CONFLUENT

Ultrafast Laser Cutting of Low Mass Superelastic Nitinol Parts

M. D. Shirk, J. E. Harrington, C. Trepanier, and T. W. Duerig

SMST2017

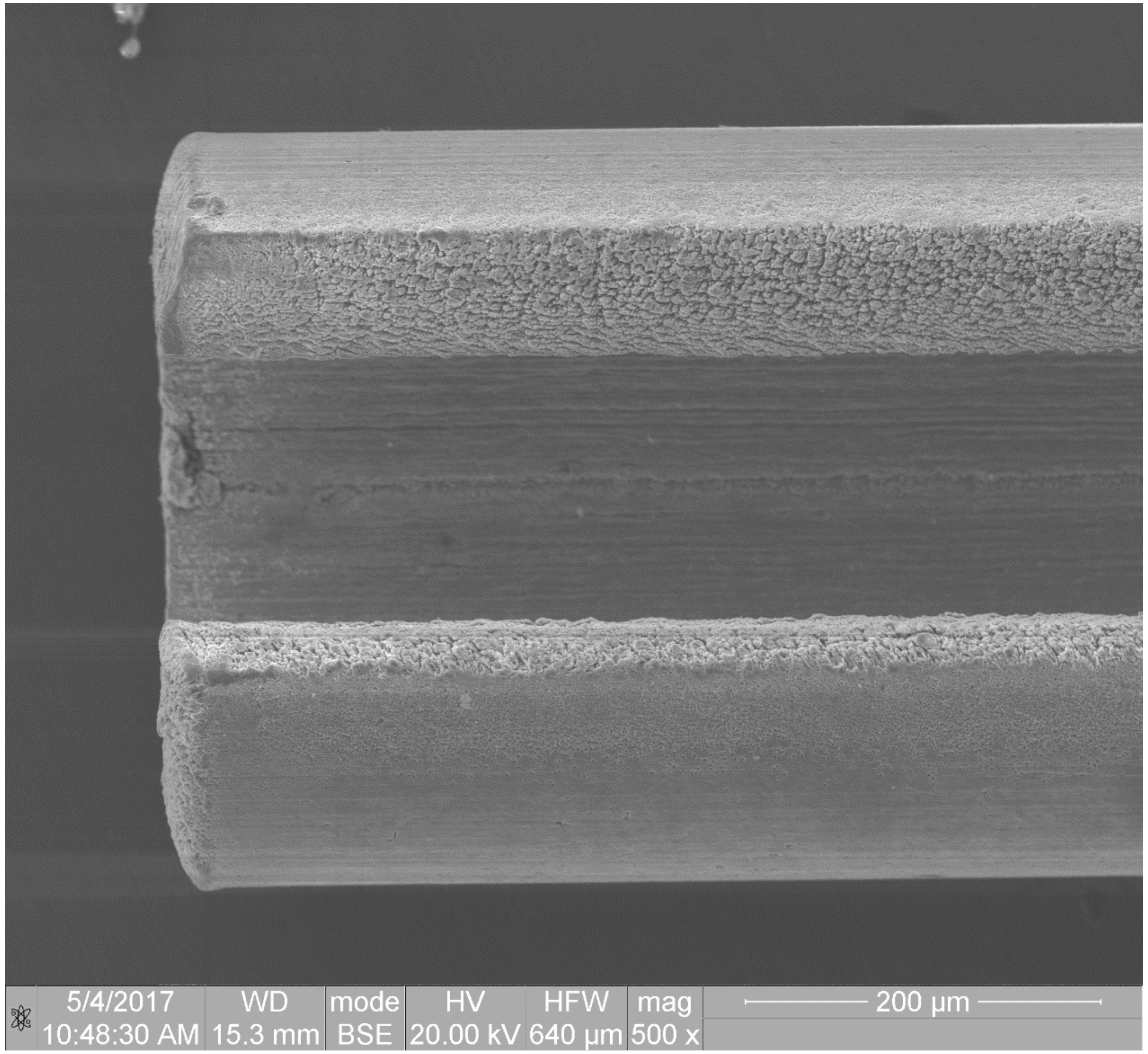
SHAPE MEMORY AND SUPERELASTIC TECHNOLOGIES CONFERENCE AND EXPOSITION

How can one cut up nitinol (SE 508) small diameter tubing (<0.5 mm) into small parts?

- What are the constraints on the process?
- What are the concerns?
- Why use ultrafast lasers over other laser technology?
- What is meant by “Ultrafast” when speaking of these lasers?
- Why use DSC instead of other methods to characterize thermomechanical properties of the parts?

Test coupon

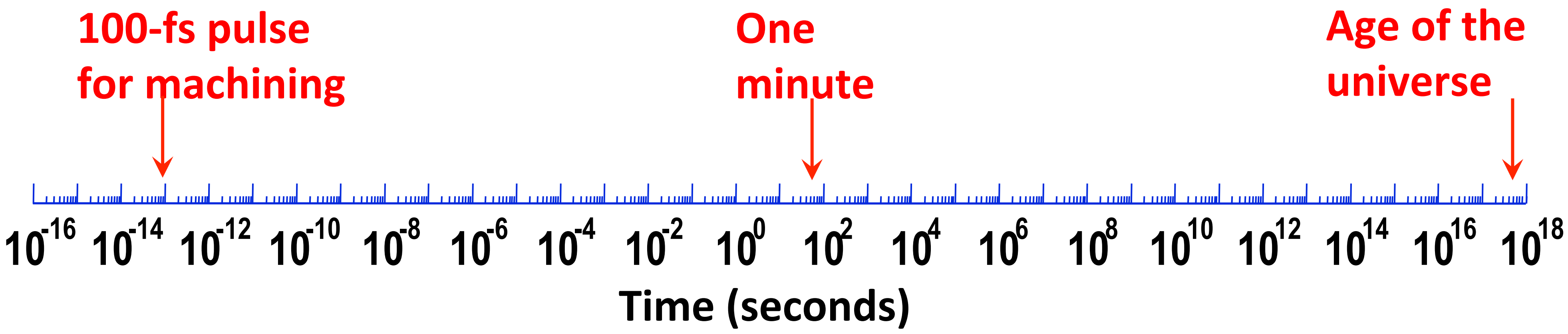
- Cut from small tube < 0.5 mm diameter
- SE508 nitinol
- Part length ~1 mm in length
- Tubing wall <100 μm
- Radial cut, 2 axial cuts, radial cut to length
- **Laser Process should not change thermomechanical properties**



Process constraints and concerns

- Cutting speed has to be fast enough to make parts that are economically viable
- Water assist is impractical due to tube diameter and part size
  - No 2nd surface protection from overburn
  - No thermal sink to keep temperatures low
- Parts are too small to remove dross or post process individually
- Parts are too small to remove from tumbling media
- Parts are too small to easily test mechanically

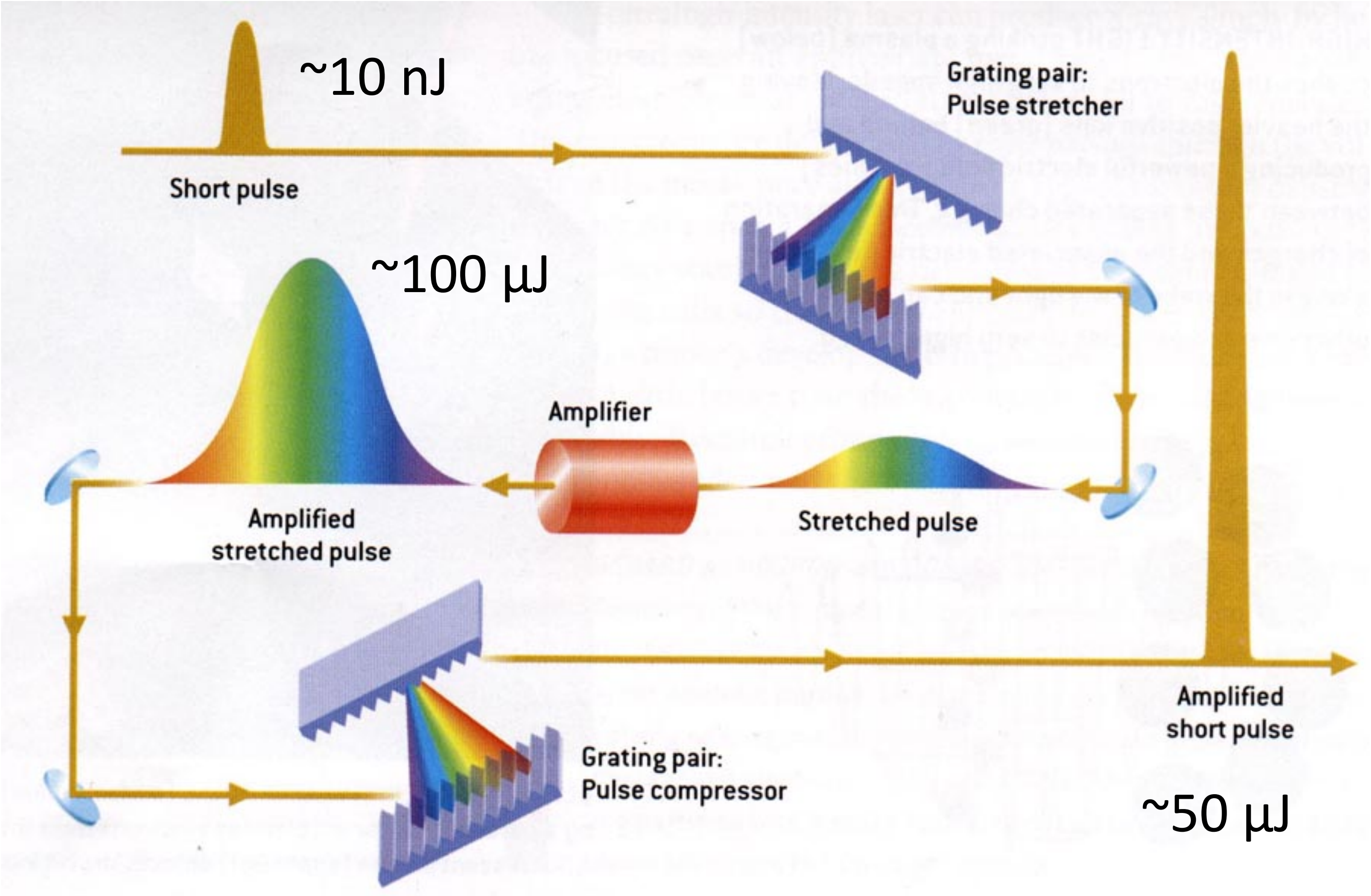
BACKGROUND: Ultrafast laser machining condenses interaction down in all 4 dimensions: X,Y,Z, Time



One nanosecond = One billionth of a second (10^{-9} sec)
One picosecond = One trillionth of a second (10^{-12} sec)
One femtosecond = One quadrillionth of a second (10^{-15} sec)

Light travels 30 cm (1 foot) in one nanosecond
Light travels 30 microns (≈0.001”) in 100 femtoseconds

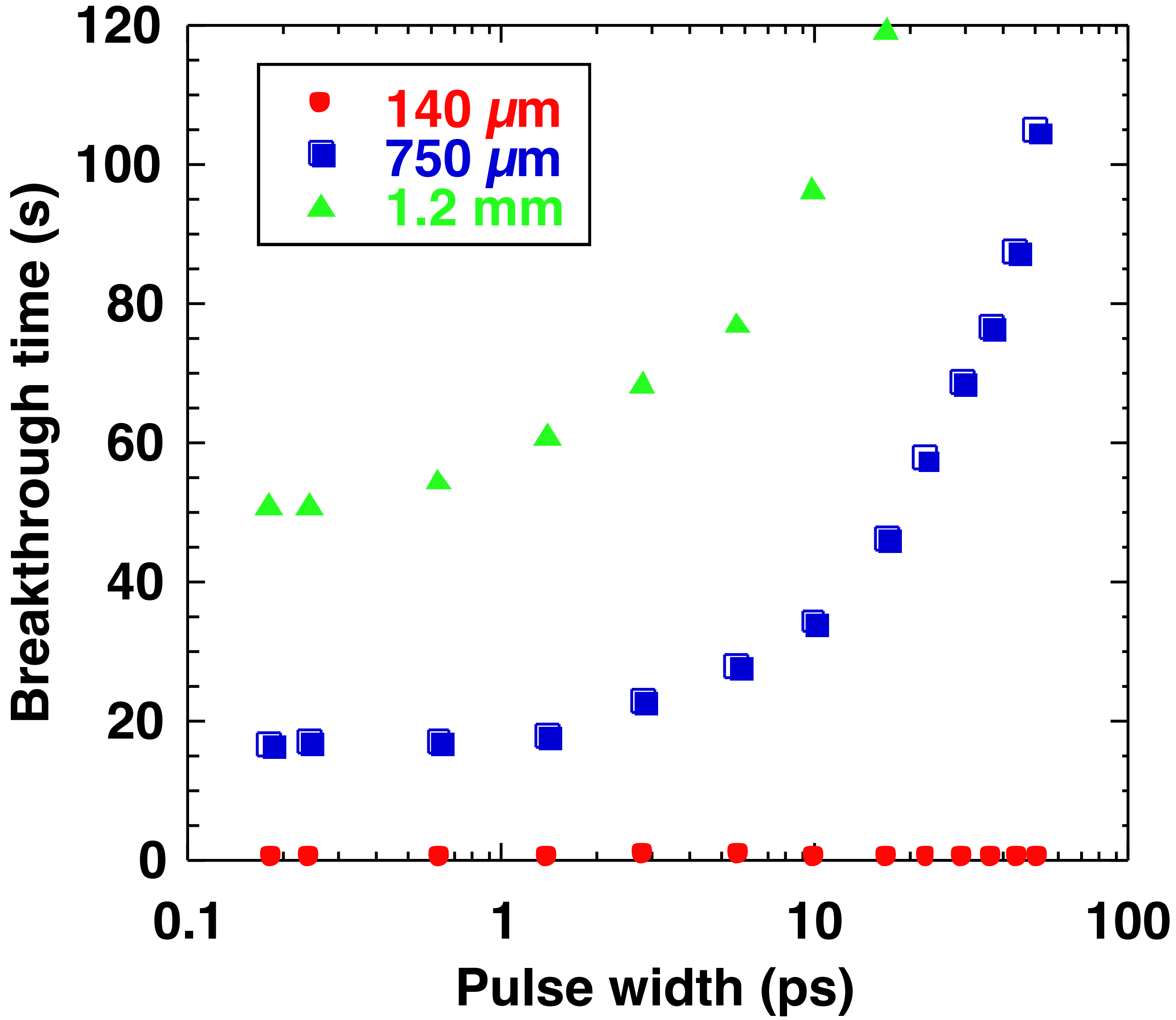
BACKGROUND: How do lasers make ultrashort (< 3 ps) pulses?



https://cuos.engin.umich.edu/researchgroups/hfs/facilities/chirped-pulse-amplification/

- Laser oscillator emits short, broad spectrum pulse (shorter the pulse, broader the spectrum)
- Gratings in pulse stretcher uses chirp to stretch pulse so that it can be amplified
- Stretched pulse is amplified
- Amplified pulse is passed through compressor – reverses chirp
- Gratings are expensive
- Laser is complex to set up due to Stretcher/Compressor architecture
- Lose a lot of photons in compressor

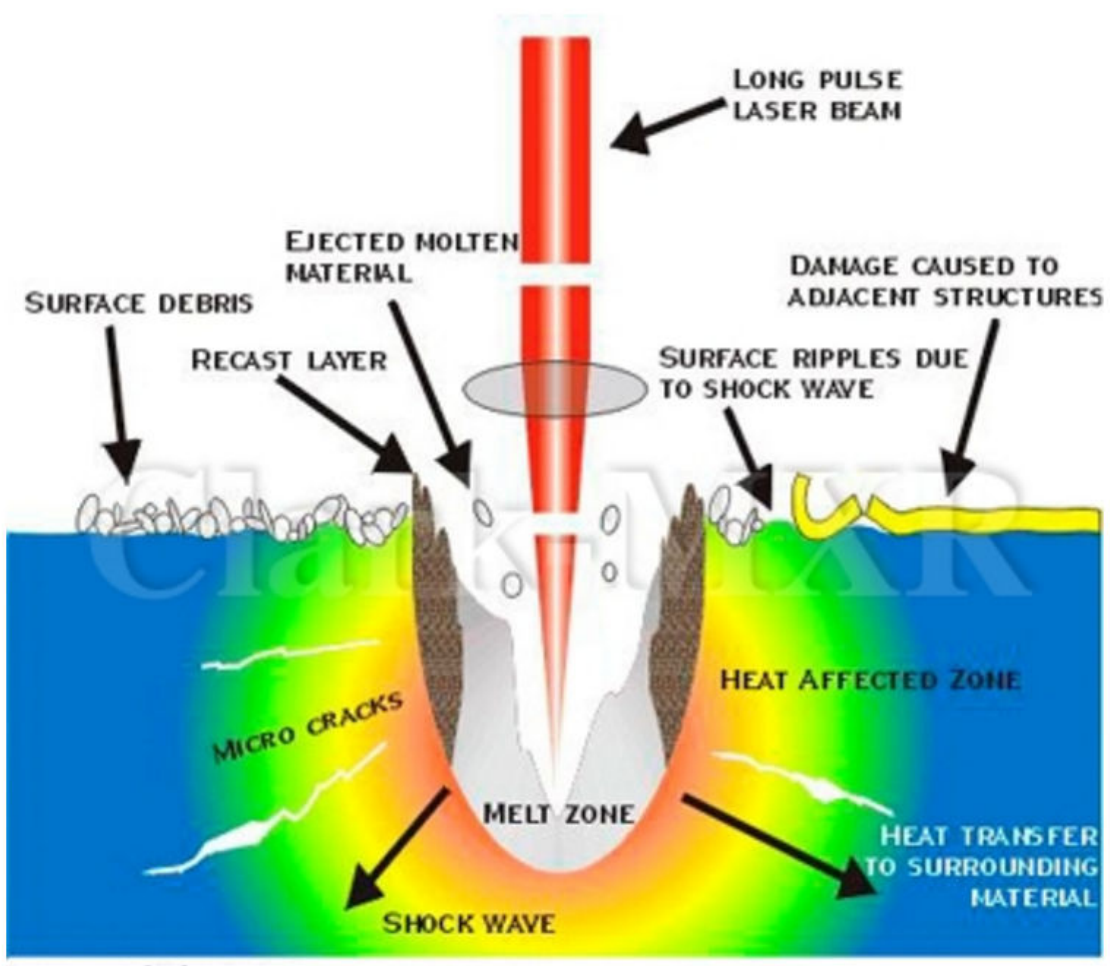
BACKGROUND: **For cutting thicker material 1-2 ps is an important inflection point – The physics change there.**



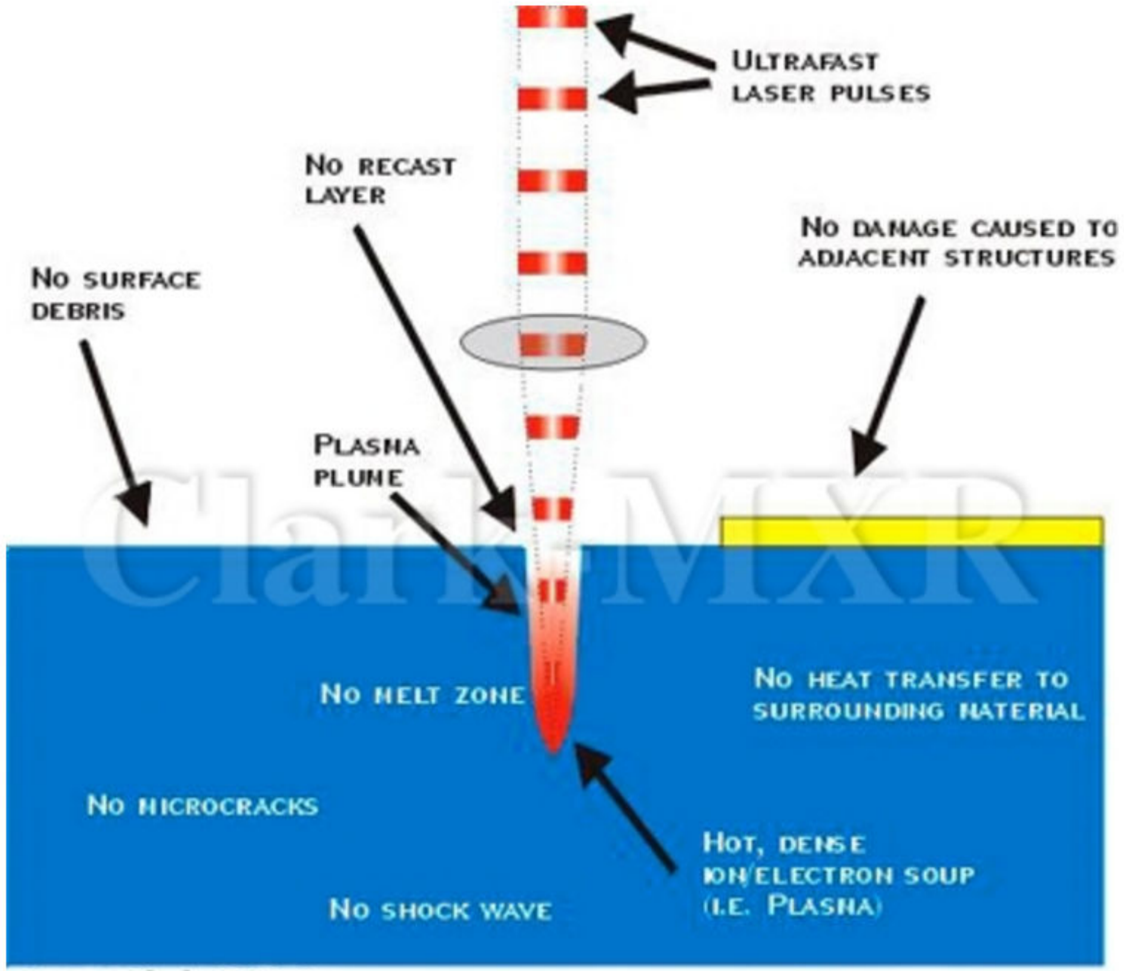
- **time to drill through 316 stainless steel at 12 J/cm^2 and 1kHz**

Femtosecond Laser Materials Processing
P. S. Banks, B. C. Stuart, A. M. Komashko, M. D. Feit, A. M. Rubenchik, and M. D. Perry
Photonics West 2000 Symposium, San Jose, CA

BACKGROUND: Heating of bulk from laser beam



© 1999 Clark-MXR, Inc.

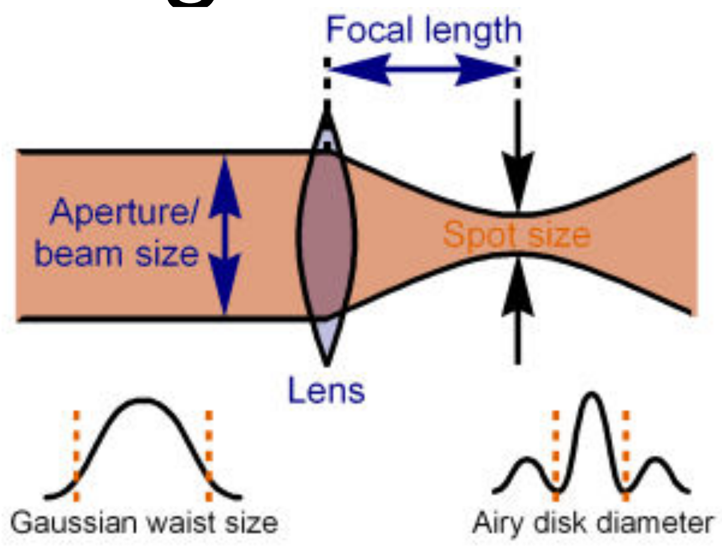


© 1999 Clark-MXR, Inc

Ultrafast results in non-negligible heat transfer to the part.

What variable are important for laser machining?

- Fluence (F)
  - Pulse energy (E)
  - F/# - Controls focused spot size (2w at 1/e^2) and depth of focus



http://www.calctool.org/CALC/phys/optics/f_NA

$F/\# = (Fl/D)$

$2w = (4\lambda/\pi)(Fl/D)$

$F = 2E/\pi w{\uparrow}2$

- Pulse repetition rate –pulses per second (kHz)

BACKGROUND: Where could the heat come from for ultrafast ablation?

Laser absorption

- Gaussian wings below ablation threshold
- Interactions with previous pulses ejecta

Plasma interaction with side walls

- Large aspect ratio (depth:diameter) increases effect
- Hotter plasma exacerbates (too much fluence/intensity)

Thermal conduction and shock waves

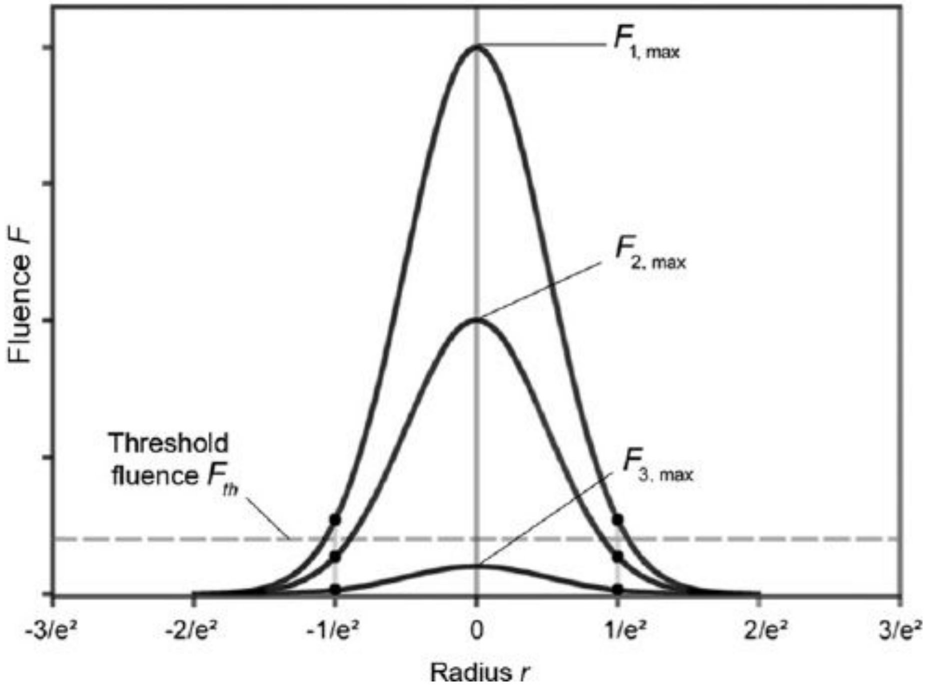
- Residual hot material
- Shock waves caused by Newton's 3rd law

S. Darvishi et al, Optics and Lasers in Engineering 50(2) · October 2011

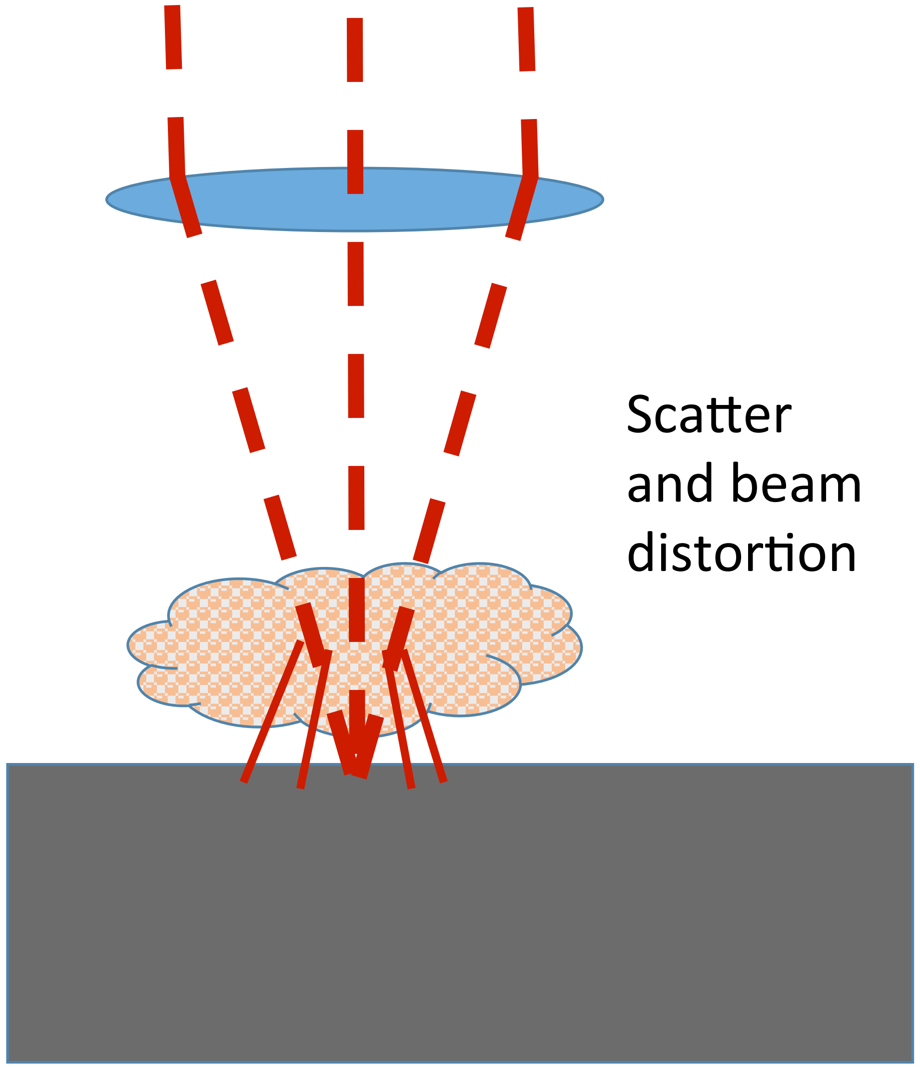
BACKGROUND: Where could the heat come from?

Laser absorption

- Gaussian wings below ablation threshold
- Interactions with previous pulse’s debris



S. Darvishi et al, Optics and Lasers in Engineering 50(2) · October 2011

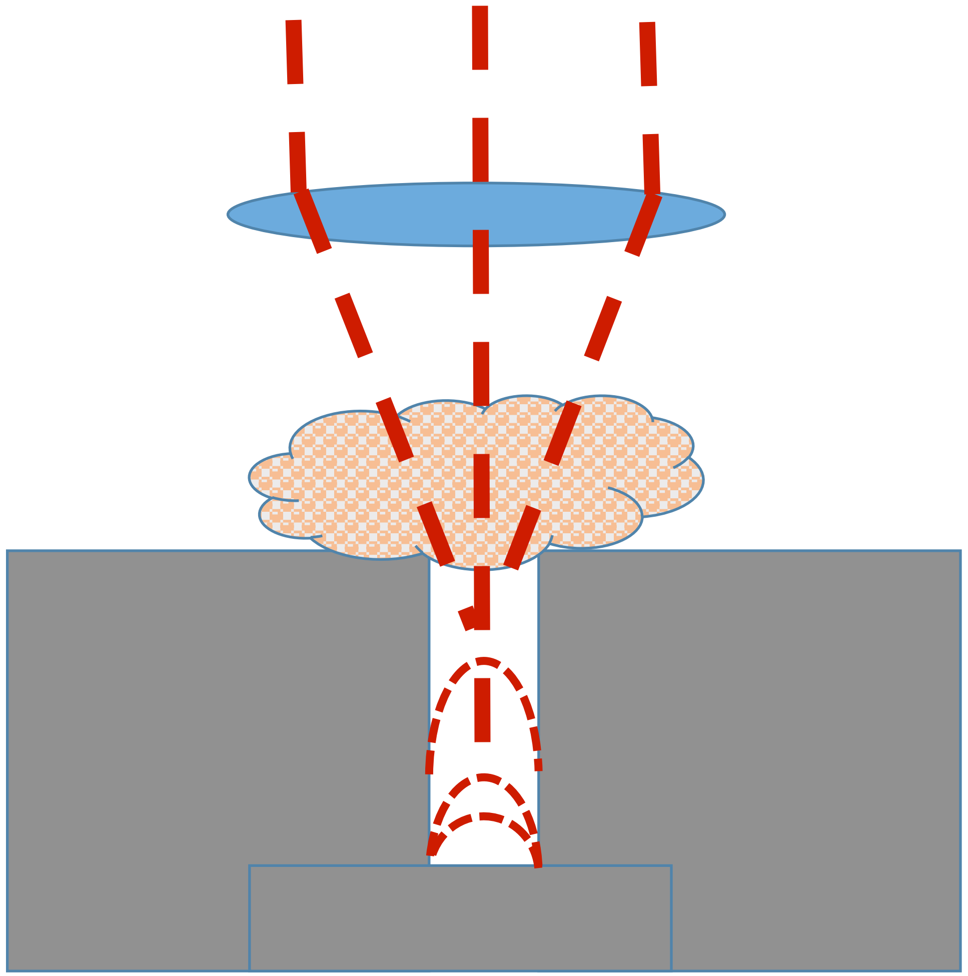


Scatter and beam distortion

BACKGROUND: Where could the heat come from?

Plasma interaction with side walls

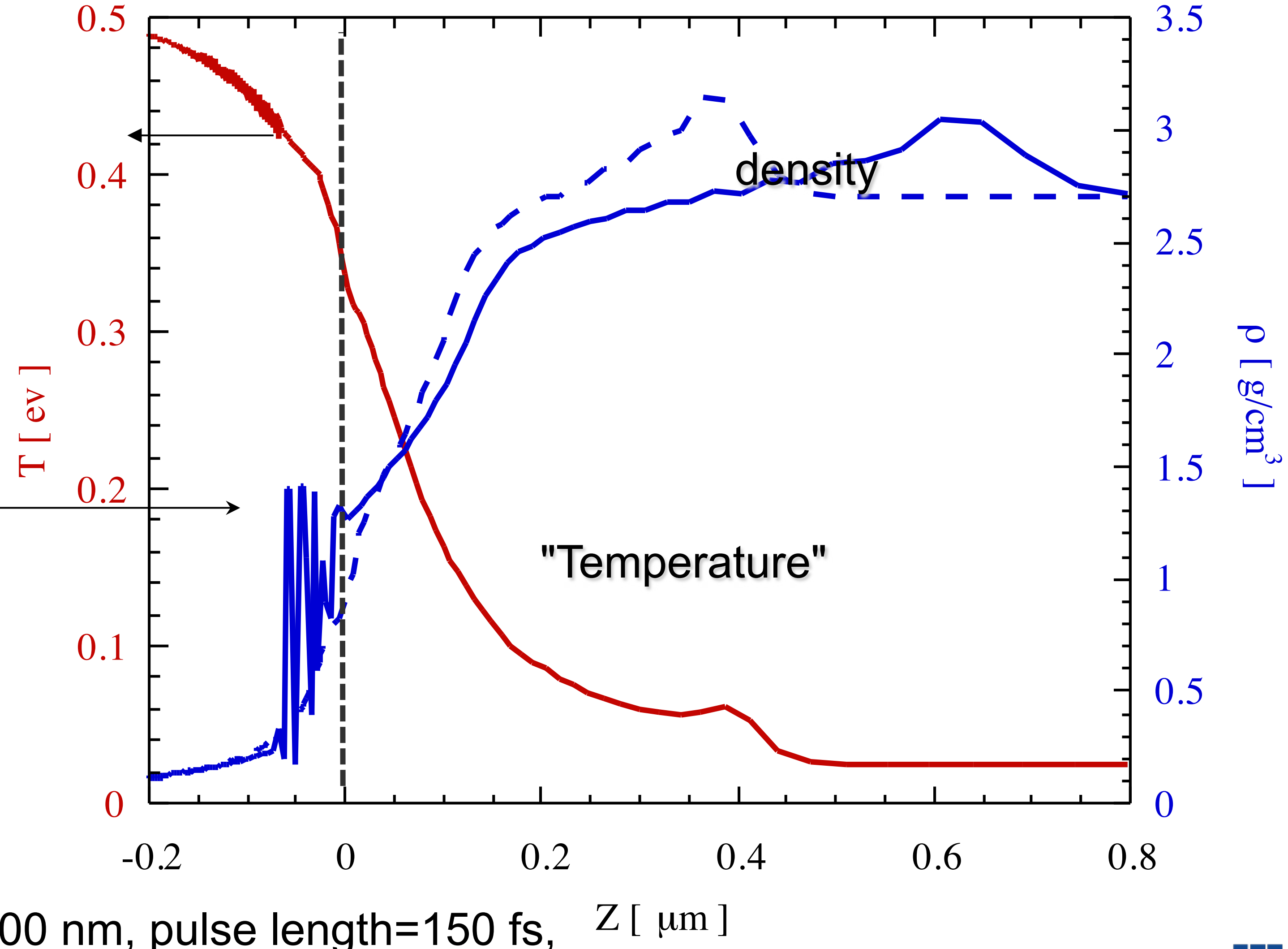
- Large aspect ratio increases effect
- Hotter plasma exacerbates



The hotter and more constrained the expanding material is, the more energy it will redeposit in the part.

Plasma interaction + shock waves

HYADES (Radiation/hydrodynamics simulation) shows spatial distribution of density and temperature at 50 ps (dashed line) and 100 ps (solid line) after the laser pulse

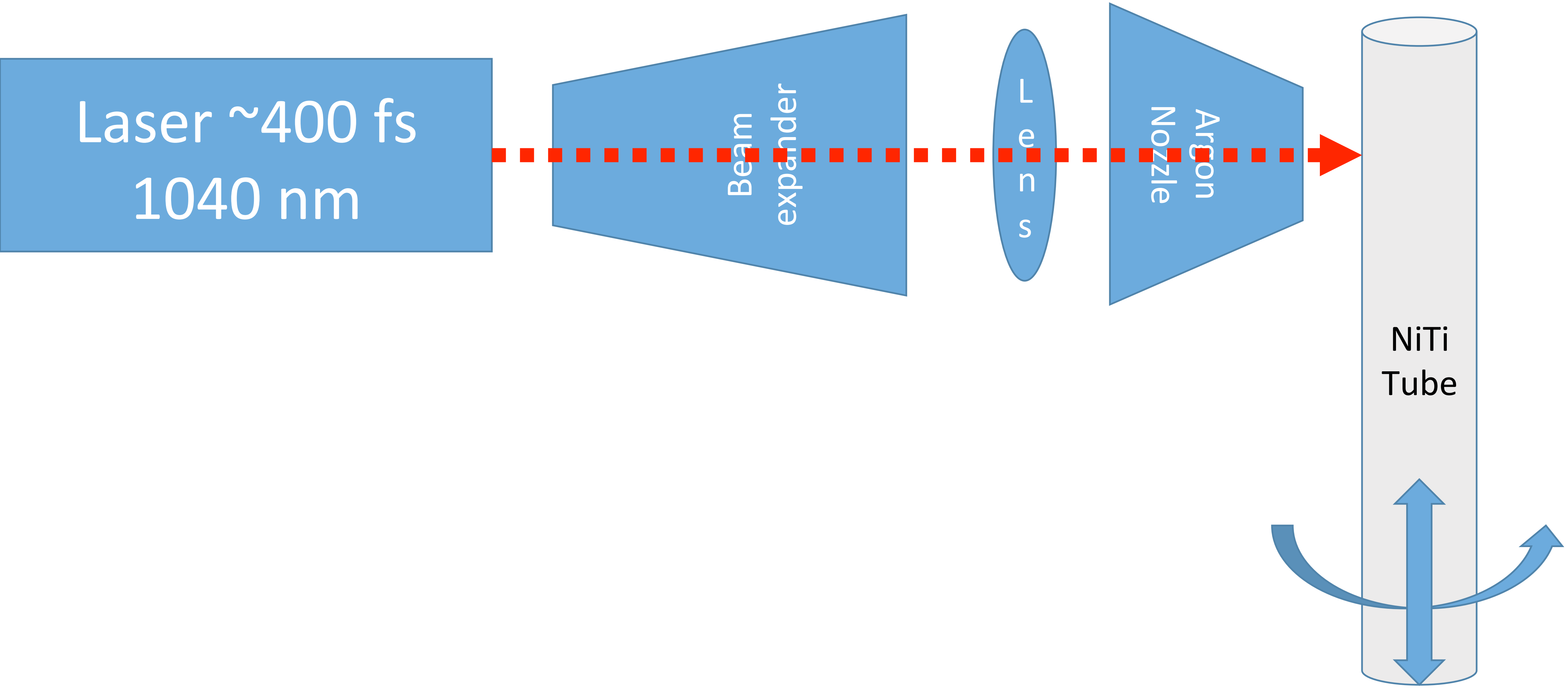


Unstable,
overheated
fluid

A. Rubenchik

Aluminum, wavelength=800 nm, pulse length=150 fs, intensity=10^{13} W/cm^2, normal incidence, absorption ~ 18%

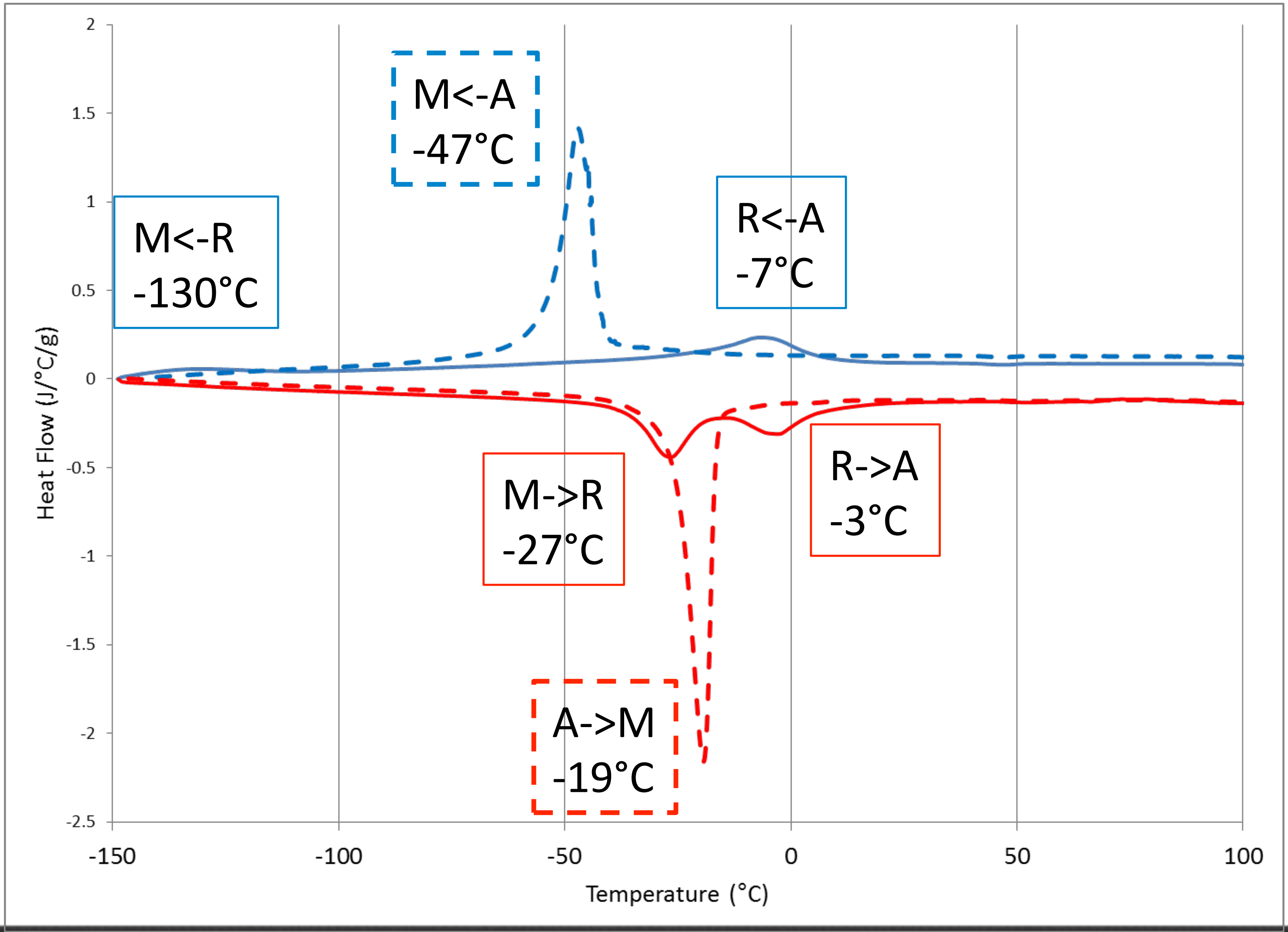
EXPERIMENT: Simplified tube cutter setup



Experimental ranges

	Pulse Energy	Pulse Rate	F/#
Maximum	40 uJ	200 kHz	33
Minimum	10 uJ	100 kHz	16

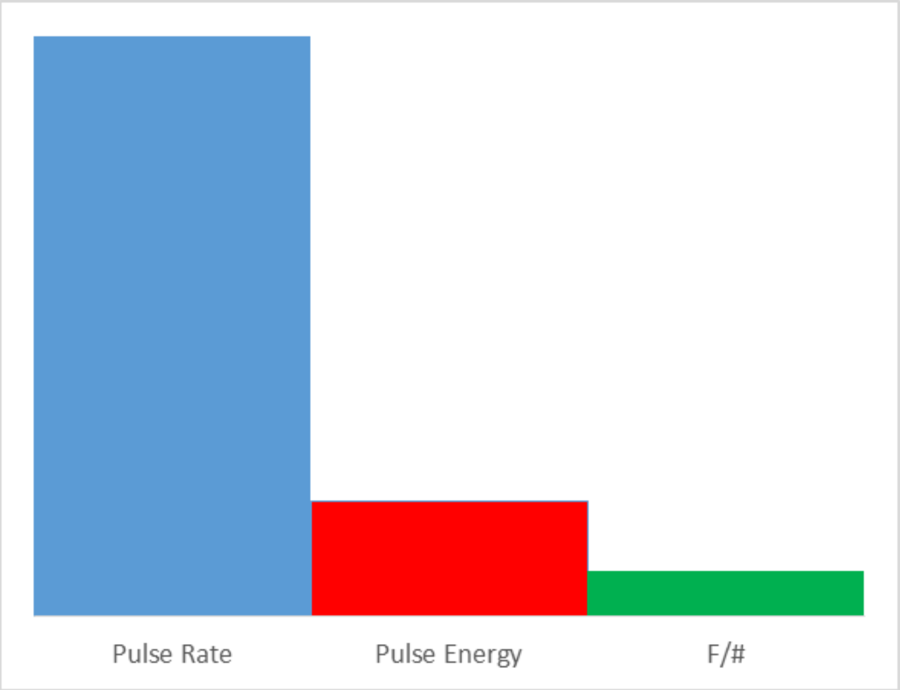
DATA: Solid lines shows DSC of untreated material. Dotted lines are from first attempt at femtosecond cutting



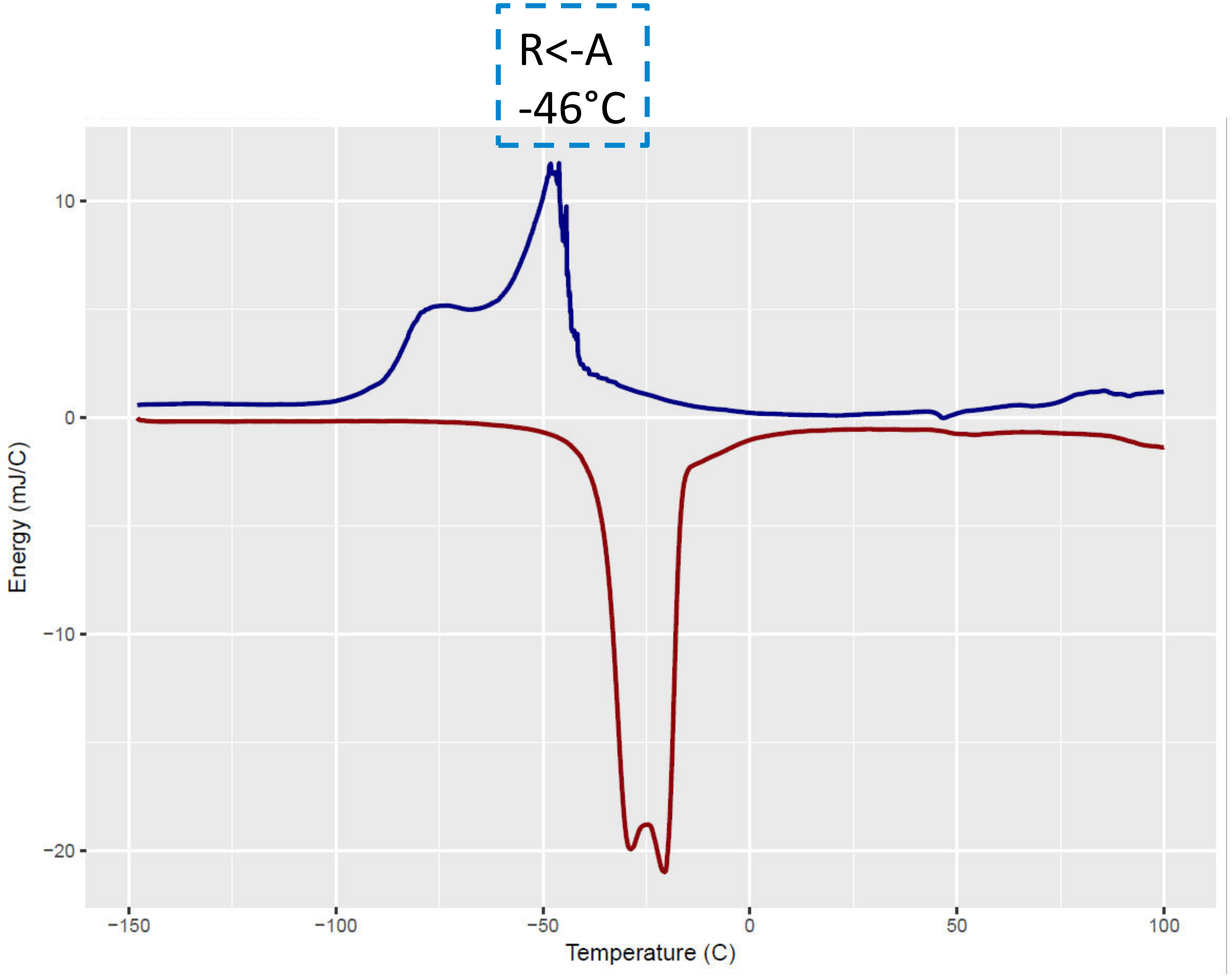
Peaks have narrowed and shifted.

Bottom line is these parts got very hot!!!

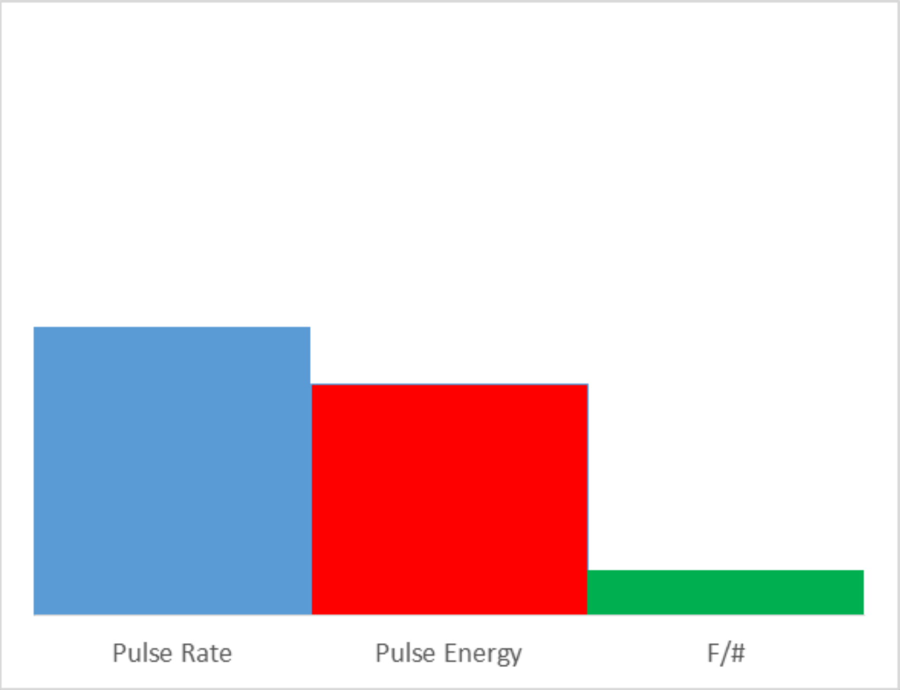
Fully annealed, likely > 800 C



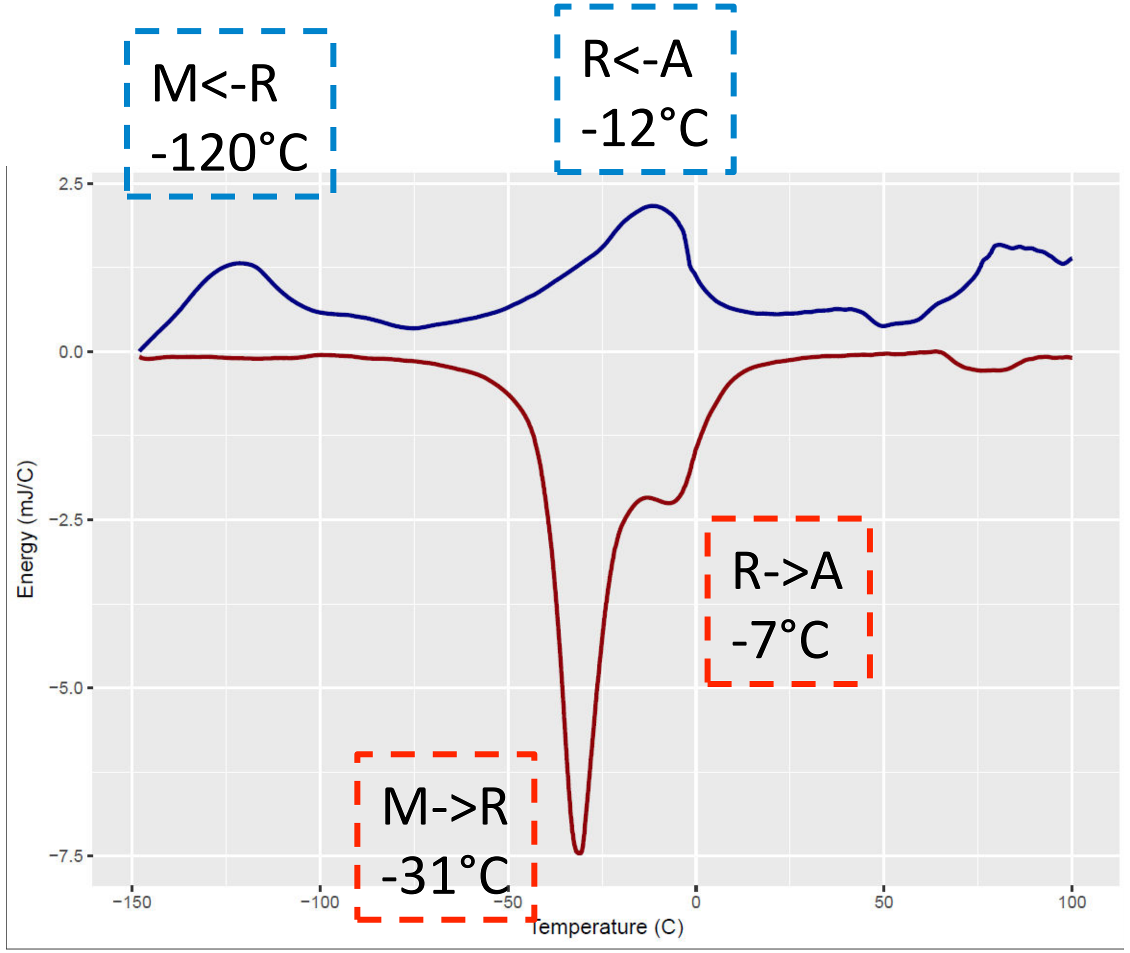
Reduced heating with reduced pulse repetition rate.

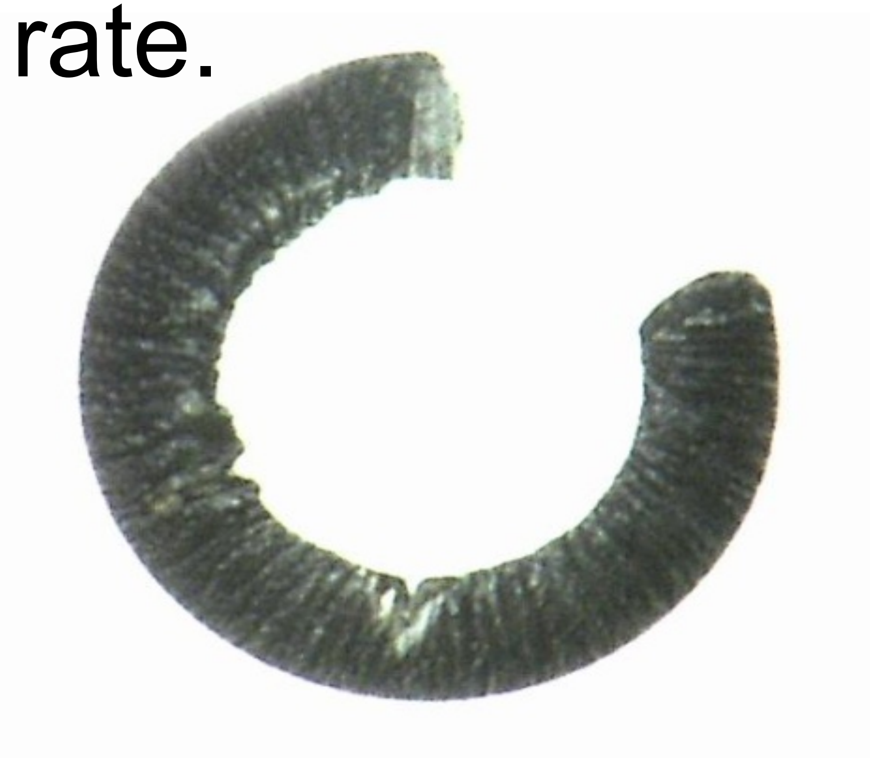

R<-A
-46°C

This run shows result of the experiment to reduce pulse rate from 200 kHz to 100 kHz with original optics (F/#~16).
Peaks are broader than initial treatment, but still show evidence that the material is highly annealed.



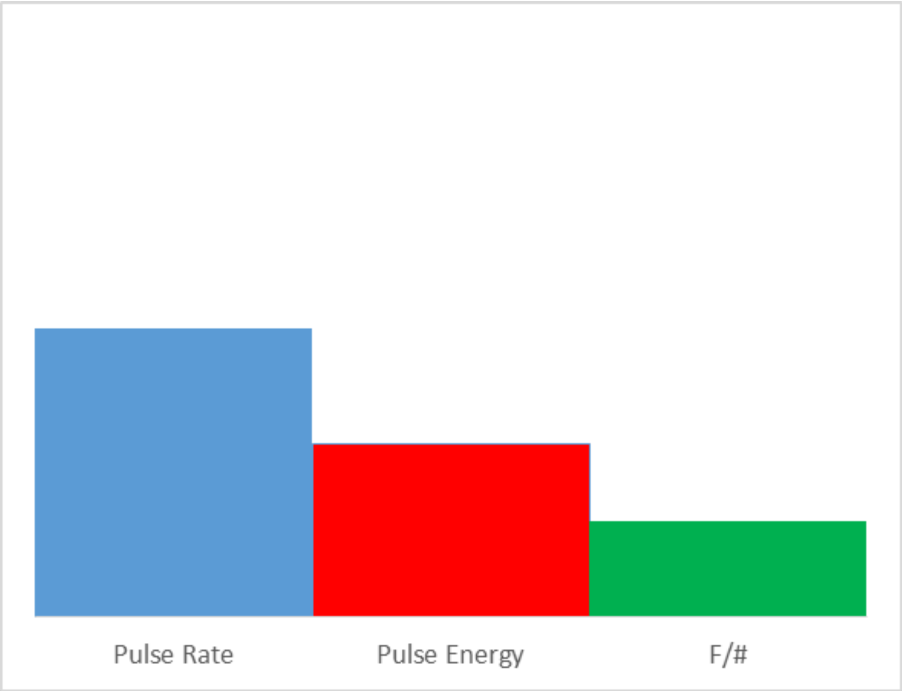
Reduced heating with reduced fluence (both F/# and pulse energy) and pulse repetition rate.



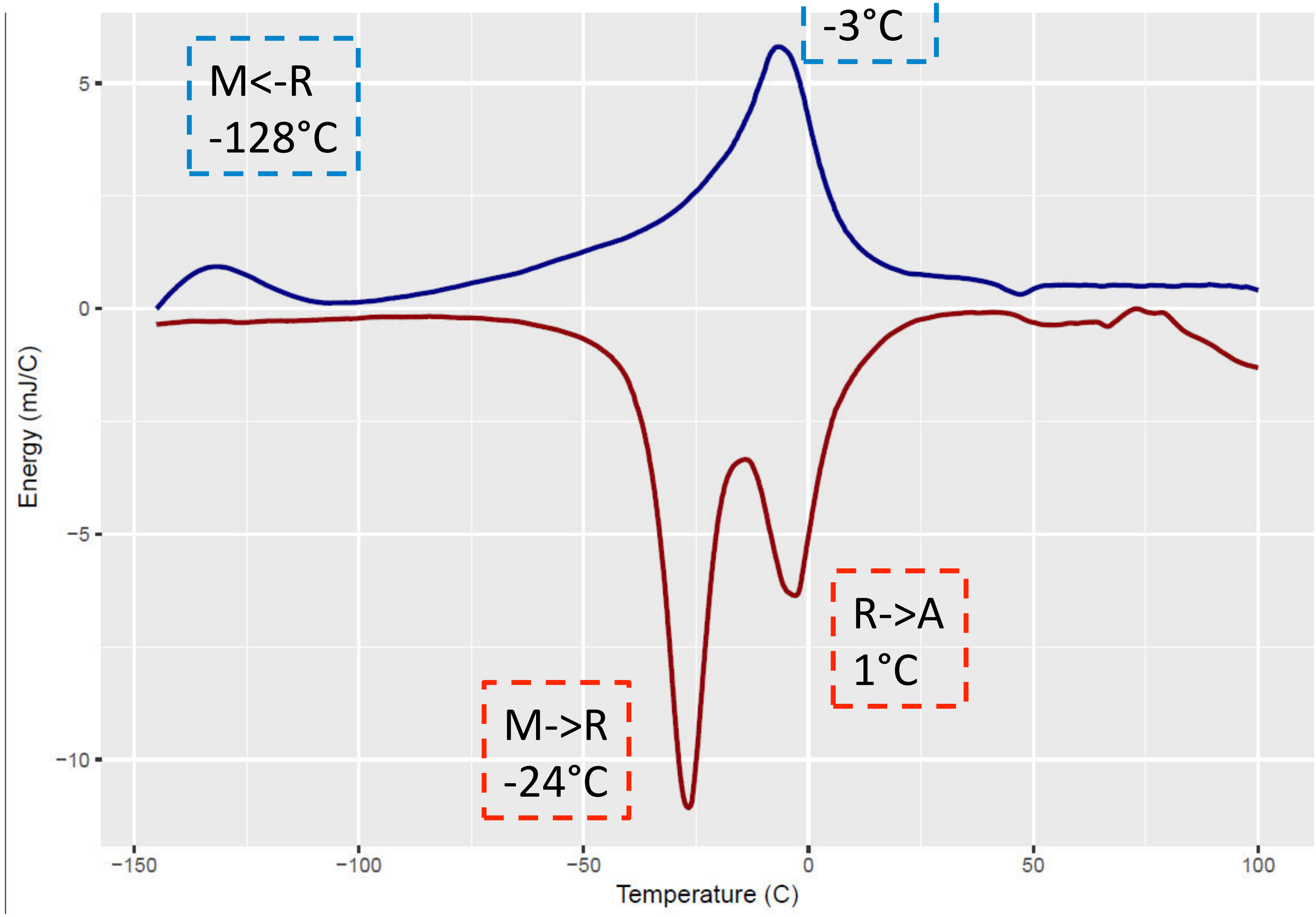


This sample had considerable overburn as well.

DSC peaks were much closer to starting tubing but there is still evidence of annealing



Optimal settings: No shift in peaks from base material.



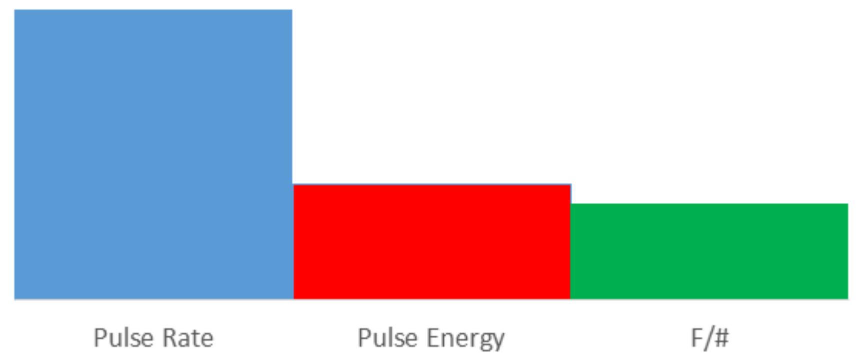
R<-A
-3°C

M<-R
-128°C

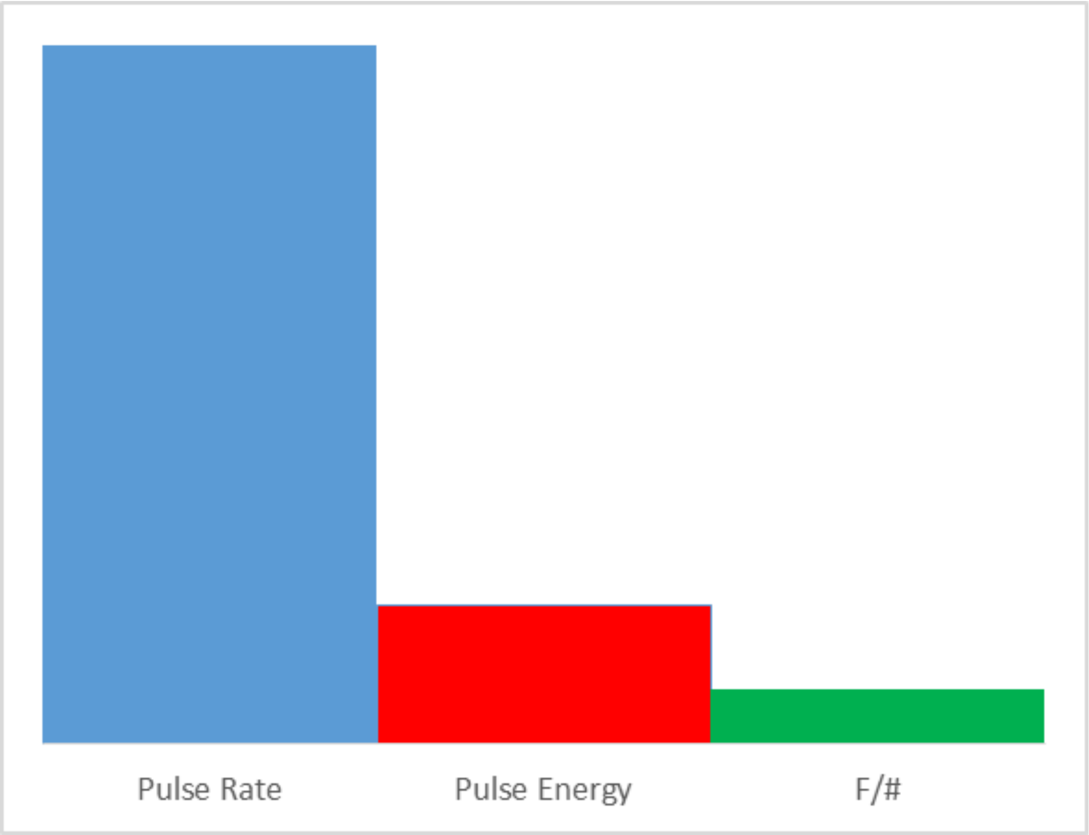
R->A
1°C

M->R
-24°C

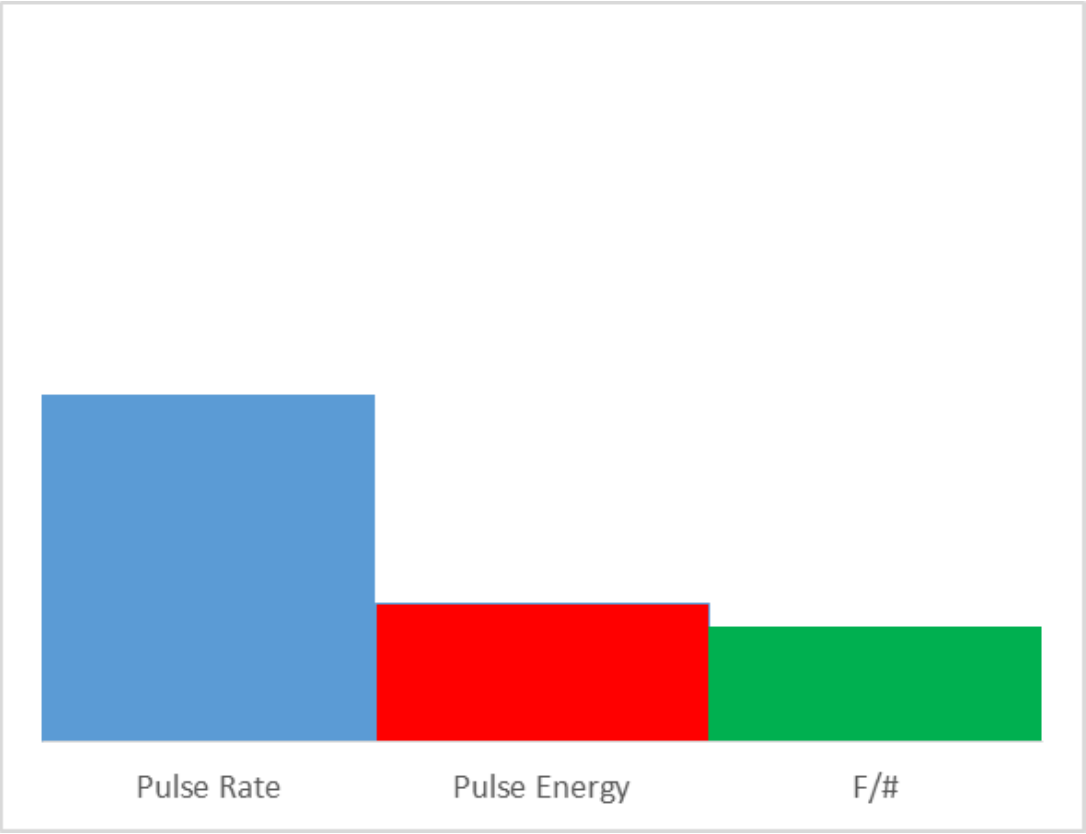
This condition showed no overburn.



Optimization of pulse rate, F/#, and pulse energy were all necessary to yield an athermal process.



Starting conditions



Final conditions

Conclusions

- Low mass parts can be heated up to very high temperatures with ultrafast laser cutting
- Optimizing process parameters is critical to maintaining nitinol properties
- DSC was a sensitive tool to assess how much heat was actually transferred to the parts.

Ultrafast lasers are often claimed to be "cold cutting", but it is clear that the story is more complicated than that. Fluence, pulse repetition rate, and cut aspect ratios can all make significant difference in the actual process

Thank you

Michael Shirk, PhD

michael.shirk@confluentmedical.com