Optical Optimization of Ion-Trapping Apparatus

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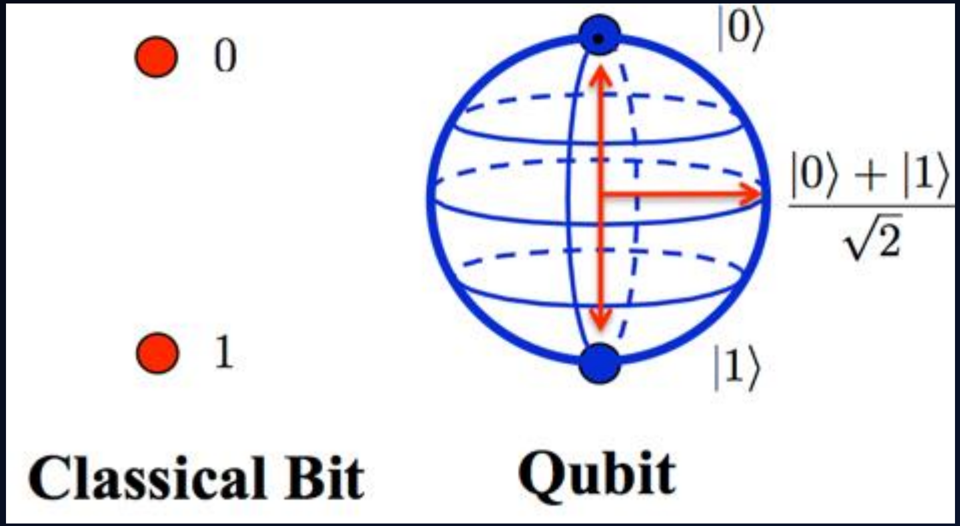
Outline

- Background
  - Overview of quantum computing
- Experiment & Apparatus
  - Ion Trapping
- My Project
  - Imaging the trapped ions with an objective lens setup

Overview of Quantum Computers

- Instead of binary bits, QC's run on Qubits
- Qubits obey exploit two principles of quantum mechanics:
  - 1) superposition – can be 0, 1, or both
  - 2) entanglement – states of two different qubits can be correlated

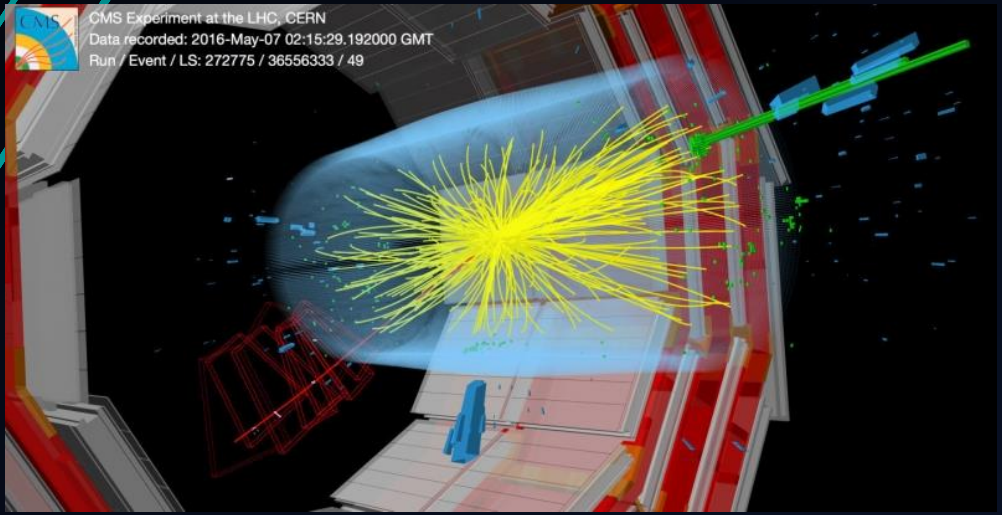


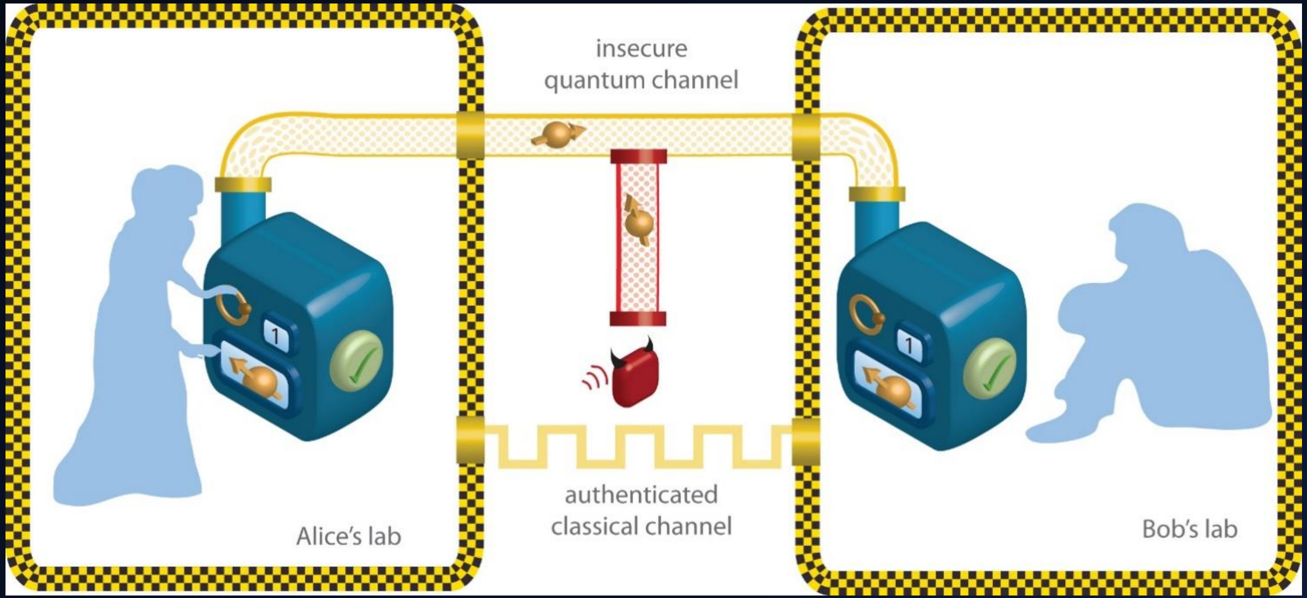
http://qoqms.phys.strath.ac.uk/research_qc.html

Quantum Computing Applications

- Ability to model quantum systems
  - Such as high-Tc superconductors
- Better searching algorithms
- Cryptography, factorization of large numbers

LEFT: Proton-proton collision from LHC. Take from https://home.cern/about/updates/2016/05/2016-physics-season-starts-lhc-0
RIGHT: Diagram of how encrypted communication would work. Taken from http://cdn.phys.org/newman/gfx/news/hires/2013/justhowsecur.jpg





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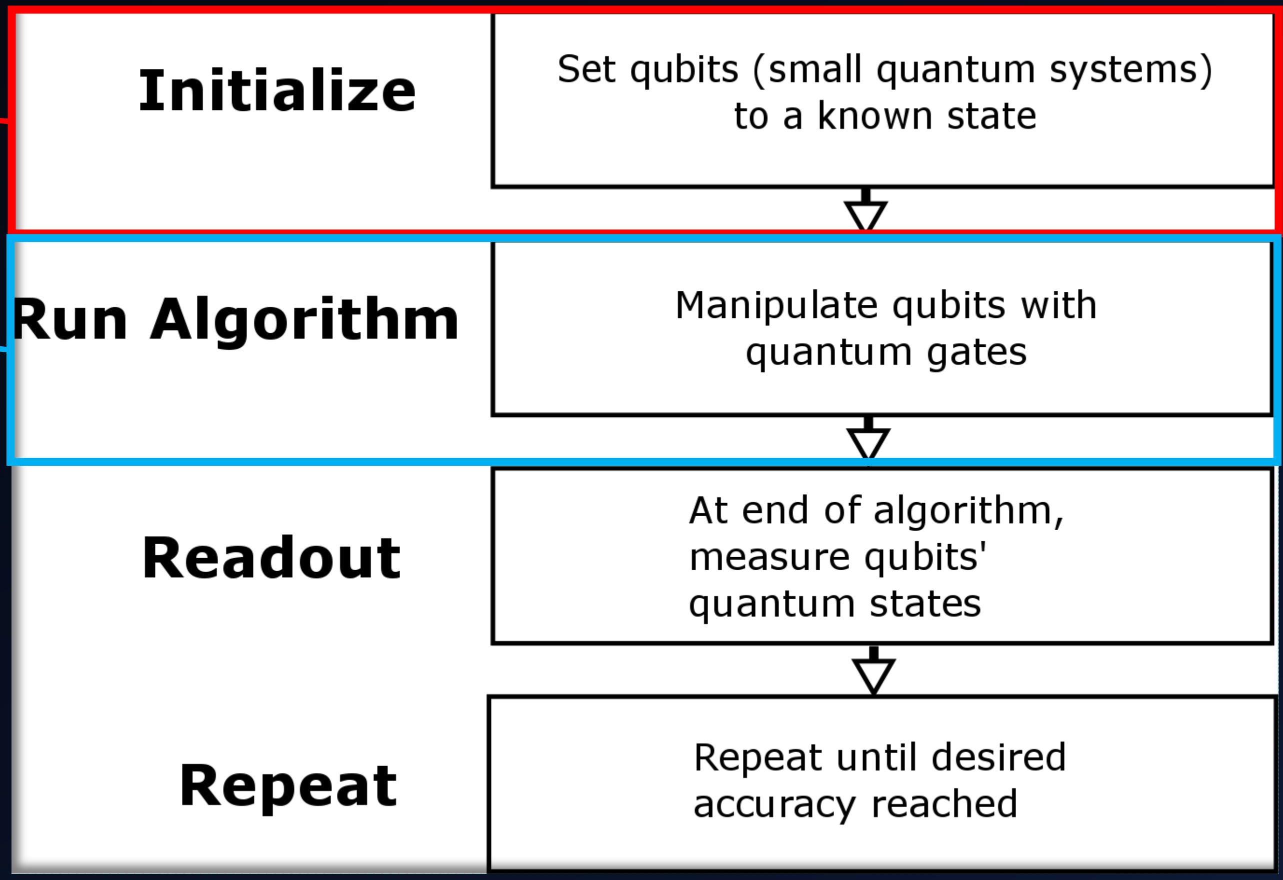
Quantum Computer Runtime

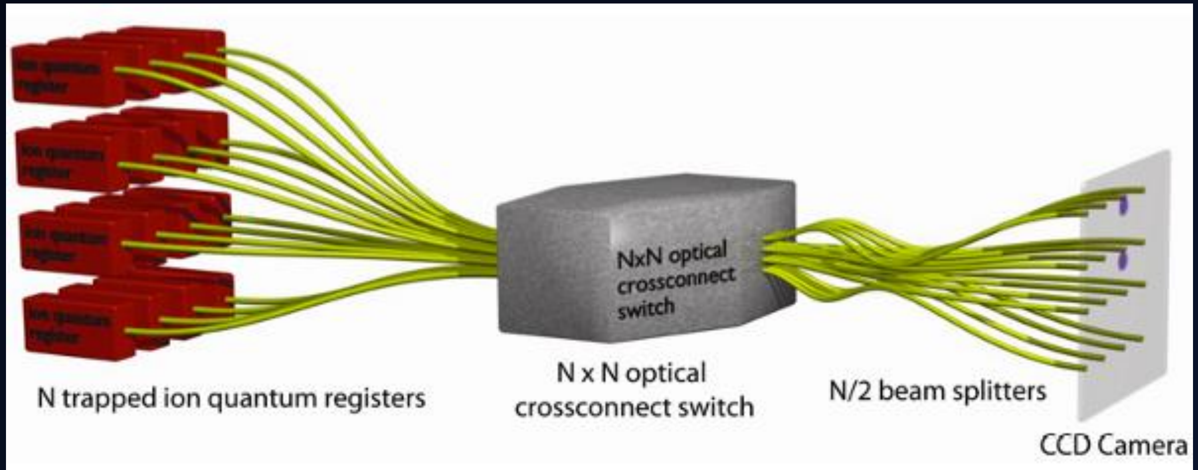
Initialize spin at ground state of ion

Change of states = Energy transitions driven by lasers



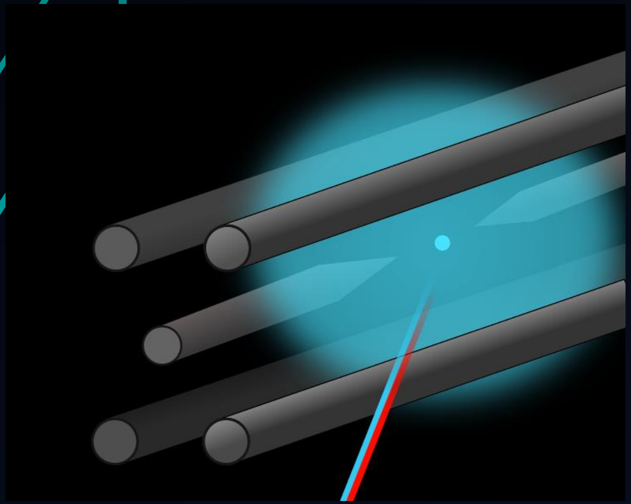
Why Trapped Ions?

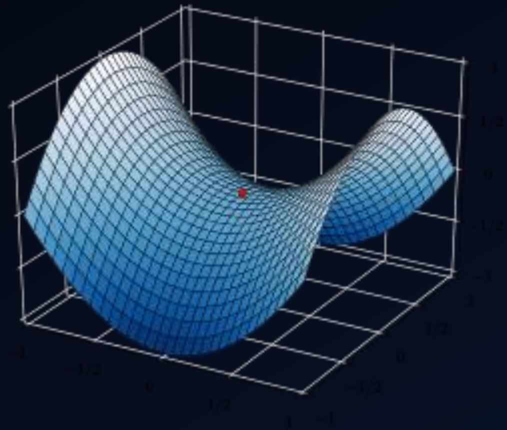
- Advantages:
  - Ions isolated in vacuum chamber
    - Long coherence times
  - Short operation times from quantum gates (microseconds)
  - Basic requirements of quantum computation have been demonstrated
- Disadvantages:
  - Scalability; difficulty increases with more qubits

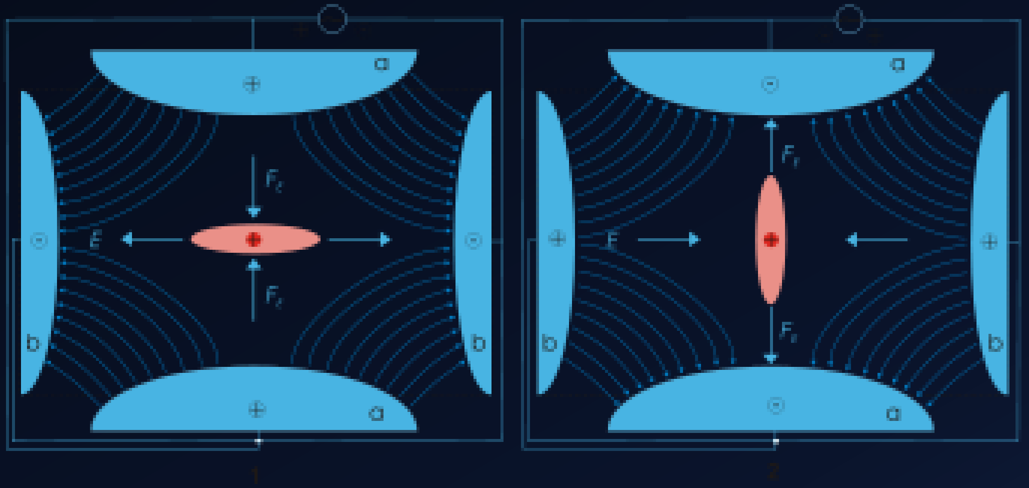


Realizing the Trapped-Ion Computer

- Use ions as qubits
- Ion Traps
  - radio frequency and DC voltages form “oscillating saddlepoints”







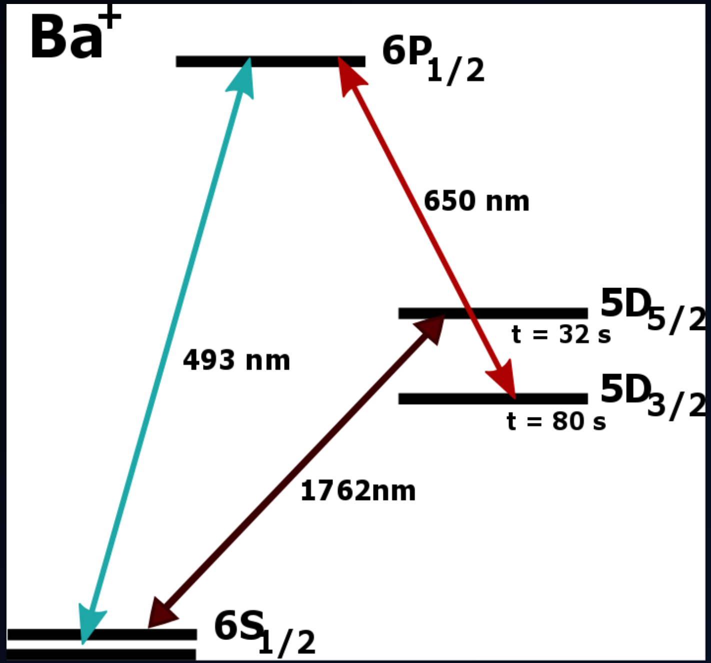
Trapping Using Ba+ 138 and Yb+ 171

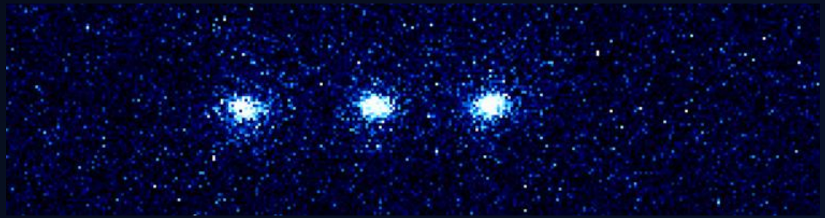
BA+ 138

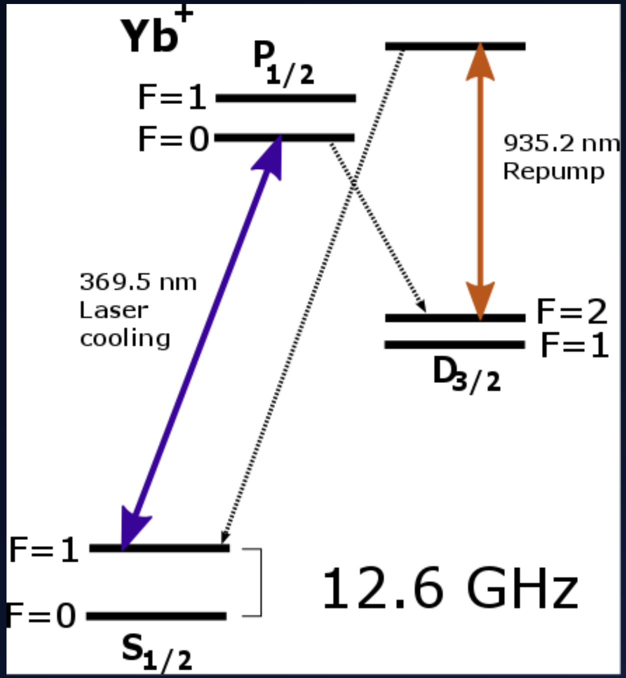
- Transitions in visible light spectra

YB+ 171

- Yb: initialization, readout, coherence time





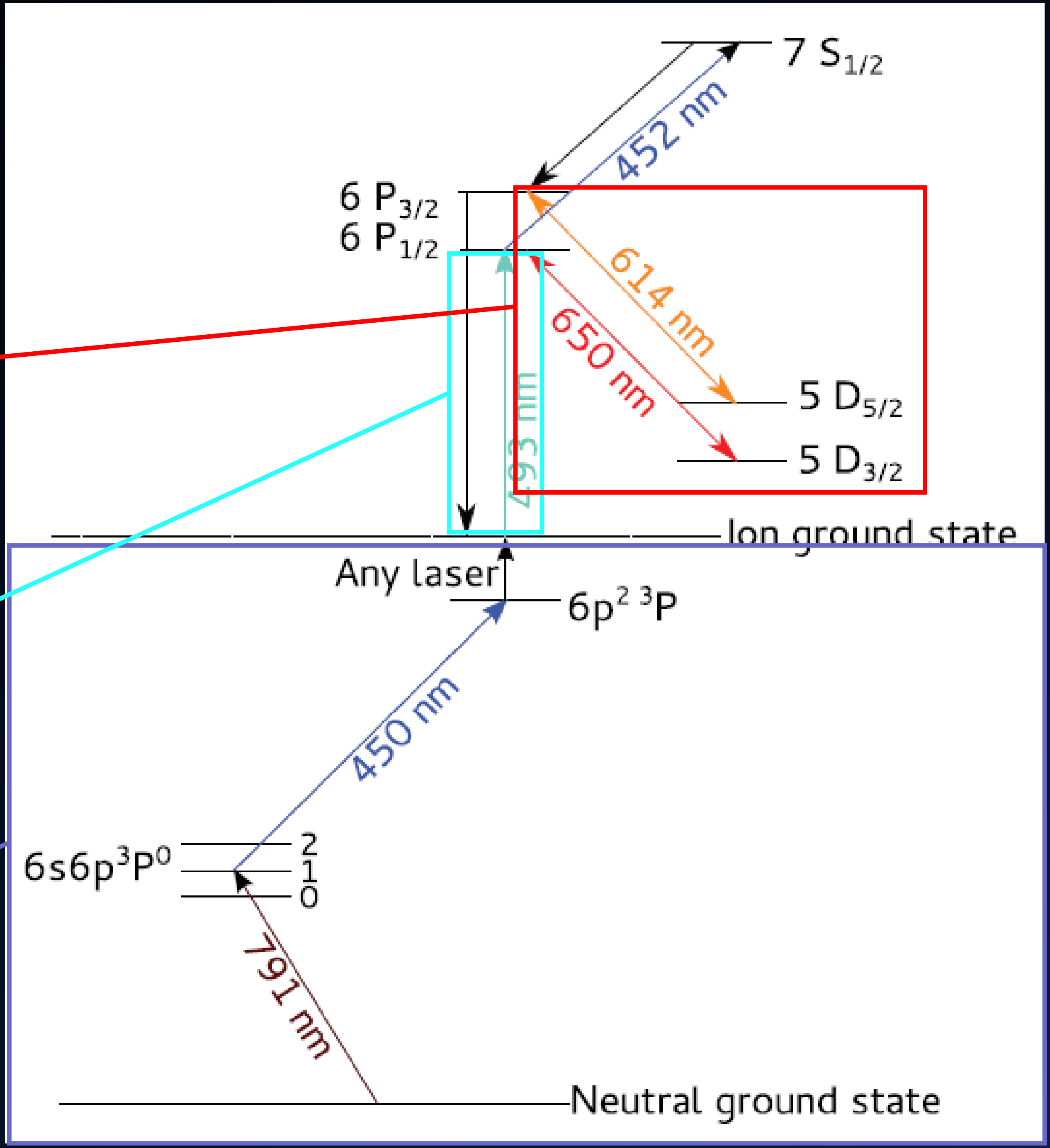


Shelving: pump ions that transition to 5 D states back to 6 P states using 614 and 650 nm lasers

493 nm laser is shined at ground state ion (Doppler cooling), transition to 6 P state

791 nm laser drives transition to ion ground state

450 nm UV flash completes ionization phase



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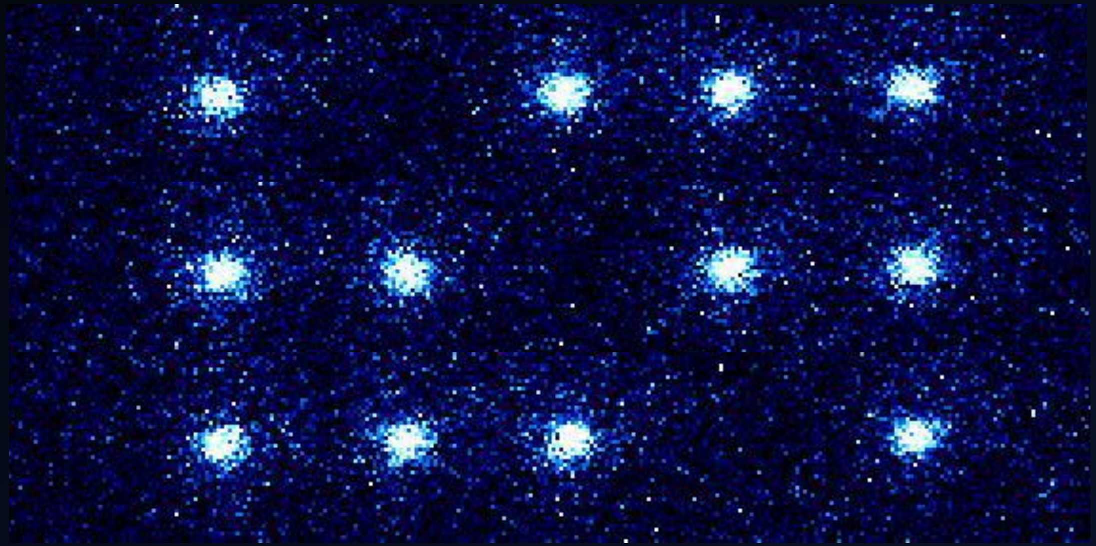
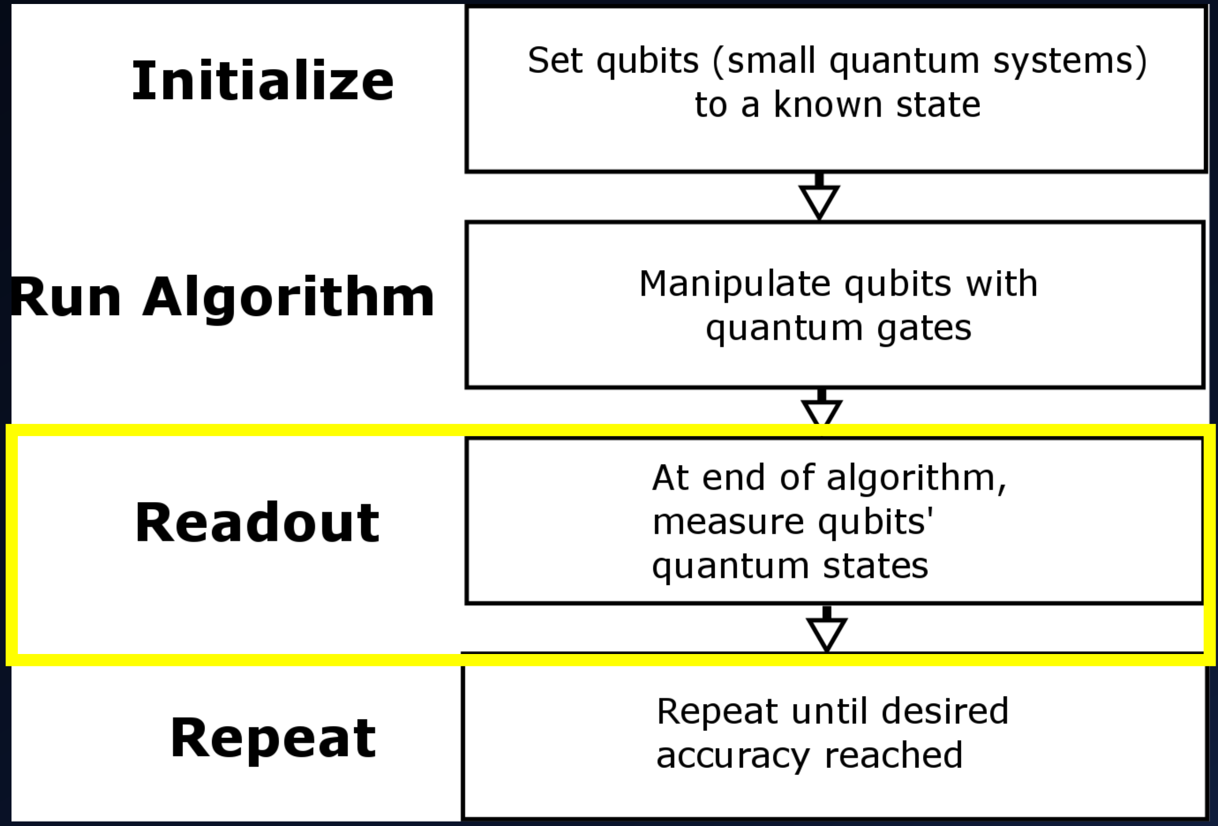
Trapped Ion Imaging

- Qubit/ion states get read out as image captured by camera after quantum gate transformations
  - 0 = “bright” ion
  - 1 = “dark” ion





Trapped Ion Imaging

- Problem: Imaging system wasn't collecting a lot of light
  - Formed bad images
- Solution: Simulate and implement the optimal lens setup
  - Need to find following:
    - Which lenses to use
    - Optimal distance between ion and objective lens

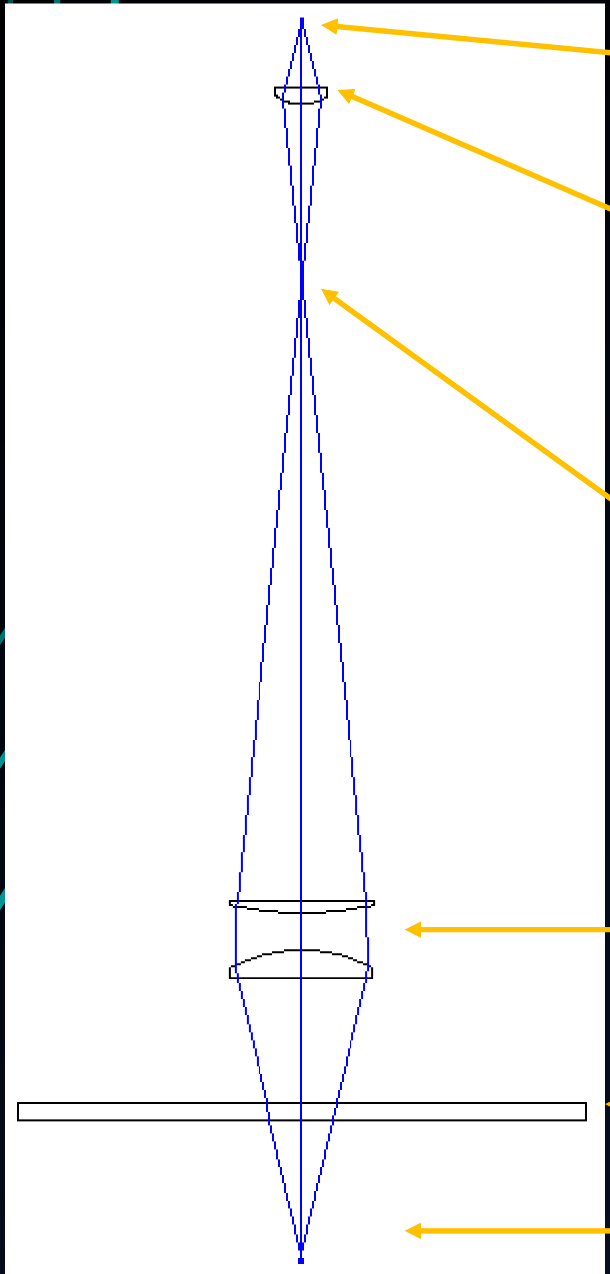


Image captured by camera

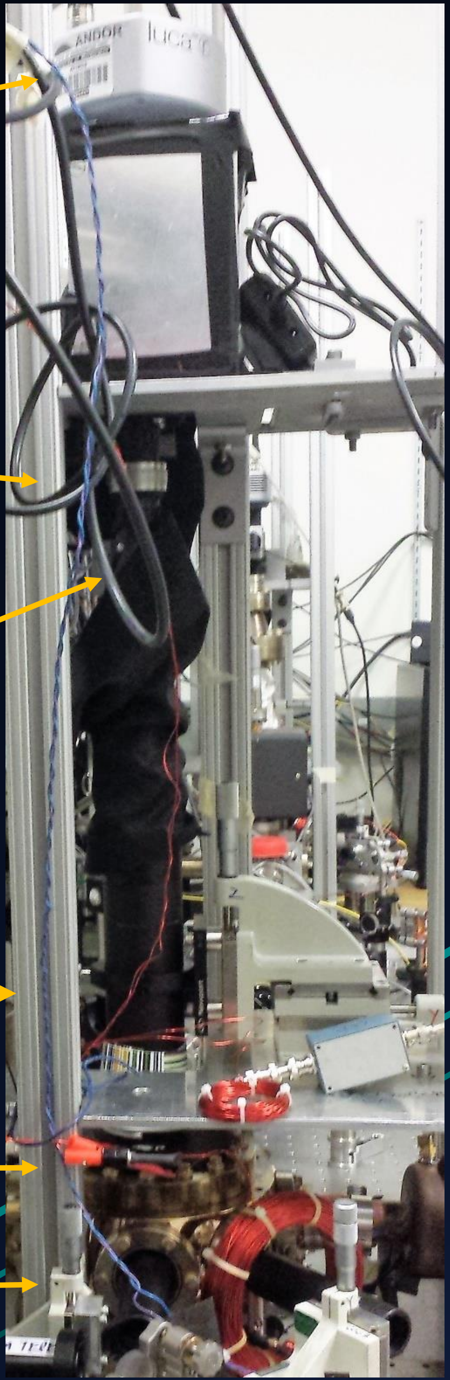
Secondary lens

Magnified Image formed by objective lens

Objective lens setup: aspherical lens on bottom, plano-convex on top

Vacuum viewport

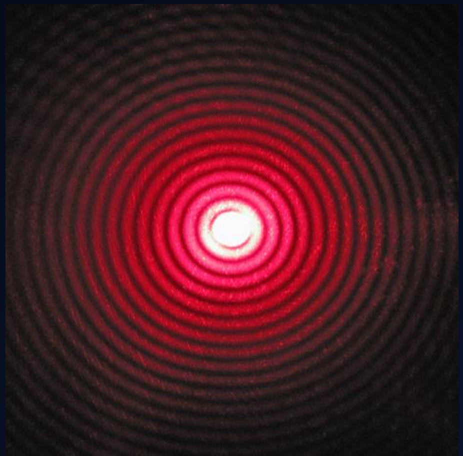
Ion



Measuring Effectiveness

POINT SPREAD FUNCTION

- Diffraction image of point object
- i.e. an intensity distribution of focal point

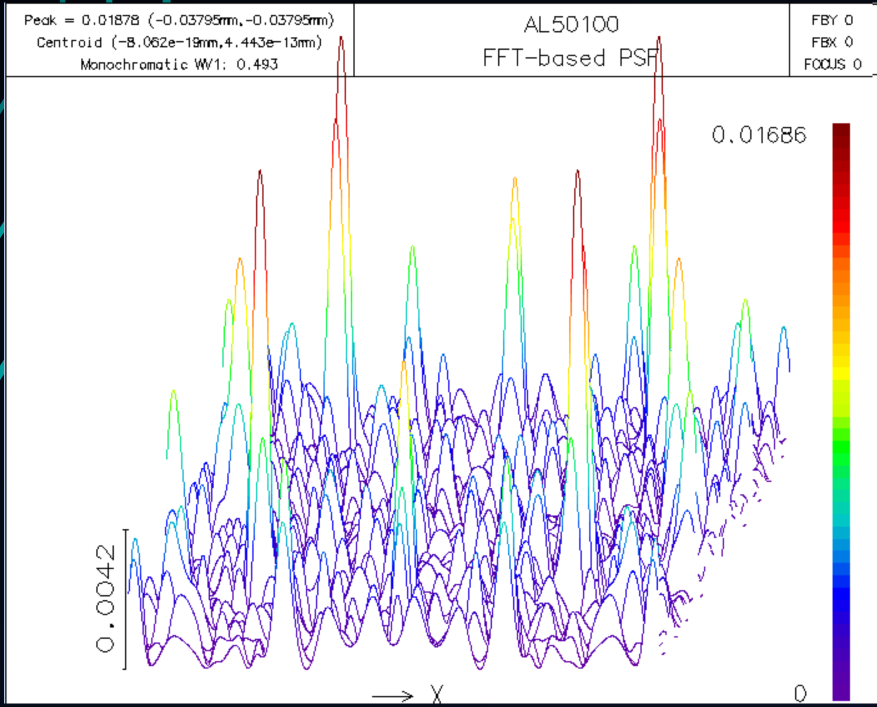


ENSQUARED ENERGY

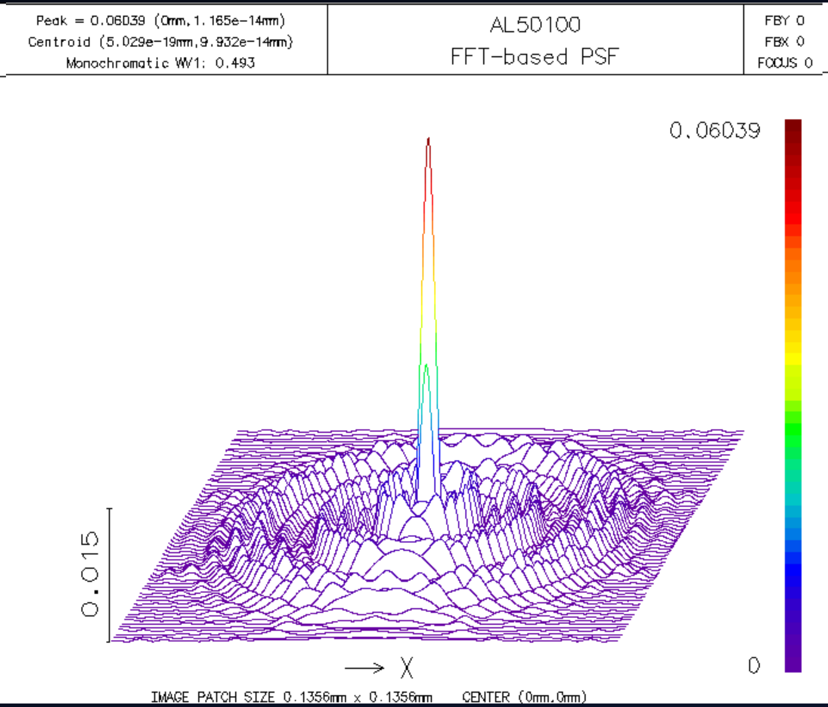
- Uses PSF to measure energy
- Fraction of energy concentrated in a spot as a function of how big that spot is

Point Spread Function

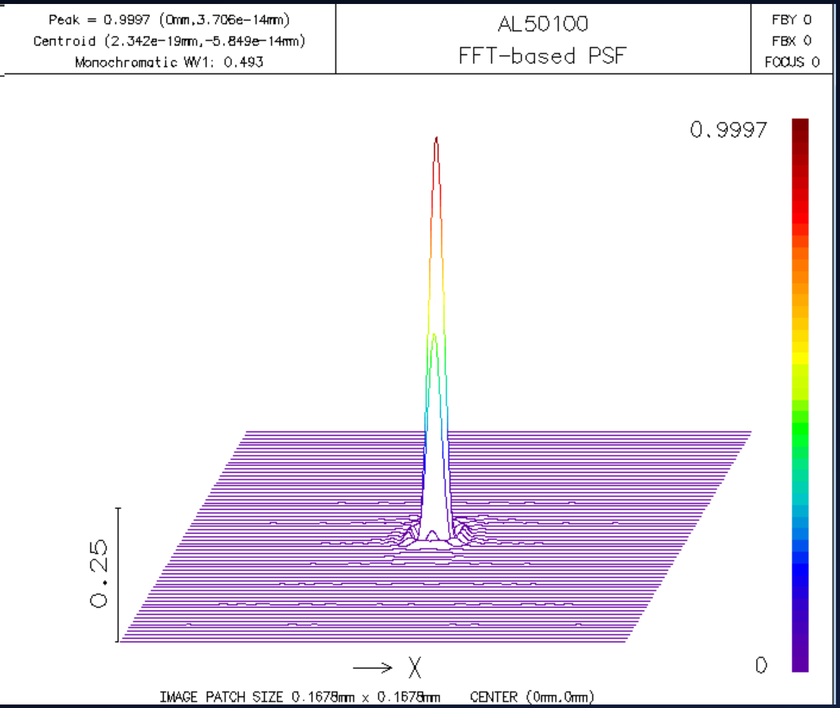
ORIGINAL PLANO-CONVEX SETUP



INITIAL POSITION OF NEW SETUP

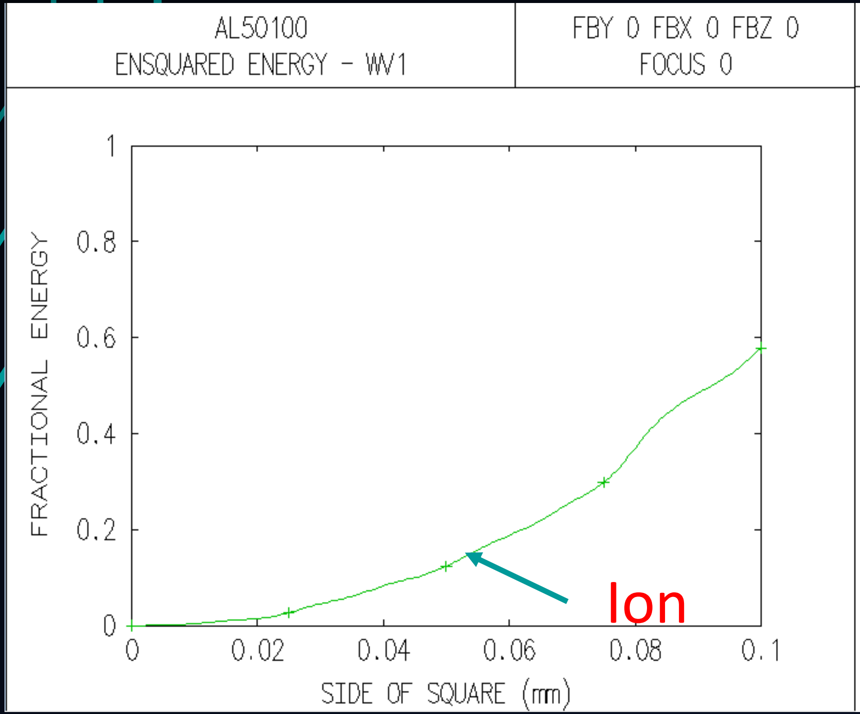


OPTIMAL



Ensquared Energy

ORIGINAL PLANO-CONVEX SETUP



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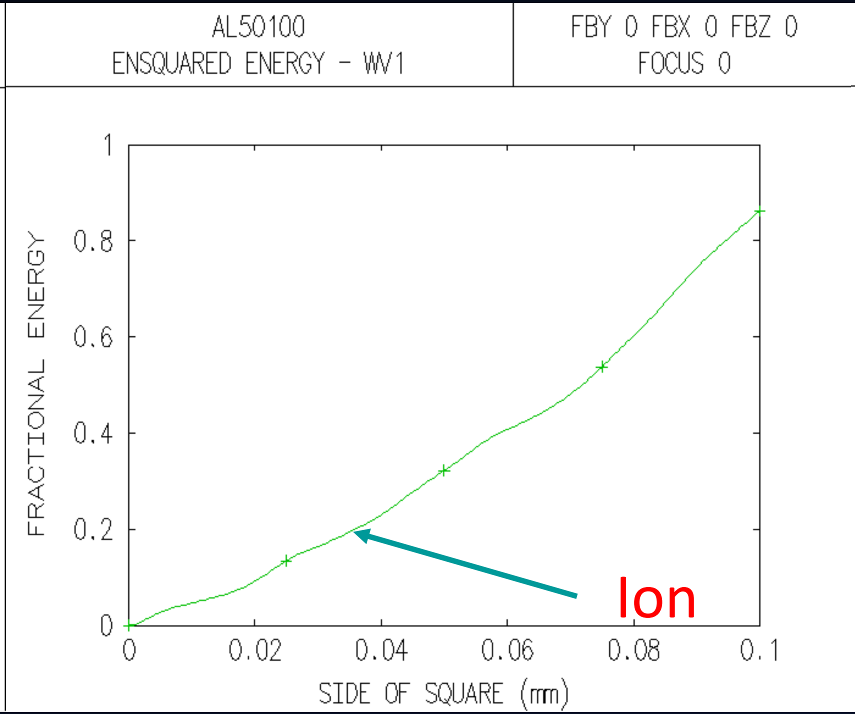

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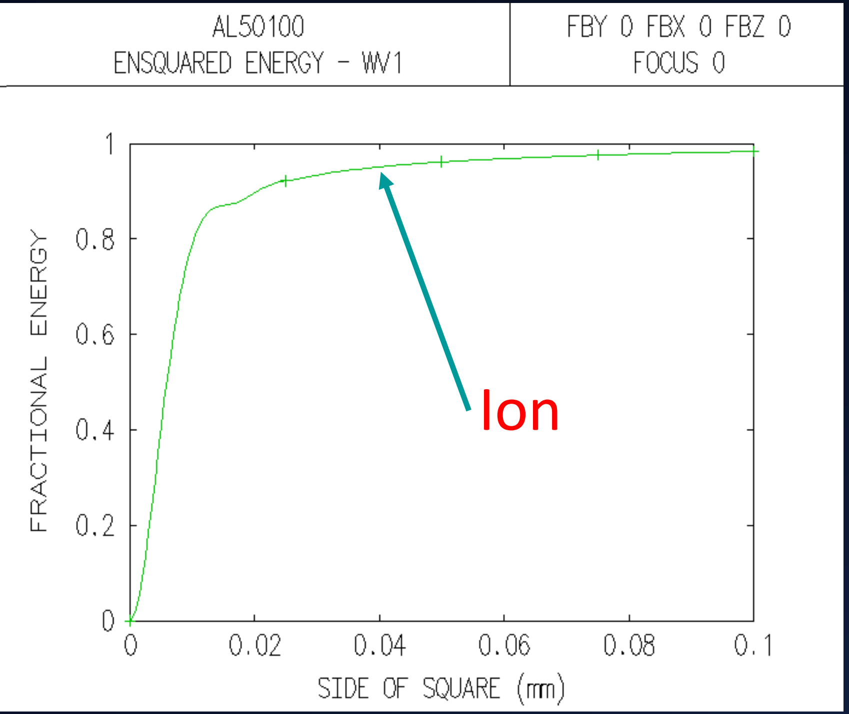
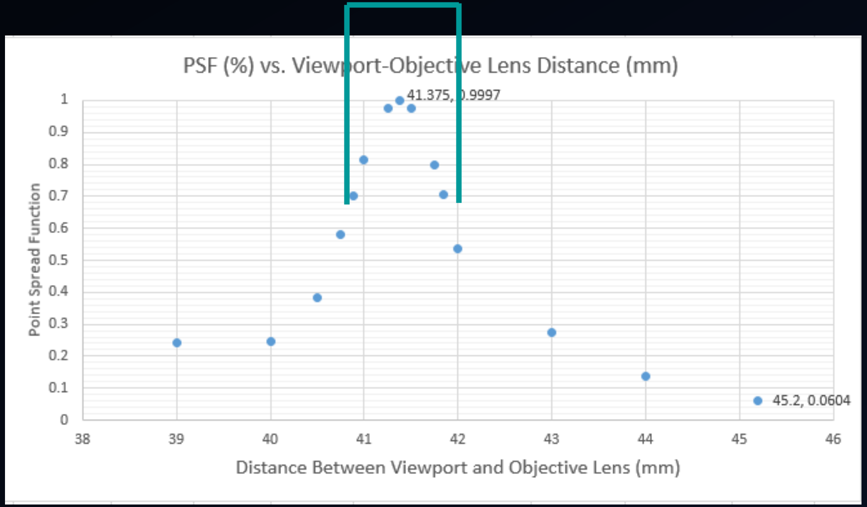


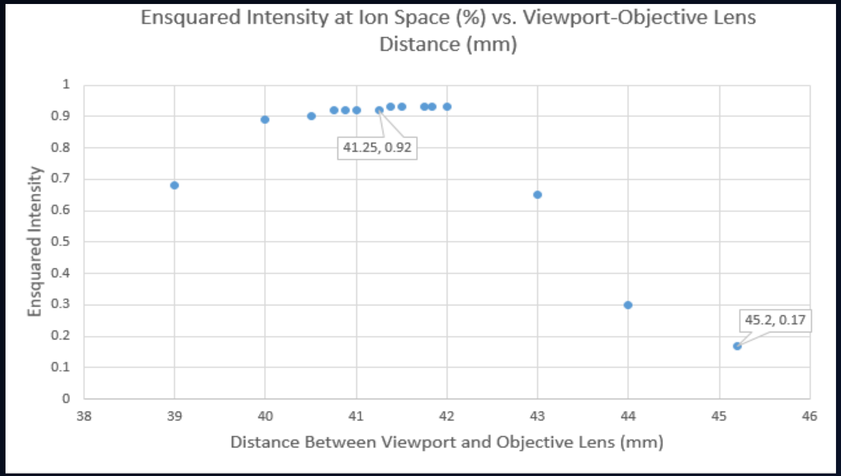
Very Little Room for Error!

Viewport-Objective lens distance error

~1 mm spacing for >70%

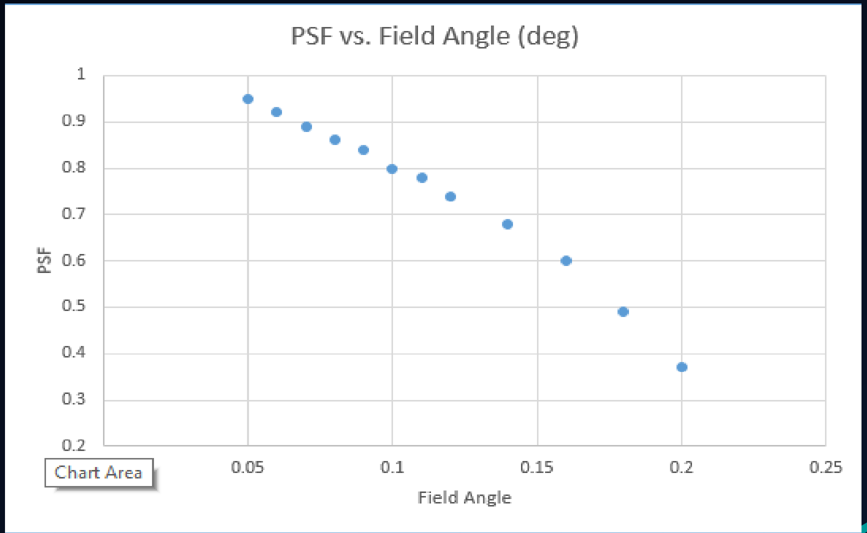


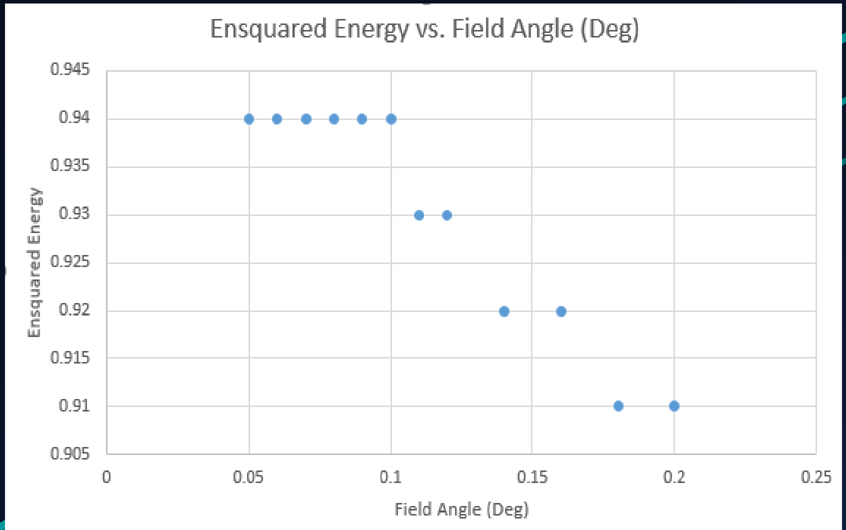
~2 mm spacing for >90%



Ion-lens misalignment error (comatic aberration)

Steady drop-off after 0.05 degrees of misalignment





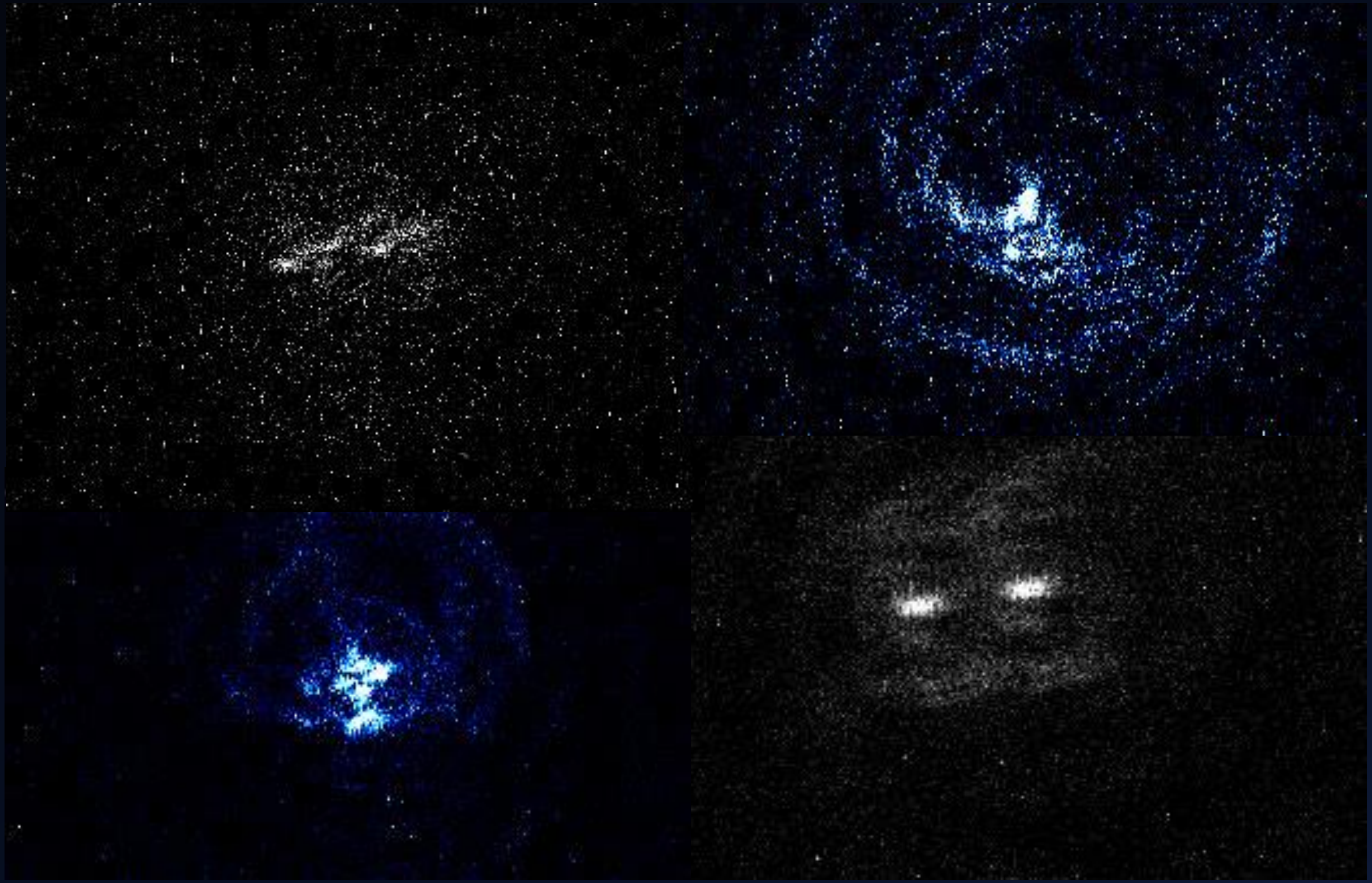
Results

Top left: OL at the wrong working distance

Top right: OL near the working distance, before adjusting for comatic aberration

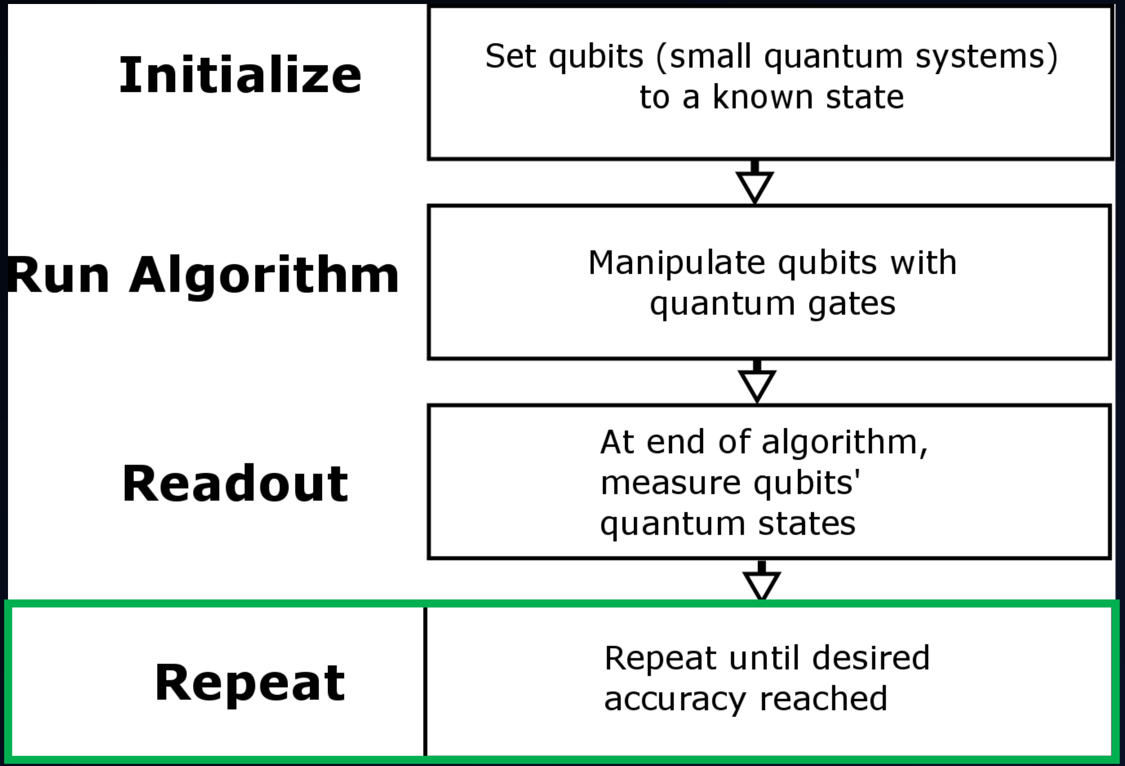
Bottom left: 1st adjustment attempt at adjusting to working distance

Bottom right: OL at the right working distance, partially adjusting for comatic aberration



Future Work

- Measurements are inherently probabilistic
  - Keep making measurements until accurate



Thank you!

References

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Scalability

Method: many ion traps, coupled by photons
Use two kinds of ions- 138 Ba^+ and 171 Yb^+

“Qubit” ion vs “Cooling/ Entangling” ion