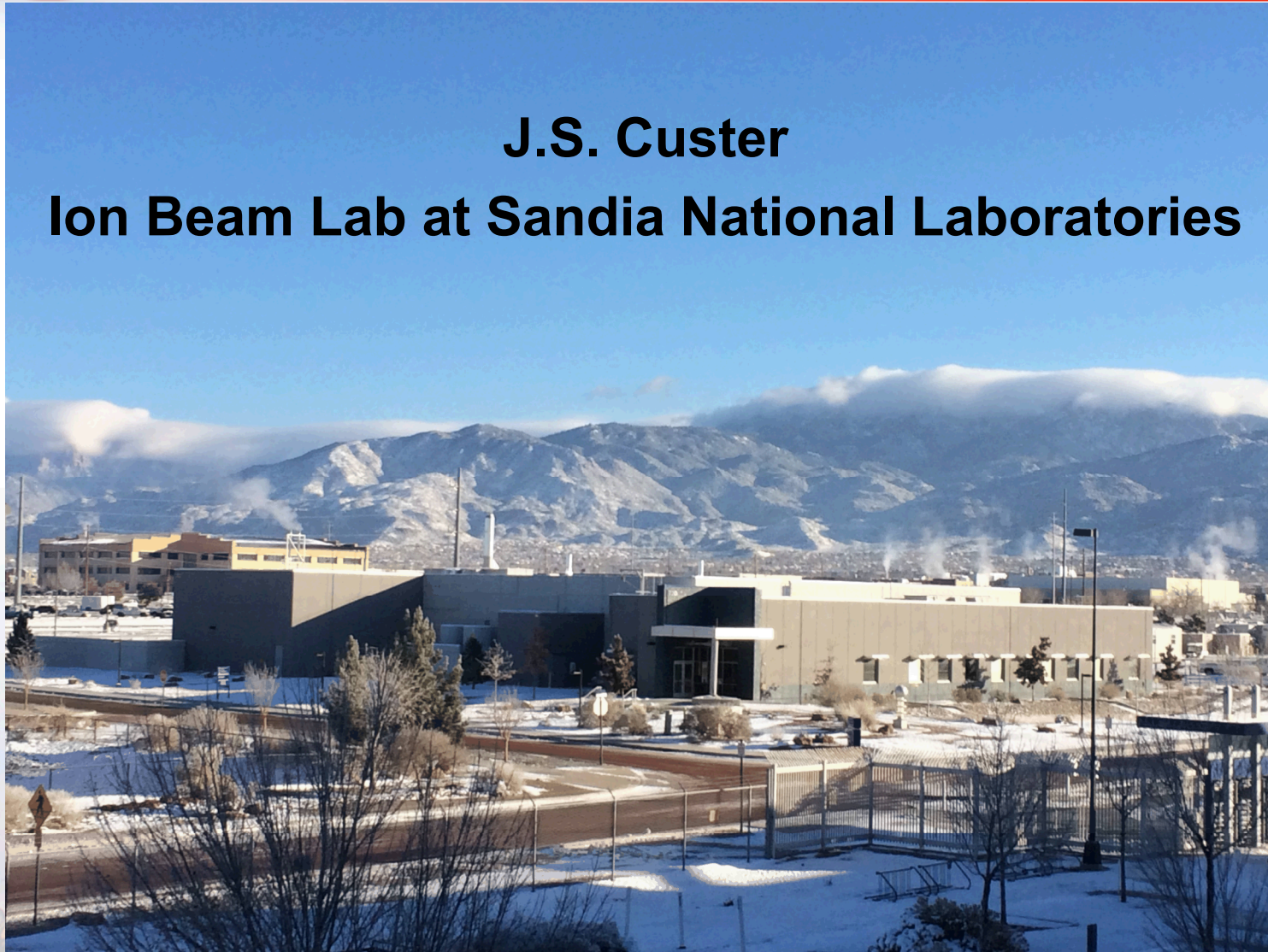


Single-Ions for Materials Science

SAND2016-6342C

J.S. Custer Ion Beam Lab at Sandia National Laboratories



This work was supported by the US Department of Energy, Office of Basic Energy Sciences.

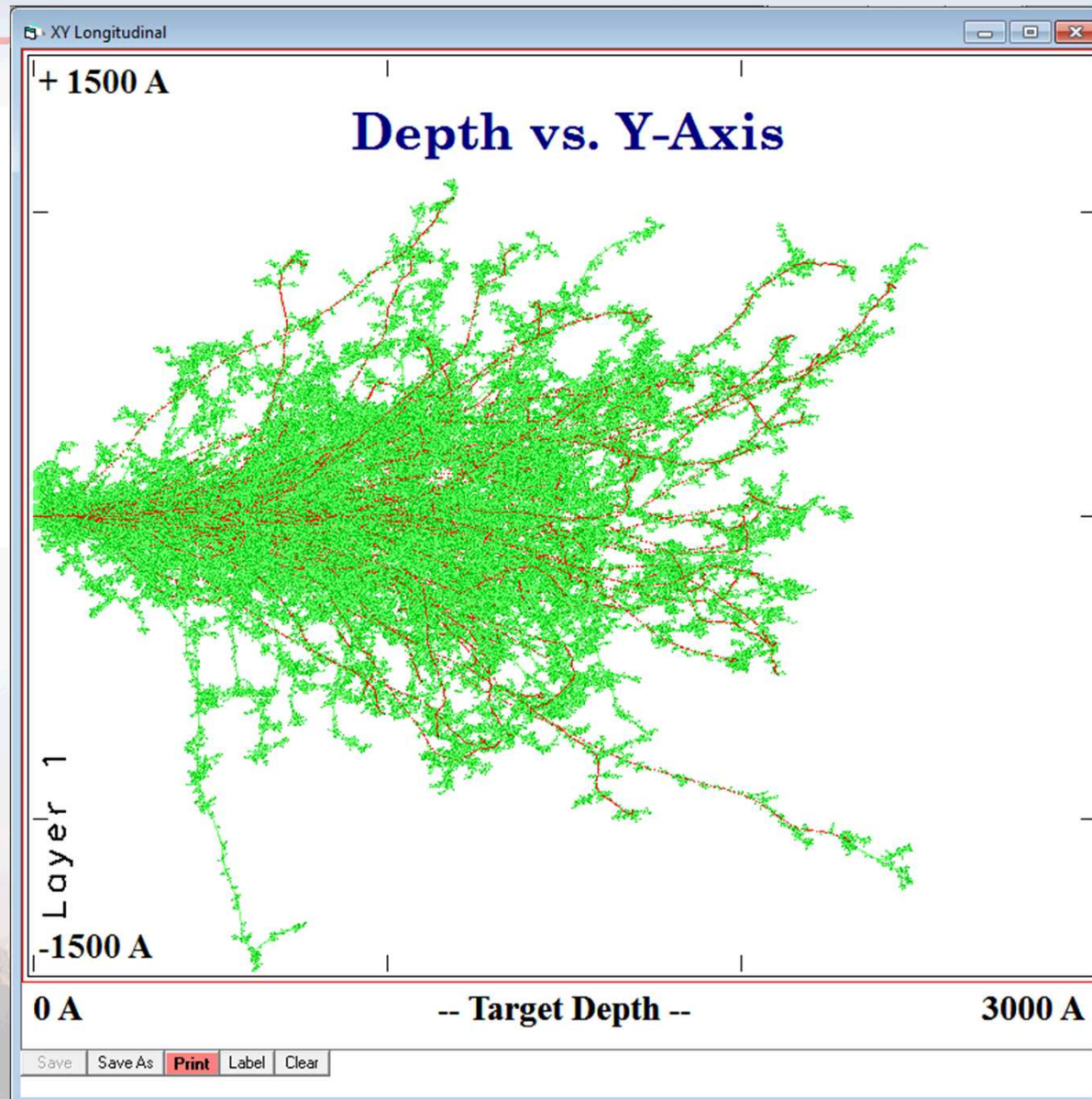


Sandia National Laboratories

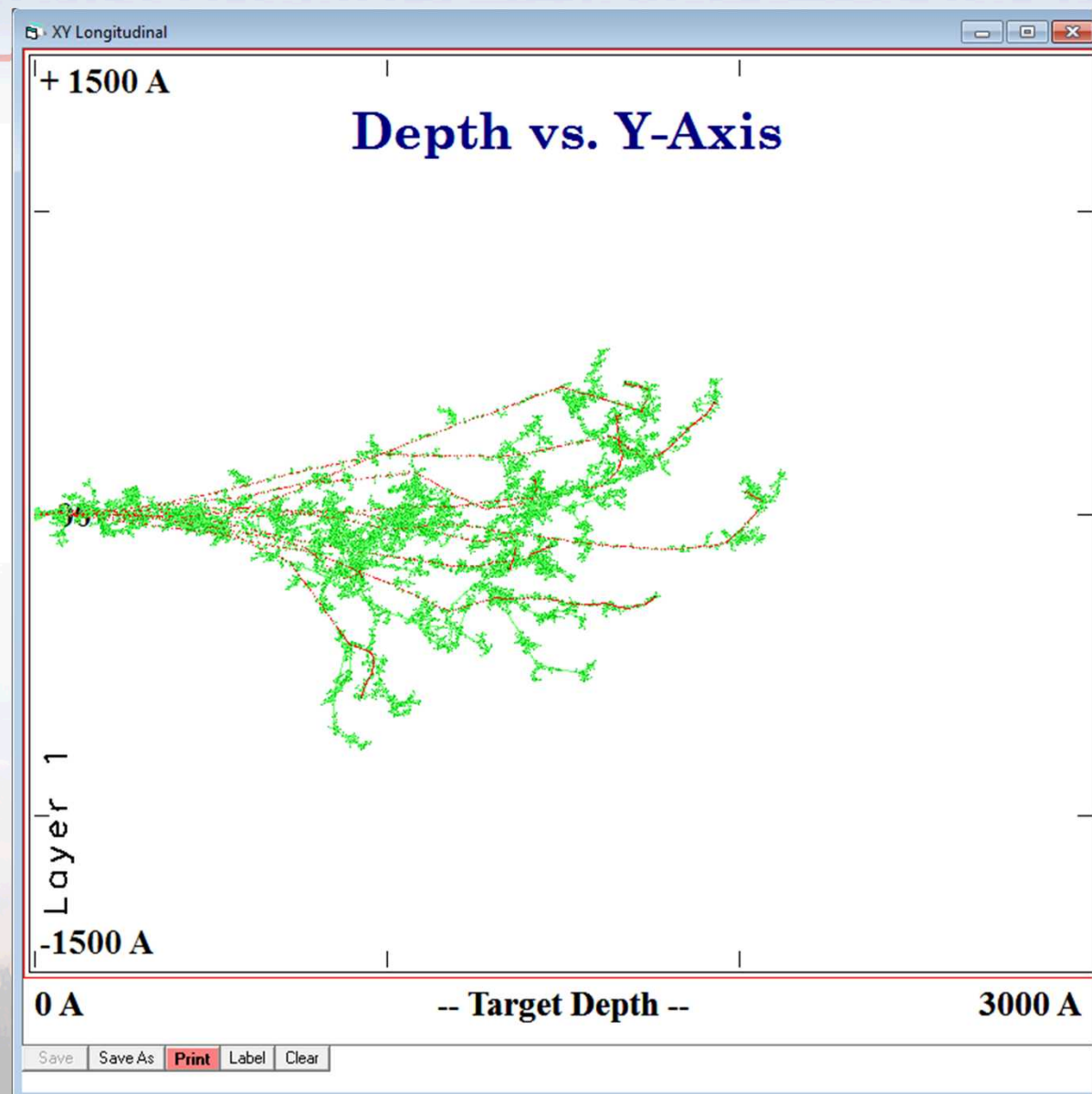
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

We have all used SRIM (TRIM)

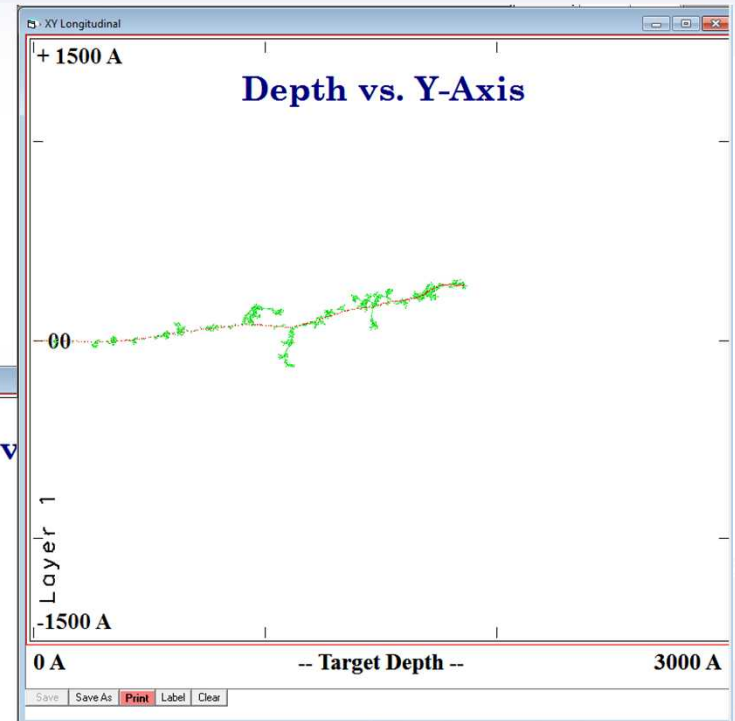
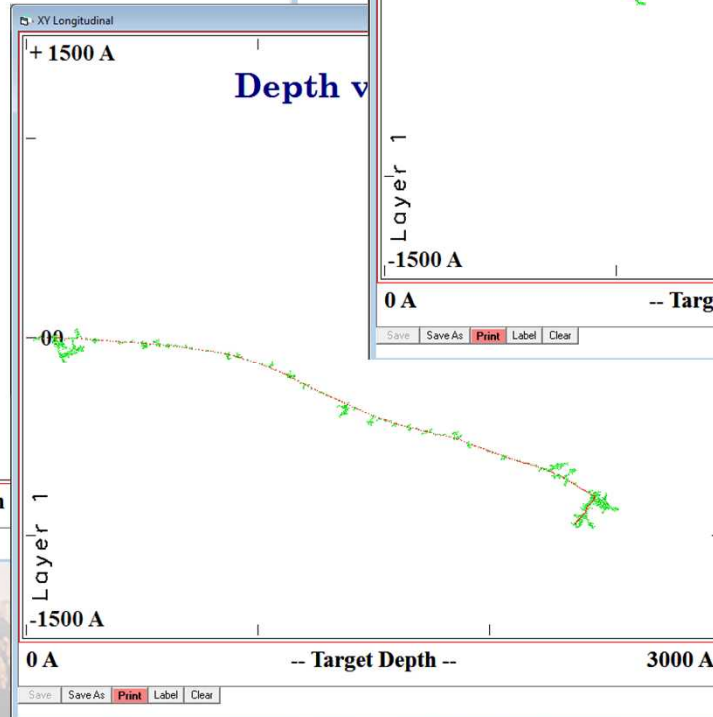
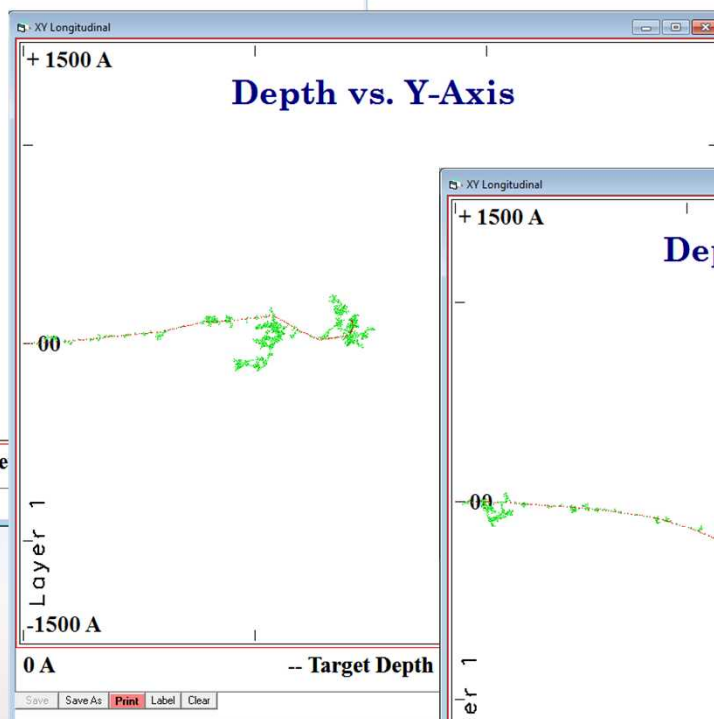
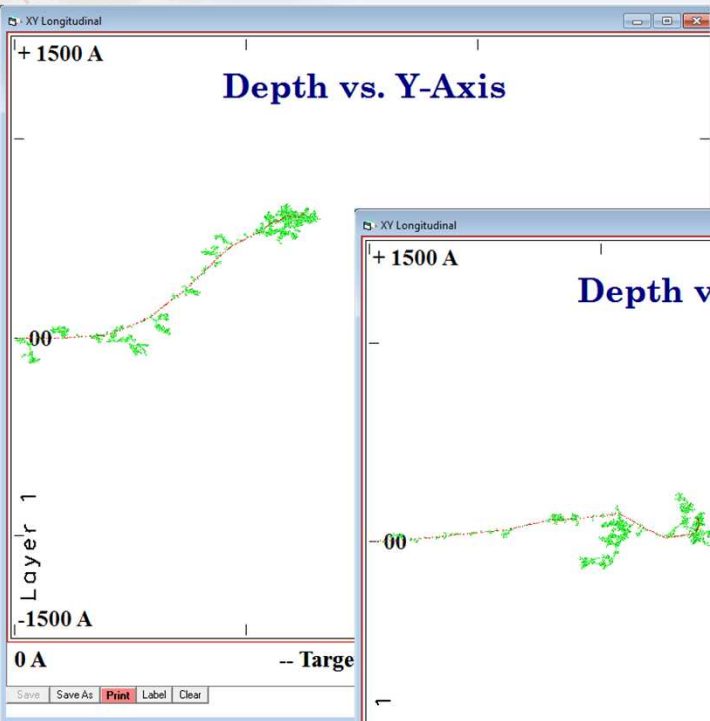
- 100keV Si -> Si
- 100 ions
- Big mess of damage!
- Lots of different ion paths
- Stochastic variability
 - Where it ends up
 - Displacement damage
 - Electronic excitation



- Only 10 ions now
- Individual character starts to show



A Single Ion is not an Average Ion





Single Ion Materials Science

■ What can a single ion *Do*?

- Long history of single event effects
- Direct imaging of single ion strikes
- Damage, bubble nucleation, ...
- On path to dynamic TEM (nsec-resolved imaging)

■ What can you use a single ion *For*?

- One, and only one, placed in just the right spot
- *Quantum bits*
- Single photon sources



Just One Ion...

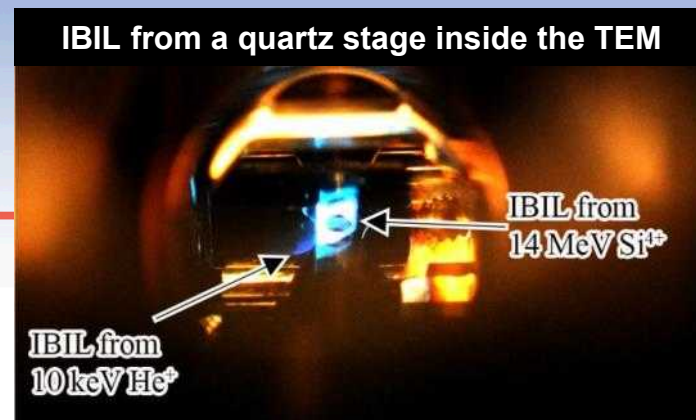
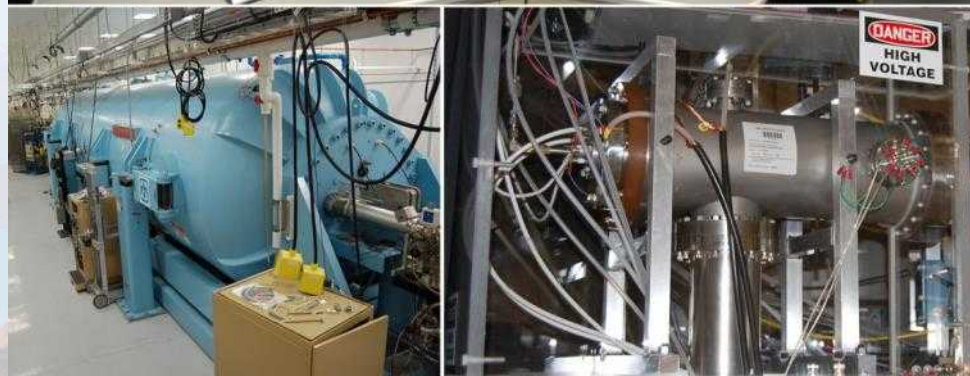
- Long history of Single Event Effects (e.g. satellite electronics)
- III-V transistor undergoing SEE testing on our MicroOne microbeam line (George Vizkelethy).
 - (Transistor set up to fail – no current limit)



Sandia's Concurrent *In situ* Ion Irradiation TEM Facility

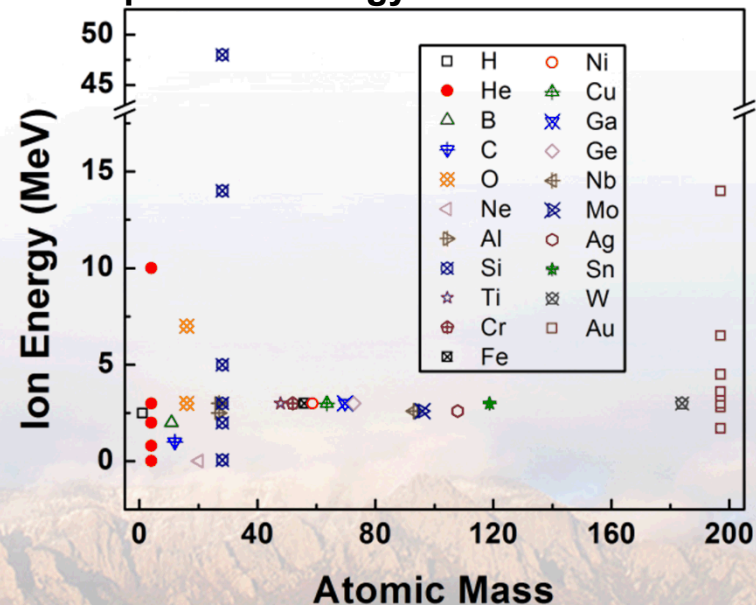
Khalid Hattar, Dan Buller

6 MV Tandem - 10 kV Colutron - 200 kV TEM



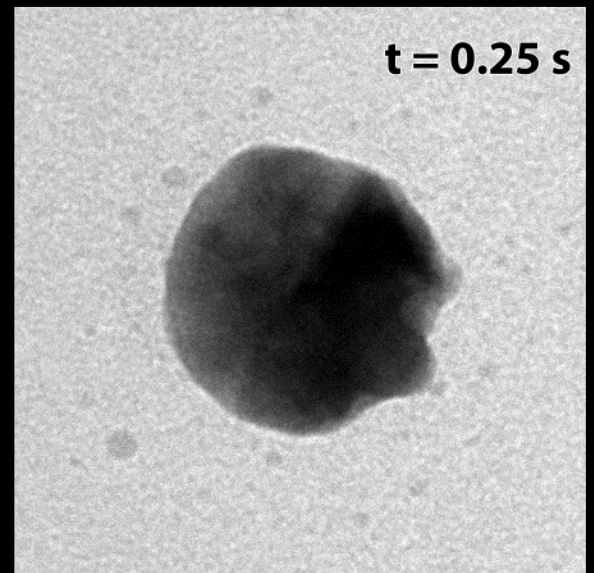
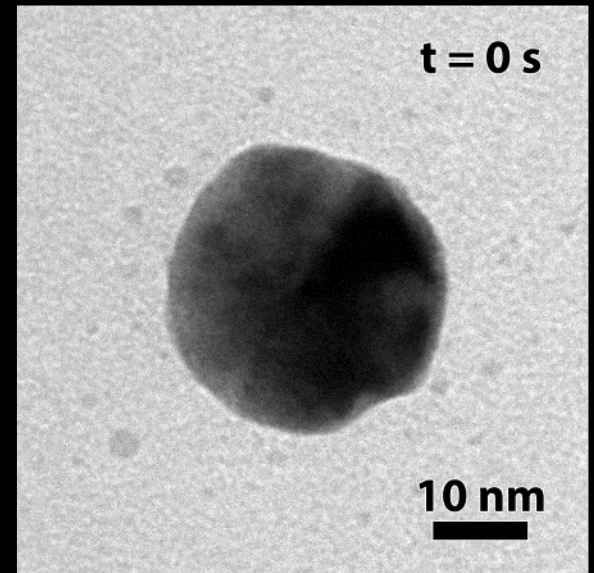
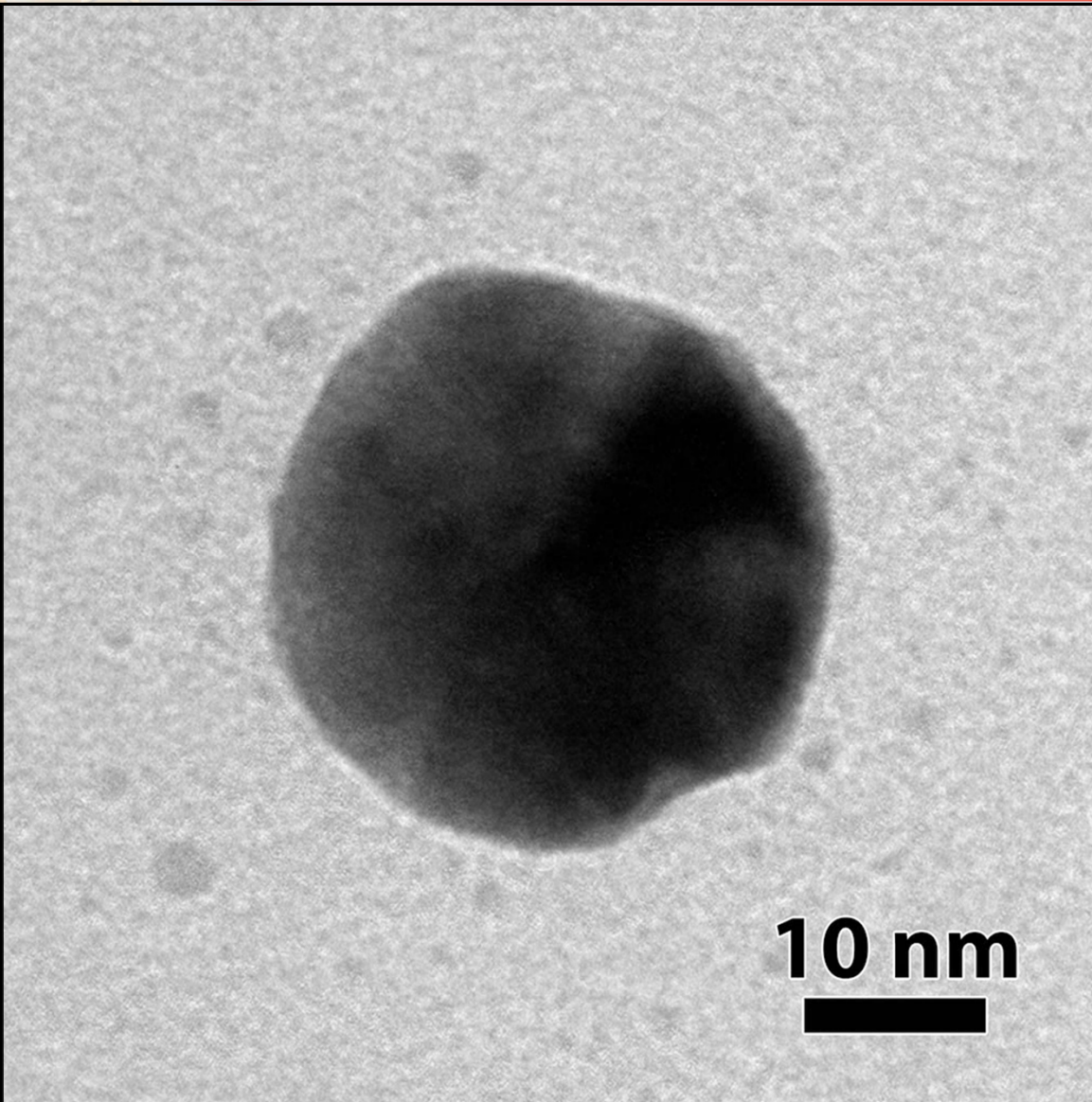
Direct real time observation
of ion irradiation,
ion implantation, or both
with nanometer resolution

Ion species & energy introduced into the TEM



Single Ion Effects in 20 nm Au nanoparticle: 46keV Au ions (range ~7nm)

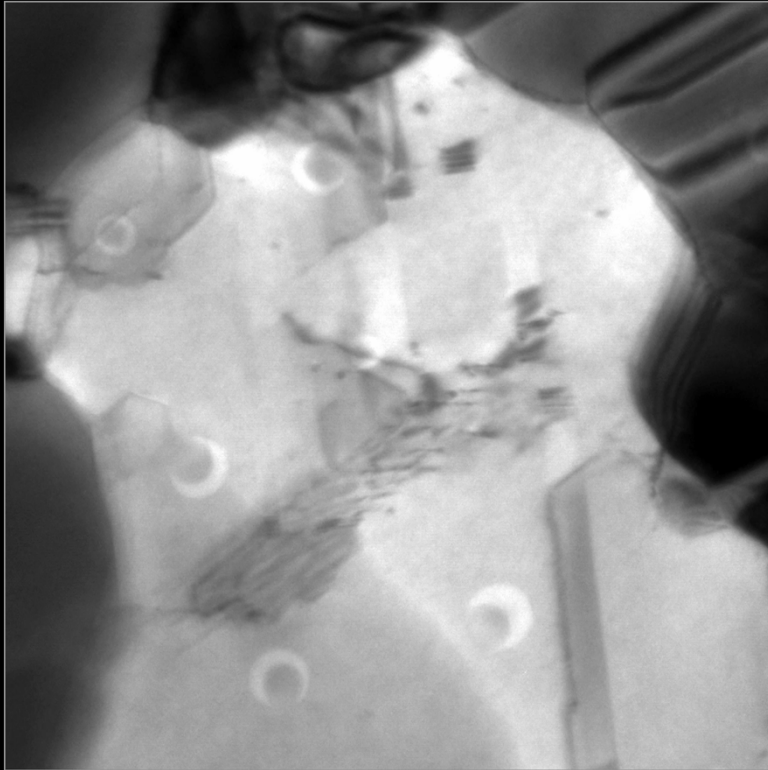
Khalid Hattar, Daniel Bufford



Single Ion Strikes – 2.8MeV Au⁴⁺ into/through Au film

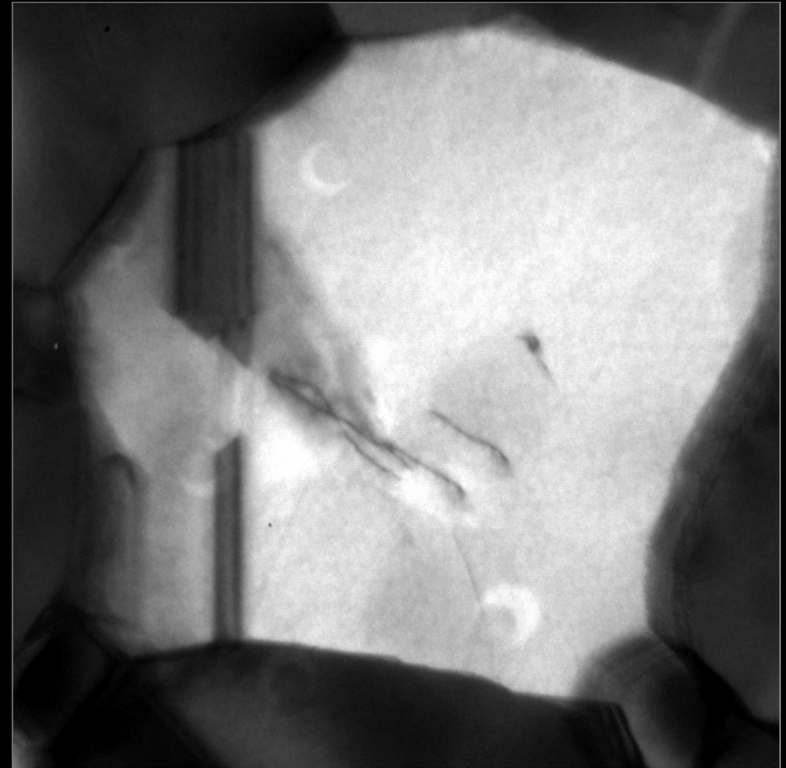
Khalid Hattar with collaborators C. Chisholm and A. Minor (UC Berkeley)

7.9×10^9 ions/cm²/s



VS

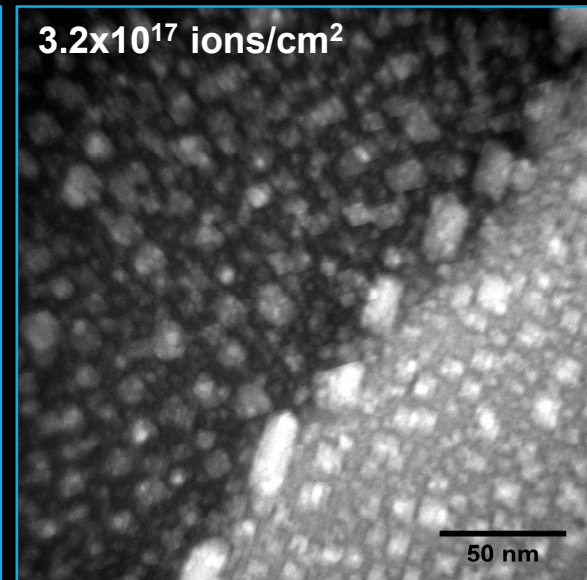
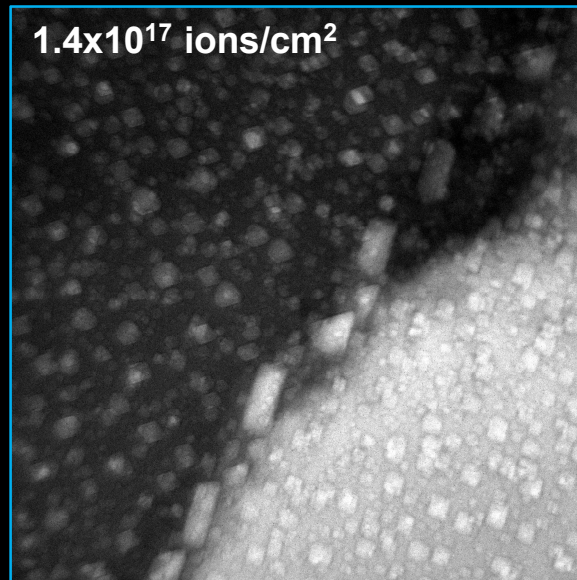
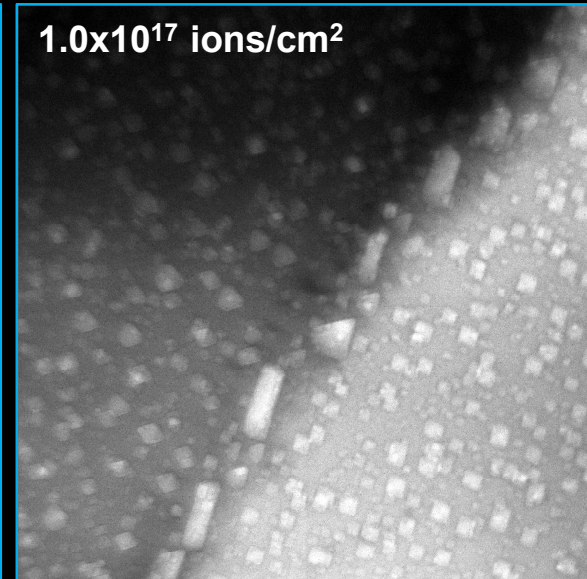
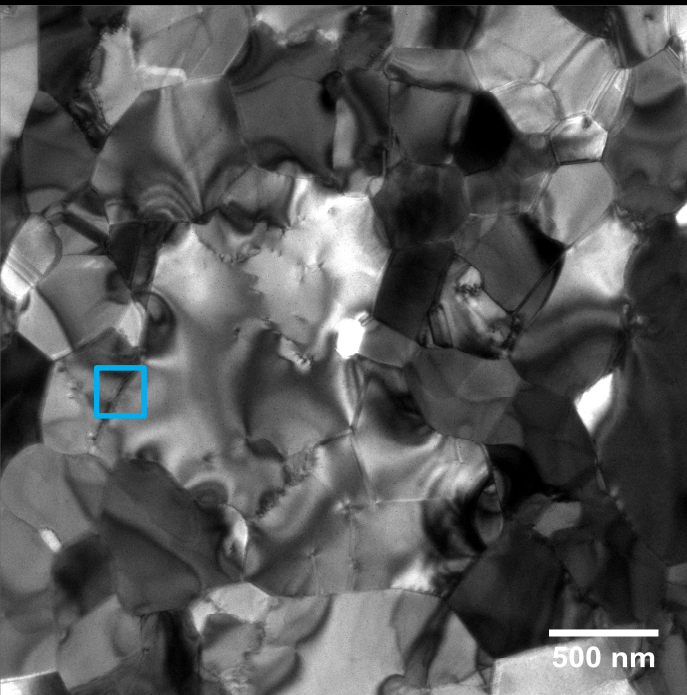
6.7×10^7 ions/cm²/s



Improved vibrational and ion beam stability permits us to work at 120kx or higher permitting imaging of single cascade events

In situ Implantation: He into Au

Khalid Hattar with collaborators C. Chisholm and A. Minor (UC Berkeley)



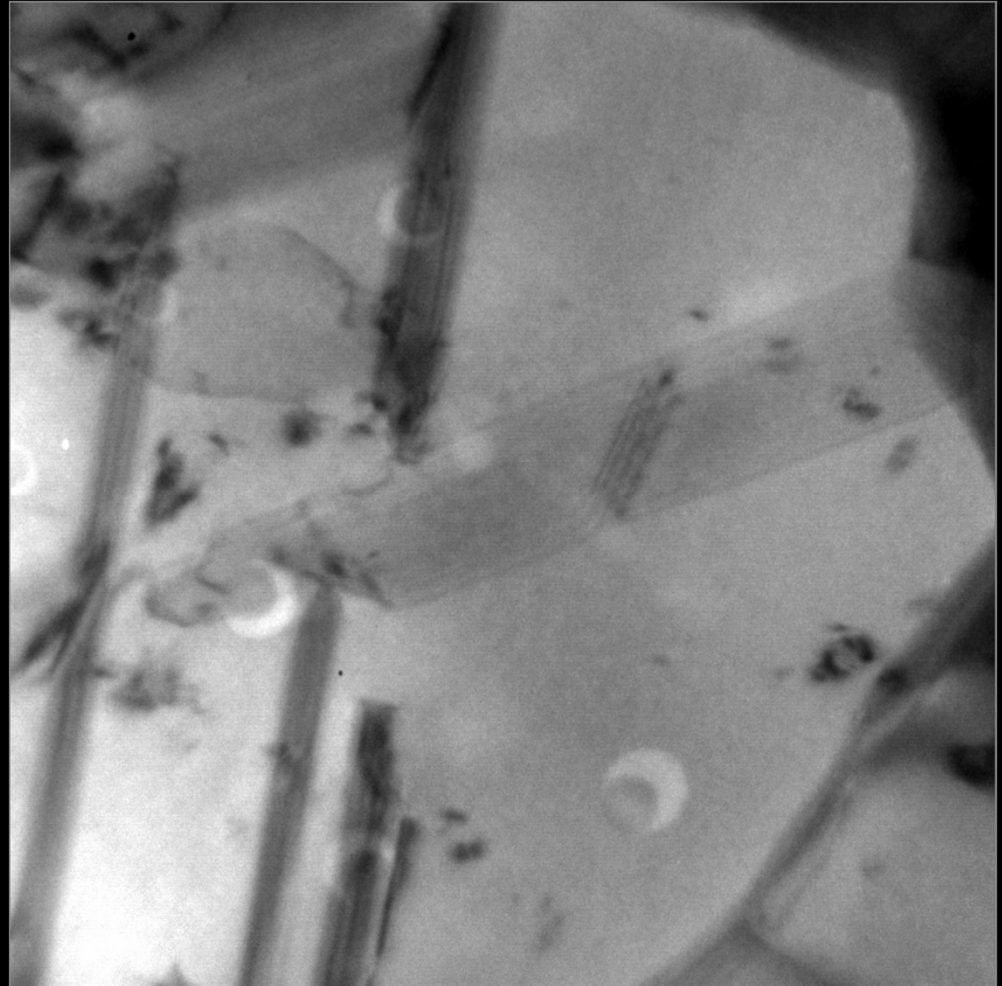
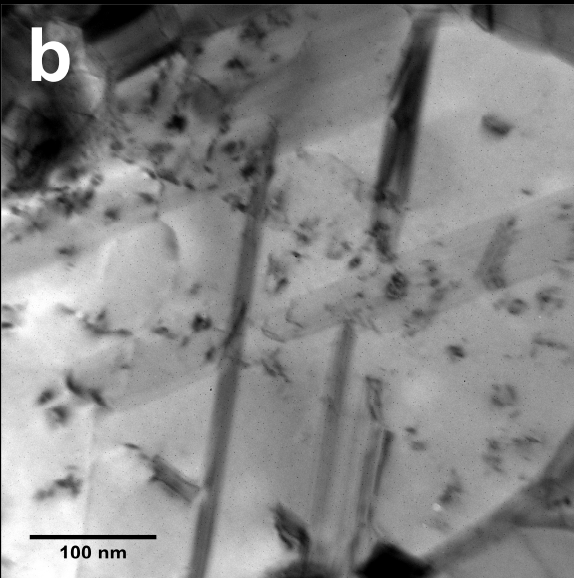
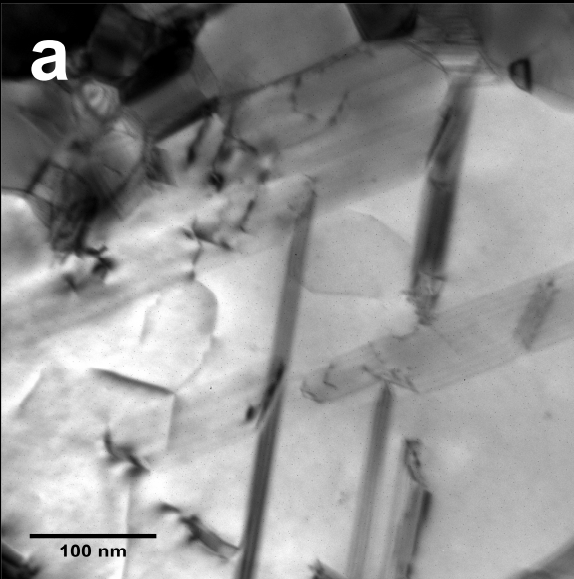
Au implanted with 10keV He⁺

He bubble formation on grain boundary and in the bulk

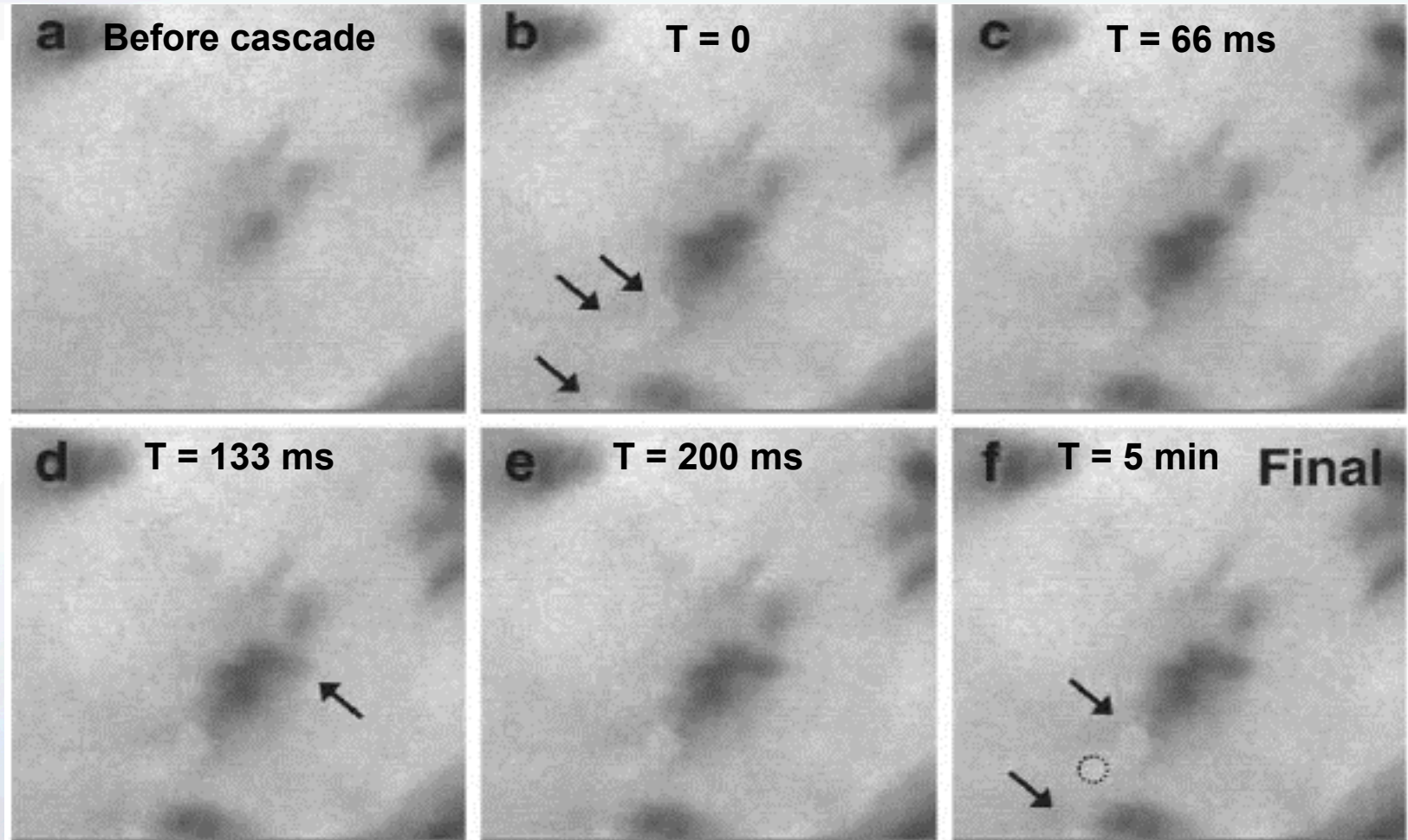
In situ Concurrent Implantation & Irradiation

Collaborators: C. Chisholm & A. Minor

**He⁺ implantation and concurrent Au⁴⁺ irradiation:
Transient bubble formation and dissolution**



Concurrent Irradiation: Transient He Bubble formation at Cascade





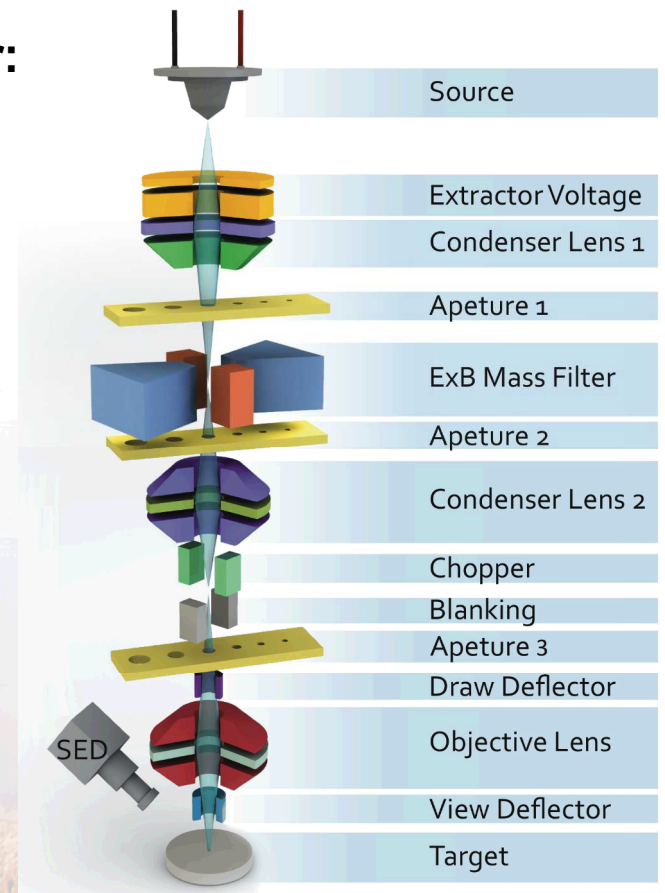
Devices with Single Ions

- **Demonstrated imaging and measuring of the effects of single ions on materials, with some control of where the ion strikes (e.g. microbeam)**
- **But, a wide range of applications for *placing* one ion in a specific place**
 - Quantum bits – donors in Si devices
 - Single photon sources – impurity-defect complexes in diamond
- **Need:**
 - Device design with single ions in mind
 - High precision targeting
 - Detection/confirmation of ion entering sample
 - Single ions



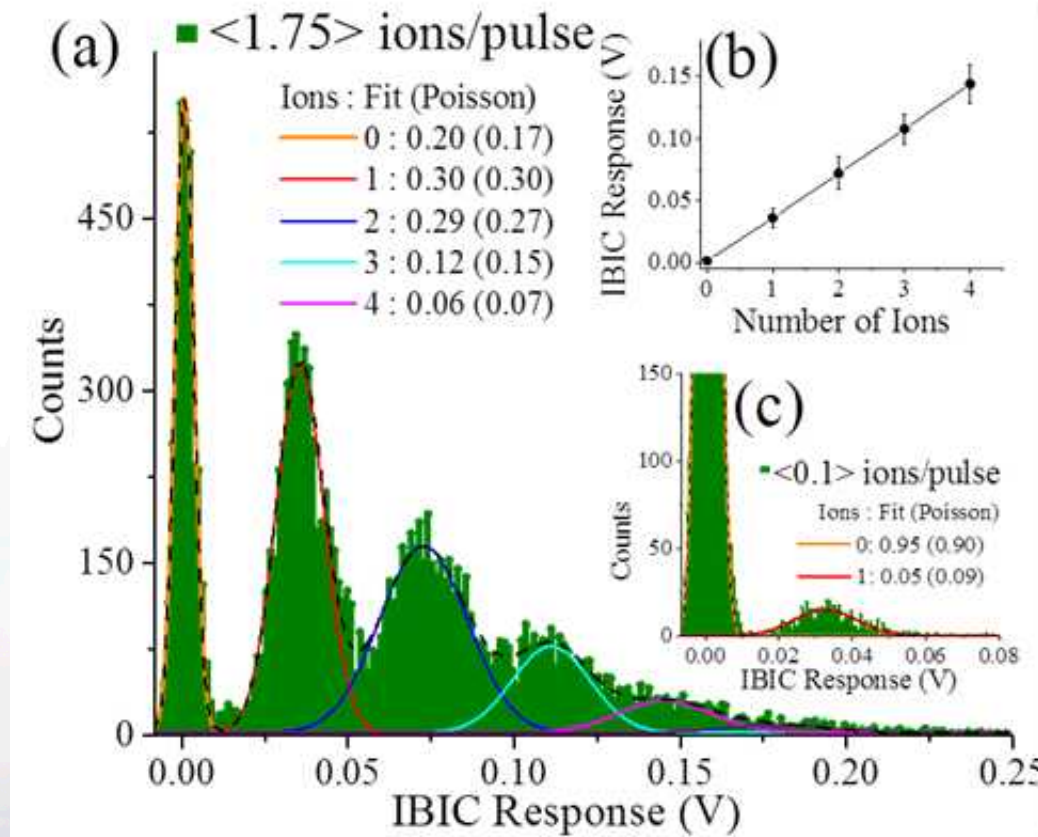
Precision Targeting

- **The Ion Beam Laboratory has a number of microbeams**
 - One micron resolution not good enough
- **AND (A&D Company, Ltd. Japan) NanoImplanter:**
 - ~15nm spot size
 - 100keV column
 - Liquid metal ion source
 - Li, Si, P, Cu, Ga, Sb, Pt, Au so far at SNL
 - Can easily resolve ^{121}Sb vs ^{123}Sb in ExB filter
- **Chopper/Blanker in column to generate fast pulses with specified average ions/pulse**
- **Target is an EBL stage for precision alignment and movement**



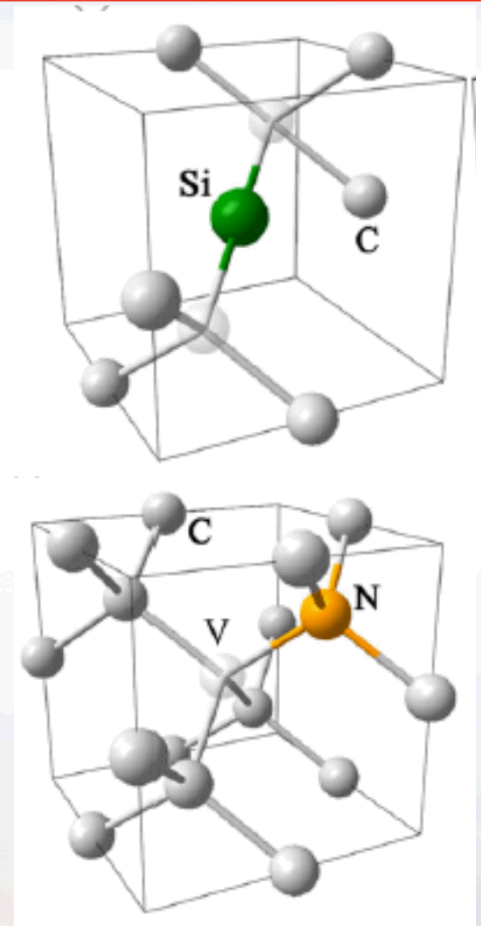
Demonstrate Measuring Single Ions

- Use blanker/chopper to create pulse train with specified *average* ions/pulse
- Collect charge from device and generate ion-beam induced charge signal (V) for each pulse
- Plot the histogram
 - 1.75 ions/pulse (a)
 - 0.1 ions/pulse (b)
- IBIC response varies
 - Electronic stopping varies
 - Charge collection efficiency varies



Where is a single ion desired?

- Impurity-defect centers is diamond
- Ion-beam materials science dream:
You actually *want* lattice damage!
 - (Well, you still need a specific impurity-defect center)
- Problem: reported yield from
implant + anneal experiments is
generally $< 10\%$
- Team: John Abraham, Ed Bielejec,
Jose Pacheco, Dan Perry



Source: I. Aharonovich et al.,
Rep. Prog. Phys. 74 (2011) 076501

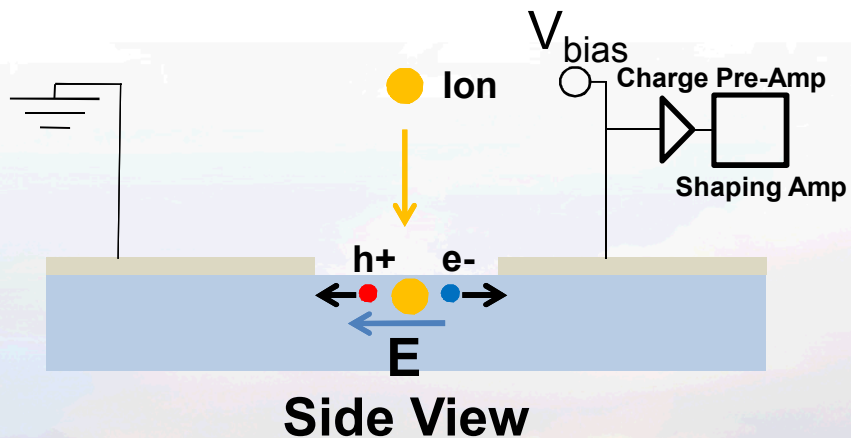


Sandia National Laboratories

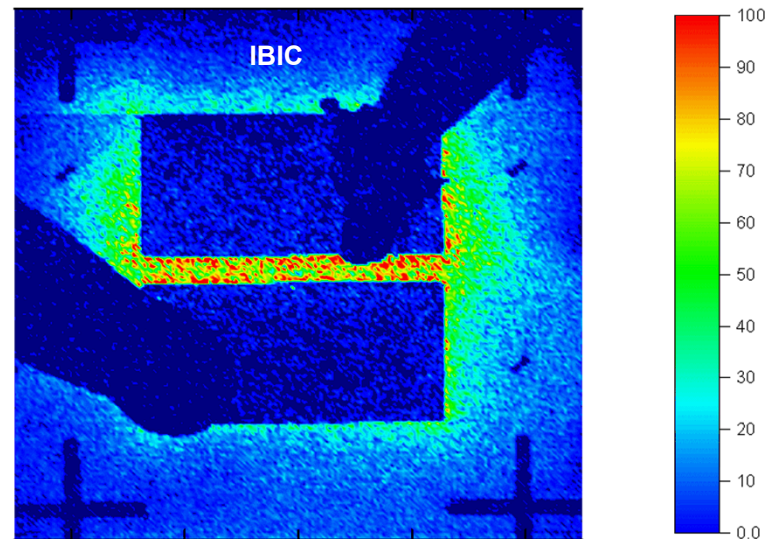
Counting Ions in Diamond

- It takes very little to make an ion-beam induced charge collector
- No diode needed – apply a field across a gap and collect charge

Ion Beam Induced Charge (IBIC):

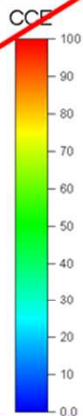
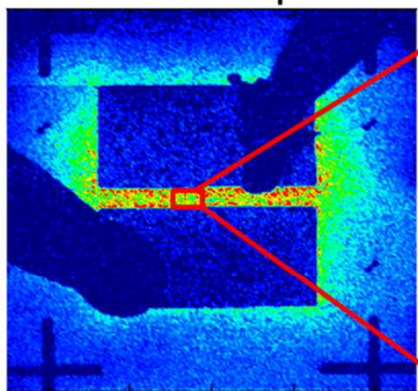


$$CCE = \frac{\text{Charge Collected}}{\text{Charge Deposited}} \times 100$$

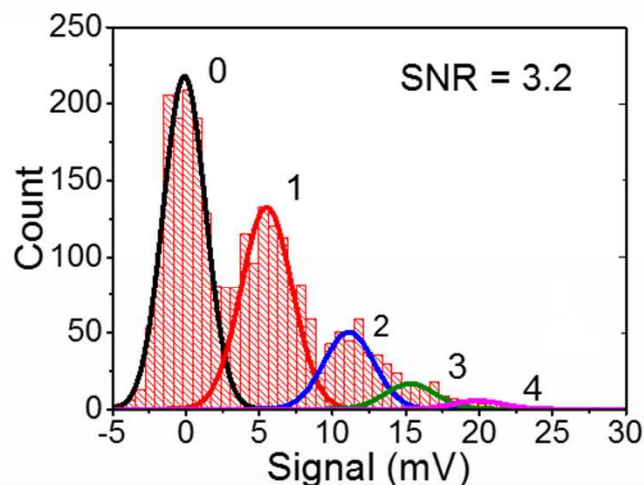


Single Ion Detection in Diamond Demonstrated

IBIC Map



Quantized Detection $\langle 0.65 \rangle$ ion

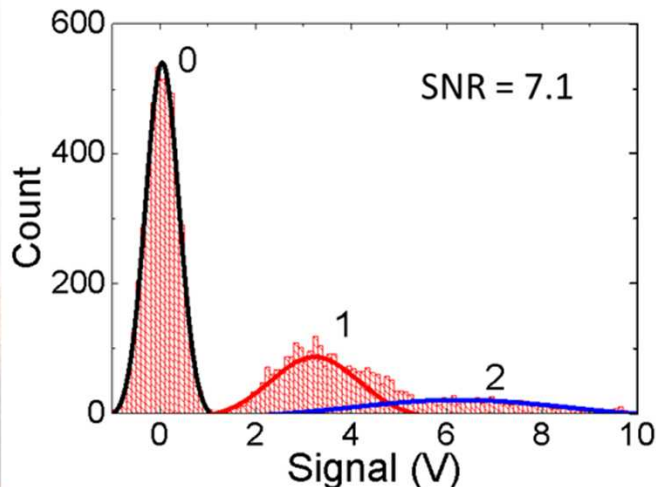


$$SNR = \frac{\mu_{signal}}{\mu_{noise} + \sigma_{noise}}$$

Signal amplitudes match
Poisson statistics to 4%

Optimizing gain
for single ion
detection

Single Ion Counting $\langle 0.2 \rangle$ ion

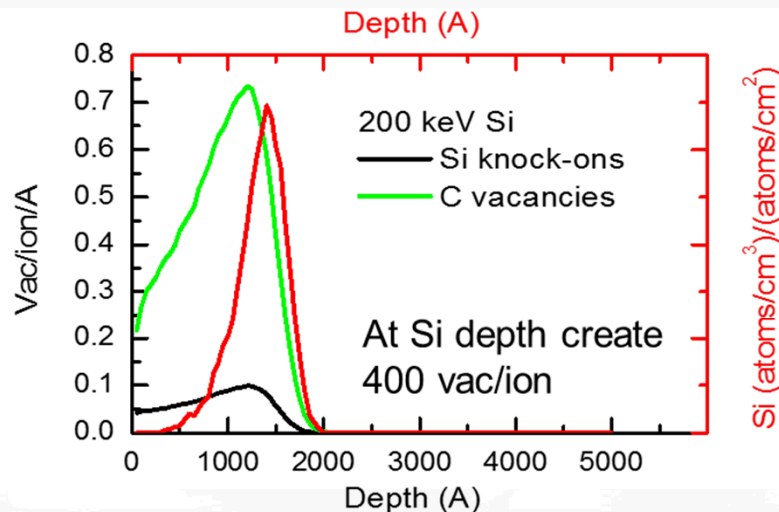


Single Ion Detection in
Diamond with SNR ~ 10

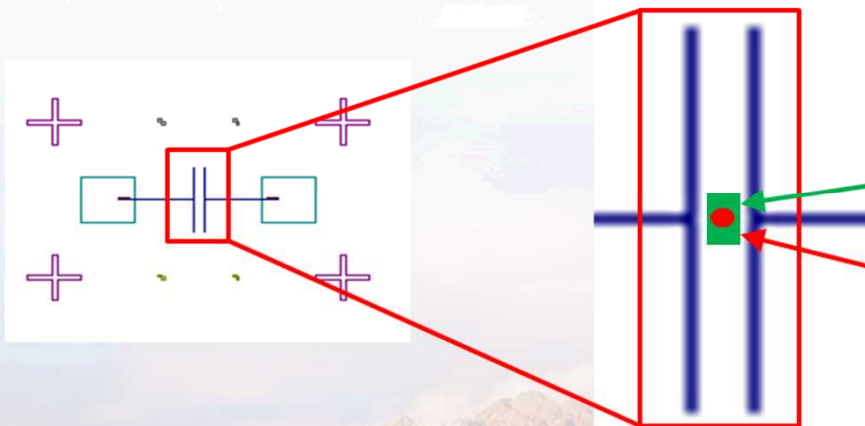
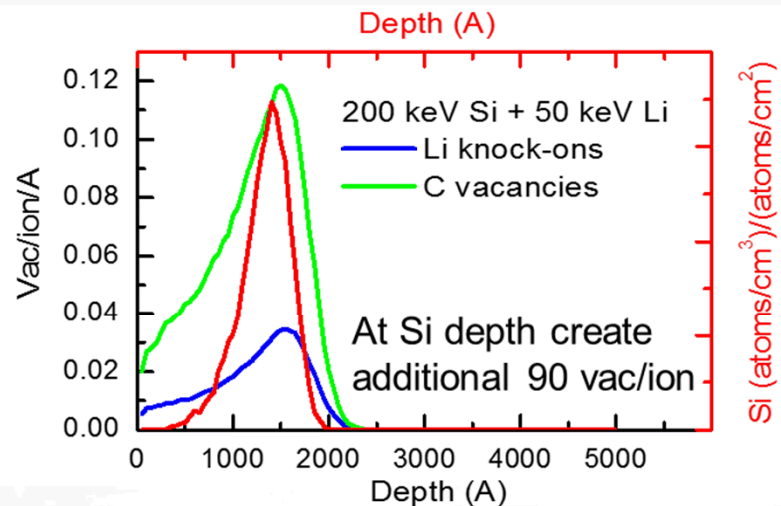


Path to Improving Yield:

200 keV Si



200 keV Si + 50 keV Li



- 1.) Align to markers
- 2.) **Implant 50 keV Li area**
- 3.) Switch to Si beam, realign
- 4.) **Implant 200 keV Si spots**

Alignment with <20 nm resolution

Use the direct write capability of the nl to introduce excess C vacancies at the appropriate depth relative to the Si implants





Single Ions for Materials Science

- From small ions grow big problems (SEE in electronics)
- On the cusp of nanosecond(s) time-resolved in-situ imaging of single ion effects in materials
- We have demonstrated everything needed to put a single ion where you want it to do something interesting

