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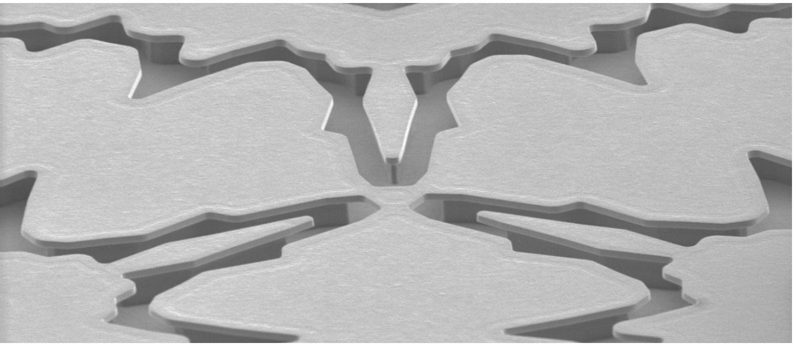

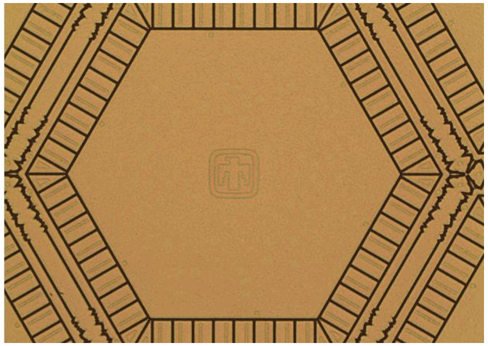

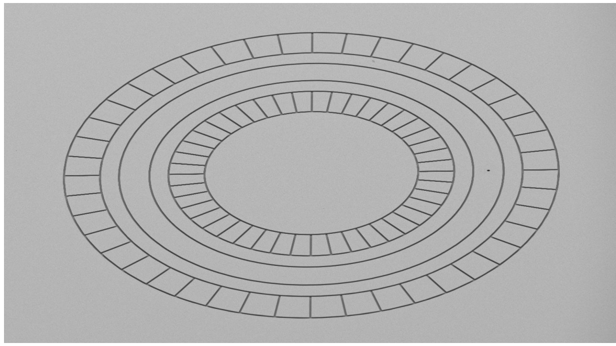

Sandia Micro-fabricated Ion Traps for the MUSIQC architecture

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Christian Arrington, Francisco Benito, Robert Boye, Susan Clark, Rob Ellis, Ray Haltli, Edwin Heller, Drew Hollowell, Shanalyn Kemme, Becky Loviza, Jonathan Mizrahi, Anathea Ortega, David Scrymgeour, Jon Sterk, Boyan Tabakov, Chris Tigges, Amber Young, Daniel Stick and Matthew Blain,

August 23rd, 2013

IARPA

UNM

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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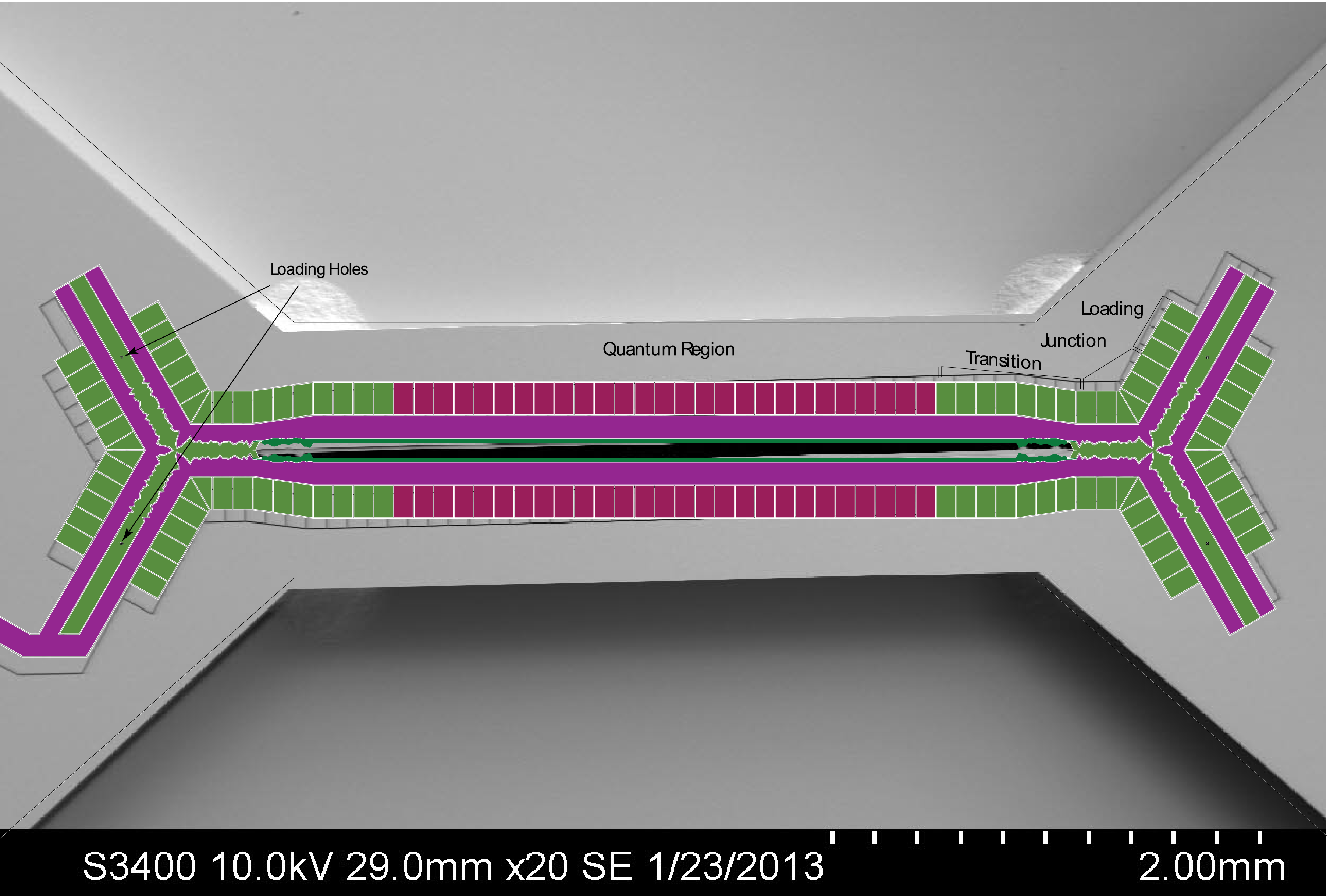
MUSIQC system integration

- Trapped ion chain quantum register
  - trap chain of ions
  - micromotion compensation
  - control over principal axes
  - individual addressing (optical access)
  - low scatter
  - sufficiently high trap frequencies
  - sufficiently low heating rates

- Remote entanglement
  - micromotion compensation
  - optical access
  - light collection

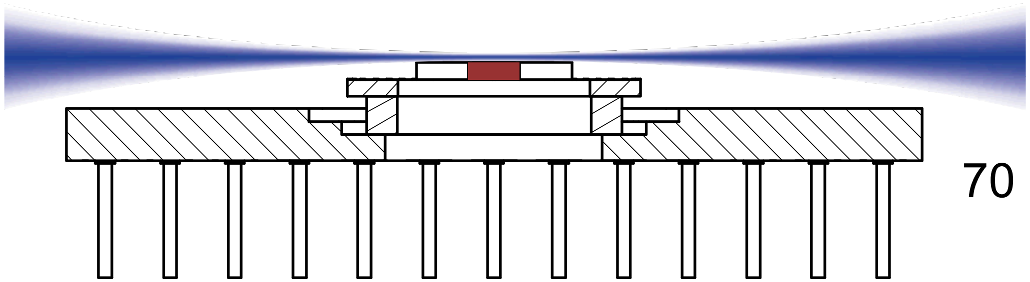
- Integration
  - shuttling, separation and recombination of chains
  - sympathetic cooling
    - re-arranging different ion species

Schematic

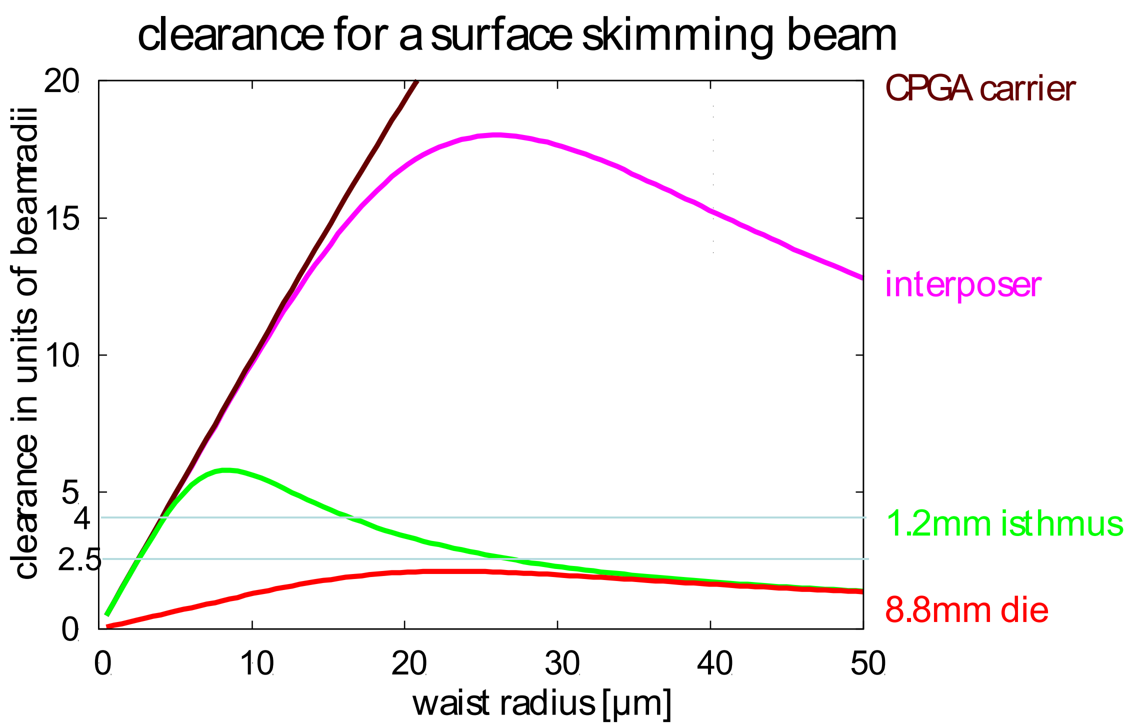


Loading Holes
Quantum Region
Transition
Junction
Loading
S3400 10.0kV 29.0mm x20 SE 1/23/2013
2.00mm

High Optical Access trap *beam clearance*



70 μm ion height



4: $<2\times10^{-14}$

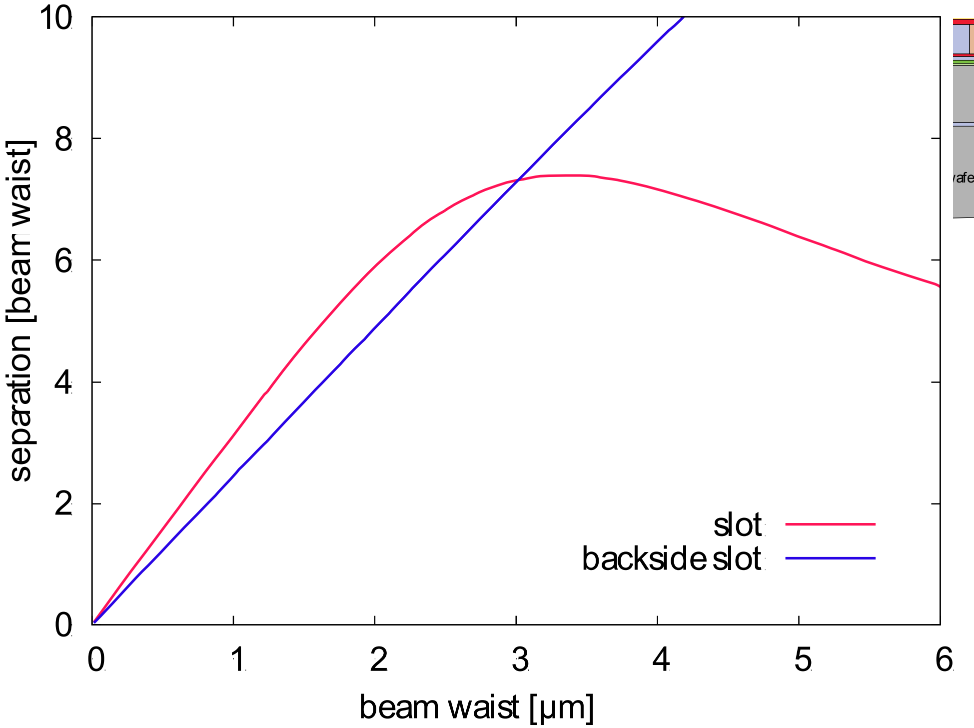
3: $<2\times10^{-8}$

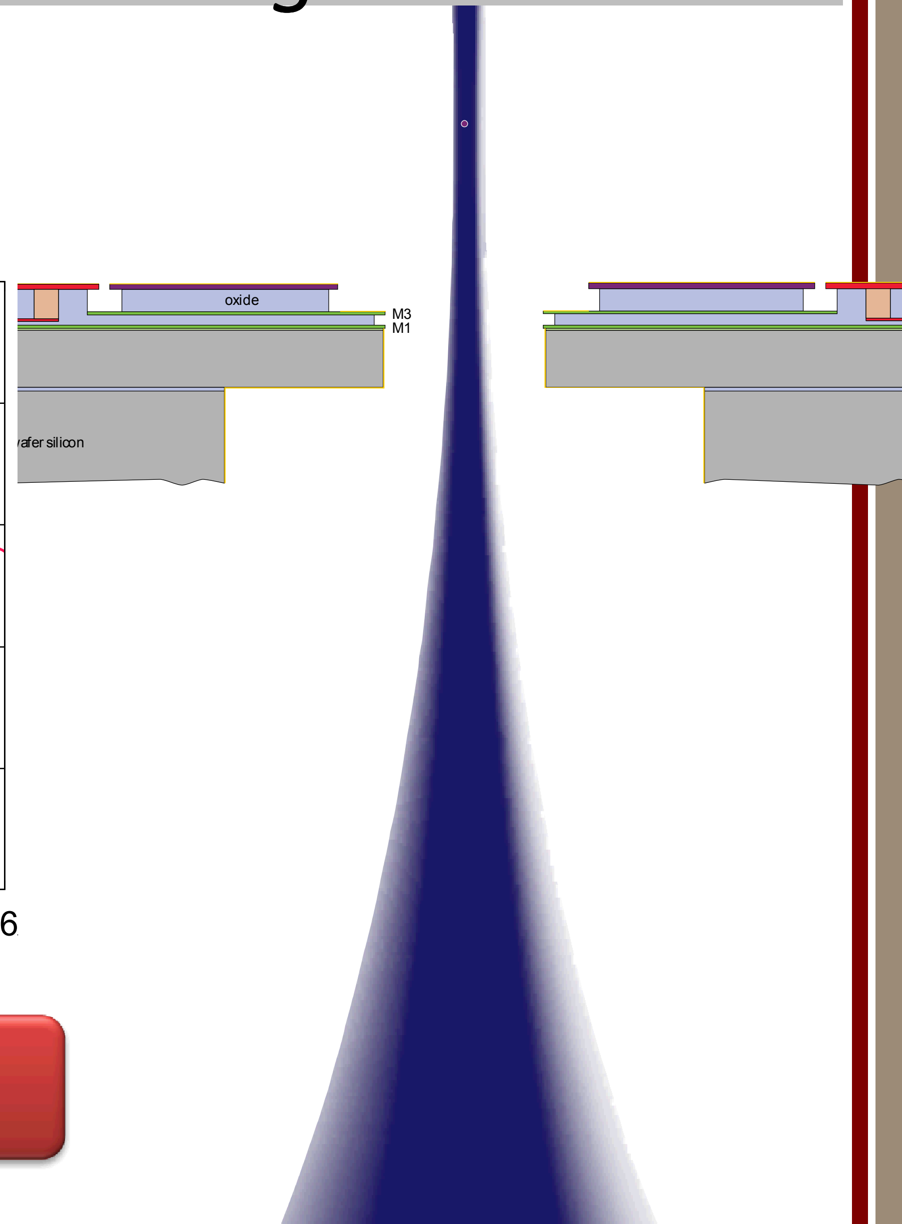
2.5: $<3\times10^{-6}$

4 μm waist is possible

Optical access
through central slot

Clearance of vertical beam





<2µm focus possible

Design tradeoffs
HOA trap

Property	Advantage	Disadvantage
widened rf rails	• double the trap frequency • four times trap depth • more harmonic potential	• control electrode distance • harder to rotate axes
inner electrodes on M3 grounded	• space for rf rails	• no easy way of rotating principal axes

Trap comparison

Compared for $^{171}Yb^{+}$ at 300V rf amplitude, 45MHz rf frequency

Trap	frequency	depth	ion height	stability q
Thunderbird	1.5 MHz 2.2 MHz (31.8 MHz rf)	58 meV 110 meV	80µm	0.1 0.2
Cavity-trap	1.2 MHz 1.9 MHz (28.4MHz rf)	≈40 meV ≈95 meV	100µm	0.08 0.2
HOA trap	3.2 MHz	213meV	68µm	0.2

compared to Thunderbird:
more than twice the trap frequency for same parameters
50% increased trap frequency for constant q

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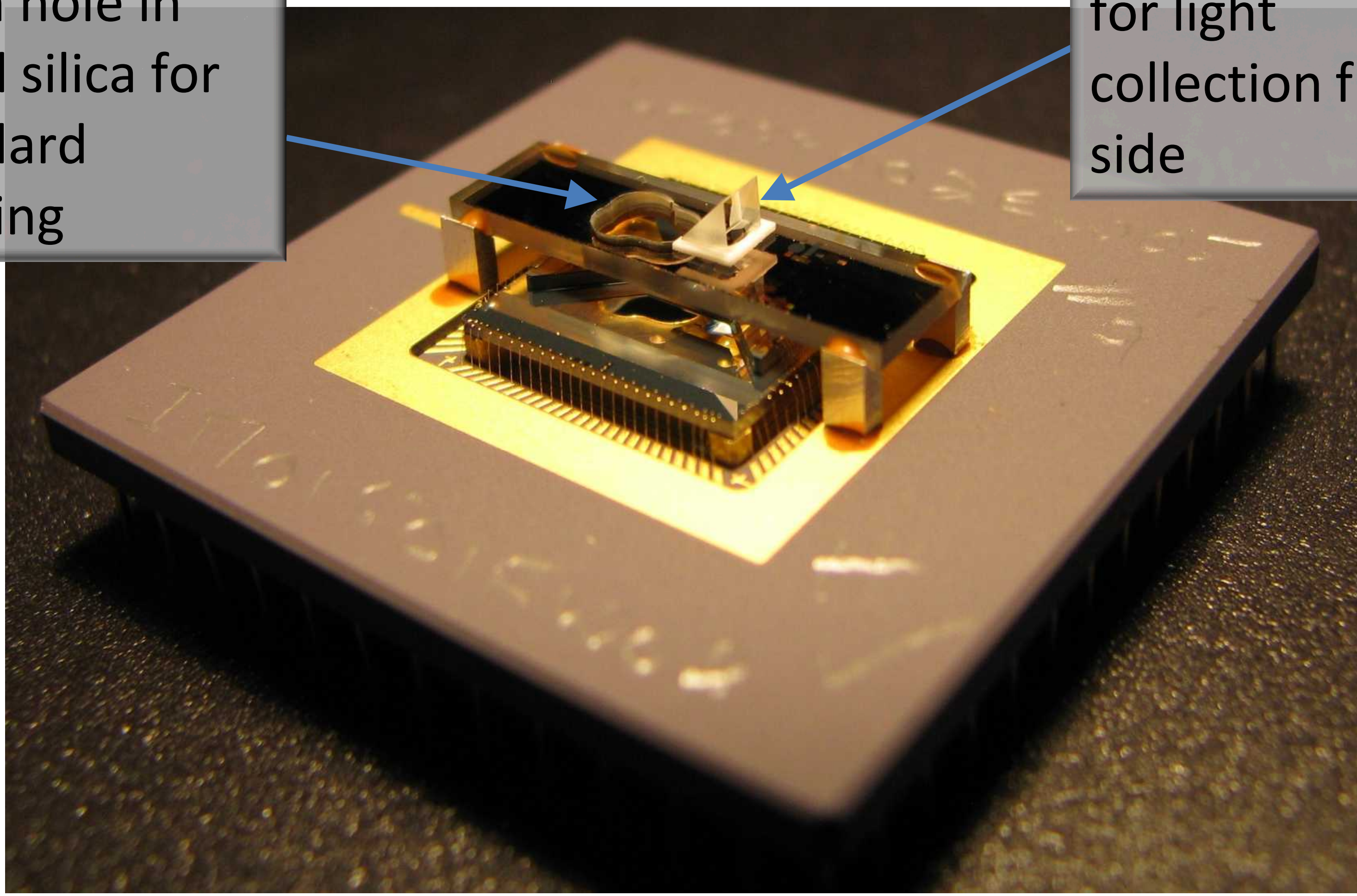
HOA + optic

Open hole in fused silica for standard imaging

Turning prism for light collection from side



MUSIQC system integration

HOA trap as delivered in Phase 2

- Trapped ion chain quantum register
  - trap chain of ions
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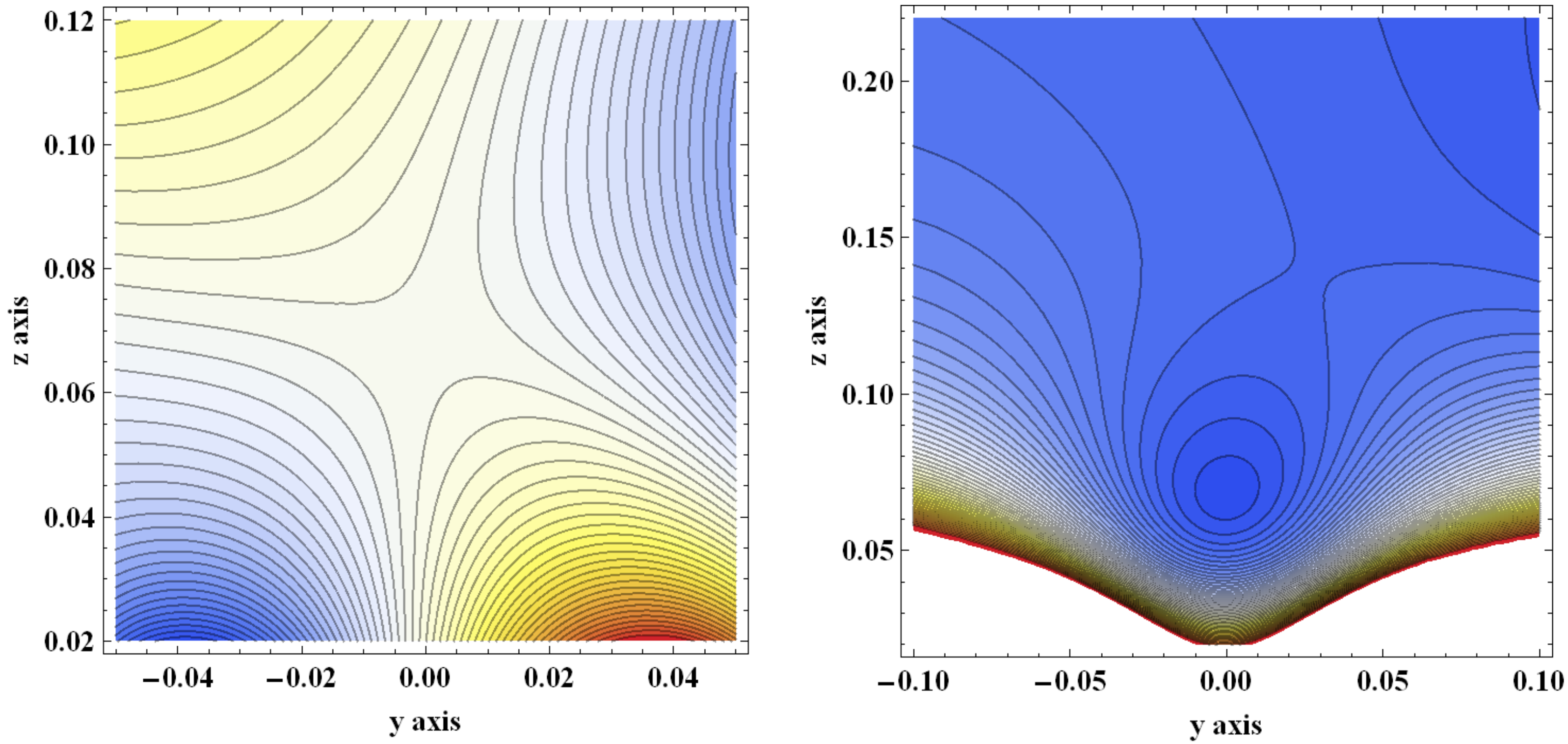
HOA suggested improvements Part 1

- Control voltage on inner DC electrodes
  easily rotate the principal axes maintaining linear trap
- Improved routing to limit maximum lead length and resistance
  reduce pickup of rf voltages
- Reduce isthmus width to 1mm (from 1.2mm)
  even better optical access
- Electrode markers
  ease beam alignment
- Wirebonding markers
  automatically align wirebonding device (more efficient packaging)
- Improve ground connection

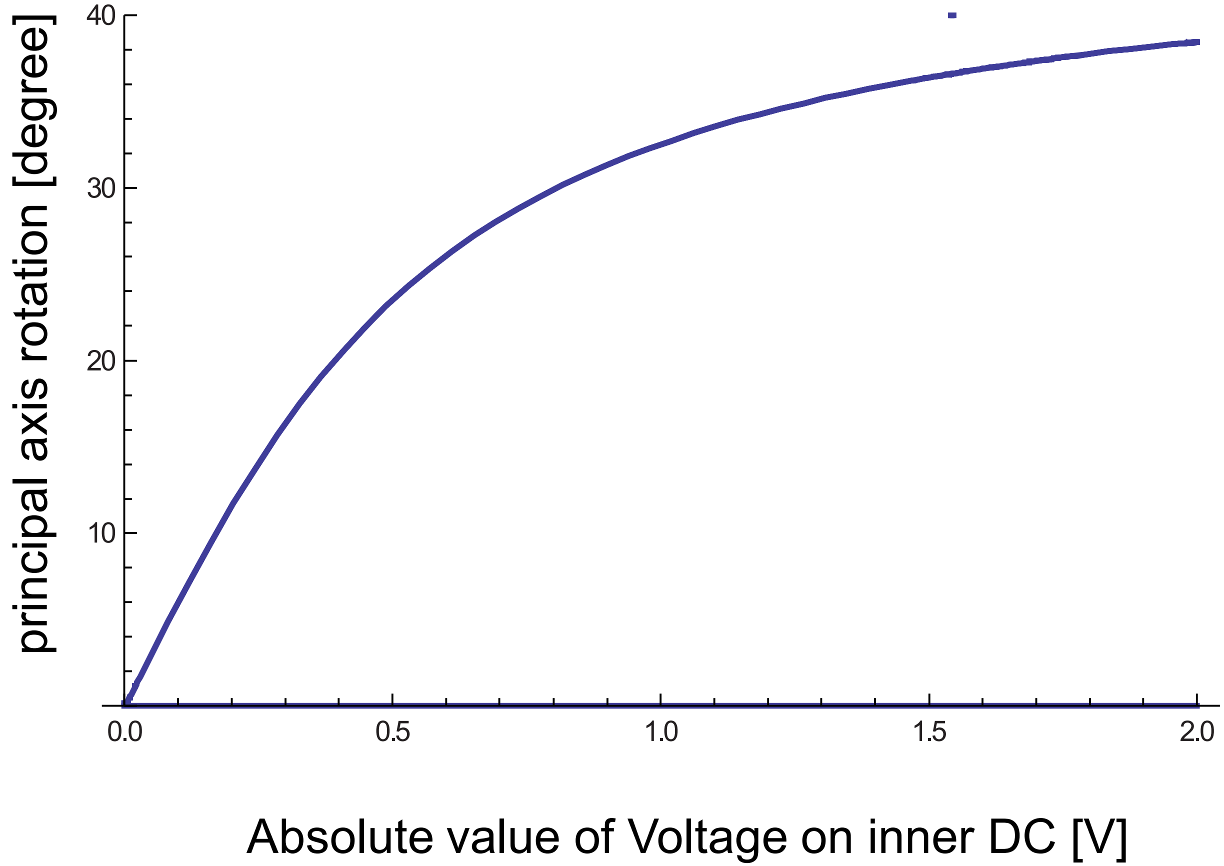
Improvements
HOA trap

- Convert inner ground electrodes to split inner DC electrodes



Yb: All control voltages <5V; Axial 500kHz, radial 2.8MHz, 3.1MHz
250V rf @ 40MHz

Principal axes rotation *with split inner DC*



MUSIQC system integration

HOA including improvements

- Trapped ion chain quantum register
  - trap chain of ions
  - micromotion compensation
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HOA remaining challenges

Good:

- Highly open optical access:
  parallel to surface 4μm, through slot 1.2μm (4 beam radii separation)
  adequate for individual addressing
- Trap frequency > 3 MHz (Yb) with q ≈ 0.2
  $^{171}Yb^{+}$ at 300V rf amplitude, 45MHz rf frequency
- Trap depth 200 meV
- Long linear trap with separate regions for remote entanglement and ELU
  designed for intended protocols
- Interposer with trench capacitors

May need improvement:

- DC electrodes are far from ions:
  separating and combining ions to/from chain necessitates low axial trap frequencies
- Narrow leads due to space constraints on isthmus
- Shunt capacitor directly below electrode: further reduce pick-up
- Your suggestions or input

HOA further improvements

- Segment the inner DC electrode instead of outer electrodes
  ability to create trapping potentials with higher spatial frequencies
  better separation and recombination of chains (needs simulation)

- Adapt electrode sizes to intended operations
  smaller electrode size for separating and recombining of ions
  define regions for special purposes

- Integrate trench capacitors underneath trap electrodes
  fabrication risk
  better shunting of rf pick-up

- Trap geometry might need to depend on intended use

Your requirements, suggestions, criticism is crucial to the success of the next version of this trap!

MUSIQC system integration

HOA including improvements

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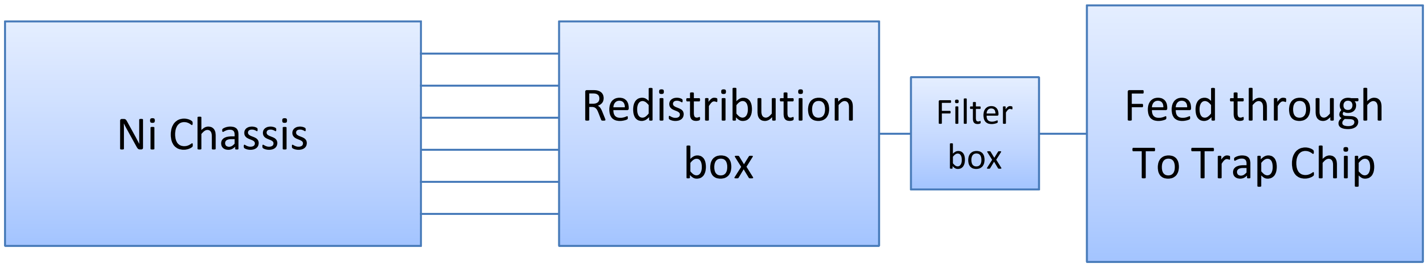
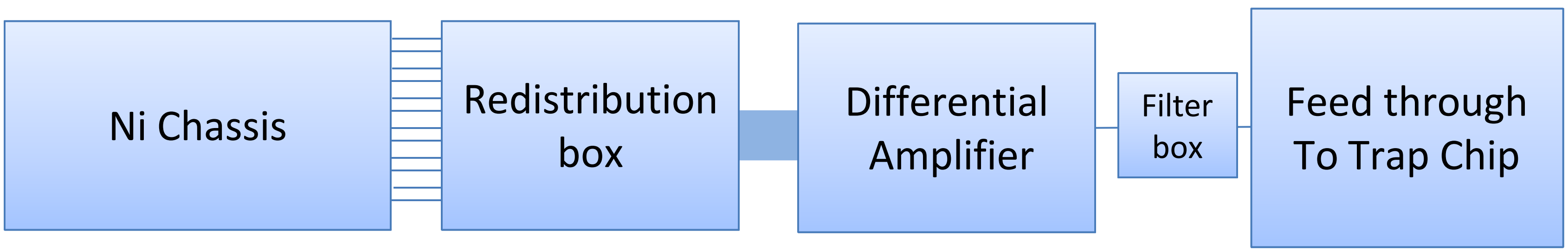
Voltage Control Systems

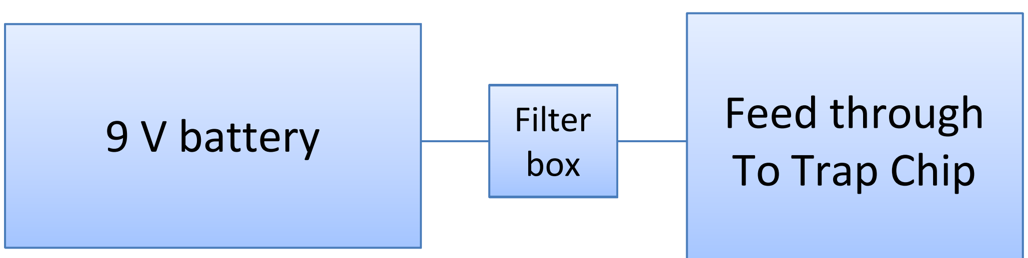
1. Ni Chassis with 48 control channels



2. Ni Chassis with 96 control channels

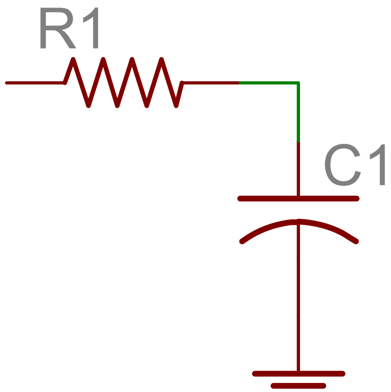


3. 9 V battery pack 9 control channels

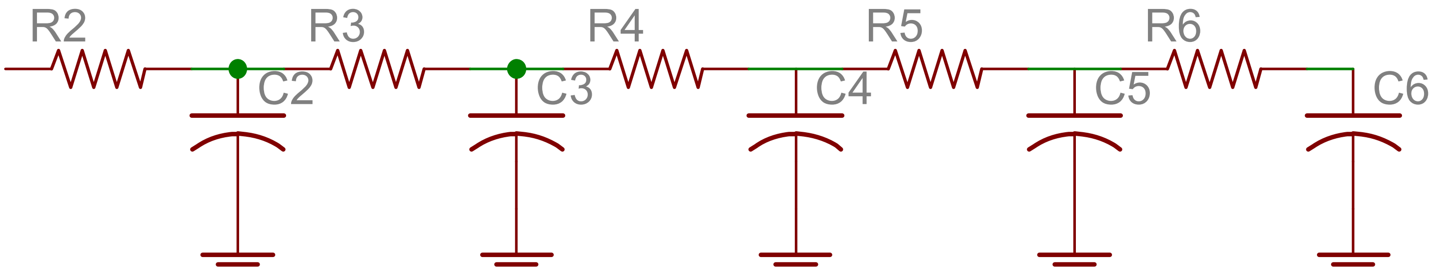


Filter box

Single stage filter



Five stage filter



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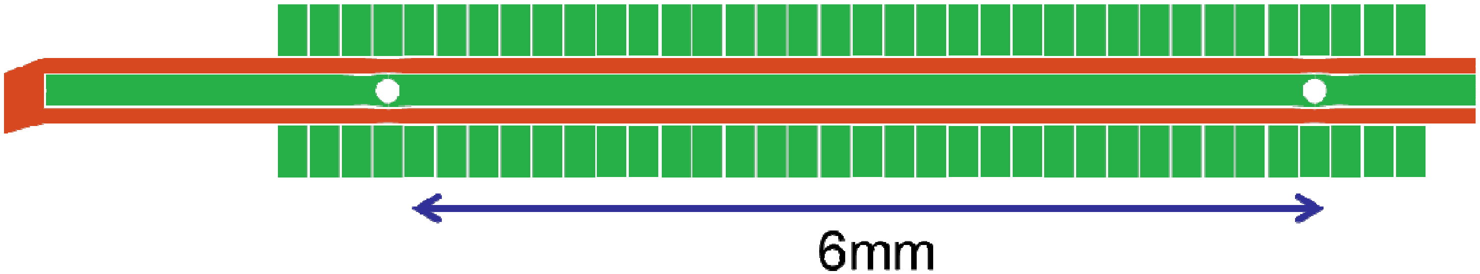
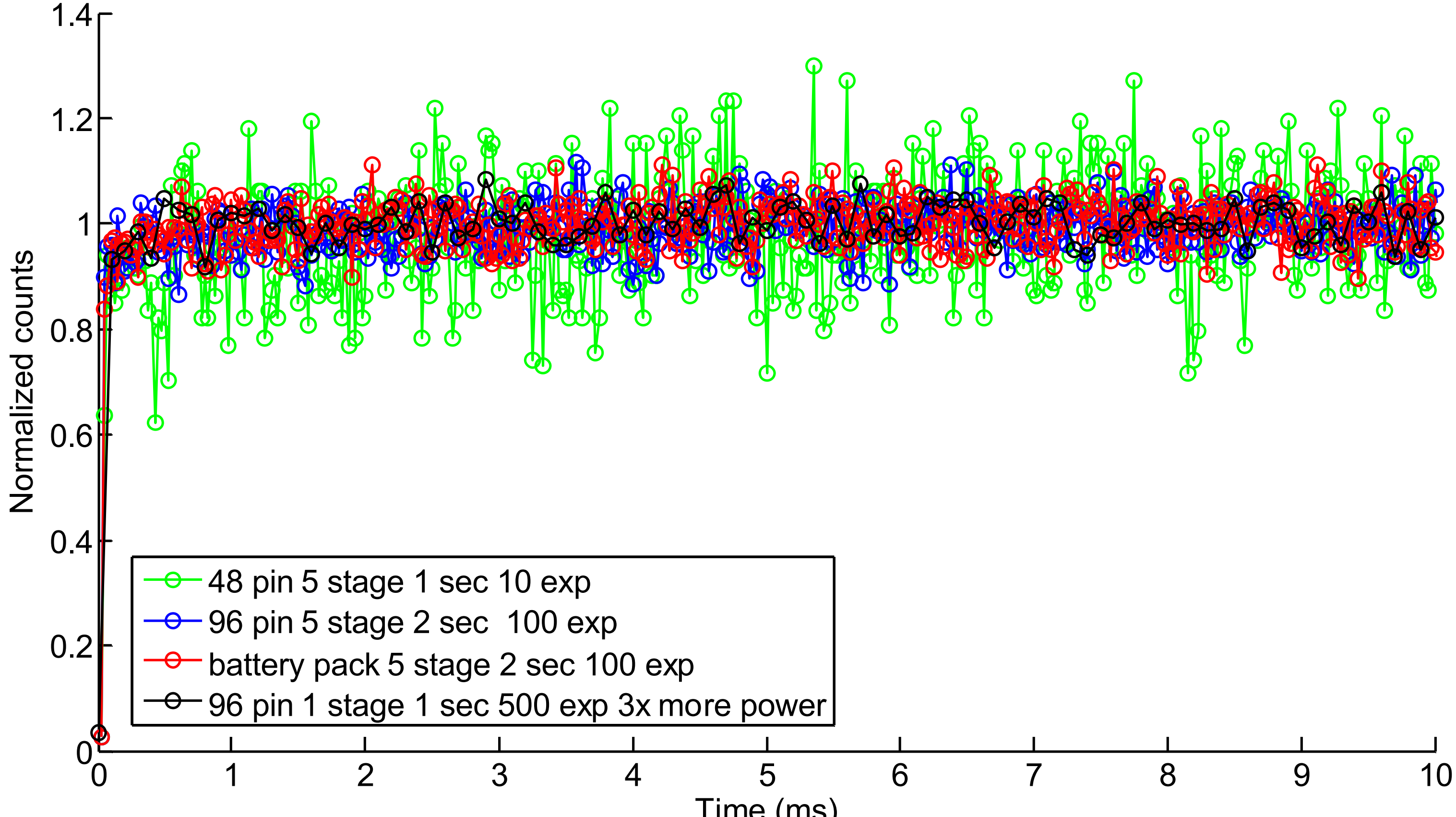
Heating Rate Results



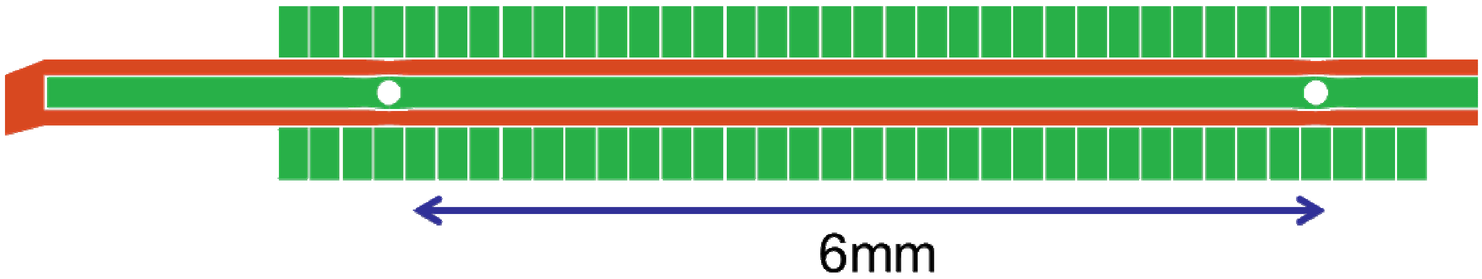


Take away

- If using the 48 pin chassis with 1 stage filters It was difficult to keep ion in the dark
- We feel the ability to collect the Doopler recooling curves with out loosing the ion for longer times suggest the heating rate is lowest and equivalent to the battery pack in the 96 pin chassis with differential amps and 5 stage filtering.

System	Filter (cut off freq)	Dark time
Battery	5 stage (30 kHz)	2-3 sec
NI with Diff amp	5 stage (30 kHz)	2-3 sec
NI with Diff amp	1 stage (300 Hz)	0.5-1 sec
Ni without Diff amp	5 stage (30 kHz)	0.5-1 sec
Ni without Diff amp	1 stage (300 Hz)	<0.5 sec

Heating trap surface



- Resistance between to two wire bonds on the center electrode is 4.4 Ω.
- Running a current of 0.65 Amps for 36 hours increases resistance to 6.6 Ω.
- Estimate temperature of trap to 200 ° C to attempt to back surface contaminants off to reduce the heating rate.
- Dark lifetime seems to get worse after heating along could heat the ion to 200 ms before losing the ion.
- Post analysis suggest no damage to the trap.

Reducing trap heating rates

Experiments from NIST show that sputter cleaning can reduce heating rates
However,

- Sputter cleaning gold can short the trap
- Ar ion guns are bulky and hard to integrate for QIP experiments

Exploring alternatives:

- Inductively coupled plasma
  - Energies sufficient to remove physisorbed contaminants
  - Compatible with CPGA package and QIP experiments
- Passivated surface
  - Au nitrite?

Acknowledgements

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CQuIC

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UBC

MagiQ

Georgia Tech Research Institute
Problem. Solved.

Michigan

The University of Sydney

Washington