Laser Micromachining of Optical Structures and Surfaces

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Development of a Laser Micromachining Process for the Fabrication of SiC Mirrors

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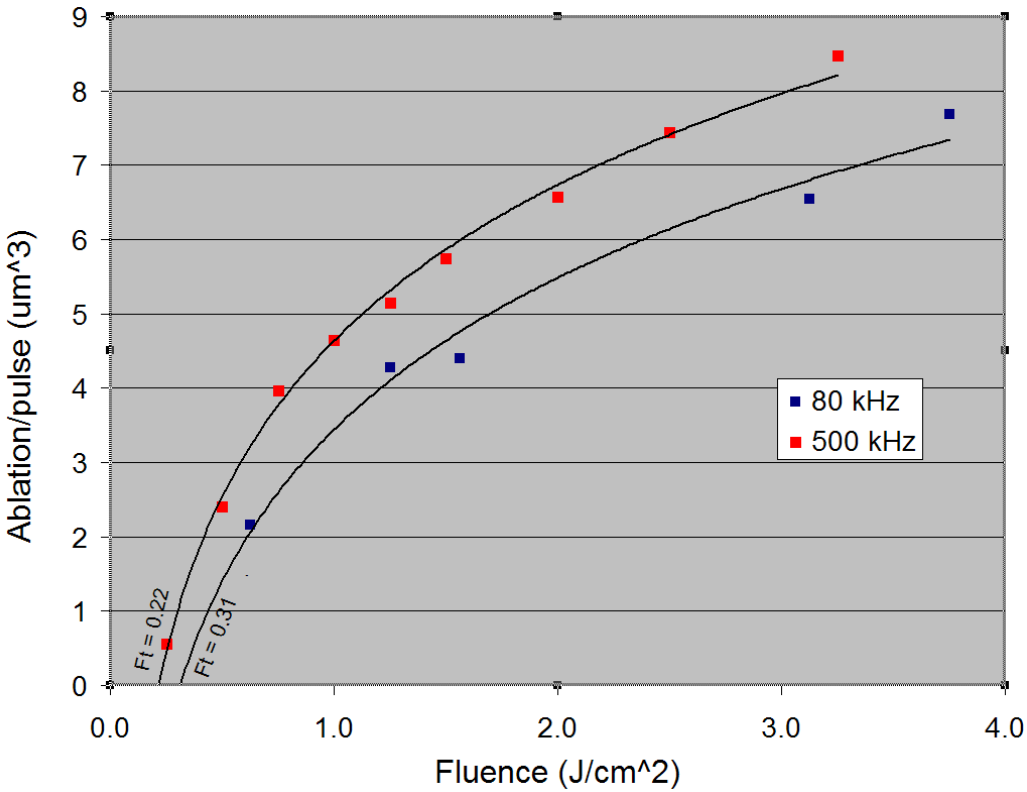
Program Goals

- Gain practical understanding of pulsed laser ablation of SiC materials being considered for mirrors.
  - Ablation data
  - Machining quality
  - Practical ablation rate
  - Roughness
  - Laser control issues
- Develop laser micromachining algorithms for arbitrary shaping of SiC blanks (e.g. aspheres)
  - Guidance from metrology
- Develop laser micromachining workstations for practical mirror shaping.
  - Scan head guidance.
  - Direct focus w/ translation/rotation stage.

Laser and Materials

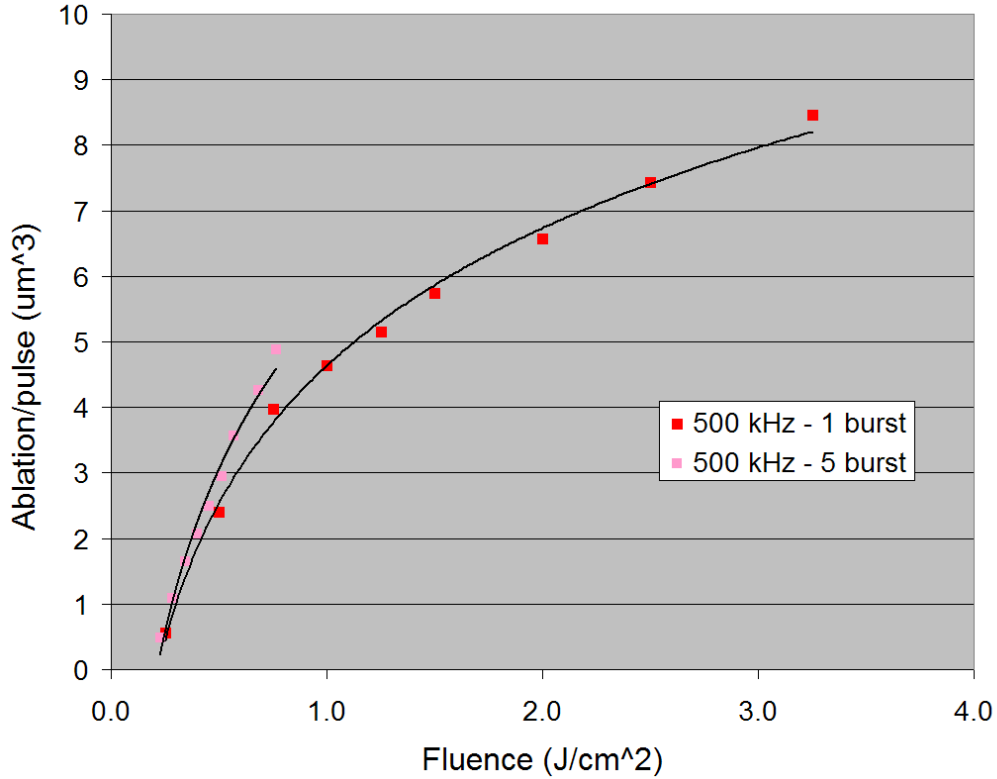
- Picosecond pulses expected to give direct ablation that avoids leaving extended heat affected zone.
- SuperRAPID by Lumera
  - Pulse duration ~10-14 ps
  - Wavelength choices 1064, 532, 355 nm
  - Pulse frequency from 10 – 640 kHz
  - Burst mode option releases selected number of pulses at 50 Mhz with each trigger of the laser.
  - Nominal max power = 10W (a 50W version will be available soon.)
- Experimentation focused on two SiC materials
  - Trex SiC: relatively smooth initially
  - Poco SuperSiC-2: very rough, but easy to make near net shape

Ablation Curves for SiC



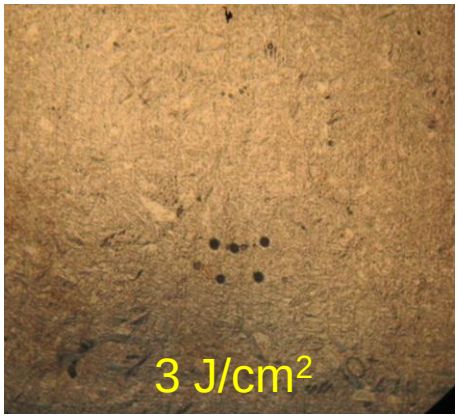
- Ablation/pulse characterized by logarithmic fit. (Bayes Law)
- Threshold fluence, F_t ~ 0.2-0.3 J/cm^2.
- Higher frequency pulses remove more material – local heating due to pulse overlap
- Ablation/pulse is comparable for Trex and Poco materials.

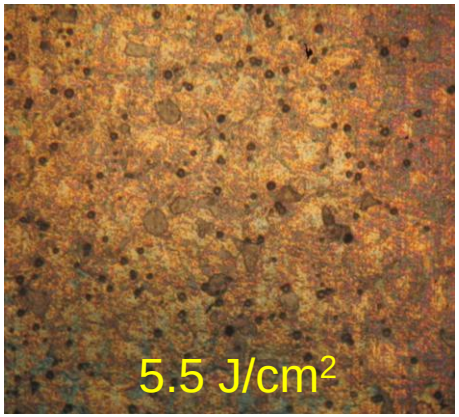
Burst Mode Ablation

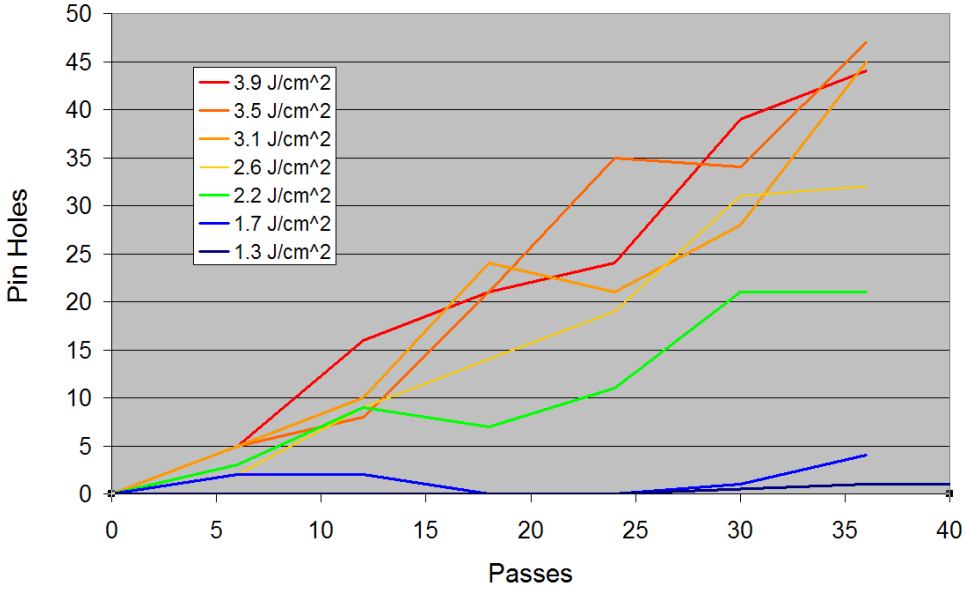


- Burst mode releases multiple pulses at 20 ns intervals (~100% overlap).
- Tests performed at 5-burst.
- The average pulse in a burst removes more material than a lone pulse
- Heating by initial pulses in burst probably facilitates ablation by later pulses in burst.

Pin Holes







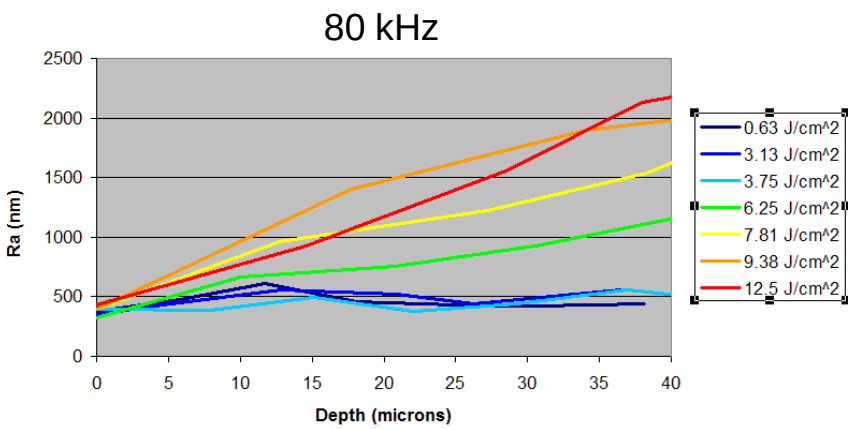
- Picosecond ablation at > 2 J/cm^2 leads to pin holes.
- Number of pin holes increases with number of passes by the laser.
- Observed in both form in both Trex and Poco.
- Cause of pin holes not known. Perhaps local impurities vaporize to create a bubbles.

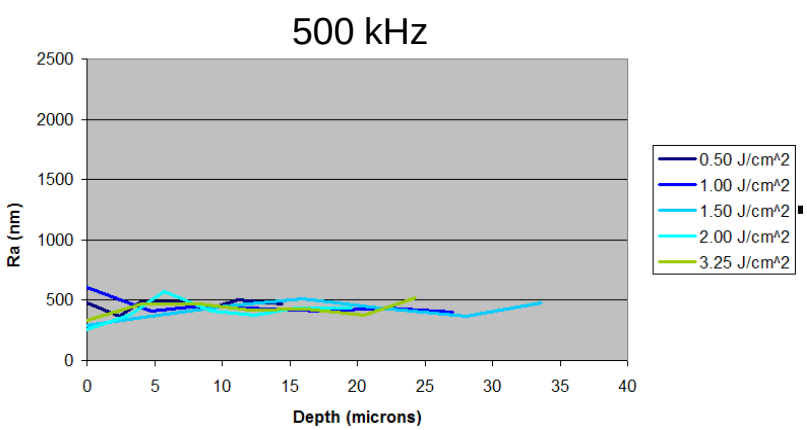
Surface Roughness

With picosecond ablation

- Fluence > 4 J/cm^2 increases roughness
- Fluence < 4 J/cm^2 can mildly reduce roughness
- Effects growth with total depth of ablation (i.e., # of laser passes).

Examples of roughness of Trex SiC specimen as a function of fluence and depth of ablation.



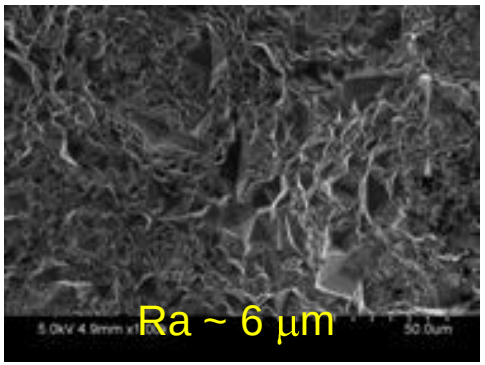


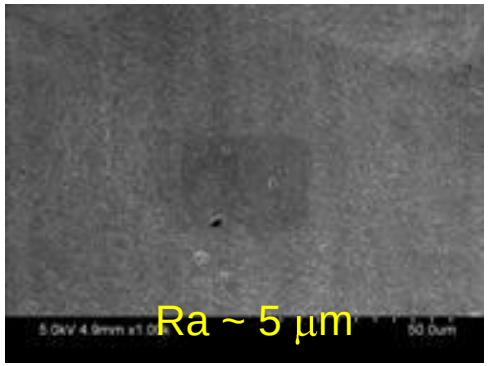
Smoothing of Poco SiC

Original surface

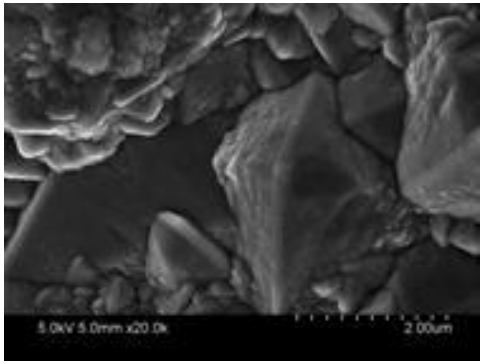
Ablated surface
Fluence = 3 J/cm^2
To depth of 40 μm

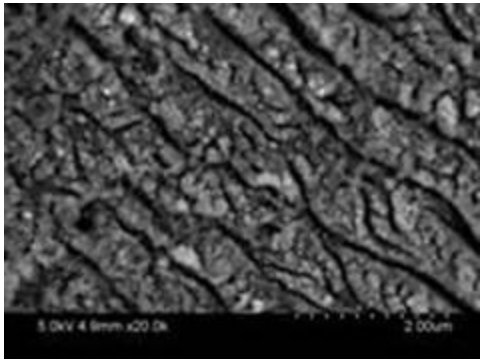
1000 x
50 micron





20000 x
2 micron





Mirco-roughness (Ra excluding spatial wavelengths > 100 μm)

~ 2.2 μm ~ 1.4 μm

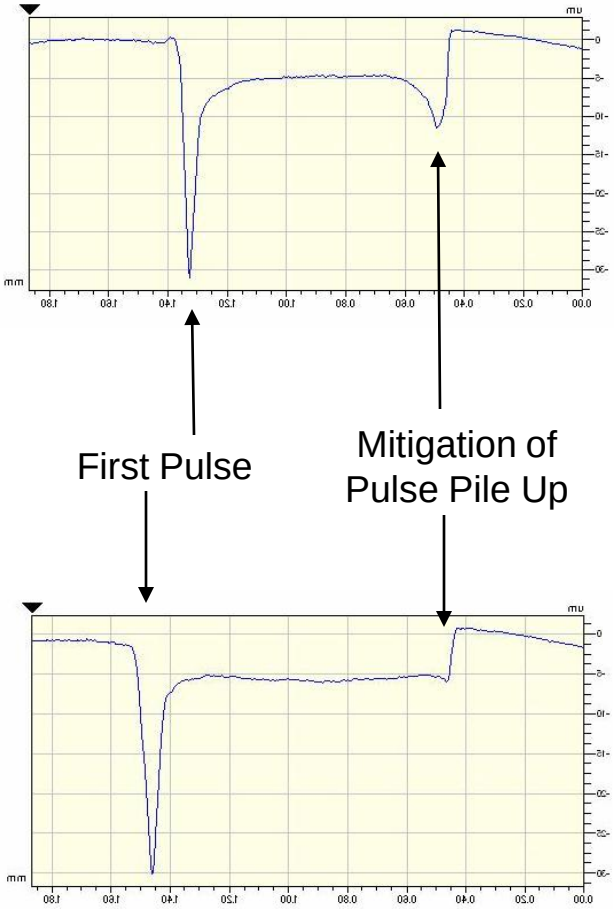
Even ablation of Poco SiC

- changes overall surface height variation only slightly,
- greatly smoothes the micro-texture.

Laser Control

Overmachining may be caused by

- Pulse Pile Up
  - High pulse overlap during acceleration of guidance mirrors
  - Exaggerated at high pulse frequency
  - Can be mitigated by allowing extra acceleration distance, at the cost of extra machining time
- First Pulse
  - First pulse(s) in a machining pass are larger due to energy build up in laser amplifier
  - Exaggerated at high pulse frequency
  - Mitigation
    - Block first pulse
    - Distrubute first pulses over surface
    - Work at lower pulse frequency



Practical Ablation Rate

The highest useful ablation rate determined by consideration of the effects presented

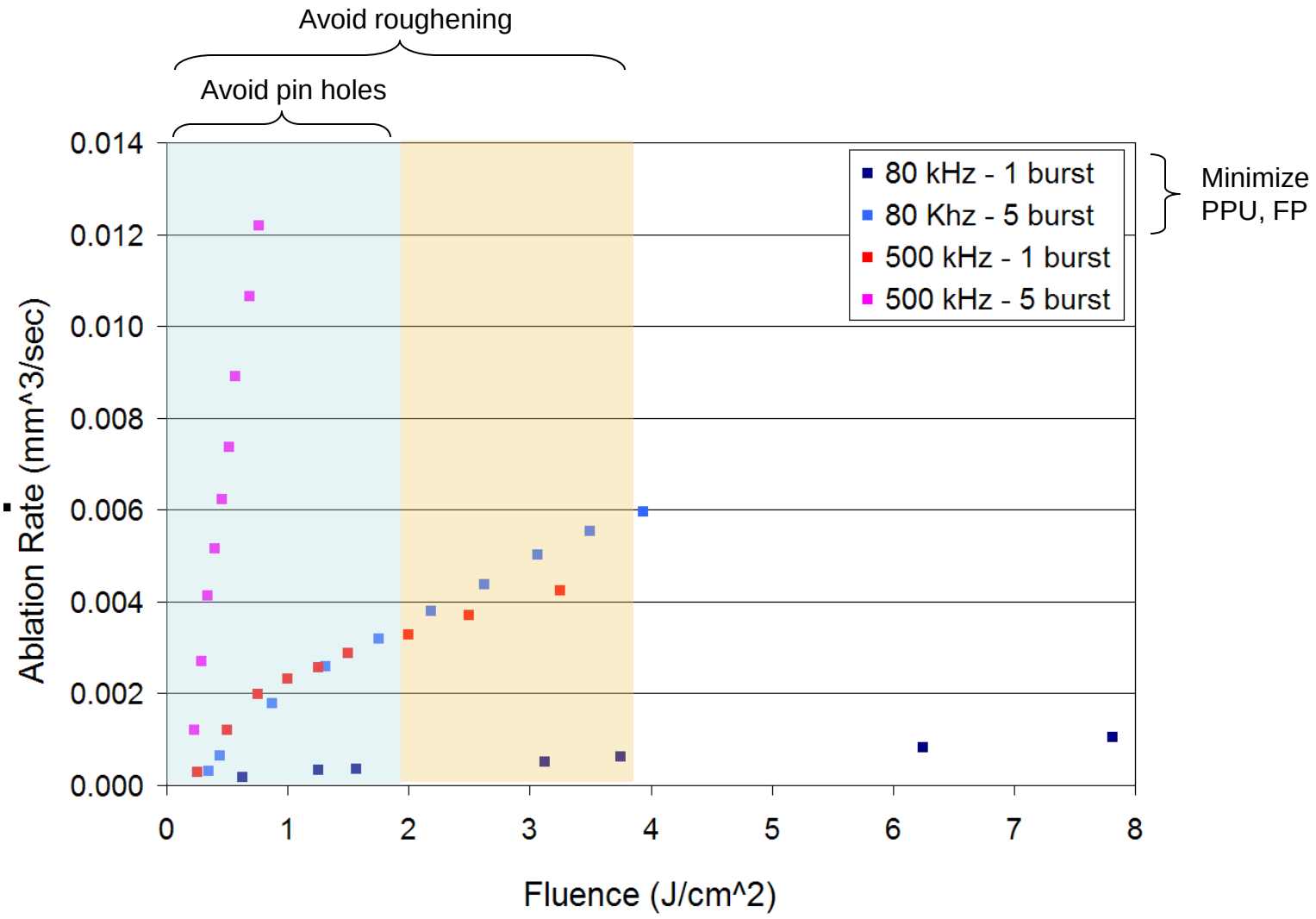
- Maximum ablation rate
  = Ablation per pulse x Frequency
- Avoidance of pin holes
- Avoidance of worsening roughness

Work at high frequency, burst mode to get high removal rate even at low fluence.

- Minimization of pulse pile up
- Minimization of first pulse

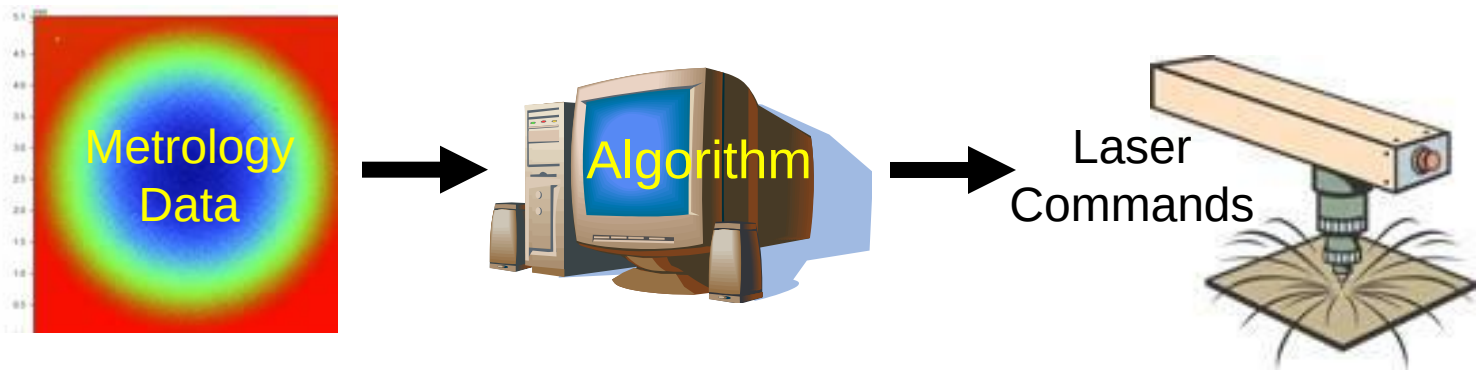
Work at low frequency to avoid or mitigate these effects.

Potential Ablation Rates



Mircomachining Algorithm

(STTR partner contribution)



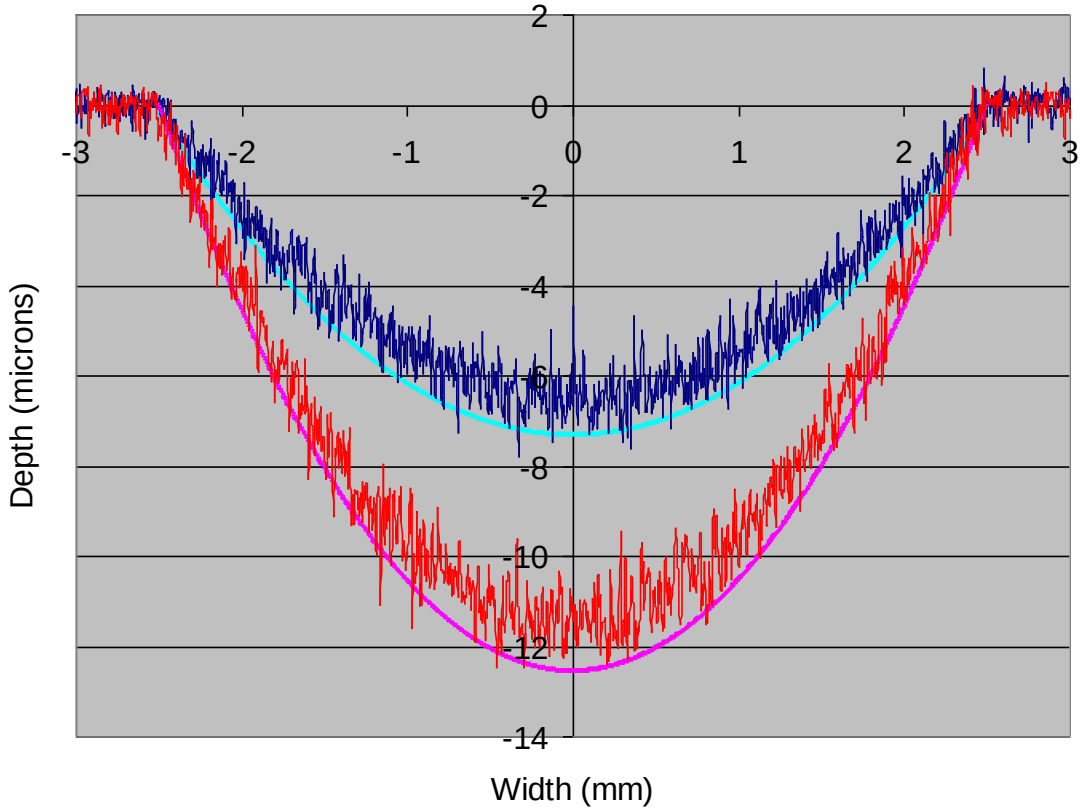
- Algorithm to generate laser path commands for machining in Cartesian coordinates complete. Polar version under development.
  Inputs:
    - Experimentally determined material removal rate
    - Pulse diameter and overlap
    - Metrology data set
    - Desired final shape

  Output:
    - Laser commands to machine near to, but not past, desired surface.

- After execution of laser machining, new metrology is taken and final shape approached more closely at lower power.

Example of Iterative Machining

- Commands generated by laser path algorithm machine to approach a 18” radius spherical surface starting from flat.
- Metrology from spherically machined surface is used as input to generate commands to machine the surface further down to a parabola.



Sphere
Avg distance from target surface = 650 nm
Ra = 370 nm

18 inch radius sphere
Ablation to sphere
12.5 um deep parabola
Ablation to parabola

Parabola
Avg distance from target surface = 820 nm
Ra = 550 nm

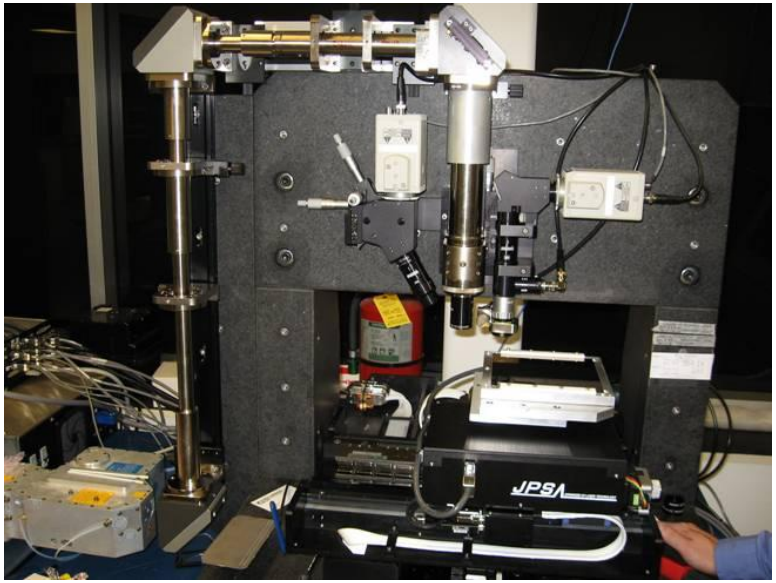
Workstation Development

Final major goal of program is to develop a workstation for practical iterative machining of SiC mirrors.

- Scan Head driven workstation put into service at the start of the program to develop basic data and show proof of principle.
  - 3 axis (X,Y,Z)
  - Positioning accuracy ~ 20 μm
  - Requires coordination of scan head position/acceleration and laser triggering
- Direct Focus workstation
  - Designed and built during program to address limitations of scan head workstation
- Metrology development

Direct Focus Workstation

- Integrated by JPSA
  - Four axis (X,Y,Z,θ)
  - Direct focus $\rightarrow$ smaller spot
  - Stages with < 2 micron accuracy
  - Vision system
  - 6” turntable
  - Position synchronized output

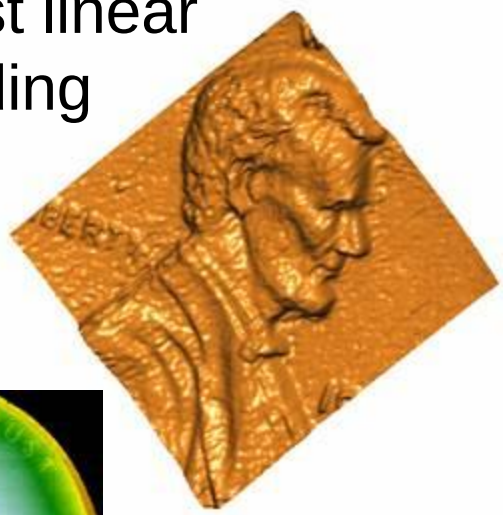


- Will enable
  - Greater positioning accuracy
  - Elimination of laser path acceleration when working in θ.
  - Room for metrology to be added at end of long X-axis.

Metrology Development

(STTR partner contribution)

- Primary metrology method is white light interferometry. Necessary for final accuracy.
- WSU has developed a low cost metrology system, based on distortions of a cast linear shadow, that may be valuable in guiding initial iterative machining.
  - Low cost
  - Easy integration to workstation
  - Rapid data collection
  - X-Y resolution ~ 15 μm
  - Z resolution ~ 10 μm



Conclusions

- Basic data for picosecond ablation of SiC has been collected and analyzed – appropriate regimes for operation have been identified.
- An algorithm for metrology guided specification of laser machining paths to produce arbitrary shapes has been developed.
- A demonstration of metrology guided iterative machining has shown the feasibility of shaping SiC to withing the tolerances desired - within 1 μm of figure and < 700 nm roughness.
- The pathway to further improvements utilizing new, more accurate laser workstation is clear.