How Physics Meets Engineering: Examples for Photovoltaic Modules and Additive Manufacturing

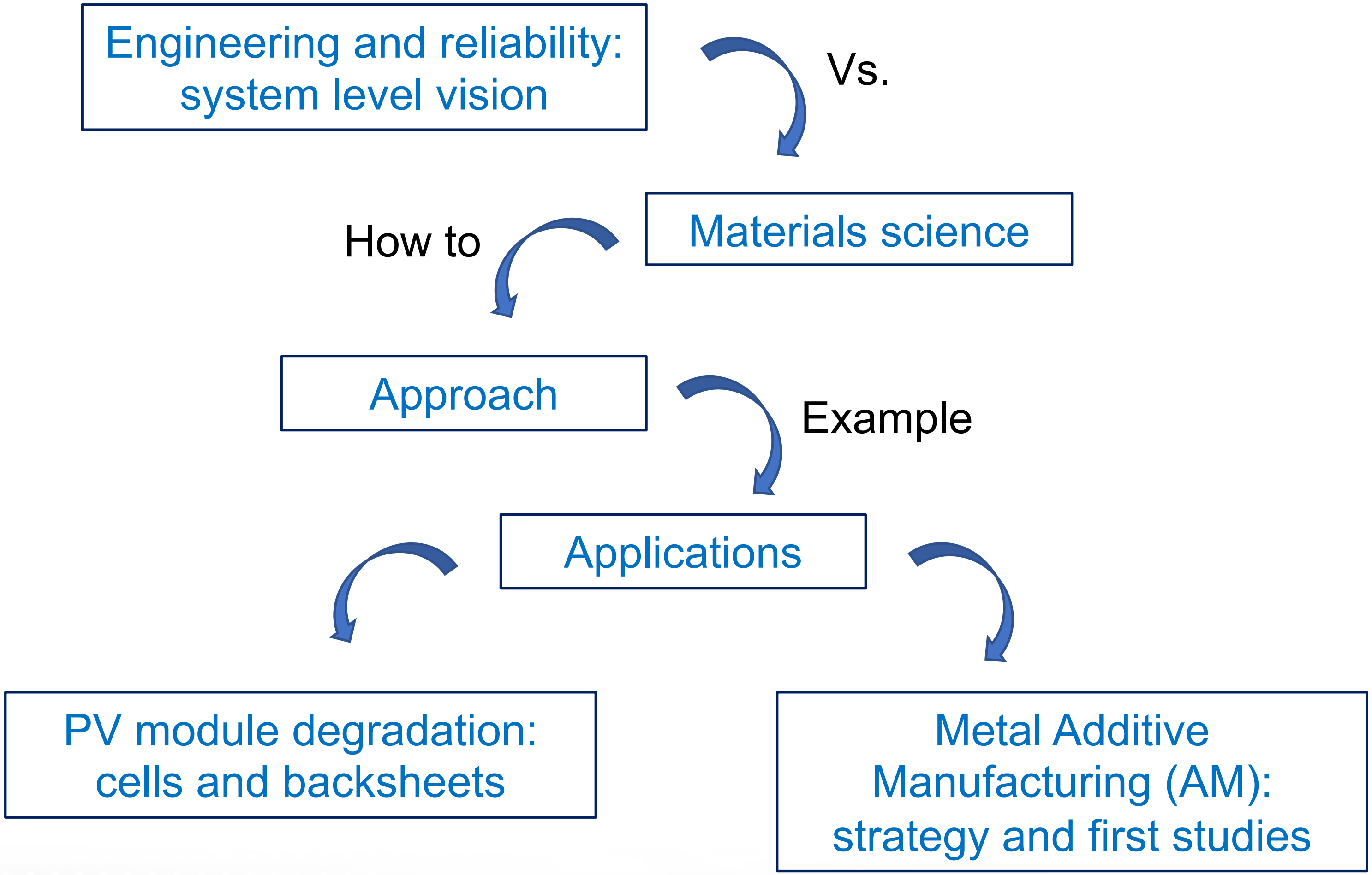
Dr. Alessandra Colli

Seminar at Alba Synchrotron - May 8, 2019

BROOKHAVEN NATIONAL LABORATORY

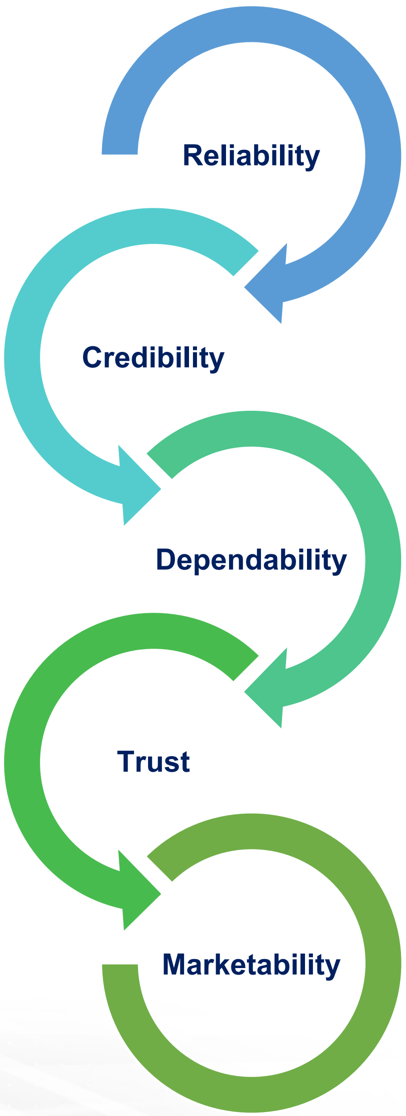
U.S. DEPARTMENT OF ENERGY

Overview


Engineering and reliability: system level vision
Vs.
Materials science
How to
Approach
Example
Applications
PV module degradation: cells and backsheets
Metal Additive Manufacturing (AM): strategy and first studies

Reliability

Reliability is a **probability**, which incorporates the concepts of *failure(-free)*, *function*, working *conditions*, and *time*.



Negative Interactions

Why	How	When	Where
•Mechanical, functional, interface failure. •Primary, secondary, command failure. •Basic, intermediate failure. •Parallel, cascade failure. •Direct, indirect, root causes. •Main, supplemental cause. •Inducing factors. •Hardware-, human-, system-induced failures.	•Random, wearout, initial failure. •Demand, run failure. •Persistent, intermittent failure. •Active, latent failure. •Omission, commission error. •Independent, dependent failure.	•Recovery failure. •Initiating, enabling event. •Routine, cognitive error. •Lapse, mistake.	•Internal, external events. •Active, passive failure.

H.Kumamoto, E.J. Henley, Probabilistic Risk Assessment and Management for Engineers and Scientists, IEEE Press, 1996

Two Problematic Aspects:

Time

Reliability is not always considered at the early stages of a development. It is usually deployed at later stages, with consequent significant effort for re-engineering existing systems.

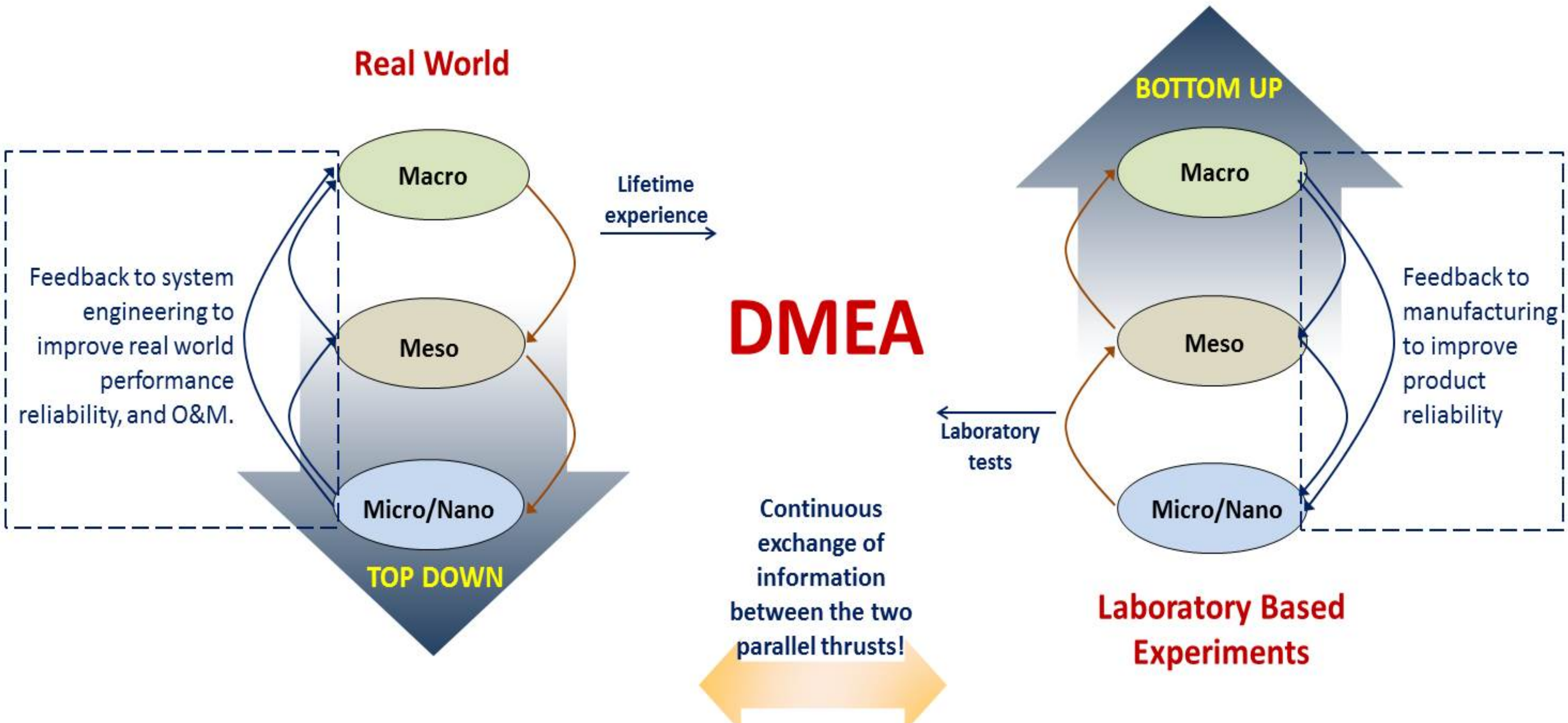
Communication

Reliability acts at system level.

Materials science deals with the basic structure and properties of materials, but misses the holistic view of the system (real world).

Our Proposed Solution

The Dynamic Material Evolution Analysis (DMEA) approach helps improving product functionality and reliability by understanding the time-evolution of physical/chemical behavior of materials in highly complex and industrially relevant systems.



Photovoltaic Modules

Long Island Solar Farm (LISF)

Started operation in fall 2011. Area ~200 acres.

32 MW (AC). 44,000,000 kWh/year (usage of ~4,500 homes).

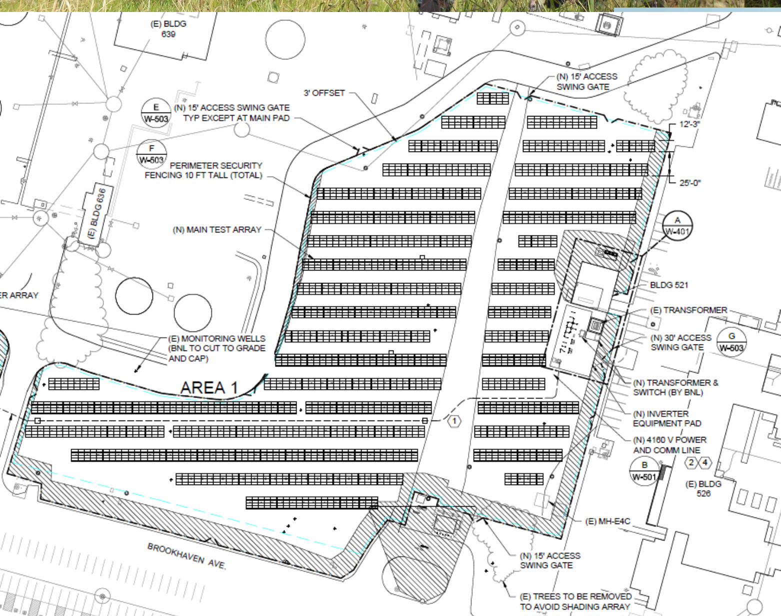
Deploys BP Solar polycrystalline silicon modules 225/230 W.

Info: https://www.bnl.gov/SET/LISF.php

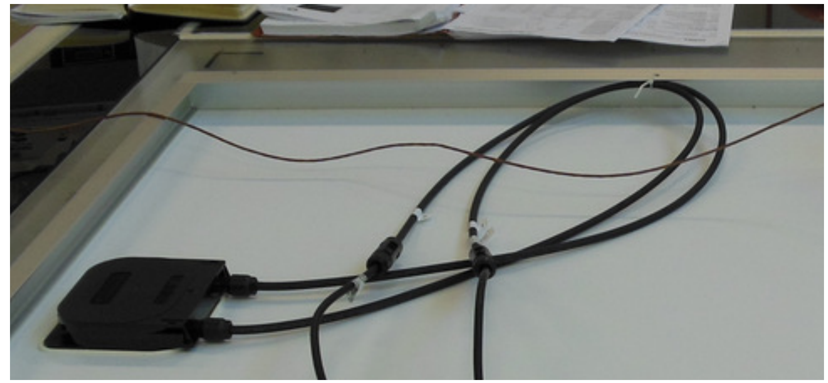
U.S. DEPARTMENT OF ENERGY

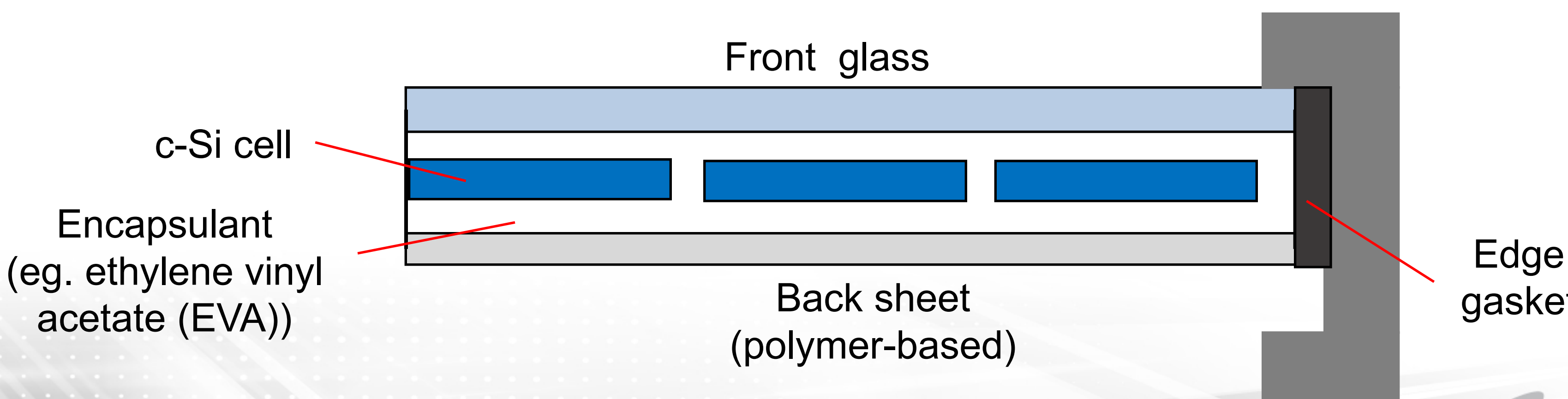
BROOKHAVEN NATIONAL LABORATORY

1 MW PV Research Array



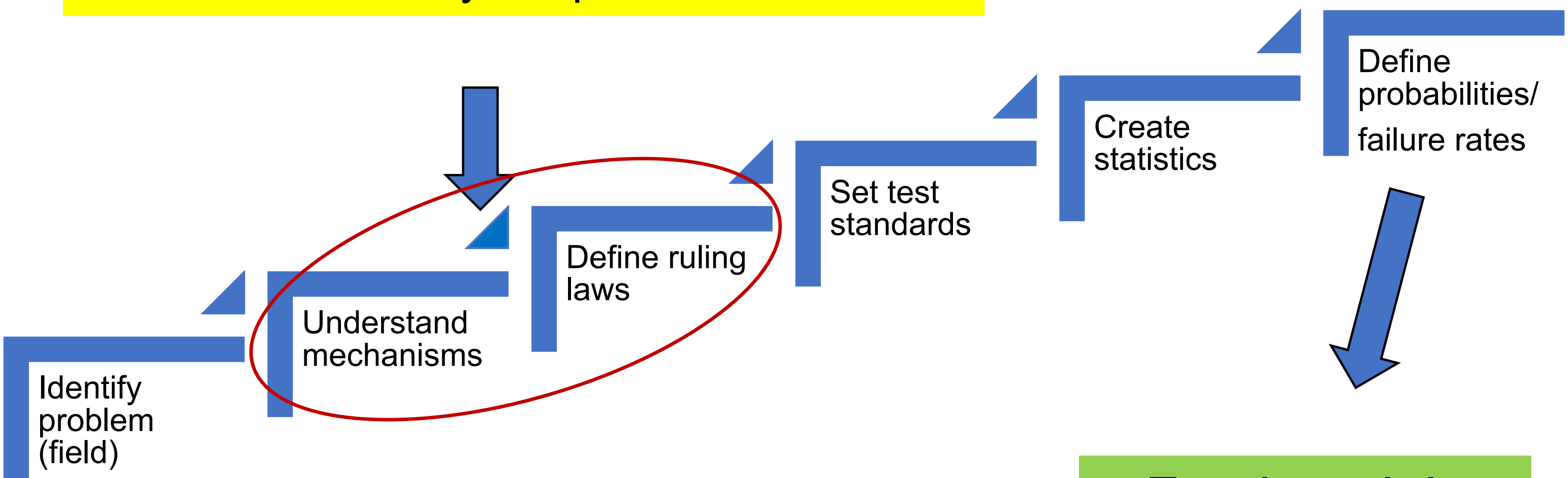
Crystalline Silicon PV Module Structure





Modeling PV Module Lifetime

Degradation mechanisms need to be addressed by materials studies (e.g. using X-ray techniques) - at the moment not extensively adopted in PV.



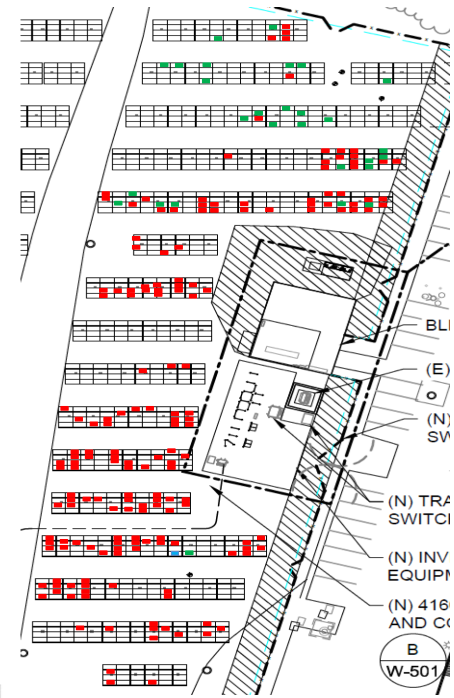
Feed models

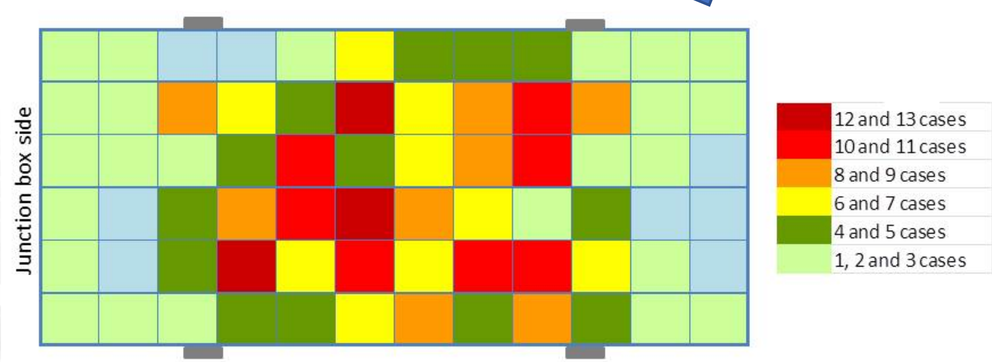
Failure Mechanisms for PV modules

Broken glass / cells / interconnects, hot spots, arcs, bypass diode failure, delamination, corrosion, light induced degradation, potential induced degradation, ground faults, shunts.

Cracks in Silicon PV cells are of interest.

Visual inspection of Brookhaven Lab's PV research array shows 24% of modules affected by cell cracks.





U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

Cracks in Crystalline Silicon PV Cells

Cause

- Intrinsic material stress/strain
- Wafer cutting
- Cell manufacturing process
- Module lamination
- Shipping/handling
- Module mounting support
- Module working conditions (elt.)
- Module degradation/delamination
- Environment (wind, snow)

Micro-crack

↓

Damaging crack

Consequence

- Loss of performance
- Increased resistance and heating
- Hot spots
- Metallization/contacts rupture

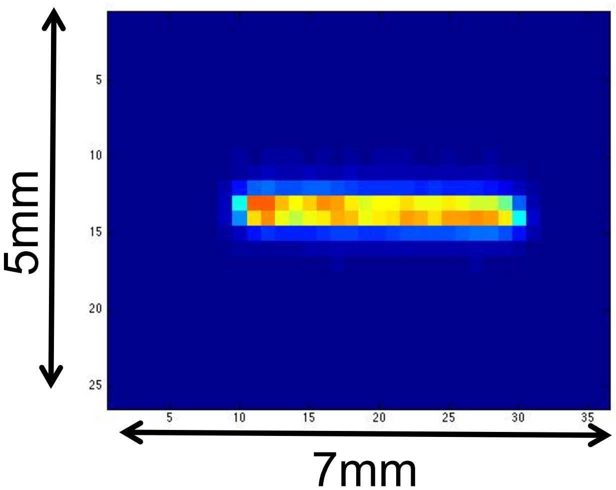
The Manufacturing Process Impact

- Cell movement, phosphorous diffusion, ARC deposition.
- Contact firing: cells are rapidly heated to peak temperature of 780-900 C followed by rapid cooling (fast process for contact quality and to avoid silver diffusion in junction).
- Lamination is conducted at ~150 C, with applied vacuum.

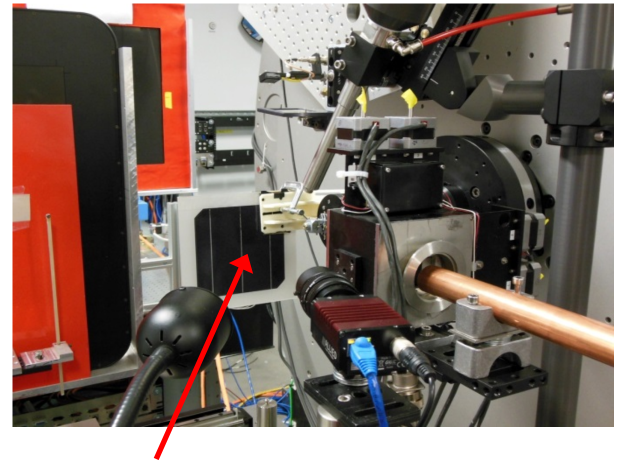
Lamination introduces stress on the cell.

Stress and Cracks in PV Modules: First Experiments at NSLS II 28-ID-2 (XPD)

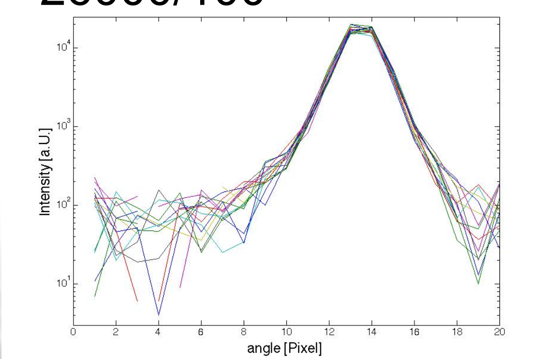
BNL Co-Authors: K. Attenkofer and E. Dooryhee



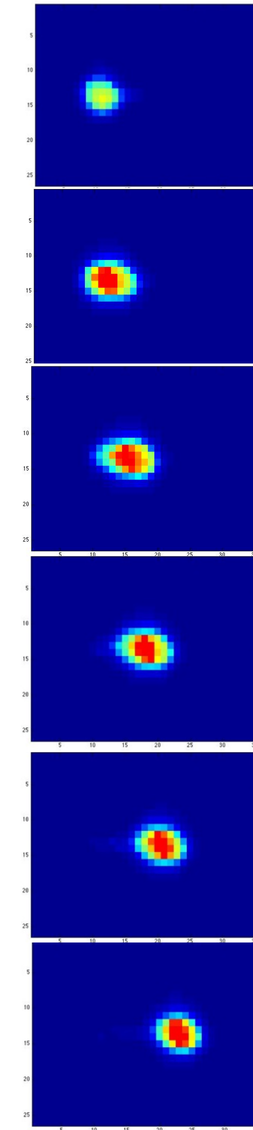
Reflected beam in Laue geometry at 34.5 keV



Signal to Background: 26000/100



0.02 degrees rotation between frames

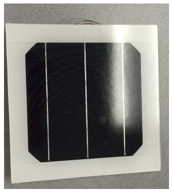


Results:

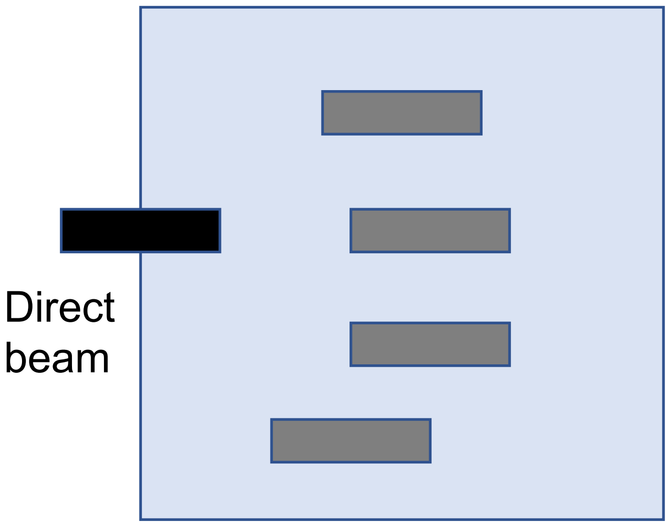
- Signal/Background ~ 300
- Bend of cell in wafer is 0.2 degrees.
- Setup needs to be improved to provide strain analysis.

First XRD Imaging Results for a PV Module Structure

BNL & SBU Co-Authors: K. Attenkofer, B. Raghothamachar, and M. Dudley

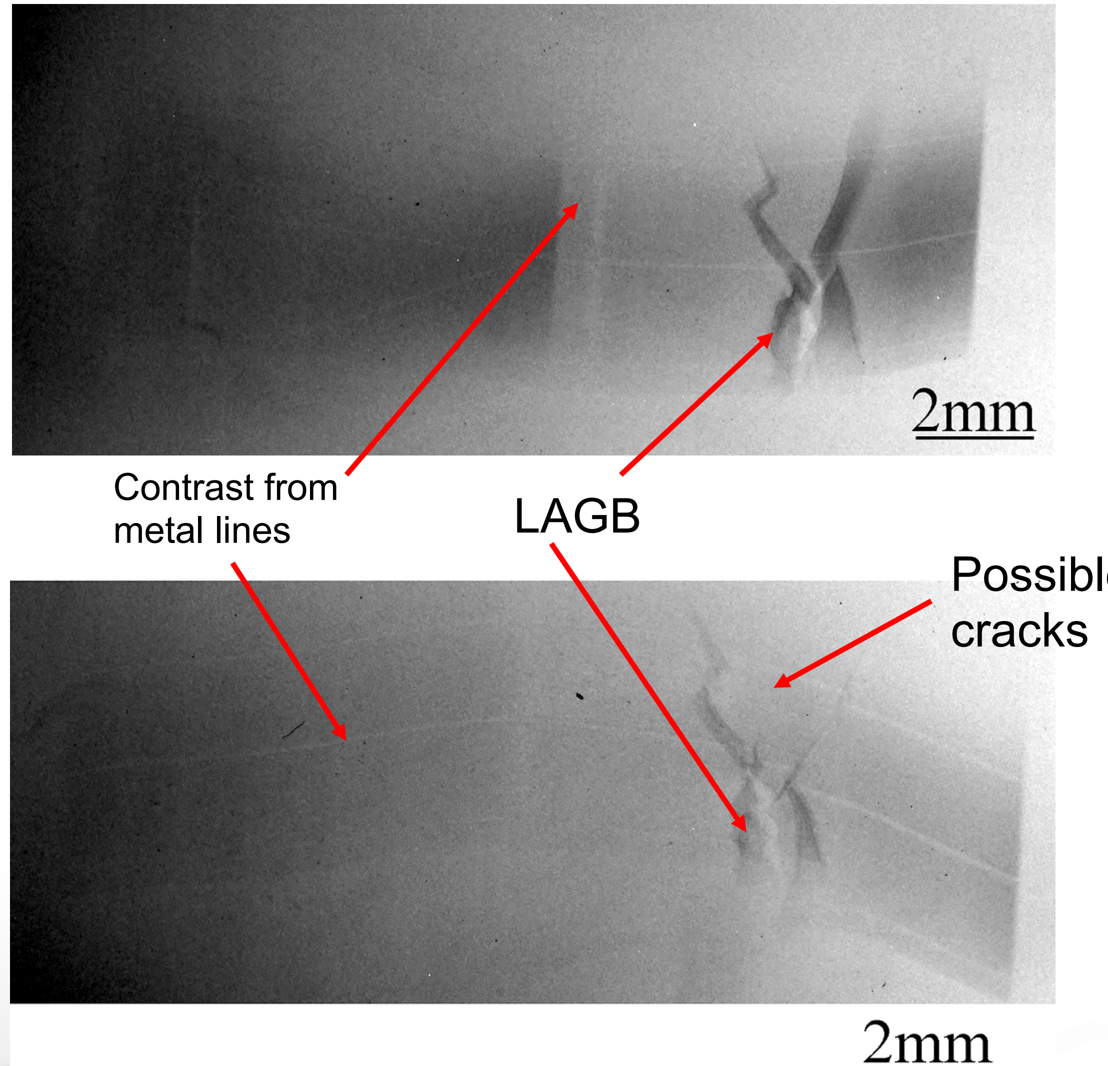


XRD images used white beam at 1-BM-B beamline station at Argonne Lab - APS.



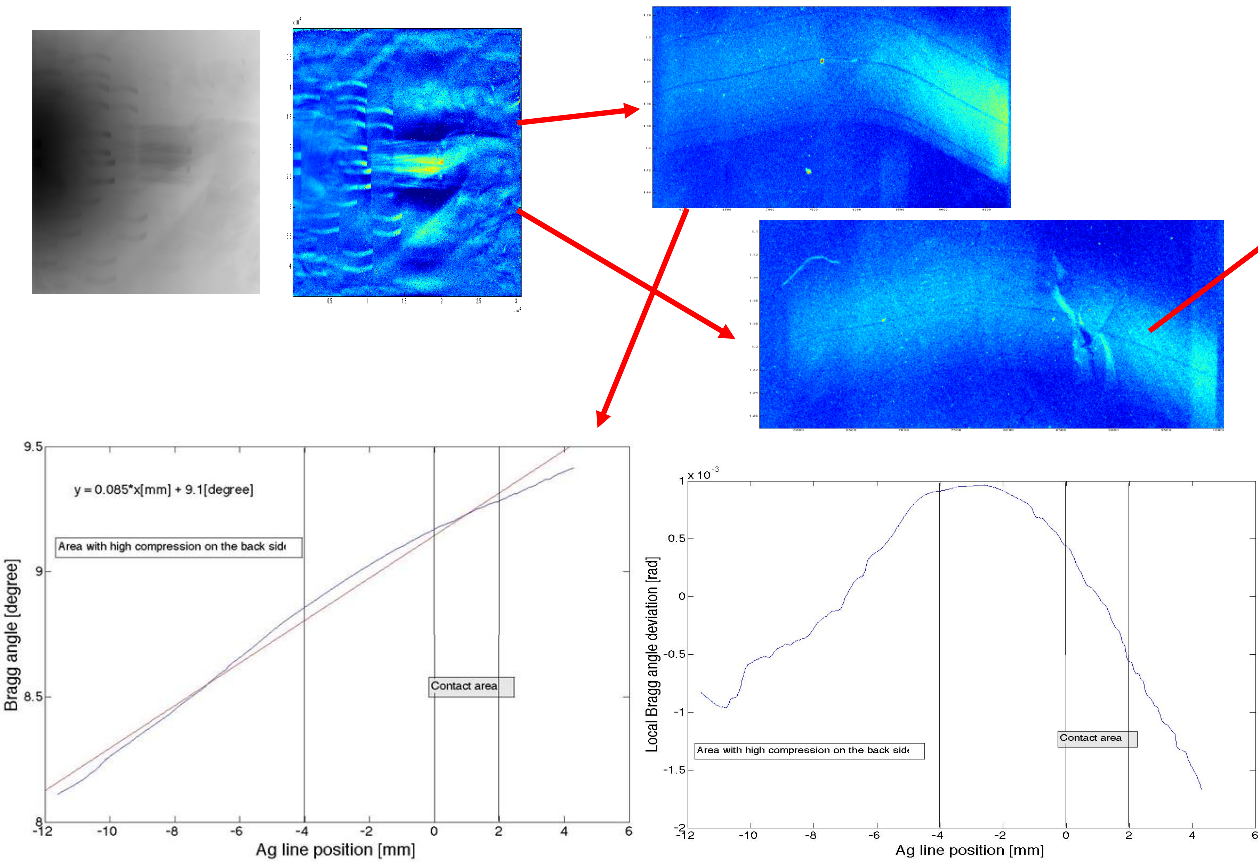
X-ray film

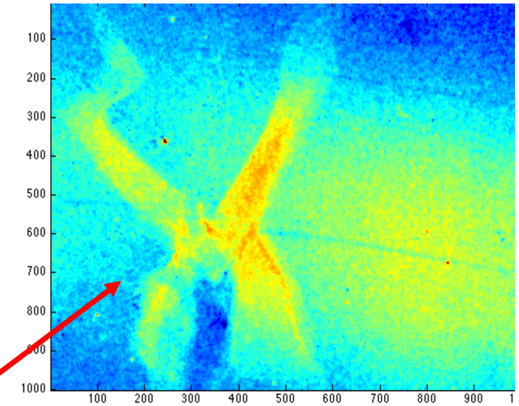
Area covered limited by size of beam used (5mm V X 25mm H)



U.S. DEPARTMENT OF ENERGY

Data Analysis



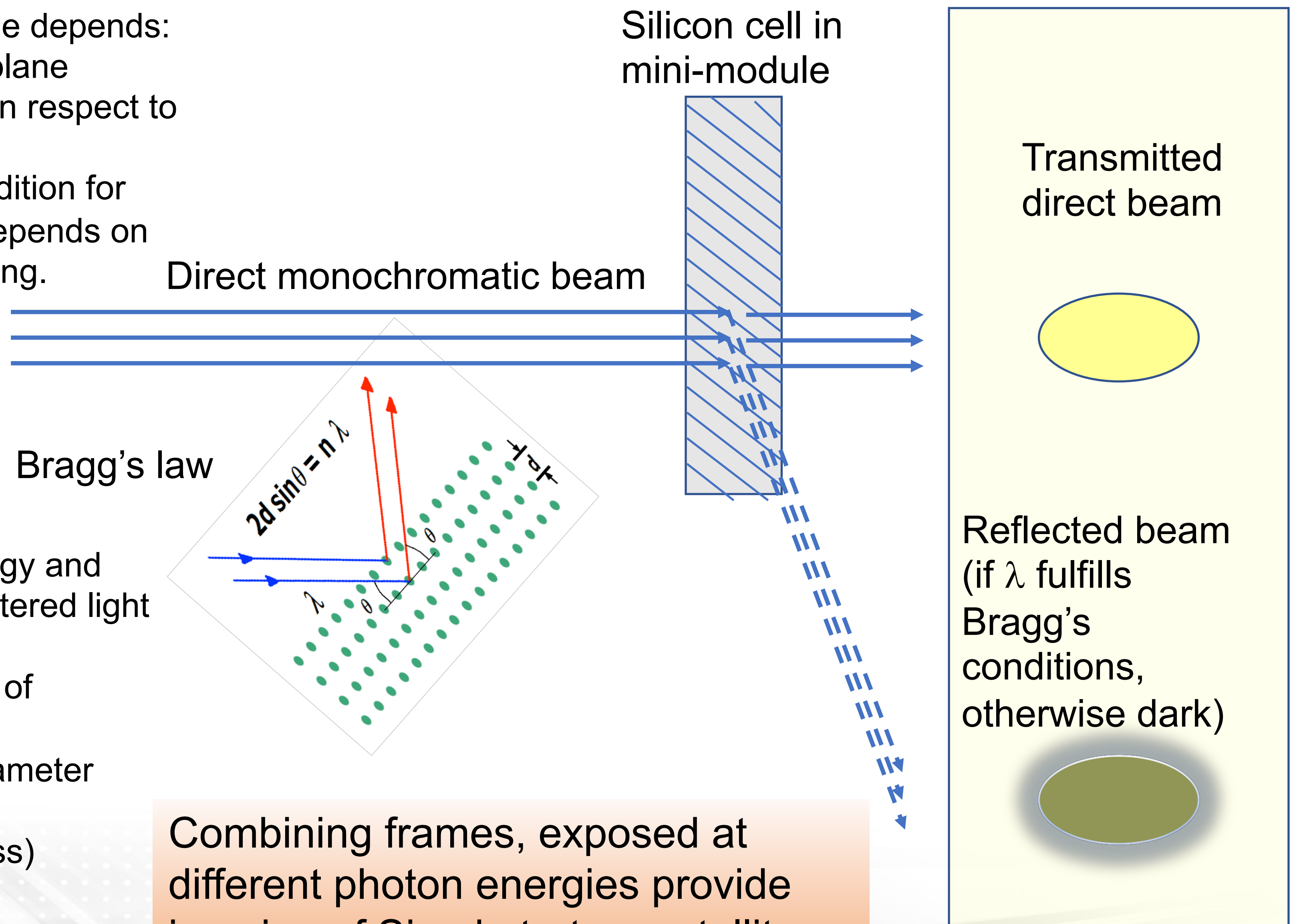


Area of 4.5mm x 3.5mm. The individual pixel represents a 4x4 μm2 area on the film. The crack appears to be localized under the busbar.

Using the position of the middle contact line, the Bragg angle for each pixel in the line was calculated and plotted versus the beam width. The result shows a strong bend of the wafer in direction of the scattering vector which can be approximated with a linear function. This linear function represents a cylindrical bend.

Using a Monochromatic Beam

Scattering angle depends:
- Scattering plane orientation in respect to beam.
- Energy condition for reflection depends on lattice spacing.



Scanning energy and observing scattered light reveals:
- Orientation of crystallite
- Lattice parameter variations (strain/stress)

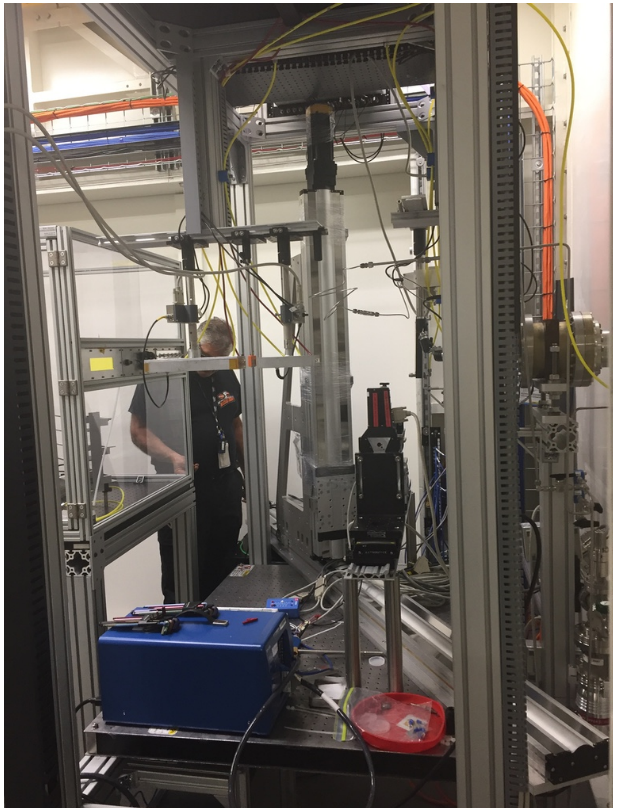
Combining frames, exposed at different photon energies provide imaging of Si-substrate-crystallites.

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

Measures Taken at NSLS II 8-ID (ISS)

BNL Co-Author: K. Attenkofer



PV module stage holder at NSLS II – ISS

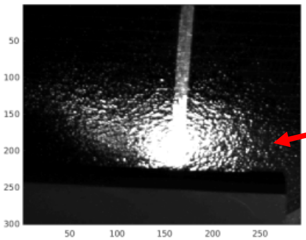
Inner Shell Spectroscopy (ISS) Beamline Specifications

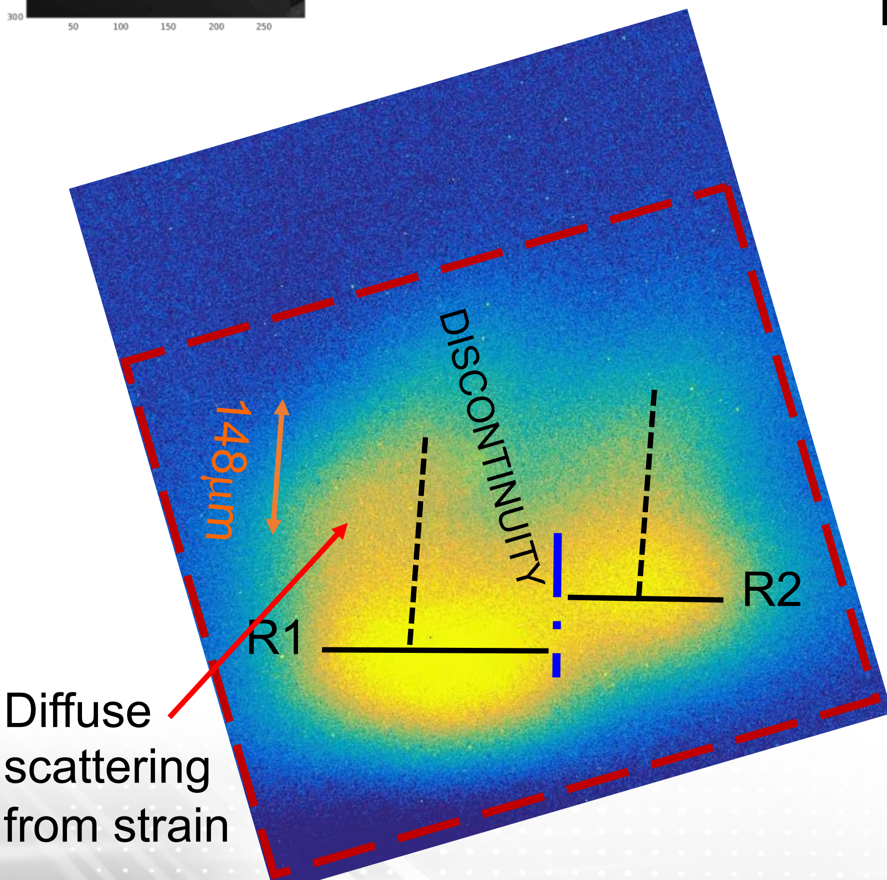
The ISS beamline is a high flux, fast-scanning (high throughput) damping wiggler spectroscopy beamline, with in situ and operando instrumentation integrated in the beamline architecture and data acquisition system.

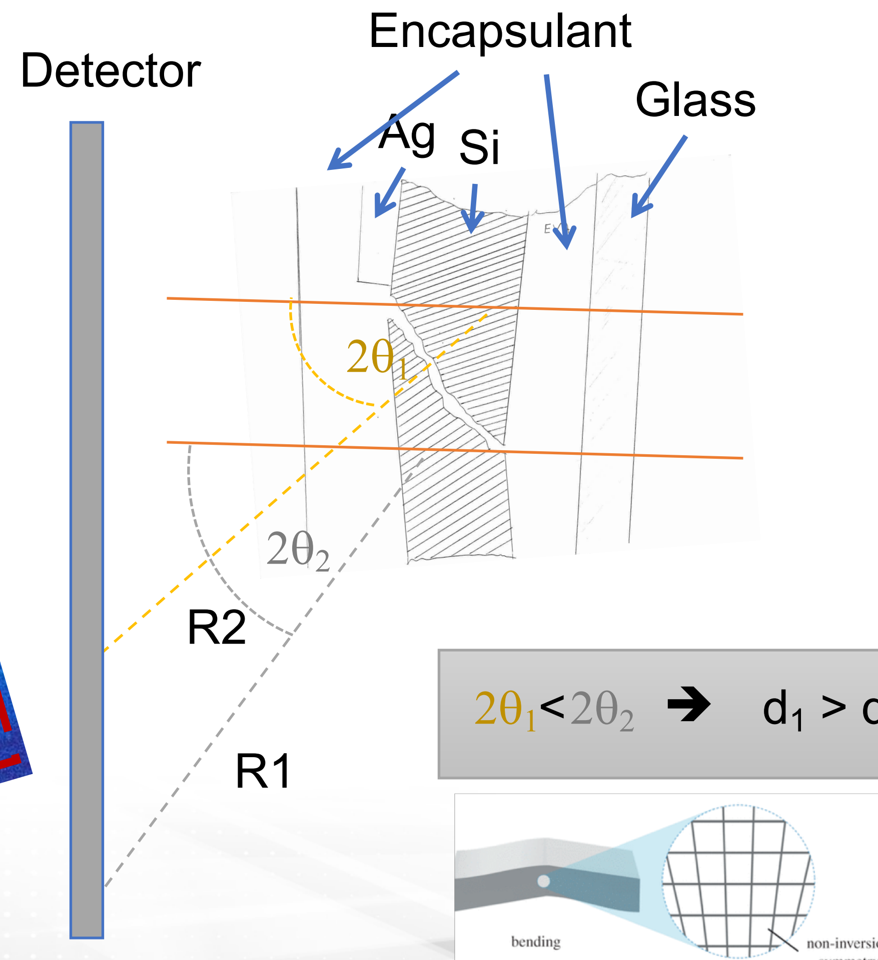
- Monochromatic beam.
- Energy range: 5 –36 keV

Analysis

- The approach simulates a pink beam, but knowing exactly the energy of each reflection.
- Monochromatic beam energy around 30 keV.
- Diffraction image reconstructed from a set of scans taken over a range of about 600 eV.







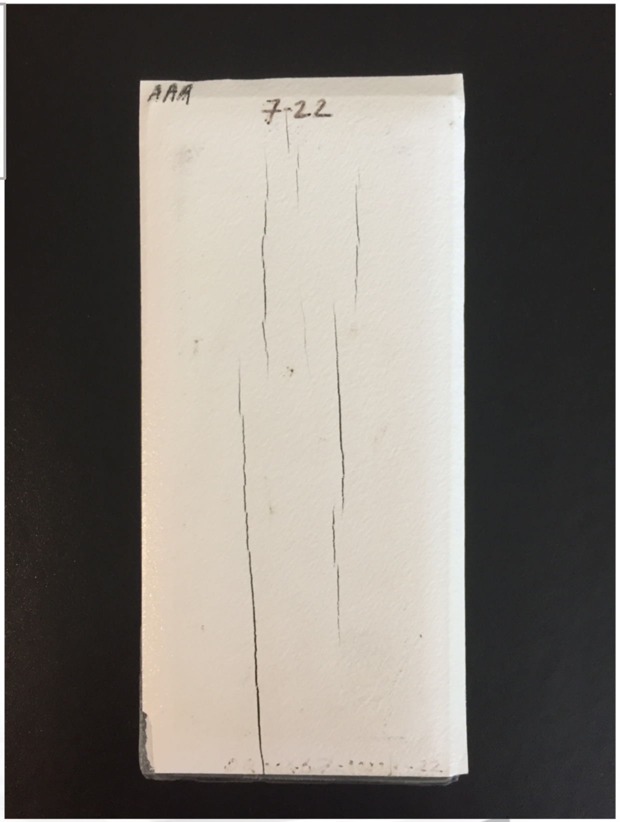
$2\theta_1 < 2\theta_2 \rightarrow d_1 > d_2$

Module Backsheet Aging and Morphology Changes

BNL & DuPont Co-Authors: K. Yager, M. Fukuto, R. Li, K. Roy Choudhury

- SAXS/WAXS measurements have been taken for the following samples, in pristine and aged conditions:
  - PA-based
  - Tedlar-based
  - PET-based
  - PVDF-based
- Samples are laminates of glass/EVA/backsheet of the size of 2.5” x 5.5”.
- Front glass 3.2 mm.

PA aged sample showing cracks



Pristine sample

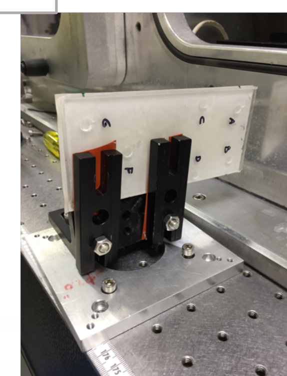
Processing and Measurement

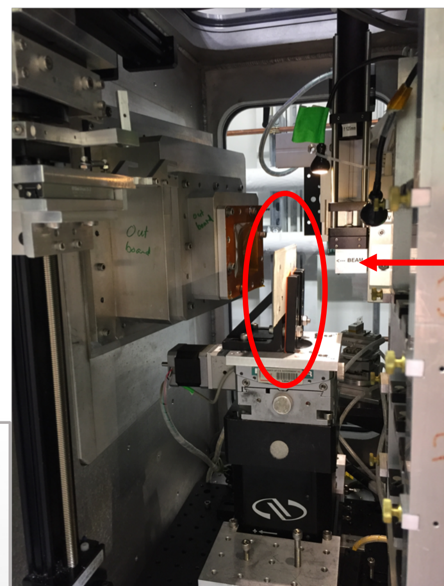
Teflon masks have been prepared to allow HF etching of glass

HF etching for about 48 hrs (considered rate 0.96 µm/min)

Tedlar aged sample with etched glass spots

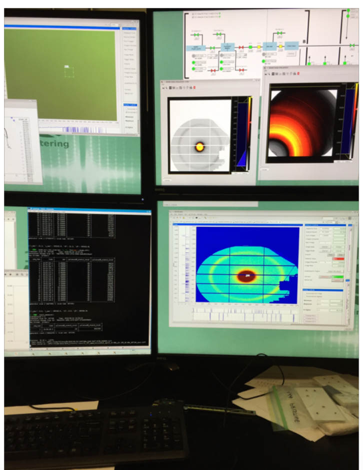
Sample placed on holder





BEAM
Energy 17 keV

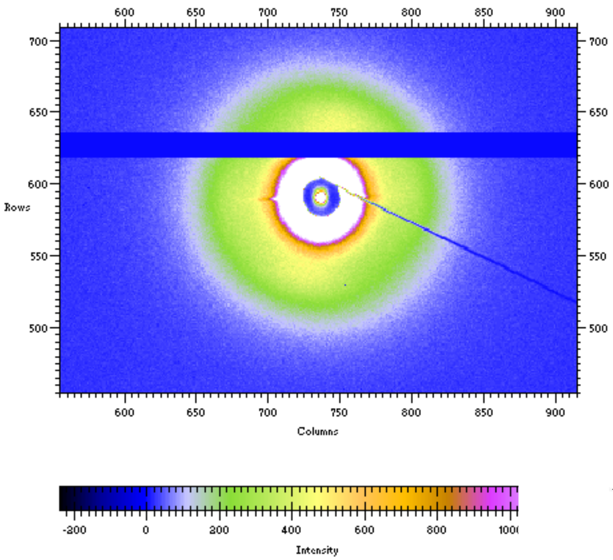
NSLS II 11-BM (CMS)



SAXS/WAXS measurements

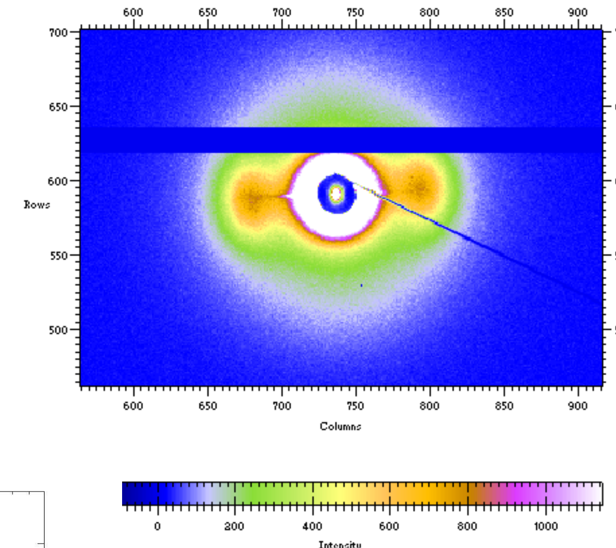
SAXS Analysis Overview: PVDF

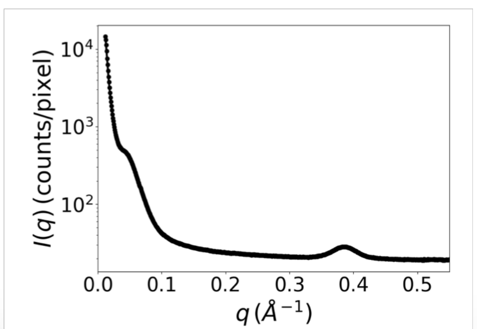
Pristine sample

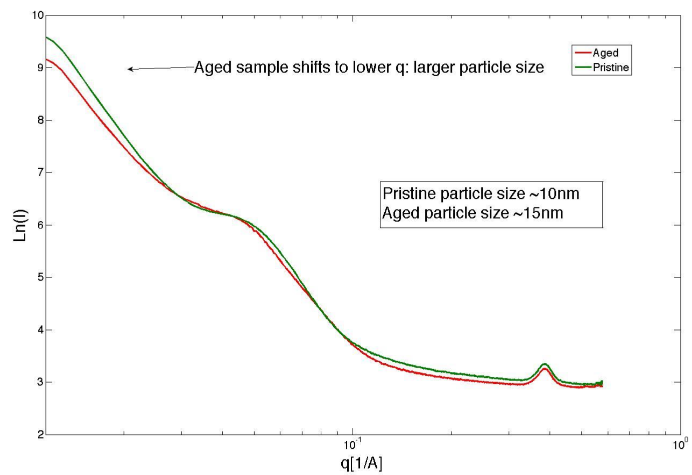


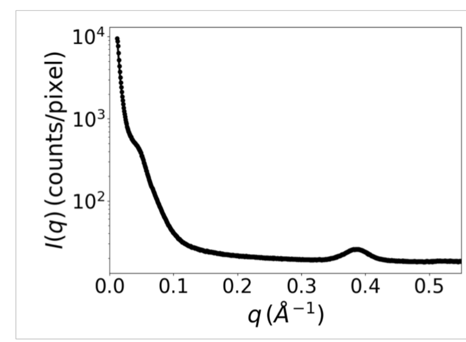
- Major changes in the SAXS patterns for PVDF-based samples.
- Strong orientation, indicating increased alignment with aging (lamellar structure).

Aged sample





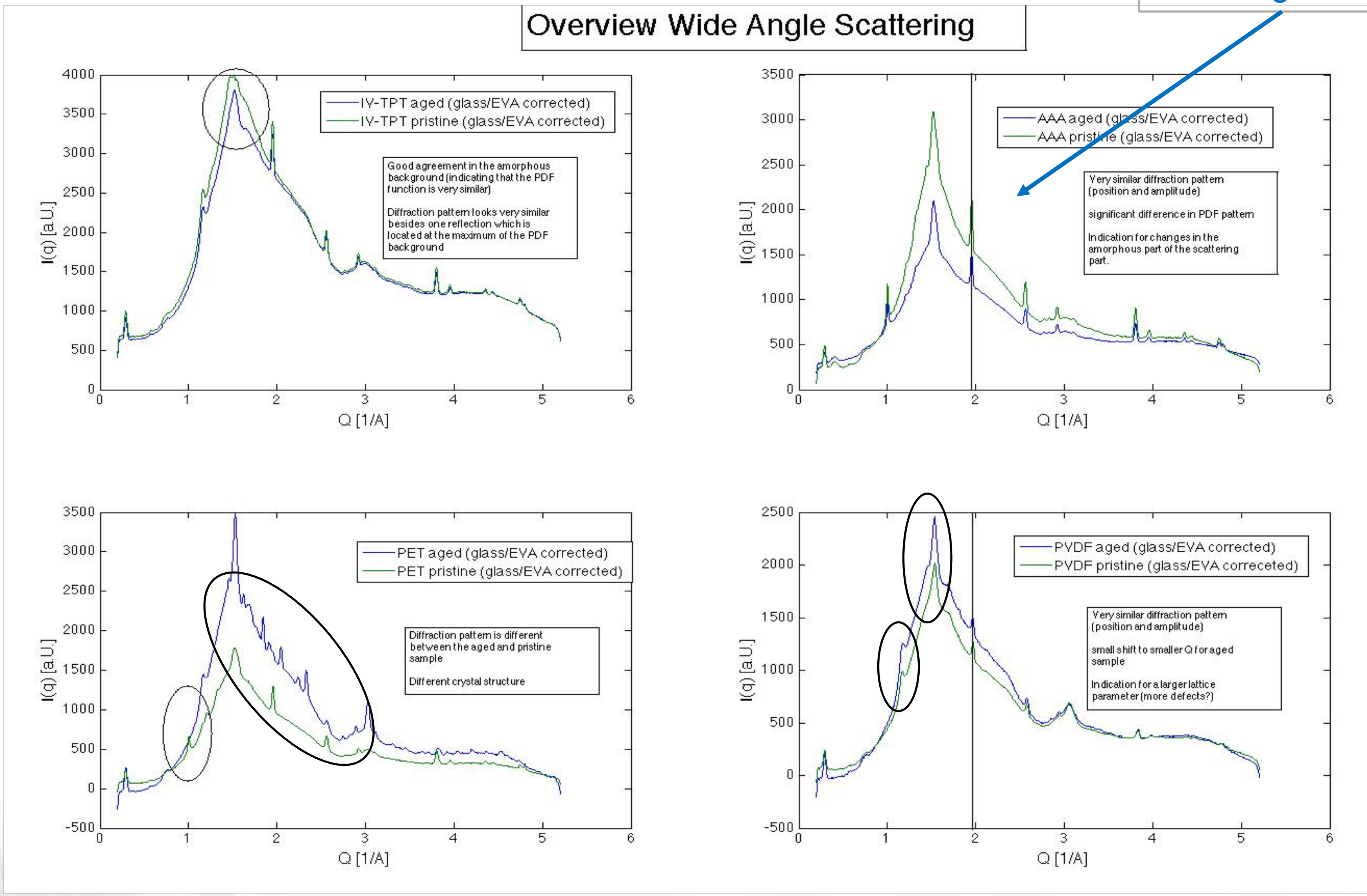




Sphere structure

WAXS Analysis Overview

Only case showing cracks

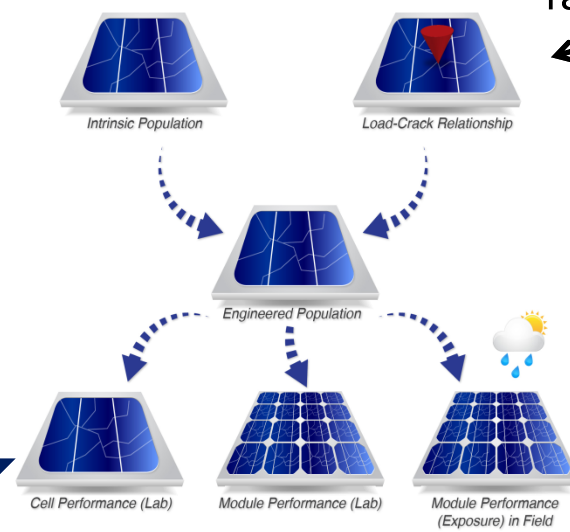


DMEA Application to Understand Cracks in PV Modules

Understanding crack evolution in bare cells and full PV modules using both bottom-up and top-down analysis methods.

BOTTOM UP

Flow of raw cells

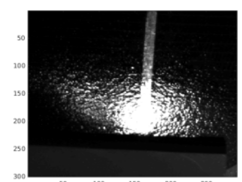


TOP DOWN

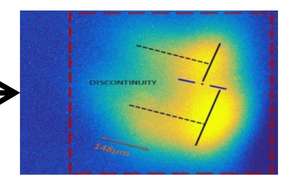
SYSTEM environmentally degraded

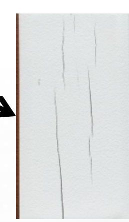
PV mini-module with backsheet cracks

Mini-module



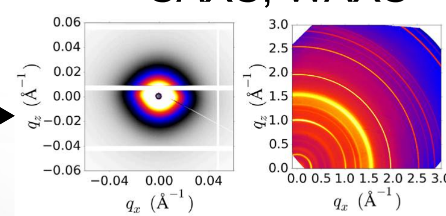
XRD





Sample engineered on system design requirements

SAXS, WAXS



Summary

- PV modules are composite structures that are influenced by structural, manufacturing and environmental factors acting in concert.
- XRD has shown a high degree of stress affecting the PV cell within the laminated module.
- We can obtain information about stress/strain and cracks both using pink and monochromatic beams.
- Busbar contacts define areas of high strain impact, for both cell and backsheet.
- Work still has to be done to correlate stress/strain from different sources within the module.

Additive Manufacturing (AM) of Metals

Overview on Metal AM

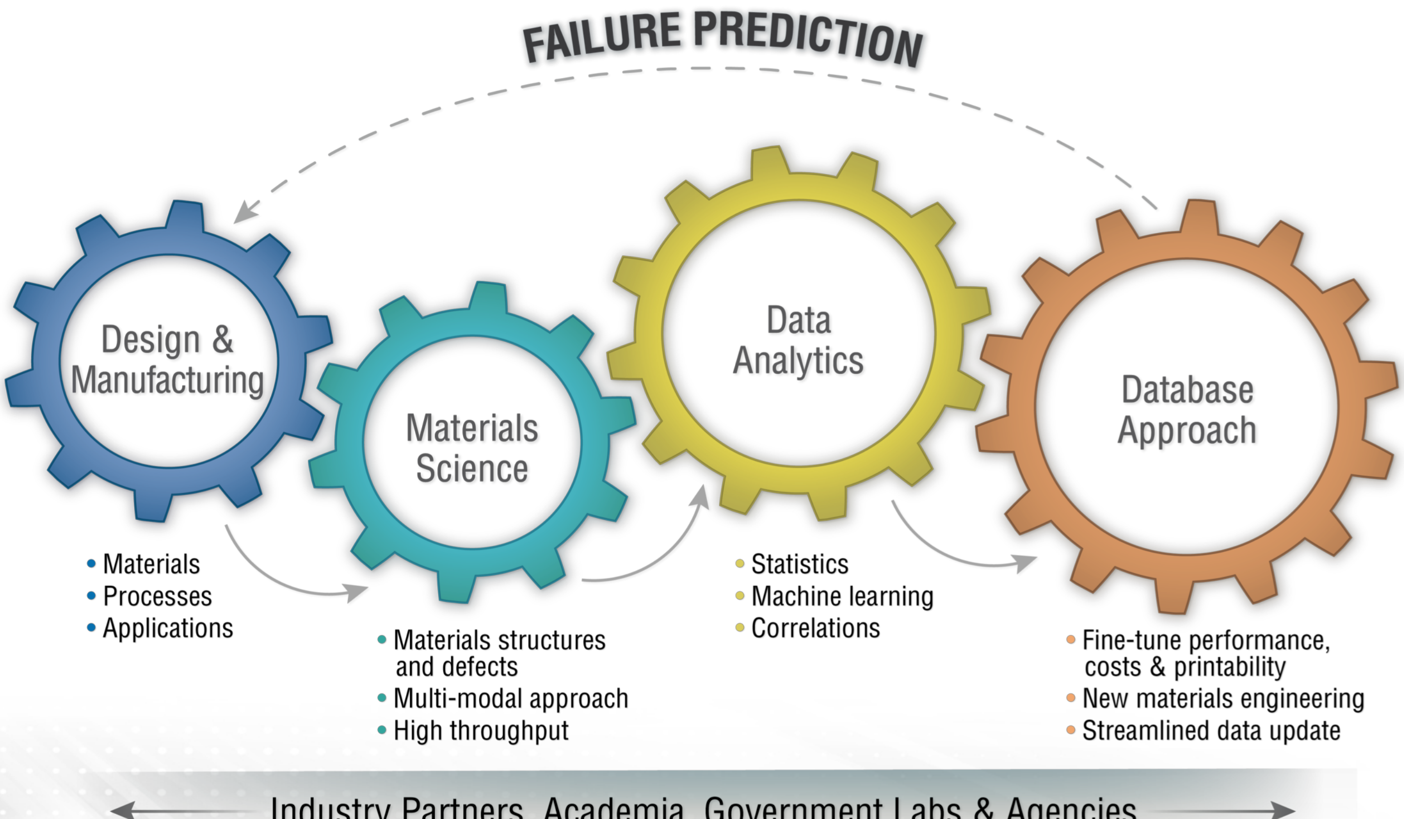
Materials and process parameters drive a successful metal AM production.

- Different processes, different outcomes, diverse applications.
- Fast changing field – processes and input material.
- Some outcomes from the Brookhaven Lab's Industrial AM Workshop on Metals (April 25, 2019):
  - Different models with large variability.
  - Need to benchmark quantitative measurements.
  - Need for in-situ time resolved investigation of post processing.
  - Investigate away from / below the melting pool (pressure waves, vaporization, cooling rates).
  - Residual stress should be investigated as function of depth.
  - Anisotropy and different grain sizes can complicate measurements.
  - Control surface finish and variability - machine to machine, run to run.
  - Synchrotron techniques should be used in parallel with metallurgical lab experiments.
  - Need for new thinking, new approaches, new access to User's Facilities.

Need for data, data, data…

Brookhaven Lab Metal Additive Manufacturing Strategy

The Metal Additive Manufacturing Strategy of Brookhaven Lab aims at combining techniques which provide **multi-length scale information** on statistically relevant ensembles with **data analytics** to correlate specific structural defects with failure probability. Ultimately, the approach allows establishing a **database** of reference information to verify and validate 3D printed structures and materials for superior performance and extended durability.



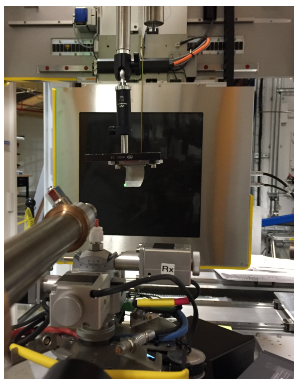
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

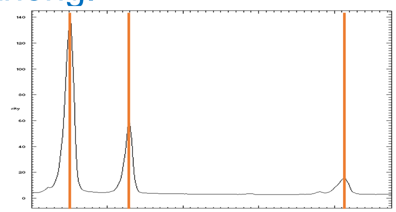
Preliminary Experiments Performed at NSLS II 28-ID-1 (PDF)

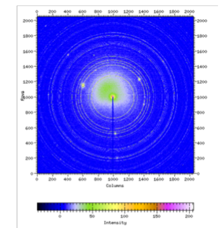
Nickel superalloy aviation engine turbine blades in collaboration with GE Global Research.

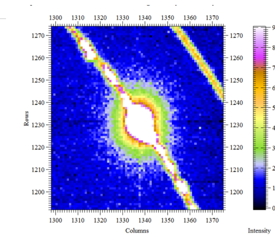
A. Colli, Y. Gao, E. Dooryhee, M. Abeykoon, J. Bai, H. Zhong.



- Two samples compared: as-grown conditions vs. annealed.
- A measurement grid with 32 spots has been applied.
- X-ray diffraction with energy of 74.4 keV (λ=0.1667 Å).
- Samples thickness: max 2.5 mm



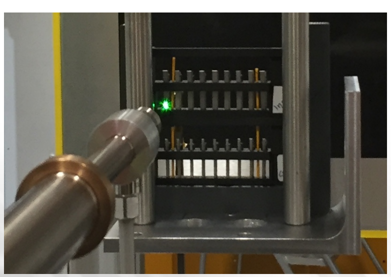


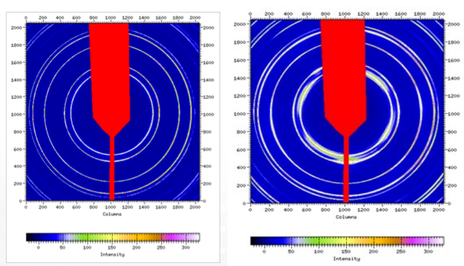


Residual stress in the as-grown sample is visible in the strong peak asymmetry.
Large crystallites show in the annealed sample, calling for elemental segregation.

CoCr and IN718 printed under different conditions of laser power and speed in collaboration with RPI.

A. Colli, S. Rock, D. Lewis, E. Dooryhee, M. Abeykoon.

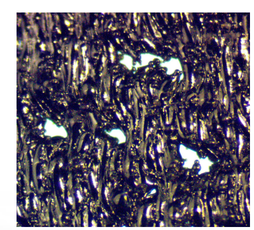




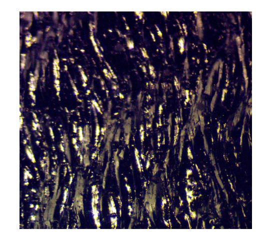
CoCr, 260 W, 500 mm/s, 1 laser pass (left) and 8 laser passes (right)

Different orientation strengths have been detected.

The printing variables highly impact the resulting material.



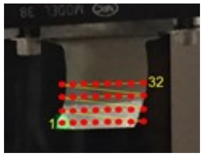
IN718, 140W, 700mm/s

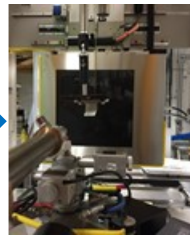


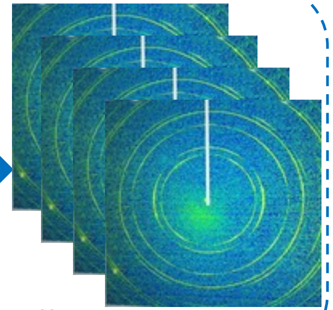
IN718, 230W, 500m/s

Need for Data Analytics

Experiment 1 - Multiple points



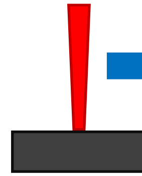




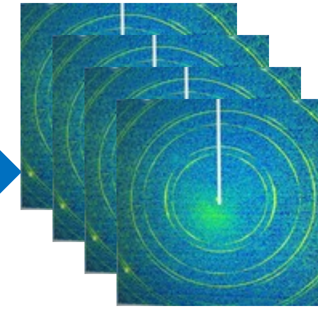
N diffraction patterns

Experiment 2 - Multiple samples

Laser 3D printing process



Variables tuning

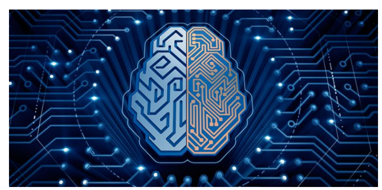


M diffraction patterns

Descriptors from the XRD and PDF experiments (example): crystal orientation, segregation, stress, alignment, average interatomic distances (peak position), structural disorder (peak width), average coordination properties, particle size effect.

Database information

INFORMS



AI

DRIVES

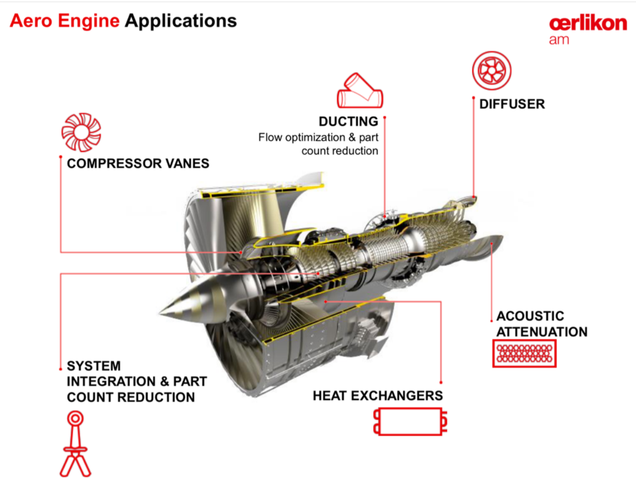
User's defined objectives and descriptors

Models & Theories

CORRELATIONS

Define needs for further atomistic investigations

Brookhaven Lab Is Working Along Two Thrusts



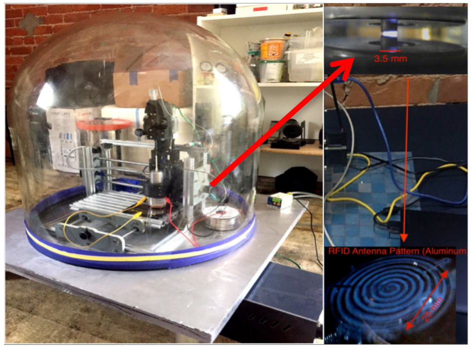
Source: S. Kelly, Industry Perspective on Critical AM Applications, BNL Industrial AM Workshop on Metals and Ceramics, 25 April 2019.

Structural Components

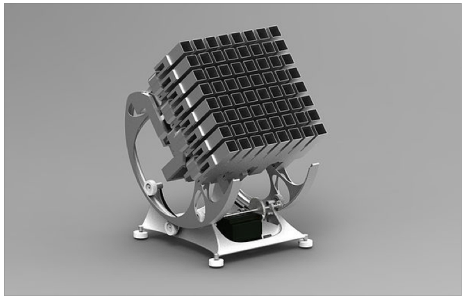
- High-reliability applications
- Integrity
- Testing and standards

Functional Components

- High-precision printing
- Performance
- New printing methods and metrology



Source: Obsidian, plasma-based printing process, www.obsidianam.net



Source: Optisys, antenna array, patent pending, www.optisys.tech

- Defense and civil applications.
- Achieve failure prediction of components.
- New alloys and applications for low weight and high efficiency.

- Defense and research applications.
- Possibility to combine the printing of different materials.
- Possible applications in QIS.
- New (meta)materials.

Overall Conclusions

- Synchrotron X-rays are proven to allow understanding of material properties and changes in engineering structures.
- The first level of knowledge is defined by identifying correlations, defined through **data analytics**: high throughput of data through fast characterization is necessary to create valuable statistics.
- A lot still has to be done in metal AM. Areas of high interest are identified in:
  - Failure prediction analysis and modeling.
  - Alloy definition and phase interfacial energy.
  - Postprocessing effects.
  - Process repeatability.
  - New applications and material engineering.

Thank you for your attention!

Contact:

Dr. Alessandra Colli

acolli@bnl.gov

+1-631-344-2666