sample surface. The detected decrease in the silver nanoparticle size is discussed in terms of simultaneous melting of silver nanoparticles and the glass matrix due to the absorption of laser radiation.

Session 4: Simulations and Measurement Techniques

Measurement Issues in Pulsed Laser Propulsion

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Abstract: A variety of measurement techniques have been used throughout the history of laser propulsion. Often, these approaches have suffered from inconsistencies in definitions of the key parameters of the physics of laser-induced impulse generation, *e.g.* pulse energy, spot area, imparted impulse, and ablated mass. The limits and characteristics of common measurement techniques will be explored regarding laser propulsion. The idea of establishing some standardization system for laser propulsion data is introduced, so that results may be considered by the general community with more certain understanding of particular merits and limitations. In particular, minimum requirements for a literature study are proposed. Some international standards for measurements are already published, but modifications or revisions may be necessary for application to laser propulsion. Issues relating to development of standards will be discussed, as well as some examples of specific experimental circumstances in which standardization would have prevented misinterpretation of data.

Numerical study on the thermal-mechanical shock failure mechanism for annular-focusing laser thrusters

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Abstract: The plasma temperature for laser propulsion can reach above 10000K, hence, the thermal-mechanical shock and damage of thrusters will be a key problem for laser propulsion in the future. In this paper, a series of numerical simulations for Myrabo's annular-focusing lightcraft was carried out both for single and multiple laser pulses. The results indicate that the main factor causing temperature increase is the transmission absorption of the laser beam, the second one is the thermal radiation, and the convection heat transfer between the wall and the high-temperature gas can be ignored. The 100 pulse simulation result shows that at the 65th pulse, some elements appear tension failure because the material strength reduces with temperature increase, and at the 91st pulse, some elements reach the melting temperature. It seems the mechanical damage appears earlier than the thermal damage, and finally at about 100 pulses the thruster structure will be disintegrated with partially fracture and melting. The computation results can explain the experimental phenomena well.

Energy Absorption Structure of Laser Supported Detonation Wave

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Abstract: In Repetitive Pulsed (RP) laser propulsion, when the high energy laser beam is focused in the thruster, Laser Supported Detonation (LSD) wave is generated. This LSD wave converts the laser energy to the enthalpy of the blast wave, which will then apply impulse to the wall of the thruster. Therefore, the energy absorption structure and sustaining condition of LSD wave are important to be understood, which was still not clear though some visualized experiments have been conducted by Ushio, et al. before. In this paper, 2-wavelength Mach-Zehnder interferometry is brought to investigate the electron density distribution of the LSD area. At the same time, the temperature of the laser induced plasma is measured by an emission spectroscopy experiment, and calculated based on the assumption of local Saha equilibrium. The results show that in LSD, the electron density has a peak (as high as $2\text{x}10^{24}[\text{m}^{-3}]$) behind the shock wave. The irradiating laser pulse can be entirely absorbed before reaching the position of this peak. As a result, a new peak is always generating in front of the old one and this propagation has the same velocity as that of the blast wave. In this way, a high heating ratio is sustained right after the shock front. However, as the laser pulse energy becomes lower, the propagating peak cannot catch up with the blast wave anymore, which leads to a termination of the LSD wave. From this study, it is found that for sustaining the LSD wave, a sufficiently thin laser absorption layer is necessary.

Computational Model of Collisional-Radiative Nonequilibrium Plasma in a Gas-Driven Type Laser Propulsion

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Abstract: A time-dependent collisional-radiative model for air plasma has been developed to study effects of nonequilibrium atomic and molecular processes on population densities in a gas-driven type laser propulsion. This model consists of 15 species: e^-, N, N^+, N^{2+}, O, O^+, O^{2+}, O^-, N_2, N_2^+, NO, NO^+, O_2, O_2^+, and O_2^- with their major electronic excited states. Many elementary processes are considered in the number density range $10^{12}/\text{cm}^3 \le N \le 10^{19}/\text{cm}^3$ and temperature range $300\text{K} \le T \le 40{,}000\text{K}$. We then present results of comparison with an existing collisional-radiative code to validate our model. Additionally, an unsteady nature of laser-generated air plasma is investigated. Since ionization relaxation time is the same order as the time scale of a pulse laser, effects of unsteady ionization are important for estimating air plasma states. Moreover, we will report results of appropriate conditions for local thermodynamic equilibrium in that density and temperature range.

Session 5: Laser Ablation Propulsion I

Usage of Polyacetal Powders as Laser Ablation Propulsion Propellant

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Abstract: We examined the usage of polyacetal powders in laser ablation impulse performance experiments with a TEA CO_2 laser as an energy source. Two kinds of powders, 40 μm and 200 μm in diameter, were examined. Laser ablation impulse was measured using a piezoelectric force sensor. The controllability of the impulse performance is the main subject of the investigation.

Thrust Generation with Low-Power Continuous-Wave Laser and Aluminum Foil Interaction

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Abstract: The micro-Newton thrust generation was observed through low-power continuous-wave laser and aluminum foil interaction without any remarkable ablation of the target surface. To evaluate the thrust characteristics, a torsion-balance thrust stand capable for the measurement of the thrust level down to micro-Newton ranges was developed. In the case of an aluminum foil target with 10 micrometer thickness, the maximum thrust level was 6 micro-Newtons when the laser power was 20 W. It was also found that the laser intensity, or laser power per unit area, irradiated on the target was significantly important on the control of the thrust even under the low-intensity level.

Experimental study of polymeric propellants seeded with metallic powder for laser propulsion

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Abstract: The propulsion performance of POM seeded with metallic powder has been studied experimentally with CO_2 lasers. The results show that metallic powder can improve the propulsion performance of POM if the condition is proper. The maximum C_m of POM seeded with micron aluminum powder increases from 12dyne/w to 21.72dyne/w. When this material is put into a cylindrical tank, the measured maximum impulse coupling-coefficient and specific impulse can raise to 61.64dyne/w and 727.32s, respectively. The corresponding energy usage ratio is over 100%, which indicates that the aluminum powder may have a chemical reaction with the oxygen in the air under the constraint condition.

Experimental Study of Laser Micro-Propulsion for Different Thickness of Propellant

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Abstract: In order to protect the laser focus lens, the target as a transmission structure is used as propellant of laser micro-propulsion. The target includes a layer of transparent base and a layer of solid propellant, and the thickness of the target is under 100 _m. Laser beam through the transparent layer ablates the propellant, then the micro jet induced by the ablation will not pollute the focus lens. In this article, targets with three different thicknesses of propellant are ablated by a 1.8 W, 980 nm LD and the diameter of the focused laser spot is 50 _m. It can be concluded from the experiments that the thickness of propellant can influence the propulsion performance greatly, with the increase in thickness, impulse coupling coefficient (C_m) increases, specific impulse decreases. This will benefit us to optimize the parameter of laser micro-propulsion thruster and promote the propulsion performance.

A Model for Laser Ablation Mass Removal and Impulse Generation

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Abstract: To the present day, literature efforts at modeling laser propulsion impulse often used empirical models. Recently, a simple physical approach was demonstrated to be effective for predicting many practical properties of laser ablative impulse generation under vacuum. The model used photochemical mass removal and energy conservation to predict parameters such as the peak momentum coupling coefficient, the optimal fluence position at which this maximum is reached, and various critical properties related to the laser ablation threshold. Although the current model understanding is not complete, improvements in the treatment of mass removal and ambient pressure are expected to allow this type of model to be broadly applicable to many diverse applications using laser ablation impulse generation. In this paper, we also introduce an alternative formulation of the model incorporating photothermal mass removal. Implications and limitations of the model formulation in its initial stage of development are discussed, particularly concerning critical fluence effects and directions for improvement.

Session 6: Laser Ablation Propulsion II

Critical Fluences and Modeling of CO_2 Laser Ablation of Polyoxymethylene from Vaporization to the Plasma Regime

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Abstract: Recent interest in modeling laser ablation of polymers at long wavelengths has led to an improved model allowing a thorough description of laser ablation impulse generation from vaporization to the plasma regime. In this paper, details are provided about the derivation of the model as it relates to CO_2 laser ablation of polyoxymethylene propellant and its application to laser propulsion. A thorough discussion is included regarding parameters commonly used in laser propulsion experiments, such as momentum coupling coefficient, specific impulse, and ablated mass density. A CO_2 laser was operated at energies up to 10 J to ablate polyoxymethylene targets in air and vacuum conditions. Critical effects predicted by the models are discussed in relation to the experimental data, including specifically the threshold fluences for vaporization and plasma, and the fluence for optimal coupling.

CO_2 Laser Ablation Propulsion Area Scaling with Polyoxymethylene Propellant

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Abstract: The topic of area scaling is of great importance in the laser propulsion field, including applications to removal of space debris and to selection of size ranges for laser propulsion craft in air or vacuum conditions. To address this issue experimentally, a CO_2 laser operating at up to 10 J was used to irradiate targets. Experiments were conducted in air and vacuum conditions over a range of areas from about 0.05-5 cm^2 to ablate flat polyoxymethylene targets at several fluences. Theoretical effects affecting area scaling, such as rarefaction waves, thermal diffusion, and diffraction are discussed in terms of the experimental results. Surface profilometry was used to characterize the ablation samples. A CFD model is used to facilitate analysis, and key results are compared between experimental and model considerations. The dependence of key laser propulsion parameters, including the momentum coupling coefficient and specific impulse, are calculated based on experimental data, and results are compared to existing literature data.

Appropriate hardware for laser ablation propulsion for DM ram jet

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Abstract: In this paper, we specify hardware requirements as to the appropriate laser, and also the material properties of the spacecraft in detail. The aim of this paper is to propose what would be needed for an actual prototype experiment to be run, to show that laser beam ablation would be able to safely accelerate a spacecraft, without damaging essential instrumentation used for the boost of the spacecraft. This paper is almost all material science and laser physics, with little referencing of the ramjet, to be used afterwards, Specifics as to what sort of external pulsed laser could be used to burn off a plasma plume from a solid metal propellant, thus producing thrust. The measured specific impulse of small ALP setups is very high at about 5000 s (49 kN·s/kg), and care needs to be taken not only to accelerate the proposed craft to high velocities, but to protect instrumentation which will be used in the interstellar ramjet.

Survey of CO_2 Laser Ablation Propulsion with Polyoxymethylene Propellant

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Abstract: Polyoxymethylene (POM) has been widely studied as a laser propulsion propellant paired to CO_2 laser radiation. POM is a good test case for studying ablation properties of polymer materials, and within limits, for study of general trends in laser ablation-induced impulse. Despite many studies, there is no general understanding of POM ablation that takes into account the ambient pressure, spot area, fluence, and effects from confinement and combustion. This paper reviews and synthesizes CO_2 laser ablation propulsion research using POM targets. Necessary directions for future study are indicated to address incomplete regions of the various parameter spaces. Literature data is compared in terms of propulsion parameters such as momentum coupling coefficient and specific impulse, within a range of fluences from about 1-500 J/cm^2, ambient pressures from about 10^{-2}-10^5 Pa, and laser spot areas from about 0.01-10 cm^2.

Investigation on Momentum Coupling Coefficients of aluminum target irradiated by TEA CO_2 Laser

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Abstract: Air breakdown by focused laser pulse on/near the surface of metal shows different characteristics comparing with one in free air. Momentum coupling coefficients of the aluminum target irradiated by TEA CO_2 laser pulses were investigated. In the experiments, TEA CO_2 laser pulses were focused on the surface of the aluminum target with different energy fluence in the air pressure of 100 kPa, 49 kPa, 20 kPa and 0.1 kPa. When decreasing laser energy fluence on the target surface from 61.5J/cm^2 to 5.1 J/cm2 at the air pressure of 100 kPa, coupling coefficient increases from 47.4 N/MW to the maximum of 87.4 N/MW, then decreases to 41.2 N/MW, the maximum is obtained at the fluence of 11.8 J/cm^2. When decreasing the air pressure, the fluence for the maximal coupling coefficient increases. The different characteristics of "surface" air breakdown and "free" air breakdown was also compared in this paper.

Experimental Investigation of Liquid-propellant Laser Propulsion with a Horizontal Momentum Measuring Lever

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Abstract: Thrust performance of Liquid-propellant Laser Propulsion (LLP) is seriously influenced by factors like laser parameters, choice of propellants and ablation materials. For the purpose of studying these influences, a series of impulse measuring experiments for various propellants and ablation materials were conducted. The key device is a Horizontal Momentum Measuring Lever, which covers a C_m measuring range from 10^3 Ns/MJ to about $1.6x10^4$ Ns/MJ. A Nd:YAG laser was used as the laser source. From the result, it is found that laser energy density plays an important role on LLP efficiency, higher energy density leads to higher C_m and I_{sp}. Highest C_m of about 10^4 Ns/MJ with the I_{sp} of 3.57s was achieved by focusing the laser to a average energy density of $8.83x10^8$W/cm^2. Besides that, it is also found that when the energy density is certainly high, C_m of LLP increases steadily with the increase of propellant thickness, which gives a potential way to further improve the thrust performance of LLP.

Session 7: Advanced Concepts

Carbon Dioxide and Power Satellites: A Comprehensive Mitigation Proposal and Financial Analysis

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Abstract: A small number of people have been working for the past year on ways to reduce the cost of power from space to the point that it could entirely displace fossil fuels and even put carbon dioxide back in empty oil fields as synthetic oil. The challenging part is reducing the cost of transport to GEO by a factor of ~200. Our work has been on "pop up and push," i.e., rocket boost to a few hundred km and ablation laser for the rest of the delta V to GEO. This takes advantage of the high thrust of chemical rockets and the high exhaust velocity of lasers. The problem with this scheme is that a substantial number of very expensive lasers have to be in place before the first launch.

Recently another option has come to our attention, the Skylon Spaceplane designed by Reaction Engines Ltd, in the UK. By using air in place of oxygen to 26 km and Mach 5.5, a Skylon can get into LEO with a modest (12 t) payload. We obtained information on performance, development and production cost from Reaction Engines.

We have created a pro forma financial model using the cost information provided by Reaction Engines, our knowledge of the cost and physics of lasers propulsion, informal estimates of the design cost for high kg/kW space based solar power plants and propulsion lasers and the 2016 delivery time for the PG&E/Solaren contract.

Photovoltaic Concentrator Based Power Beaming for a Space Elevator Application

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Abstract: The MClimber team, at the Student Space Systems Fabrication Laboratory of the University of Michigan has developed a prototype space elevator for competition in the NASA sponsored Power Beaming (Climber) Competition. It incorporates a photovoltaic laser concentrator panel as well as a medium range laser collimating and pointing system that tracks the space elevator and maintains beam incidence on the panel. The panel uses solar concentrator cells to collect the laser energy that is transmitted over distances that could exceed 1.1 kilometer from the ground. It also contains a tilt control mechanism so that the laser strikes the cells close to perpendicular. This paper will deal with the design, construction, and testing of this space elevator prototype, specifically its power generation and expenditure and its beam and attitude control systems.

CO_2 Laser Ablation Propulsion Tractor-Beams

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Abstract: Manipulation of objects at a distance has already been achieved with no small measure of success in the realm of microscopic objects of nanometer to micrometer scale size in applications like laser trapping and laser tweezers. However, there has been relatively little effort to apply remote control concepts to macroscopic systems. A space tractor beam could be applied to, *e.g.*, removal of orbital debris, facilitation of spacecraft docking, adjustment of satellite attitude, station keeping, *etc*. In this paper, the concept of a CO_2 laser propulsion tractor beam is explored. Cooperative, layered polymer targets were used for remote impulse generation using a CO_2 laser operated at up to 10 J output pulse energy. These experiments demonstrated intentional switching between thrust directional parity (*i.e.*, between forward and reverse thrust). Results are presented in the context of polymer ablation modeling work and with a consideration of confined ablation effects.

A conceptual design of omni-directional receiving dual-beam laser engine

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Abstract: A conceptual design of Omni-Directional Receiving Dual-Beam Laser Engine (ODLE) is proposed. It has following features: (1) Its optical system is completely separated from the thrust system and can be adjusted in all direction to track the incident laser beams. (2) The dual-beam configuration can reduce 50% of the power requirement for each laser, and a laser relay can be carried out if needed during launching process. Both plane and conic spiral launch trajectories into the LEO with ODLE are proposed. The simulated results indicate that the transmission distance of laser beam for the latter is less than that of the former and can reduce significantly the divergence and energy loss of laser beams.

Phat Photon Lasers

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Abstract: The initial theoretical finding that eventually led to laser development was Einstein's prediction, based upon statistical considerations, that the energy of quanta of light be given by Planck's constant times the frequency of the light. A new theoretical development based upon Weyl's gauge field theory predicts that photon energies are quantized with the energy given by N^2hn. While the stimulated and spontaneous emission probabilities are proportional to $1/N^2$ the Rayleigh scattering cross section diminishes by $1/N^8$. This reduction in the scattering cross section means that a laser emitting phat photons with N>1 will lose less energy traveling through the Earth's atmosphere than lasers using N=1. This reduction in energy losses through the atmosphere means increased efficiency for Earth based beamed propulsion applications. This presentation discusses the fundamental theory, emission probabilities, and cross section calculations.

Session 8: Space-Based BEP Applications

Appropriate laser ablation propulsion for boosting a proposed DM ram jet to sufficient velocity to work in the SOLAR system as a start for an interstellar probe to reach operational velocity for a DM ram jet to work

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Abstract: Following the introduction of the necessity of appropriate beam energy boosting of a spacecraft to high velocities for a DM ram jet to work, in the AIBEP November 2009 conference, the author wishes to go to specifics as to what sort of external pulsed laser could be used to burn off a plasma plume from a solid metal propellant, thus producing thrust. The measured specific impulse of small ALP setups is very high at about 5000 s (49 kN·s/kg), and care needs to be taken not only to accelerate the proposed craft to high velocities, but to protect instrumentation which will be used in the interstellar ram jet.

Solar power satellites: Creating the market for beamed energy propulsion

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Abstract: Solar power satellites (SPS) offer the potential of virtually unlimited electricity generation and transmission to earth. Technologically, these massive monuments of engineering now appear feasible, four decades after being proposed. Economically, the high cost of reaching geosynchronous orbit will keep SPS grounded unless launch costs can be greatly reduced from the current $20,000 a kilogram. Chemical rockets will not be able to achieve the necessary costs or reliability. Beamed energy propulsion (BEP) should provide the needed economies by drastically reducing the cost of reaching orbit by two orders of magnitude – to approximately $200 a kilogram. To move BEP from the laboratory to a functioning system will require a sustained commitment of billions of dollars over several years. Only SPS can provide the thousands of tons of payloads necessary to justify a government investment in this radical ground-based launch system. The BEP community needs to work with the SPS community to promote the development of low-cost access to orbit to make SPS economically feasible.

You Can't Get There From Here . . . Or Can You? Economical Launch Systems As A Prerequisite For SPS

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Solar power satellites (SPS) offer the potential of virtually unlimited electricity generation and transmission to earth. Technologically, these massive monuments of engineering now appear feasible, four decades after being proposed. Economically, the high cost of reaching geosynchronous orbit will keep SPS grounded unless launch costs can be greatly reduced from the current $20,000 (2,000,000 yen) a kilogram. Chemical rockets will not be able to achieve the needed savings. Ground-based launch systems should be able to provide the needed economies. Beamed energy propulsion (BEP) promises to drastically reduce the cost of reaching orbit by two orders of magnitude – to approximately $200 (20,000 yen) a kilogram. To move BEP or the space elevator from the laboratory to a functioning system will require a sustained commitment of billions of dollars over several years. Only SPS can provide the thousands of tons of payloads necessary to justify investing in these radical ground-based launch systems. The SPS community needs to promote the development of low-cost access to orbit to make SPS economically feasible.

Laser propulsion device for space vehicles

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Abstract: To the present time, a few devices of laser propulsion engines were developed by using the dominant mechanisms of laser propulsion. Generally these mechanisms are laser ablation, laser breakdown of gases, and laser detonation waves that are induced due to extraction of an internal energy of polymer propellants. In the paper, we consider the Aero-Space Laser Propulsion Engine (ASLPE) developed earlier, in which all of these mechanisms are realized via interaction of laser radiation with polymers both in CW and in repetitively pulsed modes of laser operation. The ASLPE is considered to be exploited as a unit of a laser propulsion device being arranged onboard space vehicles moving around the Earth or in interplanetary missions and intended to correct the vehicle orbits. To produce a thrust, the power of the solar pumped lasers designed to the present time is considered in the paper. The problem of increasing the efficiency of the laser propulsion device is analyzed as applied to space missions of vehicles by optimizing the laser propulsion propellant composition.

Laser Propulsion Applications for Space Research

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Abstract: The launch of satellites is now one of the important scientific directions in space research. About 700 satellites of various sizes are orbiting around the Earth at various altitudes. As a rule, these relatively large-scale satellites are equipped with rather expensive equipment onboard and usually require much chemical fuel for launching. A lot of problems can be solved using small-scale satellites of up to several kilograms weight launched to low-altitude Earth orbits by high power lasers. It should be noted, that only a small fraction of satellite mass is spent for a laser plasma plume to achieve the first cosmic velocity, because the velocity of laser plasma, about 10-100 km/s, can be reached even when the intensity of CO_2-laser radiation is relatively small. It allows us to decrease the launching cost by one hundred times as compared to the cost of chemical-fueled rockets.

Flight Experiments on Energy Scaling for In-Space Laser Propulsion

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Abstract: As a preparatory study on space-borne laser propulsion, flight experiments with a parabolic thruster are carried out on an air-cushion table. The thruster is mounted like a sail on a puck, allowing for laser-driven motion in three degrees of freedom in artificial weightlessness. Momentum coupling is derived from point explosion theory for various parabolic thruster geometries with respect to energy scaling issues. The experimental data are compared with theoretical predictions. Vertical free flights allow for a comparison of both measurement techniques. Experimental results of air-breakdown threshold and POM ablation inside the thruster are compared with fluence data from beam propagation modeling.

High-I_{sp} Operation of Pulsed Laser-Electric Hybrid Accelerator for Space Propulsion Applications

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Abstract: A fundamental study of a newly developed rectangular pulsed laser-electromagnetic hybrid thruster was conducted, in which laser-ablation plasma was induced through laser beam irradiation onto a solid target and accelerated by electrical means instead of direct acceleration only by using a laser beam. The performance of the thrusters was evaluated by measuring the mass per shot and impulse bit. As results, significantly high specific impulses ranging from 5,300 ~ 7,100 sec were obtained changing with the charge energies of 0.1 and 8.6 J, respectively. In addition, the typical thrust efficiency varied from 11.8 to 21.3% depending on the charge energy.

Session 9: Laser and Microwave BEP

Space Experiments to Advance Beamed Energy Propulsion

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Abstract: High power microwave sources are now available and usable, with modification, for beamed energy propulsion experiments in space. As output windows and vacuum seals are not needed, space is a natural environment for high power vacuum tubes. Application to space therefore improves reliability and performance but complicates testing and qualification. Low power communication satellite devices (TWTs, etc) have already been through the adapt-to-space design cycle and this history is a useful pathway for high power devices such as gyrotrons.

In this paper, space experiments are described for low earth orbit (LEO) and lunar environment. These experiments are precursors to space application for beamed energy propulsion using high power microwaves. Power generation and storage using cryogenic systems are important elements of BEP systems and also have an important role as part of BEP experiments in the space environment.

Computational study of microwave-supported ionization front using PIC-DSMC method

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Abstract: In a microwave-beaming rocket, a high power microwave ionizes atmospheric air inside of a thruster, and an ionization front drives a shock wave. So far, these processes have been studied experimentally, and it was found that the ionization front has filamentary structures. These structures depend on the ambient pressure and disappear at 0.2 atm or less. In addition, the thrust drops down drastically at this pressure. Thus it is believed that there are any correlations between filamentary structures and detonation or deflagration waves driven by microwave. At the ionization front, free electrons may form a filament due to self-focusing via collision with neutral particles or interaction with the microwave. In this study, we have developed a two-dimensional PIC-DSMC code and will report simulation results of the microwave-supported ionization front for examining the mechanism of the filamentary structures.

Propagating Structure of a Microwave Driven Shockwave Inside a Microwave Rocket

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Abstract: The thrust generation process of a microwave rocket is similar to a pulse detonation engine, and understanding the interactions between microwave plasma and shock wave is important. Shadowgraph images of the microwave plasma generated in a tube under atmospheric air were taken. The observed plasma and shock wave were propagating one dimensionally at constant velocity inside the tube. In order to understand the flow field inside the rocket, one dimensional CFD analysis was conducted. With the change of microwave power density, structure of the flow field was classified into three regimes: Microwave Supported Combustion (MSC), Chapman Jouguet MSC (C-J MSC), Overdriven Microwave Supported Detonation (MSD). The structure of an Overdriven MSD was different from a structure of a chemical detonation, which implied the existence of preheating in front of the shockwave. Furthermore, the flight performances were optimized when the microwave power density is tuned to have a C-J MSC in the vehicle.

Preliminary Numerical Investigation on Microwave Beamed Energy Thruster

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Abstract: The repetitive-pulse microwave beamed energy thruster is a new kind of propulsion device. Since the propulsive energy is provided to the system by beamed energy transmitted from the ground and the atmospheric air is used for the propellant, it is expected to have the advantages of high specific impulse, high payload ratio and low cost launch. Therefore, it has potential wild application for aircraft in the future. In this paper, the numerical simulations on microwave beamed energy thrusters were preliminarily investigated. The method combines the self-similarity solution for the point explosion at the first stage and the flux vector splitting scheme at the second stage, and it was utilized to calculate the high temperature plasma flow field produced by the focused microwave beam and the momentum coupling coefficient of the thruster which is defined as the ratio of propulsive impulse to input power. For the parabolic reflector model with a focal length of 15 mm, the results show that in the case of single pulse at 15 J microwave power, the maximal thrust is 153.255 N, and the corresponding coupling coefficient is about 417.64 N/MW. The model predictions are in agreement with experimental results under similar conditions. In future work, we will simulate the multi-pulse simulation of the parabolic reflector model taking into account a moving object with the dynamic mesh method.

Evaluation of Beam-Homogenization Optics with High Intensity Laser Power Beaming for Wireless Power Transmission

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Abstract: High intensity laser power beaming (HILPB) is currently being developed as a method to achieve wireless power transmission (WPT) for space and terrestrial applications. There are many aspects that are under investigation to allow the HILPB system to progress toward higher optical to electrical conversion efficiency and output power density. In this paper, the effects of beam shaping optics on the photovoltaic receiver are quantified in terms of system performance. It is demonstrated that there is approximately a 10% absolute improvement in the conversion efficiency of the photovoltaic cells when using a uniform profile beam versus a TEM_{00} beam under high irradiance levels, resulting in a total receiver output of 44.6 watts.

High Intensity Laser Power Beaming Architecture Configured for Terrestrial Missions

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Abstract: High intensity laser power beaming (HILPB) is currently being developed as a way to achieve wireless power transmission (WPT) for space and terrestrial applications. In this paper, the system architecture and hardware results for a terrestrial application of HILPB are presented demonstrating continuous conversion of high intensity optical energy directly to electrical-mechanical energy at power densities as high as 13.6 watts/cm^2.