Space Debris Management and Mitigation 4 :
Mitigation & Remediation

A Systematic Study of Laser Ablation for Space Debris Mitigation

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TIFPA

The Trento Institute of Fundamental Physics and Applications
is a joint initiative of

the Institute National for Nuclear Physics (INFN),
the University of Trento,
the Bruno Kessler Foundation (FBK) and
the Province of Trento Heathcare Agency (APSS).

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Laser Ablation for Space Applications

The activities at the TIFPA in the context of the interdisciplinary experiment *New Reflections* of the INFN concern the use of laser ablation for debris mitigation and propulsion.

- Simulaton programs to define the required laser performance for debris removal and satellite propulsion

- Measurements of the coupling coefficients relating the incident laser power to the induced mechanical force for aluminium (debris) and candidate propellant materials

TIFPA Groupe New Reflections

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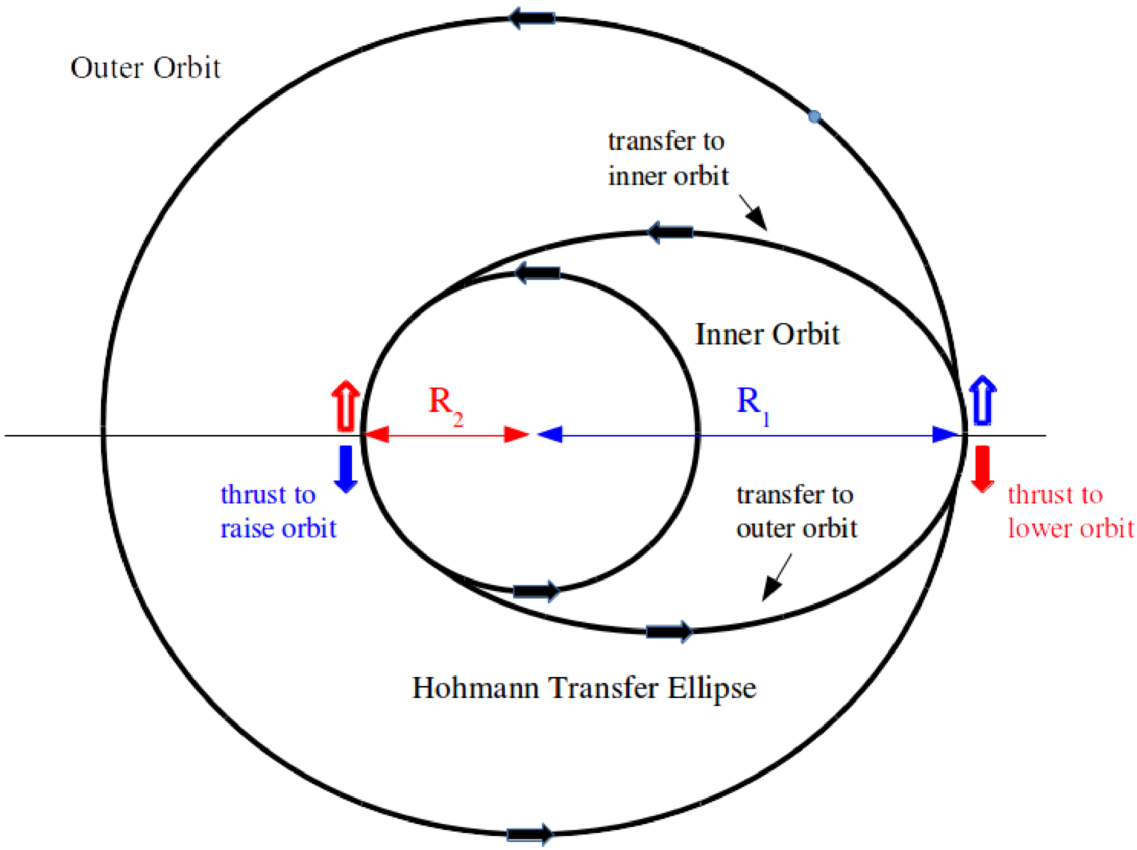
The physics of laser ablation is studied at the pulse laser deposition facility of the IdEA Laboratory. The members of the group include material scientists, and physicists with a wide experience in the field of particle detectors, AMS01 (Space Shuttle), AMS02 (ISS), and HEPD (CSES satellite), as well as participation in related application studies (active magnetic radiation shields) funded by ESA, NASA and the European Union FP7 programme (SR2S).

Orbital Mechanics

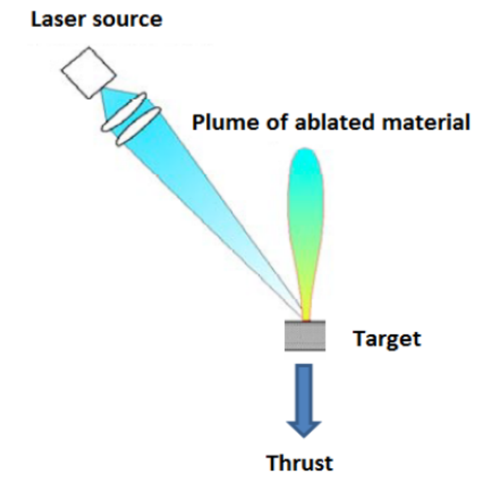
The Hohmann transfert is used to raise or lower the altitude of a satellite



Impulse required to lower the altitude

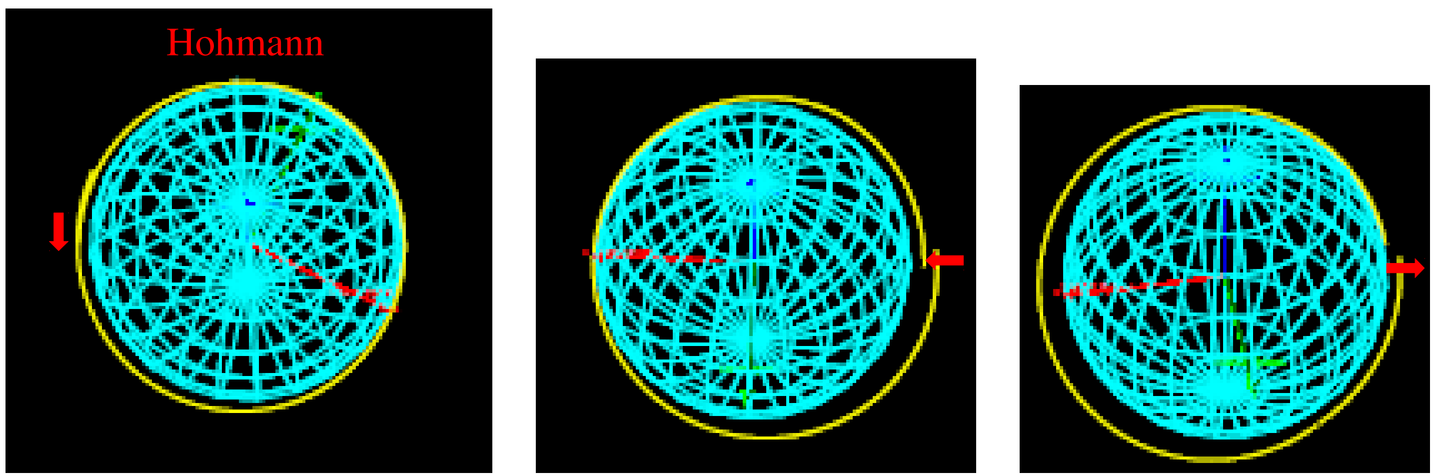
$$m\Delta v = MG \cdot \left(\sqrt{\frac{1}{R_1}} - \sqrt{2\frac{R_2/R_1}{R_1+R_2}} \right)$$

Debris Mitigation



Laser ablation refers to the ejection of matter from a material heated to high temperature by a laser beam. The ejected mass produces a thrust in the opposite direction, normal to the illuminated surface. With respect to a Hohmann transfer, a laser on the ground will deliver an impulse with a component directed in the vertical direction. A space laser may engage debris targets at lower and higher altitudes.

The modification of the trajectory of a 500 kg mass in a circular orbit at 600 km by a thrust directed oppostion to the orbital velocity (left), and in the radial directions toward the Earth (center) and zenith (right).



In each case, the result is an elliptical orbit whose perigee approaches the Earth. The debris is effectively eliminated when it enters the upper atmosphere (~200 km).

Debris Simulation

- Debris is represented as a point mass *M*.
- The Jacchia-Bowman 2008 model is used to calculate the air density.
- Surface-area-to-mass ratio *A/M* is chosen to yield a constant ballistic coefficient, $\beta^* = C_D \cdot A/M = 0.1 \quad (C_D = 1\text{-}2)$
- The laser beam delivers 1N force along the line-of-sight between the debris and laser positions.
- Space laser operated while the debris approaches the laser position and the line-of-sight is not obscured by the Earth or atmosphere.
- Ground laser operated during the approach of the debris to the laser position and the angle of elevation of the line-of-sight $\psi_z \leq 45^\circ$, corresponding to an atmospheric transmission efficiency 75-82%.
- The simulation is run until the perigee of the debris mass attains 200 km (in one case presented 100 km), or the time limit of 120 days is reached.

Debris Orbit and Laser Deployment Scenarios

Debris mass orbital elements at epoch

a	e	i	Ω	ω	θ
7170 km	0.001	100°	0°	180°	180°

Orbital elements of the dedicated satellite (SAT) and the ISS

	a	e	i	Ω	ω	θ
SAT	6885 km	0.001	80°	180°	90°	0°
ISS	6780 km	0.0016	52°	128°	99°	313°

The starting position of the debris mass is the apogee~(800 km) of the polar orbit. The orbit is representative of the major part of the debris population in LEO. The SAT is in a polar orbit, while the laser on the ISS views the debris mass from lower latitudes.

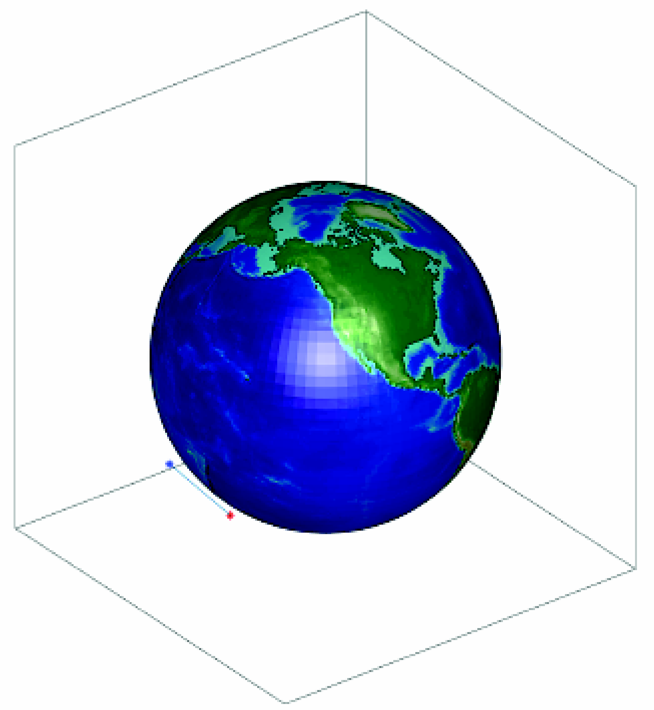
An equatorial site ground laser (GEQ) is positioned on the x-axis of the Earth Centered Inertial reference at epoch. A northern polar site laser (NPO) is placed to have the debris mass at its zenith at epoch.

Debris Orbit and Laser Deployment Scenarios

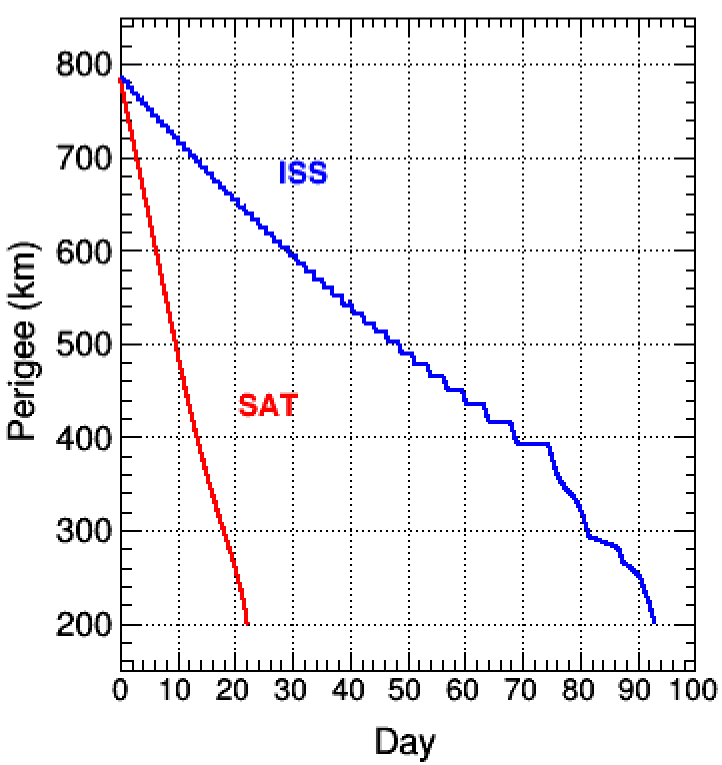
The orbital direction of the debris mass (i = 100^O) is opposite to the rotation of the Earth and to the orbital directions of the SAT and ISS.

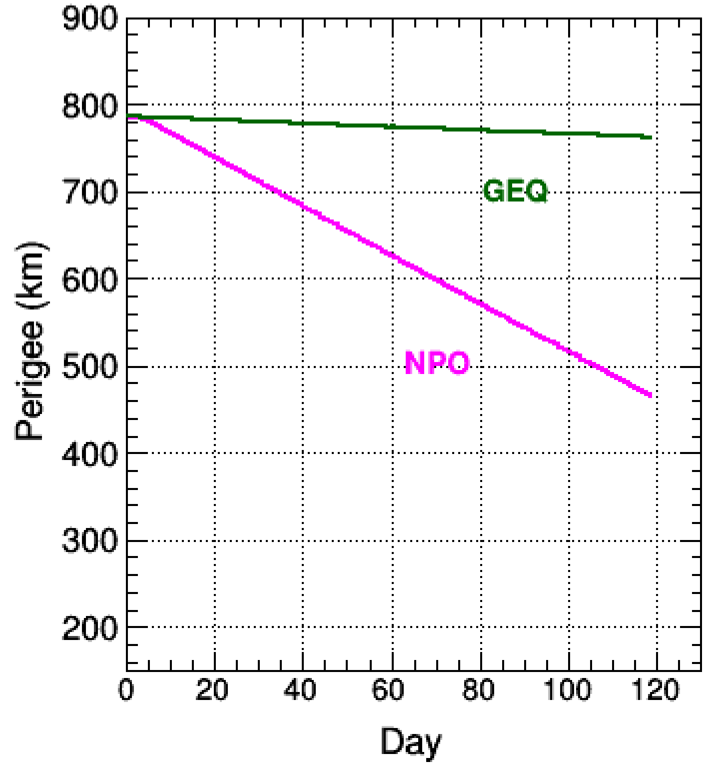
The epoch Jan. 1, 2010, h.00:00:00.0 is chosen for the simulation start.

The debris mass and SAT positions at epoch



Simulation Results for a 500 kg Debris Mass



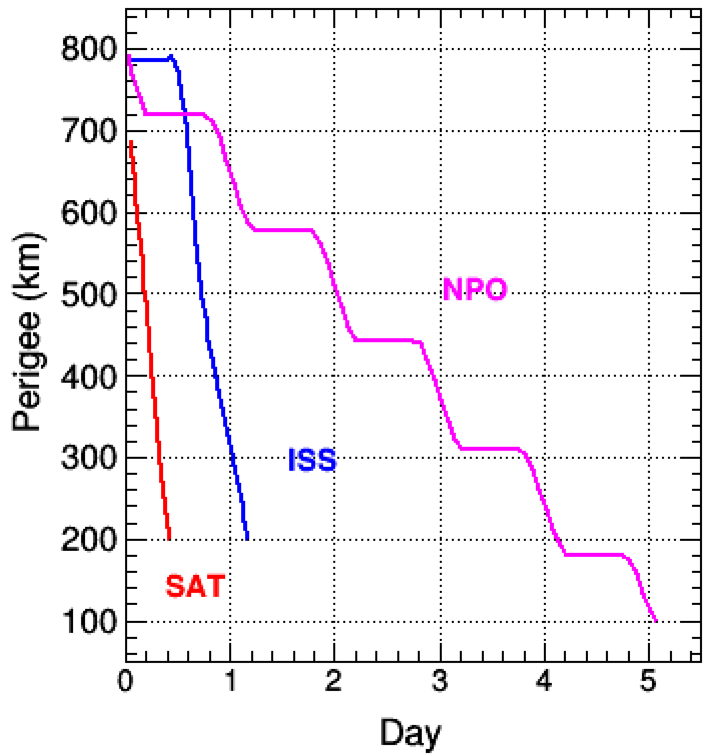


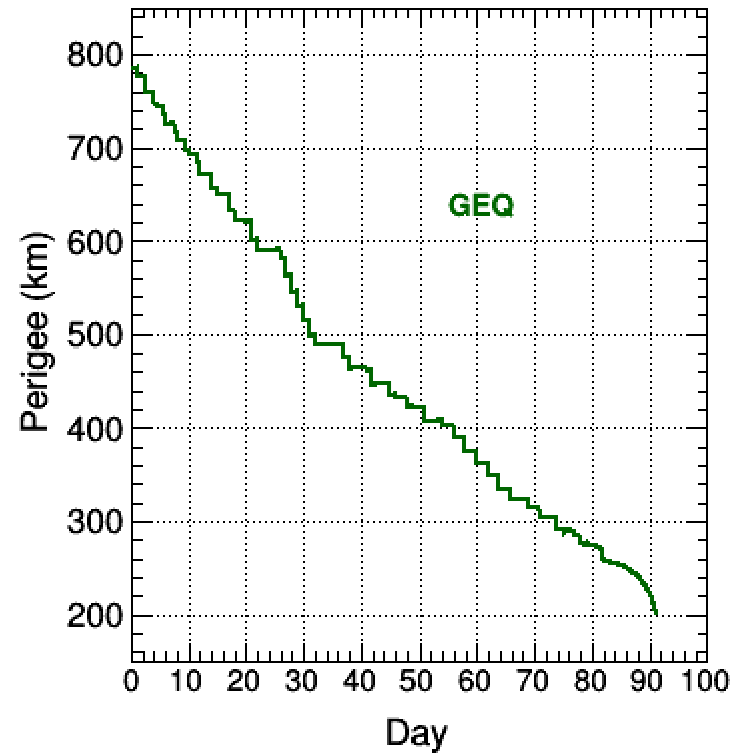
	t_{tot}	t_{laser}	Impulse	Alt. Final
	d	h	Ns	km
SAT	22.1	41.5	$1.5 \cdot 10^5$	200
ISS	92.9	66.0	$2.4 \cdot 10^5$	200
GEQ	120.0	4.7	$1.7 \cdot 10^4$	762
NPO	120.0	26.4	$9.5 \cdot 10^4$	464

t_{tot} is the total simulation time

t_{laser} is the time the laser is on

Simulation Results for a 10 kg Debris Mass





	t_{tot}	t_{laser}	Impulse	Alt. Final
	d	h	Ns	km
SAT	0.43	0.83	$3.0 \cdot 10^3$	200
ISS	1.16	1.32	$4.8 \cdot 10^3$	200
GEQ	91.1	1.78	$6.4 \cdot 10^3$	200
NPO	4.15	1.00	$3.6 \cdot 10^3$	100

t_{tot} is the total simulation time

t_{laser} is the time the laser is on

Impulse and Laser/Target Parameters

The expression[1] for the impulse delivered by a laser energy E_o is

$$m \Delta v = \left(\frac{E_o T_{tel} T_{atm}}{\pi \phi^2 (R)} \right) S C_m$$

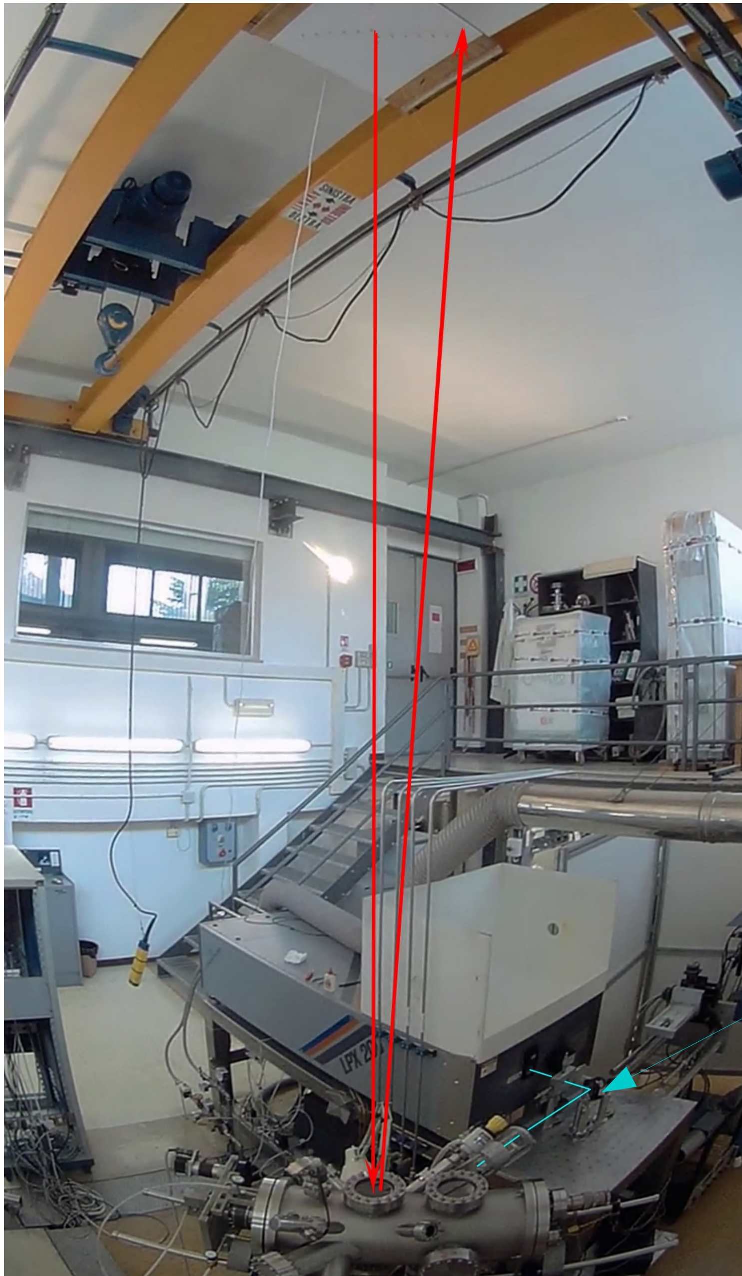
where $\phi^2(R)$ is the beam spot at the range R. S and m are surface area and mass of the debris target. T_{tel} and T_{atm} are the telescope and atmosphere transmission efficiences. CLEANSPACE reported a value of the coupling coefficient for the conversion of laser pulse energy to kinetic energy in aluminum,

$$C_m = 2.0 \mu N / W$$

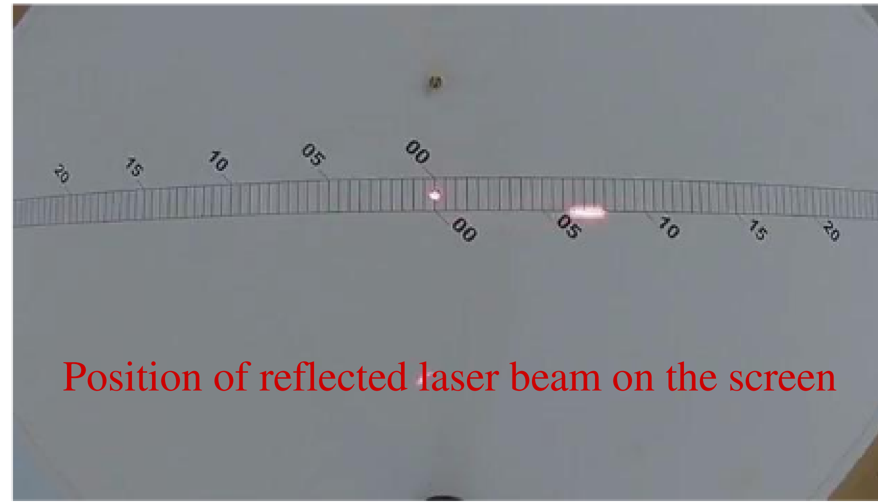
for the power density range between 0.5 and 0.8 GW/cm^2, with 27 ns pulse, at $\lambda = 1.06$ µm. The value is a factor two smaller than the result obtained by the IdEA Laboratory in Trento.

[1] *Changes of Space Debris Orbits after LDR Operation,*
E. Wnuk, J. Golebiewska, C. Jacquelard and H. Hang
CLEANSPACE project of EC Seventh Framework Programme

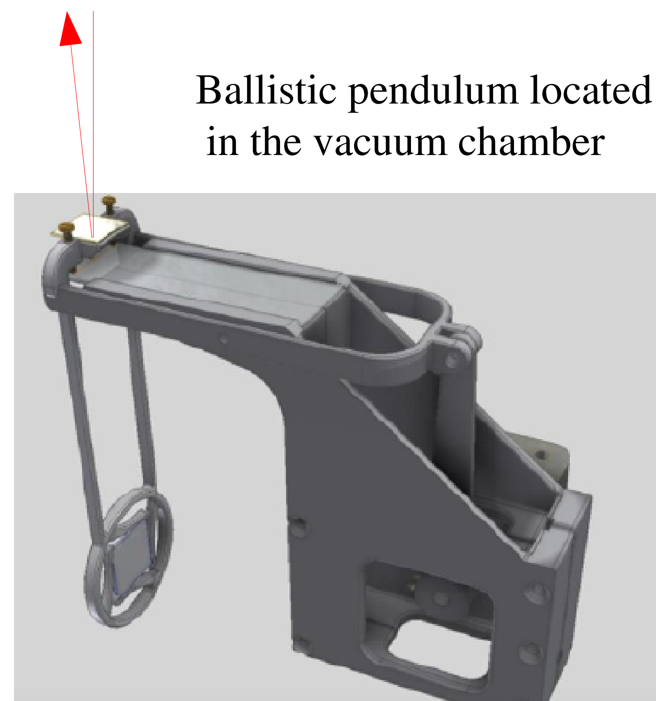
C_m Measurement of the Laboratory IdEA at the University of Trento



440 mJ, 20 ns
pulsed laser beam

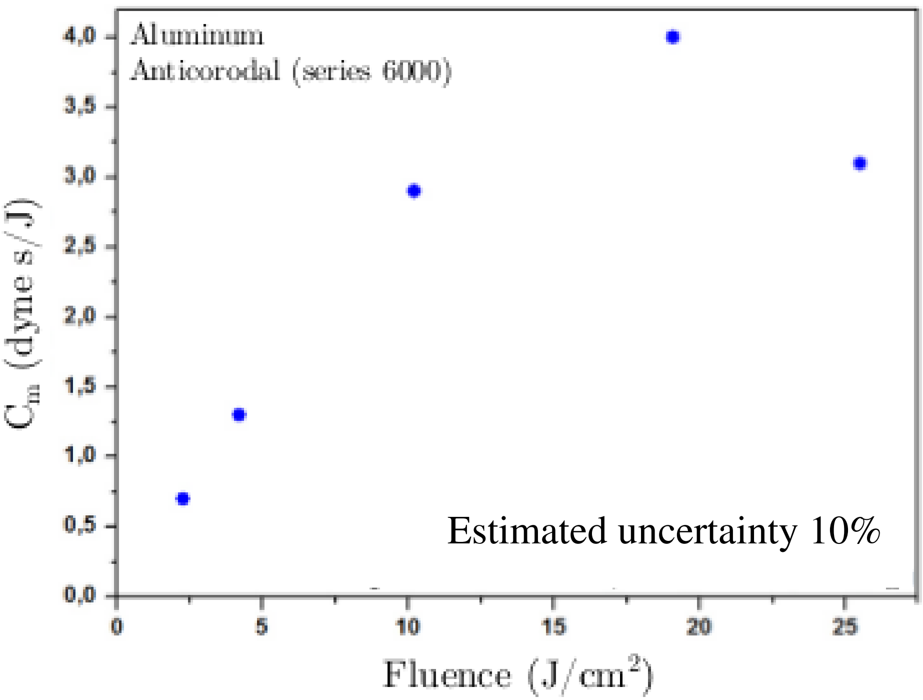


Ballistic pendulum located
in the vacuum chamber

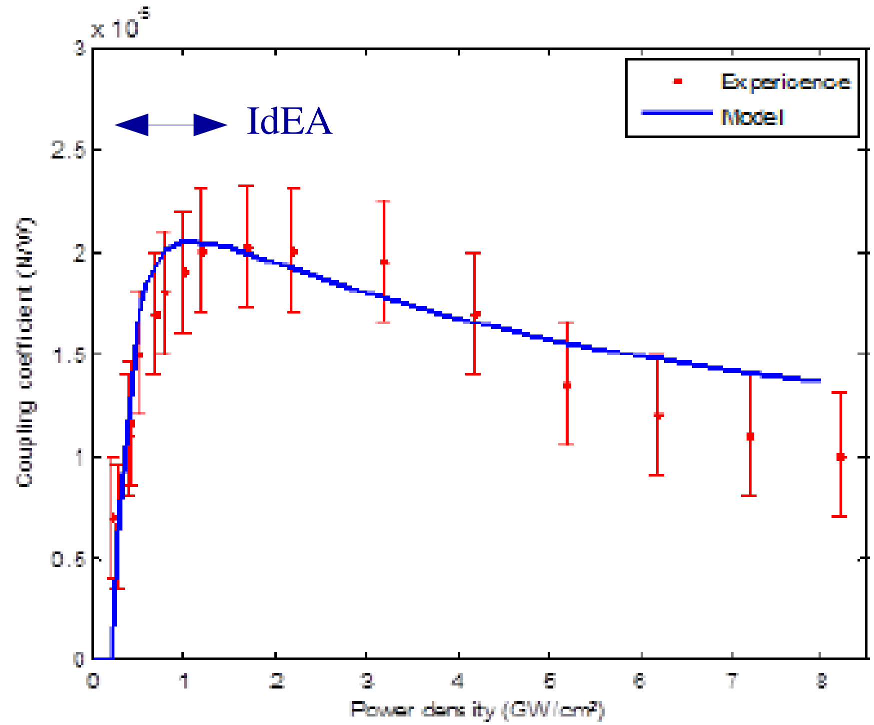


Aluminum Coupling Coefficient Measurements

IdEA



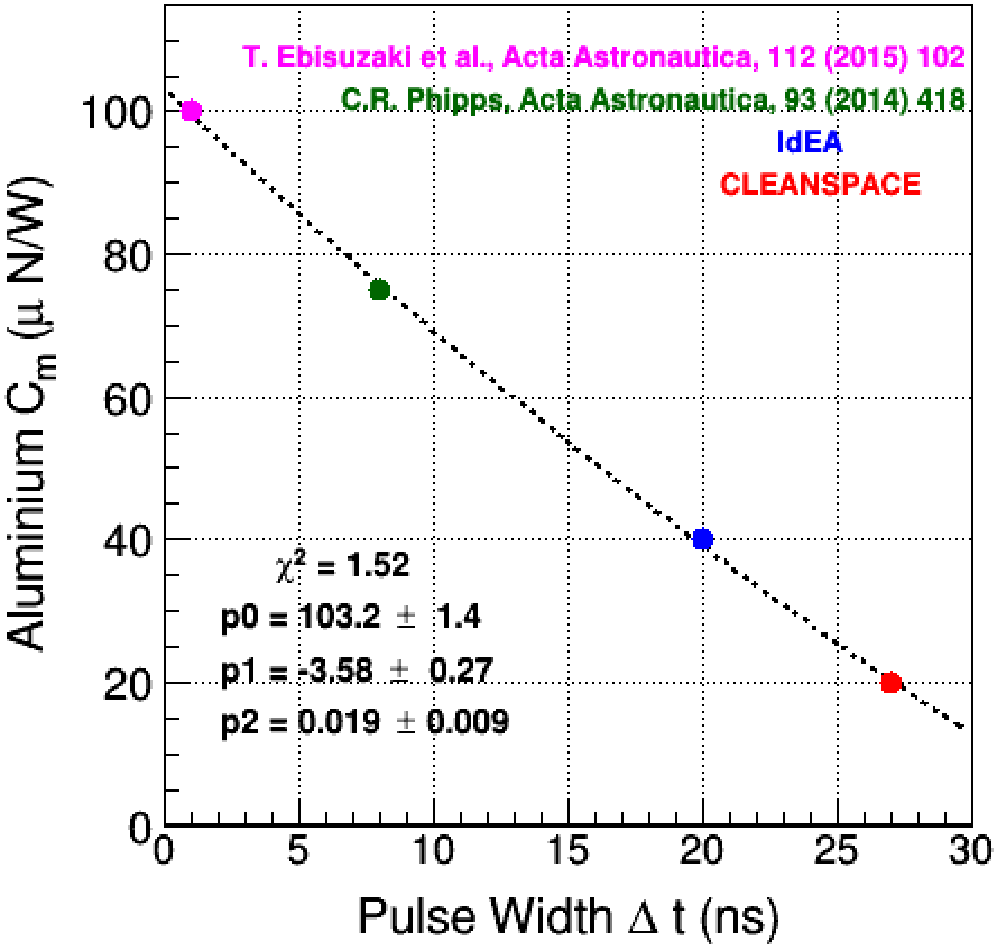
CLEANSPACE



Maximum :
4 dyne/W @ 18 J/cm² ⇒ 40 µN @ 0.9 GW/cm²
Threshold :
~2.5 J/cm² ⇒ ~0.1 GW/cm²
Power densities corresponding to 20 ns pulse width

Maximum :
20 µN/W @ 1 GW/cm²
Threshold :
~0.2 GW/cm²
27 ns pulse width

Aluminum Coupling Coefficient Measurements



Variation with pulse width described by a 2nd order polynomial fit

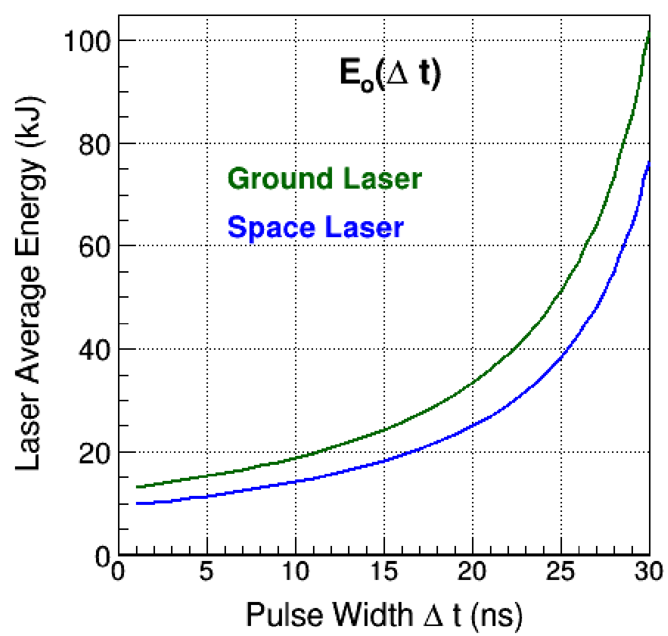
Laser Parameters Compatible with the Simulation Results

The simulation results are obtained with $m\Delta v$ = 1 Ns.
The corresponding laser energy E_o is given by the expression

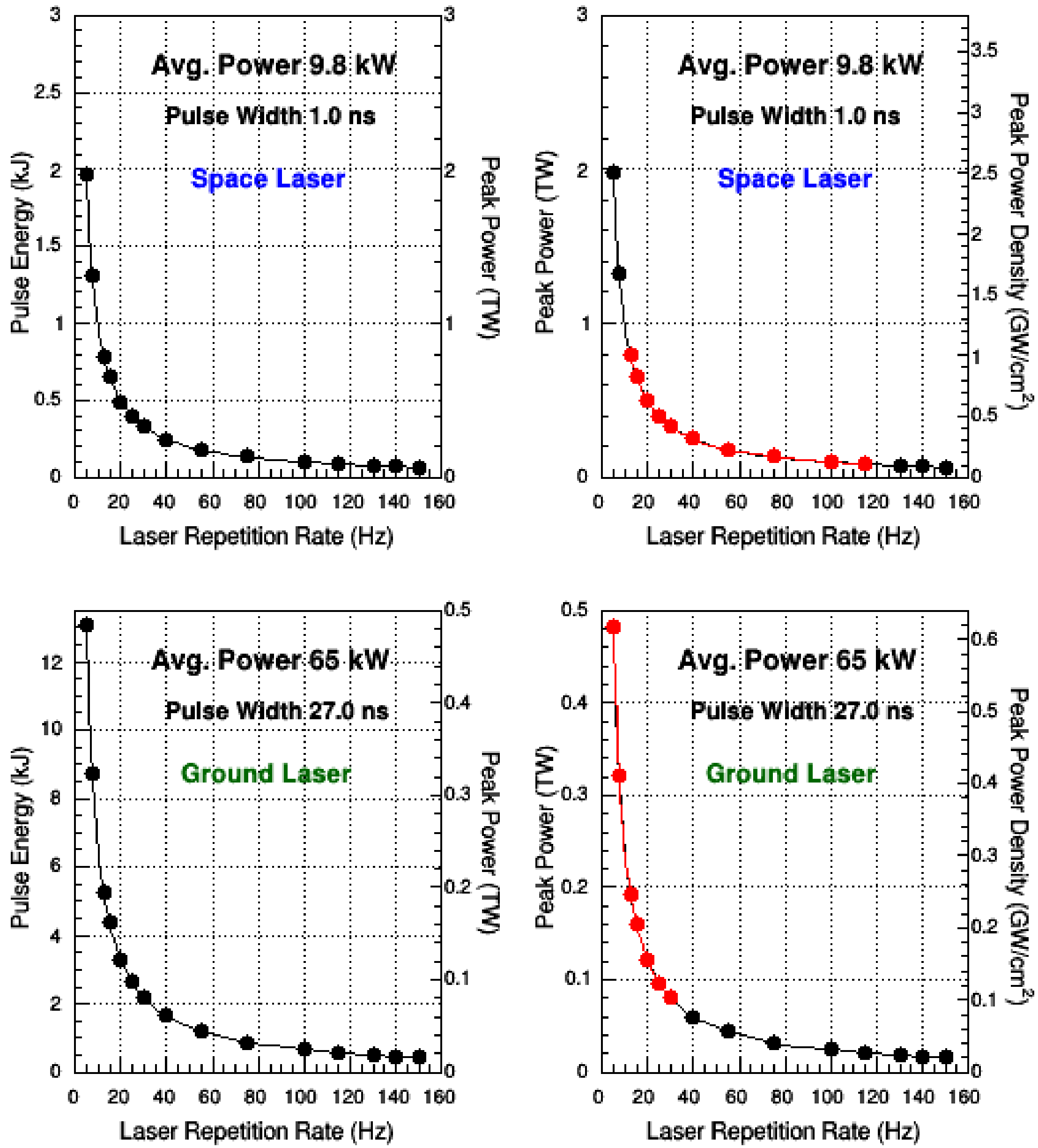
$$E_o = \left(\frac{1\,Ns}{T_{atm} \cdot T_{tel} \cdot C_m(\Delta t)} \right) \left(\frac{\pi \phi^2(R)}{S} \right)$$

with

- debris surface S = 1 m²
- ϕ = 0.5 m, 1 m diameter circular spot size at the target
- $T_{tel} = 0.8$
- T_{atm} = 1.0 for the space lasers, T_{atm} = 0.75 for the ground lasers
- $C_m(\Delta t)$ coupling constant defined by laser pulse width



Pulsed Laser Configurations - Examples



Ablation range in aluminium between threshold, 0.1 GW/cm^2 and 1.0 GW/cm^2

Summary

- A simulation was developed to evaluate the performance of ground and space lasers for debris mitigation. The results presented for the polar orbit debris masses demonstrate the avantage of a laser deployment specfic for this debris population, in particular for a ground laser.

- The aluminium coupling constant measured by the IdEA Laboratory with a pulse width of 20 ns is a factor of two higher than the value reported by CLEANSPACE for a pulse width of 27 ns. The decrease of C_m with increasing pulse width observed in the data between 1 and 27 ns is described by a 2^{nd} order polynomial fit.

- The pulsed laser configurations compatible with the simulation results illustrate the optimal parameter range for ablation, and provide an indication of the variation of energy within the possible range of parameters. Low pulse widths and sufficiently high repetition rates are particulaly suited to space lasers where power is a critical issue.

- The preliminary results are indeed indicative. The simulation does not include the details of the laser operation, the next step in our *systematic* approach.

- The laser systems required for debris removal are sufficiently powerful to produce an effect comparable to a weapon system. The development of weapon-type lasers is not possible in Italy. The competences of the Trento group are *a priori* better adapted to the propulsion application and the development of efficient propellants.

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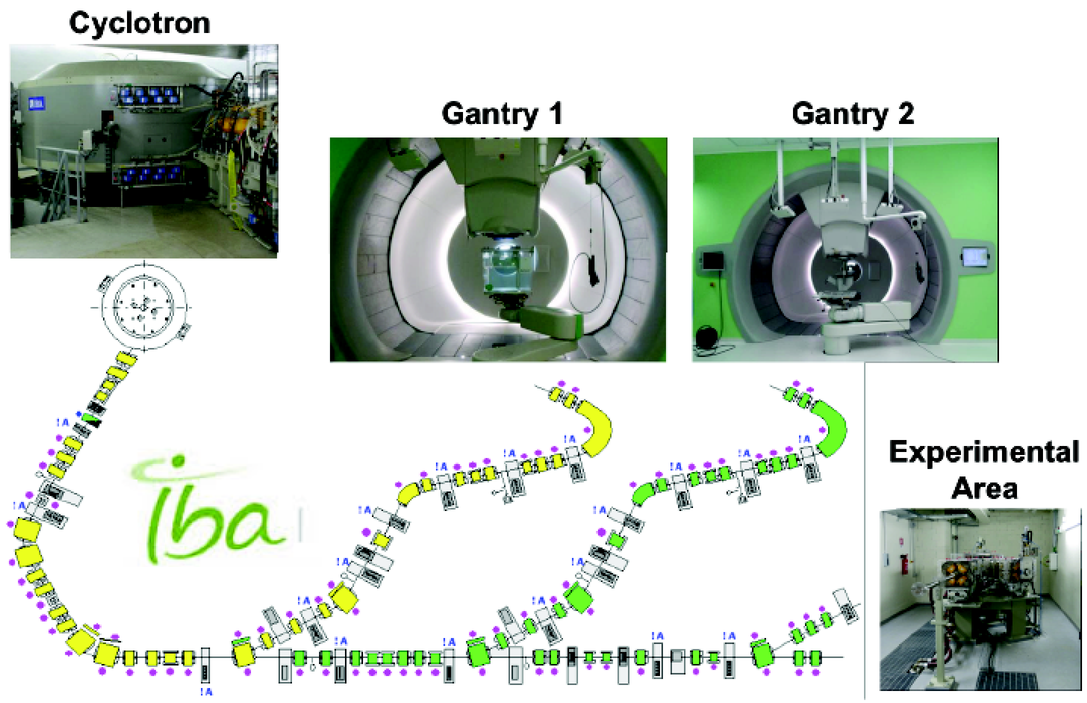

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30^{O} Beam Line Dedicated to Space Radiation and Experimental Physics