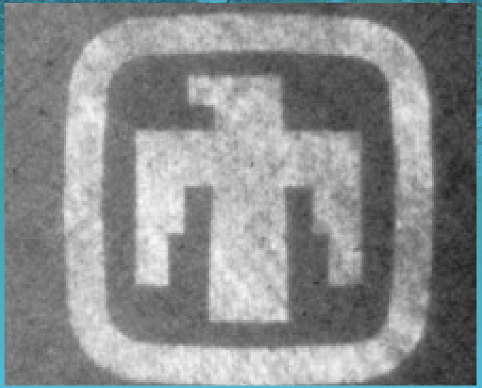
SAND2022-15067C

Sandia National Laboratories

Focused Ion Beam Capabilities at the Sandia Ion Beam Laboratory



Michael Titze

11/02/2022

U.S. DEPARTMENT OF ENERGY NNSA

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SAND2022-10363 C

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SNL

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(Source Development)

ORNL

Jonathan Poplawsky
(Low Energy Implant)

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(Source Development)

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Ania Jayich

Hyunseok Oh

Ian Hedgepeth

Dirk Bouwmeester
(Diamond Membranes)

CUNY

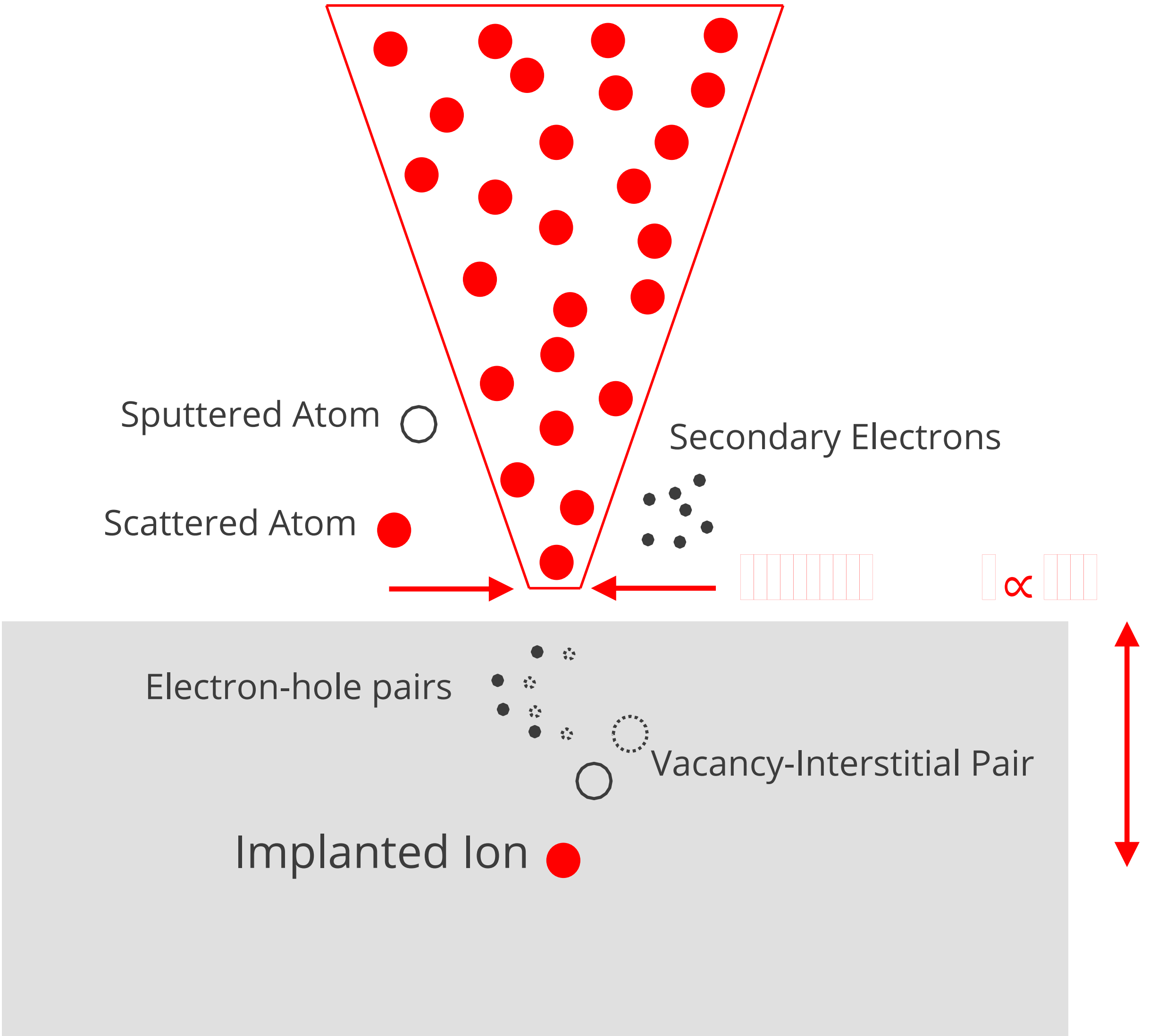
Carlos Meriles

Artur Lozovoi
(Quantum Diamond NV Sensing)

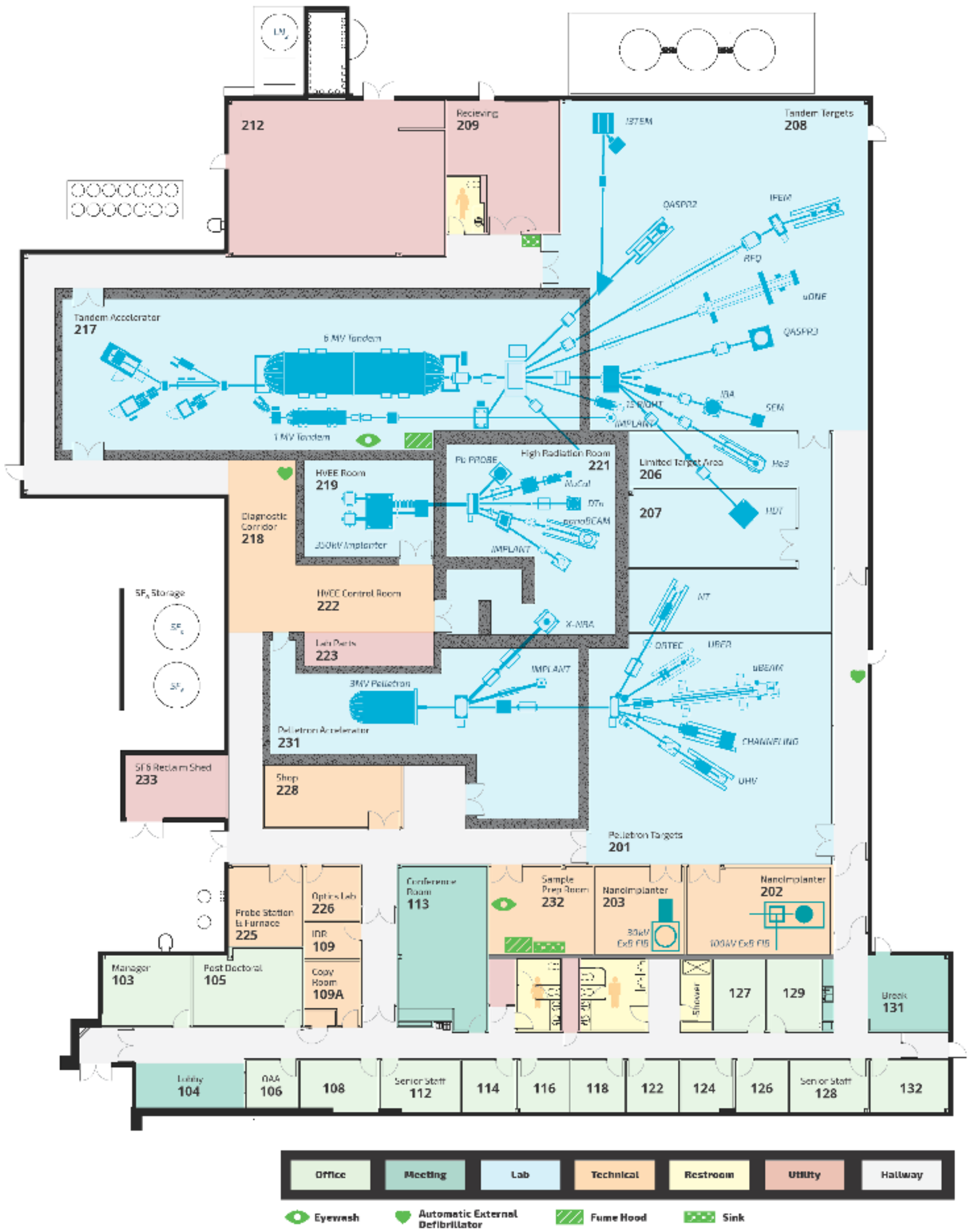
Outline

- Overview of the Sandia Ion Beam Laboratory
- Focused Ion Beam Capabilities
  - High Energy Range (≥1 MeV)
  - Medium Energy Range (10 – 200 keV)
  - Low Energy Range (< 10 keV)
- Conclusion

Focused Ion Beam Implantation



building 720
ION BEAM LABORATORY



Sandia's Ion Beam Laboratory (IBL)

7 Operational Accelerators and >25 end-stations

(including *in-situ* DLTS, PL, TEM, SEM, 1200°C heating, etc…)

Operational

(1) 6 MV Tandem Accelerator

(2) 3 MV Pelletron Accelerator

(3) 1 MV Tandem Accelerator

(4) 350 kV HVEE Implanter

High energy focused micobeams 1 μm

(5) 100 kV ExB FIB nanoImplanter

(6) 35 kV ExB FIB Raith Velion

(7) 35 kV Zeiss HeIM

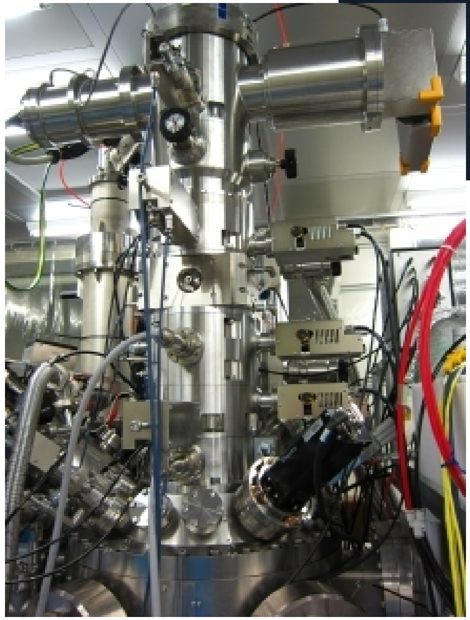
Installing

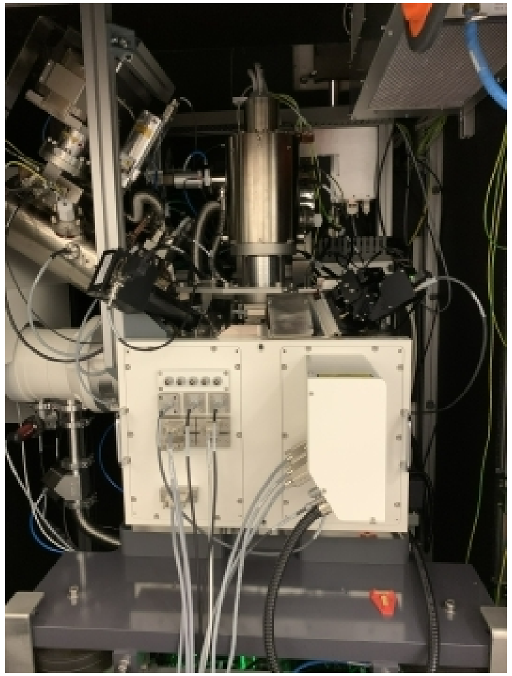
(8) 35 kV Plasma FIB

Low energy focused nanobeams <1 to 20 nm

Energy Ranges for Focused Ion Beam Implantation

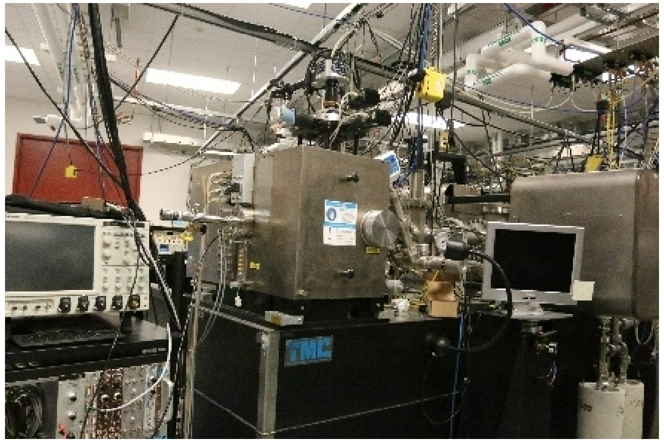
- High Energy (> 1 MeV)
  - Specialized high energy ion accelerators
  - Best achievable spot sizes ~ 1μm
- Medium Energy (10 – 200 keV)
  - Where FIB systems like to run
  - SED imaging / Single ion counting possible
  - Best achievable spot sizes ~ 10 nm
- Low Energy (< 10 keV)
  - Using FIB in non-standard energy regime
  - Targeting single (few) atomic layers
  - Targeting resolution ?
  - How to get there





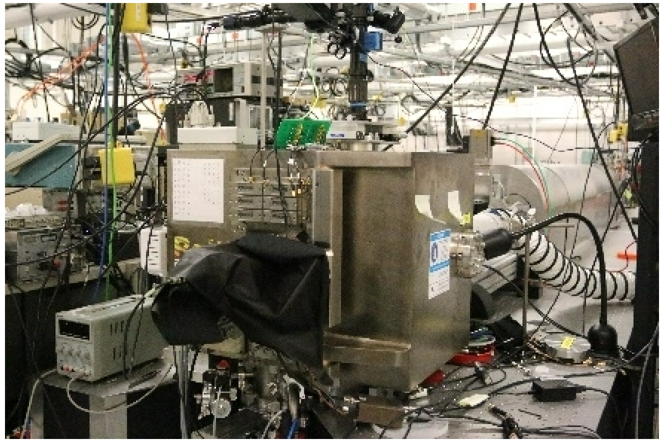
High Energy Focused Ion Beam Implantation

6 MV Tandem
(microONE)



- High resolution interferometer stage
- Spot size <1 μm
- Energy 0.8 – 70 MeV
- H to Au

3 MV Pelletron
(Light Ion Microbeam)



- High resolution interferometer stage
- Spot size <600 nm (H)
- Energy 0.25 – 3 MeV
- H, He, N, Ar, Xe, …

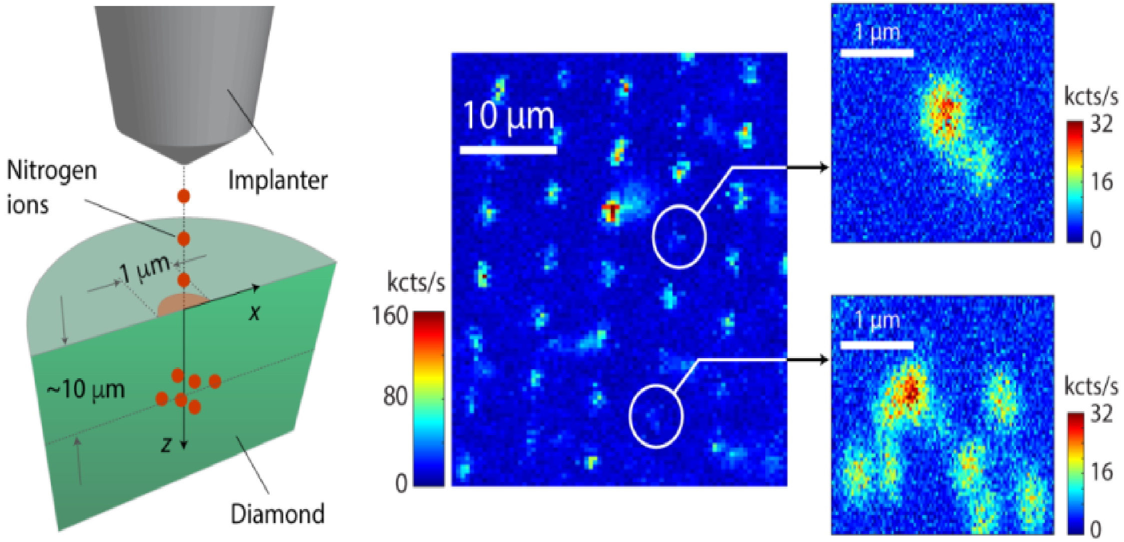
All equipped with Lithography Software for Patterning

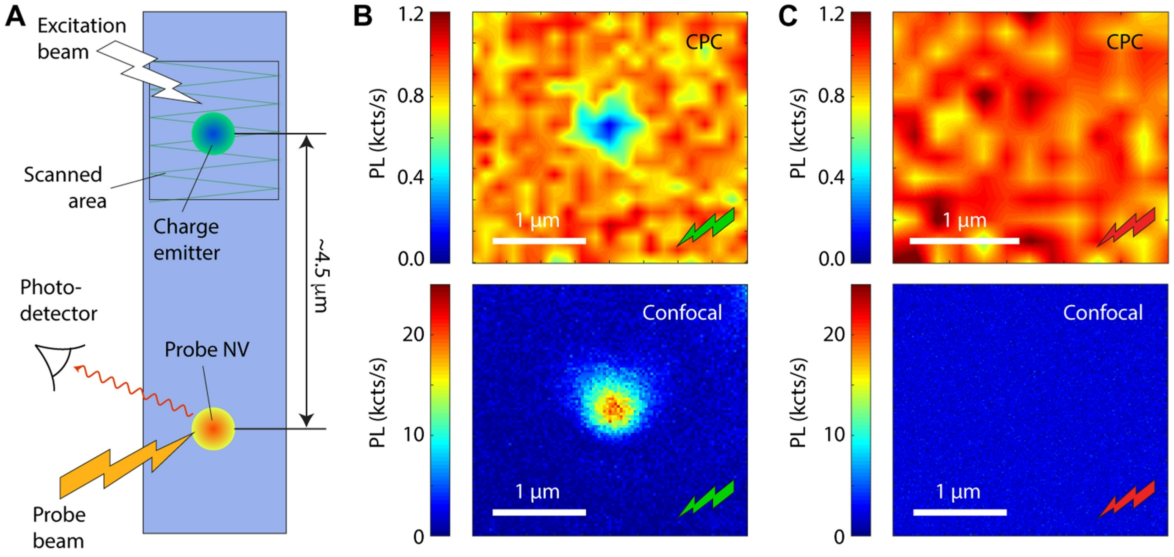
Example of High Energy Ion Implantation – NV Quantum Sensing

C. Meriles @ CUNY

6 MV Tandem

- 20 MeV N ion microbeam





Deep Implantation to shield the implanted ion from surface noise
→ NV sensing its crystal environment

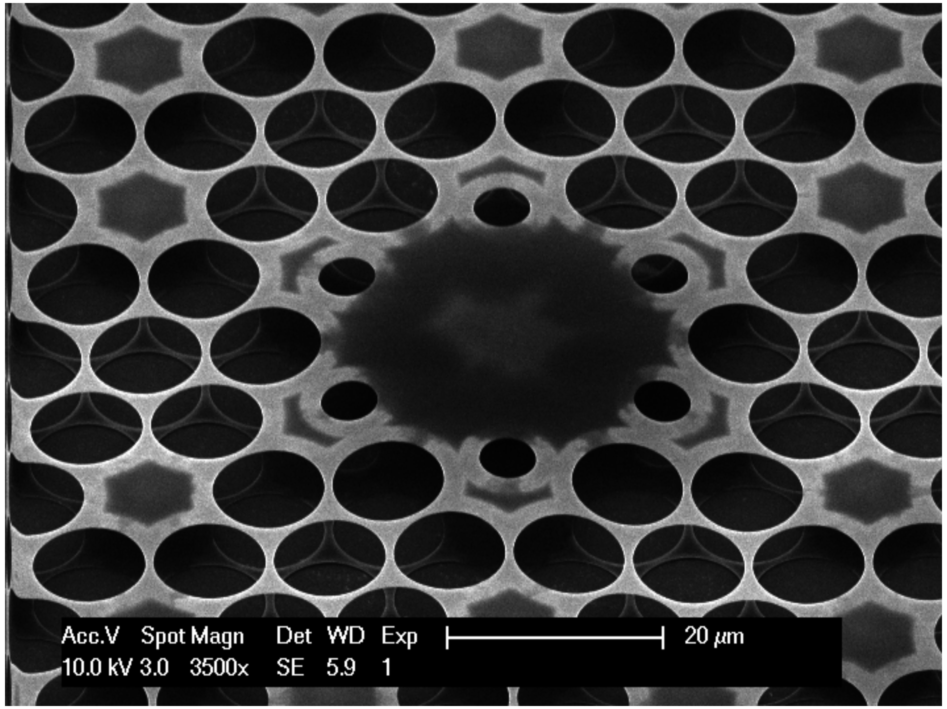
A. Lozovoi et al., Nature Electronics, 4, 10 (2022)

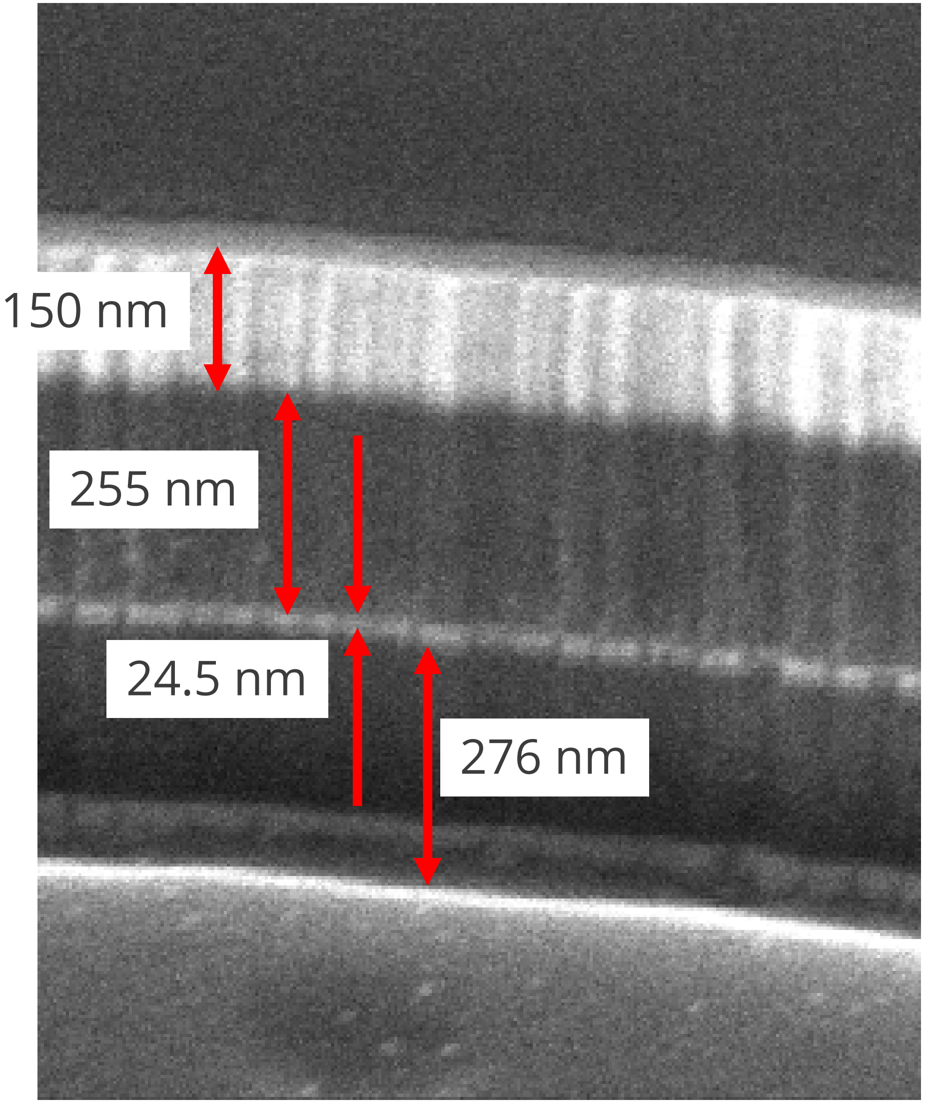
Membrane Fabrication using Ion Implantation

3 MV Pelletron

A. Jayich @ UCSB

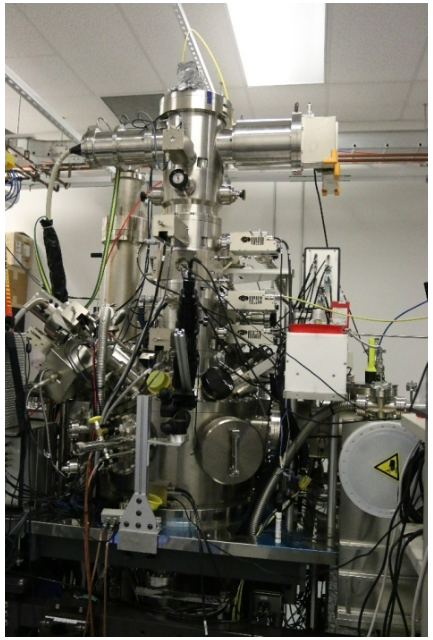
- Three energies create a thick double membrane
  - 370 keV, 200 keV, 110 keV each at 10^{17} He/cm^2





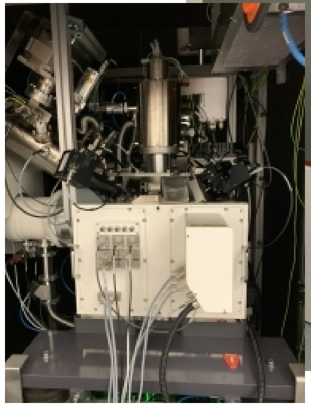
Low Energy Focused Nanobeams < 1 nm – 20 nm Spot Size

100 kV A&D FIB100NI
(nanoImplanter)



- High resolution interferometer stage
- Spot size <10 nm (Ga)
- Energy 10 – 200 keV
- 1/3 periodic table

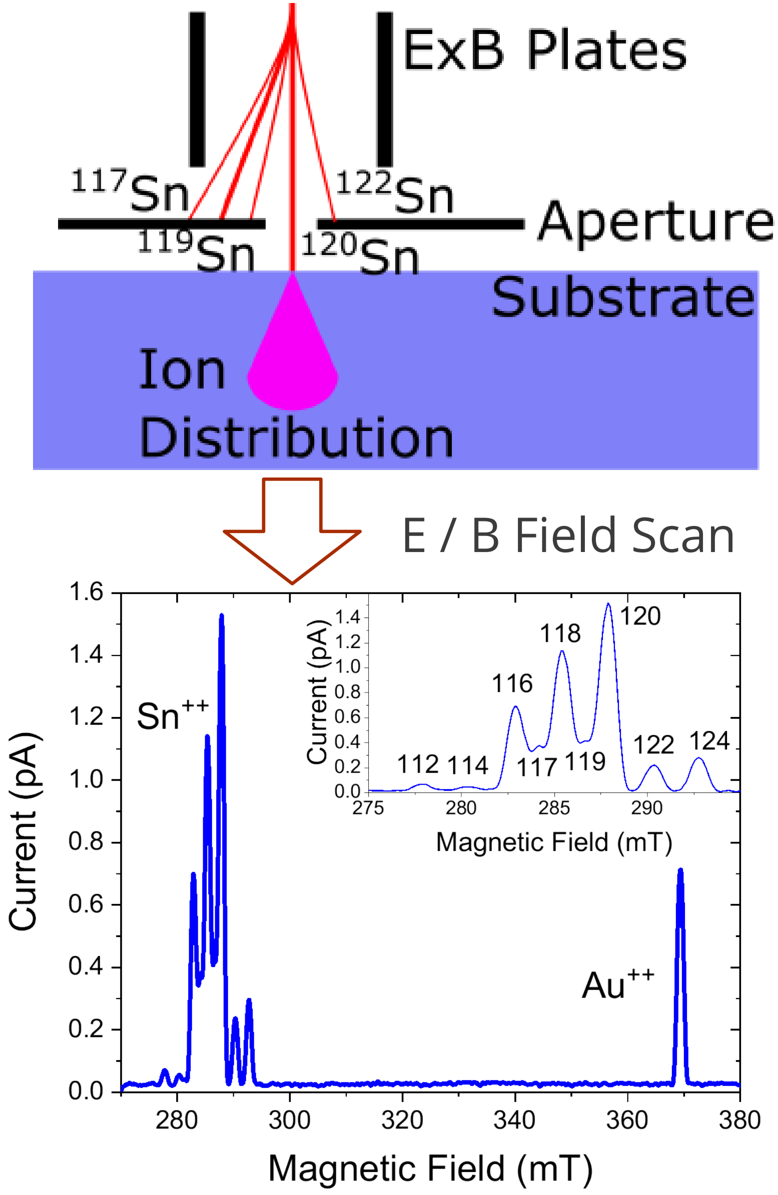
35 kV Raith Velion
(Velion)



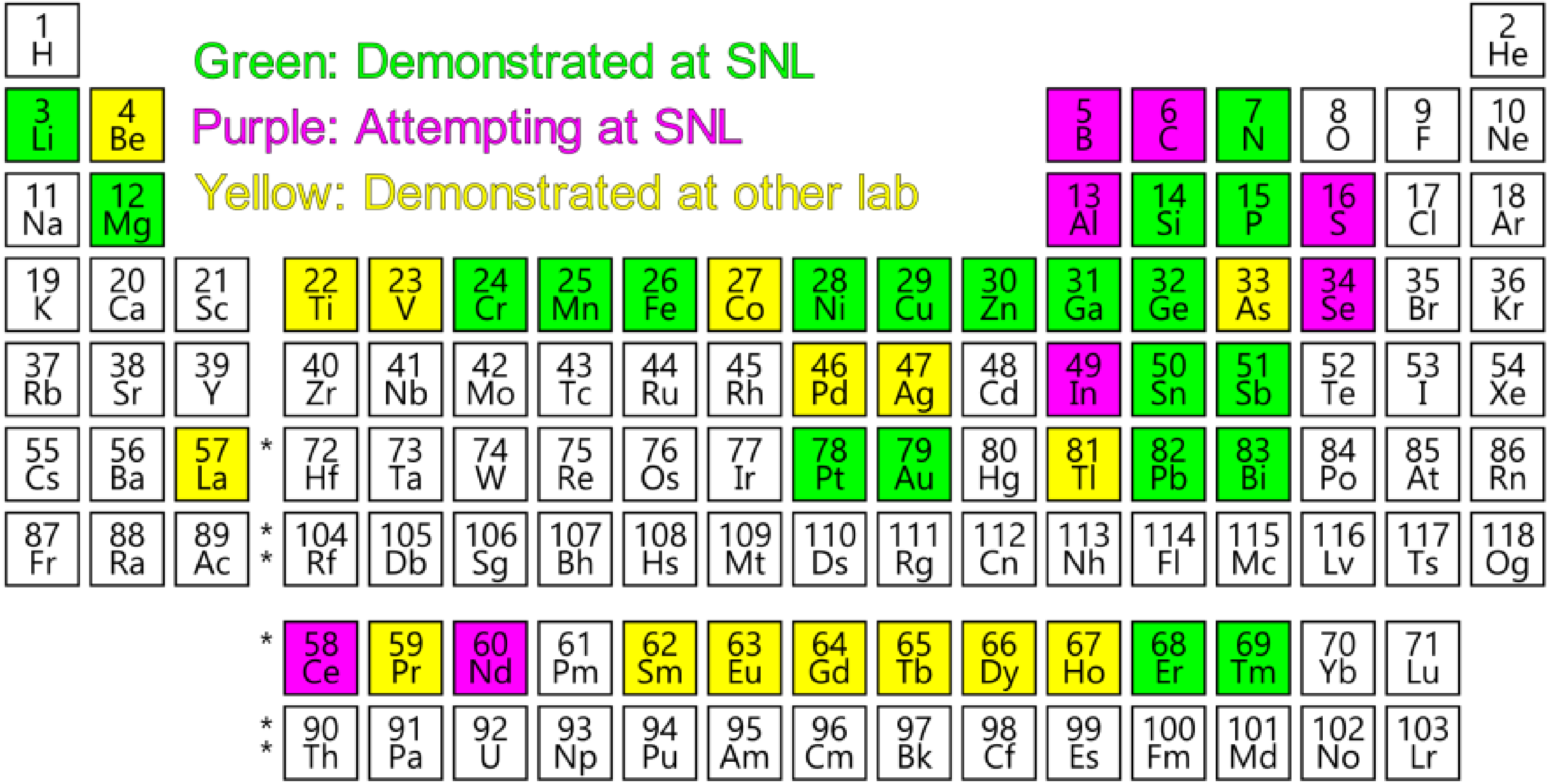
- High resolution interferometer stage
- Spot size <6 nm (Ga)
- Energy 1 – 70 keV
- 1/3 periodic table

All equipped with Lithography Software for Patterning

Liquid Metal Alloy Ion Sources – Available Ions



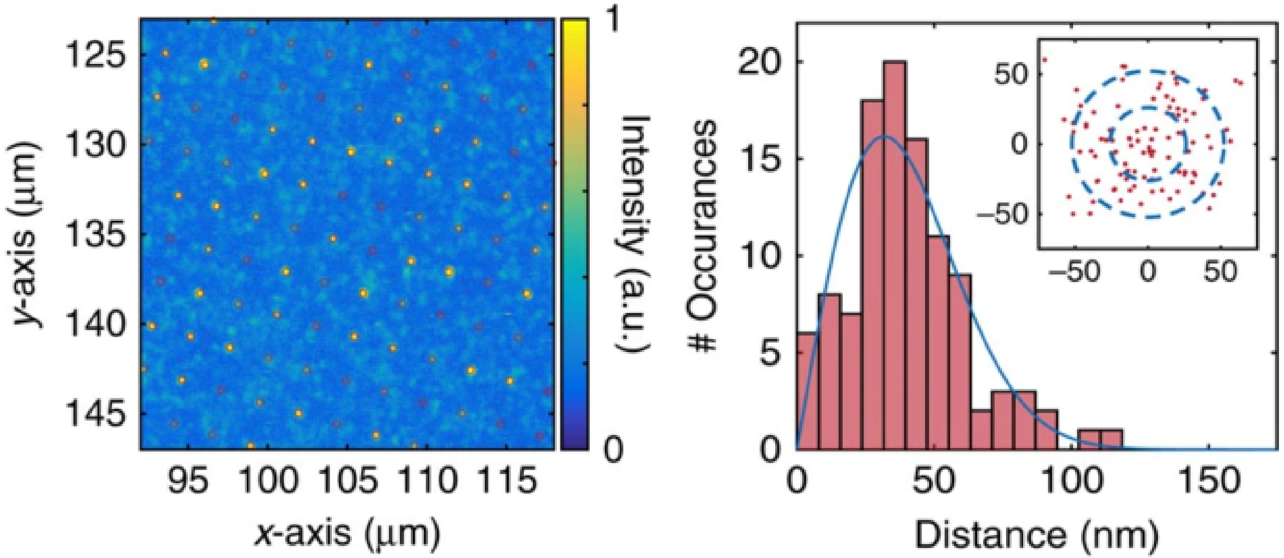
Added 8 new elements over past 3 years



Adapted from L. Bischoff et al., Appl. Phys. Rev., 3 (2016)

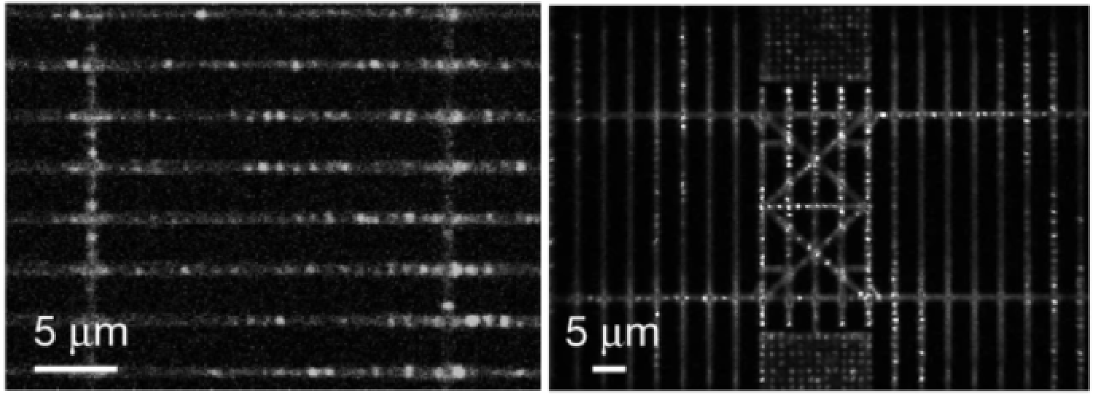
FIB Enabled Quantum Optics

< 50 nm Targeting Resolution



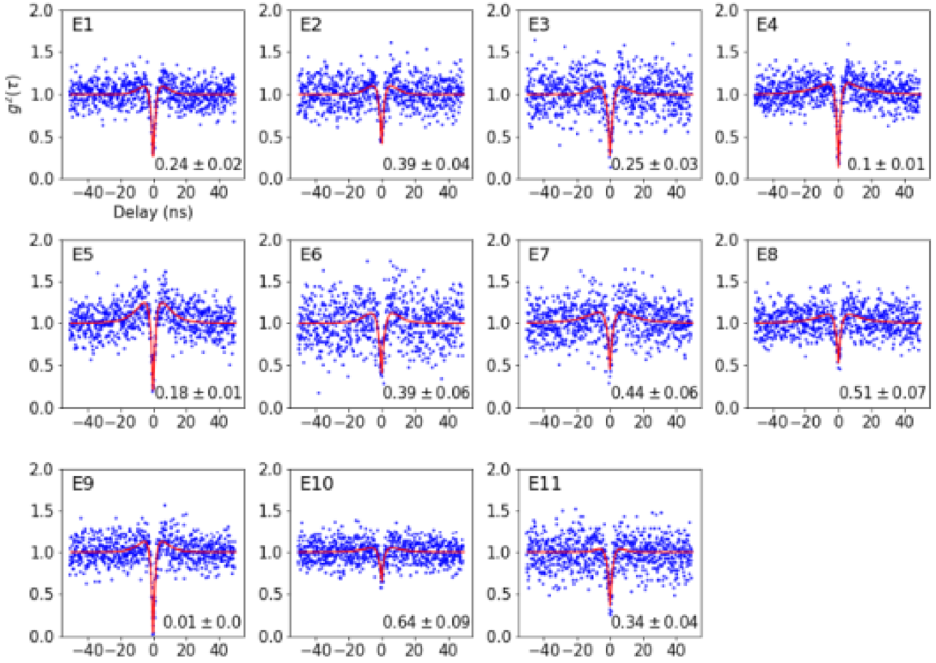
T. Schroder et al., Nat. Communs., 8, 15376 (2017)

Scalable Implantation



N. Wan et al., Nature, 583, 226 (2020)

Forming Single Photon Emitters

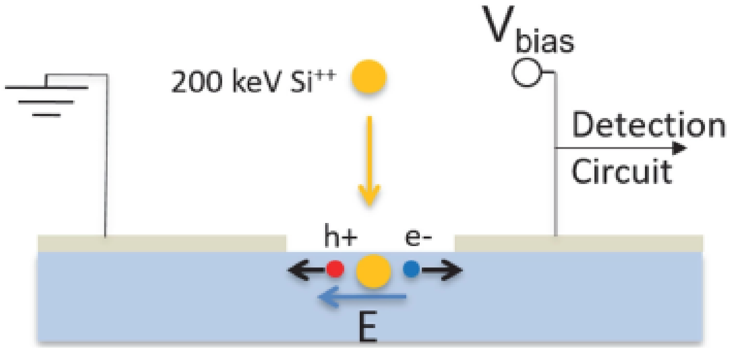


M. Titze et al., Nano Lett. (2022)

Example of Medium Energy Implantation – Single Ion Counting

100 kV nanoImplanter

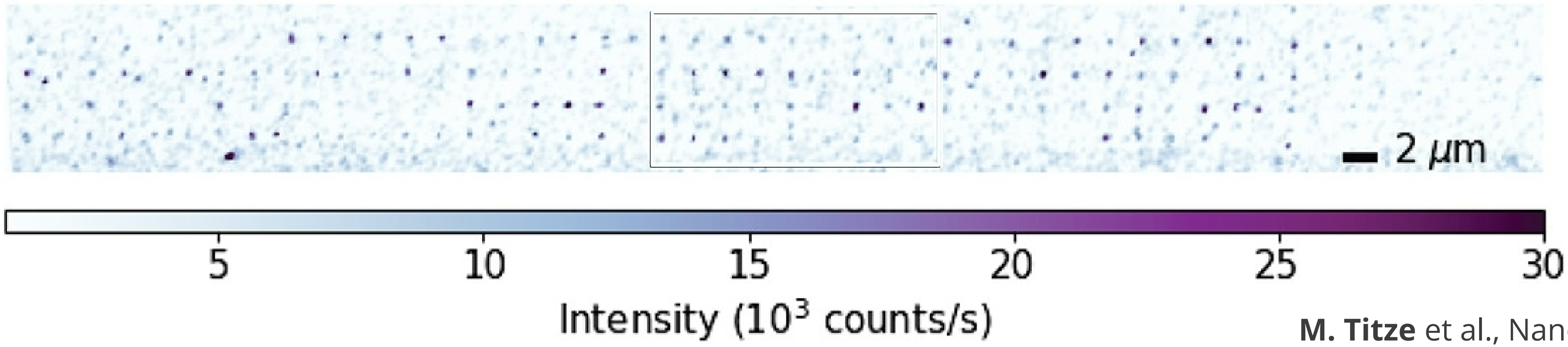
- 200 keV Si^{++}
- 100 kV A&D nanoImplanter



Side View

Deterministic placement of single ions
- +4/-1 % error bar on ion #
- < 40 nm targeting resolution

Pathway to creating scalable single photon emitters



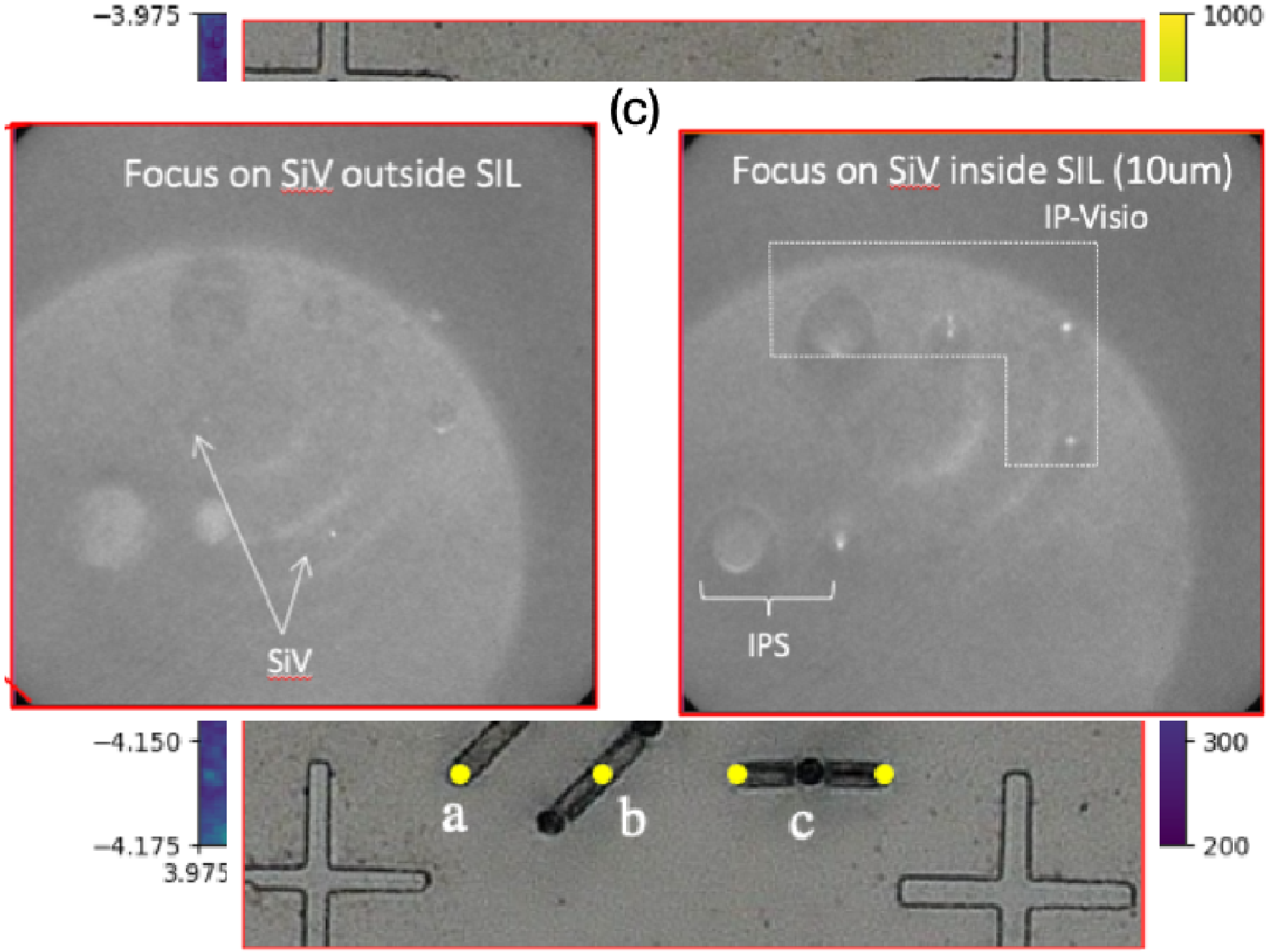
M. Titze et al., Nano Lett. (2022)

Color Center Implantation for Coupling to Solid Immersion Lens

A. Mounce @ SNL

35 kV Raith VELION

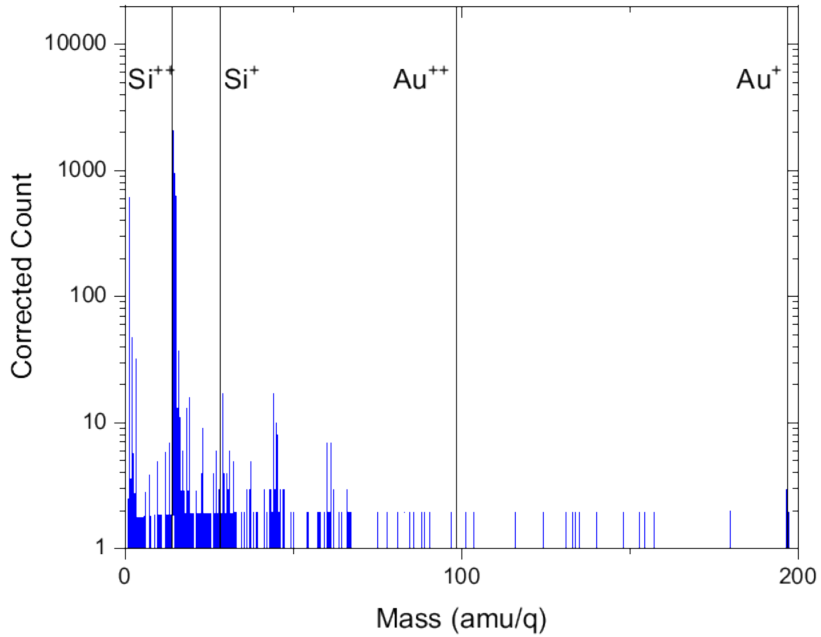
1. Start out with *patterned* electronic grade diamond
2. Implantation of Si, anneal to form SiV
3. Confirm SiV creation by PL
4. Fabricate photonic structures over implant region
5. Remeasure PL

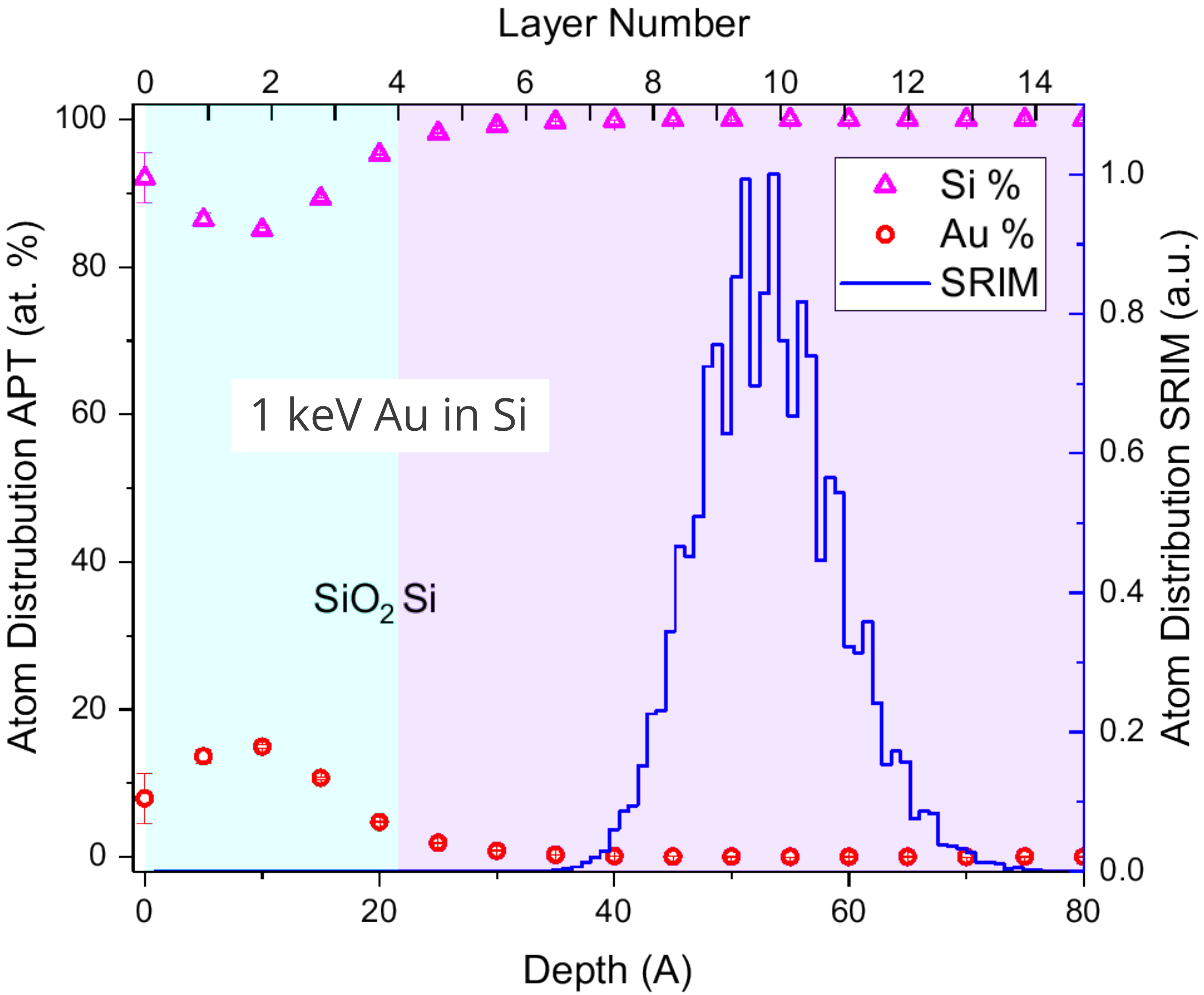


Atom-Probe Tomography on Ultra-Low Energy Implanted Sample

35 kV Raith VELION

- SRIM overestimates range by **6X**
- Indicates that 100s of eV will be sufficient to target single atomic layers
  - Can do (at cost of spot size) with ~15 eV energy spread



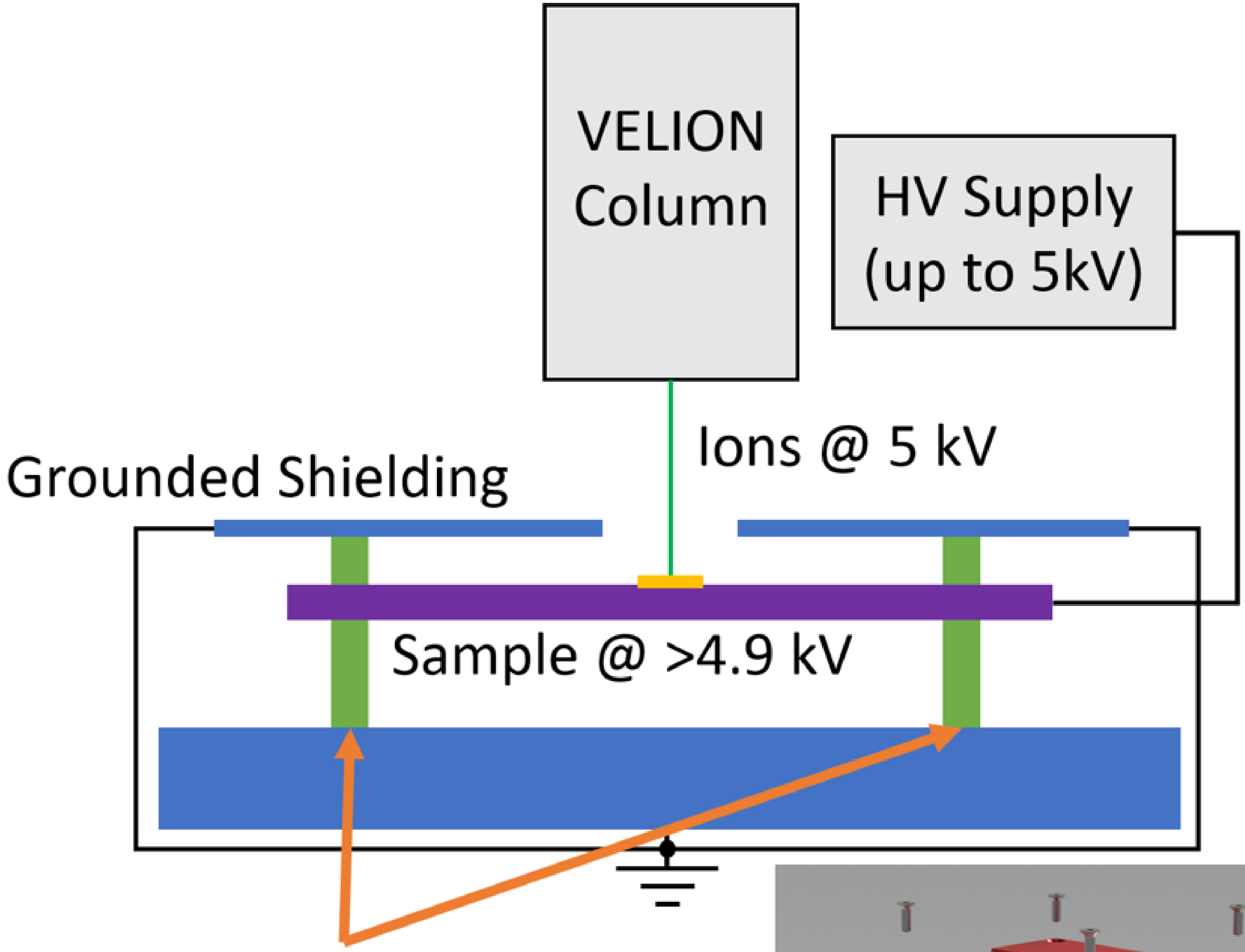


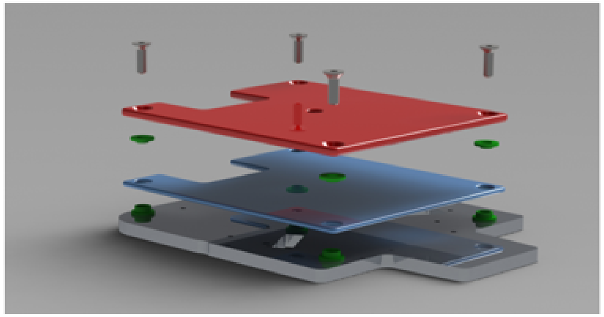
Expanding the Energy Range to eV

- 1 keV Au stops within 4 atomic layers of SiO_2
- To target atomic layers of 2D materials
  - Stopping in a single layer
  - Lower mass ions interesting for their optical properties

→ Need even lower energy

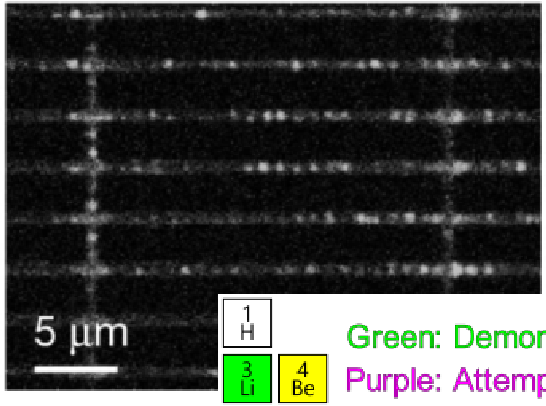
- Biased sample holder to decelerate ions

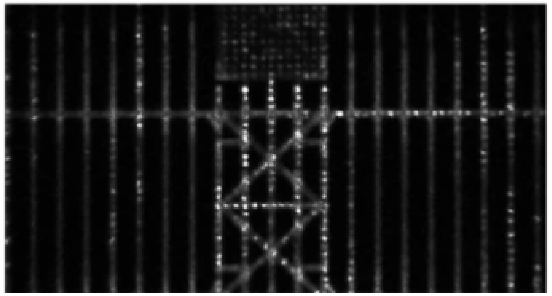


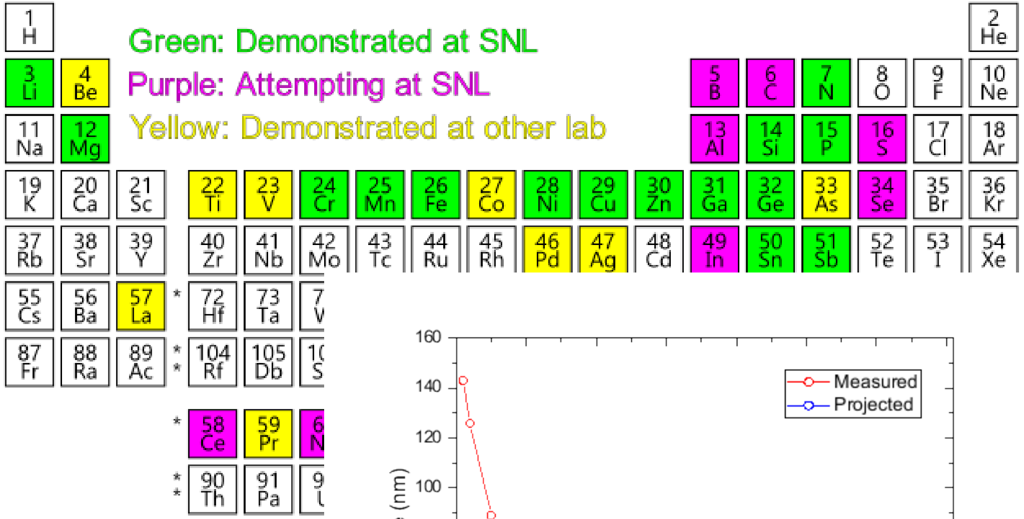


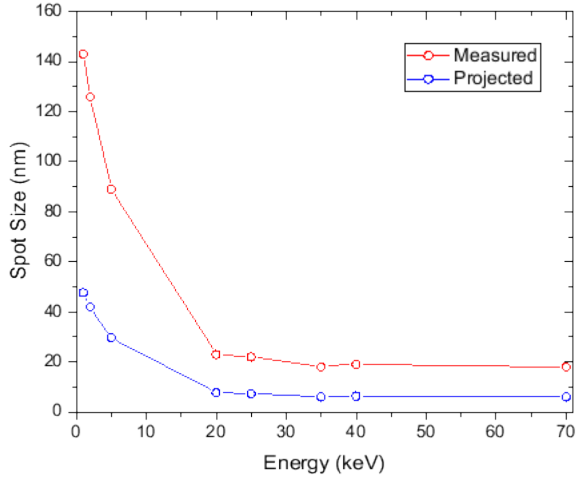
Conclusion

- Focused ion beam implantation is an enabling capability for scalable quantum optics experiments
- Tailoring the ion to the application is enabled through use of LMAIS in ExB FIB
- Wide energy range is available allowing targeting of specific device layers



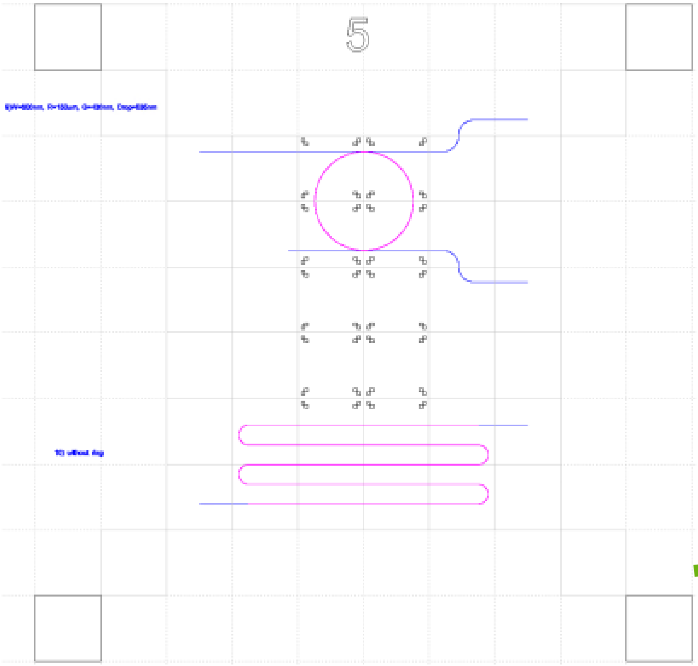




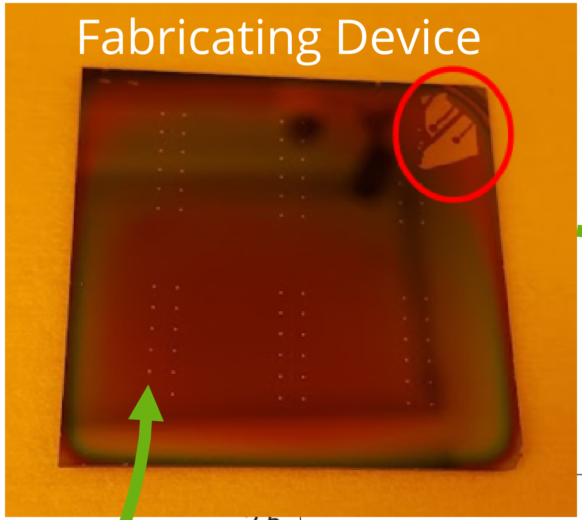


Interaction with CINT Users – Design to Manuscript

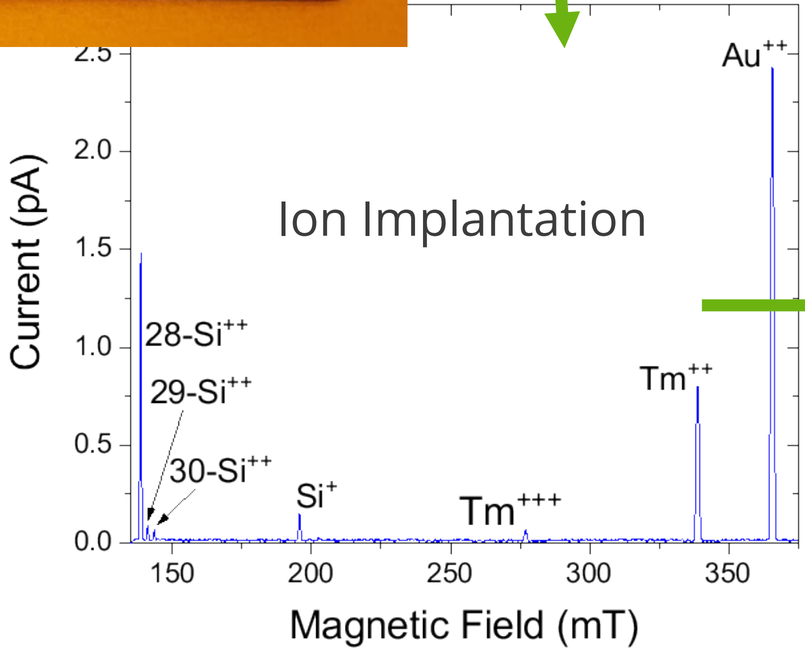
M. Hosseini @ Purdue



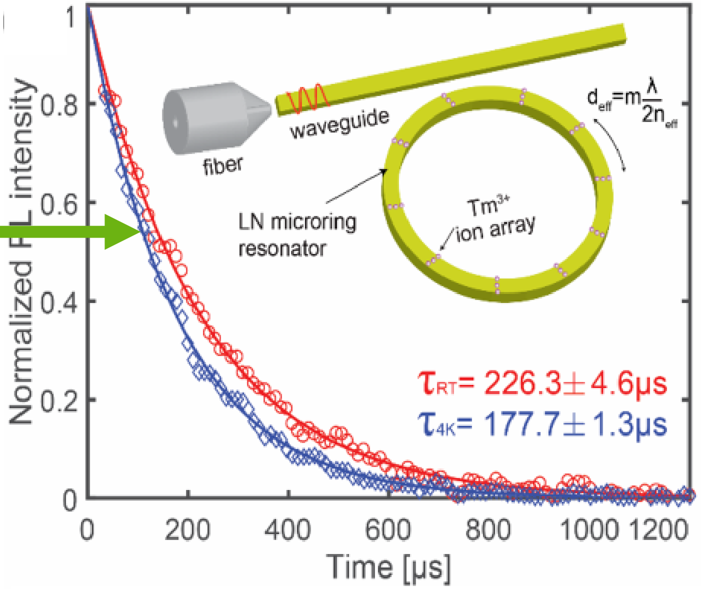
Discussion of design feasibility



Tm for $LiNbO_3$ Photonics



Post-Processing
+ Measurement



Dongmin Pak, …, M. Titze et al. (in review)

How can YOU access these capabilities? CINT User Proposal

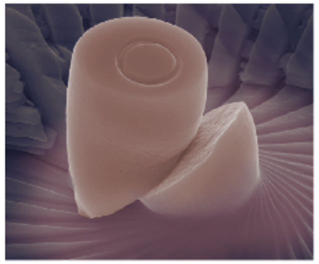
THE CENTER FOR INTEGRATED NANOTECHNOLOGIES

One Scientific Community Focused on Nanoscience Integration

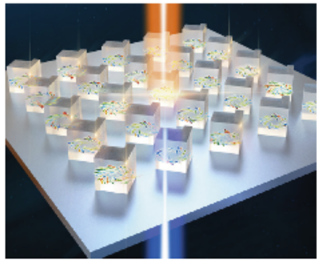
The Center for Integrated Nanotechnologies (CINT) is a Department of Energy Office of Science Nanoscale Science Research Center. CINT offers world-leading scientific expertise and specialized capabilities to create, characterize, and integrate nanostructured materials at a range of length scales, from the nano- to meso-scale. It is jointly operated by Los Alamos and Sandia national laboratories and leverages the unmatched scientific and engineering expertise of the host labs.

Science Thrusts

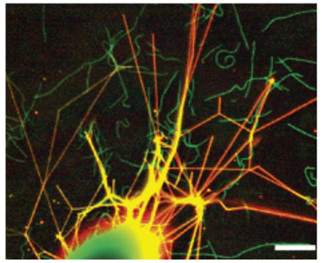
Integration is the key to exploiting the novel properties of nanoscale materials and creating new technologies. CINT's scientific staff and capabilities are organized around four interdisciplinary science thrusts which address different challenges in nanoscience integration.



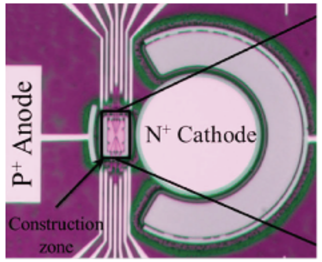
In-Situ Characterization and Nanomechanics
Developing and implementing world-leading capabilities to study the dynamic response of materials and nanosystems to mechanical, electrical, or other stimuli.



Nanophotonics & Optical Nanomaterials
Synthesis, excitation, and energy transformations of optically active nanomaterials and collective or emergent electromagnetic phenomena (plasmonics, metamaterials, photonic lattices).



Soft, Biological & Composite Nanomaterials
Synthesis, assembly, and characterization of soft, biomolecular, and composite nanomaterials that display emergent functionality.



Quantum Materials Systems
Understanding and controlling quantum effects of nanoscale materials and their integration into systems spanning multiple length scales.

User Program

CINT is an Office of Science national user facility. CINT helps the international research community perform cutting-edge research in the areas of nanoscience and nanotechnology, and is available free of charge for open science. As a user facility, CINT has the structure and mission to collaborate widely across academia, industry, and within DOE labs. Access is via peer-reviewed technical proposals. Proprietary research may be conducted in accordance with Federal regulations for full-cost recovery. CINT cannot provide funding to users.

The Center for Integrated Nanotechnologies (CINT)

https://cint.lanl.gov/