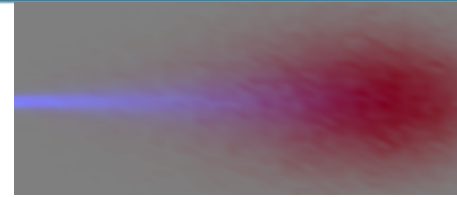
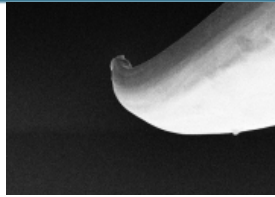
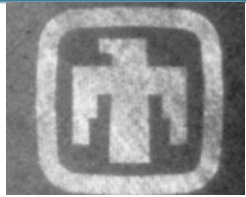




Focused Ion Beams for Deterministic Nanometer-Scale Quantum Device Fabrication



Michael Titze, Heejun Byeon, Vigneshwaran Chandrasekaran, Anthony Flores, Han Htoon, Andrew Mounce, Ed Bielejec

08/17/2021

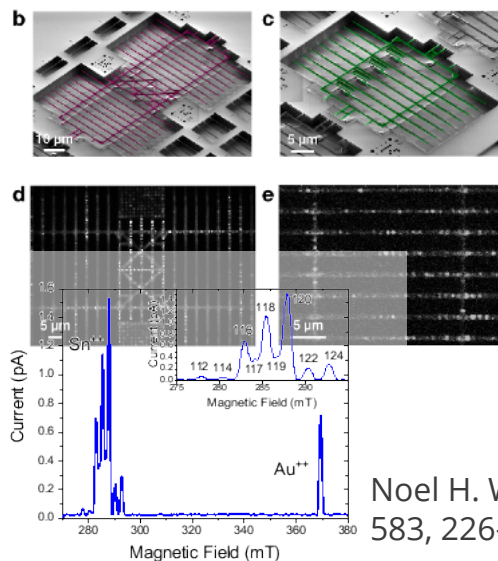
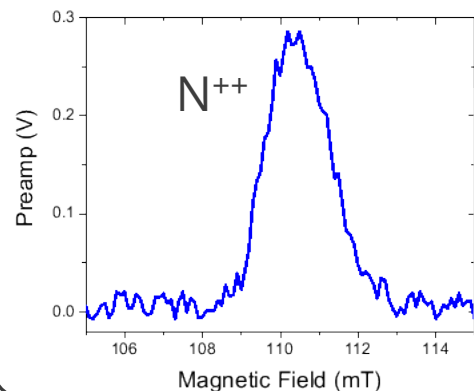


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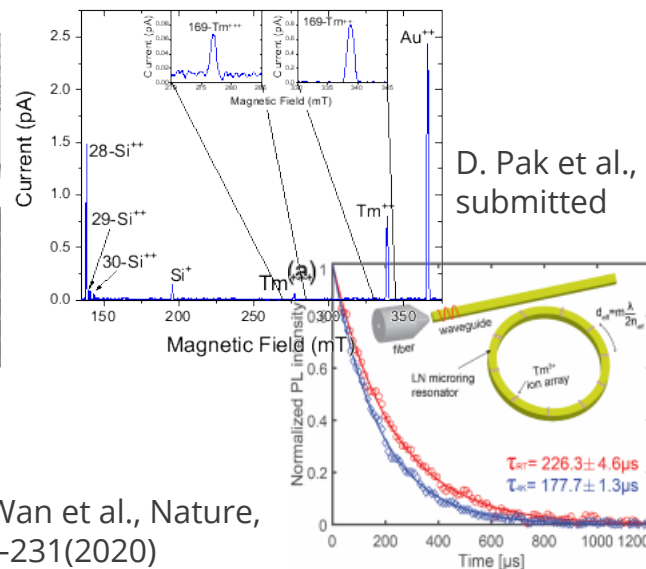
Outline



LMAIS Source Development



Noel H. Wan et al., Nature, 583, 226–231(2020)



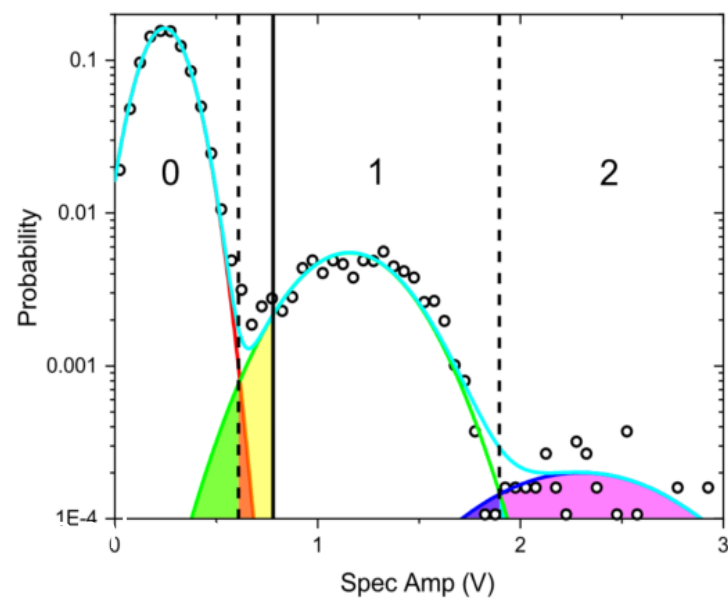
D. Pak et al., submitted

Hydrogen 1 H 1.00794																	Helium 2 He 4.002602																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
Lithium 3 Li 6.941	Boron 5 B 10.811	Carbon 6 C 12.011	Nitrogen 7 N 14.007	Oxygen 8 O 15.999	Fluorine 9 F 18.998	Neon 10 Ne 20.180											Sodium 11 Na 22.990																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
Beryllium 4 Be 9.0122	Neon 10 Ne 20.180	Carbon 6 C 12.011	Nitrogen 7 N 14.007	Oxygen 8 O 15.999	Fluorine 9 F 18.998	Neon 10 Ne 20.180	Aluminum 13 Al 26.982	Silicon 14 Si 28.086	Phosphorus 15 P 30.974	Sulfur 16 S 32.06	Chlorine 17 Cl 35.453	Argon 18 Ar 39.948											Calcium 20 Ca 40.078																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
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Potassium 19 K 39.098	Neon 10 Ne 20.180	Carbon 6 C 12.011	Nitrogen 7 N 14.007	Oxygen 8 O 15.999	Fluorine 9 F 18.998	Neon 10 Ne 20.180	Aluminum 13 Al 26.982	Silicon 14 Si 28.086	Phosphorus 15 P 30.974	Sulfur 16 S 32.06	Chlorine 17 Cl 35.453	Argon 18 Ar 39.948	Calcium 20 Ca 40.078	Scandium 21 Sc 44.956	Titanium 22 Ti 47.88	Vanadium 23 V 50.942	Chromium 24 Cr 52.00	Manganese 25 Mn 54.938	Iron 26 Fe 55.845	Cobalt 27 Co 58.933	Nickel 28 Ni 58.69	Copper 29 Cu 63.546	Zinc 30 Zn 65.38	Gallium 31 Ga 69.723	Germanium 32 Ge 72.64	Arsenic 33 As 74.922	Selenium 34 Se 78.96	Bromine 35 Br 79.904	Krypton 36 Kr 83.8	Strontium 38 Sr 87.62	Yttrium 39 Y 88.906	Zirconium 40 Zr 91.224	Niobium 41 Nb 92.906	Molybdenum 42 Mo 95.94	Technetium 43 Tc 98.906	Ruthenium 44 Ru 101.07	Rhodium 45 Rh 102.91	Palladium 46 Pd 106.42	Silver 47 Ag 107.87	Cadmium 48 Cd 112.41	Indium 49 In 114.82	Tin 50 Sn 118.71	Antimony 51 Sb 121.76	Tellurium 52 Te 127.60	Iodine 53 I 126.91	Xenon 54 Xe 131.29	Cesium 55 Cs 132.91	Barium 56 Ba 137.33											Radium 88 Ra 226																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
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131.29	Cesium 55 Cs 132.91	Barium 56 Ba 137.33	Francium 87 Fr 223	Radium 88 Ra 226	Actinium 89 Ac 227	Thorium 90 Th 232	Protactinium 91 Pa 231	Uranium 92 U 238	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Mn 101	Uun 102	Uuu 103	Uub 104	Uut 105	Uuq 106	Uup 107	Uuh 108	Uus 109	Uuo 110	Uu11 111	Uu12 112	Uu13 113	Uu14 114	Uu15 115	Uu16 116	Uu17 117	Uu18 118	Uu19 119	Uu20 120	Uu21 121	Uu22 122	Uu23 123	Uu24 124	Uu25 125	Uu26 126	Uu27 127	Uu28 128	Uu29 129	Uu30 130	Uu31 131	Uu32 132	Uu33 133	Uu34 134	Uu35 135	Uu36 136	Uu37 137	Uu38 138	Uu39 139	Uu40 140	Uu41 141	Uu42 142	Uu43 143	Uu44 144	Uu45 145	Uu46 146	Uu47 147	Uu48 148	Uu49 149	Uu50 150	Uu51 151	Uu52 152	Uu53 153	Uu54 154	Uu55 155	Uu56 156	Uu57 157	Uu58 158	Uu59 159	Uu60 160	Uu61 161	Uu62 162	Uu63 163	Uu64 164	Uu65 165	Uu66 166	Uu67 167	Uu68 168	Uu69 169	Uu70 170	Uu71 171	Uu72 172	Uu73 173	Uu74 174	Uu75 175	Uu76 176	Uu77 177	Uu78 178	Uu79 179	Uu80 180	Uu81 181	Uu82 182	Uu83 183	Uu84 184	Uu85 185	Uu86 186	Uu87 187	Uu88 188	Uu89 189	Uu90 190	Uu91 191	Uu92 192	Uu93 193	Uu94 194	Uu95 195	Uu96 196	Uu97 197	Uu98 198	Uu99 199	Uu100 200	Uu101 201	Uu102 202	Uu103 203	Uu104 204	Uu105 205	Uu106 206	Uu107 207	Uu108 208	Uu109 209	Uu110 210	Uu111 211	Uu112 212	Uu113 213	Uu114 214	Uu115 215	Uu116 216	Uu117 217	Uu118 218	Uu119 219	Uu120 220	Uu121 221	Uu122 222	Uu123 223	Uu124 224	Uu125 225	Uu126 226	Uu127 227	Uu128 228	Uu129 229	Uu130 230	Uu131 231	Uu132 232	Uu133 233	Uu134 234	Uu135 235	Uu136 236	Uu137 237	Uu138 238	Uu139 239	Uu140 240	Uu141 241	Uu142 242	Uu143 243	Uu144 244	Uu145 245	Uu146 246	Uu147 247	Uu148 248	Uu149 249	Uu150 250	Uu151 251	Uu152 252	Uu153 253	Uu154 254	Uu155 255	Uu156 256	Uu157 257	Uu158 258	Uu159 259	Uu160 260	Uu161 261	Uu162 262	Uu163 263	Uu164 264	Uu165 265	Uu166 266	Uu167 267	Uu168 268	Uu169 269	Uu170 270	Uu171 271	Uu172 272	Uu173 273	Uu174 274	Uu175 275	Uu176 276	Uu177 277	Uu178 278	Uu179 279	Uu180 280	Uu181 281	Uu182 282	Uu183 283	Uu184 284	Uu185 285	Uu186 286	Uu187 287	Uu188 288	Uu189 289	Uu190 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490	Uu391 491	Uu392 492	Uu393 493	Uu394 494	Uu395 495	Uu396 496	Uu397 497	Uu398 498	Uu399 499	Uu400 500	Uu401 501	Uu402 502	Uu403 503	Uu404 504	Uu405 505	Uu406 506	Uu407 507	Uu408 508	Uu409 509	Uu410 510	Uu411 511	Uu412 512	Uu413 513	Uu414 514	Uu415 515	Uu416 516	Uu417 517	Uu418 518	Uu419 519	Uu420 520	Uu421 521	Uu422 522	Uu423 523	Uu424 524	Uu425 525	Uu426 526	Uu427 527	Uu428 528	Uu429 529	Uu430 530	Uu431 531	Uu432 532	Uu433 533	Uu434 534	Uu435 535	Uu436 536	Uu437 537	Uu438 538	Uu439 539	Uu440 540	Uu441 541	Uu442 542	Uu443 543	Uu444 544	Uu445 545	Uu446 546	Uu447 547	Uu448 548	Uu449 549	Uu450 550	Uu451 551	Uu452 552	Uu453 553	Uu454 554	Uu455 555	Uu456 556	Uu457 557	Uu458 558	Uu459 559	Uu460 560	Uu461 561	Uu462 562	Uu463 563	Uu464 564	Uu465 565	Uu466 566	Uu467 567	Uu468 568	Uu469 569	Uu470 570	Uu471 571	Uu472 572	Uu473 573	Uu474 574	Uu475 575	Uu476 576	Uu477 577	Uu478 578	Uu479 579	Uu480 580	Uu481 581	Uu482 582	Uu483 583	Uu484 584	Uu485 585	Uu486 586	Uu487 587	Uu488 588	Uu489 589	Uu490 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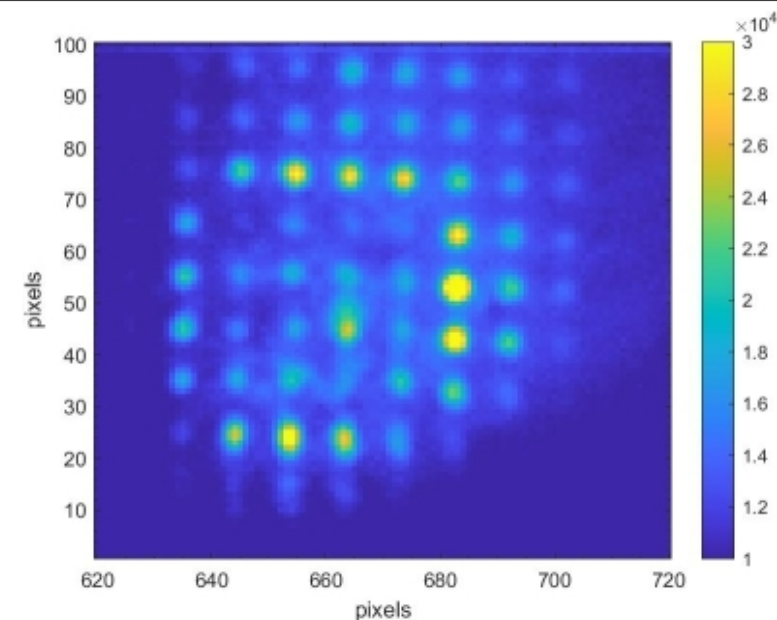
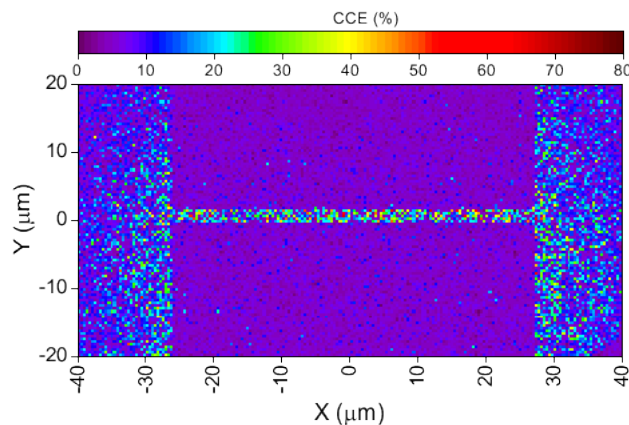
*Lanthanide series

**Actinide series

57	La	58	Ce	59	Pr	60	Nd	61	Pm	62	Sm	63	Eu	64	Gd	65	Tb	66	Dy	67	Ho	68	Er	69	Tm	70	Yb
89	Ac	90	Th	91	Pa	92	U	93	Np	94	Pu	95	Am	96	Cm	97	Bk	98	Cf	99	Es	100	Fm	101	Md	102	No



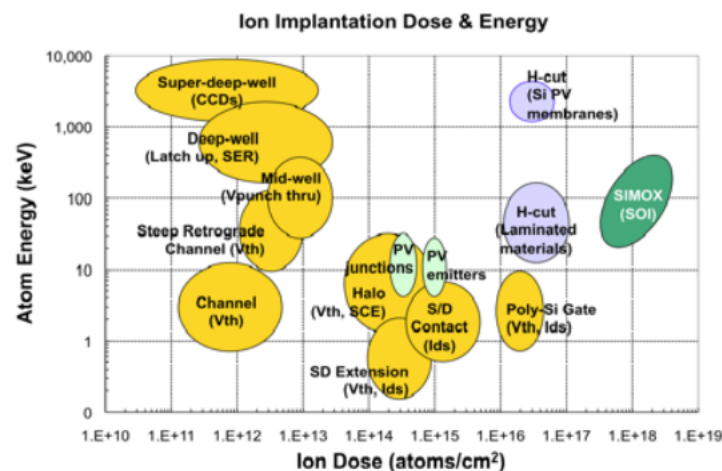
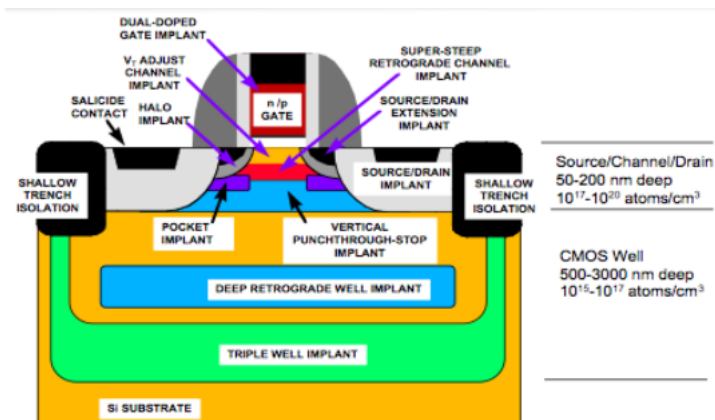
In-Situ Counting + Photoluminescence



Ion Implantation and Irradiation for Device Fab

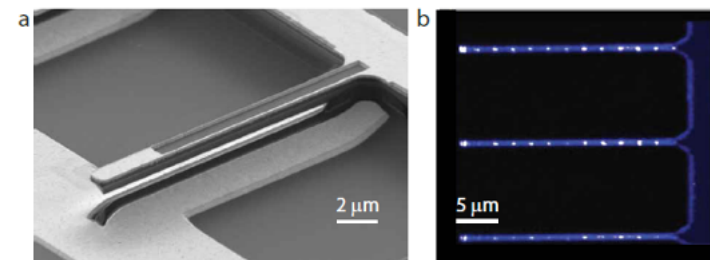


Ion Implantation has been a work-horse for the semiconductor industry

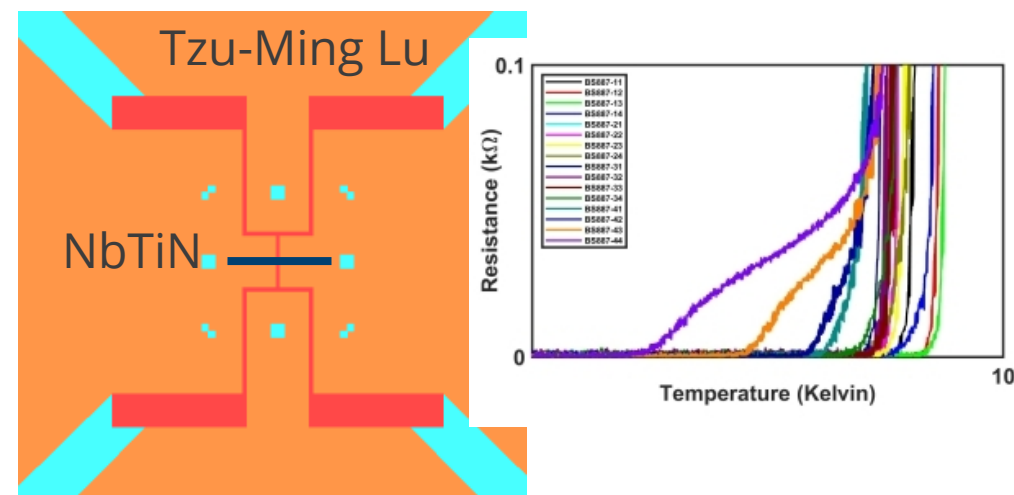


S. B. Felch, *et al.*, Proceedings of PAC2013, Pasadena, CA (2013)

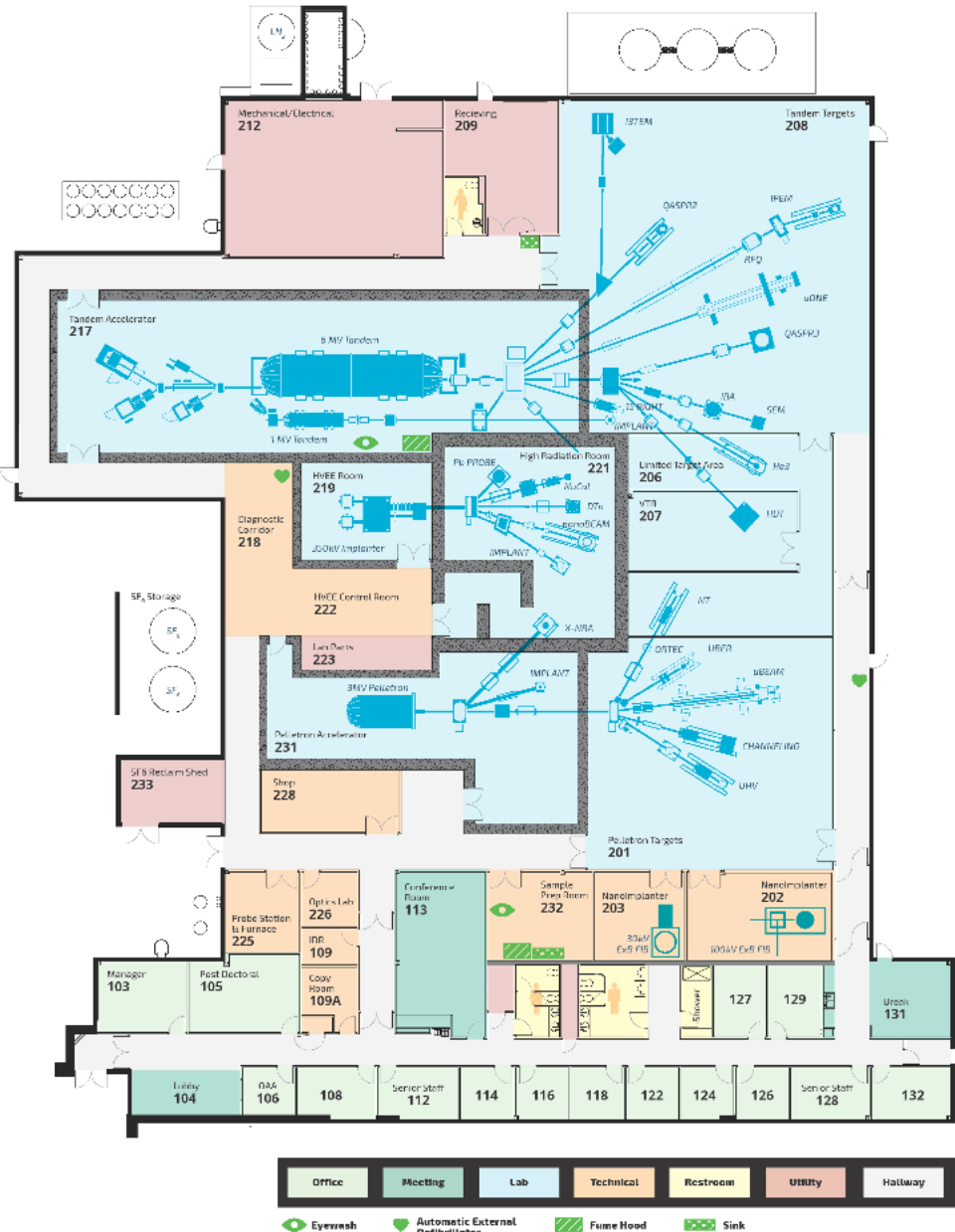
Our work is centered on localized implantation and fabrication based on a deterministic number of implanted ions



Y. Sohn, *et al.*, Nat. Communications **9**, 2012 (2018)



Focused Ion Beam implantation for fabrication of single atom devices and nanofabrication



Operational

(1) 6 MV Tandem Accelerator

Radiation effects testing

(2) 3 MV Pelletron Accelerator

Ion beam analysis and displacement damage

(3) 1 MV Tandem Accelerator

Support I3TEM and "replace" HVEE for ions

(4) 350 kV HVEE Implanter

>90% usage for mono-energetic neutrons

(5) 100 kV ExB FIB nanolimplanter

High spatial resolution implantation

(6) 35 kV ExB FIB Raith Velion

Higher spatial resolution at lower energies

(7) 35 kV Zeiss HeIM

<0.5 nm beam spot, high resolution imaging

Installing

(8) 35 kV Plasma FIB

Gas sources – O, N, Ar, Xe, etc...

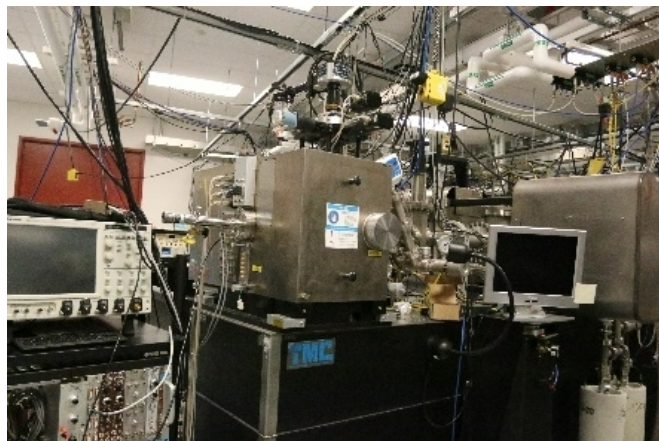
High energy
focused
micobeams
1 μm to mm's

Low energy
focused
nanobeams
<1 to 20 nm

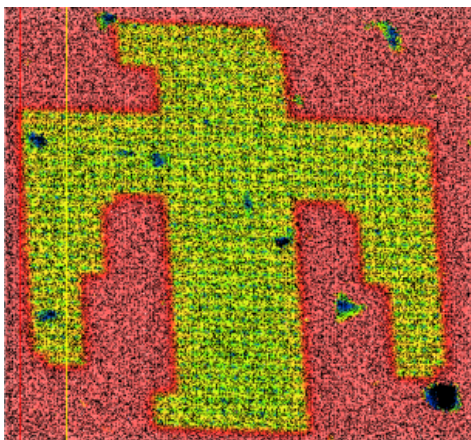
High Energy Microbeams $\sim 1 \mu\text{m}$ to mm's



- 6 MV Tandem microbeam (microONE)

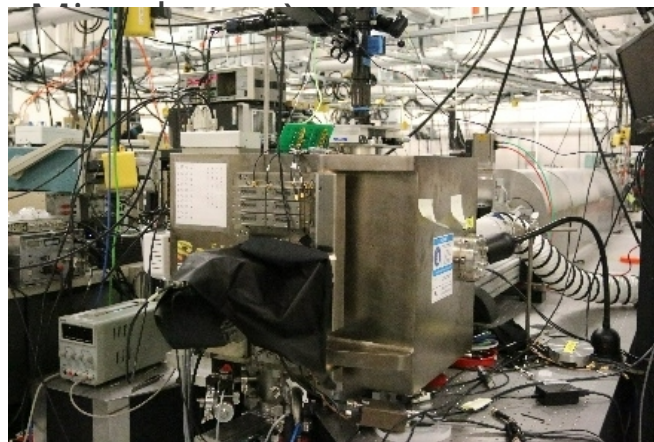


- High resolution laser stage
- Spot size $< 1 \mu\text{m}$
- Energy 0.8 – 70 MeV
- H to Au

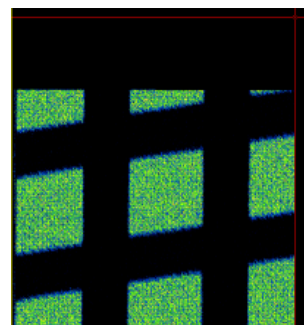


IBIC on
PIN diode

- 3 MV Pelletron microbeam (Light Ion)

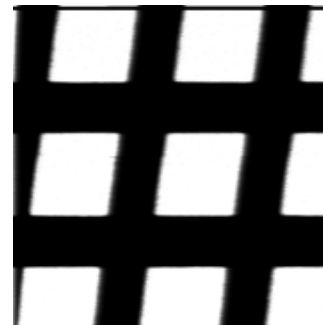


- High resolution laser stage
- Spot size $< 600 \text{ nm}$
- Energy 0.25 – 3 MeV
- H, He, N, Ar, Xe, ...



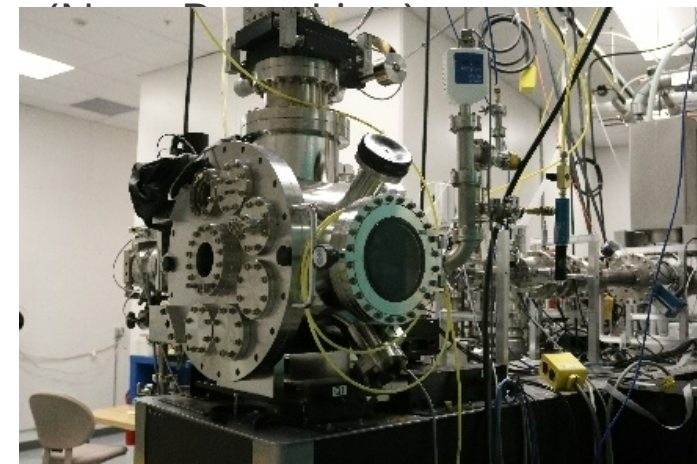
12.5 μm

IBIC on PIN
diode

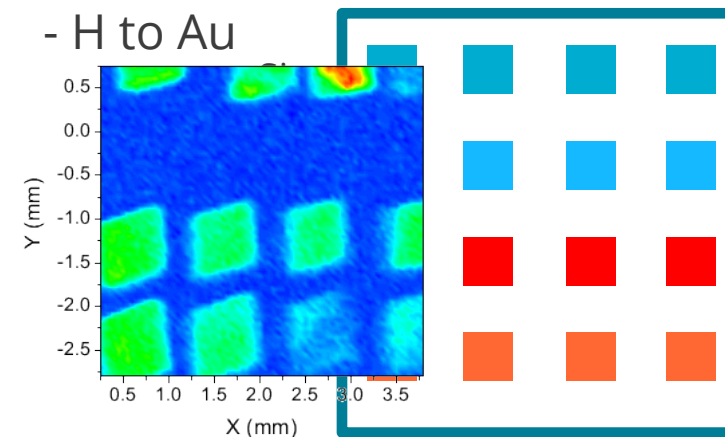


SED on PIN
diode

- 350 kV HVEE microbeam



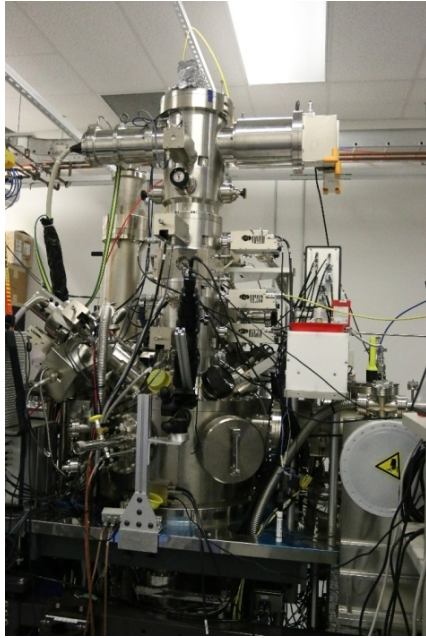
- Piezo stage
- Spot size $< 1 \mu\text{m}$
- Energy 20 – 350 keV
- H to Au



Low Energy Nanobeams <1 to 20 nm



- 100 kV A&D FIB100NI (nanolmplanter)



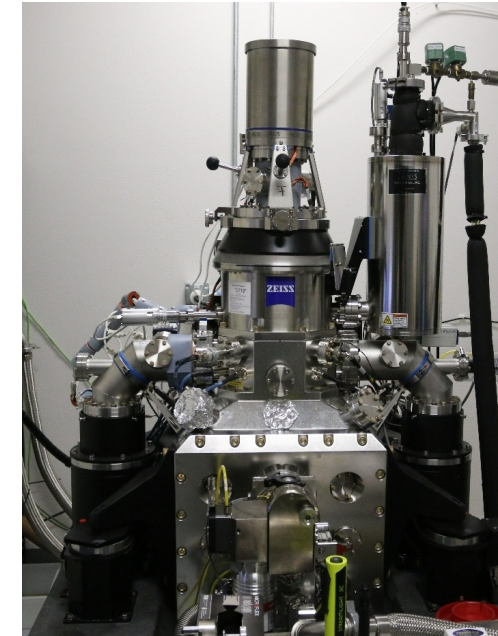
- High resolution laser stage
- Spot size <10 nm (Ga)
- Energy 10 – 200 keV
- 1/3 periodic table

- 35 kV Raith Velion (Velion)



- High resolution laser stage
- Spot size <6 nm (Ga)
- Energy 5 – 70 keV
- 1/3 periodic table

- 35 kV Zeiss Orion Plus (HeIM)



- Piezo stage
- Spot size <1 nm
- Energy 10 – 35 keV
- He, **N**, likely other gases

All equipped with Lithography Software for Patterning

Low Energy Nanobeams <1 to 20 nm



- 100 kV A&D FIB100NI
(nanolimplanter)

- 35 kV Raith Velion
(Velion)

- 35 kV Zeiss Orion Plus
(HeIM)

hydrogen 1 H 1.0079																	helium 2 He 4.0026	
lithium 3 Li 6.941	beryllium 4 Be 9.0122																	
sodium 11 Na 22.990	magnesium 12 Mg 24.305																	
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80	
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29	
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununilium 110 Uun [271]	unununium 111 Uuu [272]	unubium 112 Uub [277]		ununquadium 114 Uuq [289]				

Purple – running at SNL

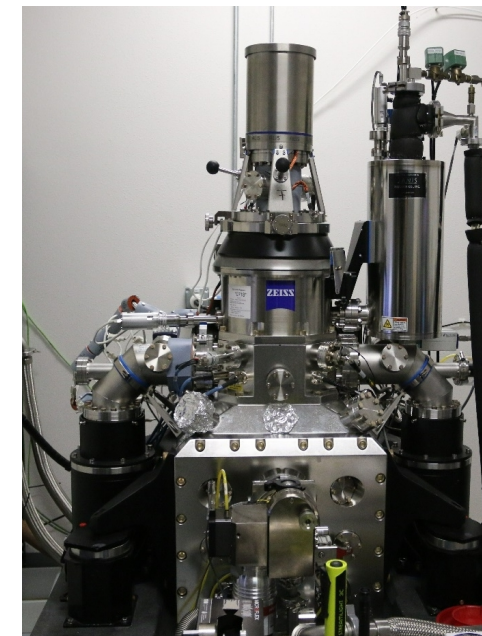
Yellow – attempting at SNL

Green – demonstrated at other labs

Purple – running at SNL

Yellow – attempting at SNL

Green – demonstrated at other labs



- Piezo stage
- Spot size <1 nm
- Energy 10 – 35 keV
- He, N, likely other gases

* Lanthanide series

** Actinide series

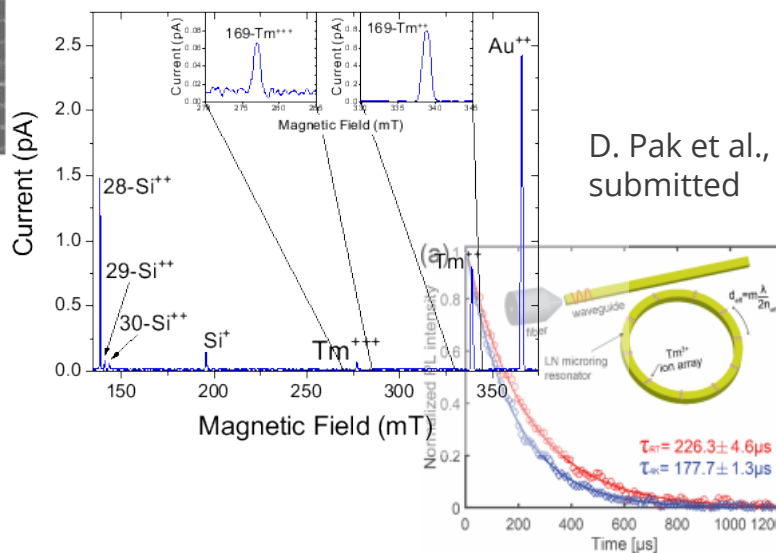
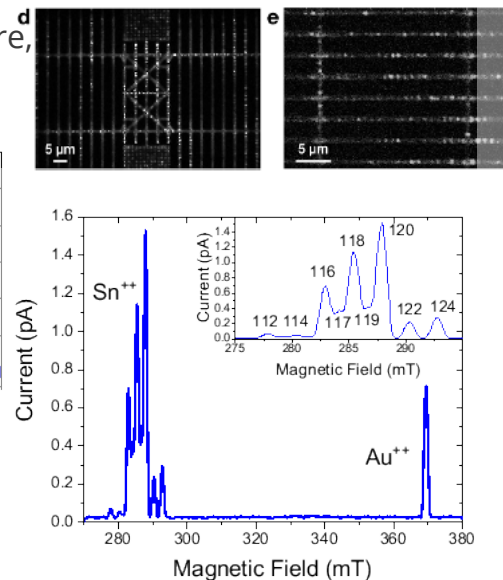
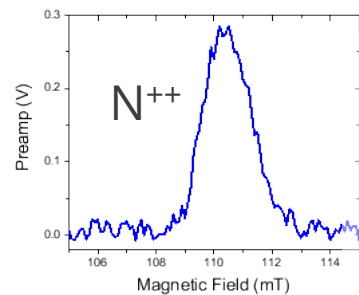
lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

arning

LMAIS Source Development



Noel H. Wan et al., Nature, 583, 226–231(2020)



D. Pak et al., submitted

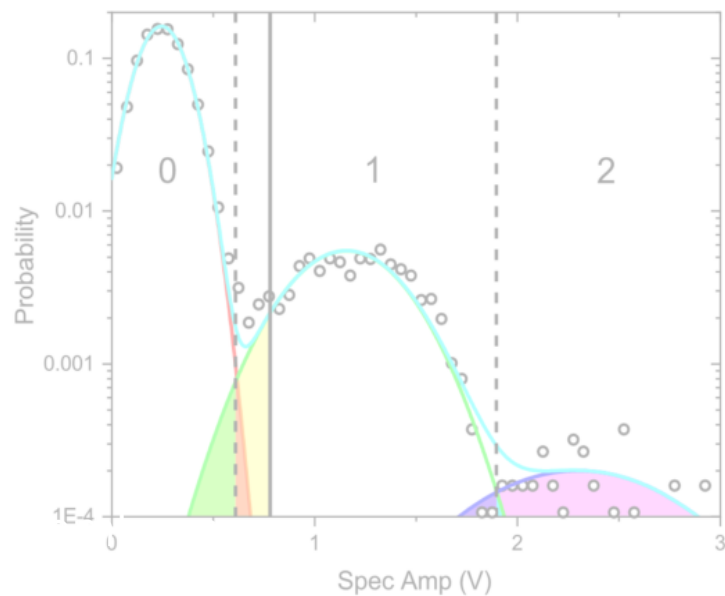
Currently supporting 15 Users

Hydrogen 1 H 1.0079																	Helium 2 He 4.0026	
Lithium 3 Li 6.941	Boron 5 B 10.811	Carbon 6 C 12.011	Nitrogen 7 N 14.007	Oxygen 8 O 15.999	Fluorine 9 F 18.998	Neon 10 Ne 20.180											Argon 18 Ar 39.948	
Sodium 11 Na 22.990	Magnesium 12 Mg 24.305	Aluminum 13 Al 26.982	Silicon 14 Si 28.086	Phosphorus 15 P 30.974	Sulfur 16 S 32.065	Chlorine 17 Cl 35.453	Argon 18 Ar 39.948											Krypton 36 Kr 83.801
Potassium 19 K 39.098	Calcium 20 Ca 40.078	Scandium 21 Sc 44.956	Titanium 22 Ti 47.883	Vanadium 23 V 50.942	Chromium 24 Cr 51.996	Manganese 25 Mn 54.938	Iron 26 Fe 55.845	Cobalt 27 Co 58.933	Nickel 28 Ni 58.693	Copper 29 Cu 63.546	Zinc 30 Zn 65.38	Gallium 31 Ga 69.723	Germanium 32 Ge 72.630	Arsenic 33 As 74.922	Selenium 34 Se 78.96	Bromine 35 Br 79.904	Krypton 36 Kr 83.801	
Rubidium 37 Rb 85.468	Strontium 38 Sr 87.62	Yttrium 39 Y 88.906	Zirconium 40 Zr 91.224	Niobium 41 Nb 92.906	Molybdenum 42 Mo 95.94	Technetium 43 Tc 98	Ruthenium 44 Ru 101.07	Rhodium 45 Rh 102.91	Palladium 46 Pd 106.42	Silver 47 Ag 107.87	Cadmium 48 Cd 112.41	Indium 49 In 114.82	Sn 50 118.71	Sb 51 121.76	Te 52 127.60	Iodine 53 I 126.91	Xenon 54 Xe 131.29	
Cesium 55 Cs 132.91	Barium 56 Ba 137.33	Lanthanum 57 La 138.91	Hafnium 58 Hf 178.49	Tantalum 59 Ta 180.95	Tungsten 60 W 183.85	Rhenium 61 Re 186.21	Osmium 62 Os 190.23	Iridium 63 Ir 192.22	Pt 64 195.08	Au 65 196.97	Hg 66 200.59	Tl 67 204.38	Pb 68 207.2	Bi 69 208.98	Po 70 209	At 71 210	Rn 72 222	
Francium 87 Fr 223	Radium 88 Ra 226	Actinium 89 Ac 227	Rutherfordium 90 Rf 261	Dubnium 91 Db 262	Seaborgium 92 Sg 266	Berkelium 93 Bk 267	Hassium 94 Hs 277	Mt 95 268	Ununennium 96 Uue 288	Unbinilium 97 Uub 289	Untrium 98 Uut 290	Unquadrium 99 Uuq 291	Unpentium 100 Uup 292	Unsextium 101 Uus 293	Unseptium 102 Uuh 294	Unoctium 103 Uuo 295	Unnonium 104 Uun 296	

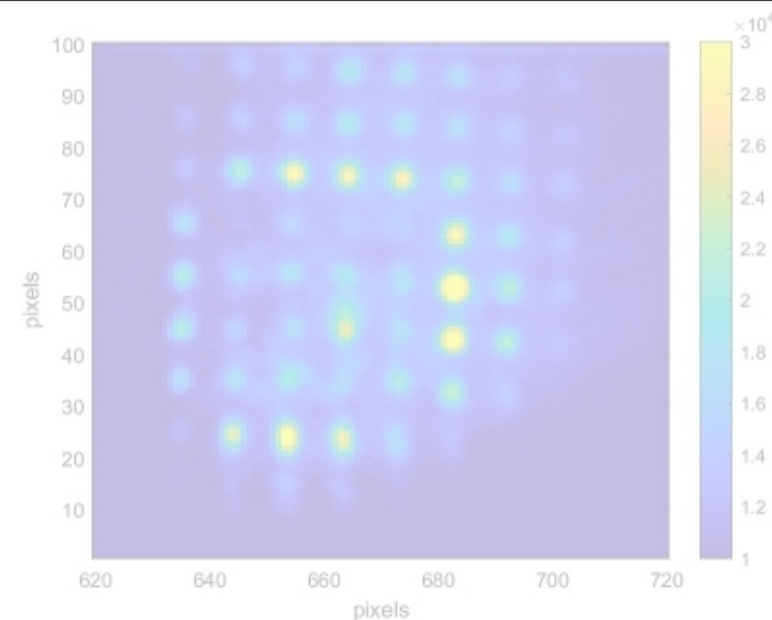
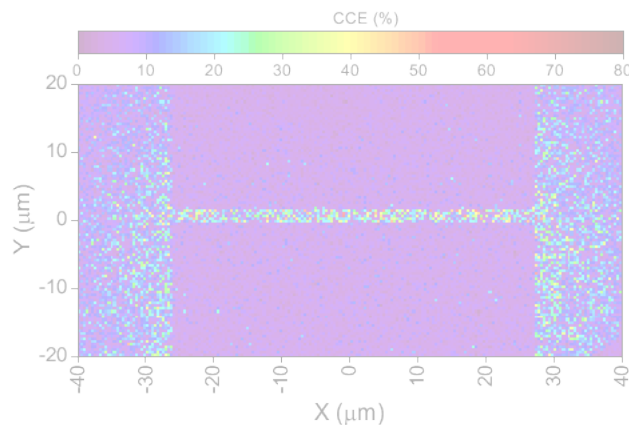
*Lanthanide series

57	58	59	60	61	62	63	64	65	66	67	68	69	70
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
89	90	91	92	93	94	95	96	97	98	99	100	101	102
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

** Actinide series



In-Situ Counting + Photoluminescence

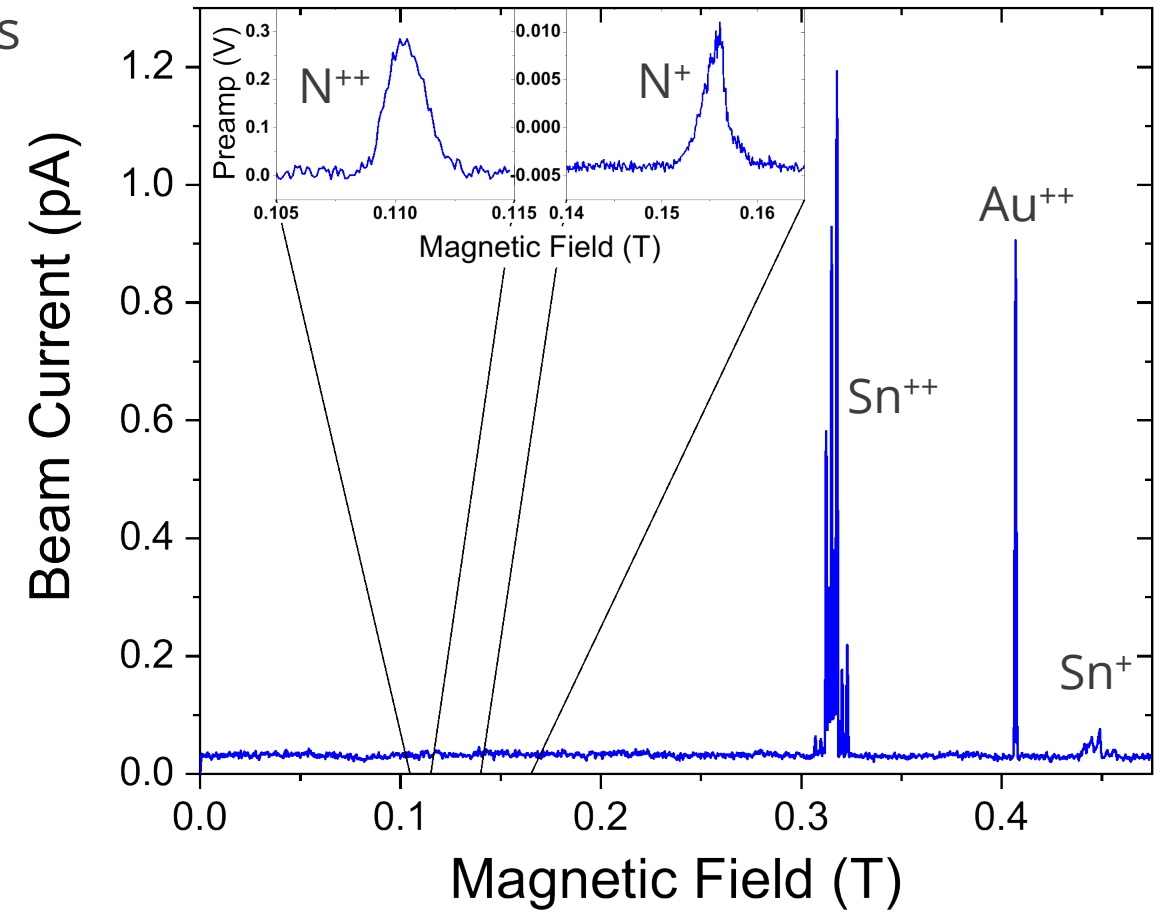


N Source - Characterization



Three parameters are important for ion sources

1. Mass Spectrum



N Source - Characterization

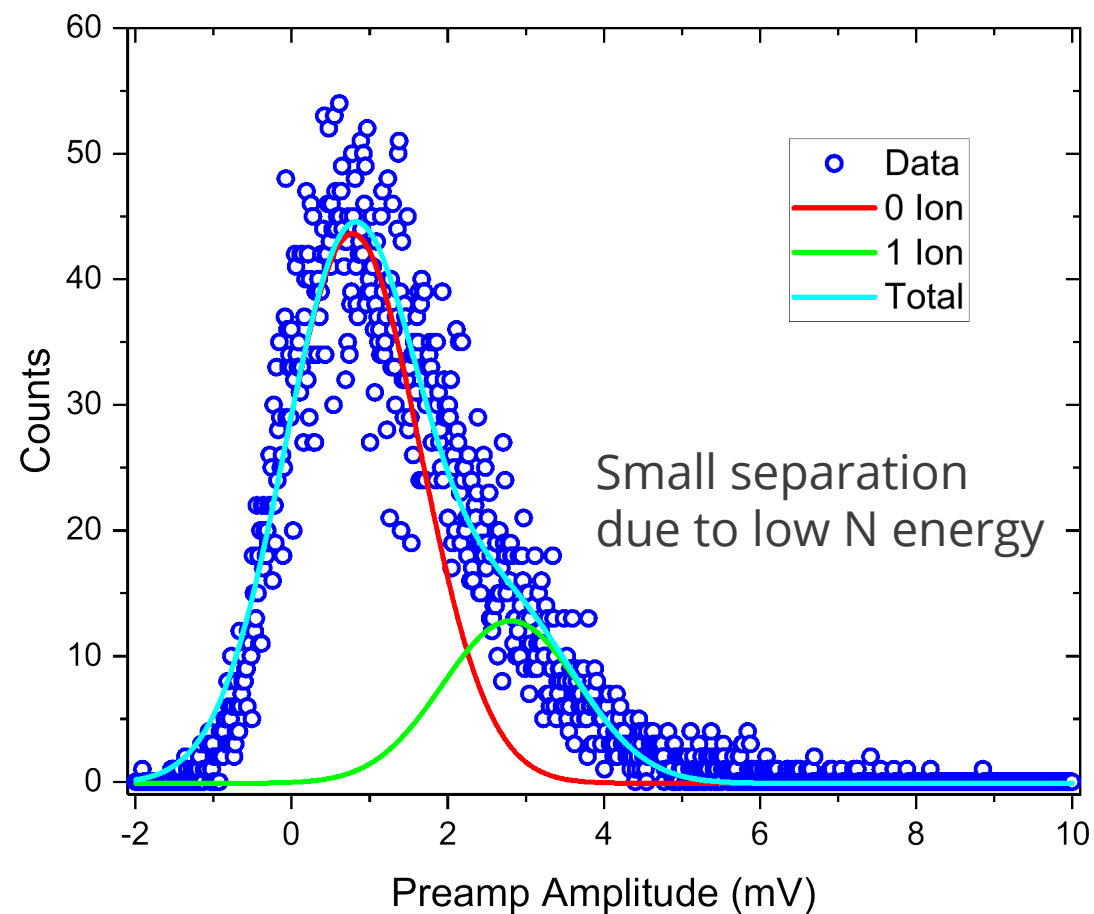


Three parameters are important for ion sources

1. Mass Spectrum ☒
2. Beam Current

- 25 μs pulselength
- 0.48 ions/pulse

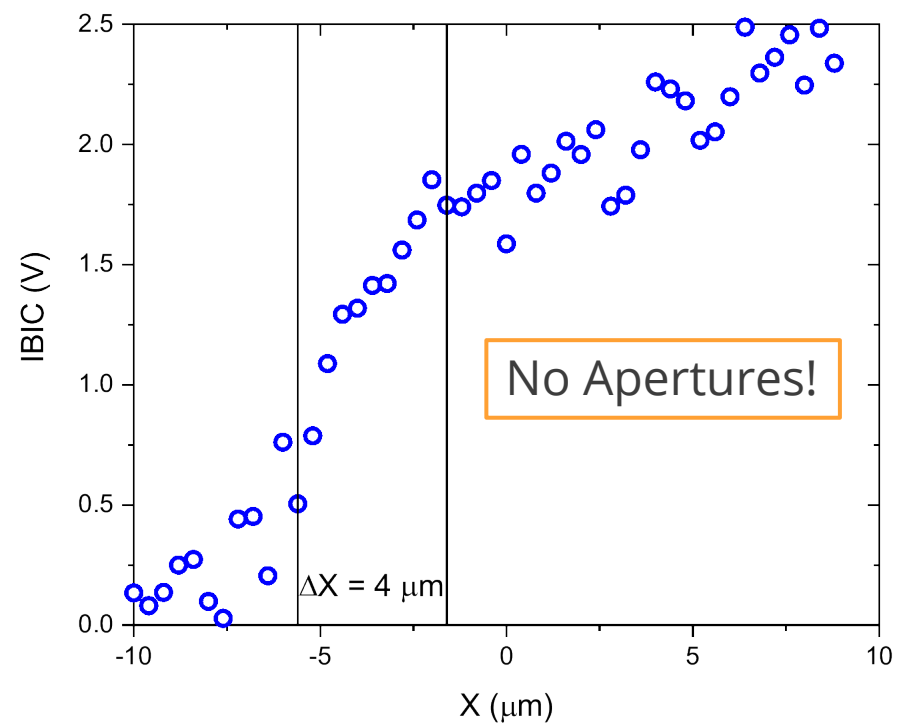
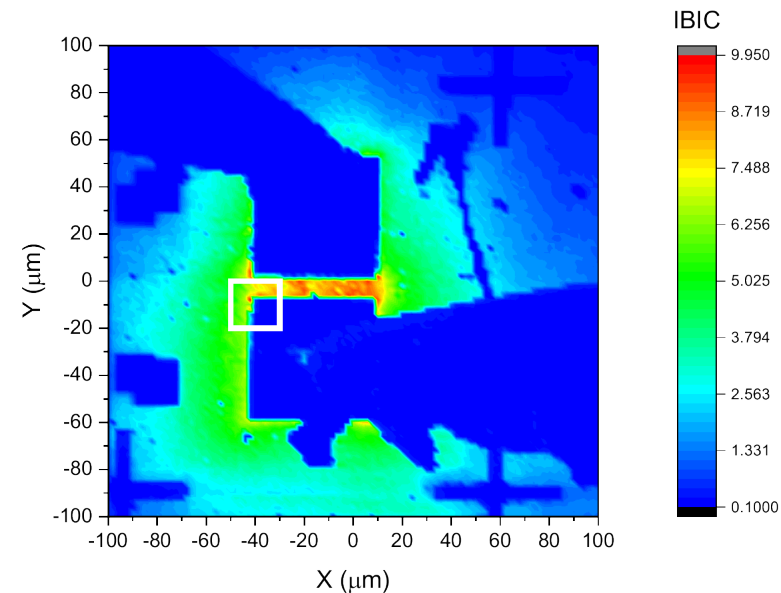
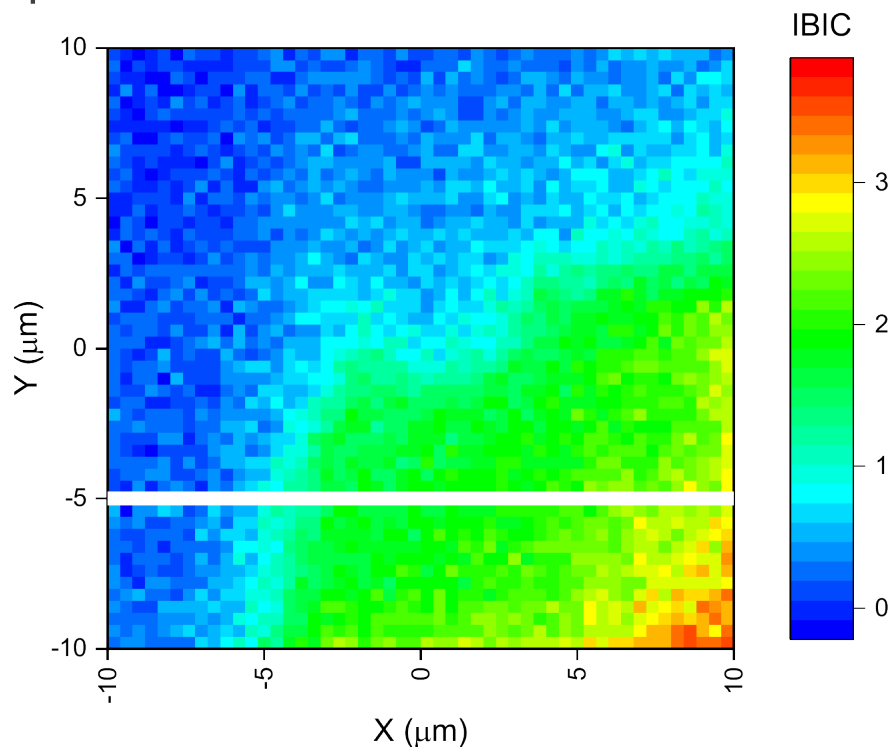
$\langle 1 \rangle$ ion every 50 $\mu\text{s} \equiv 20 \text{ k ions/s}$



N Source - Characterization

Three parameters are important for ion sources

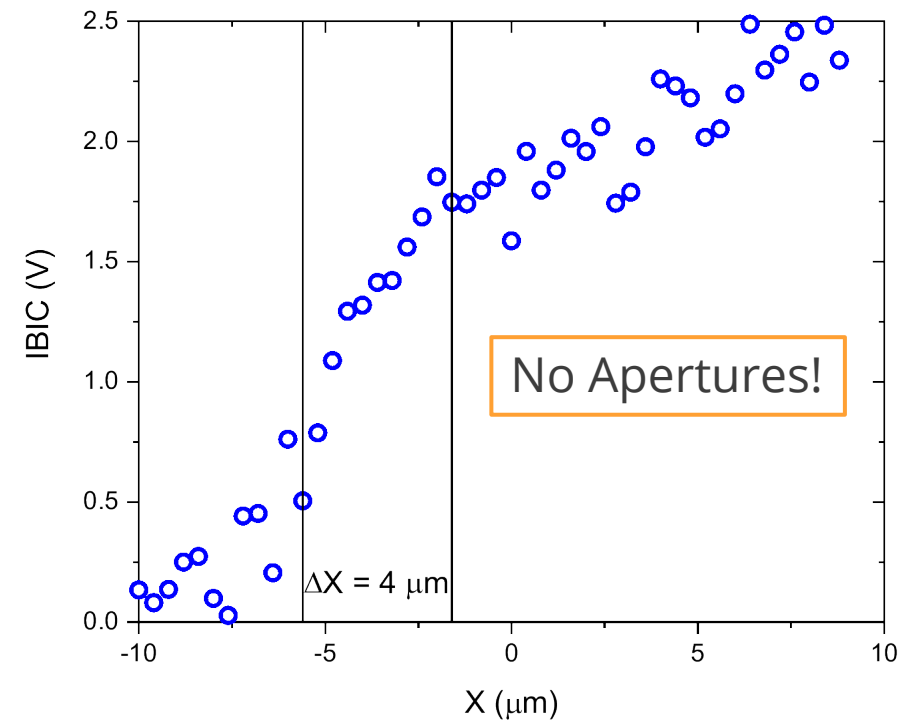
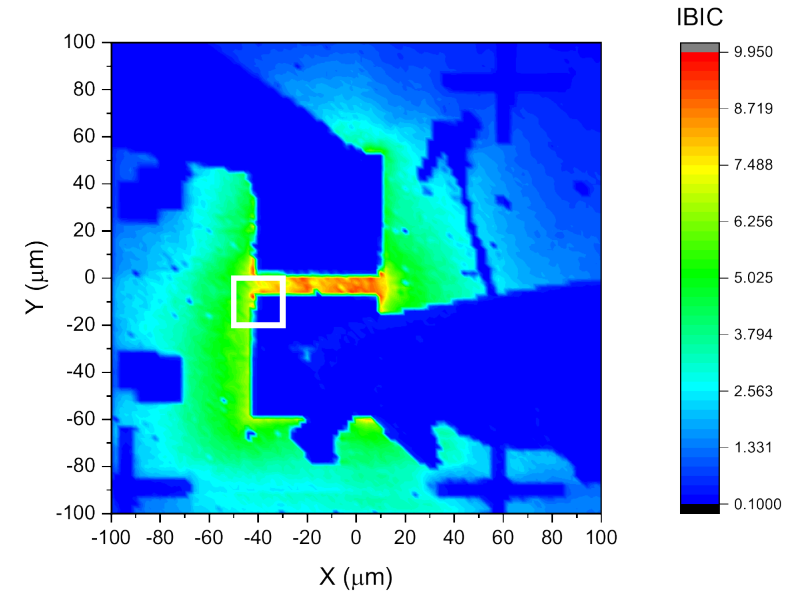
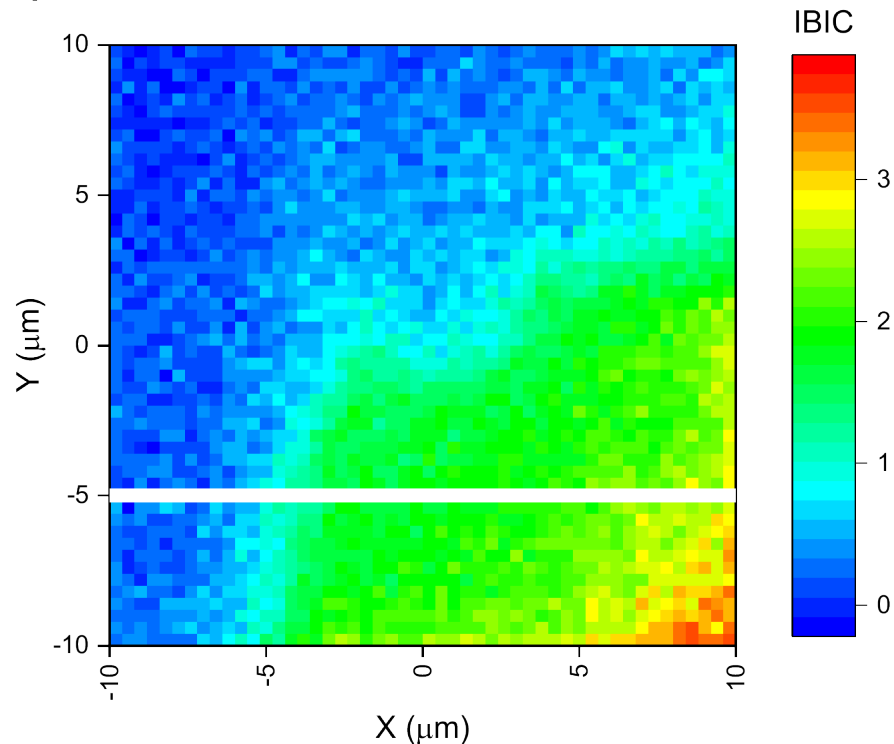
1. Mass Spectrum ☒
2. Beam Current ☒
3. Spot Size



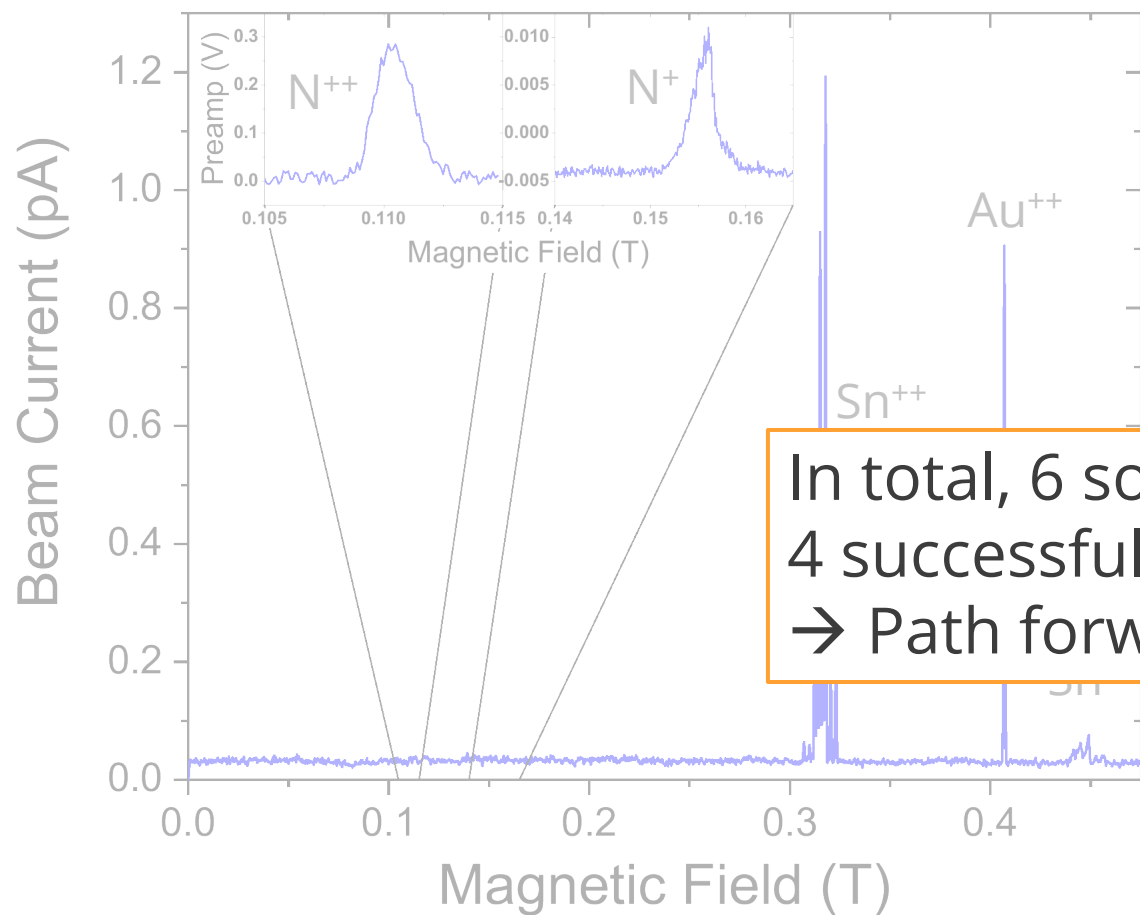
N Source - Characterization

Three parameters are important for ion sources

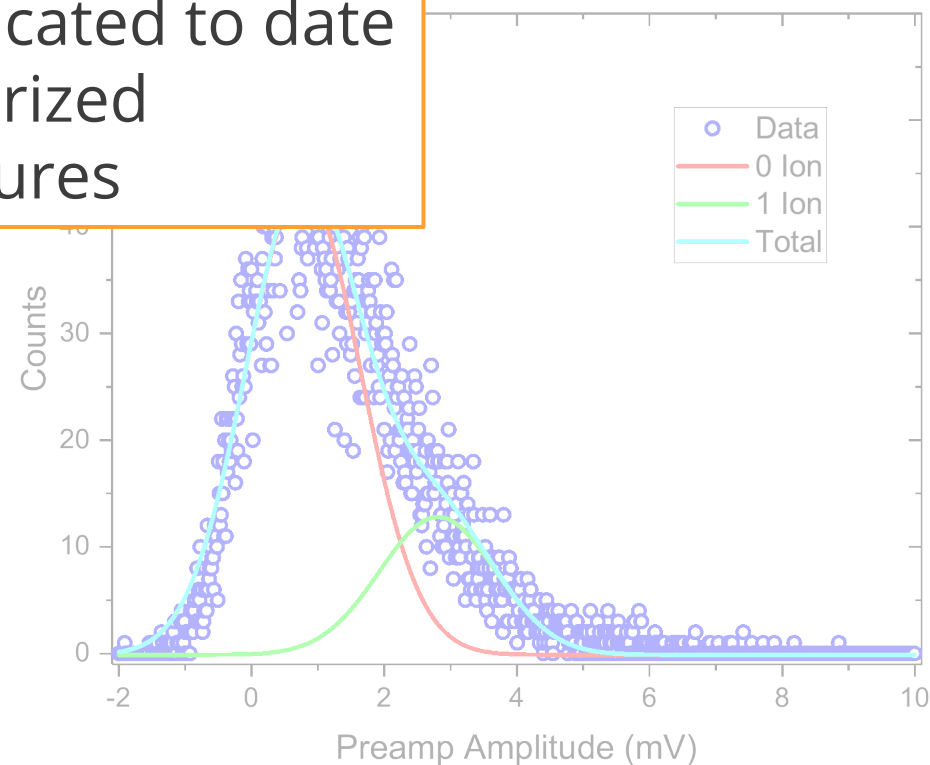
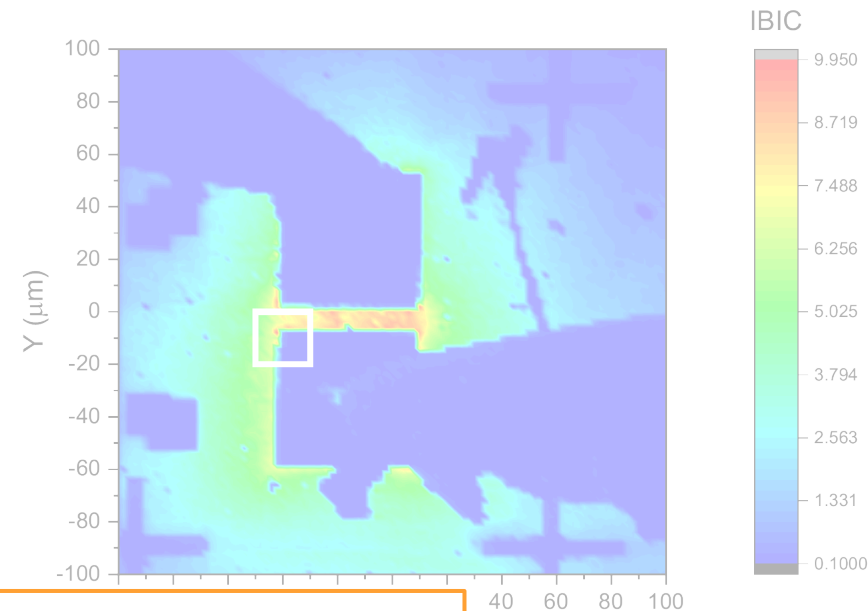
1. Mass Spectrum ☒
2. Beam Current ☒
3. Spot Size ☒



N Source - Characterization



In total, 6 sources fabricated to date
4 successfully characterized
→ Path forward: Apertures



Single Photon Sources

Three main candidates

1. Atoms & Ions

- Requires ultracold atoms
- Hard to scale up
- Fixed emission at transition lines

Quantum Applications require single photon sources to distribute information

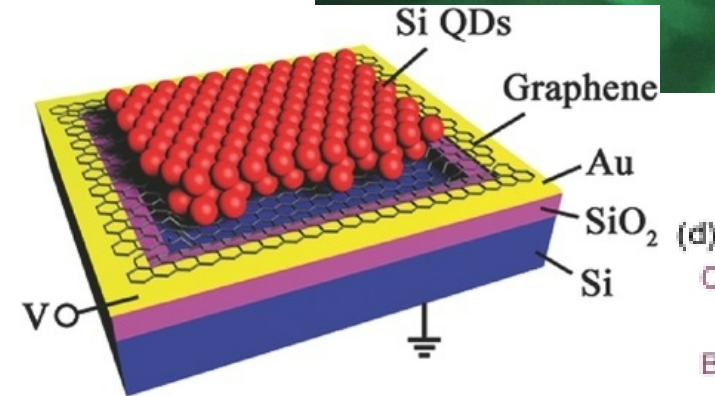
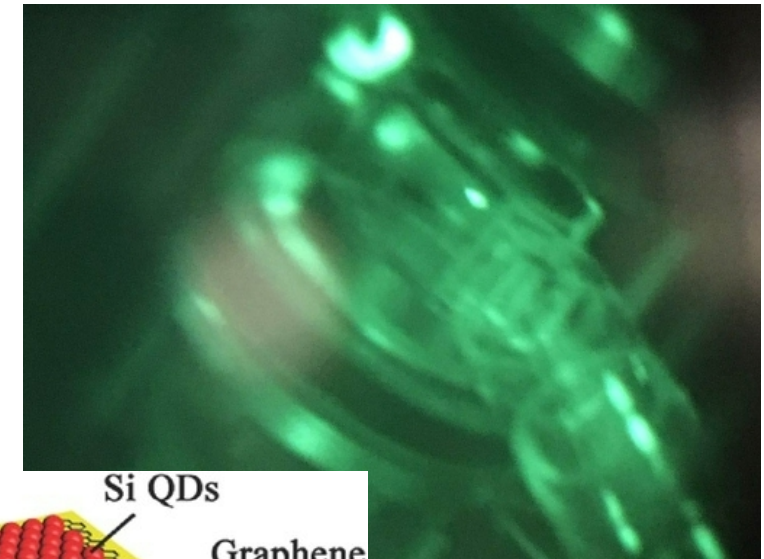
2. Quantum Dots

- High brightness
- Poor indistinguishability

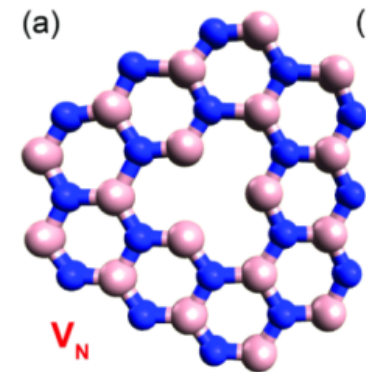
3. Defect Emitters

- Artificial Atoms embedded in semiconductor lattice
- Potential for scalable fabrication
- Examples are SiV in diamond, V_{Si} in SiC, unknown defects in GaN, unknown defects in 2D TMDs

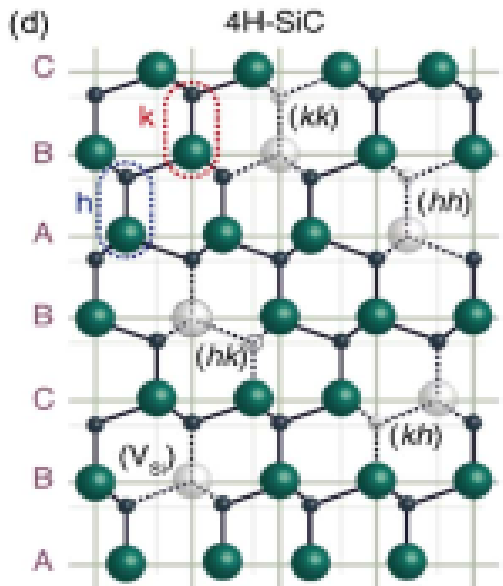
Defect emitters combine benefit of atom-based high fidelity sources with room-temperature operation and scalability of solid-state system



T. Yu, Adv. Mater., 28: 4912 (2016)



T.T. Tran, arXiv1504.06521

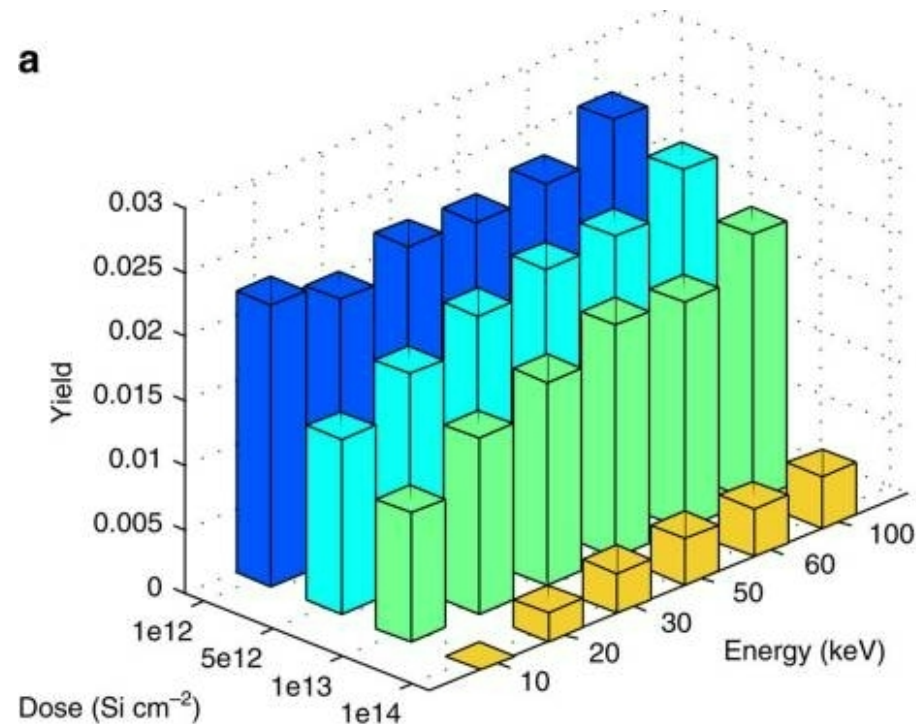


F. J. Heremans et al., Proc. IEEE 104, 10 (2016)

Deterministic Creation of Single Photon Sources

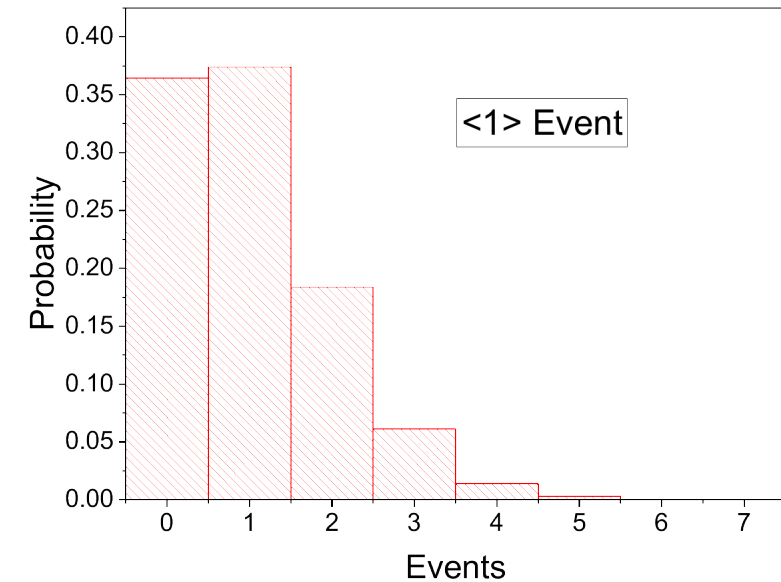
Task: Create single optically active defect / impurity emitter at a defined location (i.e. inside optical cavity)
Issue: Poisson Statistics for low #s

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



<30> Si/location

Fabricating
Device

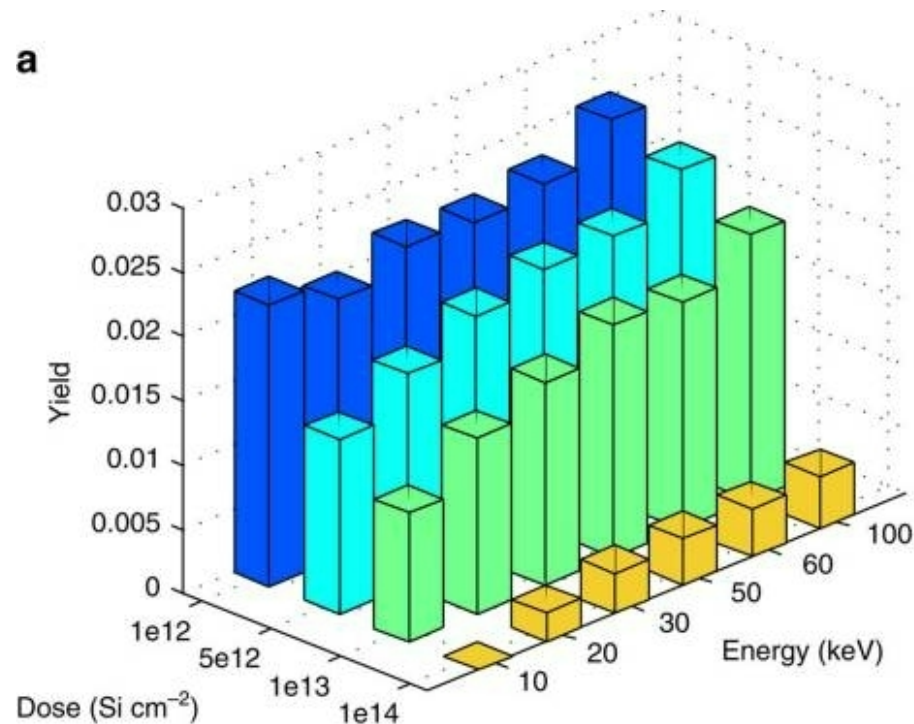


Deterministic Creation of Single Photon Sources

Task: Create single optically active defect / impurity emitter at a defined location (i.e. inside optical cavity)
Issue: Poisson Statistics for low #s

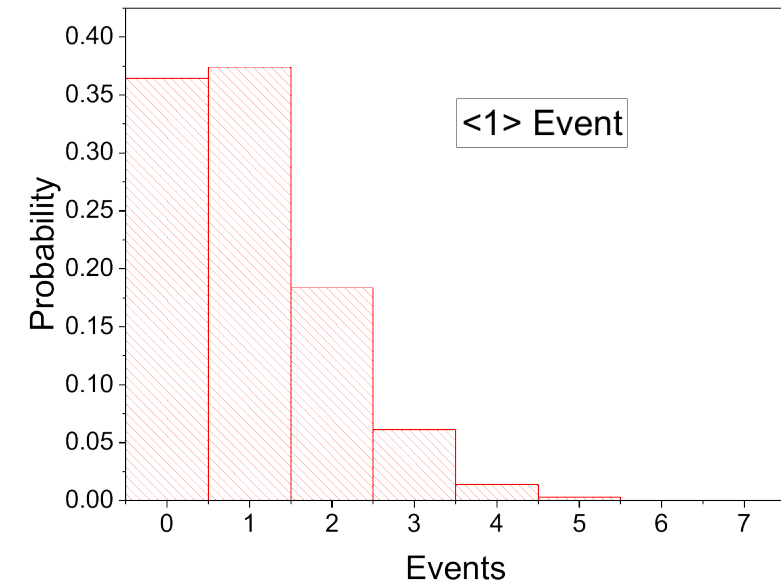
$$\text{Yield} = \frac{\# \text{SiV}}{\# \text{Si}}$$

In-situ counting:
Improve #Si



<30> Si/location

Fabricating
Device



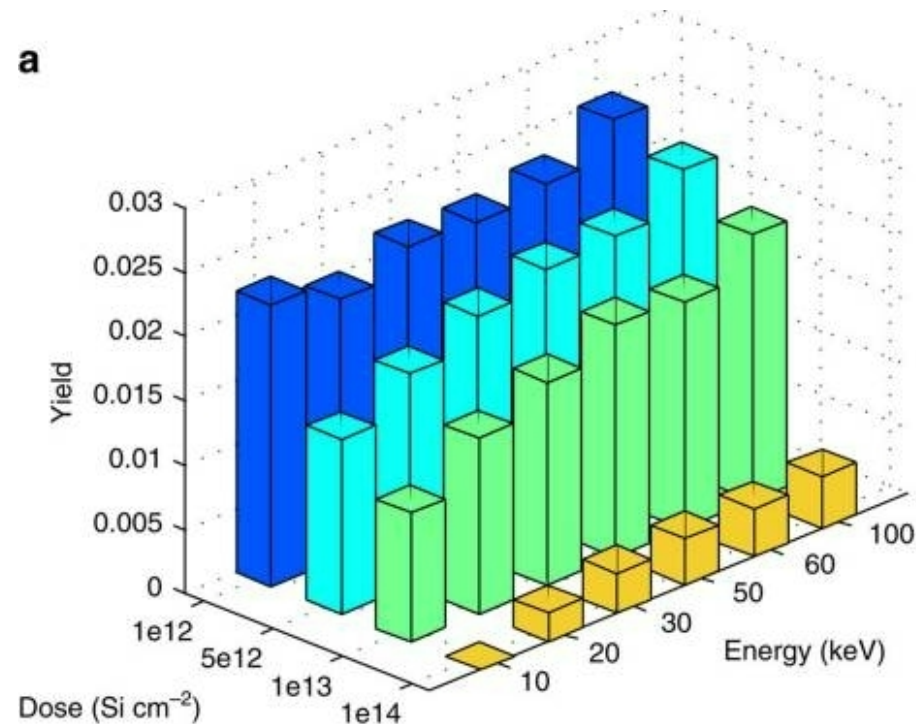
Deterministic Creation of Single Photon Sources

Task: Create single optically active defect / impurity emitter at a defined location (i.e. inside optical cavity)
Issue: Poisson Statistics for low #s

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

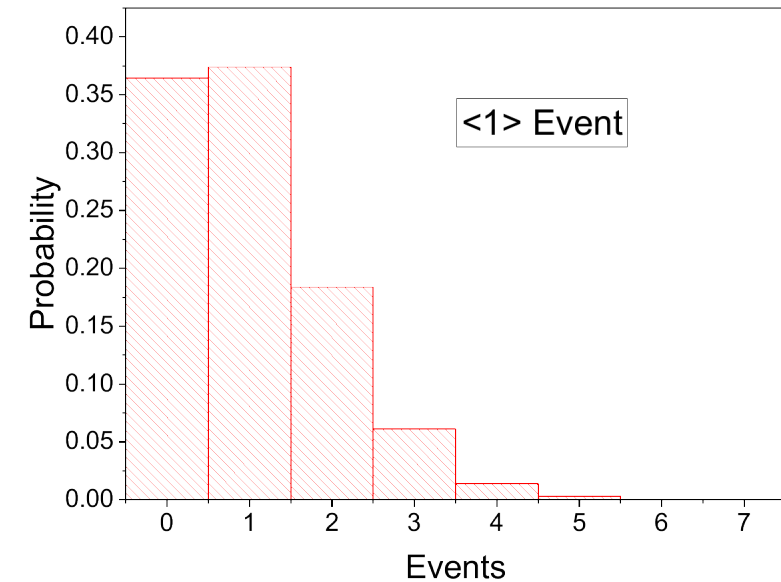
In-situ PL:
Improve #SiV

In-situ counting:
Improve #Si



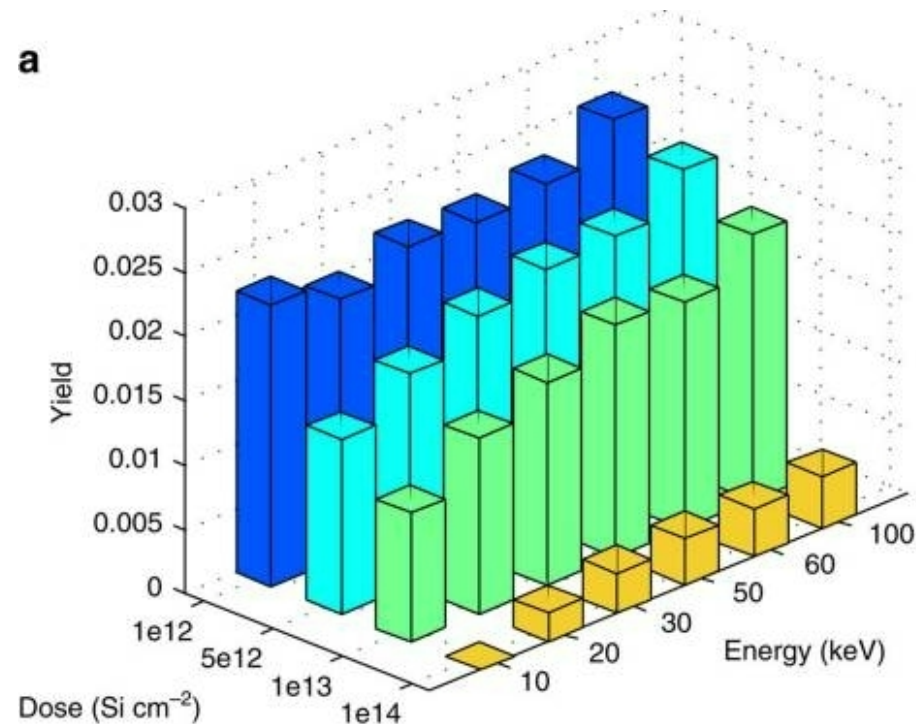
<30> Si/location

Fabricating
Device



Deterministic Creation of Single Photon Sources

Task: Create single optically active defect / impurity emitter at a defined location (i.e. inside optical cavity)
Issue: Poisson Statistics for low #s



T. Schröder et al., Nat. Commun., 8, 15376 (2017)

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

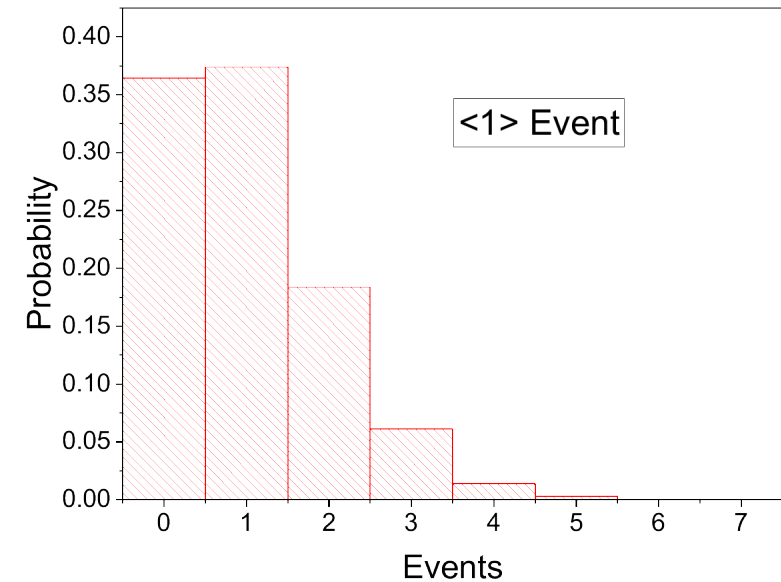
In-situ anneal: Increase Yield

In-situ PL: Increase #SiV

In-situ counting: Improve #Si

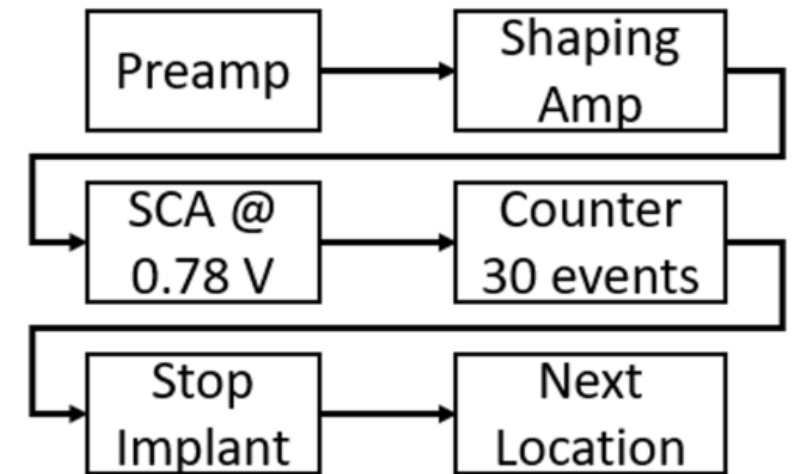
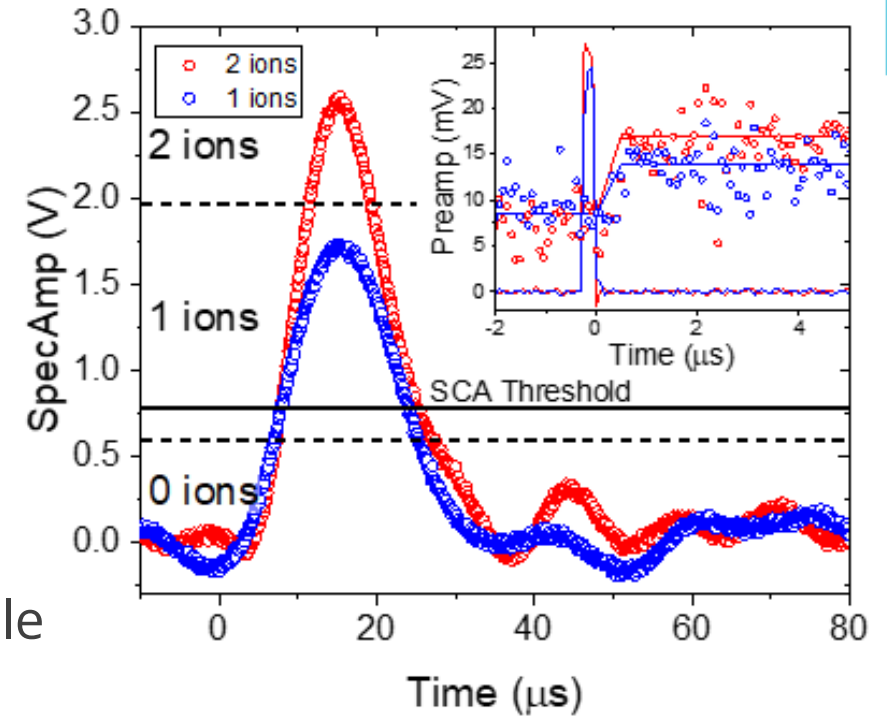
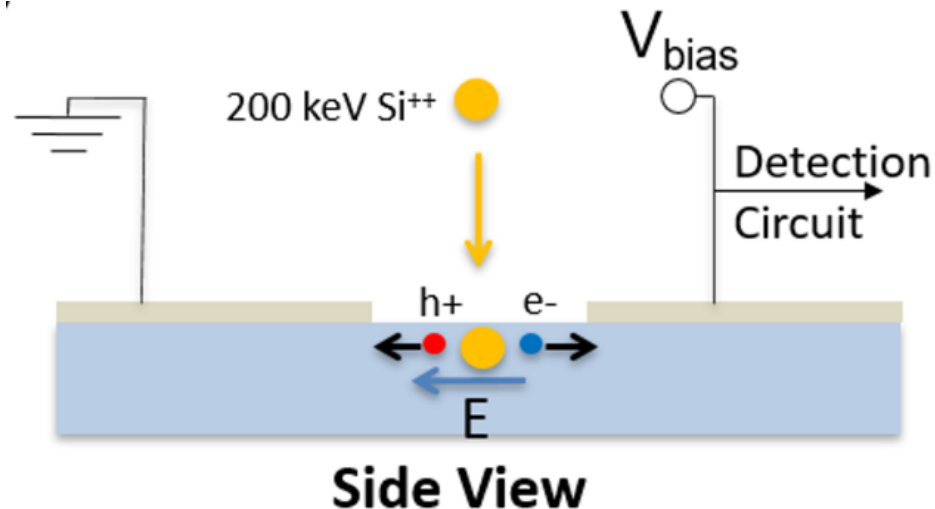
<30> Si/location

Fabricating Device

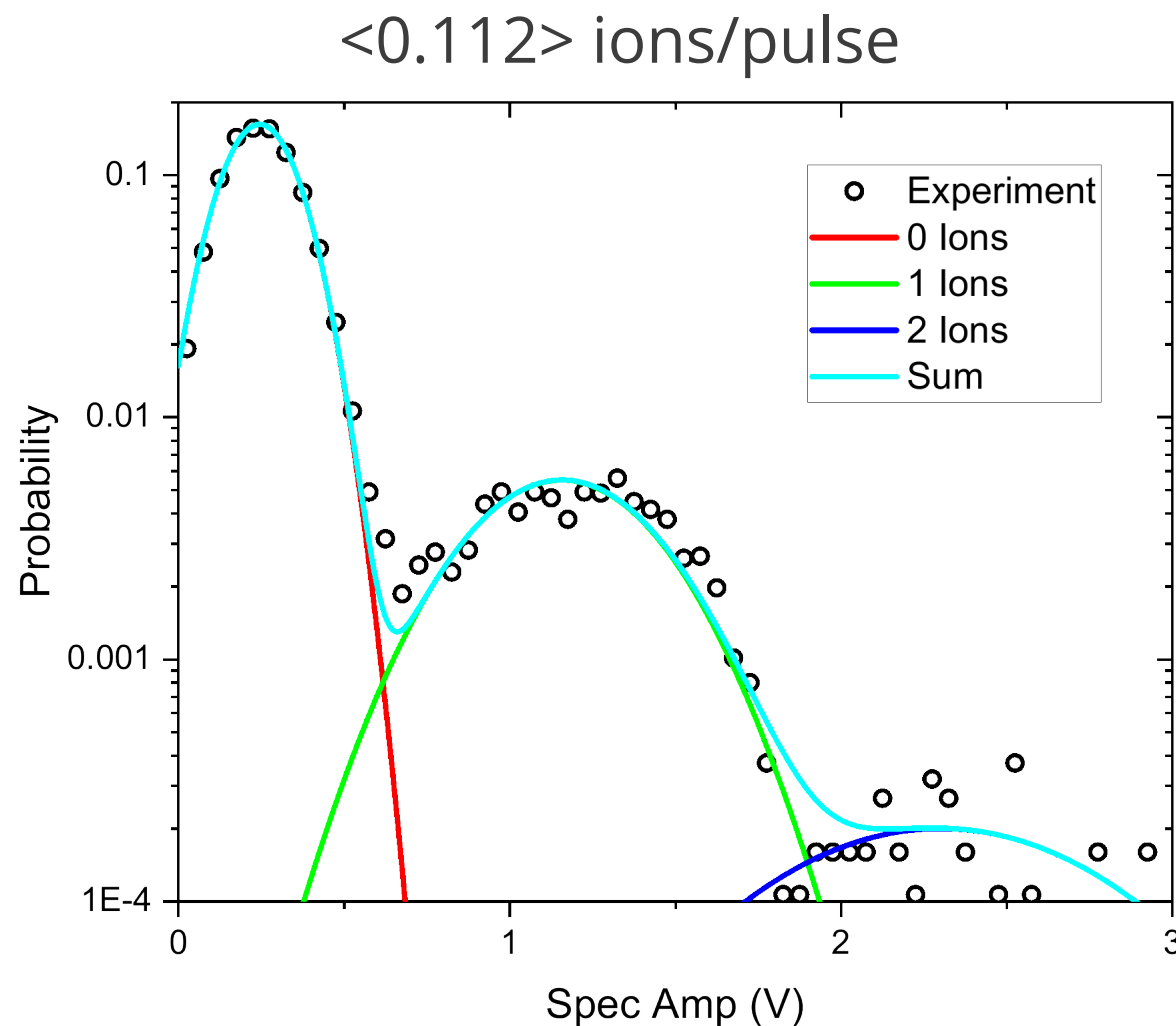


Experiment Setup

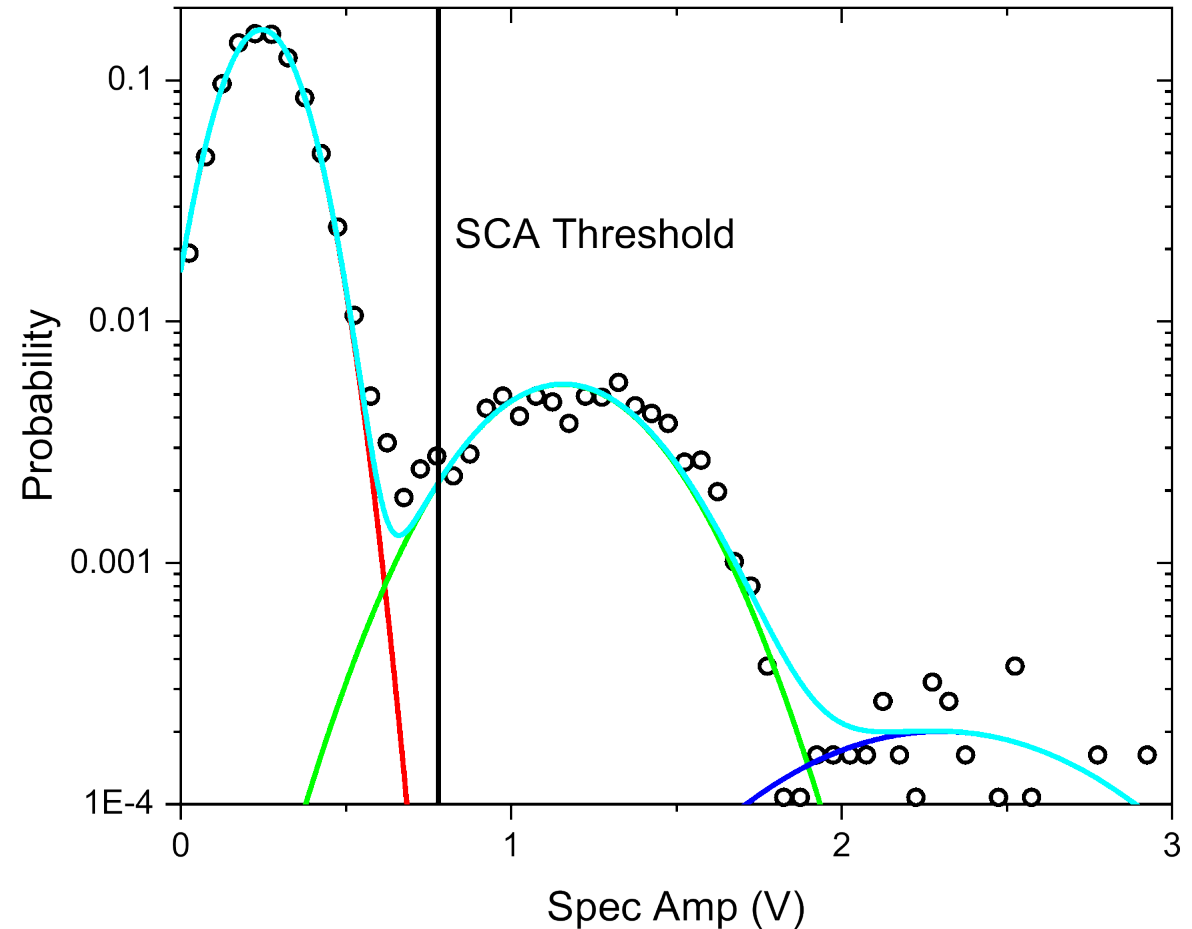
- Ion counting relies on e-h pairs generated by ion
 - ~12000 e-h pairs per ion
- Other counting techniques use secondary electrons
 - Fails for non-flat geometries
- Two in-situ electrical probes for contacting the sample
 - Bias field makes e-h pairs separate
- Induced charge gets collected by probes



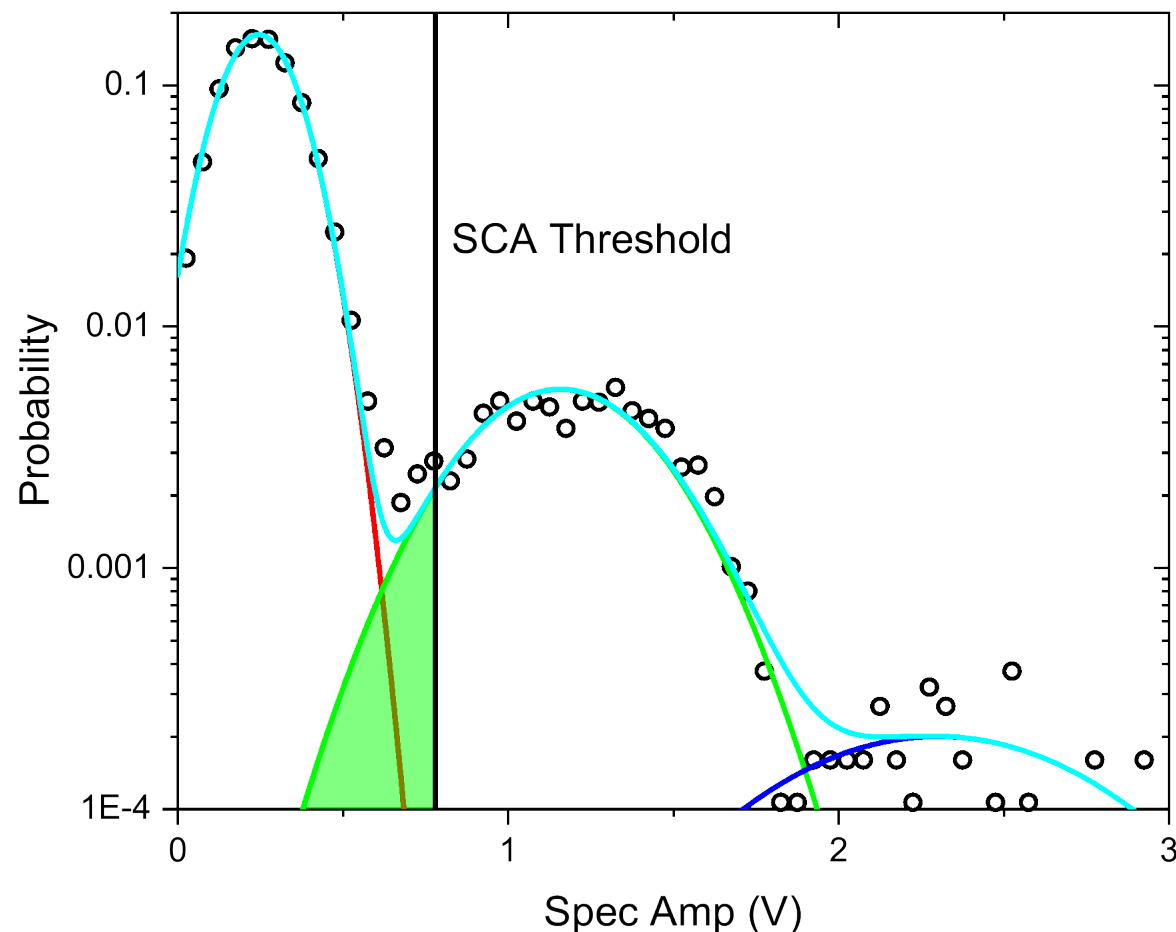
- Histogram of SpecAmp amplitude shows Poisson statistics of ion emission
- From histogram derive errors on counting measurement



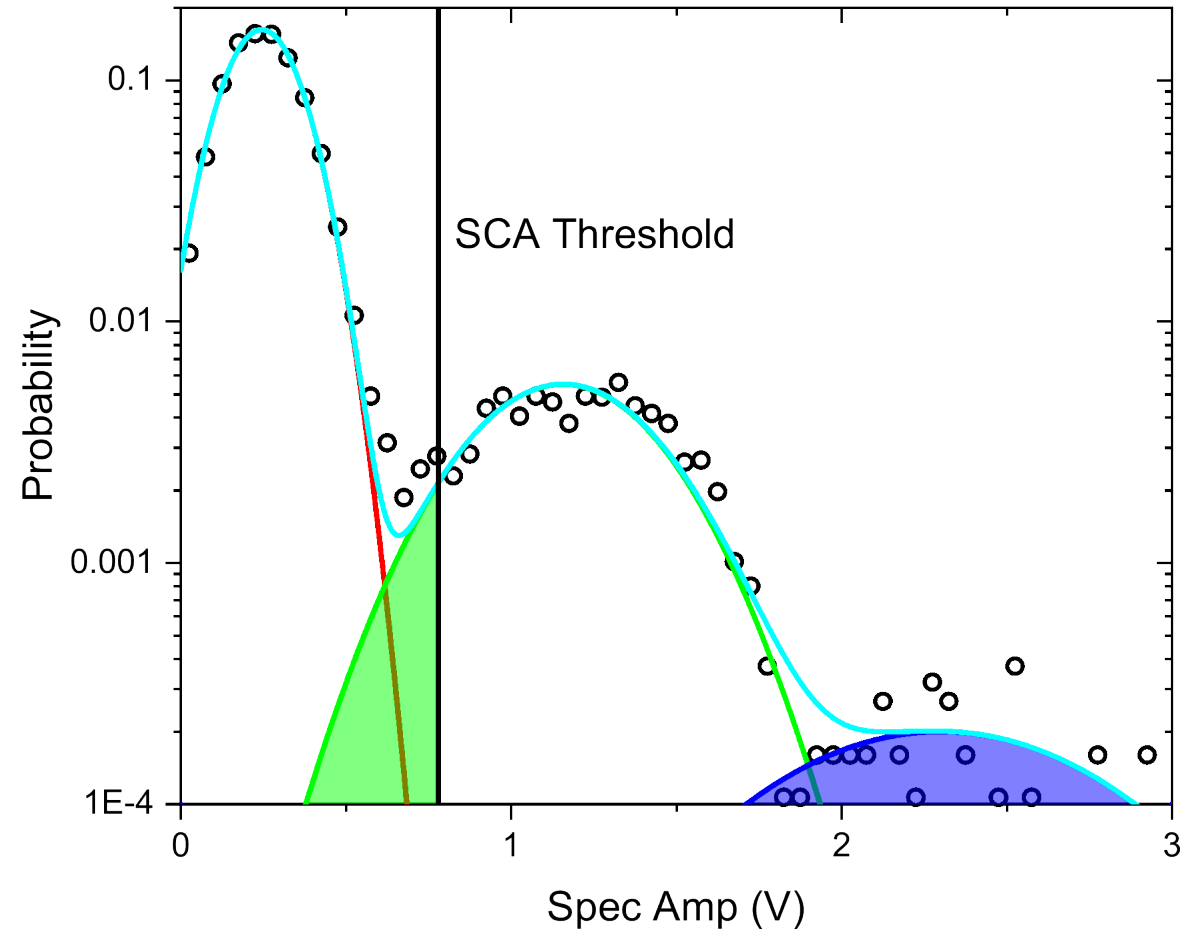
- Histogram of SpecAmp amplitude shows Poisson statistics of ion emission
- From histogram derive errors on counting measurement
 1. False Positives - < 1 ppb



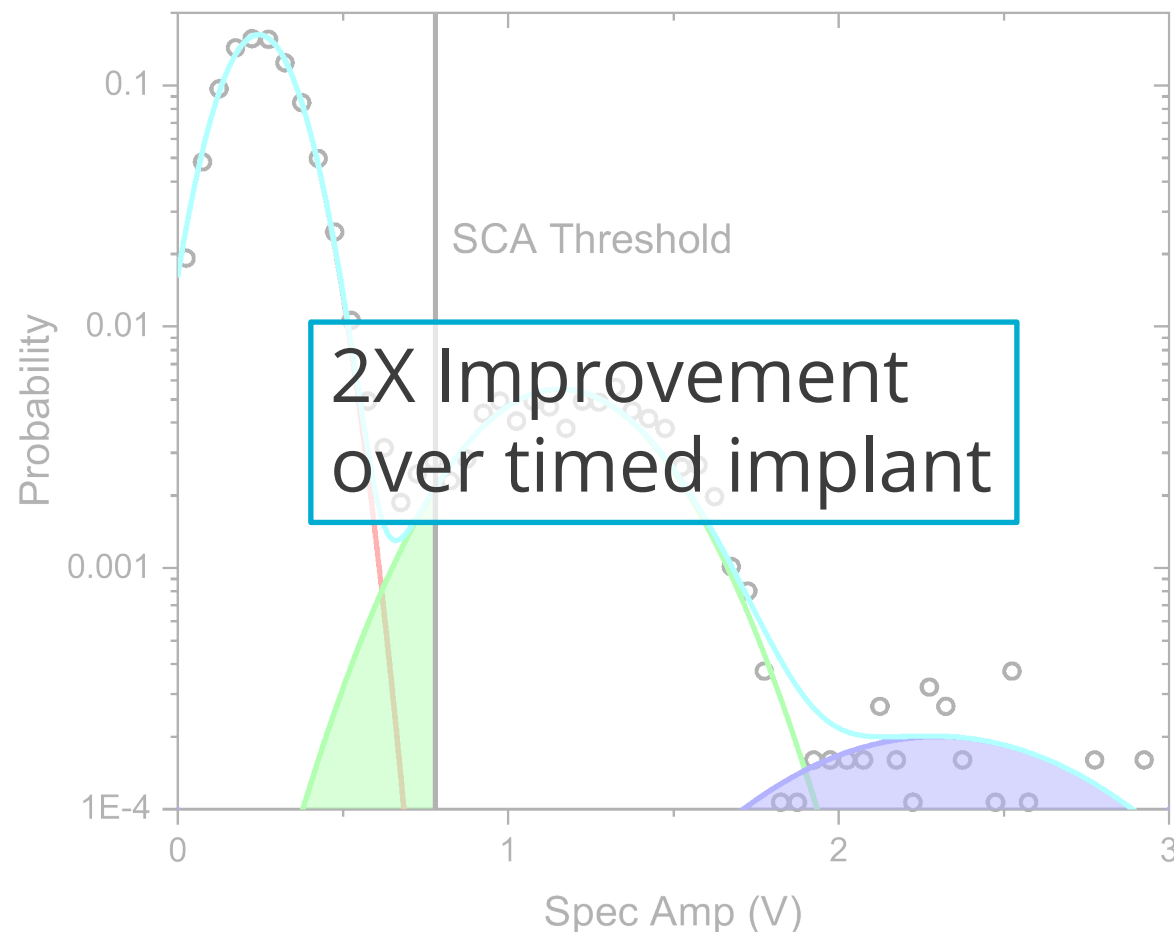
- Histogram of SpecAmp amplitude shows Poisson statistics of ion emission
- From histogram derive errors on counting measurement
 1. False Positives - < 1 ppb
 2. False Negatives +8.6 %



- Histogram of SpecAmp amplitude shows Poisson statistics of ion emission
- From histogram derive errors on counting measurement
 1. False Positives - < 1 ppb
 2. False Negatives +8.6 %
 3. Multiple Ions +5.8 %

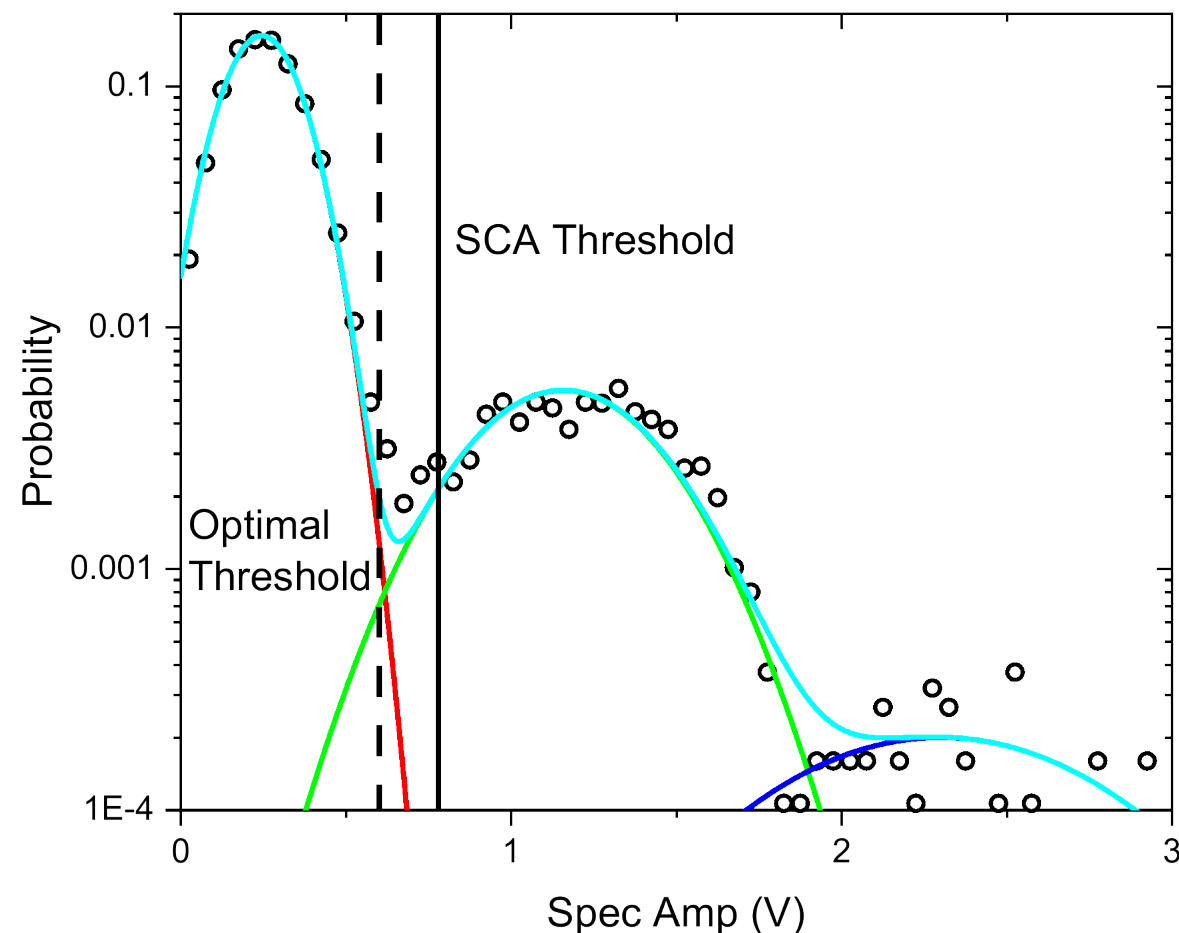


- Histogram of SpecAmp amplitude shows Poisson statistics of ion emission
- From histogram derive errors on counting measurement
 1. False Positives - < 1 ppb
 2. False Negatives +8.6 %
 3. Multiple Ions +5.8 %
- For implantation of 30 ions
Total Error: + 14.4 % / - 0 %
Timed Error: +/- 18.3 %



Ex-Situ Analysis

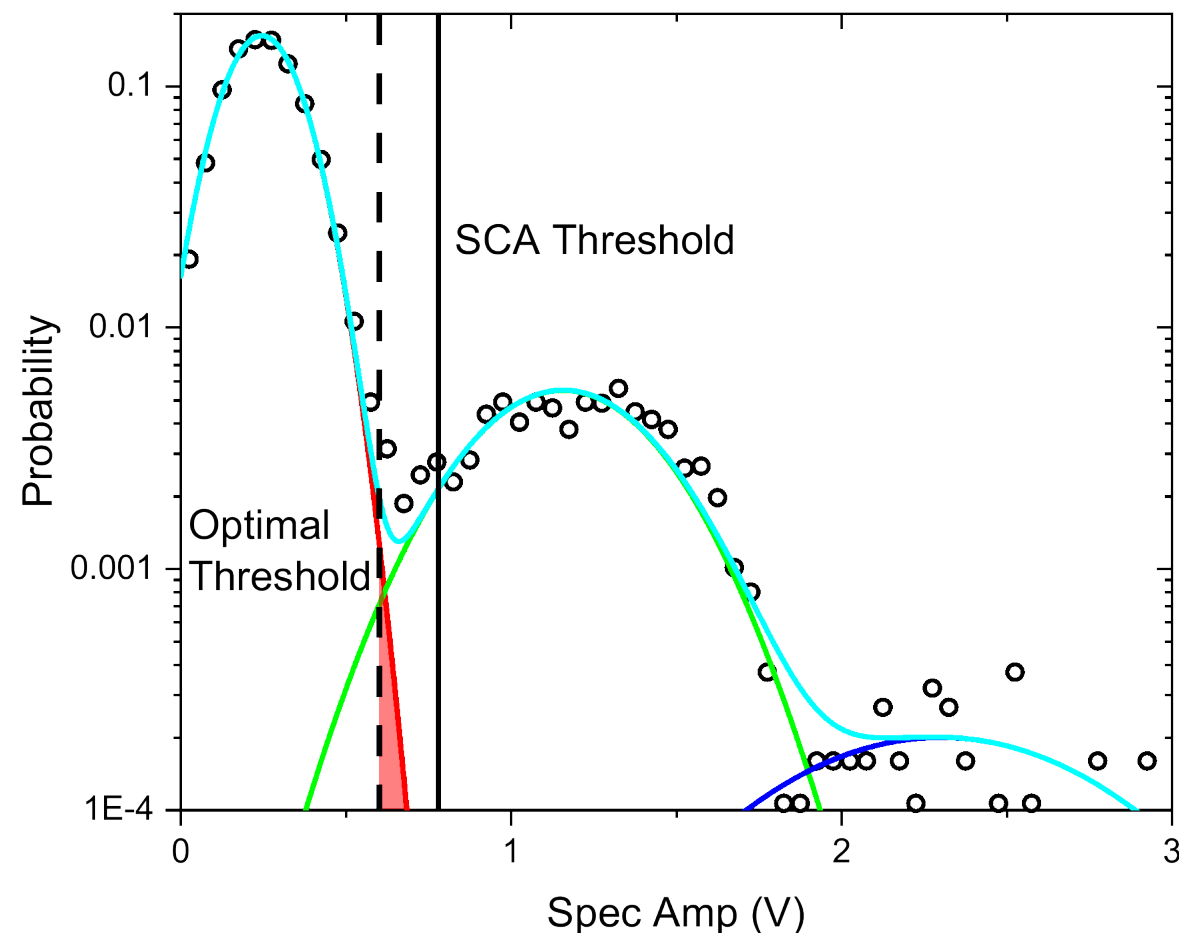
- In-situ measurement allows determination of number of ions per implantation spot post-implantation
- New and reduced errors



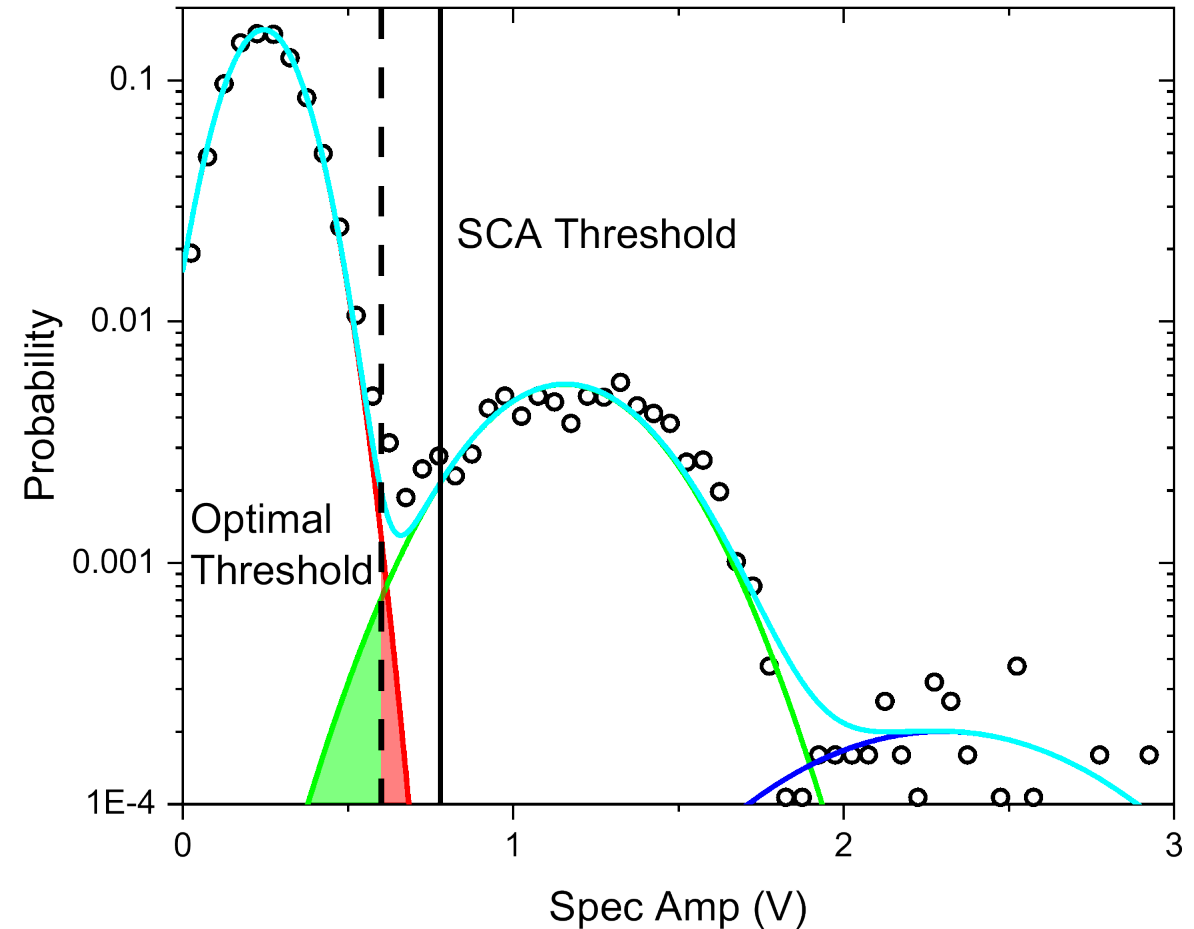
Ex-Situ Analysis



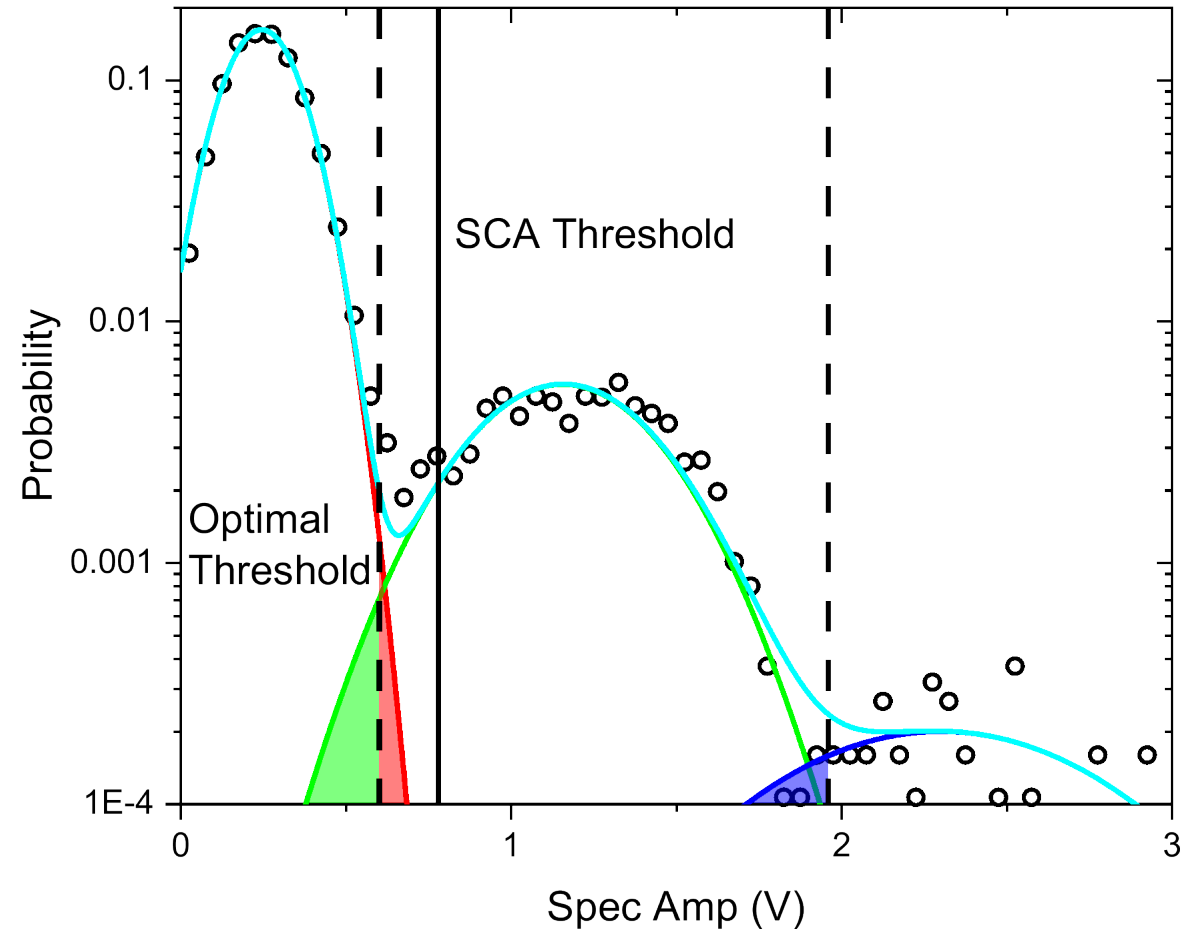
- In-situ measurement allows determination of number of ions per implantation spot post-implantation
- New and reduced errors
 1. False Positives -0.9 %



- In-situ measurement allows determination of number of ions per implantation spot post-implantation
- New and reduced errors
 1. False Positives -0.9 %
 2. False Negatives +2.3 %



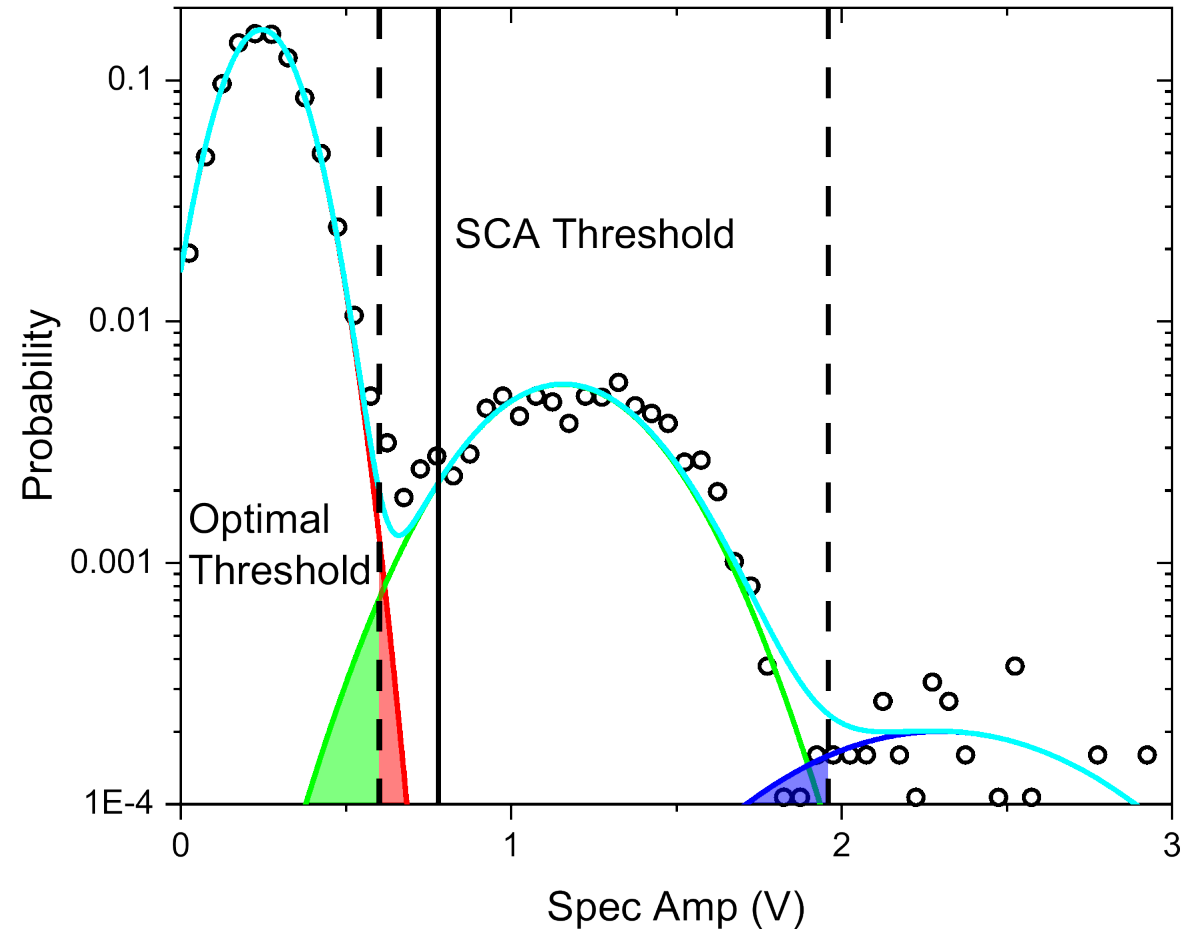
- In-situ measurement allows determination of number of ions per implantation spot post-implantation
- New and reduced errors
 1. False Positives -0.9 %
 2. False Negatives +2.3 %
 3. Multiple Ions +1.7 %



Ex-Situ Analysis



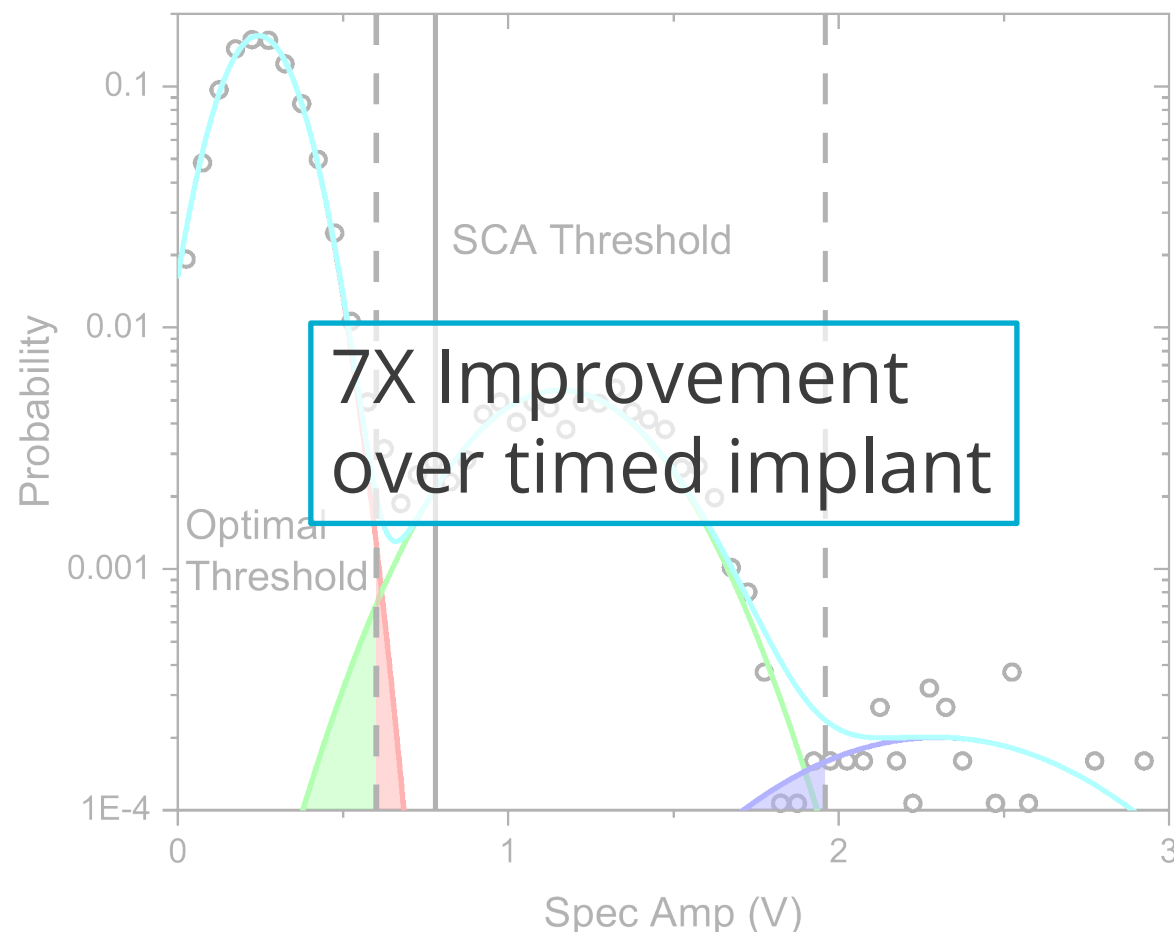
- In-situ measurement allows determination of number of ions per implantation spot post-implantation
- New and reduced errors
 1. False Positives -0.9 %
 2. False Negatives +2.3 %
 3. Multiple Ions +1.7 %
 4. Single as Double -0.2 %



Ex-Situ Analysis



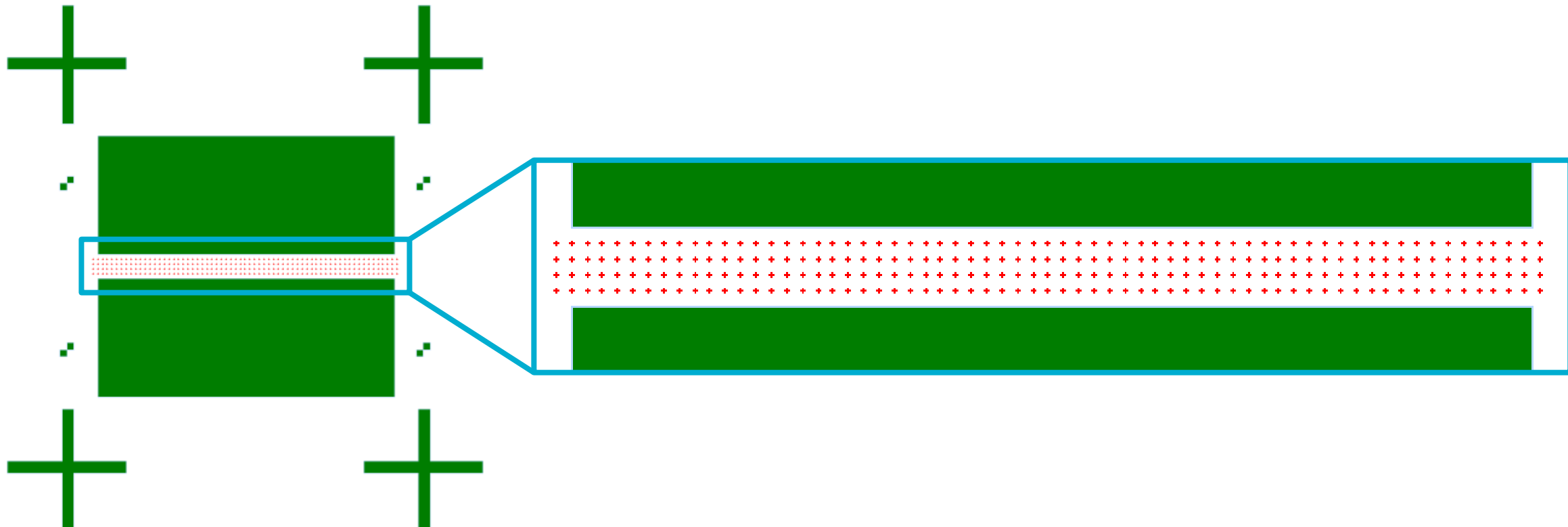
- In-situ measurement allows determination of number of ions per implantation spot post-implantation
- New and reduced errors
 1. False Positives -0.9 %
 2. False Negatives +2.3 %
 3. Multiple Ions +1.7 %
 4. Single as Double -0.2 %
- For implantation of 30 ions
Total Error: + 4.0 % / - 1.1 %
In-Situ Error: + 14.4 % / - 0 %
Timed Error: +/- 18.3 %



Implanted array



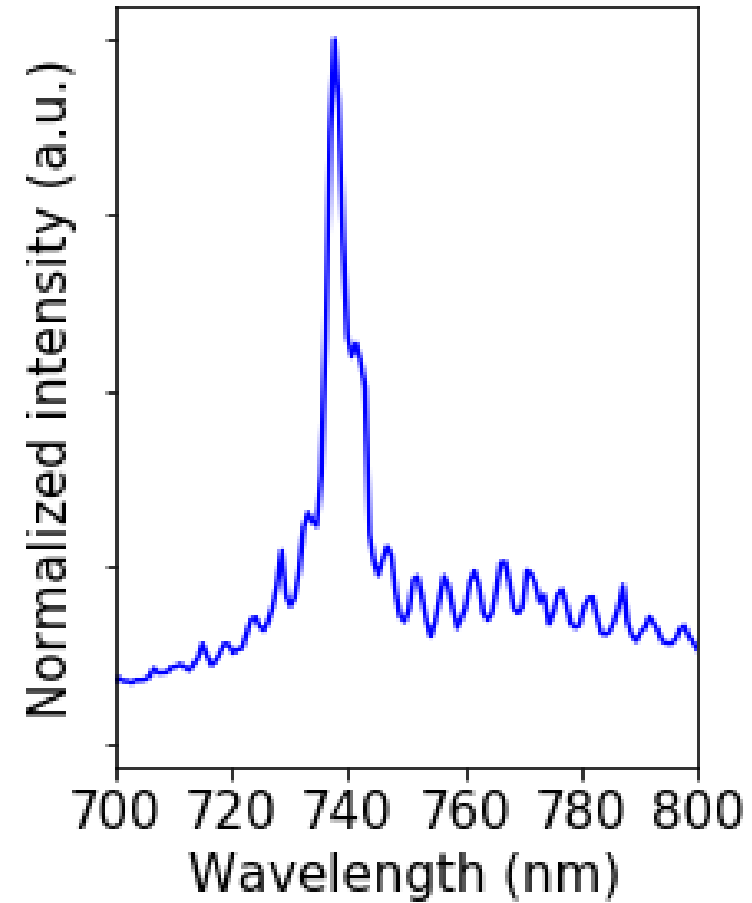
- In total implanted 5 working areas with 10, 20, 30 ions/location
- Each location has counted number of ions
- Can determine number of ions per spot with 5% error bar for each location



Photoluminescence Experiment



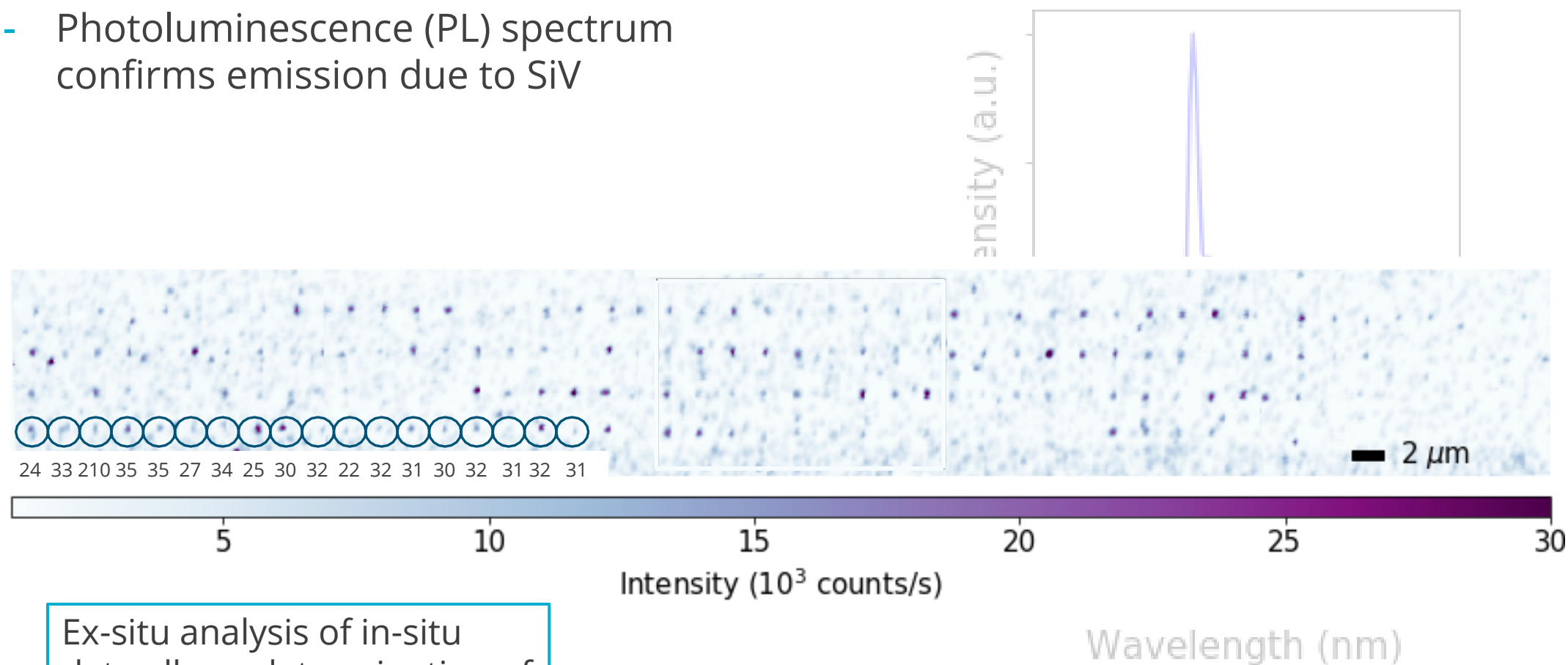
- Photoluminescence (PL) spectrum confirms emission due to SiV
 - 738 nm emission wavelength
 - ~4 nm full-width half maximum linewidth





Photoluminescence Experiment

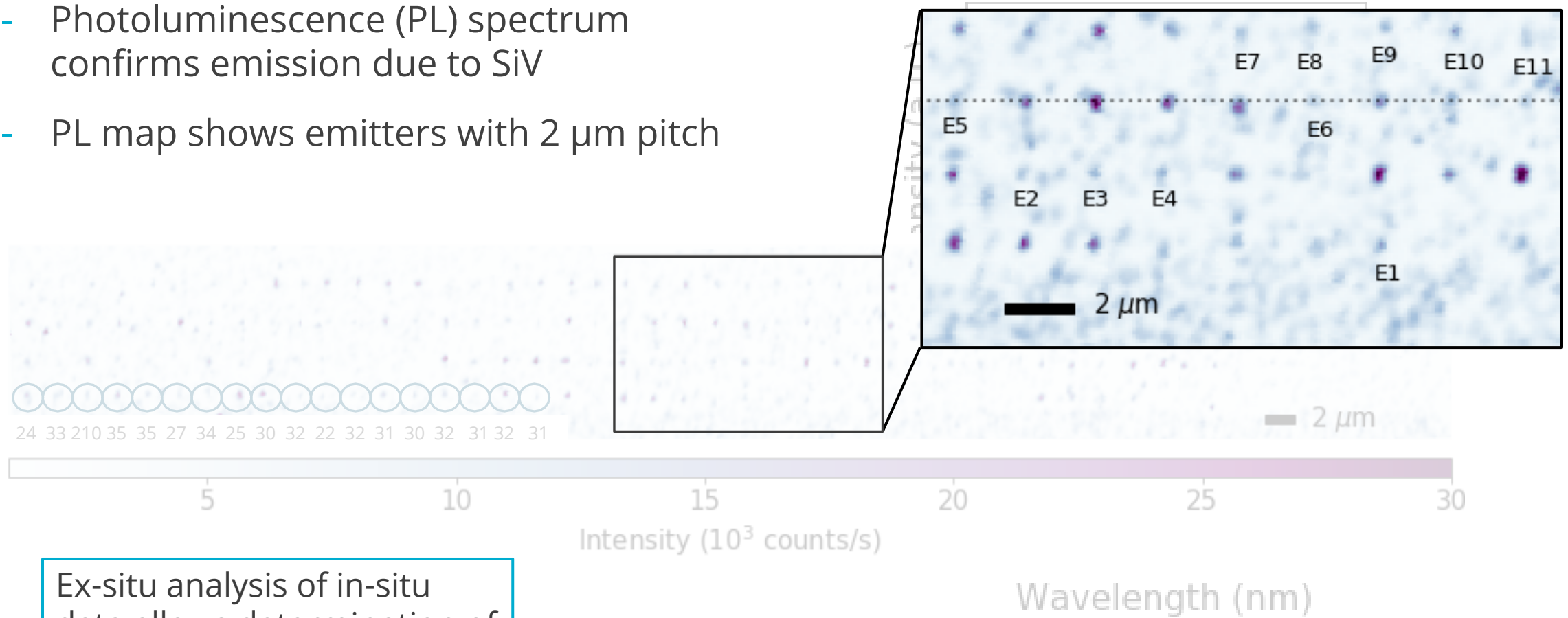
- Photoluminescence (PL) spectrum confirms emission due to SiV



Ex-situ analysis of in-situ data allows determination of #ions/spot with 5% accuracy

Photoluminescence Experiment

- Photoluminescence (PL) spectrum confirms emission due to SiV
- PL map shows emitters with 2 μm pitch

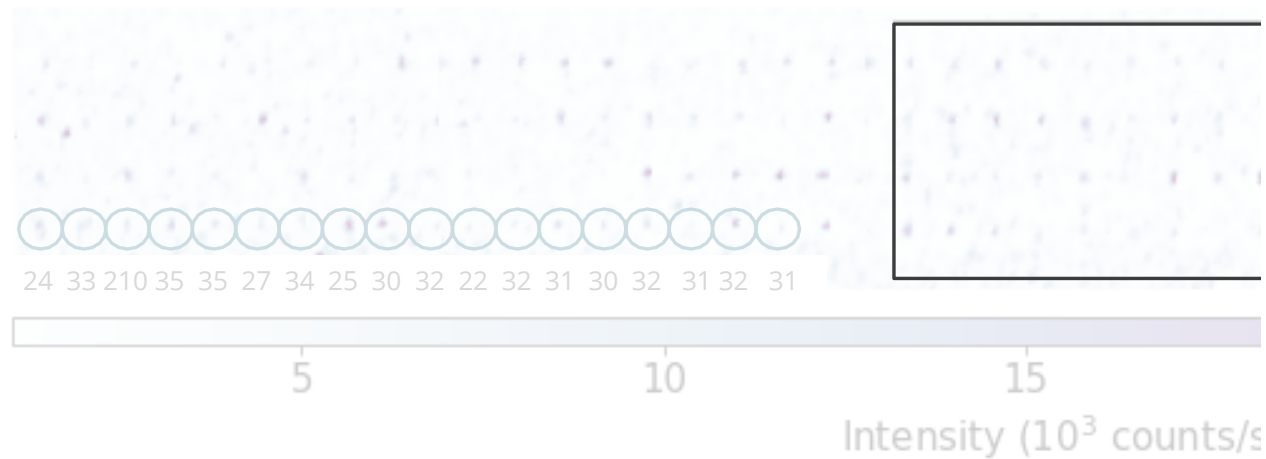


Ex-situ analysis of in-situ data allows determination of #ions/spot with 5% accuracy

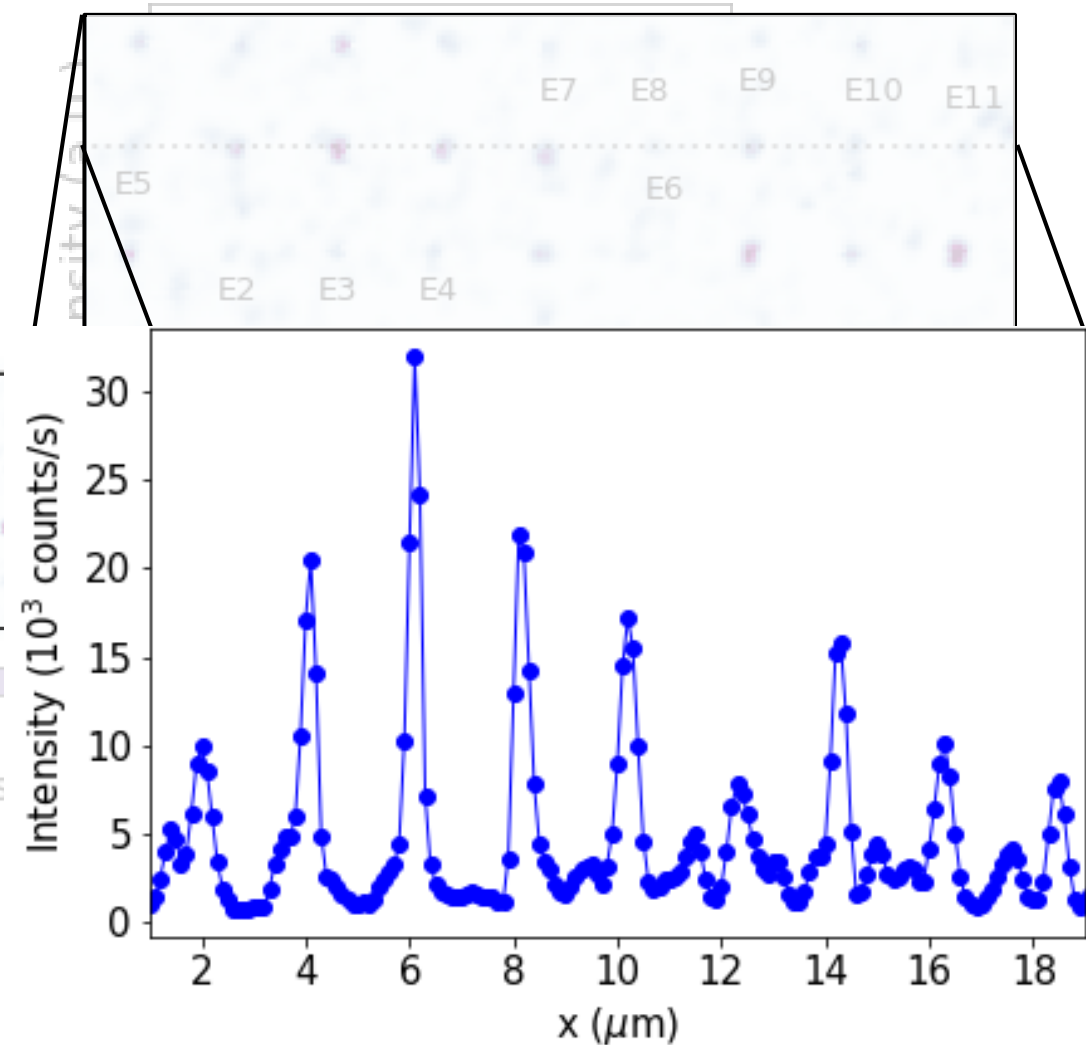


Photoluminescence Experiment

- Photoluminescence (PL) spectrum confirms emission due to SiV
- PL map shows emitters with 2 μm pitch



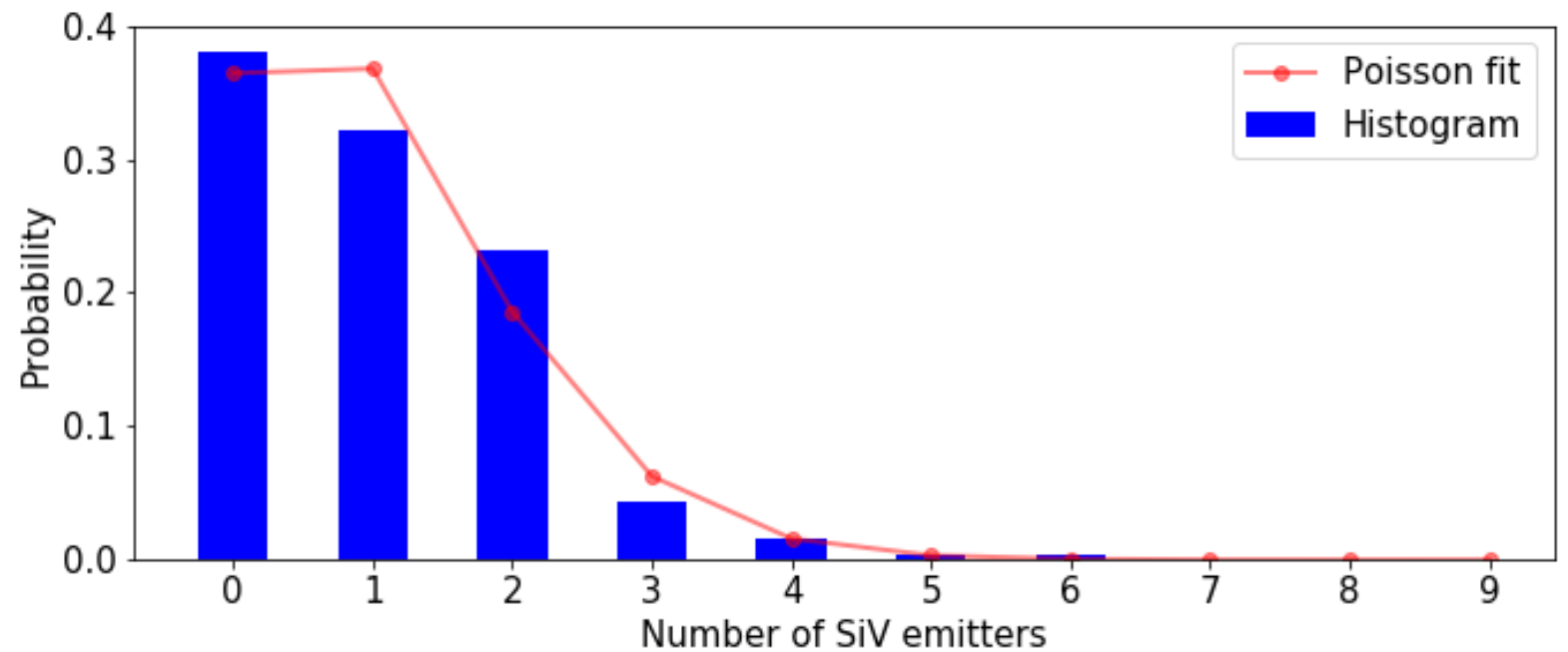
Ex-situ analysis of in-situ data allows determination of #ions/spot with 5% accuracy





Photoluminescence Experiment

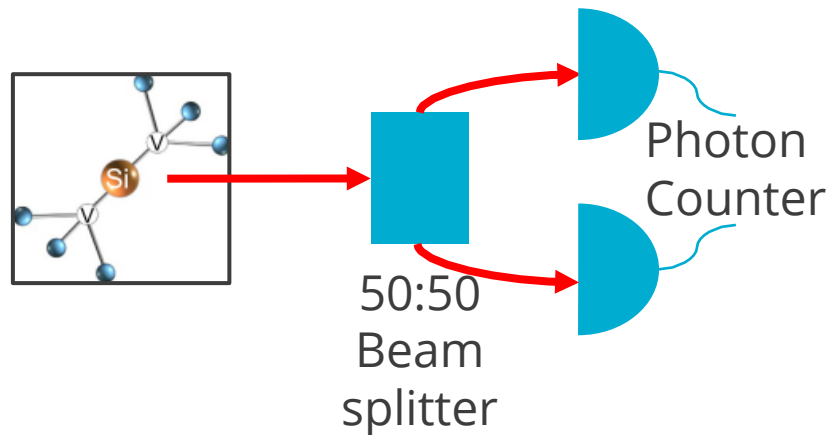
- Bin PL into 0,1,2,... SiV
 - Countrate of single emitter 10.7 ± 0.2 kcps
 - From binning get frequency of 0,1,2,... emitters
 - Fit histogram to Poisson distribution
- Avg. # emitters = 1.01 ± 0.07



Error on # emitters
matches counting error



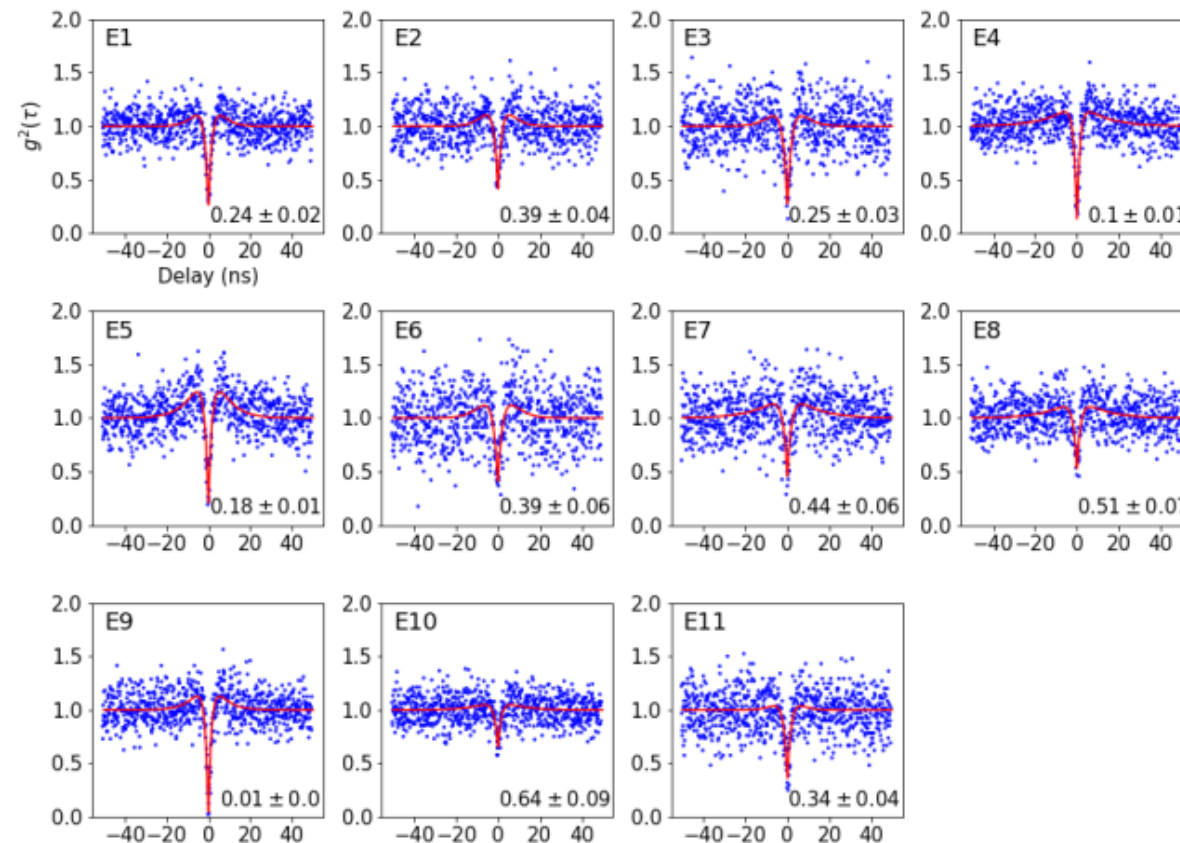
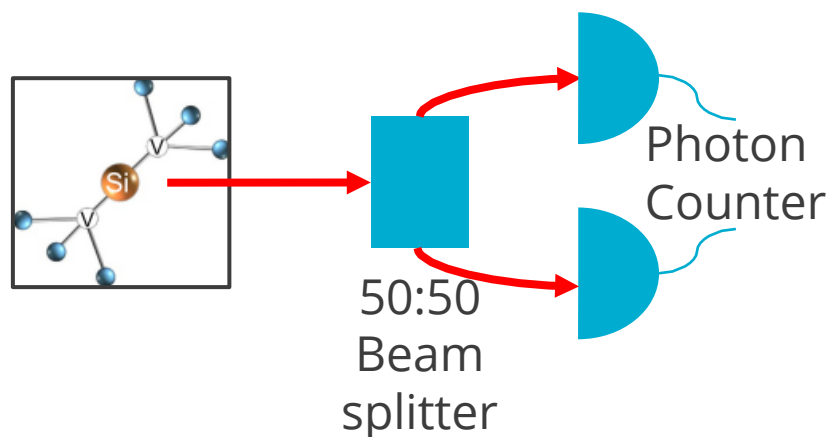
- PL alone not enough to confirm single emitter
- Use Hanbury-Brown-Twiss interferometry to confirm single photon emission
 - If single, only detect at one photon counter



Hanbury-Brown-Twiss



- PL alone not enough to confirm single emitter
- Use Hanbury-Brown-Twiss interferometry to confirm single photon emission
 - If single, only detect at one photon counter

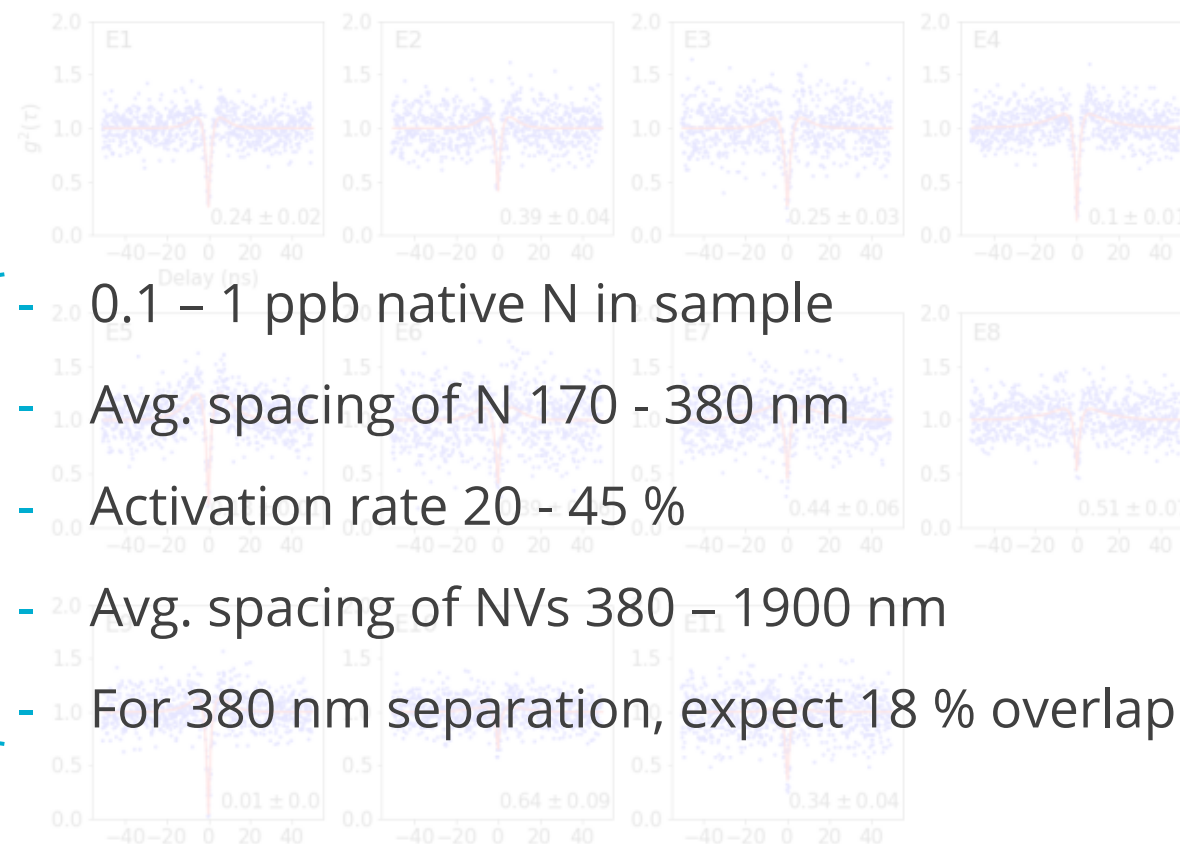


Not all locations identified as single emitters from PL are single emitters

Hanbury-Brown-Twiss



- 18 % of emitters classified as single emitters based on their PL are not single emitters
- Possible explanation is overlap between SiV and NV
 - NV would be activated during high-temperature activation anneal for forming SiV

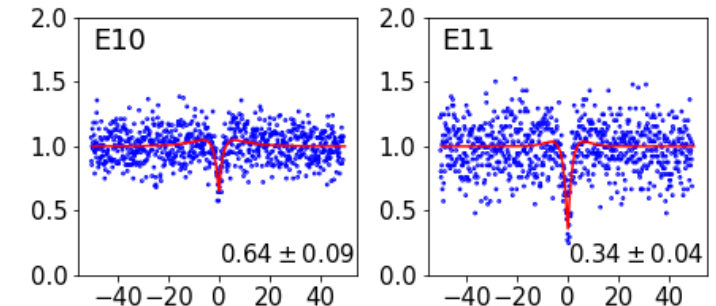
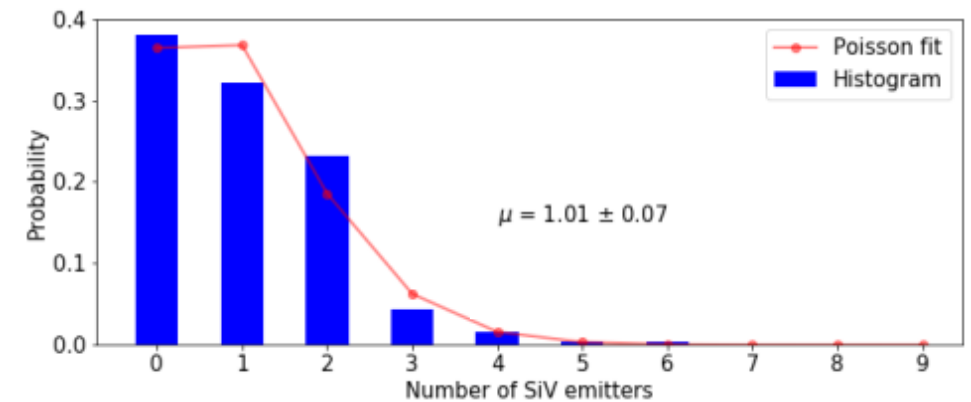
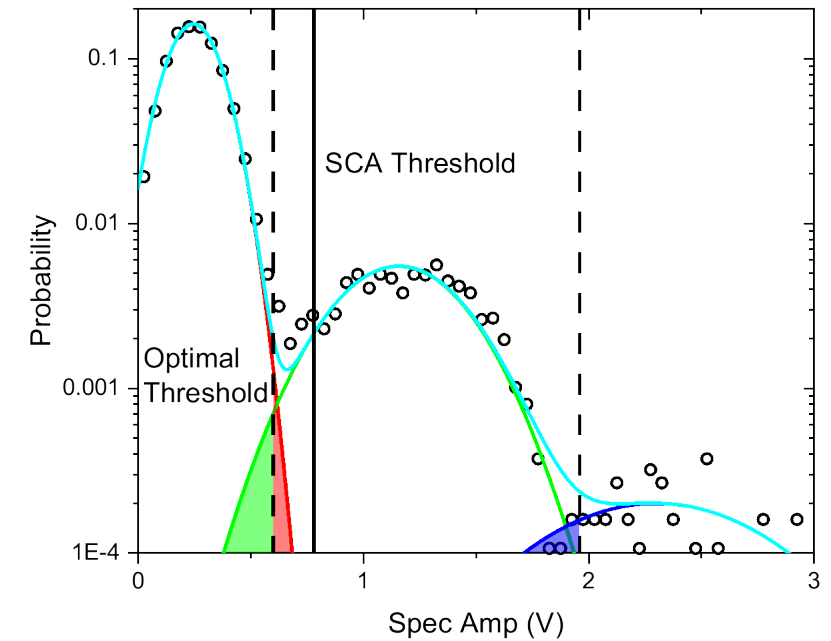


- 0.1 – 1 ppb native N in sample
- Avg. spacing of N 170 - 380 nm
- Activation rate 20 - 45 %
- Avg. spacing of NVs 380 – 1900 nm
- For 380 nm separation, expect 18 % overlap

Not all locations identified as single emitters from PL are single emitters

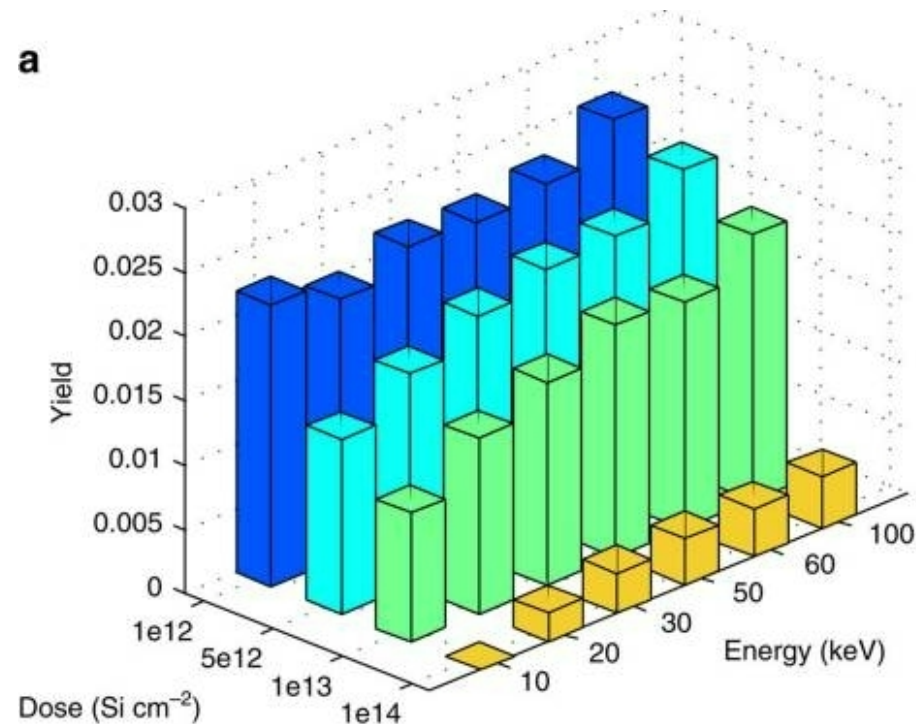
Conclusion of In-Situ Counting

- In-situ single ion counting can improve confidence on number of ions to 5 %
- For implantation of 30 ions / $\langle 1 \rangle$ SiV, 7X improvement over timed implantation
 - For implantation of fewer ions, improvement will be even greater
- PL confirms we implanted $\langle 1 \rangle$ 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



Deterministic Creation of Single Photon Sources

Task: Create single optically active defect / impurity emitter at a defined location (i.e. inside optical cavity)
Issue: Poisson Statistics for low #s



T. Schröder et al., Nat. Commun., 8, 15376 (2017)

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

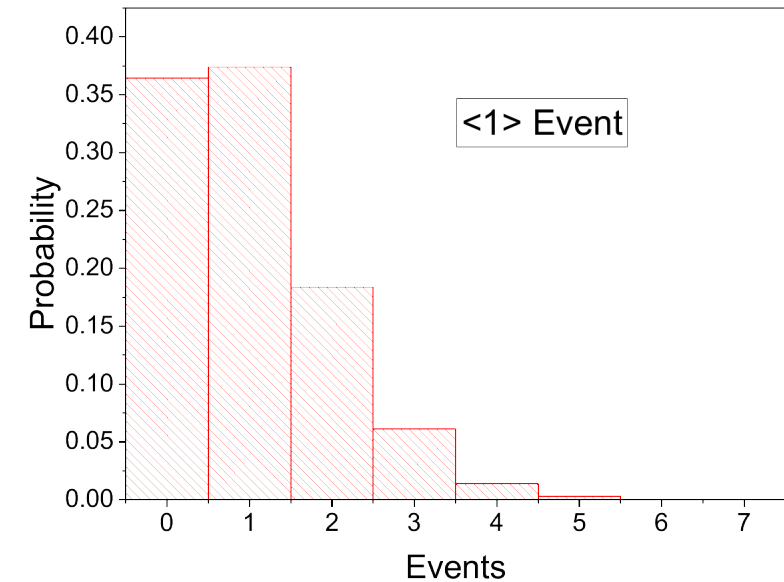
In-situ anneal: Increase Yield

In-situ PL: Increase #SiV

In-situ counting: Improve #Si ✓

<30> Si/location

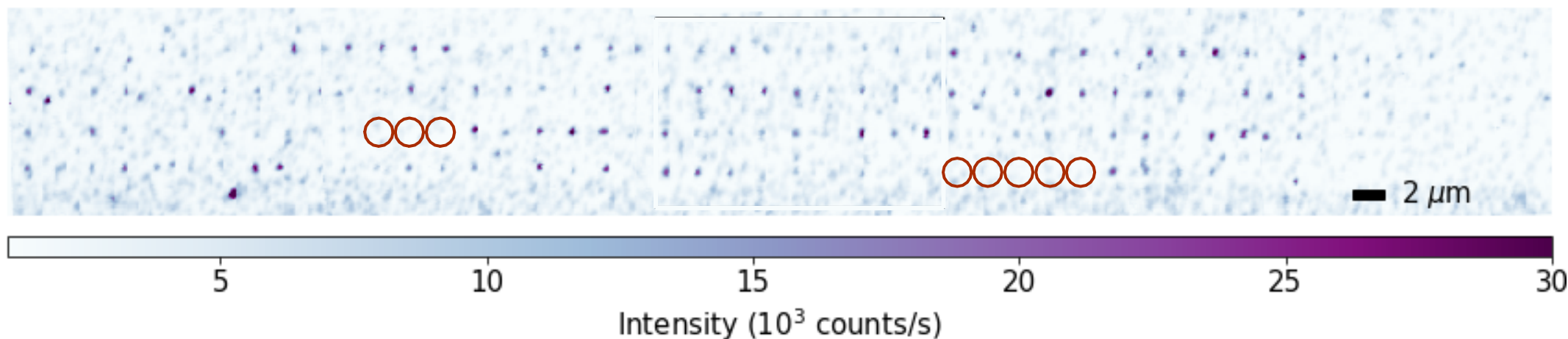
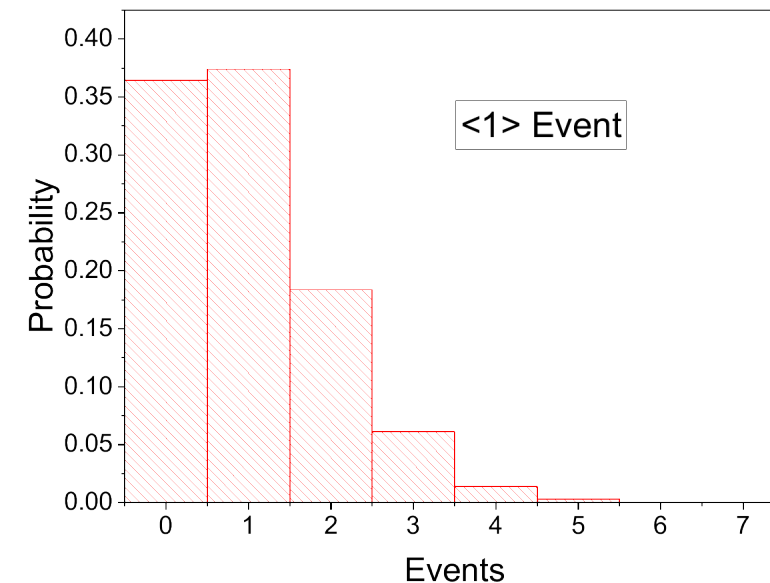
Fabricating Device



Improvements - In-Situ Photoluminescence



- Low conversion yield from implanted ions to optically active emitters requires in-situ feedback
- Array of $\langle 1 \rangle$ emitters will have 40 % no emitters and 20 % double or more emitters, only 40 % “useful” sites
- Photolumuminescence is a way to confirm emitters are created
 - Caveat: Not necessarily singles



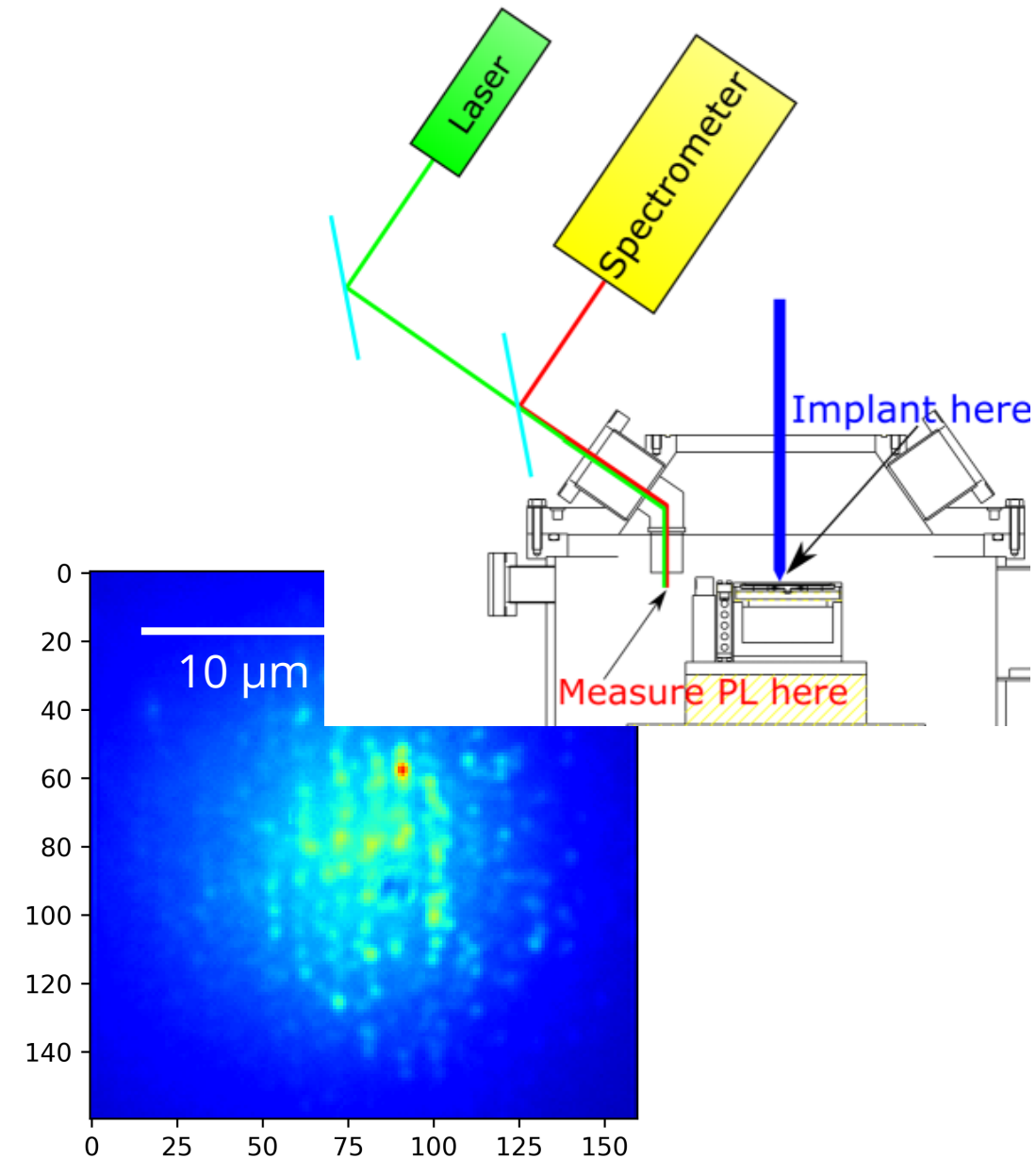
In-Situ Photoluminescence - Experiment



- V_{Si} in SiC has ~10 % conversion yield from implanted Li to optically active emitter [1]
- V_{Si} does not require high-temperature annealing to activate

In-situ method:

1. Measure background PL



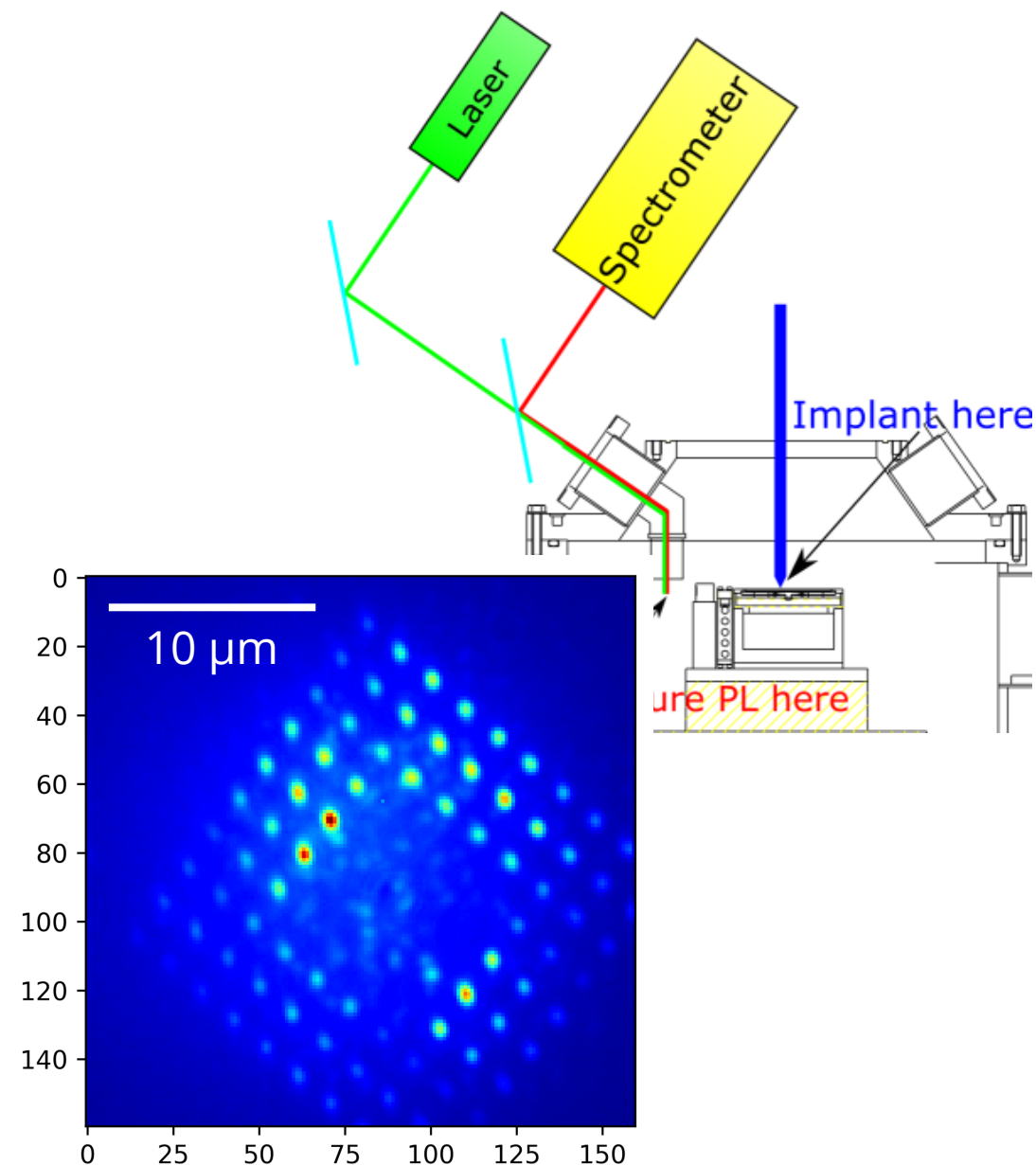
In-Situ Photoluminescence - Experiment



- V_{Si} in SiC has ~10 % conversion yield from implanted Li to optically active emitter ^[1]
- V_{Si} does not require high-temperature annealing to activate

In-situ method:

1. Measure background PL
2. Implant



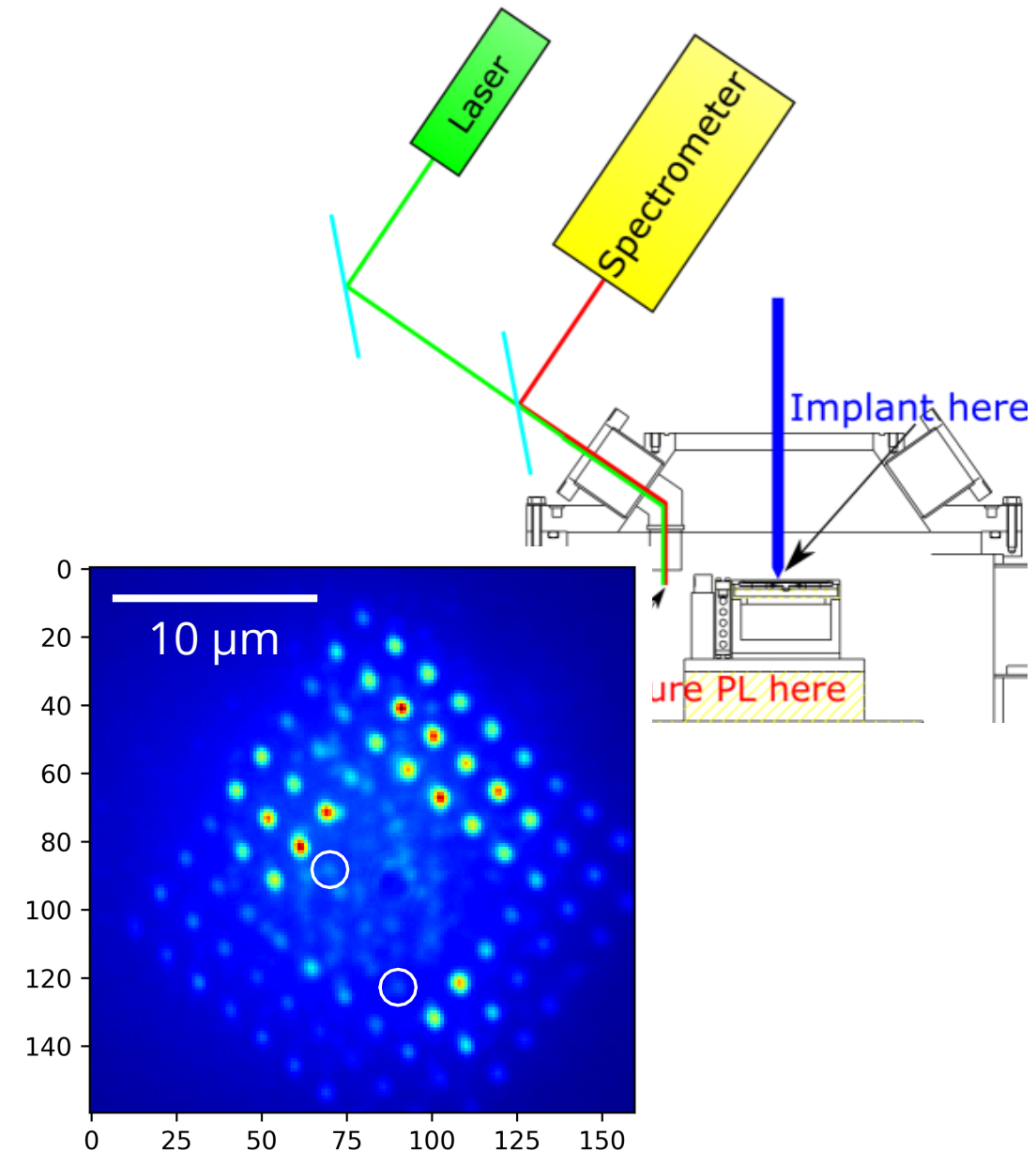
In-Situ Photoluminescence - Experiment



- V_{Si} in SiC has ~10 % conversion yield from implanted Li to optically active emitter [1]
- V_{Si} does not require high-temperature annealing to activate

In-situ method:

1. Measure background PL
2. Implant
3. Measure PL
4. Implant locations that do not have PL
5. Repeat 3 + 4 until full array



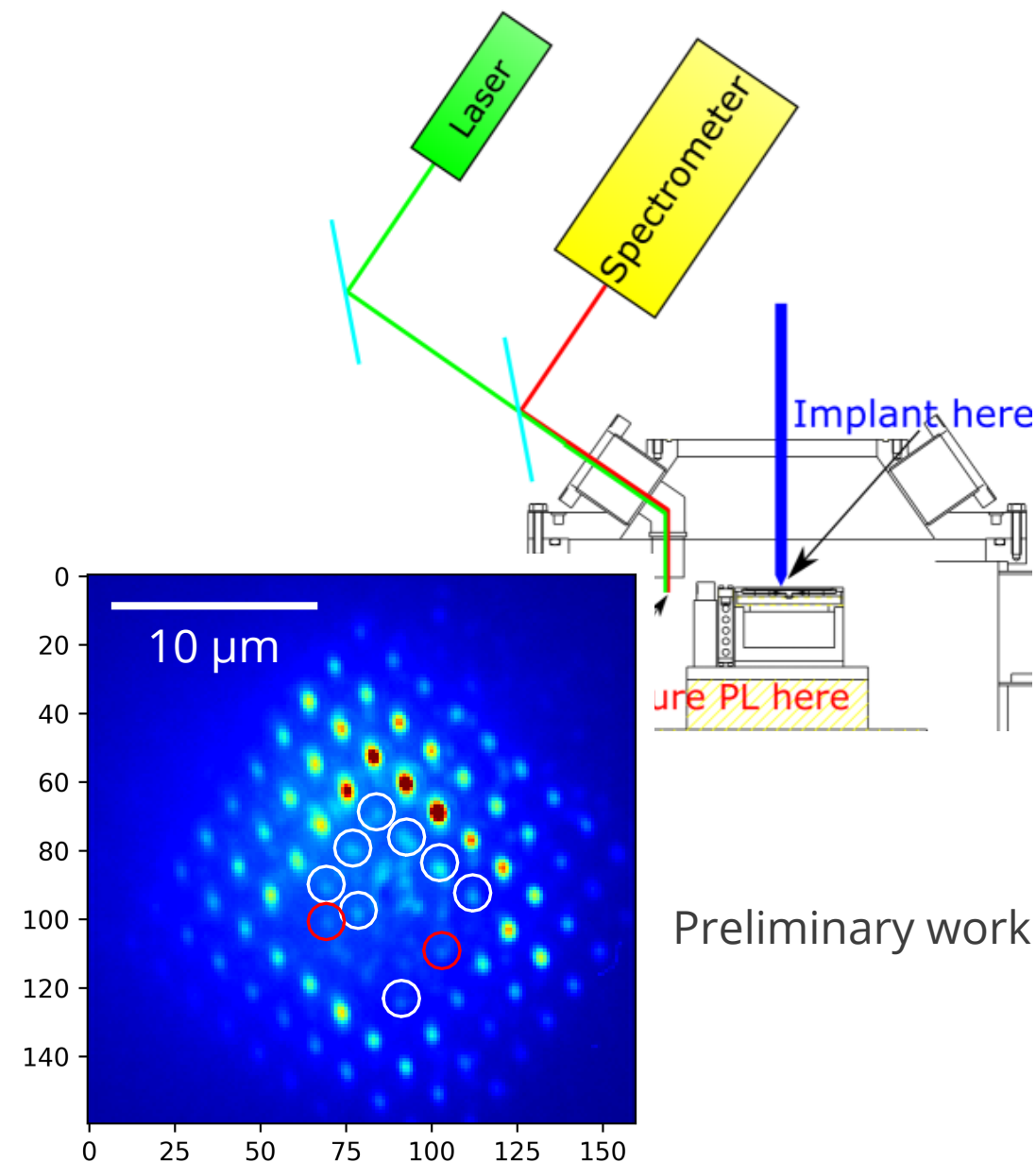
In-Situ Photoluminescence - Experiment



- V_{Si} in SiC has ~10 % conversion yield from implanted Li to optically active emitter [1]
- V_{Si} does not require high-temperature annealing to activate

In-situ method:

1. Measure background PL
2. Implant
3. Measure PL
4. Implant locations that do not have PL
5. Repeat 3 + 4 until full array



Acknowledgements



Anthony Flores, George Burns, Aaron Katzenmeyer, Barney Doyle, Ed Bielejec

All Projects

Membranes

N Source

All Projects

Tom Harris, Deanna Lopez

Diamond Si, SiC, GaN, AlN

Andrew Mounce, Heejun Byeon, Jacob Henshaw, Luca Basso, Maziar Ziabari, Mike Lilly

N Source + Counting

Membranes

Hot Implant

Vigneshwaran Chandrasekaran (LANL), Han Htoon (LANL), Yongqiang Wang (LANL)

In-Situ PL

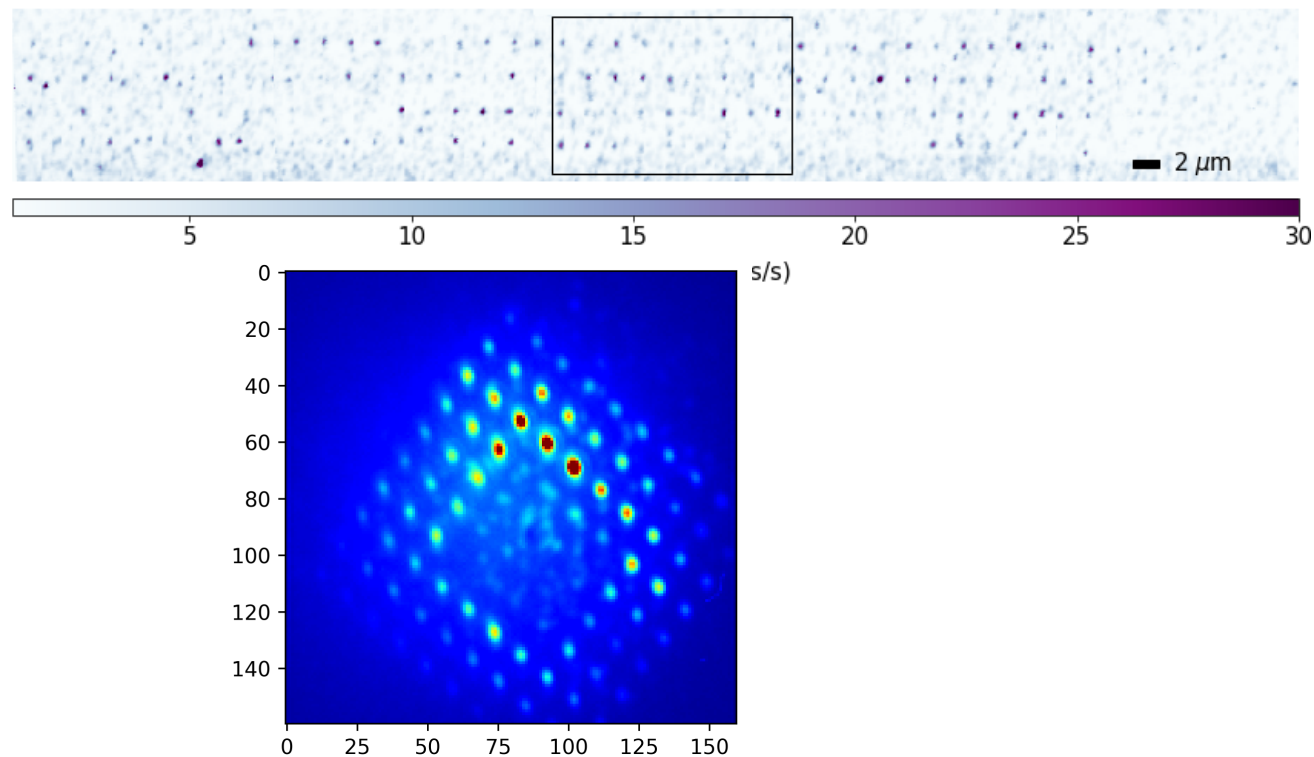
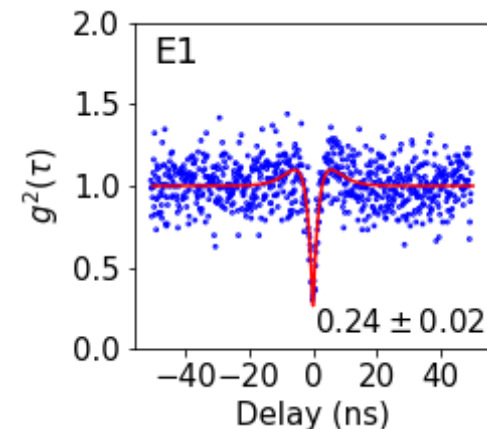
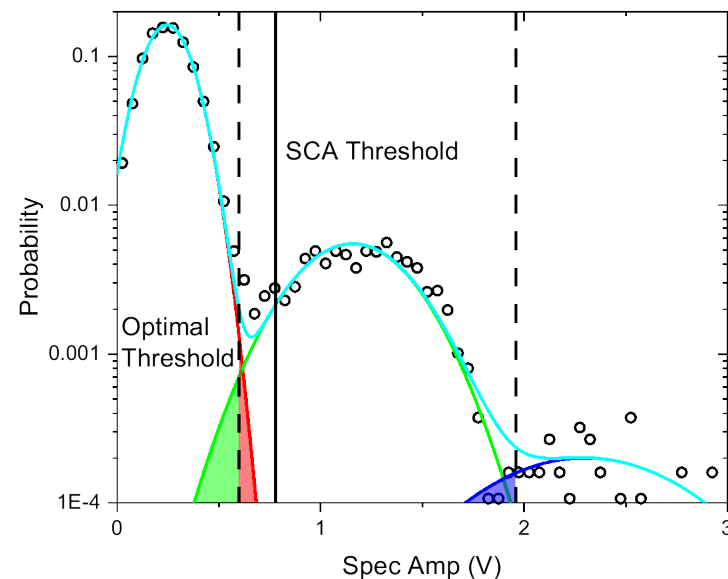
N Source

IBL, Fab, Optics



Summary

- In-situ ion counting improves confidence in ion number
 - Crucial for high-yield emitter fabrication
 - Better understanding of the yield for low number of ions
- In-situ photoluminescence allows fully deterministic creation of emitters
 - Caveat: At the moment, no high-temperature annealing, only vacancy-type defects
 - So far only made arrays, not yet confirmed single emitters



N Source - Improvements



- Higher beam current
 - Thinner foil implanted to the same level gives higher relative concentration
 - Fabrication in higher pressure N atmosphere may lead to more N absorption during melting
- Detection fidelity
 - N^{++} creates about 3.5x more e-h-pairs → Better separation between 0 and 1 peak in histogram
- Spot size
 - Currently align using Sn^{++} beam → $\Delta v/v > 50\%$, large error in aperture positions
 - Instead align to N while monitoring IBIC signal

Motivation



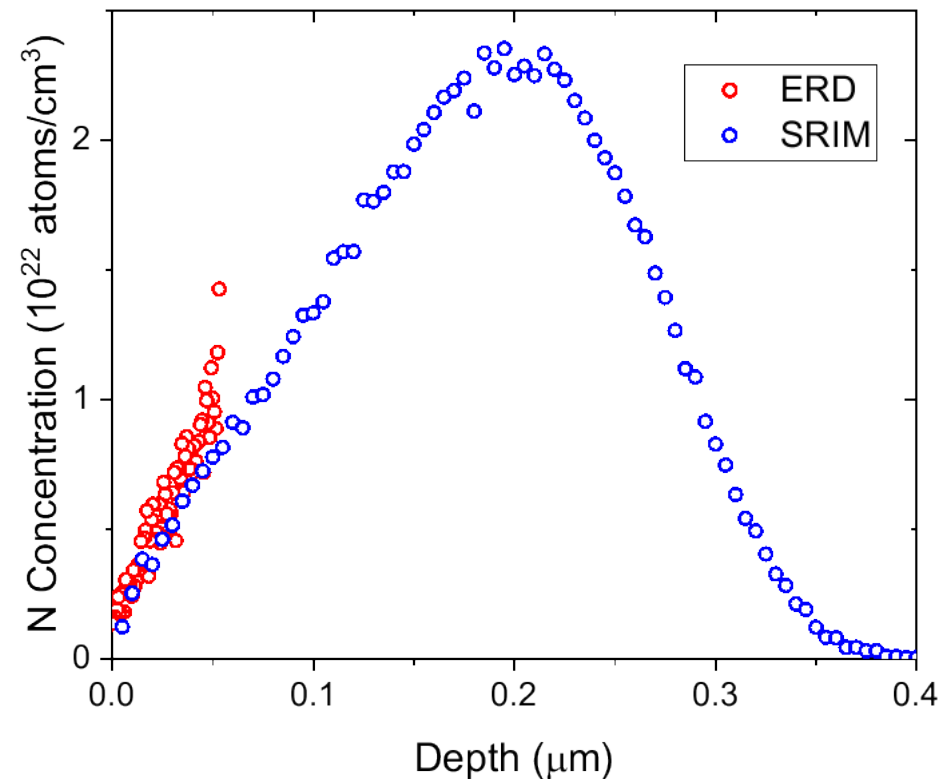
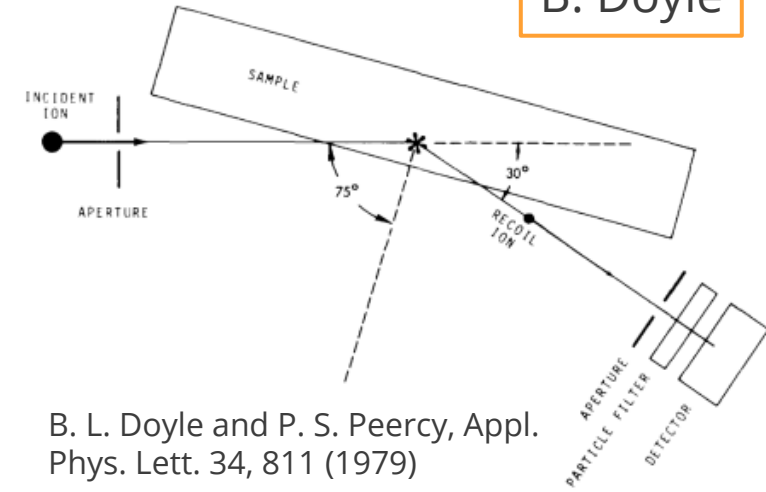
- Quantum Devices require nm-scale positioning
 - Exchange Coupling: 10s of nm
 - Optical Cavities: 10s of nm
 - FIB has 10s of nm spot size, ideally suited
- Tailoring of quantum properties requires implantation of different ion species
 - ExB FIB with LMAIS
 - N Source
- To get quantum properties in a device, need 1 color center / donor / etc.
 - Poisson statistics kick in
 - Counted implantation
 - In-situ PL
 - Ways to improve yield
 - Hot Implants
 - In-situ Annealing

N Source - Implantation + ERD

Y. Wang
B. Doyle

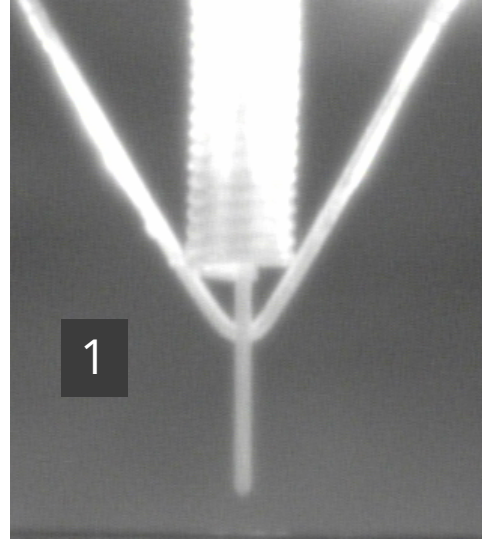


- Implanted a $\text{Au}_{80}\text{Sn}_{20}$ 200 μm thick foil with N up to 5×10^{17} ions/ cm^2
 - Level based on solid-solubility limit for H
- ERD: 50 nm of foil as expected
 - Cannot interrogate deeper due to multiple-scattering of deep ions
- From N concentration expect 3k N ions/s at 1 pA total beam current



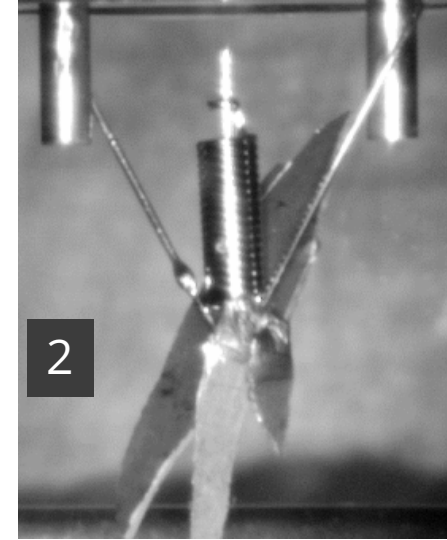
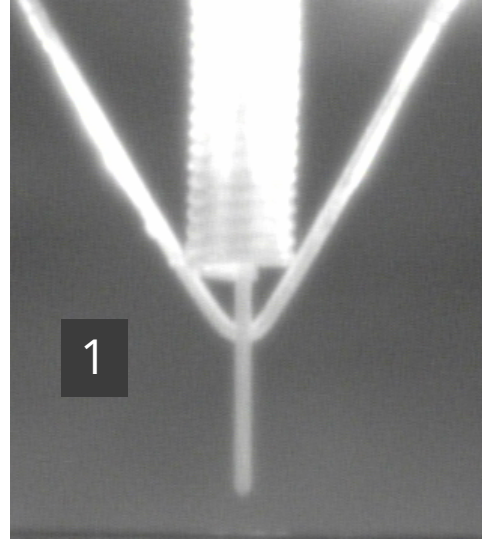
N Source - Tip Fabrication

1. W tip is heated to remove surface contaminants



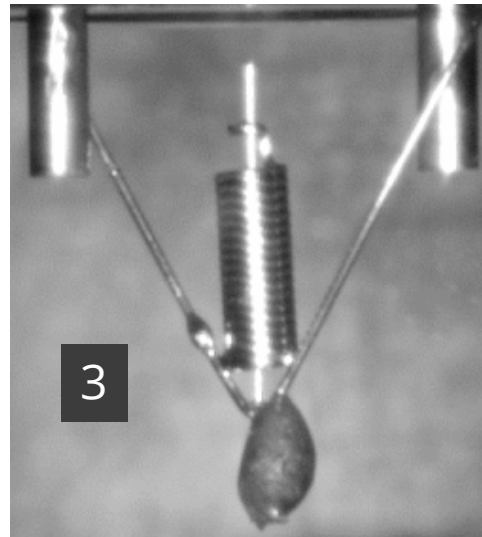
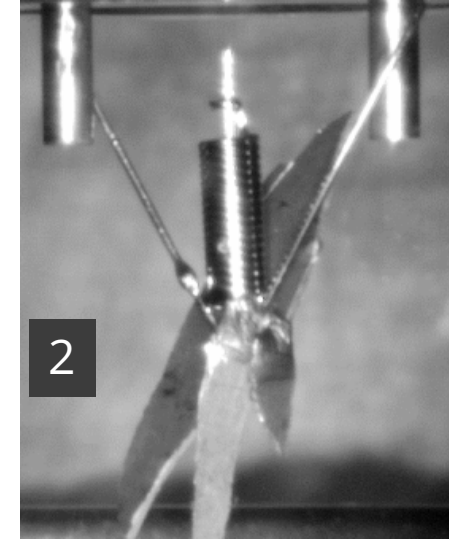
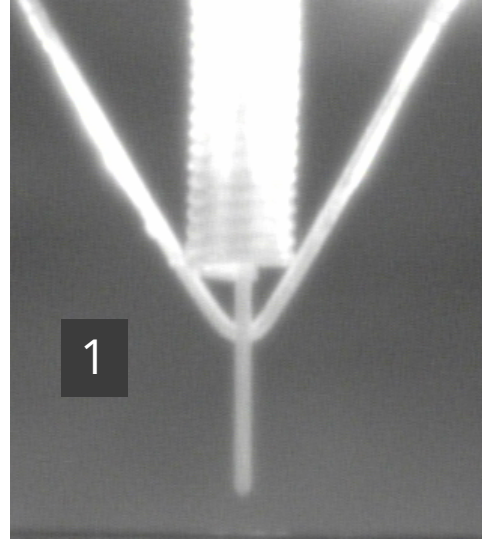
N Source - Tip Fabrication

1. W tip is heated to remove surface contaminants
2. Foil is tack welded to the tip



N Source - Tip Fabrication

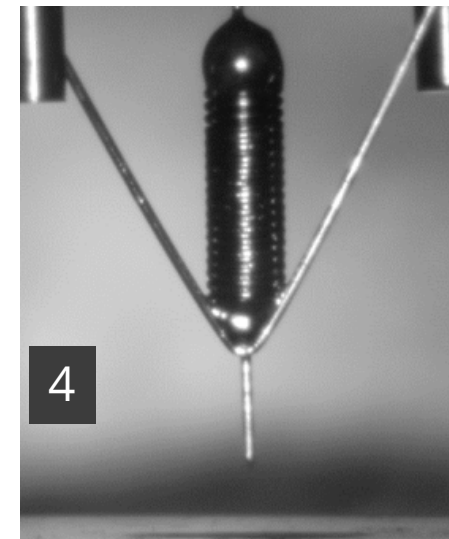
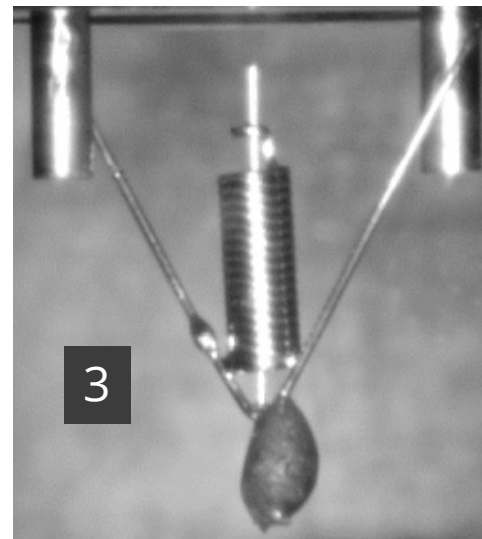
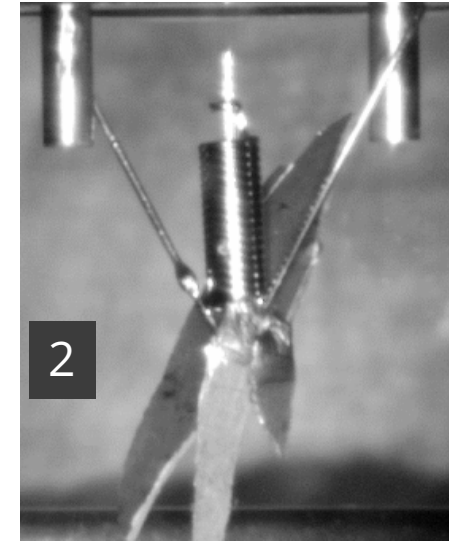
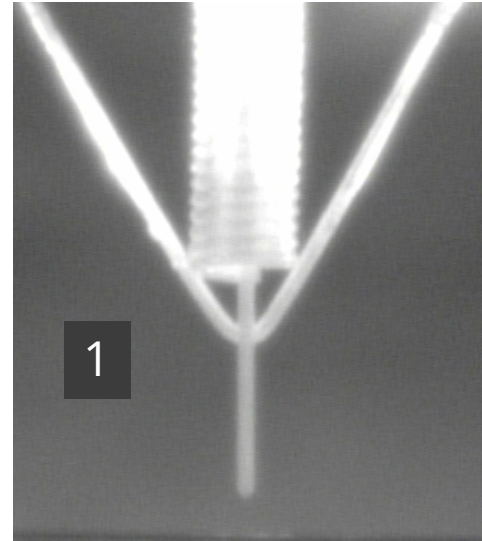
1. W tip is heated to remove surface contaminants
2. Foil is tack welded to the tip
3. Tip is heated to melt foil onto tip



N Source - Tip Fabrication

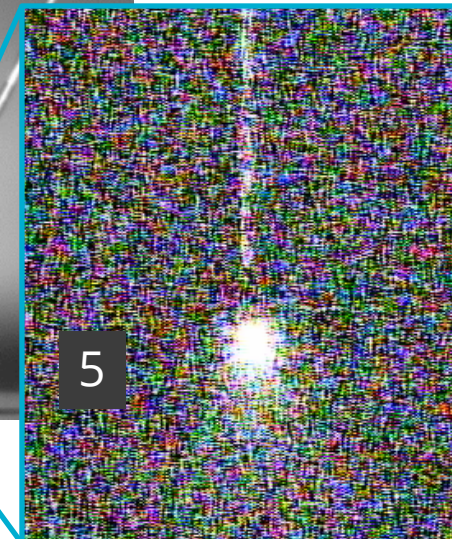
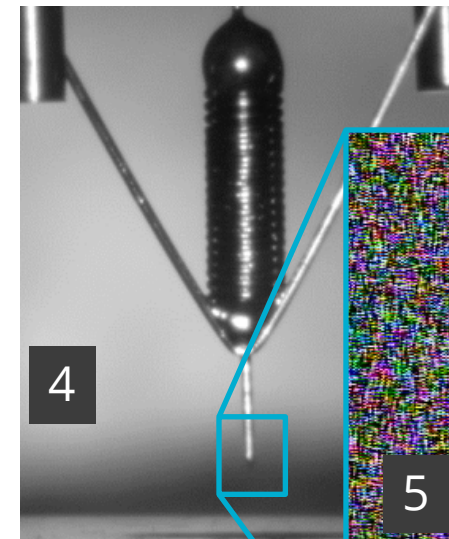
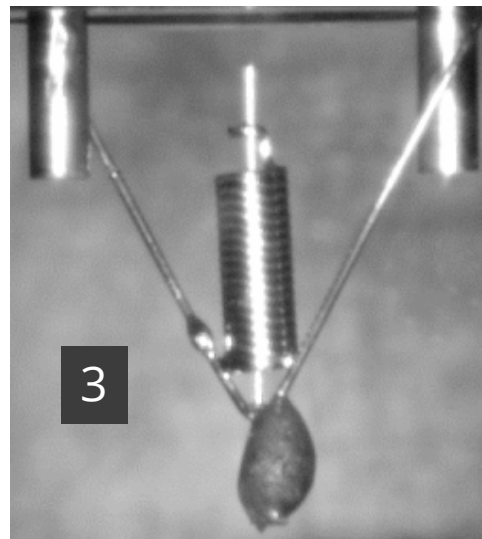
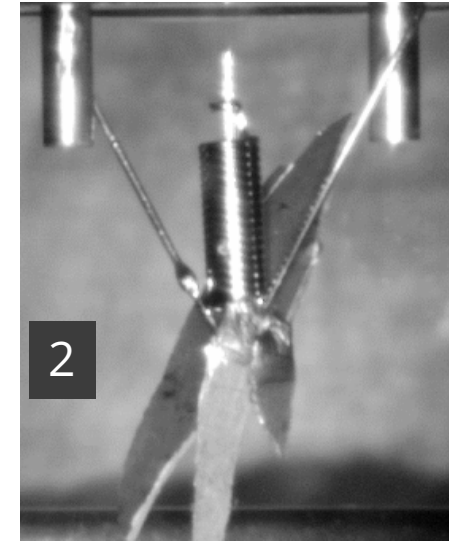
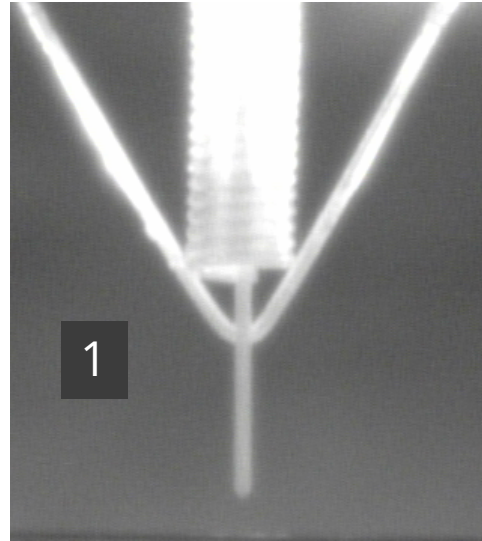


1. W tip is heated to remove surface contaminants
2. Foil is tack welded to the tip
3. Tip is heated to melt foil onto tip
4. Repeat steps 2. + 3. until tip + parts of reservoir is filled



N Source - Tip Fabrication

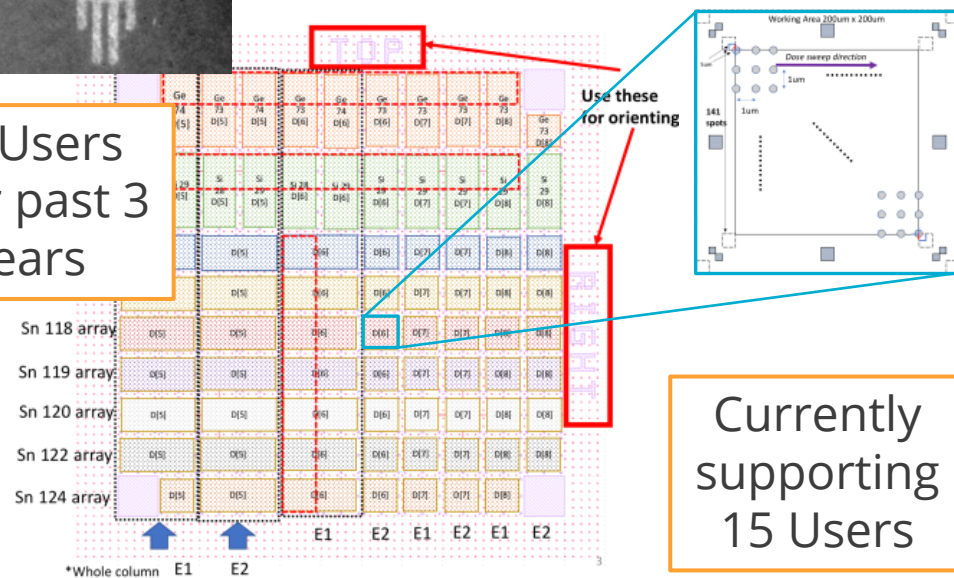
1. W tip is heated to remove surface contaminants
2. Foil is tack welded to the tip
3. Tip is heated to melt foil onto tip
4. Repeat steps 2. + 3. until tip + parts of reservoir is filled
5. Test tip emits
6. Install tip into nanoImplanter





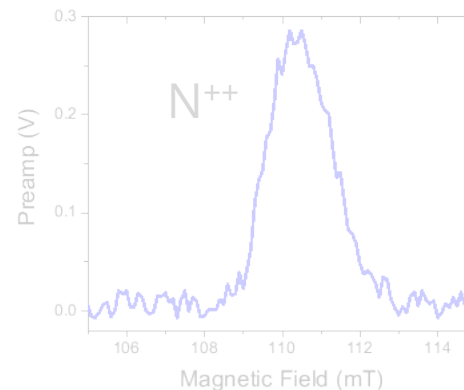
User Support

25 Users
over past 3
years



Currently
supporting
15 Users

LMAIS Source Development



Hydrogen 1 H 1.008																	Helium 2 He 4.003				
Lithium 3 Li 6.941	Boron 5 B 10.811																Carbon 6 C 12.011	Nitrogen 7 N 14.007	Oxygen 8 O 15.999	Fluorine 9 F 18.998	Neon 10 Ne 20.180
Sodium 11 Na 22.990	Magnesium 12 Mg 24.305											Aluminum 13 Al 26.982	Silicon 14 Si 28.086	Phosphorus 15 P 30.974	Sulfur 16 S 32.06	Chlorine 17 Cl 35.45	Argon 18 Ar 39.948				
Potassium 19 K 39.098	Calcium 20 Ca 40.078	Scandium 21 Sc 44.956	Titanium 22 Ti 47.88	Vanadium 23 V 50.942	Chromium 24 Cr 52.00	Manganese 25 Mn 54.938	Iron 26 Fe 55.845	Cobalt 27 Co 58.933	Nickel 28 Ni 58.69	Copper 29 Cu 63.546	Zinc 30 Zn 65.38	Gallium 31 Ga 69.723	Germanium 32 Ge 72.64	Arsenic 33 As 74.922	Selenium 34 Se 78.96	Bromine 35 Br 79.904	Krypton 36 Kr 83.80				
Rubidium 37 Rb 85.468	Sr 87.62	Yttrium 39 Y 88.906	Zirconium 40 Zr 91.224	Niobium 41 Nb 92.906	Molybdenum 42 Mo 95.94	Technetium 43 Tc 98.00	Ruthenium 44 Ru 101.07	Rhodium 45 Rh 102.91	Palladium 46 Pd 106.42	Silver 47 Ag 107.87	Cadmium 48 Cd 112.41	Indium 49 In 114.82	Tin 50 Sn 118.71	Antimony 51 Sb 121.76	Te 127.60	Iodine 53 I 126.91	Xenon 54 Xe 131.29				
Cesium 55 Cs 132.91	Ba 137.33	* 57-58	Lu 174.967	Hf 178.49	Ta 180.948	W 183.84	Re 186.207	Os 190.23	Ir 192.22	Pt 195.084	Au 196.967	Hg 200.59	Tl 204.38	Pb 207.2	Bi 208.98	Po 209	At 210	Rn 222			
Francium 87 Fr 223	Ra 226	** 89-102	Lr 262	Rf 261	Db 262	Sg 266	Bh 264	Hs 277	Mt 268	Unun 110 Uu			Unun 111 Uu	Unun 112 Uu	Unun 114 Uu			Unun 116 Uu			



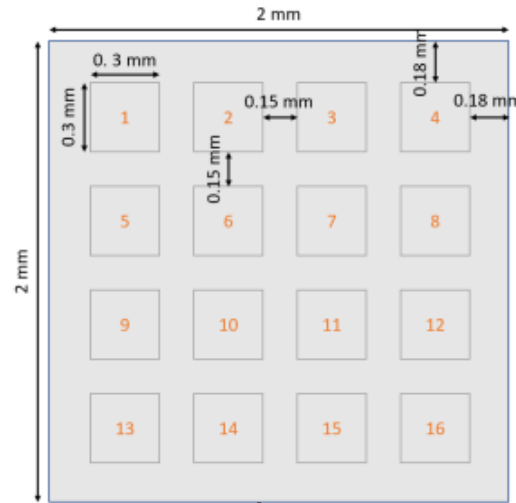
User Support

Localized Smartcuts for Diamond Membranes

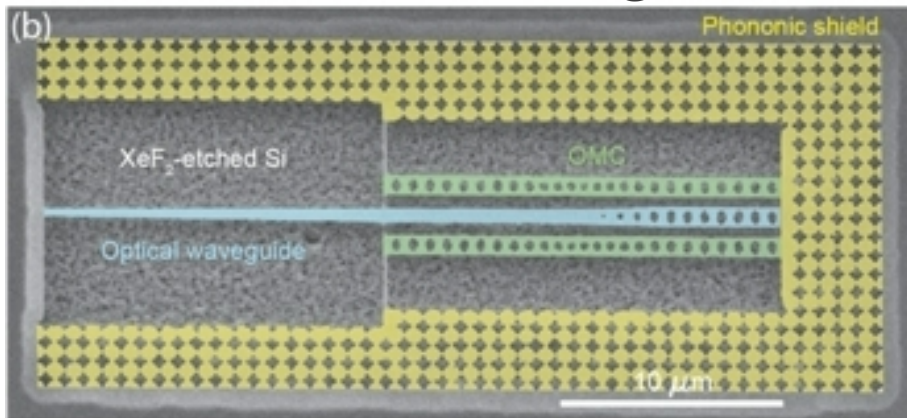
HVEE Nanobeamline

Rapid prototyping enabled by focused ion beams

- Different Energy / Dose in each area



A. Jayich
@ UCSB



J. V. Cady et al., Quantum Sci. Technol., 4, 2 (2018)

Local Damage to Simulate Dark Matter Strikes

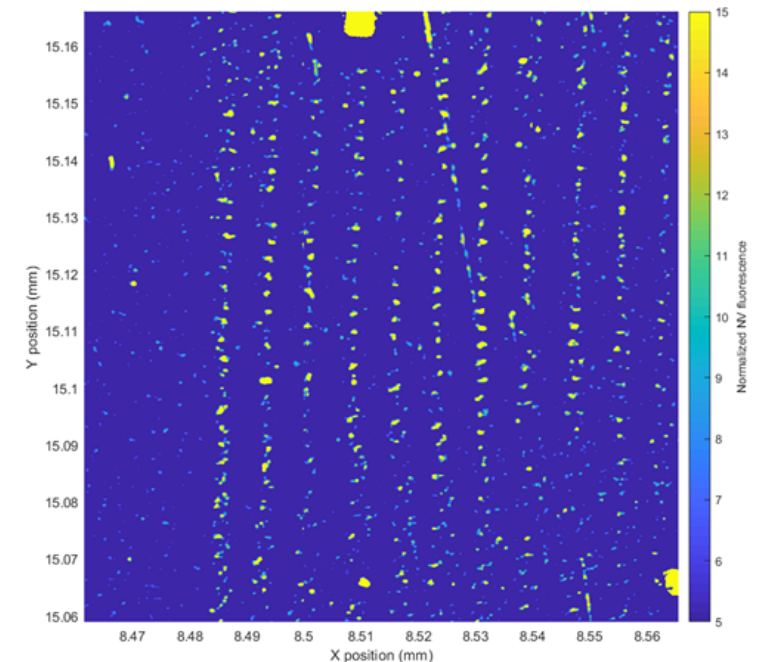
Tandem MicroOne beamline

36 working areas over a 1x1mm² area

- Different Energy / Dose at each area

1x1 μm² beamspot for localized damage events

R. Walsworth
@ U Maryland

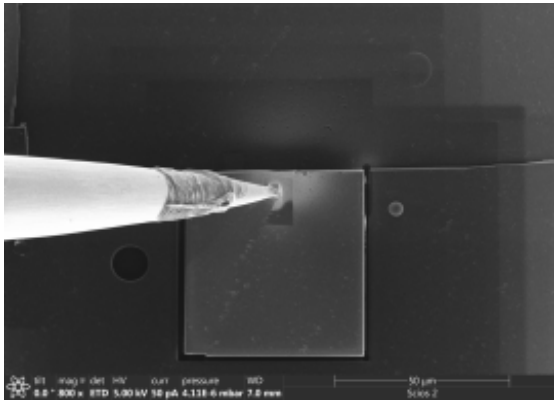




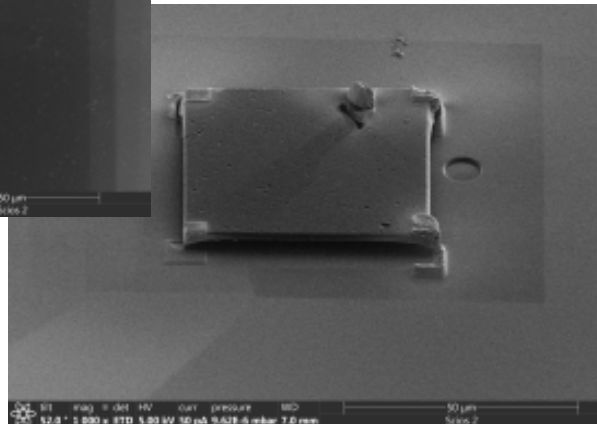
User Support

Membrane Formation for High-Sensitivity Sensors

Pelletron implant beamline



L. Basso
@ CINT



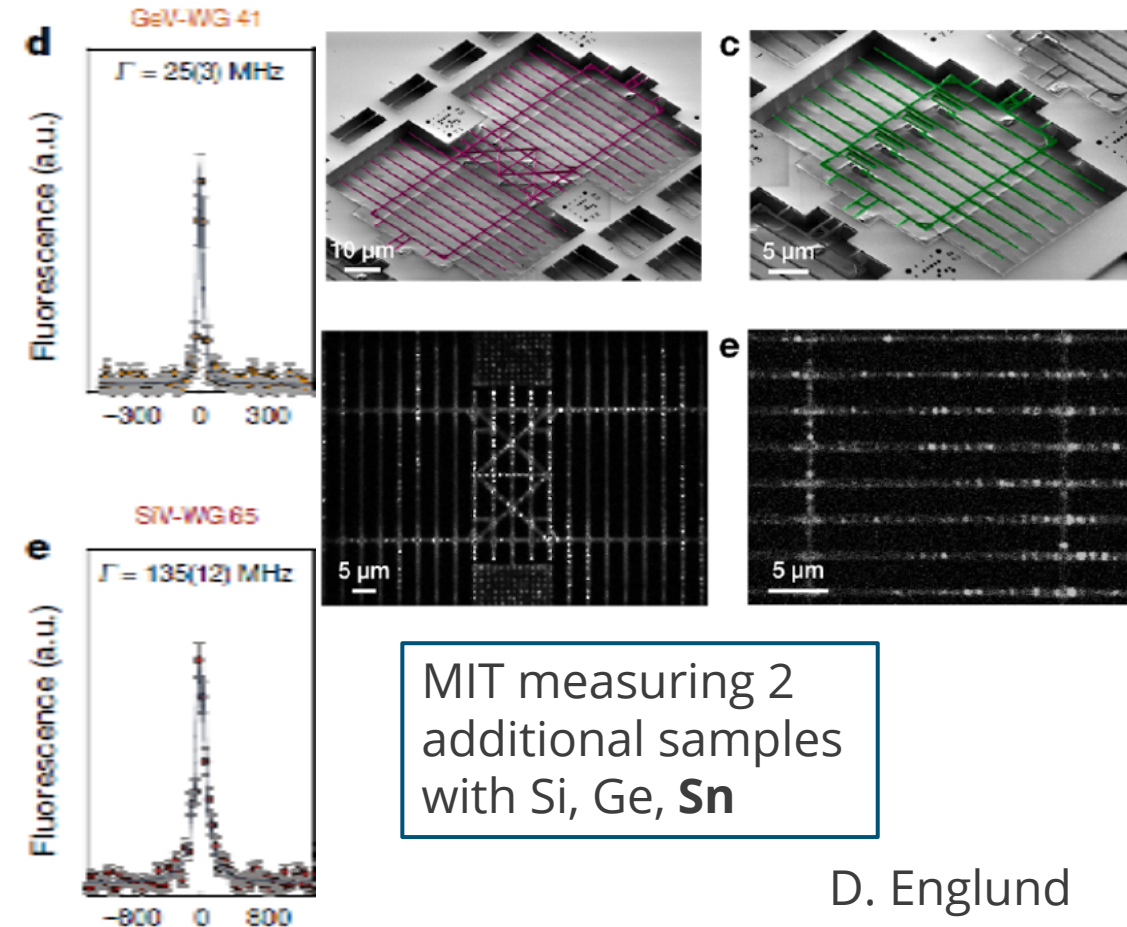
550 nm

M. Loncar
@ Harvard

A. Mounce
@ CINT

Nanoimplantation for Diamond-Based Photonics

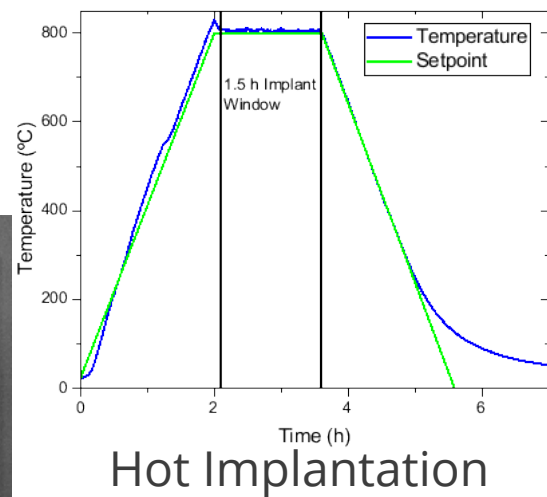
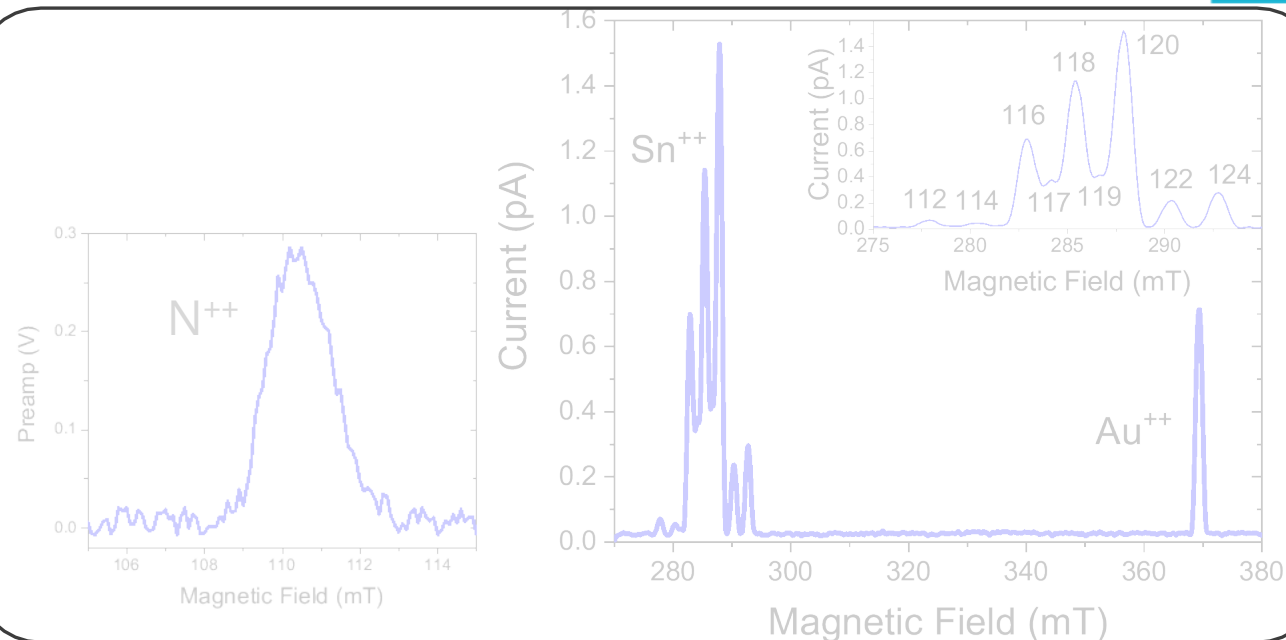
Nanoimplanter for <50 nm spot @ 200 keV



MIT measuring 2
additional samples
with Si, Ge, **Sn**

Noel H. Wan et al., Nature,
583, 226–231(2020)

D. Englund
@ MIT



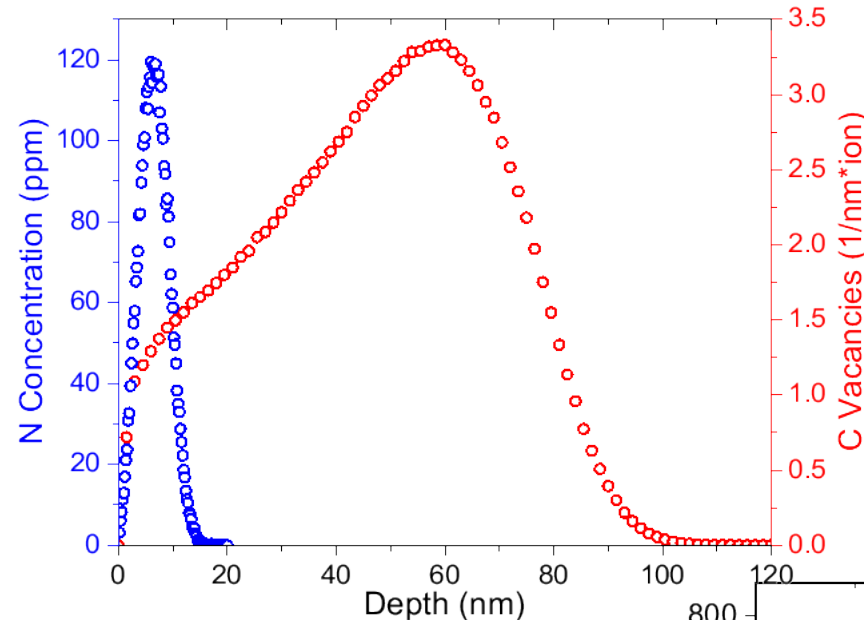
Hot Implantation for Improved NV Formation



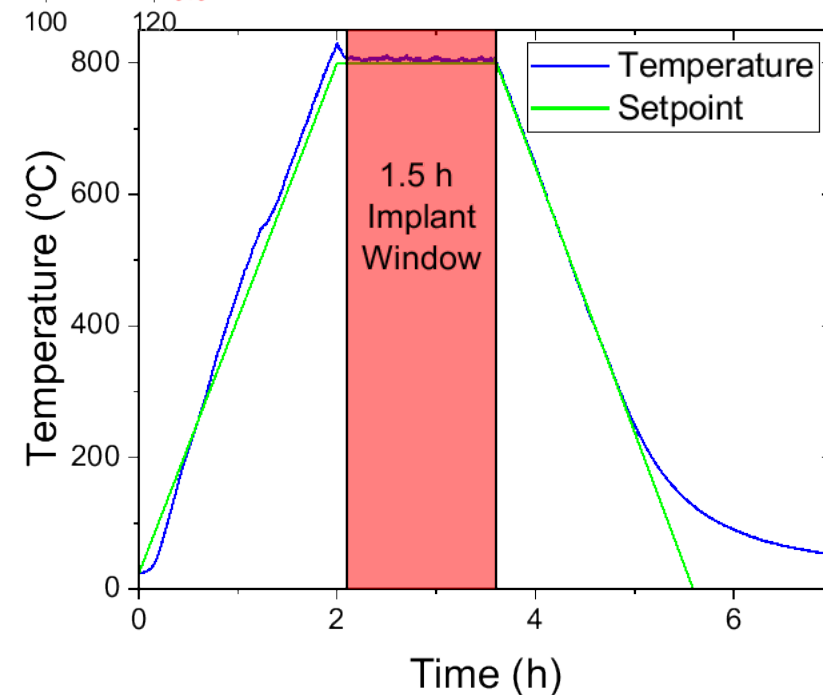
- NV creation is mostly vacancy-limited

Solution:

1. Implant 46 keV C into diamond
→ Create vacancies
2. Heat sample during implant
→ NV activation anneal



Ramp rate not to exceed 400 °C/h

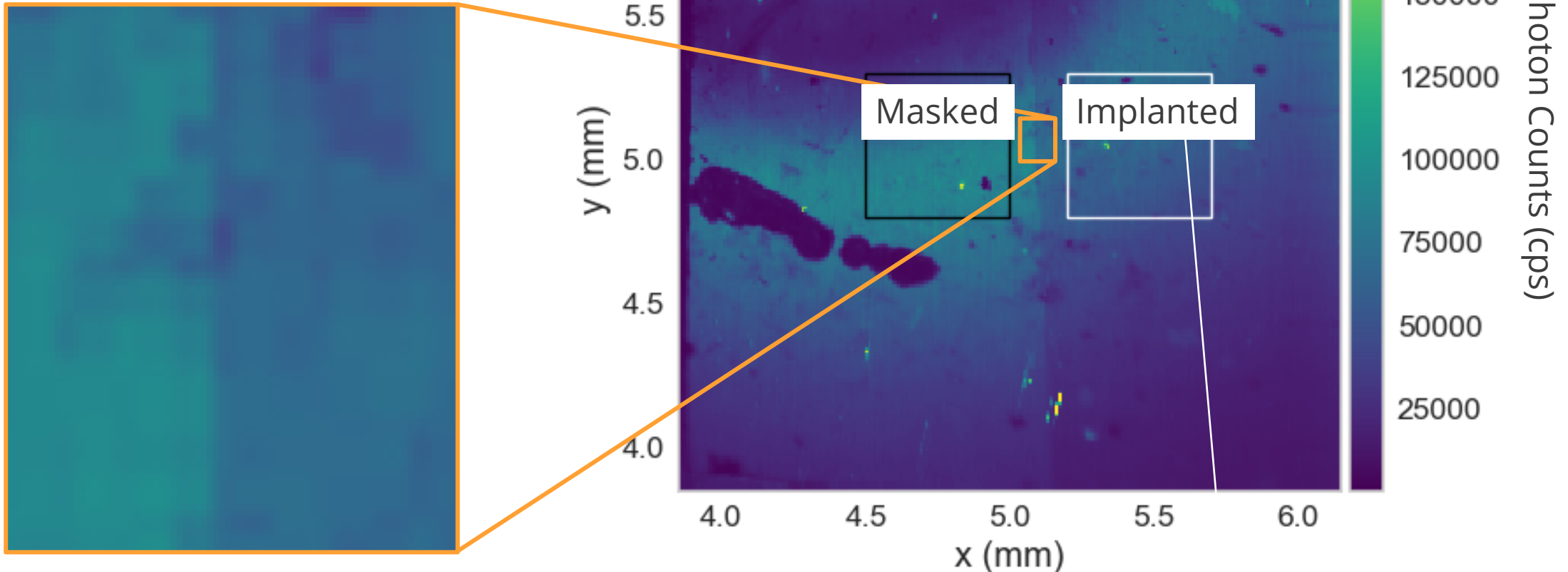


Results for Hot Implanted Diamonds

M. Ziabari
M. Lilly

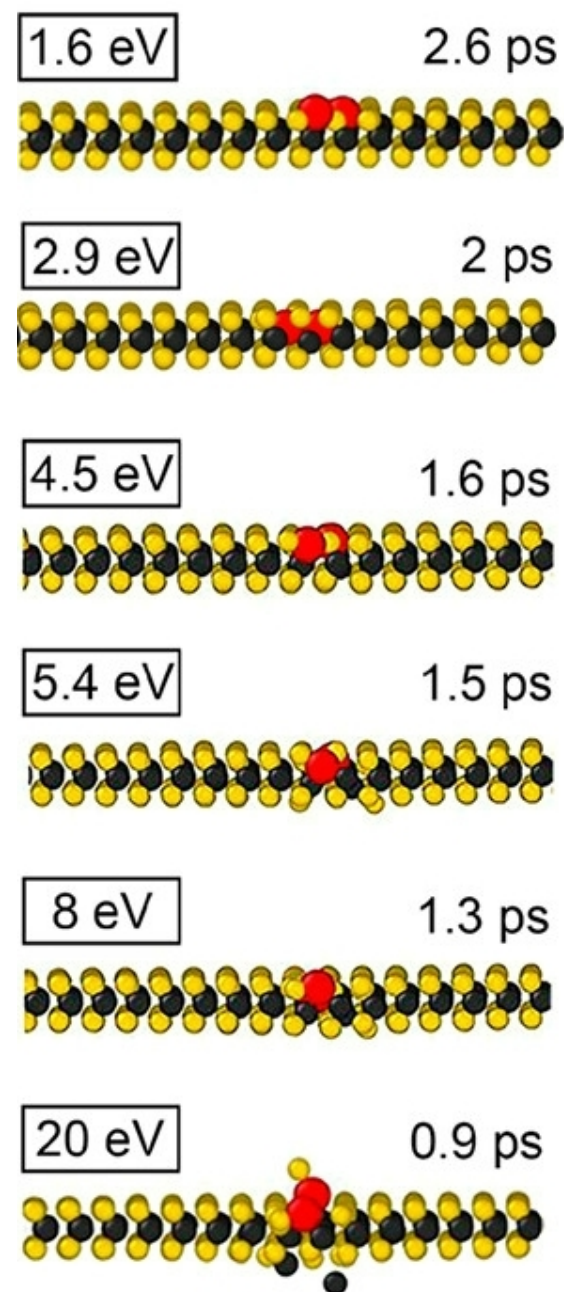


- Very preliminary results, but show different T_2 between masked and implanted area, $0.39 \mu\text{s}$ vs $1.4 \mu\text{s}$
 - Increased T_2 leads to higher sensitivity



Impurity Doping in 2D Materials

- To implant 2D materials require ion stopping within atomic monolayers
 - 10s to 100s of eV ion energy for deterministic stopping in atomic monolayers
- New VELION can implant < 5 keV @ <100 nm spot size

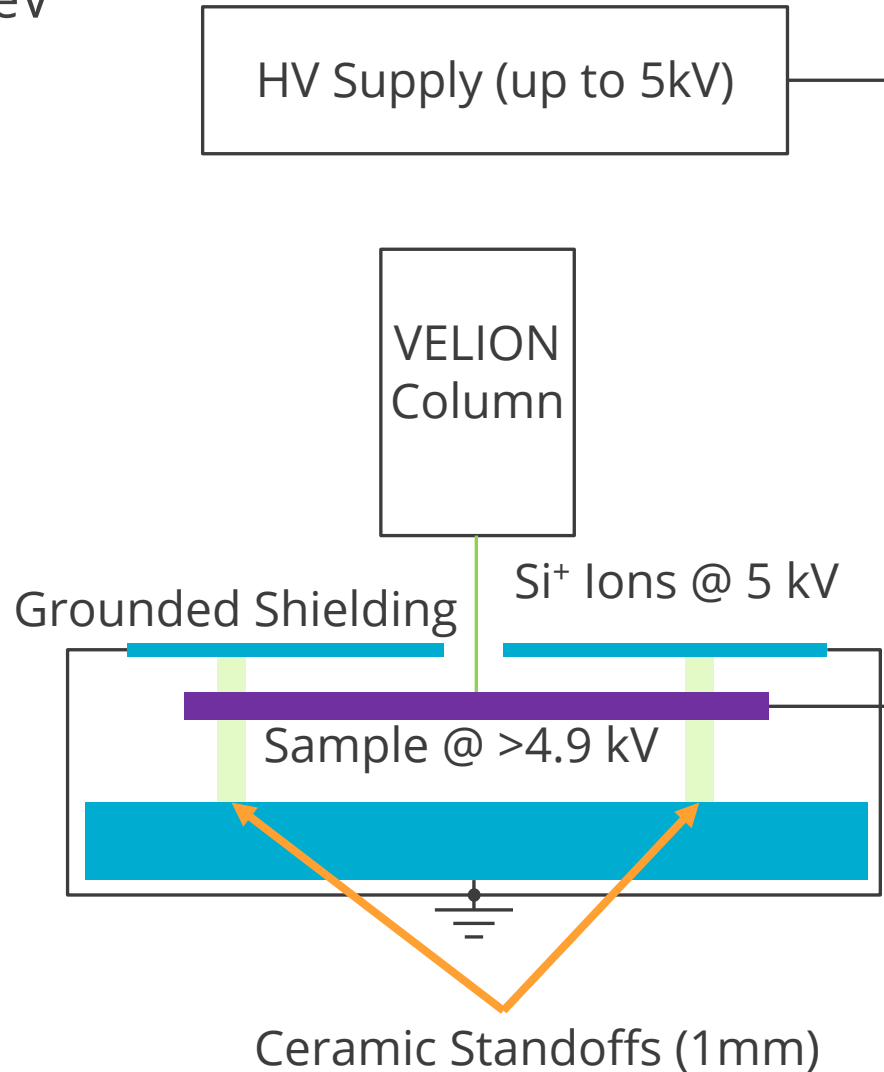


Ultra-Low Energy Implantation

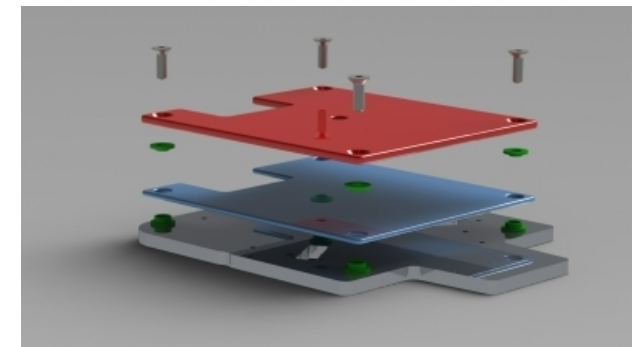


- New VELION can implant < 5 keV @ < 100 nm spot size
 - Bias sample to reduce ion landing energy to eV range
- Caveat: What will be our spot size?
 - SIMION simulations
 - Few μm : Useful for yield measurement
 - < 1 μm : Can be useful for photonics

Currently pursuing through CNMS user project with A. Belianinov

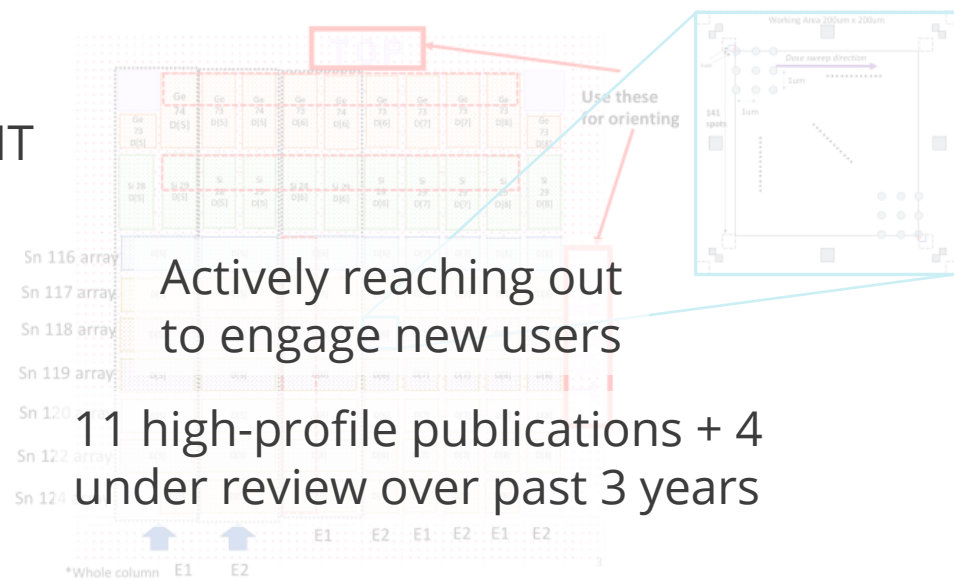


FY 22 LDRD Idea, PI
BES infrastructure





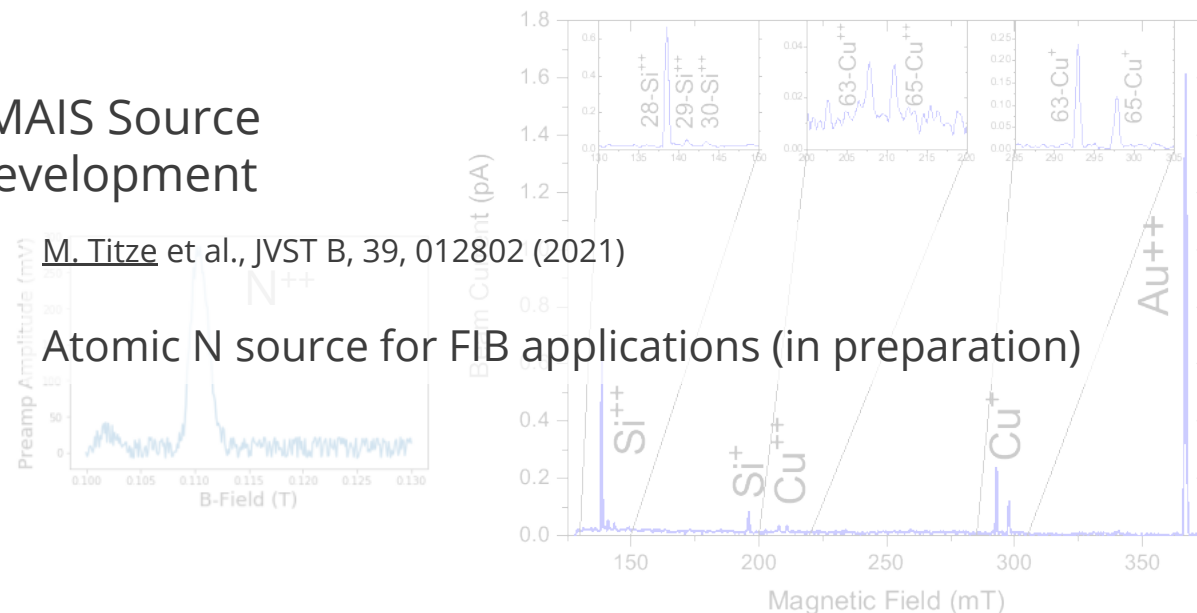
CINT



LMAIS Source Development

M. Titze et al., JVST B, 39, 012802 (2021)

Atomic N source for FIB applications (in preparation)



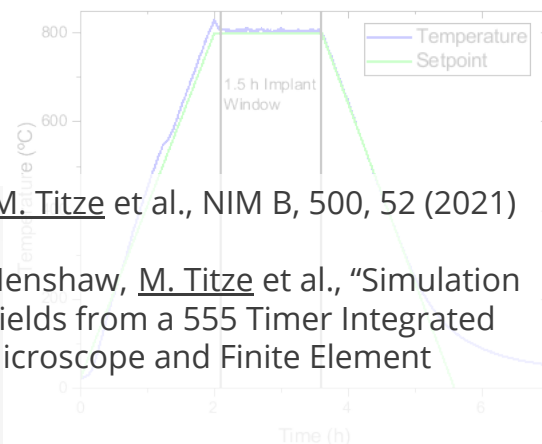
Improving Diamond NV Sensors

P. Kehayias, J. Henshaw, M. Ziabari, M. Titze et al., NIM B, 500, 52 (2021)

P. Kehayias, E.V. Levine, L. Basso, J. Henshaw, M. Titze et al., "Simulation and Measurement of the Magnetic Fields from a 555 Timer Integrated Circuit using a Quantum Diamond Microscope and Finite Element Analysis" (in preparation)

Membranes

A. Mounce: Quantum Sensing for Quantum Materials (BES Infrastructure, renewed)



In-Situ Counting + Photoluminescence

Towards Deterministic Creation of Single Photon Sources in Diamond using In-Situ Ion Counting (in preparation)

A. Katzenmeyer: In-situ laser annealing (FY22 LDRD Idea)

H. Htoon: Deterministic Placement and Integration of Quantum Defects (BES Infrastructure)

