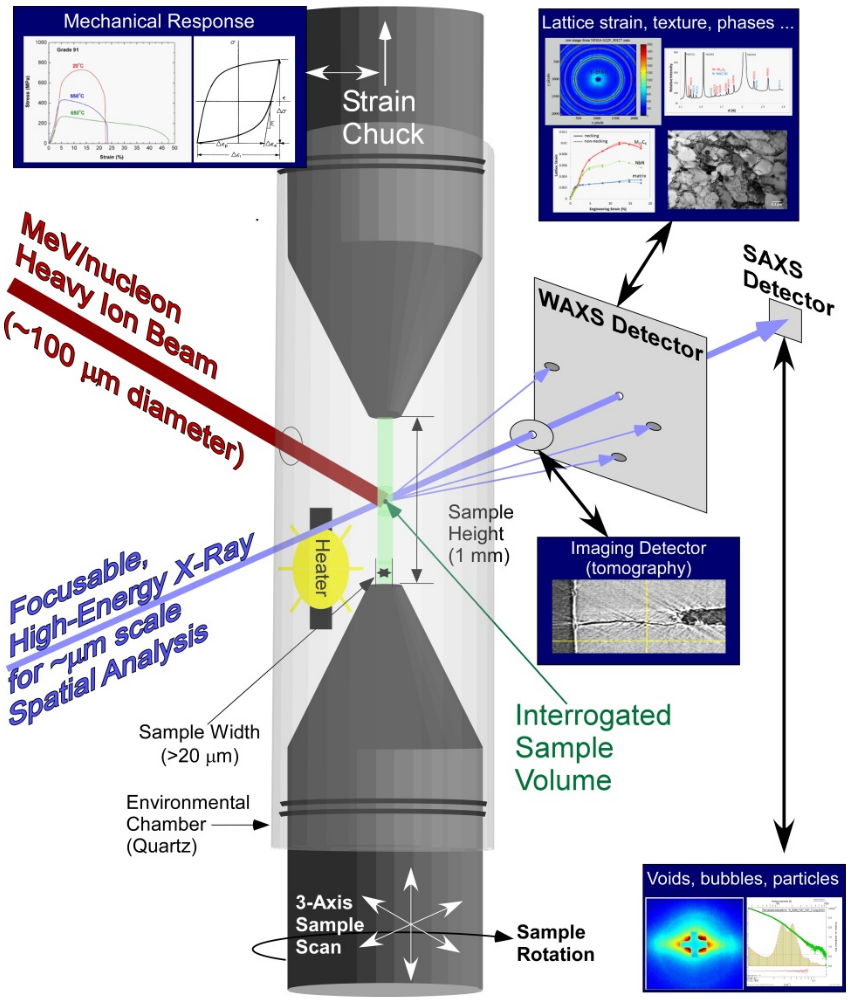
Proposed XMAT (EXtreme MATerials) Beam Line at APS

Mike Pelline, Hussein Khalil- Argonne National Laboratory

- **New capability for materials development employing a high-energy ion accelerator at Argonne's Advanced Photon Source (APS)**
  - Accelerator technology based on the Argonne Tandem Linear Accelerator System (ATLAS)
  - Leverages planned upgrade of APS; enhanced x-ray beam emittance and coherence
- **Ion irradiation of material samples at APS allows *in situ* studies of radiation damage using X-ray analysis techniques**
  - Under controlled stress, temperature, and environmental conditions
- **Would advance understanding and modeling of irradiation effects**
- **Would greatly accelerate the evaluation of materials and fuels irradiated to high damage doses**



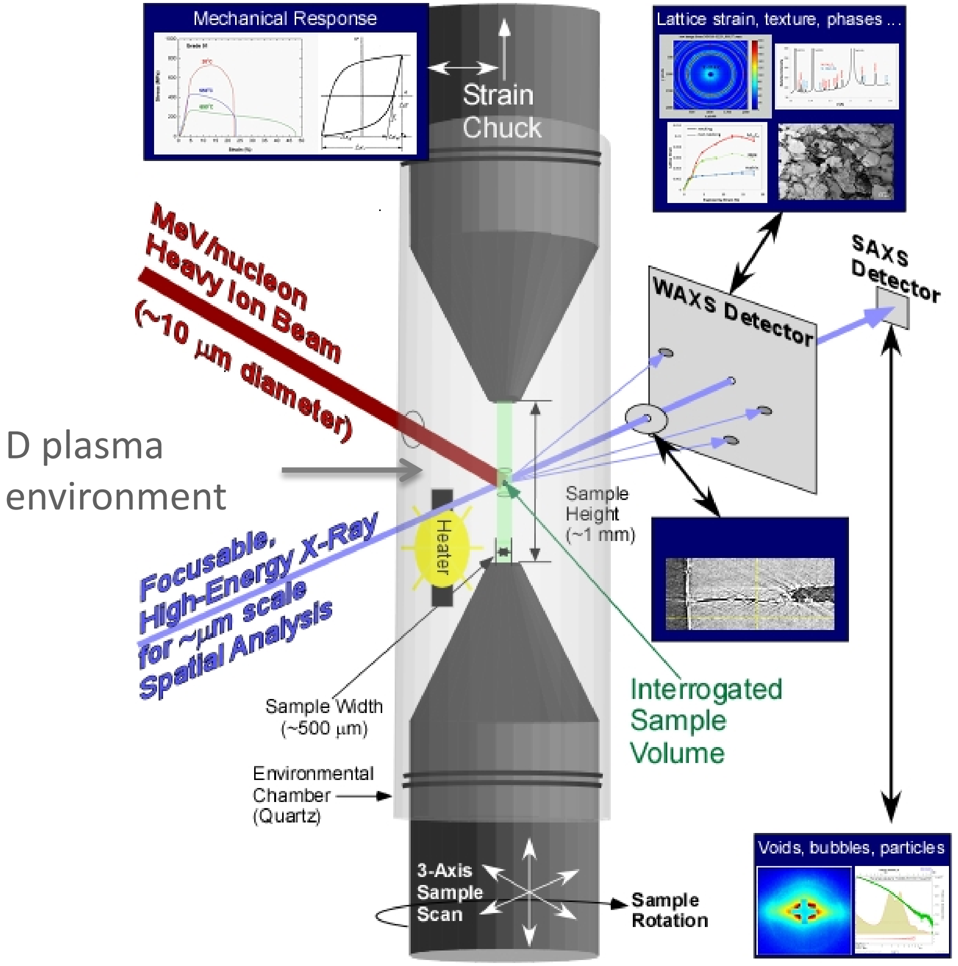
Some Critical Fusion Issues it Addresses

- **FES strategic goal:** Support the development of the scientific understanding required to design and deploy the materials needed to support a burning plasma environment
- FES Advisory Committee Strategic Planning (Draft, 9/21/2014)
  - Experimentally validated integrated predictive capabilities: spectrum of plasma experimental facilities supported by a vigorous diagnostics
  - Taming the plasma-material interface: The Panel concluded that the most cost-effective path to a self-consistent solution to the plasma-materials-interface challenge requires the construction of a prototypic high-power, high-fluence linear divertor simulator. Results from this facility will be iterated with experimental results on suitably equipped domestic and international tokamaks and stellarators, as well as in numerical simulations.
- XMAT could become this simulator. Crucially it would provide *in operando* testing of plasma facing materials at operating conditions (using heavy, MeV/nucleon ions as energetic neutron proxies)

Proposal - eXtreme MATerials beamline (XMAT)

A new beamline at APS for *in situ* studies of nuclear energy materials under irradiation, temperature, stress, and environment.

XMAT will provide x-ray probes for *in-situ* study of materials in simulated nuclear reactor environments, enabling rapid evaluation of materials performance under extreme service conditions including structural materials and for the first time nuclear fuels.



XMAT is made possible by combining three of Argonne's unique capabilities:

1. **Energetic, Heavy Ion Beams (ATLAS)**
2. **Focusable, High Energy X-Rays (APS)**
3. **Multi-modal Imaging (APS)**

Opportunity Window -> APS/ATLAS Upgrades

XMAT Members: First step in building community consensus for concept.

External Board

- **Todd Allen**, Idaho National Laboratory/ University of Wisconsin
- **Mark Kirk**, Argonne National Laboratory
- **Arthur Motta**, Pennsylvania State University
- **Bob Odette**, University of California at Santa Barbara
- **Simon R. Phillpot**, University of Florida
- **Andrew Sowder**, EPRI
- **Jim Stubbins**, University of Illinois (chair)
- **Jeff Terry,** IIT
- **Gary Was**, University of Michigan
- **Brian Wirth**, University of Tennessee, Oak Ridge National Laboratory
- **Steve Zinkle**, Oak Ridge National Laboratory

Argonne Team

- **Michael Pellin**, PSE
- **Meimei Li**, NE
- **Latif Yacout**, NE
- **Jon Almer**, APS
- **Tom Ewing, NE**
- **Hawoong Hong**, APS (XIS)
- **Jerry Nolen**, PHYS
- **Marius Stan**, NE
- **Di Yun**, NE

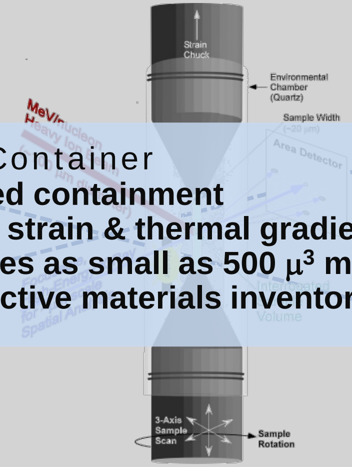
What’s Unique? – High-Energy, Heavy-Ion Irradiation

In Situ, High Energy Ion Irradiation (HEI)

- **Damage Rates to 25 DPA/hour (controllable)**
- **Damage Doses to >2000 DPAs**
- **~ 1 MeV/nucleon heavy ion irradiation (e.g. 150MeV Xe)**

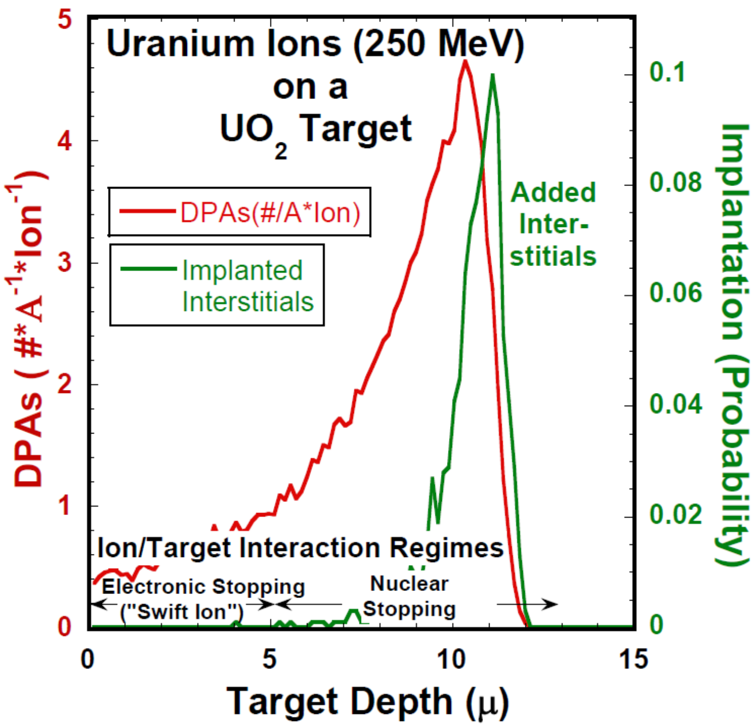
X-Ray Line (30<E<100 keV)

- **Diffraction: Shape, size, orientation of single grains**
- **Scattering: defect distributions, aggregate response**
- **SAXS: nanoscale voids, bubbles, particles**
- **Tomography: three dimensional imaging, scattering**



Sample Container

- **Isolated containment**
- ***In situ* strain & thermal gradients**
- **Volumes as small as 500 μ^3 minimizing radioactive materials inventories**



Ion damage provides rapid controllable, non-activating radiation damage, but material interactions are more complicated than neutrons.

HEI/X-Ray study allows interpretation by:

- Spatial separation of irradiation effects
- Deeper penetration removing “surface sinks”
- 6-8 μm depth damage -> neutron-like

While providing

- Damage Doses to > 2000 Dpa
- Controllable damage rates up to 25 DPA/hour

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For Fusion the use of heavy, energetic ions is crucial.

- XMAT achieves >2000 DPA total doses because of the unique properties of MeV/nucleon ions. This allows studies to the high doses expected.
- XMAT provides a high and easily variable damage rate, this allows characterization of the dose *rate* dependence of materials changes – crucial to accelerated materials testing.
- These ions easily penetrate a H isotope plasma and allow sample heating and strain testing *during irradiation.*
- *The XMAT accelerator can also deliver energetic protons or deuterium ions – their penetration depth is enough to understand bulk effects!*

What's Unique? – High-Energy, Focusable X-Rays

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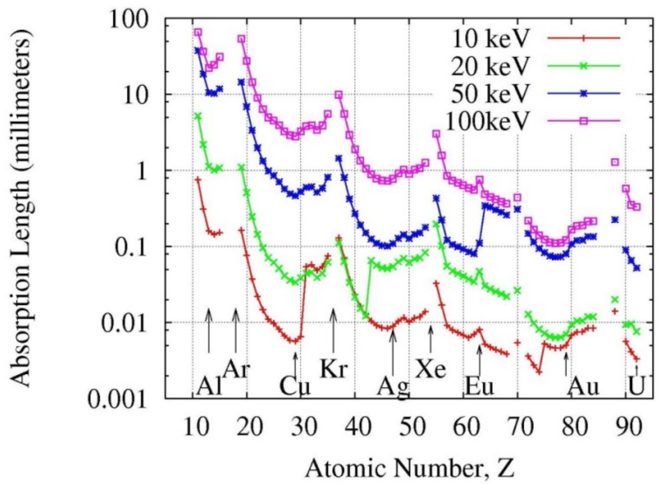
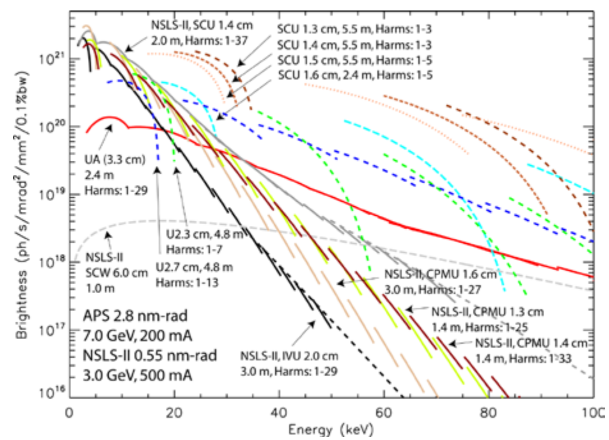
The key to understanding radiation damage is *in situ* study of the 3-dimensional evolution of microstructure at the mesoscale.



Higher x-ray energy->penetrate deeply into a sample – **"bulk" effects (including actinides)**.



High brilliance, high flux ->high resolution (mesoscale analysis)

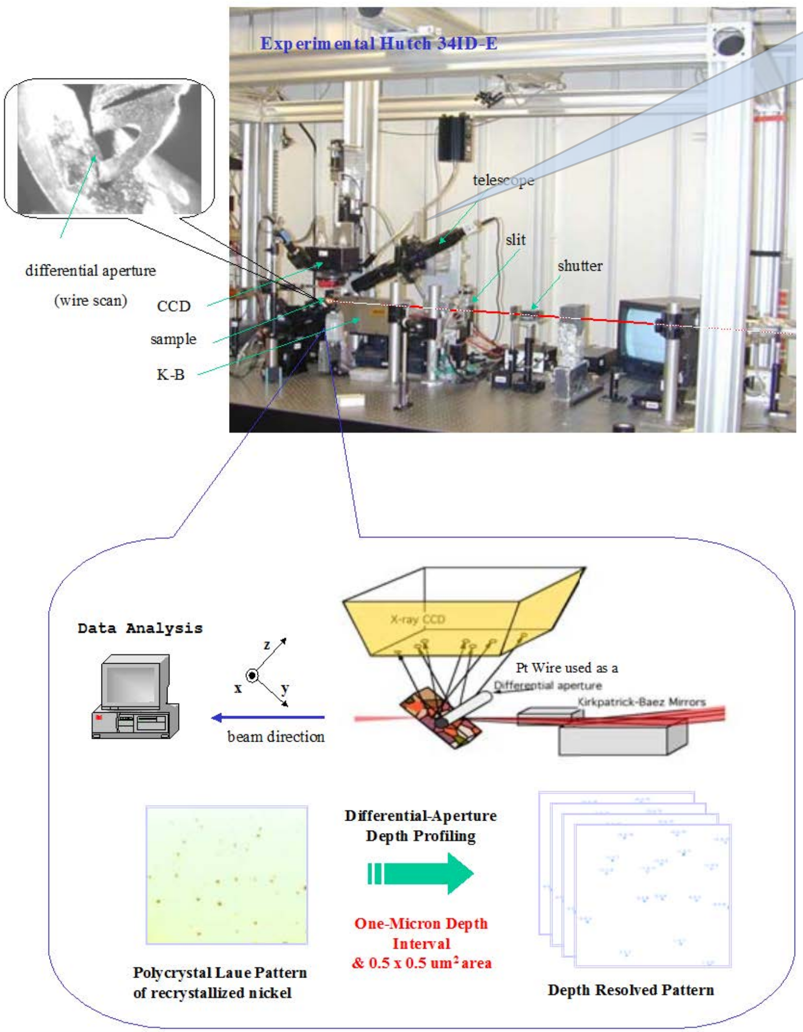
A Sequential Test

Ion and X-ray Radiation

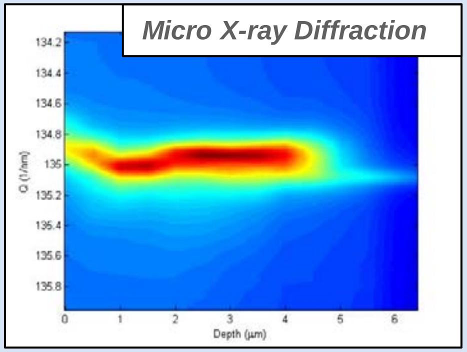
APS Sector 34

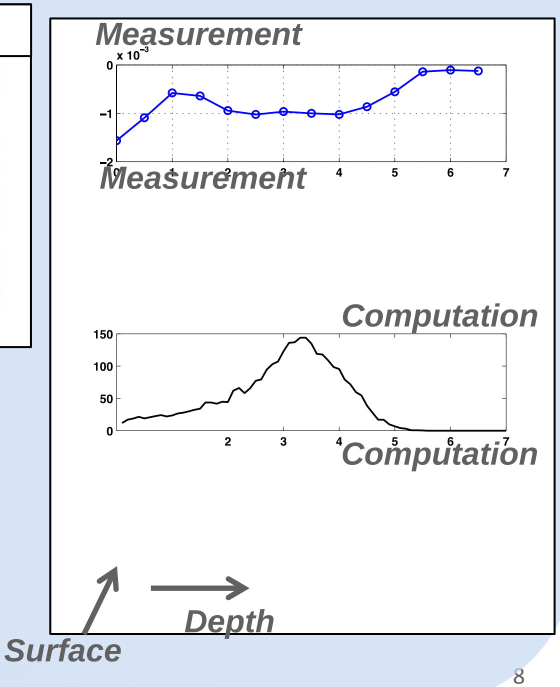
Micro-beam:
0.5 × 0.5 μm²

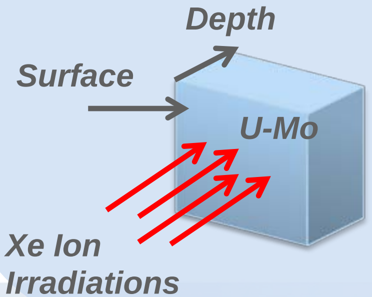
Schematic of 3-D X-ray Diffraction Microscope



Characterization of High Energy Xe Ion Damage in U-10Mo Metallic Alloy Fuel







Hard X-rays Critical to Radiation Research

- Real materials, real environments, real time

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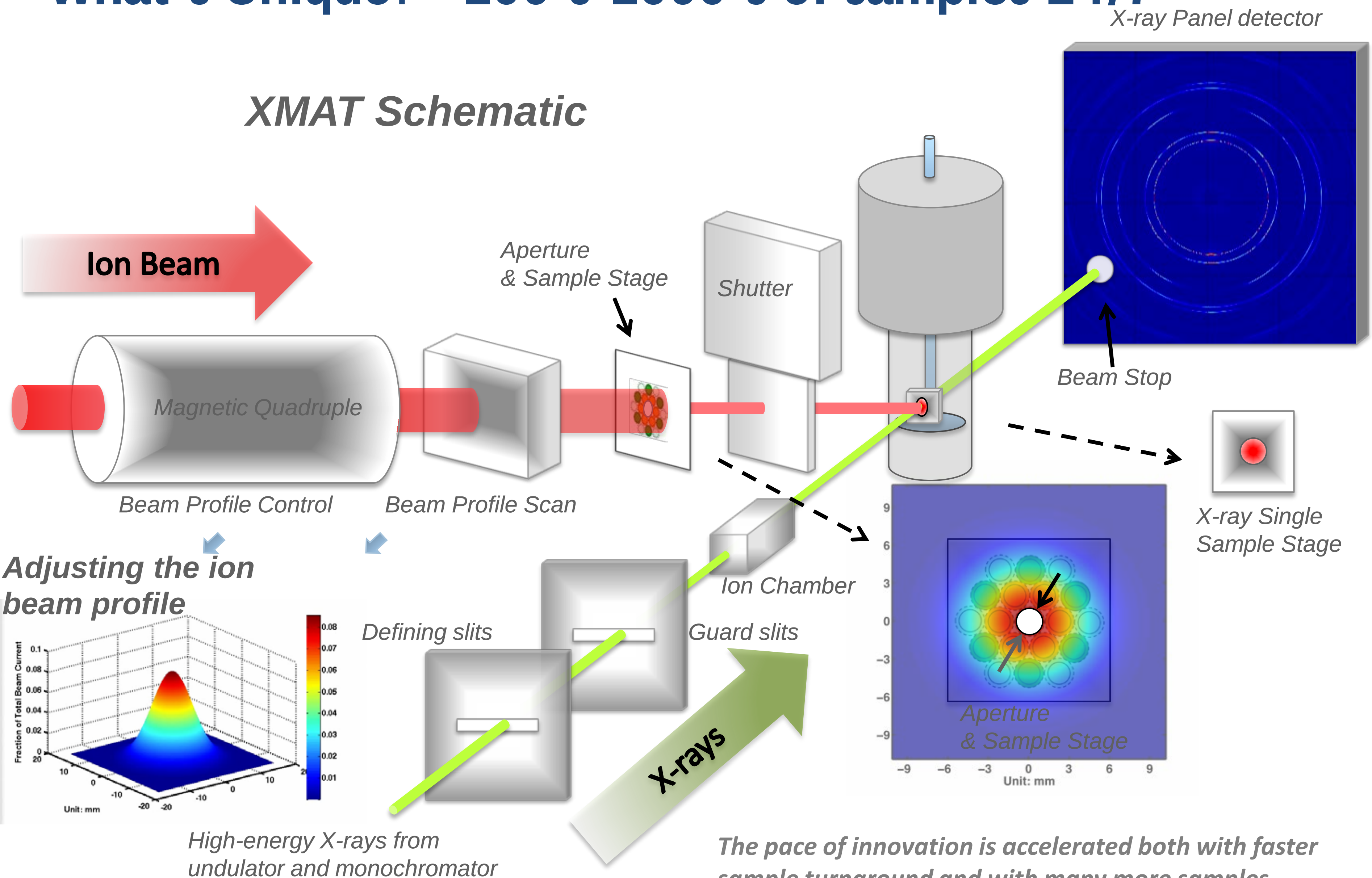
- ***Focusable*** allows mesoscale 3-D imaging
- Deep penetration
  - Bulk behavior
  - Environmental chambers
- Spatially resolved (inhomogeneity)
  - Resolve complex structures
  - Direct comparison with simulations on same length scales

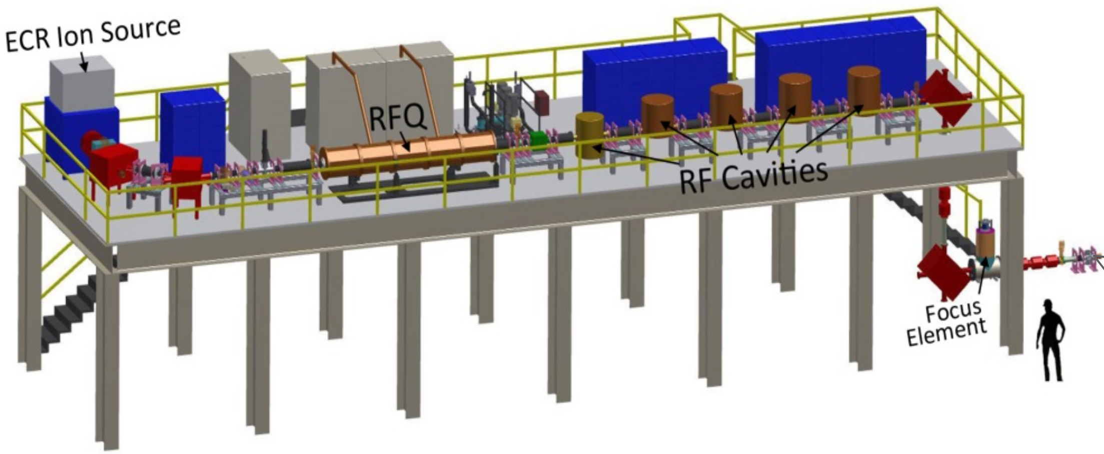
- In situ, real-time studies
  - Dynamics
  - structural evolution
- Unit mechanisms and collective effects in complex engineering materials
  - Multiple probes for concurrent, multi-scale characterization

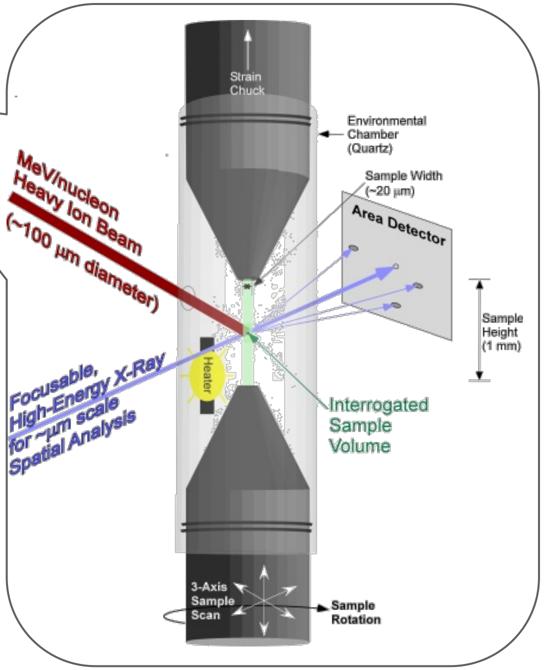
What's Unique? - 100's-1000's of samples 24/7

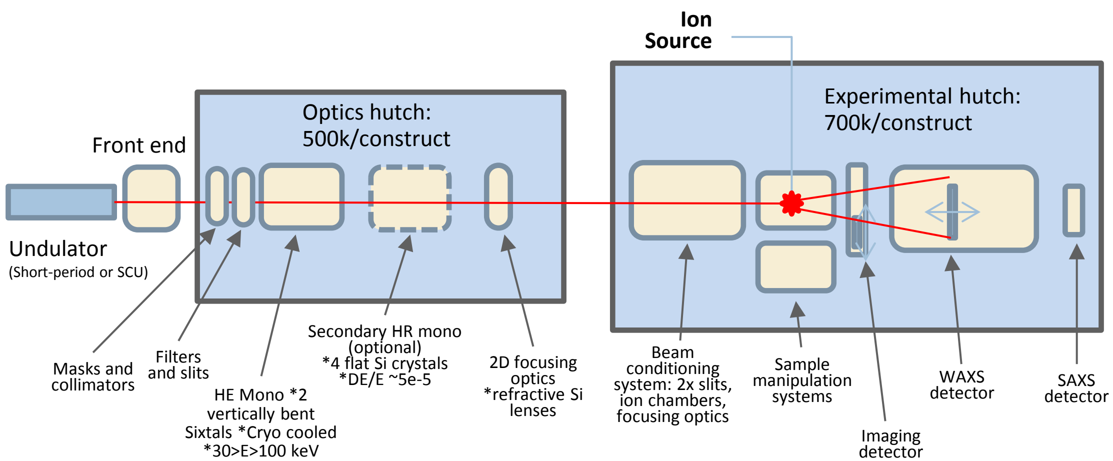


The pace of innovation is accelerated both with faster sample turnaround and with many more samples irradiated.

XMAT Layout


ECR Ion Source
RFQ
RF Cavities
Focus Element


Strain Chuck
Environmental Chamber (Quartz)
Sample Width (~20 µm)
Area Detector
Sample Height (1 mm)
MeV/nucleon Heavy Ion Beam (~100 µm diameter)
Focusable, High-Energy X-Ray for ~µm scale Spatial Analysis
Heater
Interrogated Sample Volume
3-Axis Sample Scan
Sample Rotation


Ion Source
Front end
Optics hutch: 500k/construct
Experimental hutch: 700k/construct
Undulator
(Short-period or SCU)
Masks and collimators
Filters and slits
HE Mono *2 vertically bent Sixtals *Cryo cooled *30>E>100 keV
Secondary HR mono (optional) *4 flat Si crystals *DE/E ~5e-5
2D focusing optics *refractive Si lenses
Beam conditioning system: 2x slits, ion chambers, focusing optics
Sample manipulation systems
Imaging detector
WAXS detector
SAXS detector

The APS Upgrade & XMAT

The APS is already the brightest source of high-energy x-rays in the western hemisphere making it the ideal source for XMAT.

1) The planned APS upgrade would improve the emittance of the x-ray beam by a factor of ~100, with direct benefits on spatio-temporal resolution.

2) The enhanced coherence of the x-ray beam will enable phase-contrast imaging at high energy, to reveal fine features in absorption contrast.

What would this mean for XMAT?

Consider the following image and the recognition improvement offered by 100 fold enhancement.

A 100 fold resolution improvement