Proceedings of the First European Conference on Space Debris, Darmstadt, Germany, 5-7 April 1993 (ESA SD-01)

ACTIVE SHIELDING AND REDUCTION OF THE NUMBER OF SMALL DEBRIS WITH HIGH-POWER LASERS

W. O. Schall

DLR - Institut für Technische Physik, Stuttgart, Germany

ABSTRACT

The use of high-power lasers is suggested for shielding against small debris and for the removal of such objects from LEO. For collision protection the debris can be completely vaporized by the laser radiation. But vaporization with high ablation rates also allows changes in the debris trajectory by using the rapidly exhausting vapor as a propellant. If a laser or a relay mirror is located at a parallel co-orbit to a space station it could be used more efficiently to turn the debris trajectory such that it passes the station at some safe distance. However, all debris that comes into the range of the laser can be forced to descend down into Earth's atmosphere as a preventive action even more efficiently. Involved disciplines, like laser beam-target interaction, and the optical and geometrical constraints, are reviewed and power requirements assessed. Finally, the state of the art of laser technology is briefly summarized.

1. INTRODUCTION

Presumably about ten times the number of registered objects in low earth orbit (LEO) has a size in the range of 1 - 10 cm, here called "small debris" (Refs. 1 - 3). No reasonable passive shielding for space vehicles and platforms against a fatal hypervelocity impact by such an object is known to date (Ref. 4). It is assumed that at altitudes of 1000 and 1500 km a critical object density has already accumulated, making catastrophic collisions between small debris and a larger body likely within this decade (Ref.3). Even at lower altitudes, where man is present, the collision risk is non-negligible anymore and grows continuously.

Passive and smart sweepers have been suggested for the mitigation of this potential threat by the active removal of debris (Refs. 4 - 7). Some of these types are excessively bulky and pose a threat by themselves (free floating mechanical shields). Others are of only short lived nature (i.e. the defender concept) or suitable only for the retrieval of large objects (i.e. tether systems).

Lasers of moderately high powers can be used for the active shielding of a space platform, but even more so for the preventive cleaning of LEO from nearly all small debris. In the past decade much effort has been put into the development of the technology of high-power lasers, the understanding of laser/matter interaction and the technology for target acquisition and tracking, among others by the strong engagement in the military field. With the recent change of the strategic situation more and more of this technology may be disclosed for further civilian use. In parallel laser material processing is maturing and using lasers of ever higher powers for industrial applications.

Larger actions are now undertaken to have a closer look at our space environment and validate the presently existing theoretical models of debris formation and distribution. Procedures are discussed under the space faring nations - and sometimes already applied - to reduce the continuous increase of the object density in LEO. However, to come up with binding formal international treaties will still be a long and exhaustive way to go. So far, reluctance has been seen to invest anything in developing means for a removal of existing or future space debris. Even if from now on all direct generation of debris could be stopped at once, the current population is still there. Above a certain altitude it will not be cleaned out by natural processes within a foreseeable future. Instead, the current population will eventually lead to collisions and thereby increase the population significantly. Also not all space faring agencies will rigorously obey all restrictions to the production of waste, nor will it be possible to avoid unintentional explosions under all circumstances. Although perhaps at a reduced rate, the object density in orbit will continue to rise to a finally unacceptable level for man to be sent up in space over an extended time. Once debris has caused a fatal accident and taken the life of astronauts it could well mean the sudden end of man's presence in space for an undeterminate time due to a complete loss of public acceptance. *Therefore we must start to develop means for the removal of space debris now.*

High-power laser technology allows an almost complete removal of old and new small debris within a decade of operation! Even if the rate of satellite deployment in orbit is continued and none is removed after its lifetime the collisional risk can be stabilized at an acceptable level for the next hundred years (Fig. 1) (Ref. 8). The installation of a laser system at the space station as part of the improved shielding efforts would be a first step in achieving this goal. Instead of adding further passive shielding mass to the station a gradual cleanup of the orbital environment of the station is achieved and constantly less evasive manoeuvres will be needed.

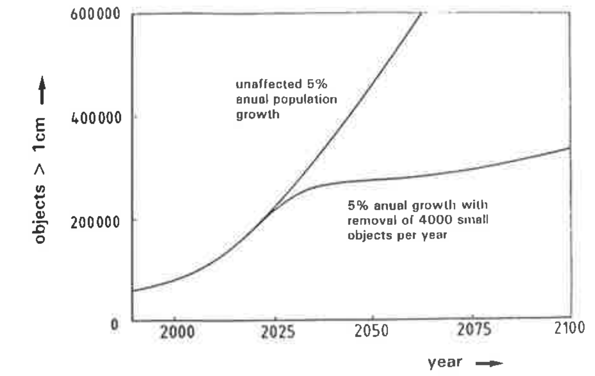

Figure 1. Population increase of small debris with and without active removal of 4000 objects per year (after Ref. 8).

2. INTERACTION OF LASER RADIATION WITH SPACE DEBRIS

In laser material processing the generally applied simple effect is the generation of heat within or on the surface of the treated workpiece. With sufficiently high power and long interaction time it is possible to vaporize and even ionize any material. At even higher powers and very short pulses it is possible to surpass the tensile strength of the material and disrupt it by a thermal shock or ablate layers from its surface. These processes can serve to break down solid objects into smaller pieces or turn it into a rapidly dissipating vapor cloud. The required minimum energy for this process is the enthalpy value of the desired thermodynamic state of the material. Although not being outside of today's technical capabilities a simple analyses shows that the required lasers for destroying metallic pieces are very big. Therefore, complete vaporization is not the preferred process in any case.

The thermal effect of laser radiation not only produces vapor but in certain cases also a considerable vapor pressure and hence a mechanical force. The vapor blows off and imparts a rocket like impulse on the object. In Fig. 2 the overlay of two successive frames of a video illustrates the reaction of a freely suspended acrylic glass sample to a 6 kW laser beam which irradiates the sample from the left for less than 10 milliseconds. Analogously, the generation of thrust on an orbital object into a controlled direction can be applied to change its *orbital energy*. For example, the perigee can be lowered and by this the natural lifetime in space shortened. In the extreme an object can be shot down into the atmosphere at once, where it burns up. Fig. 3 demonstrates the energy savings for this latter procedure in comparison to a complete vaporization. Thrust can also change the *flight direction* of a debris particle in order to prevent a hit with a precious object. In this shielding application the laser beam must irradiate the target under an angle to the flight path. It requires the laser source or a relay mirror being located aside from the satellite that should be protected.

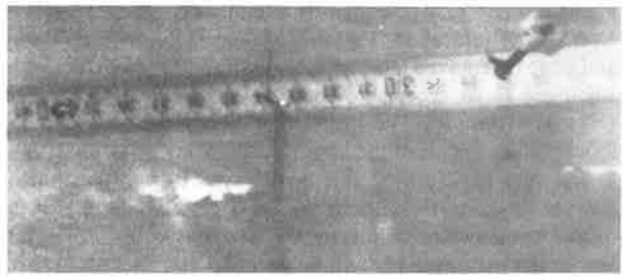

Figure 2. Displacement of a 1 cm^3 acrylic cube within 40 ms after irradiation with a 6 kW CO_2-laser (double exposure).

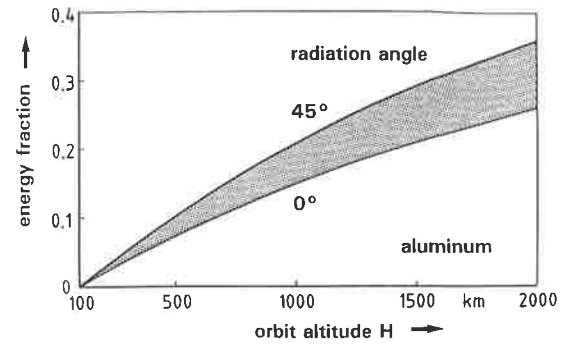

Figure 3. Energy savings for propelling aluminum debris down into the atmosphere over a complete vaporization.

The debris size, for which the application of high-power laser radiation is appropriate, depends on the flight path of the debris relative to the laser source and on the laser energy which can be deposited on the debris. With the use of transmitting and focusing optics every laser beam has a definite range where it can interact with matter in a desired way. It is natural to take advantage of this range and intercept every reachable object, that could pose a more immediate threat at some later time.

Since the orbits of the laser source and of the debris will have different inclinations and because small particles rapidly change their ascending node a whole orbital shell may be cleaned up eventually. Therefore, the employment of a high-power laser system goes immediately beyond a pure shielding application. In fact, the procedure can be extended to even clean up the whole LEO environment. For this purpose a laser will be installed on an Autonomous Debris REmoval Vehicle (ADREV) that can reach other altitudes, too. Fig. 4 shows an artists concept of an ADREV.

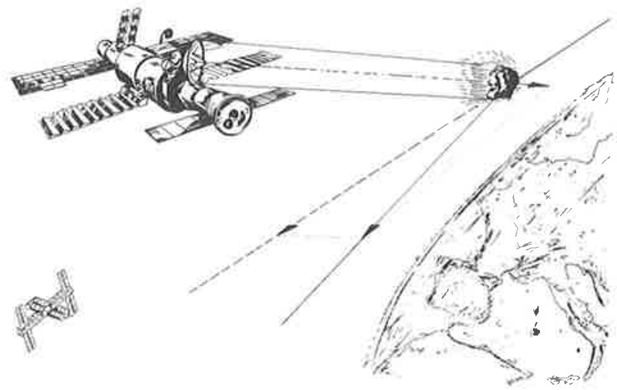

Figure 4. Concept of a laser equipped Autonomous Debris REmoval Vehicle (ADREV).

3. PHYSICAL CONSIDERATIONS

3.1 Laser/matter interaction

The key process for the effectiveness of the method is the conversion of radiation power into thrust. A very wide range of instantaneous power densities (intensities) can be delivered onto a target with two basic types of lasers: Continuous wave (cw) and pulsed lasers. The latter can emit one single high-energy pulse (sp) or a whole train of it (rp - repetitively pulsed). Table 1 summarizes qualitatively the basic differences for some relevant parameters.

A *cw laser* vaporizes the material after establishing an equilibrium between the heat supply to the irradiated surface and the conductive losses to the bulk material. The dwell times, i.e. to achieve evaporation, depend on the intensity, the absorption characteristics of the material at its surface, and the dimensionality of the heat conduction problem. The dwell time is generally inversely proportional to the square of the intensity. Depending on the material, metals or polycarbons, it differs by several orders of magnitude. This is due to very different absorptivities, heat conductances, and vapor enthalpies. Metals have high reflectivities and show only surface absorption. Short wavelengths are favorable for these materials, while polycarbons absorb ideally at wavelengths $> 3\ \mu m$. However, it is expected that most of the debris is soot blackened (Ref. 9) or otherwise contaminated. The initial absorption is therefore probably higher and the wavelength dependence less pronounced. Furthermore, as the heating proceeds the absorption goes up as well. The thrust producing pressure is a linear function of the intensity. For the calculation of the total exerted impulse on the debris the fundamental rocket equation can be used, which takes into account the mass loss from the vaporization. An example is given in Ref. 7. This procedure requires the assumption of an average exhaust velocity, which is a function of the heating of the vapor and thus of the power density. - One disadvantage for cw lasers may be seen for rotating or tumbling particles if the exposed surface is changing continuously.

Rotation of the debris is irrelevant for *pulsed* acceleration. In this case the pulse length of the order of microseconds is much smaller than any characteristic angular motion time. The much higher intensities on the target lead to new thermodynamic states and fluid mechanic processes in the irradiated matter. Pressures can reach Megabars and thus accelerations are tremendous. If a double pulse is applied in a way that the second pulse creates a laser supported detonation wave in the vapor exhausted by the first pulse even higher mechanical impulses are possible. In the pulsed regime the pressure grows proportional to the intensity as $I^{2/3}$. In many experiments with very different settings of laser wavelength λ, intensity I, pulse length τ, and exposed material (Ref. 10), a very general dependence for the impulse coupling coefficient c_m has been found. c_m is defined as the mechanically transferred impulse in dyne seconds or Newton seconds per Joule of laser pulse energy. Almost independent of the irradiated material ($\pm 10\%$)

$$c_m\ [\text{dyne s/J}] = 6.0/(I\,\lambda\,\sqrt{\tau})^{0.3}. \qquad (1)$$

Many individual data show that there exists an optimum pulse intensity of about 10^8 W/cm^2. Higher intensities lead to a continuous drop of c_m due to internal thermodynamic losses in the vapor plasma. Hence, for the pulsed case we can directly infer the required laser pulse characteristic from the knowledge of the necessary total impulse.

It should be born in mind that for large plane surfaces the evaporated material will blow off perpendicular to the surface and hence the thrust vector will be perpendicular. For an irregularly shaped or curved surface we can assume, that the average thrust vector lies in the line of the laser beam. Vapor blowing sideways will only partially contribute to the acceleration into the desired direction. It is therefore appropriate to assume a directional efficiency.

	cw	rep. pulsed
	POWER TIME	POWER TIME
irradiation time τ	100 ms - s	100 ns - μs, 100 Hz
target intensity I	10^4 - 10^6 W/cm^2	10^8 W/cm^2
pressure dependence p	$\propto I$	$\propto I^{2/3}$
pressure range	1 - 10 bar	Mbar
impulse dependence	$\int p\,dt$	$\propto (I\,\lambda\,\sqrt{\tau})^{-0.3}$

Table 1. Comparison of cw and rp laser beam characteristics.

3.2 Laser beam optics

Two quantities define the effective range of a laser: The required intensity on the target and the size of the target. If we intend to irradiate the whole exposed surface of diameter d without losses, this diameter corresponds to the local diameter of the laser beam at the target. Because a laser beam expands with distance R from the source according to its diffraction angle, a focusing optic is used in almost any laser material processing application to concentrate the power on a certain spot size. In our case the spot size corresponds to the object diameter. A mirror type telescope is adequate for transmitting and focusing the laser beam over a large distance. The diameter of the focus is a function of the ratio of the diameter of the director mirror D_0 to the laser wavelength λ. The ratio is of the order of 10^6. For a laser beam of good quality (near Gaussean) we find for the maximum laser range a realistic value

$$R_m = (0.6\ldots0.7)d\,D_0/\lambda, \qquad (2)$$

where d is the diameter of the intercepted particle. If the intensity in the focus on the target for the desired thrust mechanism is assumed we can immediately deduce the required laser power. It has to increase with the square of the debris diameter.

Due to much higher peak powers pulsed lasers have another distinct advantage over cw lasers. This is illustrated by the following example: Let us assume we want to intercept a debris particle with optimum intensity conditions at a distance of 50 km. With $D_0/\lambda = 10^6$ the minimum focal diameter is 7.5 cm. Ideally a pulsed laser requires an intensity of 10^8 W/cm^2. If for practical reasons we don't want to exceed a pulse energy of 1 kJ this results in a pulse power of $7 \cdot 10^9$ Watts and a pulse length of 150 ns. At a repetition rate of 100 Hz a laser of moderate 100 kW of average power needs to operate for 1.5 s. Here a size/mass model has been used, where $m \propto d^{2.26}$ (Ref. 11). For cw operation an intensity of $5 \cdot 10^5$ W/cm^2 may be sufficient. But this still corresponds to a cw power of 35 MW for a few milliseconds. Such a power level is out of scope for a laser in orbit in the very next future. A cw laser of only 1 MW could intercept particles of that size to a distance of just 10 km.

3.3 Orbital geometry

The altitude of the debris orbit and the desired perigee altitude after the impulse transfer define the necessary incremental velocity Δu and therefore the kinetic energy change that is required. However, except for a direct collision trajectory there will be an angle α between the flight path of the particle and the direction of the impulse (generally the direction of the laser beam) (Fig. 4). The actually required impulse increases with the angle α and too large an α, i.e. $>45°$, would require excessive impulses. With $\alpha_m=45°$ as an arbitrary restriction the averaged total velocity increment amounts to about 1.3 Δu.

The distance R_0, at which a particle is passing the source, in combination with the angular limitation for the laser beam interaction α_m and the relative closing velocity define the available engagement time. This time is approximately inversely proportional to R_0. As R_0 becomes larger than about half the maximum laser range this time tends towards zero. On the other hand, a near hit trajectory allows engagement times from 100 to more than 200 ms per km of laser range. For example, a laser range of 50 km would give an engagement time from at least 2 to a maximum of 10 s.

If the orbit of the laser is not pre-selected by that of a space station, which has to be shielded, it is helpful to choose the inclination as close as possible to the main bands of the debris. This reduces the closing velocity; more time is available and less average laser power is needed. The inclinations of the main debris bands center around 65° and close to 100° (Refs. 1, 12).

3.4 Stationary laser for shielding applications

With the described factors we can now discuss some of the needs for a shielding application, for example for a space station. Because of the generally very high closing velocity (11 km/s in the average) we cannot expect to be able to bring an incoming particle to a halt. A reduction in velocity by about 3 km/s is equal to evaporate more than 90% of it. The application of tensile shocks may in a few cases (ceramics) be sufficient to disrupt the material into pieces that are small enough to be absorbed in a rudimentary bumper shield. However, in general we will have to vaporize the debris completely. But if the laser beam is effectively emitted at some distance from the space station, we can apply the thrust method to deviate the flight path enough so that the debris misses the station. This situation has been analyzed and Fig. 5 displays the energy savings for a passage distance of 200 m as a function of the laser source offset d_m (d_m could be the distance of a relay mirror as well). In this special application the energy savings are only about 50 to 60%. If instead for such an application a laser of full power is used, it has also the double range for the potential elimination of debris on near collision trajectories. A larger laser saves also the additional weight and complication of flying itself or a steerable relay mirror on a co-orbit several kilometers away.

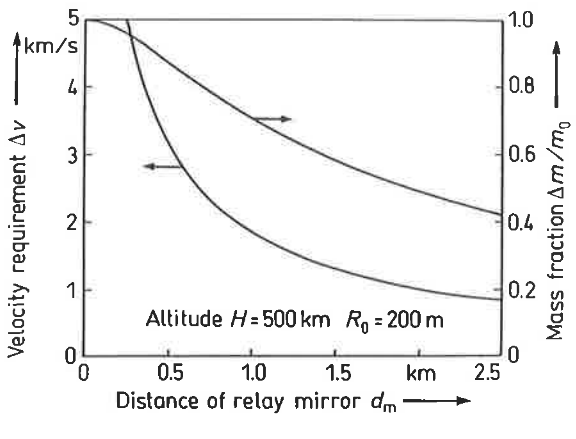

Figure 5. Velocity and mass requirements for deviating a collision trajectory by 200 m, using a displaced laser source or a relay mirror. The assumed closing velocity is 11 km/s.

The need for a protection system for the space station Freedom right now is a probability game and for pure shielding a laser would have to operate only by chance. Its employment is therefore only justified, if it also saves some weight of the bumper shields for even smaller debris and of course time and fuel for space station displacements. Down to what size debris particles can be eliminated is only a question of their detectability. But the laser could and should be used to preventively reduce the threat for a collision as well. Of the total number of small debris in the range of 1 to 10 cm the number of debris >5 cm accounts for less than 20%. If it is decided to remove all debris ≤ 5 cm within the laser range, the collision probability can be reduced over time to less than 20% of the present value. For the remaining larger debris an escape manoeuver may be justified. In principal the power requirements are reduced then by a factor of 4. Even allowing full vaporization of the debris the power saving is still one half. The method of a preventive active shielding could be the first stage in a more extended policy for debris removal.

3.5 Cleaning procedures for LEO

If a certain laser power/energy characteristic is assumed, together with a size/mass model for the typical debris, then one is able to relate the object specific laser ranges (those belonging to a certain debris size) to the orbital parameters inclination and altitude. Fig. 6 shows an example for an inclination difference $\delta = 42°$ taken to be the maximum. An orbital tube of diameter R_0 can then be cleaned out. In Ref. 11 this has been analyzed for a laser of 100 kW average power. A mission strategy can be defined to change the orbit of a laser equipped ADREV such that first a whole shell around the globe of thickness $2R_0$ can be cleared. For example this could be achieved by shifting the ascending node of the orbit by 180° in steps of overlapping tube diameters. As a next step the orbit of the ADREV could be raised by an equivalent altitude step to clear another shell of similar thickness. Although prohibitive from the point of view of propulsion fuel requirements it is still interesting to find out what the minimum time for such an undertaking could be. Fig. 7 shows the result for a mission beginning at an altitude of 400 km and eventually approaching 2000 km. The debris population distribution for this is taken from Ref. 1 and only circular orbits are assumed. It is seen,

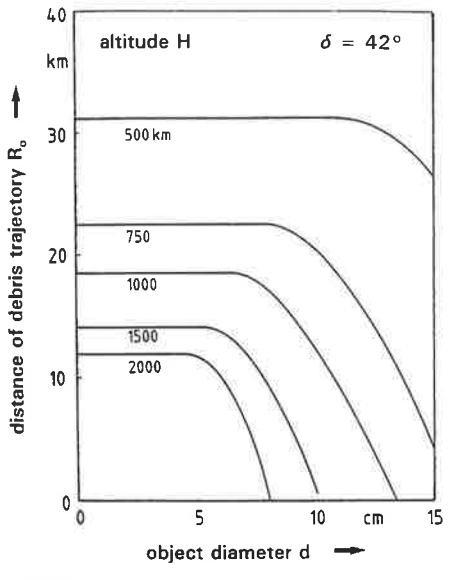

Figure 6. Laser range R_0 as a function of debris size and altitude for a relative orbit inclination of 42° and an average laser power of 100 kW.

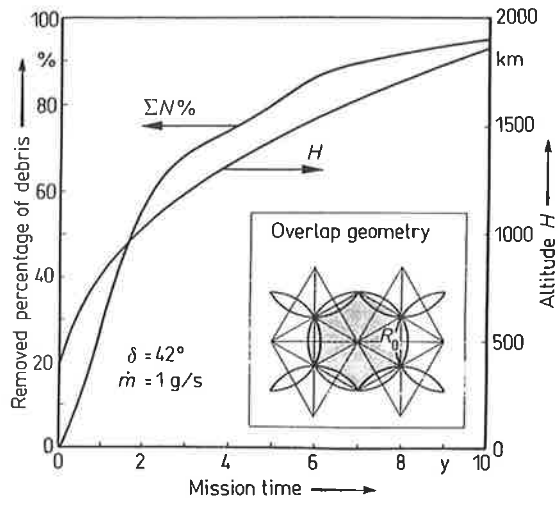

Figure 7. Cleaning time of LEO for debris with a maximum inclination difference of 42° using the flight strategy shown in the insert.

that under these ideal conditions LEO can be cleaned from small debris to a very large percentage within less than 10 years. The less demanding lower altitude range up to 1300 km, containing about 75% of all debris in LEO could be cleaned in even half the time. The time is independent of the actual population density of the debris. The total number of particles enters only into the calculation of the total energetic requirements for the laser (Sec. 4.3).

In the practical application a different strategy may be much more economical: The intentional climbing of the ADREV can be anticipated by placing it on an elliptical orbit, enclosing the altitude range that should be cleaned. For the continuous change of the ascending node the natural precession of the orbital plane of an inclined orbit due to Earth's oblateness and other perturbing effects can be employed. The need for a propulsive shift of the orbit can thus be minimized.

4. SYSTEM REQUIREMENTS

Beside the propulsion unit for orbital motion every removal system will require certain common subsystems: A debris detection and tracking system for the derivation of the exact debris trajectory; this must be combined with the pointing system for the laser beam director; the laser itself and an energy storage unit for supplying the high-power laser.

4.1 Debris detection, tracking and pointing

On-board debris detection is already under development for the basic assessment of the debris population and for early warning of the space station crew (Ref. 4). Active and passive methods must be applied to continuously monitor those sectors where debris may close in. Passive methods make use of CCD cameras in the visible and infrared. They allow the detection over sufficient distances and can measure angular velocities. It will be helpful to have an early warning for one or more orbit revolutions in advance, to narrow down the observational sector on close approach. In this phase radar (30 GHz) or lidar will give the final information about the particle trajectory and provide the lock-on of the pointing system on the target. Most precise pointing is achieved upon a debris glint signal when nonlinear optical methods are used, like a phase conjugate mirror or arrayed active mirrors.

The diameter of the beam director should be as large as possible, in particular for infrared radiation. It is the state of the art today to produce extremely light weight mirrors with diameters >1 m. Light weight is also important for the rapid coarse positioning of the director mirror.

4.2 High-power lasers

Several types of high-power lasers have the potential for the envisioned application, but are at a different state of development. For a matured anti-debris system we would call for a minimum power of 200 kW cw or 50 kW repetitively pulsed power. However, early experiments in space for the validation of the method can be started with lower powers and still have a beneficial effect at the lower altitudes and for the large majority of smaller particles. For the few larger ones it is perhaps not possible to shoot them out of orbit at once, but a notable shortening of the orbital lifetime can always be achieved.

Table 2 summarizes possible laser candidates in the order of their wavelength. It is seen that those lasers with the highest demonstrated power are of the chemical and/or gasdynamic type. The HF-laser especially was developed to a power range of more than 1 Megawatt (Alpha-Laser) for SDI applications in space. The whole system, including a 4 m beam director and fuel is rated at approximately 50 tons (Ref. 13). The laser gas is spent after lasing. The specific power in the table gives an idea of how much laser gas is needed for producing a certain amount of radiation energy. At present repetitively pulsed lasers have not quite achieved the power levels of cw lasers, but are rapidly improving. There is still a technical problem in the long term operation of lasers that use electron beams for excitation. In principle a diode pumped solid-state laser would be ideally suited for space applications. However, it is not clear yet, if these lasers can be scaled to high enough average powers with an acceptable beam quality. Currently possibilities are investigated to improve the beam quality and phase-couple several lasers, both using nonlinear optic methods.

For two cases the necessary amount of expendable laser fuel has been estimated:

1) A stationary shielding laser is operated at an altitude of 500 km and at an inclination of 28°, being in use for approximately 30 years. A long term annual increase rate of 2.5% of the number of debris was assumed, starting from an initial population of 70,000 small objects. In addition, it was considered that debris from an altitude up to 700 km over the time seeps down into the range of the laser. The totally required energy sums up to 1,200 MJ for a cw laser, if a coupling efficiency of 33% is taken into account. If the laser were an HF-laser with 200 J/g, only 6 tons of fuel would be needed over the whole 30 years. In comparison a pulsed laser at the same wavelength would have to spend about 800 MJ of energy.

2) An ADREV is used and roams across all altitude ranges at a highly inclined orbit to remove virtually all small debris. For a pulsed laser about 6 GJ will have to be expended for a total number of 10^5 objects, using a wavelength around 1 μm. The energy roughly doubles for a 10 μm CO_2-laser. A high inclination brings an energy saving of a factor of 2 over a low inclination. For a coupling efficiency of 33% a cw operation requires here the same amount of energy. The fuel required for an HF-laser would then sum up to 45 tons. For this application recycling of the laser fuel would be preferable, in particular if a laser of much lower specific energy is used. In the case of a non-chemical excitation a high electrical efficiency is of additional importance.

Laser	Type		λ	P, E_p	Fuel	Spec.Power	Comments
CO_2	gasdynamic el.discharge e.d.+e-beam	cw cw rp	10.6 μm	$\gg$100 kW 50 kW >10 kW >100 J	spent/ repumped c.c. c.c.	20J/g - -	Good beam quality difficult Poor efficiency $\eta \rightarrow 20$ % e-beam lifetime?
CO	gasdyn.+ed. e-beam	cw sp	5 μm	>100 kW >1 kJ	cc/spent/ repumped	>50J/g	$\eta \rightarrow 20$ %, small volume.
HF	combustion+ gasdynamic e.d.+e-beam	cw rp	2.7 μm	>1 MW >5 kJ	spent spent	>200J/g >250J/l	Extremely efficient. Aggressive gas. For rp demanding technology.
O_2/I	chemical	cw rp	1.3 μm	>35 kW >16·cw	spent	50J/g	Part of fuel storable as solid. Exhaust somewhat corrosive.
s.st. s.st.	lamp pumped diode pumped	rp rp	1.1 μm	100 kW ? >1 kW	- -	- -	Poor beam quality. Difficult scaling. Cooling problems. Requ. beam combining.
KrF/ XeCl	e-beam	sp	.25-.3 μm	>1 kJ 1kW	c.c.	>12J/l	Difficult e-beam technology. Lifetime? Large volume.

Table 2. Characteristics and realized data of high-power lasers. For e-beam excited lasers a rep. rate of 100 Hz appears feasible. (P: power, E_p: single pulse energy, s.st.: solid state, e.d.: electric discharge, c.c.: closed cycle; in contrast fuel "repumping" is meant to collect the spent gas in a container and gradually recompress it to the initial state).

5. CONCLUSIONS

Basically all disciplines of shielding and removal of small debris with high-power lasers are physically understood. The method is feasible and superior to other methods. Some technical developments for long term space operation are necessary, but no technological breakthroughs are needed. The laser must be of moderately high power only and it should preferably be of pulsed mode. A laser for a pure shielding application alone probably does not pay. However, it can and should then be used to also shoot out of orbit all debris that passes in its vicinity. The rapid redistribution of small debris by natural forces brings it about, that a whole orbital shell is eventually cleared out. After some early validating experiments in space, this application could be the first major step in a space cleaning strategy. Subsequent missions would involve an autonomous vehicle to clear all LEO.

Since a shielding laser can be used against all small debris that can be detected early enough, the space station bumper shield could be matched to correspondingly smaller, undetectable debris only and considerable weight savings appear possible.

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