SAND2013-6598C

Progress towards attaining an equidistant ion chain in a microfabricated surface ion trap

Prepared in fullfillment of the requirements of Ph.D. program in Physics at The University of New Mexico

Boyan Tabakov[†]
Adviser at SNL: Daniel Stick

[†]Center for Quantum Information and Control, University of New Mexico

Sandia National Laboratories

Outline

1. Microfabricated surface ion traps crash course
2. Ring trap: challenges overcome
3. Ring trap: status
4. Outlook

Ion trapping: motivation and history

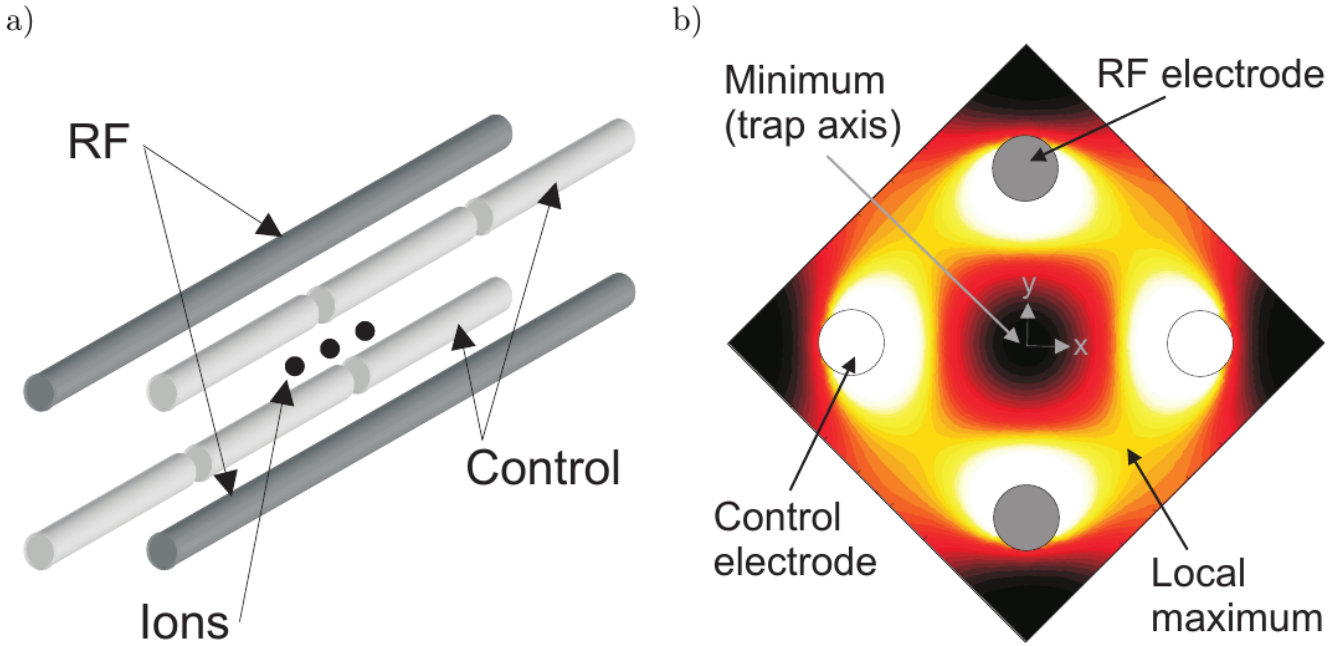
Microfabricated surface ion traps crash course

- non-magnetic quadrupole mass filter (Paul trap, RF trap, ion trap)
  - Wolfgang Paul, Helmut Steinwedel (1953). "Ein neues Massenspektrometer ohne Magnetfeld"
  - Nobel Prize 1989
- trapping and cooling
  - D. J. Wineland, R. E. Drullinger, and F. L. Walls (1978). "Radiation-Pressure Cooling of Bound Resonant Absorbers"
  - Nobel Prize 2012
- quantum information processing (QIP)
  - two qubit gate proposed 1995: Cirac and Zoller
  - implemented 1995: Monroe, Meekhof, King, Itano, and Wineland
- rapid development ever since
  - surface geometry 2005: Chiaverini
  - microfabrication 2006: Stick
  - microfabrication AND surface geometry 2008: Seidelin

Operating principles

Microfabricated surface ion traps crash course

- Earnshaw's theorem
- mechanical analog
- radial confinement: RF pseudopotential
- axial confinement
- secular frequencies
- micromotion, excess micromotion

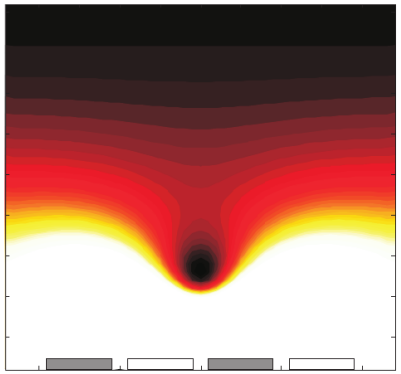


Chiaverini *et al.*, arXiv:quant-ph/0501147v2

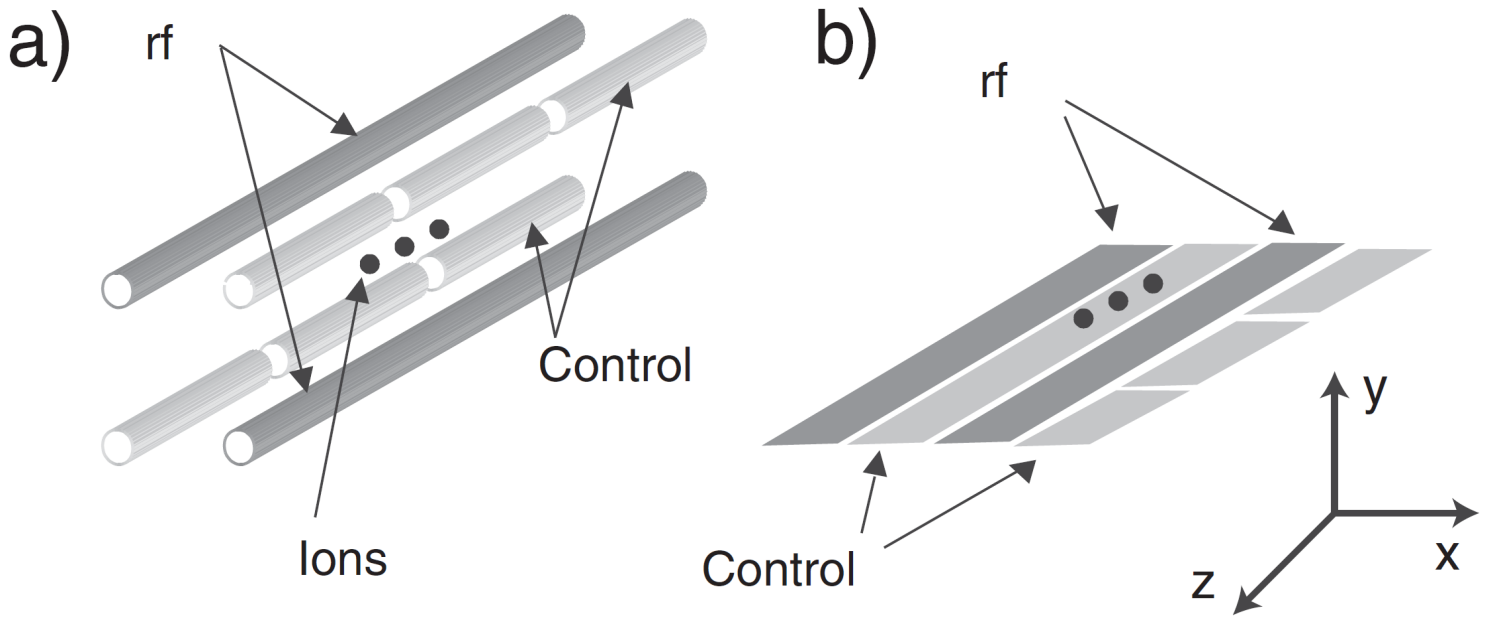
Mapping to a surface

Microfabricated surface ion traps crash course

- numerical simulations
- shallow trap ∼0.1 eV
- limited optical access, charging



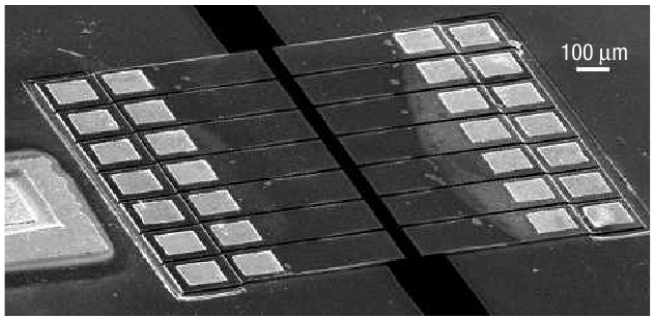
Chiaverini *et al.*, arXiv:quant-ph/0501147v2



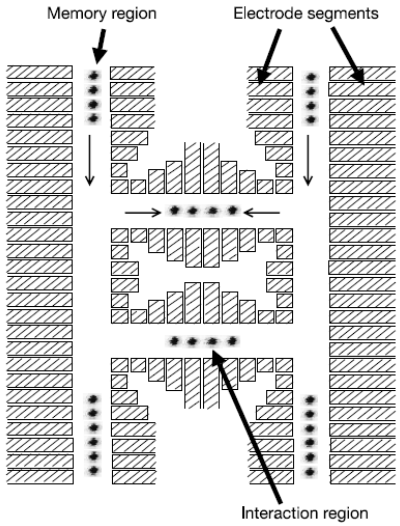
Trap fabrication

Microfabricated surface ion traps crash course

- standard microfabrication techniques, just like an IC
- scalable architectures



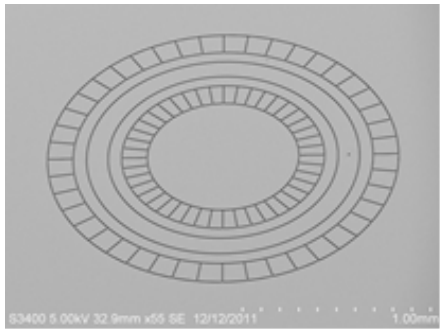
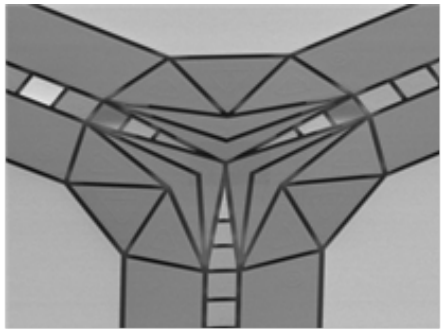
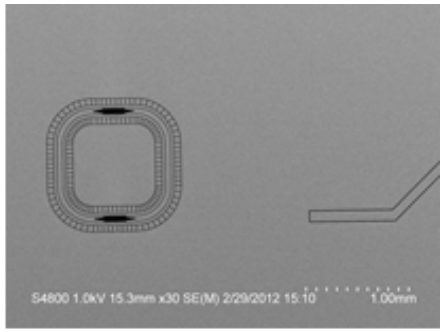
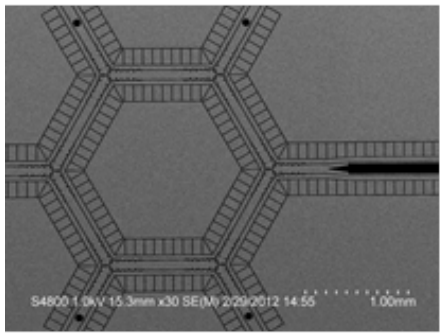
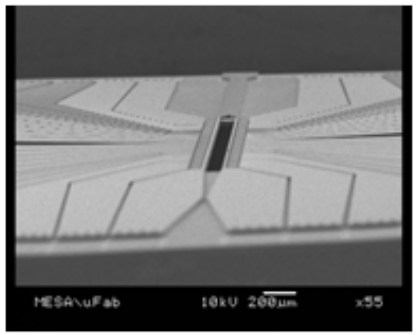
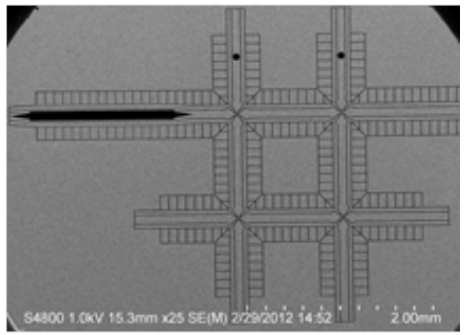
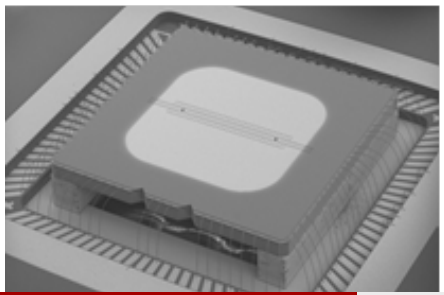
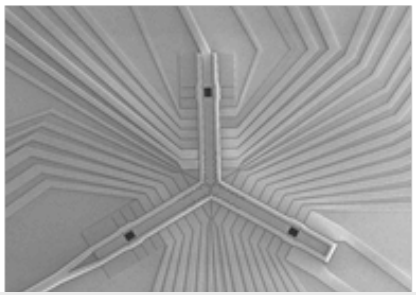
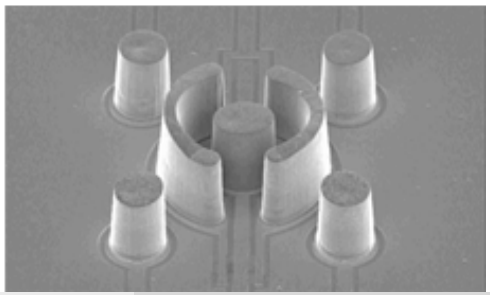
Stick *et al.*, Nature Physics 2, 36 - 39 (2006)



Kielpinski *et al.*, Nature 417, 709 (2002)

Abundant design options

Microfabricated surface ion traps crash course

Trapping in the lab

Microfabricated surface ion traps crash course

Trapping in the lab

Microfabricated surface ion traps crash course

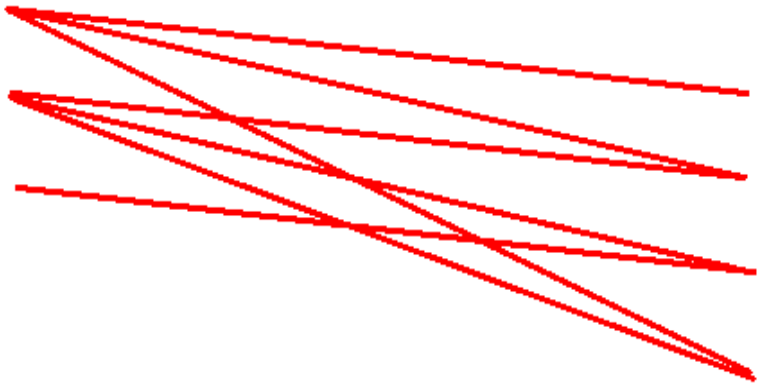
- trapping volume created or maintained
- PI light focused on some portion of it
- neutral species oven turned on
- right velocity and density for atoms reached
- some atoms ionized in trapping volume
- optional: ions shuttled to different trapping location
- ions cooled and fluorescence detected, oven turned off
- some experiment is attempted

Experimental challenges

Microfabricated surface ion traps crash course

what ~~is bound to~~ can possibly go wrong:

- micromotion
- heating
- dust
- UHV
- RF pickup



- micromotion
- heating
- dust
- UHV
- RF pickup

Project motivation

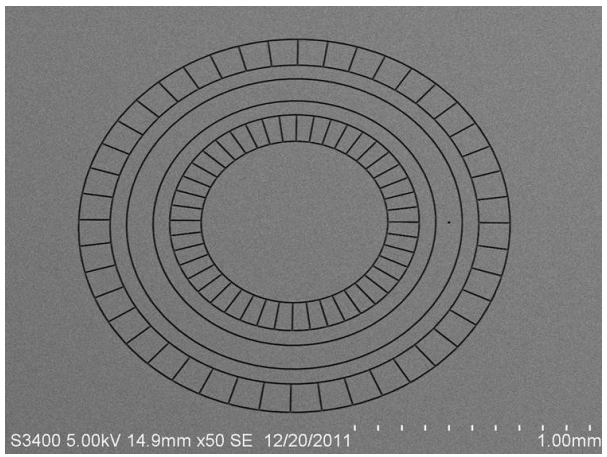
Ring trap: challenges overcome

motivation

- large crystal of equidistant ions, periodic boundary conditions
- 200 Ca^+ ions, $\sim$125 kHz axial confinement (20 μm apart) without DC
- quantum simulations (MQCO)

specific challenges

- cool that large crystal without charging the surface
- no extra fields in the trapping volume minimum everywhere, at the same time

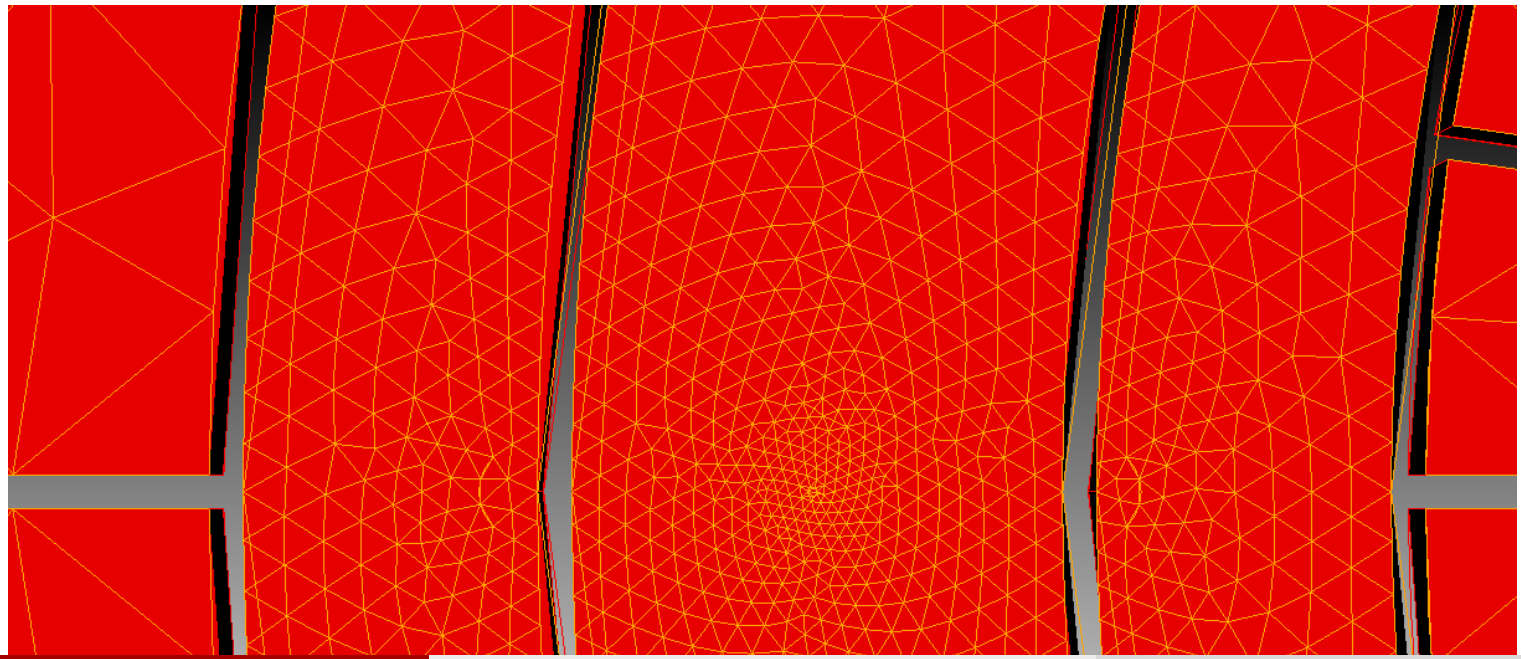


Trap production: Target parameters

Ring trap: challenges overcome

preliminary design by Dan Stick

- 80 μm trapping height
- RF drive 40 MHz @ 300 Va
- 10 Va DC solutions
- center DC electrode
- 625 μm trapping radius
- 7 μm wide gaps
- 10 μm loading hole
- 96 control channels



Trap production: Optimization

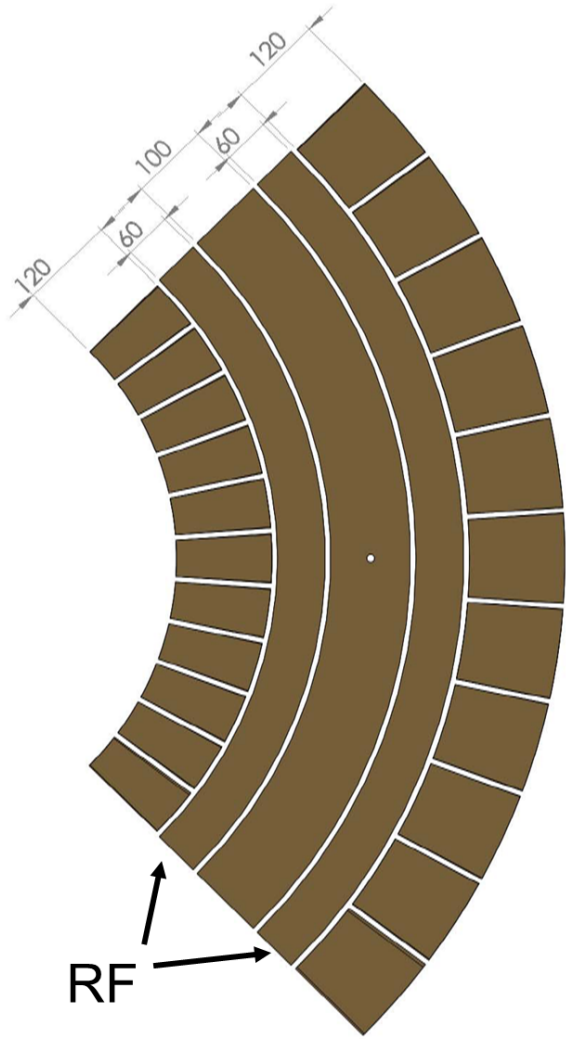
Ring trap: challenges overcome

optimization for trap depth, numerical simulations to examine effects of

- electrode proportions
- multiple metal layers
- top level metal RF lead proximity
- loading hole size
- meshing strategy

fabricated with

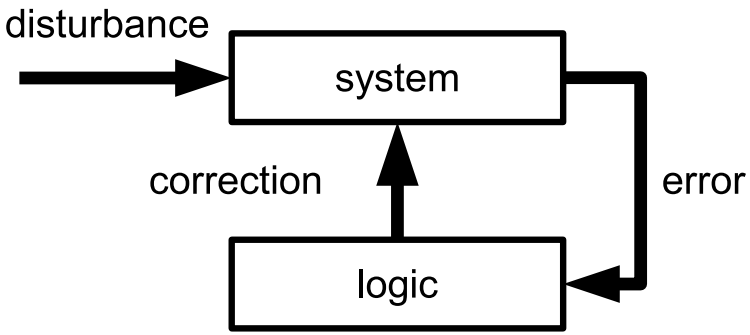
- Al surface (retired)
- Au coating (in chamber)



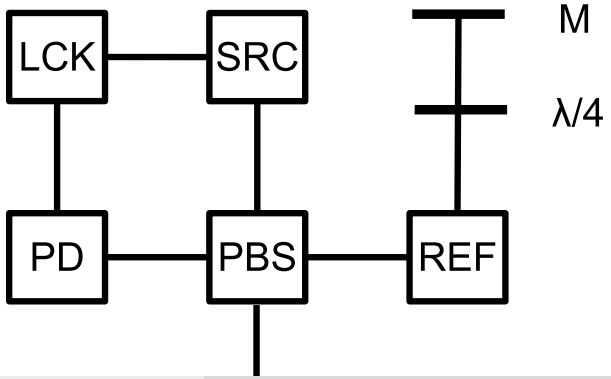
Stable light sources: Rb reference

Ring trap: challenges overcome

maintain a number of light sources within a few MHz of respective target frequency



- employ electronic locks
  - maintain system status
  - digital, analog algorithms
  - Pound-Drever-Hall technique (PDH lock)
- lock to a Rb reference
  - very own ECDL
  - frequency modulation saturated absorption spectroscopy

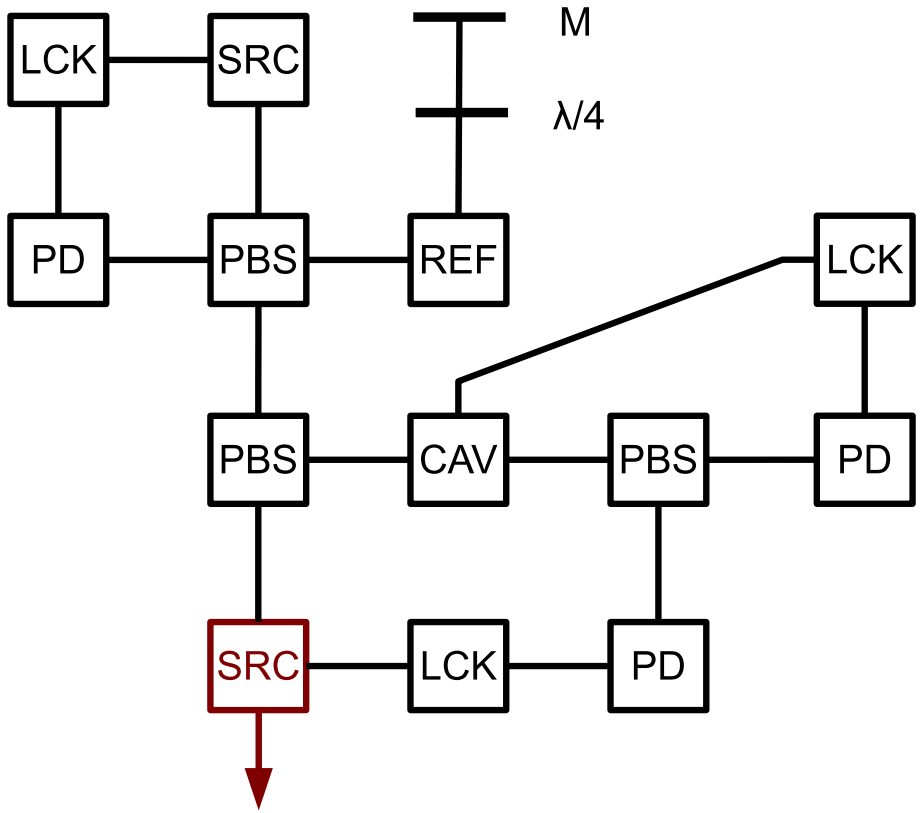


Stable light sources: Transfer cavity

Ring trap: challenges overcome

keep cooling light tightly locked to Rb reference

- employ transfer cavity
  - lock cavity to reference
  - lock sources to be stabilized to cavity



Stable light sources: Wavemeter lock

Ring trap: challenges overcome

for over-saturated transitions, keep frequencies reasonably close to target

- employ software lock on wavemeter with an optical switch
  - lock wavemeter to reference (in stock software)
  - generate and deliver correcting voltages to lasers (PZT, current) to maintain frequency as seen by wavemeter
  - smoothness limited by hardware/software update rates, $\sim$ 100 ms

Experimental control: Waveforms

Ring trap: challenges overcome

generate DC control voltages on up to 96 channels robustly

- implemented with NI chassis and cards
- outdated, proprietary software solution replaced
- new Python based code from scratch
  - transparent, less documentation needed
  - robust
  - scriptable
  - rapid GUI wrapping
  - easy to improve upon

Experimental control: Instrumentation

Ring trap: challenges overcome

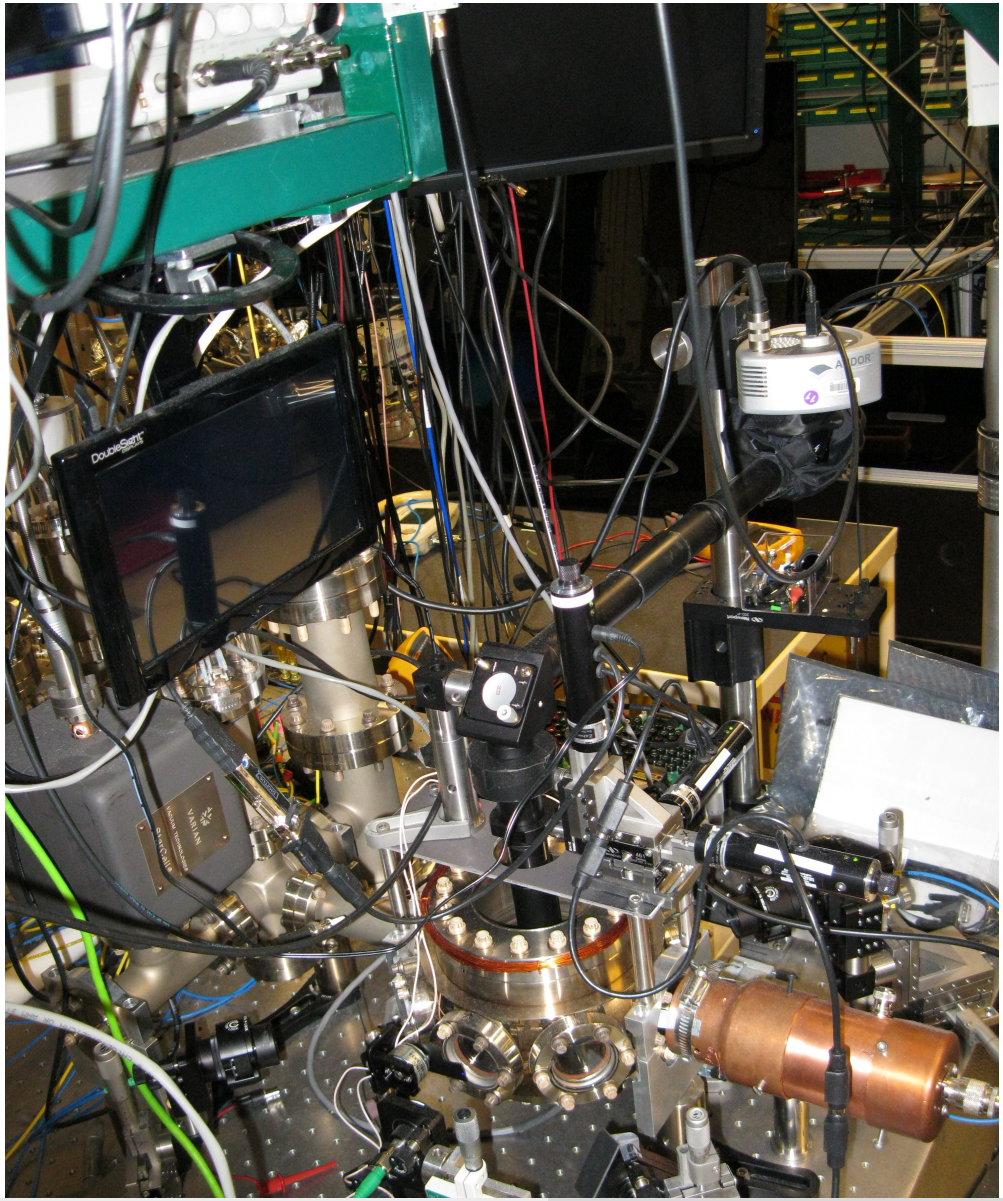
complement the waveform generation suite for a complete experimental control solution

- Python based code from scratch
- implemented for various instruments found in the lab: scopes, function generators, power meters, wavemeter
- provides a framework in which
  - devices communicate
  - measurements are taken and may be monitored
  - data is stored raw and/or analyzed
  - convoluted algorithms can be scripted

Ring trap specific: Experimental setup

Ring trap: challenges overcome

- what
- a
- mess
- !



Ring trap specific: Filters in vacuo

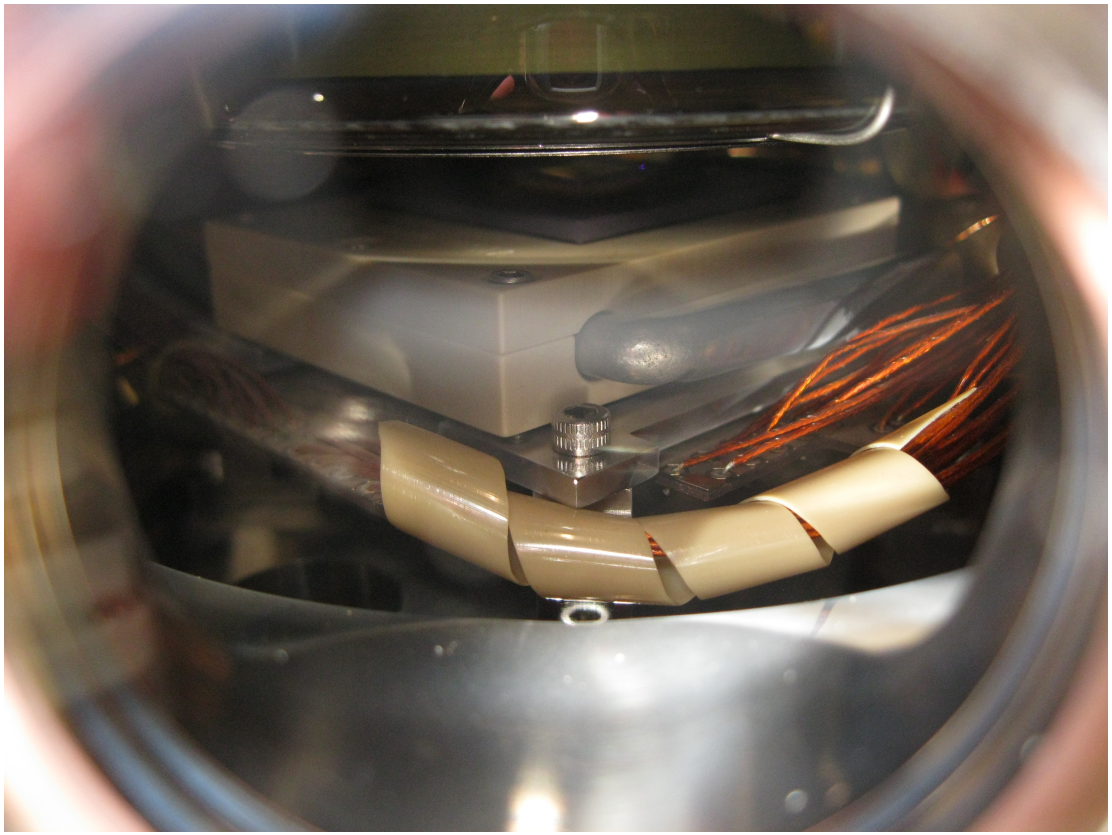
Ring trap: challenges overcome

innovation

- ZIF socket
- low pass filters

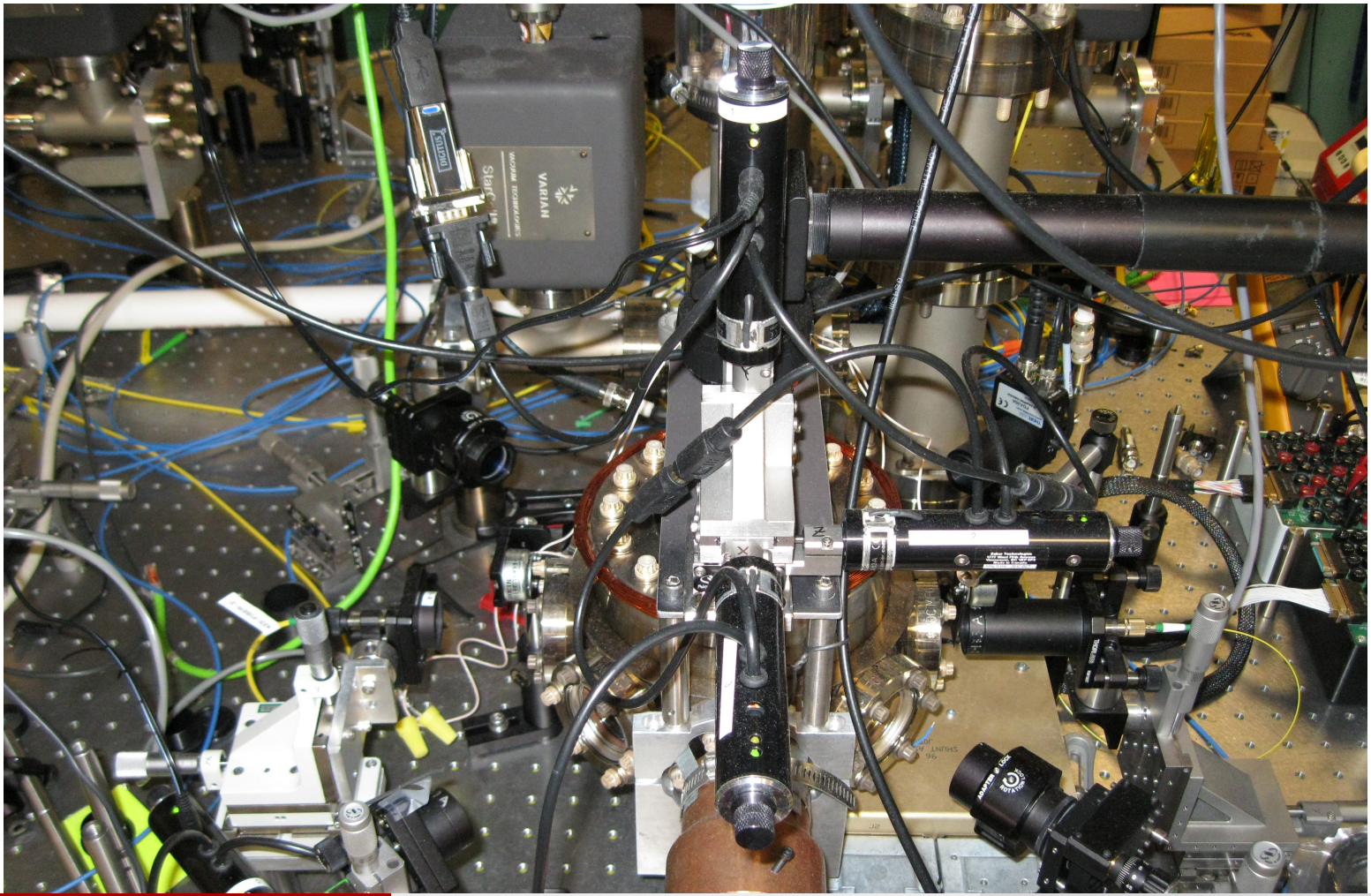
extra layer of uncertainty

- unknown voltages delivered
- unknown local effect on UHV
- unknown improvement



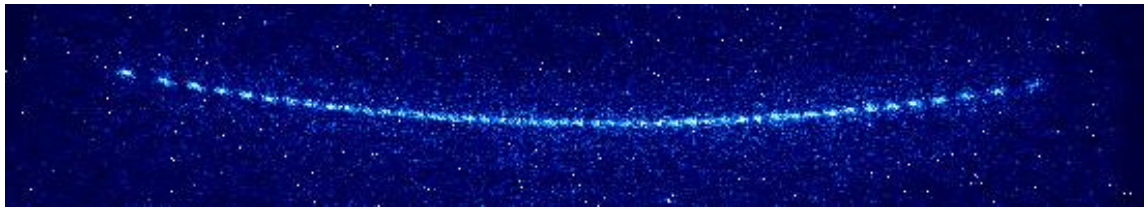
Ring trap specific:
No smart laser placement? Use motors.

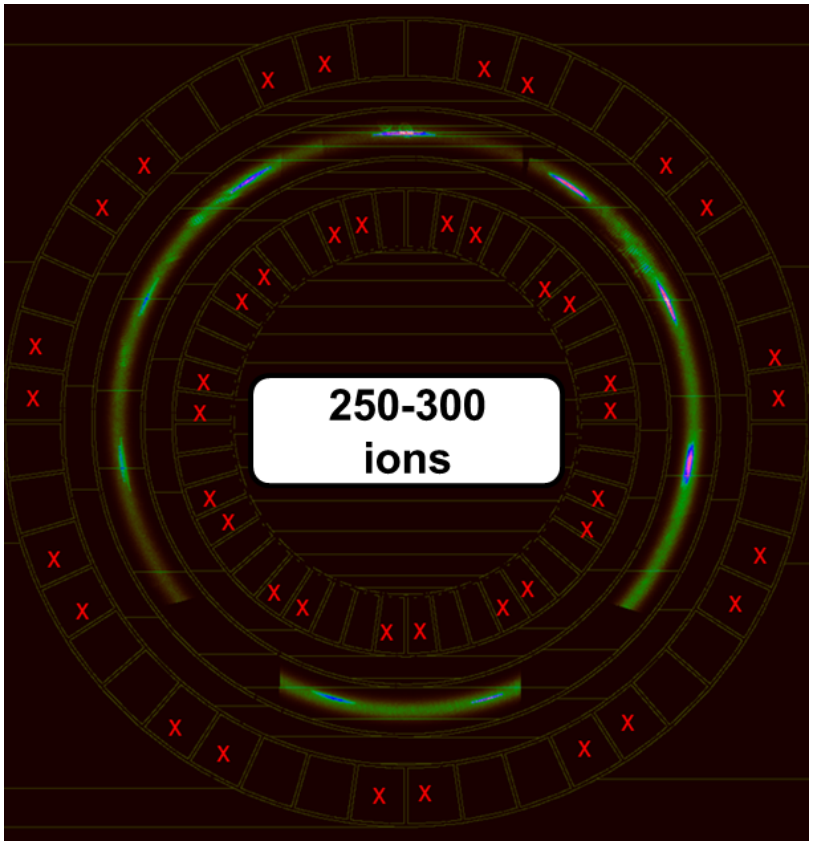
Ring trap: challenges overcome

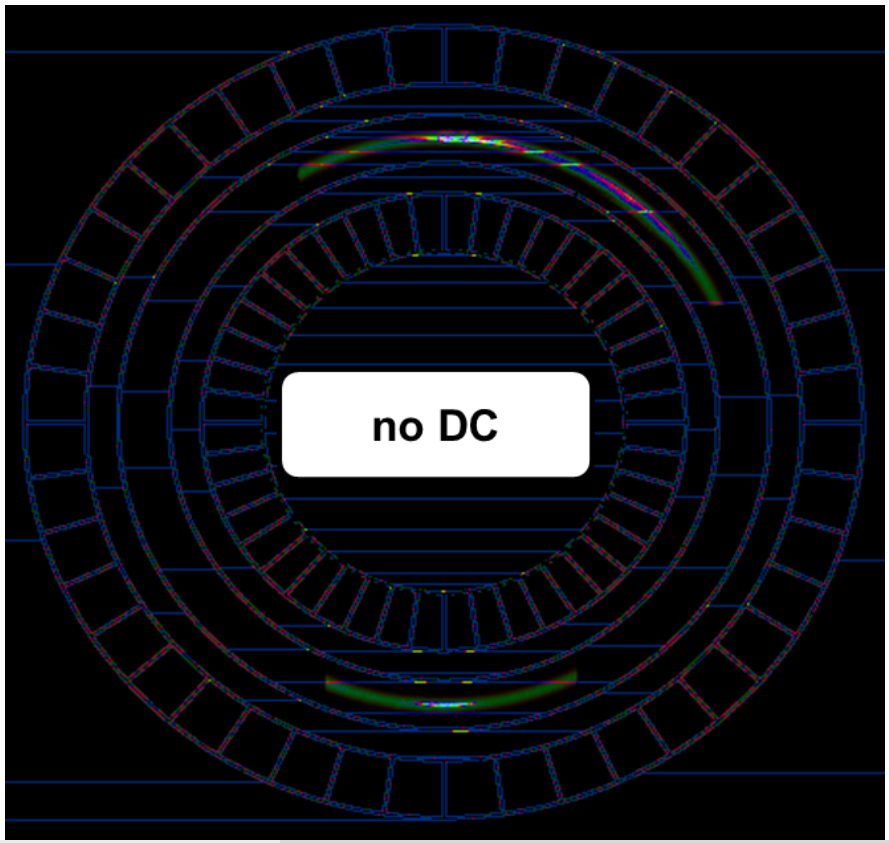


Filling the ring with ions

Ring trap: status

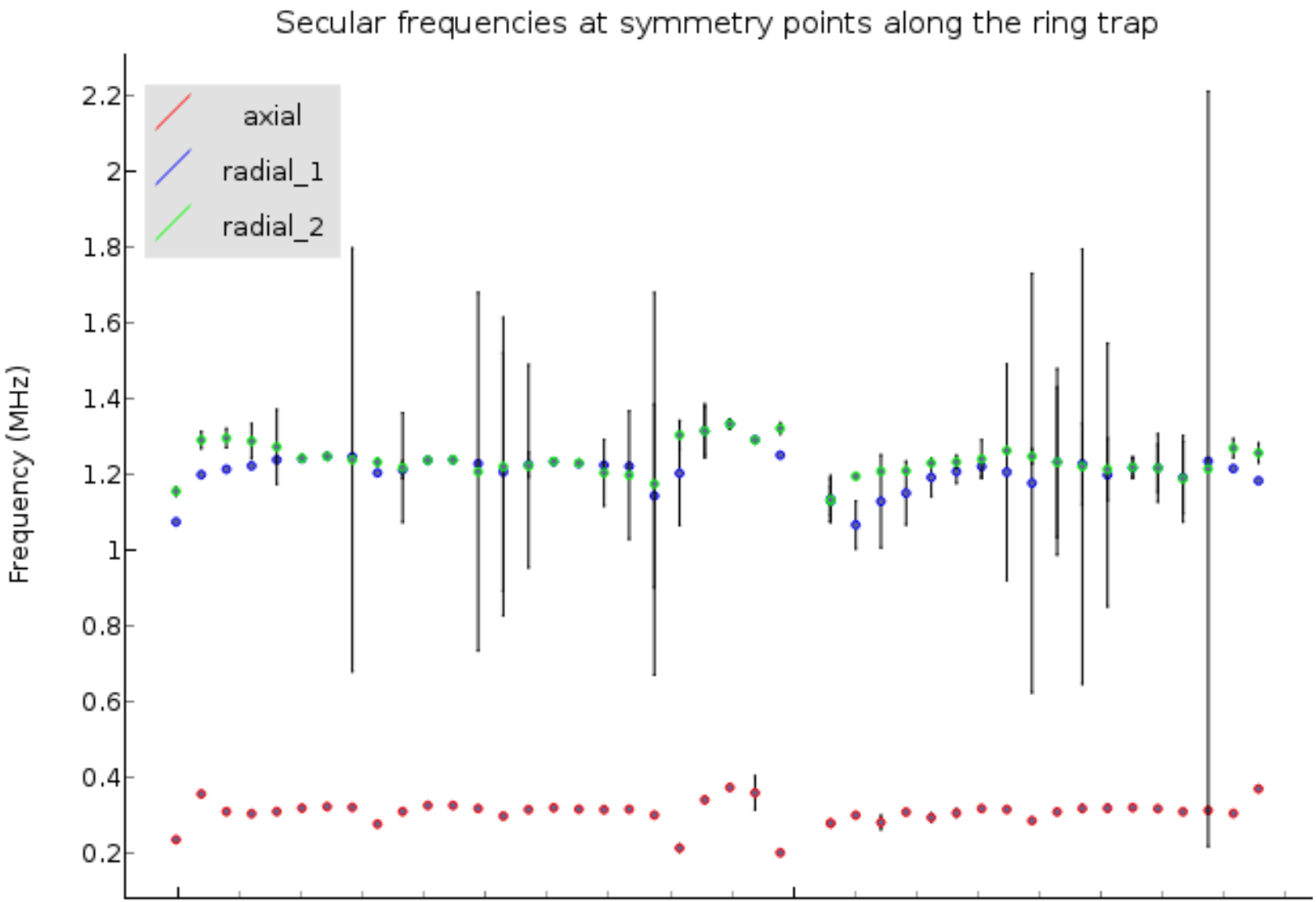






Secular frequencies

Ring trap: status



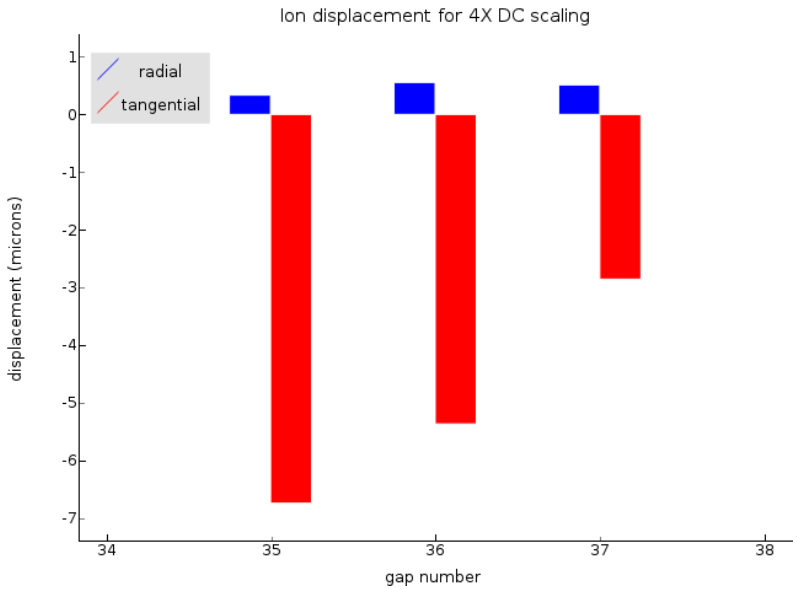
Tangential fields correction: Math

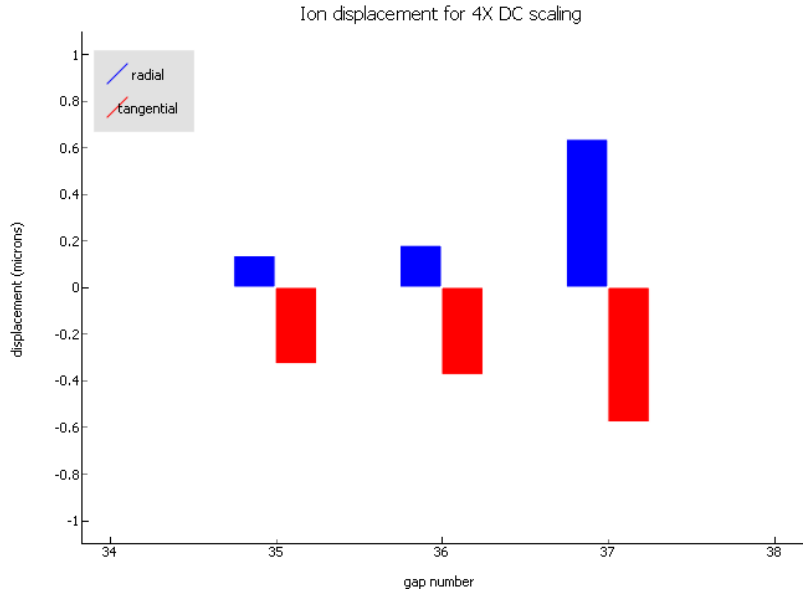
Ring trap: status

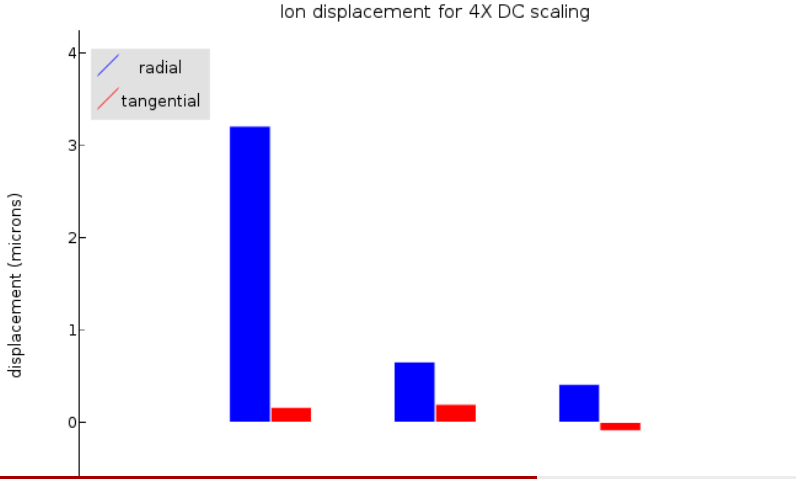
- assume long range fields
- the tangential field seen by an ion is $E_t = \frac{x}{qm\omega^2}$
- measure the secular frequency ω at a number of locations
- scale the DC solution at those locations to infer the displacement x
- assign nonoverlapping set of electrodes that will correct at specific location
- simulate the field due to unit correcting voltage from each source at each correction location
- weigh the correcting voltages so that the correction negates the tangential field

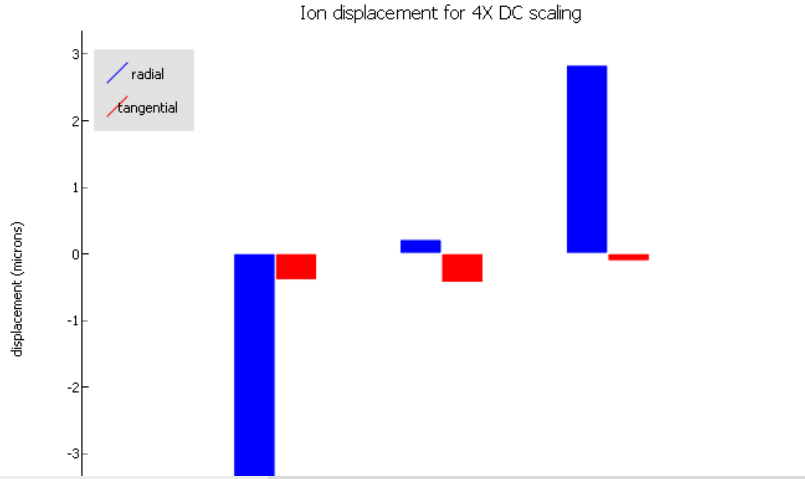
Tangential fields correction: Results

Ring trap: status









The equidistant ion chain

Outlook

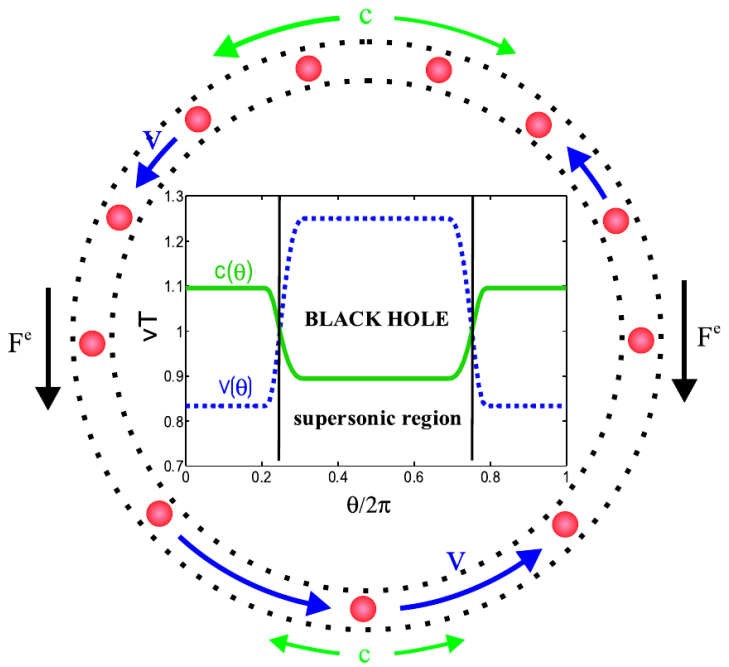
- explore a few more strategies for correcting
- find use for the radial displacement information
- prepare correction for the whole ring
- relax potentials, infer secular frequencies from ion spacing
- publish
- change trap if needed
- improve setup if needed

Beyond quantum simulations: Acoustic black holes

Outlook

B. Horstmann, B. Reznik, S. Fagnocchi, and J. I. Cirac. *Hawking Radiation from an Acoustic Black Hole on an Ion Ring* . DOI: 10.1103/PhysRevLett.104.250403

- $\sim$ 1 in 200 000 force resolution

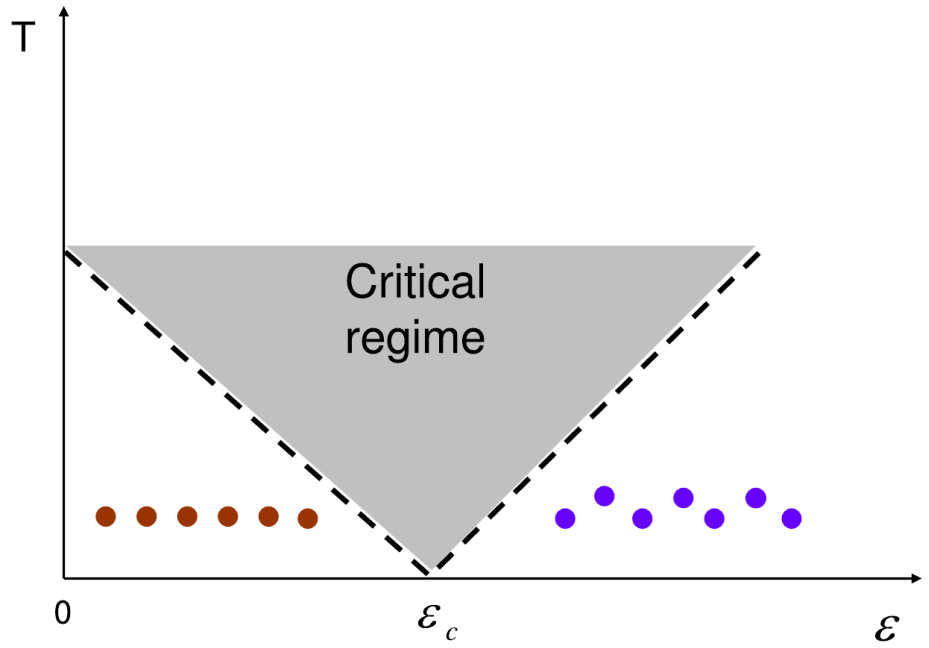


Beyond quantum simulations: Quantum phase transitions

Outlook

E. Shimshoni, G. Morigi, and S. Fishman. *Quantum Zigzag Transition in Ion Chains* . DOI: 10.1103/PhysRevLett.106.010401

- $\sim$ 1 Hz frequency resolution
- $\sim$ 1 μK temperature



Beyond quantum simulations: If it doesn't work...

Outlook

Look for experiment that is less technologically demanding

Acknowledgments

At UNM: administrative staff and faculty
Elsewhere: Hartmut Häffner, David Moehring
At SNL: Matthew Blain, Kevin Fortier, Francisco Benito, Craig Clark, Mike Descour, Ray Haltli, Jon Sterk, Chris Tigges, Peter Maunz, Dan Stick
At home: Katia, Kossara, and Koubrat

This work is part of the Multi-Qubit Coherent Operations (MQCO) program supported by the Intelligence Advanced Research Projects Activity (IARPA).

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the US Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.