FAILURE of Nd:YVO_4 AMPLIFIER CRYSTALS

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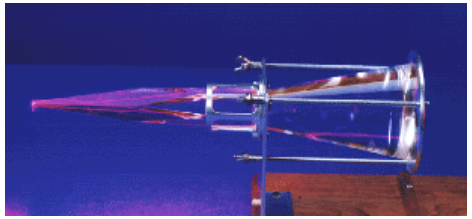
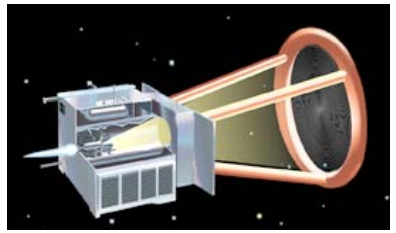
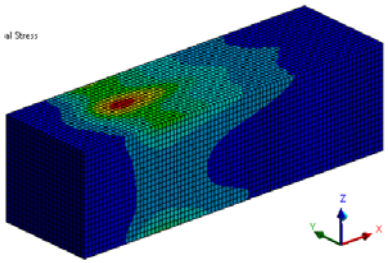
Fractography of Advanced Ceramics VI
2019

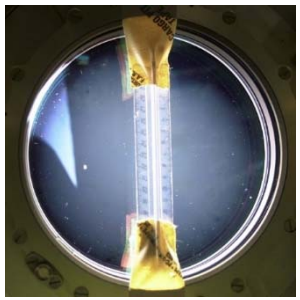
Ceramics are used in Many NASA Applications

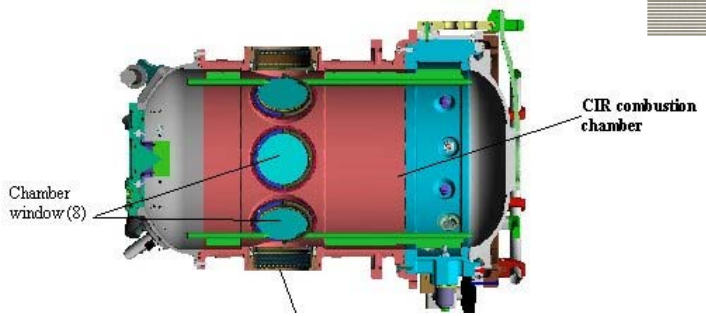
- Solar concentrators
- Laser amplifiers
- Specialty windows
- Spectrometer components
- Low expansion mounting plates
- Lenses







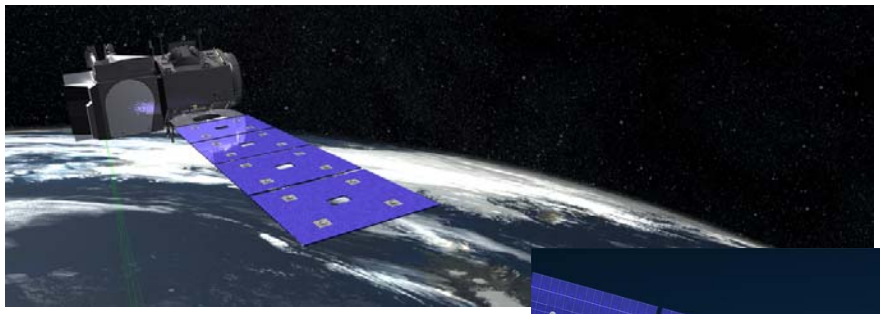


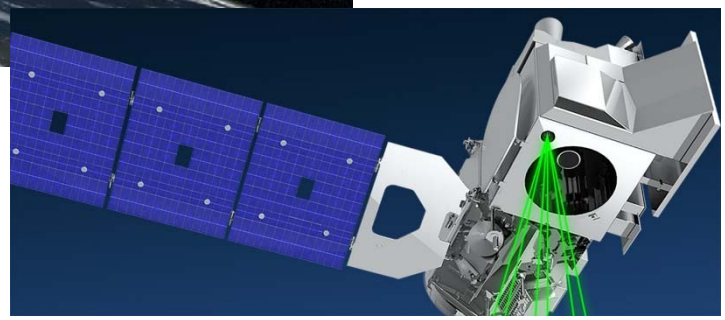


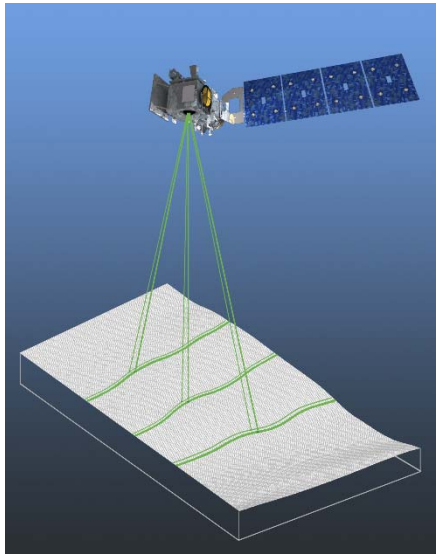
ICESat-2

Ice, Cloud, and Land Elevation Satellite

- The four ICESat-2 science objectives are
  - Measure melting of ice sheets and sea level rise
  - Measure changes in the mass of ice sheets and glaciers
  - Estimate and study sea ice thickness
  - Measure the height of vegetation in forests worldwide





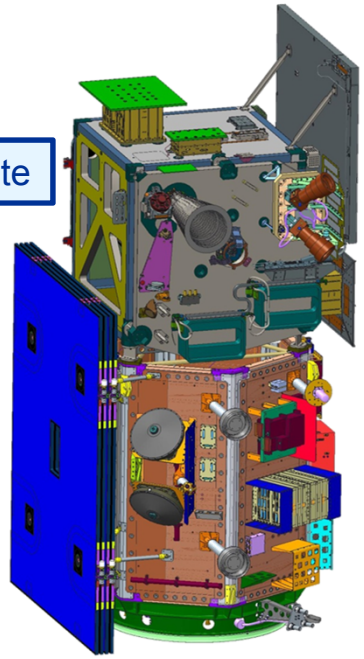


ICESat-2

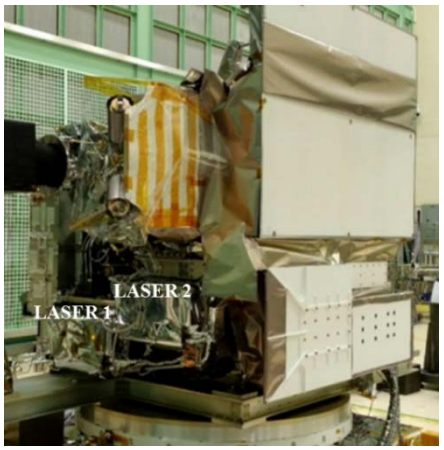
Ice, Cloud, and Land Elevation Satellite

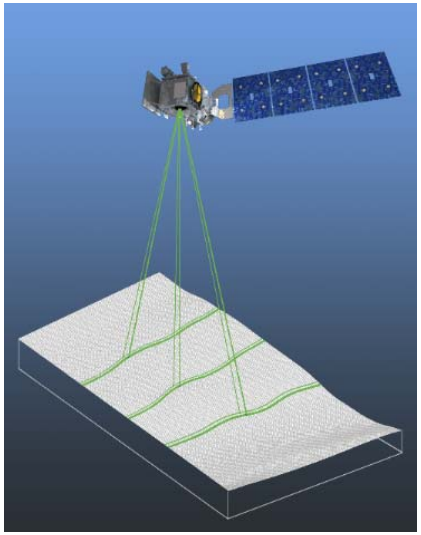
- ICESat-2 carries a single instrument – the Advanced Topographic Laser Altimeter System (ATLAS):
  - ATLAS measures the travel times of lasers pulses to calculate the distance between the spacecraft and Earth's surface
  - ATLAS carries two lasers, one primary and one backup.

ICSat-2 Satellite



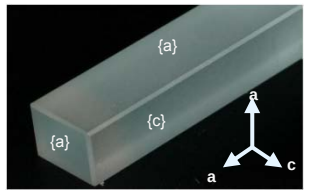
ATLAS Instrument



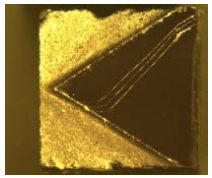


Within the System are Nd:YVO_4 Crystals

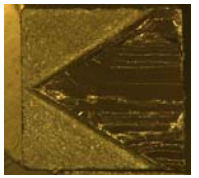
- The YVO_4 single crystals are laser “slabs”
- Elastic modulus = 220 GPa <a> axis
- Fracture toughness = 0.48 MPa√m
- Fracture strength = 46 MPa (~7 ksi)



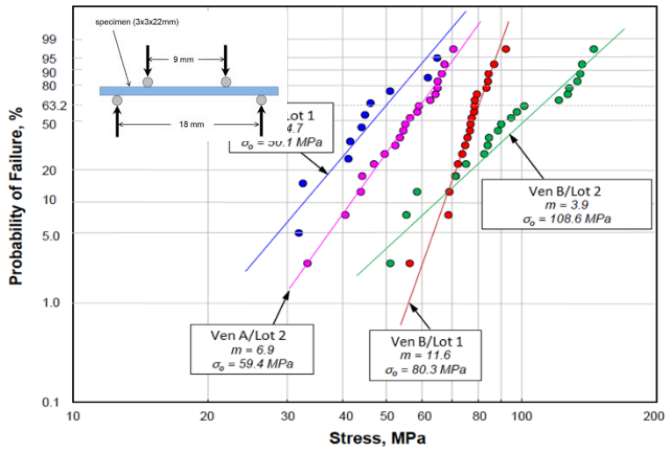
Air, a-a



Air, a-c



➢ Very brittle!!



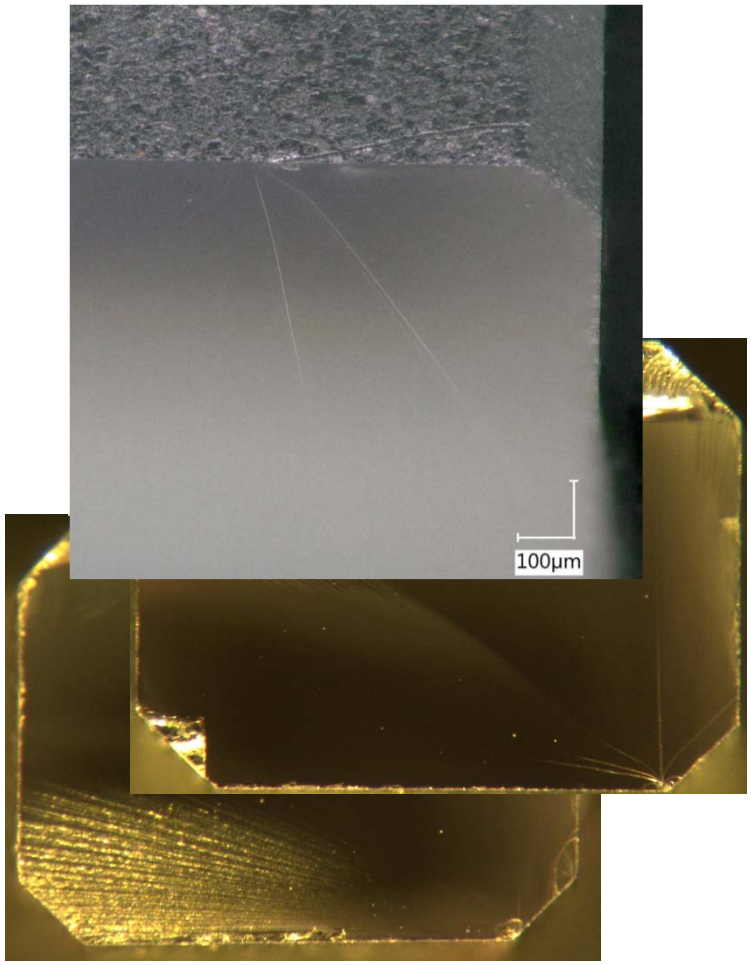
Surfaces of the Crystals

- Diamond ground, with surfaces that tend to be damaged (chips, scratches, etc.):

- One would expect surface failure.

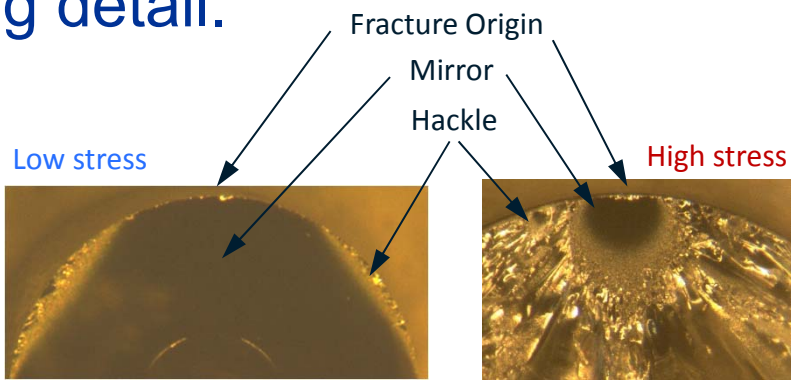
Failure of the Crystals

- Indeed, strength test specimens fail from surface flaws:



Failed Crystals in Hardware

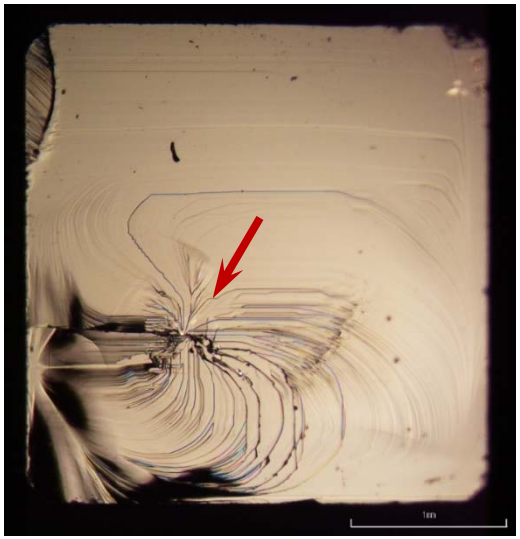
- Four failures are of particular interest:
  - Two that failed unexpectedly in flight hardware; these brought me into the project.
  - Two failed during bench testing while attempting to understand the prior failures; these created confusion about the nature of failure.
- I'll discuss these in varying detail.

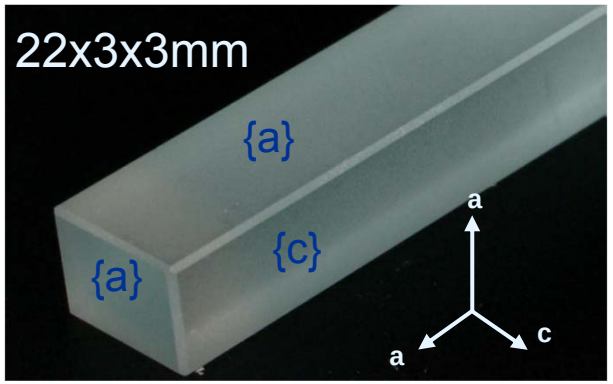


First Pump-to-Failure Amplifier Crystal

- Failed During Bench Testing -

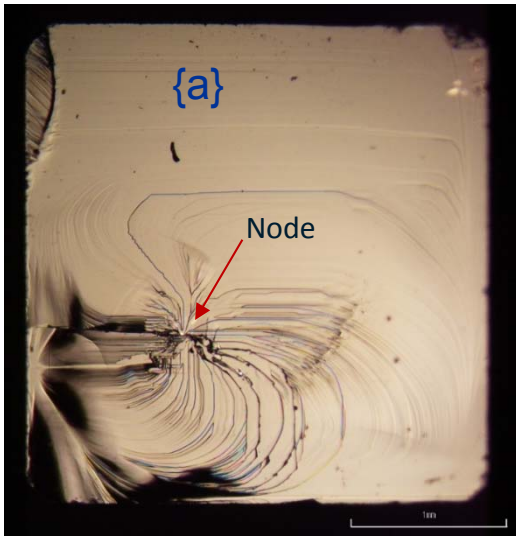
- During routine bench testing of a laser amplifier slab, the control loop was lost and the crystal over-pumped until fracture occurred.
- Disassembly revealed a fracture near one end, with the location of fracture thought to be near the center.





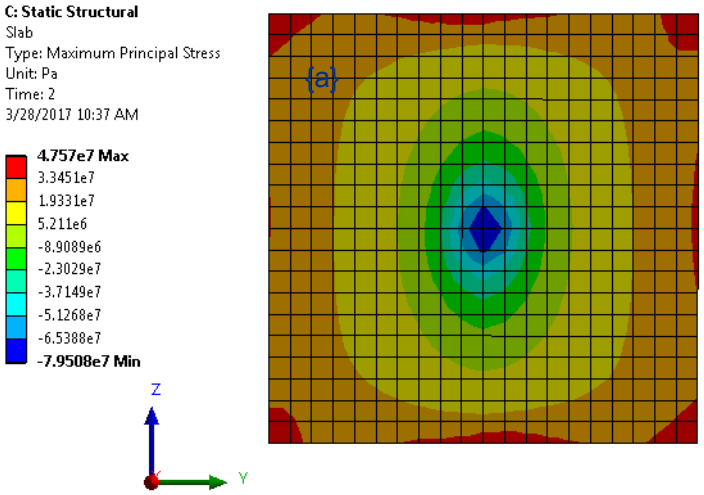
Over-pumped Crystal:

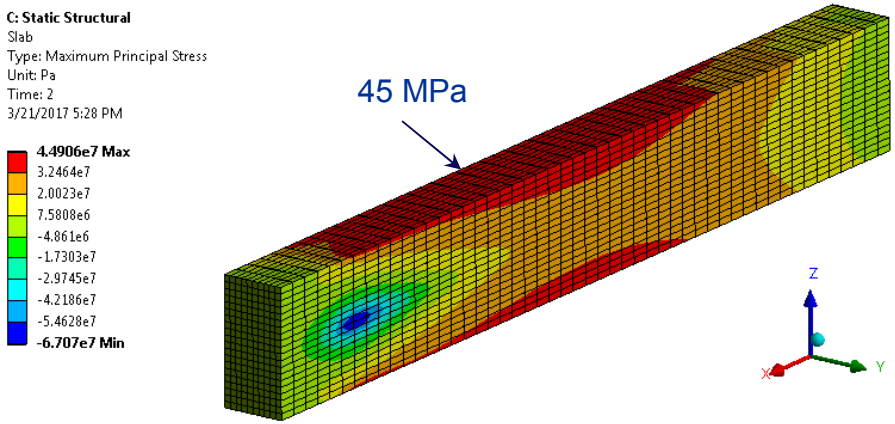
- Pronounced swirl at a central “node:”
- Failure located on the {a} crystal plane without macroscopic rotation from the {a} plane.
- Some felt that failure occurred from the center “node”…..



Stress State at High Power

- X-axis principal stresses:

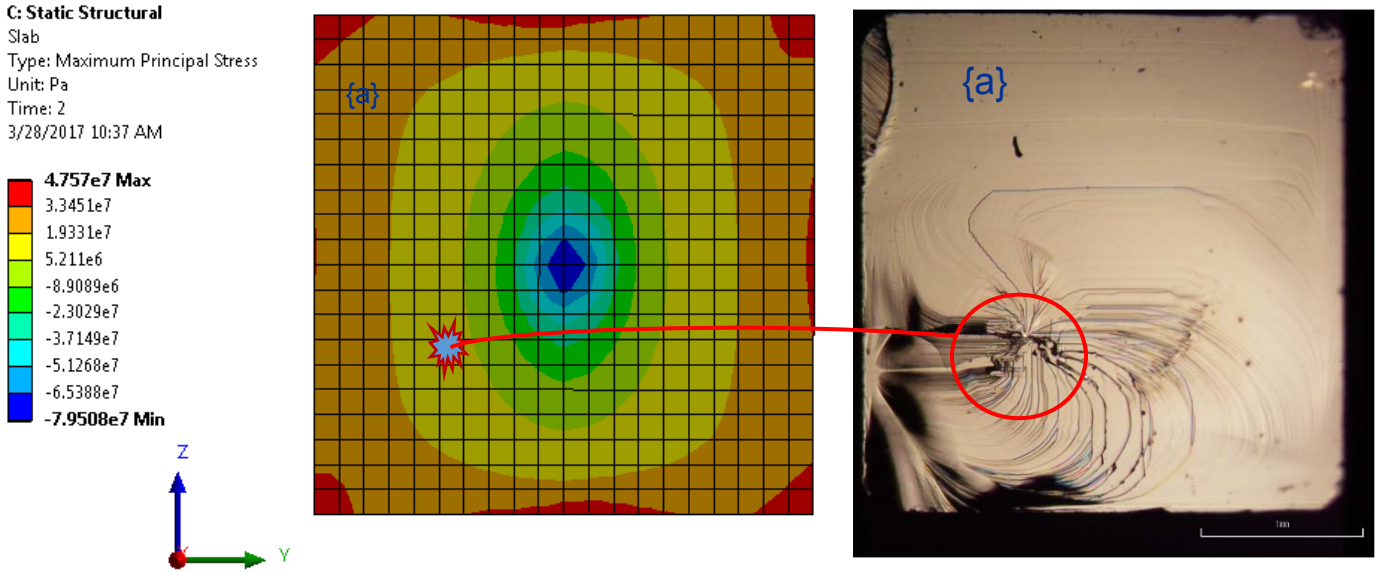




- Center compression with edge tension, where the worst flaws are often located.
- Compressive strength is >> tensile strength.

Location of Speculated Origin

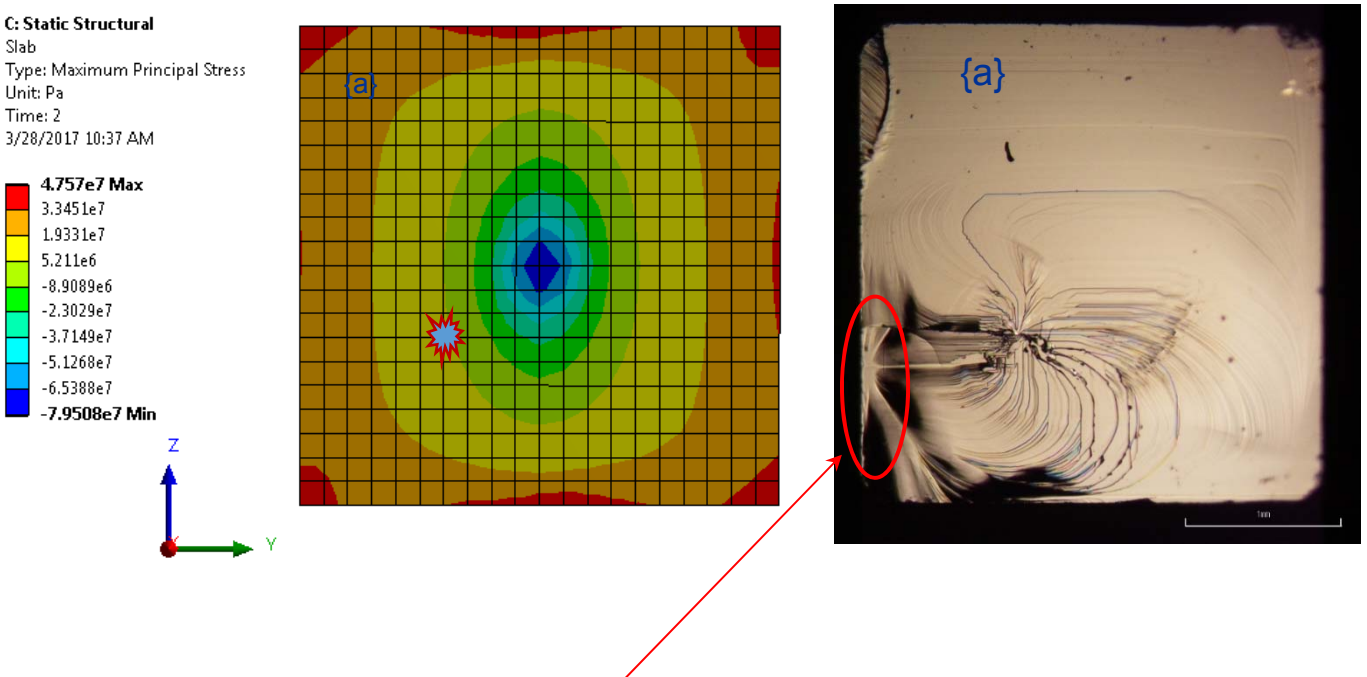
- Speculated origin is on the border of compression and tension, with low tensile stresses (5 MPa):



- Could the origin be elsewhere? The surface?

Other Fracture Features

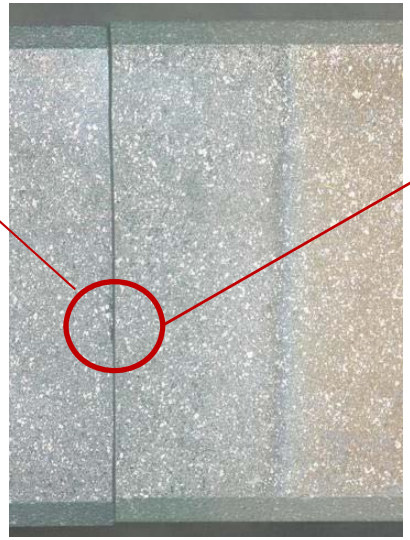
- Let's consider surfaces where stresses and damage are high:

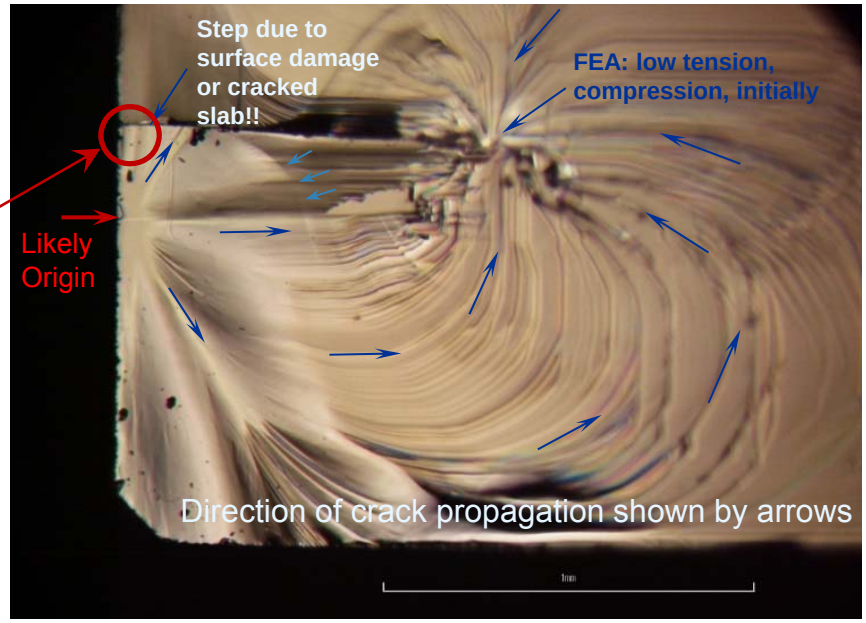


- At the surface a star-like feature is apparent – single crystal mirror?

Surface Damage and Classic Mirror

Surface damage or post fracture edge chipping

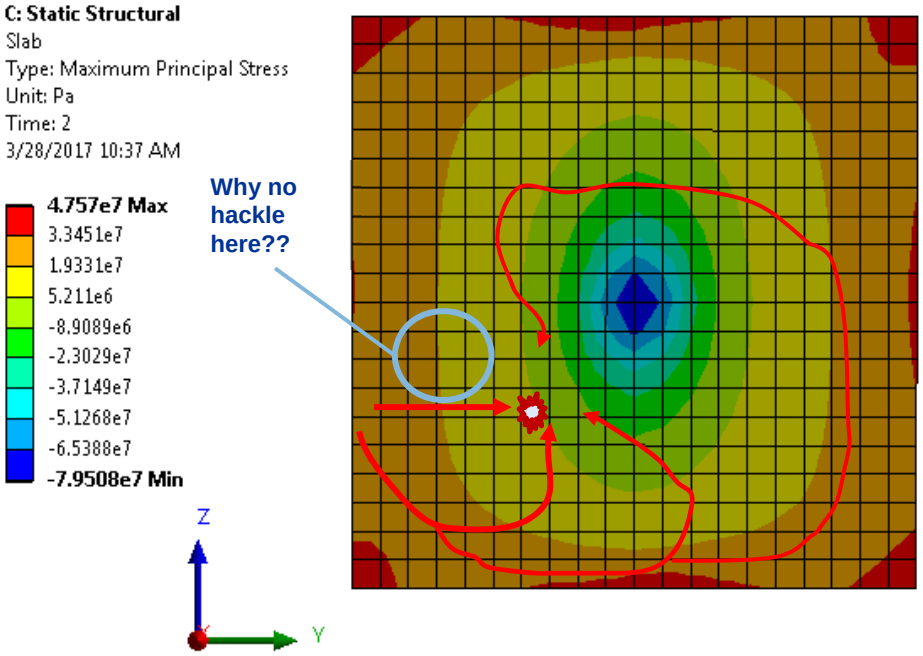


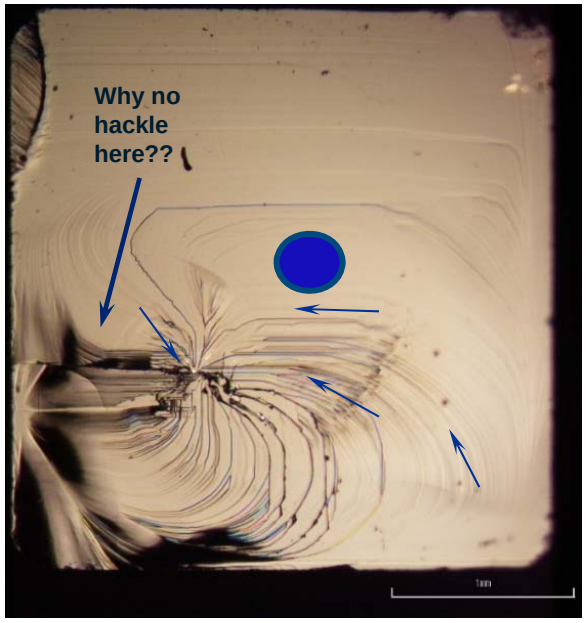


- But why the coalescence of rivers marks to a central region of compression??

River Marks Follow Tensile Stress Pattern…

- As the crack grows, it spirals, avoiding the center compression, changing the center to tension until the cracks paths converge (?).
- The crack remains on the cleavage plane rather than tracking along the beam long axis:

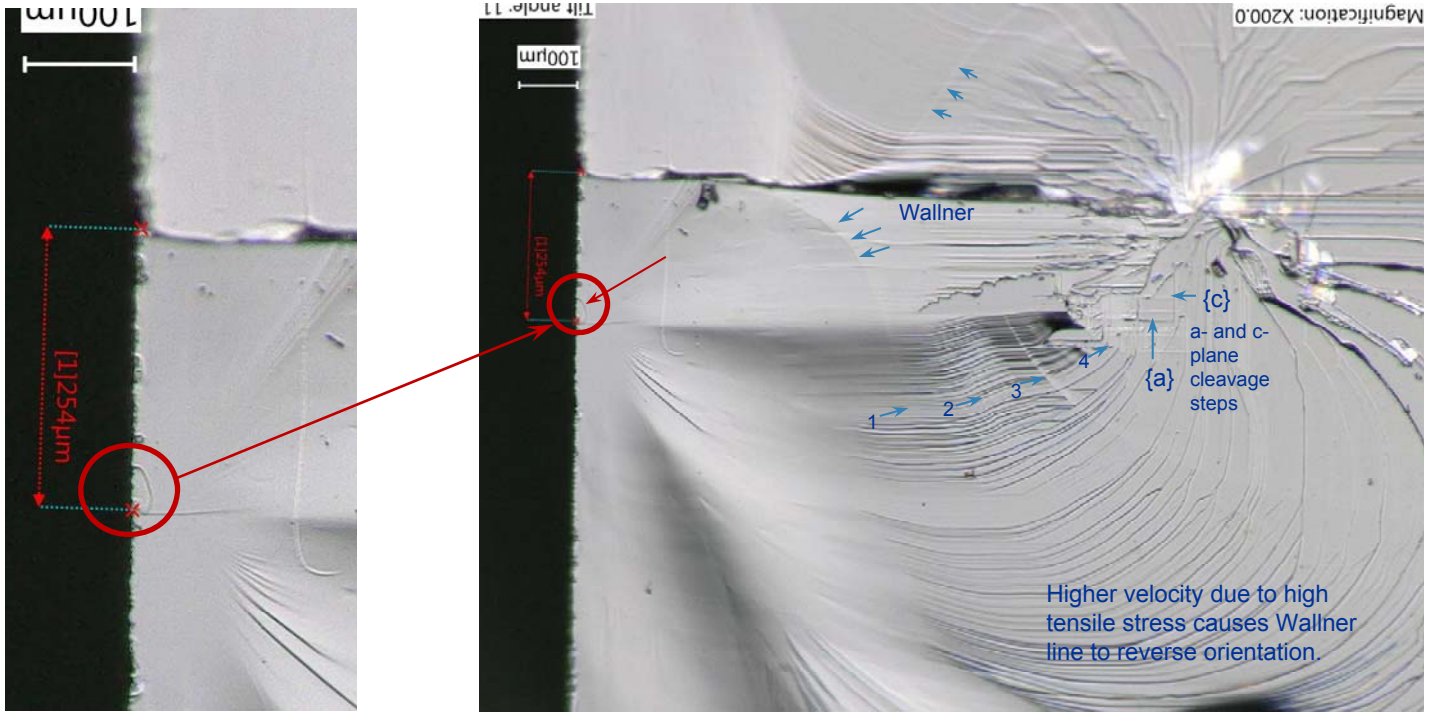




- No mirror or hackle markings on one side of the origin…….

"All Roads Lead to Rome" (or away!)

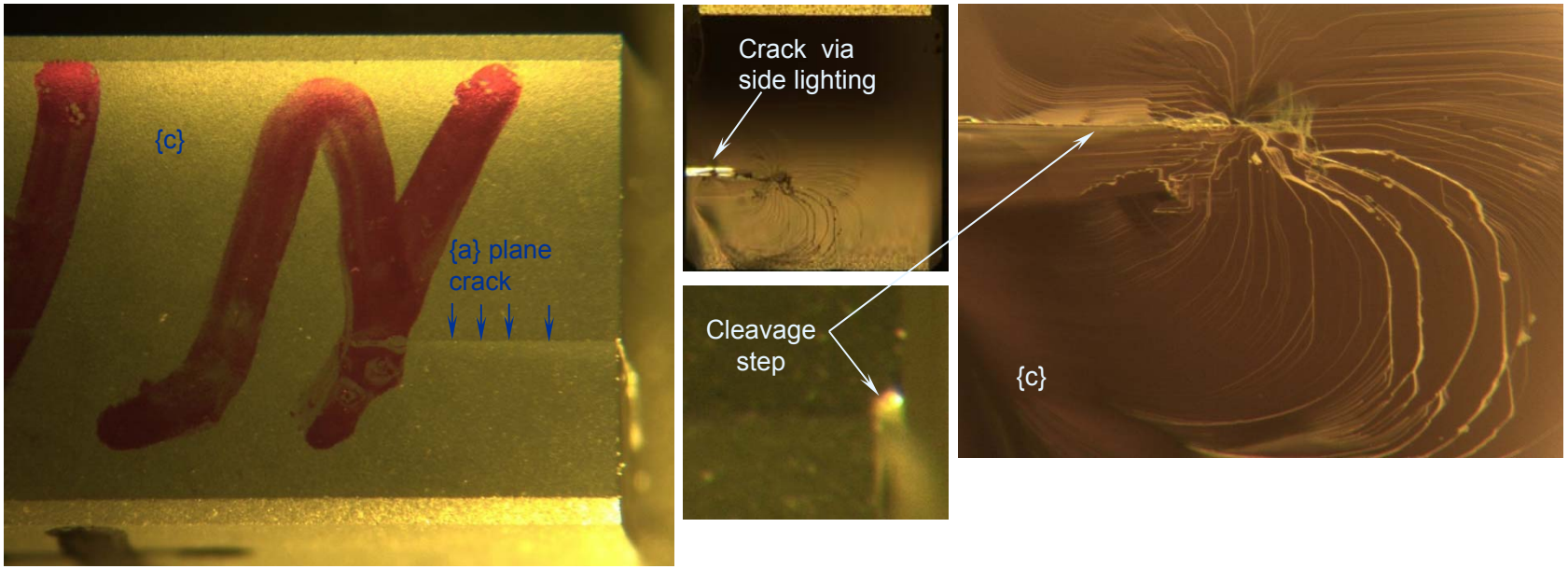
- Origin appears to be the corner of a small, semi-circular surface crack.
- Growing crack wraps around one side of the step…..Unusual pattern:



- "Rome" is the interface between tension and compression where the crack front stalls? But that hackle……..

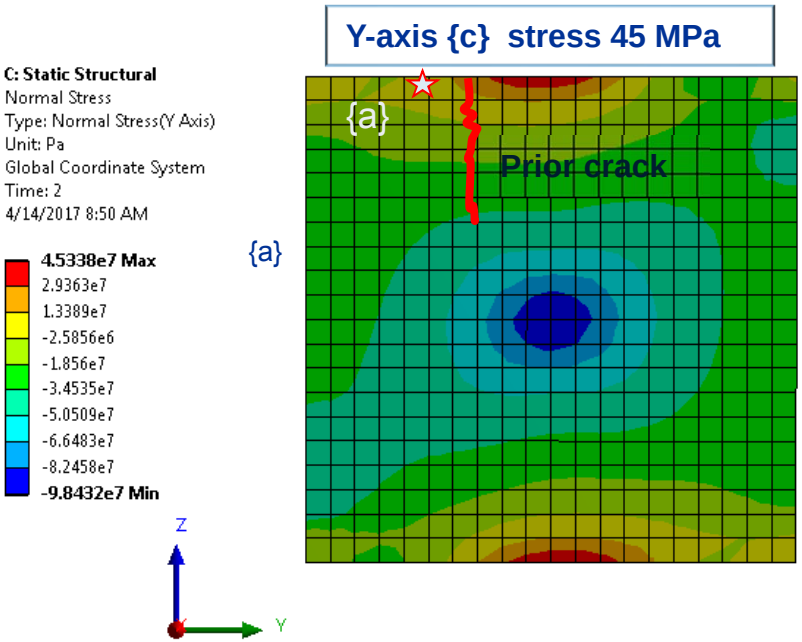
Why no Hackle on one Side of the Origin?

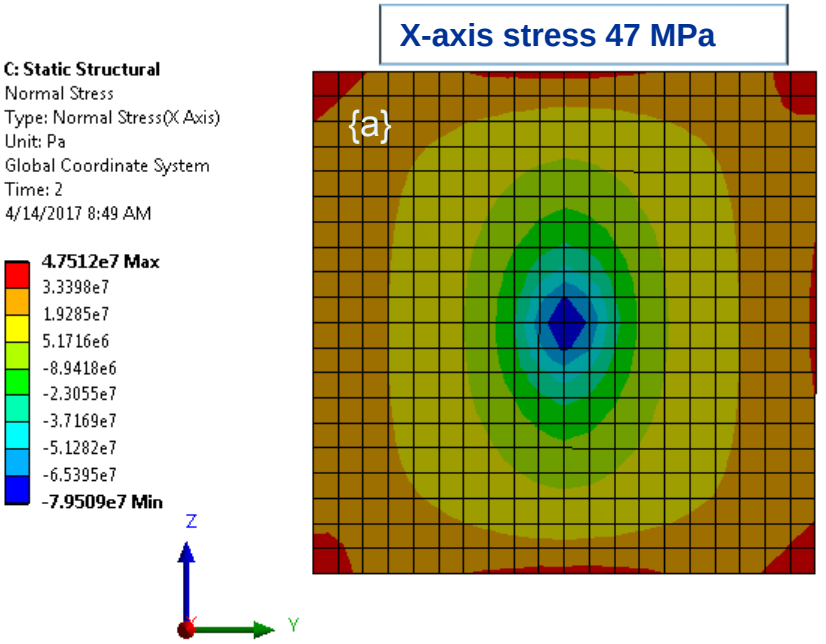
- By side lighting, we see that the slab was cracked, likely prior to the fracture:



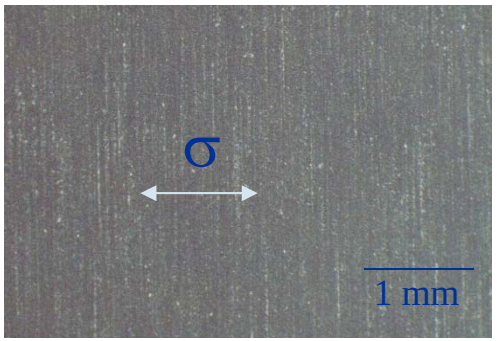
- Crack wrapped around the prior, longitudinal crack plane like a screw, creating the cleavage step.

X and Y Direction Stresses are Similar:

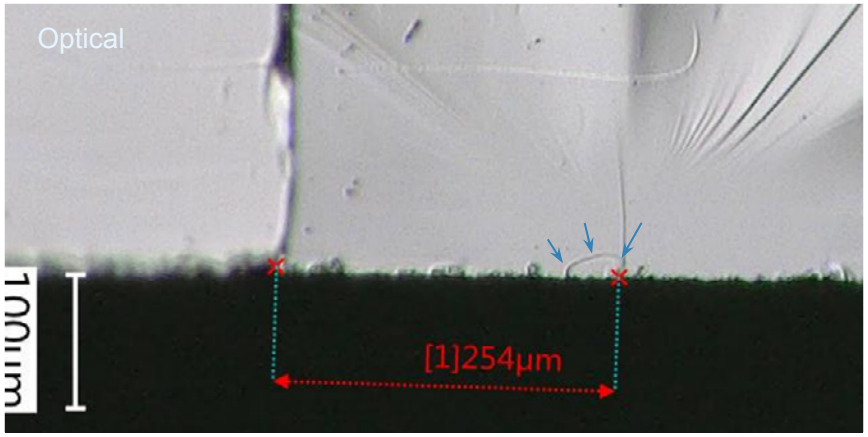


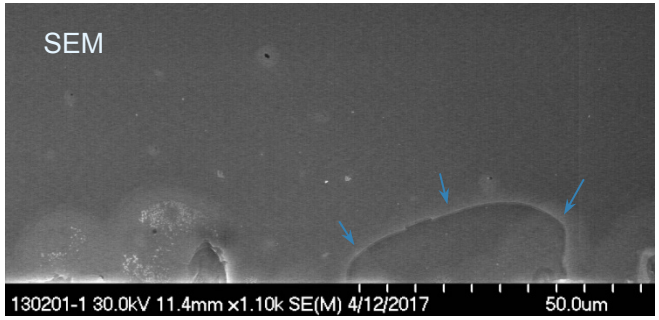


- Grinding is usually in the x-direction, and the stresses are similar on both the x- and y-directions, so longitudinal cracking is likely.
- Longitudinal crack was in tension, drawing in the propagating crack.....creating the “node.”



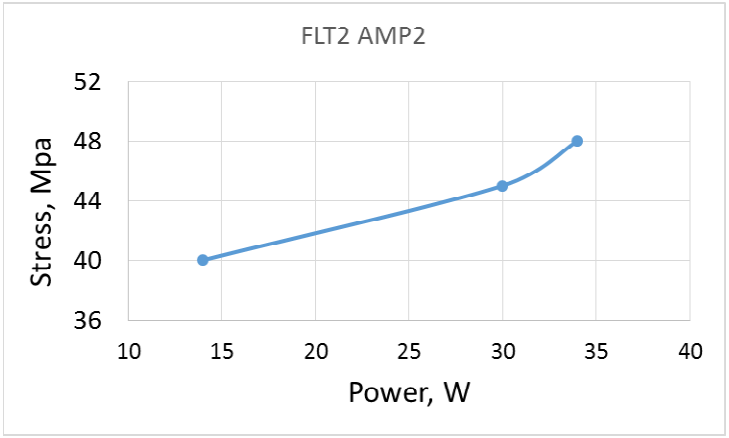
Estimated Stress (Fractographic and FEA)





$$S_f = \frac{K_{Ic}}{Y\sqrt{a}}$$

Stress (MPa)	Meas. Type	a (mm)	2c (mm)	Y surface	Y depth	KIc MPa√m
70.0	OPT	0.021	0.052	**1.30**	1.30	**0.42**

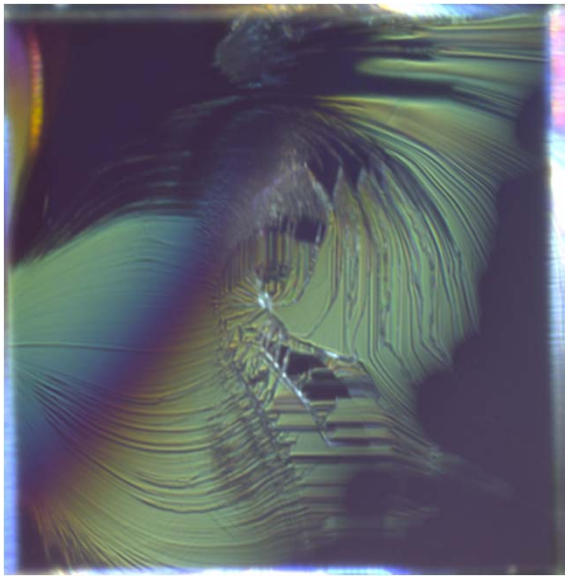


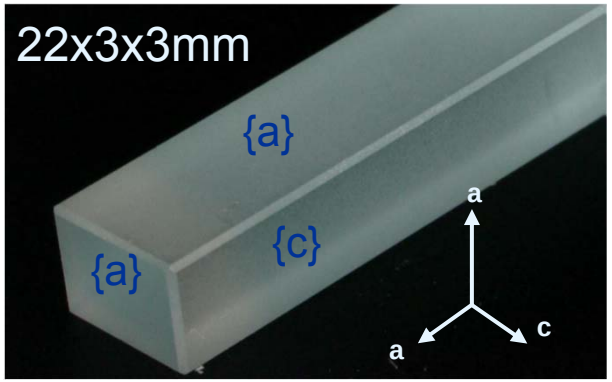
- High stresses are estimated, implying that the stresses were higher due to the prior longitudinal crack or that the pump level, which was unknown, was very large.

Second Pump-to-Failure Amplifier Crystal

- Failed During Bench Testing -

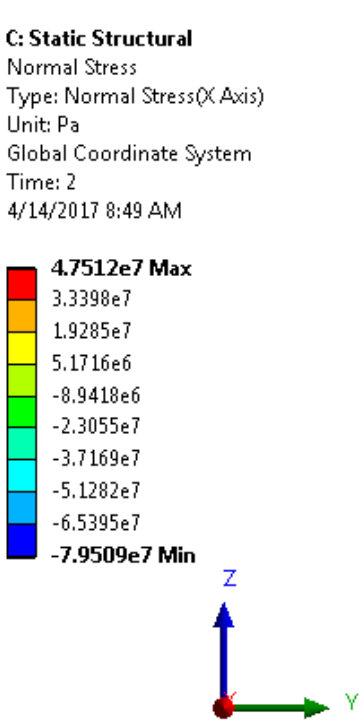
- Controlled bench test of a laser amplifier slab (single crystal) to induce crystal failure via over-pumping.
- Disassembly revealed a fracture near one end, with the location of fracture thought to be near the center.



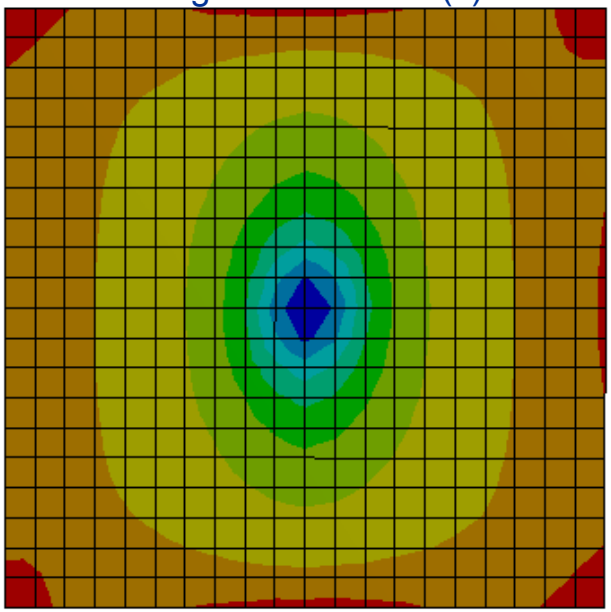


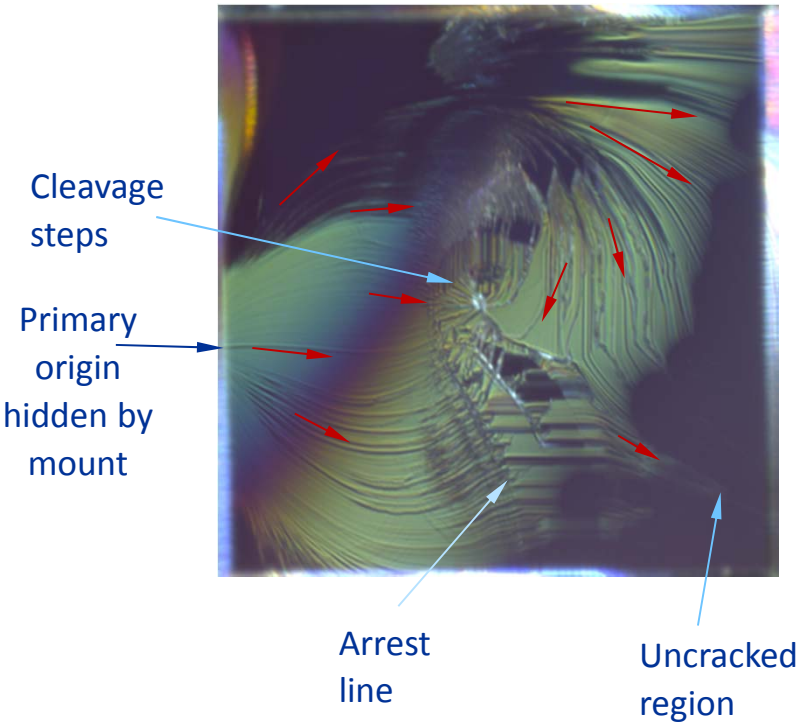
Slab: Pump-to-Failure Fracture

- "Node" is more centrally located (compression) and no cleavage step or prior longitudinal crack is apparent:



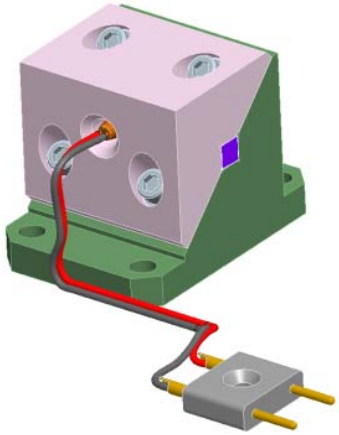
Longitudinal stress (x):

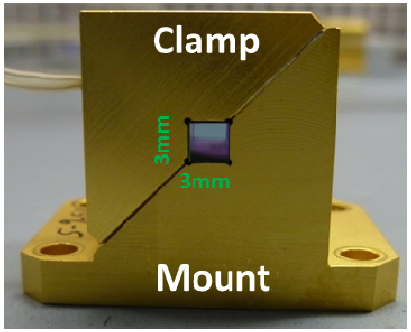




- Crack wrapped around central compression region and stalled.
- Stress state changed and fracture continued by failing central ligament.

Amplifier Assembly Overview

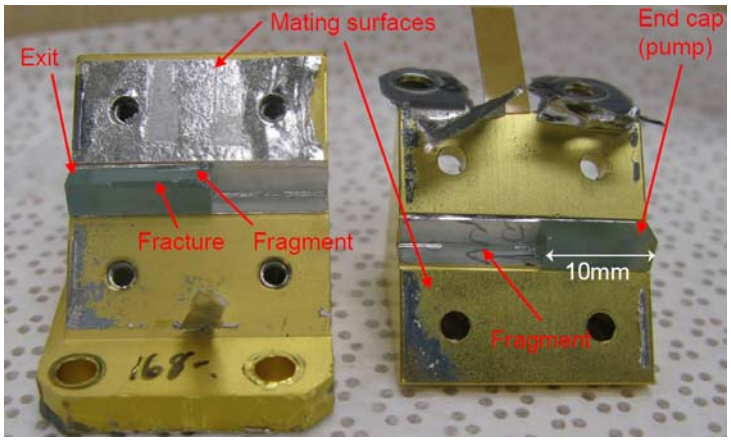


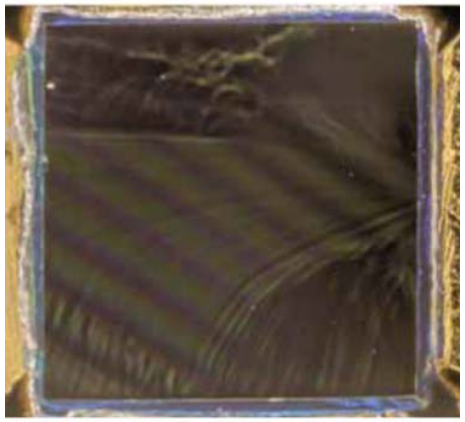


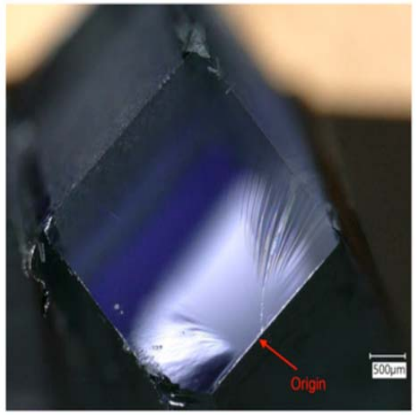
- The Nd:YVO_4 crystals are clamped between two gold plated heat spreaders with an indium foil thermal interface material.
- The indium foil thickness was custom selected to achieve uniform and simultaneous contact between all five planar surfaces.
- Four bolts are used to attach the clamp to the mount securing the crystal.

First Flight Amplifier Fracture

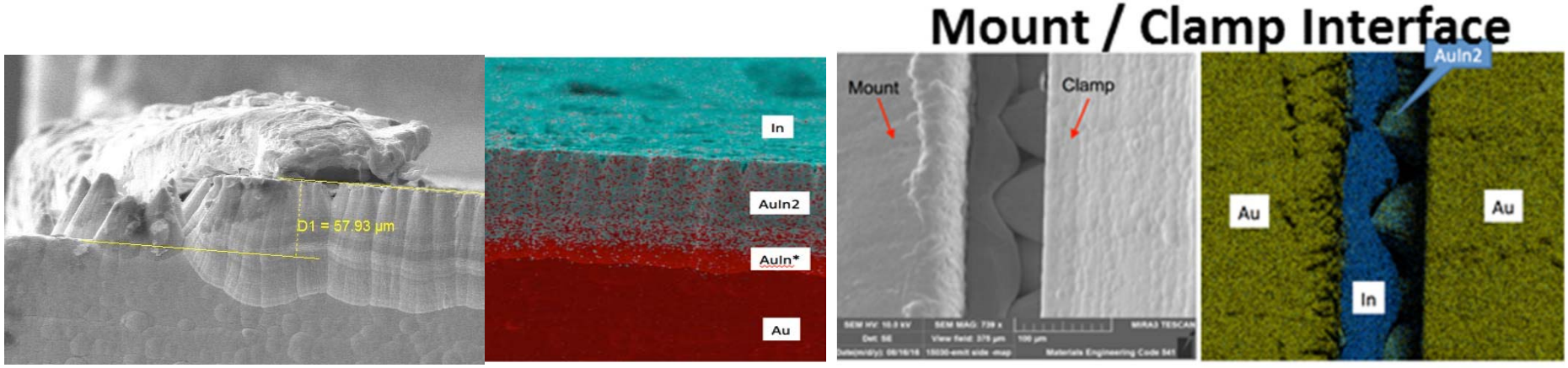
- The crystal fractured about 10 mm inboard of the input face and originated in the middle of the c-facet.
- There were no obvious surface defects or corresponding mount defects at the fracture origin.
- Applied stresses were low.
- Implies that the crystal was under higher mechanical loads (pressure).
- But why?







Time Dependent Crystal Loading



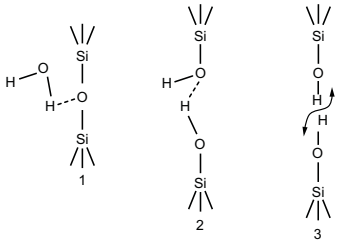
- Fractography indicated that gold and indium were forming gold-indide ($AuIn_2$) over time.
- The resulting $AuIn_2$ material is stiffer, harder and more brittle than indium; and more significantly, occupies 15% more volume.
- Intermetallic and indium are incompressible. The additional volume is displaced, resulting in higher preloads on the crystal, and eventual fracture.
- Not due to overpumping…

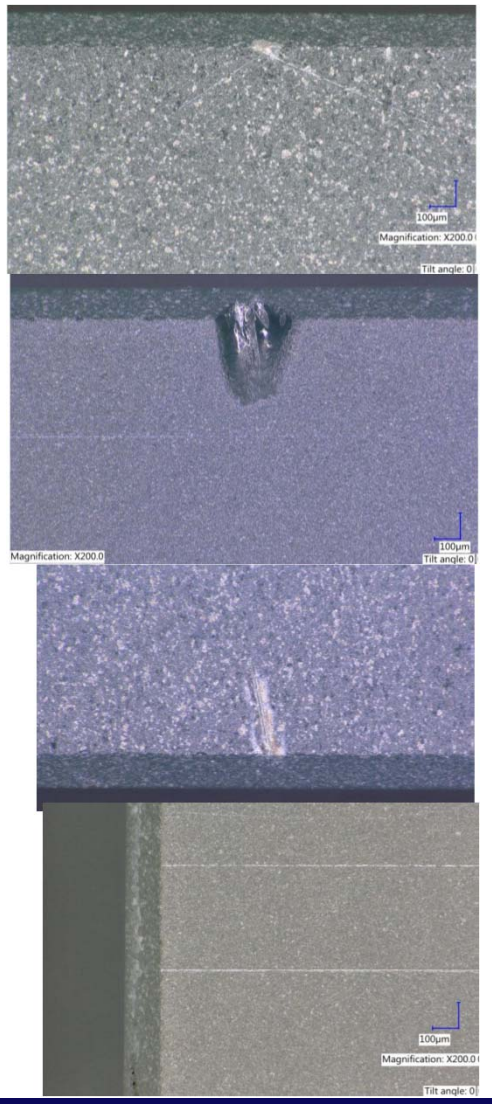
Redesign Philosophy

- Failure resulted from several sources:
  - Au-In reactions (worst element)
  - poor crystal finishing and handling
  - low toughness and slow crack growth

- Re-design & qualification was needed:
  - Lowed the stresses
  - Quantified the transient reliability:

- Weakest Link Behavior:
  - Structure is analogous to a chain with many links of differing strength
  - Catastrophic failure occurs when the weakest link is broken
  - A longer chain is weaker





Conclusions

- For the first slab, cracking started from an {a}-plane semi-elliptical crack located on one side of a prior, longitudinal {a}-plane crack.
- The crack wrapped around the prior, {a}-plane crack by following high tension regions near the surface, creating a large cleavage step.
- As the crack spiraled around and inward, compression regions diminished until central tension occurred via stress redistribution. Stopped spiraling inward at the prior crack tip.
- The prior crack acted as a concentrator, attracting moving crack.
- For the second slab, cracking started from the surface.
- The crack wrapped around both sides of the central compression region and stalled until stress redistribution allowed further fracture, forming the central node.
- Two flight hardware fractures were from the surface and driven predominantly by chemical reactions…..

ICESat-2 Integration After Redesign

- ICESat-2 was integrated at the Orbital/ATK facility in AZ.
- EMI testing completed in April.
- Transported to Vandenberg AFB in May for integration onto the rocket.
  - The system was powered on for the last time on Earth in mid-June 2018!

ICEsat-2 Launched from Delta II Pad SLC 2W

Vandenberg AFB – California 9-15-2018

Mobile Service Tower (MST) in place (around vehicle) for Integration and Fairing install

MST rolls back to here the day before Launch

- SLC-2W has been used for launches since 1966
- Delta II has been launched since 1989 (98.6% success)
  - ICESat-2 was the last launch & the 100th consecutive successful launch
- Delta II 7420-10C (7000 series, 4 boosters, 2nd stage with Aerojet AJ10, no third stage) is 38.9 meters tall