Direct-Drive Target Design: High Average Power Laser Program

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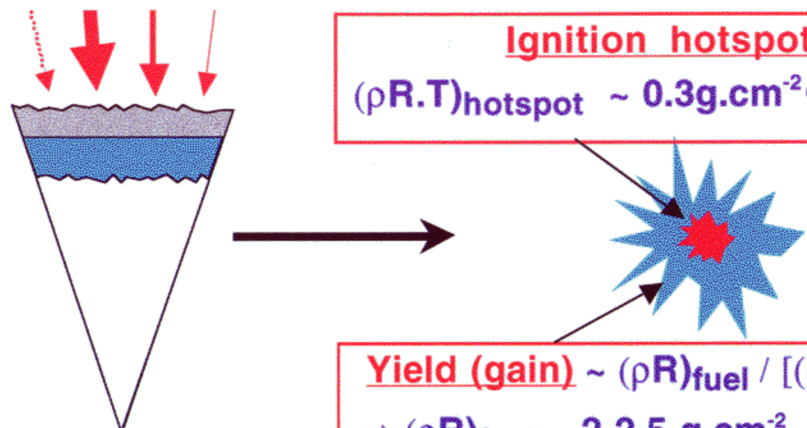
Critical Issues in the Design of A High Gain Direct-Drive Target for Inertial Fusion Energy

Laser-target coupling	⇐	*Beam geom., intensity, λ, ablator design (scale lengths)…*
Target isentrope control (ablator/fuel)	⇐	*Pulse shaping…*
Implosion symmetry (low modes)	⇐	*Beam geometry and balance…*
Implosion stability (higher modes)	⇐	*Laser imprint, inner/outer surface finish, target build, adiabat control, λ, …*
Ignition and propagating burn	⇐	*All of the above!*

High(er)-mode stability is (probably) the greatest source of uncertainty.

Success with high-gain direct-drive targets for IFE will depend fundamentally on our ability to achieve Rayleigh-Taylor stabilization



Ignition hotspot:

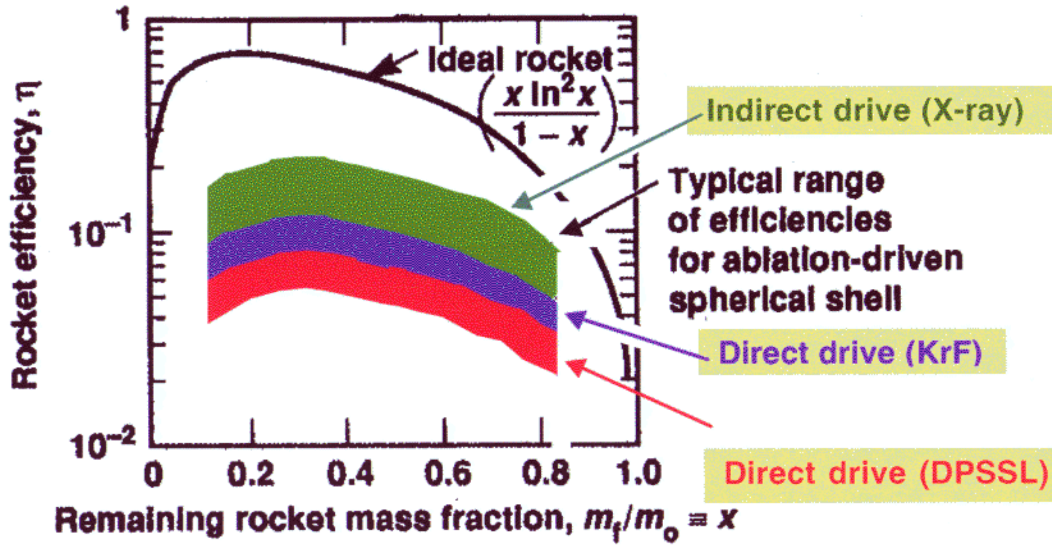
$(\rho \mathbf{R.T})_{\mathbf{hotspot}} \sim 0.3\,\mathrm{g.cm^{-2}}@12\,\mathrm{keV}$

Yield (gain) $\sim (\rho \mathbf{R})_{\mathbf{fuel}} / [(\rho \mathbf{R})_{\mathbf{fuel}} + 6]$

$\Rightarrow (\rho \mathbf{R})_{\mathbf{fuel}} \sim 2\text{-}2.5\ \mathrm{g.cm^{-2}}$

It's the Wavelength Stupid!
DPSSLs (0.349μm) –v– KrF (0.248μm)

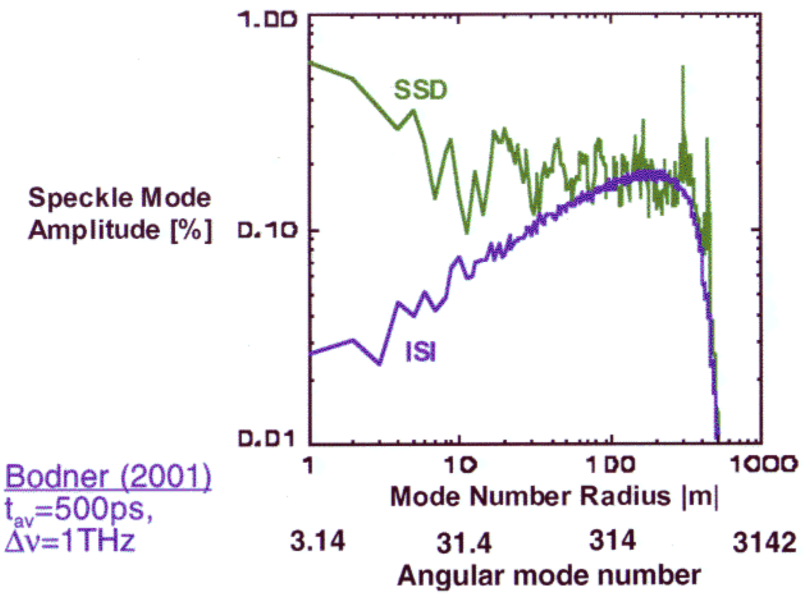
- **Higher ideal implosion velocity**
  - – $V_{implosion} = V_{exhaust} \bullet \ln(m_f/m_i)$
  $= P/(dm/dt) \bullet \ln(m_f/m_i) \sim (I\,\lambda^2)^{1/3} \bullet \ln(m_f/m_i)$



- **Lower coupling (rocket) efficiency**
  - Laser energy is deposited in target corona at $n \le n_{crit} \sim 1/\lambda^2$ So factor of ~2 lower critical density for DPSSLs

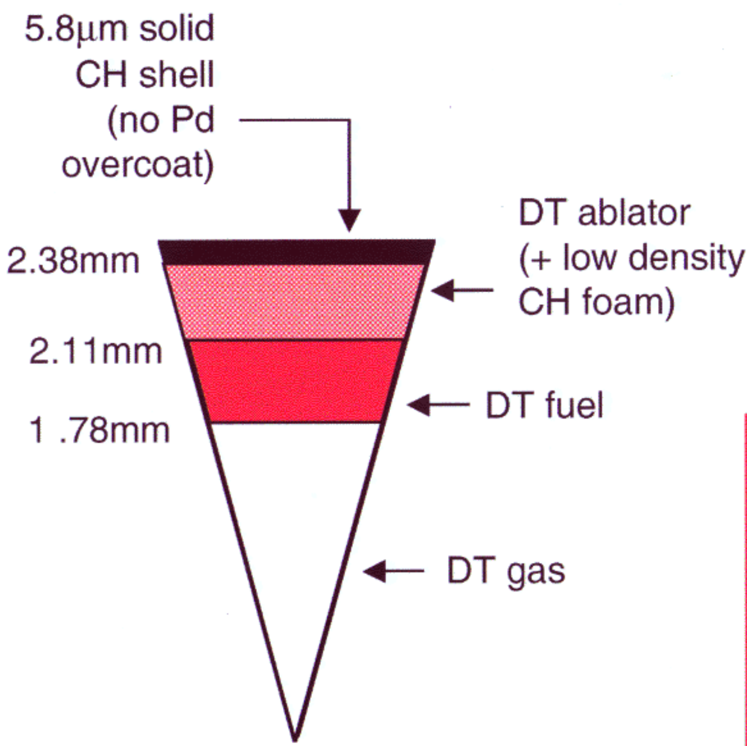
- **Lower ablation velocity for stability**
  - – $V_{ablation} = (dm/dt)/\rho \sim \alpha^{3/5}\, I^{-1/15}\, \lambda^{-14/15}$

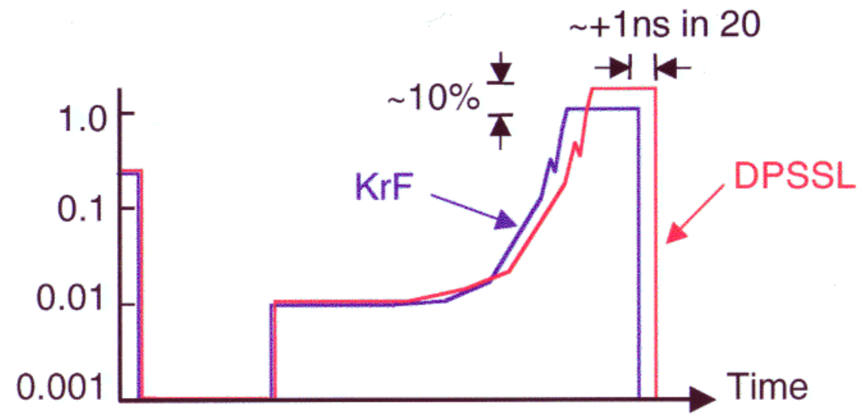
- **Less optimum (?) beam-smoothing**
  - DPPSLs use SSD
  - KrF can use either ISI or SSD



Bodner (2001)
t_{av}=500ps,
Δν=1THz

KrF and DPSSL Give Comparable 1-D Peformances within ~10%





	KrF	DPSSL
• λ	*0.248μm*	*0.349μm*
•Yield	*350MJ* ⟷	*350MJ*
•Timing	*0*	*~+0.8ns*
•E_{laser}	*2.9MJ*	*3.2MJ*
•Gain	*120*	*110*
•Max ρR	*2.11 g/cm²*	*2.18 g/cm²*
• KE margin	*31%*	*29%*
• Velocity	*3.30e7cm/s*	*3.16e7cm/s*

Pulse Shape Tailoring of the Adiabat Profile can Improve Stability without Compromising Ignition

- High gains and minimum drive energy for ignition require low fuel adiabats α *(Herrmann et al)*, where: $\alpha = P/P_{Fermi}$

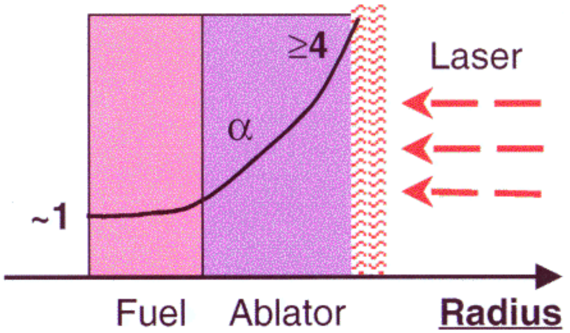
$$E_{ign} \sim \alpha^{1.8} v^{-6} P^{-0.8}$$

- But ablation velocity is a key factor in shell stability and increases with increasing adiabat

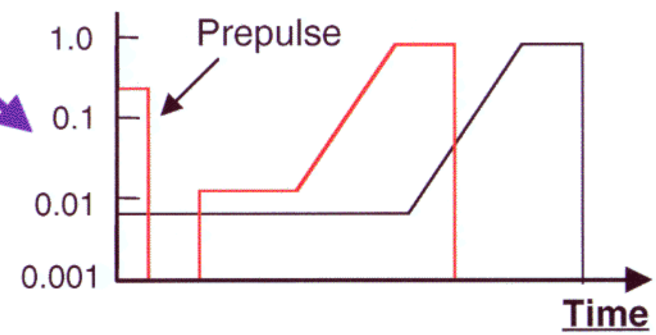
$$\gamma_{RT} \sim c_1\sqrt{Akg} - c_2 k V_A$$

$$V_A \sim \frac{\dot{m}}{\rho} \sim \alpha^{3/5} I_{laser}^{-1/15}$$

- Tailoring the adiabat profile through the fuel and ablator can improve stability without compromising ignition and high gain



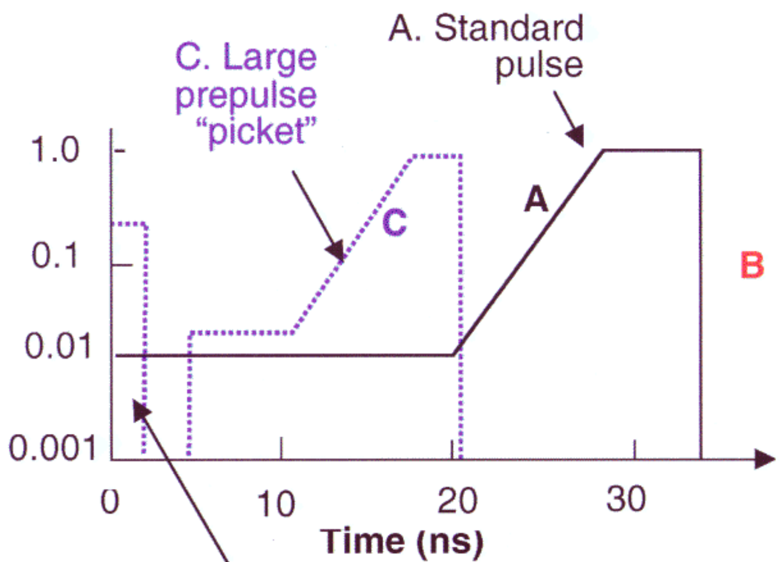
- Adiabat tailoring is achieved by a picket “stake” pulse – low energy prepulse with main pulse separated by power shut-off (*Lindl, Verdon, Betti*)



- Adiabat shaping may also be achievable with radiation preheat (*Bodner*)

Decaying Shock from Prepulse Produces High Ablator Adiabat while Maintaining Low Fuel Adiabat

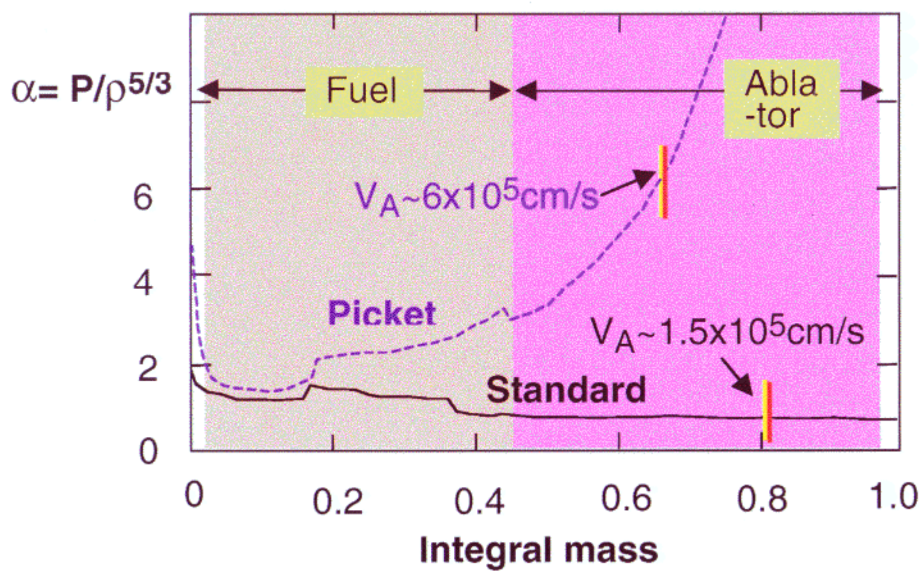
Laser Pulse Shape Power



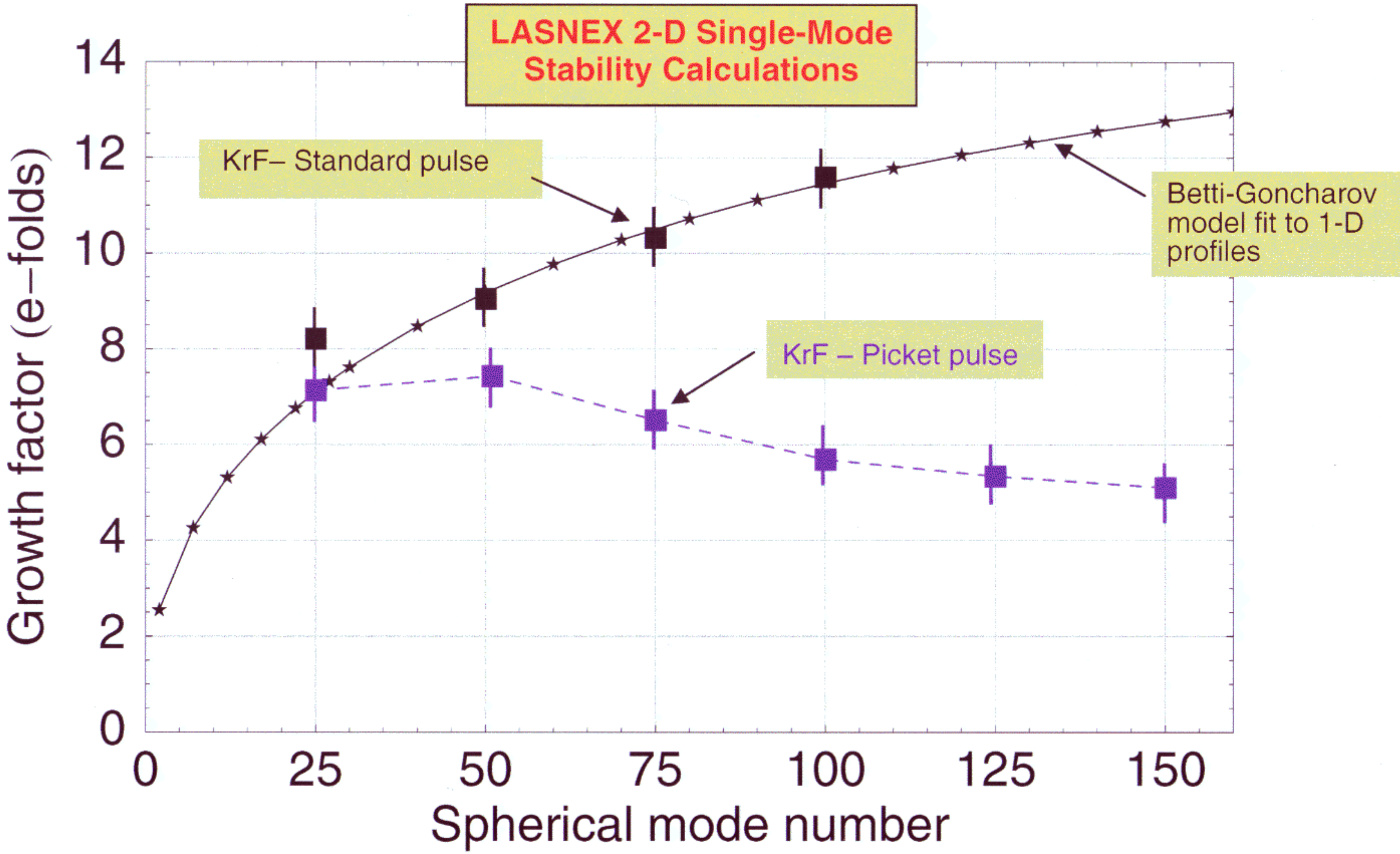
Picket Prepulse:

Power Fraction	Energy Fraction
20%	2.1%

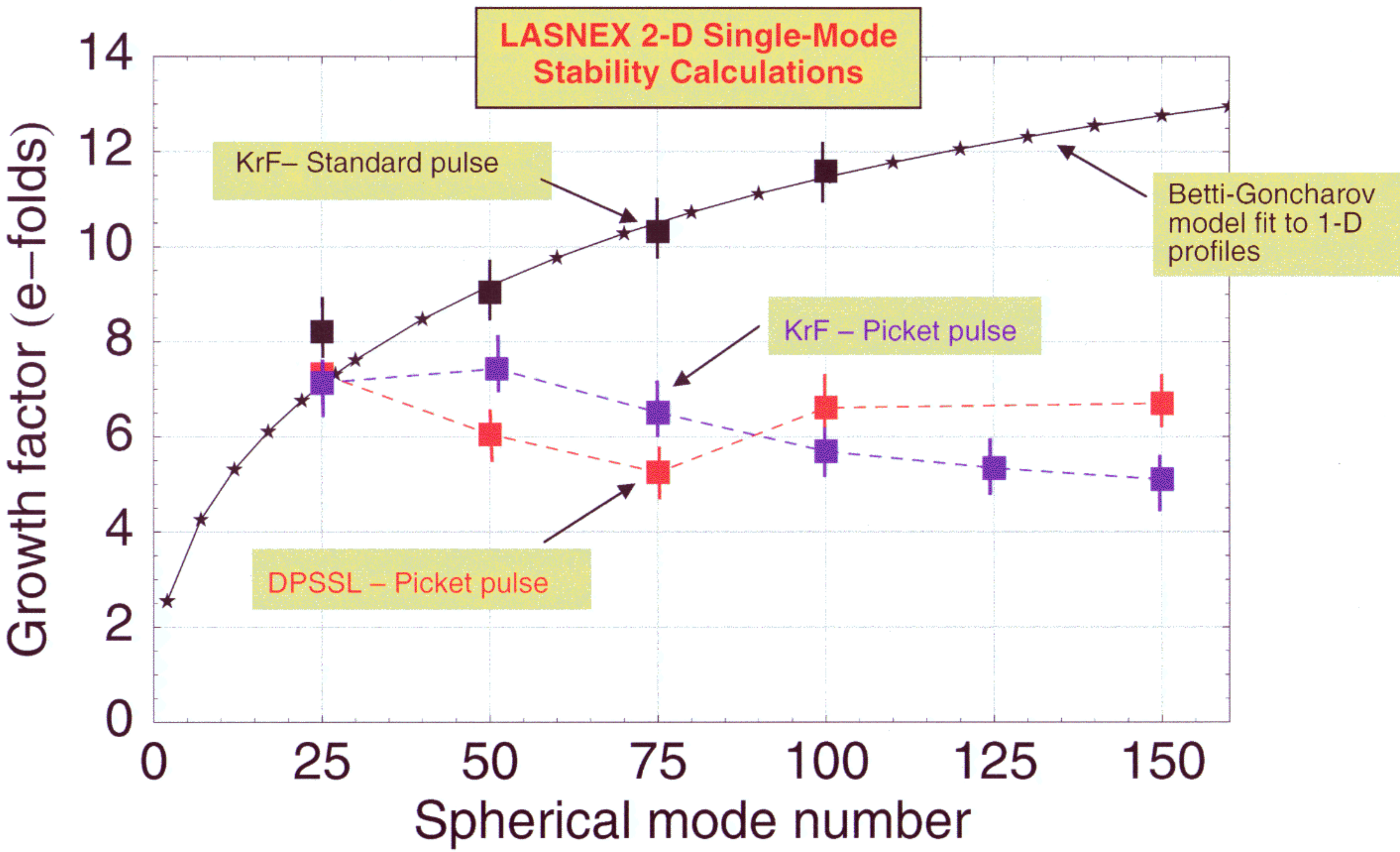
Adiabat Profile at Time of ~30% Peak Drive Power



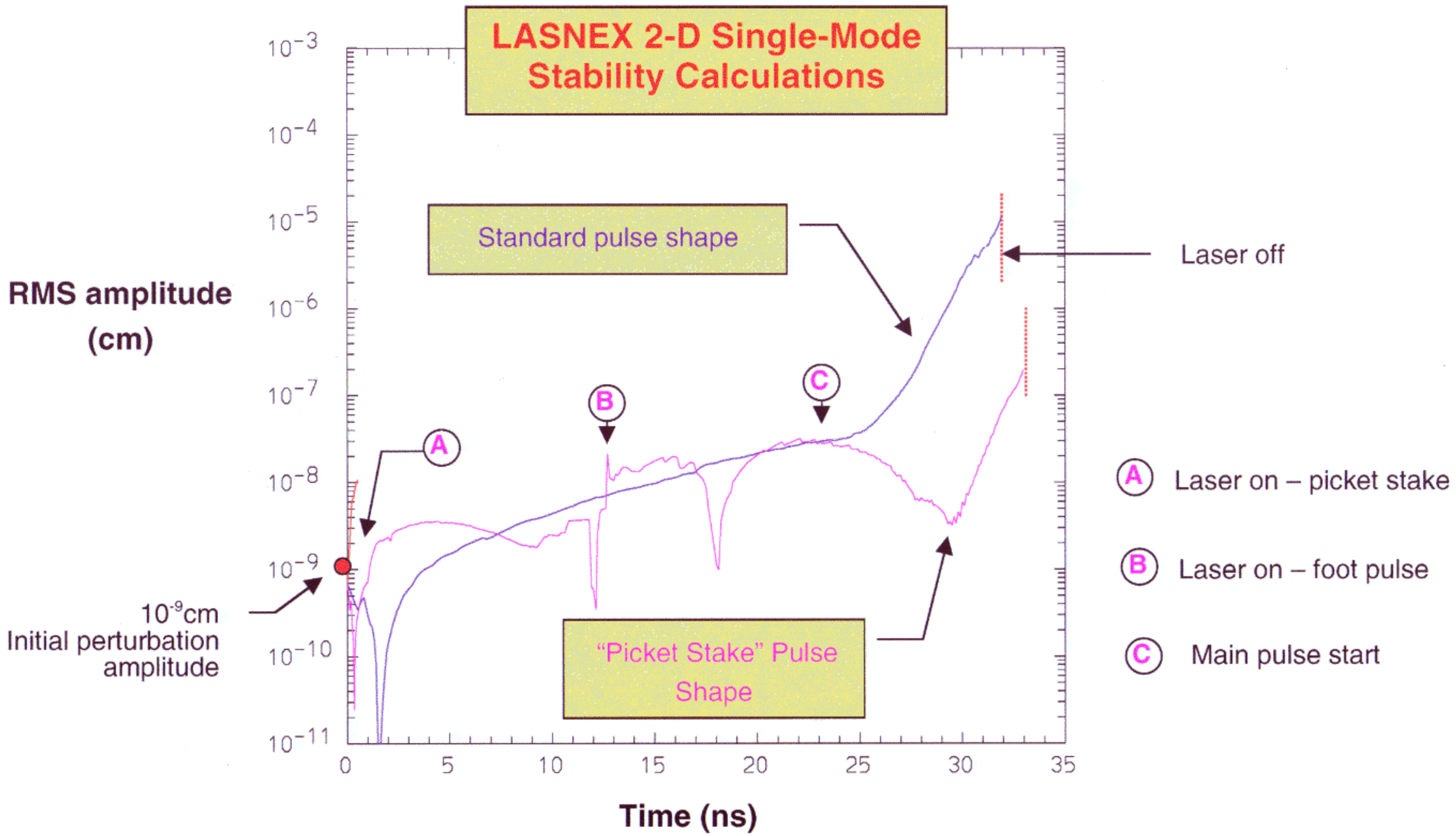
Shaping the KrF Laser Pulse Offers Large Improvements in Stability for the Same Direct Drive Target



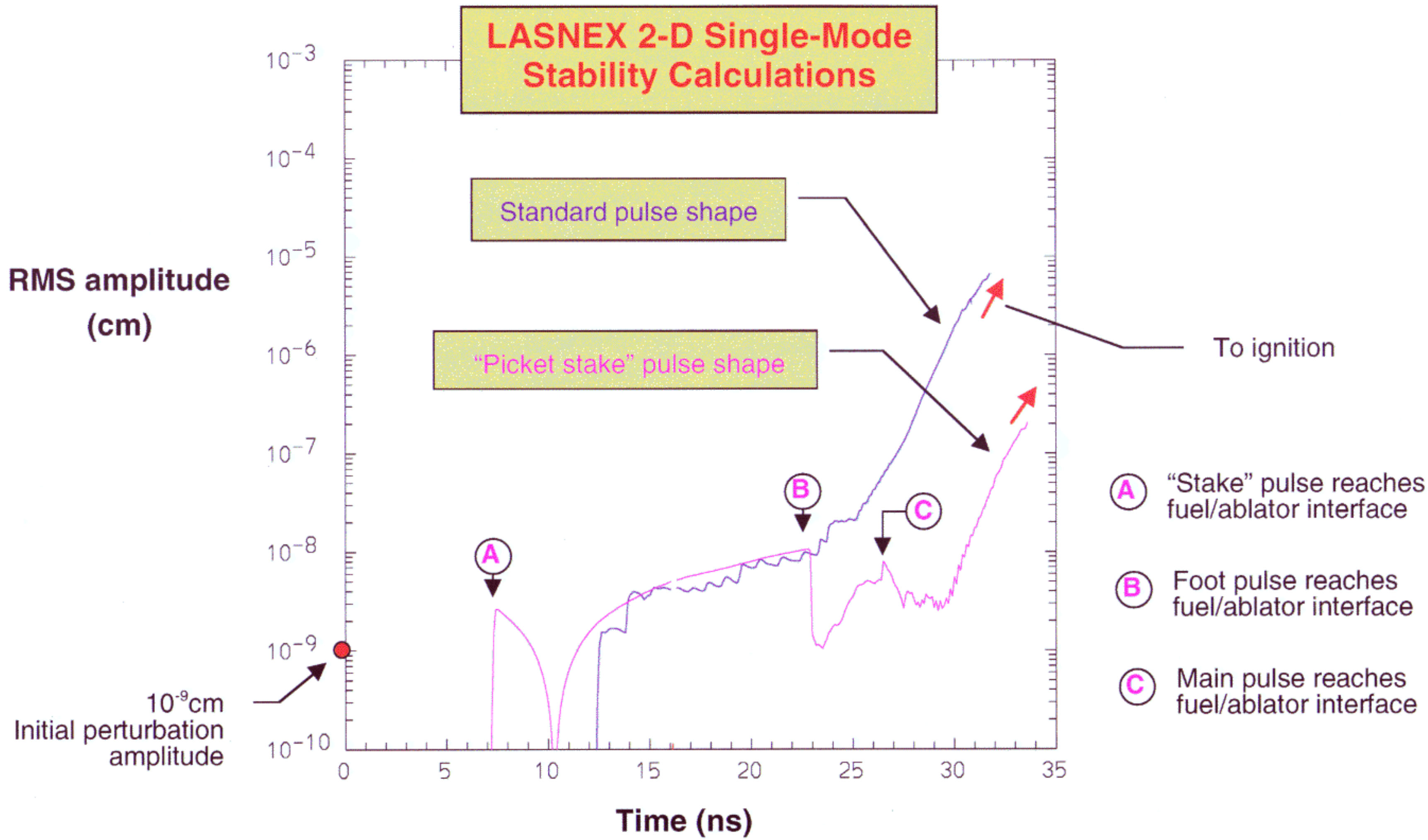
KrF and DPSSL Picket Pulses Give Comparable Stability.



Instability Growth at the Ablation Front @ $\ell = 50$ – Note Multiple Shock Behavior of Amplitude Growth for Picket Pulse



Instability Growth at the Fuel/Abl Interface @ $\ell = 50$ – Note Multiple Shock Behavior of Amplitude Growth for Picket Pulse

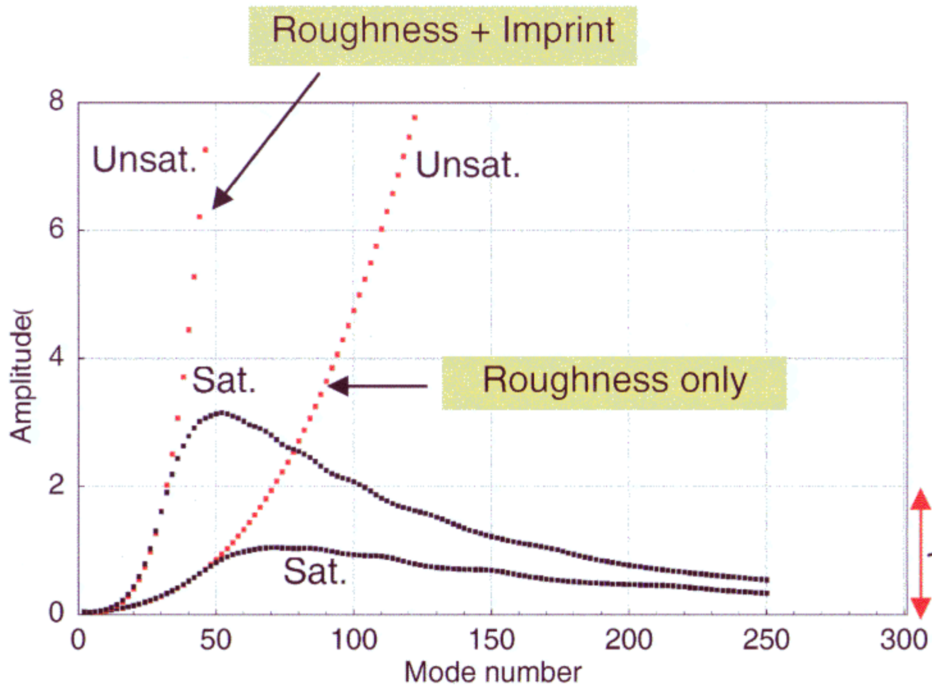


Instability Growths for Tailored Adiabat Capsules are Less Sensitive to Assumptions of Saturation Models

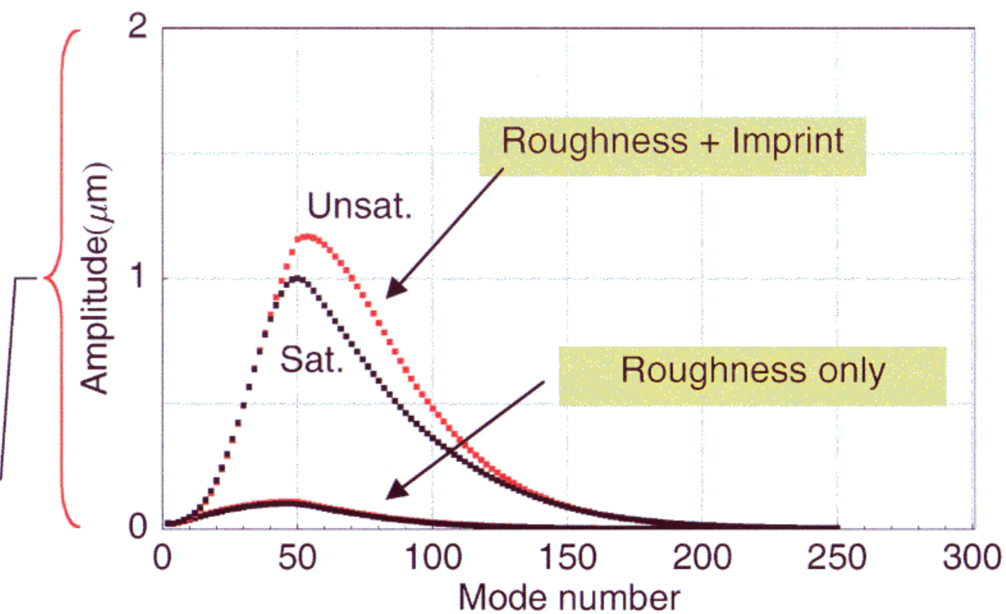
Haan saturation model:

$$a(t_{final},l) = \underbrace{a_0(l)\ Exp[\int_{t=0}^{t=t_{sat}}\gamma(t,l)dt]}_{\text{Exponential growth to saturation}}\ \underbrace{(1 + \int_{t=t_{sat}}^{t=t_{final}}\gamma(t,l)dt)}_{\text{Linear (with time) growth after saturation}}$$

where $t = t_{sat}$ when $a(t_{sat}, l) = C_{Haan}\lambda/(2\pi l)$

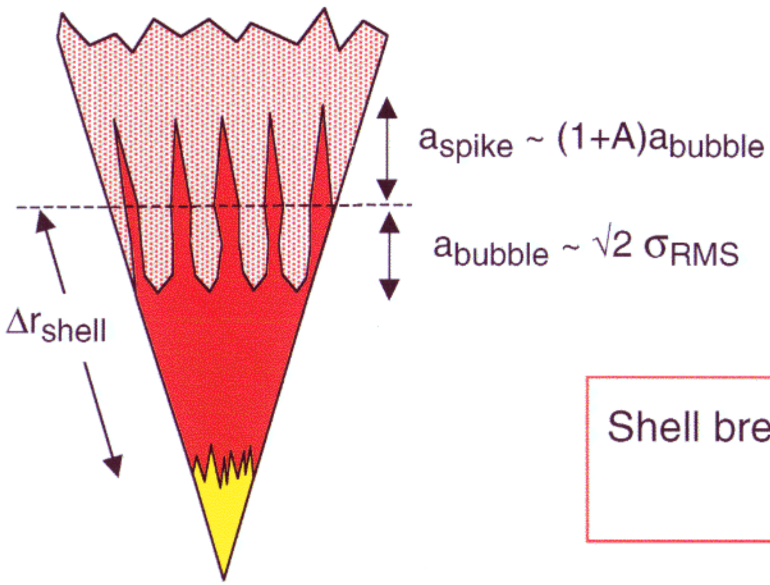


A. Standard Pulse Shape



C. Large Prepulse

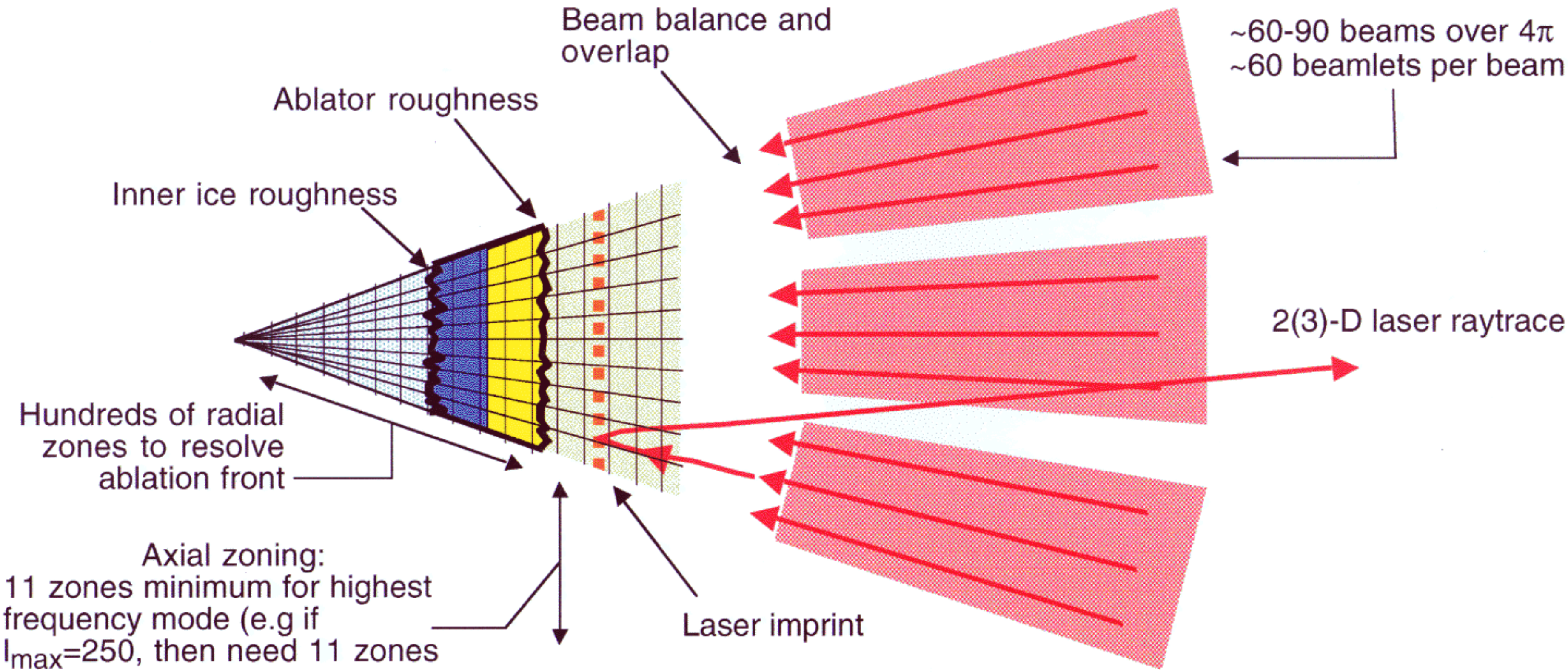
Resulting Shell Breakup Fraction at Late Time is Modest for the Tailored Adiabat Case



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
A. Standard	2.4	430	180	0.83	1.83
C. Large prepulse (large "picket")	3.1	360	110	0.015	0.15

No One has Yet Performed a Full, End-to-End, 2(3)-D Multimode Implosion with Real 2(3)-D Beams



Axial zoning:

- 11 zones minimum for highest frequency mode (e.g if l_{max}=250, then need 11 zones over 0.72°)
- But wedge angle must accommodate λ/2 for lowest frequency mode (e.g if l_{min}=5, then need 36° wedge angle)

This example would need

- ~550 axial zones,
- ≥500 radial zones
- ≥275,000 zones total
- ≥5500 rays (≥10per axial zone)
- Weeks of Lasnex run time