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Impact of Target Altitude Restrictions on Laser Performance

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IMPACT OF TARGET ALTITUDE RESTRICTIONS ON LASER PERFORMANCE

by

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ABSTRACT

This report estimates the impact of Raman restrictions and shielding penalties separately and together. Its goal is an overall assessment of likely impact rather than a review of the details of missile trajectories, Raman physics, and shielding techniques, whose individual treatments matter less than their overall integration. Raman scattering could produce a factor of 2-3 reduction on the performance of repetitive-pulse lasers with large fluences in each small pulse. Radio-frequency free-electron lasers (RF FELs), which have more frequent pulses with less energy in each, are impacted less. Shielding gives an independent penalty of about a factor of 2, but the combined effect of altitude and shielding penalizes lasers with large pulses by factors of 3-10. Those factors are significantly larger than any other factors differentiating between the two types of FELs.

I. INTRODUCTION

This report explores the impact of restrictions on the altitudes at which lasers can engage their targets on directed energy defenses' overall effectiveness. It also discusses the interaction between engagement altitudes and shielding penalties and estimates their combined impact on defensive systems, which could approach an order of magnitude in engagements of interest.

II. DOWNLINK RAMAN

Raman scattering can shift energy from the laser beam to parasitic beams at different frequencies and significant angles from the main beam. If the scattering occurred at altitudes much greater than the targets', the scattered beams would not deposit usefully on the target, placing a lower limit on the altitudes at which irradiation can begin. The physics of the conversion processes is understood, as is the magnitude of the Raman gain expected under typical conditions.[1] Since Raman scattering amplifies noise, it is difficult to control. It is possible to manipulate the intensities and phases of input parasitic beams to minimize their growth. The reductions in Raman conversion could be significant, but have not been demonstrated in the field; the possibility remains that Raman losses could be large.[2]

The Raman conversion efficiency depends on the beam's intensity. Thus, low-power continuous-wave beams from chemical lasers are little affected, while repetitively pulsed lasers are affected more strongly. The interaction strength depends on the peak intensity and the duration of each pulse, or the fluence transmitted per pulse. That is small for radio-frequency free-electron lasers (RF FELs), whose pulses are small and frequent. For a given average fluence, however, the fluence per pulse is much larger for induction FELs (IFELs), which are pulsed only about one thousandth as often. Estimates indicate that IFELs could be limited to targets at altitudes of ≥80 km, but that RF FELs could interact down to 0-20 km.[3] That difference in altitude is sometimes described as producing a "factor of 2" difference in their effectiveness against missiles that burn out below 100 km, but the combined effect of Raman and shielding penalties could be larger. This report is concerned with the impact of Raman scattering on laser and shielding effectiveness, so it studies the range 0-100 km parametrically as the altitude at which irradiation could begin.

III. MISSILE METRICS

Current missiles burn out at ≈600 s and ≈600 km altitude; whether the lasers start to interact at 20 or 100 km has little impact. Even for midterm missiles, which might deploy by ≈300 km and 300 s, the impact is modest. The principal concern is missiles that could burn out at 100-120 km in ≤100 s, which might be deployed in the long term (≈20 years), when FELs could be deployed for boost-phase defense. For the performance estimates of interest here, the details of missile trajectories are not critical; the impact of interaction altitude restrictions can be estimated with a simple model of fast-missile metrics. Fast boosters have an approximate altitude-velocity (z-v) relationship

$$z \approx \sin\theta \cdot v^2/2a \approx v^2/5a, \qquad (1)$$

where z is the altitude at which the missiles' velocity reaches v, a is the missiles' average acceleration, and $\theta \approx 25^\circ$ for minimum-energy trajectories. Fast boosters with $a \approx 10$ g's = 0.1 km/s^2 could be built with modest structural and payload penalties relative to current boosters. Such fast boosters would reach the required a burn-out velocity $v_b \approx 7.5$ km/s at altitude

$$z_b \approx \approx v_b^2/5a \approx (7.5 \text{ km/s})^2 \div 5 \cdot 0.1 \text{ km/s}^2 \approx 110 \text{ km}, \qquad (2)$$

which is about as low an altitude as it could begin to deploy decoys without differential deceleration of the decoys disclosing them.[4,5] The burn-out time of 10 g missiles would be

$$t_b \approx v_b/a \approx 7.5 \text{ km/s} \div 0.1 \text{ km/s}^2 \approx 75 \text{ s}. \qquad (3)$$

The maximum time available for the laser to engage the missile is the sum of t_b and the time to deploy the decoys, t_d, which is $t_d \approx 300$ s for near-term missiles, e.g., ≈30 s per reentry vehicle (RV). For the developed serial busing used on SS-18 and -24s deployment times could only be reduced by de-MIRVing the missiles, i.e., by reducing the number of multiple RVs carried on each, or by going to individual buses on each RV, which would roughly halve the number of RVs carried on each missile. Fast-burn single-RV missiles could reduce the deployment time to

10-30 s, for roughly twice the cost per RV; a minimum $t_d \approx 20$ s would give a total minimum engagement time of

$$t_e = t_b + t_d \approx 75 + 20 \approx 95 \text{ s}, \tag{4}$$

which approaches an order-of-magnitude reduction from the current 600 s. Even if the reduction in the defenses' effectiveness by Raman limitations was only linearly proportional to that of the engagement time, 20-50 s differences could be significant in the long term.

IV. ALTITUDE RESTRICTIONS

It takes a time $t \approx \sqrt{(5z/a)}$ for a continuously accelerating booster to reach altitude z. If the laser could not irradiate it during that time, the useful engagement time would be reduced to

$$T = t_b + t_d - t. \tag{5}$$

The performance of lasers that operate serially would be reduced to a fraction f of what they could achieve in the absence of altitude restrictions, where

$$\begin{aligned} f &= (t_b + t_d - t)/(t_b + t_d) \\ &\approx 1 - t/t_e = 1 - \sqrt{(5z/a)}/t_e, \end{aligned} \tag{6}$$

which is shown in Fig. 1. Chemical or RF FELs could irradiate targets essentially at the ground, for which $f \approx 1$. If IFELs were unable to irradiate targets below 80 km, their performance would be reduced by a factor of ≈3 relative to RF FELs; if they were limited to 100 km, their performance would be reduced by a factor of ≈4. The performance of RF FELs that could reach the ground would be a factor of 100/33 = 3 better than IFELs; if the RF FELs could reach 20 km, their engagement ratio would be better by a factor of 67/33 ≈ 2. The middle and top curves show that these penalties are reduced by about a factor of 2 for longer deployments.

V. MISSILE HARDENING

Mid- to long-term boosters would, however, presumably be hardened against lasers. If the lasers could reach essentially to the ground, all of the boosters' stages would have to be hardened uniformly. If, however, the lasers could only reach down to 60-80 km, it would not be necessary to harden the first stage, which could burn out at a lower altitude. This would eliminate the payload penalty for shielding the large first stage. The American Physical Society (APS) report on DEWs discusses hardening upper stages only, as could be the case for IFELs.[6,7] "Directed Energy Concepts for Strategic Defense," shows that shielding all stages increases the payload penalty by about a factor of two, which could eliminate most of the missiles' payload.[8] For the same payload reduction, boosters subject to attack only at high altitudes could be made about twice as hard as those that could be attacked at any altitude, which means that IFELs would take twice as long to negate each of the boosters that they could reach.

The net effect is that lasers' effectivenesses would be reduced by another factor of about 2 for $z > 60$-80 km, but the estimate can be made more precise. If the first stage burned out at altitude $z_1 \approx 60$ km and time t_1, the previous calculation would not be modified for $z \geq z_1$, but for lower z the number of kills would be reduced roughly linearly in excluded time. For lasers that could reach the ground and kill missiles in t_o seconds the number of kills would be

$$N_o \approx \Sigma_0^{te}\, dt/t_o = t_e/t_o. \tag{7}$$

For lasers that could not start irradiation before the missiles reached z the number of kills would be

$$N_z \approx \Sigma_t^{te}\, dt/t_z, \tag{8}$$

where t_z is the kill time at altitude z where engagement begins. If t_z increases linearly with z from t_o at $z = 0$ to $\approx 2 \cdot t_o$ at z_1,

$$\begin{aligned} N_z &= \Sigma_t^{t1}\, dt/t_z + \Sigma_{t1}^{tb+td}\, dt/t_z \\ &\approx \{[\Sigma_z^{z1}\, dz\sqrt{(5/4az)}] + (tb+td-t1)\}/t_o(1+z/z_1) \\ &\approx [\sqrt{(5/a)}(\sqrt{z_1}-\sqrt{z}) + (te-t1)]/t_o(1+z/z_1). \end{aligned} \tag{9}$$

The efficiency under both altitude and hardening restrictions is N_z/N_o, which is shown in Fig. 2. For long-term 20 s deployments, the penalty for the restriction of operation to $z \geq 100$ km is about a factor of 10; for 20 km it is about a factor of 2. Thus, lasers that could reach the ground would perform better by a factor of $1/(0.15) \approx 6$ than those limited to operation above

80 km; those that could reach 20 km would perform better by a factor of 0.5/(0.15) ≈ 3. Dropping IFELs' interaction altitude one or two scale heights from a nominal 80 km wouldn't change these results significantly, since that would only increase the time available for irradiating first stages by ≈15 km ÷ 0.4·(3-7.5 km/s ≈ 5-10 s. If RF FELs could penetrate to 20 km, dropping IFELs to 60 km would still leave a ratio of 0.5/(0.2) ≈ 2.5, which represents a larger disparity between the two FEL concepts than any other unresolved system issues.

VI. SUMMARY AND CONCLUSIONS

This report estimates the impact of Raman restrictions and shielding penalties separately and together. Its goal is an overall assessment of likely impact rather than a review of the details of missile trajectories, Raman physics, and shielding techniques, whose individual treatments matter less than their overall integration. Raman scattering could produce a factor of 2-3 reduction on the performance of repetitive-pulse lasers with large fluences in each small pulse. RF FELs, which have more frequent pulses with less energy in each, are impacted less. Shielding gives an independent penalty of about a factor of 2, but the combined effect of altitude and shielding penalizes lasers with large pulses by factors of 3-10. Those factors are significantly larger than any other factors differentiating between the two types of FELs.

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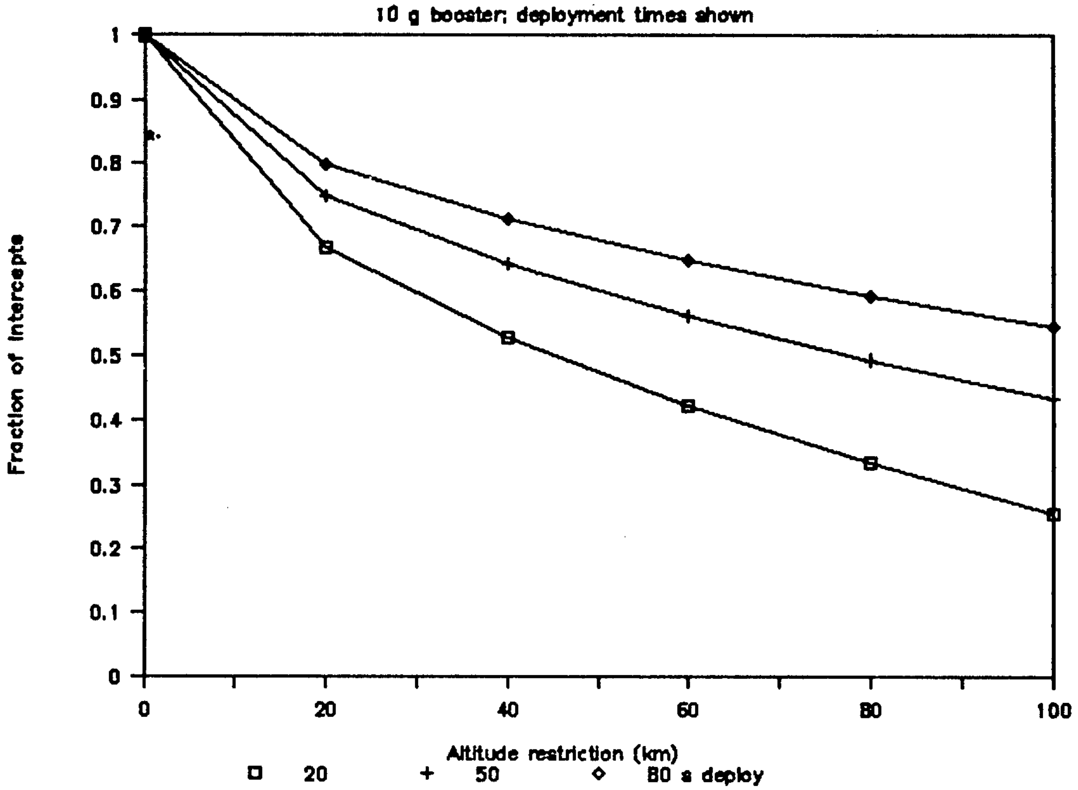

Fig. 1. Penalty for altitude restriction.

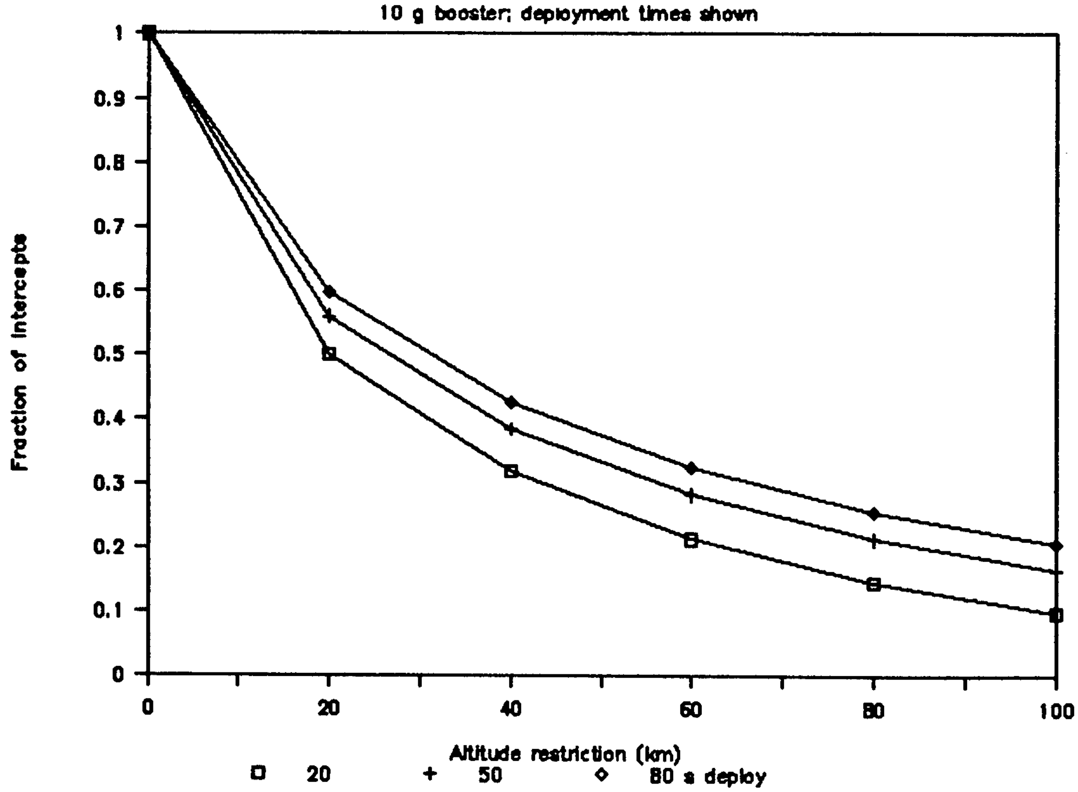

Fig. 2. Penalty for altitude and shielding.

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