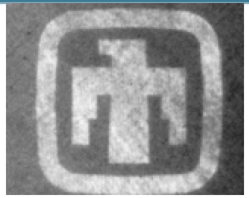
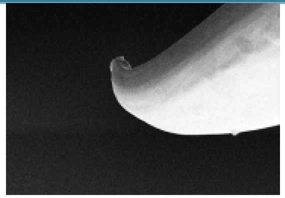
SAND2021-15473C

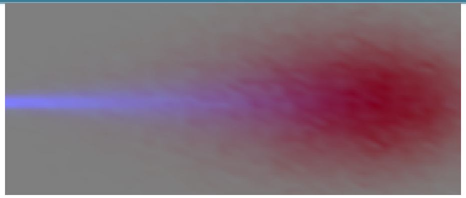
Sandia National Laboratories

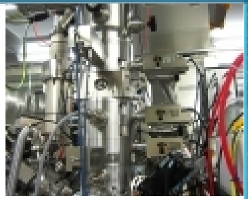
In-Situ Ion Counting for Deterministic Placement of Single Photon Emitters

Center for Integrated Nanotechnologies
CINT
Sandia
Los Alamos









FIB Capabilities available for user projects

Michael Titze, Heejun Byeon, Anthony Flores, Jacob Henshaw, Tom Harris, Andrew Mounce, Edward S. Bielejec

12/07/2021

U.S. DEPARTMENT OF ENERGY
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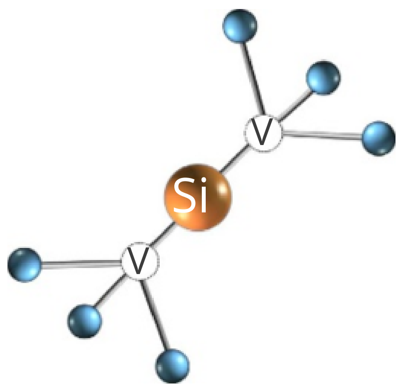
Deterministic Ion Implantation

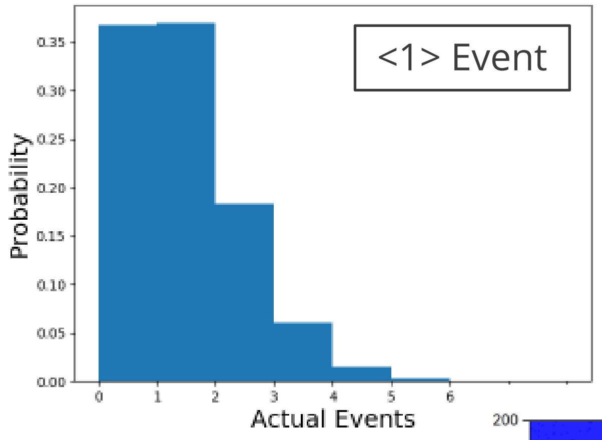


Y. Zhou et al., Nat. Comm. 8, 14451 (2017)

- Solid-state defects enable scalable quantum applications
- Color-centers are possible candidate
  - Single photon emitters require low number of ions
    - Precisely measure the conversion yield

Typical Ion Implantation Experiment:

- Measure Beam Current, then do timed implantation
  - No real-time feedback of beam current
  - Limited by Poisson statistics

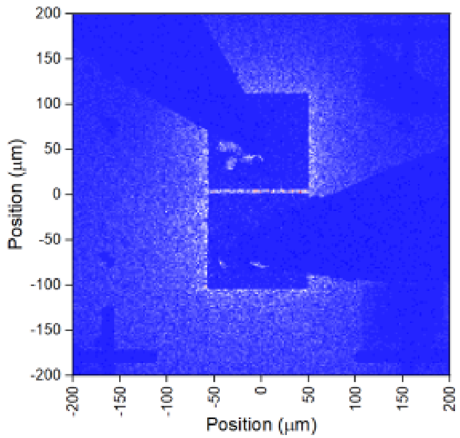


Our approach:

In-situ counting → Detect ions as they are implanted

In-situ photoluminescence → Detect color centers as they are formed

See EQ01.03.03 V. Chandrasekaran for details



Problems with Deterministic Defect Creation

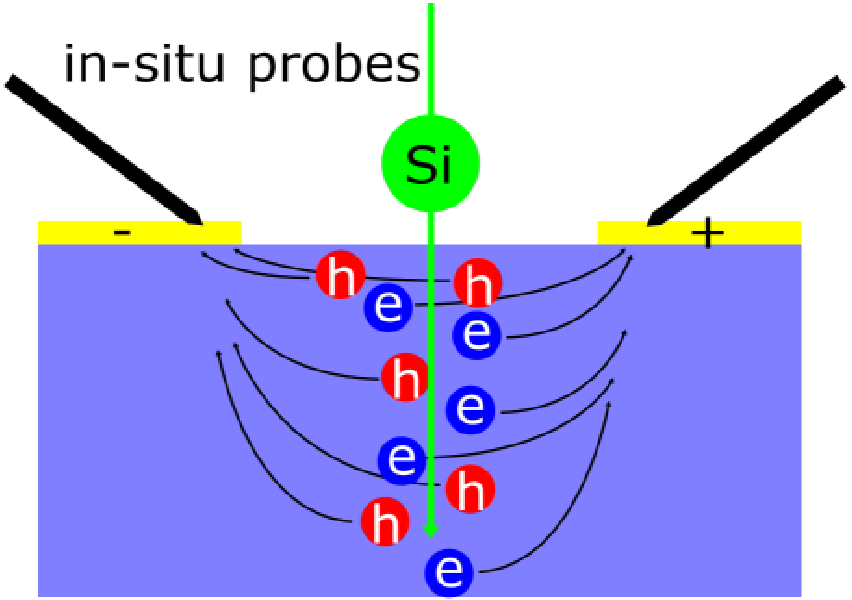
1. Few-ion implants dominated by Poisson statistics

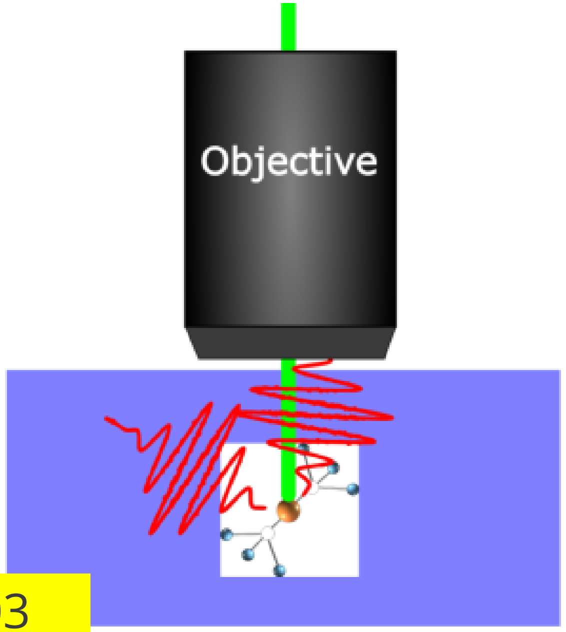
→ In-situ counting of ions can beat Poisson statistics

$$\text{Yield} = \frac{\#\text{Measured SiV}}{\#\text{Implanted Si}}$$

2. Low yield of optically active defects

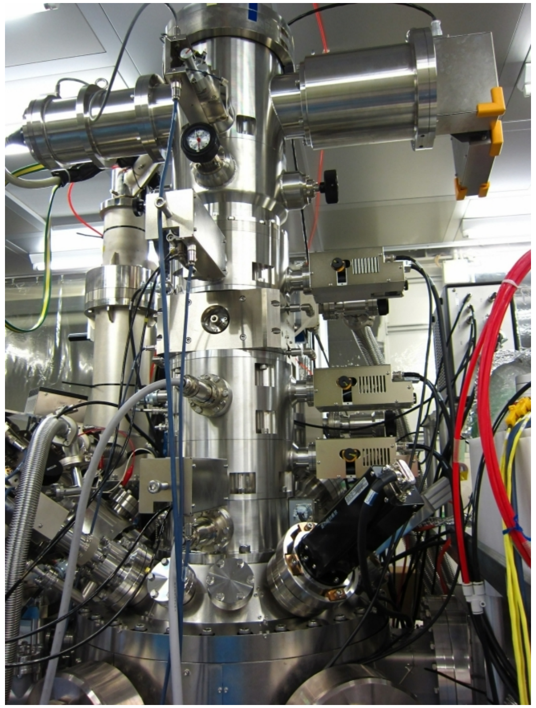
In-situ photoluminescence (PL) measures color centers





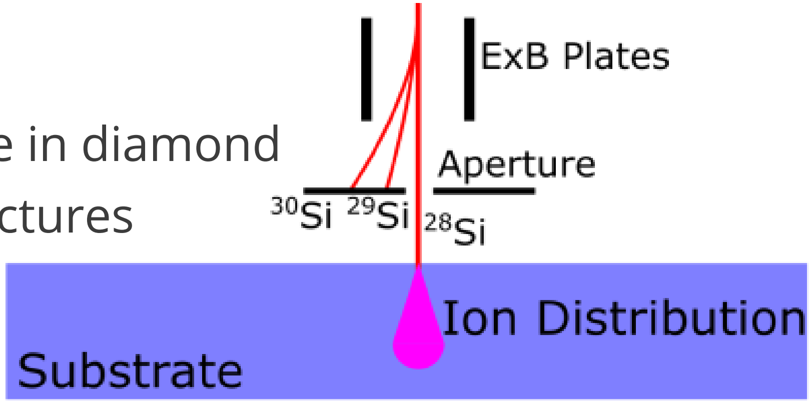
See EQ01.03.03
V. Chandrasekaran
for details

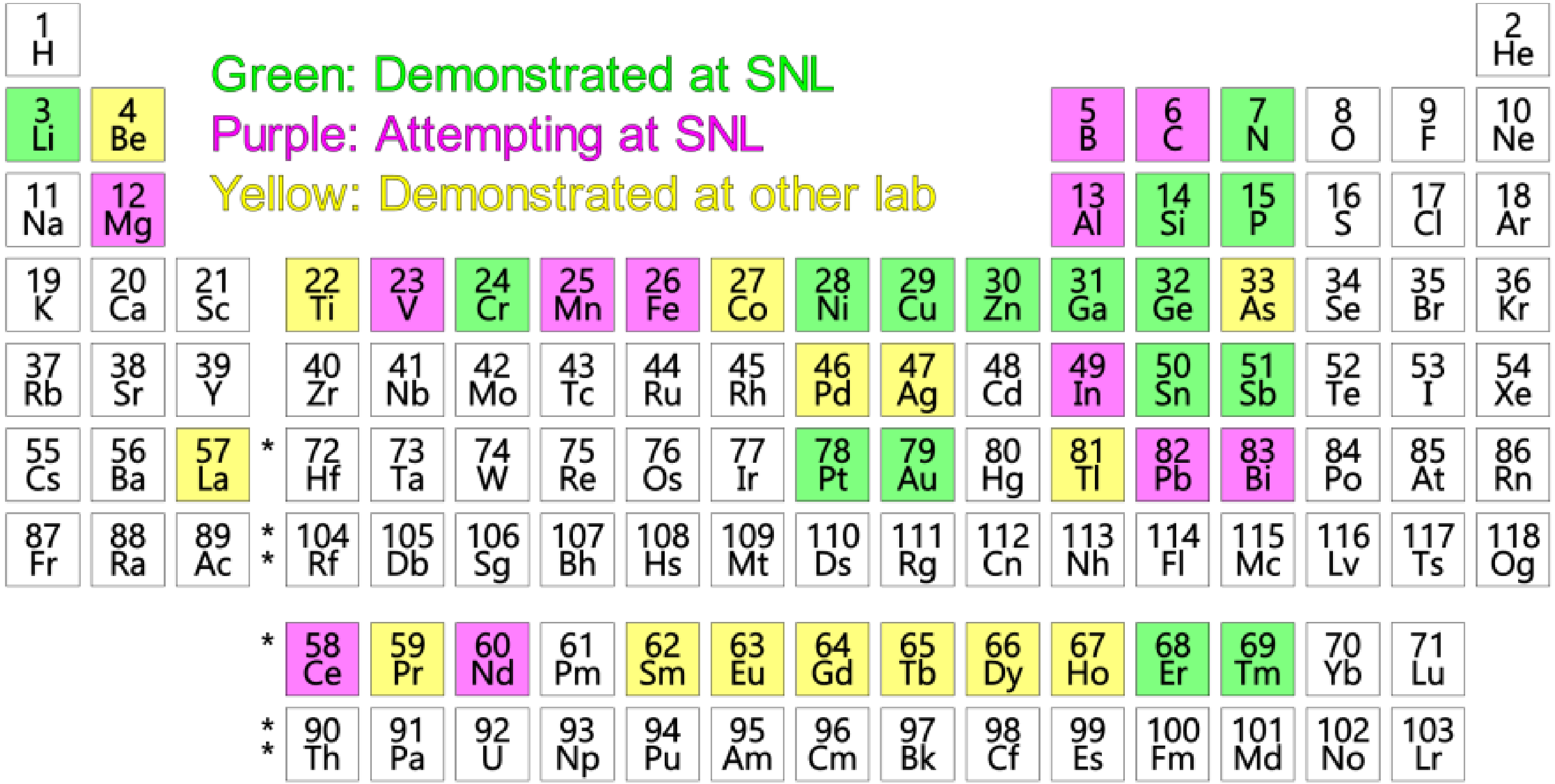
Ion Implantation for Defect Creation



<u>A&D nanoImplanter</u>

- Acceleration up to 100 kV → Si^{++} 130 nm range in diamond
- Beam spot size <20 nm → Targeting nanostructures
- ExB mass filter → Isotopic Resolution
- Direct write lithography → Rapid Prototyping





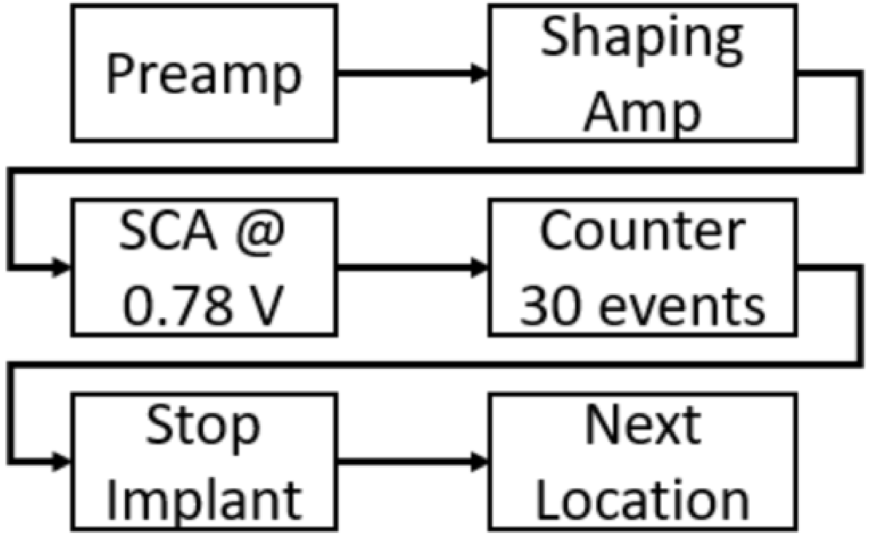
In-Situ Ion Counting

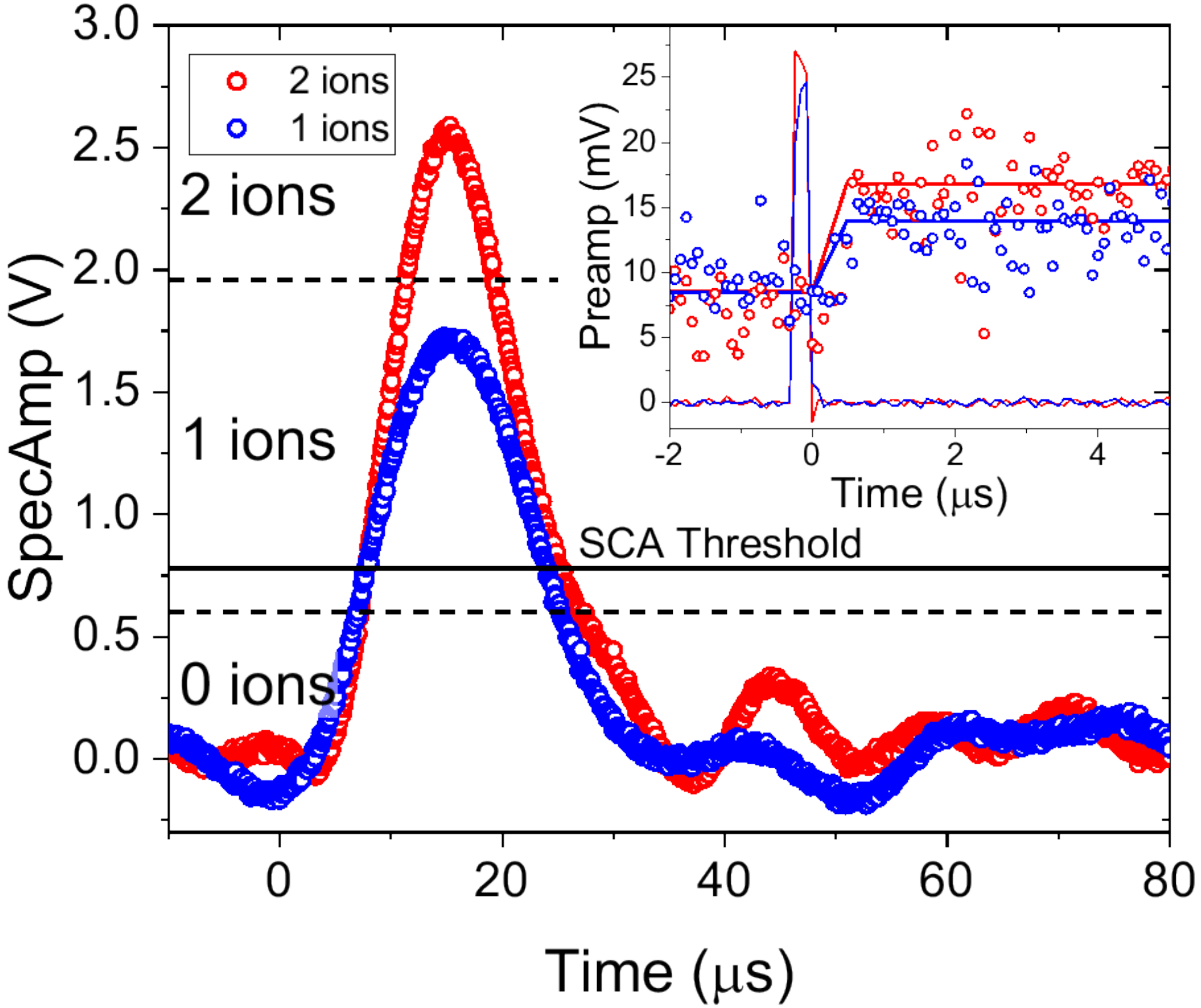
Experimental Setup:

Triggered Implantation

Count Ions using SCA

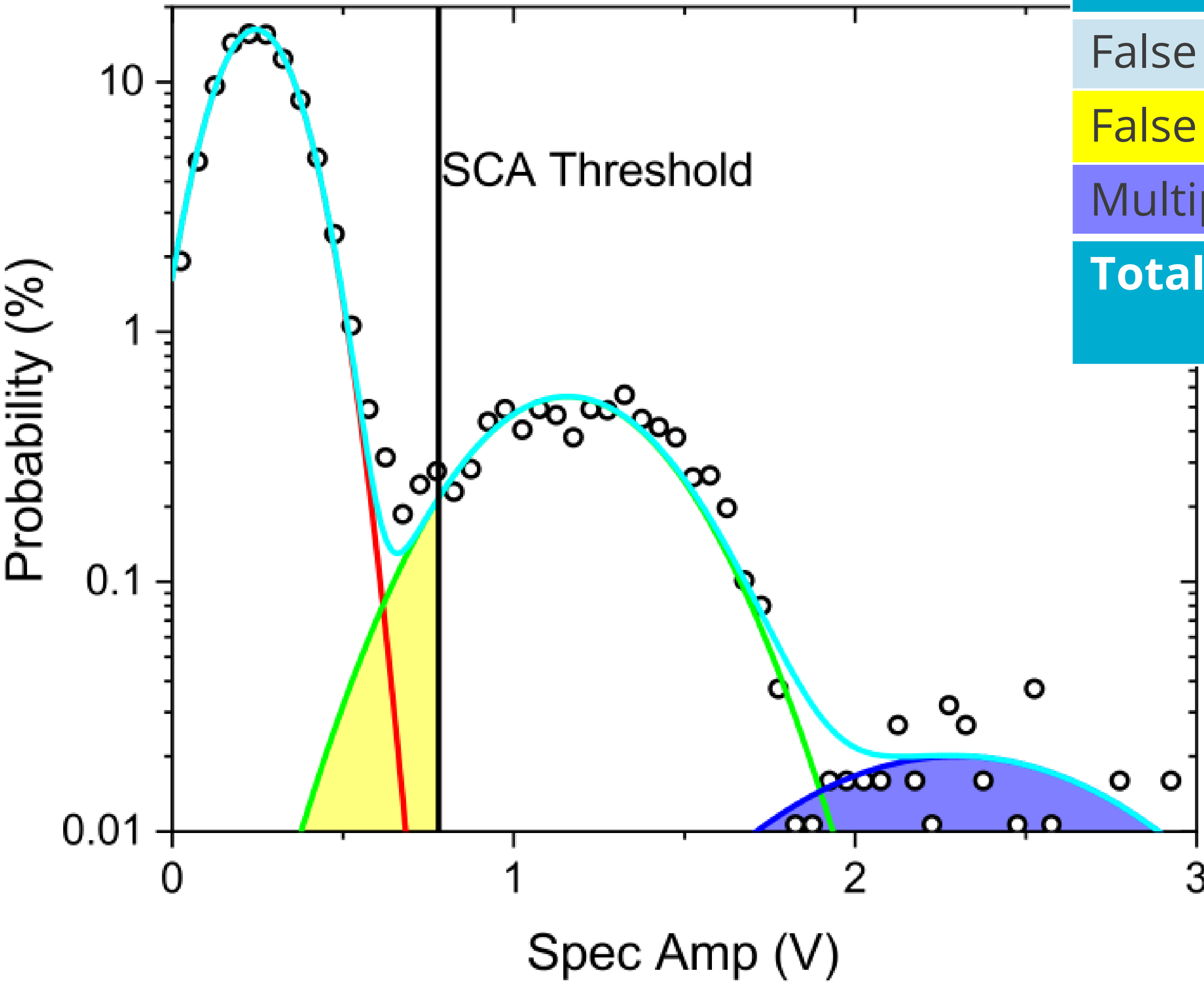
All Events are recorded on oscilloscope

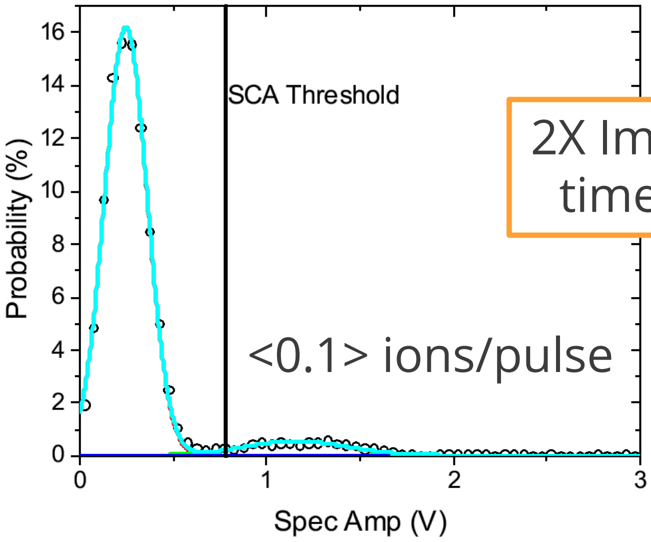




In-Situ Ion Counting – Errors

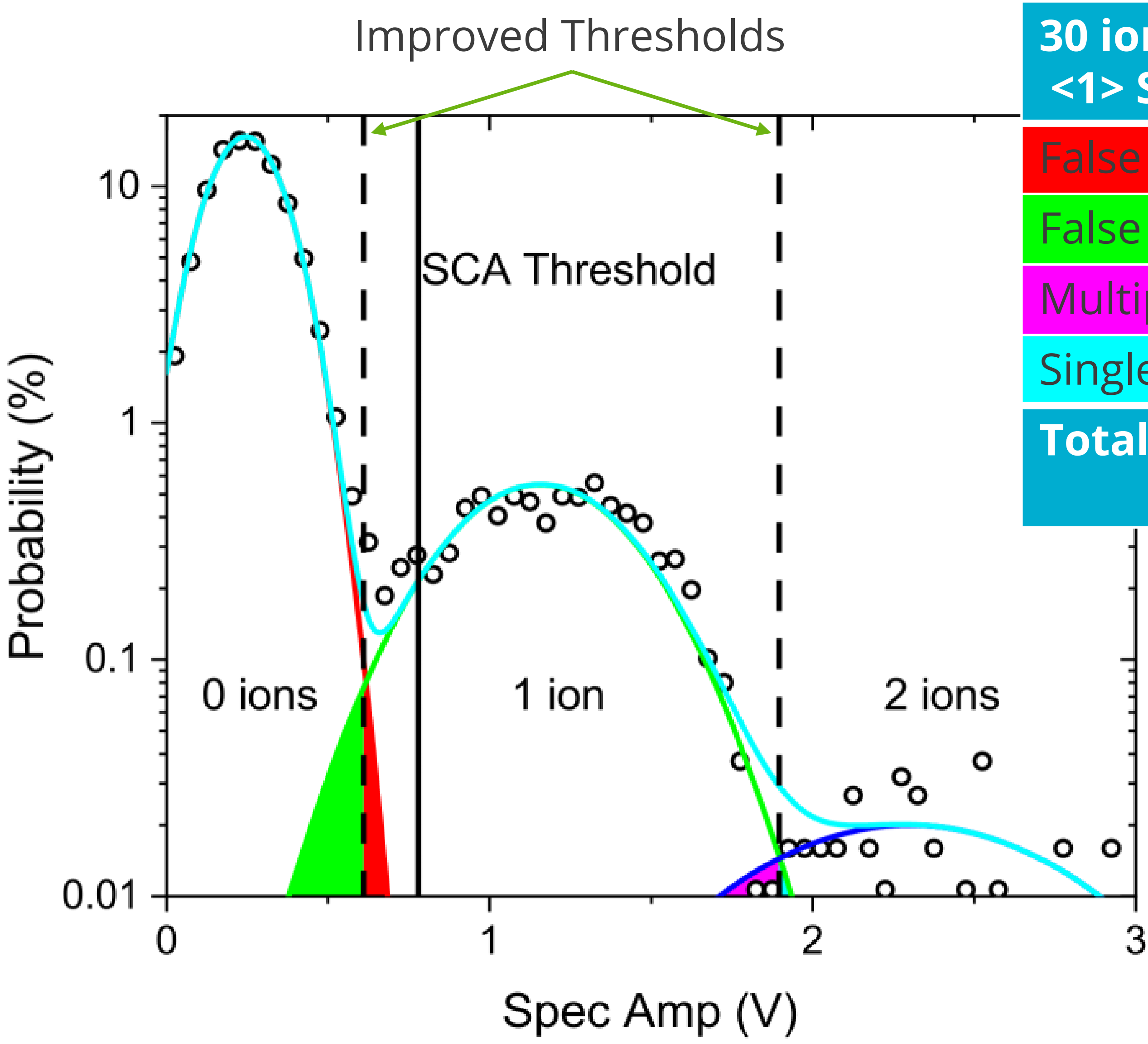
30 ions / <1> SiV	Timed	In-Situ
False Positives	-	< –1 ppb
False Negatives	-	8.6 %
Multiple Ions	-	5.8 %
Total	**+18.3 / –18.3 %**	**+14.4 / –0 %**





2X Improvement over timed implantation

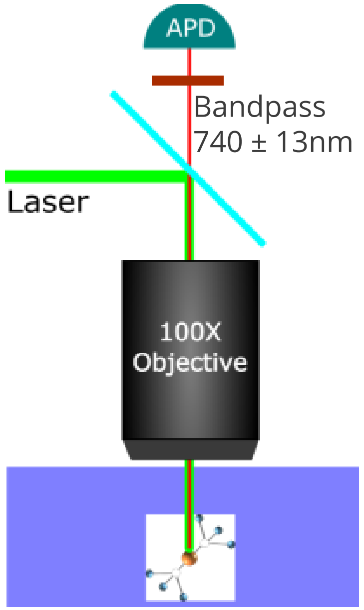
Post-Implantation Analysis – Improved Errors



30 ions / <1> SiV	Timed	In-Situ	Post-Analysis
False Positives	-	< –1 ppb	2.3 %
False Negatives	-	8.6 %	–0.9 %
Multiple Ions	-	5.8 %	1.7 %
Single as Double	-	-	–0.2 %
Total	**+18.3 / –18.3 %**	**+14.4 / –0 %**	**+4.0 / –1.1 %**

7X Improvement over timed implantation

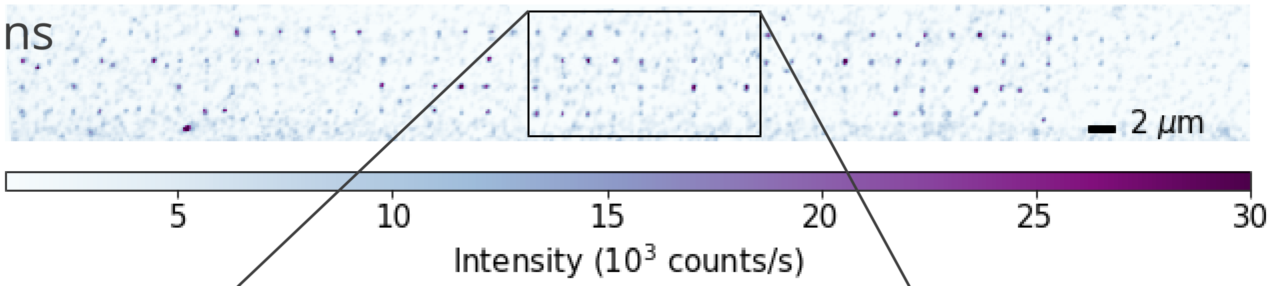
Photoluminescence of Counted Sample

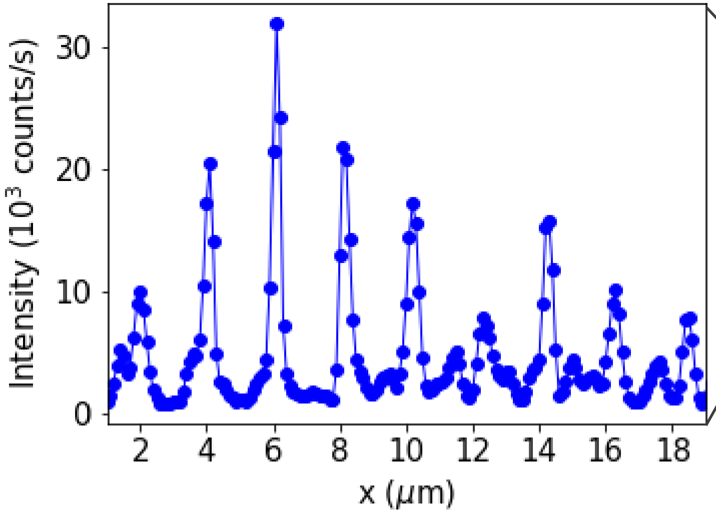


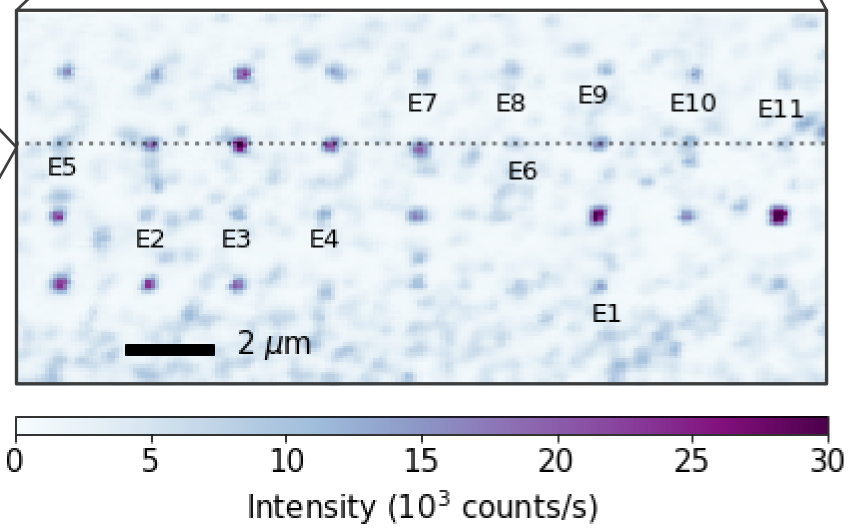
$$\text{Yield} = \frac{\#\text{Measured SiV}}{\#\text{Implanted Si Ions}}$$

High confidence in implanted # of ions

→ Instead of +/- 5 ion error bar on #Si ions, reduce to +1.2/-0.33 ions







Yield Measurement on Counted Sample

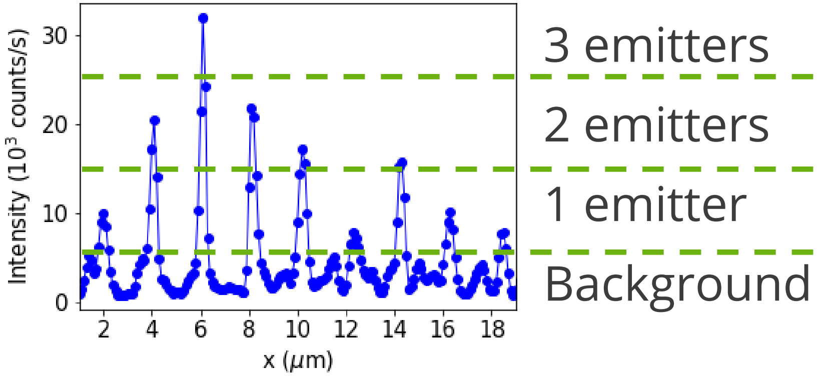
Implanted <33.8> ions/spot

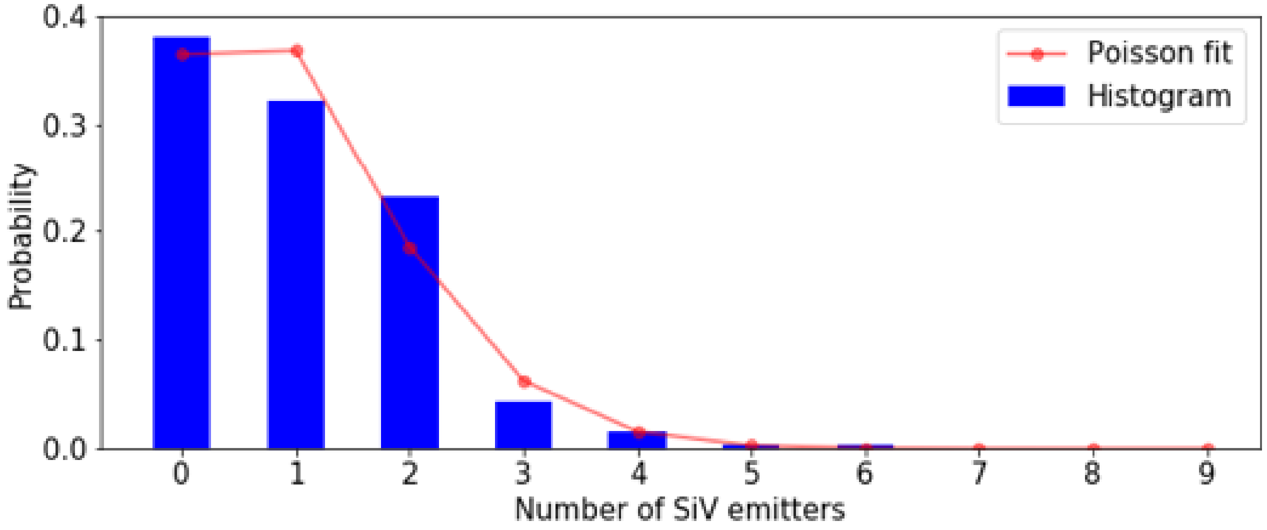
<1.01> ± 0.07 emitter per location

$$\text{Yield} = \frac{1.01 \pm 0.07}{33.8 + 1.4/{-0.4}} = 2.98 \begin{matrix} +0.21 \\ -0.24 \end{matrix} \,\&$$

Is our classification correct?

→ Hanbury-Brown-Twiss interferometry

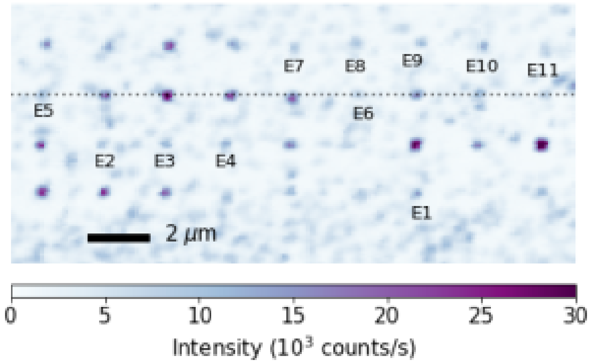




Our error ≤ **10 %**,
literature reports ≥ 30 %

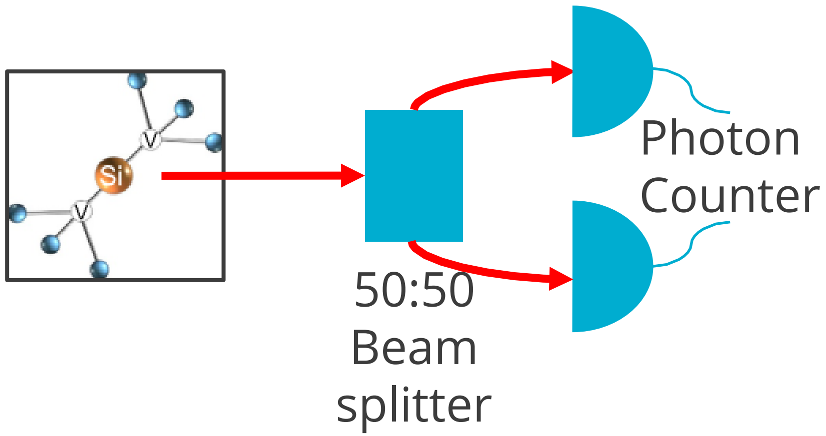
S. Lagomarsino et al., Front. Phys., 8, 626 (2021)

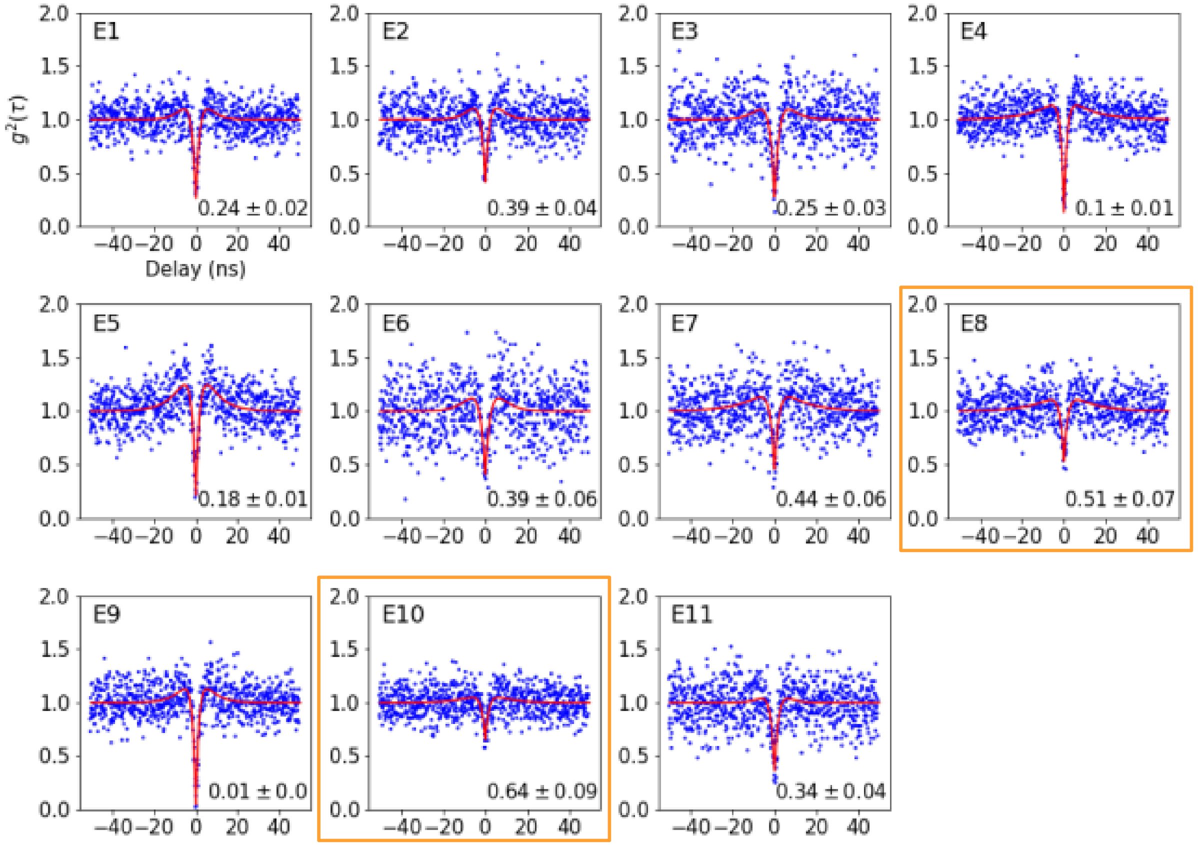
Hanbury-Brown-Twiss Interferometry



Single emitter will emit only 1 photon at a time

→ Only 1 photon at each counter at any time





18 % of locations identified as single emitters from PL are not single emitters

Discussion – Additional Emitters

18 % of emitters classified as SPE by PL contain a 2nd emitter

Possible explanation: Overlap between SiV + NV

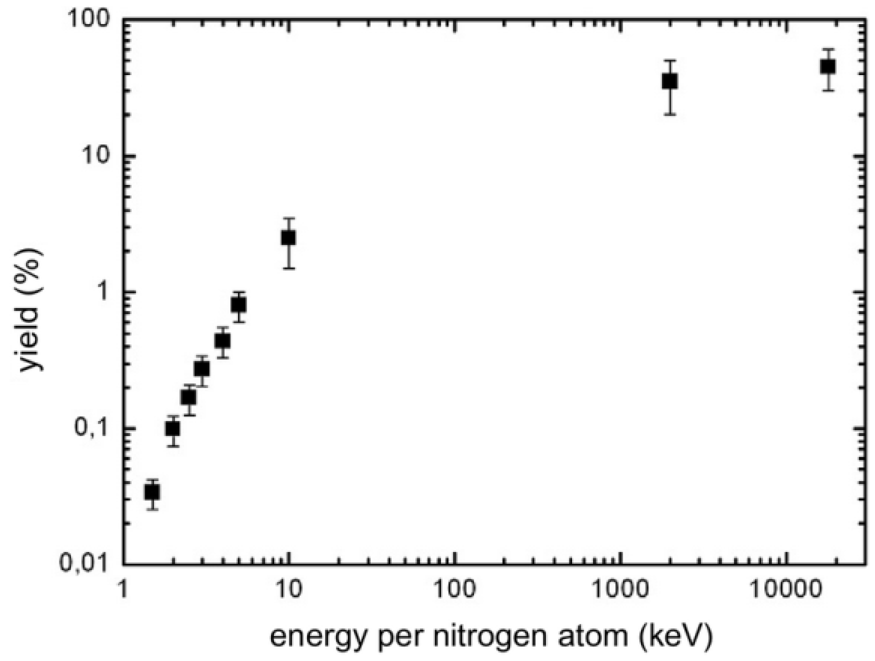
NV is created from native N during high-temperature anneal

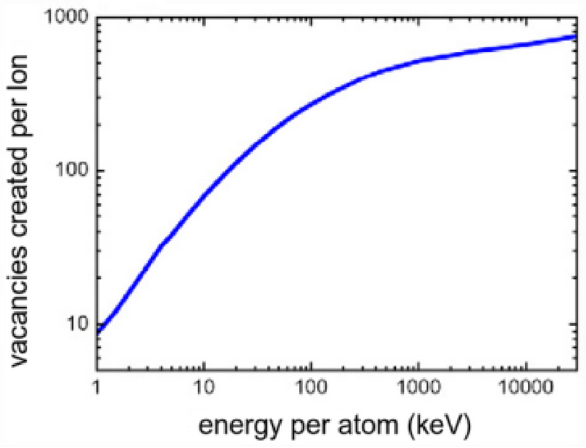
Average NV Separation (nm)		Native N Content	
		1 ppb	0.1 ppb
Conversion Yield	45 %	230	497
	10 %	381	820

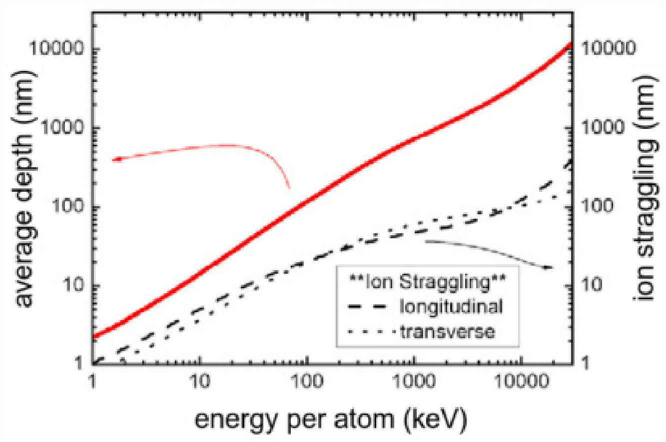
Our excitation volume is 340 nm and 18 % of emitters have 2nd emitter

→ If due to NV ~10 % conversion yield, 1 ppb N content

→ If due to SiV, yield 3.54 %



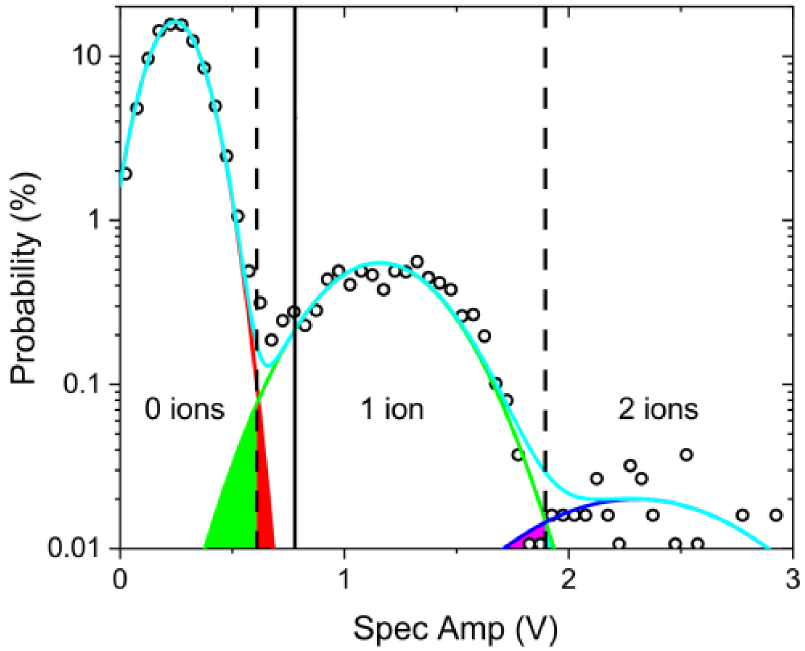


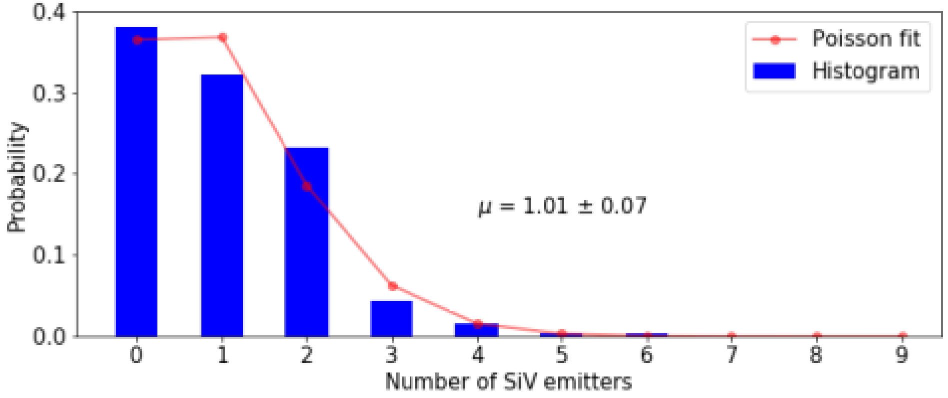


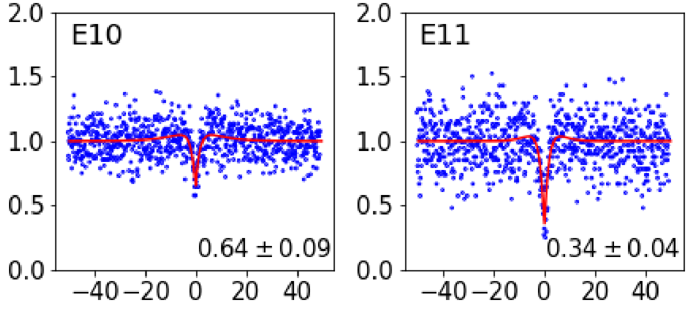
S. Pezzagna et al., New J. Phys., 12, 065017 (2010)

Conclusion of In-Situ Counting

- In-situ single ion counting can improve confidence on number of ions to +4 / -1.1 %
- For implantation of 30 ions / <1> SiV, 7X improvement over timed implantation
  - For implantation of fewer ions, improvement will be even greater
- PL confirms we implanted <1> SiV
- HBT shows that 18 % of locations classified as single emitters based on PL are not single emitters
  - Likely due to natively occurring N being converted to NV during high-temperature annealing

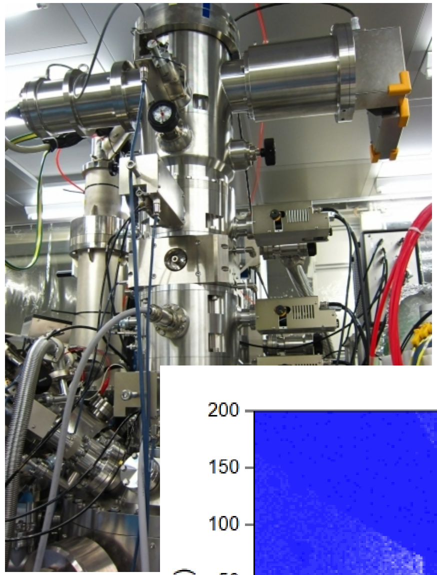




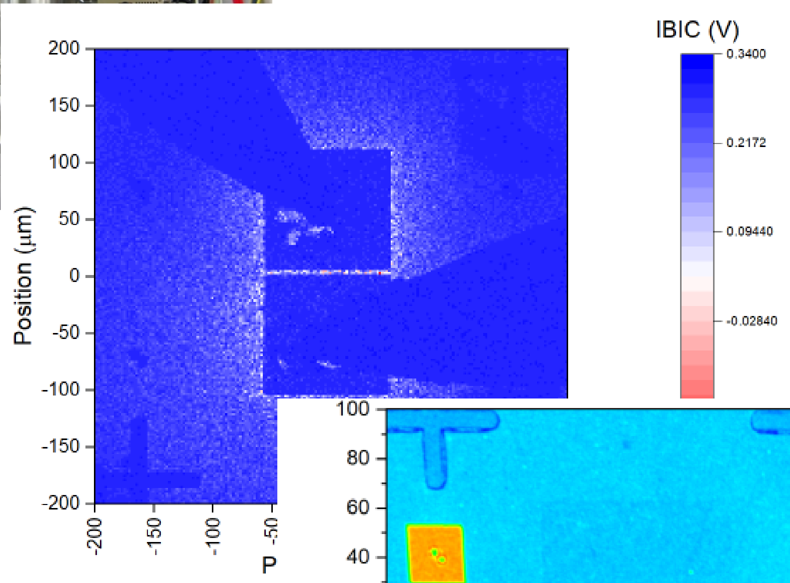


Conclusion

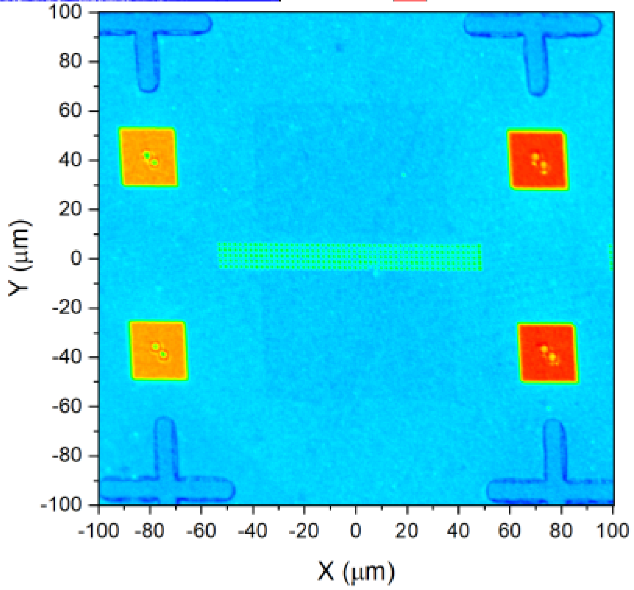
- Demonstrated high-resolution implantation for scalable quantum applications
- Low yield is roadblock to making devices
    - In-situ ion counting and in-situ PL for deterministic defect centers
    - Future in-situ laser annealing will enable SiV, GeV, … in diamond



FIB Implantation

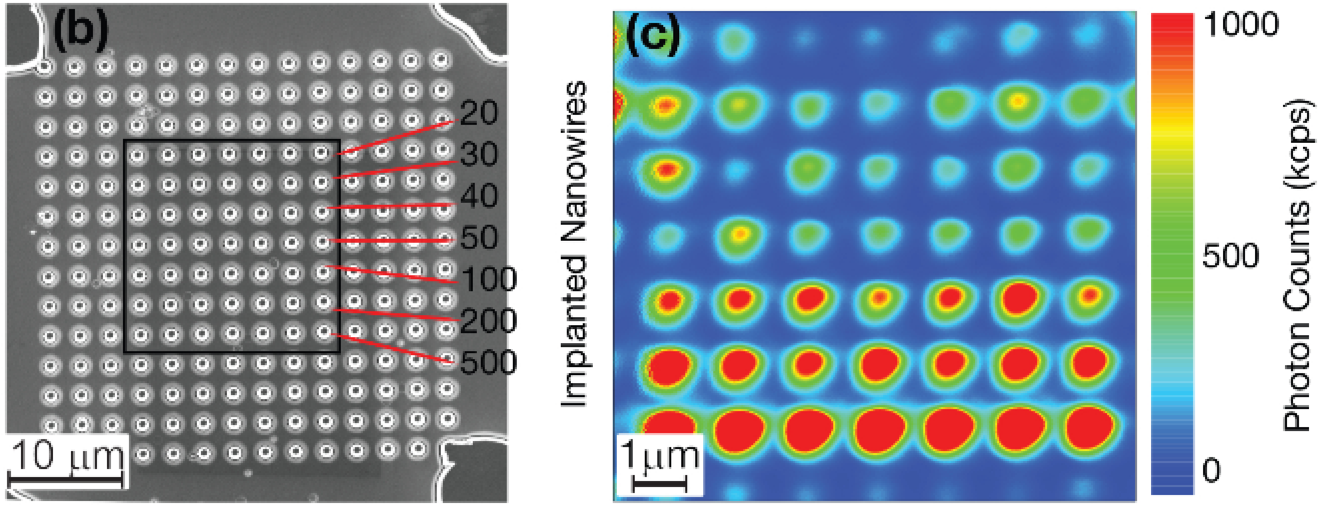


Integration into Nanostructures

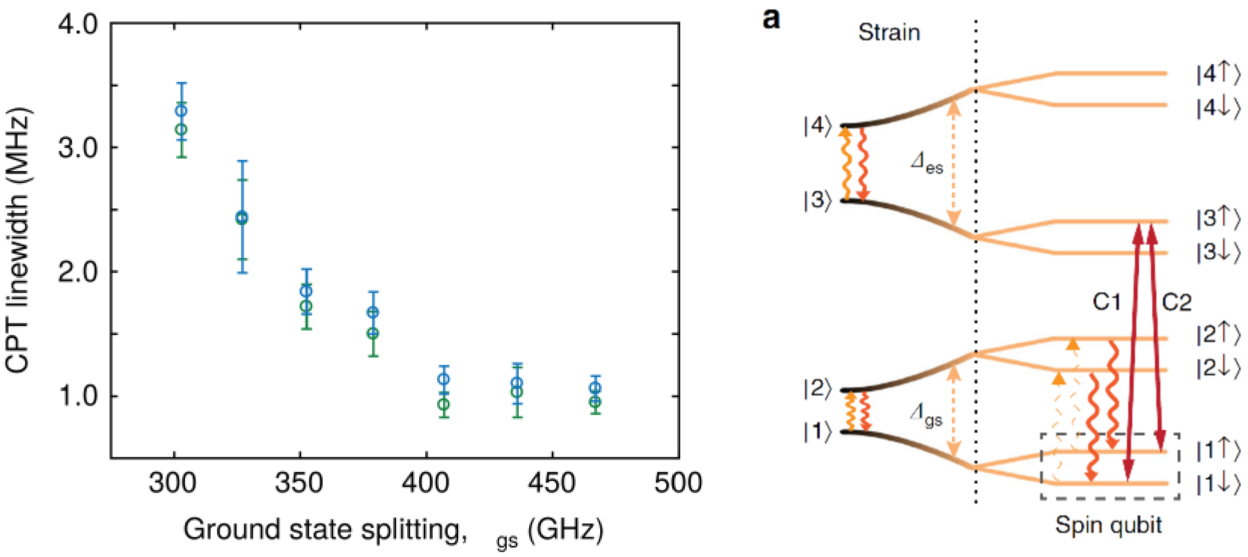


Enabling new devices

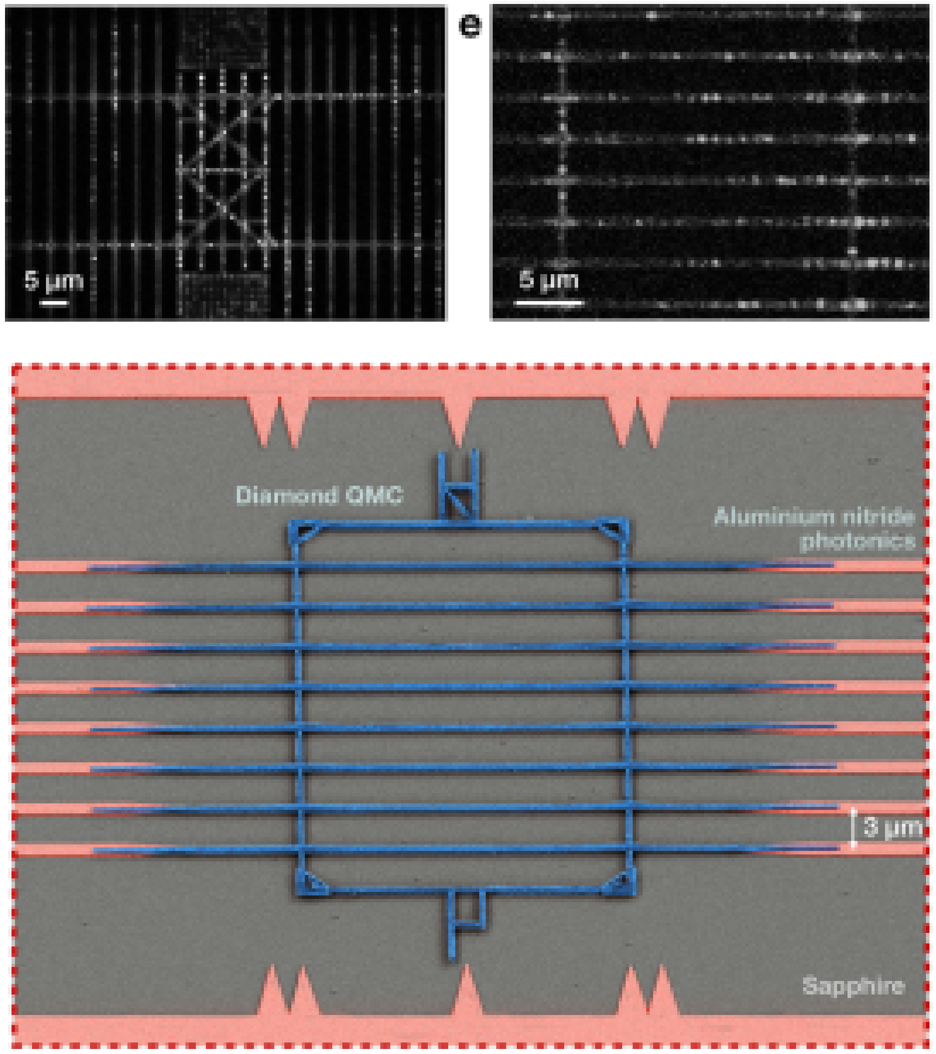
Examples of FIB Implantation



L. Marseglia et al., Opt. Express 26, 80 (2018)



Y.-I. Sohn et al., Nat. Commun. 9, 2012 (2018)



Noel H. Wan et al., arXiv 1911.05265 (submitted)