Nonlinear-optical Approach to overcome industrial pollution of space

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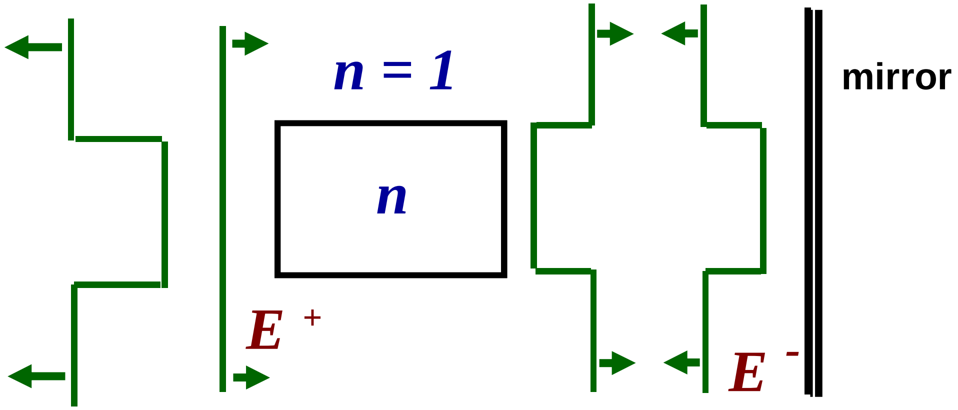
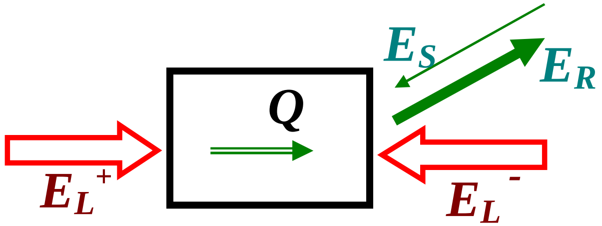
Space debris threats and application of phase conjugation methods for concentrating the debris illumination

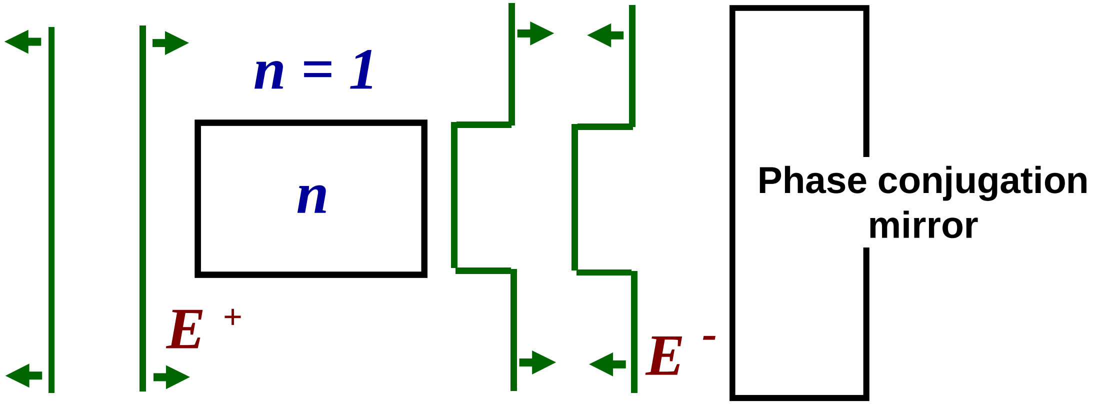
- Nearly 90% of orbital debris has dimensions ~ 1-5 cm. This debris is not tracked and is only detectable using special phased array radars.
- Debris removal demands an increase in illumination laser energy, though the concentration of the orbital debris reflected laser illumination (debris signal) is restricted by the influence of atmospheric turbulence.
- Space debris illumination concentration by laser point narrowing can be achieved by means of non-linear optical phase conjugation of the debris scattered illumination.
- When phase conjugation compensates for turbulent distortions, the conjugated signal will be concentrated on the debris to an accuracy that is determined not by the turbulent scattering angle ($\sim 10^{-5}$ rad), but instead by the receiving aperture of the nonlinear optical amplifier (e.g., $\sim 5 \cdot 10^{-7}$ rad for a receiving aperture of 200 cm).

What is phase conjugation and four wave mixing?

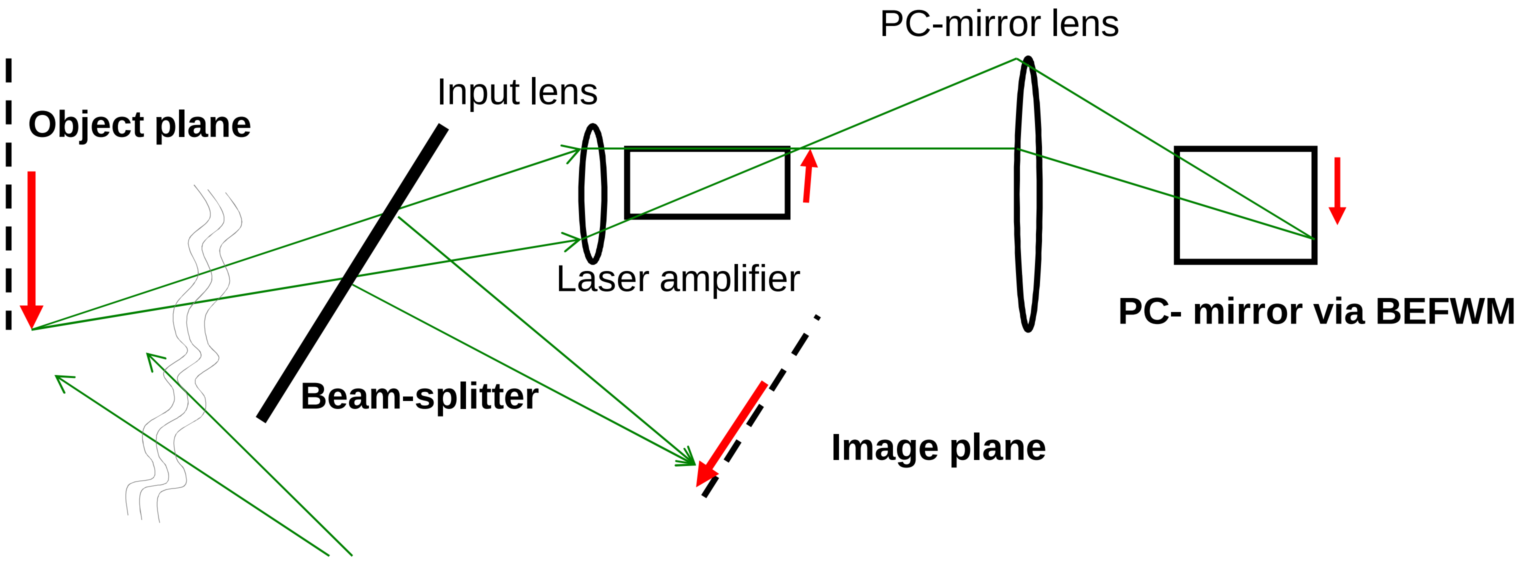




Brillouin enhanced four wave mixing



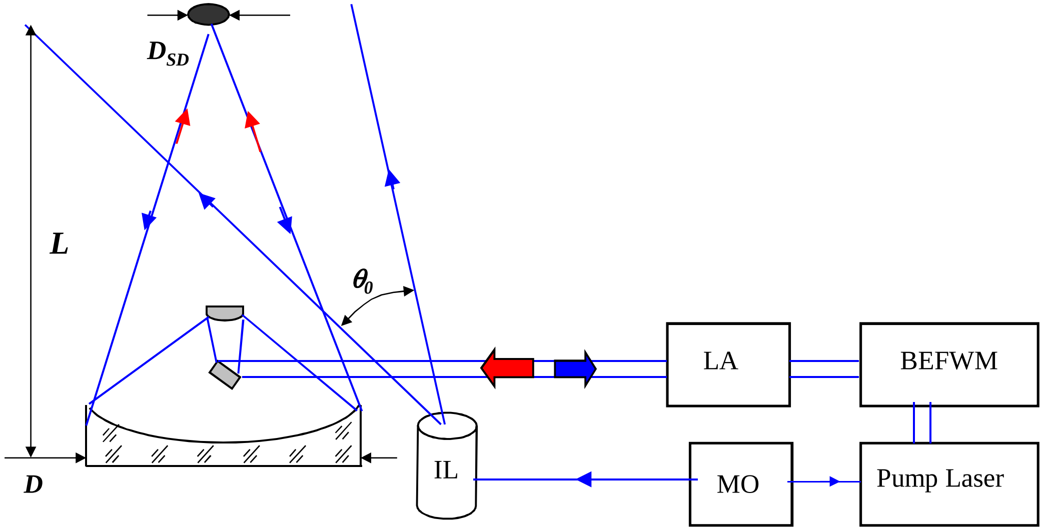
Non- linear optical (BEFWM) laser image amplifier



- The sensitivity is limited by quantum noise and is near $4.8 \cdot 10^{-19}$ J (approximately two photons) per pixel;
- Extremely narrow frequency band corresponds to two frequency-temporal modes (input spectral band ~ 0.001 nm and response time of ~ 30 nsec);
- Comparatively wide field of view (350 X 350 pixels in image);
- High coefficient of amplification (amplifies weak signal by ~ 10^{12}).

Kulagin O.V., Pasmanik G.A., Shilov A.A. «*Amplification and phase conjugation of weak signals*», Sov. Phys. Usp. Vol. 35, № 6, pp. 506–519. (1992)

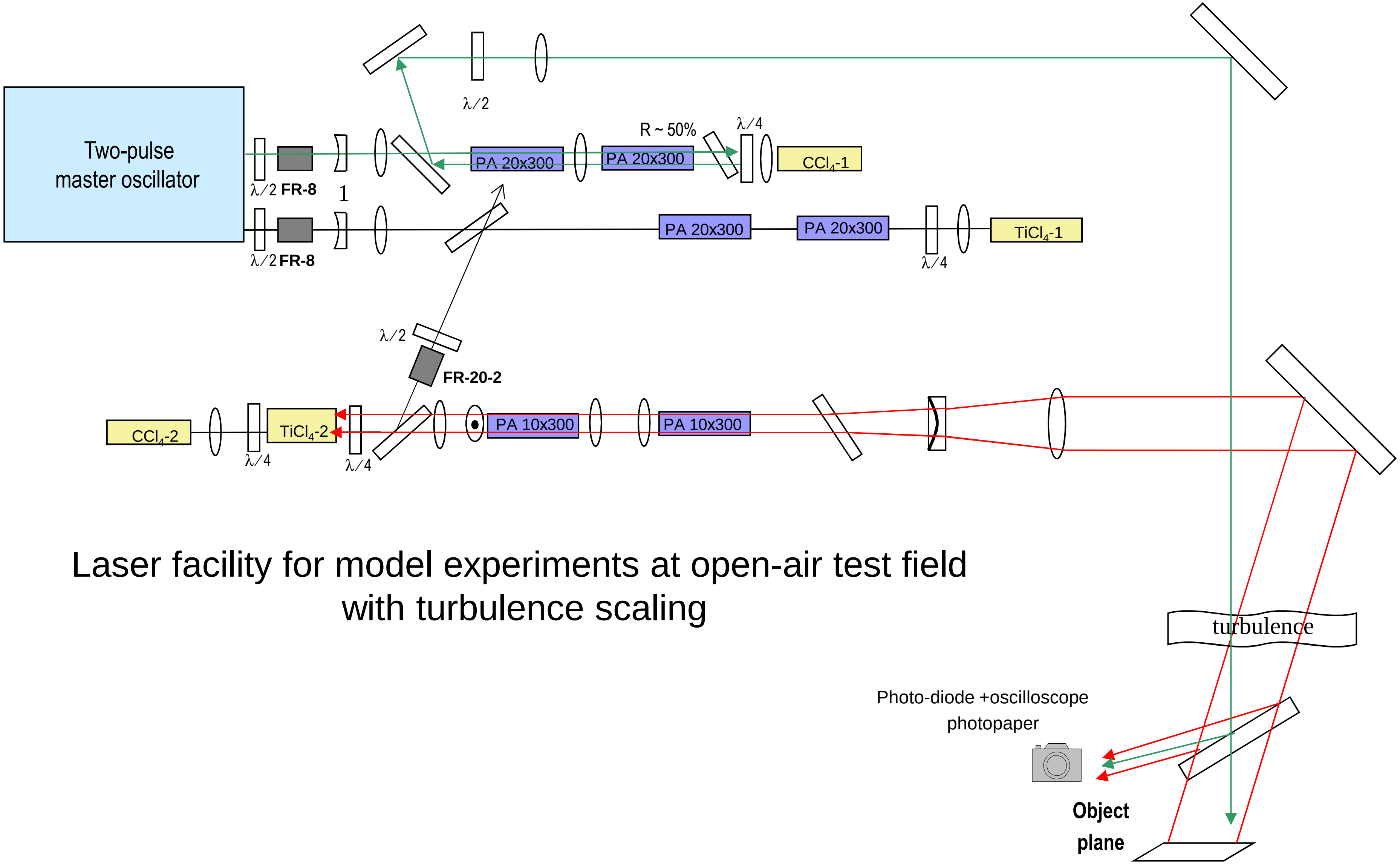
Efficient enhancement of space debris illumination by nonlinear-optical image amplifier with BEFWM



LA – laser amplifier, MO – laser–master oscillator, IL – illumination laser,
L **– distance to target,** ***D*** **– primary mirror diameter,** θ_0 **– illumination angle**

A two-step concentration of orbital debris laser illumination is sufficient for debris observation by the nonlinear optical system at distances from 600 to 800 km. The observations can be made any time of the day

The scheme for concentrating illumination



Laser facility for model experiments at open-air test field
with turbulence scaling

Creation of artificial turbulence

Desired r_0 ~ 1-2 см

$$r_0 \approx (k^2 C_n^2 L)^{-3/5}$$

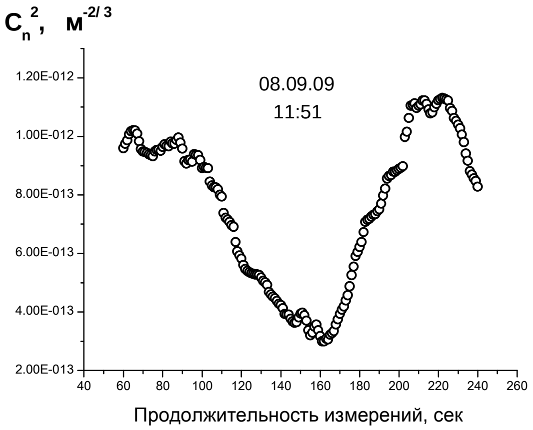
$$C_n^2 \approx 10^{-12} C_T^2$$

C_n^2 = $[cm^{-2/3}]$ C_T^2 = $[\deg^2/cm^{2/3}]$

$$C_T^{\,2}|z_1-z_2|^{2/3} = (dT/dz)^2\,|z_1-z_2|^2$$

Three heating-fans (MASTER B15) provide the required 50 kW

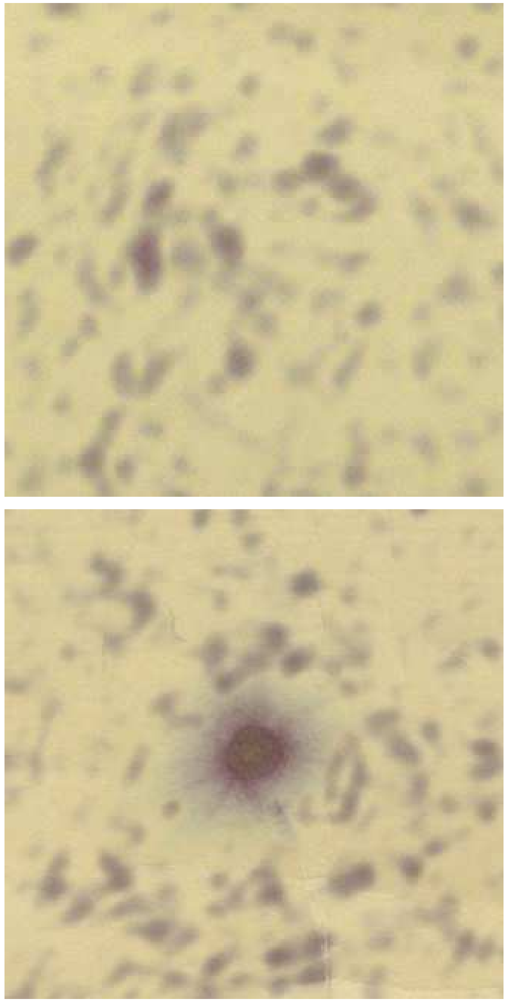
Measurements of turbulent strength along the path

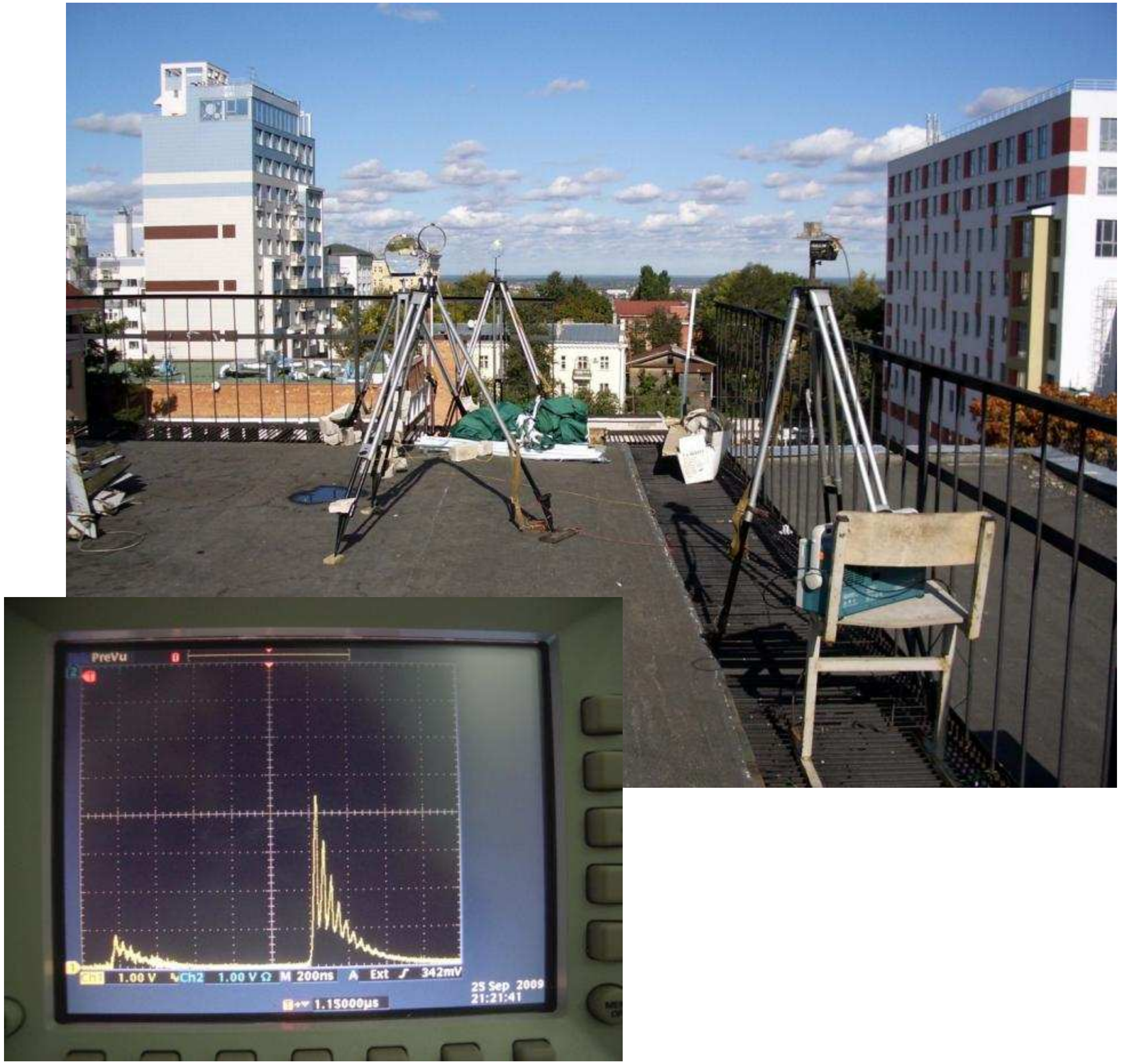


With heating $\mathbf{C_n^2}$ = (4-20-170)*10^{-14}m $^{-2/3}$

Without heating $\mathbf{C_n^2}$ = (2-5-7)*10^{-14}m $^{-2/3}$

Detection of illumination concentration on remote target





Active action on space debris using intense lasers

Physical mechanisms of recoil impulse generation:

- Developed surface evaporation of the debris

The maximum efficiency of recoil impulse at a laser intensity of $I \sim 10^6$ W/cm^2

- Optical breakdown in the vapor. Laser-plasma absorption

For near IR lasers (λ=1.06 μm): $I > 5\times10^8$ W/cм^2

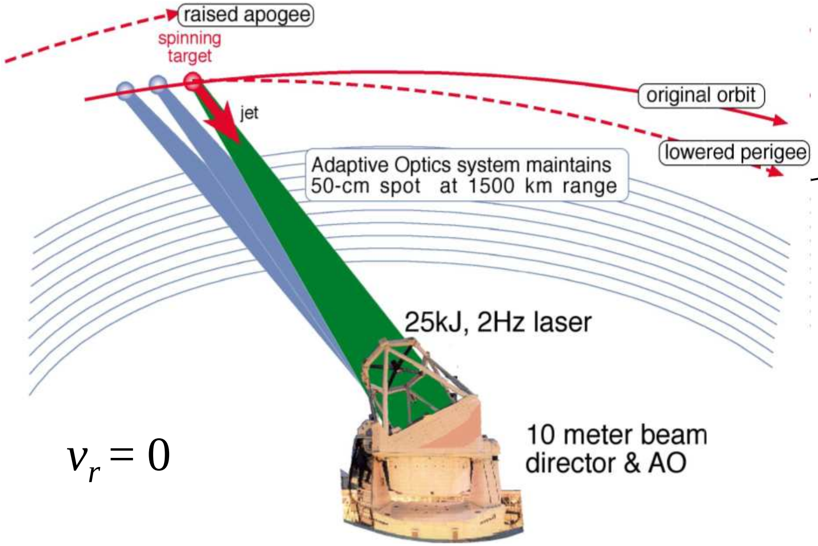
Propulsion of SD object to elliptical low-perigee orbit

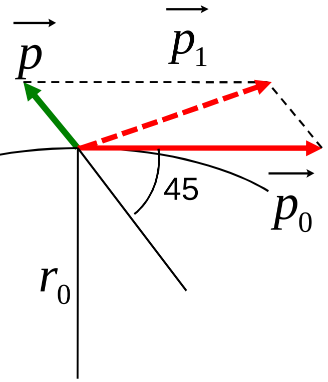
$$E = \frac{mv^2}{2} - \frac{G \cdot M \cdot m}{r}$$

Total energy of SD object

$$v = v_r + v_\varphi \quad \vec{L} = [\vec{r}, \vec{p}] = m \cdot v_\varphi \cdot r$$

$$r_{\min} = \frac{-GMm}{2E}\left(1 - \sqrt{1 + \frac{2L^2E}{(GM)^2 m^3}}\right) \qquad v_r = 0$$





Round orbit: E_0, v_0, L_0, p_0 → Elliptical orbit: E_1, v_1, L_1, p_1

Recoil change of energy and angular momentum:

$$\Delta E = E_1 - E_0 = \frac{m}{2}(v_1^2 - v_0^2) = \frac{p^2}{2m} - \frac{p \cdot v_0}{\sqrt{2}}$$

$$\Delta L = L_1 - L_0 = -\frac{p \cdot r_0}{\sqrt{2}}$$

SD object: m = 1 kg; $v_0 = 7.62$ km/c

at $r_0 = R_3 + h_0$ = 6371 km + 500 km

this SD object shifts to desirable r_{min} = 200 km

if recoil momentum is provided p = 114 kg·m/c

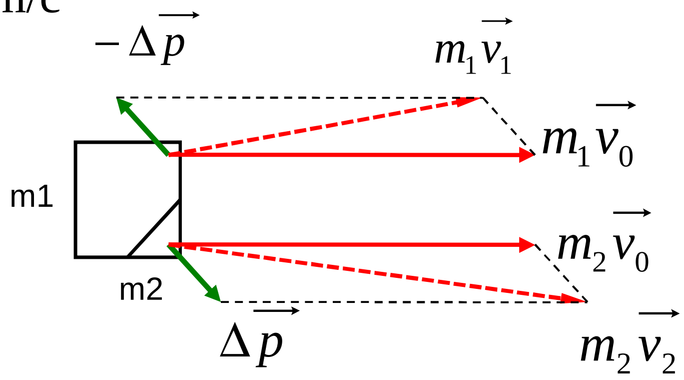
taking into consideration a mass defect Δm caused by evaporation we have p = 106.7 kg·m/c

Laser energy evaluation for SD object propulsion

It is assumed for SD m = 1 kg, velocity v_0 = 7.62 km/c
a rebound velocity of vapoured part – v_{Al}
(in the movable frame of reference)
we have got v_{Al} from relation:

$$\frac{m_{Al}\, v_{Al}^{2}}{2} = \frac{3}{2} kT$$

For Aluminium atom $m_{Al} = 4.484 \cdot 10^{-26}\ кг$
And temperature T = 2770 K v_{Al} = 1.60 km/c and Δm = 6.7% m



We have got a desirable energy of laser pulse by using Aluminium parameters

Melting heat $\lambda = 3.9 \cdot 10^5$ J/kg
Evaporation heat $L = 9.22 \cdot 10^6$ J/kg
Heat capacity c = 930 J/(kg·K)

$$W = \Delta m(\lambda + L + c\Delta T) = \Delta m(3.9 \cdot 10^5 + 9.22 \cdot 10^6 + 930 \cdot 2770) = 807\ \text{kJ}$$

As a conclusion, a laser pulse energy of 1 kJ (at repetition rate of 100 Hz and efficiency of conversion into the recoil pulse ~10%) is acceptable to provide desirable propulsion during one pass of SD object by orbit

Hence, a laser output ~ 1kJ x 10 ns x 100 Hz looks sufficient for small LEO orbital debris removal using non-linear optical laser energy concentration.