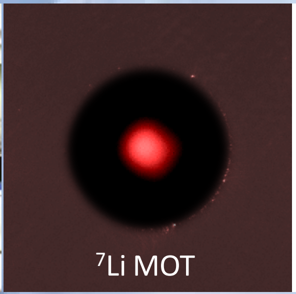

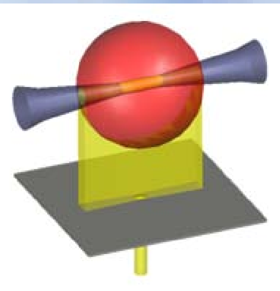

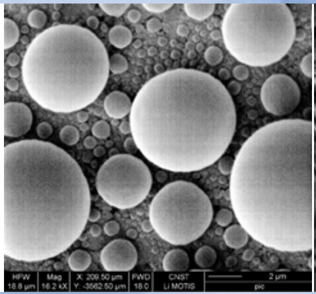

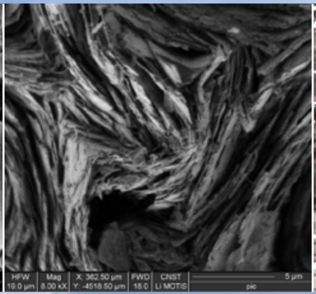

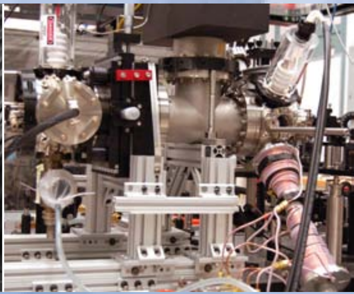

MOTIS: A Magneto-Optical Trap-Based Cold Ion Source

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COLDBEAMS, Nimes, France, October 1, 2012

CNST Center for Nanoscale Science & Technology

MARYLAND NANOCENTER

NIST National Institute of Standards and Technology • U.S. Department of Commerce

How can FIBs be improved?

Focused ion beams: an indispensable tool for:

nanofabrication, milling, imaging, surface analysis, etc

Fundamental FIB characteristics:

Current → More makes everything more efficient – picoamps sufficient for many applications

Spot size → Smaller allows more precision – <10 nm good, <1nm desirable

Ionic species → Wide choice allows new processes – heavy for milling, light for imaging, reactive for beam chemistry, specific for doping

Beam energy → Wide choice allows more control – *high* for efficient milling, *low* for reduced sample damage, milling depth control, backscatter analysis

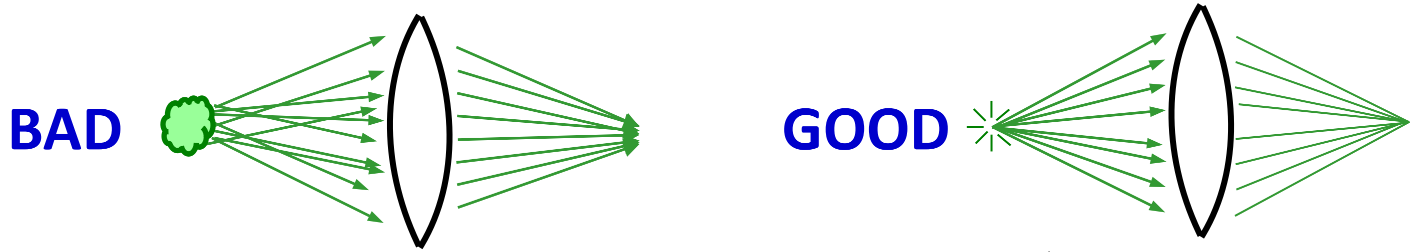
Stability → The longer the better – some milling and imaging can be *slow*

The trick: balance tradeoffs, get as much as possible!

How to keep a small focal spot?

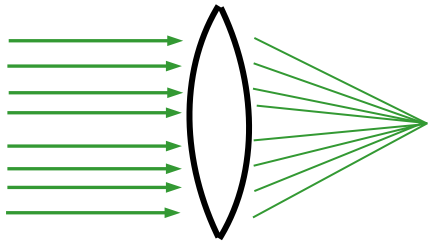
1. Keep aberrations, Coulomb interactions under control
2. Keep source ***emittance*** small

$\varepsilon = (<x>^2 <x'>^2 - <x\,x'>^2)^{1/2}\sqrt{U}$ $\longrightarrow$ Volume in transverse phase space: ***conserved!***



NOTE:

Reducing angular spread also works:

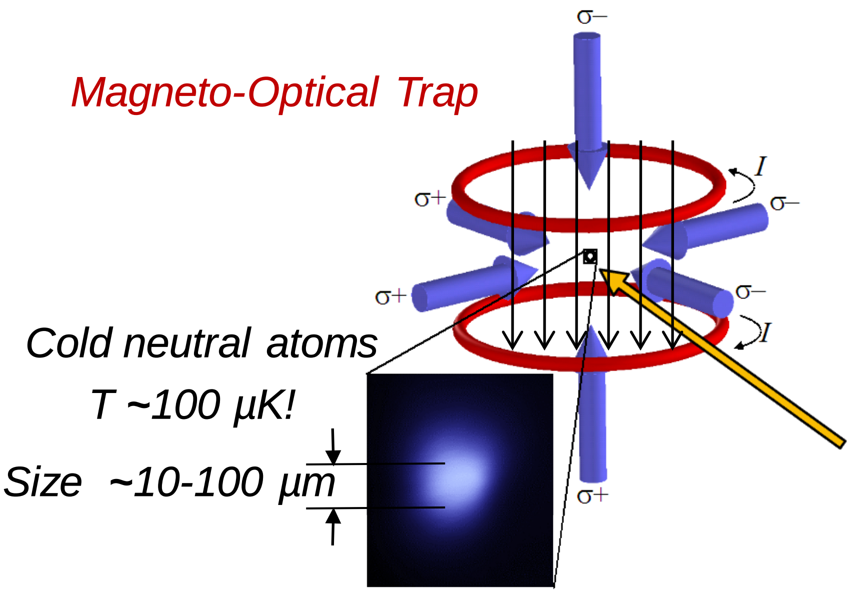


Advantages:

- Completely equivalent to small source
- Moves virtual source far away
- Demagnification becomes very large
  - ➢ *Less sensitive to vibrations*
- Current density is smaller (fewer Coulomb interactions)

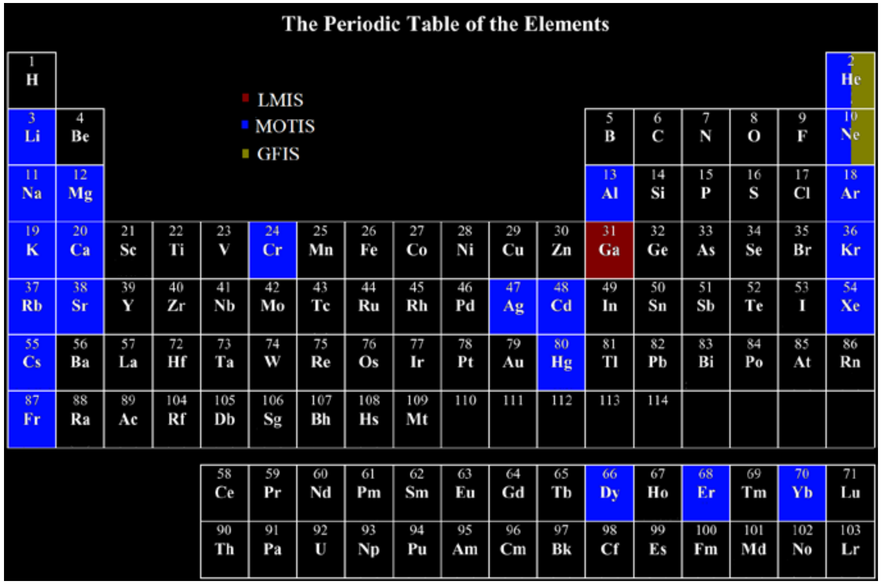
Not many ways to do this with ions!

Magneto-Optical Trap Ion Source



Ultracold temperature of MOT
→ Small transverse velocities
→ Low divergence
→ Emittance = $\sigma\ (kT/2)^{1/2}$

- Choice of 22+ ions

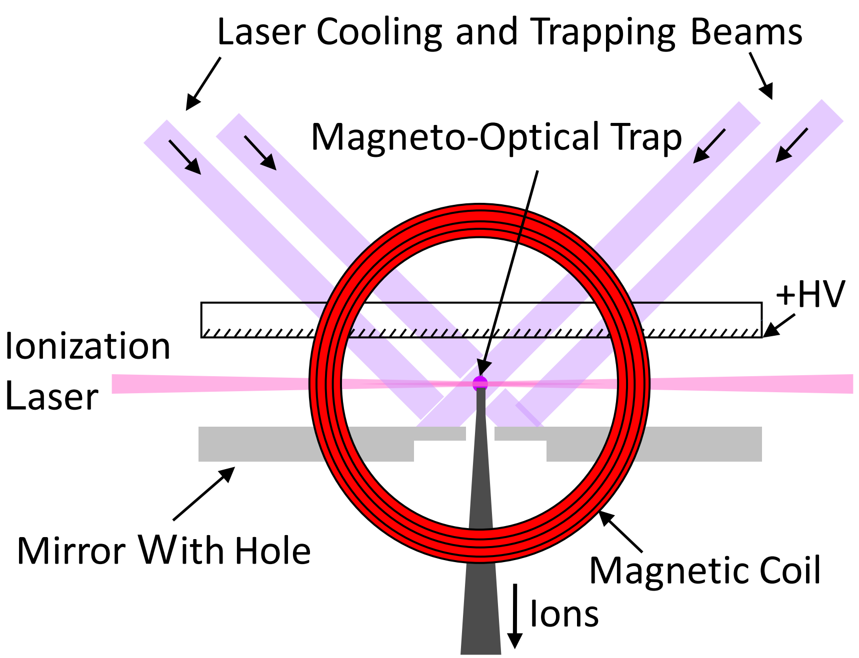


- Ionize with another laser and extract with a uniform electric field

- Low energy spread
  - Inherent spread ~neV
  - Practical spread: geometry-dependent, ∝ E

- Long term stability
  - No finicky tip
  - Macroscopic quantities of ion beam material

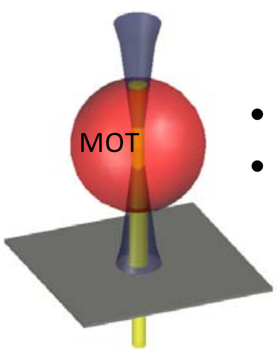
MOTIS Source Geometry



- "W" trapping beam configuration
- Another retroreflected beam ⊥ page
- Top window with ITO conductive coating
- Trapped atoms are ionized and extracted through hole in bottom mirror

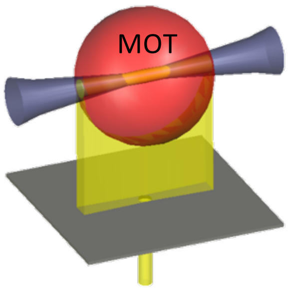
Two modes of ionization:

Axial mode



- More current
- Larger ΔU

Transverse mode

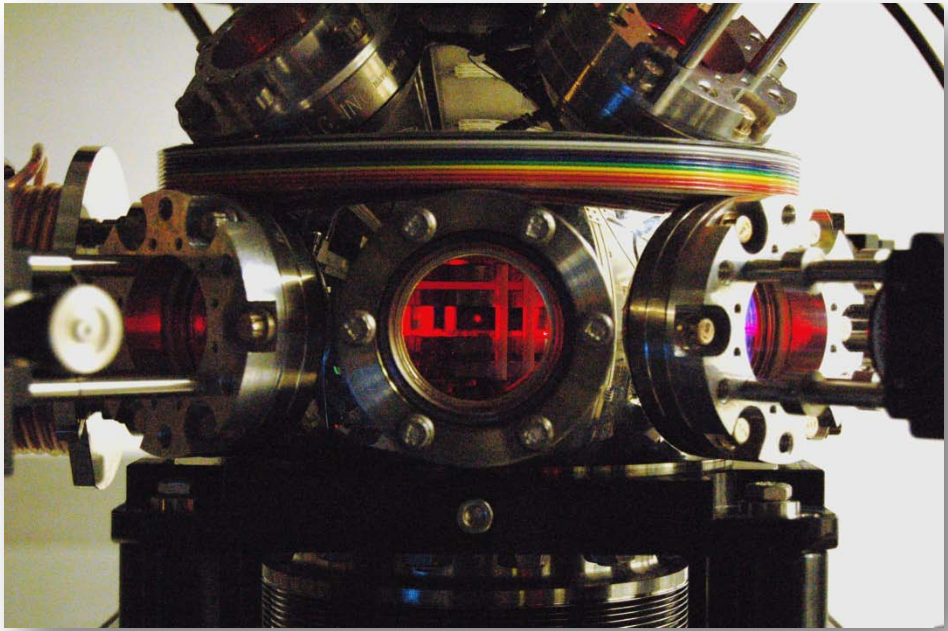


- Less current
- Smaller ΔU

Realization: Lithium MOTIS

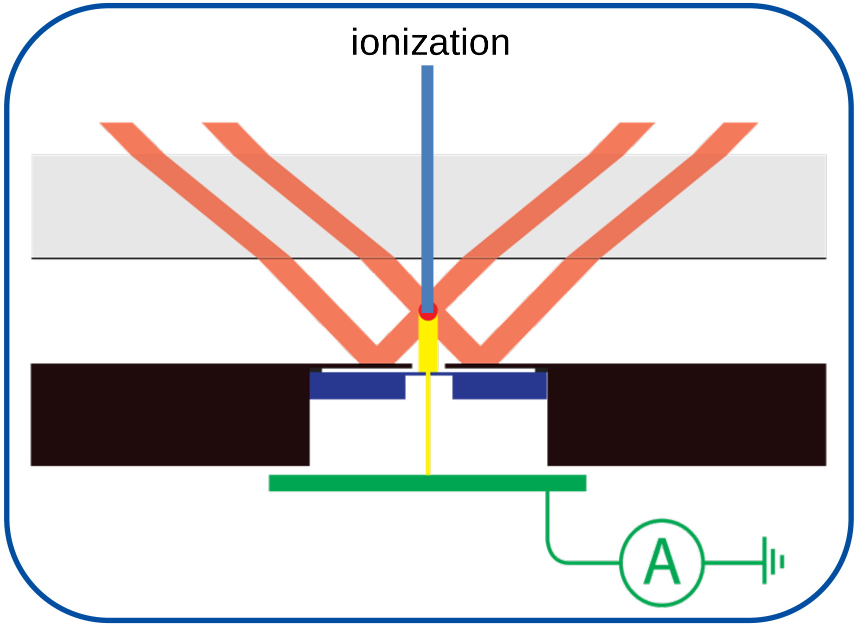
Why lithium?

- Light ion, low sputtering, good for microscopy
- Interaction with sample should be very different from gallium or helium
- Compact, convenient lasers for cooling



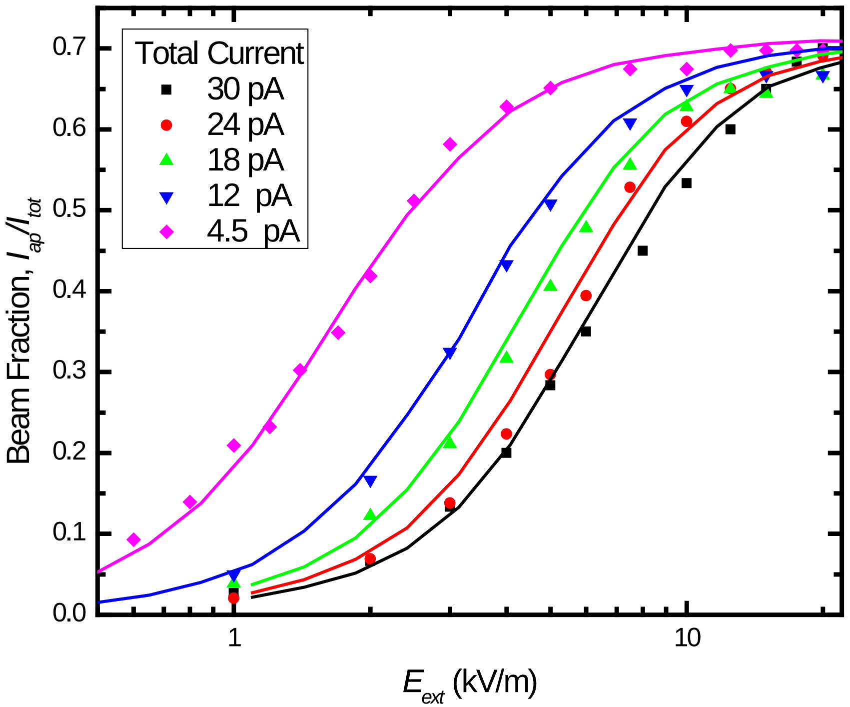
Laser cooling @ 671 nm
Ionization @ 350 nm

How much useful current?



- Axial mode – high current
- Up to 60 pA observed
- Insert 20 µm aperture in beam
- Measure fraction of current that gets through vs I_{tot} and V

Monte Carlo simulations



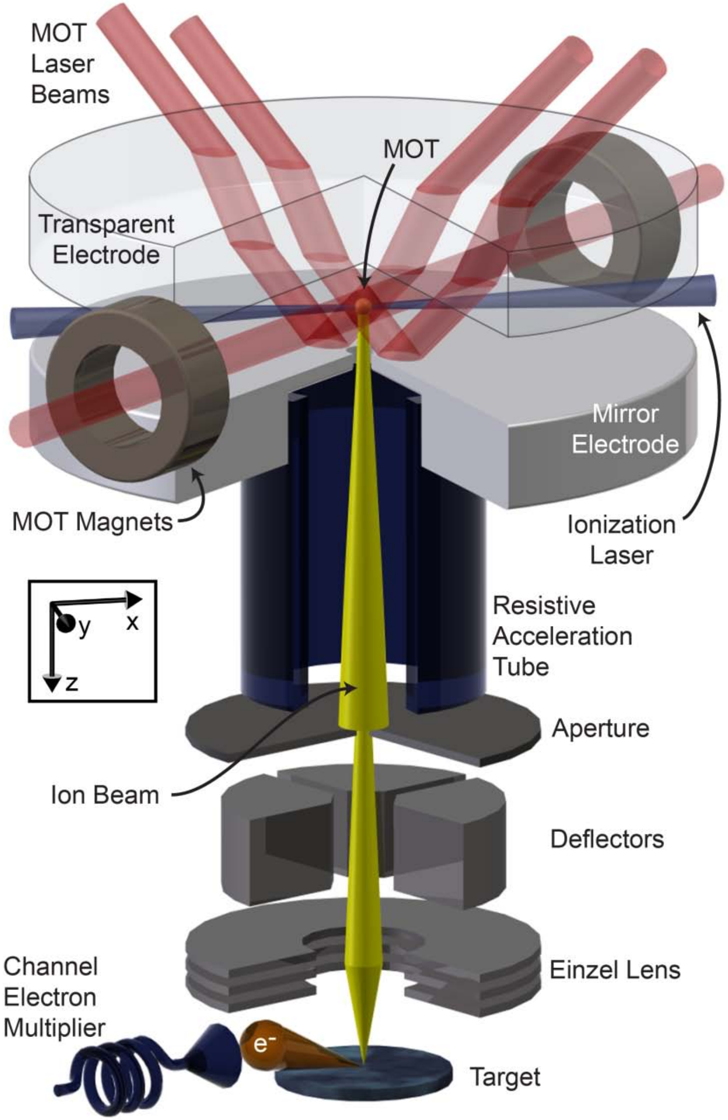
- Current fraction depends on:
  - ➢ Extraction field
  - ➢ Total current

→ *Coulomb effects*

- Can eliminate effects with more E field

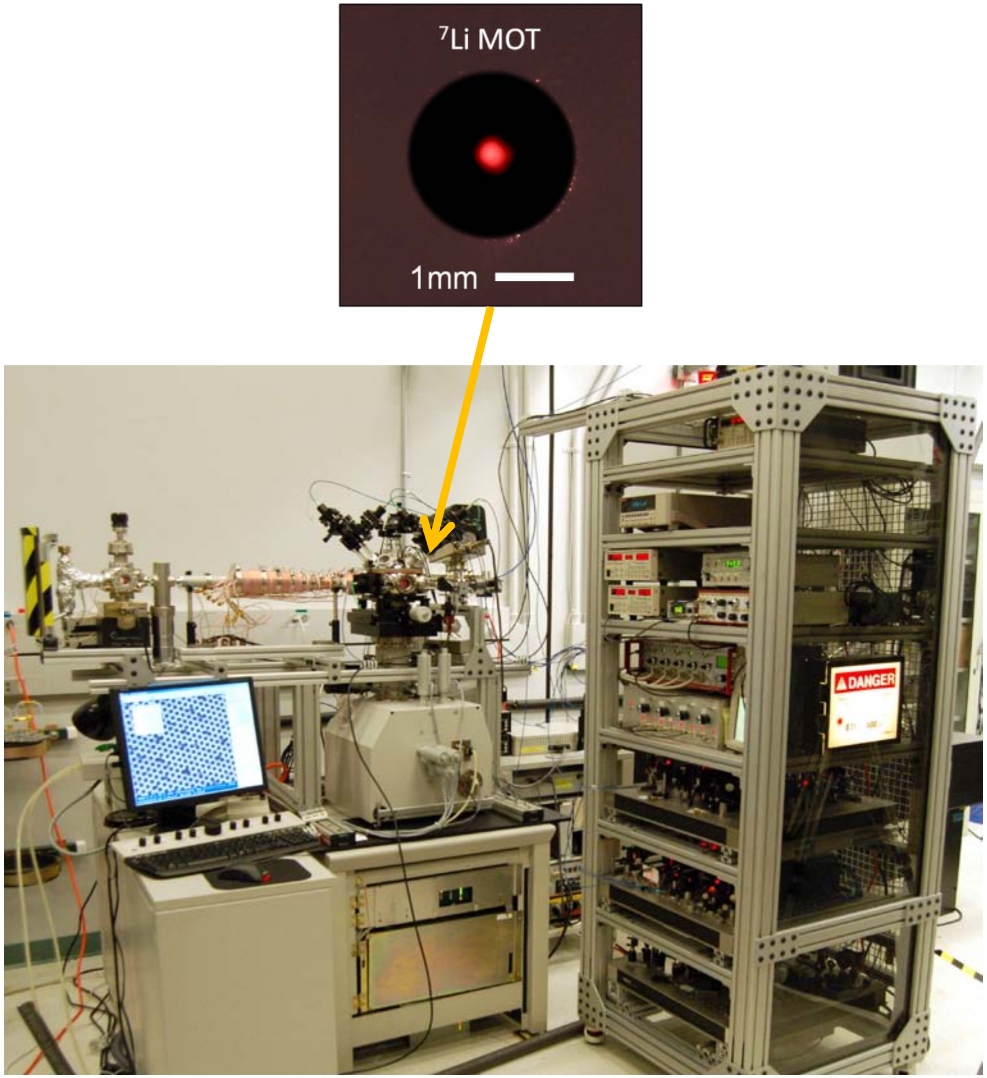
→ ***MOTIS is a well-characterized, calculable source***

Li ion microscope

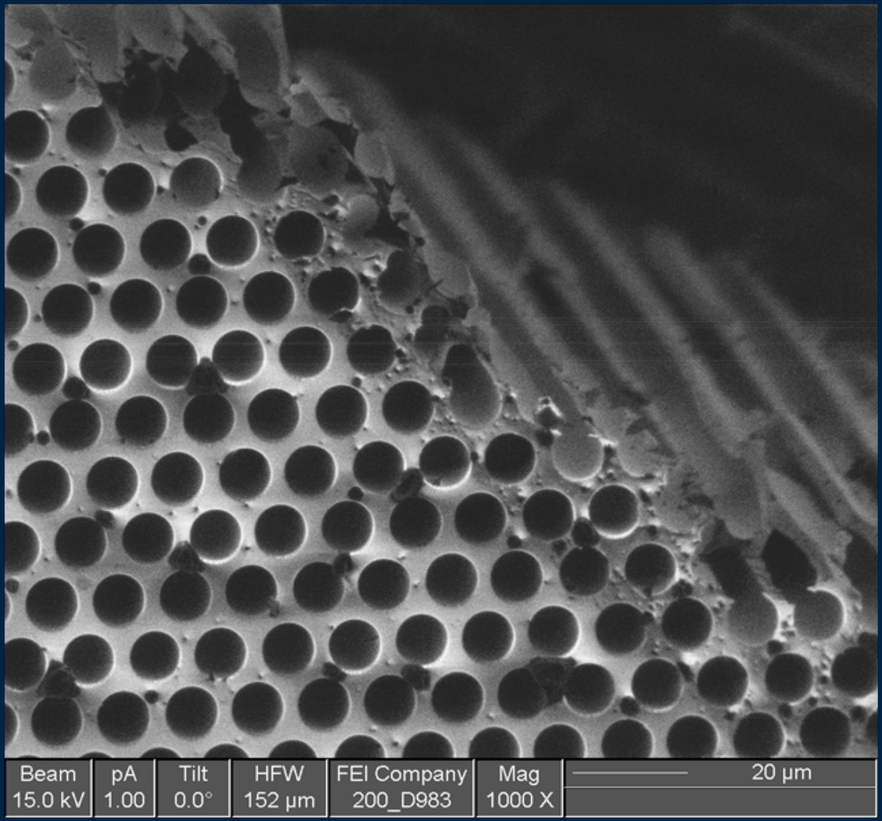


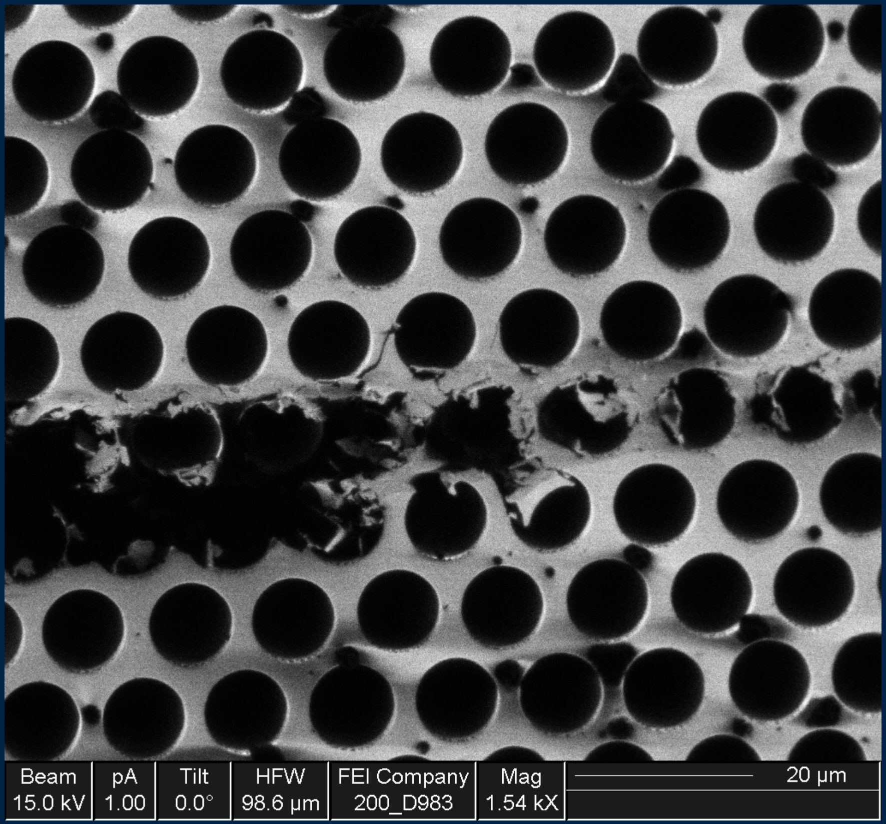
Lithium ion microscope

- Mount MOTIS on commercial FIB column, supplied through collaboration with FEI Co.
- Laser cooling lasers and optics in rack, coupled by fibers
- Ionization laser is doubled Ti:sapphire, coupled by fiber (not shown)
- Beam scanning, image acquisition handled by FIB system



Lithium MOTIS Images



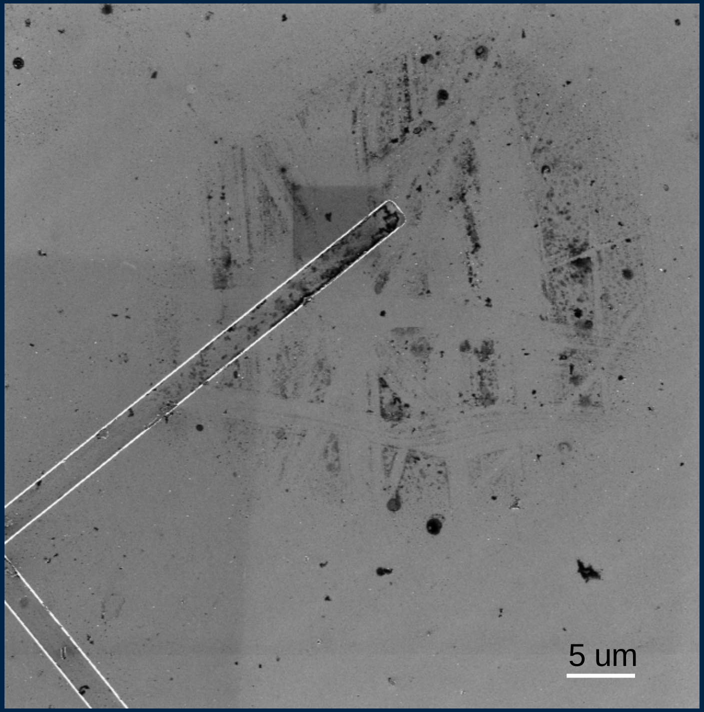


Sample: broken microchannelplate

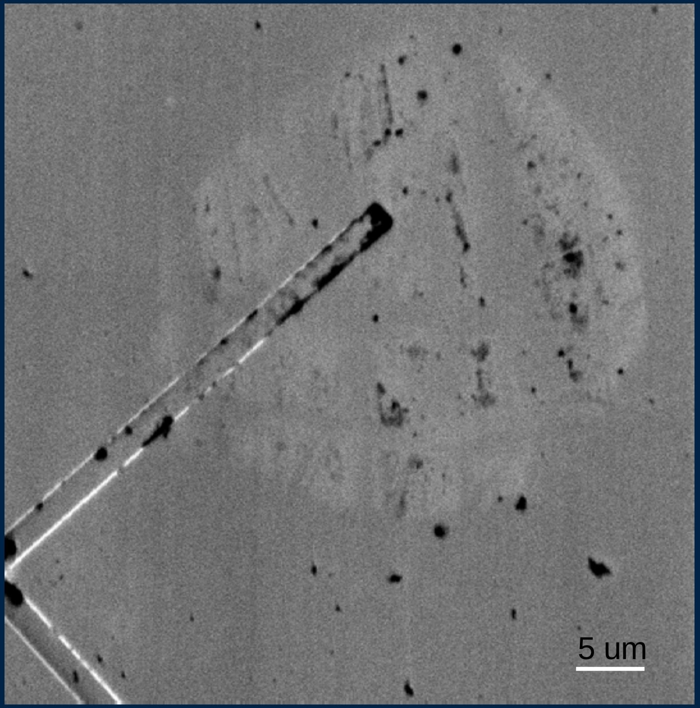
Lithium MOTIS Images

Comparison between SEM and Li MOTIS

Sample: Si with unknown contamination



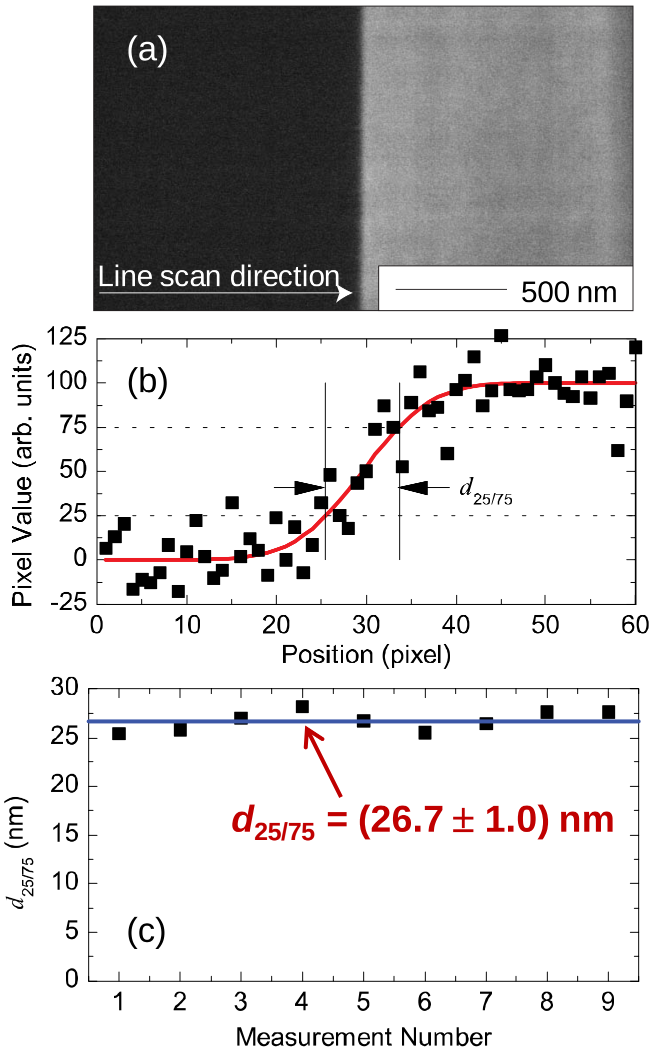
SEM: 1 kV, 10 nA



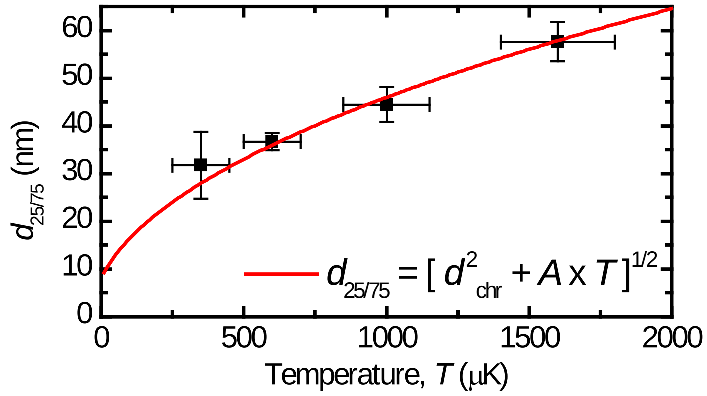
Li MOTIS: 2 kV 10 pA

Beam measurements

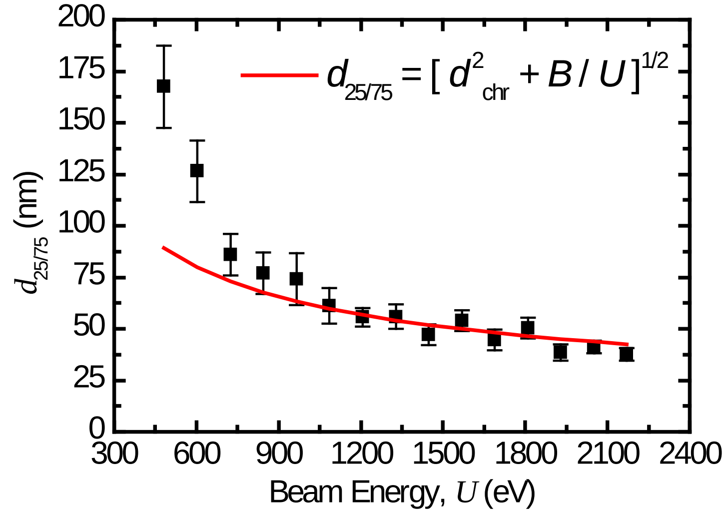
2 keV, 1 pA beam



Beam width vs MOT temperature

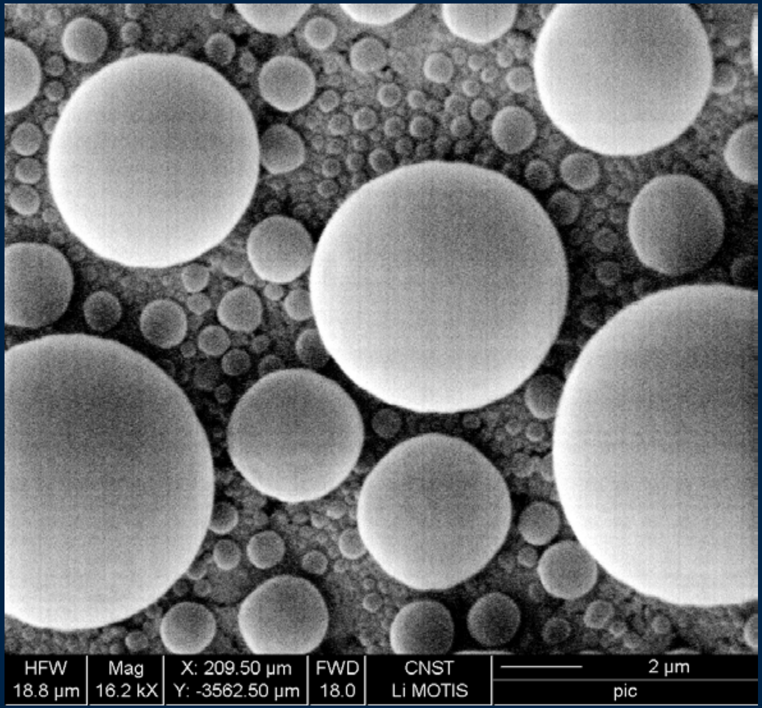


Beam width vs beam energy

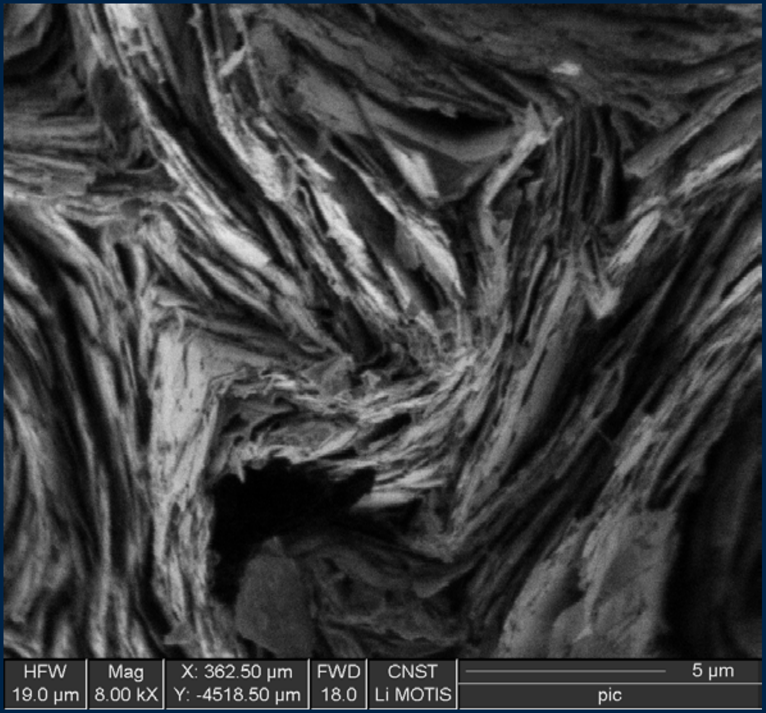


Lithium MOTIS Images

Best resolution to date: 27 nm at 2 kV



Sample: tin balls on carbon



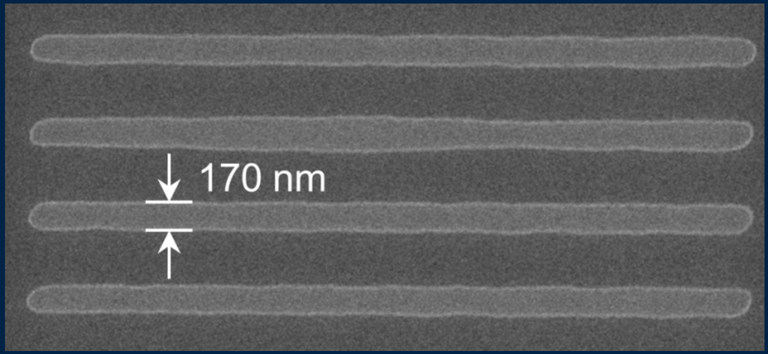
Sample: graphite

Applications

Li ion beam lithography

With D. Winston, K. Berggren, MIT

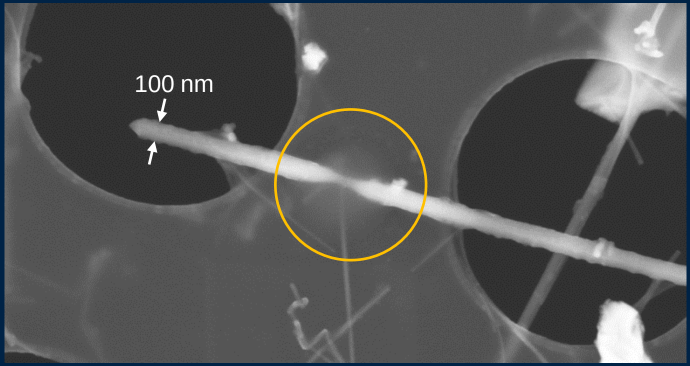
- HSQ on Si
- New species could improve resolution, clarify nuclear vs electronic stopping



Li implantation in Si nanowires

With S. Wagesreither, A. Lugstein, TU Wein

- Investigate local diffusion of Li



Li implantation in WO_3

With D. Ruzmetov, A. Talin, CNST

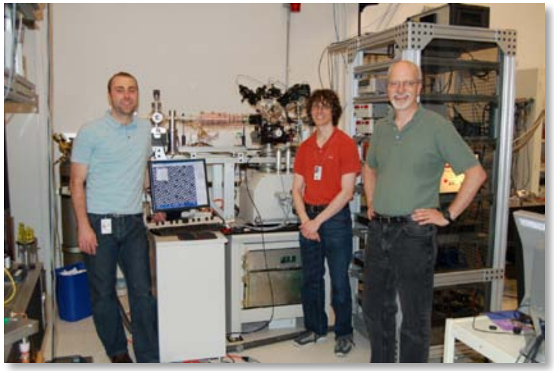
- Modify optical properties on the nanoscale
- Observe Li migration under electric field

Outlook

MOTIS has a "bright" future…

- Construct high voltage Li system
- Bring present source to diffusion limit – and beyond?
- Consider other species, e.g. Cs, Er, etc.
- Explore wide range of applications
    - Li implantation
    - Ion lithography
    - Surface modification/damage by Li FIB
    - Secondary yield of Li ion beam from a range of materials
    - Beam chemistry
    - Biological samples
    - Imaging of complex oxides
    - High quality polishing of ion milled surfaces for TEM prep
    - Backscattered ion energy analysis
    - Implantation lithography
    - etc…

AND consider options for even brigher sources (see poster)



Thanks to…

J. Orloff, FEI
M. Maazouz, FEI
G. Schwind, FEI
C. Rue, FEI
D. Winston, MIT
K. Berggren, MIT
S. Wagesreither, TU Wein
A. Lugstein, TU Wein
Y. Greenzweig, Intel
S. Tan, Intel
R. Livengood, Intel
D. Ruzmetov, CNST
A. Talin, CNST
K. Twedt, CNST