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# DPSSL-Driven Targets: A Whiter Shade of Green?

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***Lawrence Livermore National Laboratory***

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**Princeton Plasma Physics Laboratory**

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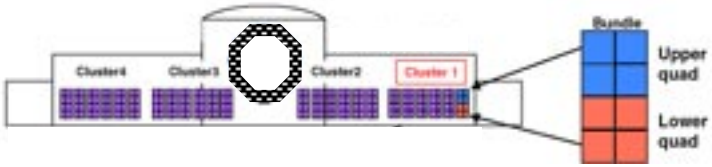
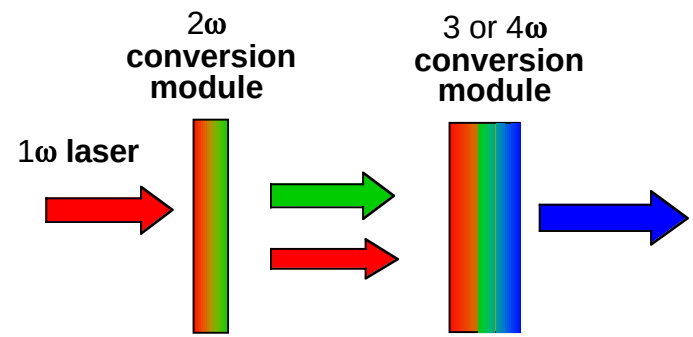
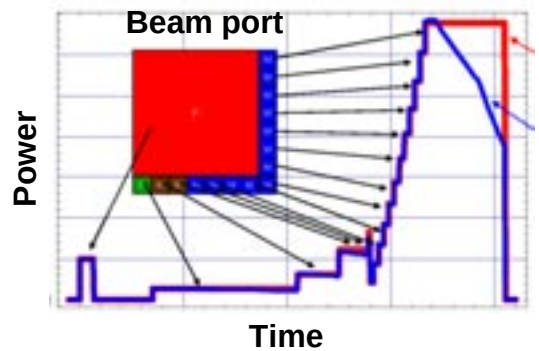
# We are Investigating the Systems Issues for Direct Drive Targets with DPSSL Drivers

- We are updating our DPSSL design for: (a) systems design integration (laser/chamber/target), (b) calibrating our systems models, and (c) future integrated power plant study
- We seek the optimum laser frequency in the range 1ω → 4ω by optimizing target and driver performance
- We are developing design concepts for beam delivery (final optics, beam segmentation, no. beams….) that meet target requirements (energy, pulse shape, smoothing, zooming…)
- A near-term step will be to update laser architecture and cost scaling



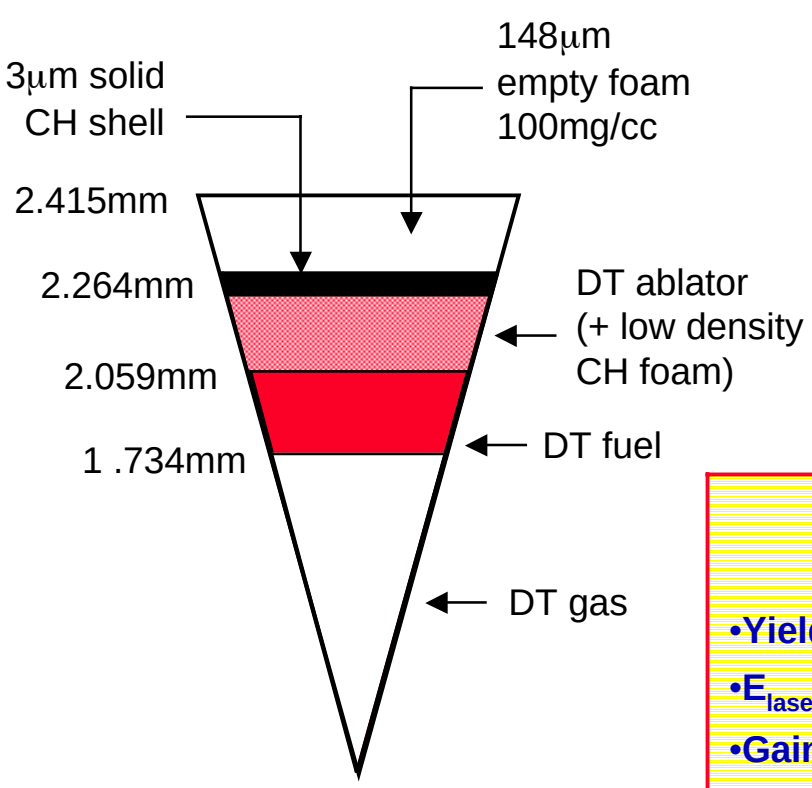
# What is The Optimum λ for DPSSL-Driven Targets?

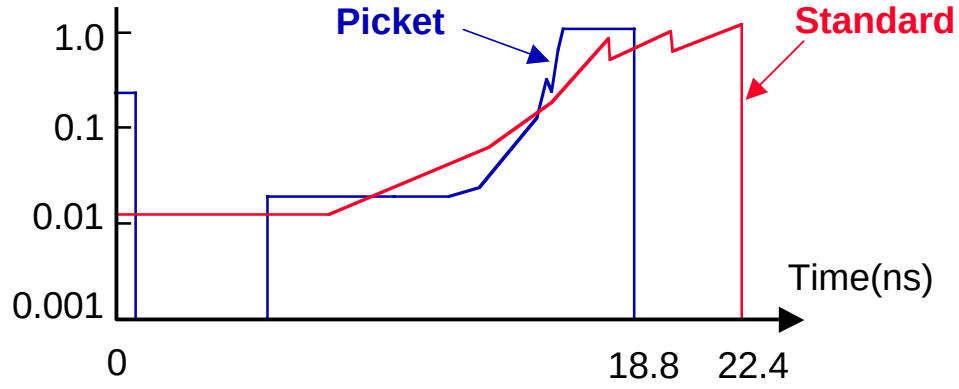
| | 1ω | 2ω | 3ω | 4ω |
|---|---|---|---|---|
| λ(μm) | 1.05 | 0.53 | 0.35 | 0.26 |

- Target gain……..
- Imprint (standoff, bandwidth)……...
- Laser-plasma interactions……..
- Target stability……..
- Laser efficiency (wallplug → target)….
- Optics damage/lifetime……
- Integration complexity……
- Systems optimum (COE?)……..

NB: KrF is at 0.25μm

# HAPL Direct Drive Target – Picket and Standard Pulse Shapes Trade Gain for Stability



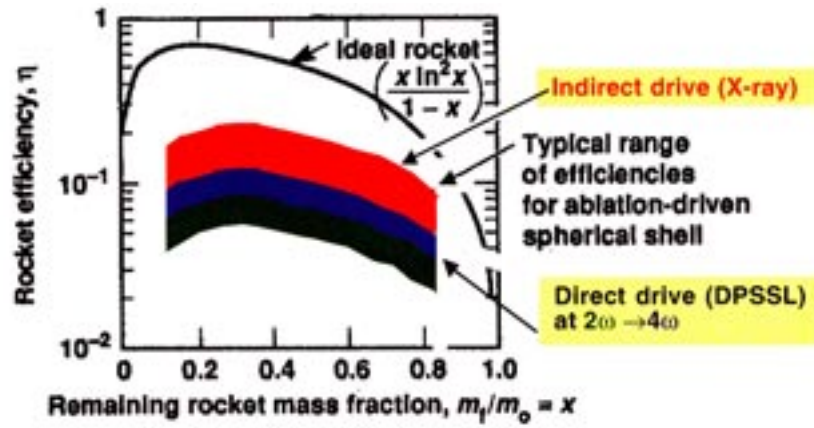




## KrF at 0.25μm (1ω)

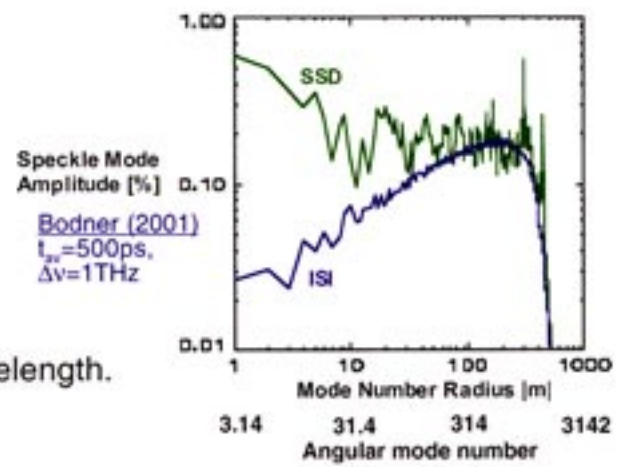
| | Picket | Standard |
|---|---|---|
| •Yield (MJ) | 343 | 384 |
| •$E_{laser}$ (MJ) | 2.94MJ | 2.44MJ |
| •Gain | 117 | 157 |
| •Max ρR (g/cm$^2$) | 2.22 | 2.86 |
| •Velocity | 3.25e7 | 2.99e7 |
| •In-flight adiabat $\alpha_{IF}$ | 2.31 | 1.65 |
| •Shell breakup fract | 0.15 | 1.8 |

# Target Physics Issues: DPSSLs and Increasing Wavelength

- **Higher ideal implosion velocity**
  - $V_{implosion} = V_{exhaust} \cdot \ln(m_f/m_i)$
  - $= P/(dm/dt) \cdot \ln(m_f/m_i) \sim (I\,\lambda^2)^{1/3} \cdot \ln(m_f/m_i)$
- **Lower coupling (rocket) efficiency**
  - Laser energy is deposited in target corona at $n \leq n_{crit} \sim 1/\lambda^2$ So greater solid angle and less collisional plasma

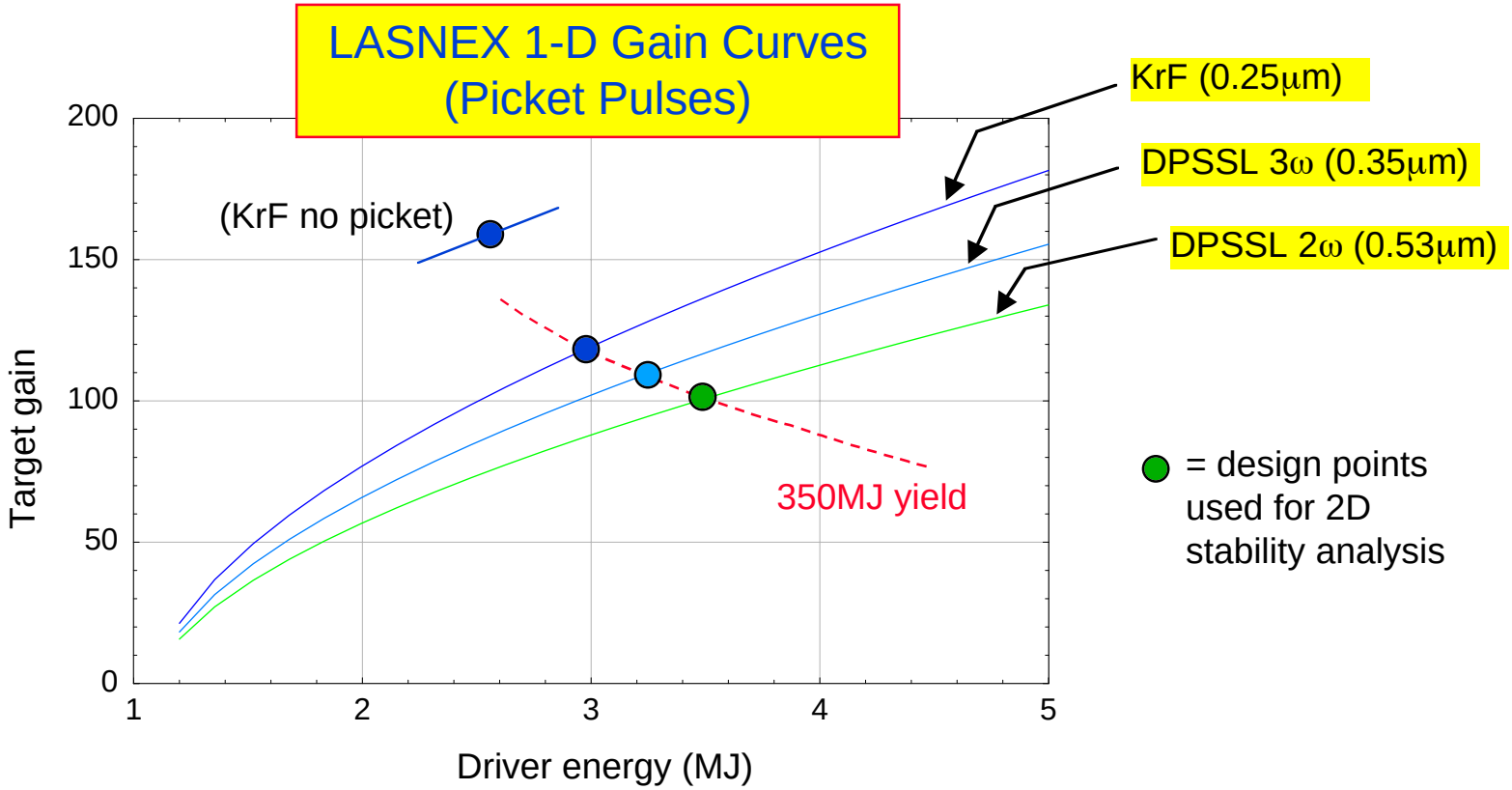



- **Lower ablation velocity for stability**
  - $V_{ablation} = (dm/dt)/\rho \sim \alpha^{3/5}\, I^{-1/15}\, \lambda^{-14/15}$
- **What about beam-smoothing and imprint?**
  - KrF uses ISI
  - DPPSLs can only use SSD
  - But greater standoff (smoothing) at longer wavelength.

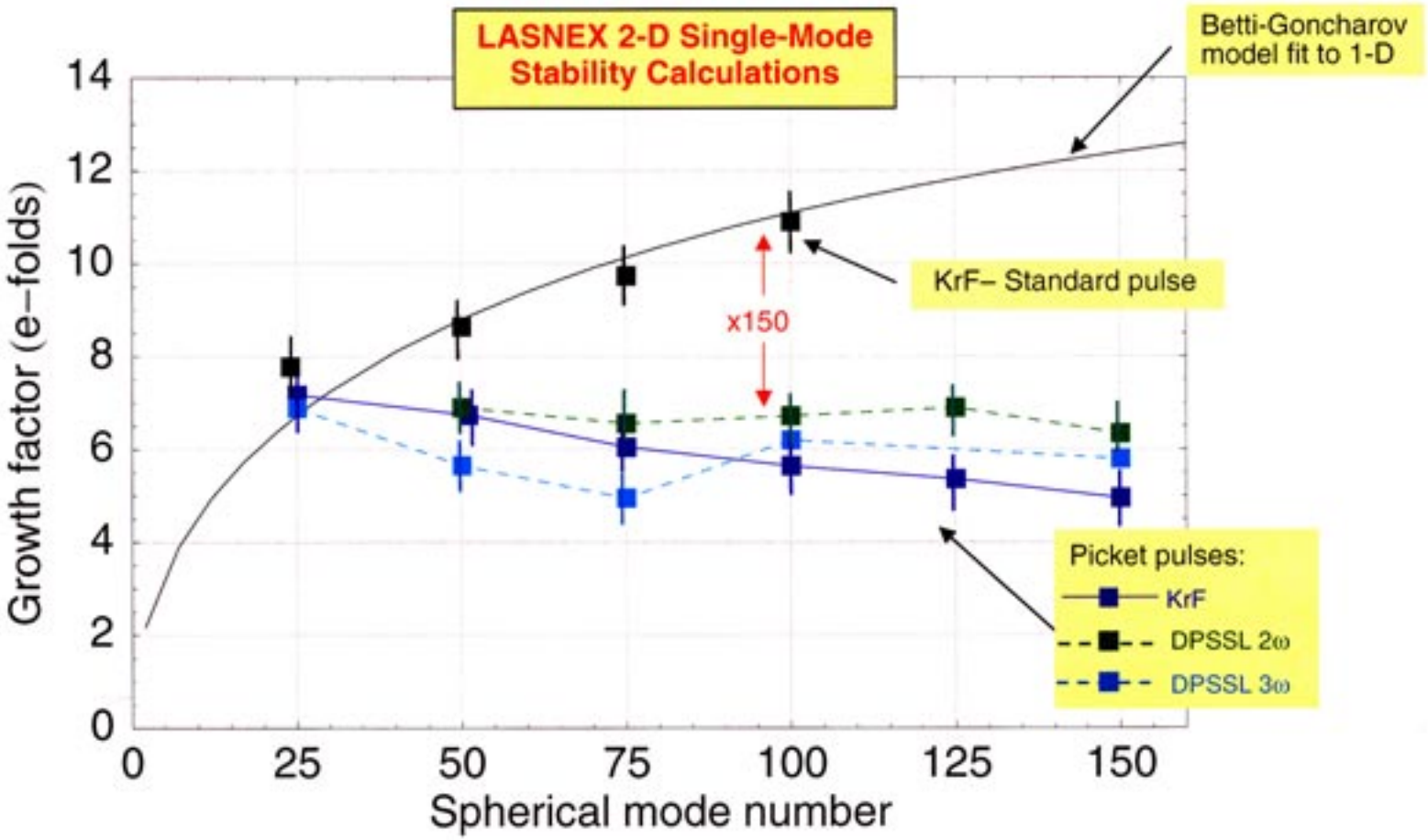



LJP LLNL 10/20/04

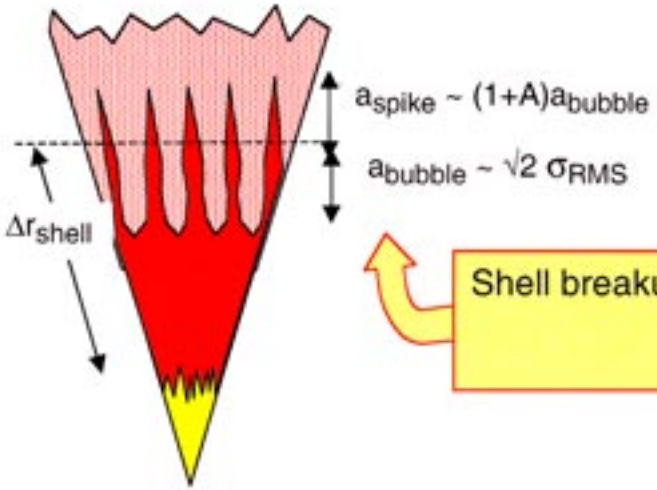
# Gain Decreases with Increasing Wavelength



# 2D R-T Growth: There is Less Ablation Velocity Stabilization at Longer Wavelengths



# Shell Breakup at Late Time is Probably Acceptable for DPSSL @ 2ω; Imprint Must be Addressed




Shell breakup fraction = $a_{bubble} / \Delta r_{shell}$
Require $\leq 30\%$

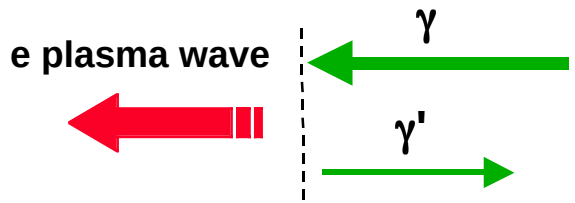
| Pulse Shape | Laser (MJ) | Yield (MJ) | Gain | Max Shell Breakup Fraction | |
|---|---|---|---|---|---|
| | | | | Roughness Only | Roughness + Imprint |
| Standard KrF | 2.4 | 380 | 160 | 0.83 | 1.83 |
| Picket KrF | 2.9 | 340 | 120 | 0.015 | 0.15 |

DPSSL @ 2ω is probably comparable to picket KrF

# Laser Plasma Instabilities are a Concern at Longer Wavelength

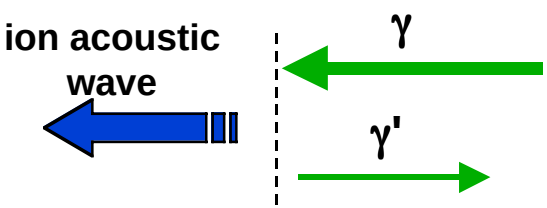
- Stimulated Raman Scattering (SRS)

  $I_{threshold} \sim 40 / (L_\rho \lambda)$



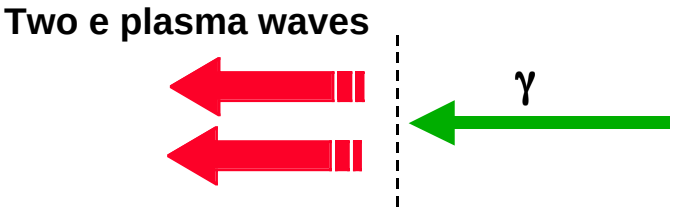

- Stimulated Brillouin Scattering (SBS)

  $I_{threshold} \sim 1.7T_e(n_c/n) / (L_v \lambda)$



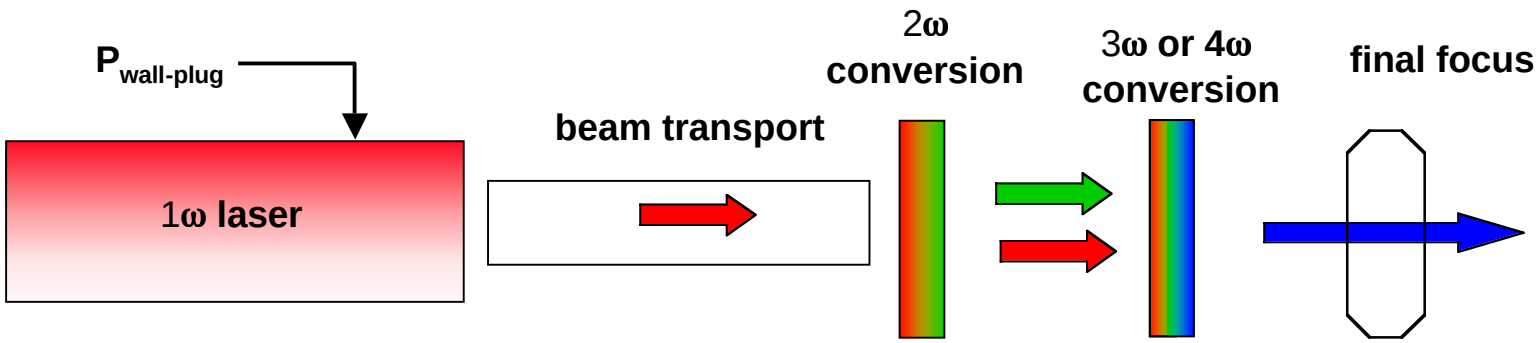

- Two-Plasmon Decay (TPD)

  $I_{threshold} \sim 0.54T_e / (L_\rho \lambda)$




- These cause:
  - Suprathermal electrons that preheat fuel (SRS, TPD)
  - Reduced efficiency due to scattered light (SRS, SBS)
  - Filamentation resulting in intensity peaking ⇒ instabilities (all)
  - Net result is $I_{threshold} \sim 1 / \lambda^{1.7}$ so factor of ~2 lower for $3\omega \rightarrow 2\omega$

# The Laser System Gets Harder at Higher Frequency




## Freq. Conversion Efficiency

| | |
|---|---|
| 1 ω | 100% |
| 2 ω | ~90% |
| 3 ω | ~80% |
| 4 ω | ≤80% |

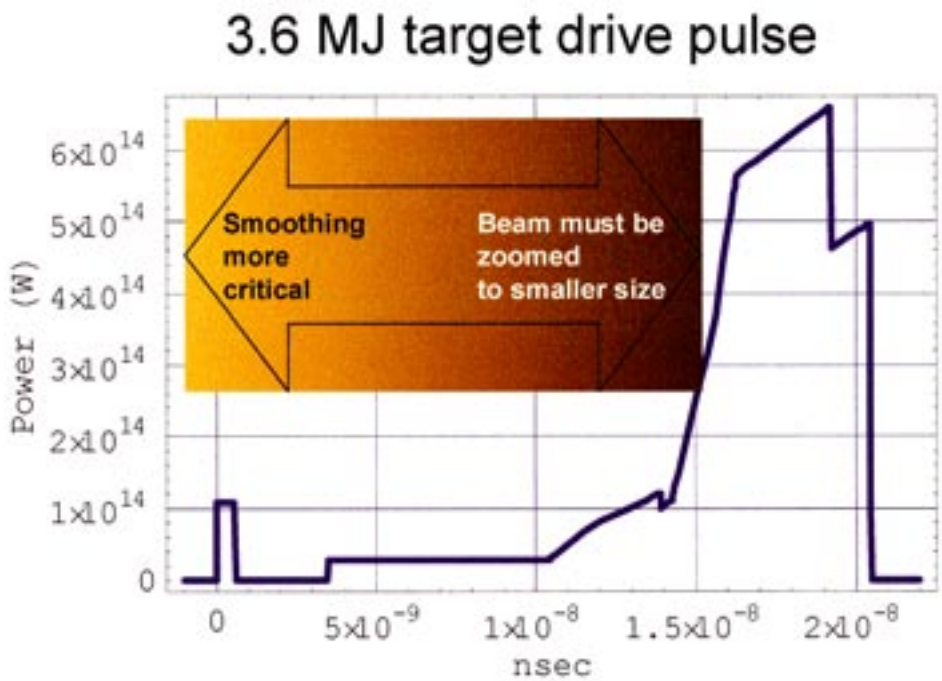
NB: For ideal square pulse but these constitute our pulse shape!

## Damage Growth Threshold

| | |
|---|---|
| 2 ω | ~15 J/cm$^2$ |
| 3 ω | ~5 J/cm$^2$ |

# We Are Investigating the Construction of a Drive Pulse Using "Port Bundles"

Proposed 2ω drive pulse



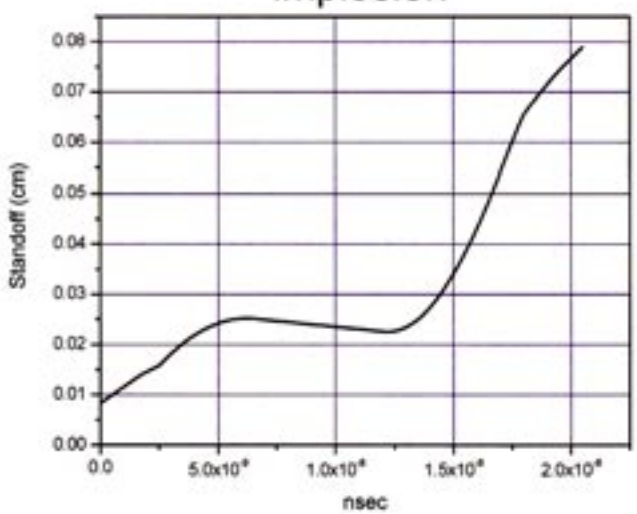

- Target considerations:
  - Beam smoothing through speckle averaging is required to eliminate laser imprint
  - Dynamic zooming of laser spot to follow imploding target is required for efficient utilization of laser energy
- Chamber considerations:
  - Minimization of solid angle dedicated to laser ports is desired to minimize neutron leakage and achieve adequate tritium breeding

# Imprint Smoothing Imposes a Limit on the Product of Illumination Sold Angle and Laser Bandwidth

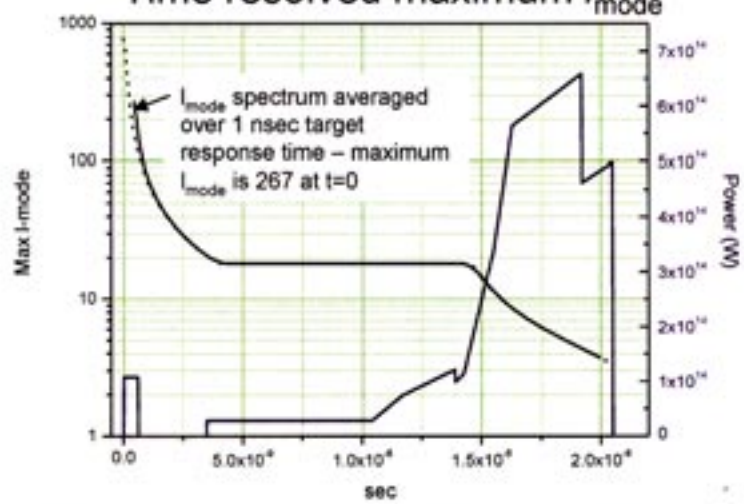
"… low spatial frequency speckle relevant to direct drive is fundamentally determined by the product of the optical bandwidth and the illumination solid angle," – Josh Rothenberg

$$\sigma_{tot}^2 = \frac{1}{(\Delta\nu\cdot\tau)\Delta\Omega_{tot}\left(d_{targ}/\lambda\ell_{\substack{\text{mode}\\ \text{max}}}\right)^2(\pi/2)}$$

Standoff for 0.48 cm diameter target implosion



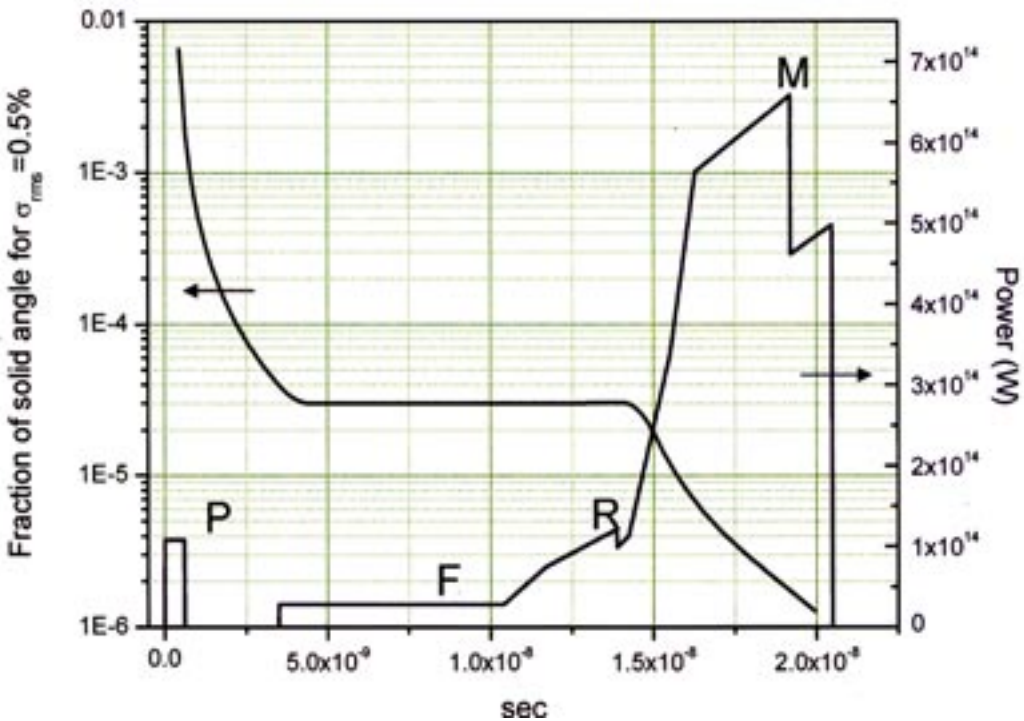

Time resolved maximum $l_{mode}$




$k_{imprint}\cdot d_{standoff} > 2$ or $l_{mode} > 2r_{critical}/d_{standoff}$ – condition for coronal thermal smoothing of laser imprint where $d_{standoff}$ is distance between ablation front and critical radius

# Solid Angle Fraction Needed to Achieve 0.5% $\sigma_{rms}$ Between l=0 and Max l-Mode that Impacts Imprint

$$\Delta\Omega_{tot} = \frac{1}{(\Delta\nu\cdot\tau)\left(\sigma^2_{\substack{tot \\ \ell=0-\ell_{max}}}\right)\left(d_{targ}/\lambda\ell_{\substack{\text{mode} \\ \text{max}}}\right)^2(\pi/2)}$$

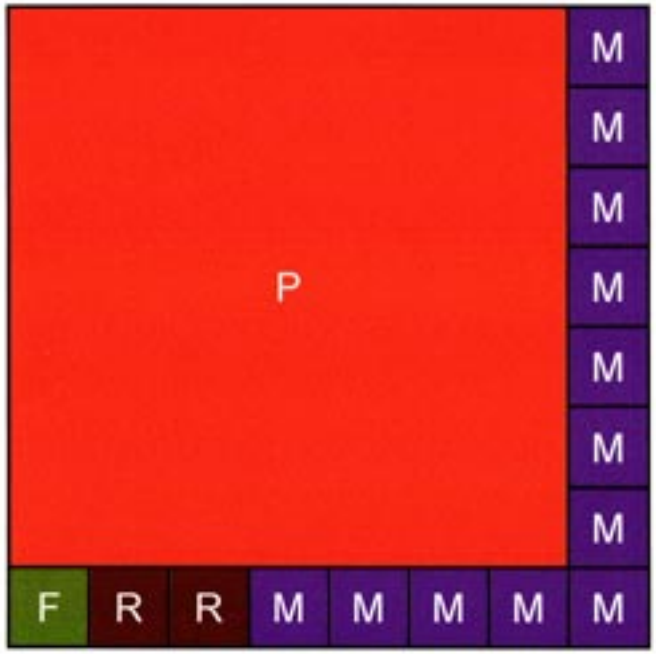



- Target integration time, $\tau$, is 1 nsec
- $d_{targ}$ ~ 4.8 mm
- $\lambda$ = 523.5 nm
- $\Delta\nu_{2\omega}$ = 300 GHz
- $\sigma_{tot}$ = 0.5%

The earliest portion of the pulse, the picket, requires the largest solid angle to achieve smoothing (~1% of 4$\pi$)

# Because Target is Most Susceptible to Imprint at Early Times, Picket Requires Largest Port Bundle Area

Single aperture at 20 m from target

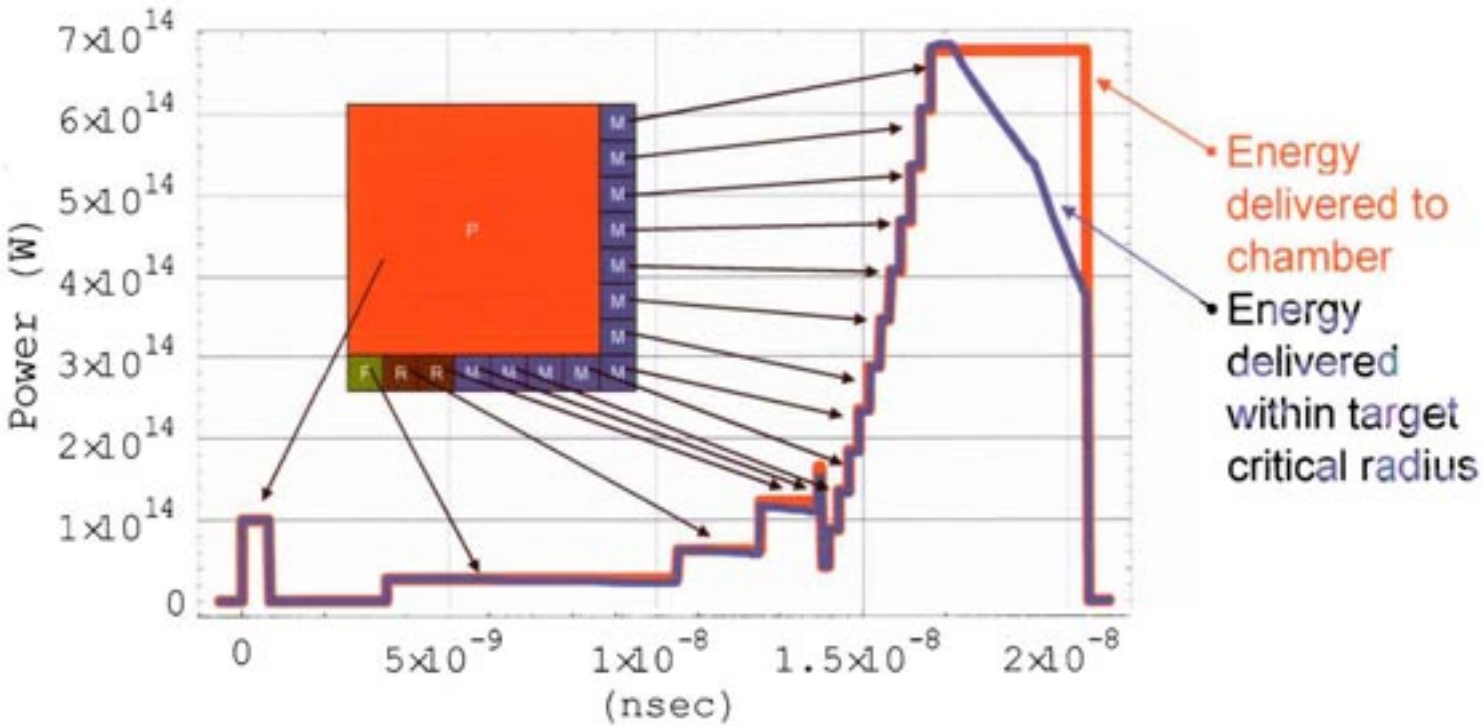



- Each of the 16 aperture sources ~2.6 $kJ_{2\omega}$
- Picket aperture is 72 cm x 72 cm
  $\Delta\Omega/4\pi$ = 0.99%
- All other apertures are 10.3 cm x 10.3 cm
  $\Delta\Omega/4\pi$ = 0.3%
- Total solid angle dedicated to ports is 1.3%:

$$\frac{\Delta\Omega_{total}}{4\pi} = \frac{N_{ports} A_{port}}{4\pi r^2} = \frac{96(72cm + 10.3cm)^2}{4\pi(2000cm)^2} = 0.013\,(1.3\%)$$

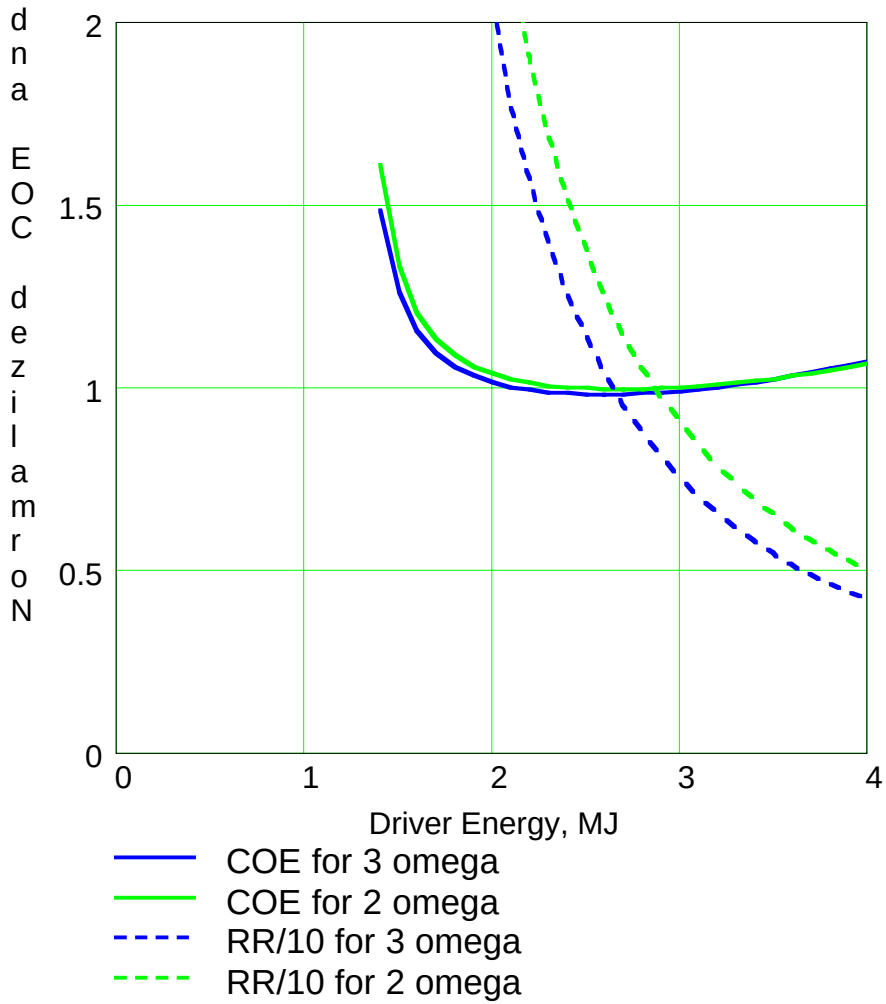
- 10.3 cm beam aperture is consistent with 20 m standoff of final optic, 5 TDL beam, and ~4.8 mm target size
- Spot size at target with 5 TDL beam: $d_{target} = \frac{F\lambda}{d_{beam}} TDL = \frac{20x10^3 mm \cdot 0.5235\mu m}{10.3x10^4 \mu m} 5 = 0.51mm$

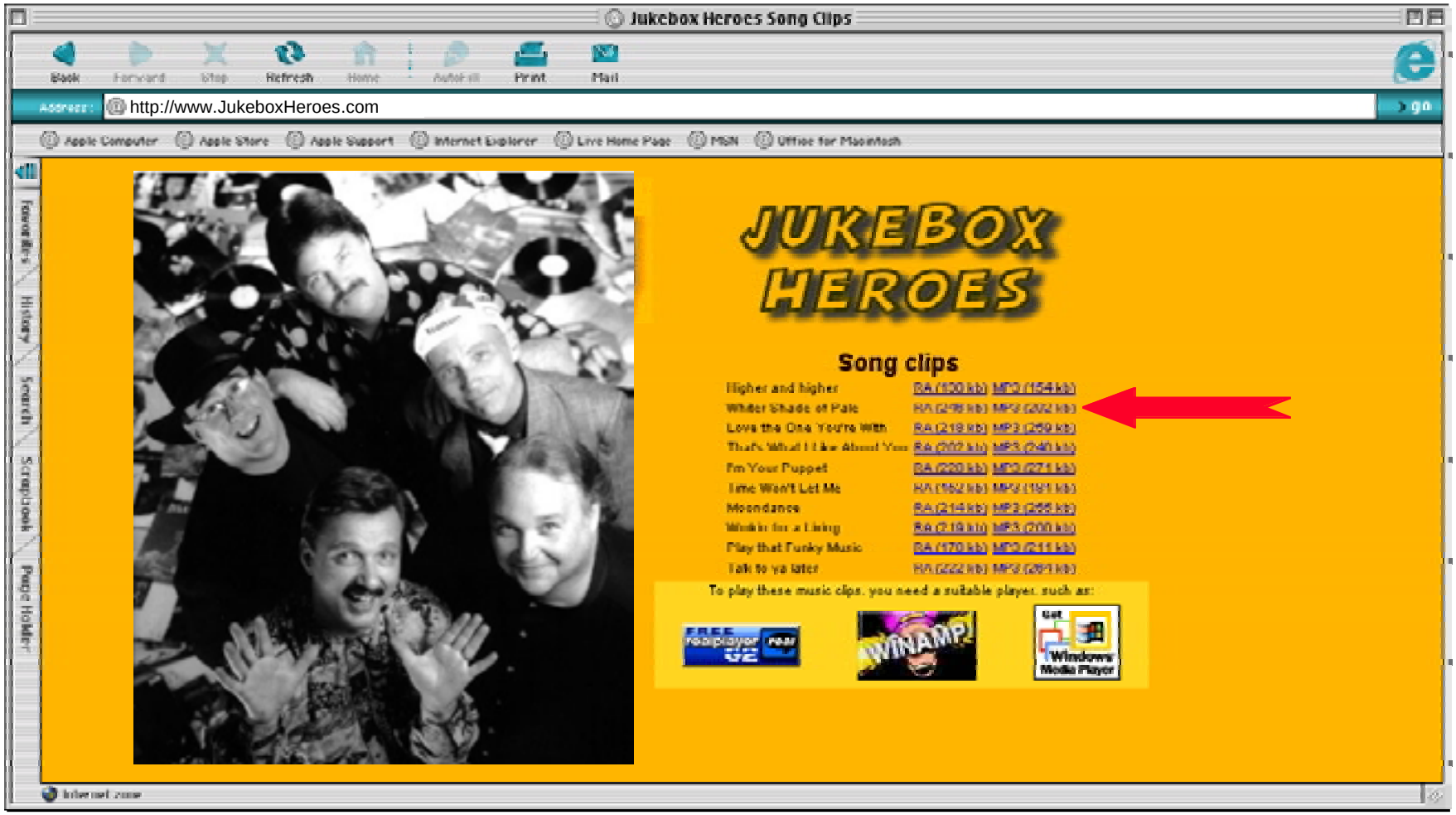
# Pulse Construction from Port Bundles Uses Only Rectangular Pulses (→ High Harmonic Conv. Efficiency)




- Total Pulse Energy = 4.02 MJ
- With zooming as shown, 3.55 MJ falls within time resolved critical radius (88% of pulse energy)
- Without zooming, only 2.52 MJ falls within time resolved critical radius (63% of pulse energy)

# Preliminary Comparison Shows that COE with 2ω is About Same as with 3ω




- Net power = 1000 MWe
- Sombrero cost scaling for power plant
- Linear cost scaling for laser ( = $500/J, Orth study)
- No cost penalty for 3ω optics
- Laser efficiencies:
  - 9.5% for 2ω
  - 8.4% for 3ω

# A Whiter Shade of Green (Pale)