Plasma formation from micron-scale defects on ultra-pure aluminum rods*

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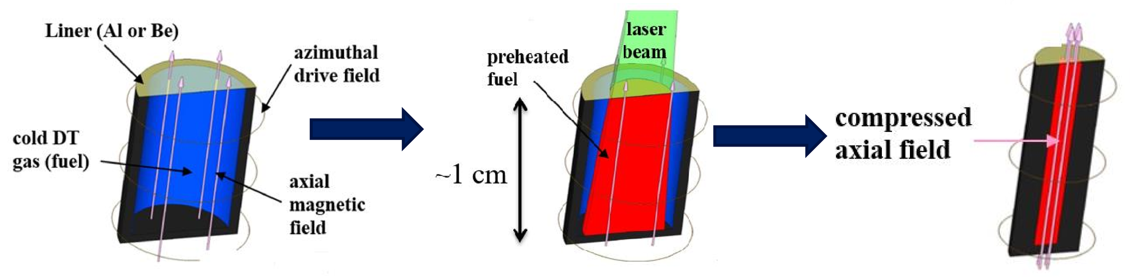
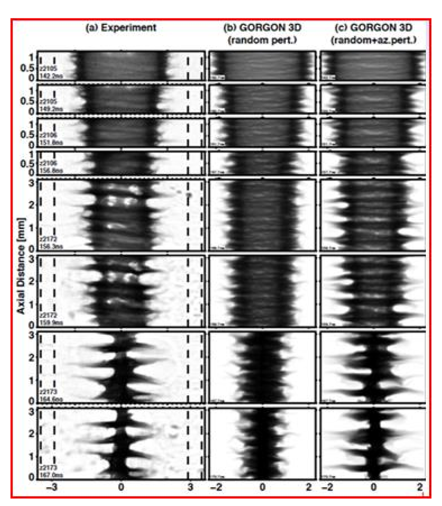
Magnetized Liner Inertial Fusion (MagLIF):



S.A. Slutz *et al.*, PoP **17**, 056303 (2010)

•20 MA of current flows through cylindrical beryllium liners (about 500 µm thick wall)
•Fuel/liner is axially magnetized, then fuel is laser heated
•Liner is accelerated to nearly 70 km/sec, compressing the premagnetized/preheated fuel
•Fusion-relevant conditions are achieved, but limited by Magneto-Rayleigh Taylor (MRT) instabilities

Gomez, M. R. et al. Phys. Rev. Lett. 113, 155003 (2014)

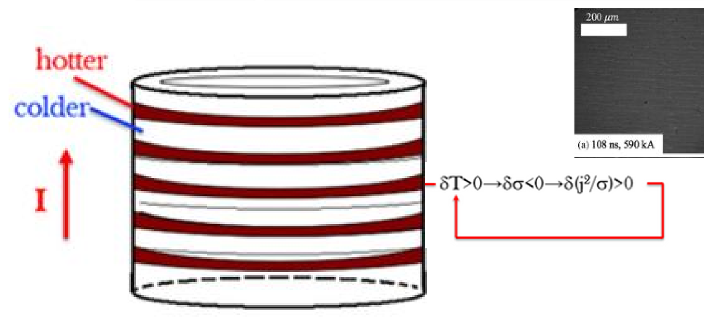


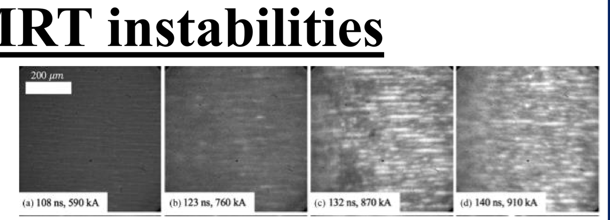
McBride *et al.*, PRL **109**, 135004 (2012)

- Simulations which add an artificial azimuthally correlated seed perturbation better match experimental data. These perturbations do not match experimental liner initial conditions. Some phenomenon is generating them dynamically.
- One simulation-supported hypothesis is that this behavior is caused by a phenomenon called the electrothermal instability (ETI), which generates azimuthally correlated temperature and density perturbations called strata/striations.

Ryutov *et al.*, Rev. Mod. Phys. **72** 167 (2000)
Oreshkin *et al.*, PoP **15**, 092103 (2008)

Electrothermal instabilities (ETI) are thought to seed MRT instabilities



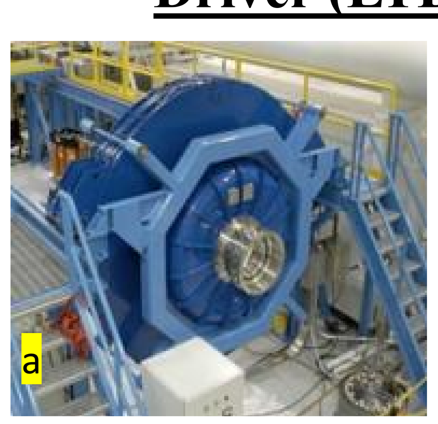


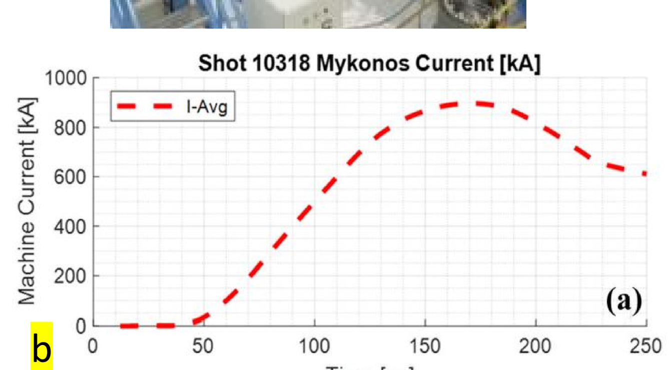
Discrete strata can be seen on ohmically heated, thick aluminum

- ETI is a Joule heating-driven instability.
- In a metal (dη/dT>0), the dominant mode manifests as hot/cold bands- "striations"
- In a plasma (dη/dT<0), the dominant mode manifests as plasma filaments
- ETI can seed the Magneto Rayleigh Taylor (MRT) instability

MRT seen on a liner

Mykonos-V is a five stage Linear Transformer Driver (LTD) voltage adder





Machine specifications

At full-charge voltage:
•≤1 MA into 0.5 ohm load
•500 kV pulse
•Rise time (10%-90%) of 80 ns through target
•Pulse width (FWHM) of 160 ns
•LTD module made of five, three-meter diameter LTD cavities

Figure a.) Mykonos device at SNL
Figure b.) Example current pulse

Barbell targets with engineered defects provide insight on ETI

Observation: Low intensity emissions, a likely result from overheated inclusions in alloyed aluminum, drive ETI in Z pinch targets.
Objective: Experimentally study the evolution of ETI from targets with well-understood and well-characterized engineered defects for comparison with simulations.

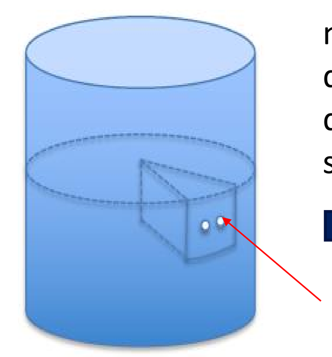
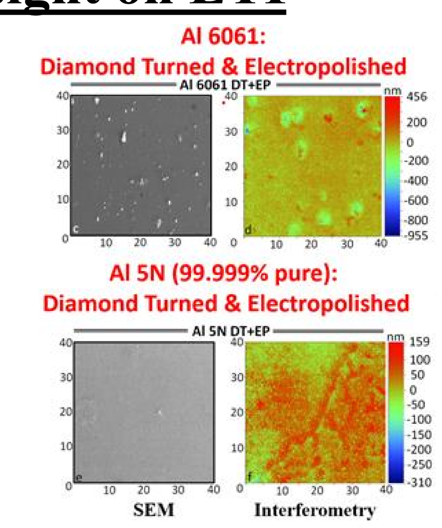


Figure a.)

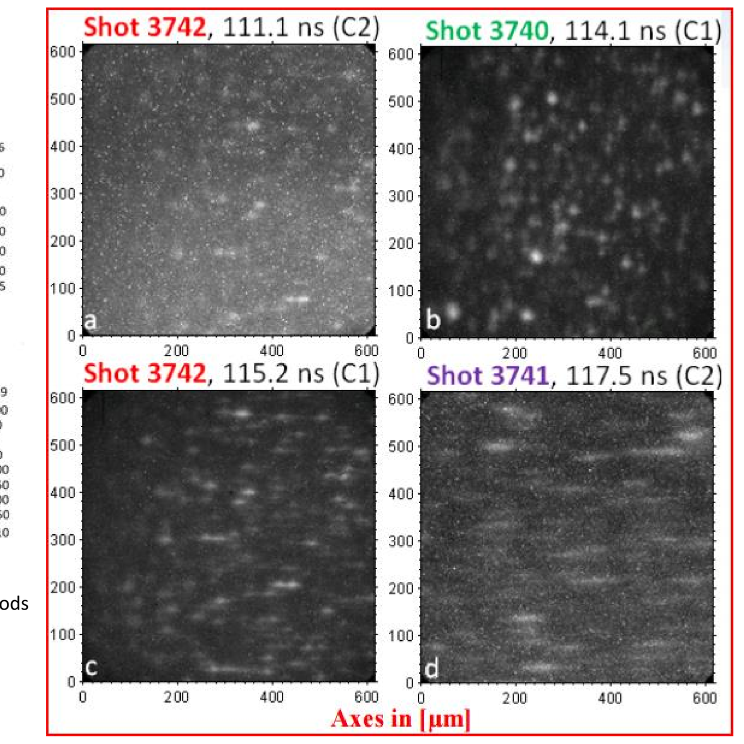
-Ultra-high purity aluminum loads are diamond-turned to near perfect finish (surface roughness Ra < 10nm), then defects are added. These defects range from12-48 um in diameter, depths from 3-12 um, and between-divot spacings of 36-288 um.

Defect is largest perturbation on the current density

-Engineered defects (motivated by the study of alloys) will allow for the investigation of well-characterized perturbations that are predicted to drive ETI.



Diamond turning and electropolishing methods are being used on aluminum targets +to decrease surface roughness



Non-uniform emissions are shown to evolve quickly from Al 6061 surfaces, as seen in the figure above.

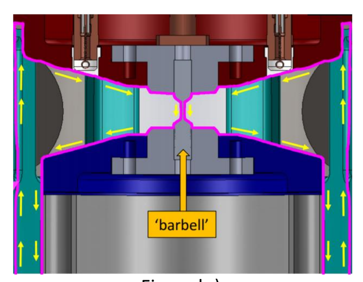


Figure b.)

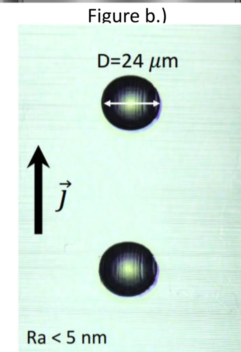


Figure c.)

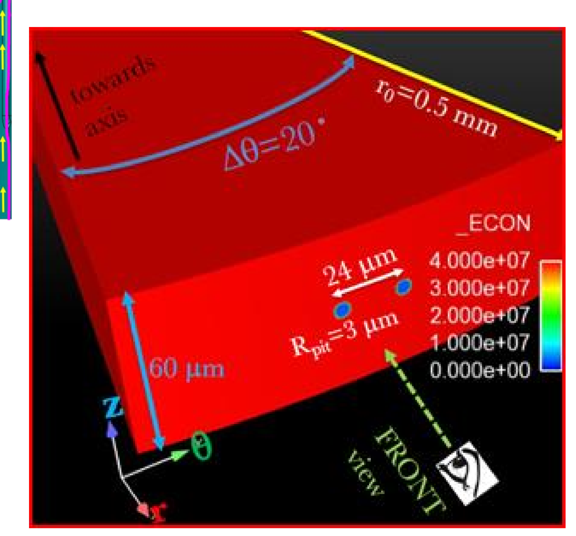


Figure d.)

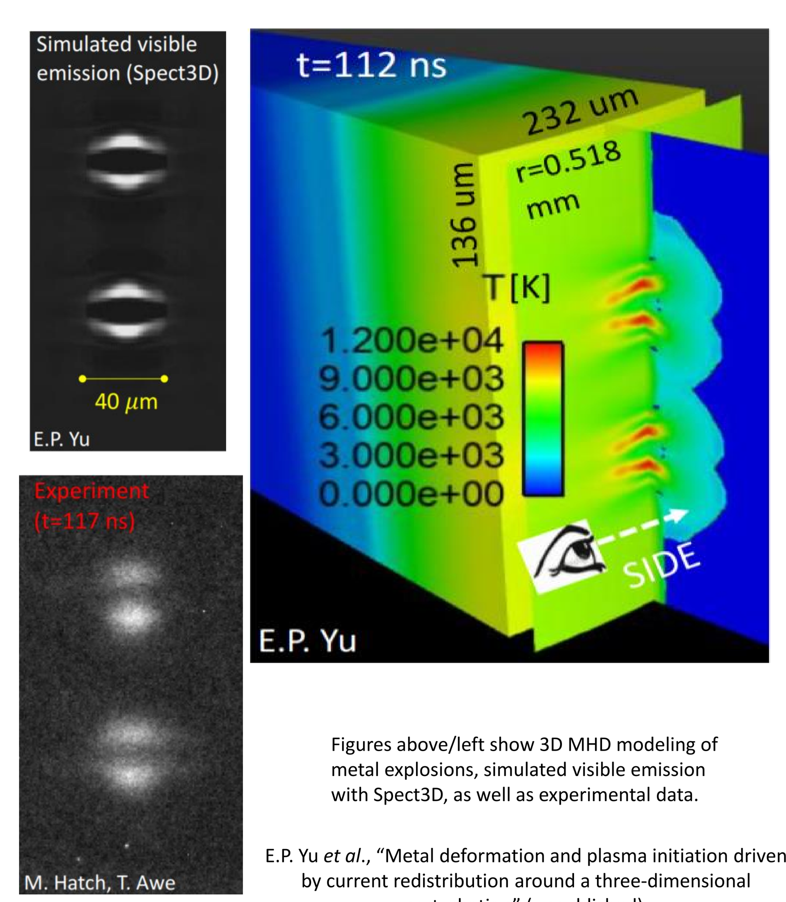
Examples of engineered defects can be seen in Figure a). Figure b) shows the barbell target mounted in the Mykonos device, with yellow arrows showing current direction. Figure c) displays a confocal microscopy image of a barbell with engineered defects. Figure d) displays the initial perturbation geometry for a 3D MHD simulation of barbell target with micron scale engineered defects.

Various patterns of engineered defects have been designed to study how spatial differences impact ETI evolution

•Axially and azimuthally aligned engineered defects are being shot on Mykonos to compare emission patterns with simulations
•Defects with diameters ranging from 12 to 48 um across and depths ranging from 3 to 12 um will be utilized to study similarity (theory that current density amplification is independent of divot size)
•Epoxy will be used on some targets to represent behavior of resistive inclusions and provide information on how ETI responds to a dielectric coating

		Side at 0 degrees					Side at 180 degrees				
Target type	# of targets	# of defects	diameter	depth	axial c-to-c	arc length c-to-c	# of defects	diameter	depth	axial c-to-c	arc length c-to-c
3	8	2	12 um	3 um	0	36 um	2	12 um	3 um	0	72 um
4	8	2	12 um	3 um	36 um	0	2	12 um	3 um	72 um	0
5	8	2	24 um	6 um	0	72 um	2	24 um	6 um	0	144 um
6	8	2	24 um	6 um	72 um	0	2	24 um	6 um	144 um	0
8	8	2	48 um	12 um	0	144 um	2	48 um	12 um	0	288 um
9	8	2	48 um	12 um	144 um	0	2	48 um	12 um	288 um	0

Chart showing relevant engineered defect target types used for experiments



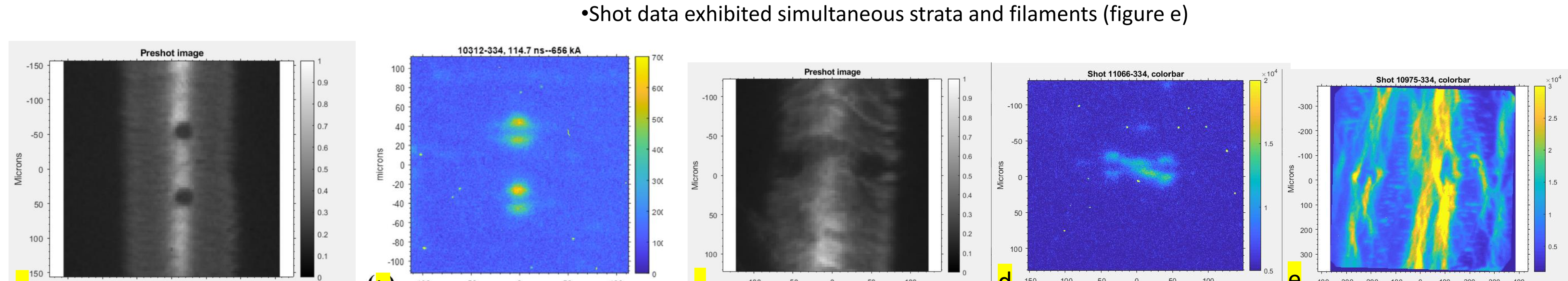
Figures above/left show 3D MHD modeling of metal explosions, simulated visible emission with Spect3D, as well as experimental data.

E.P. Yu *et al.*, "Metal deformation and plasma initiation driven by current redistribution around a three-dimensional perturbation" (unpublished).

Engineered defects exhibit two bright emission spots per pit as ETI evolves

•Theory, simulation, and experimental data are being used to better understand the evolution of micron-scale features into larger structures
•Hydrodynamic expansion causes pits to transform into bumps, then current converts from flow around the pit into the bump, resulting in two bright emission spots ("cat eyes")
•In experiments, axially and azimuthally aligned divot targets are used to study the solid metal state and plasma state evolution of ETI
•12-frame imaging captures multiple phases of ETI evolution. High resolution images are captured with 2 and 3- ns intensified CCDs.

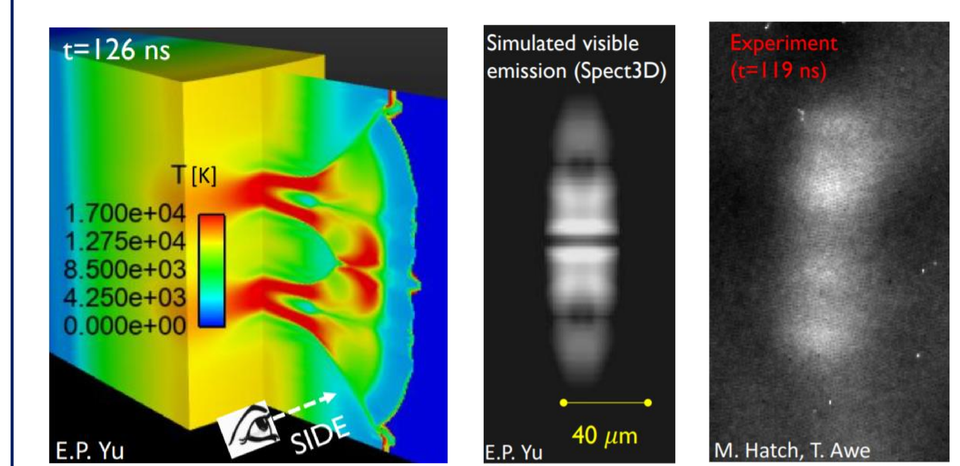
Experimental observations Awe *et al.*, Phys. Plasmas **28**, 072104 (2021);)
•Cat eye emission is pronounced for type 5, 6, and 8 targets, and less pronounced for types 3 and 4, which have smaller divot diameter/depth/c-to-c spacing
•Both axially oriented and azimuthally oriented divots exhibit cat eye emission structures (see figures b and d below)
•Communication/collective behavior is seen for the first time between isolated defects (figure d)
•Locations of peak cat eye emissions are symmetric about (but spaced further than original diameter of) engineered defects
•Shot data exhibited simultaneous strata and filaments (figure e)



Figures a.) and b.) Respectively, preshot image and shot data from axially aligned engineered defects. Figures c.) and d.) Respectively, preshot image and shot data from azimuthally aligned engineered defects. Figure e.) Shot data exhibiting both strata and filaments

Plasma filaments form between divots in both simulation and experiments

•The hot spots described in the previous section explode, leaving a crater from which exploding plumes erupt
•Plasma filaments can be seen connecting divots
•Theory, simulation, and experimental data show evidence of this phenomenon

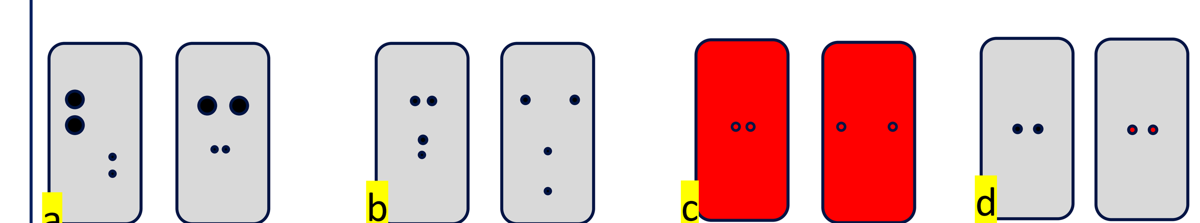


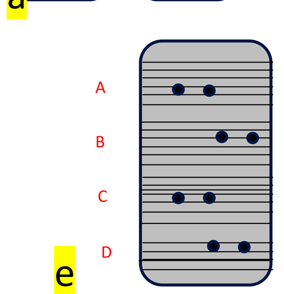
Figures to the left show 3D MHD modeling of plasma formation, simulated visible emission with Spect3D, as well as experimental data.

Future work includes novel target designs

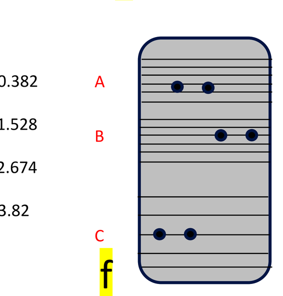
•The next engineered defect campaign will combine initial designs onto single targets to ensure identical current density of areas of focus and to compare:
- Different divot diameters/depth/c-to-c divot spacing (fig. a)
- Axial vs. azimuthal divot orientation (fig. b)
- Close vs. separate divot spacing with epoxy coating (fig. c)
- Epoxy-filled vs. void divots (fig. d)

•Sinusoidal perturbations are theorized to amplify current density, even for very smooth surfaces (low amplitude roughness) so long as wavelength is also small
•Targets with multiple sections of varying sinusoidal amplitudes but constant wavelength will be studied to determine how the varying ratio A/λ drives surface heating and plasma formation. (fig. e)
•Divots machined into each of these perturbed regions will inform dominance of either engineered defects or sinusoidal current density amplification at various A/λ
•Targets with multiple sections of varying wavelength will test the importance of the A/λ ratio compared to changes in amplitude only (fig. f)
•Divots will be machined into each of these perturbed regions as well
•Targets will be coated with epoxy to avoid plasma filamentation veiling of the areas of interest





A: peak-to-valley amplitude A = 0.382 µm, J = 1.05
B: peak-to-valley amplitude A = 1.528 µm, J = 1.2
C: peak-to-valley amplitude A= 2.674 µm, J = 1.35
D: peak-to-valley amplitude A = 3.82 µm, J = 1.5
- λ= 24 µm for all sections



A: peak-to-valley amplitude A = 1.528 µm, J = 1.2, λ= 24 µm
B: peak-to-valley amplitude A = 3.056 µm, J = 1.4, λ= 24 µm (Twice the amplitude as section A but with same λ= 24 µm)
C: peak-to-valley amplitude A = 3.056 µm, J = 1.2, λ= 48 µm (Twice the λ of section A&B, but with same amplitude as section B)

•New diagnostics for future work include:
- improved laser shadowgraphy to diagnose plasma dynamics
- a multi-diode array to measure multiple locations for large-scale temperature gradients
- infrared avalanche photodiodes to observe low temperature surface emission

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