Determining the Fine Structure Constant with Bose-Einstein Condensate Interferometry

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Outline

- Introduction
  - Fine Structure Constant
  - Bose-Einstein Condensate Interferometry
- Discussion of REU project work
  - Helping choose a direction for future work
  - Analyzing experimental timing precision
  - Building frequency generator needed for the future experiment

The Fine Structure Constant, α

- Dimensionless combination of fundamental constants

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$$

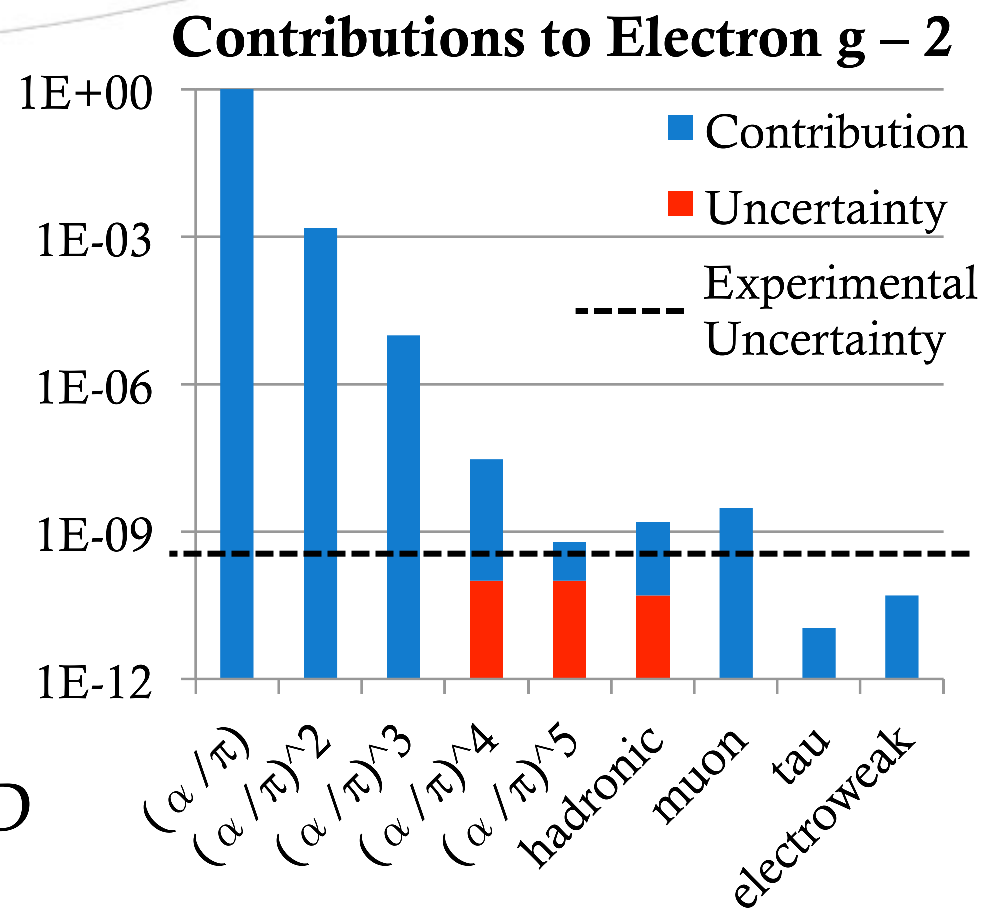
- Strength of electromagnetic coupling in QED
- Magnitude of relativistic corrections in atomic physics

"… undoubtedly the most fundamental pure (dimensionless) number in all of physics. "
-David Griffiths

"… all good theoretical physicists put this number up on their wall and worry about it"
-Richard Feynman

Best Measurements of α

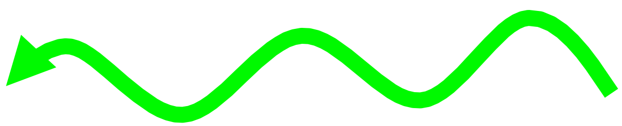
- Electron g – 2
  - 0.25 ppb (Harvard[1])
  - Calculation requires >10,000 Feynman Diagrams
- Atom Recoil
  - 0.7 ppb (France[2])
  - **0.1 ppb (Our goal)**
- Comparison tests QED



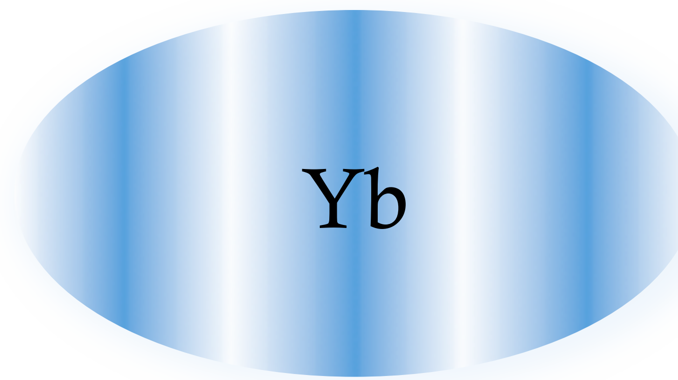
Adapted from Alan Jamison 2014 thesis

[1]R. Bouchendira, et al. PRL (2011)
[2]D. Hanneke, et al PRL (2008)

Atom Recoil Measurements



$$p = -\hbar k$$



$$\psi = e^{i(kx - \omega_{rec} t)}$$

Time-dependent Schrödinger Equation:

$$\left[\frac{-\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x)\right]\psi = \frac{-\hbar}{i}\frac{\partial}{\partial t}\psi \Rightarrow \boxed{\frac{(\hbar k)^2}{2m_{Yb}} = \hbar\omega_{rec}}$$

Using ω_{rec} to Measure α

- Recoil frequency combines with precisely known constants to give an expression for α .

$$\alpha^2 = 4\pi \frac{R_\infty}{c} \frac{\hbar}{m_e}$$

$$\frac{(\hbar k)^2}{2m_{Yb}} = \hbar\omega_{rec}$$

$$\alpha^2 = 8\pi \frac{R_\infty}{c} \frac{m_{Yb}}{m_e} \frac{\omega_{rec}}{k^2}$$

0.0059 ppb

0.1 ppb

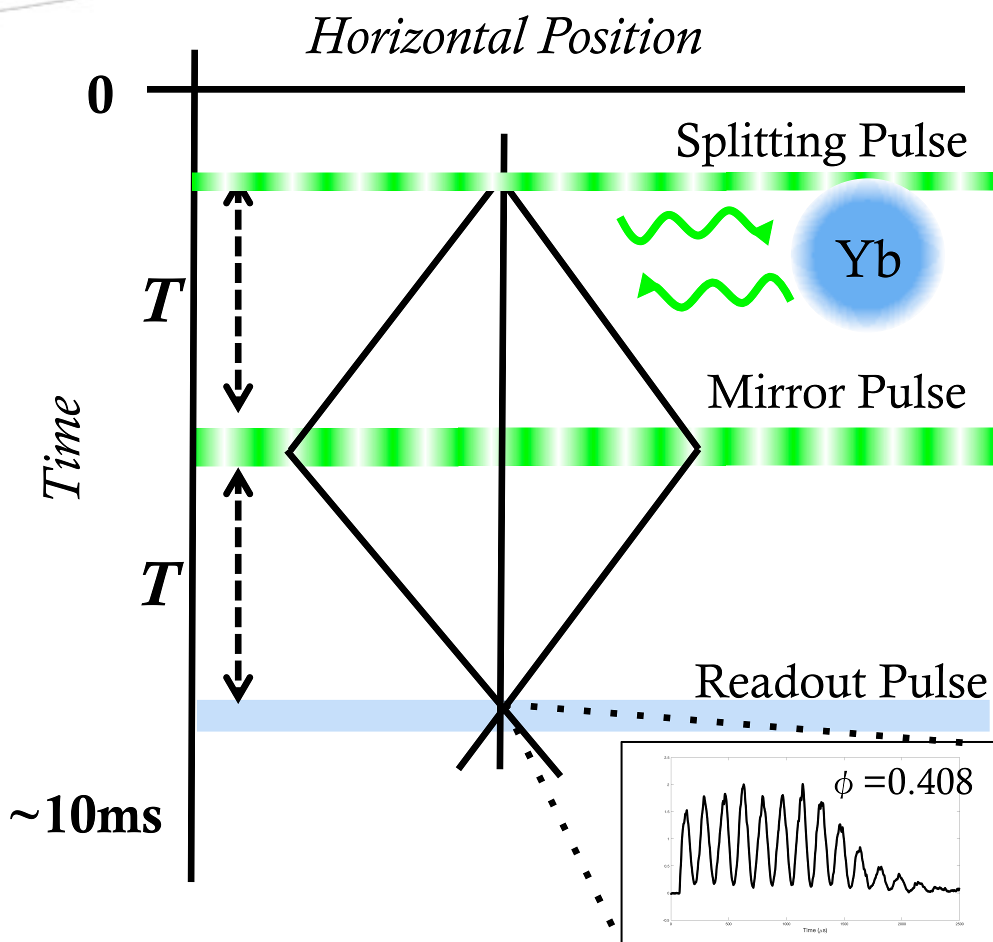
~~1.3 ppb~~

Our Goal: 0.1 ppb

Measuring ω_{rec} with Atom Interferometry

- Diffraction by standing waves of light gives precise momentum kicks with photon pairs
- Final atomic interference pattern allows precise measurement of phase.

$$\omega_{rec} \propto \frac{\partial \phi}{\partial T} = \frac{\Delta E}{\hbar}$$



Precision of Atom Interferometry

- Uncertainty in recoil frequency due to uncertainty in phase and time:

$$\omega_{rec} \propto \frac{\partial \phi}{\partial T} \Rightarrow \left(\frac{\Delta\omega_{rec}}{\omega_{rec}}\right)^2 = \left(\frac{\Delta\phi}{\phi}\right)^2 + \left(\frac{\Delta T}{T}\right)^2$$

- N = 1 Horizontal IFM: $\frac{\Delta\phi}{\phi} \approx \frac{10\,\text{mrad}}{930\,\text{rad}} = 1.1\times10^{-5}$
- Precision in $\Delta\phi$ is limited so it is necessary to increase ϕ

Increasing Phase Evolution

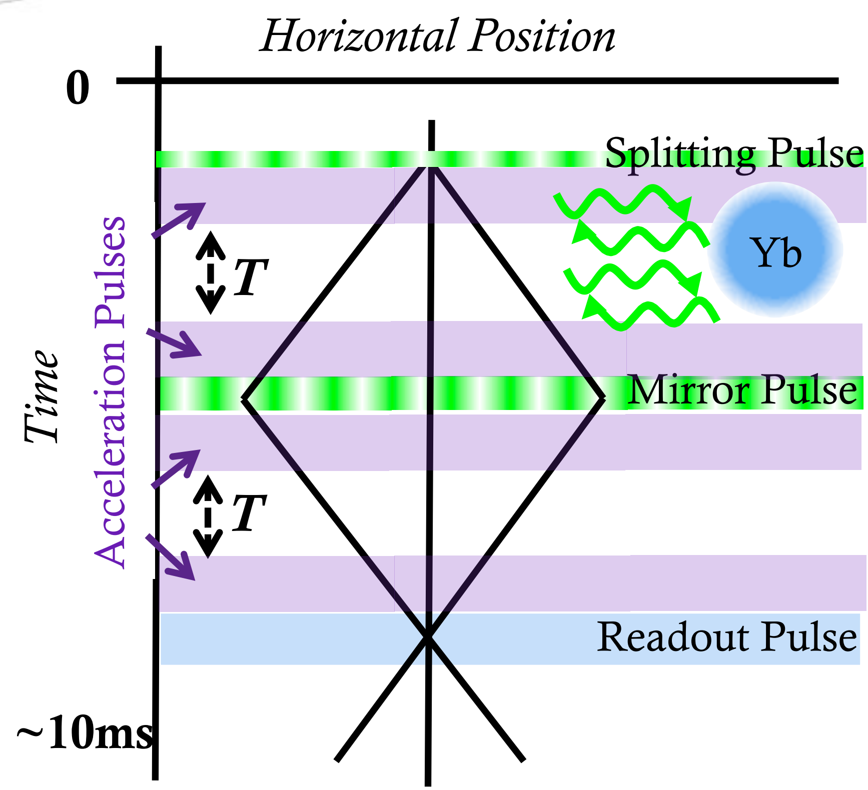
- Total phase proportional to square of number of recoils, $2N$

$$\phi = \omega_{rec}(2N)^2(2T)$$

- Have successfully accelerated up to N = 28
  - Lose evolution time

$$\phi_{\max} \approx 120{,}000 \text{ rad @ } N = 20$$

$$\Delta\phi / \phi \approx 8 \times 10^{-8}$$



My REU Project

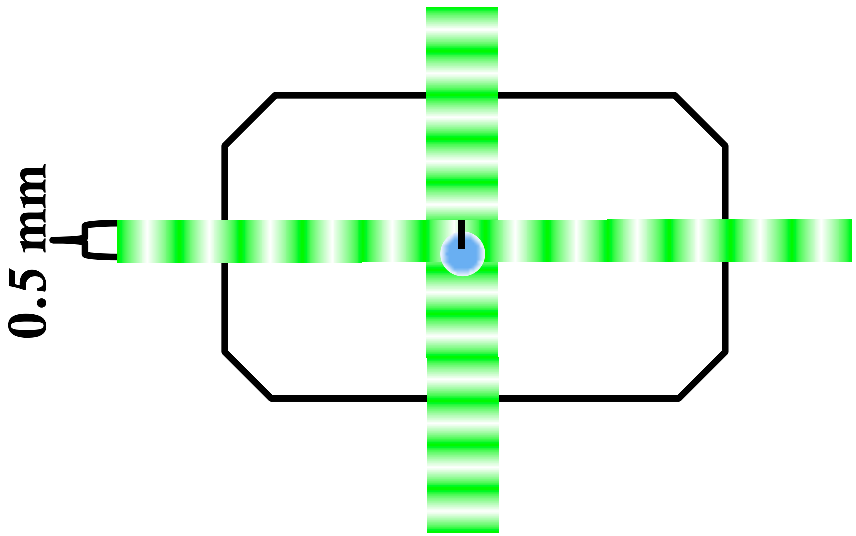
- Analyzing means to further increase ϕ
- Building programmable frequency generator for future setup
- Measuring precision for $\Delta T/T$

Next Steps to Increase Phase

Better

Horizontal Diffraction

Add vertical launch (2× Time)

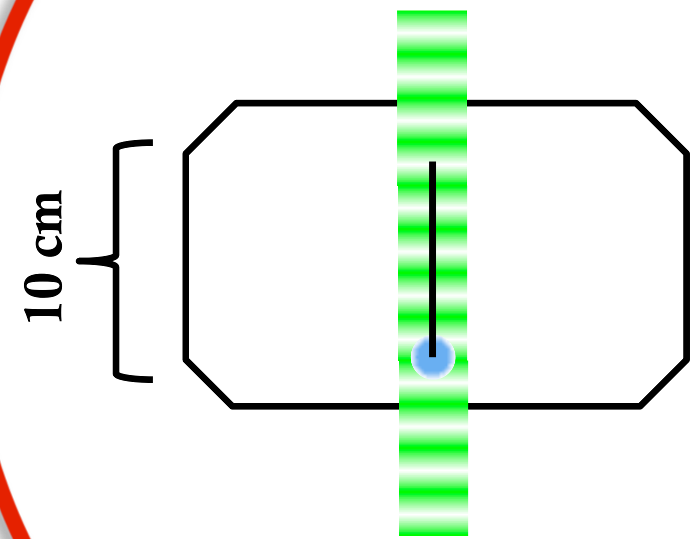


$$\Delta\phi / \phi \approx 1\times10^{-8}$$

Need $\Delta T \leq 2$ ps for 0.1ppb

Vertical Diffraction

Add vertical launch (20× Time)

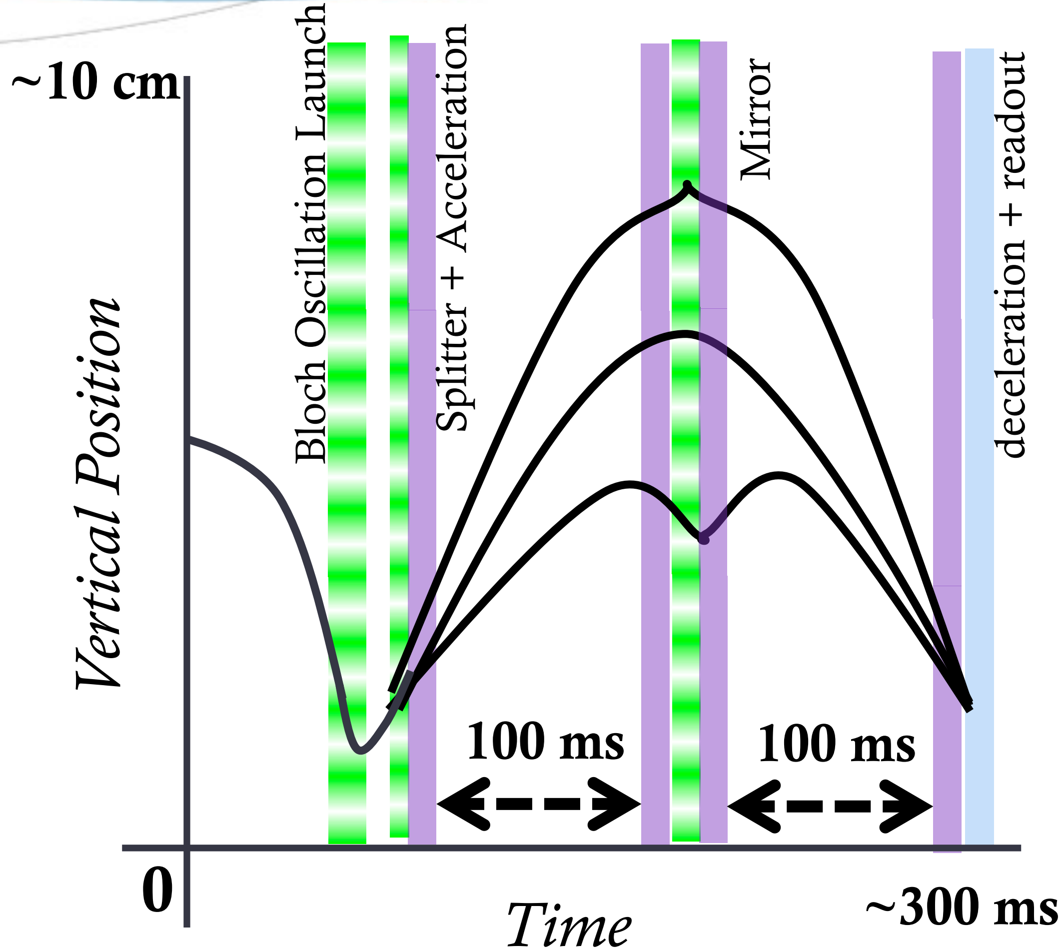


$$\Delta\phi / \phi \approx 8\times10^{-10}$$

Need $\Delta T \leq 20$ ps for 0.1ppb

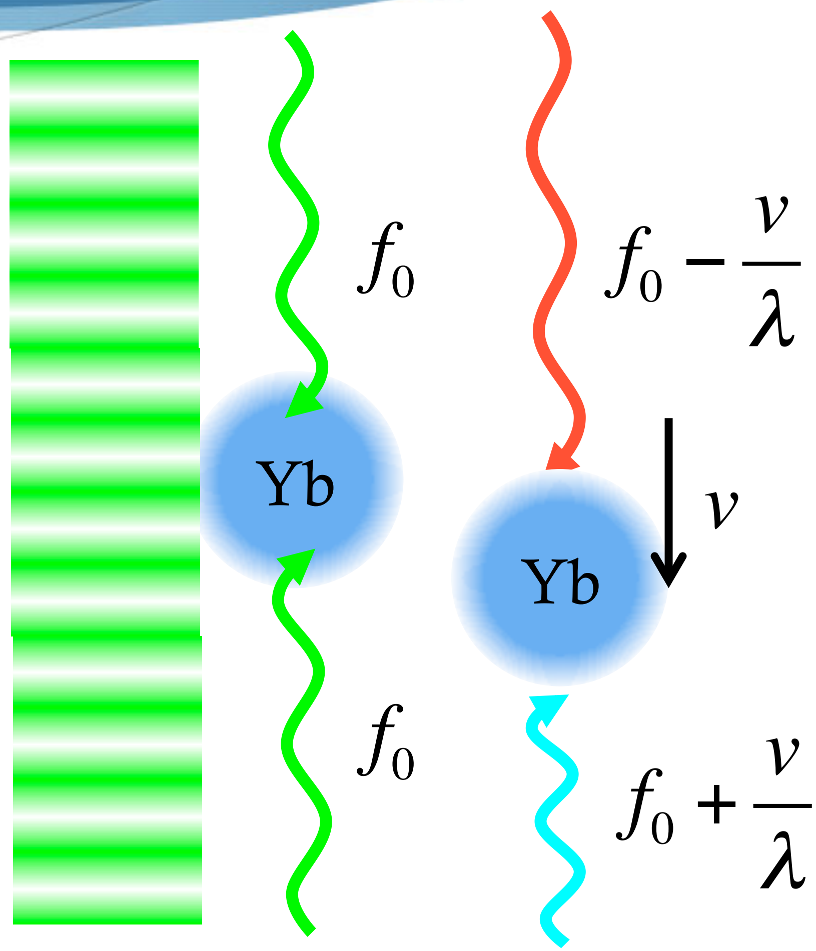
Planning for a Vertical Geometry

- Begin with vertical launch to achieve 200ms of freefall
  - Now need $\Delta T \leq 20$ ps
- Compensate standing waves for effects of gravity

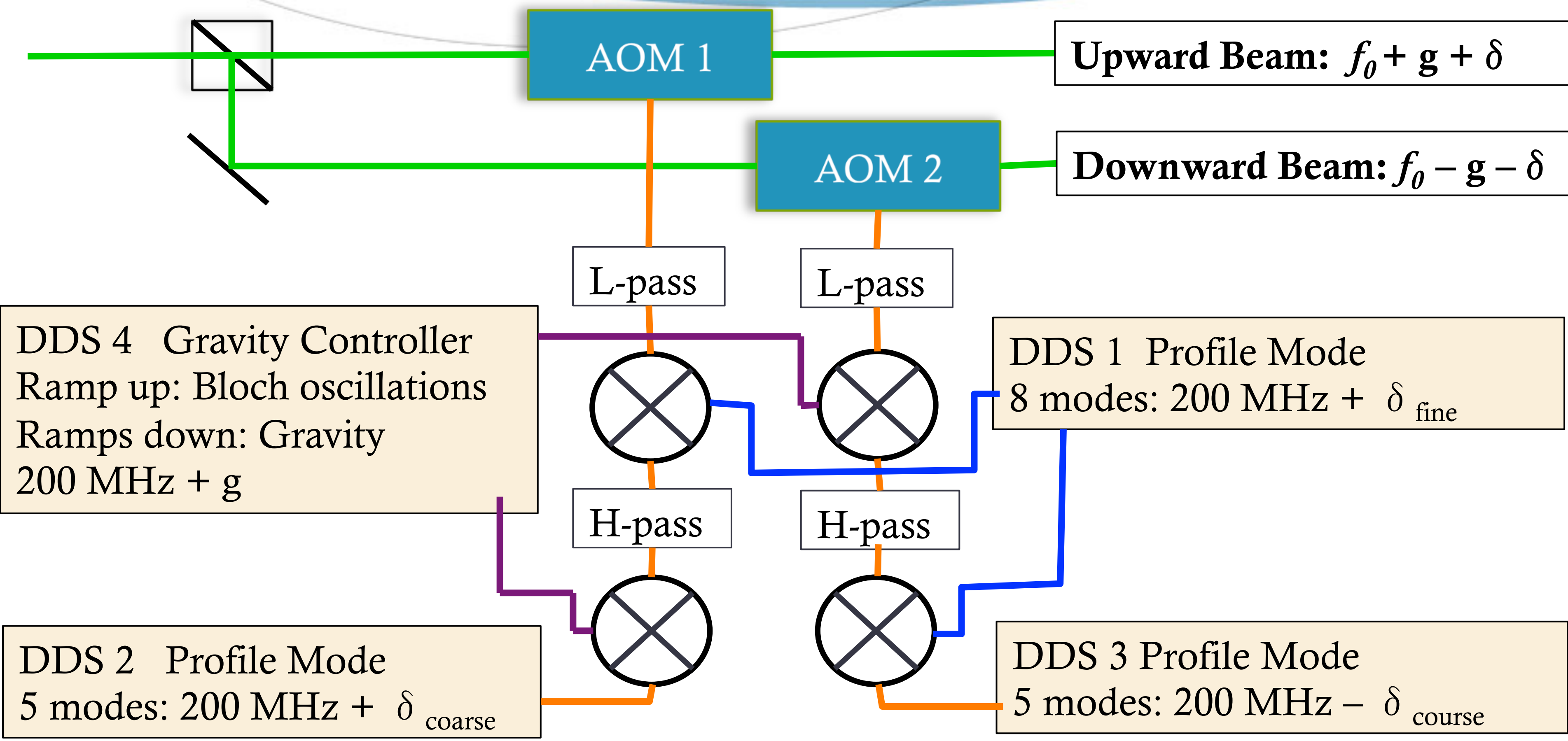


Making Diffraction Beams 'fall' with Gravity

- As atoms fall, Doppler shifts disturb standing waves
- Need to adjust frequencies at a rate of g / λ = 17.653 kHz/ms
- Use Direct Digital Synthesizer (DDS) to produce frequency sweeps

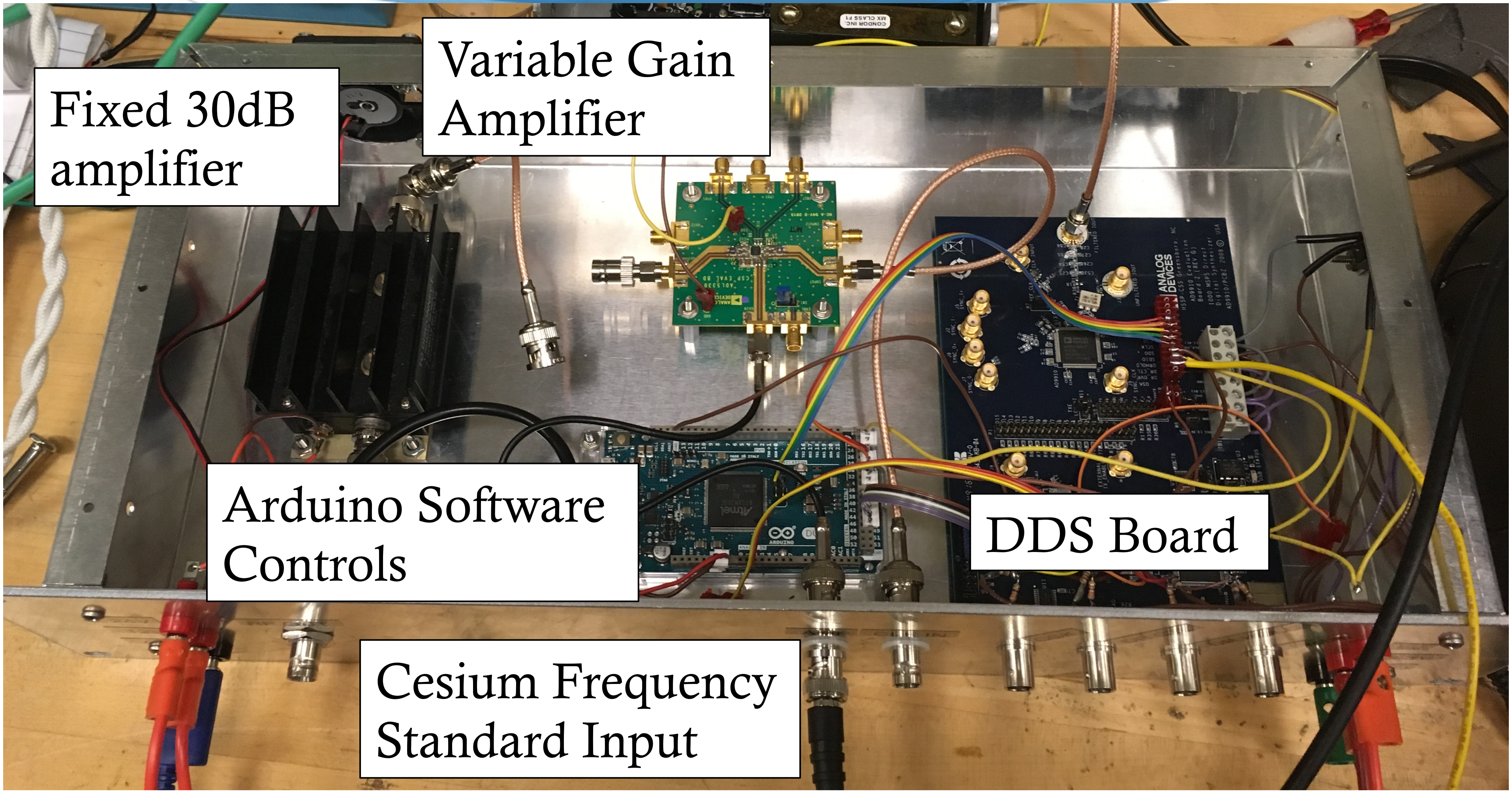


How to ‘chirp’ beams with a DDS



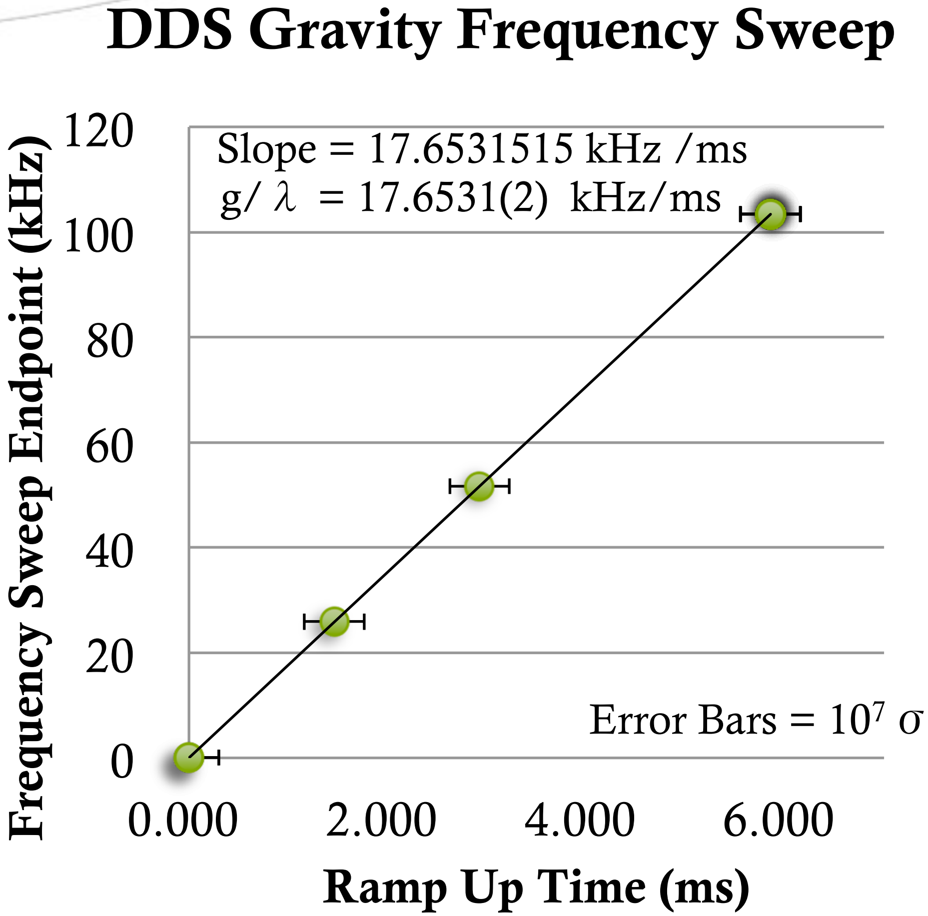
δ_{coarse} = 0, +5hk, -47hk, +53hk, -95hk, +101hk, -143hk δ_{fine} = 6hk* n (n = [0,7]) $\delta = \delta_{coarse} + \delta_{fine}$ (Through N = 73)

Building a Direct Digital Synthesizer



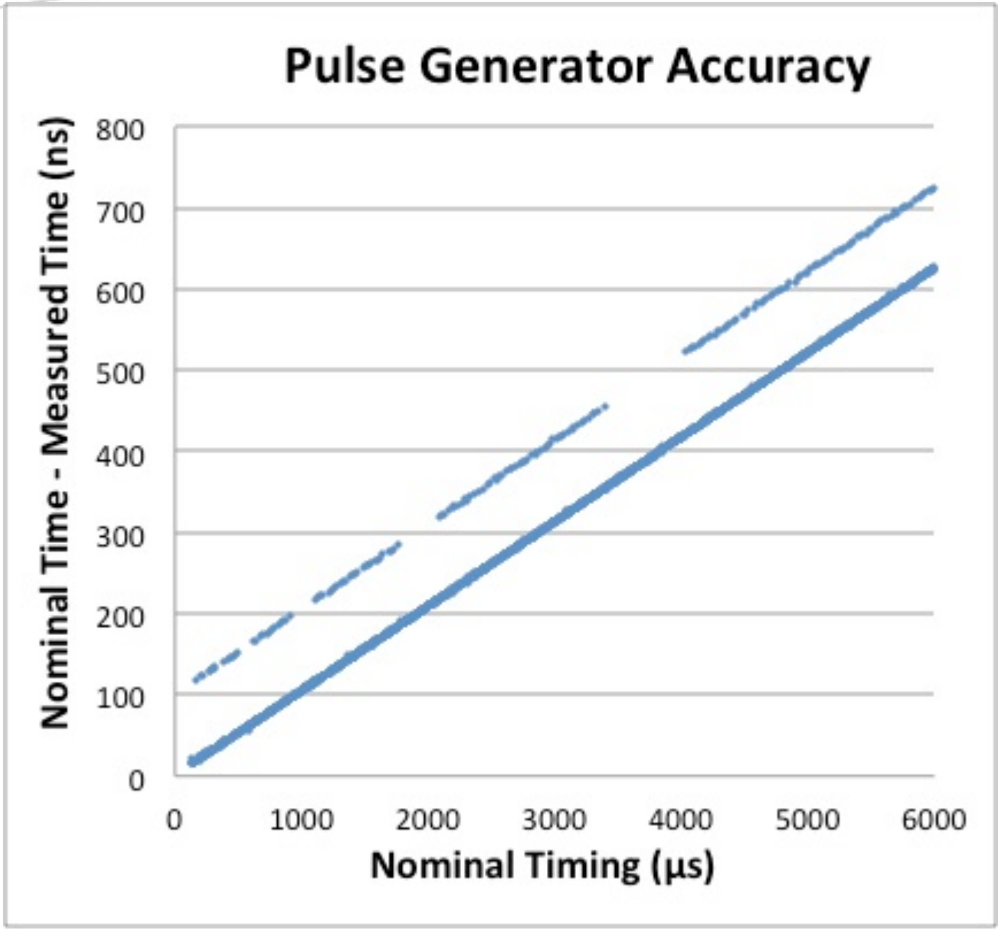
Testing the DDS

- DDS Sweep compensates for gravity with accuracy limited by knowledge of *g*
- Timing device used for testing found to be stable to within 30 ps



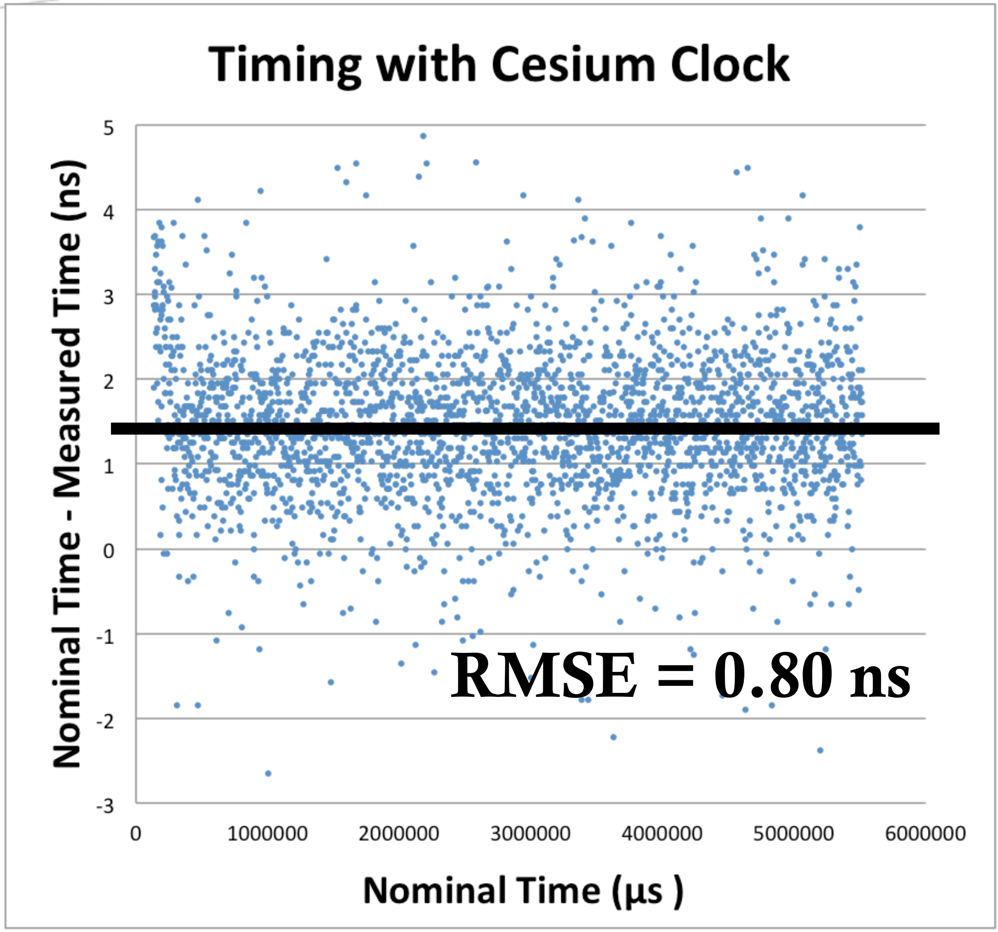
Analyzing Timing Stability

- Discovered for 104.1 ppm systematic error in timing
- Found 100 ns errors at repeatable timings



Corrected Timings

- Corrected for 104.1 ppm systematic error in timing
- Compensated for 100 ns errors at repeatable timings
- Remaining timing jitter statistical
  - $\Delta T \leq 20$ ps possible after 2500 shots (10hr)



Conclusions and Next Steps

- New DDS setup built and ready for integration into the experiment
- Discovered and corrected systematic timing variations
- Vertical setup is promising for 0.1 ppb level measurements of the fine structure constant

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