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ORION Low Cost Laser Analysis

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Section 1: Motivation for short pulse generation in ORION

1.1 SRS requires short pulses

In work performed during Phase I of NASA's ORION program, it was shown that very short pulse 1.06-μm wavelength lasers can penetrate the lower atmosphere at very high peak pulse intensity without being converted to other wavelengths and scattered in unintended directions Stimulated Raman Scattering (SRS). This gives an advantage to very short laser pulses, because it is necessary to ignite a plasma on the debris target for efficient generation of de-orbiting thrust, and the energy required to do that is less for very short pulses.

Figure 1 shows a desirable short pulse ORION operating point on the left, above the "1E-10" (100-ns pulse width) label on the horizontal axis. In the illustration, a near-term, short range (600 km) system is shown, for which 450J at 100ps is equivalent in effect on the target to 6,600 J at 40 ns.

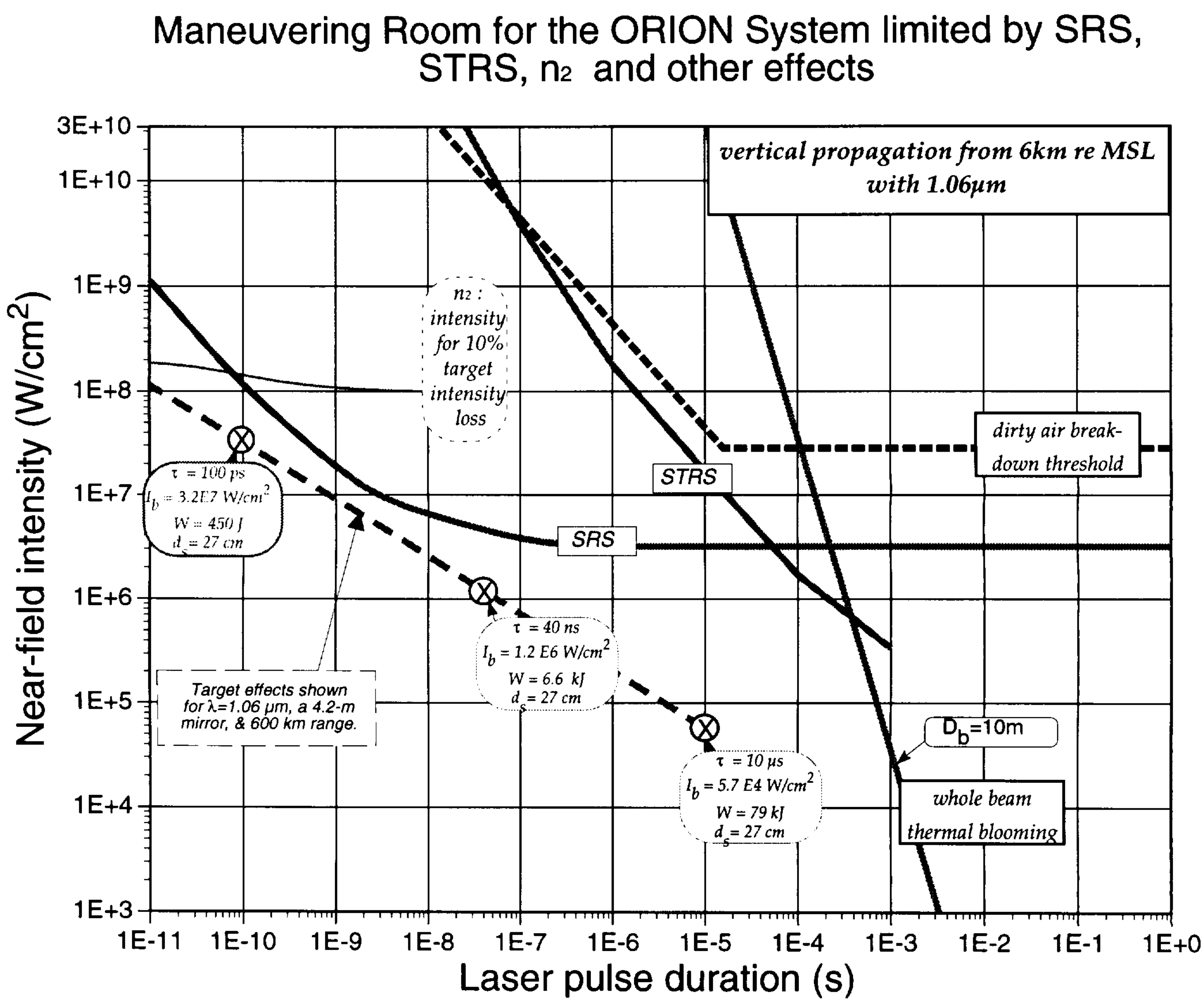

Figure 1

It is clear that the 6.6kJ laser would be more difficult and expensive to build, perhaps by as much as afactor of 10 based on construction cost of the LLNL "BEAMLET" laser.

The fact that short pulses defeat SRS is shown by upward curvature the line labeled "SRS" for pulses shorter than 10 ns.

1.2. <u>Target physics says short pulse lasers require less energy</u>

As we showed in §0 of ORION Phase I work, the required laser parameters on the ground can be connected to the target intensity required to form plasma and obtain optimum coupling, particularly to relate laser pulse energy W to mirror diameter D_b:

$$W = \frac{Ca}{ST}\left[\frac{\lambda z}{D_b}\right]^2 \tau^{\alpha} \quad . \qquad [1]$$

In this expression, C = 2.3E4 is a constant derived from optimum target coupling
α = 0.45 is an exponent derived from optimum target couling
τ is laser pulse width
T is atmospheric transmission (0.85 for a vertical path)
S is Strehl ratio ($1/N^2$ in § 0) = 0.5
a = $4/\pi$
λ is laser wavelength in cm
and z is range to target in cm.

As a reminder, this expression arises from two sources: These are a) the pulsewidth dependence of intensity for optimum coupling to a target, a feature which determines α on a strictly empirical basis, and b) the effect of diffraction over propagation distance z in determining the laser spot size on target, given the emitted beam diameter D_b, and therefore the intensity on target given a pulse energy W.

1.3 <u>Laser cost can be developed from the pulse energy dictated by target physics</u>

Also in Phase I, we developed a cost model as follows:

Where W = laser energy in joules from Eq. [1],

we have

$$\mathfrak{C}_L = 1.1 \sum_{i=1}^{4} C_i \qquad [2]$$

with the following cost elements:

Laser head[a]: C_1 = \$1.02E6*$W^{0.45}$. [2a]

Power supply[b]: C_2 = \$3.2E4*$(fW/1000)^{0.85}$ [2b]

Cooling gas flow loop[b]: C_3 = \$6.8E4*$(fW/1000)^{0.88}$*$(f/1000)^{0.083}$ [2c]

System integration[b]: C_4 = \$6.0E4*$(fW/1000)^{0.256}$ [2d]

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[a] Source: C. Phipps study of the Lawrence Livermore (LLNL) Nova-Athena-NIF (National Ignition Facility) construction and engineering design sequence, plus recent input from Lloyd Hackel at LLNL regarding 100-J, 30Hz, 10-ns laser system he has built for an illuminator at Starfire Optical Range.

[b] Source: J. P. Reilly

assuming a laser electrical to light efficiency of 4%.

Eqns. [1] and [2] can be put together, if we assume a mirror diameter of 6 m and $\lambda = 1.06\mu m$, to give a plot of estimated laser cost vs. pulsewidth selected. (Figure 2). This Figure dramatically summarizes the motivation.

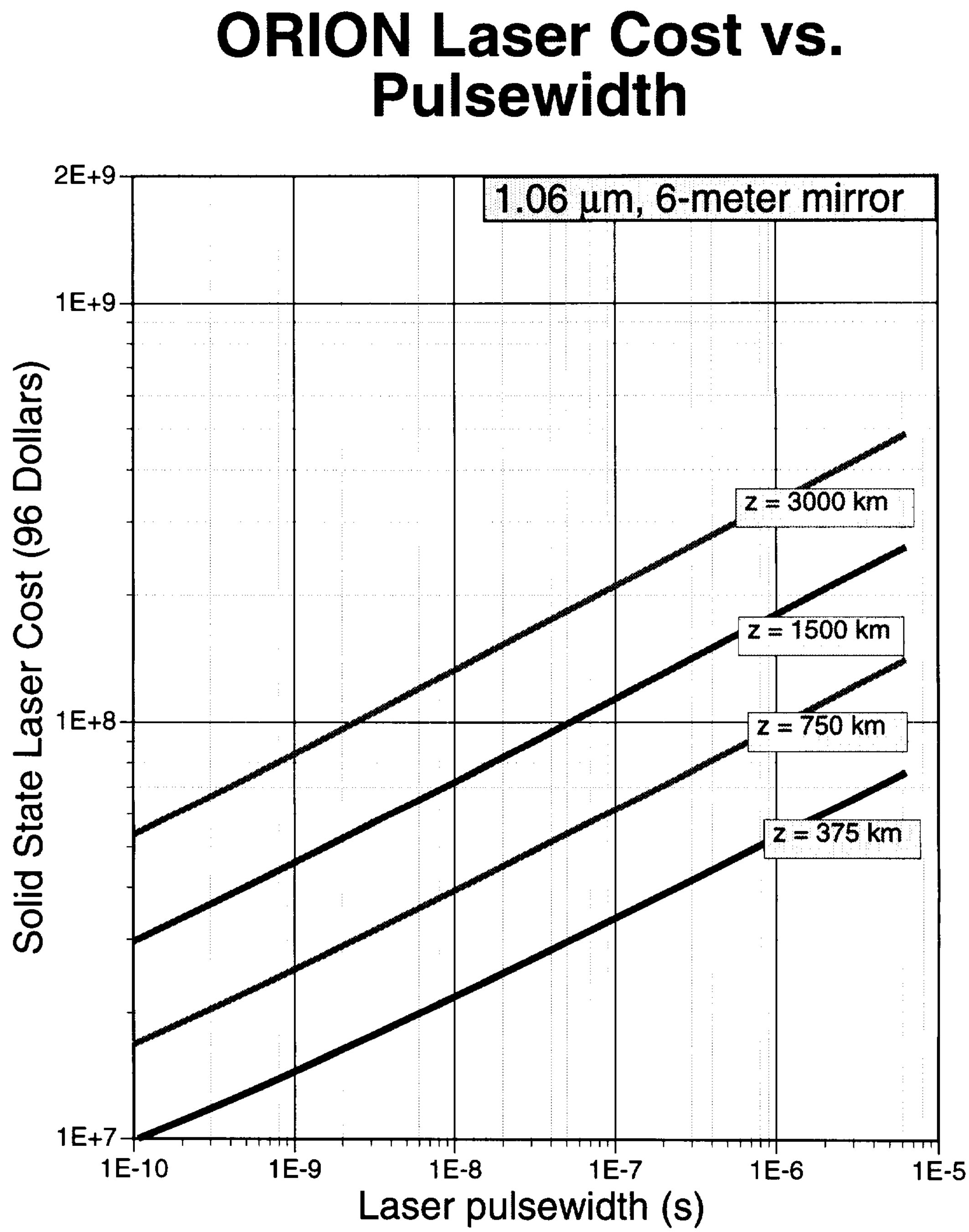


Figure 2

Alternatively, Figure 3 shows how pusher pulse energy varies with pusher pulse duration in order to ignite a plasma and optimally couple to the debris target, using the same assumptions as in Figure 2. Slant range to the target is the parameter for the 4 trends plotted. It will be seen that the ultimate system with 100ps duration requires only 6kJ per pusher pulse even at 3000 km, and just 100 J per pulse for demo ranges of order 375 km.

Midterm systems, limited as they are by currently available technology, will have to use 5 ns pulses and generate as much as 37kJ for the maximum range and about 550J for the demo.

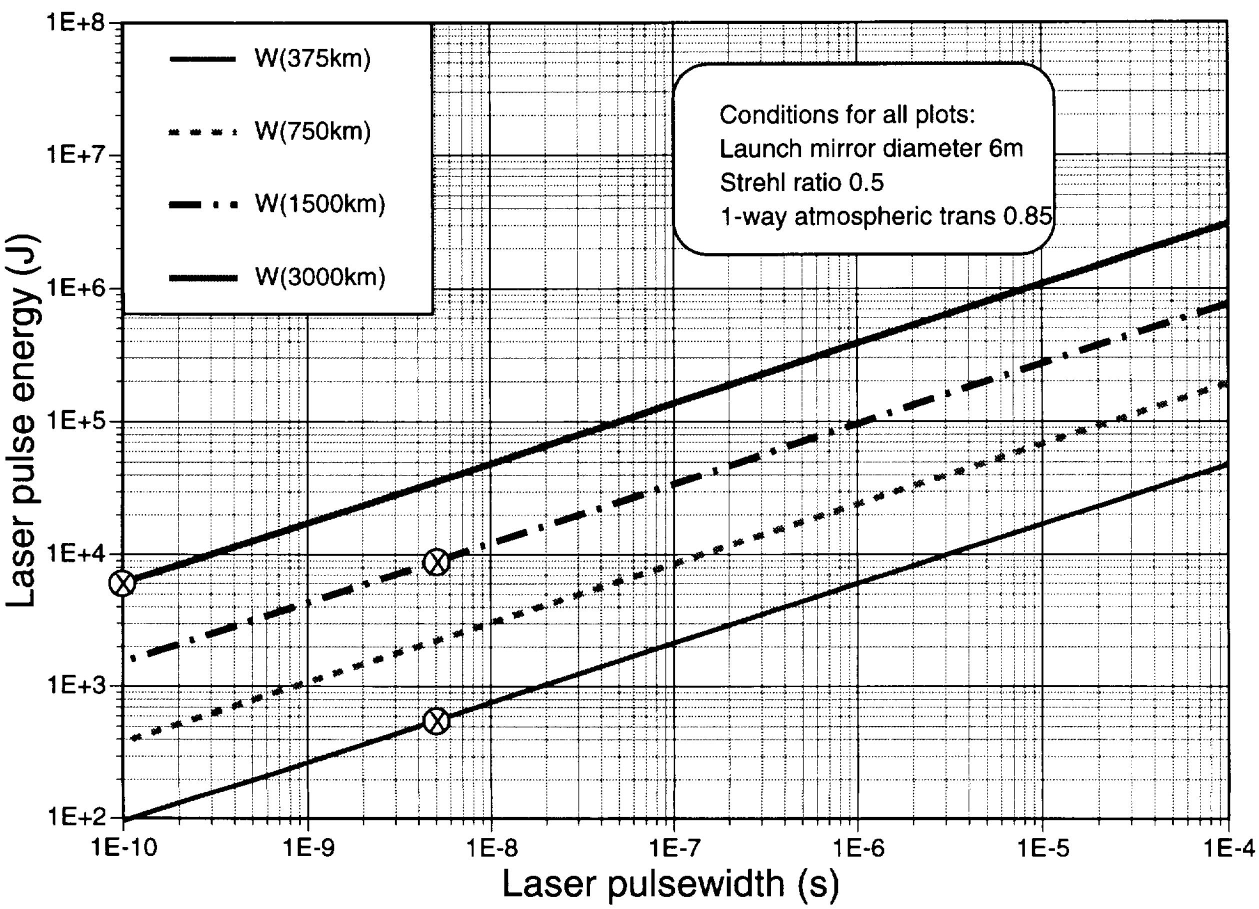


Figure 3

This is why we have discussed 30kJ lasers at 5ns for the past several months, rather than the smaller lasers we were hoping for in earlier reports.

2: Methods of short pulse generation compared

Having identified that 100-ps pulses are desirable, it remains to find efficient, low-cost ways of obtaining them from conventional solid state lasers which more readily operate in the 20–40-ns regime. In this section, we will compare the three principal methods of obtaining 100-ps pulses which have been demonstrated in the literature. Much of this work has occurred at the Lawrence Livermore Laboratory and at the Russian Vavilov Institute. Experts at either laboratory are capable of developing the actual hardware.

Two of these methods feature clever schemes to deliberately compress a longer pulse. Of these, one involves the use of a holographic grating pair to passively compress a so-called "chirped" large bandwidth pulse of about 10 ns duration. The second compression method uses the physics of Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS) or both in a cascade to provide passive compression. The third method is the "brute force" approach: make a very short oscillator pulse, and amplify it in an amplifier of adequate bandwidth.

2.1. Holographic Gratings

The beauty of this technique is its nearly perfect energy convesion efficiency (in principle). However, the difficulty is that these gratings are limited to about 1 meter in transverse dimension by current technology. Therefore, the chirped input pulse to the grating must then be not much longer than 3 ns, due to the finite speed of light.

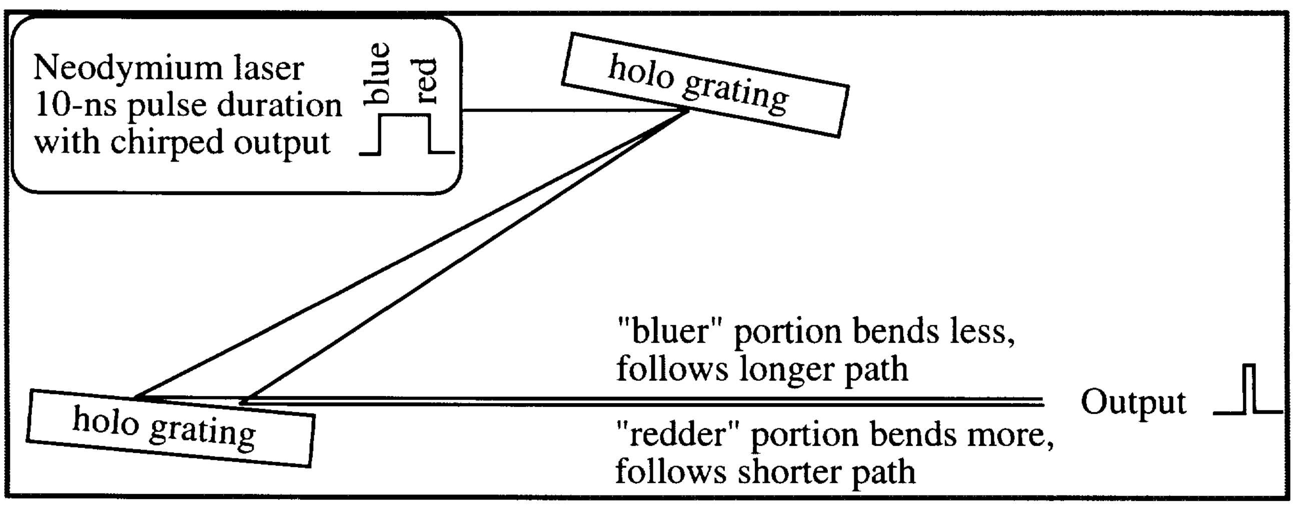


Figure 4
Holographic Grating approach to pulse shortening

That is to say, since the speed of light is 0.3 m/ns, a pulse that is 20ns long will require a 6 meter grating. Conversely, 3 ns pulsewidth, which matches the maximum size of gratings that can be made using current techniques, is too short to get good extraction and high beam quality at the same time from a neodymium system at the present time.

2.2. SBS/SRS Cascade

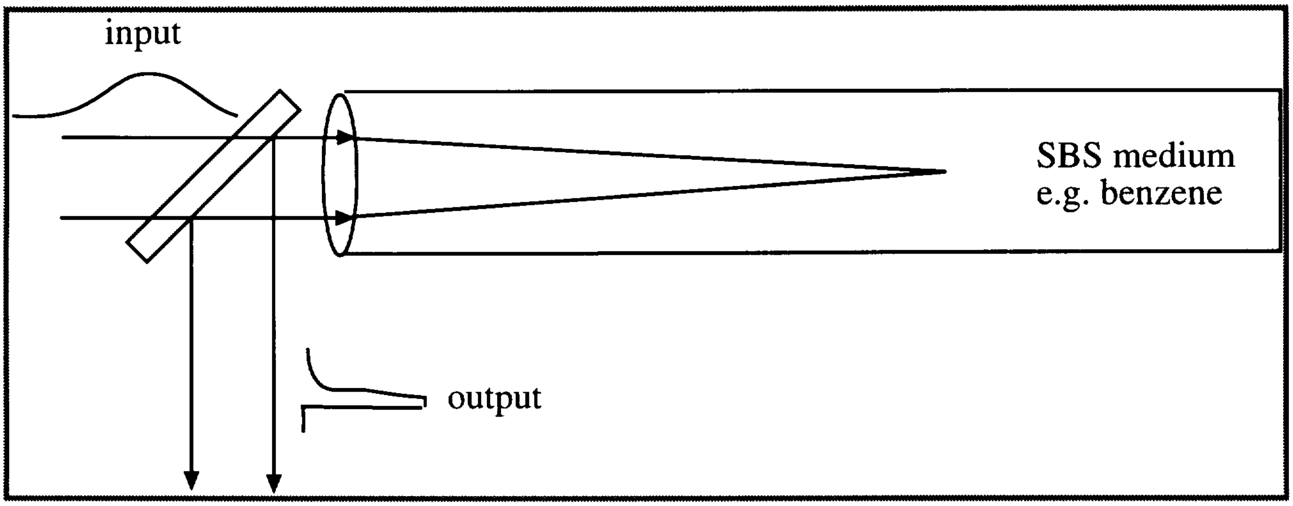


Figure 5
SBS/SRS Cascade as a pulse shortening mechanism

The advantage of this technique is its simplicity and totally passive operation in shortening a long input pulse, by as much as a factor of 10. The pulse reshaping that results is due to strong saturation of the input or pump wave by the leading edge of the counterpropagating output or "Stokes" wave. A similar diagram describes the behavior of a reverse SRS pulse compressor. SBS and SRS units can be used in cascade to obtain certain desirable effects.

Total compression ratios of about 100 have been obtained, just about what we require in the ORION system (efficient conversion to 100 ps pulses which couple efficiently to the debris target, from cheap, relatively low energy 10 ns inputs).

The problem with this technique is: low efficiency. Compression ratios of 100 go along with energy efficiency which may be as low as 2%, unacceptable for ORION. Such a low efficiency would actually make it less expensive to build and use a higher energy long pulse laser.

2.3. Amplfiying a short oscillator pulse

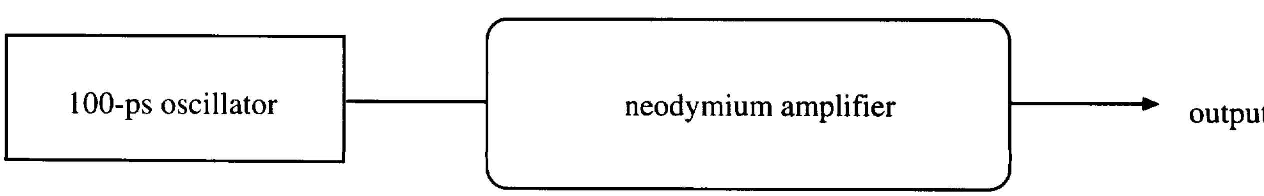


Figure 6
The "brute force" way to get short pulses

This "brute-force" approach is deceptively simple. Unfortunately, it depends, at the present time, on unattainable combinations of laser parameters. The problem is that the brightness integral or "B-integral" which determines beam breakup due to nonlinear refraction in the glass host of a solid state laser system is the same integral, apart from constants, that determines energy extraction efficiency. And, for 100-ps pulses, the result is that efficient extraction is not yet possible for 100ps pulses if high beam quality is also required.

The consequence of all this is: At this time, the best choice is a 5 ns pulse for ORION, not shorter, if that pulse is generated by a solid state laser system. We must accept the cost penalty implied by our approximate cost model (Figure 2) until technology catches up. The situation may well improve in the next year or two as efforts at solid state laser R&D labs proceed.

3: Key issues and problems for Phase II

The key problem for future resolution in ORION Phase II is as follows.

3.1 Problem Statement

The lowest order wavefront distorition for a laser beam propagating through turbulence in the atmosphere is an average tilt, which results in a pointing error. A target illumination laser, or sunlight, solves this problem in principle by actively illuminating the target. The tilt in the wavefrnt is measured by focusing the light returned from the debris as collected by the entire telescope aperture onto a sensor and measuring the displacement of the focal spot.

However, in the worst case, during the delay between launching the illumination laser beam and capturing the return signal, the target may have traveled well outside the cone including the column of air for which the adaptive optics system is set up to correct aberrations.

In that case, successive pulses of the laser produce well formed focal spots all of which miss the target.

3.2 Is there a problem?

For a particle in a circular orbit, if the local zenith angle is θ_z and the geocentric angle between the local Earth radius and the particle Earth radius is θ_E, the relativistic lead angle is determined by target velocity v, the speed of light c and these angles according to

$$\alpha = 2v/c \cos(\theta_z - \theta_E) . \qquad [3]$$

The maximum value (for a particle directly overhead in fairly low orbit) is about 50µrad (10 arc seconds) for ORION targets.

The relation for the tilt error as a function of the lead angle is[c]:

$$\sigma_{tilt} \approx 0.6 h_t \lambda_o \alpha \sec\theta_z / \{D^{7/6}[r_o(\lambda_o)]^{5/6}\} \qquad [4]$$

Assuming a turbulence layer at 5 km, a lead angle α of 50 µrad, a telescope diameter of 6 m and a value of r_o = 20 cm, the tilt angle is 75 nrads. The diffraction angle, assuming perfect

[c] H. Friedman in C. R. Phipps, *et al. Laser and Particle Beams* **14** no. 1 p. 28 (1996)

higher order correction is $\lambda/D \approx$ 180 nrads. Thus the tilt angle is considerably less than the diffraction angle and the loss factor is given by:

$$\text{Loss factor} \approx (\lambda/D)^2 / [\,(\lambda/D)^2 + \sigma_{tilt}^2] \qquad [5]$$

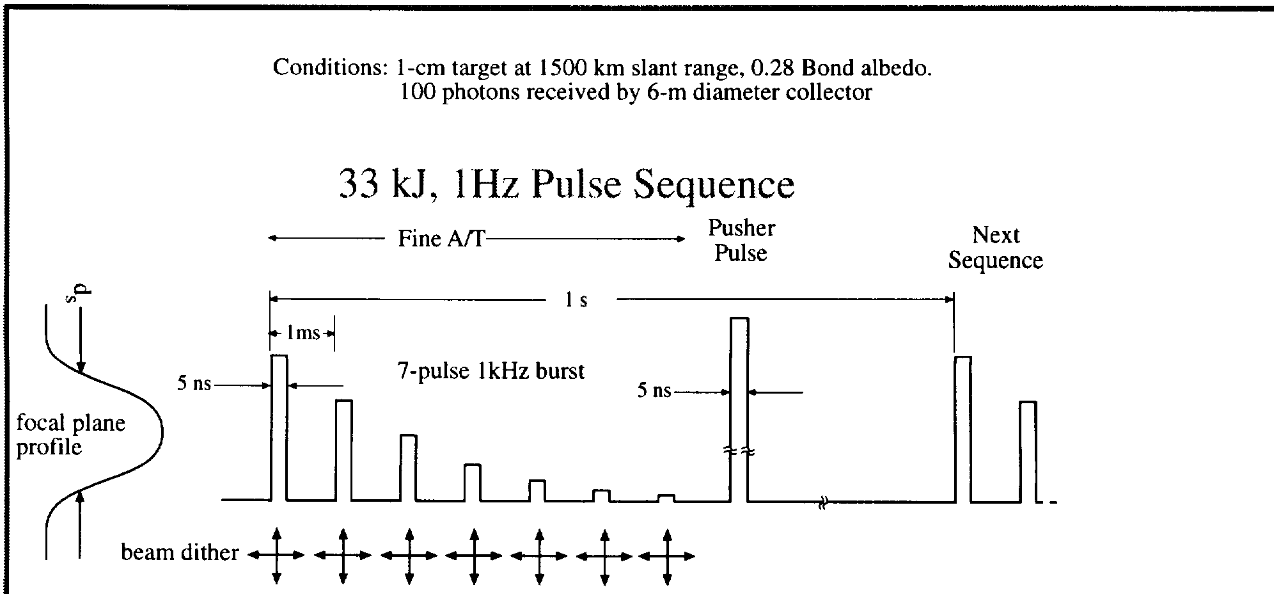
$$= 85\%$$

This figure should be interpreted as a transmission to the target, with maximum value of 1.0 (good). The loss factor can be interpreted as a 180 nrad spot jittering pulse to pulse by an amount of 75 nrad.

In principle, there should <u>not</u> be a severe problem from nonisoplanaticism due to relativistic lead angle in ORION.

3.3 <u>When there is, how can we combat it?</u>

Answer: simply by prefacing the high energy pusher pulse with a rapid (1kHz) sequence of low energy pulses, while continuously reducing the laser footprint in space from the presumed 50-m diameter handoff circle from the radar or other acquisition system down to the 0.5-m diameter required for pushing on the target.



spot size d_s (m)	50	25	10	5	2	1	0.5	
pulse energy W (J)	520	130	21	5.2	0.83	0.21	0.052	30 k
pulses	4	4	4	4	4	4	4	
total energy W_{tot} (J)	2080	520	84	21	3.3	0.8	0.2	⇒Total energy for fine A/T: 2.7kJ (9%)

Figure 7

<u>Smart beam dither solves look-ahead/tilt AO conflict</u>

The procedure is very similar to what many modern flash cameras do prior to taking a picture.

As shown in Figure 7, only the first prepulse has very much energy, because it has to illuminate a 50-m diameter circle with enough flux to get a 100-photon return from a target as small as 1cm. Successive pulses are much smaller, and the whole sequence uses only 9% of the total laser energy, including the final pusher pulse. Of course, the smaller pulses could be designed to return 10,000 photons rather than 100 photons without measurably changing the energy budget, for greater acquisition speed and reliability.

4: Recommendations

We recommend that 5ns be the ORION laser pulsewidth, for any system designed within the next 2 years.

We recommend that 100ps be the goal for future systems.

We recommend that this pulsewidth be achieved by an appropriate combination of the best procedures available at the time.

However, we predict that better pulse shortening will be available when this decision has to be made, and that the choice of how best to get 100ps pulses will be much more clear at that time than it is now.

We recommend that all-optical acquisition and tracking be employed. The cost of a radar in ORION is prohibitive, unless it is absolutely required. Cheap, sunlight-assisted wide field of view boresight telescopes can help with initial acquisition.

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We show that laser-target interaction physics demands the shortest laser pulse of which hardware is capable (but not less than 100 ps) in the ORION ground-based laser concept. We compare two leading ways to achieve such pulses - SRS/SBS cascade compression and grating compression - with the standard MOPA approach, and conclude that the first of these is most robust. However, the state of the art in laser devices will require a year or two to implement these ideas. We present a pulse format and beam footprint protocol which will solve the conflict between relativistic lookahead and beam tilt and should permit all-laser active acquisition and tracking in ORION.

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