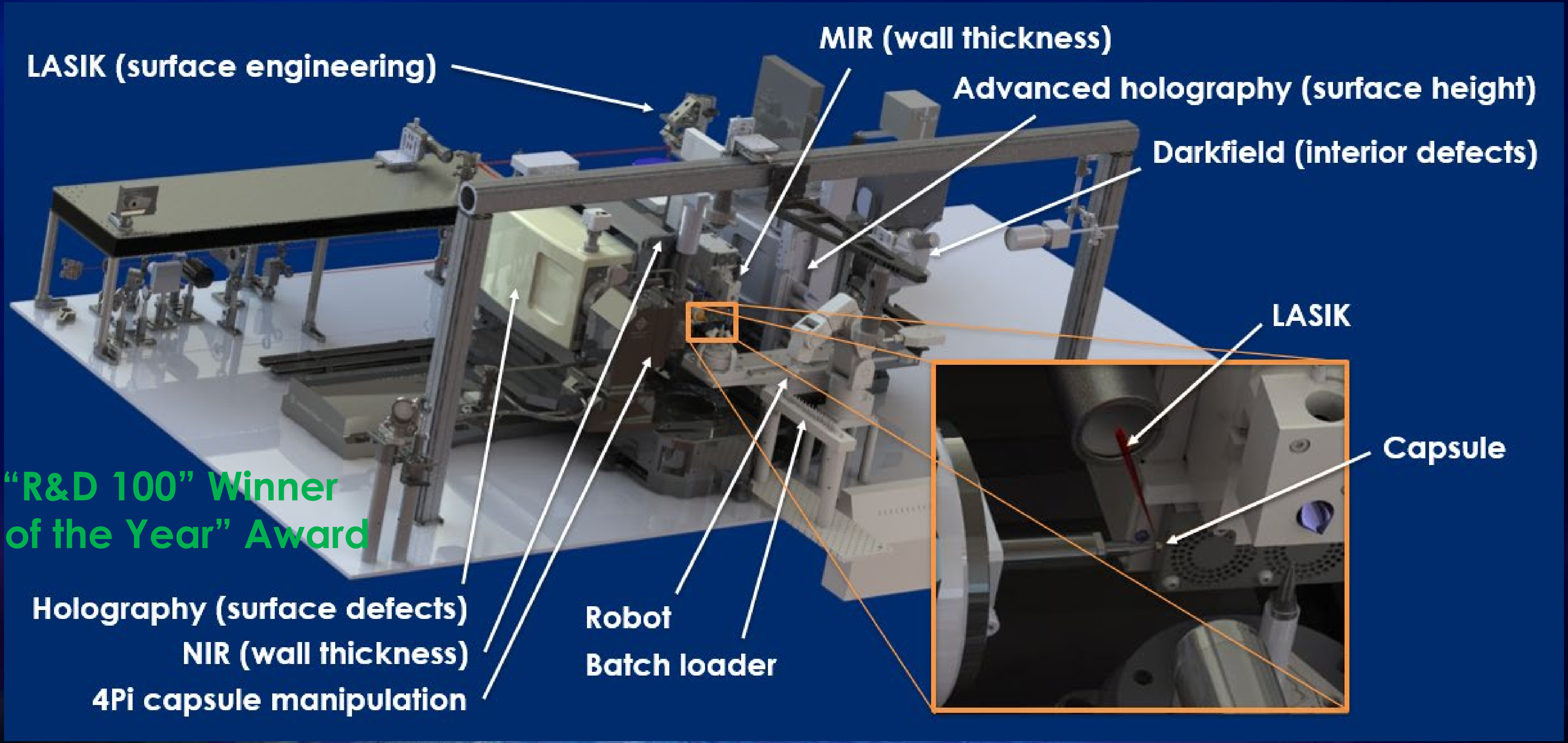
Metrology Contribution to Ignition

Haibo Huang on behalf of the GA team
Target Fabrication Specialist Meeting, August 25, 2024



2024 "R&D 100" Winner
"Team of the Year" Award

IFT\P2024-026

This work performed under the auspices of General Atomics Internal R&D funding

GENERAL ATOMICS

Metrology is Integral to NIF Success

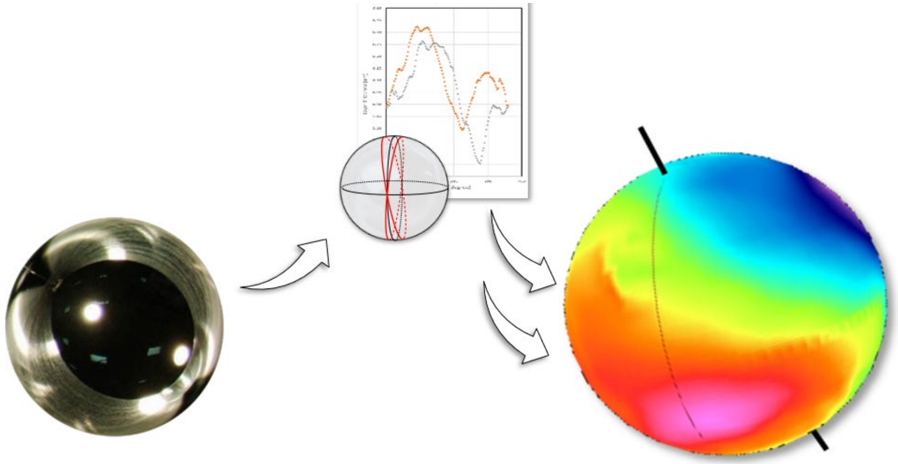
- **Target specs are very tight, metrology feedback is crucial**
  - For fabrication improvement, capsule selection, shot control, and performance modeling

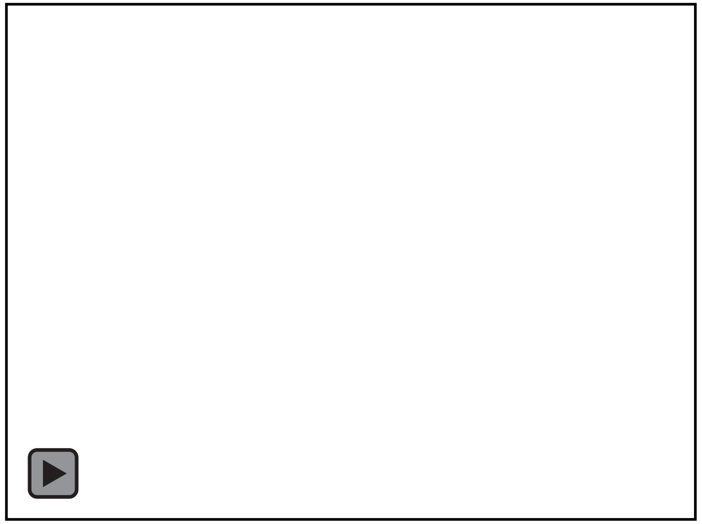
- **Metrology tools are often ablator-specific**
  - Surface defects => Holography (HDC, GDP)
  - Wall thickness, including sublayers => Compact FTIR (HDC, GDP)
  - Wall thickness variation => LUS (Be, HDC, PSS)
  - Dopant profile => EDS (HDC, GDP, Be)
  - Dopant areal density => AutoEdge (Any)
  - Other materials properties => Resonance (HDC)

- **“Integrated Metrology” is exemplified by the 4Pi system**
  - Current status, developmental needs

Guiding Principles for Capsule Metrology

- **Metrology needs are unique to ablator type and are unforeseeable**
  - Future proof via modular system design
- **Full 4Pi surface coverage**
  - As opposed to traces
- **Multiple tools sharing common (theta, phi)**
  - Complementary instruments => Deeper insights
- **Not reinventing the wheel**
  - Custom adaptation and optimizing commercial sensors
- **Robust, high precision control**
  - 2μm positional repeatability, <1μm wobble control
- **Production relevant throughput**
  - Slow tool must be paired with fast tool
- **Batch automation**
  - Via robot





GENERAL ATOMICS

“Integrated metrology” enables “data fusion”

From five instruments:

- Holography => Surface defects
- FTIR => Wall thickness
- X-ray tomography => Voids
- AFM => Surface shape
- Microscope => Optical image

The same coordinate system

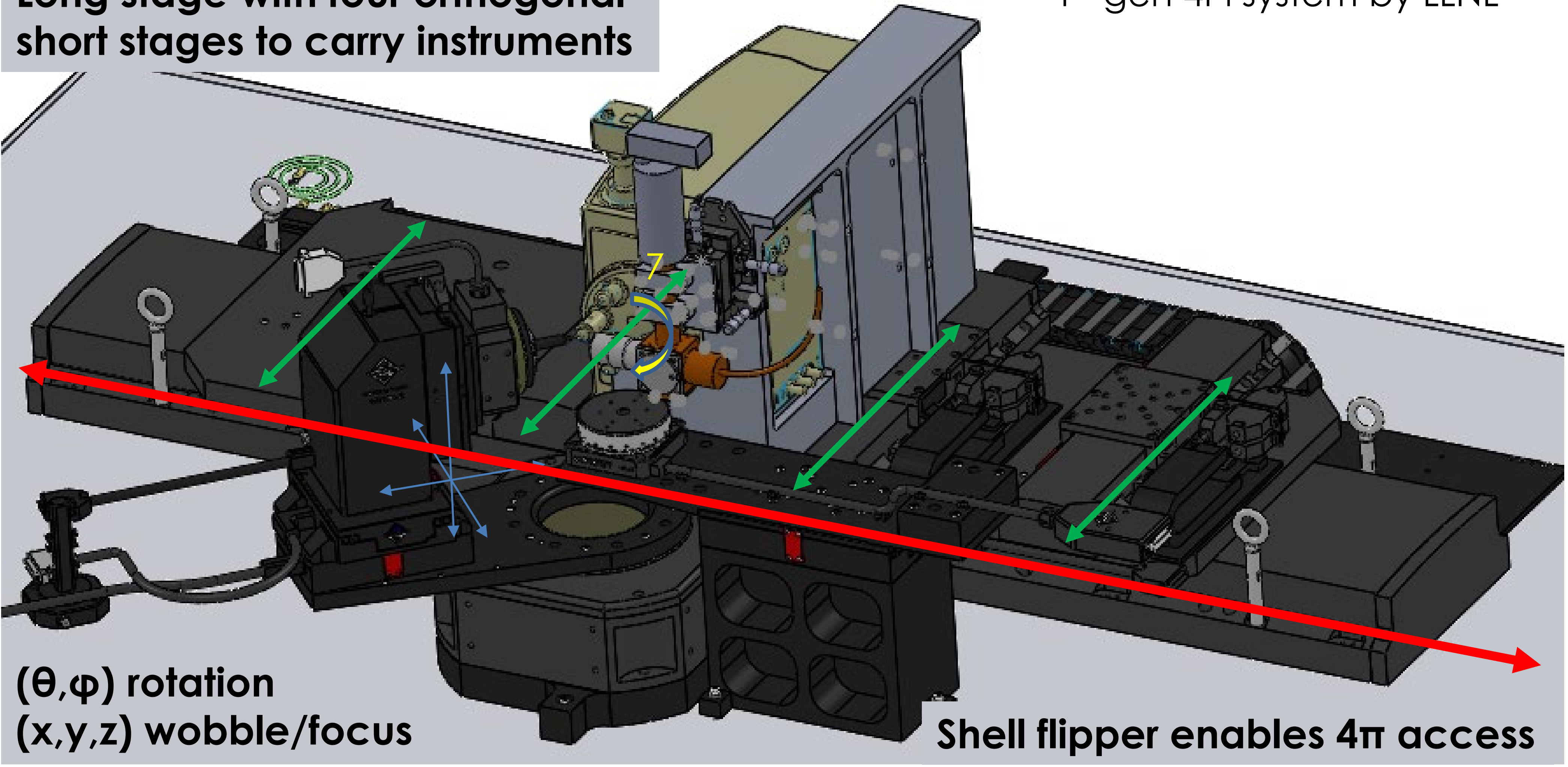
Empowers

- Target fab feedback
- Shell selection
- Performance simulation
- Shot control & offset

Conceptualizing a 12-axis 2nd-gen 4Pi system* with many instruments: Sharing common (θ, φ) is critical to benchmarking & efficiency

*Build on the success of 1st-gen 4Pi system by LLNL

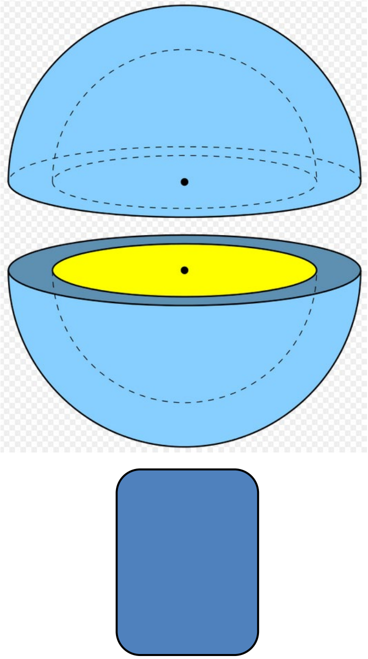
Long stage with four orthogonal short stages to carry instruments



(θ,φ) rotation
(x,y,z) wobble/focus

Shell flipper enables 4π access

2Pi + shell flipper equals 4Pi



Vacuum chuck

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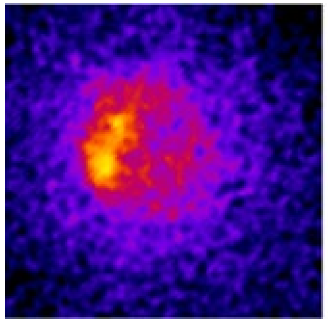
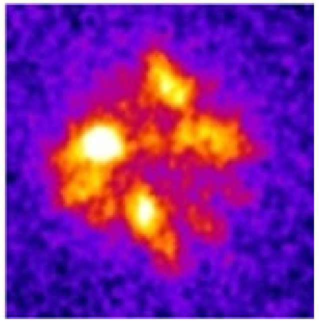
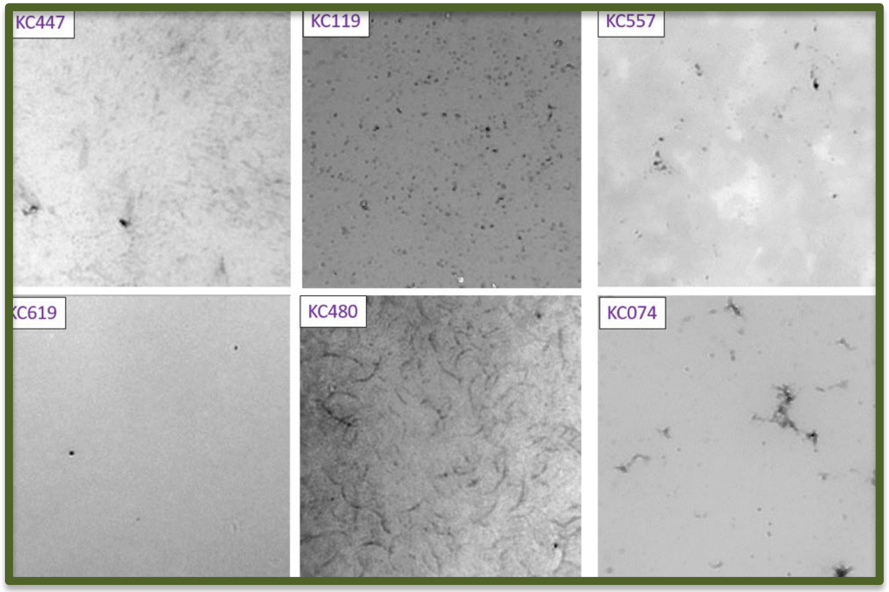
Lyncee Tec (Digital Holographic Microscope): Fast full-surface survey to find the biggest HDC pits

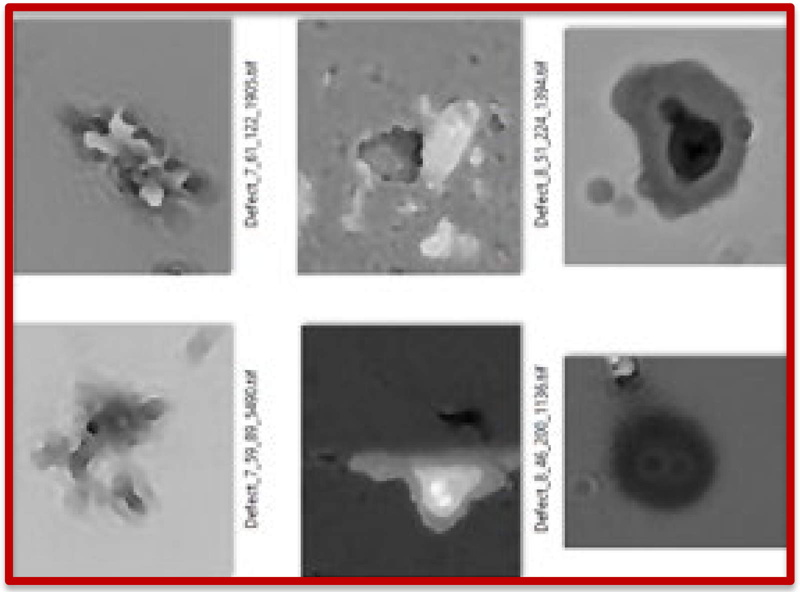
- **“Meteor showers” in NIF shots quench neutron yield**
  - Need to know largest pits
- **1 hour per shell, 100x faster than status quo**



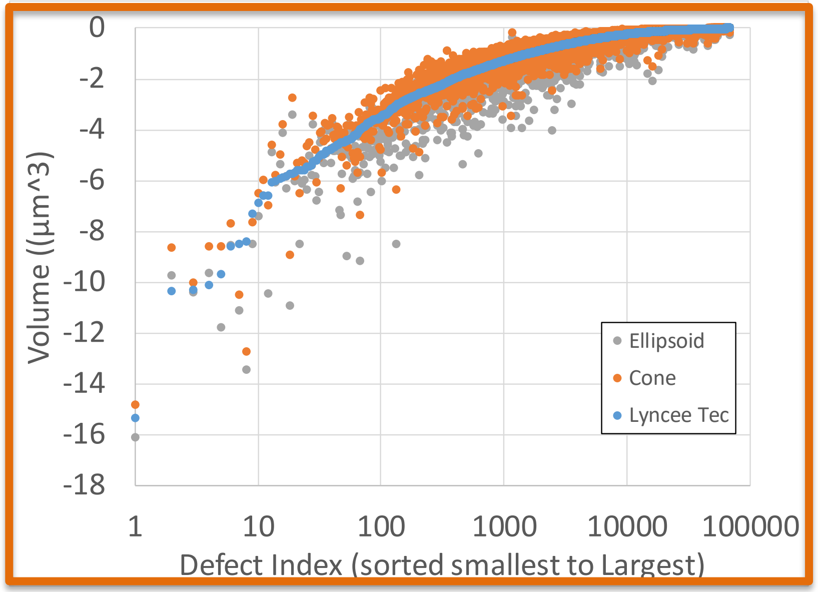




Varying morphology recorded



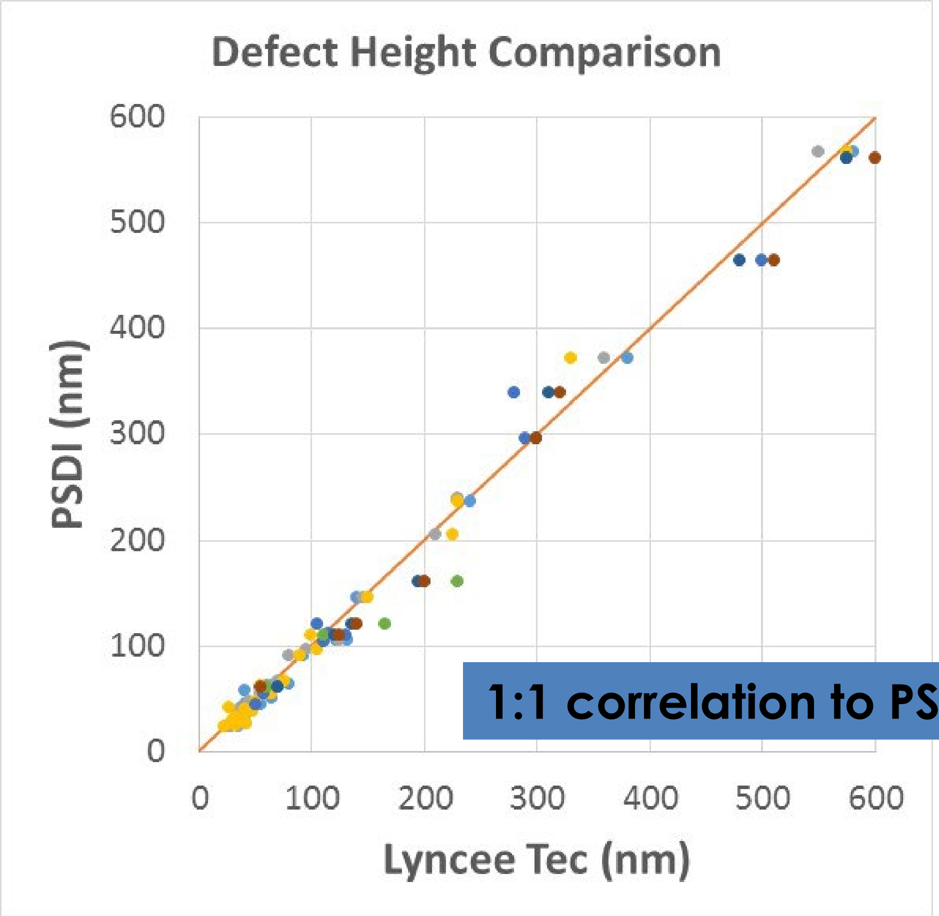
Biggest defects caught



Statistics taken

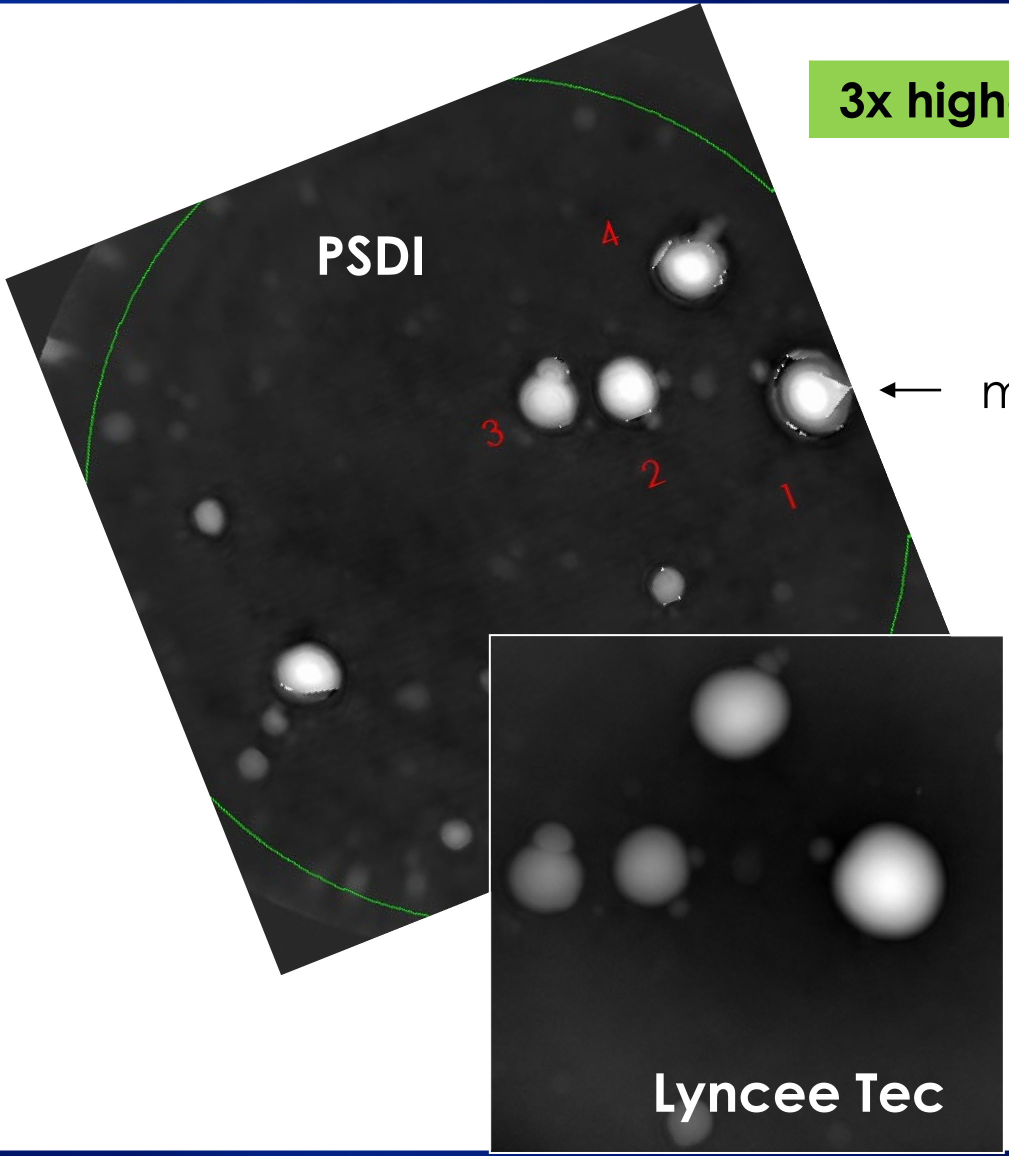
Lyncee Tec also replaced PSDI for GDP dome characterization

2x faster, 20x smaller
Vibration insensitive



1:1 correlation to PSDI

3x higher slope than PSDI



← measurement error

← No error

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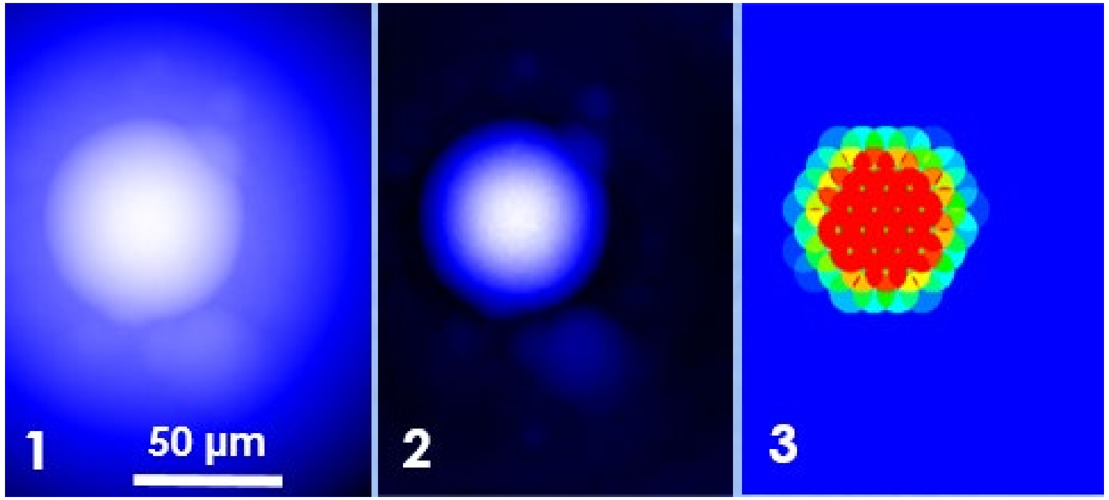
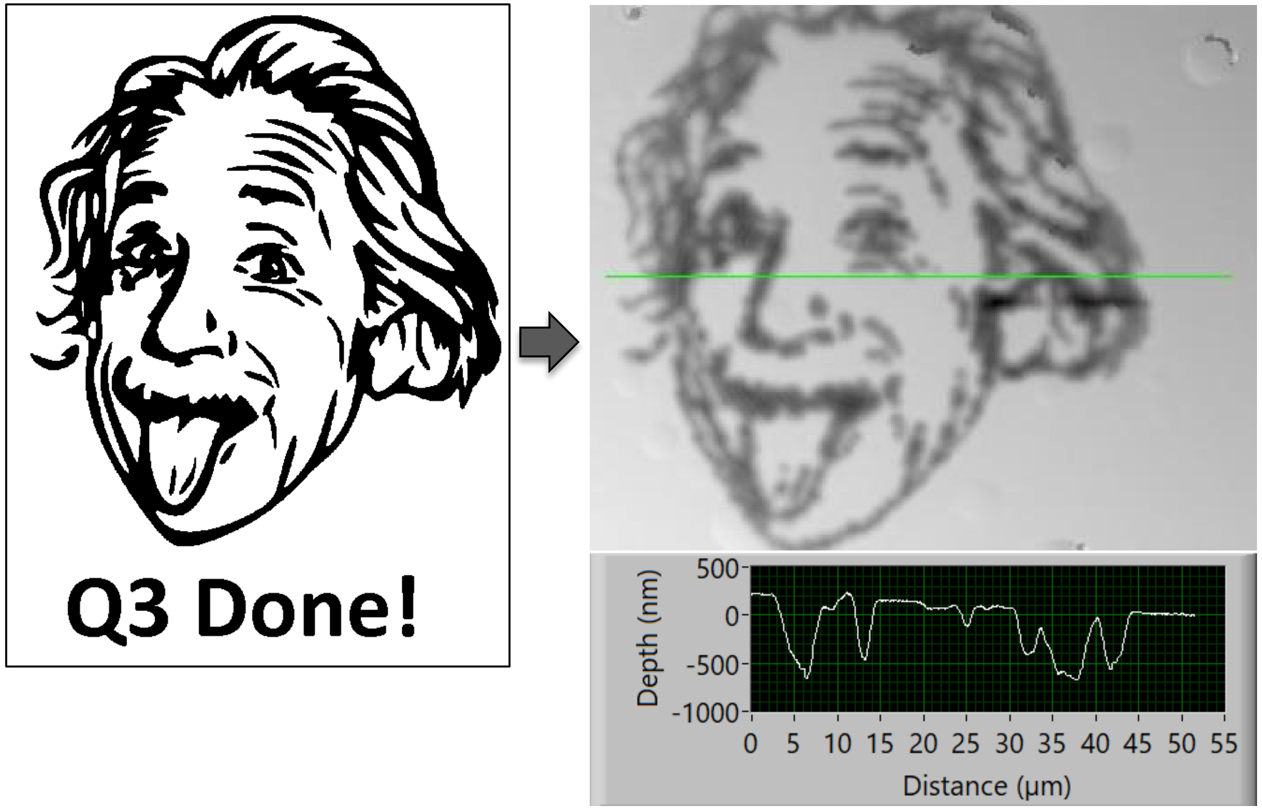
R&D topic: Use Lyncee Tec to control Lasik

Infrastructure present, capability demonstrated, need further work before production use



Remove GDP dome mass

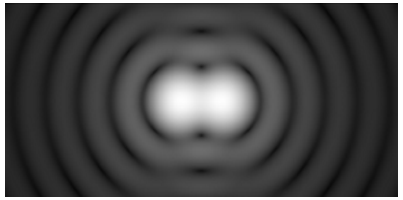


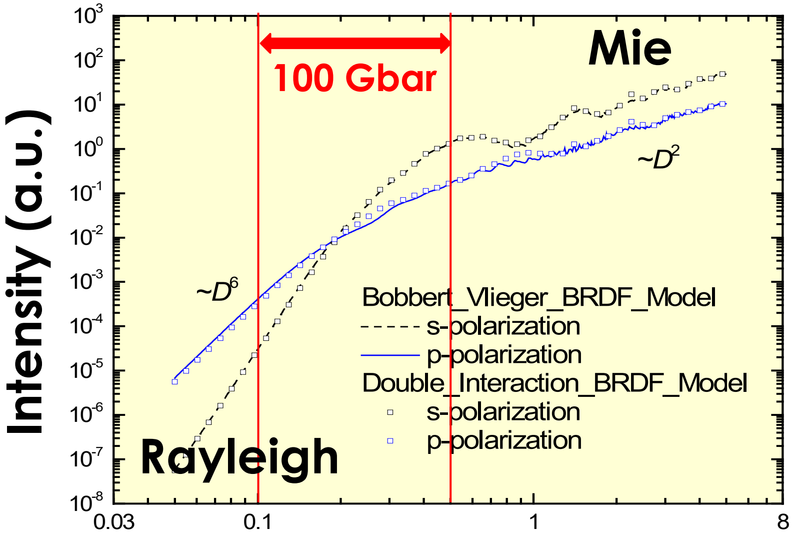
Add arbitrary engineering feature

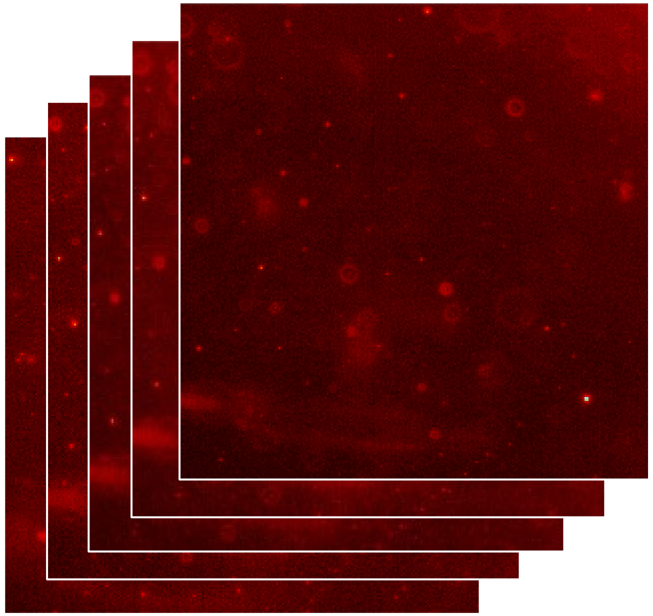
GENERAL ATOMICS

Darkfield:
Support PAMS and polystyrene vacuole inspection, also HDC & GDP

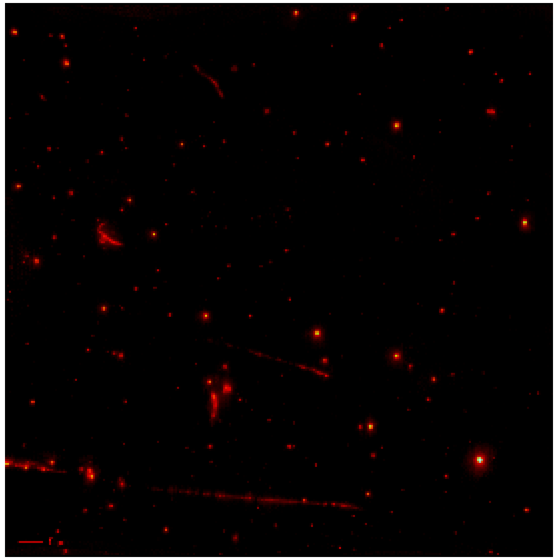
- "Direct-drive ignition": cares about defects down to 0.1 μm
- Scattering intensity correlates to volume, beating diffraction limit →
- Size calibrated by semiconductor industry standards







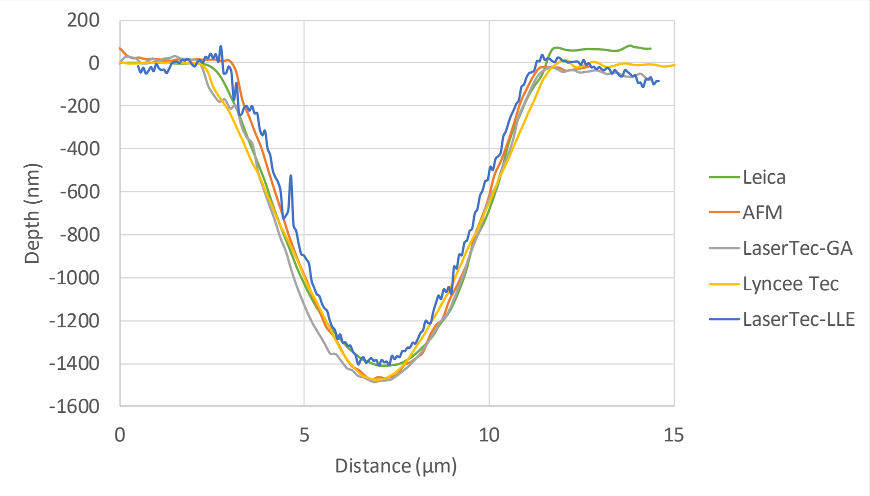
Z image stack(s)



'Starry night' visualization

Balancing performance with throughput to be production relevant

Instruments	Throughput (time per defect)	Throughput (time per shell)	Maximum slope	Minimum defect size	Comment
Holography	0.01 sec	1 hr	30-35 deg	0.5 um	Fast survey
AFM	300 sec	1000 hr	60-70 deg	0.1 um	Slow, highest fidelity
Confocal	100 sec	100 hr	50-60 deg	0.5 um	Better slope than Lyncee
Darkfield	50 sec	50 hr	90 deg	0.1 um	Superb on small defects



25° defect measured by 5 instruments

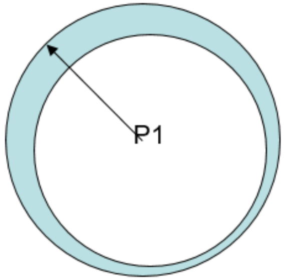
- **Metrology Strategy**
  - Pairing holography survey with AFM patch scan on top 10 defects
- **Fundamental limits**
  - All interferometers: Nyquist sampling => ¼ λ step
  - All optical tools: Multiple bounces in defects

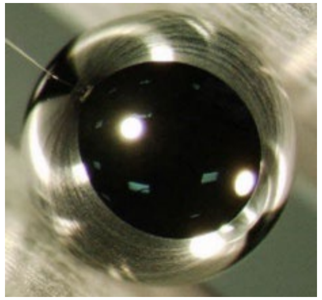
Kevin to present pits statistics, QC factors, benchmarking & AI

GENERAL ATOMICS

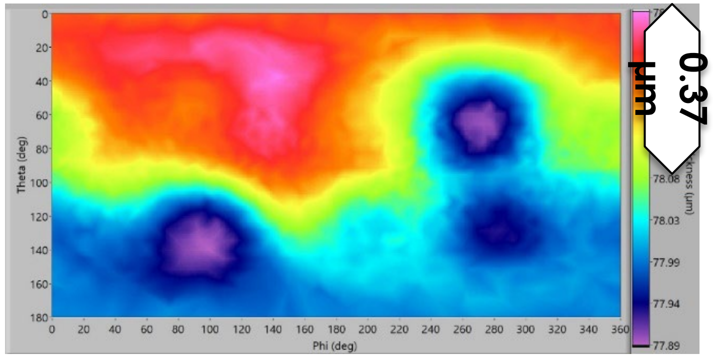
Compact FTIR:
Mid-IR system sees through full thickness HDC capsules

- **Wall thickness variation causes hot-spot drift, reduces NIF yield**
  - HDC capsules optically opaque
- **Improve measurement precision 30x**
  - Comparing to x-ray imaging
- **Identify higher modes, analyze multiple layers**





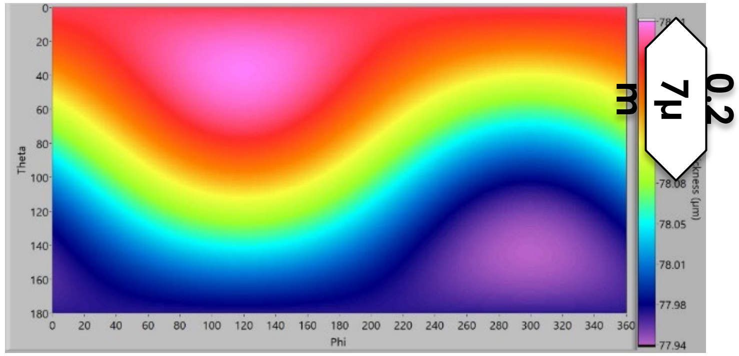
Original layer Thickness



Total Wall: 78.08 µm

-

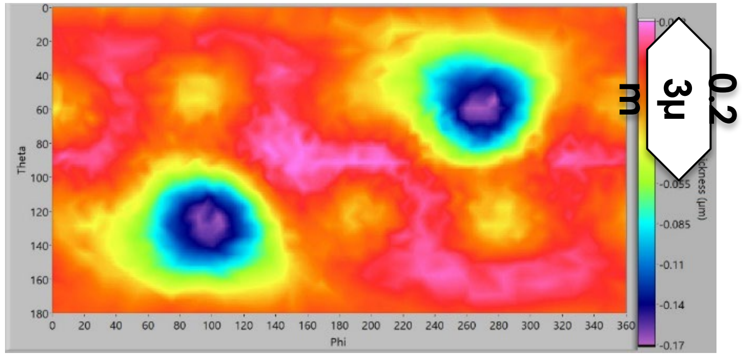
Fit for Modes 0 and 1



P1 = 0.135 µm

=

Subtract to get M2 & Higher



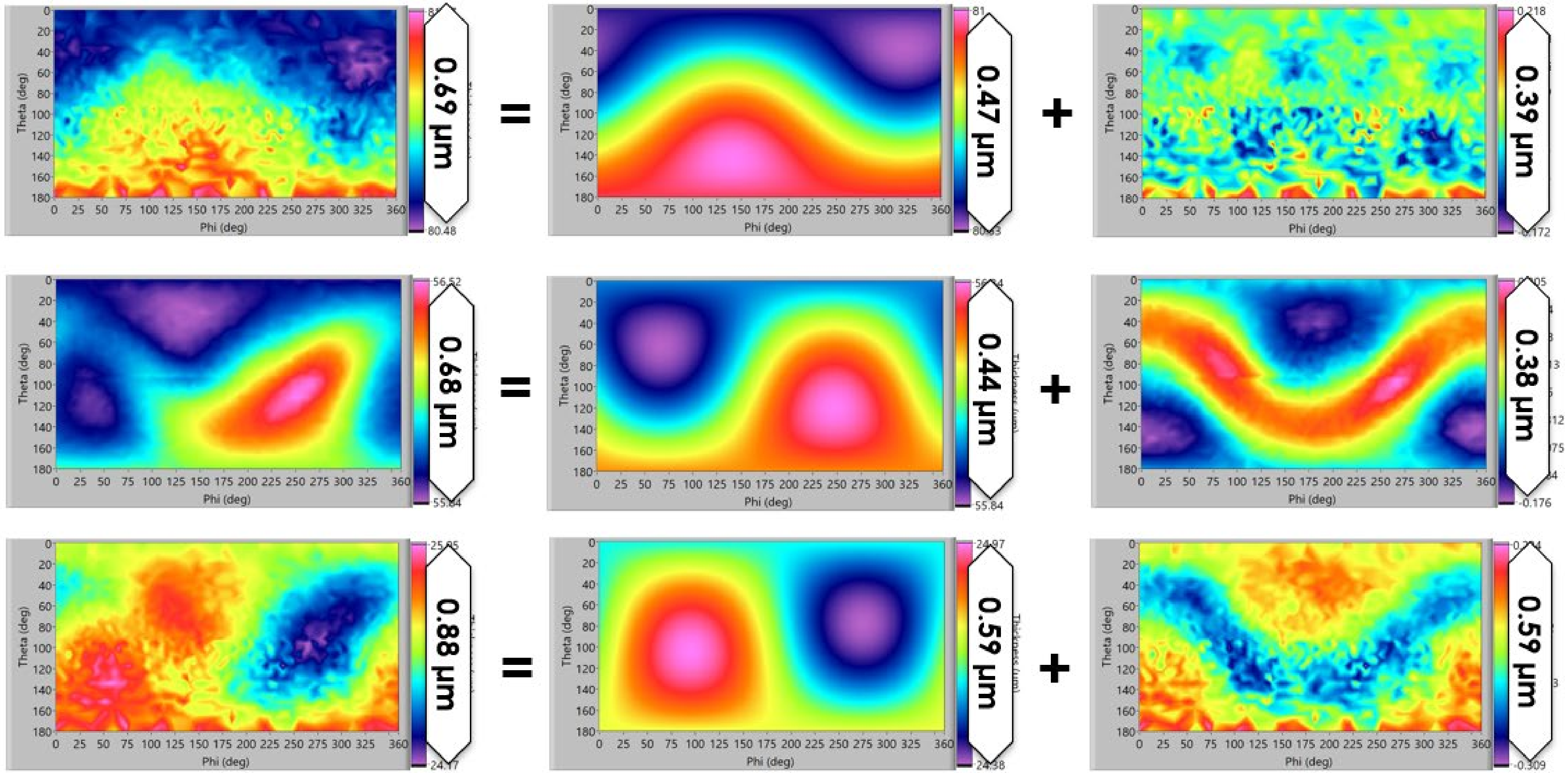
Significant M2+

Pasha will discuss transfer matrix modeling of refractive index to reveal hidden property variation

Compact FTIR can measure multiple layers and multiple modes, How can we use it for process feedback, performance simulation & control?

Deconstructing the "1.3 MJ shot" capsule into 3 layers

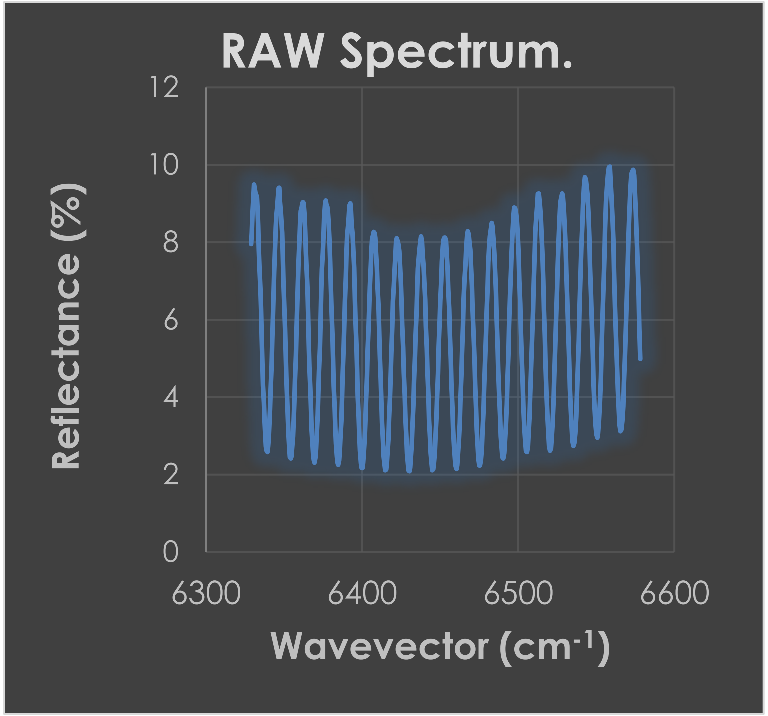
	Layer Thickness		Calculated M1 Map		Calc. M2 & Higher Map
Measured **Total Wall** 80.76 μm	0.69 μm	=	0.47 μm	+	0.39 μm
Measured **Outside undoped layer** 56.09 μm	0.68 μm	=	0.44 μm	+	0.38 μm
Calculated **Inner 2 layers** (by subtraction) 24.67 μm	0.88 μm	=	0.59 μm	+	0.59 μm

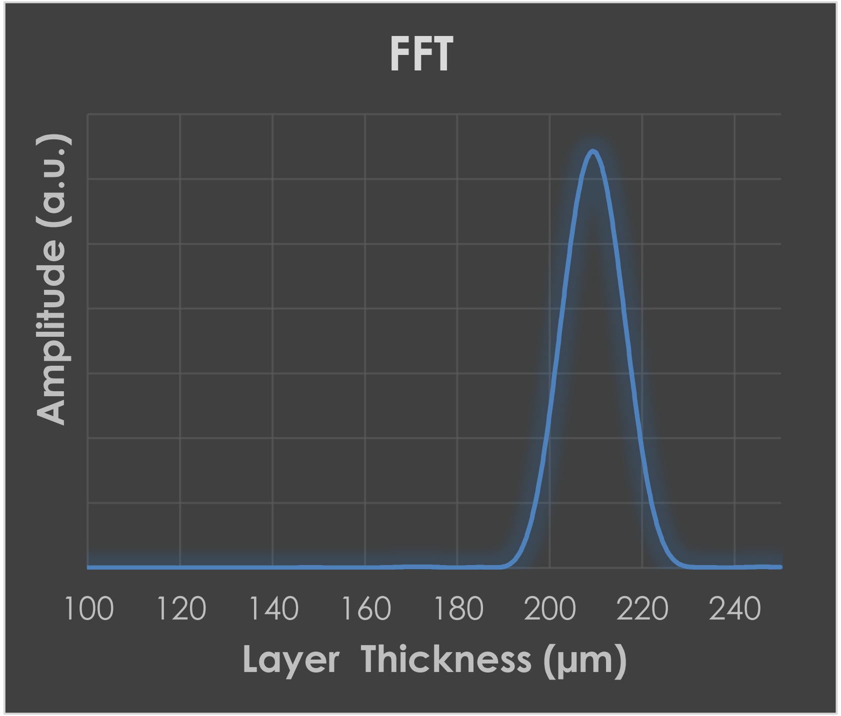


Polishing induced trench identified

Full thickness (> 200mm) GDP capsule easily measured by silicon wafer tool

- **Advantages: Simple, ready, robust**
  - Only need average refractive index value to fit total wall thickness
- **Drawback: Can't decipher sublayers**

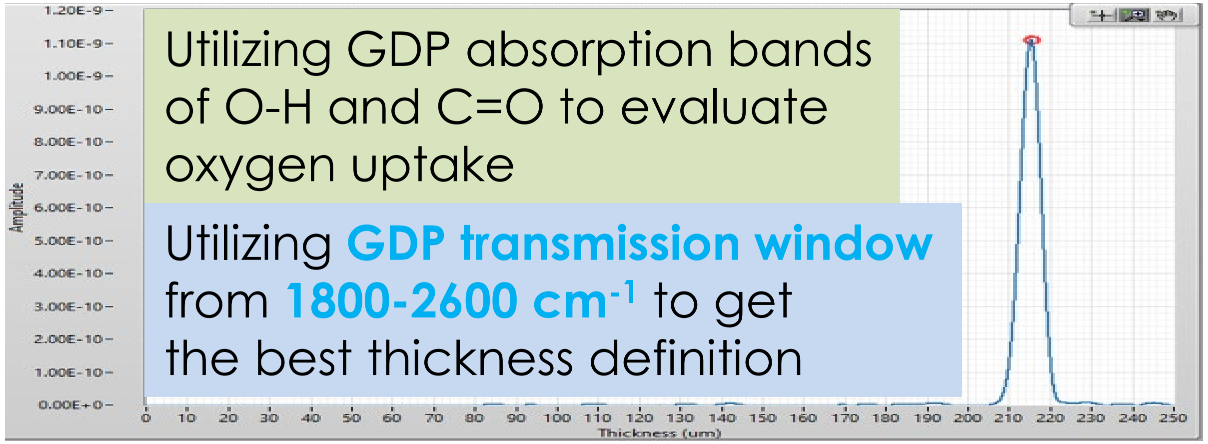




Thickness peak width inversely proportional to spectrum range: 5% range gives broad peak

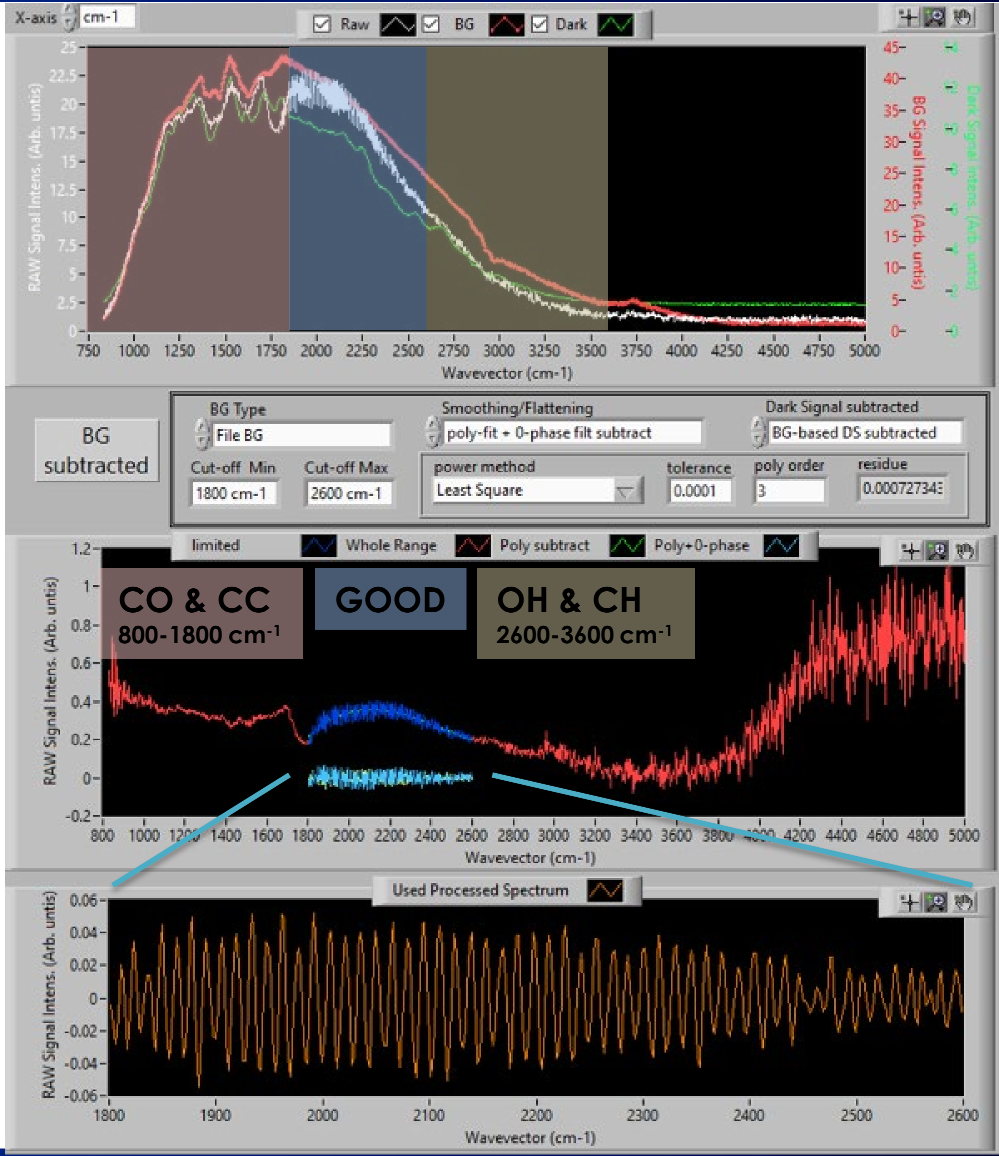
R&D topic: Enhanced GDP capability on compact FTIR

- **Anticipated capabilities**
  - Sublayer thickness
  - Oxygen areal density
- **Require GDP dispersion curve in analysis software**
  - Measure on flat GDP-on-Si
    - Measure on J.A. Woollam VASE MARK II
      - 1.7-30μm wavelength
    - Model Cauchy from Arcoptix spectrum



Utilizing GDP absorption bands of O-H and C=O to evaluate oxygen uptake

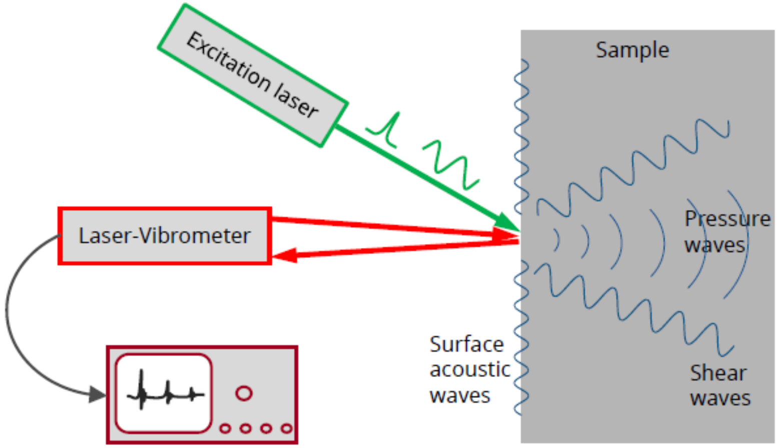
Utilizing **GDP transmission window** from **1800-2600 cm^{-1}** to get the best thickness definition



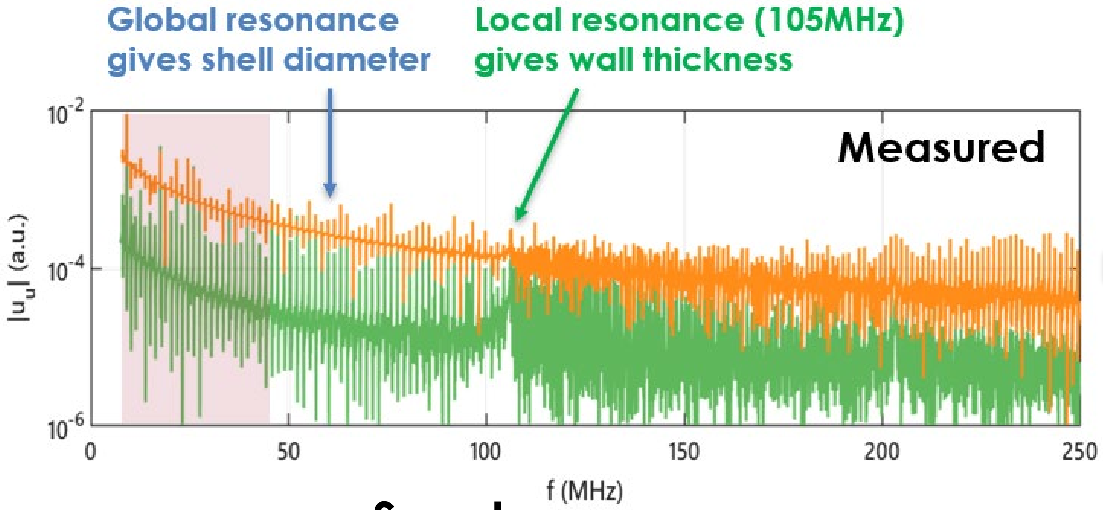
GENERAL ATOMICS

Laser Ultrasound Spectroscopy (LUS) measures HDC wall to 20nm precision

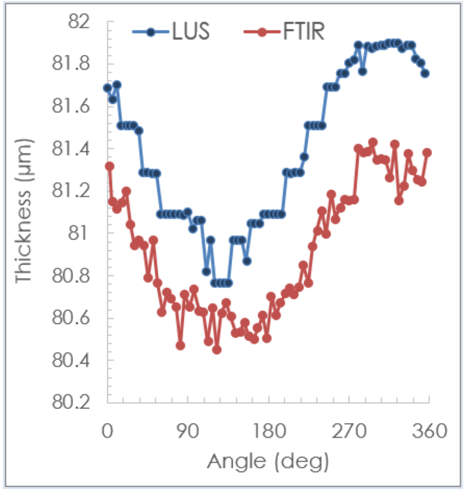
- **Using sound, instead of light to probe targets, just like using LIGO to probe the Universe**
  - Into the era of "multi-messenger science", "data fusion", "integrated metrology"
- **Multitudes of use cases in ICF, HED, NSE components**
  - Some HDC capsules are too opaque to IR, some targets are too opaque to x-ray
- **Use frequency-domain LUS to cover thickness range 5μm to 500μm**
  - Time-domain LUS has low thickness cut-off ~100μm, unsuitable for ICF/HED
- **Directly benchmarked LUS against IR to on the great circle of an HDC shell**



Concept



Spectrum

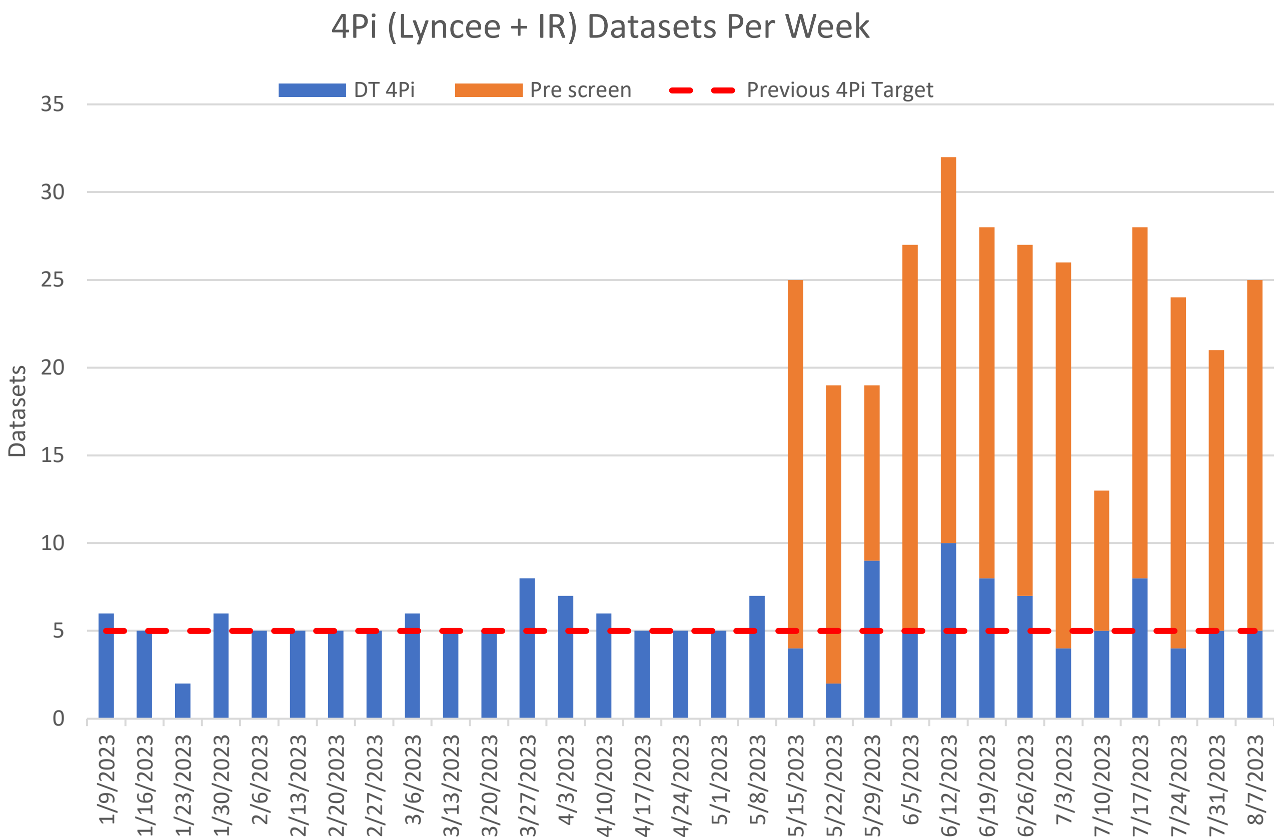


HDC Wall Thickness

GENERAL ATOMICS

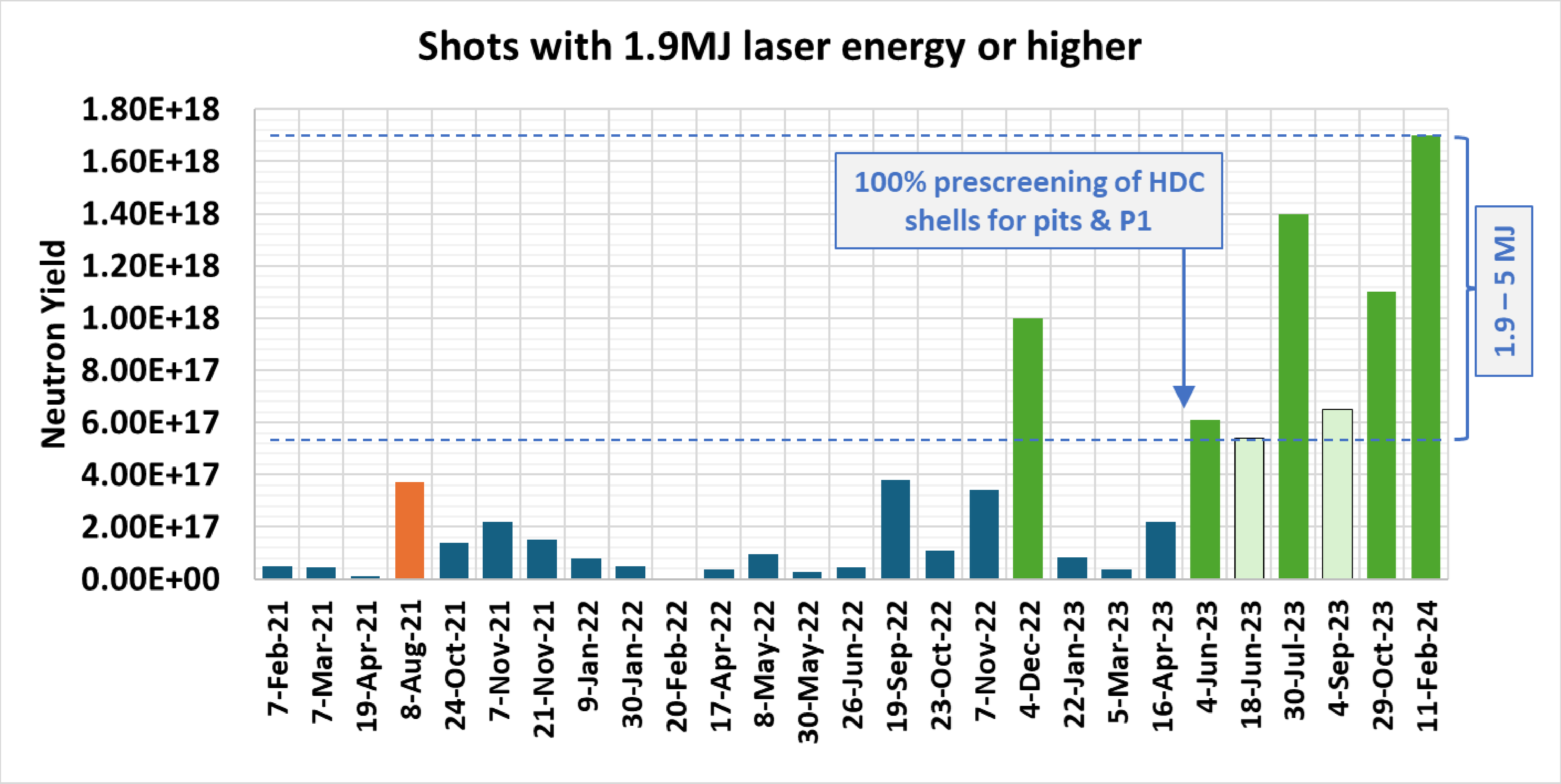
"Robotic 4Pi" instantly increased production metrology throughput by 4x

4Pi today with robotic automation



24/7 operation enabled HDC pre-screening

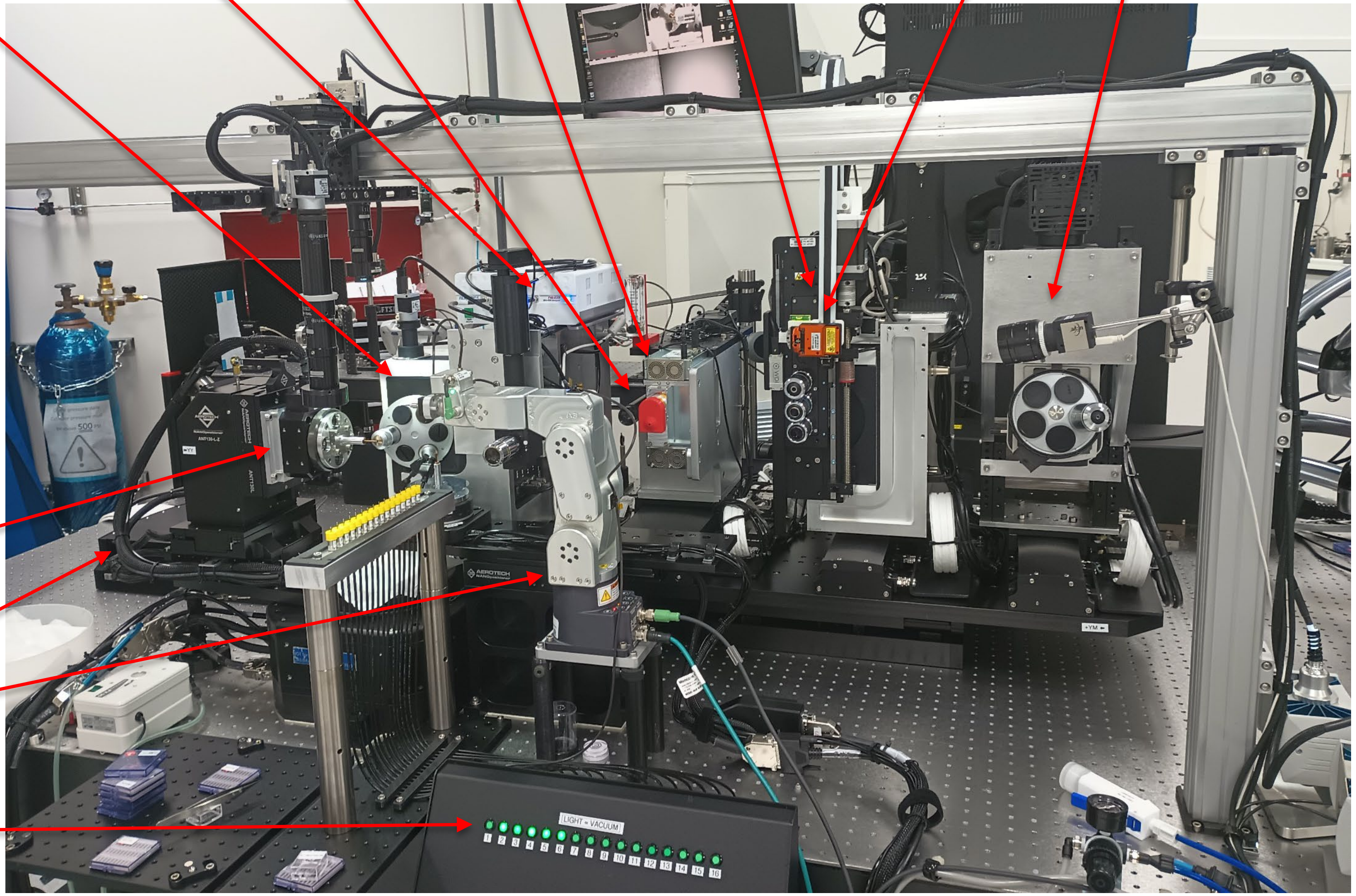
Ignition probability greatly increased after robotic prescreen



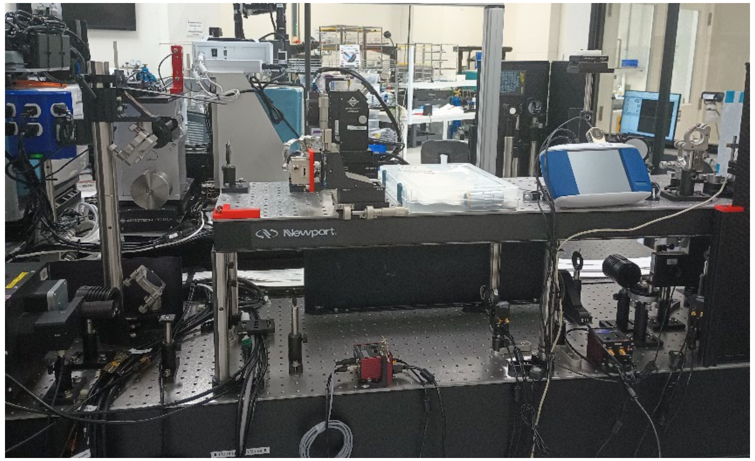
GENERAL ATOMICS

4Pi today: Solved the top 2 NNSA ICF capsule metrology challenges

(Pasha and Kevin will provide deeper dive in topical areas)



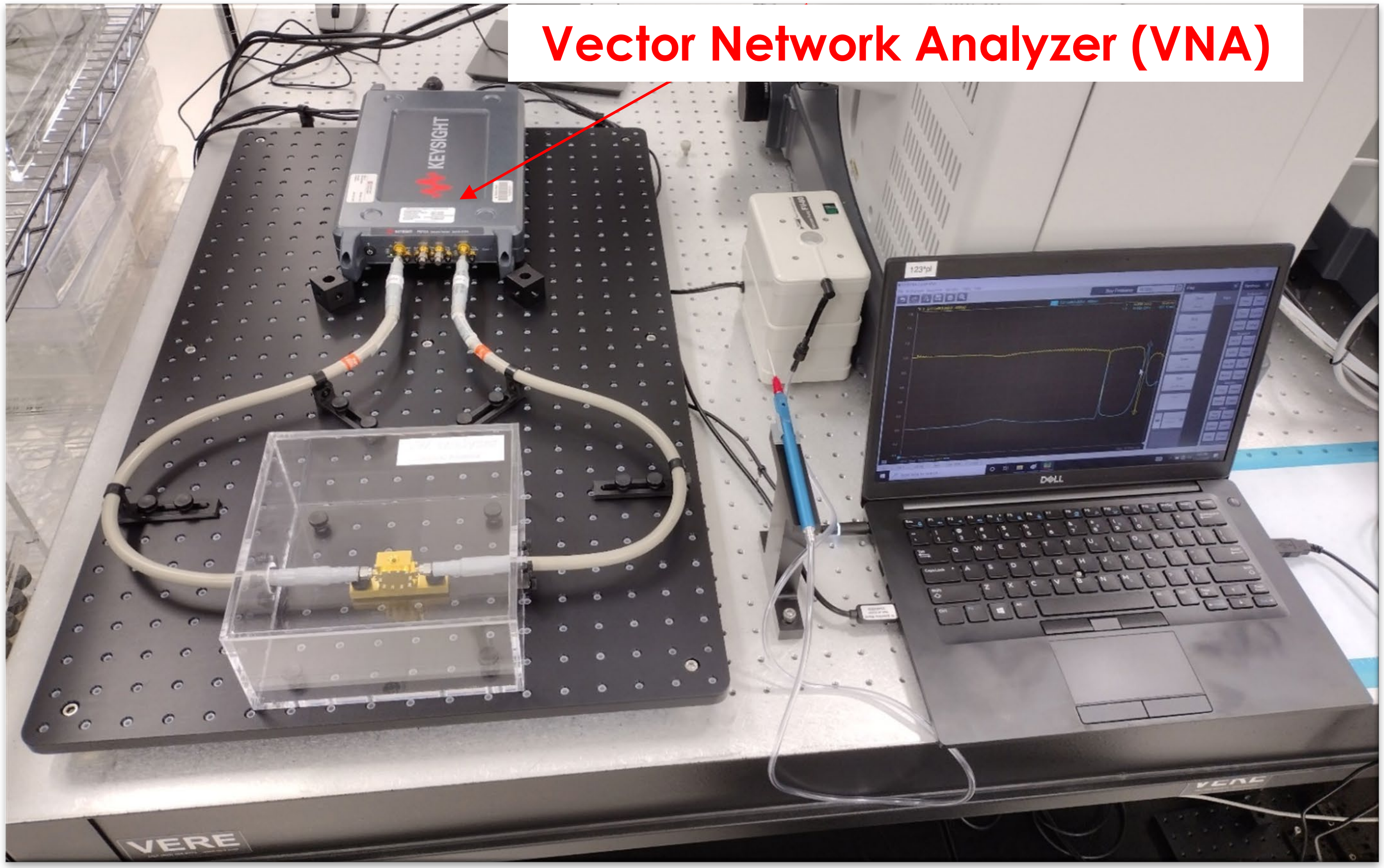
Lasik (back of the table)

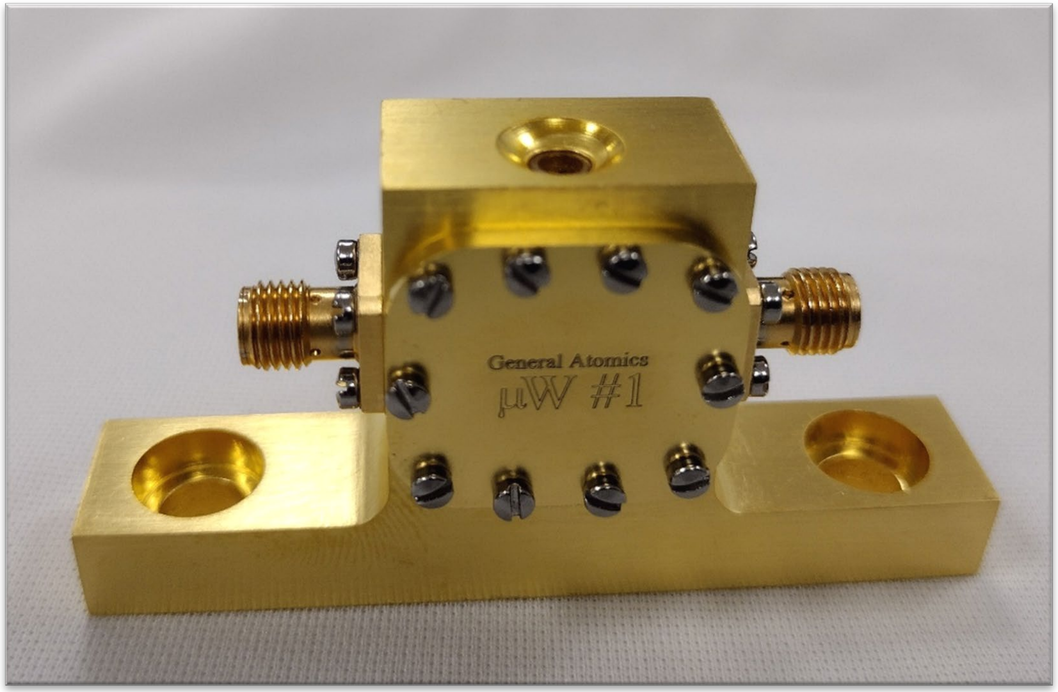


Control

Electrical conductivity measurement via microwave resonance

- **The art of "integrated metrology" is seeing the unseen**
  - Probing hidden materials property variations
  - Fast, non-destructive and ultraprecise
  - Whole shell measurement, complement other 4Pi techniques



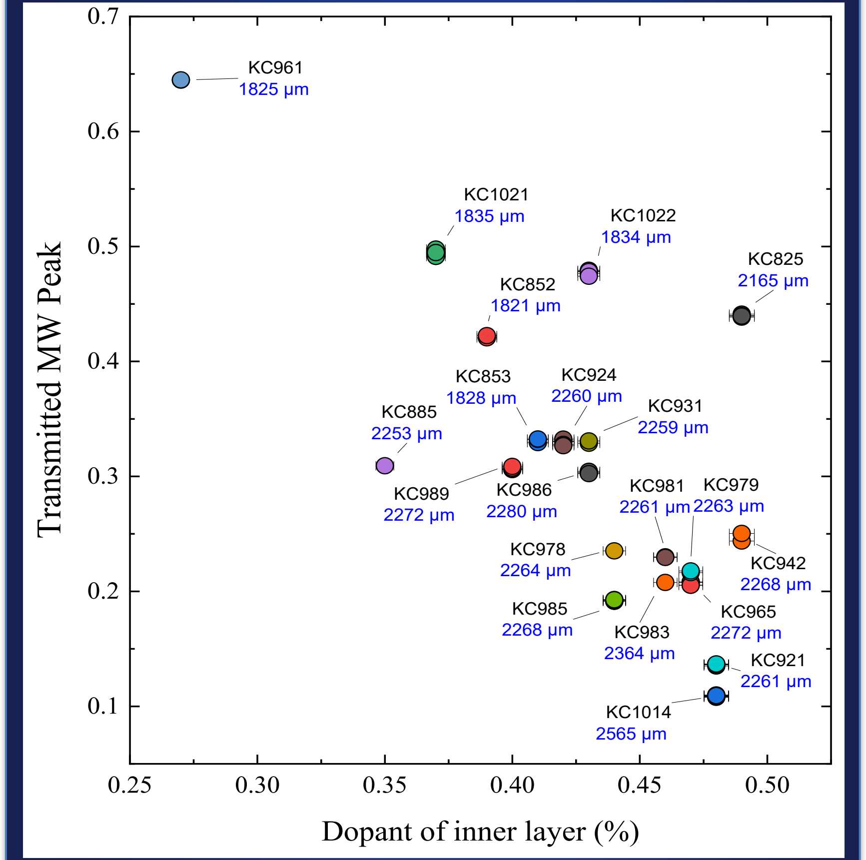


Need $40K to purchase VNA to integrate into production metrology process stream

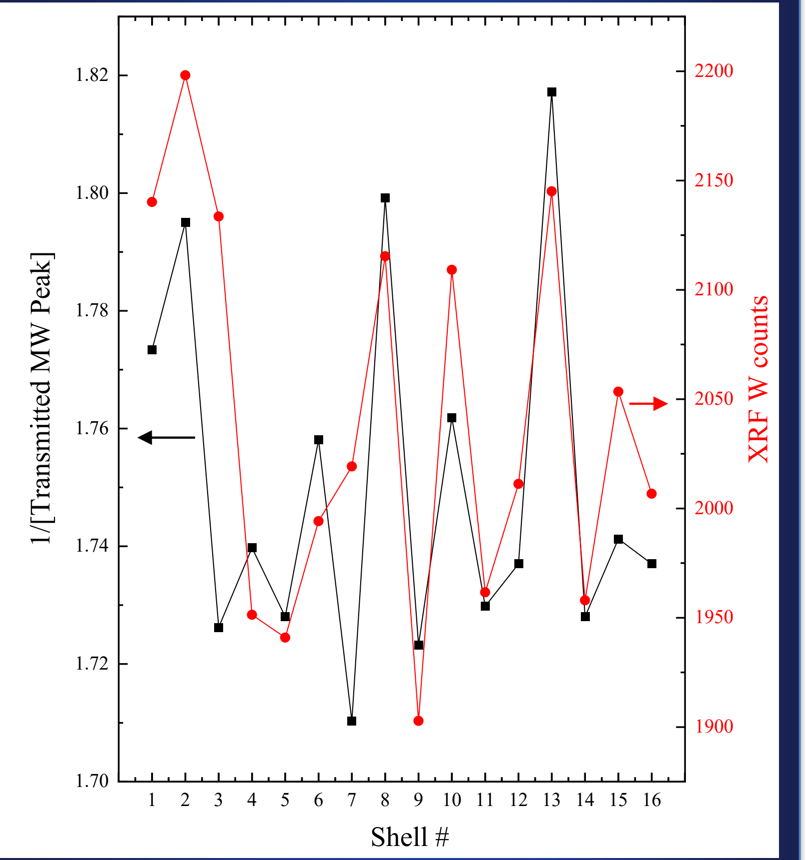
App #1: Probe & control major batch-to-batch HDC property variation
App #2: Cull silicon mandrels by resistivity to reduce CFTA plugging

What causes unexpected variations? 2 hours/batch investigation can answer many questions

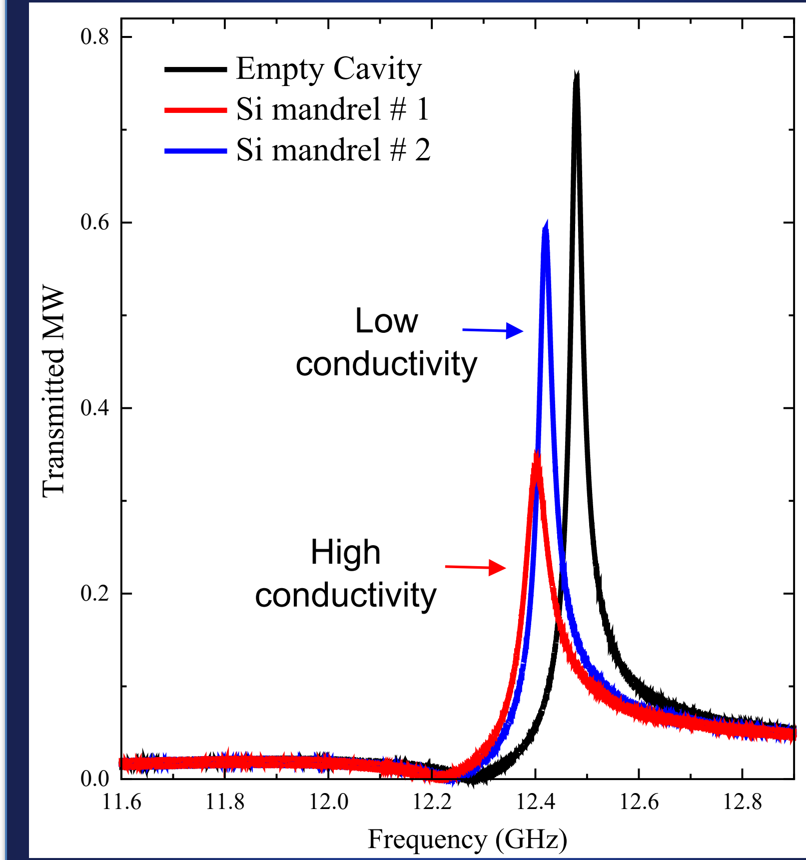
"Fingerprinting" material properties of HDC batches



Correlation of W content and conductivity

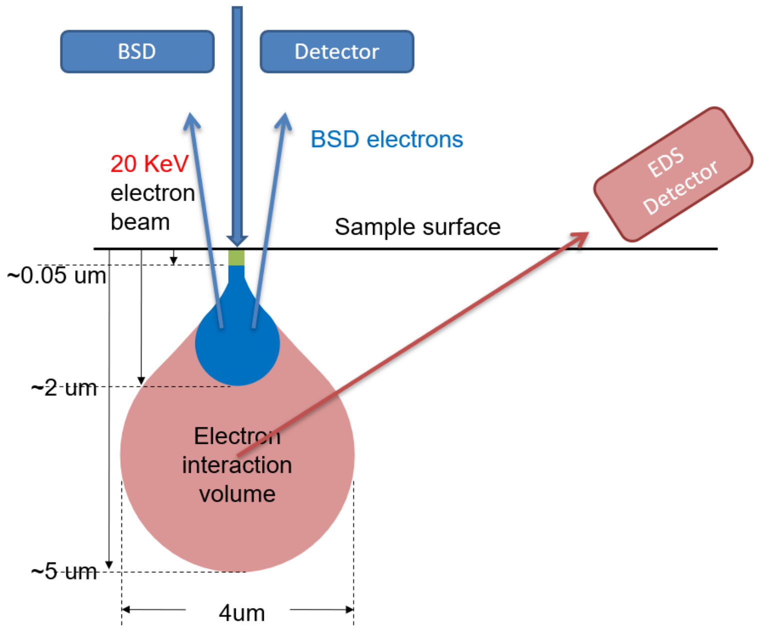


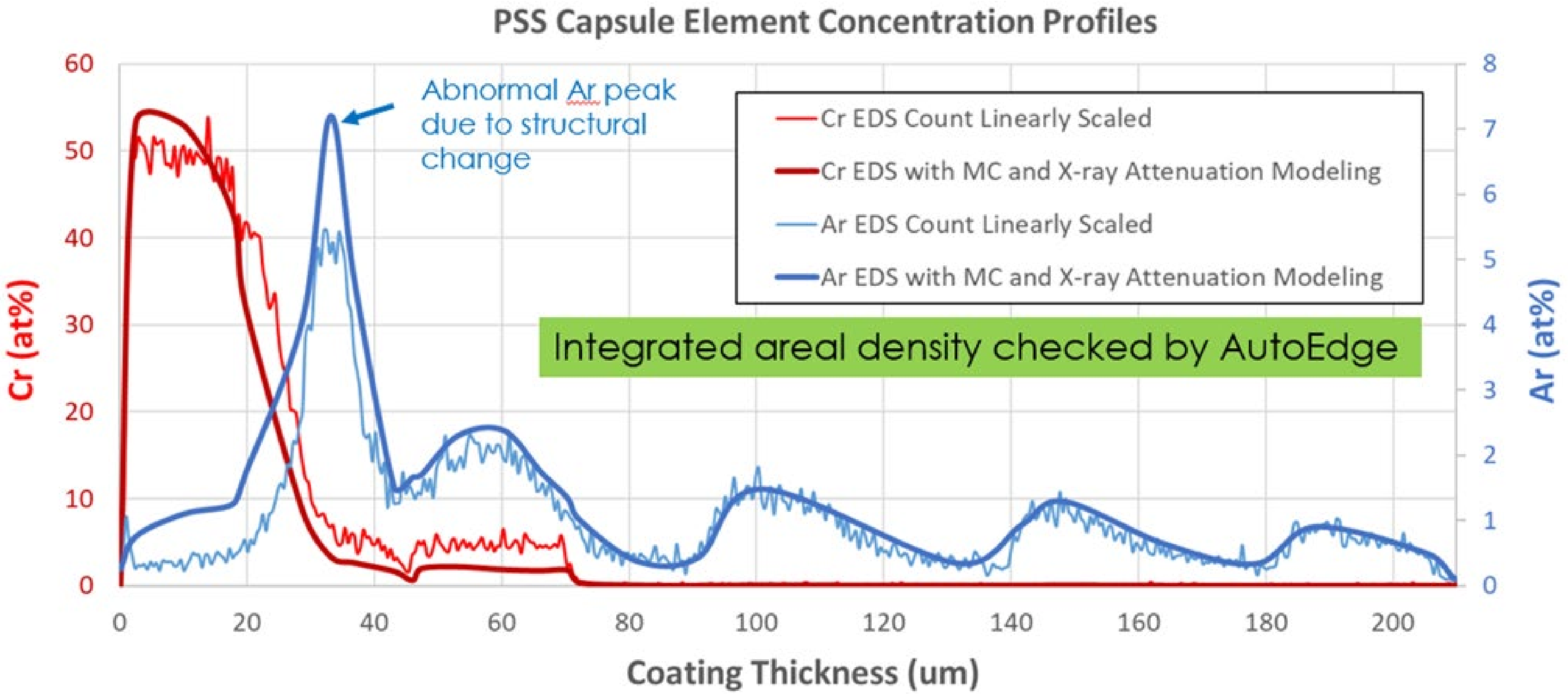
Selecting the best Si mandrel (low dopant, high homogeneity)



Dopant profile measured on polished cross-section via SEM/EDS linescan

- **XRF count rate does not scale linearly with dopant at%**
  - Monte Carlos simulation currently by ~~CASINO~~ → Consider upgrade to MCNP or GNEAT4
  - R&D topic: Moving to MCNP soon

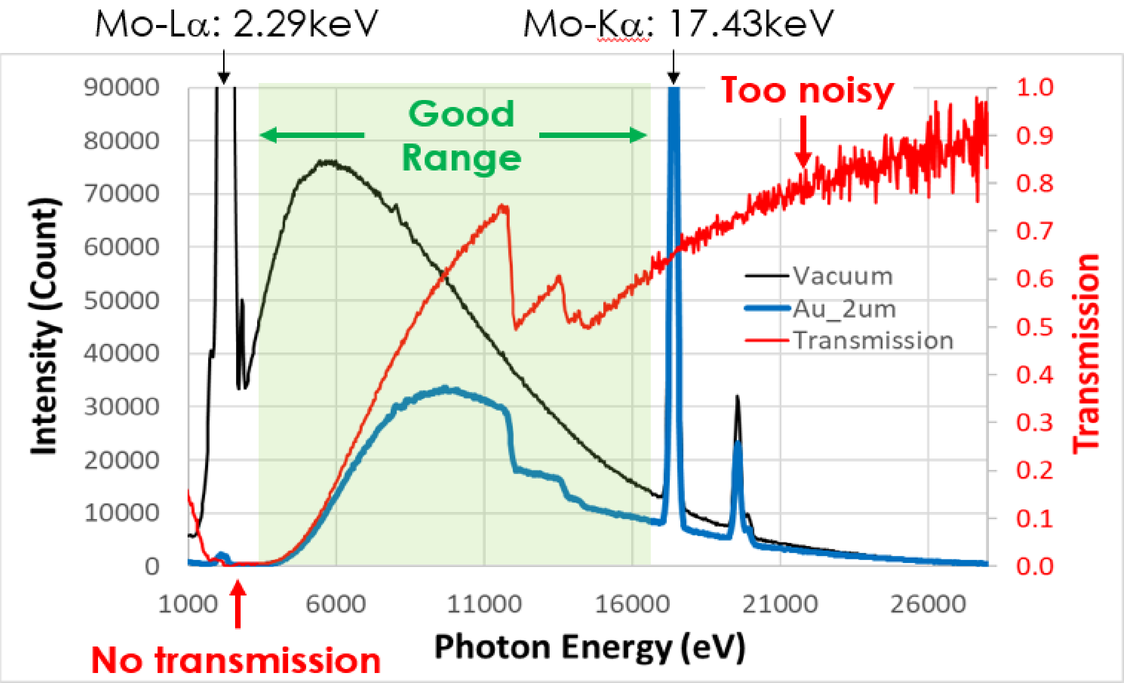




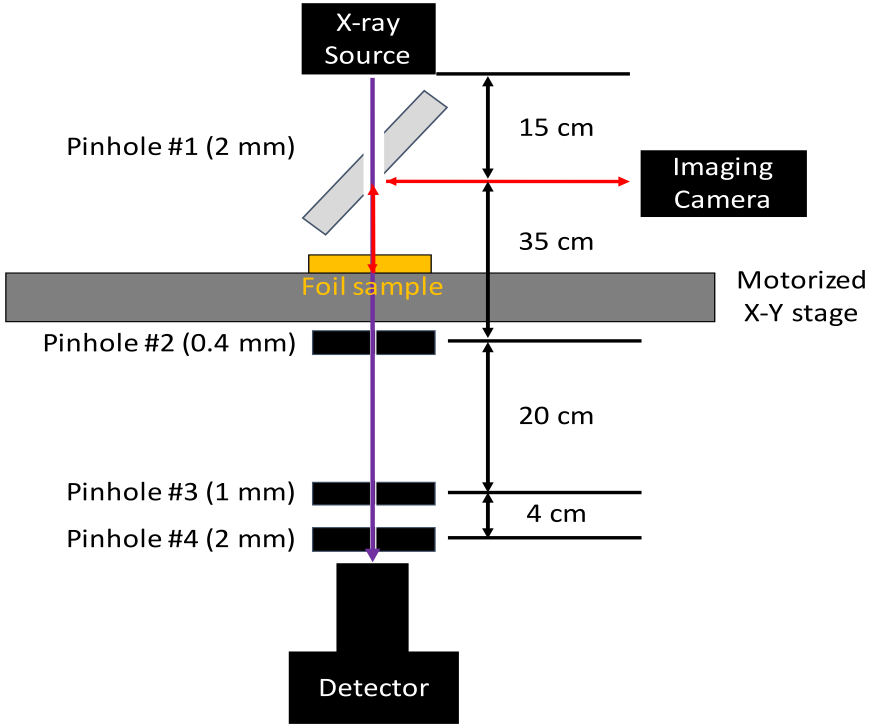
Metrology challenge: No method found so far for W > 30 at% in Be in graded dopant profiling

AutoEdge works by ratioing x-ray transmission w/ and w/o the sample

Example spectrum using Au foil



AutoEdge system

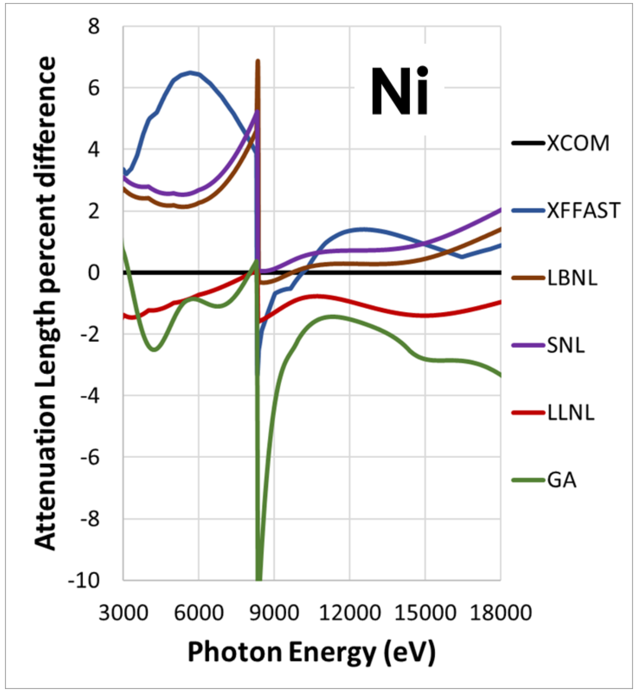


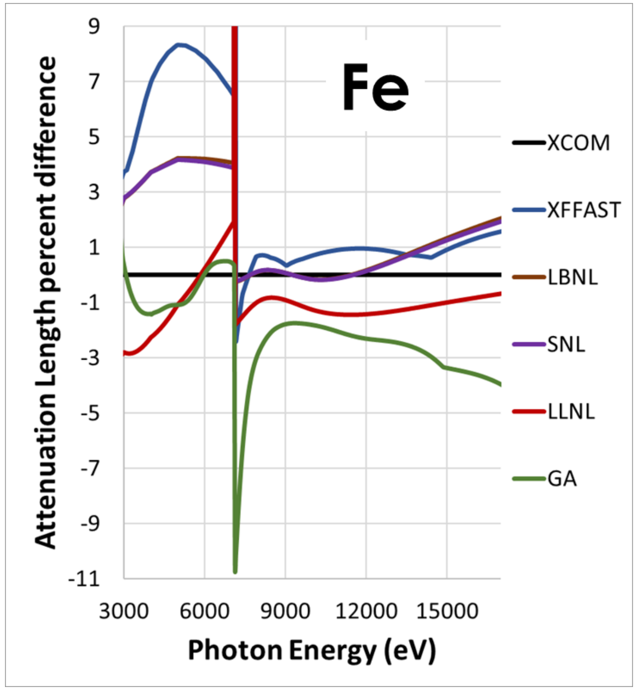
- **AutoEdge is a non-destructive standardless technique**
  - Precision controlled by photon statistics, 1% precision routinely attainable
  - Accuracy controlled by x-ray databases, 5% accuracy routinely attainable
  - Does not suffer from XRF-like error due to secondary fluorescence and scattering

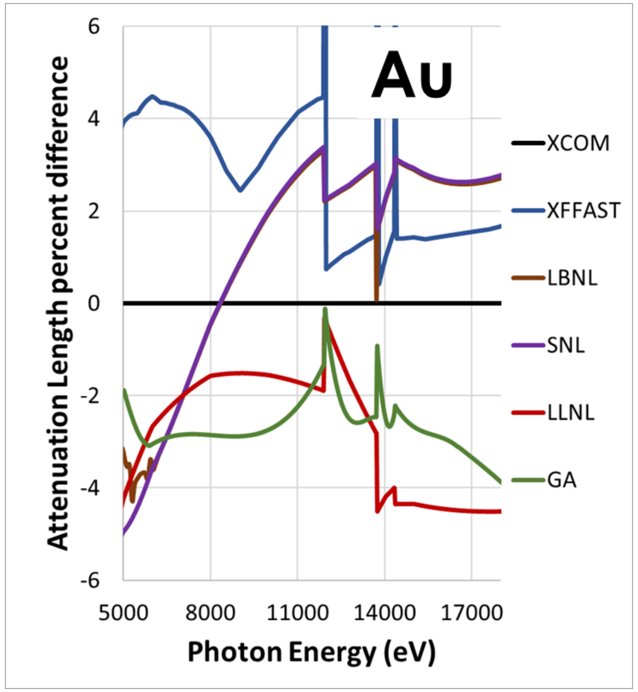
X-ray database revision improved areal density accuracy by 5x

Methodology established: Journal of Physics B: Atomic and Molecular Physics, 54, 115003 (2021)

- **X-ray opacity database to areal density is meter stick to length measurement**
  - Published database varies by 5-10%, affecting areal density accuracy by ~5%
- **Ni, Fe, Au has been calibrated to support Opacity program (thanks to LANL & GA)**
  - R&D topic: Shall we calibrate W for W-HDC capsules?



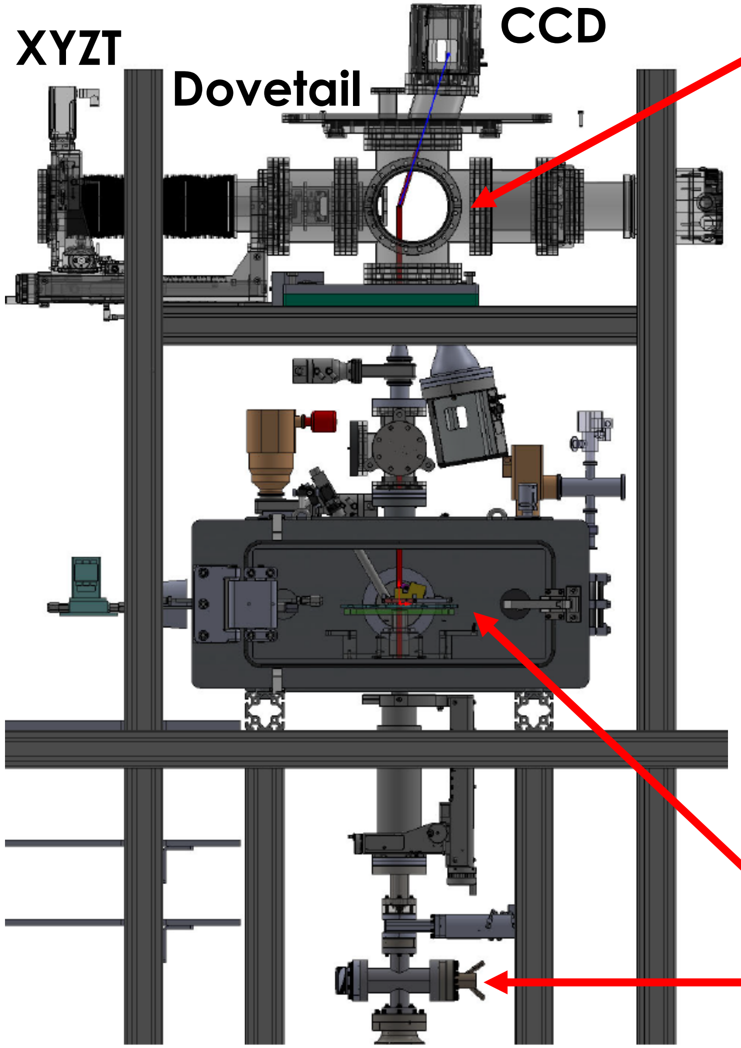




For W-dopant, do we care about the absolute areal density or only relative variation?

Soft x-ray system constructed to support versatile research initiatives

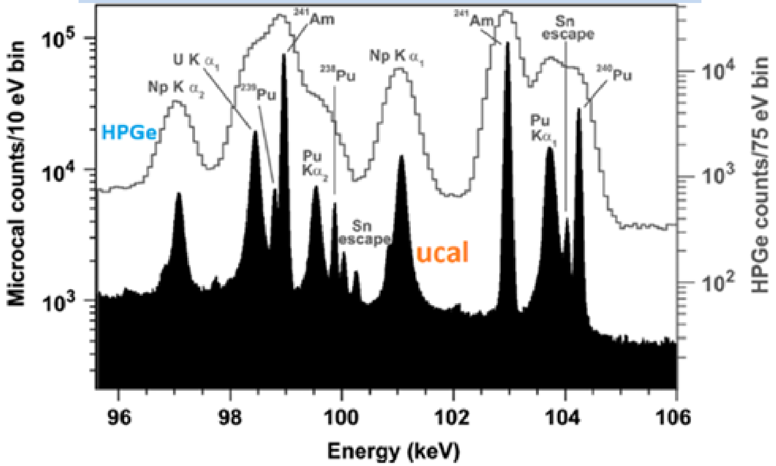
2nd gen AutoEdge



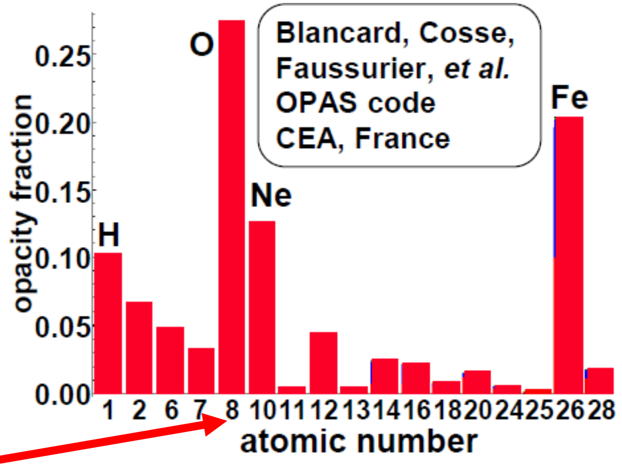
Motorized spectrometer with multiple stations

a) Internal SDD detector (replicate current AutoEdge)
b) Grating-based high-res spectrometer with x-ray CCD
c) "Bent crystal" testing station
d) Upside-down geometry compatible with quantum sensor

RadChem Coincident Detection



"Solar opacity" to FP Initiative



Vacuum chamber allows "gas cell" inside to study gas opacity

Differentially-pumped source accesses soft x-ray (0.1-3keV)

GENERAL ATOMICS

Sustained metrology investment is essential to NIF success

Esoteric specs are not met by commercial tools

- Dimension
- Composition
- Homogeneity
- Surface finish
- Defects

2026: …….
2025: Plasma diagnostics
2024: Laser Ultrasonics (Thickness)
2023: Soft x-ray (Opacity)
2022: LensAFM (surface)
2022: Darkfield (PS/PAMS vacuole)
2021: Compact FTIR (HDC wallmap)
2020: Lyncee Tec (PSDI replacement, HDC pits)
2018: Time dilation camera (NIF shot)
2017: AutoEdge (Areal density)
2016: Multiple-instrument 4Pi station
2013: Automated Spheremapper (Surface shape)
2012: Capsule Lasik (Surface dome)
2011: Batch PAMS inspection automation (Defects)
2010: Pin-hole array automation (Dimension)
2009: Quantitative EDS model (dopant)
2008: Precision radiography (Inhomogeneity)
2005: Contact radiography (Dopant profile)
2003: XFRer (Capsule dopant)

Transformational Improvements