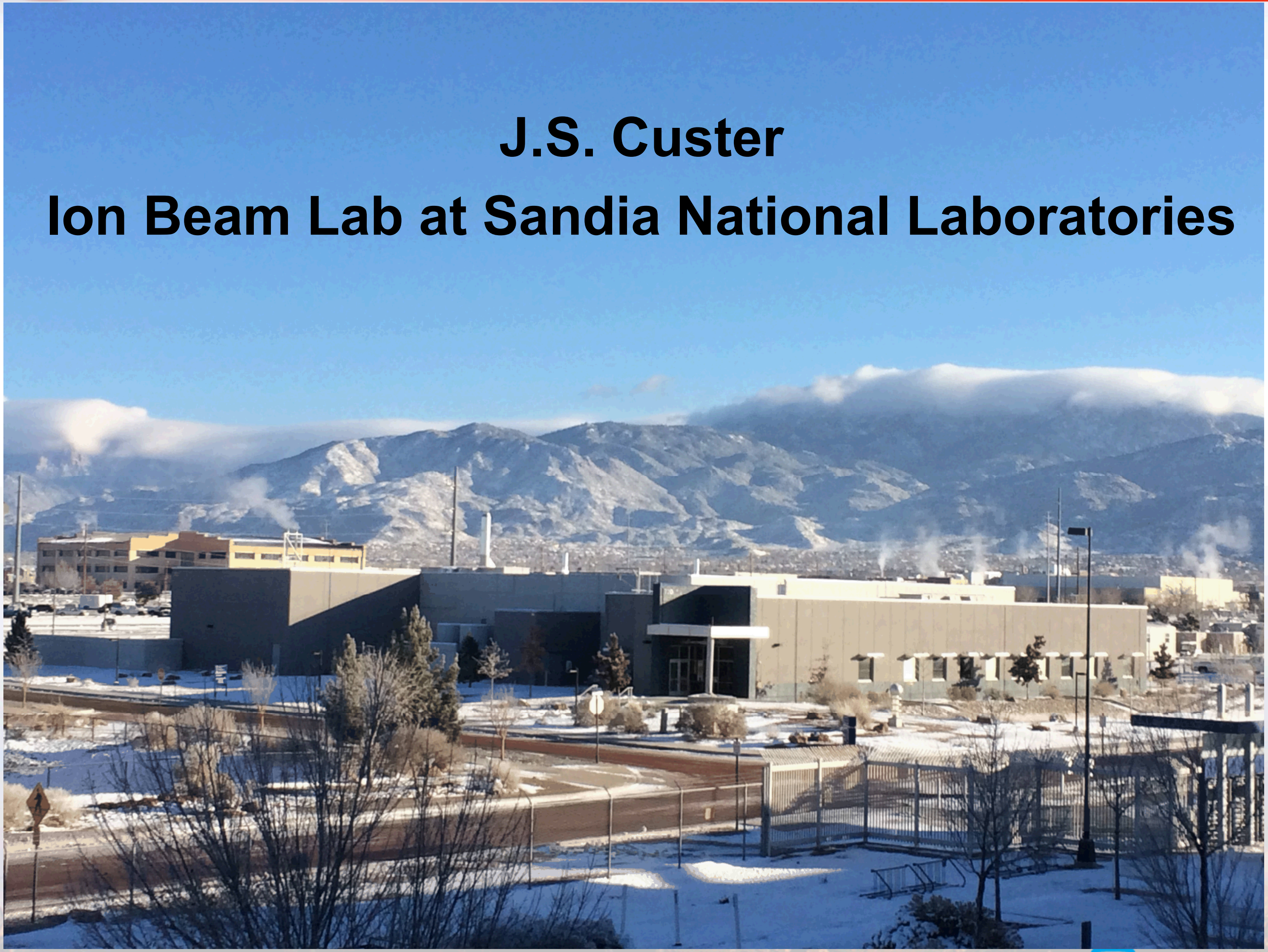
Single-Ion Materials Science

SAND2016-6567C

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

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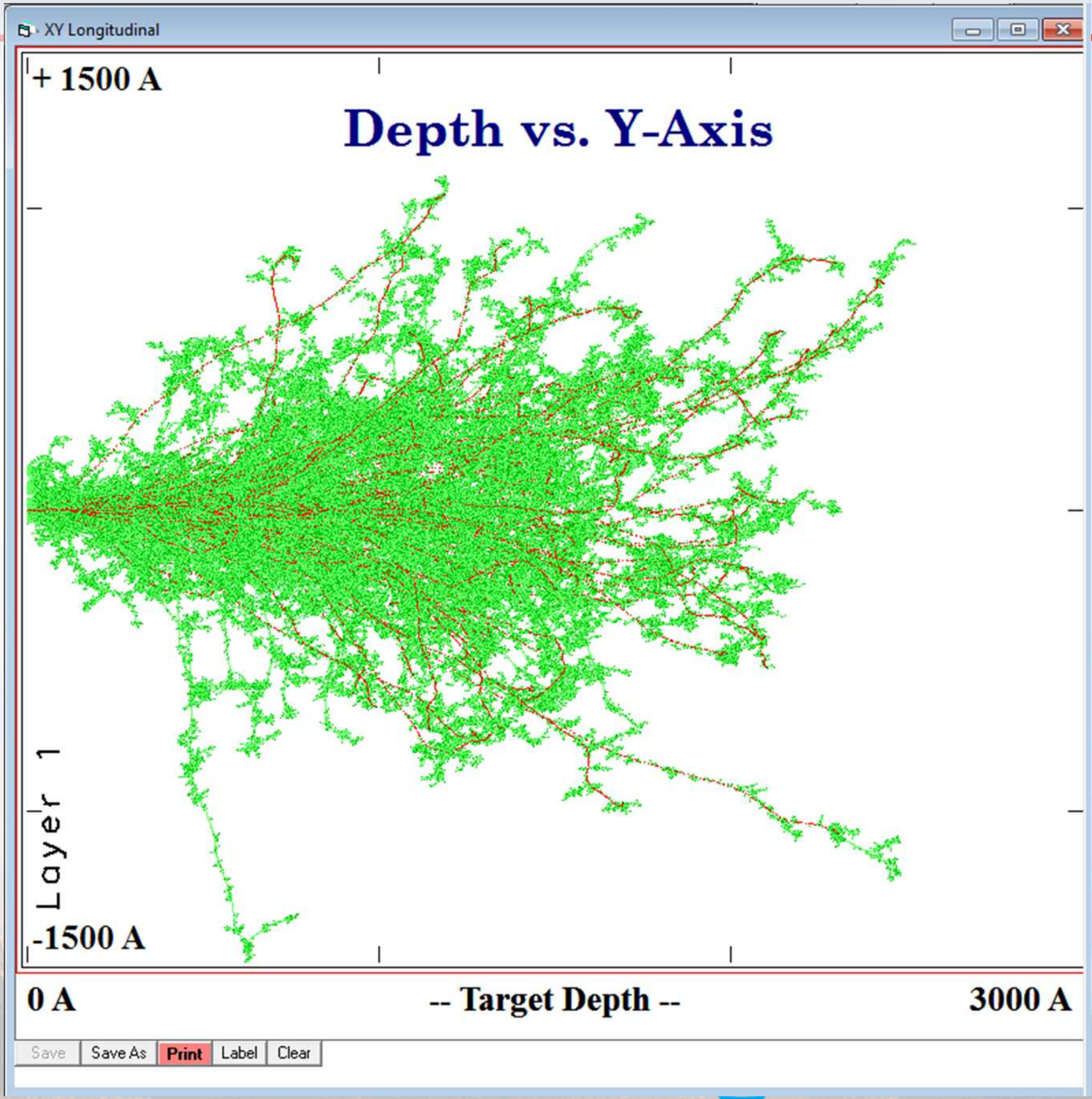
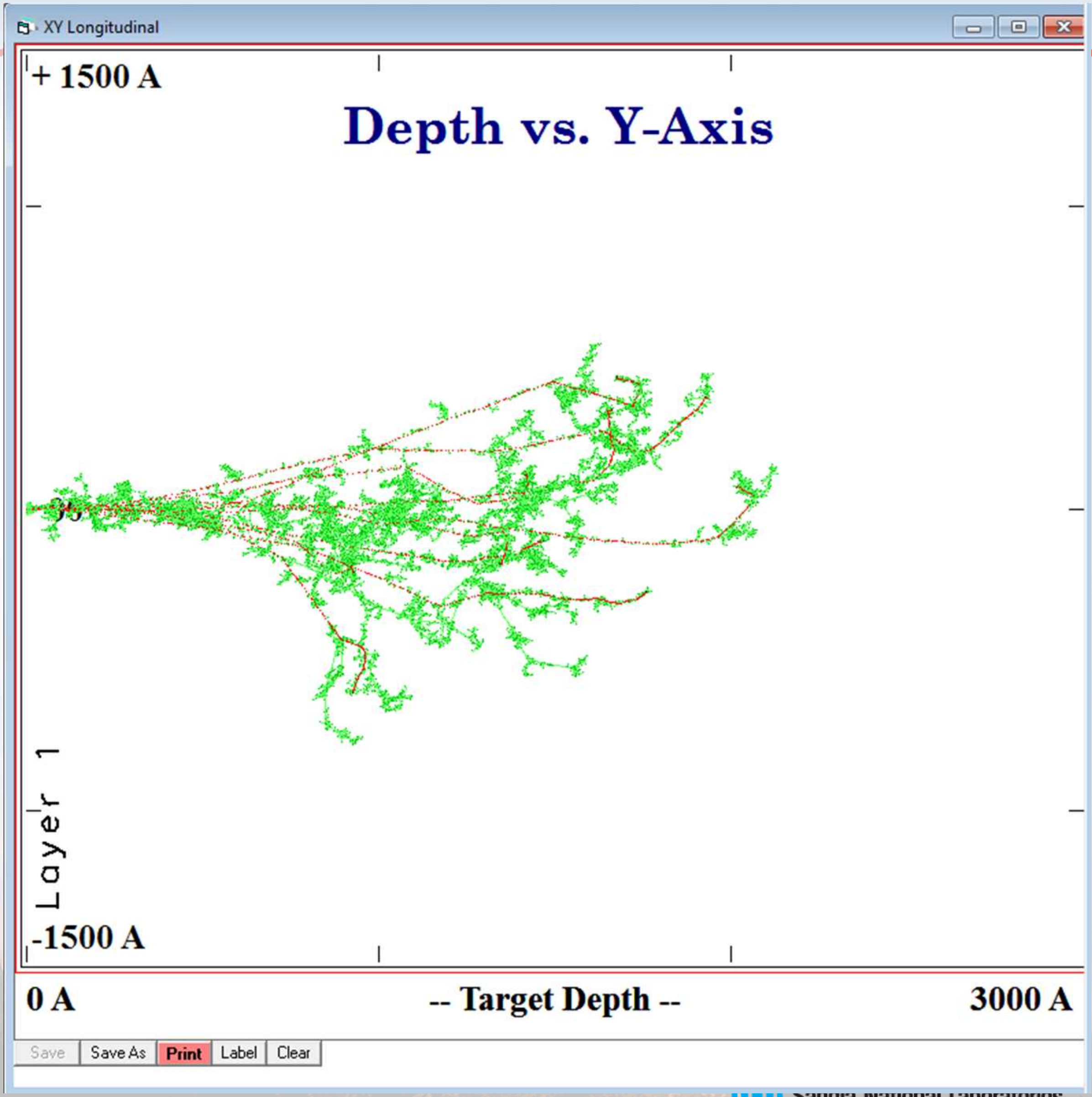
We have all used SRIM (TRIM)

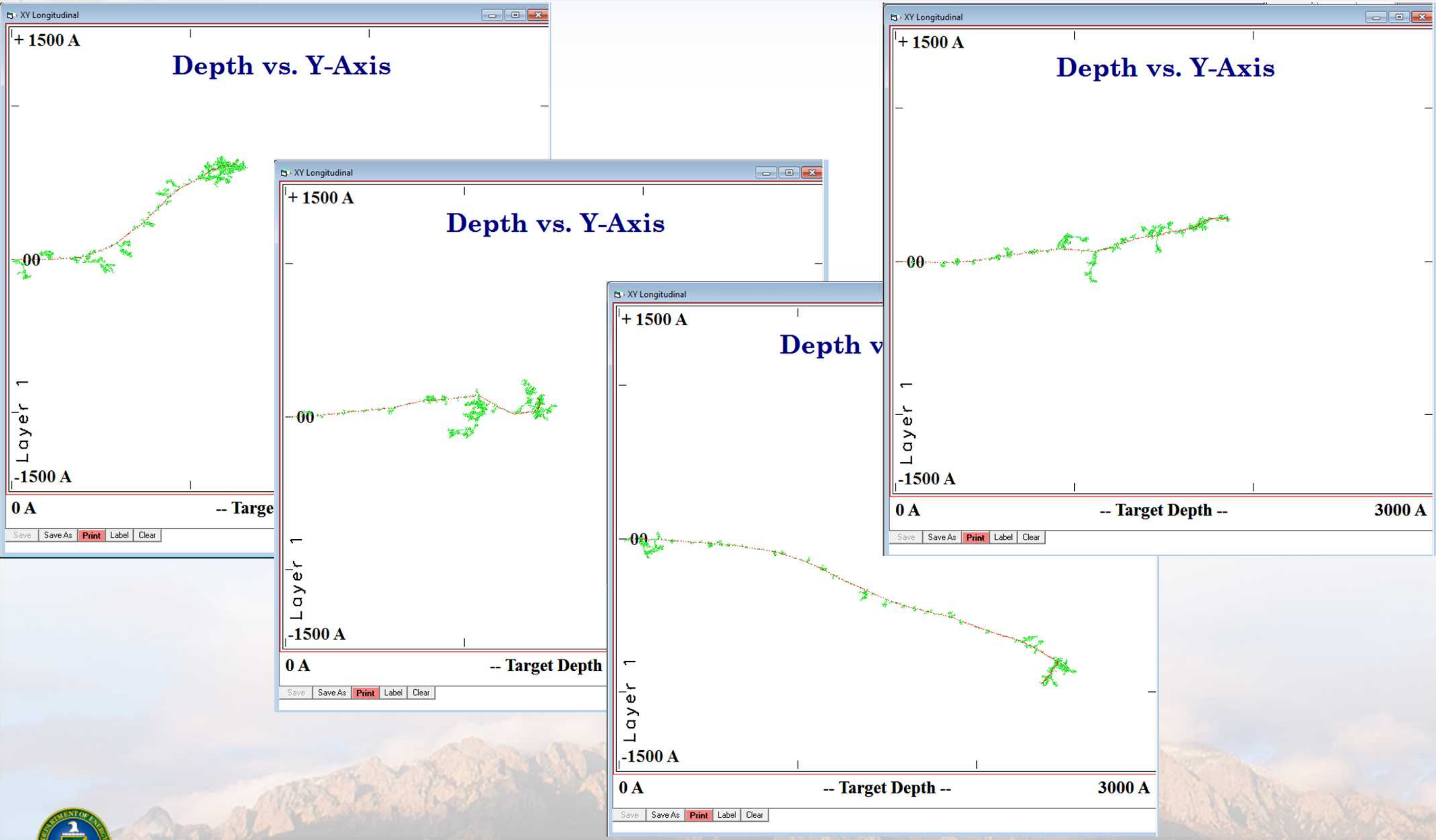
- **100keV Si -> Si**
- **100 ions**
- **Big mess of damage!**
- **Lots of different ion paths**
- **Stochastic variability**
  - Where it ends up
  - Displacement damage
  - Electronic excitation



- 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

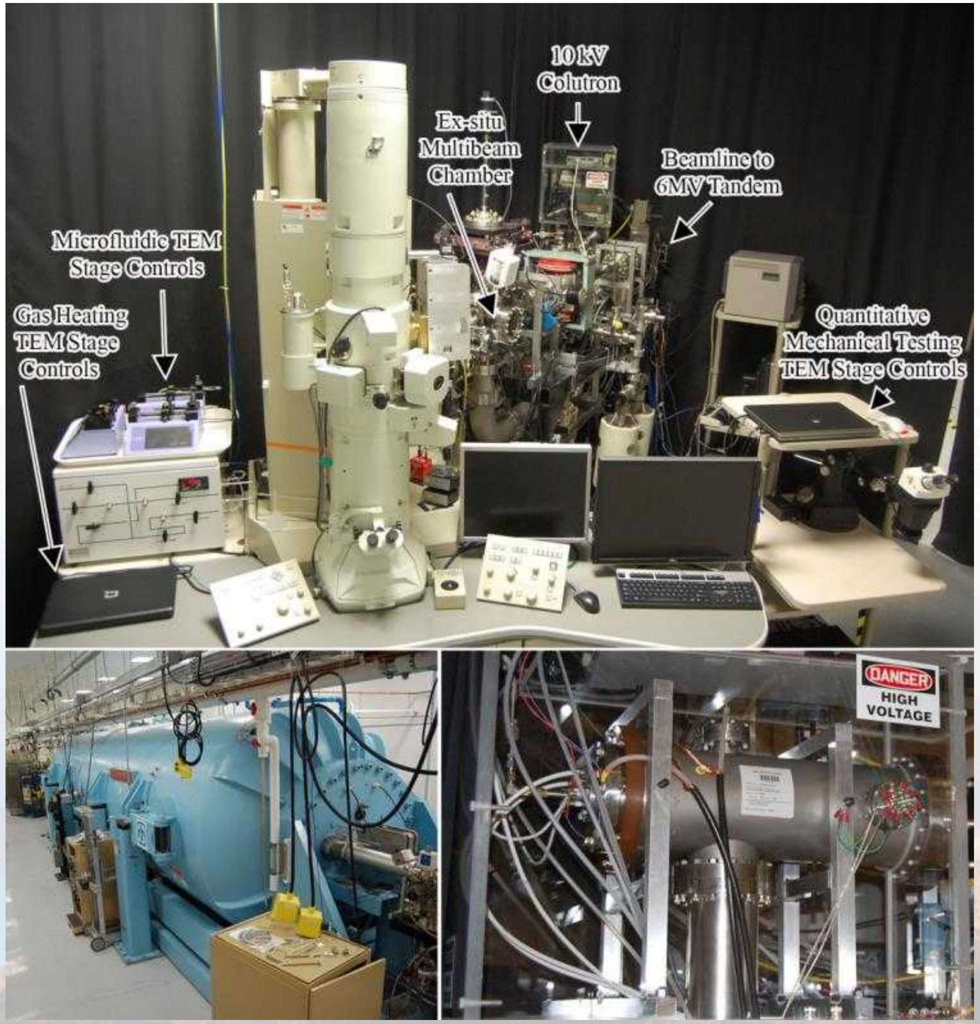
Just One Ion…

- 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)

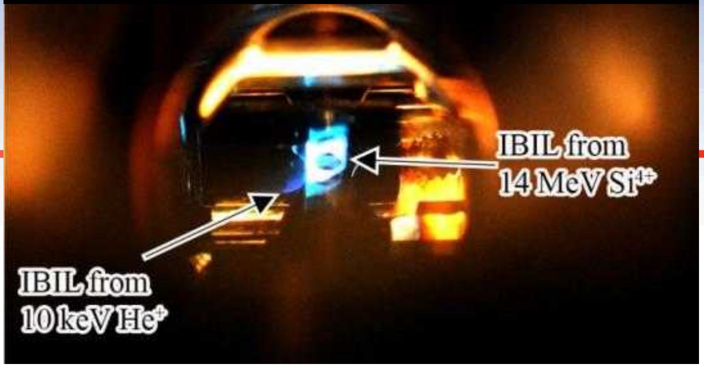
Sandia's Concurrent *In situ* Ion Irradiation TEM Facility

Khalid Hattar, Dan Buller

6 MV Tandem - 10 kV Colutron - 200 kV TEM

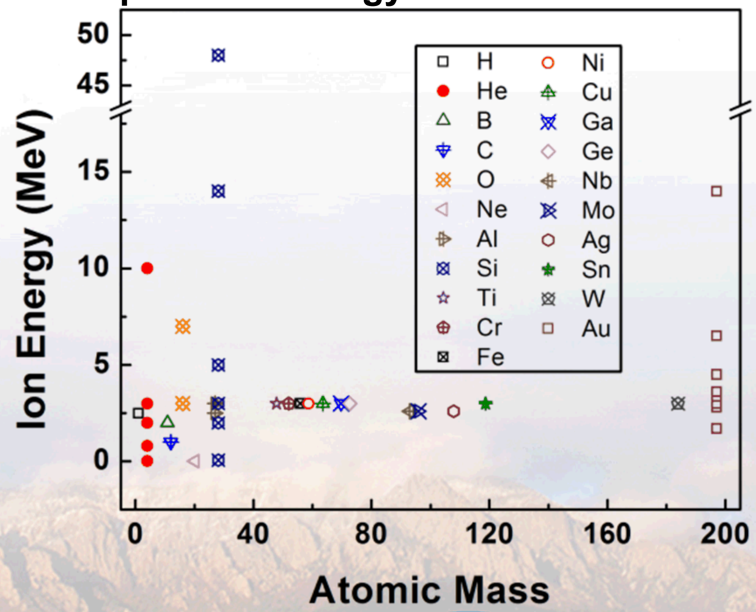


IBIL from a quartz stage inside the TEM



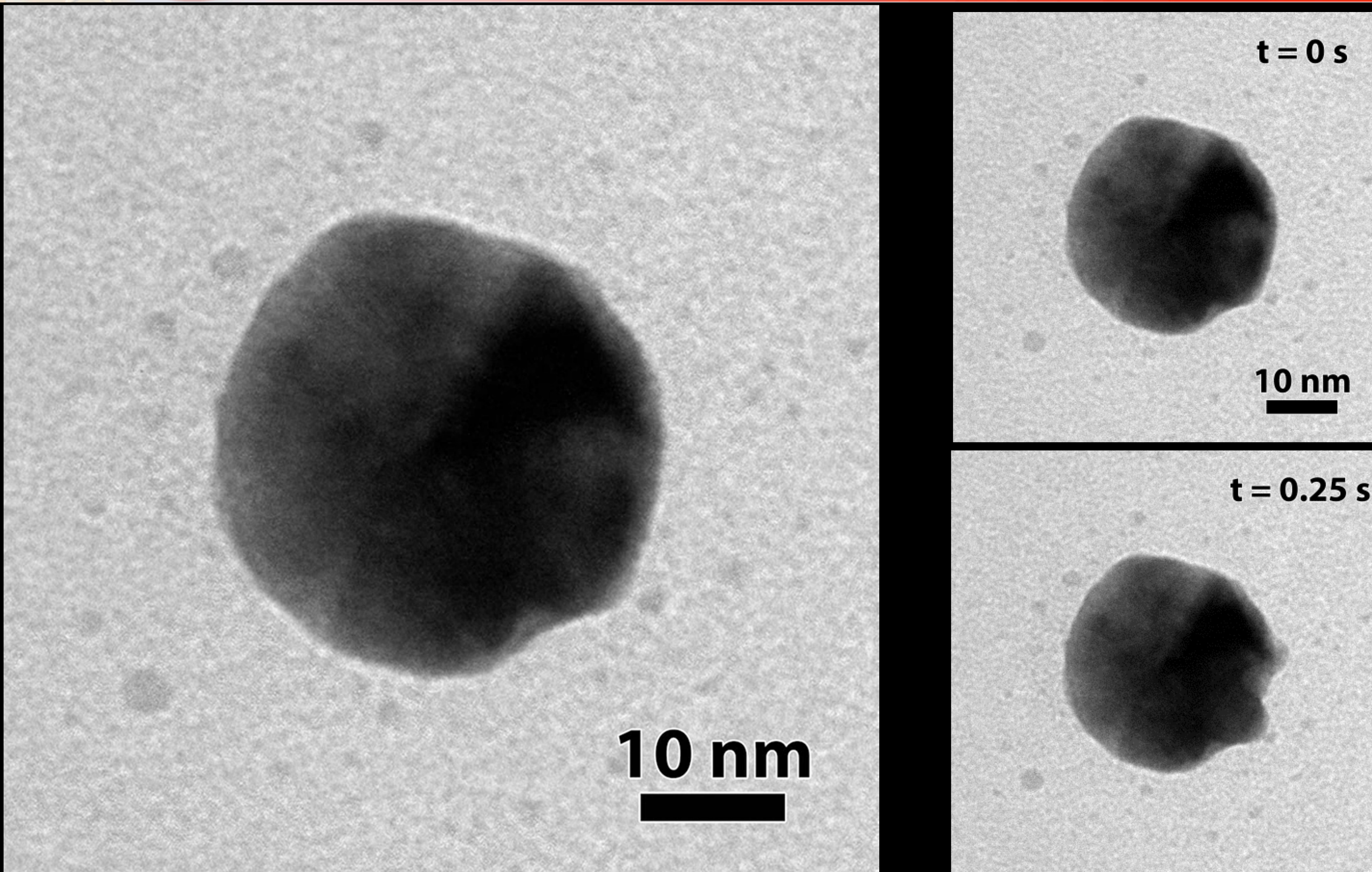
Direct real time observation of ion irradiation, ion implantation, or both with nanometer resolution

Ion species & energy introduced into the TEM



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

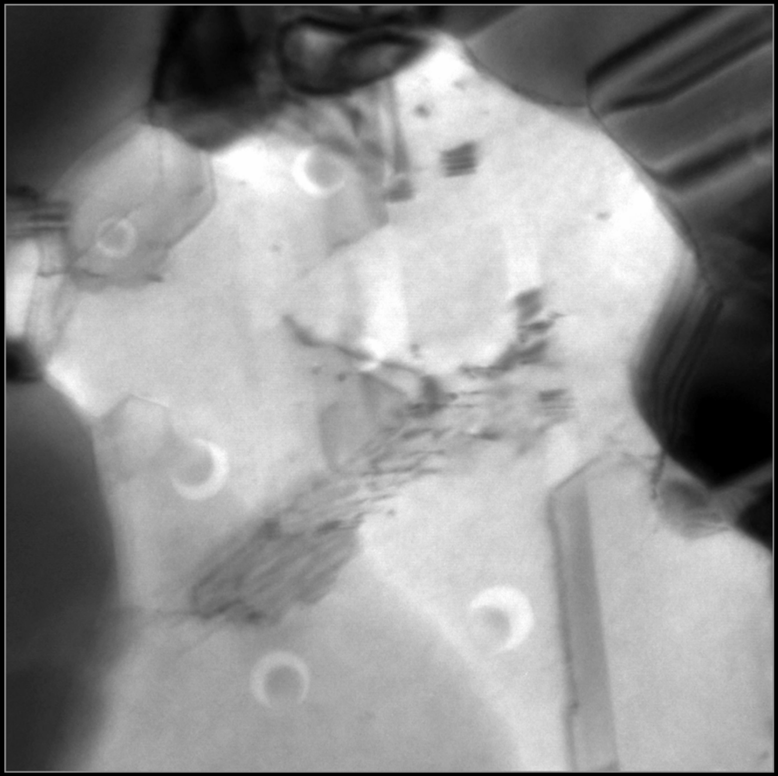
Khalid Hattar, Daniel Bufford



Single Ion Strikes – 2.8MeV Au^{4+} into/through Au film

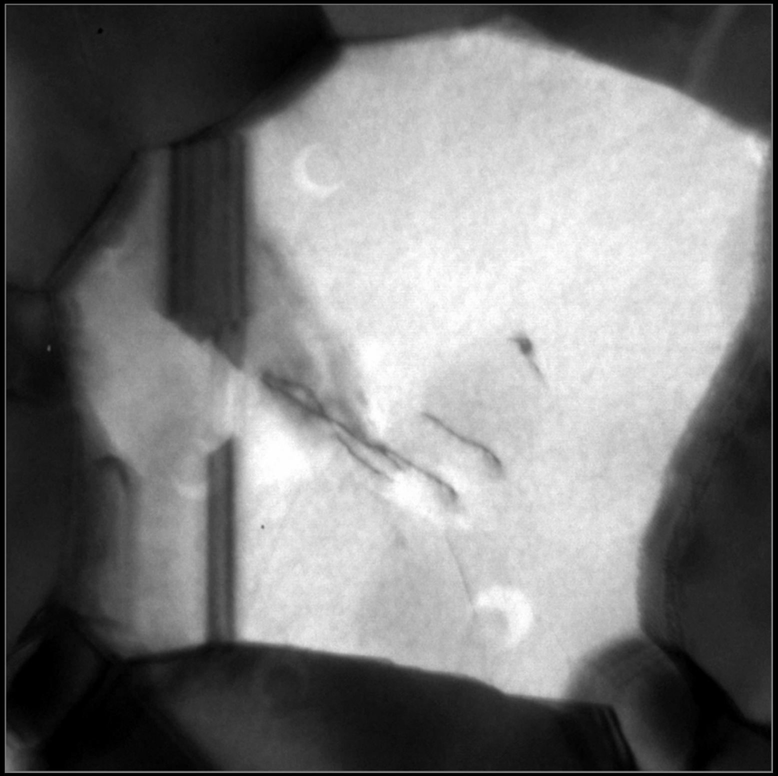
Khalid Hattar with collaborators C. Chisholm and A. Minor (UC Berkeley)

7.9×10^9 ions/cm^2/s



VS

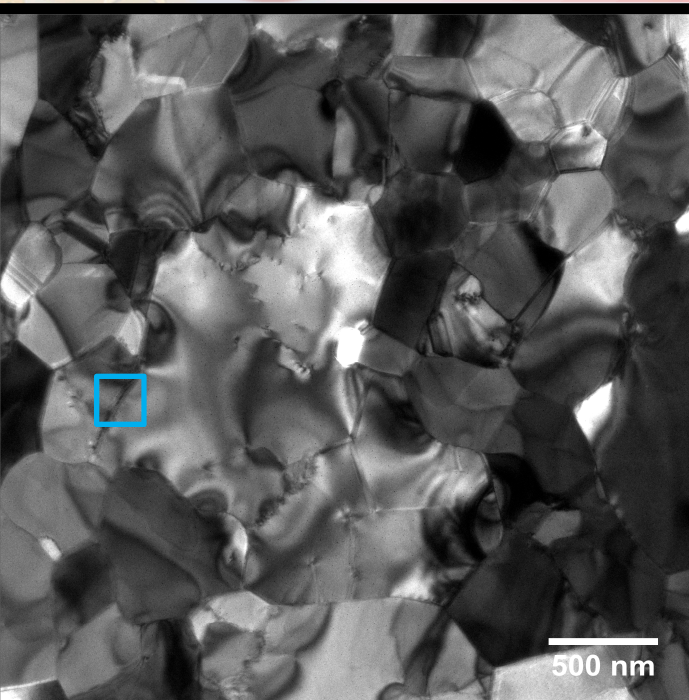
6.7×10^7 ions/cm^2/s

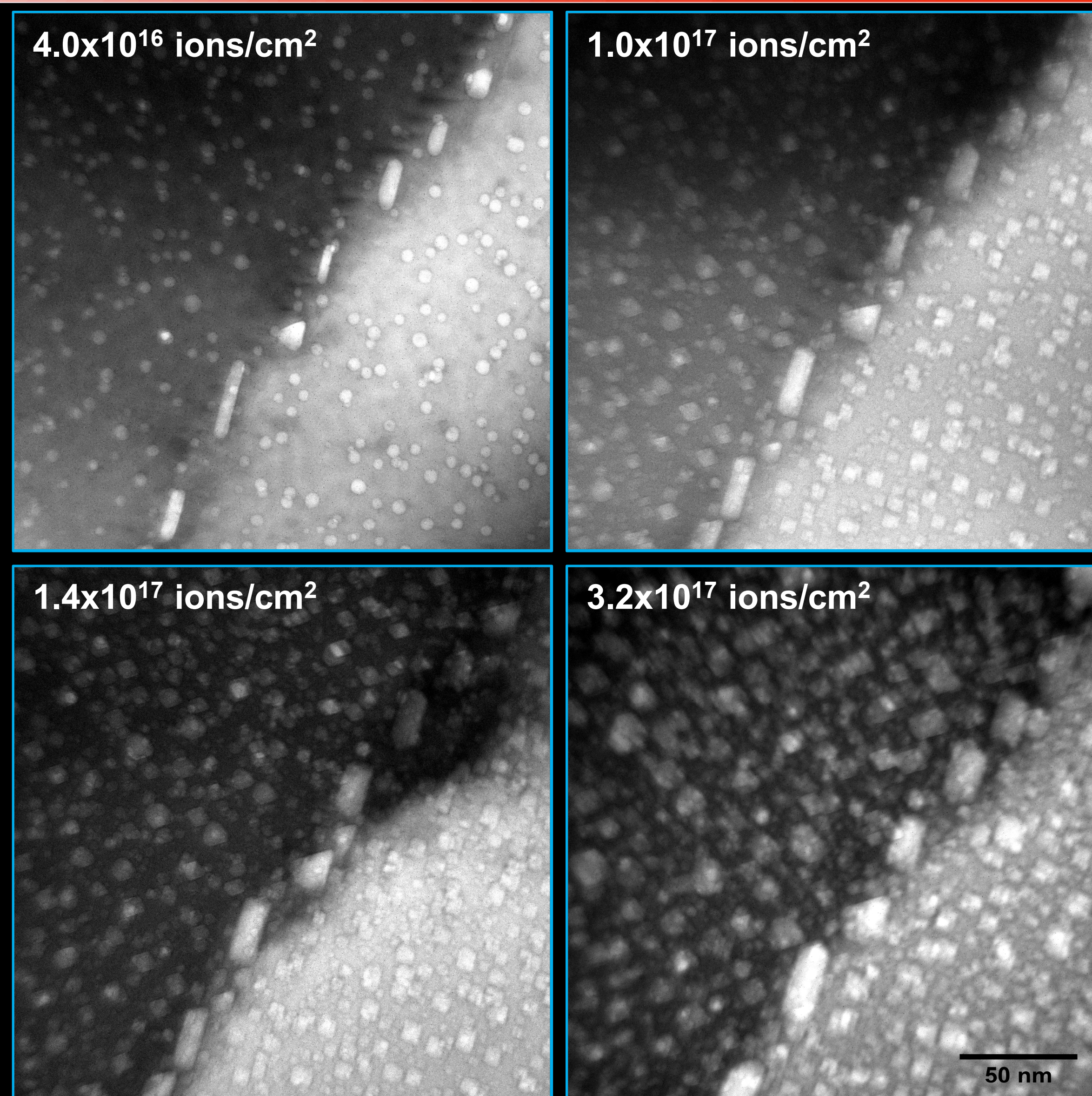


Improved vibrational and ion beam stability permits us to work at 120kx or higher permitting imaging of single cascade events

In situ Implantation: He into Au

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



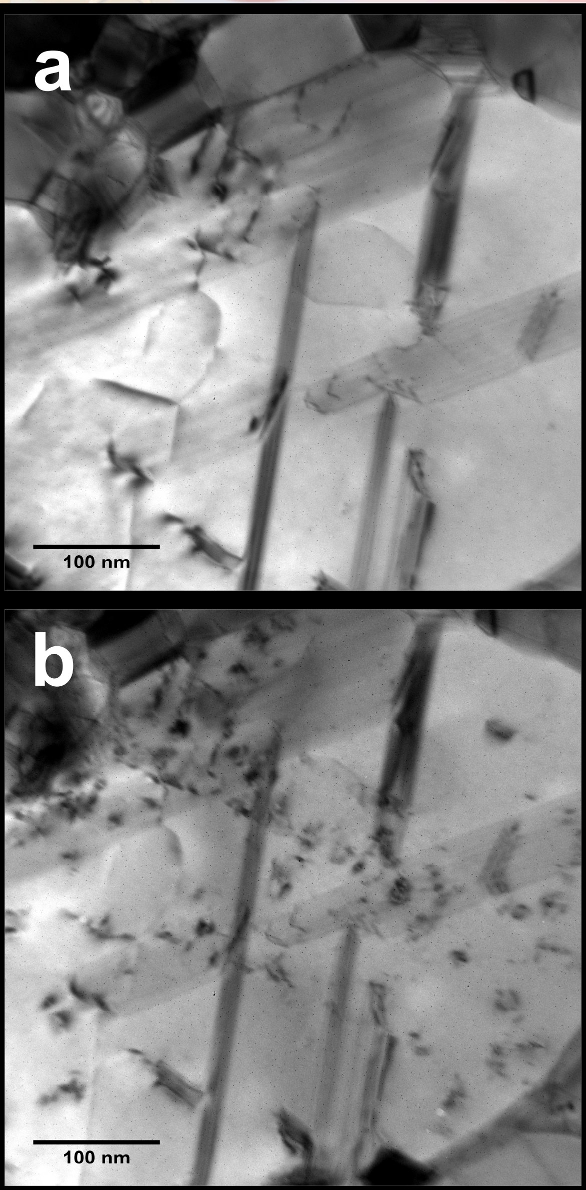


Au implanted with 10keV He^{+}

He bubble formation on grain boundary and in the bulk

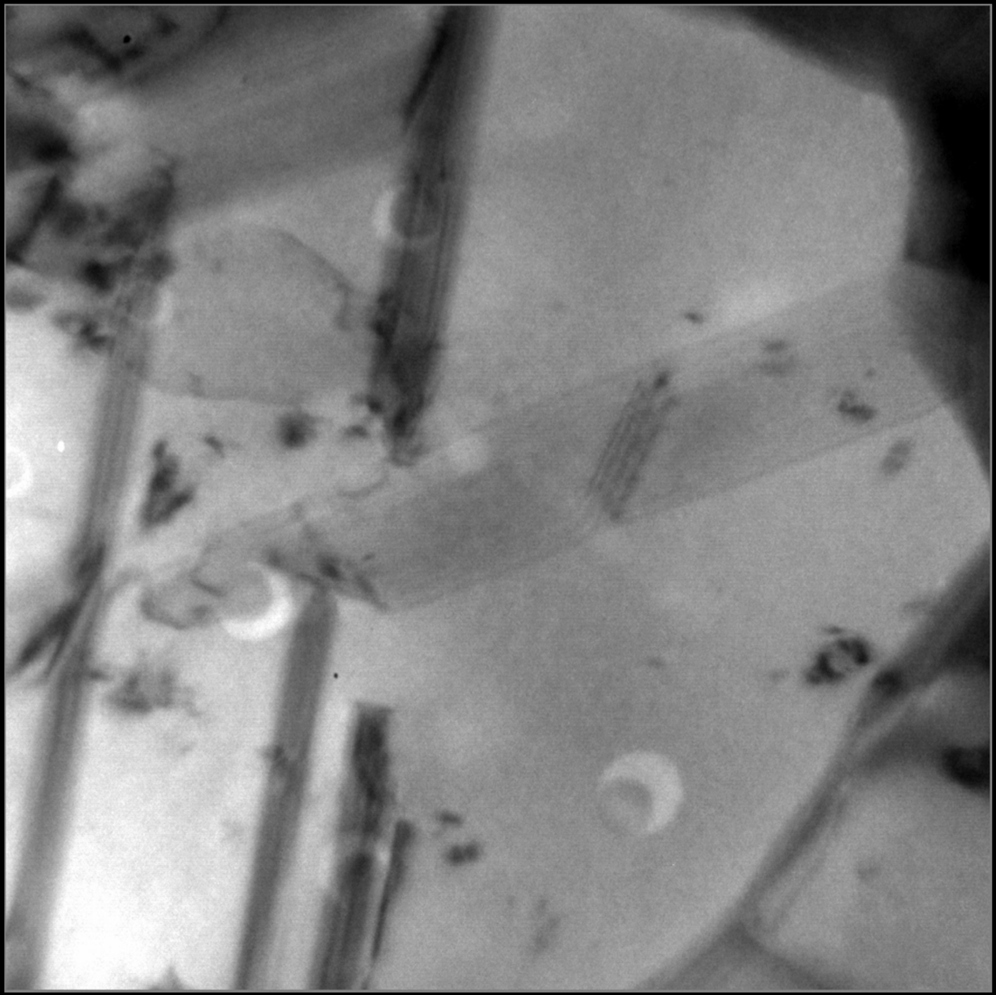
In situ Concurrent Implantation & Irradiation

Collaborators: C. Chisholm & A. Minor

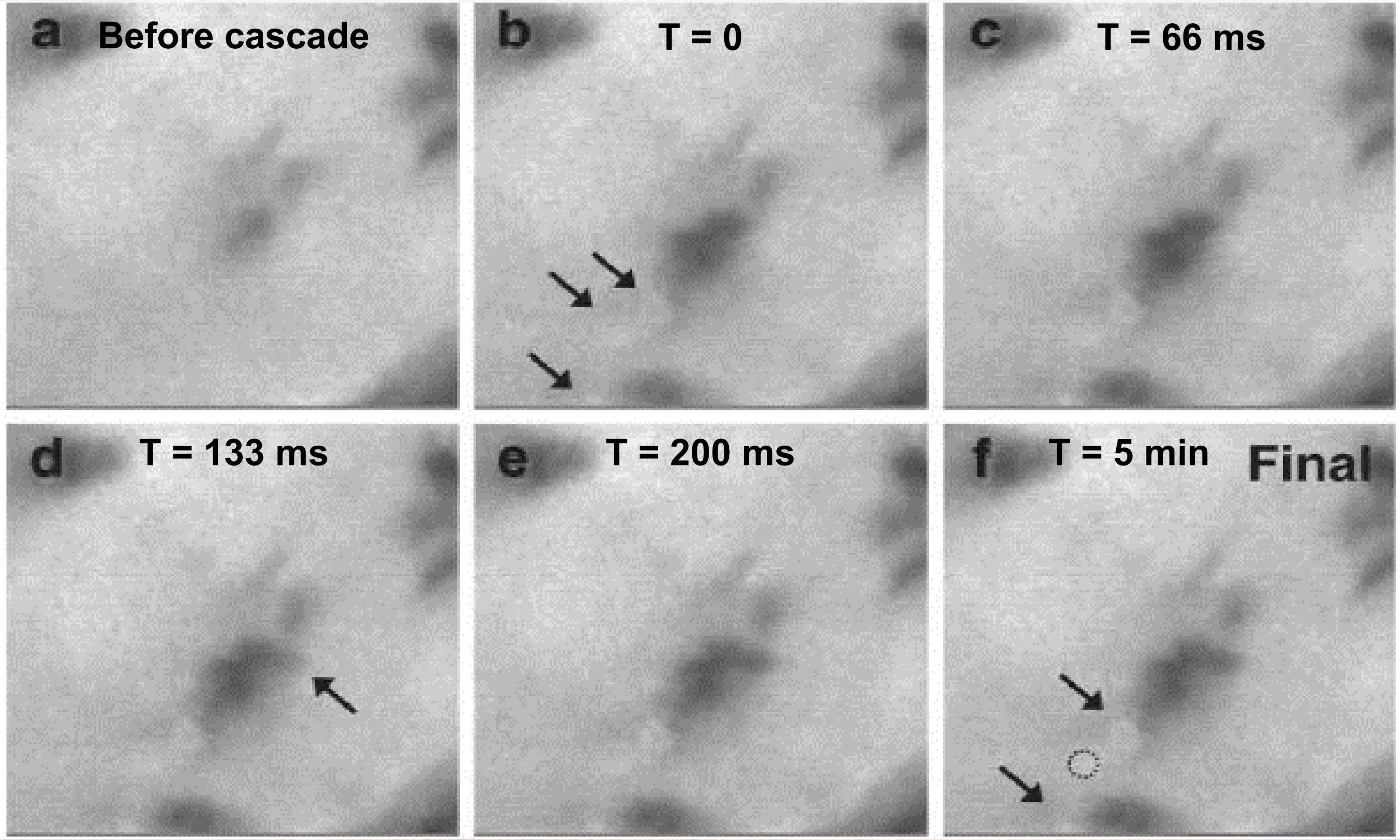


He^{+} implantation and concurrent Au^{4+} irradiation:

Transient bubble formation and dissolution



Concurrent Irradiation: Transient He Bubble formation at Cascade



Devices with Single Ions

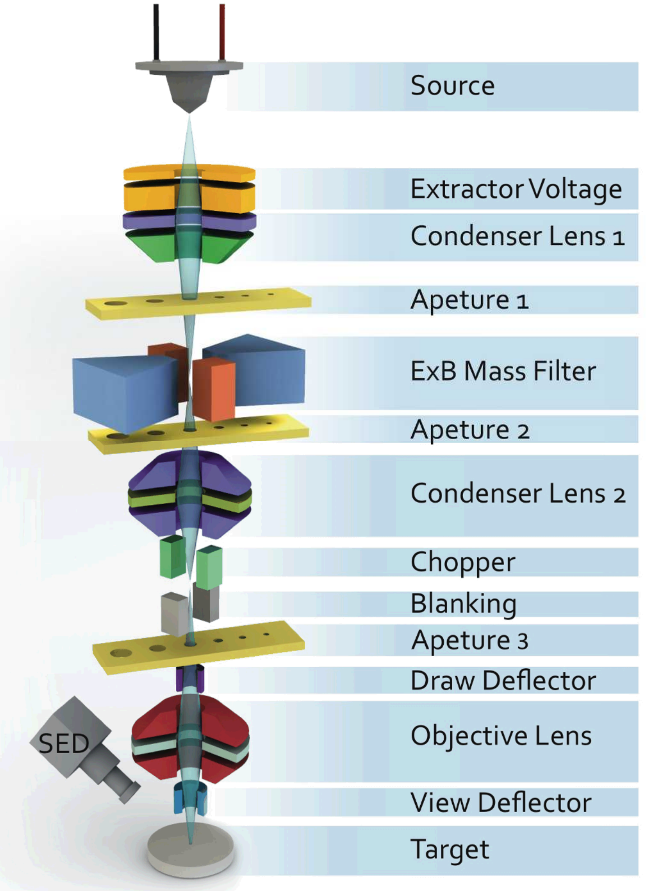
- **Demonstrated imaging and measuring of the effects of single ions on materials, with some control of where the ion strikes (e.g. microbeam)**
- **But, a wide range of applications for *placing* one ion in a specific place**
  - Quantum bits – donors in Si devices
  - Single photon sources – impurity-defect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

Applications to Quantum Bit Fabrication

- Team: J. L. Pacheco, M. Singh, D. L. Perry, E. Garratt, J. R. Wendt, G. Ten Eyck, N.C. Bishop, R. P. Manginell, J. Dominguez, T. Pluym, D. R. Luhman, M. P. Lilly, M. S. Carroll, and E. Bielejec

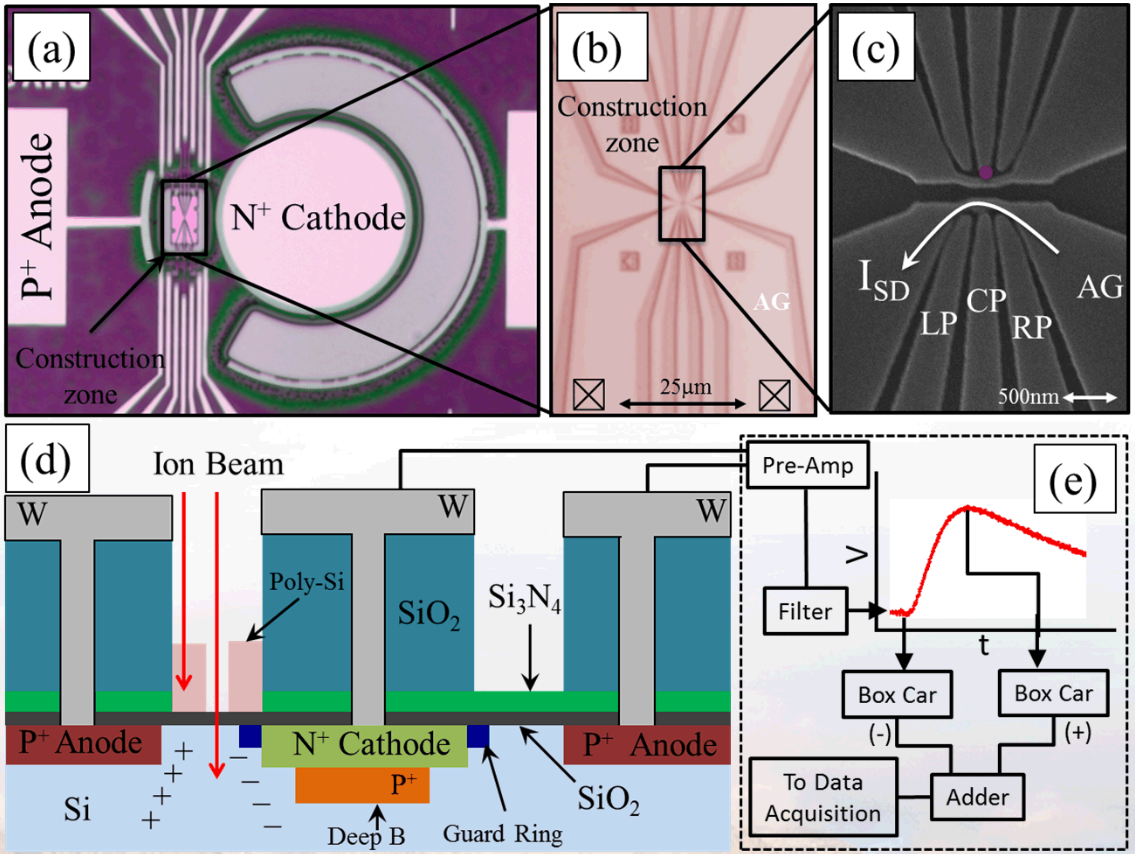
Precision Targeting

- **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**



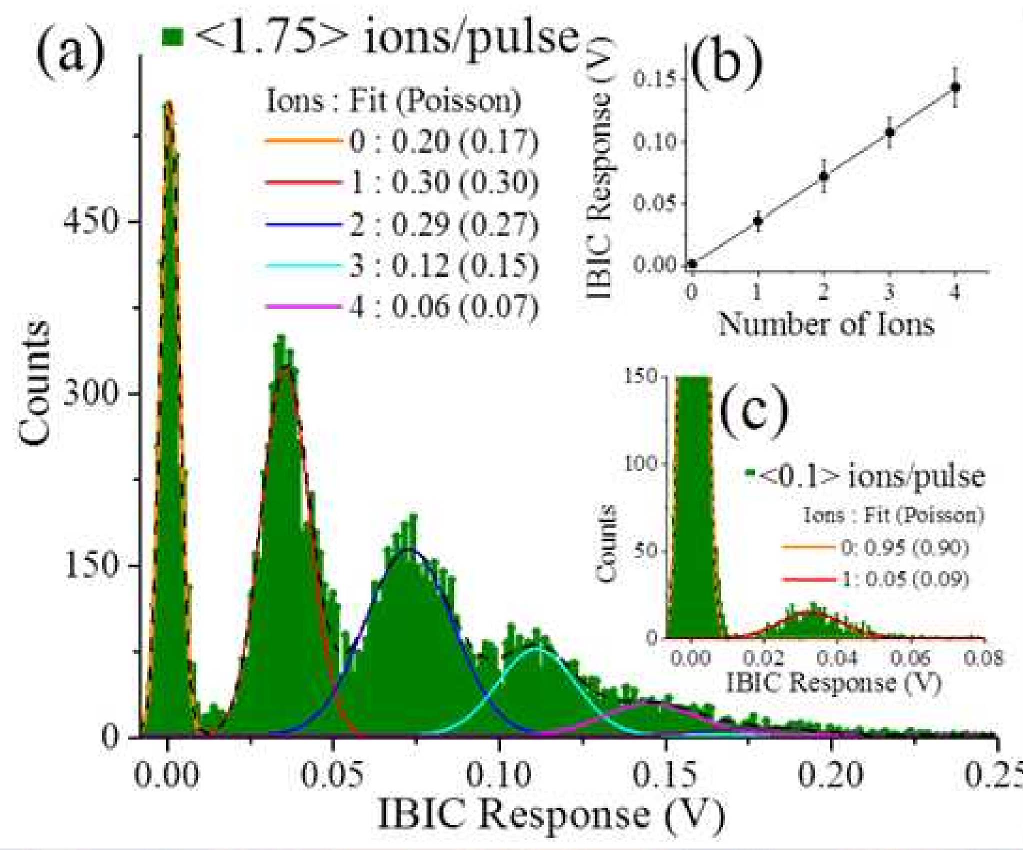
Complexities: Device + Detector

- Making a qubit is hard
- Making a quibit with integrated charge collection to detect single ions is, well, harder
- Charge generated by a single ion is highly dependent on ion/energy
- Total charge generated will vary from ion to ion (consequence of randomness in nuclear stopping)



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



Successful counted ion devices fabricated

APPLIED PHYSICS LETTERS **108**, 062101 (2016)

Electrostatically defined silicon quantum dots with counted antimony donor implants

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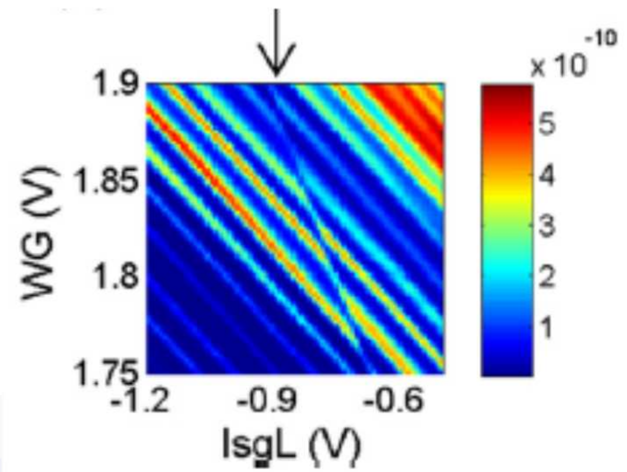
(Received 28 October 2015; accepted 6 January 2016; published online 9 February 2016)

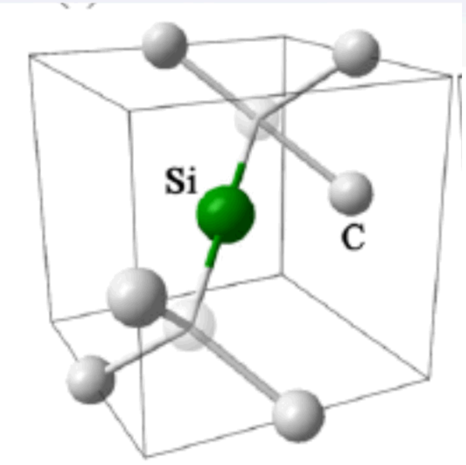
Deterministic control over the location and number of donors is crucial to donor spin quantum bits (qubits) in semiconductor based quantum computing. In this work, a focused ion beam is used to implant antimony donors in 100 nm × 150 nm windows straddling quantum dots. Ion detectors are integrated next to the quantum dots to sense the implants. The numbers of donors implanted can be counted to a precision of a single ion. In low-temperature transport measurements, regular Coulomb blockade is observed from the quantum dots. Charge offsets indicative of donor ionization are also observed in devices with counted donor implants.
[http://dx.doi.org/10.1063/1.4940421]

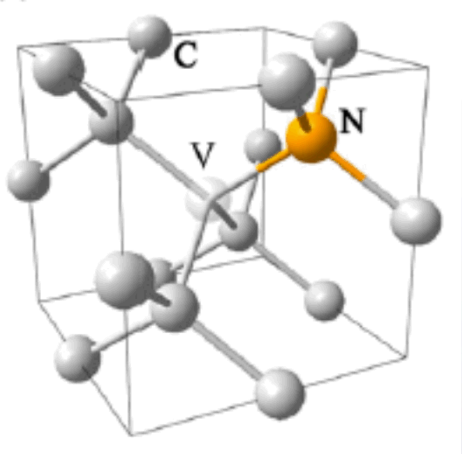


Transport measurements at 2K Show Coulomb blockade and charge offsets as expected

Where else 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**



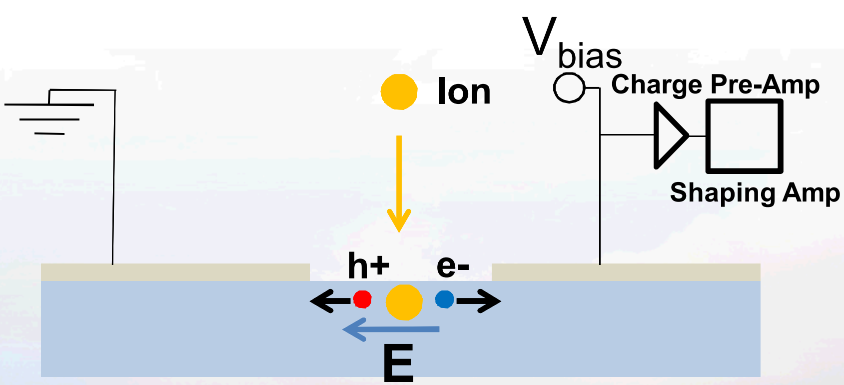


Source: I. Aharonovich et al., Rep. Prog. Phys. 74 (2011) 076501

Counting Ions in Diamond

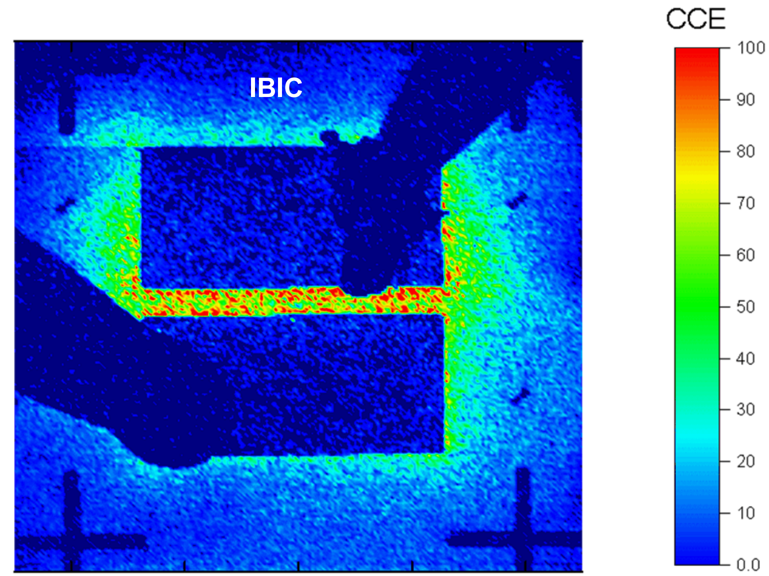
- It takes very little to make an ion-beam induced charge collector
- No diode needed – apply a field across a gap and collect charge

Ion Beam Induced Charge (IBIC):



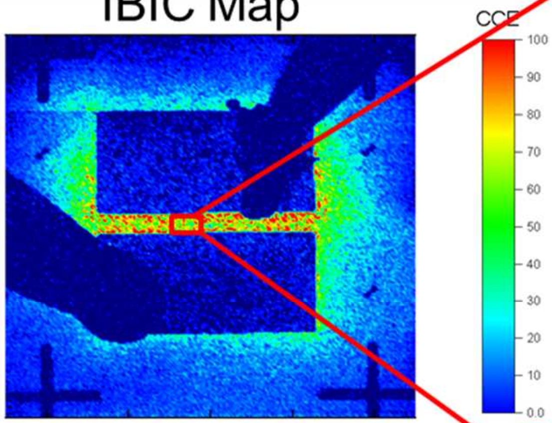
Side View

$$\text{CCE} = \frac{\text{Charge Collected}}{\text{Charge Depositied}}\ x\ 100$$

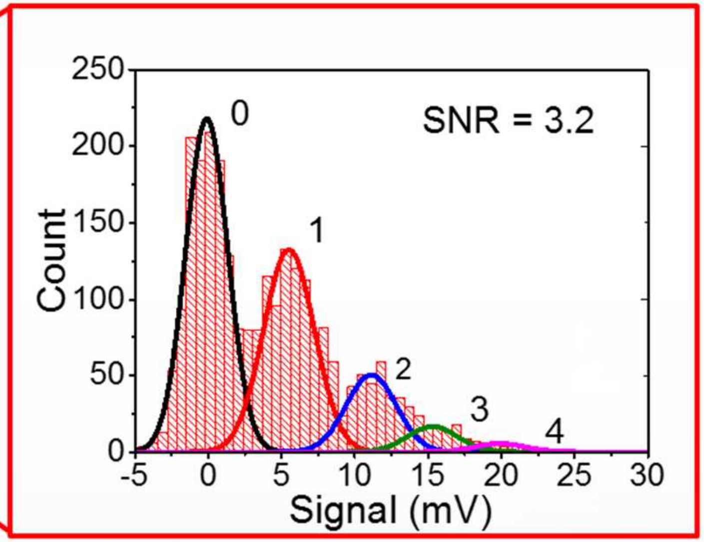


Single Ion Detection in Diamond Demonstrated

IBIC Map



Quantized Detection <0.65> ion

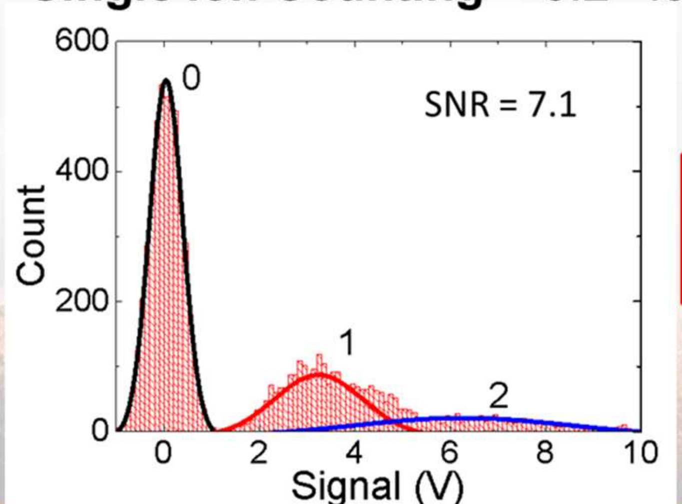


$$SNR = \frac{\mu_{signal}}{\mu_{noise} + \sigma_{noise}}$$

Signal amplitudes match Poisson statistics to 4%

Optimizing gain for single ion detection

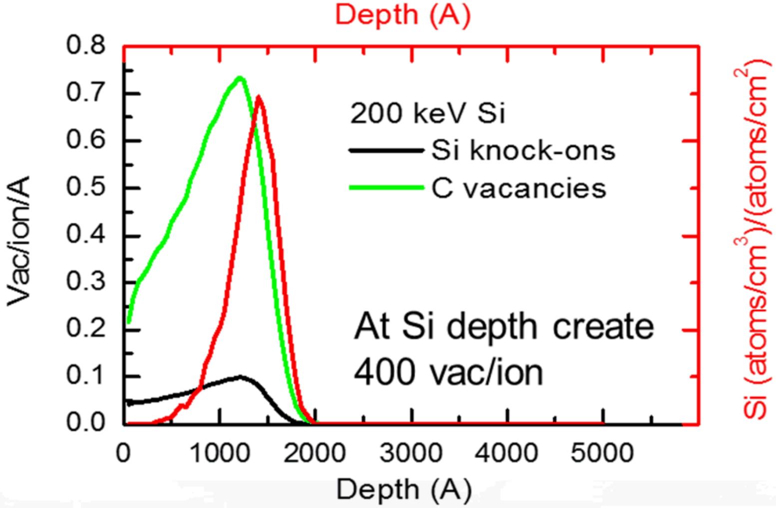
Single Ion Counting <0.2> ion



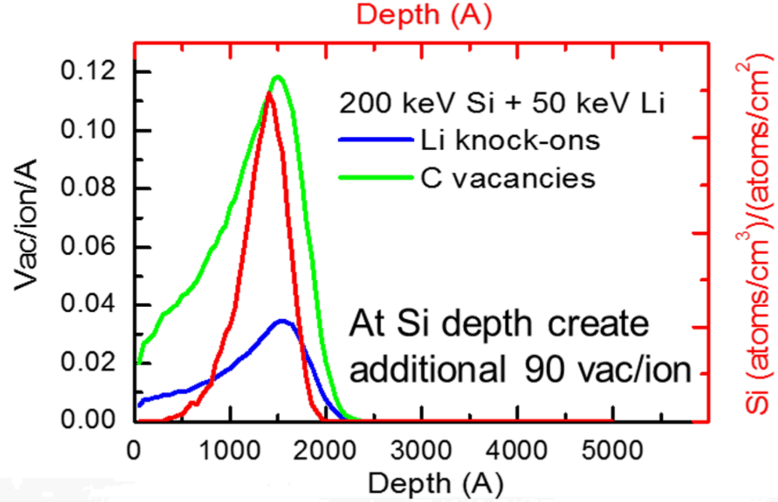
Single Ion Detection in Diamond with SNR ~10

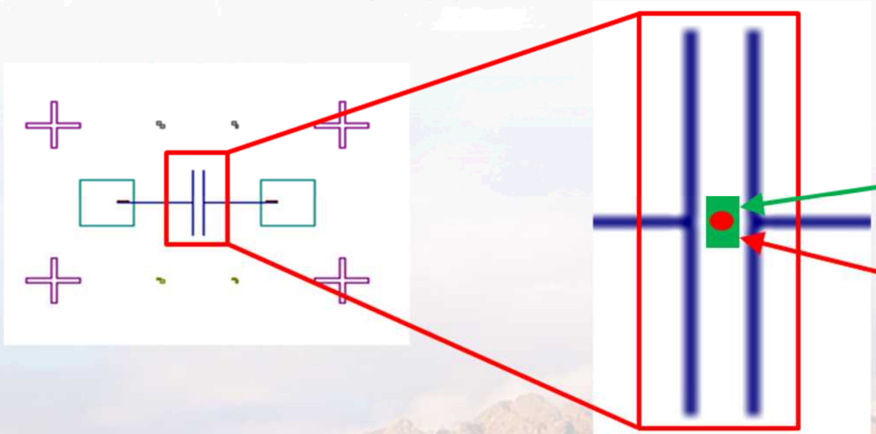
Path to Improving Yield:

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 nI 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