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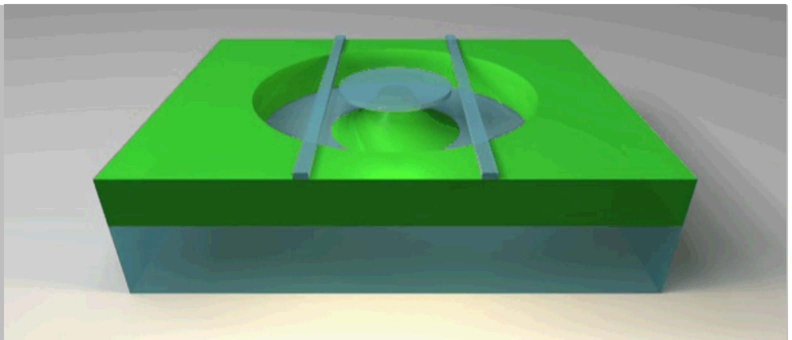
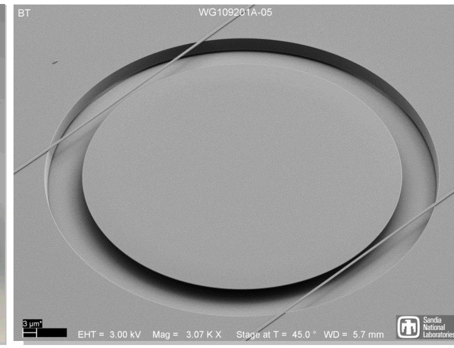
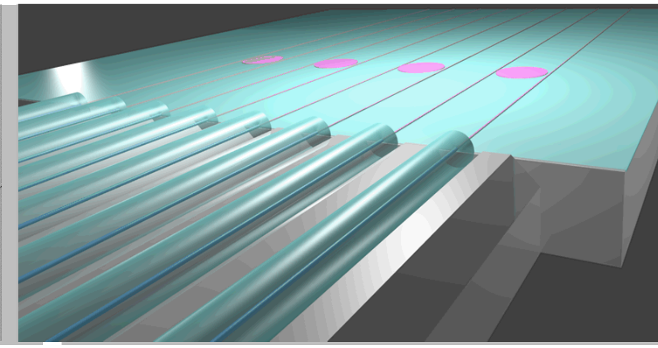






Micro-systems for Scalable QKD Components Achievements

*Ryan Camacho

Ian Frank

Matthew Tomes

Bruce Burckel

Ed Bielejec

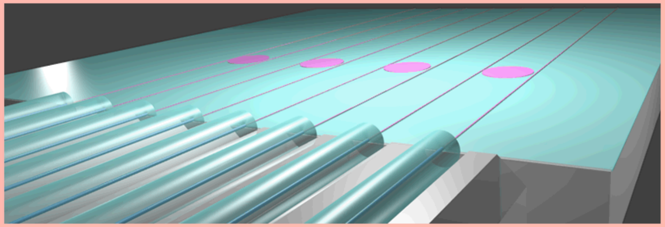
U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

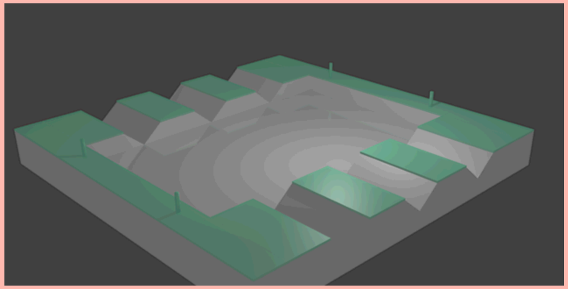
Sandia Efforts

Sandia National Laboratories

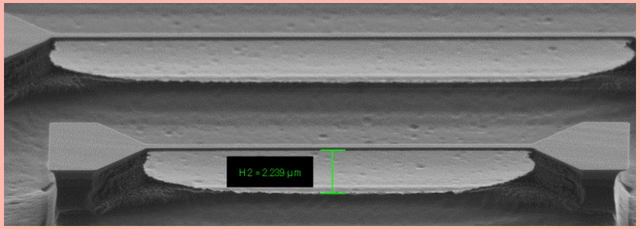
Demonstrate efficient (-1 dB) fiber – to – chip coupling, enabling quantum integration applications.



Develop simplified, scalable kinematic alignment techniques.

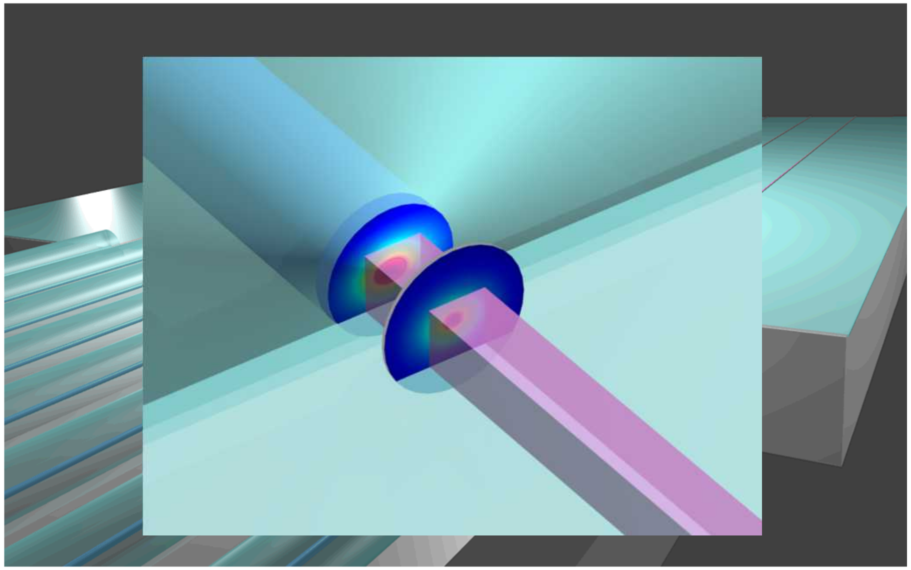


Develop targeted, deterministic ion implantation in diamond substrates. Supporting: Loncar, Englund, and Waks.

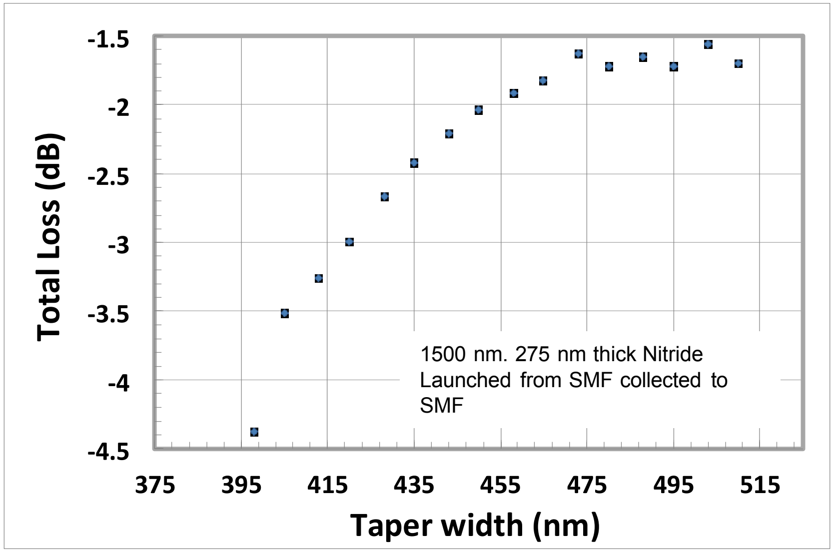


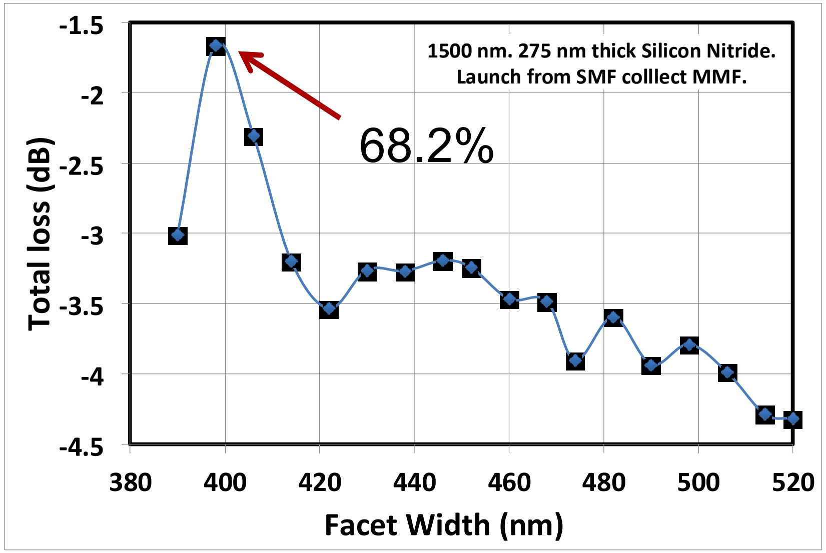
Deliver high quality, packaged, integrated resonators to Northwestern and UMBC teams.

Efficient Fiber-to-chip Coupling

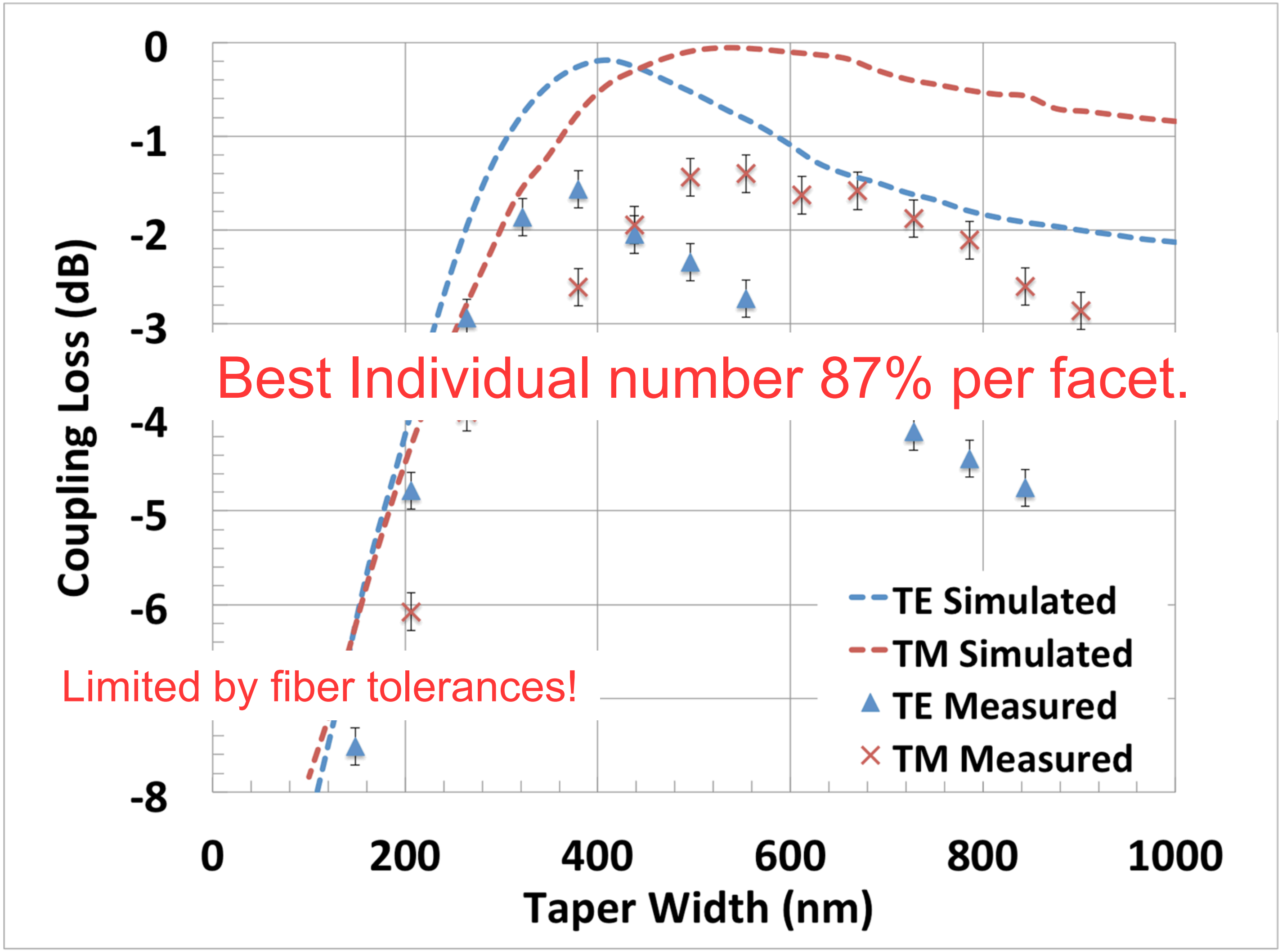


- Fiber and fiber arrays commercially available.
- Design on-chip devices to match available components.
- Do a six-axis alignment at sub-micron, milli-radian levels.
- Our goal -1 dB Total loss.





Advances in Fiber-to-chip coupling

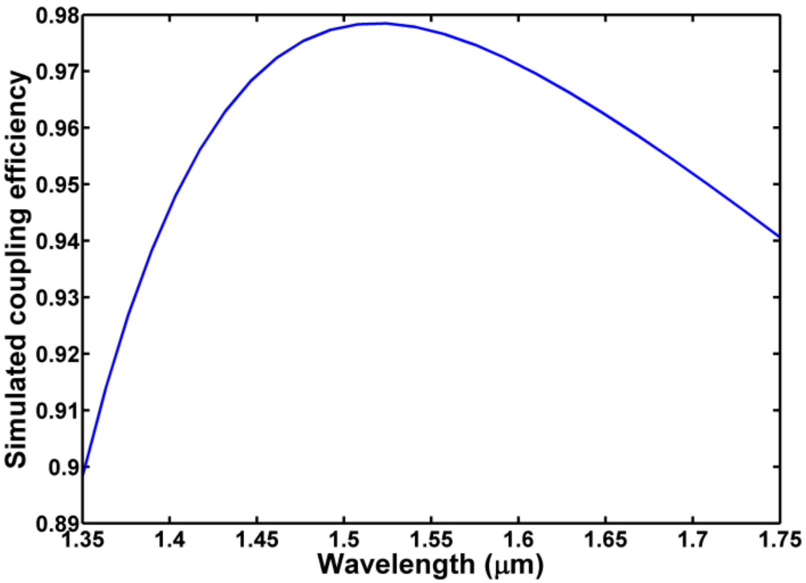


Best Individual number 87% per facet.

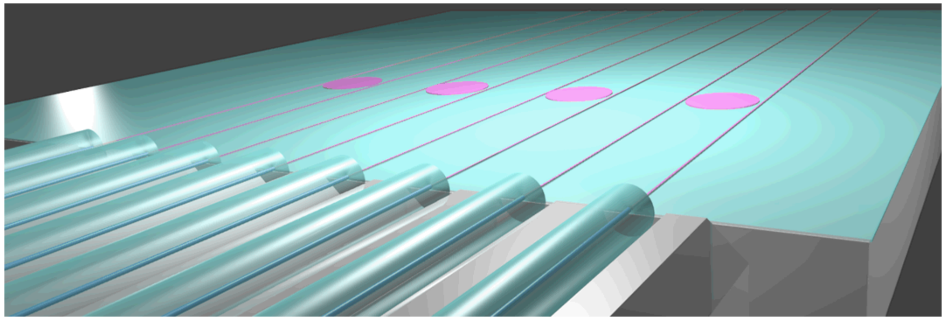
Limited by fiber tolerances!

Bandwidth and multiple facets

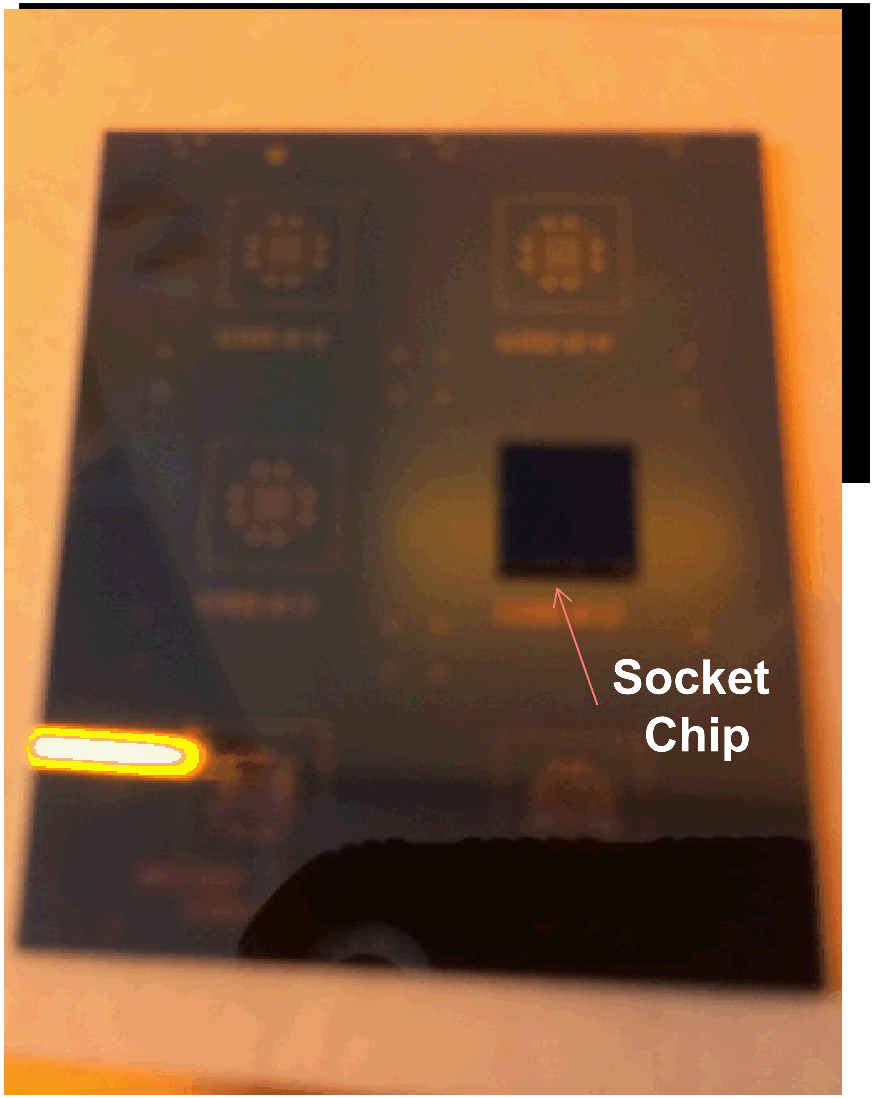
Note: will add experimental data to this.

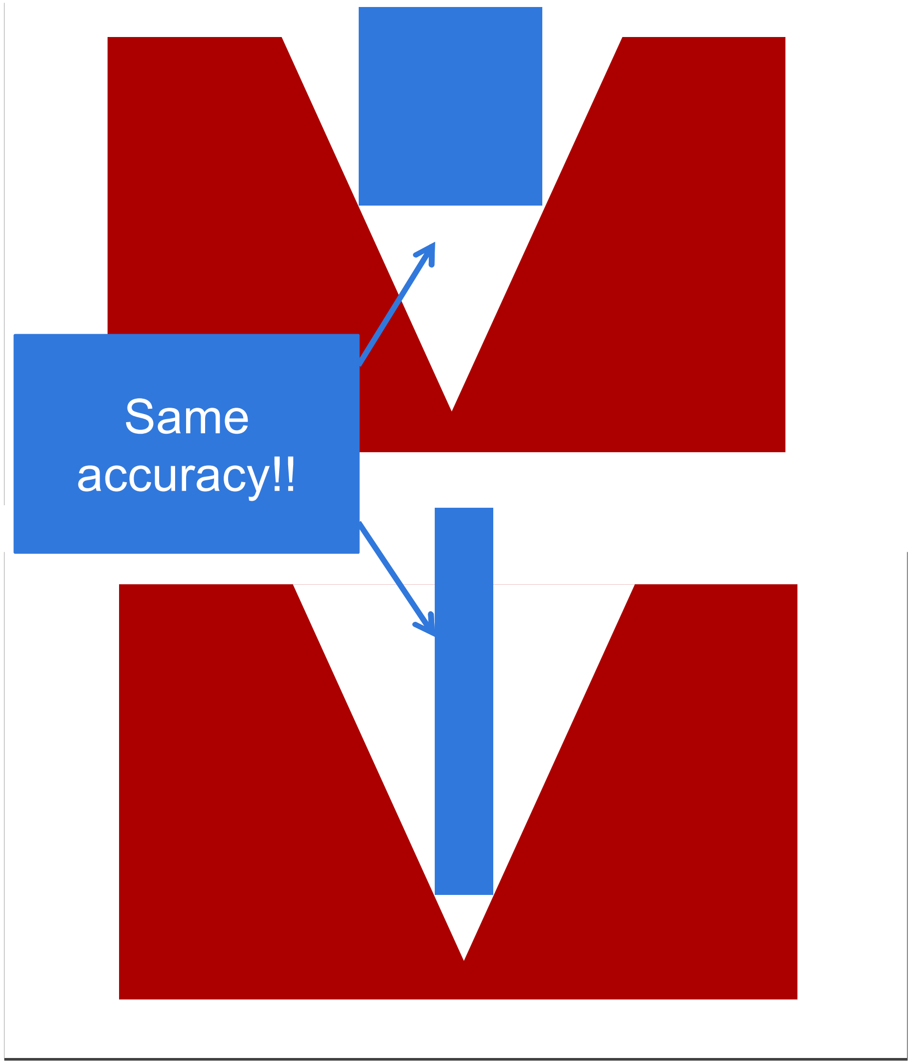


Over 80% per facet across 4 channels for TE and TM.



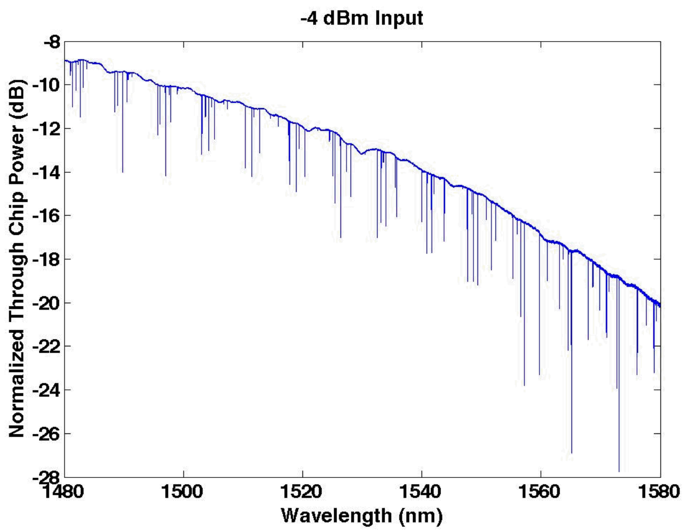
Kinematic Alignment Efforts

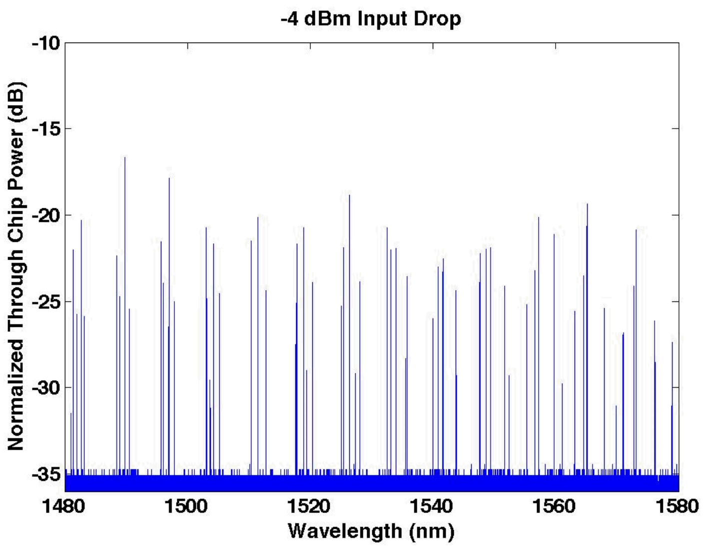




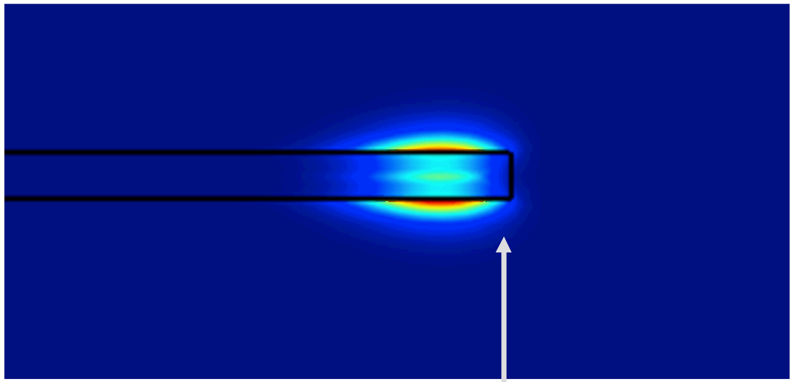
Devices for Northwestern

- Non-linear switching. Requested specifications:
  - Maximum on chip loss: 7 dB
  - Maximum off-chip loss for the through port: 8 dB
  - Maximum off-chip loss for the drop port: 6 dB
  - Qs on the order of 10^6
- Delivered device 1 – damaged during shipping.
- Delivered device 2 –
  - -9 dB total efficiency at 1500 nm compared to specified -13 dB and -15 dB.
  - Qs > 500,000 – nonlinearity makes it hard to measure.
  - Not tested yet…

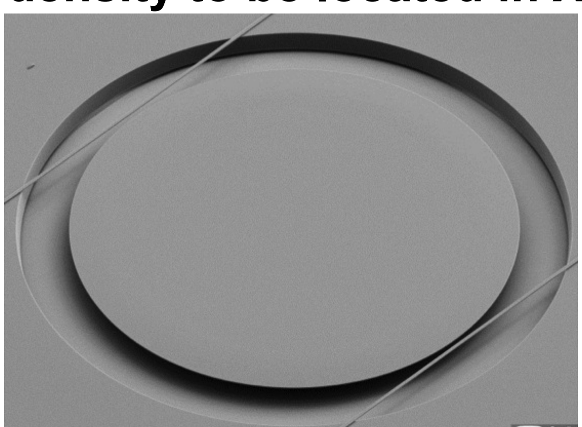




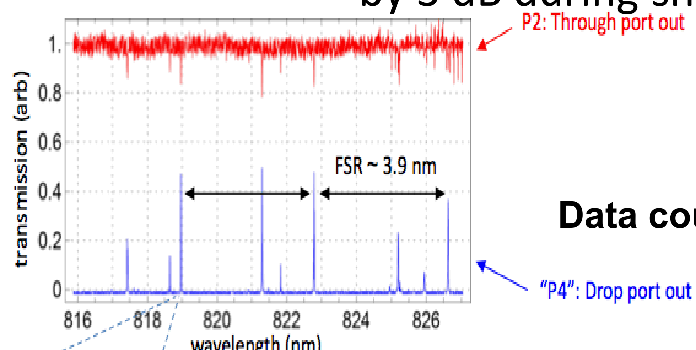
Devices for UMBC
Phase shifting micro-disks



Use of vertical polarization mode allows for up to 30% of the energy density to be located in Xe



- Requested specifications:
  - Resonance at 823 nm
  - Q > 100,000
- Delivered:
  - Resonances with FSR of 3.9 nm – thermally tunable to exact Xe line.
  - Q > 140,000
  - Coupling efficiency decayed by 3 dB during shipping.



Data courtesy of T. Pittman

Ion Beam Implantation for Color Center Formation in Diamond

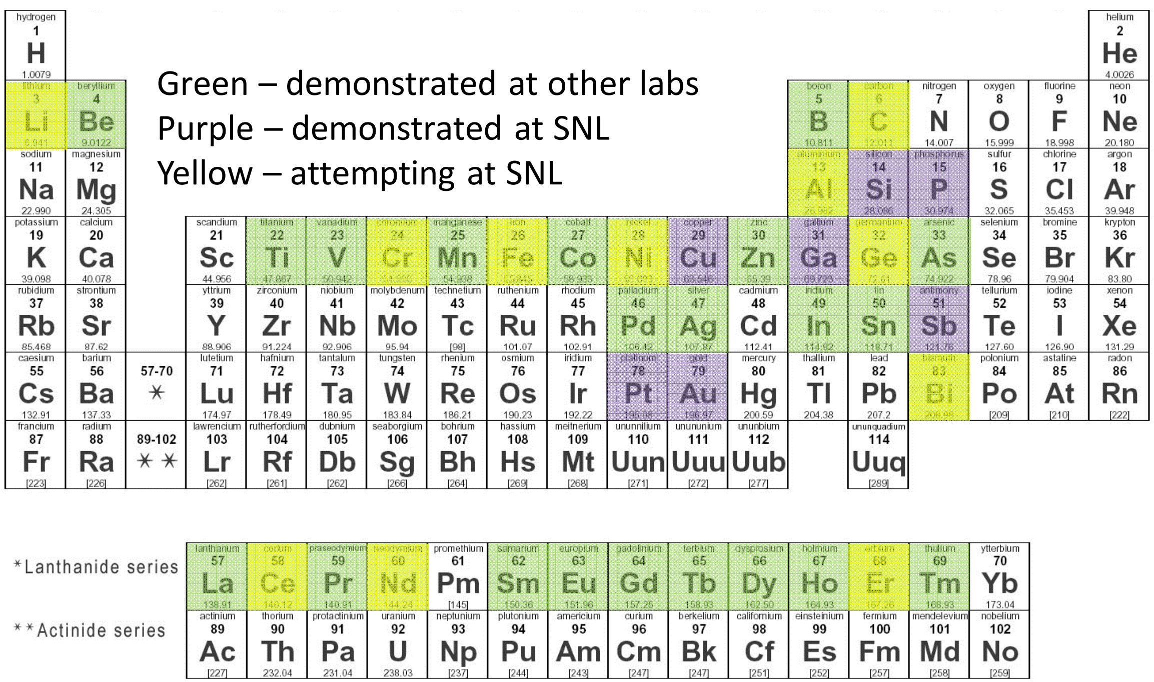
Goal – Deterministic single color center formation in diamond for single photon sources and quantum memory. Key issues:

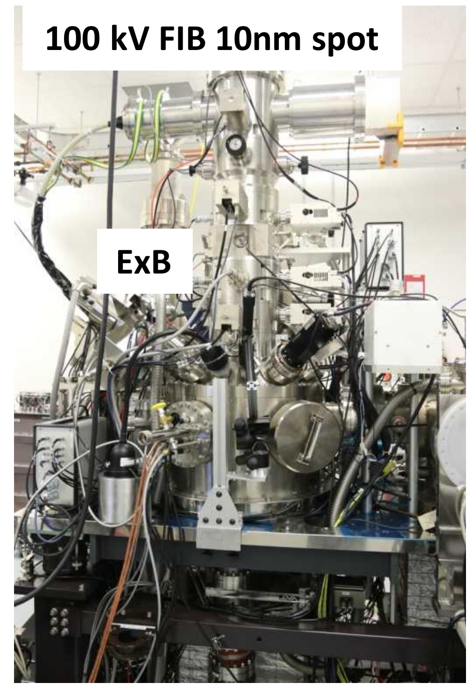
1.) Yield – need to determine the yield for shallow color centers

2.) In-situ detection – need to develop the ability to detect single ion strikes in diamond

Focused Ion Beam Implantation Capability at SNL

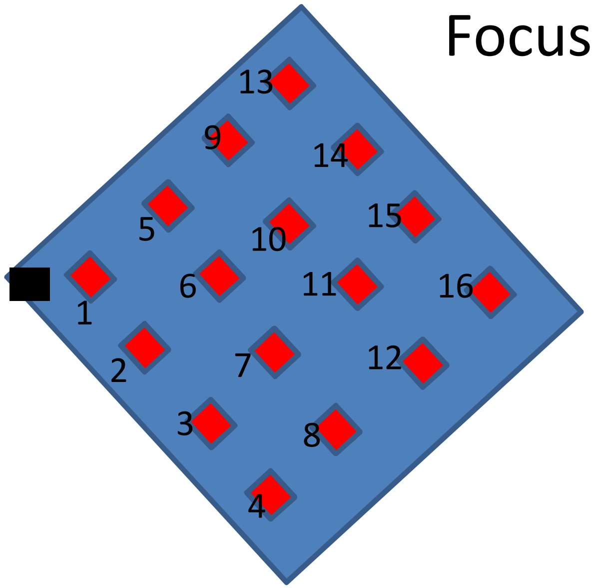
- Four accelerators with focused ion implantation capability
- Range of ion species from H to Bi
- Highlight the ***nanoImplanter (nI)***





- Variable Energy 10 -100 kV
- Fast Blanking and Chopping
- Liquid Metal Alloy Ion Source
- Mass-Velocity Filter

Focused Ion Implant Work To-date



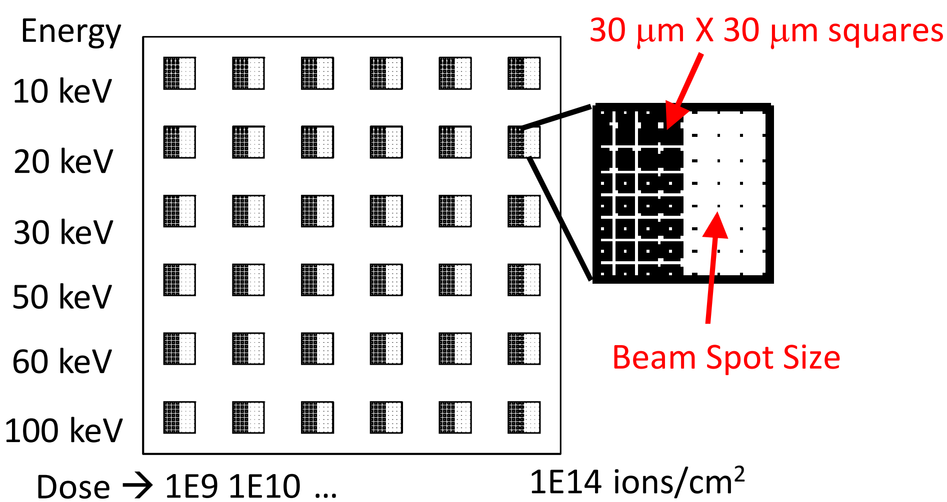
<u>1.) Implanted and annealed a series of samples using:</u>

- 800 keV N for NV creation
- 800 keV Si for SiV creation

Samples provided to **<u>E. Waks (UMD)</u>** for measurement

Vary dose over two order of magnitude to explore yield

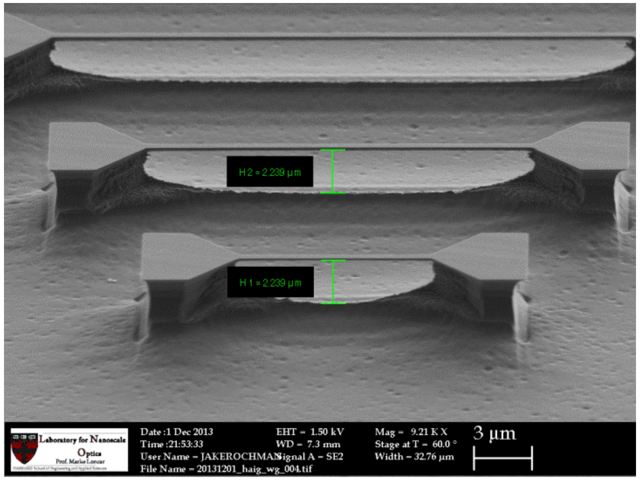
<u>2.) Si into a sample for D. Englund (MIT)</u>



- Yield tester as function energy and dose

<u>Implants underway!</u>

<u>3.) Si into a sample for M. Loncar (Harvard)</u>



We will implant 100 keV Si into the nanowires and hand off to Loncar's group. Samples in route to SNL.

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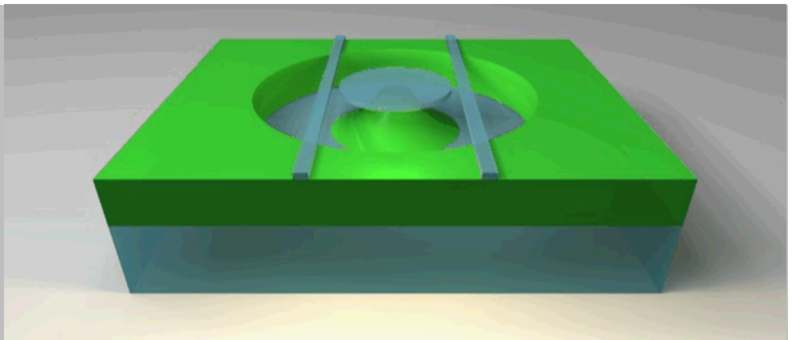

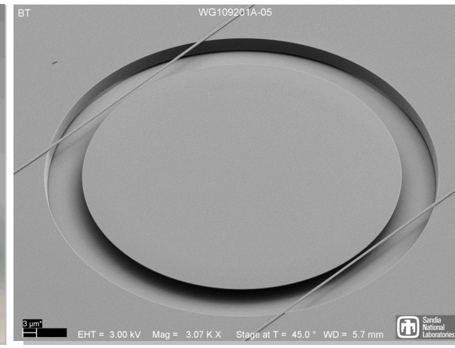

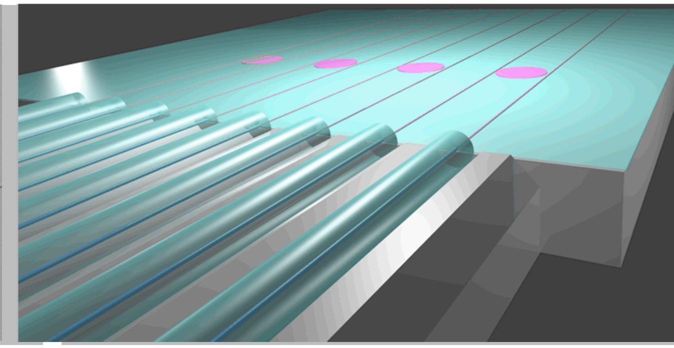

Micro-systems for Scalable QKD Components Milestones

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U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

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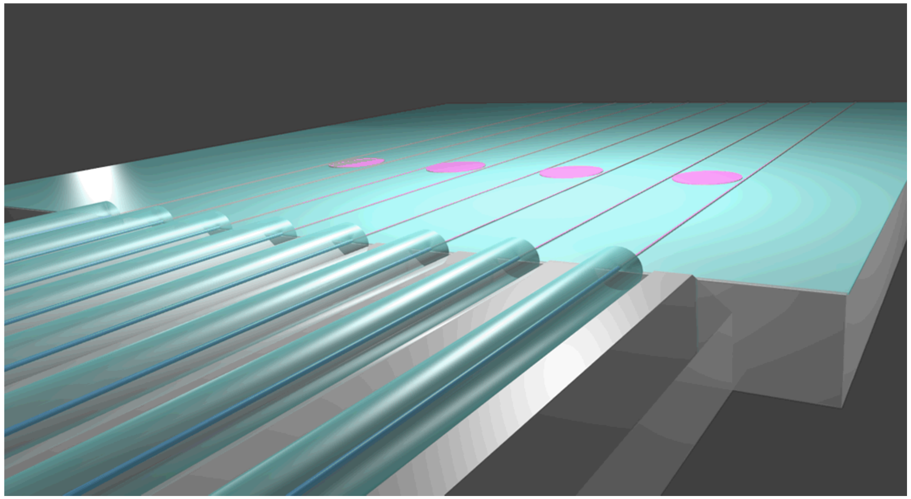
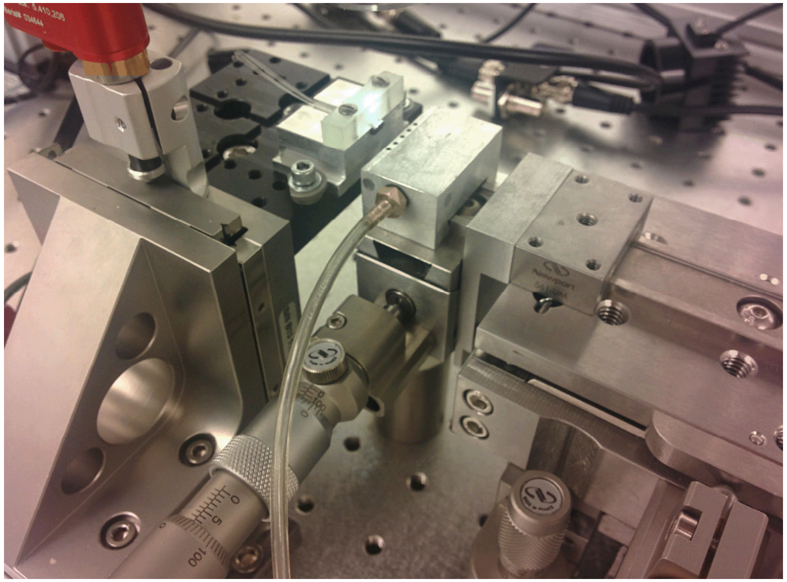
Sandia Goals for February 2016

• Improve single device. • Demonstrate coupling over 8 or 16 channels simultaneously.	• Fabricate and test kinematic bonding model. • Characterize ease of placing fibers inside of v-grooves. • Achieve better than 3 dB coupling without a 6-axis alignment.
• Characterize ion flux – color center formation relationship. • In-situ characterization of diamond color center formation. • Find recipes for deterministic characterization.	• Deliver to UMBC a micro-resonator that is critically coupled and better than 10 dB on-off efficiency. • Improve reliability of shipping bonded devices. • Test bonding at low temperatures.

Efficient Fiber-to-chip Coupling



- Improve single device efficiency by 4% per facet to get to -1 dB.
- Demonstrate better than -3 dB over 8 or 16 channels simultaneously (Constrained by fiber tolerances)



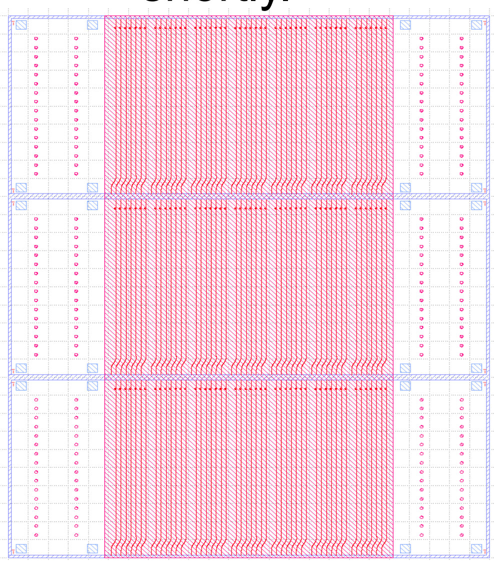
Possible sources of improvement:

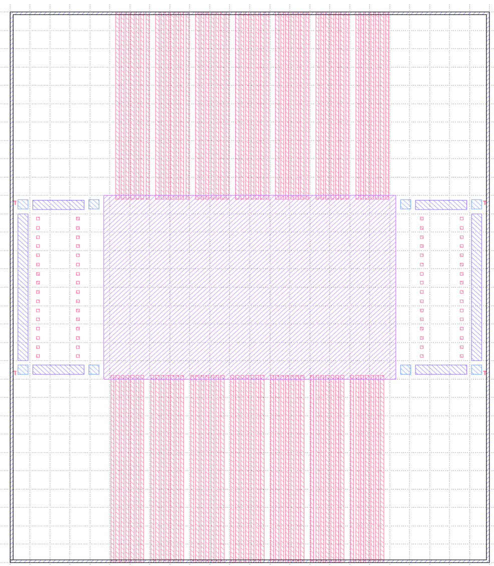
- Piezo rotation stages.
- Better chucks for fiber-array and DUT.
- Auto-collimator rotation alignment.

Kinematic Bonding

- Mask layout complete – both generic waveguide chip and generic v-groove chip.
- Started lots to determine exact crystallographic orientation for v-groove chip.
- Bonding of chips without optical components underway – will discover FC-150 tolerances shortly.

- V-groove chips start to come out in March 2015.
- Waveguide chips by May 2015.
- Fabrication lots set-to pull and test wafers at every step.
- Flip chip testing by end of May 2015.
- Demonstrate better than 3 dB without active alignment of fiber – may require a second fab iteration.



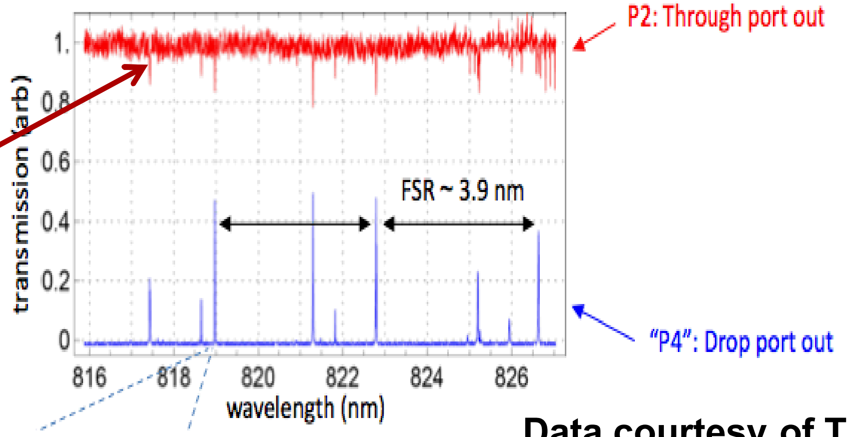


[redacted]

Deliveries to partners

For UMBC: Already have devices out of fab – should be bonded and delivered by Spring.

- Improve power drop.
- Get better than 10 dB total fiber-to-fiber efficiency.
- Improve Q.
- Vastly improve shipping and bonding reliability by applying epoxy with a micro-syringe.



Data courtesy of T. Pittman

For Northwestern:

- We have not received further instruction.
- In process are thicker micro-rings with anomalous dispersion requested by Yuping Huang.
- New epoxy and bonding techniques can improve delivered devices even more.

Ion Implantation Goals – February 2016

Progress/understanding on two main issues are needed

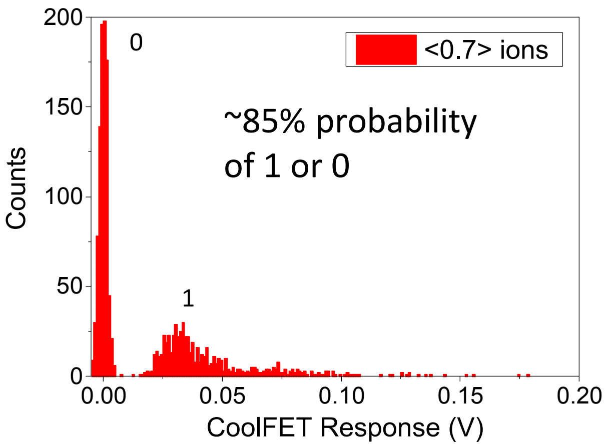
1.) **<u>Color Center Formation Yields</u>**

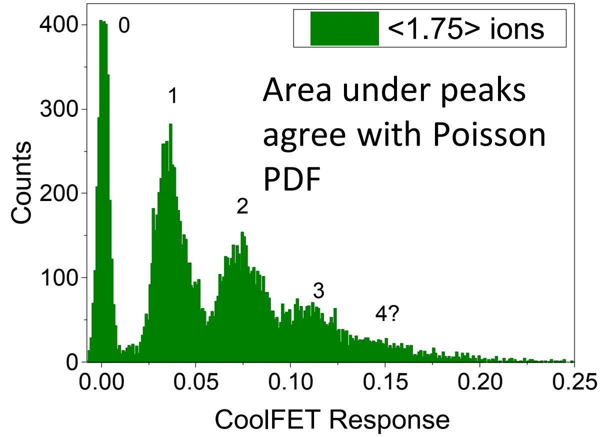
- Yield needs to be understood and/or improved as a function of color center type and implantation depth
- Yield can be improved for a given depth with pre-irradiation to damage the localized areas

2.) **<u>Deterministic Implants</u>**

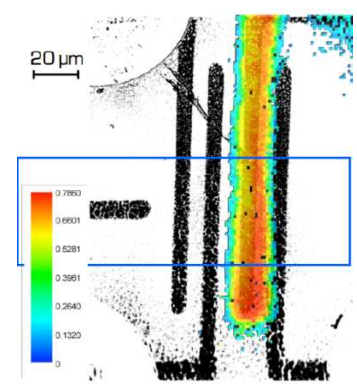
- Development of on-chip single ion detectors will be needed for single color formation (if yield can be understood/improved)
- Based on our recent success in detecting single low energy heavy ion implants using IBIC in Si we believe this pathway is doable with existing technology.

<u>200 keV Si into Si PIN diode</u>





<u>Diamond IBIC Collect Map</u>



J. Forneris, et al. axXir:1312.4734