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Ion Beam Analysis Activities at the Sandia Ion Beam Laboratory

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Consultancy Meeting in Support of the New Coordinated Research Project on Development and Application of Ion Beam Techniques for Materials Irradiation and Characterization Relevant to Fusion Technology

IAEA Vienna, Austria 2/24/2020

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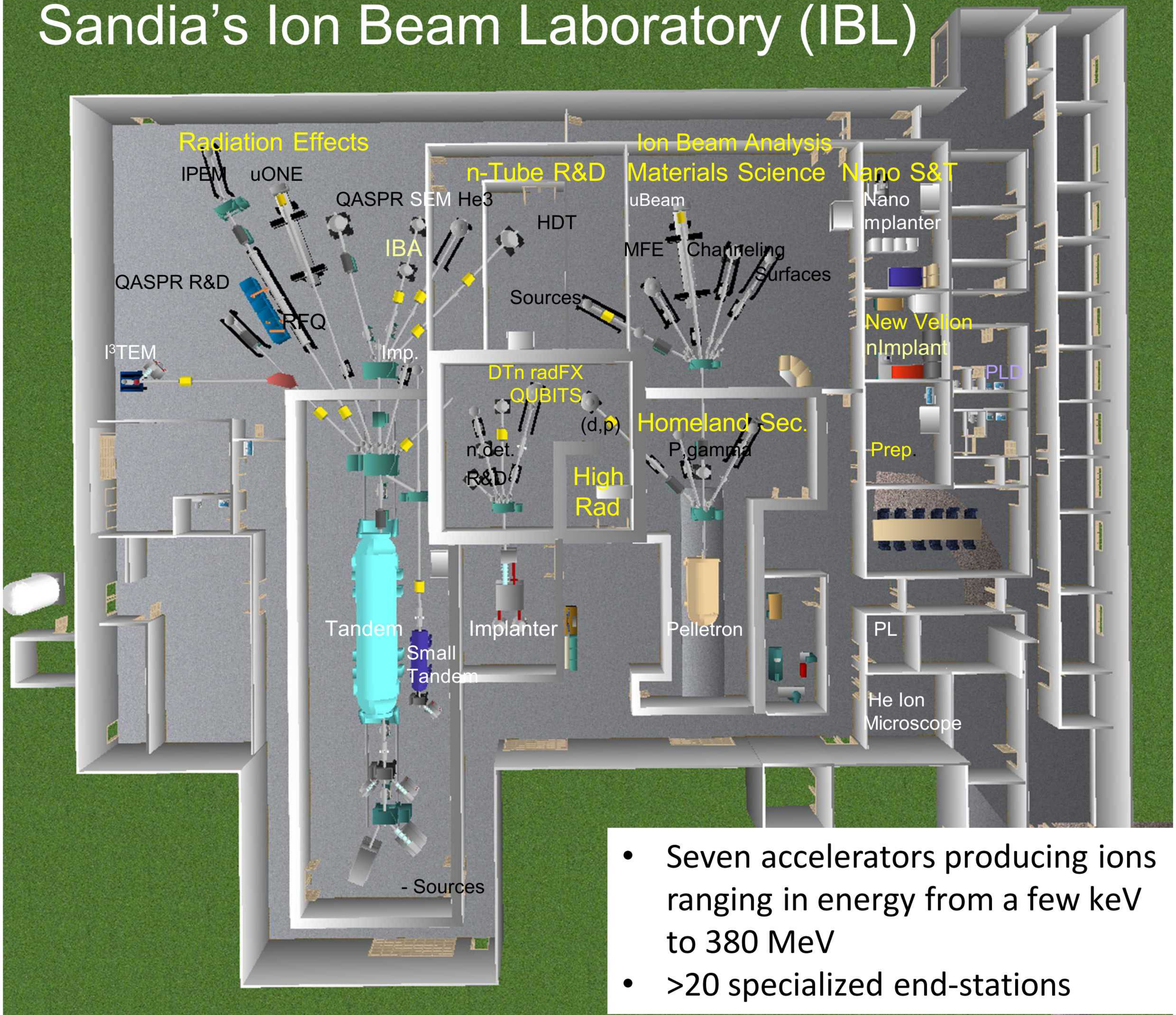
Outline

- Overview of experimental facilities at the Sandia IBL
  - Accelerators
  - End stations
- Experimental methods used for MFE, illustrated by a few projects
  - DiMES in DIII-D
  - He3 NRA for light-element depth profiling

Sandia's Ion Beam Laboratory (IBL)



- Seven accelerators producing ions ranging in energy from a few keV to 380 MeV
- >20 specialized end-stations

Ion Accelerators

- HVE-Pelletron EN Tandem (6 MV) and negative ion sources for various ion types
- Single-ended NEC Pelletron (3 MV) Model 3UH-2 (MFE)
- Small Tandem (1MV)
- HVEE 300 kV implanter
- Nano implanters
  - A&D 10-100 kV, 150-10 nm beam
  - Raith Velion 5-35 kV, ~ 6 nm beam @ 10 kV (New)
- He ion microscope (New)

End Stations

- IBA for MFE, RBS/NRA on probes or whole tiles from DIII-D (16 x 26 cm translation)
- Irradiation to produce displacement damage, high dpa or short pulsed (>10ns)
- Microbeams (~ 1-5 µm depending on count rate)
- Nanobeams for single ion implantation (QBIT research)
- I^3TEM – TEM with heavy ions from tandem and low-energy light ions (H & He) from Colutron
- Ion Channeling (with UHV, AES, LEED, and gas dosing)
- He ERD for HDT depth profiling
- DLTS to characterize carrier emission rate from defects in semiconductors
- 14 MeV DT neutron production (~$5x10^8$ n/cm^2/s) to test semiconductor device response

MFE end station

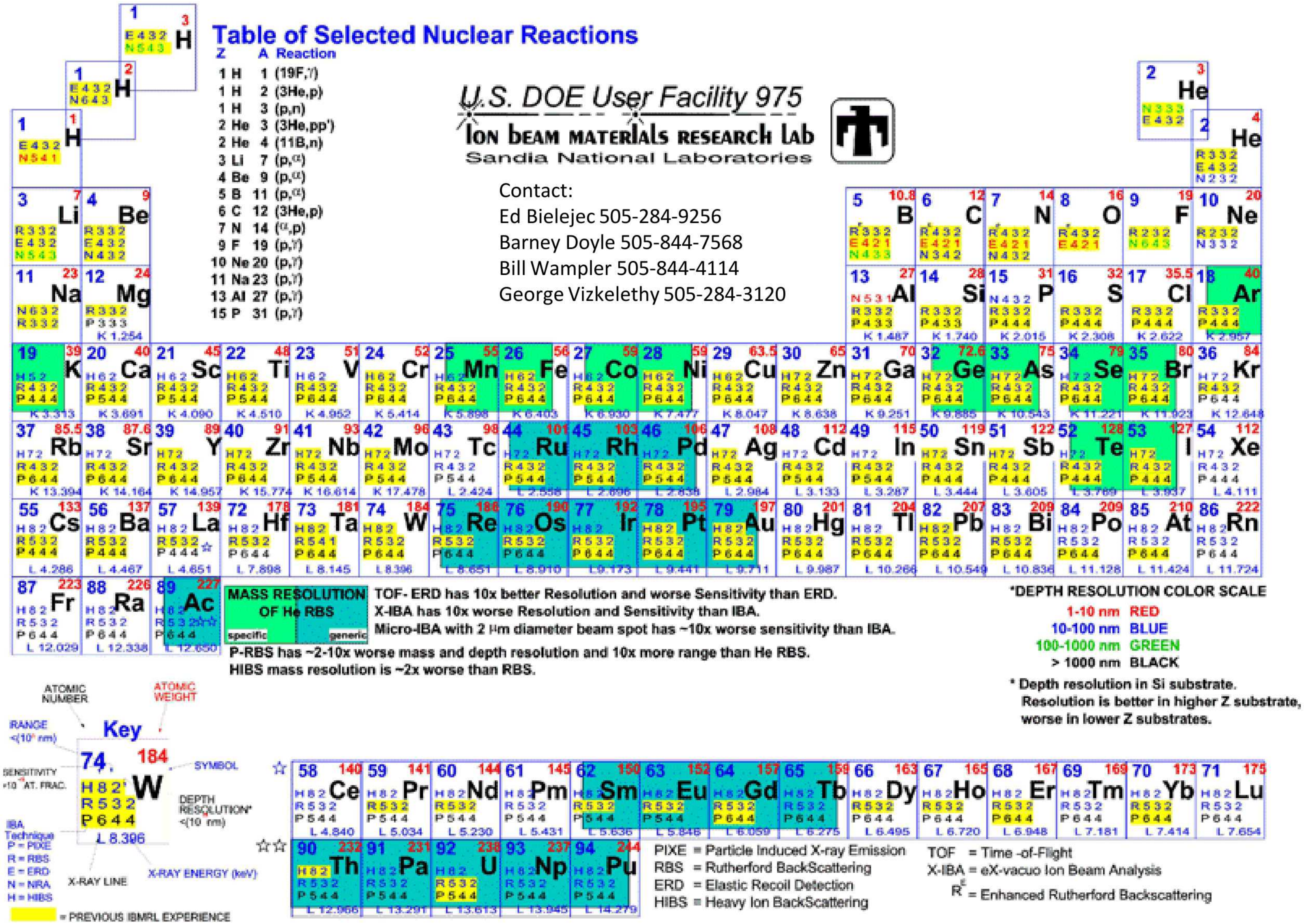
Work for MFE at the Sandia IBL is long-standing and broad in scope

- DIII-D DiMES Erosion/Redeposition
- EAST/MAPES Erosion/Redeposition for ITER
- W in WEST
- He^3 NRA for light-element depth profiling
- C^{13} methane injection in DIII-D
- Li and D retention in NSTX
- Enhanced retention of DT at displacement damage in W
- Kinetics of HDT uptake & release, surface recombination & effect of contaminants
- He ERD for HDT profiling

IBA is used to study PWI in Tokamaks

- To measure changes in near-surface composition of PFCs,
  providing insight into material erosion/transport/redeposition by the plasma,
  and data for development and validation of codes
  used to extrapolate plasma-material response to reactor conditions.
- Main limitation is that IBA is ex-situ and hence not real-time.
  Analysis of PFCs are typically either:
  - on tiles from many locations removed after long exposure to various plasma conditions, or
  - on probes exposed to well-defined plasma conditions, but only at one location.

ION BEAM ANALYSIS TABLE OF THE ELEMENTS



With links to details for each element

https://www.sandia.gov/research/facilities/technology_deployment_centers/ion_beam_lab/ion_beam_analysis_periodic_table.html or Google *IBA Periodic Table*

RBS and He^3 NRA are the principle IBA techniques used for MFE

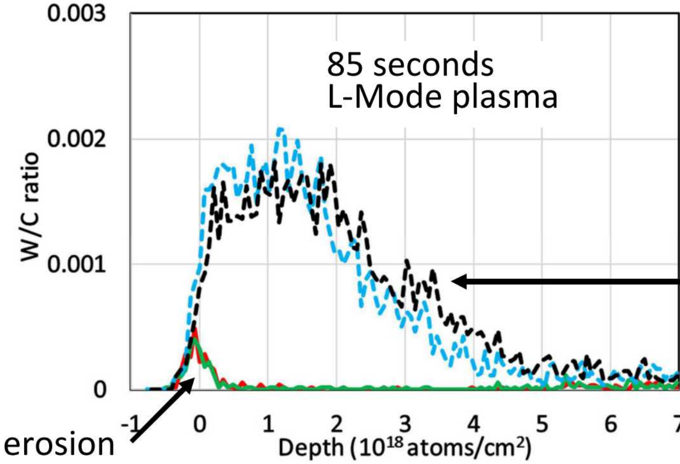
Factors influencing measurement precision for RBS & NRA

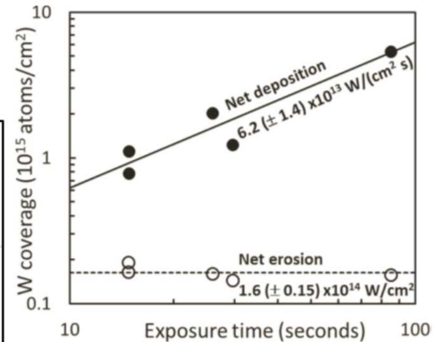
- Spectrum analysis is simpler if thin-target approximation is adequate.
  Otherwise, SIMNRA with energy dependent cross section and stopping may be adequate.
- Best to use RBS for heavy elements on light substrates, NRA for light elements.
- Coverage ratios are more accurate than absolute quantities since some uncertainties cancel.
- For absolute quantities, need reaction cross section, number of incident particles (from integrated beam current) and detector solid angle. Good practice to also use a thin-film reference sample of known coverage, which becomes the only option when the cross section is unknown.
- Cross sections for RBS are more likely to be accurate when they are near Rutherford, which limits the incident ion energy and depth of analysis.
- Thickness of a surface-layer may be determined from reaction or scattering yield, or from ion energy loss if composition is known.

DIII-D DiMES Erosion/Redeposition (RBS)

Toroidal Tungsten Ring Experiment

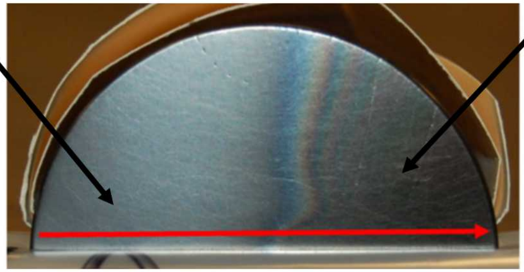
Phys. Scr. T170 (2017) 014041 PFMC16

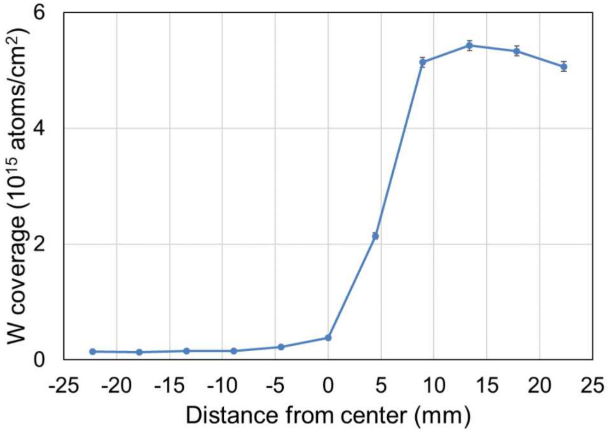




Net deposition on outboard side. Thickness & W coverage increase with exposure.

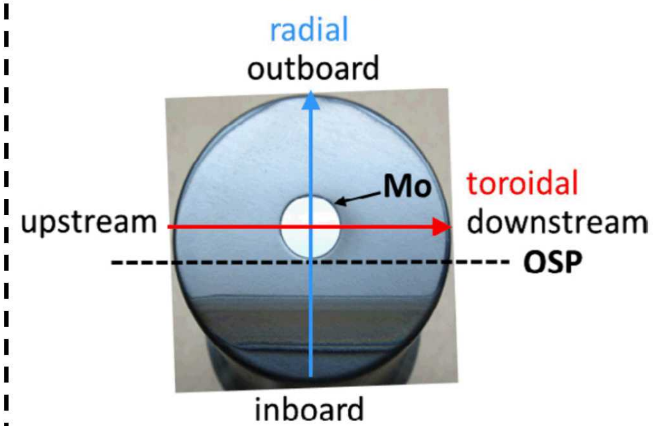
Net C erosion on inboard side. W coverage Quickly reaches steady-state.

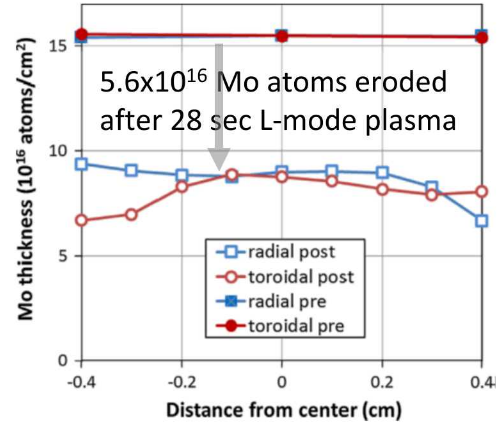


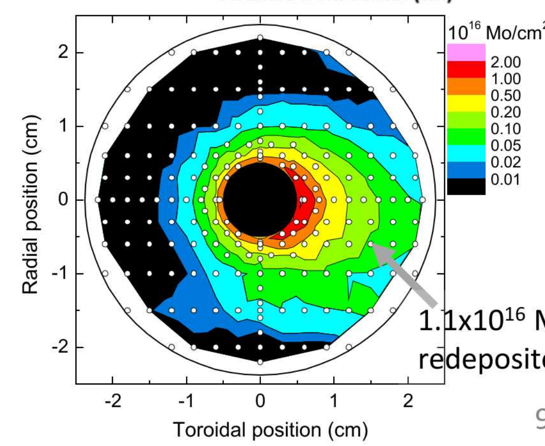


Mo erosion study

JNM 438 (2013) S822 PSI20

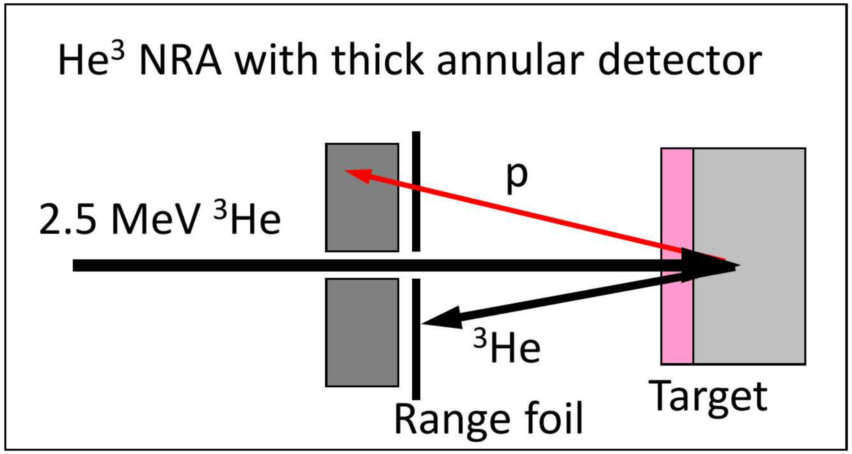






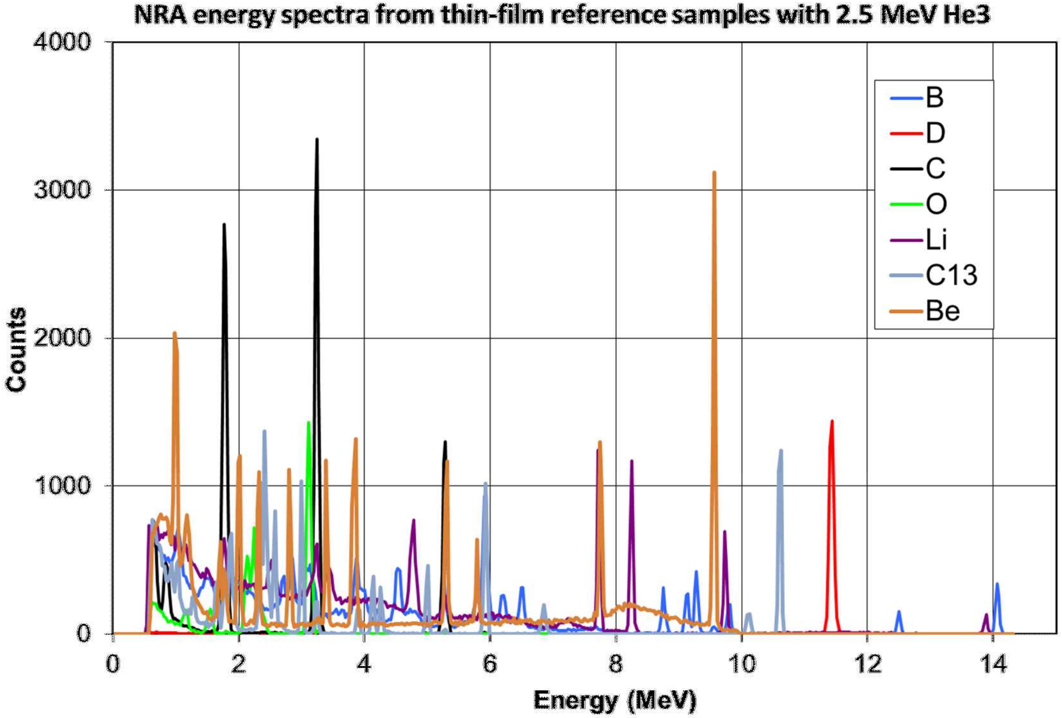
1.1x10^{16} Mo atoms redeposited (19%)

He^3 NRA for light element depth profiling



Detector must be:

- Annular to maximize sensitivity and minimize kinematic energy broadening.
- Thick to measure full particle energy (> 1mm for 12 MeV proton from He^{3}D)



He^3 NRA for light element depth profiling

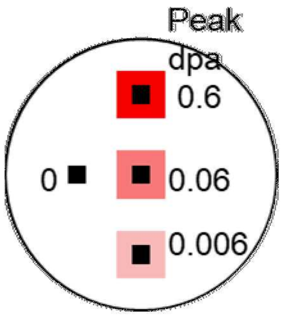
- Particle energy spectrum is measured at a single incident energy.
- Energy scale is transformed to a depth.
- Yield (counts/channel) is transformed to a concentration.
- Transforms obtained from SIMNRA with reaction cross section & stopping power.
- This method was developed at the Sandia IBL is used often for MFE.
- Simpler than alternative method of deconvoluting yield vs incident particle energy.

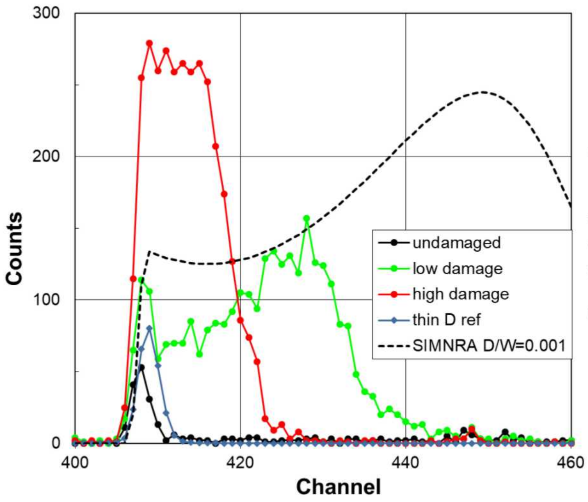
Study of D retention at displacement damage in W

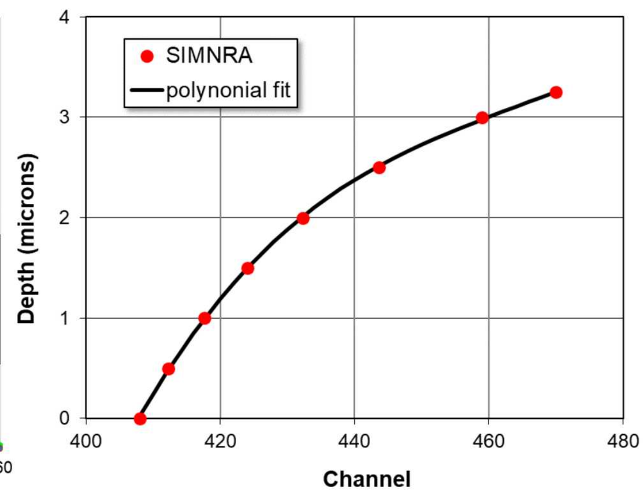
Wampler and Doerner, Nuclear Fusion 49 (2009) 115023

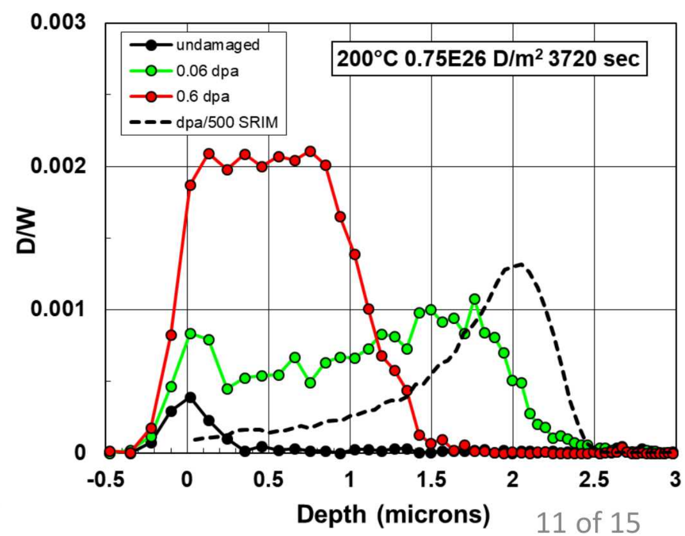
Wampler, Physica Scripta T180 (2020)

- W damaged with 12 MeV Si ions at the IBL
- Exposed to D plasma in PISCES-A at UCSD.
- Energy spectrum of protons from D(He^3,p)α measured at the IBL
- Counts vs channel transformed to concentration vs depth.
- Detection limit D/W ~ 10 appm, depth resolution ~ 0.3 µm.
- Many experiments were done including exposure in DIII-D.

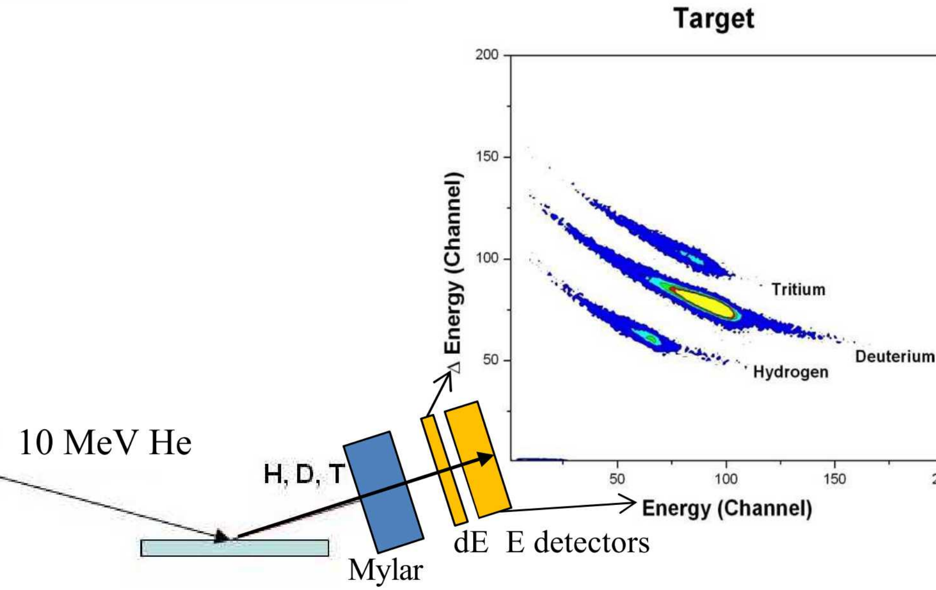






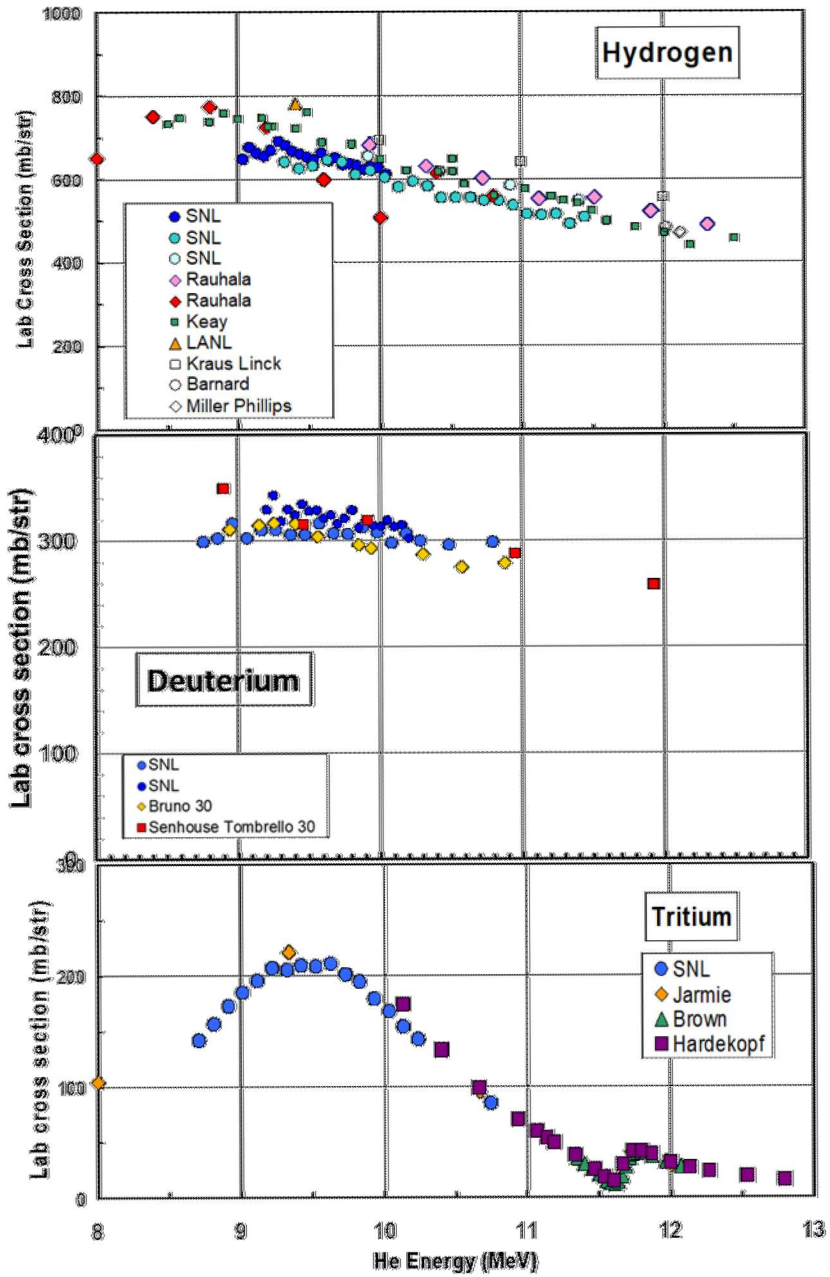


The HDT System can depth profile all three H isotopes in solids to depths of several microns



The HDT system uses 10 MeV He Elastic Recoil Detection (invented in the IBL) to quantify the concentration of H, D and T in solids. Best with smooth surfaces.

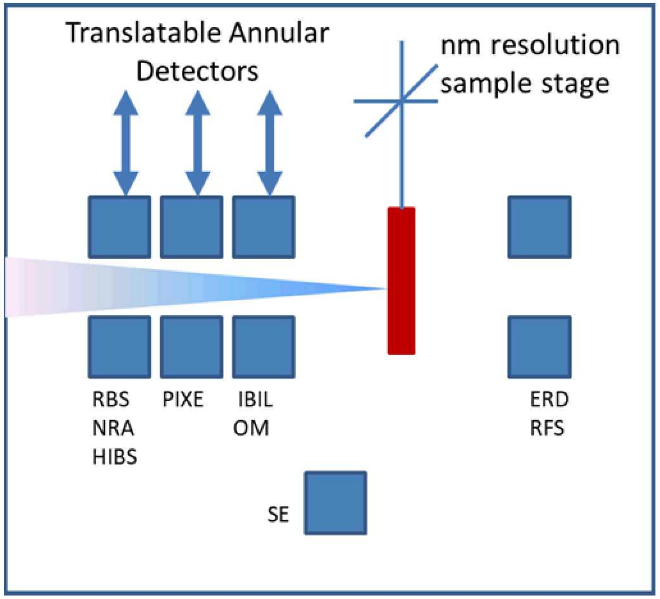
ERD cross sections for HDT were measured at the Sandia IBL in 2002



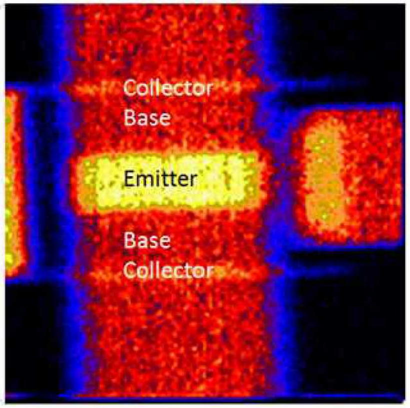
Scattering angle = 30°
Used metal-hydride thin-film samples fabricated at Sandia in which the quantity of H,D,T was independently measured by thermal desorption with mass spec analysis.

Microbeam

The micro-beam on the Pelletron provides a capability of quantitatively measuring the composition with high sensitivity in 3D at micron lateral resolution and submicron depth resolution.



5 µm Au on HBT emitter 10x50 µm



- Annular detectors provide large solid angles, enabling high sensitivity
- OM-40 “Annular” optical microscope used to position samples and for IBIL
- PIXE detector developed by Rontec and Sandia
- RBS detector also used for NRA and HIBS

Summary

- **The Sandia IBL has a broad range of experimental capabilities used for many application including IBA.**
- **These are used for a broad range of programs which include support for the US MFE program.**
- **Although a small program, the IBL has done most of the IBA for the US MFE program for decades.**
- **The IBL has broad experience with IBA methods and some unique equipment and capabilities for MFE:**
  - **End station for IBA on large objects (e.g. whole Tokamak tiles)**
  - **Depth profiling of light-elements by He3 NRA**
  - **Simulation of neutron damage by heavy-ion irradiation**
- **Other capabilities that have not been used extensively for MFE, but could be, include:**
  - **System for depth profiling HDT by He ERD (can analyze samples which contain tritium)**
  - **Microbeams**
  - **I^3TEM**
  - **14 MeV DT neutron source**