SAND2012-1263C

Magnetic field gradient effects on a trapped ion frequency standard

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Sandia National Laboratories and Jet Propulsion Laboratory

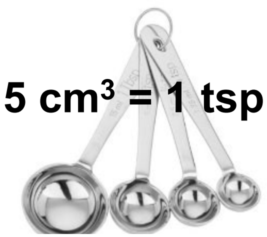
IMPACT project:
Goal: highly stable, miniature frequency standard

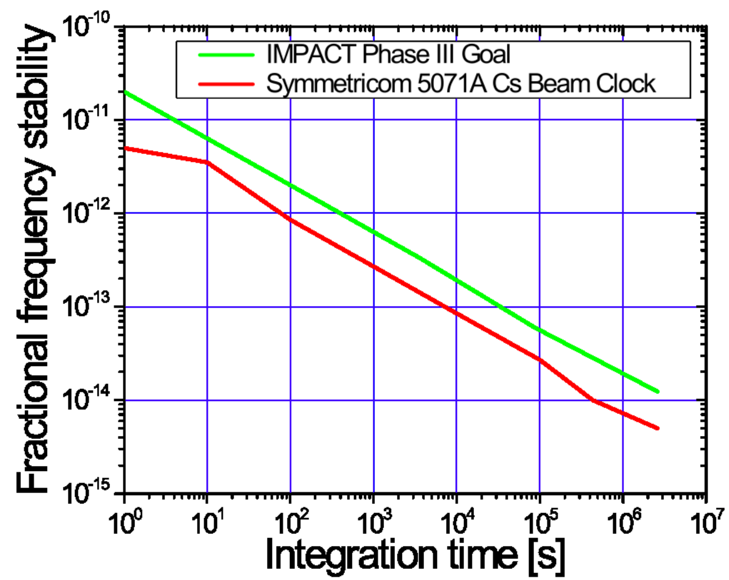
- Integrated Micro Primary Atomic Clock Technology (IMPACT)
- Achieve Cs Beam Clock performance in an extremely small and low power package
- (5 cm^3 and 50 mW)
- Applications--Excellent timing for:
- Satellites
- Rapid acquisition of GPS signal
- Pulsed radio and spread spectrum communications

Symmetricom 5071A

Miniature primary frequency standard

5 cm^3 = 1 tsp.





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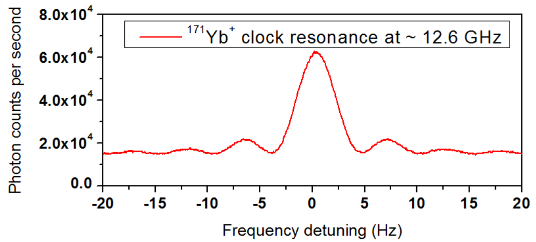
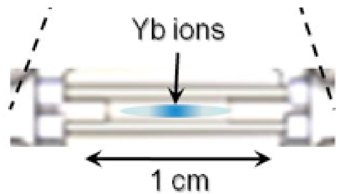
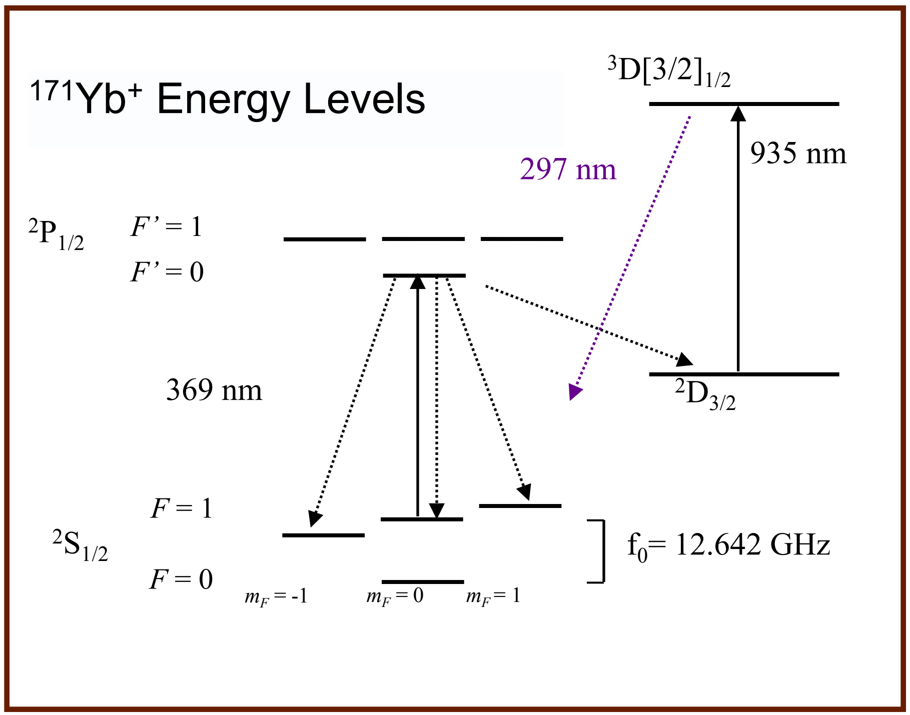
$^{171}Yb^{+}$ Ion Clock







- Our focus:
  - building & demonstrating validity of small ion trap in a small vacuum "cell"
  - exploring and mitigating the effects of our miniaturization on long-term clock stability
- Ions for a clock
  - Vacuum is more forgiving
  - Ions are very isolated – long lifetime
  - Electrical feedthroughs to inside of vacuum

IMPACT phases

- phase I : proof of principle
  - proved components, particularly small ion trap
  - make portable clock
- phase II : miniaturization / improve performance
  - shrink components / start to integrate
  - deliver working clock
- phase III : further miniaturization / best performance

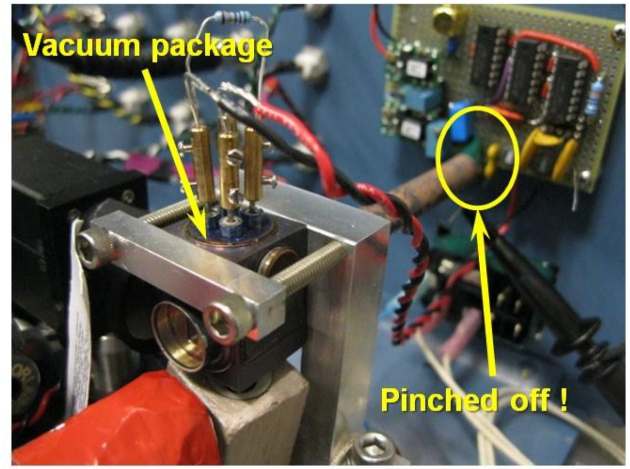
Performance of JPL Phase-I Package

phase I

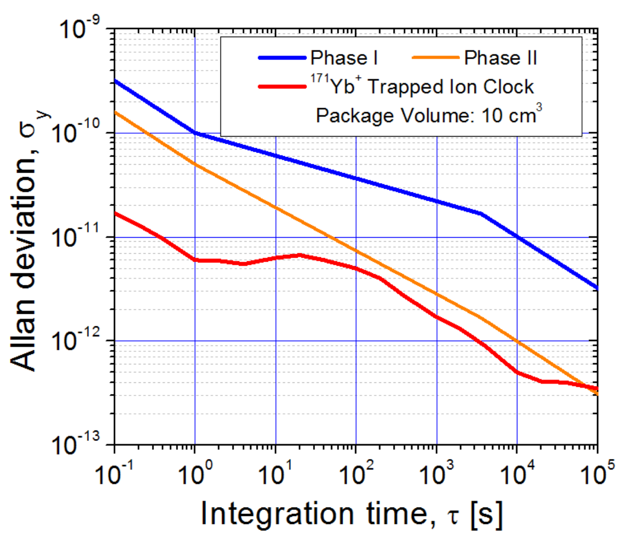
phase II

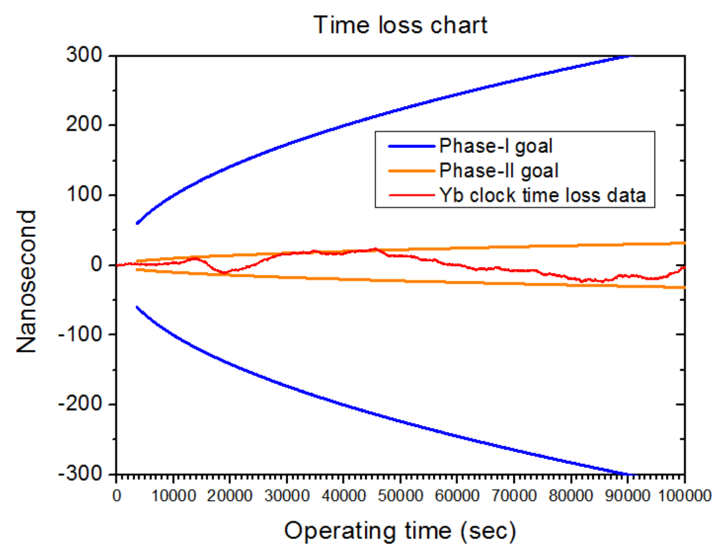
phase III

10 cm^3 Vacuum Package
Constructed by JPL



10 c.c. package in a portable demo box





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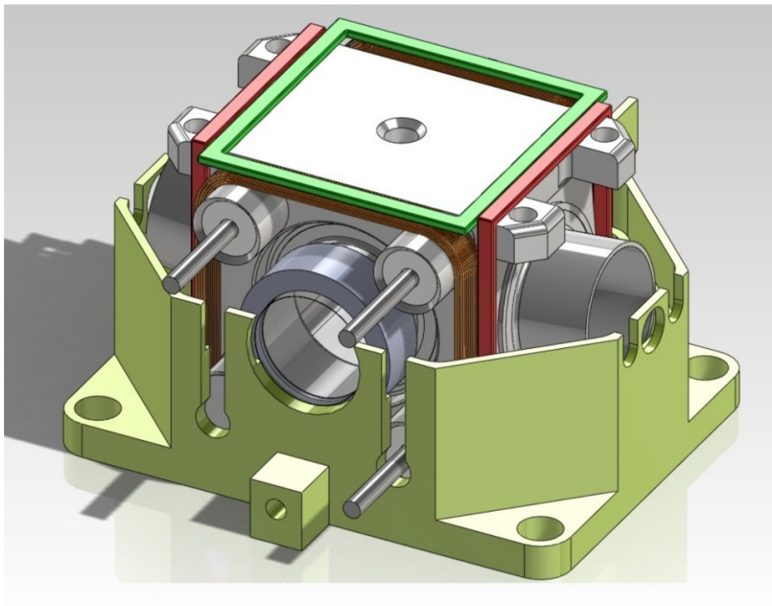
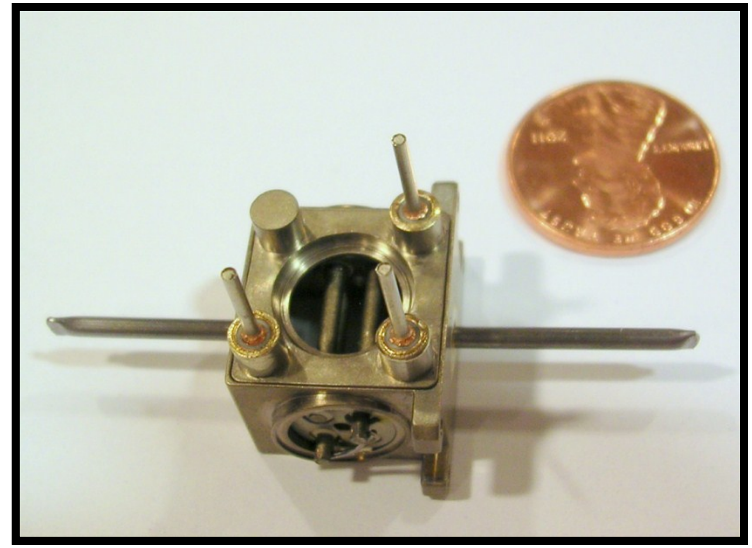
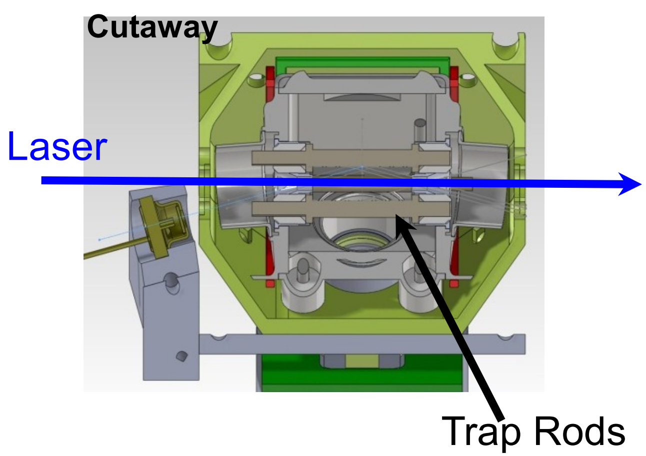
JPL-designed phase II metal package

phase II

phase III





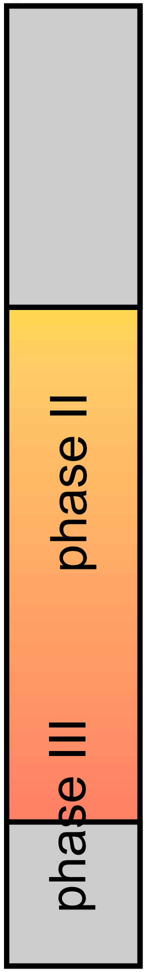


For demonstration of a complete portable clock

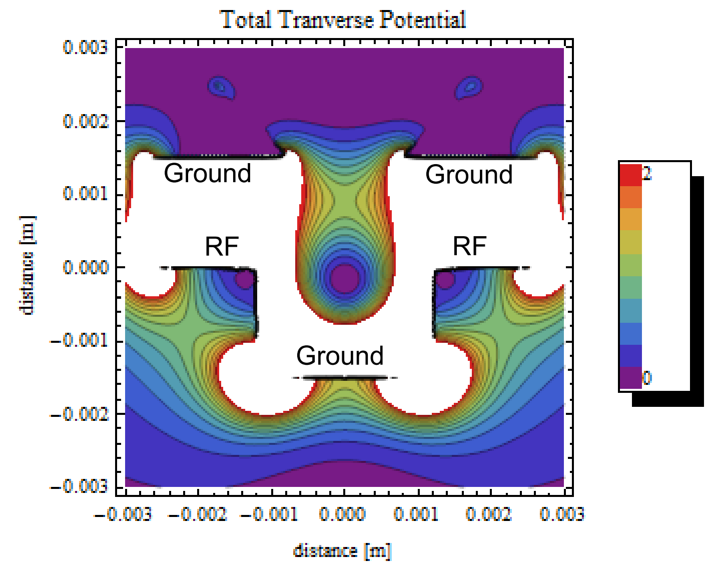
Smaller sealed Titanium package - all nonmagnetic materials

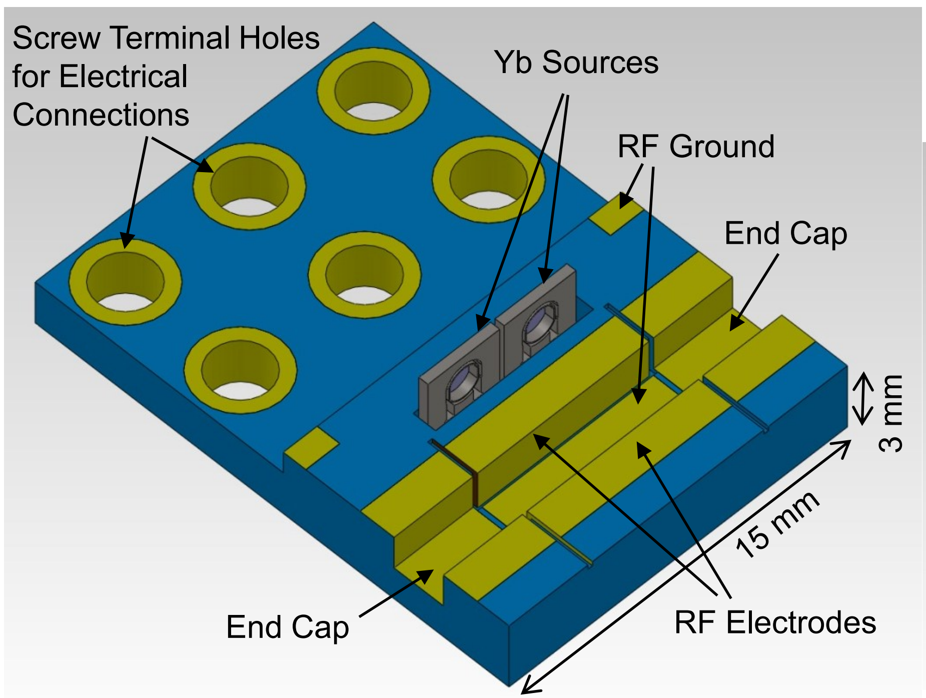
Incorporates shield and field coils to control magnetic field fluctuations which are one of our limiting factors for long-term performance

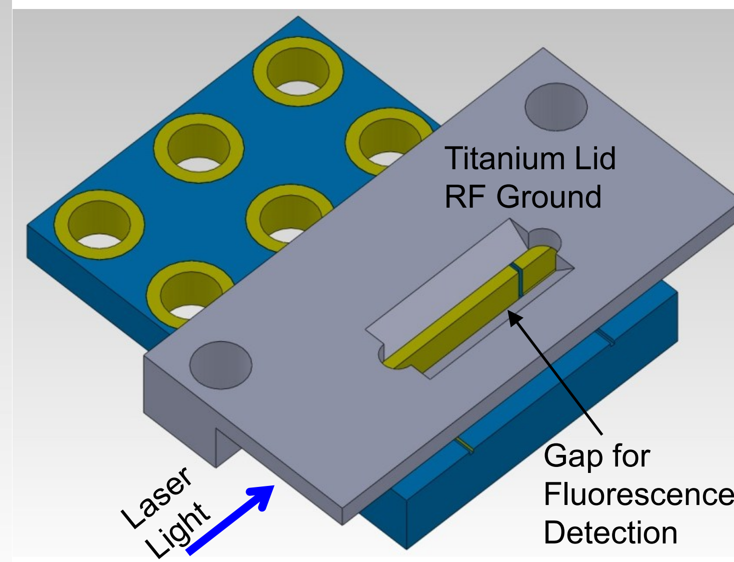
Low Temperature Co-Fired Ceramic Ion Trap



- Co-fired Ceramic Linear RF Paul Trap
- Ceramic PCB, 14 layer structure
- Ion Trap Depth = 1.2 eV @ 100 V_{RF}, 1.7 MHz
    - 46 times room temperature







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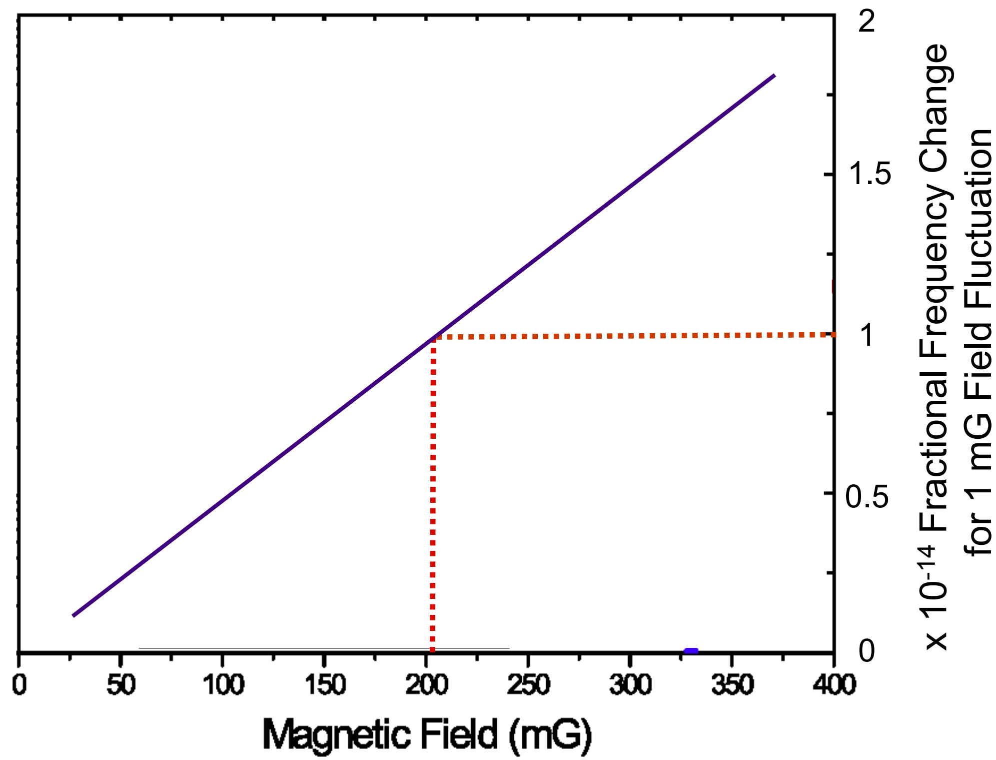
Miniaturization and stability

- Clock is getting smaller - what about the stability?
- main limiting factor in stability in phase I clock: magnetic fields

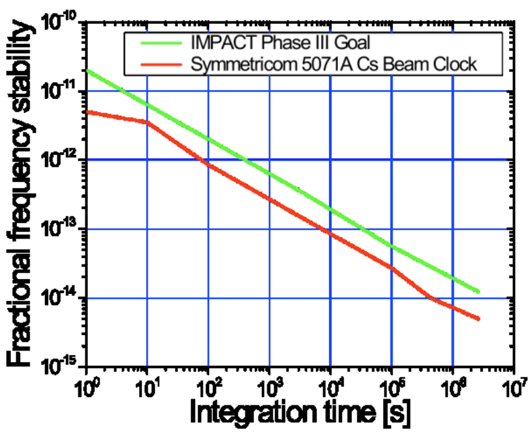
- **Bias field fluctuations** limits frequency stability due to 2nd order Zeeman shift
  - minimize stray fields with coils and shield; then we are less sensitive to fluctuations
- **Field gradients** cause broadening of the clock resonance through ion motion
  - minimize gradients due to magnetic materials
  - understand broadening and engineer trap to avoid the effect from any unavoidable gradients

Long-Term Stability: Magnetic Field Fluctuations



Effect of magnetic field fluctuations on long-term stability

$$\frac{\delta \upsilon}{\upsilon} = 4.9 \times 10^{-11} B\,\delta B$$



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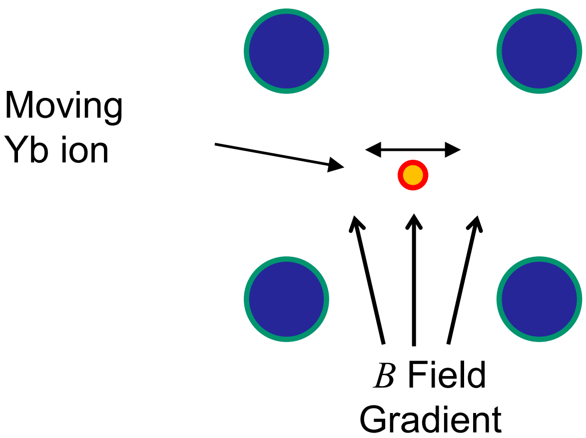
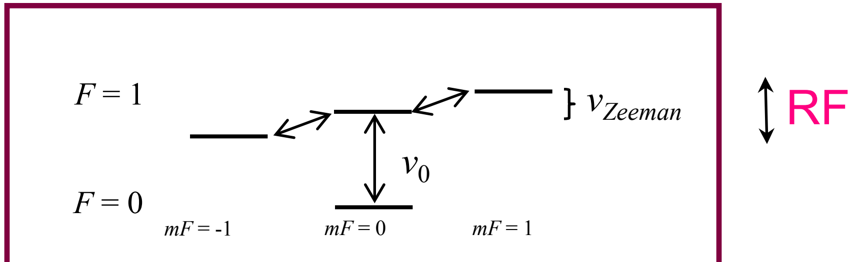
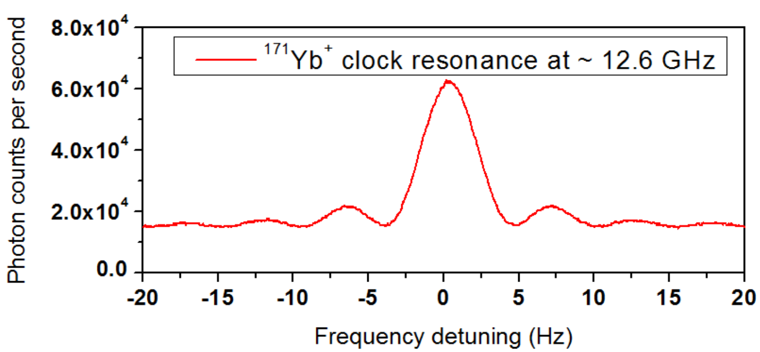
Long-Term Stability: How does ion motion affect clock operation?

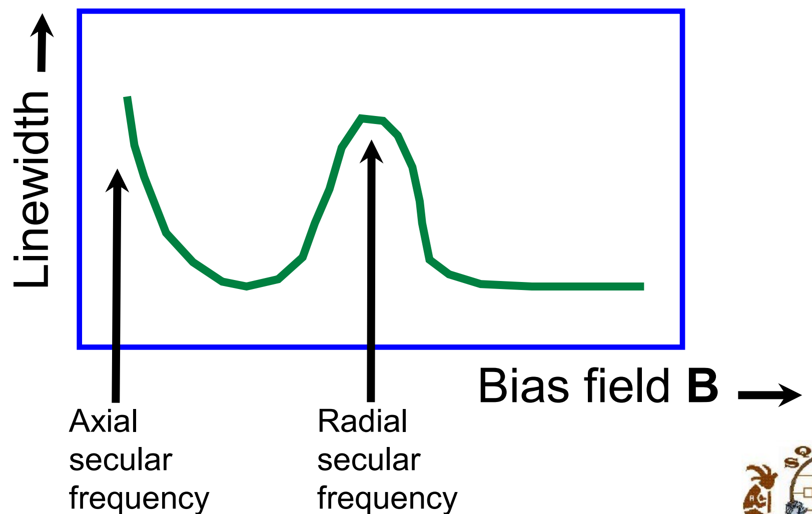
Best achieved stability: 10^{-13}
Goal: 10^{-14}



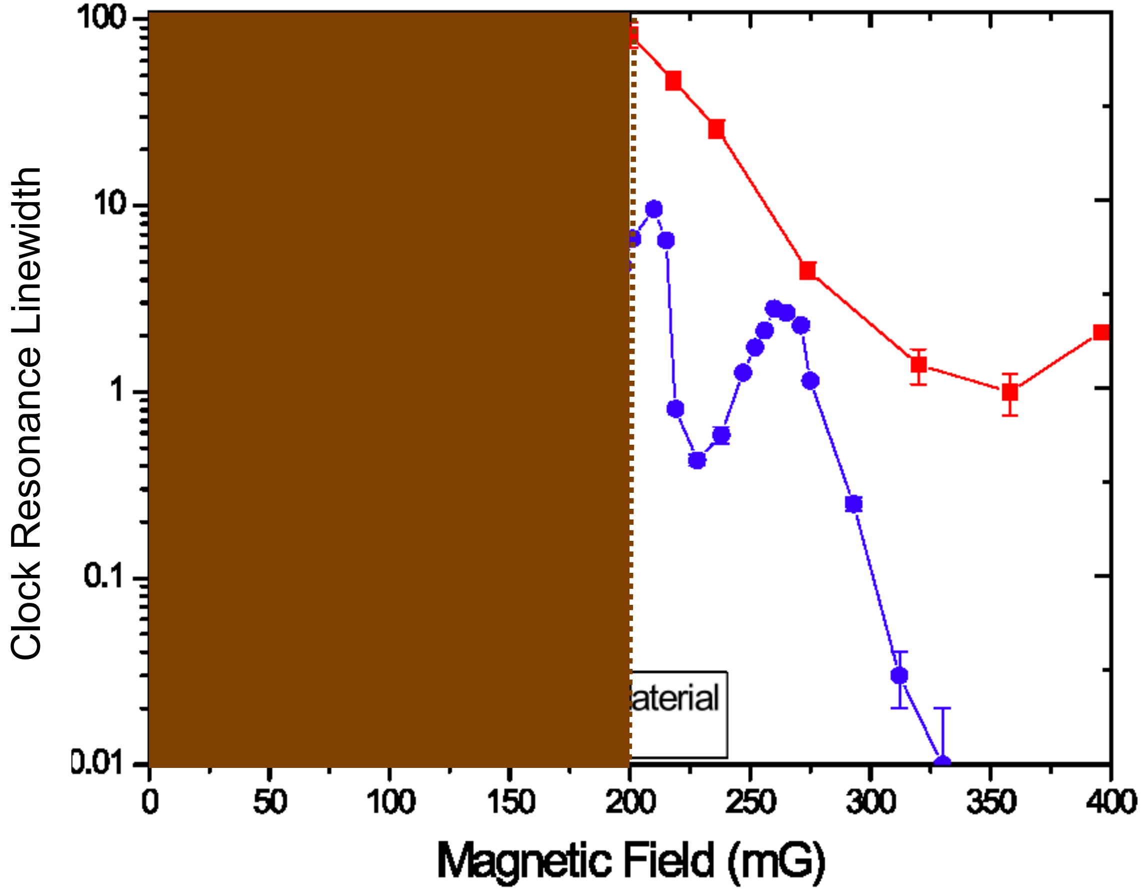


$$\nu_{Zeeman} = 1.4\ {}^{MHZ}/_{G}\ B$$





Linewidth broadening - Experiment



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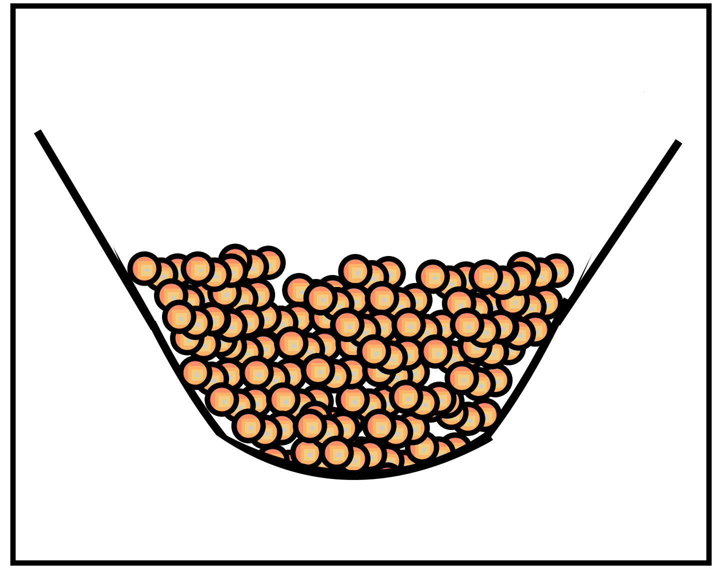
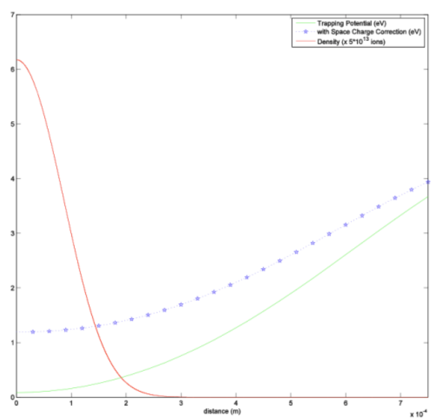
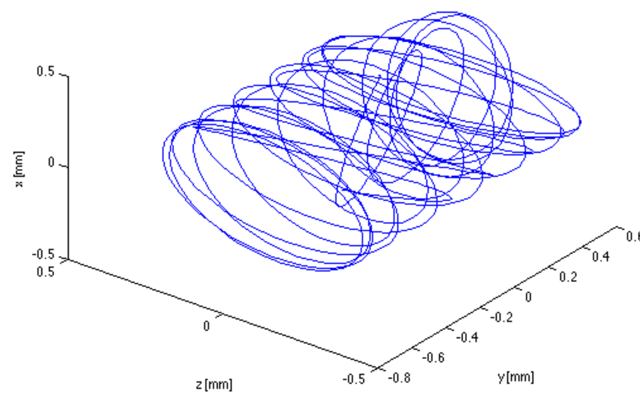
Ion Motion simulation

- Buffer-gas cooled, large ion cloud
- Model the motion: numerically calculated trap potential, space charge density, realistic trap parameters (shape and drive)
- Calculate the spectrum of frequencies of ion motion: same as the spectrum of RF frequencies seen by the ion

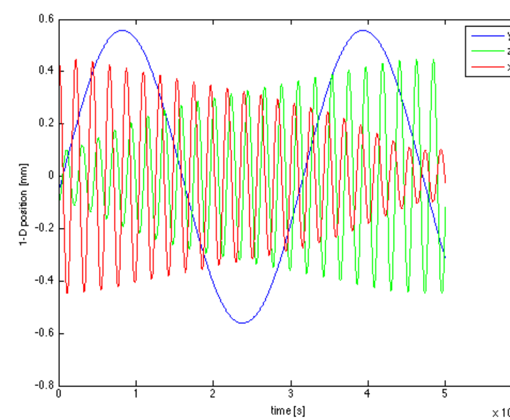




Potential with space charge correction and density

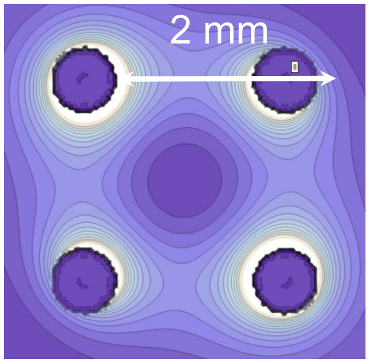


Example 3-D ion trajectory in the Ti trap for 0.05 ms



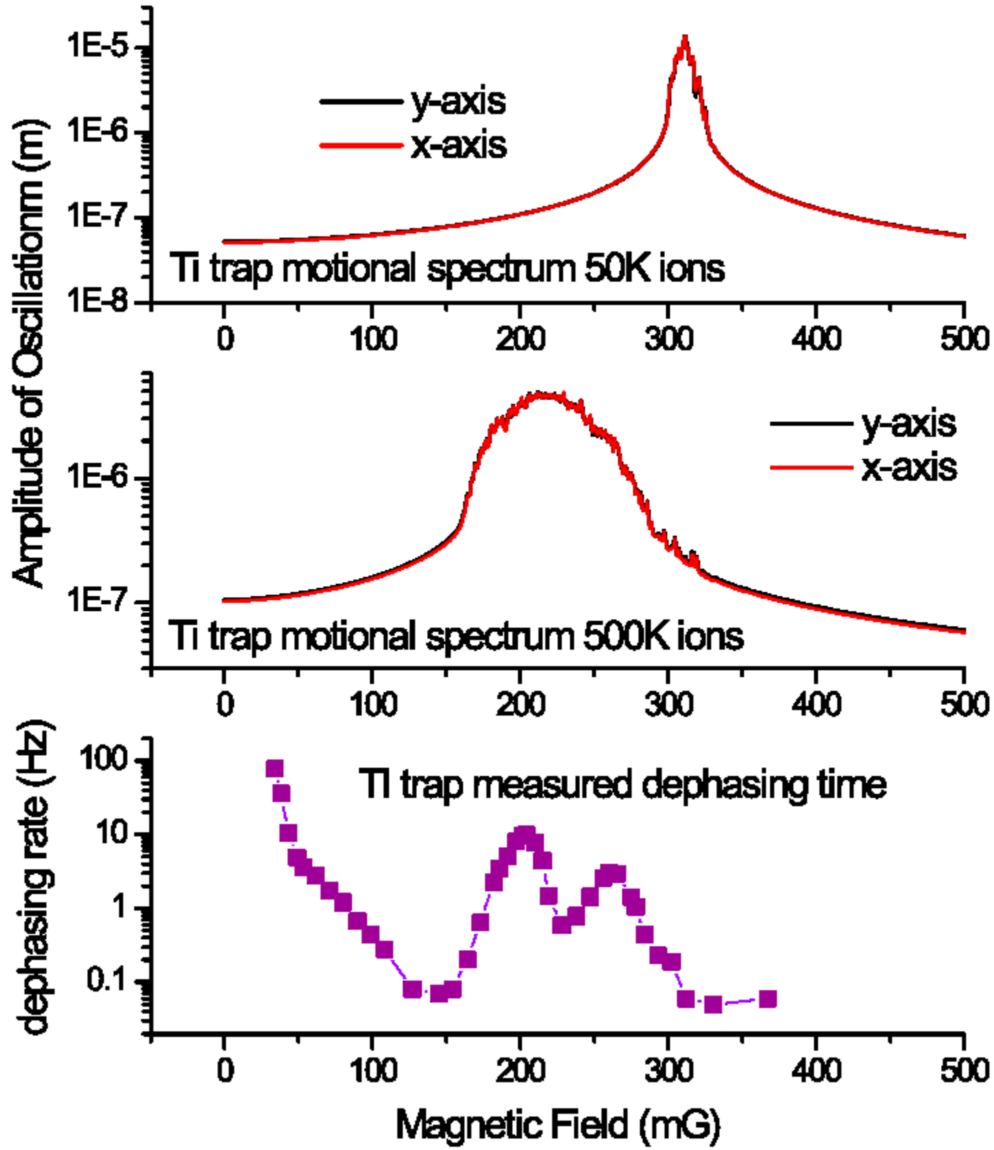
1-D projections of the motion onto each axis

Ion Motio

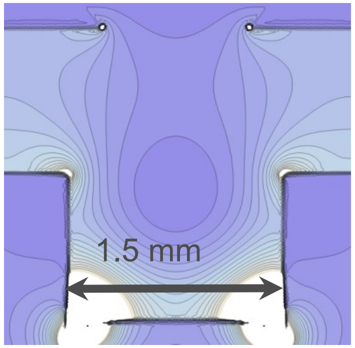


Simulated trap potential

Simulated frequency spectrum and dephasing – theory and experiment



Ion Motion



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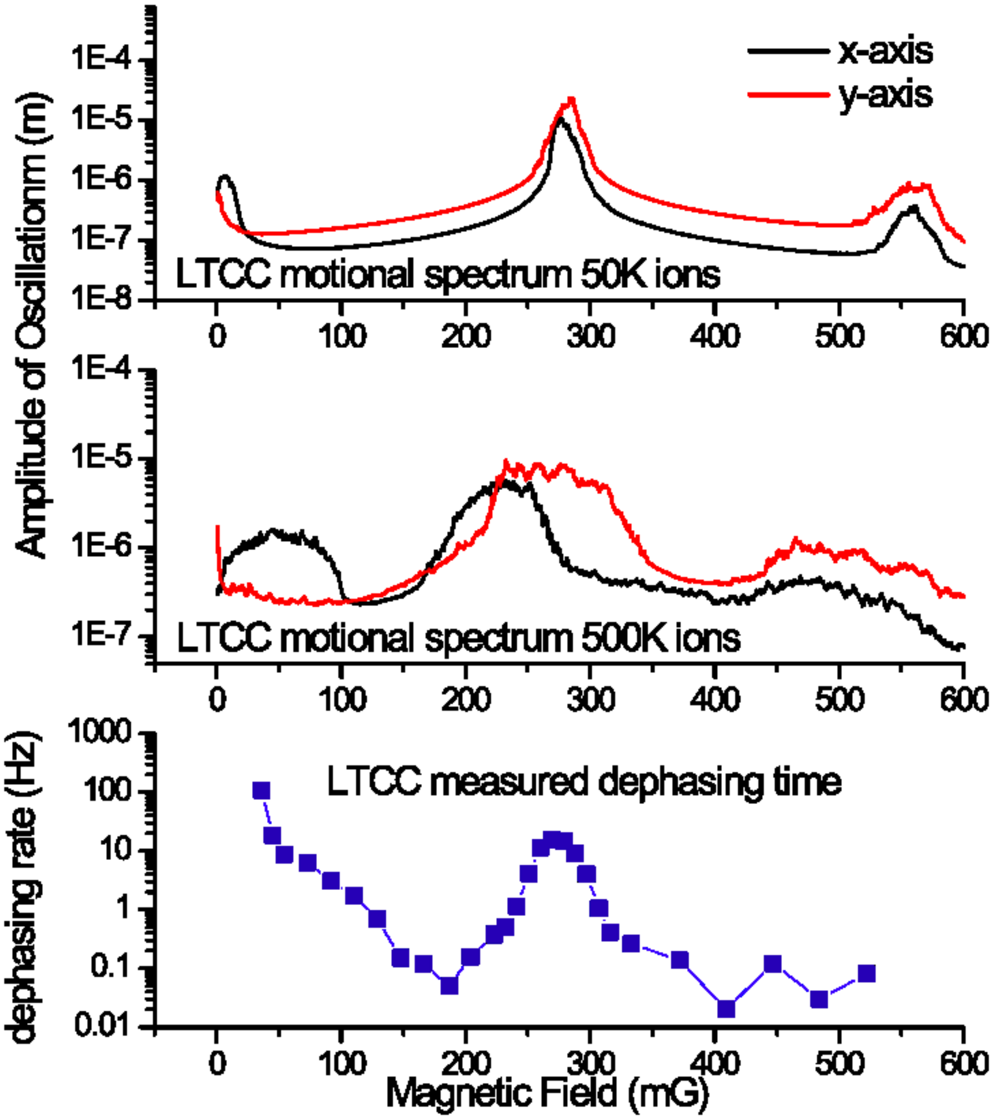
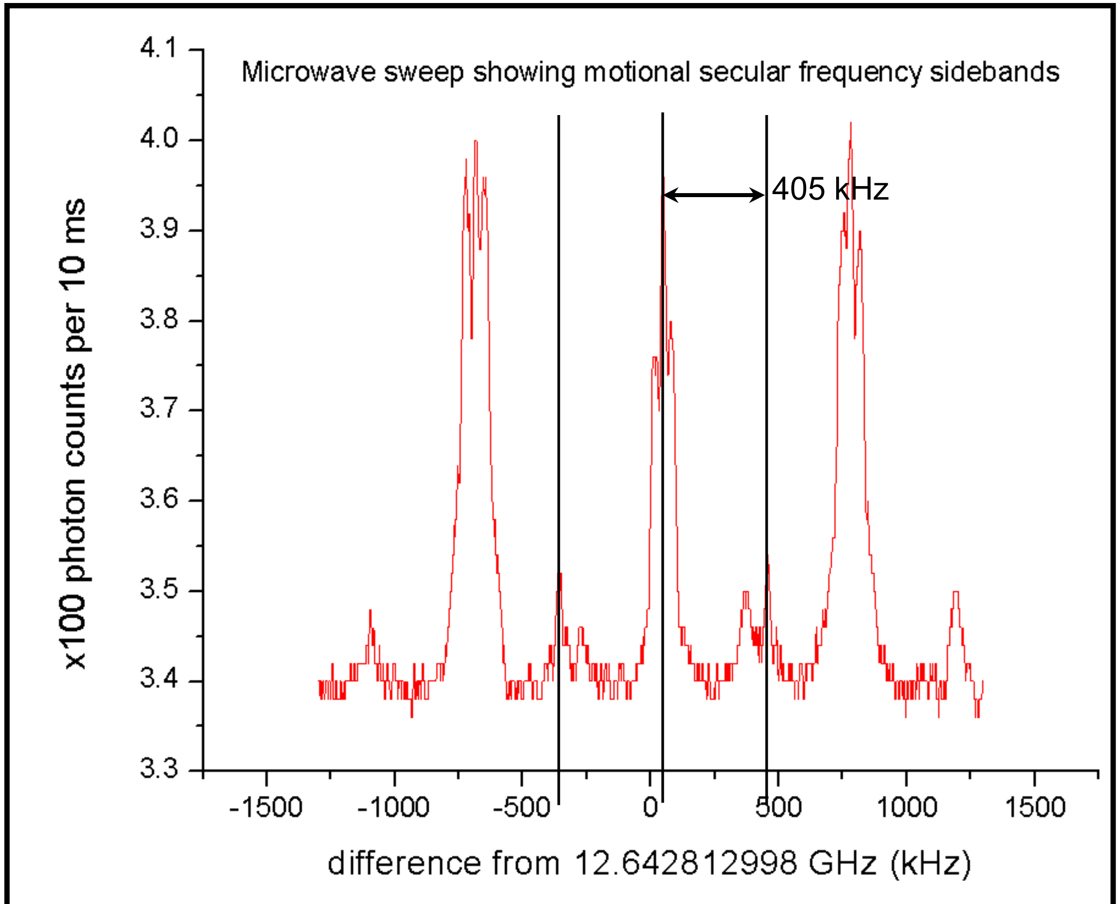
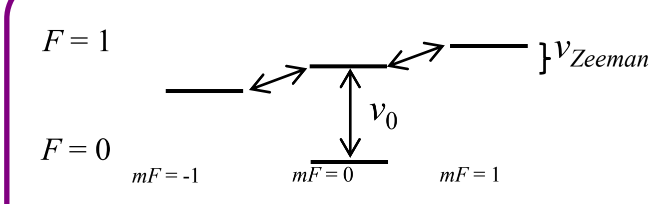


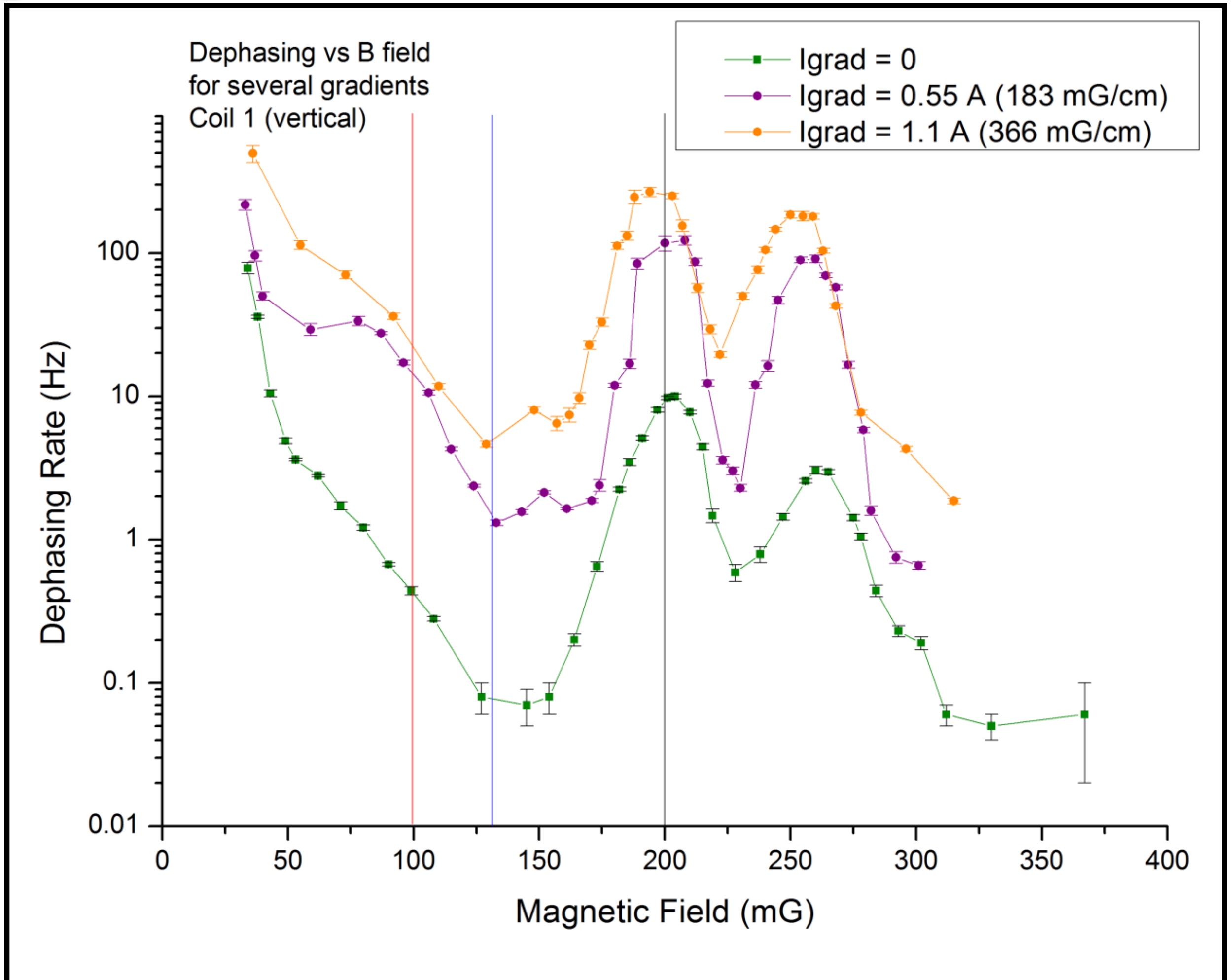
Secular frequency measurement

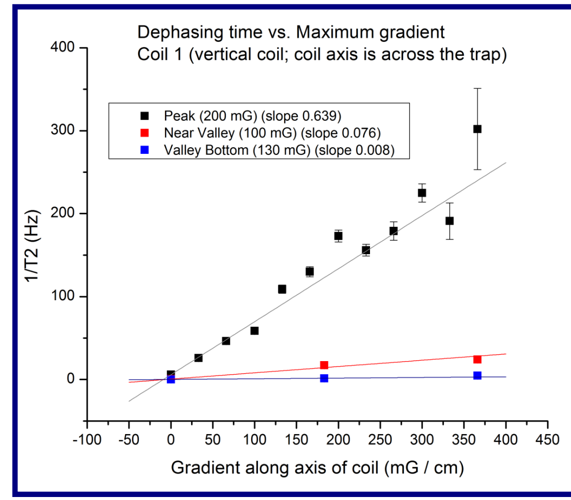




- Sidebands appear due to the modulation of the microwave field by the motion of the ions
- Sidebands are visible on all 3 m_F sublevels if mw polarization is right
- Can use this information to estimate ion number if we know the temperature

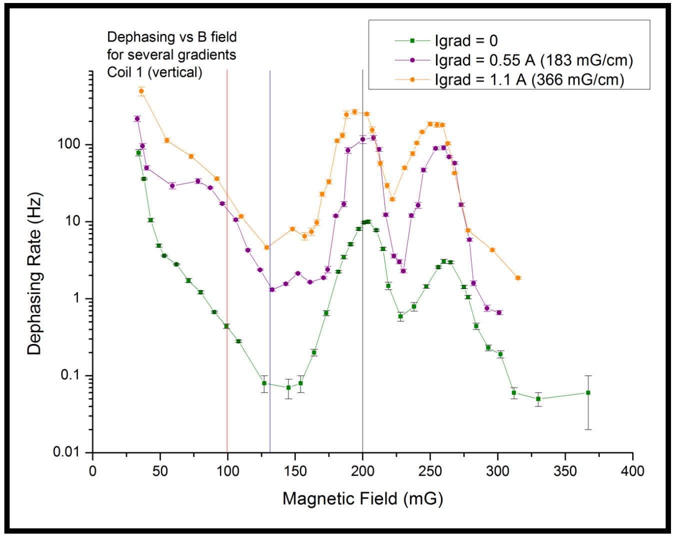
Gradient tolerance in presence of magnetic materials





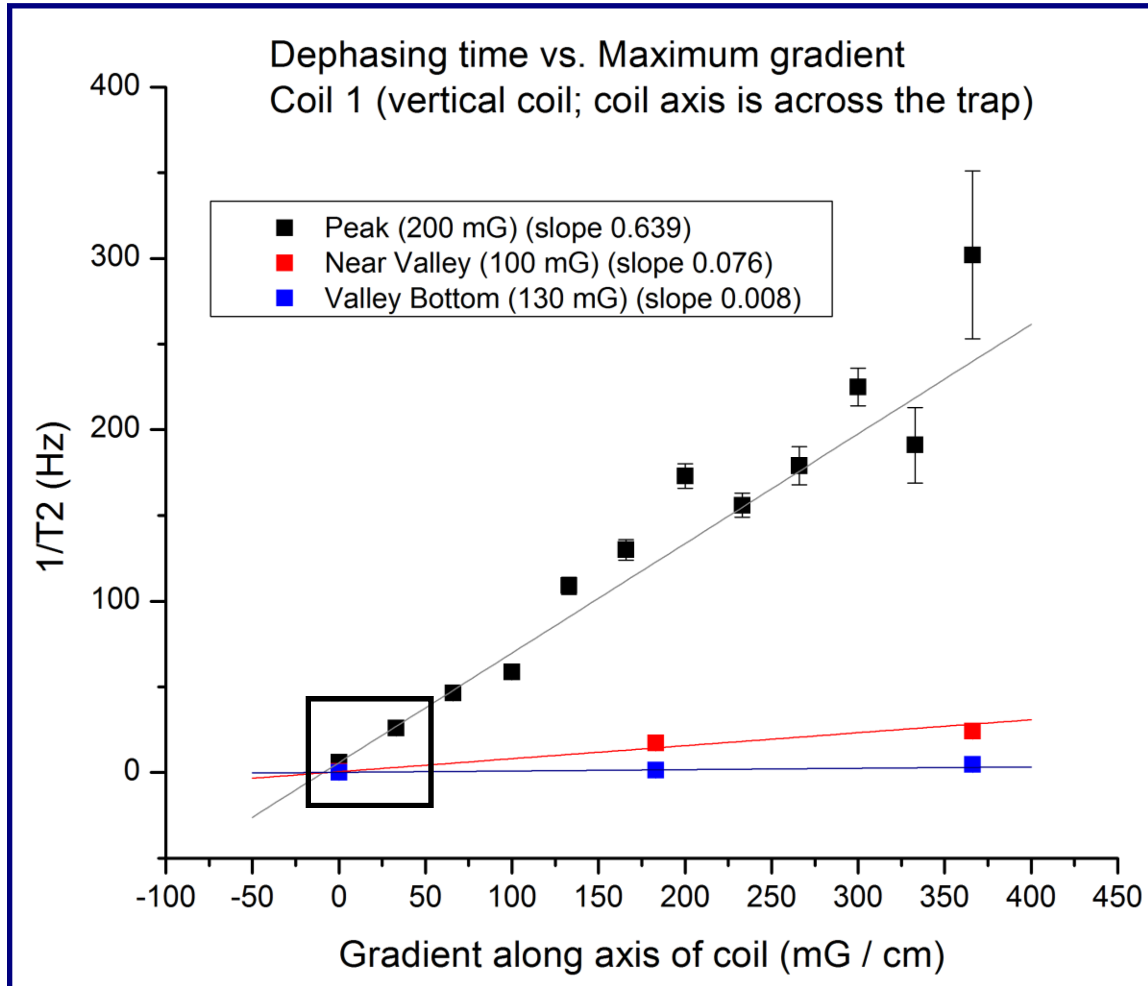
Adding gradients to characterize broadening as gradient increases

Gradient tolerance in presence of magnetic materials



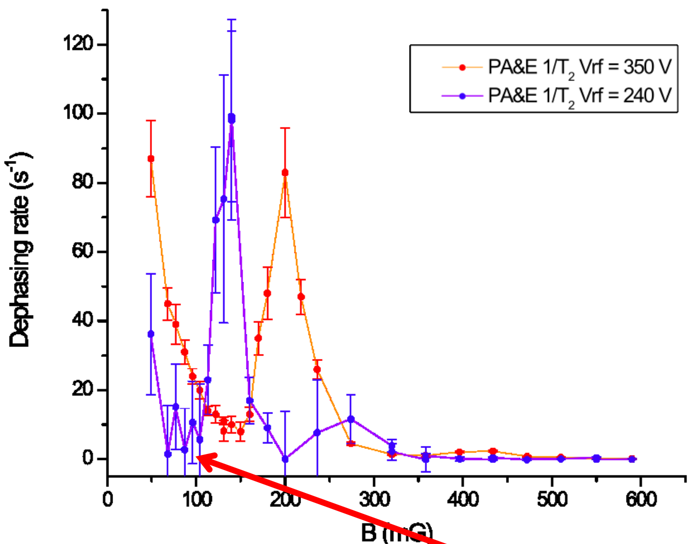
Adding gradients to characterize broadening as gradient increases

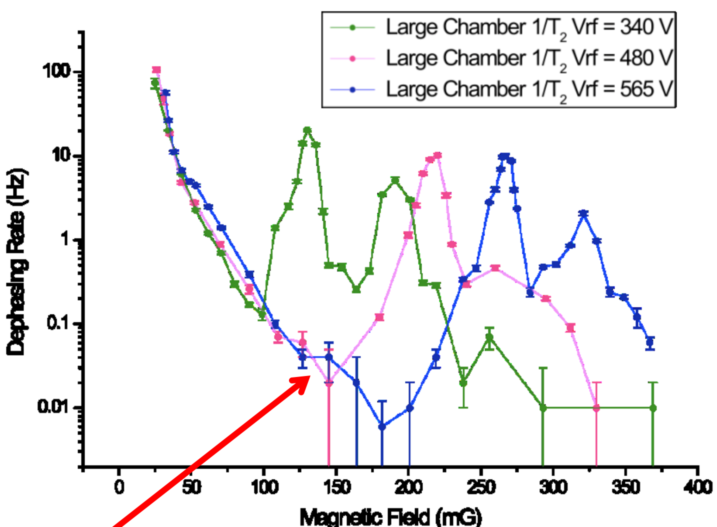
This trap: at 130 mG, up to ~100 mG/cm is tolerable



Optimizing the operating point

- We can use the “valley” point between the low-field fluctuation peak and the radial secular frequency peaks
- This “valley” is optimized when it occurs at a lower field and has the lowest linewidth
- We can manipulate the location and depth of the “valley” by changing the trap RF voltages and eliminating magnetic materials





good operating points

Conclusions

- We have developed a clock according to the IMPACT guidelines that we expect to meet phase II goals, on track for a Cesium-beam-level clock by phase three
- We have examined the effects of ion motion, field strength, and field gradients on clock operation
  - We can operate in the “optimal” range below the secular frequency resonance with the Zeeman levels, despite the presence of gradients and limitations of shielding
  - Removal of all magnetic material in manufacturing makes a substantial difference in our ability to use a lower bias field

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Thanks

IMPACT

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Nan Yu (JPL)

CQUIC
Carl Caves
Ivan Deutsch

Support

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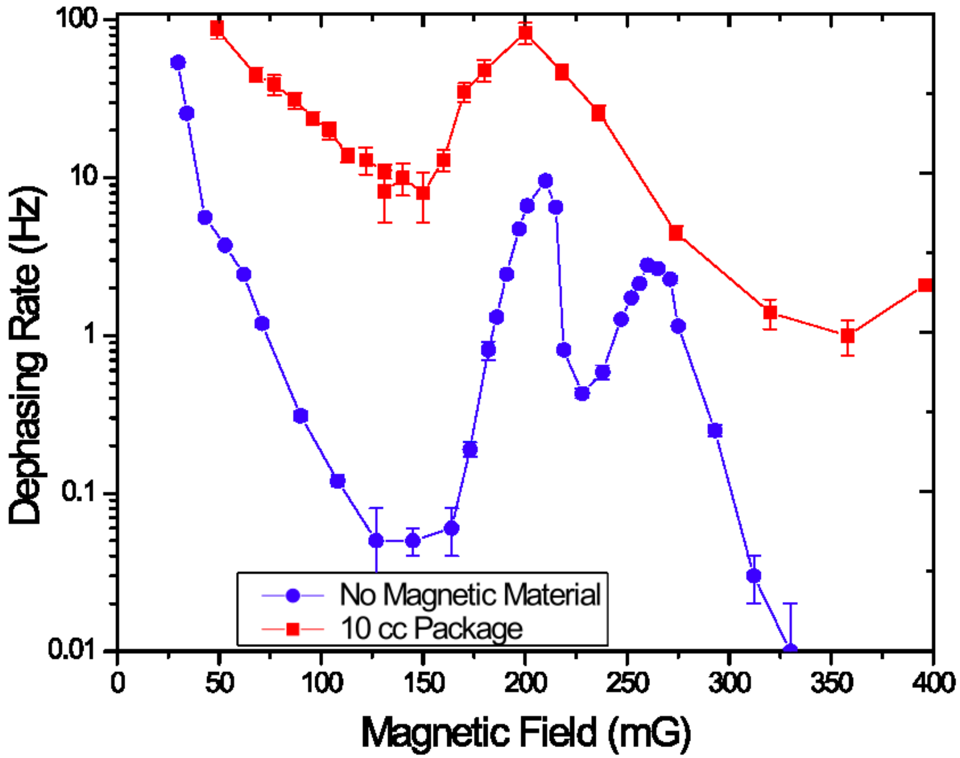
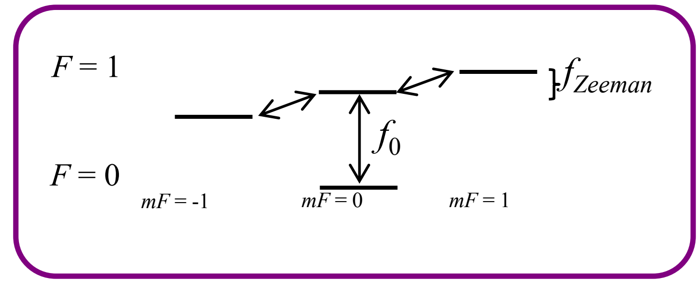
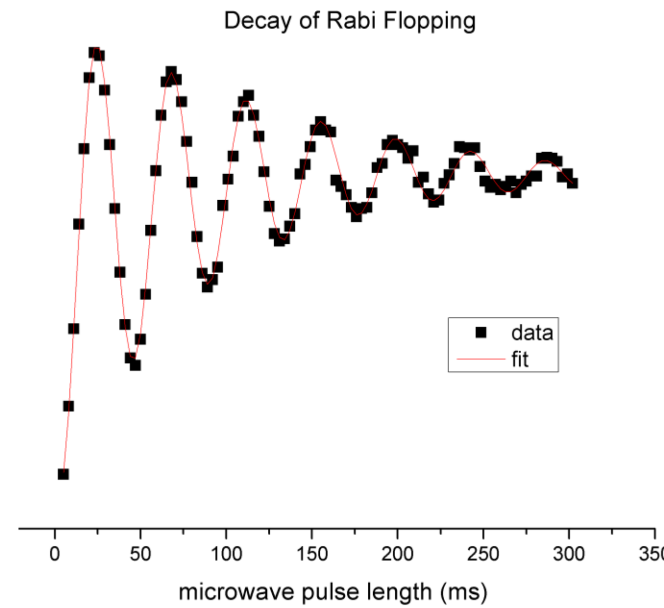
Measuring the dephasing

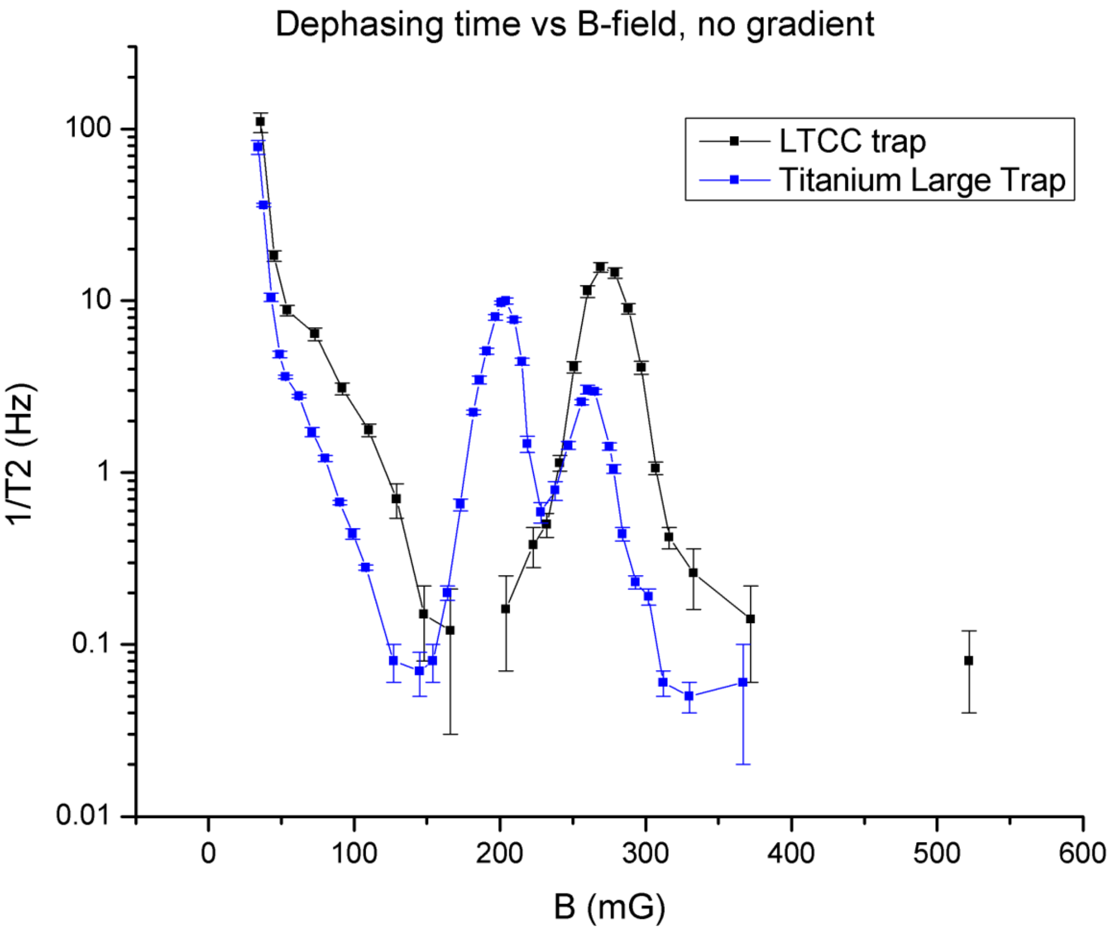


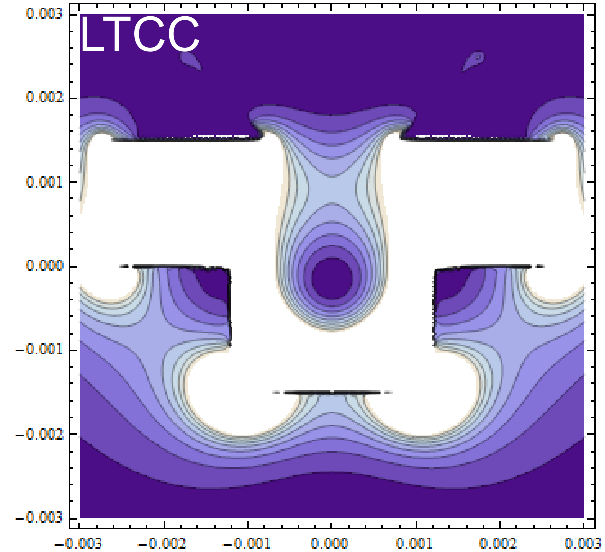


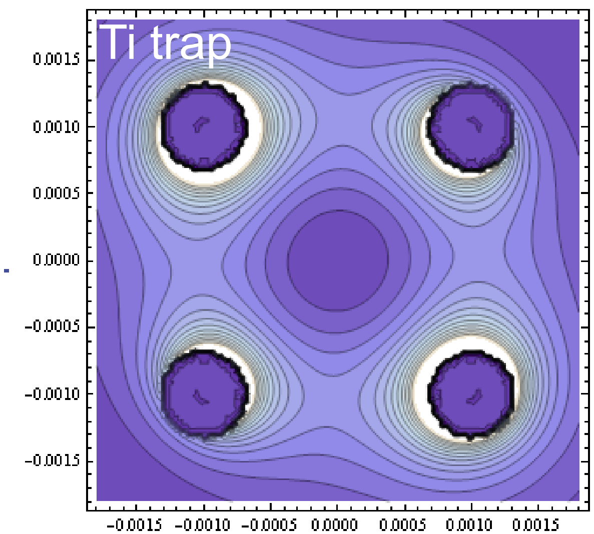


Decay of Rabi flopping due to loss to the other m_f states

Splitting of the secular frequency peaks







Symmetry of trap and number of ions?

Key Technologies for Miniaturization & Low Power

- Small vacuum ion-trap package:
- Can the vacuum level be maintain without an active pump?
- Low power RF drive for the ion trap:
- Can we reach the goals of the size and power consumption?
- VCSEL based laser sources:
- Can the VCSELs deliver enough light power for operation?
- Microwave generation (12.6 GHz) & local oscillator:
- Is there a good low-power solution?
- Yb ion generation:
- Can we find an efficient way for Yb vapor generation and ionization?
- Signal detection:
- Can we efficiently detect the weak UV fluorescence at low power?
- Miniature control electronics:
- Can we build the electronics with enough low power?

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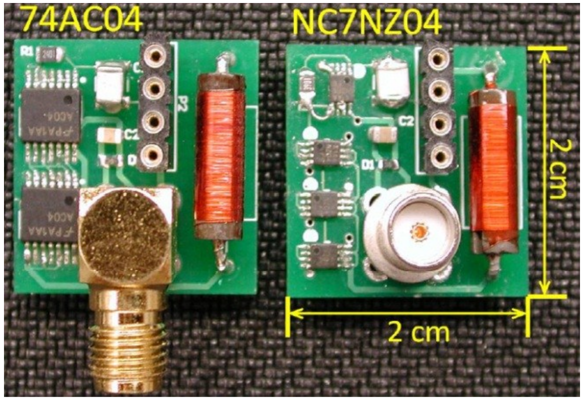
Low-Power RF Ion Trap Drive

Circuit boards of the RF drives



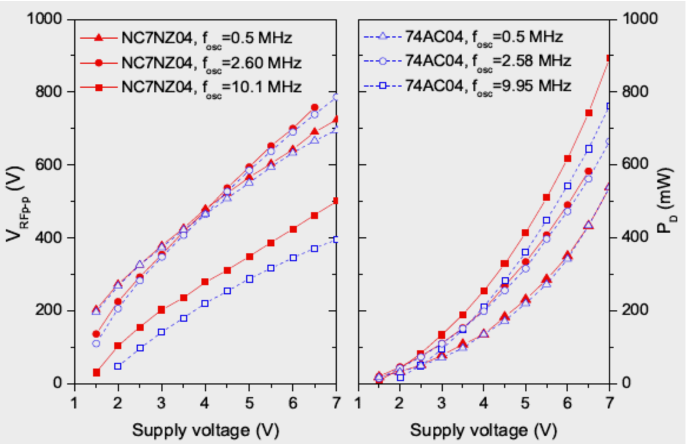
Fundamental limit of the power consumption of the RF trap by using a tank circuit:

$$P_{\min} = \frac{\omega_0 C V_{\mathrm{RF}}^2}{2Q} = \sqrt{\frac{C}{L}} \frac{V_{\mathrm{RF}}^2}{2Q}$$

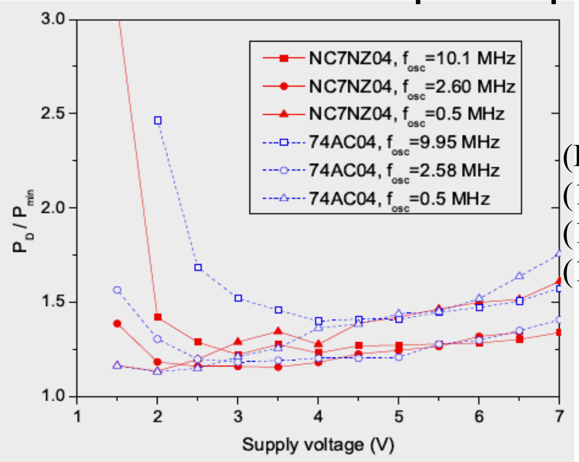
C: the total capacitive load
L: the inductance of the inductor in the tank circuit
V_{RF}: the RF peak voltage across the trap electrodes
Q: the quality factor of the resonant circuit

Because of dissipation in the circuit elements required to drive the oscillation in the LC resonator, the total power dissipation of the circuit, P_D, is always greater than Pmin. We have achieved $P_D / P_{\min} = 1.2 - 1.5$. Currently we have demonstrated ≤ 40 mW to drive the trap. Further reduction to < 10 mW is achievable by decreasing the capacitive load.

Output RF voltages and power dissipation



Efficiencies of different operation parameters



(L, C0: fosc):
(10μH, 20pF: 10MHz),
(100μH, 33pF: 2.6MHz),
(1mH, 100pF: 500kHz).

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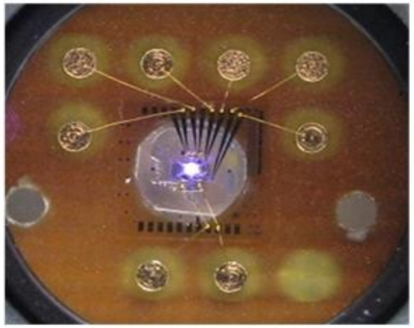
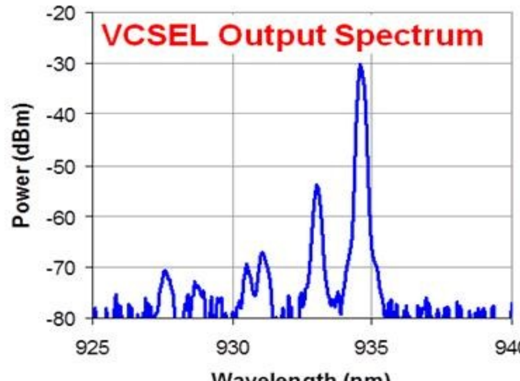
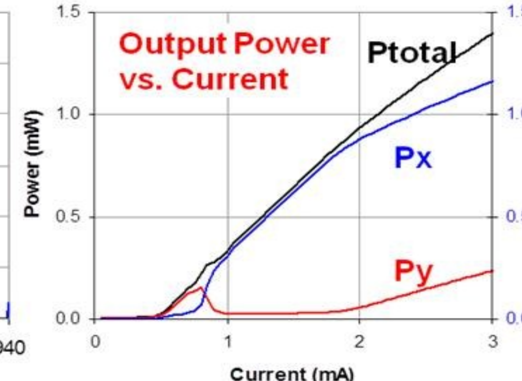
Low-Power Light Sources at 935 nm & 369 nm

Packaged 935nm VCSEL

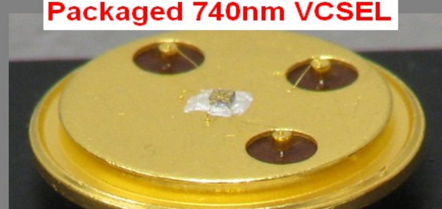




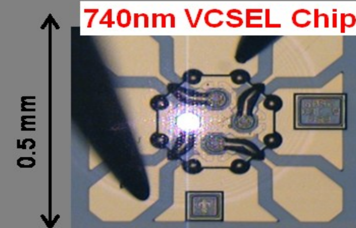


- Plan for 369 nm source
  - Develop 740-nm AlGaAs VCSEL
  - Frequency double to 369 nm in KTP

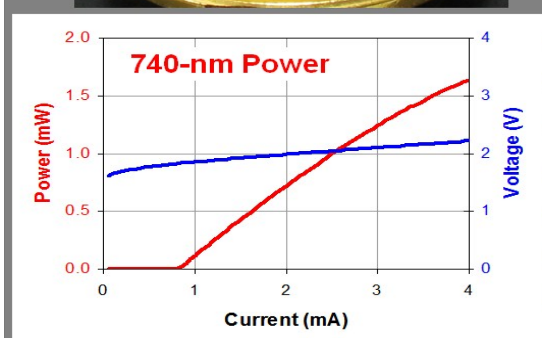
Packaged 740nm VCSEL

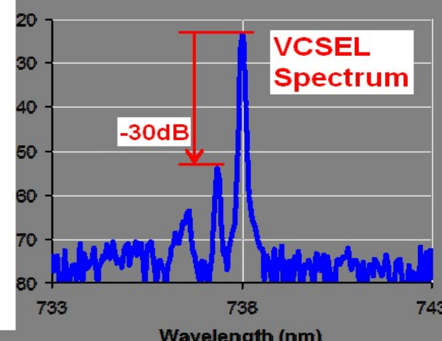


740nm VCSEL Chip

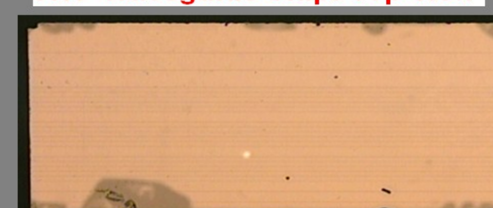


KTP Waveguide Chip





KTP Waveguide Chip: Top View



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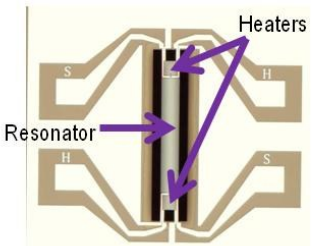
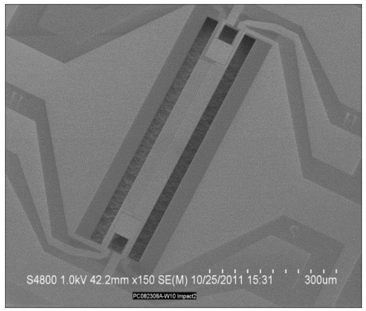
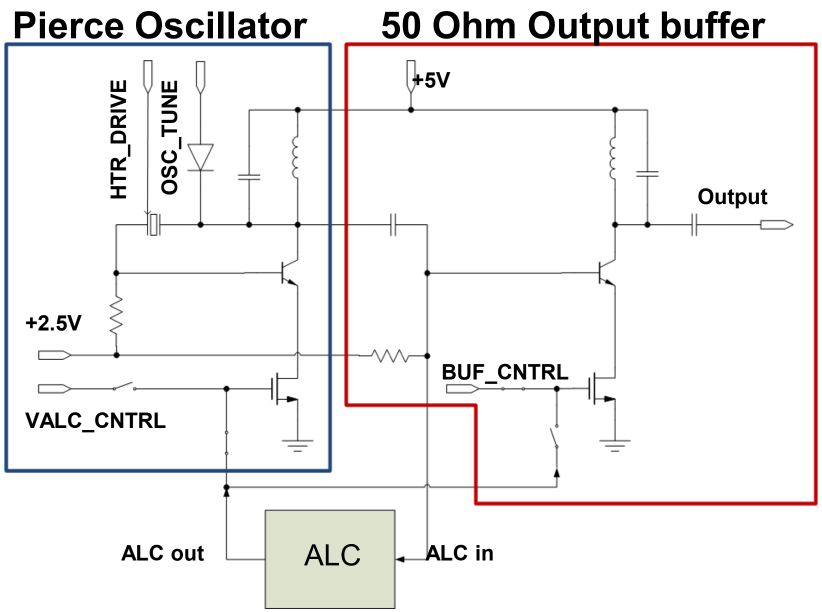
MEMS Oscillator & Yb Micro Hotplate

Microwave oscillator based on MEMS resonator



Released 2.53 GHz resonator die (~1 mm²)

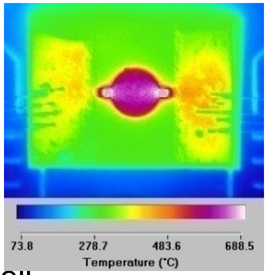




Micro hotplate Yb ovens

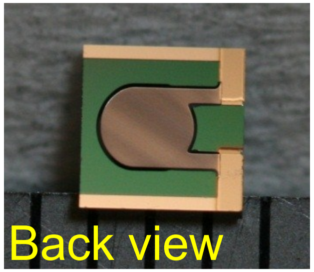
- Yb deposited into microhotplate wells by evaporation, powder deposition & liquid ammonia solvation.

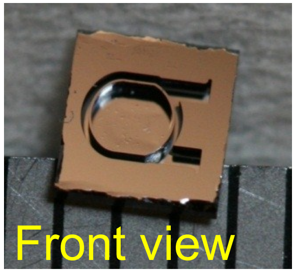
SEM & thermal images

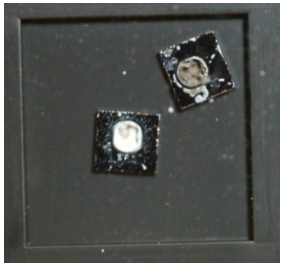


1.5 mm dia., 0.4 mm deep Yb well

Hotplates for integration into the LTCC ceramic trap have been designed and fabricated.







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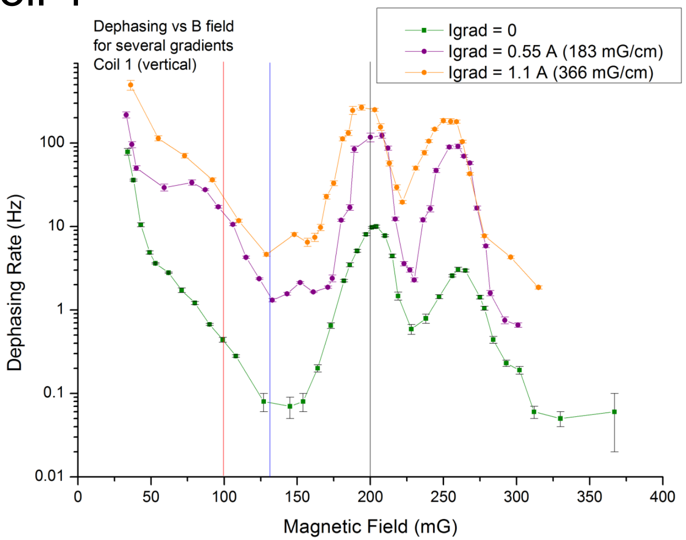
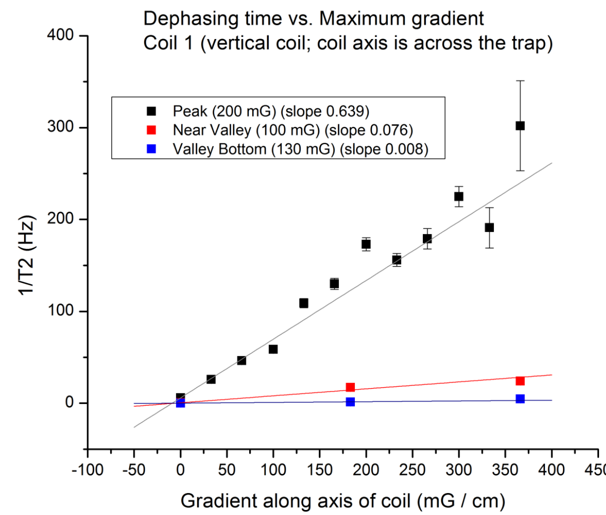
Summary

- The long coherence time of ^{171}Yb ions allows us to operate the clock at even much higher precision when the performance of the local oscillator is further improved.
- We have demonstrated the robustness of the miniature (10 c.c.) ion-trap vacuum packages. No active pump is required to maintain the vacuum level for continuous operation.
- We have first demonstrated a functioning ceramic ion trap device, which will be utilized in the future 1 c.c. ion-trap package.
- Carefully using non-magnetic material for the ion-trap device can improve the long-term clock performance dominated by the magnetic-field drift.
- We have developed various key technologies for Yb ion clock miniaturization.
- Miniature 369 nm light source is the most challenging technology.

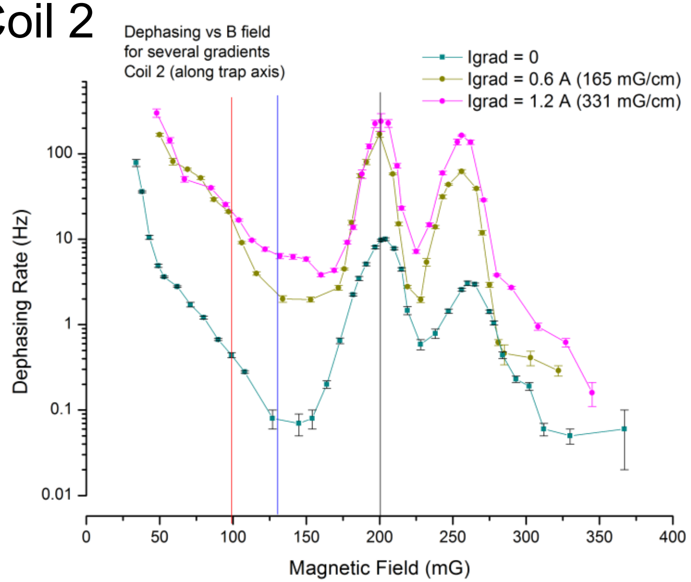
Dephasing and gradient

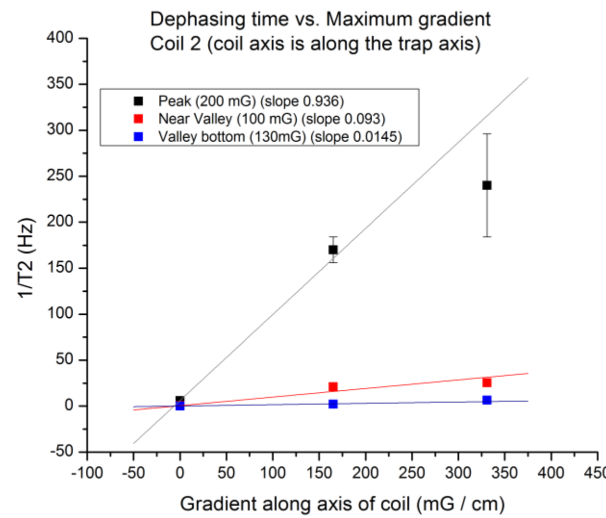
Coil 1





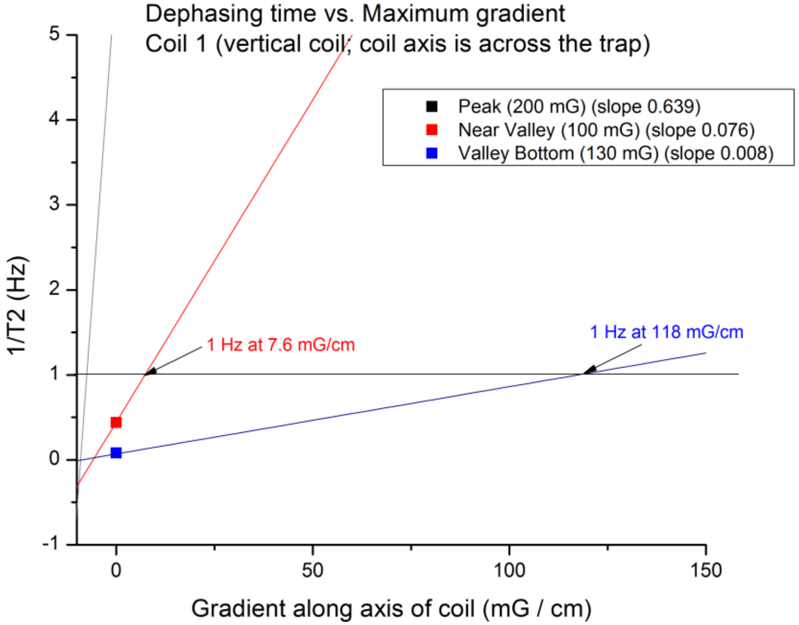
Coil 2



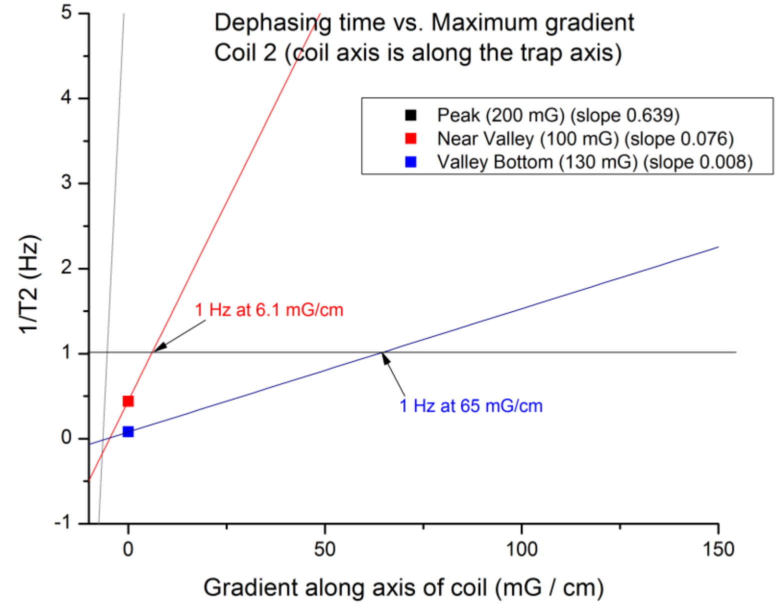


Dephasing and Gradient

Coil 1



Coil 2



At the bottom of the valley area we can have a gradient as high as 65 mG/cm (to get a 1 second dephasing time), but for these trap parameters we need 130mA to be at that valley point.

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