The Cesium Low Temperature Ion Source (LoTIS)

A new ion source for high performance FIB & SIMS

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Tech Status:

Low Temperature Ion Source (LoTIS)

LoTIS is a new Cs^+ ion source

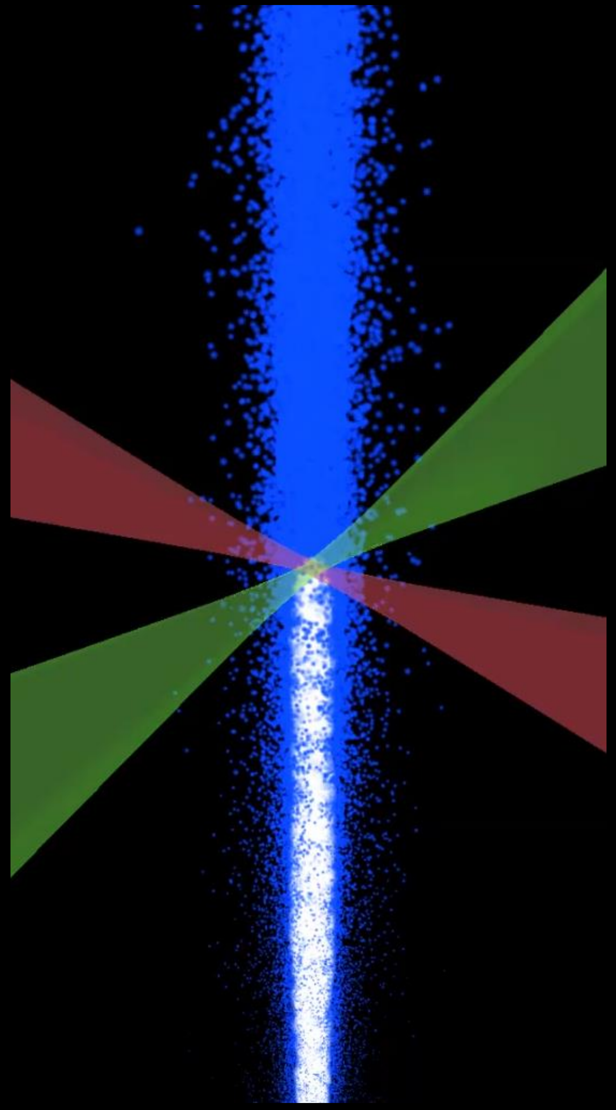
A LoTIS FIB instrument has been built and tested

- Successful circuit edits on 10 nm node chips (see talk 5A-6 coming up!)
- Imaging and milling demonstrations

LoTIS Beam Performance

- Demonstrated 2 nm spots with 1 pA, at 10 kV beam
- Provides currents >5 nA (so far)
- Performs well at low-energy
- Yields large numbers of secondary ions

Available in FIB:RETRO and SIMS:ZERO variants



Cs^+ LoTIS Pros/Cons

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Strengths

- Small Spot Sizes
- Low-Energy Performance
- High Sputter Yields
- Reduced Straggle
- High Secondary-**Ion** Yields (Cs)
- Versatile range of currents (pA-nA)

Weaknesses

- Cost*
- Cs is 'new'
- Unknown-Unknowns

Ideal Applications

- General FIB Milling
- Nanomachining (inc. Circuit – edit)
- SIMS Elemental Analysis

*Relative to Ga, Plasma, or Cs Frit *source*
But
Reasonable compared with platform overall

LoTIS Elements

1) Prepare Cold, Dense Neutral Cs Beam

2) Photoionize

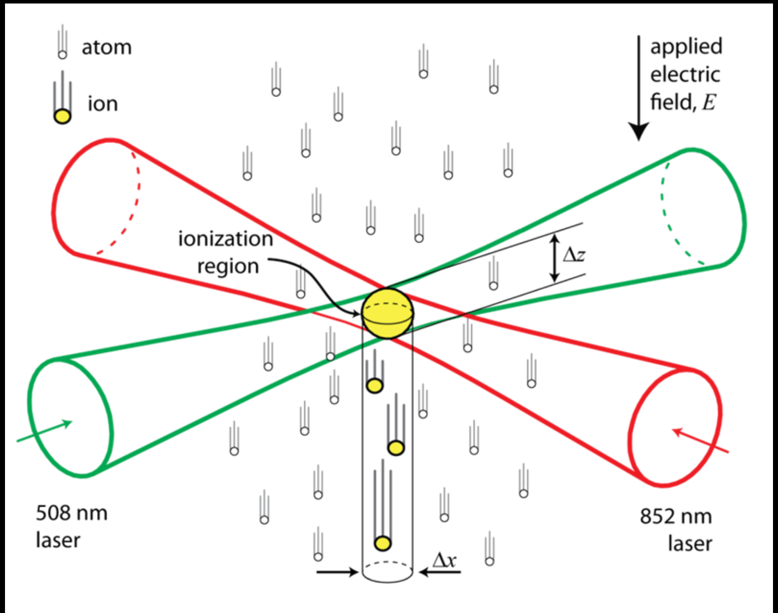
- Position two ionization lasers in flow of Cs beam
- Excite atoms in laser intersection volume

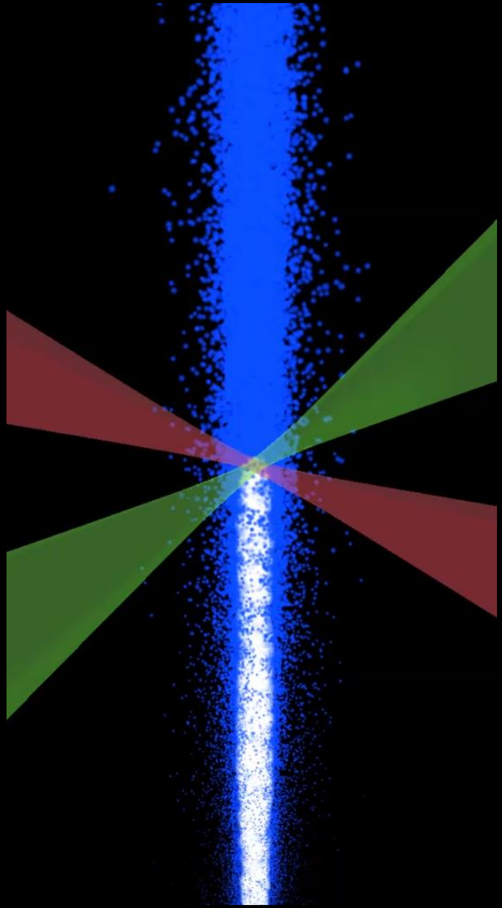
3) Accelerate and Focus Beam

- Fed into standard ion-optical column
- Uses all the same technology as normal FIB

Result:

- High Brightness
- Low Energy Spread
- Moderate Currents: (<1 pA to 10+ nA)





High Brightness: Paths to Achieve

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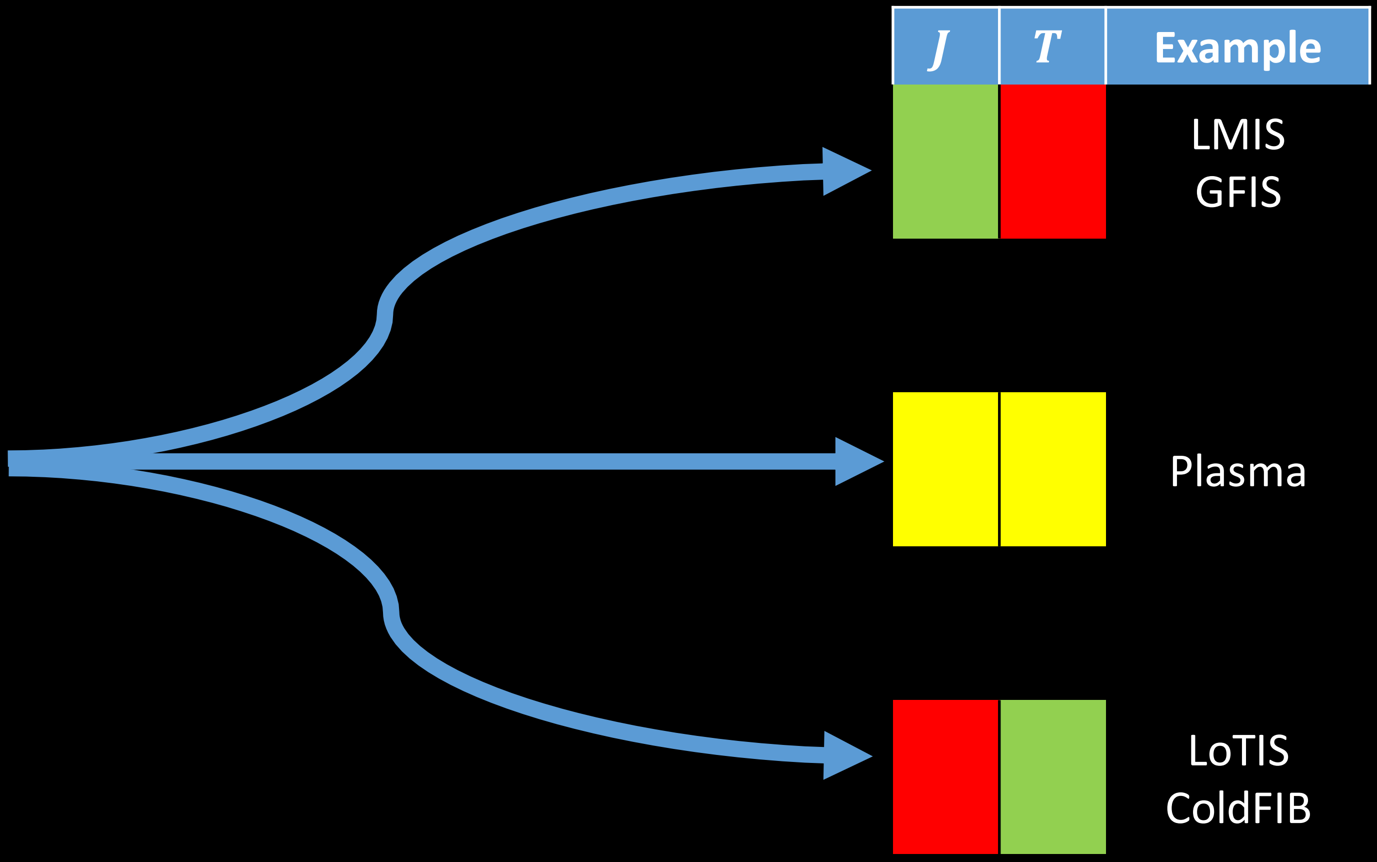
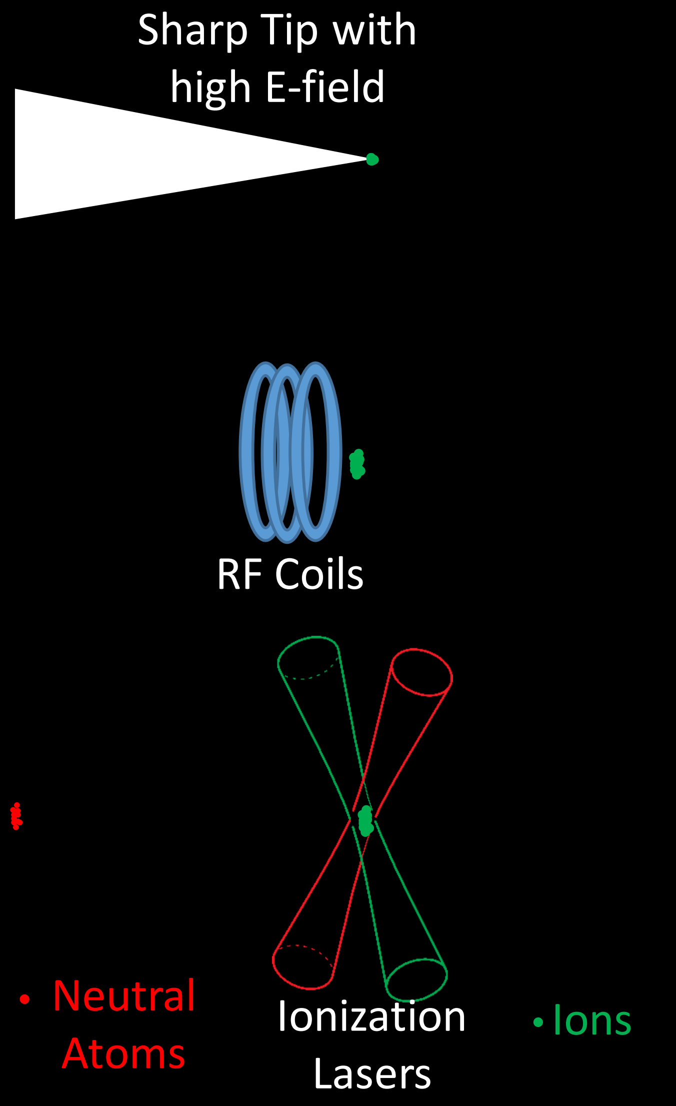
$$B = \frac{J}{\pi k_B T}$$



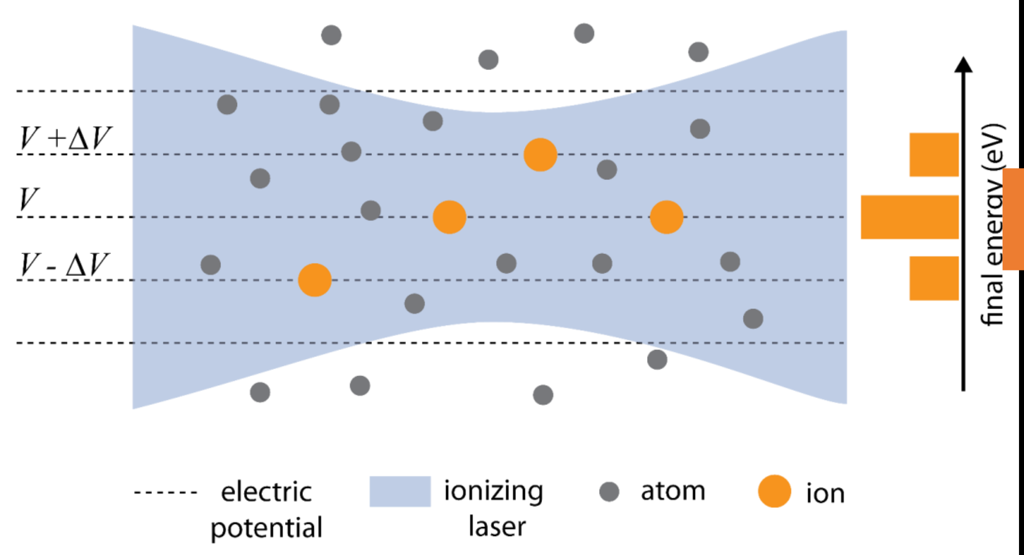


LoTIS:

$$B_{peak} = 2.4 \times 10^7 Am^{-2} sr^{-1} eV^{-1}$$

- ≈24x higher than Ga^+
- B is lower at higher currents (Coulomb)

Energy Spread



$$d_C = \alpha \frac{\Delta U_i}{U} C_C$$

(Chromatic aberration limited spot size)

Ions created at different potentials

$$\Delta U = \mathrm{e}\Delta V = eE\Delta z$$

Energy spread (ΔU) determined by:

- Spatial extent along electric field (Δz)
  - Few micron typical
- Magnitude of electric field (E)
  - Selected based on beam current

ΔU contributes to chromatic limited spot : d_C

LoTIS $\Delta U < 0.5$ eV (at pA currents)

(~10x smaller than Ga^+)

In-House FIB:RETRO

Modified FEI/Micrion ‘Vectra’ platform

- 2-3x better spot sizes and at 3x lower beam energy than LMIS
- <1 pA to few nA

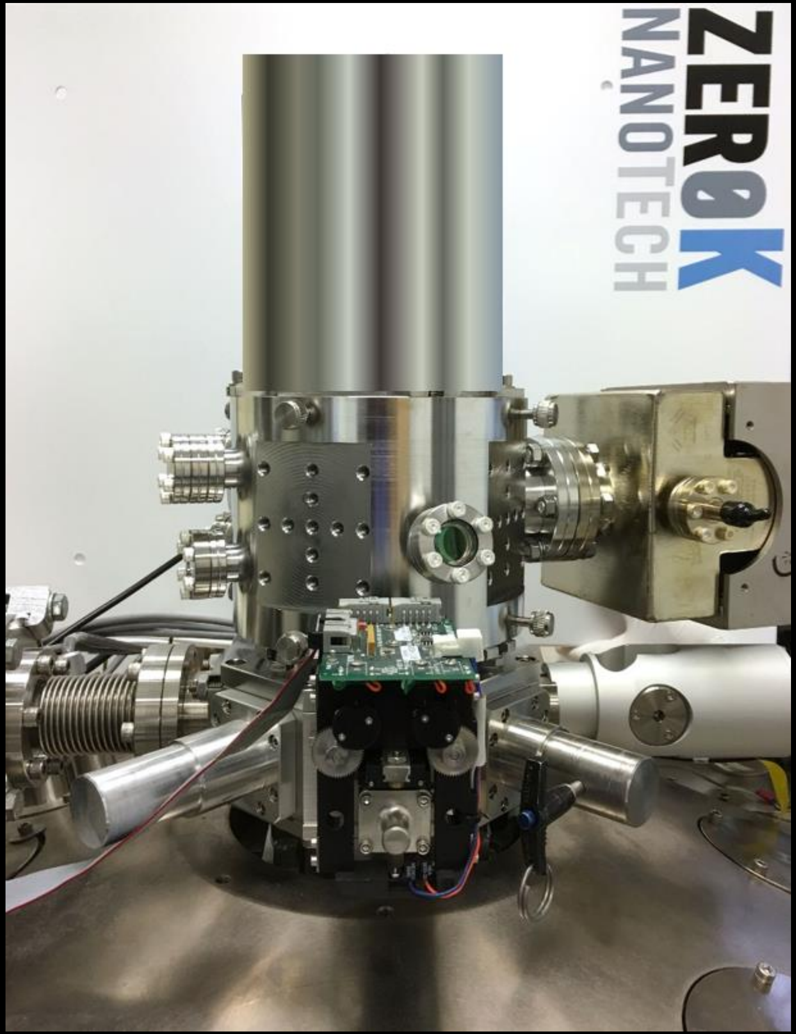
Performed 10nm circuit edits with Intel

Provides process gases: Bromine, Tungsten, TMCTS, Oxygen

Demonstrated small spot sizes for selected beam current (# on upcoming slide)

Great SNR at low beam currents (Annular MCP detector)

Capable of generating secondary ion images as well (no mass-resolving capability yet)



LoTIS

FIB:RETRO Spot Sizes

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Results below obtained are on Vectra FIB

- 18 mm working distance (30mm focal length)
- 18.4 max energy in current system
- No apertures used (these may enhance performance further but this parameter space has not yet been investigated)
- Note: Results given as a σ below. $R_{35-65} = \frac{\sigma}{1.3}, R_{16-84} = \sigma * 2$

Results not claimed to be optimal

- Comprehensive survey of lens voltages incomplete

10 kV

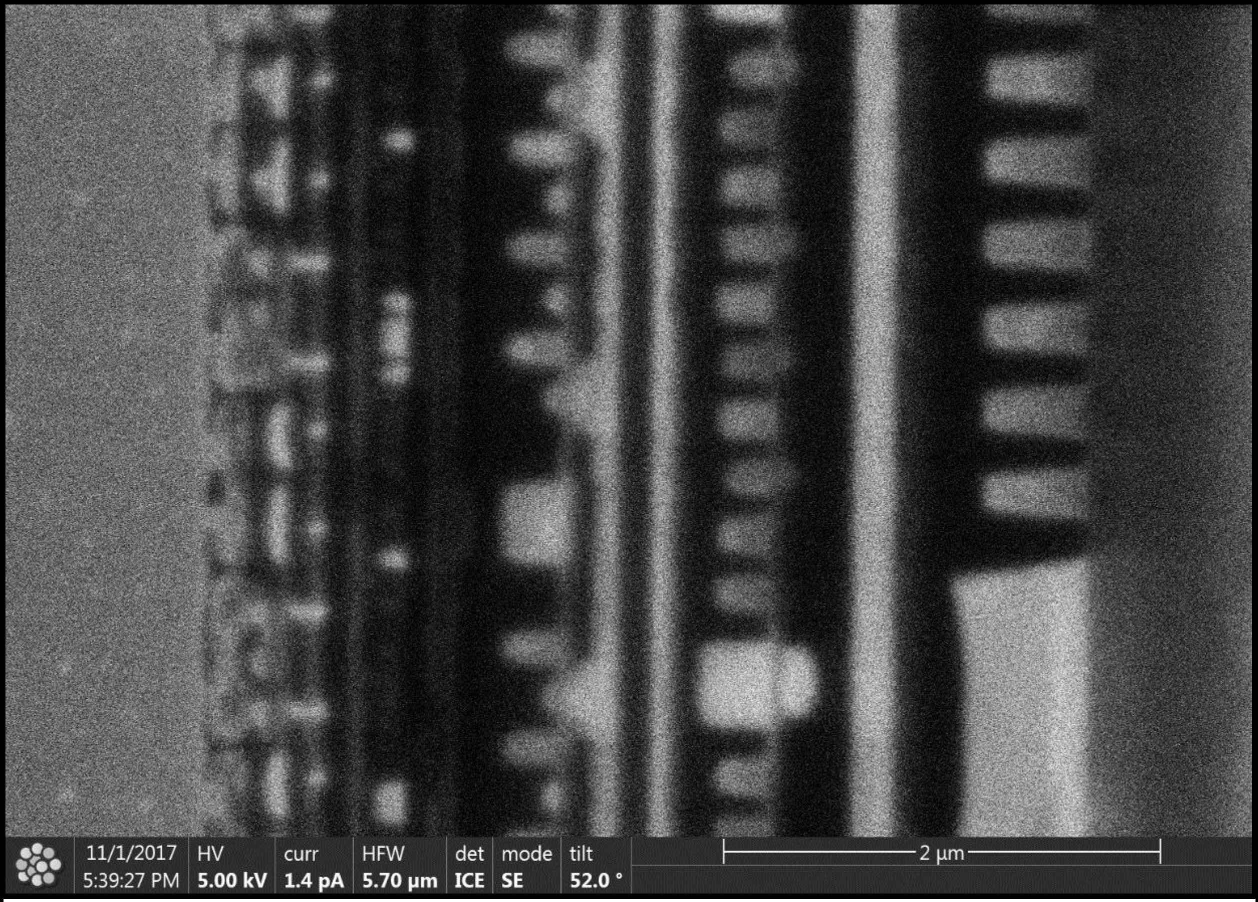
I (pA)	sigma (nm)
3	2
10	4
30	15
100	45
1000	200
4000	250*

18.4 kV

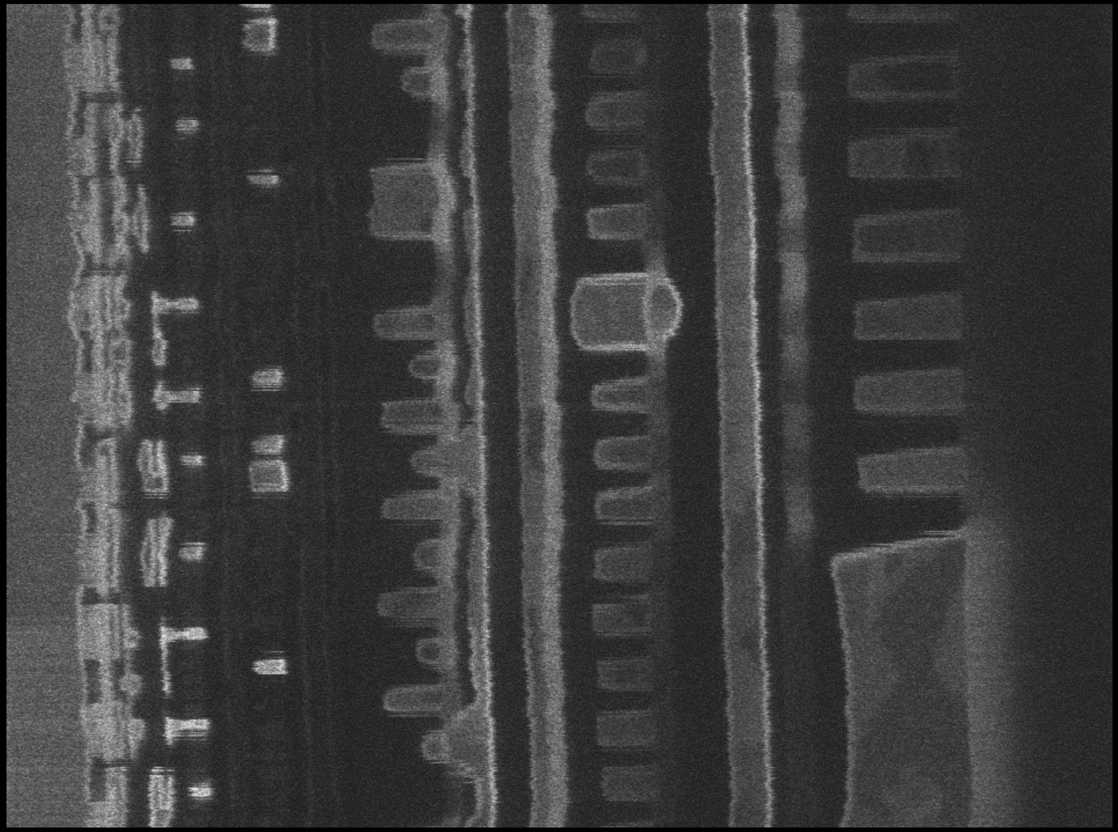
I (pA)	sigma (nm)
1.3	<2
10	3.3
100	23
1000	153

*preliminary, needs further testing

5kV FIB imaging: LoTIS vs LMIS



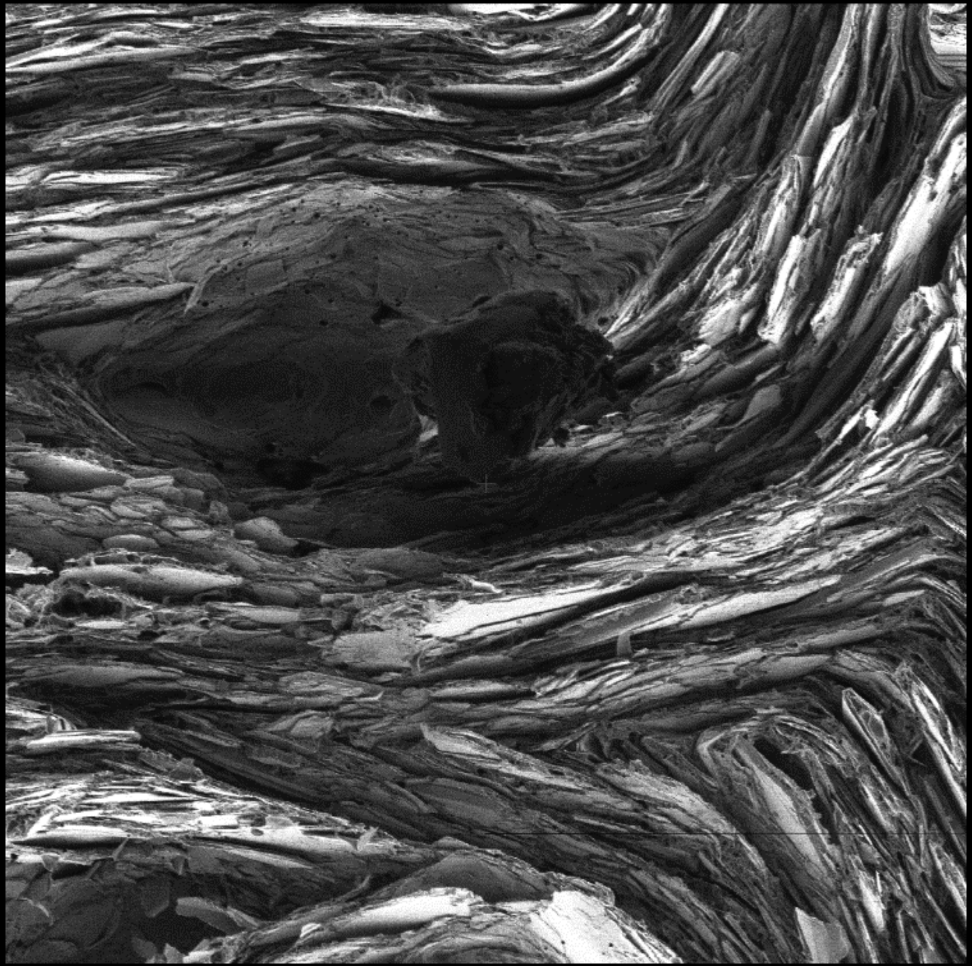
Ga⁺ LMIS: 1 pA 5 kV



Cs⁺ LoTIS: 1 pA 5 kV

Easily seen channeling contrast in LoTIS image.
Improved resolution at low energy (LoTIS: ~3-4 nm)

Secondary Electron, Ion Images

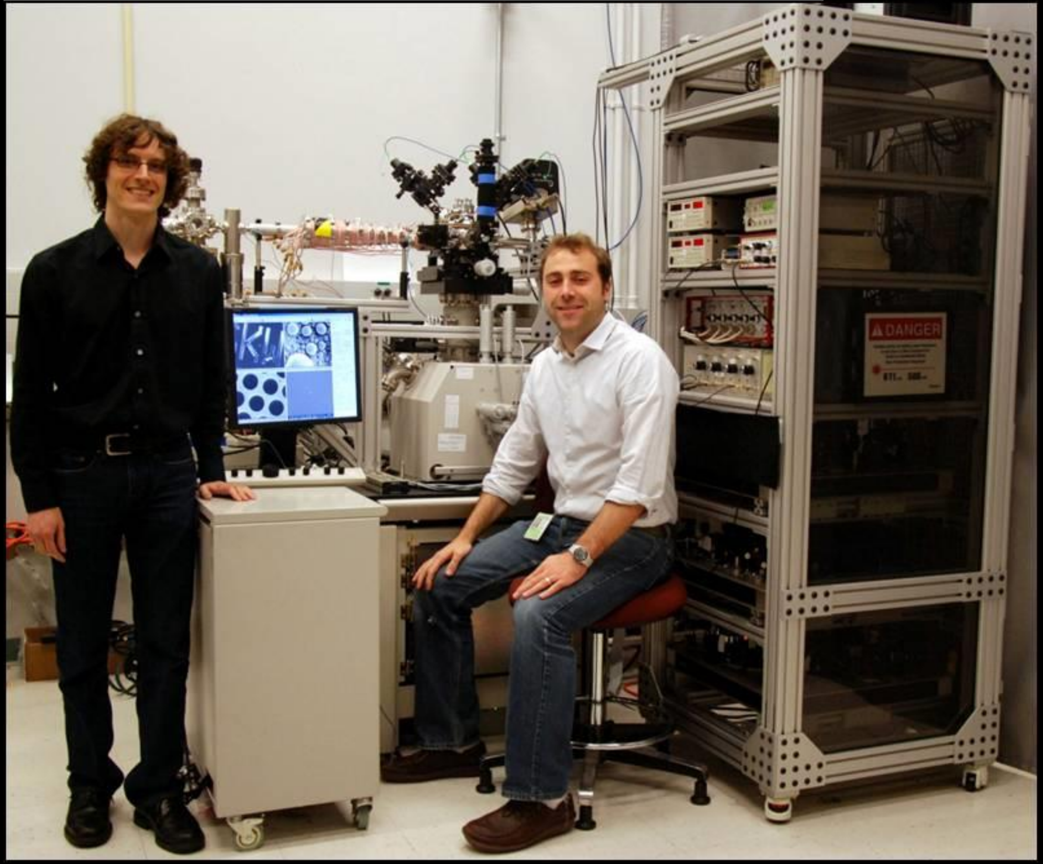


Pencil lead, 20 um FOV. Comparison of secondary electron (left) and secondary ion modalities (right).

Graphite has a low sputter rate, while the dust particle has a high sputter rate and/or high yield of positive ions.

Auxiliary Application- Lithium FIB

Generation 0 Prototype – built at NIST 2010



- Built by zeroK founders
- In service >8 years
- Retrofit FEI FIB-200
- World-unique Li^+ FIB
- Battery Research
- ~30 nm spots
- Up to ~ 1 nA beams

FIB:RETRO

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Features

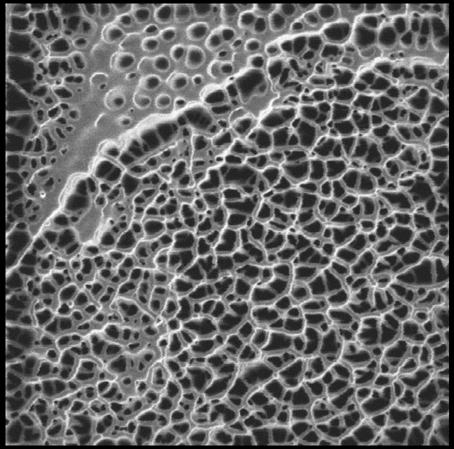
- Cs+ beam with 2 nm resolution
- Superior performance at low beam energy
- 10+ nA beam current
- Compatible with most ion beam columns & accessories

Benefits

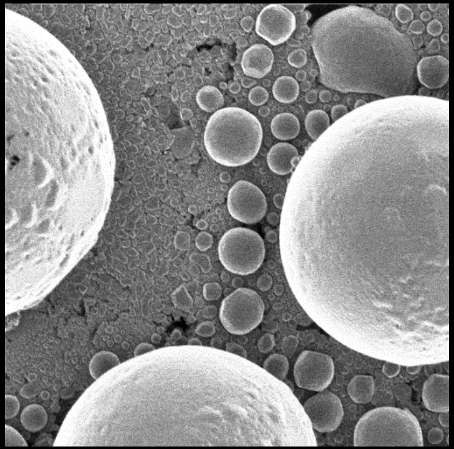
- Machine with higher precision than with Ga+
- Explore new applications with unprecedented performance
- Utilize currents up to several nA to handle a variety of tasks
- Extract additional value from existing capital equipment

Best Applications

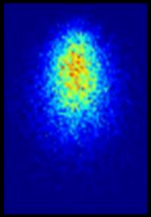
- Nanomachining
- Circuit-Edit
- Low-invasiveness milling



Fixed Cell Etch, 5 µm

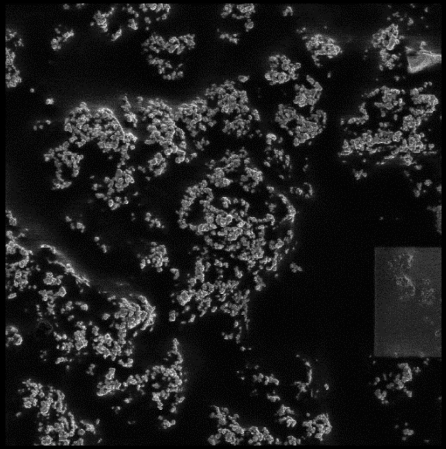


Tin Spheres 10 µm FOV



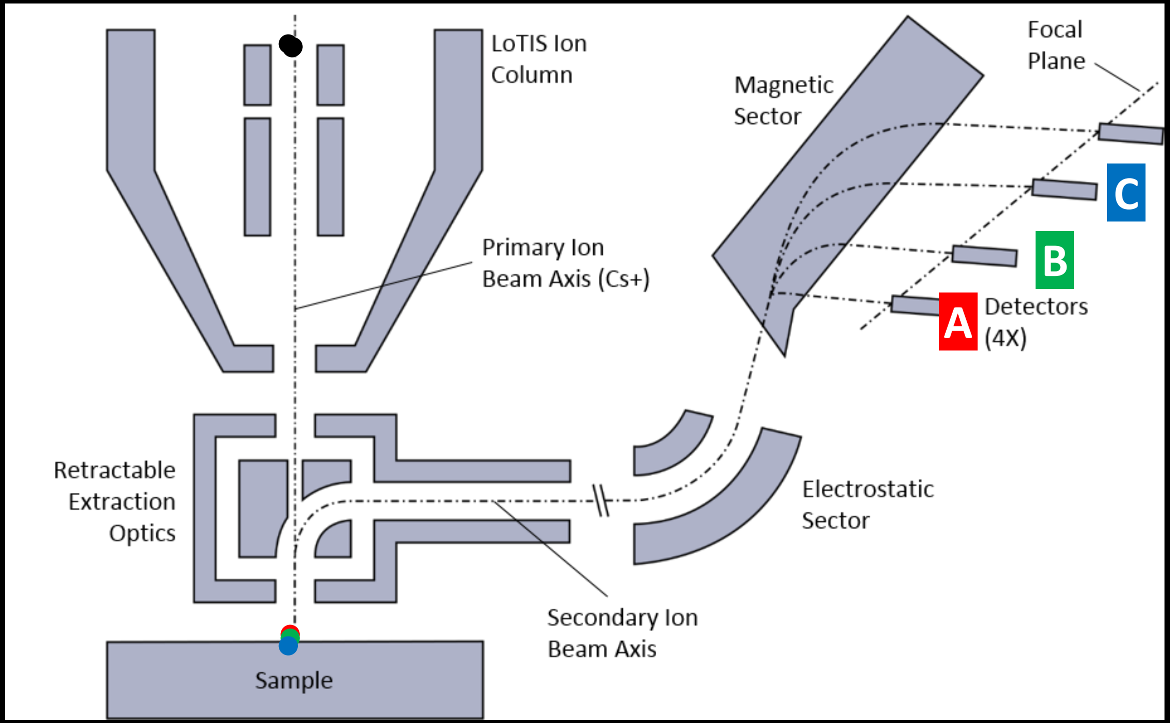
	Interaction		Focus
	Depth (nm)	Straggle (nm)	Spot Size (nm)
Ga+ (30 kV)	28	10	5
Cs+ (10 kV)	12	3.5	< 2

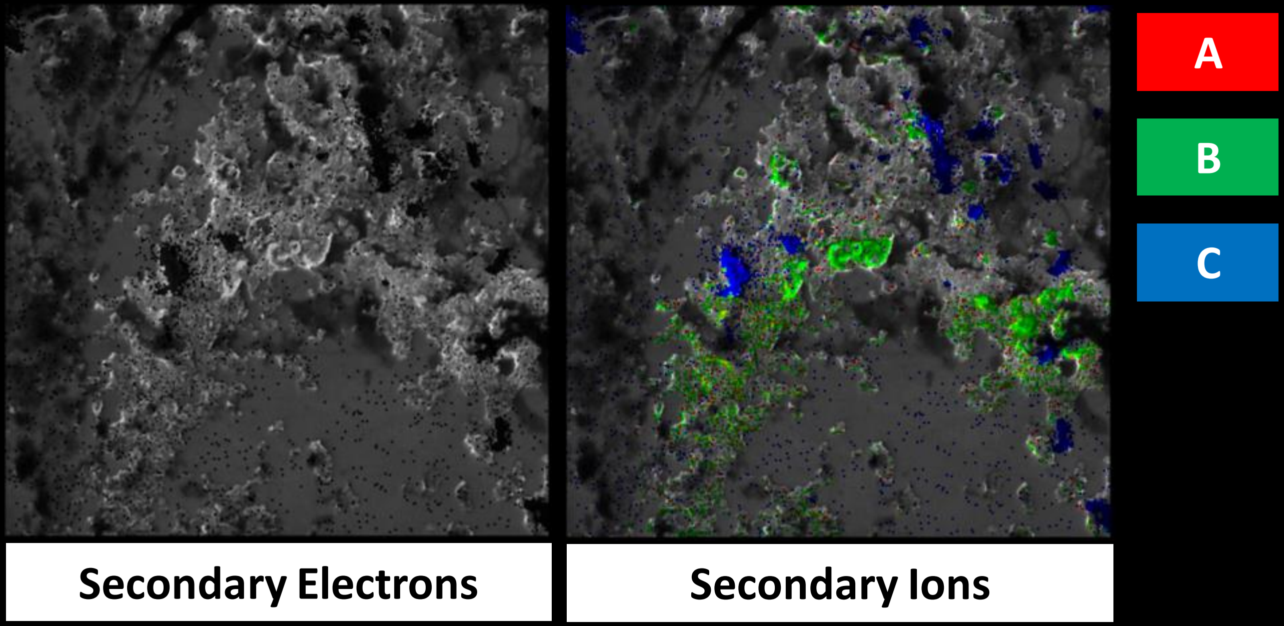
Graphite, 10 µm



Electrodag, 10 µm FOV

Secondary Ion Mass Spectrometry (SIMS)





Primary beam sputters some fraction of target material as *an ions*

Mass-spec of these ion reveals information reveals the sample's rich structure

Excellent resolutions possible in principle

In SIMS, resolution is closely coupled to ionization efficiency

- There are only so many particles in a few-nm voxel
- Example: Si is ~50 at/nm^3

Pain Points of Elemental Analysis Techniques

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EDX/EELS

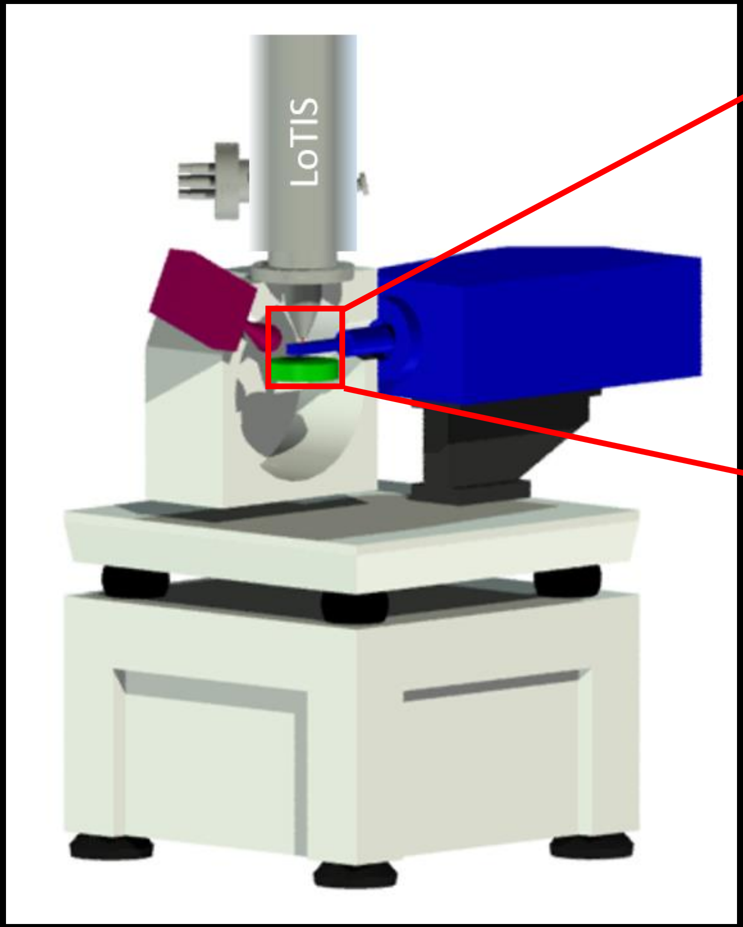
- Very Long Sample Prep Times
  - (Bulk (3D) analysis infeasible)
- Low-Z elements Challenging

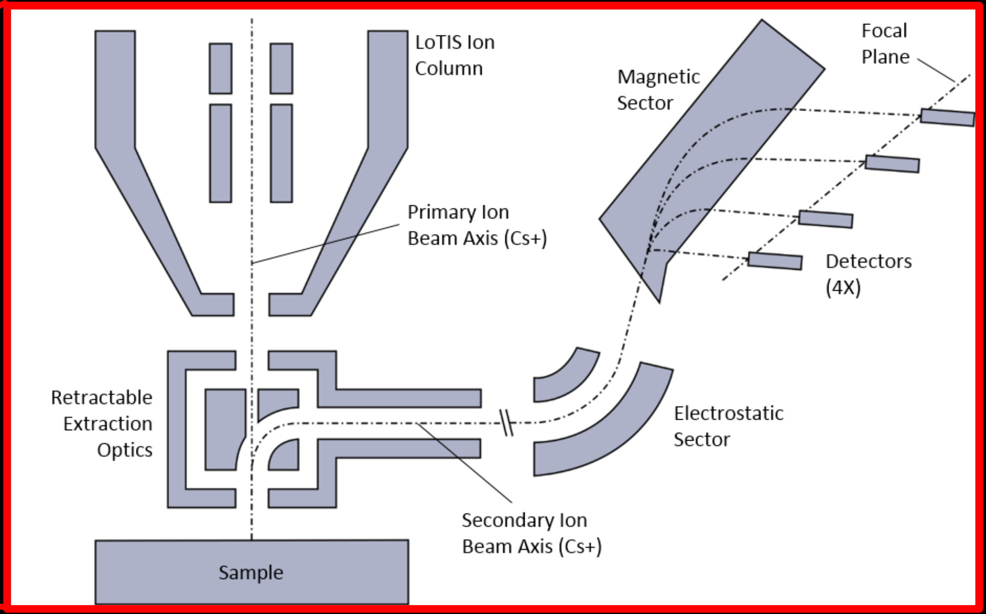
Site-Spec. SIMS

- Resolution >20 nm
  - (Even in high abundance samples)
- Can’t view all elements at once
  - (Loss of information)

These points are addressable
(with new instrumentation)

SIMS:ZERO Concept





Single-Beam FIB with high-efficiency collection of secondary ions

Multiple imaging modalities:

- Electrons, +Ions, -Ions

Performance compared with industry standard Cs focused beam SIMS

- 100x more current/area
- 10x better resolution (down to ~5 nm in non-abundance limited cases)

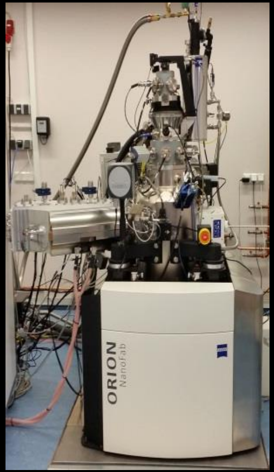
v2 will have ‘continuous‘ detector technology

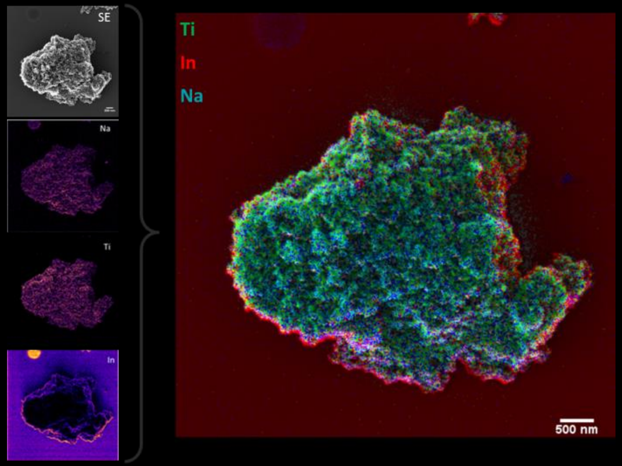
Luxembourg Institute of Science and Technology:

- RTO (Research & Technology Organization) created in 2015 out of the merger of two public research institutes in Luxembourg
- 630 employees, 75% researchers

Advanced Instrumentation for Ion Nano-Analytics (AINA) :

- Development of scientific instruments based on charged particle beams for nano-imaging and nano-analysis in materials science and life science
- Covering a large range on the TRL scale, up to TRLs 7-8
- 20 researchers and engineers specialised in charged particle optics, instrument design and nano-analytics
- 20+ years of experience in SIMS development and applications
- Successful collaborations and product launches with main instrument manufacturers (including Zeiss, FEI and Cameca)





Application Example:
SIMS:ZERO as EDX Alternative

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EDX elemental analysis is capable of few-nm resolution and can image the majority of elements well, but sensitivity is limited to a few 10's of a percent and sample prep is time consuming

Historically, SIMS has offered excellent (ppm) sensitivity but limited lateral resolution

Now, SIMS:ZERO enables creation of elemental maps with both few-nm resolution and excellent sensitivity without lamella preparation

These capabilities also make possible the creation of 3D elemental maps

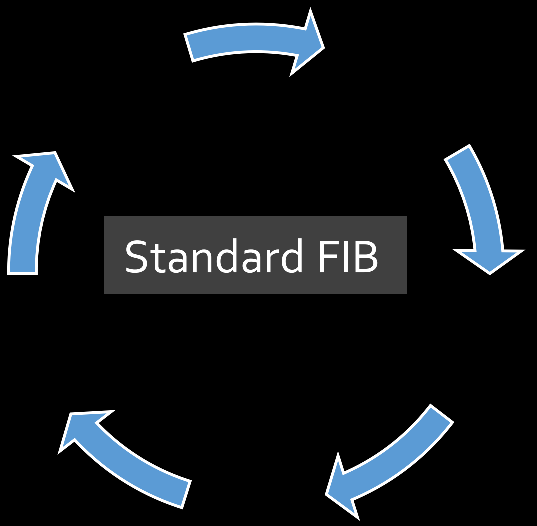
Existing Workflow - Thin Sample EDX

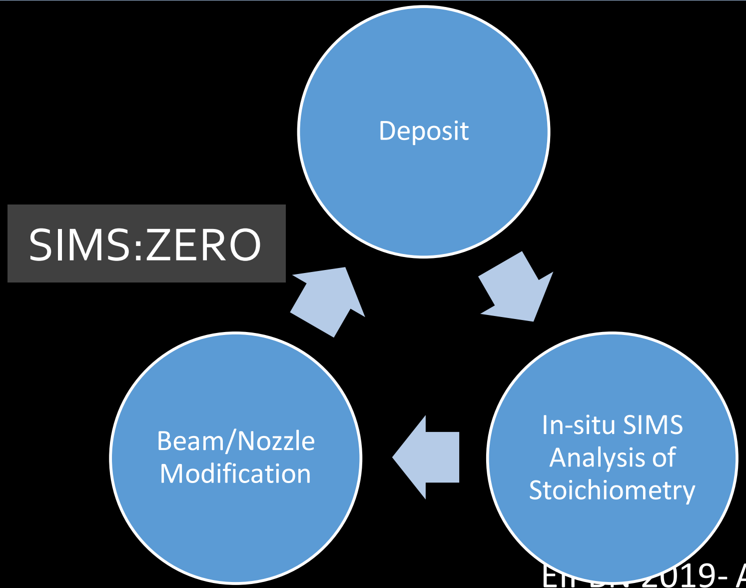
Only one shot : analysis limited to a single depth

Optimized Workflow - SIMS:ZERO

SIMS:ZERO Application Example:
In-situ FIB Deposition Stoichiometry

- Gas-assisted deposition of conductors and insulators is used in a variety of applications
- The deposition quality (e.g.: resistivity/conductivity) can be optimized through small adjustments to the ion beam and gas flow parameters
- Optimization of recipes is a time-consuming process because it requires EDX analysis and four-point probe measurements
- Yield could be improved by monitoring stoichiometry **at the time of deposition** to ensure consistency
- SIMS:ZERO enables a tight feedback loop for rapid optimization of recipes and stoichiometric monitoring during deposition





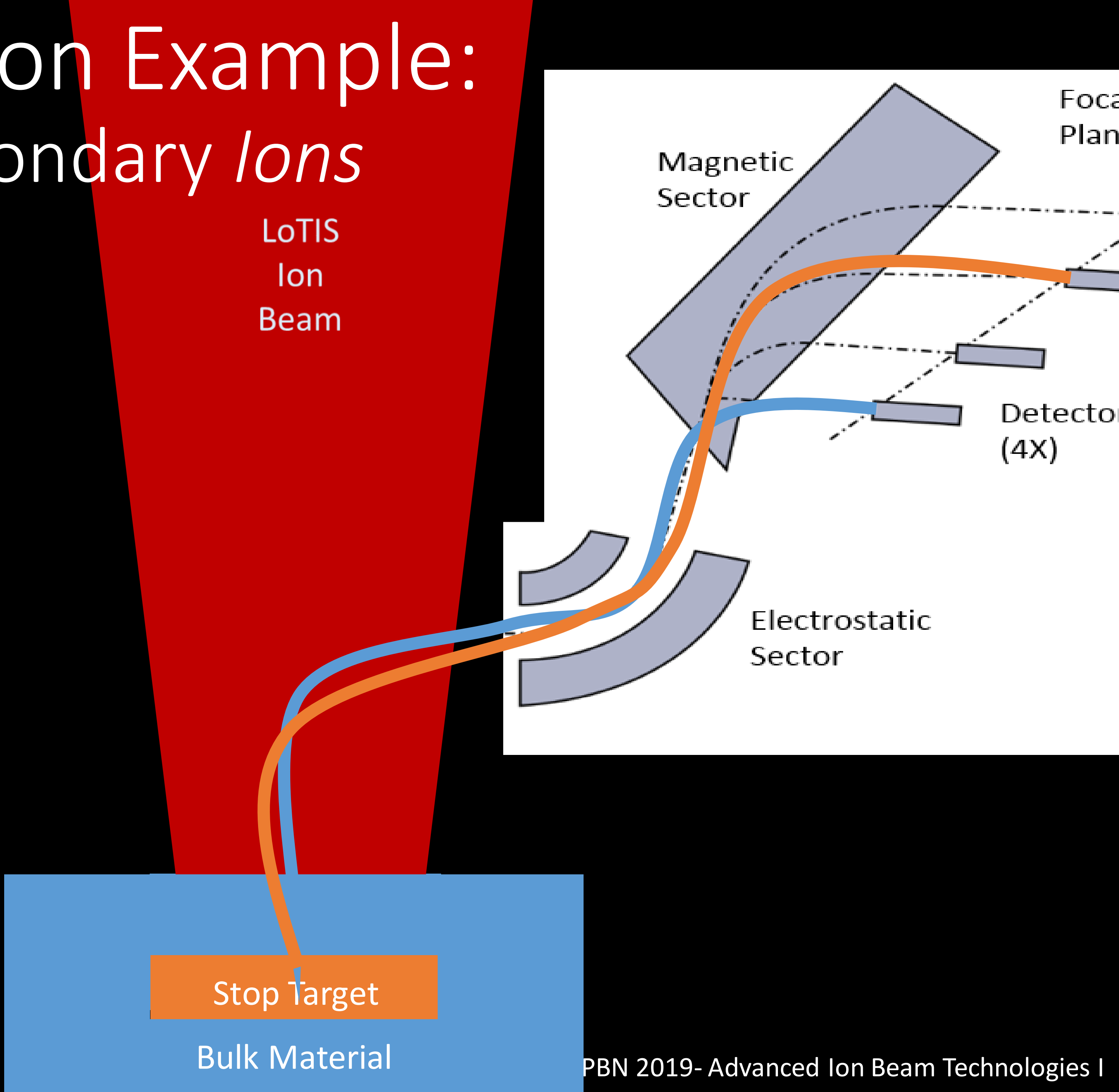
SIMS:ZERO Application Example:
Process Control with Secondary *Ions*

Endpointing: ceasing milling precisely when the desired target material has been removed.

Today, mill-stops often achieved by monitoring a secondary electron signal and stopping milling on threshold value crossings

SIMS:ZERO method not require a fortuitous correspondence between material and secondary electron yield

Multiple “binary” ion signals to feed into mill stop condition



SIMS:ZERO Impacts

Features

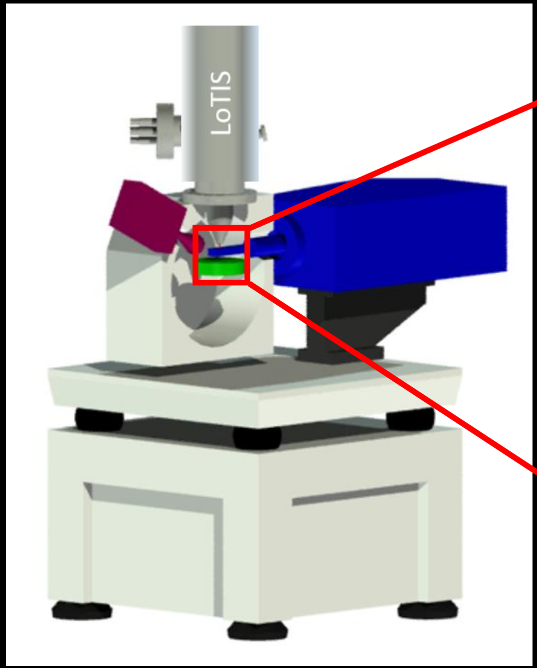
- Cs$^+$ beam with nanometer resolution
- Full-featured FIB system
- Highest-Resolution SIMS
- Parallel readout of all masses

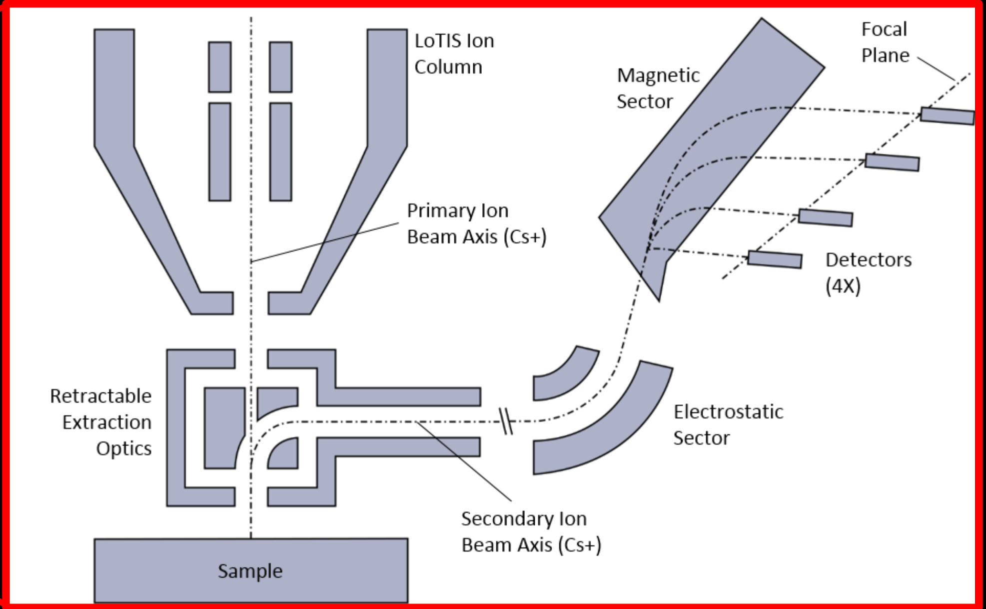
Benefits

- Obtain EDX-like spectra… without lamella Prep!
- Gather SIMS data 100x faster
- Machine with higher precision
- Endpoint using mass spectra
- SIMS process control during nanofabrication

Industry

- Semi
- Semi/Bio/Energy
- Semi/Various
- Semi
- Various





More Information

Cold Atom Ion Sources
1:40PM 5A-1

Cs Ion Coldbeam Suitability for Circuit Edit and Additional Nanomachining Applications
3:30PM 5A-6

Startup Award
Poster P3-12

Meet Adam at the Student Breakfast
Friday 6:45-7:45 AM, Lakeshore B

- Spun out of NIST in Gaithersburg, MD
- Technical Publications
  - https://doi.org/10.1088/2399-1984/aa6a48
  - https://doi.org/10.1063/1.4816248
  - https://doi.org/10.1088/1367-2630/13/10/103035

Summary

Nano
Machining
Analysis

SIMS:ZERO

High Resolution SIMS + FIB

Cs+ ion beam with nanometer resolution	Obtain EDX-like spectra... without lamella prep!
10+ nA beam current	Gather SIMS data 100X faster
Full-featured FIB system	Machine with higher precision
Highest resolution SIMS	Endpoint using mass spectra
Parallel readout of all masses	Nanofabrication process control using SIMS

FIB:RETRO

Low Temperature Ion Source technology available as a retrofit to existing FIB instrumentation

Cs+ ion source retrofit for high performance FIB	Smaller spot size & damage volume than Ga+
Li+ ion source for battery research	Compatible with most FIB columns