Laser-matter interactions confined in small high aspect ratio holes

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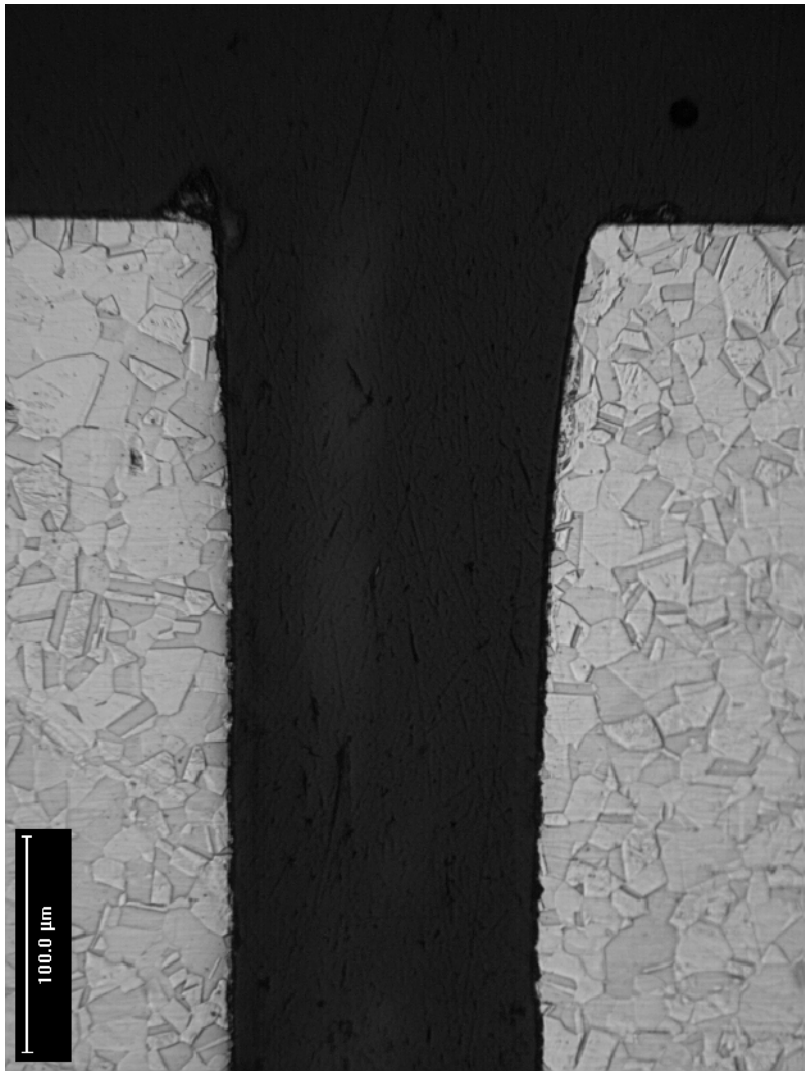
GENERAL ATOMICS

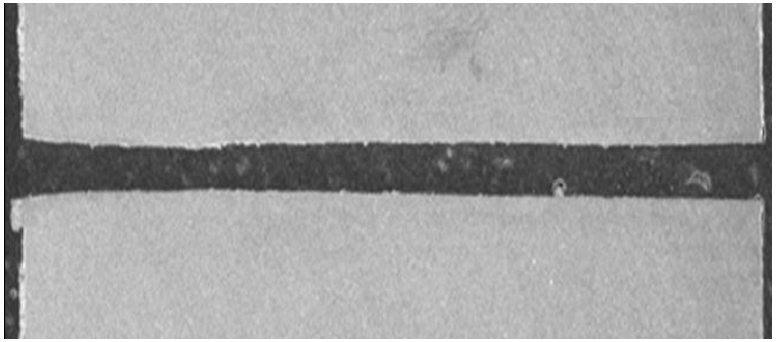
Organization of Presentation

- **Small high aspect ratio holes**
  - 5 μm < diameter < 50 μm
  - 20 < H < 80
    - Diesel fuel injectors
    - ICF capsules
- **Basic drilling technique**
  - Nanosecond double pulse
  - Simple optics
- **Limiting processes**
  - Hot plasmas
  - Plasma confinement
    - Pseudo 1-D experiments ?
  - Optical confinement
  - Redeposition and debris
- **Conclusions**
  - Combined processes limit aspect ratio
  - It's the plasma that matters, not just the lasers and the lenses.
  - Limiting processes can shape holes.



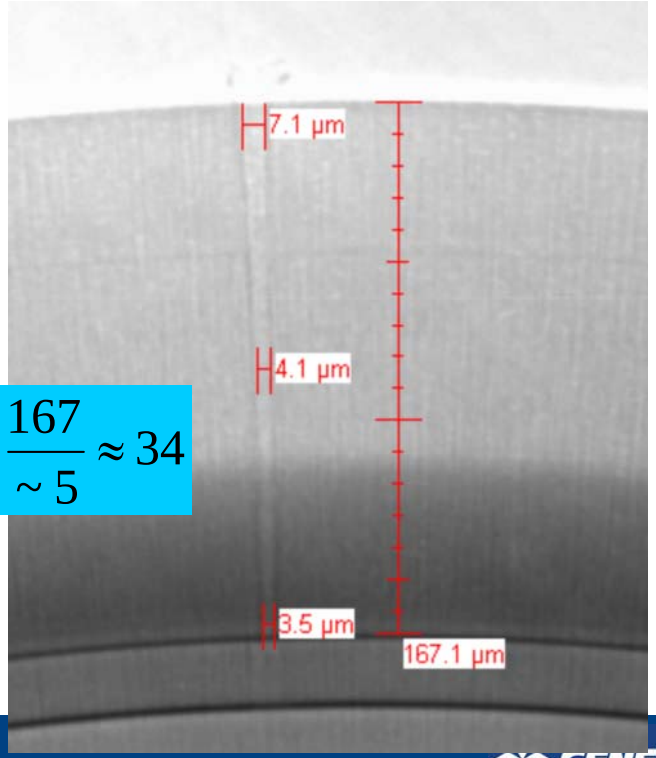
Fuel injectors and fill holes in ICF capsules are only 2 of many applications for small high aspect ratio holes.

- **Hot plasma and laser-matter interaction plays a key role.**



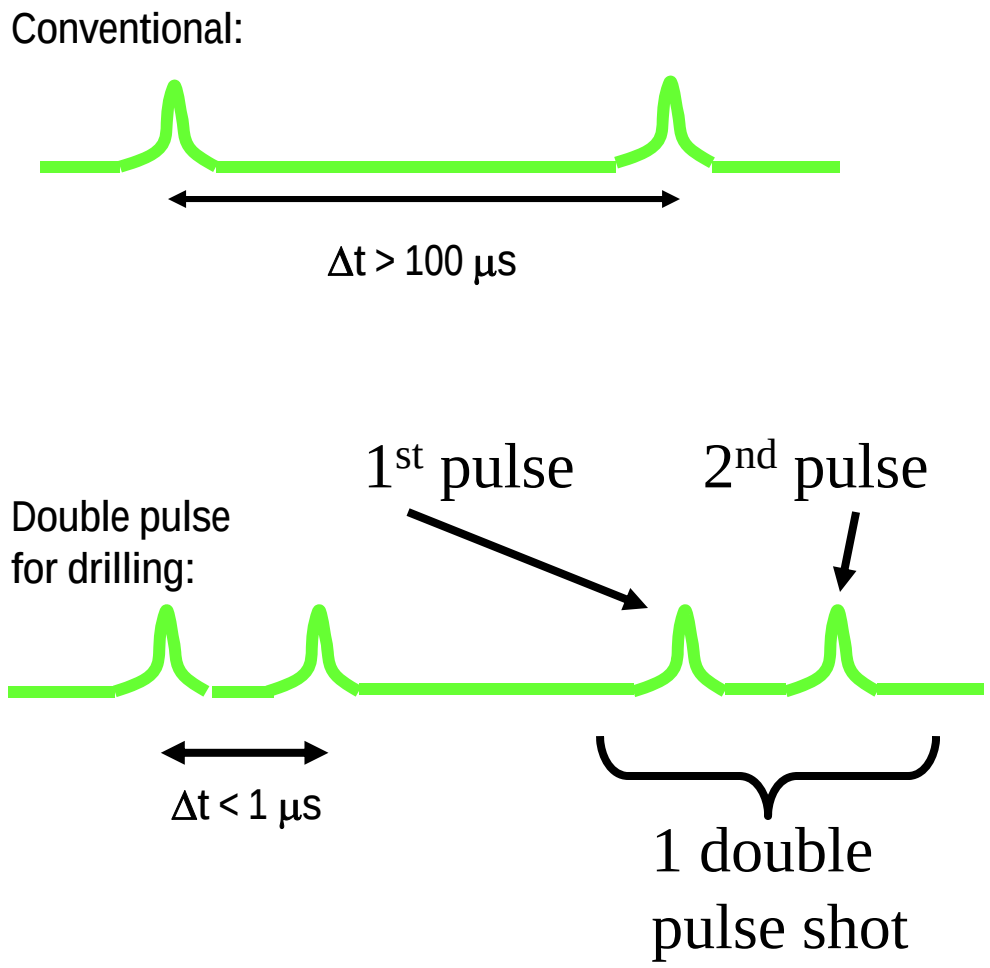
- **Diesel fuel injectors**
  - 50 μm diameter
  - > 1 mm length
  - Tool steel
  - Precision and metallurgical requirements
- **ICF capsule fill holes**
  - 5 μm diameter
  - ~200 μm length
  - Optical waveguides
  - Need to be clean

$$H = \frac{L}{d} = \frac{167}{\sim 5} \approx 34$$



The basic drilling technique is a double pulse format implemented using nanosecond lasers.

- **Substantial effort is often made to reduce laser-plasma interaction**
  - Femtosecond lasers
  - Gas assist jets
- **Double pulse format uses ablation products.**
- **Improvement in the speed and quality of percussion drilling makes this technique a good choice for the production and study of LMI in small high aspect ratio holes.**



Why use double pulse ?

Double pulse machining improves the speed of percussion drilling.

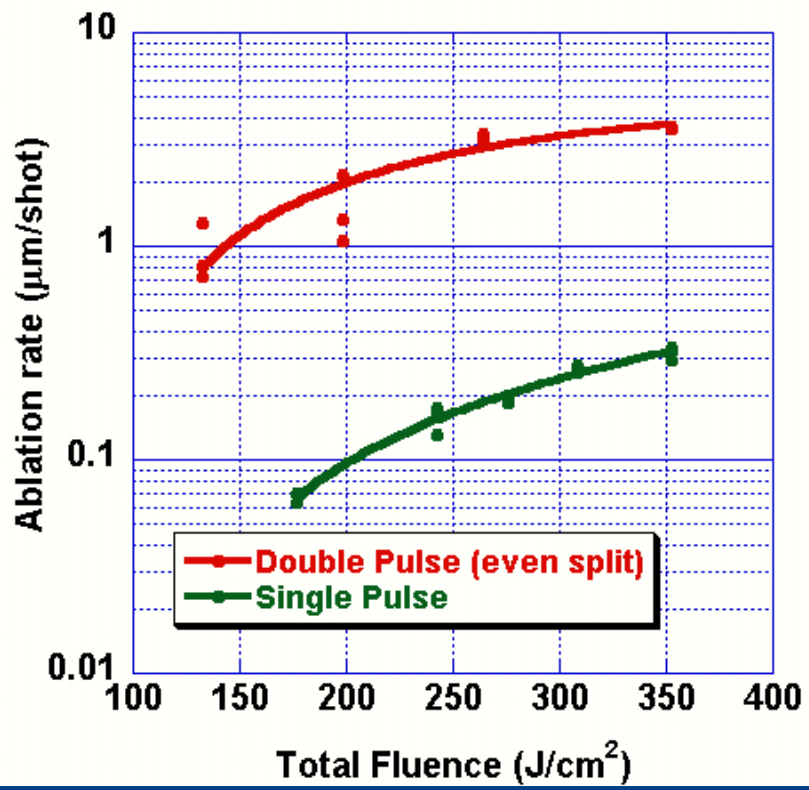
- **Enhances basic material removal rate.**
- **Improves ejection of ablation products**

- **laser:**
  - τ=4 ns,
  - λ=532 nm,
  - up to 3 mJ/pulse

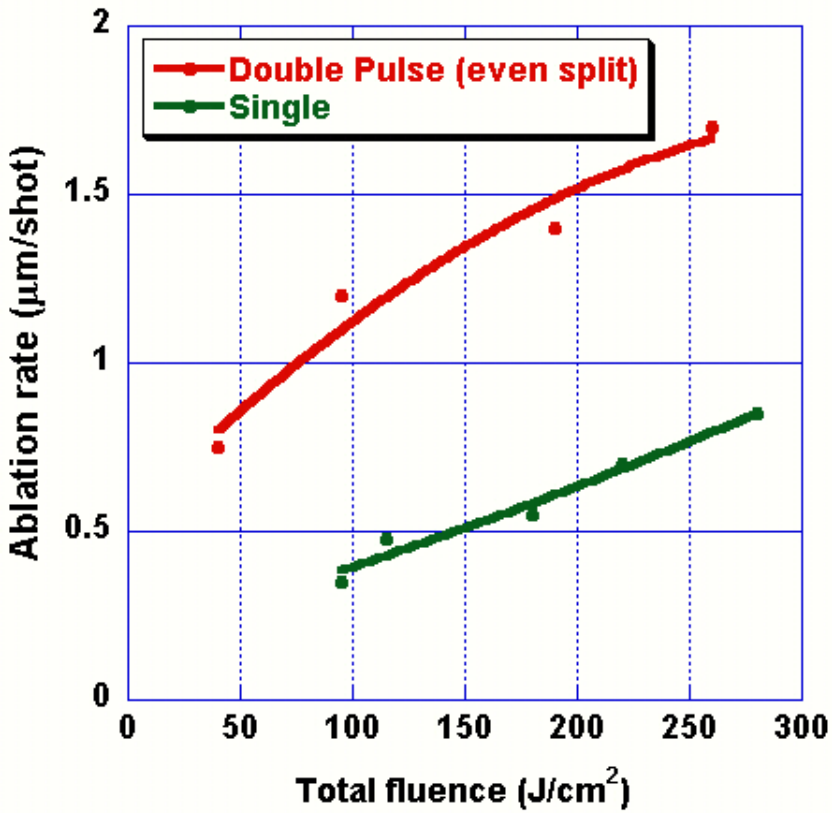
$$5\times10^{9} < \Phi_L < 10^{11} \quad W/cm^2$$

Percussion drilling in 700 μm thick silicon

λ=532 nm, 10 000 shots/s, 25 cm focal length lens, 200 ns pulse delay



Percussion drilling in 900 μm thick stainless steel



Why use double pulse ? Double Pulse machining improves the quality of percussion drilled holes.

- **Double pulse format can reliably percussion drill high aspect holes.**

800 shots

Single pulse

1 mm thick stainless steel.

200 shots

Double pulse format

A brief review of the pertinent physics of double pulse drilling is in order.

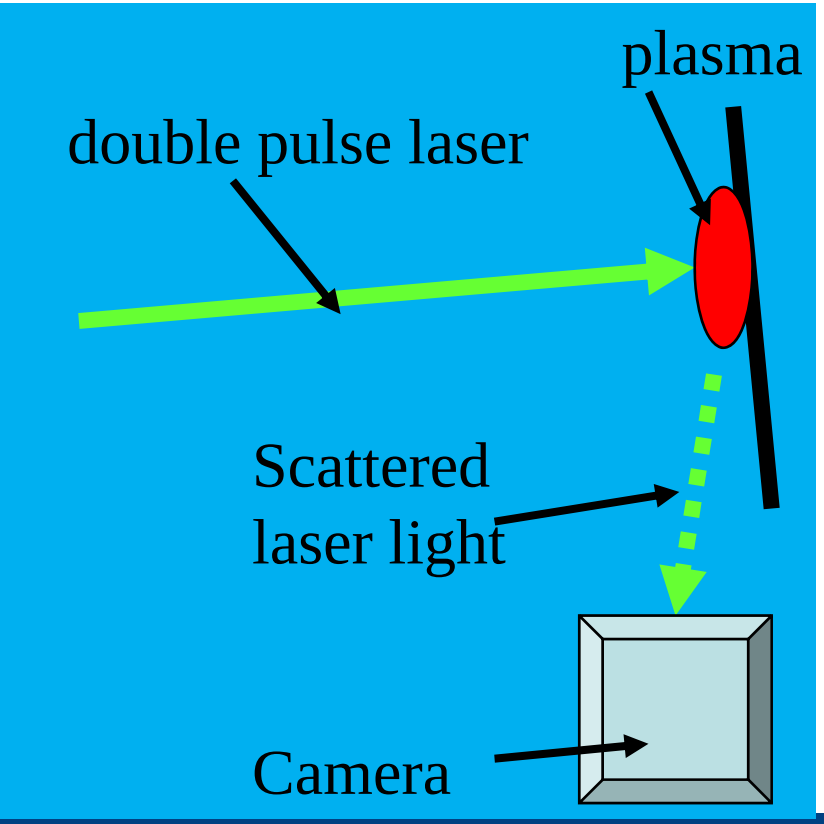
- **Modeling**
  - 1-D hydrocode
    - (limited by material models)

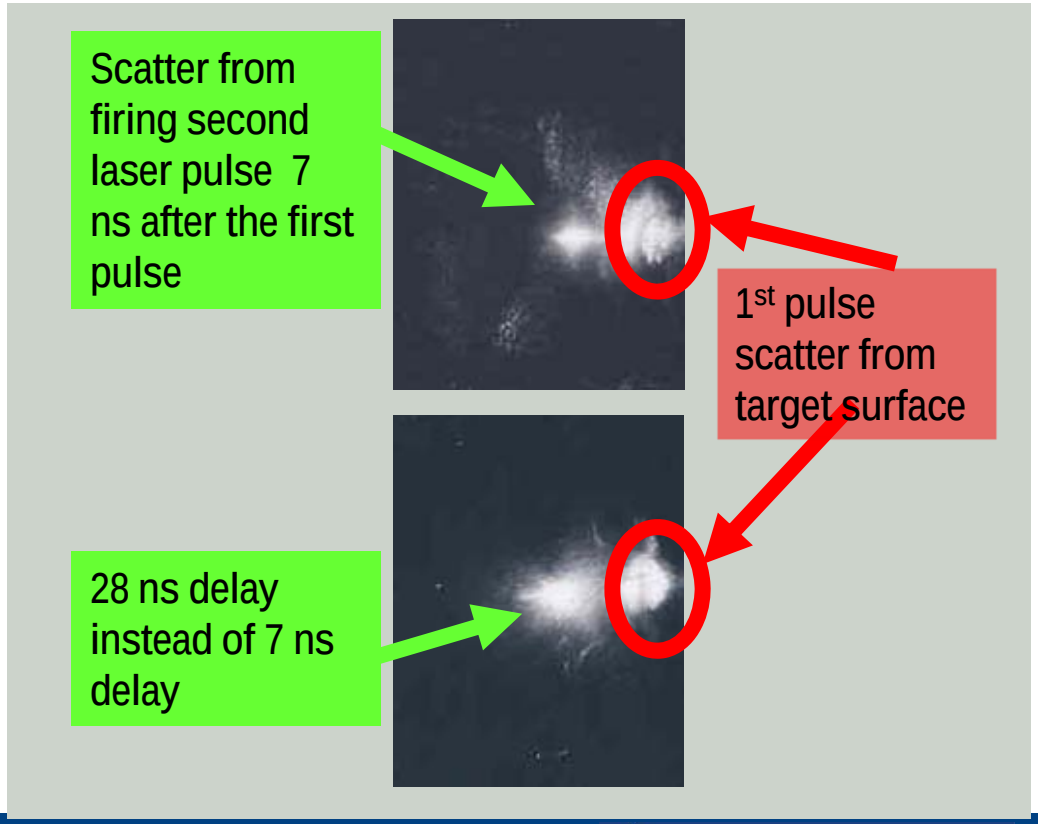
- **Experimental:**
  - Imaging of laser light reflected from the ablation plasma.
  - Nanosecond temporal resolution photography of ejecta.
  - Measurements of laser-induced ablation pressure.
  - Measurements of thermal emissions.

Images of laser light show the 2nd laser pulse scattering from material ABOVE the target surface.

- **Pictures of scattered laser light show where the 1st and 2nd pulses strike material**
- **Not a perfect diagnostic.**

- **Longer delay: heat larger and less dense volume of material?**

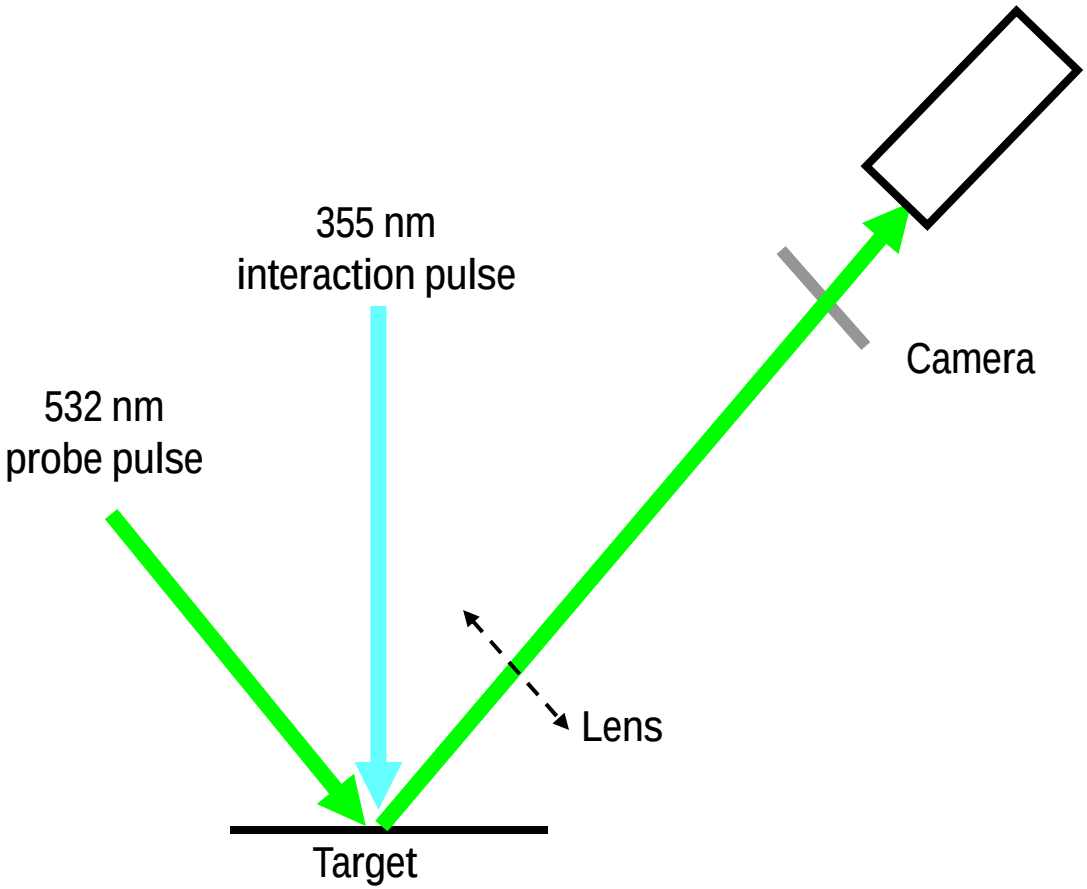




As a function of time, what does the 2nd pulse hit ?

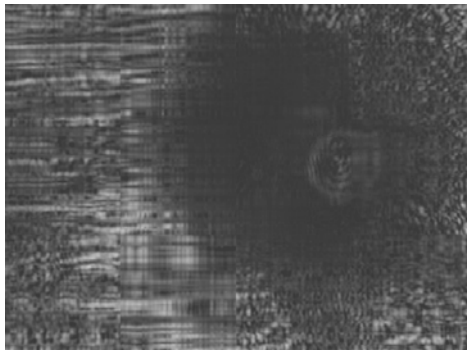
- **Time-delay pump-probe photographs visualize the target condition after the 1st laser pulse**

- **3 ns laser pulses for interaction and probe.**

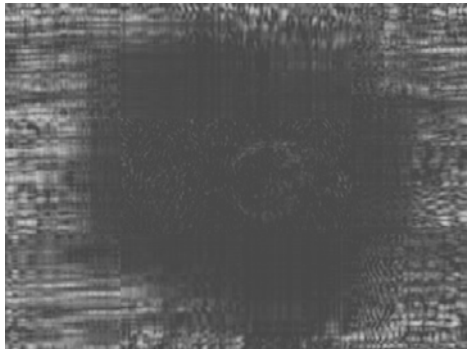


The secondary pulse hits a cloud of relatively slow, cool, matter (after 30 ns delay).

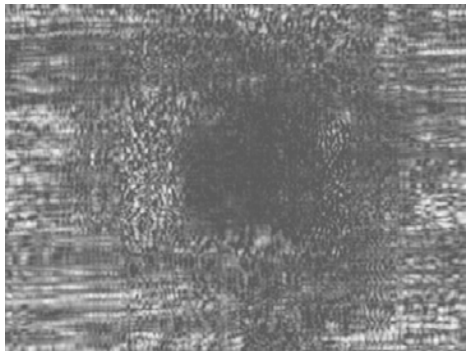
- **At times < 30 ns post-shot, the target surface is obscured by the ablation plasma**
- **At times > 30 ns, a dark cloud is visible**
  - Dark cloud is what the second pulse would hit
- **Dark cloud moves relatively slowly on ns timescales**
- **Thermal emission measurements show the cloud has cooled to ~3000 K when the secondary pulse hits it.**



11 ns post-shot: plasma plume



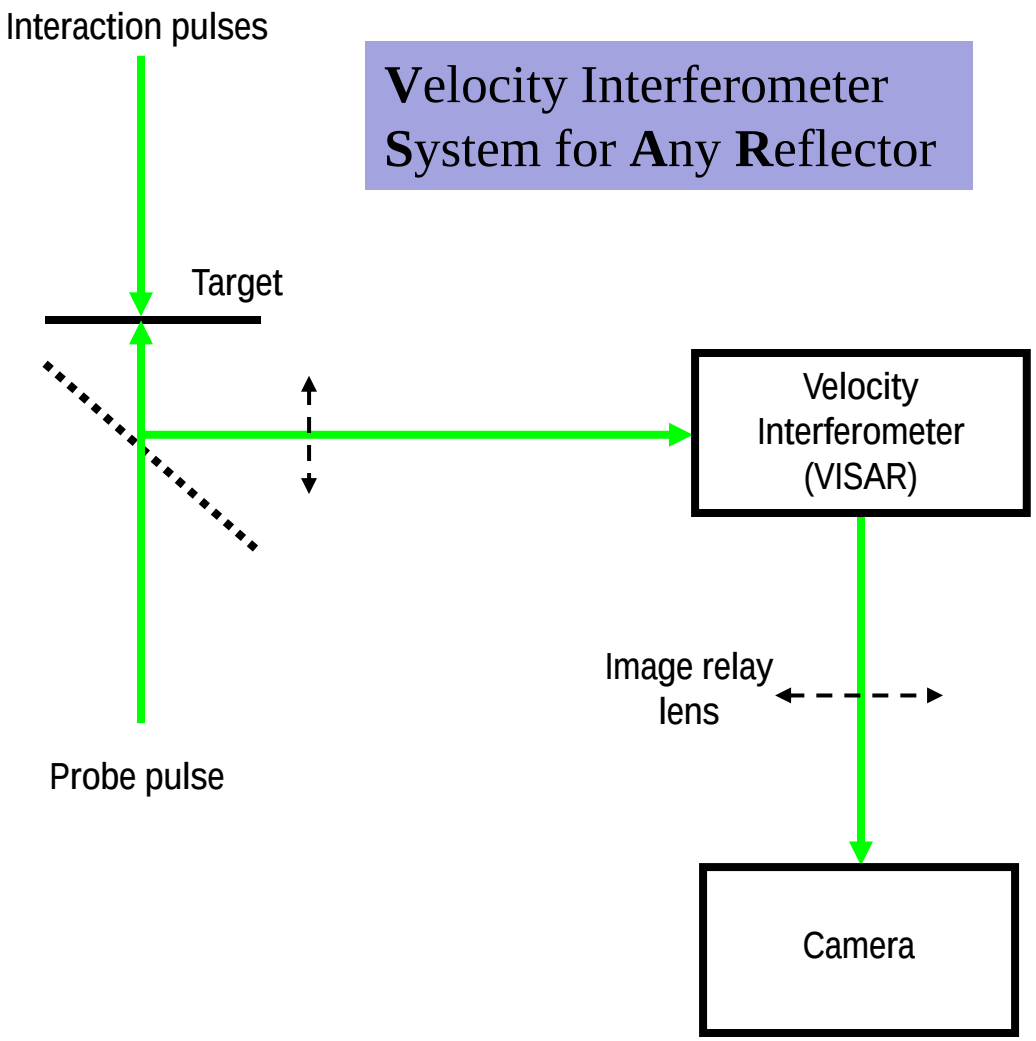
37 ns post-shot: “stationary” dark material



30 seconds post-shot: laser damage.

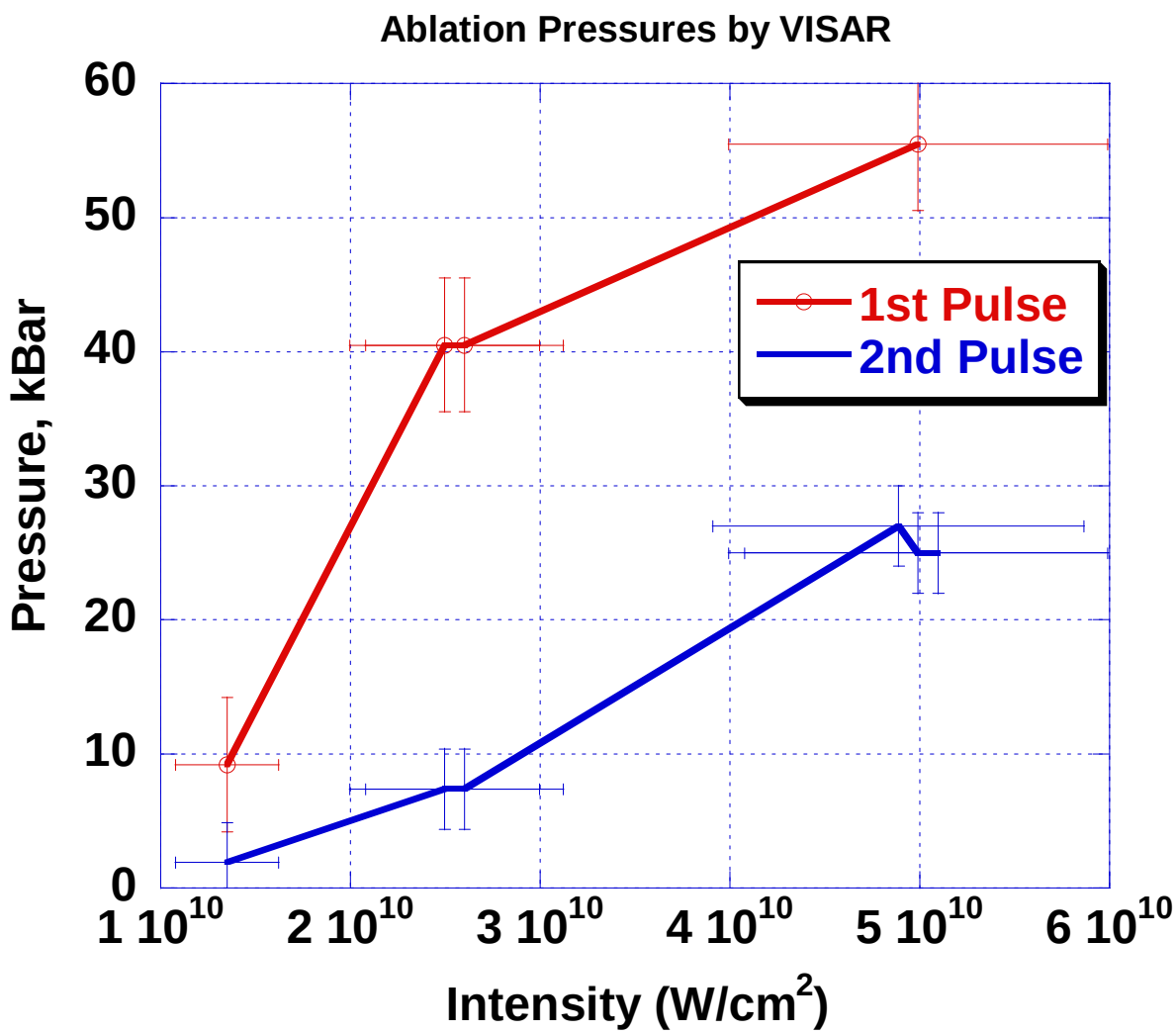
Measurements of laser induced pressure probe the interaction of the 2nd pulse with the "dark cloud".

- **VISAR measurements are used to estimate the ablation pressure**
  - 2D VISAR
  - Interpretation relies on changes in fringe contrast ratio
  - Target is 10 μm Al foil
- **3 ns interaction and probe pulses**
- **532 nm**
- **50 ns delay between first and second interaction pulses**
- **First and second pulses have same energy**



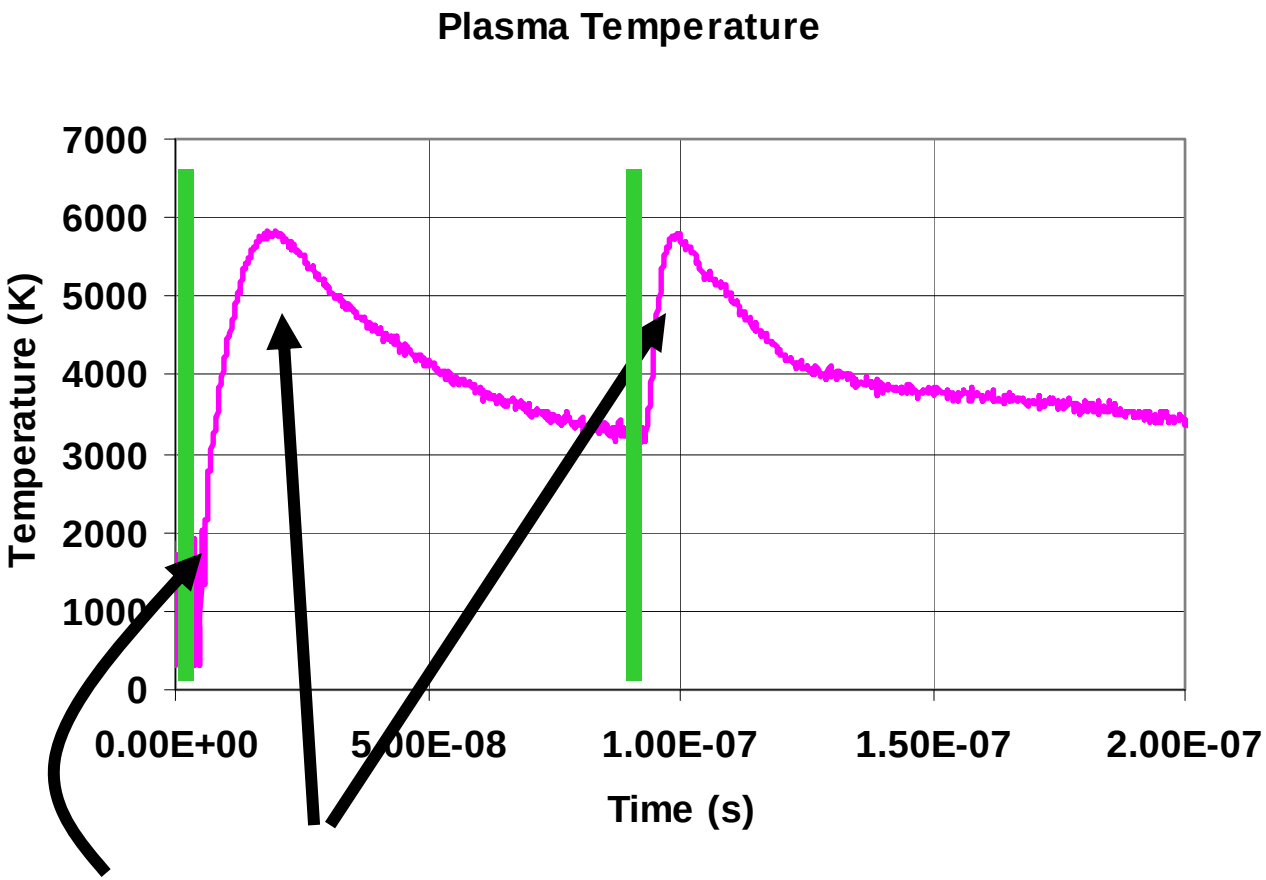
Laser ablation pressures measured with the VISAR show the secondary pulse is absorbed in the "dark cloud"

- Secondary pulse produces less than half the pressure of the primary pulse
- Secondary pulse does not primarily interact with the target.



Thermal emission measurement suggests that the 2nd pulse heats the material to similar temperatures as the 1st pulse

- Two 3 ns laser pulses are fired 90 ns apart
- First pulse is at T=0
- InGaAs photodiode, < 2 ns risetime
- Experiment conducted in normal atmosphere



Early and peak emission temperatures are underestimated due to self-absorption; not significant for later (> 30 ns after shot) times.

We now have enough data to propose a 3-stage process to explain double pulse

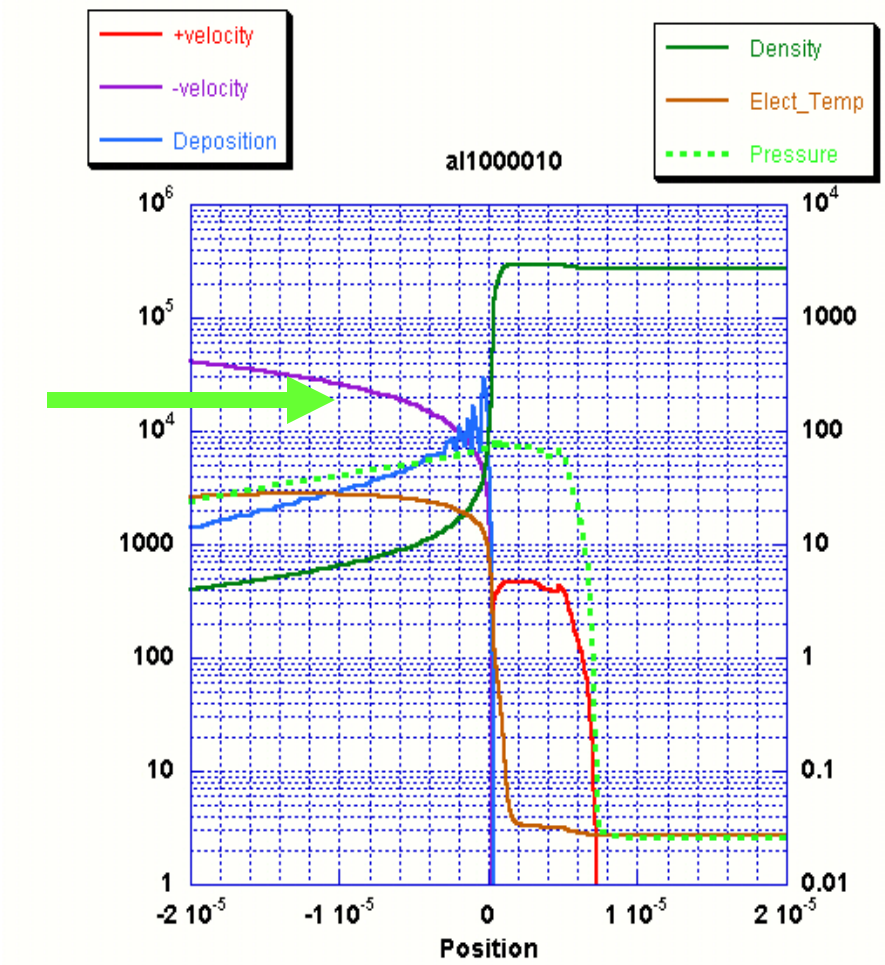
- **Stage 1: 1st laser pulse in double pulse pair.**
  - Produces high (30-50 kBar) pressures
  - Produces ablation plasma
  - Material ablation rate is compromised by the high pressure (EOS).
- **Stage 2: Time delay between 1st and 2nd pulse.**
  - Boiling and evaporation from the target may continue
  - Ablation plasma dissipates
  - "Low" temperature cloud of evaporated target material remains in front of target
- **Stage 3: 2nd laser pulse**
  - Heats low temperature cloud strongly
  - Interacts with larger volume of low density material
  - Produces thermal heat source without confining pressure (PV=nRT)
  - Ablation proceeds rapidly (>6X as fast)

For 70 μm diameter holes between 50 μm and 2 mm deep in steel, depth has little effect on speed.

Hole depth has a significant effect in aluminum.

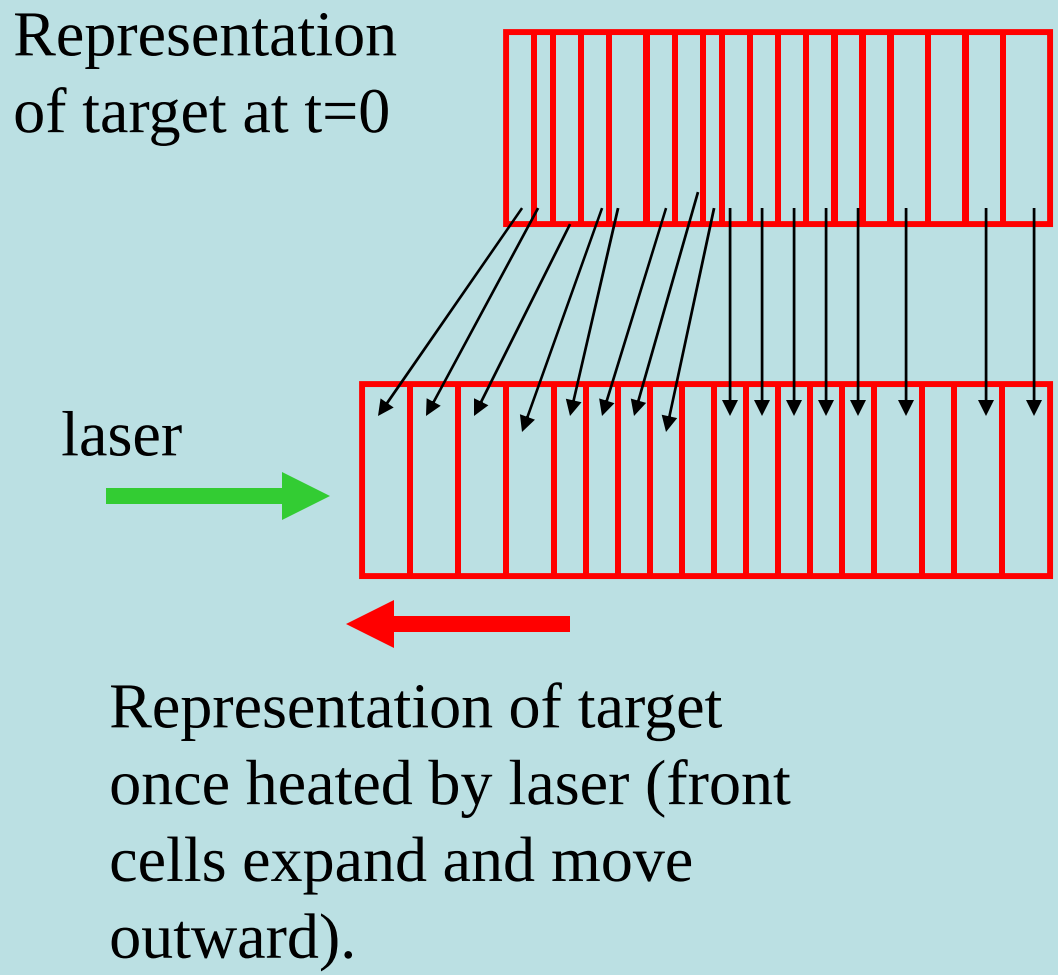
Computer modeling supports the 3-step process.

- **Hydrocode provides physical insight.**
- **Further verifies the extreme conditions of temperature and pressure.**
  - **T=300,000 K at pulse peak, not seen by emission measurement due to self-absorption at this stage.**
  - **P=60,000 Atmospheres (seen by VISAR)**
- **Units:**
  - Position in m
  - Temperature in eV (1eV=11,000 K)
  - Pressure in kBar (1kBar=1,000 atmospheres)
  - Density in kg/m^3
  - Laser Energy Deposition in 10^{16} W/m^3
    - Shows the expected self-modulation due to interference between the incident and reflected waves.



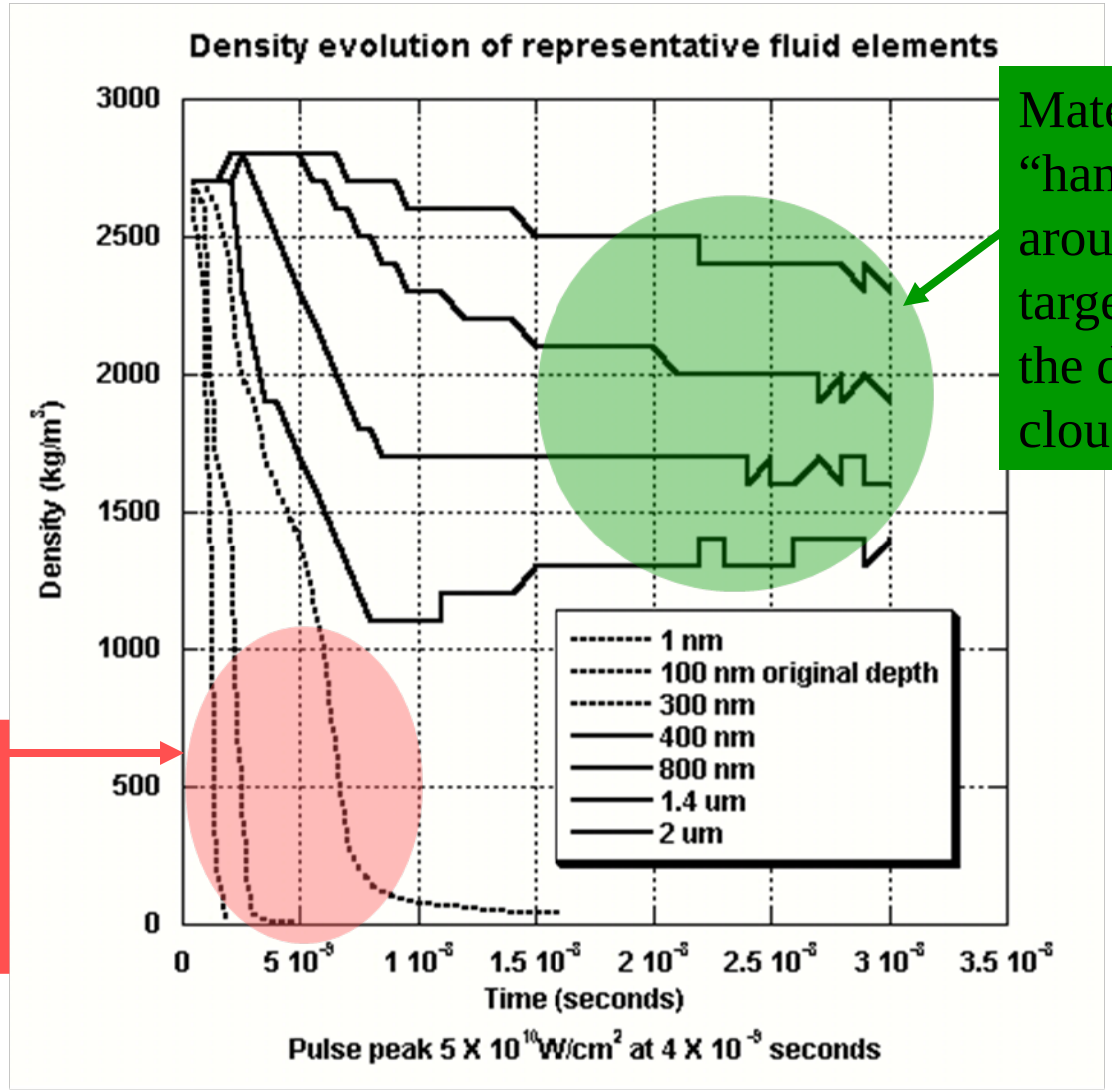
Tracking the evolution of fluid elements in the model further supports the 3-step model.

- **Finite-element fluid model calculates the evolution of each individual element.**
- **Each individual element represents a layer of target material.**
- **We can track the change of velocity, density, temperature, etc.**



Density evolution of representative fluid elements.

- **Laser pulse duration is 3 ns FWHM.**
- **Compression of underlying target material is evident at pulse peak (4 ns).**
- **Later times show the appearance of partial density layers.**
  - Hydrocode also shows they remain in the vicinity of the target.

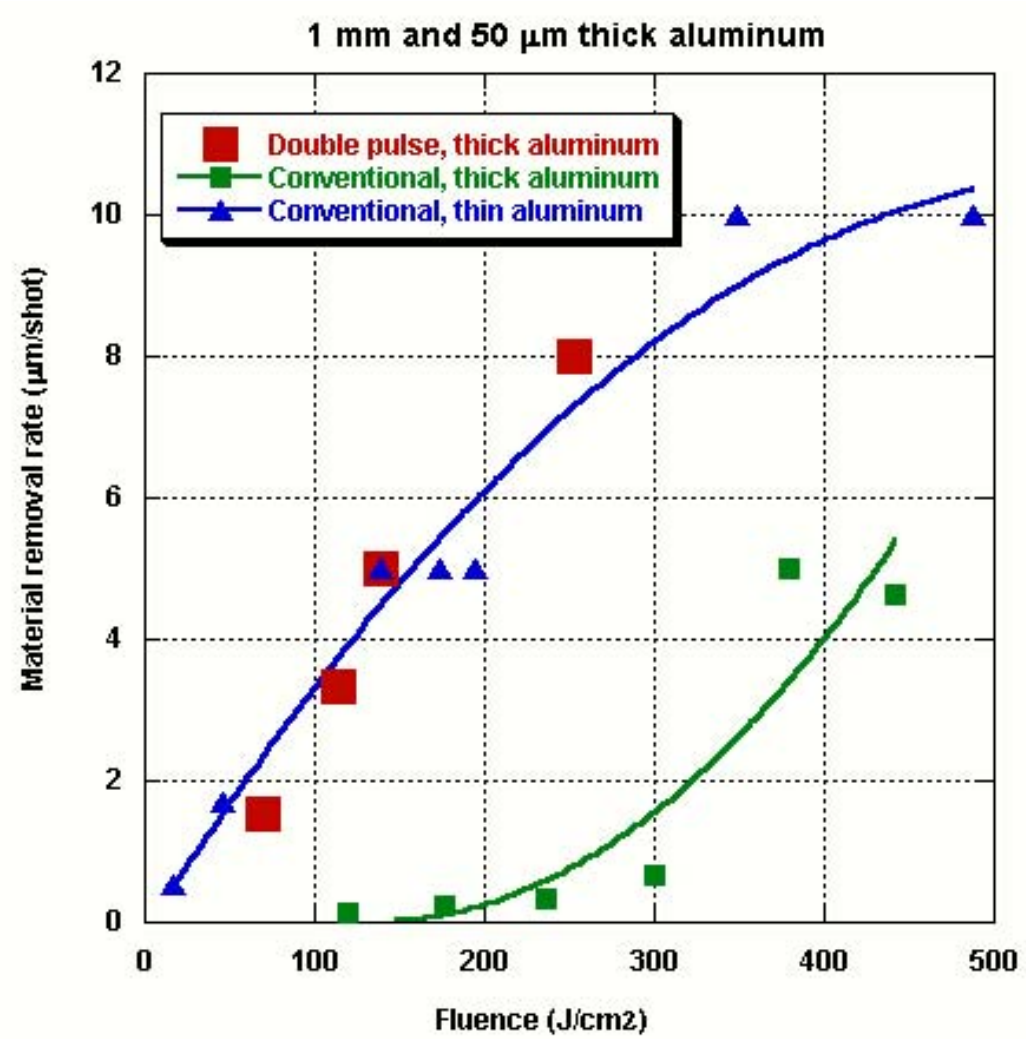


Material that "hangs around" target, i.e., the dark cloud.

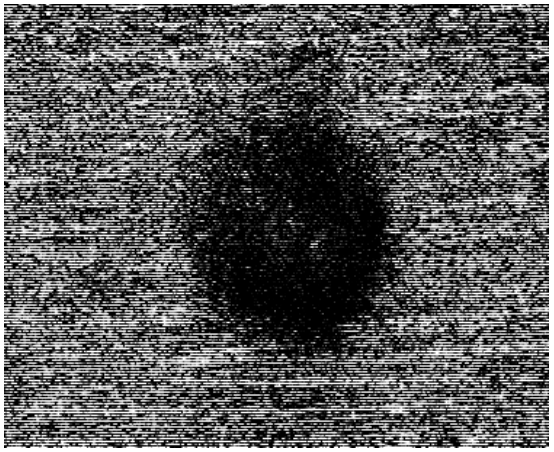
Elements that blow off (ablation plasma)

But: drilling tests show that a second mechanism dominates in some materials

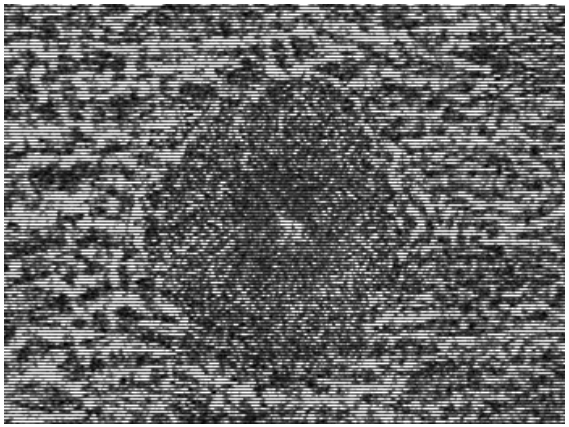
- **Drilling speed enhancement depends on depth in aluminum.**
- **Aluminum has ~5X thermal conductivity and ~1/3 total heat capacity of stainless steel.**
  - ns-resolution pictures of ejecta show aluminum produces more ejecta than steel.
  - This would be consistent with physics underlying the 3-step process.



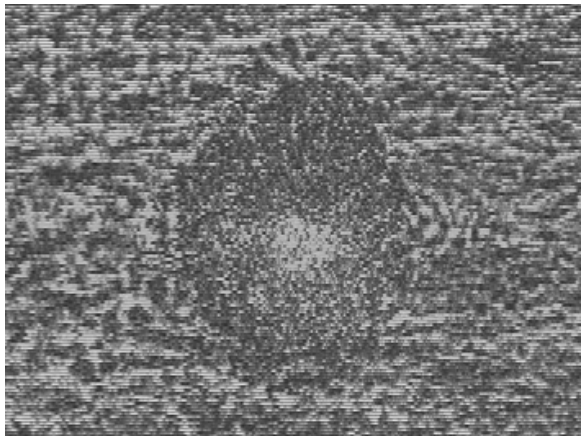
ALUMINUM PRODUCES MORE SUBSTANTIAL AMOUNTS OF EJECTA THAN STEEL



Aluminum, 200 ns after pulse



Steel, 200 ns after pulse.



Steel, 2 seconds after pulse.

Thus a 4th step needs to be added to the double pulse model:

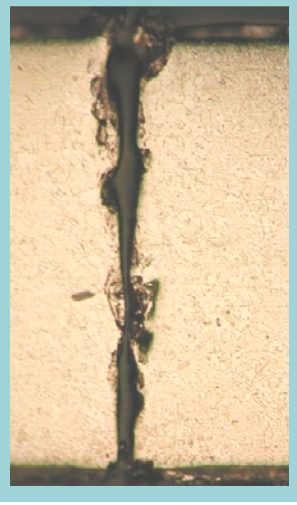
-*The secondary pulse reheats and consequently inhibits redeposition of heavy quantities of ejecta.*

Application to small high aspect ratio holes: benefits and mysteries.

- **Double pulse format inherently helps drill small high aspect ratio holes:**
  - The increased material removal efficiency
    - Reduces undesired effects on bore walls since less energy is used.
  - The 2nd pulse also helps reduce material redeposition inside the hole.

- **But, we have observed that when the aspect ratio is > 20:1,**
  - **Hole drilling efficiency drops (> 10X in some cases).**
  - **Heat affected zone appears in the bore walls.**

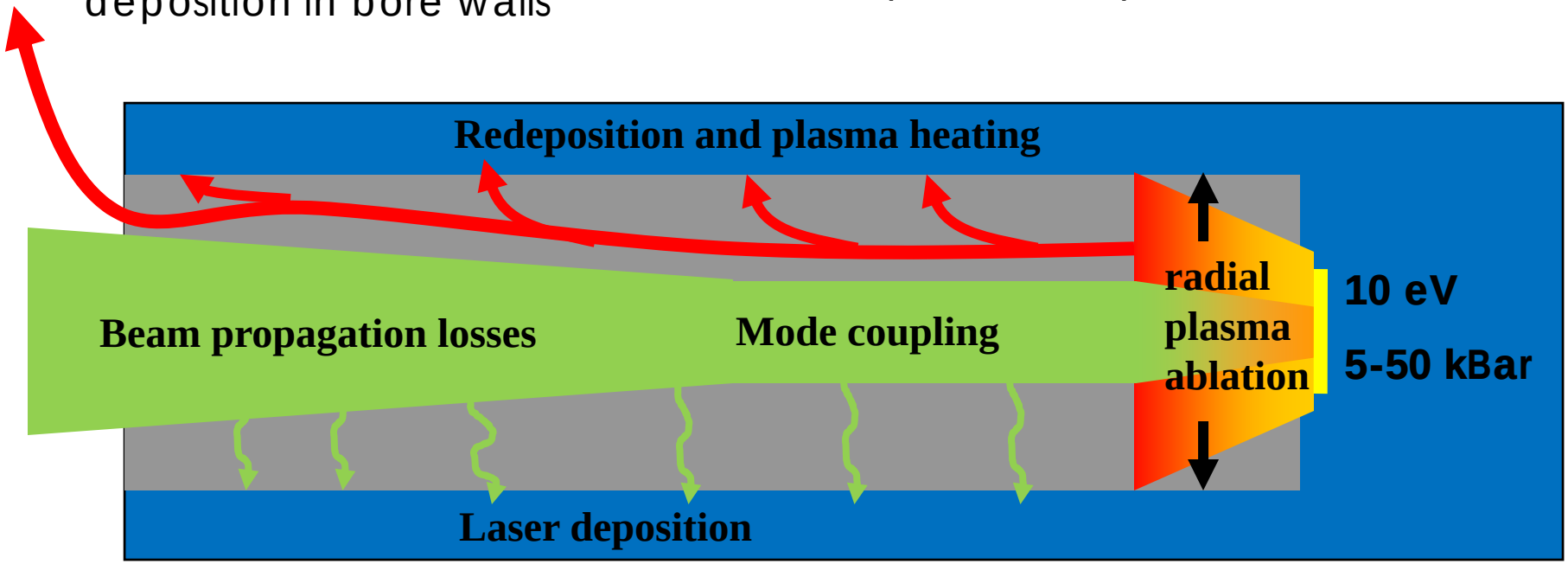
- **Recall the difference between holes drilled by 800 conventional single pulse laser shots and 200 double pulse shots (right hand image).**



Modification of the foregoing description of laser drilling to account for at least the following processes:

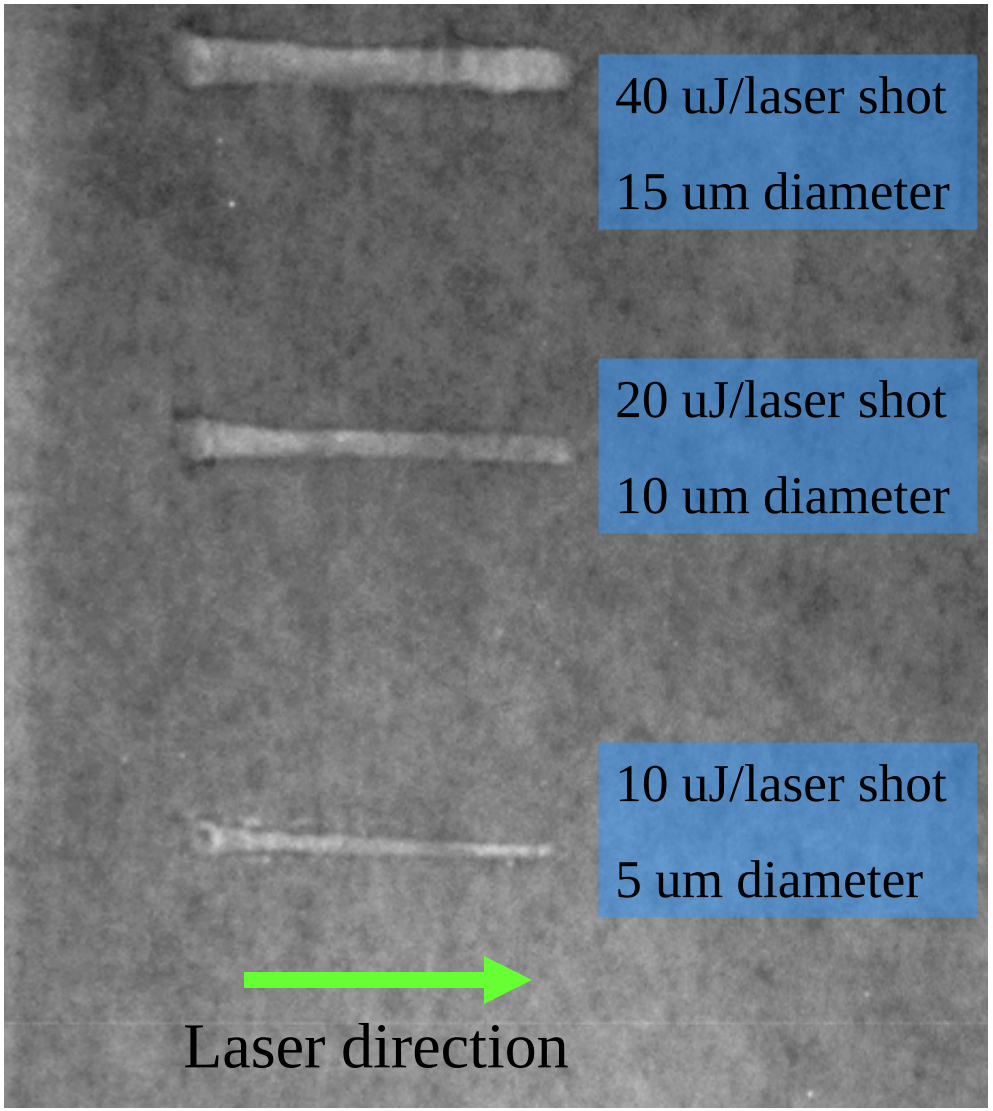
- **Plasma related:**
  - Radial hole expansion by hot plasma
  - Friction encountered by plasma exiting hole
  - Plasma thermal deposition in bore walls
- **Optical phenomena:**
  - Waveguiding
  - Propagation losses
- **Redeposition:**
  - From plasma
  - From liquid and vapor

We only begin to grasp some of these processes.



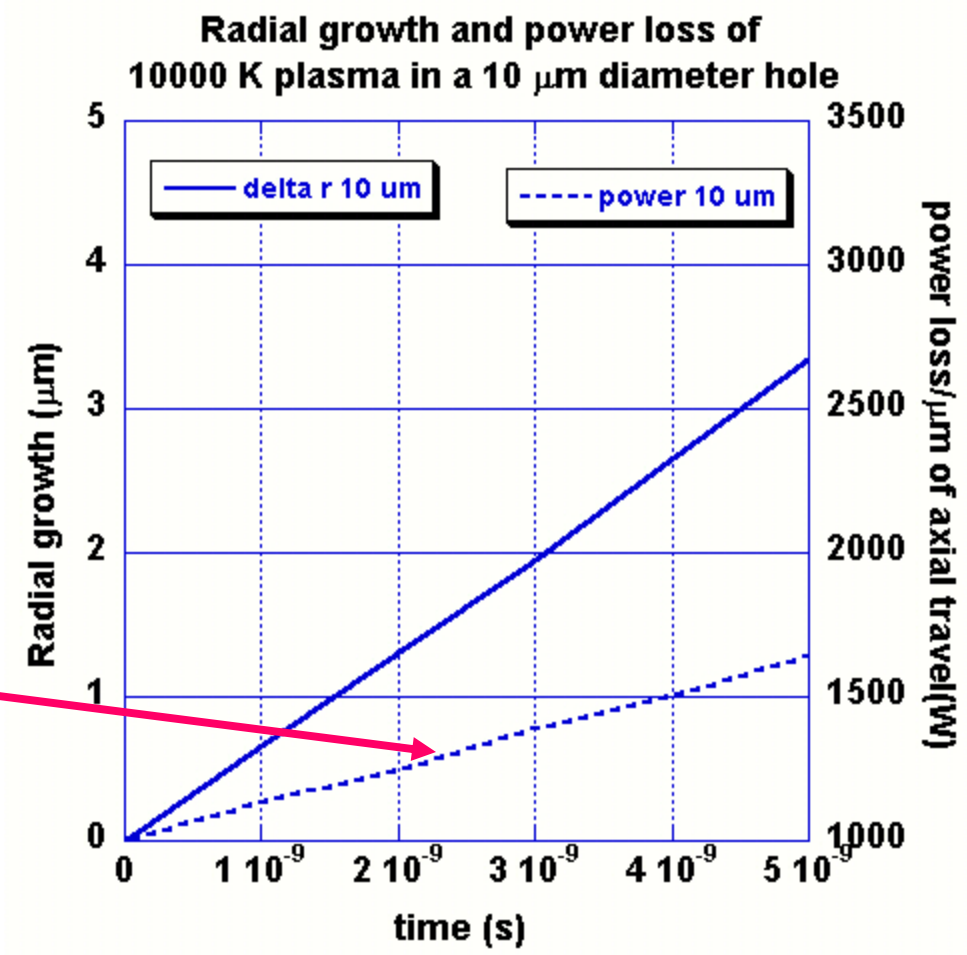
Increasing the laser intensity increases the hole size beyond what can be accounted for optically.

- **Tests in 150 um thick Al foil reveal that the hole size depends on the laser intensity.**
  - Drilling time is constant at 2000 double pulse laser shots.
  - Focal spot diameter <6um
  - Low taper in holes.
  - *Ablation plasma causes radial ablation*



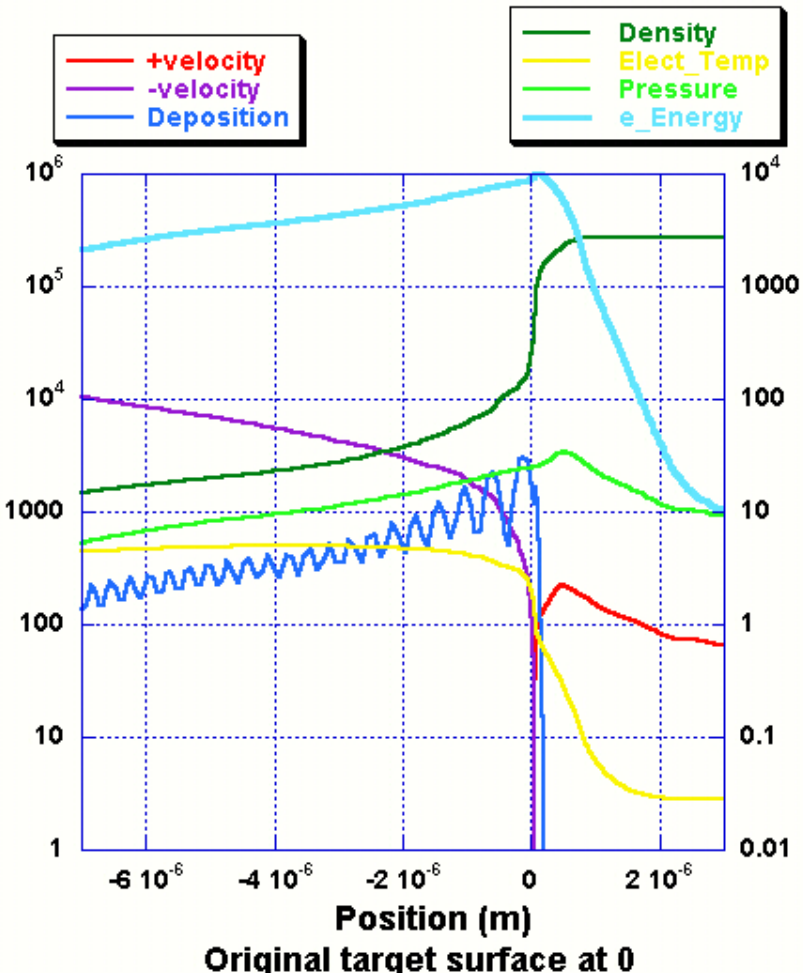
A simple calculation shows that it is plausible for a hot, energetic plasma to drive the process of radial ablation.

- $\nabla \kappa \nabla T$ **estimate**
  - Melting & vaporization
  - No heating past boiling
  - No boundary layer
  - Completely turbulent flow
- **1 μm slice of plasma at 10,000 K has a ~ kW power loss rate.**
  - μJ over nanosecond
- **Expect rapid radial growth initially.**



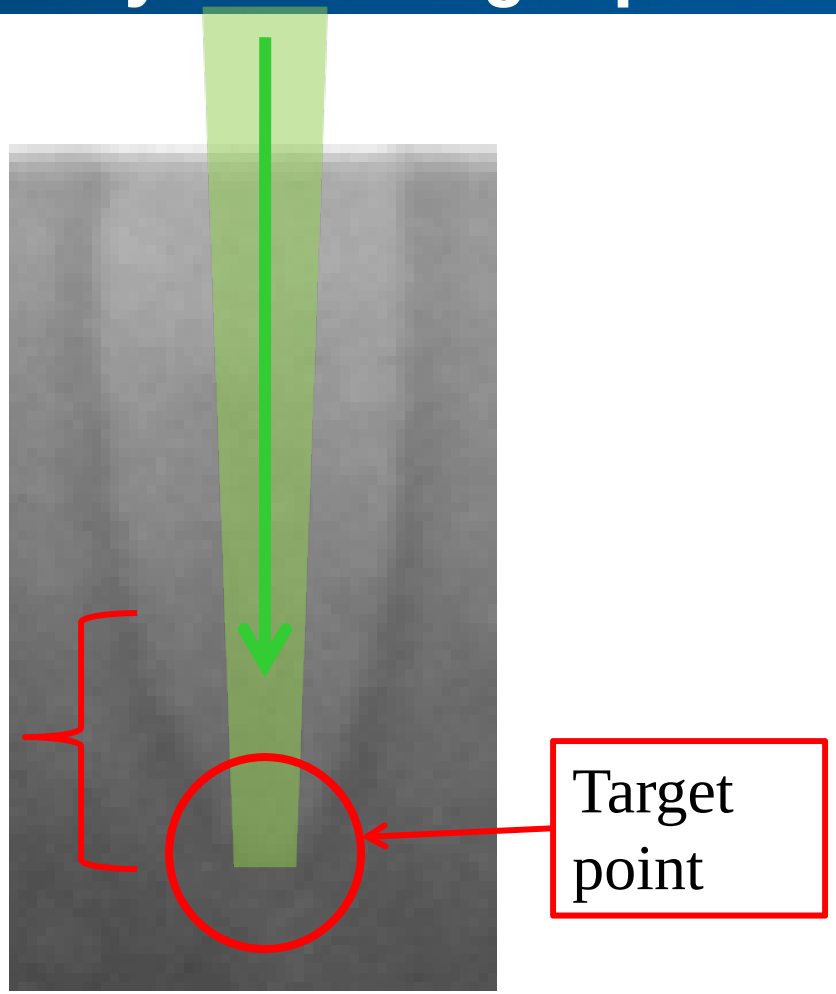
1-D hydrocode suggests the laser produced plasma is sufficiently hot and energetic to drive the radial expansion

- **Plasma**
  - expands several μm
  - lasts several ns,
  - eV temp
  - Several μJ internal energy
- **Drives radial expansion (previous slide).**
- **However, radial expansion due to any given volume of ablation plasma will be short lived:**
  - **It cools rapidly**
  - **Perhaps a few ns=a few μm.**
- **Do we have data to support this idea ?**



Blind test holes in Be are consistent with the idea of rapid radial growth in the vicinity of the target point.

- **Rapid expansion corroborates model.**
  - Radial hole growth occurs only in the vicinity of the target point.
  - Then the hole goes straight.
- **Expands from 5 μm to 20 μm in ~ 10 laser shots.**
  - 75 μJ/laser shot
  - Single pulse shots
  - 30 shots total
  - Hole measured by x-ray microscopy.



It's the plasma that matters: a simple model of plasma-bore wall interaction

- **Ability of the initial ablation plasma to carry energy to the bore wall.**
- **A simple model neglects many real-life effects:**
  - thermal conductivity of the boundary layer
  - friction
  - Cooling due to radial expansion in an enlarged hole.
  - Properties of solid material.
  - Assumes flow starts out as turbulent.
- **It may offer a "rule of thumb".**

$$R \propto \tau e$$

τ =ablation plasma duration

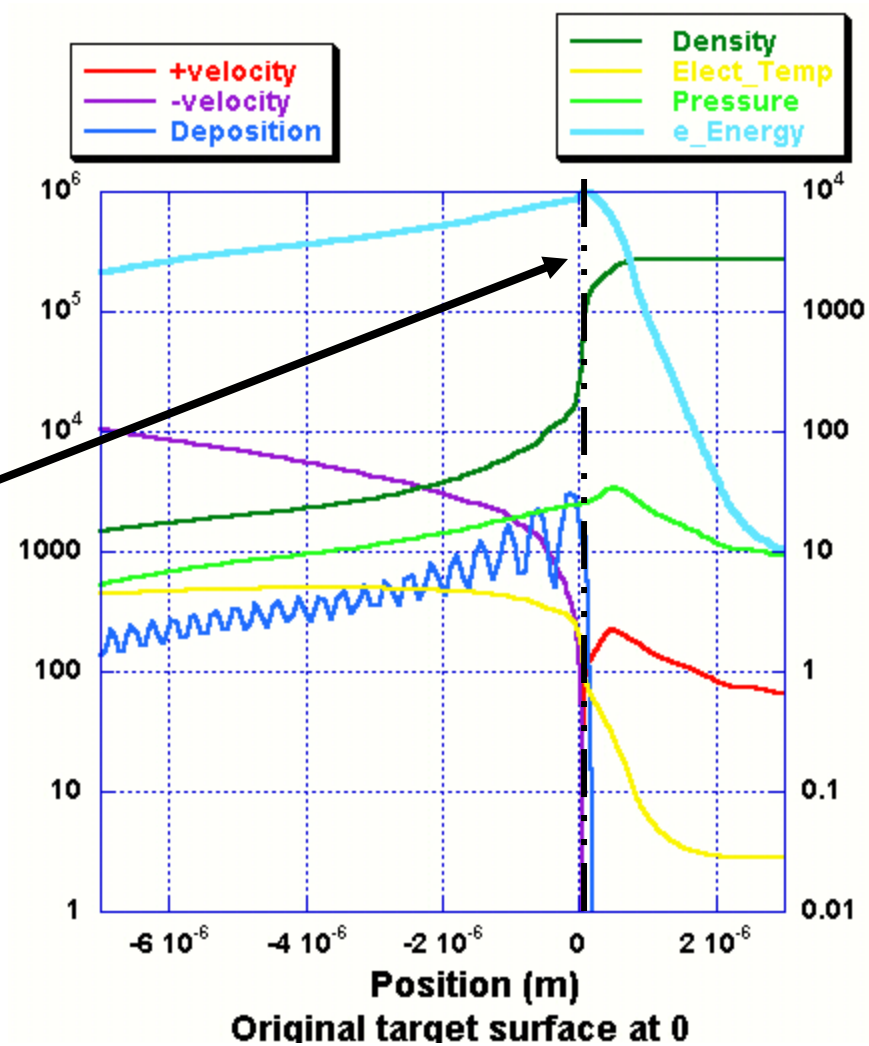
e =plasma energy density

R =maximum radial ablation rate

1-D hydrocode estimates the plasma duration and internal energy

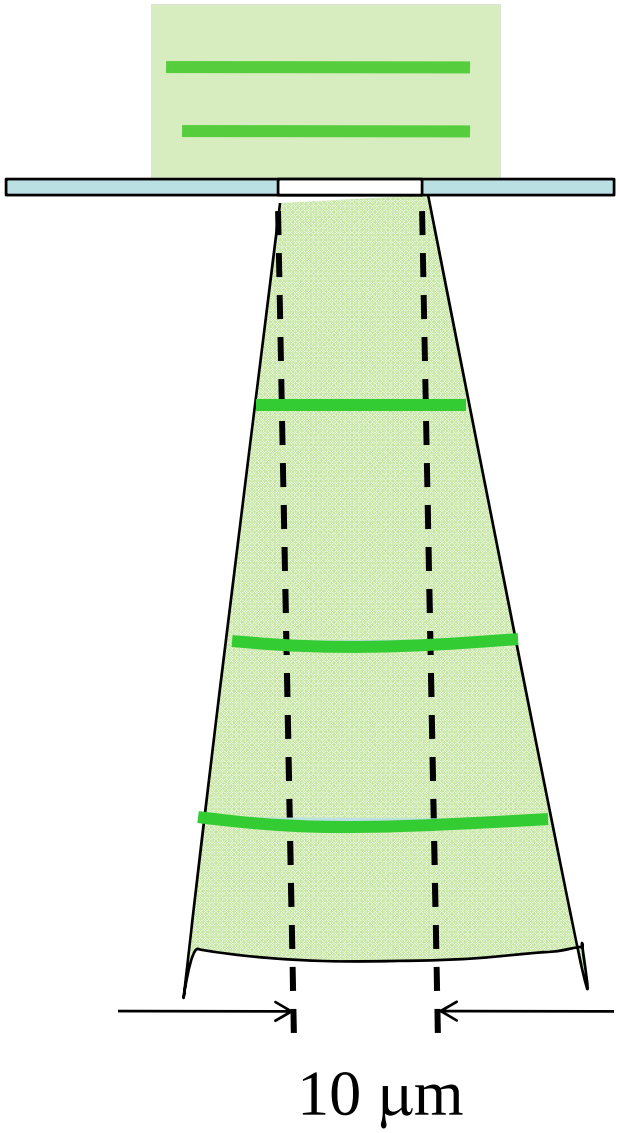
$R \propto \tau e$

- **Double pulse plasmas are less aggressive.**
  - τe=(4 ns) * (7000 J/cm3) for 1st pulse in each pair.
  - 2nd pulse plasma has much lower energy density.
  - τe=(5 ns) *(10 000 J/cm3) for single pulse of equivalent energy
  - (generally does not drill as well).
  - Plasma energy density evaluated at ablation front (i.e. velocity=0)
  - Flow friction (< 10 μm diameter) raises τe.
- **The plasma itself changes the hole size.**
  - May even dominate as Φ_L increases.
  - How aggressive are the plasmas produced by short pulse lasers ?



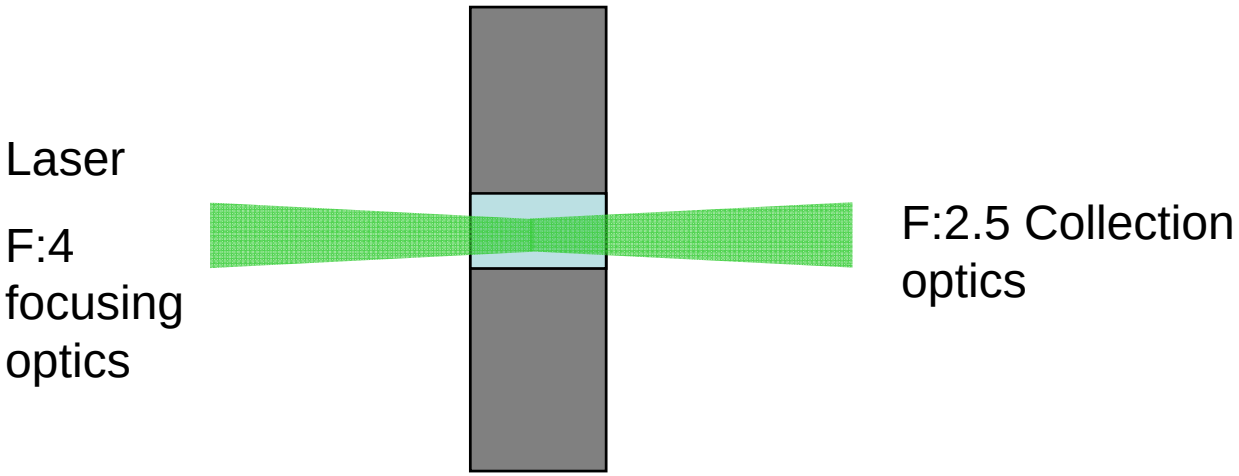
Small high aspect ratio holes must be treated as a waveguide.

- **Consider the diffraction from a 10 μm diameter aperture:**
  - At a range of only 200 μm the spot size is > 25 μm.
- **The "regular" approach to estimating the laser focal spot size in situ cannot be used.**
- **The effects of the hole on the propagation of the laser light that is drilling the hole are significant.**
  - Attenuation
  - Changing the focal spot size



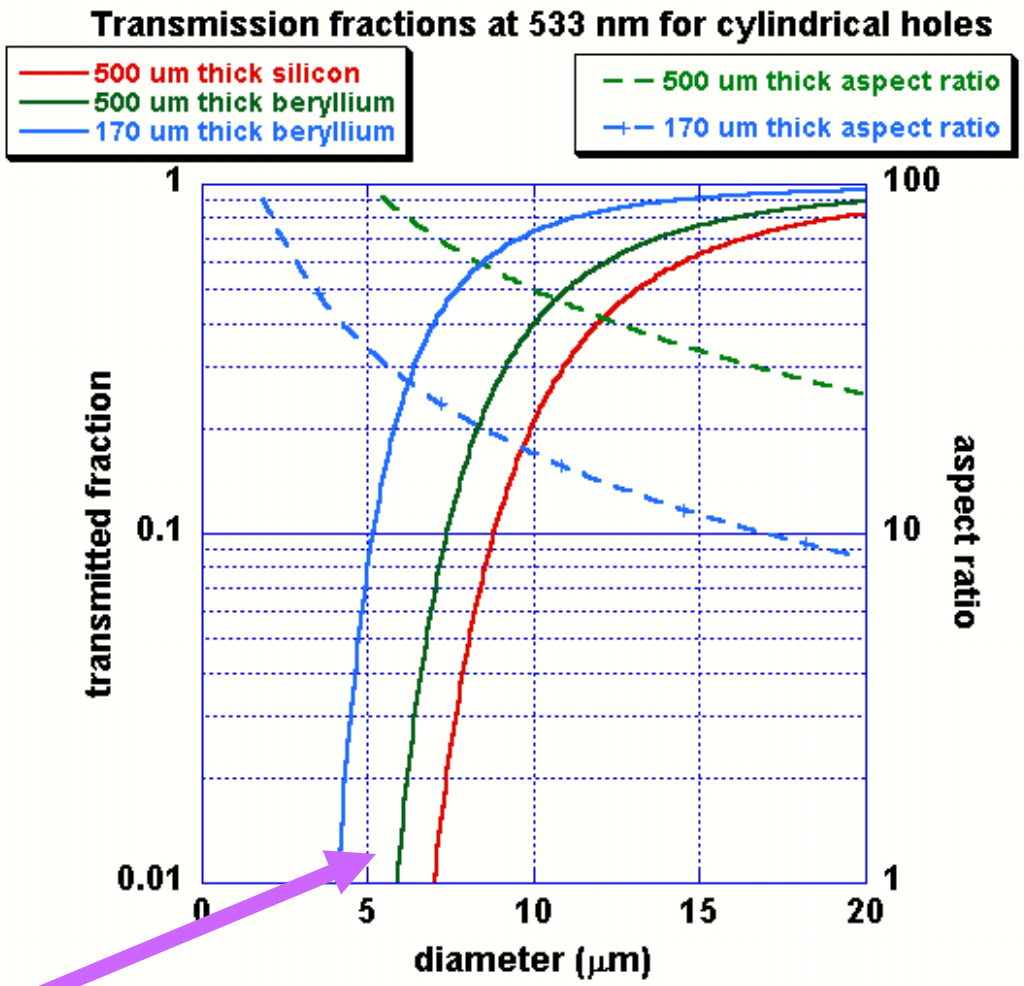
Detection of transmitted laser light yields drilling time.

- **A photodiode and oscilloscope measure the history of transmitted laser light during drilling.**



Small, high aspect ratio hole acts like a waveguide and is a limiting factor due to energy loss.

- **Small holes suffer from severe attenuation**
  - Model calculation.
  - Mode coupling (Bessels functions).
  - Attenuation
- **Best silicon hole has**
  - 80:1 aspect ratio
  - ~ 7 um diameter
  - Measured optical transmission between 1% and 10%.
- **Observed low taper in ~15 um diameter holes in 170 um thick beryllium**
  - Higher taper for 5 um diameter holes.

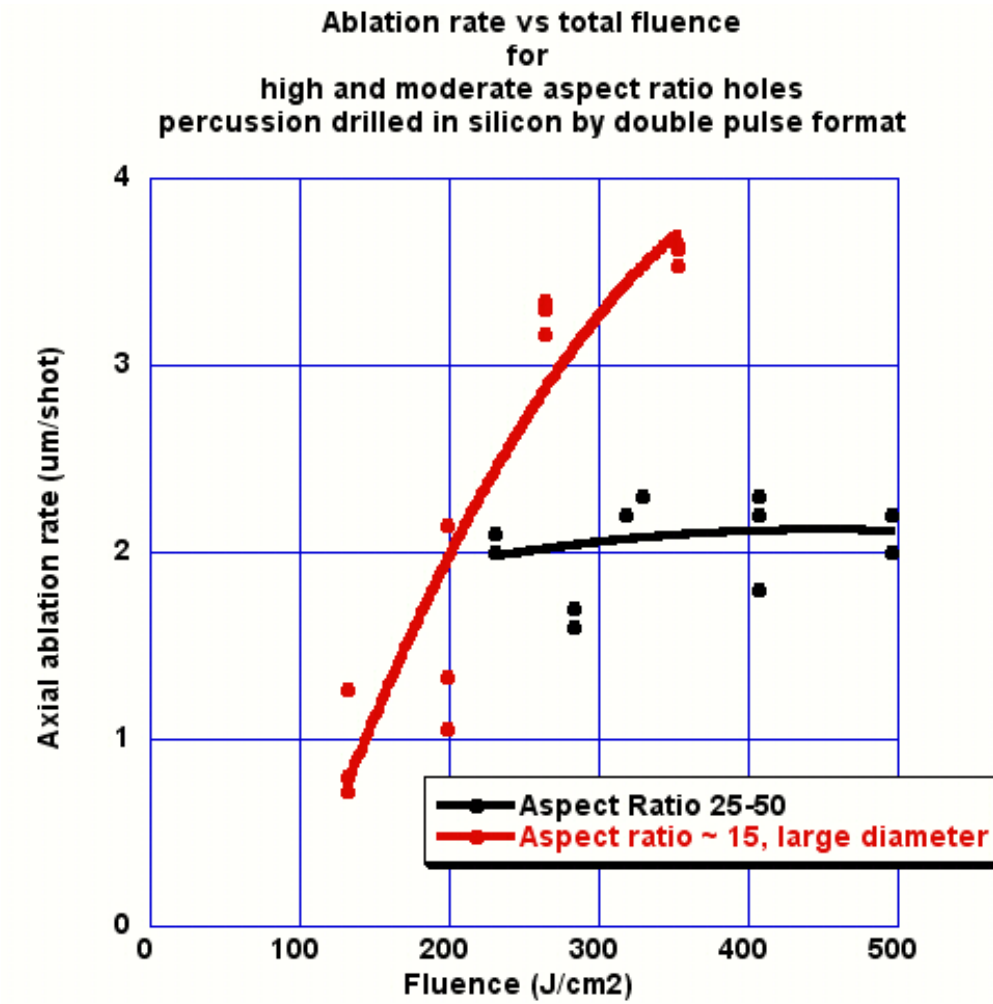


Hole drilling appears to stop when $\Phi_L < \times 10^8$ W/cm^2.

A consequence of waveguiding is that the "spot size" at the hole bottom is governed by the hole diameter.

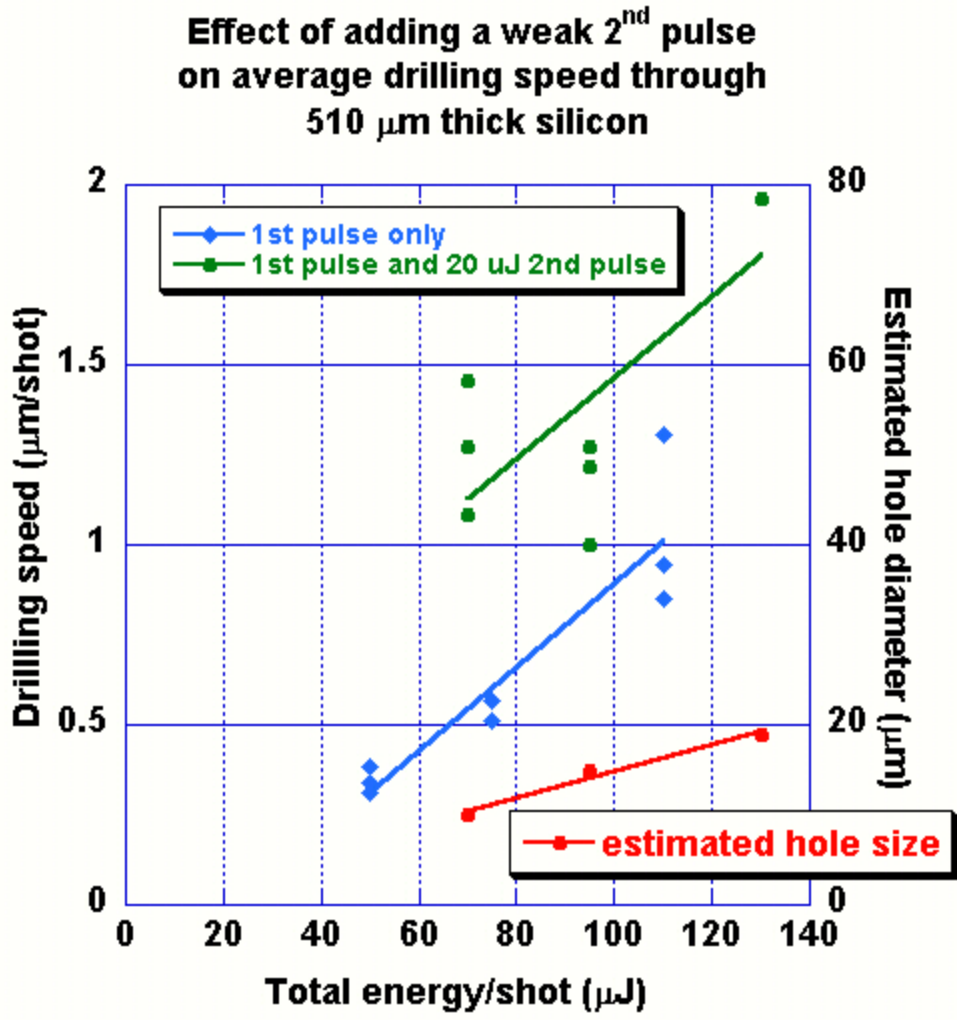
- **The size of the lowest order modes depends on the hole diameter.**
  - Larger holes = larger mode size
  - Coupling efficiencies change with hole size as well.

- **As the laser power is increased (and the laser focus does not change) then**
  - The plasma enlarges the hole
  - The mode size increases
  - The laser spot gets larger at the hole bottom
  - Moderates drilling speed (although more material is still being removed)



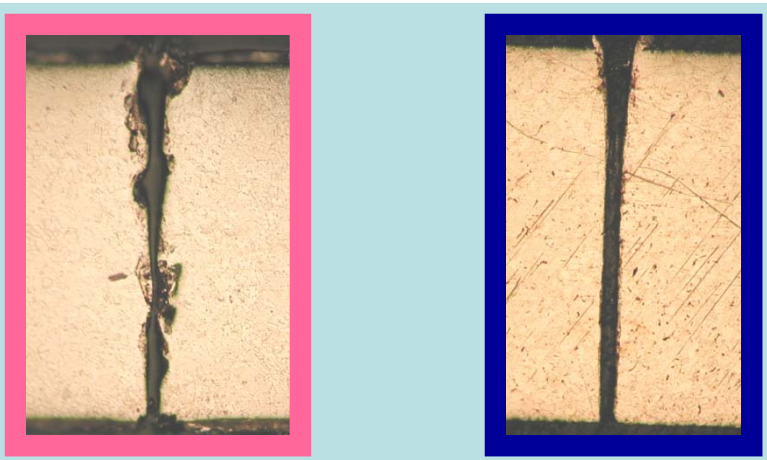
Limiting process of redeposition and debris is mitigated by 2nd laser pulse.

- **Redeposition causes self-occlusion.**
  - Any kind of laser
- **Test by adding weak 2nd pulse**
  - Attempt to avoid fresh ablation during 2nd pulse.
- **~2X drilling speed for relatively little additional energy.**
  - Test format only; not optimized for speed.
  - > 2 μm/shot when 2nd pulse is strong.

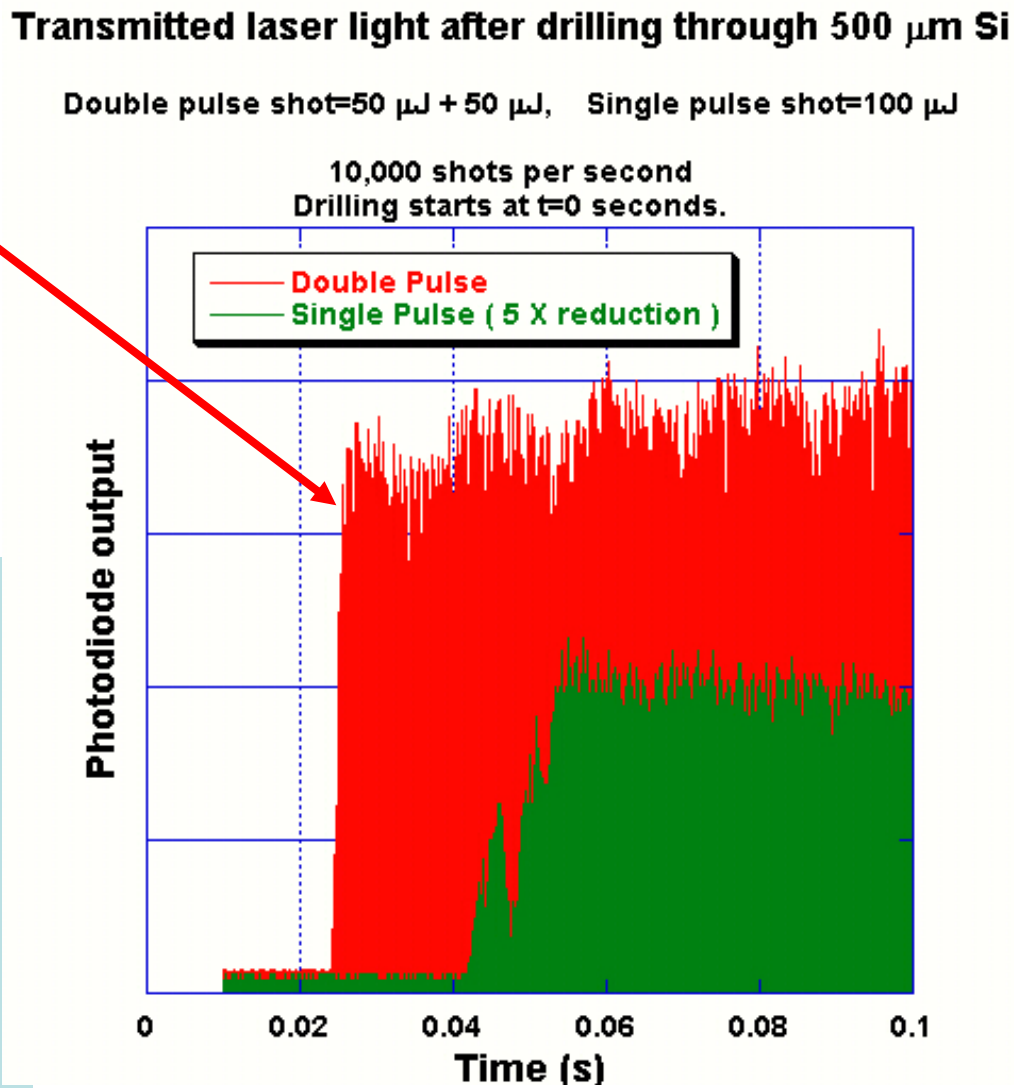


Transmission of laser pulses while drilling 500 μm thick silicon shows the limitation of redeposition.

- **Double pulse drilling shows clean breakthrough.**
  - Also 2X fast
  - Drilling started at t=0.
  - ~250 shots to get through.
- **Single pulse drilling shows a series of partial breakthroughs.**
  - Probably due to redeposition.
  - Tends to produce ugly, nasty holes.

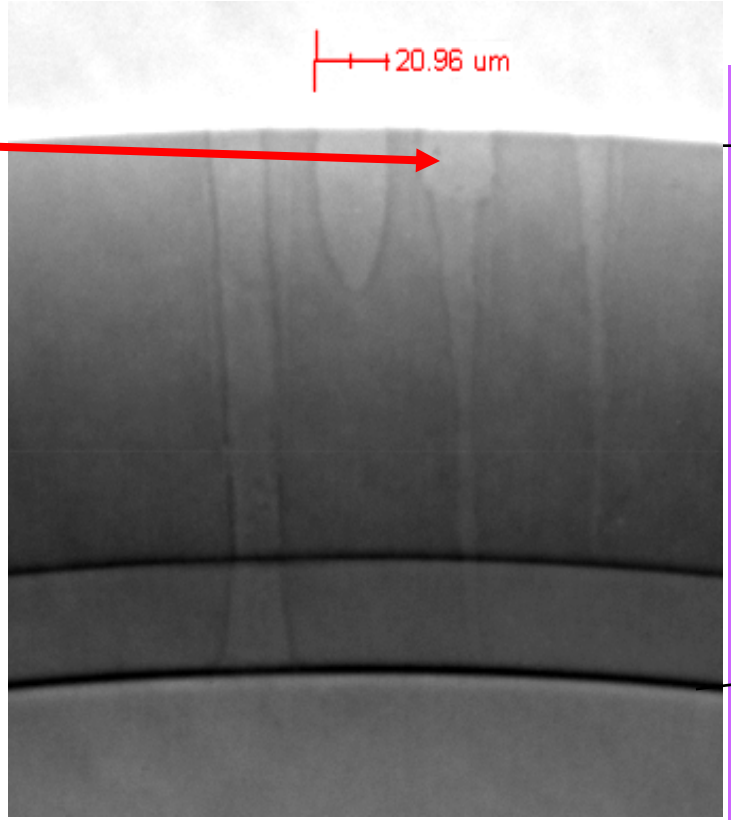


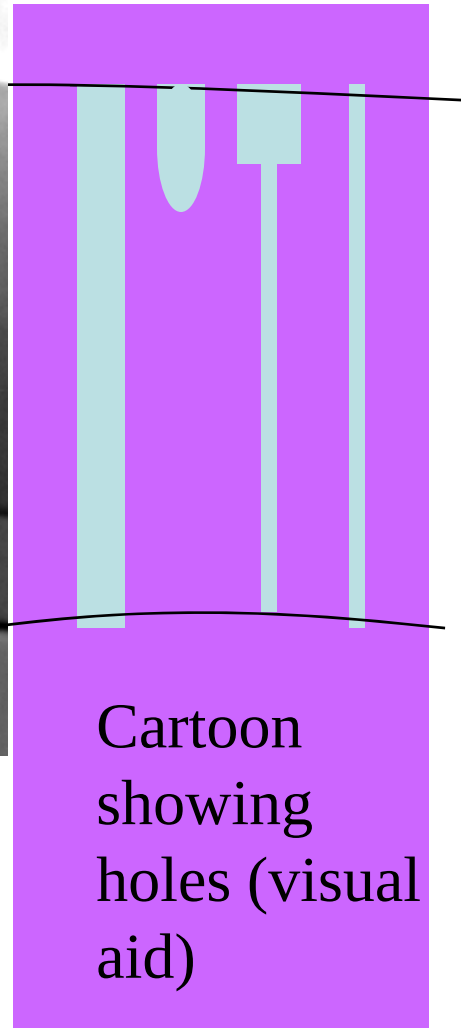
Single and double pulse format holes in steel



While these limitations restrict the aspect ratio of small holes, they readily enable fine, precise control of hole size and shape.

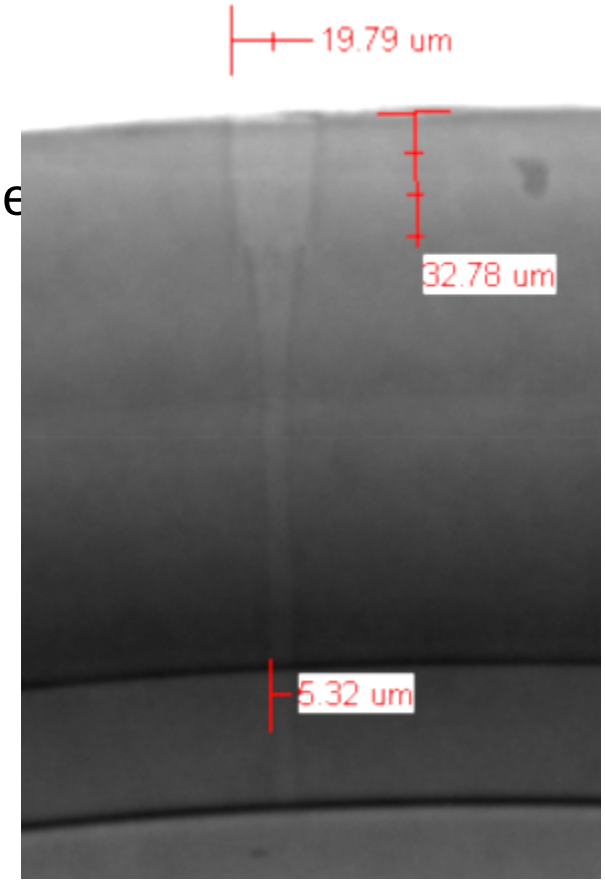
- **Tested in aluminum, beryllium, and silicon**
  - Used to produce counterbores.
- **No physical manipulation of beam or focus.**
- **Pulse format is only change.**
- **Exercising μm control on size /shape over 25,000 μm from a simple focusing lens.**





Conclusions: the limitations to aspect ratio are determined by these 3 (useful ?) processes acting in concert.

- **Radial expansion by plasma ablation increases hole size (lowers aspect)**
  - Reduces transmission losses (raises aspect).
  - Larger diameter increases optical mode size
    - Reduces laser intensity at hole bottom (lowers aspect).
- **Redeposition**
  - reduces hole size (raises aspect)
  - but degrade/blocks the hole.
  - Redeposition also helps shape the counterbores.
- **End result is a sum of all processes.**
  - 35:1 in metal and 80:1 in silicon.



Conclusions (continued)

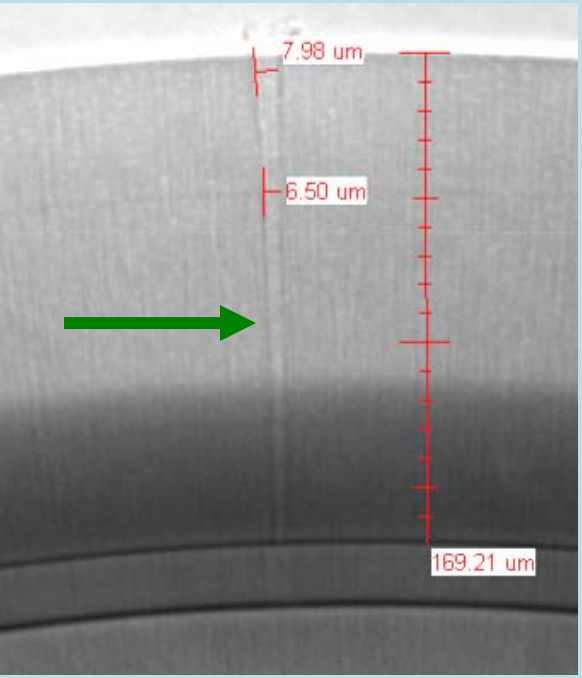
- **The double pulse format uses selected laser ablation debris to:**
  - Improve drillling speed and quality.
  - Increase material removal efficiency.
  - Increases the aspect ratio.

- **The plasma characteristics and optical waveguiding play a key role;**
  - going to femtosecond or shorter wavelength either may or may not help increase the aspect ratio of micromachined structures.

- **If you can live with turbulent flow and the need to use a secondary laser pulse to mitigate redeposition, small high aspect ratio holes may be a tool for doing pseudo 1-D laser plasma experiments.**

Why use double pulse ?

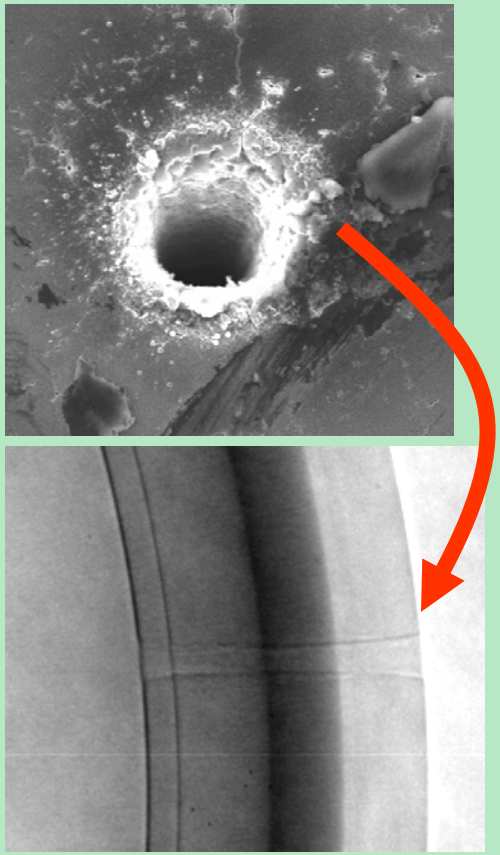
Double pulse can make good small high aspect ratio holes.

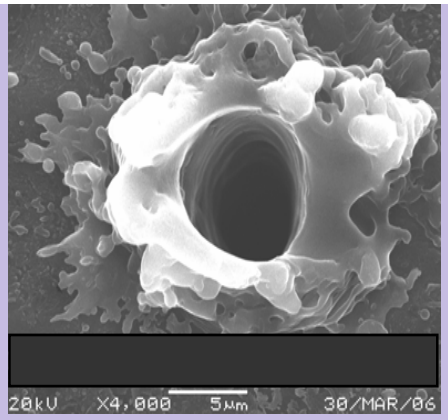


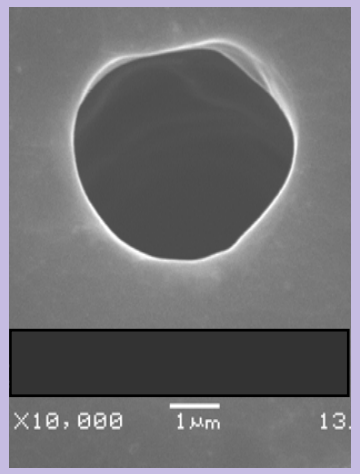
5 μm hole in 170 μm of layered beryllium

(average diameter)

25 μm hole helically drilled in 150 μm of layered beryllium



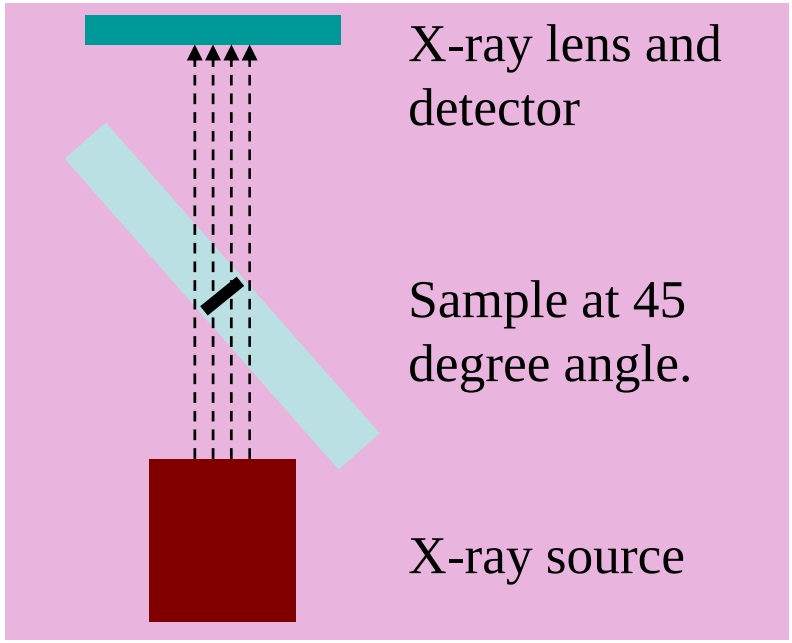


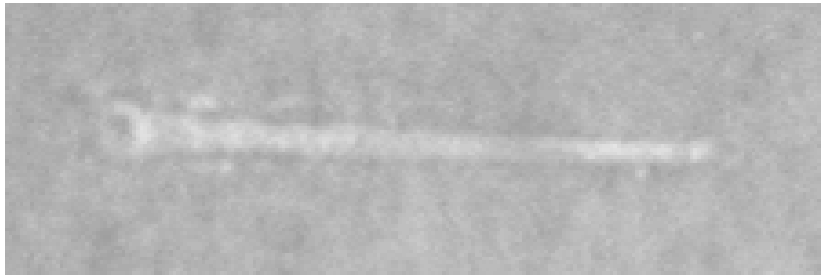


Entrance and exit of 6 μm hole in 175 μm of beryllium

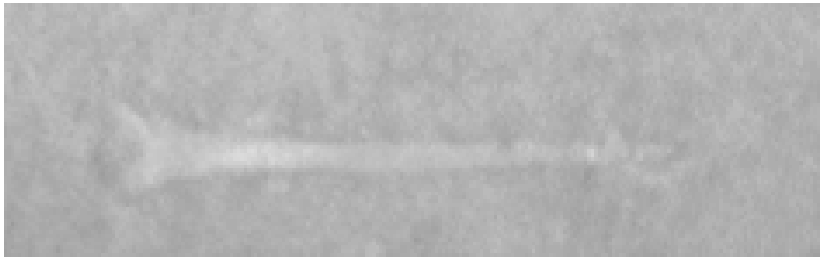
5 μm hole in 150 μm thick aluminum foil

- **Holes are measured using an x-ray microscope.**
  - Foil samples are X-rayed at a 45^0 angle
  - "compresses" apparent length of hole.





2000 double pulse shots (through)



2000 single pulse shots (not through and more taper)

Total fluence and energy is the same, 532 nm, 25 mm lens.