Towards Quantum Sensing with (Anti)Hydrogen: HAICU at TRIUMF and ALPHA at CERN

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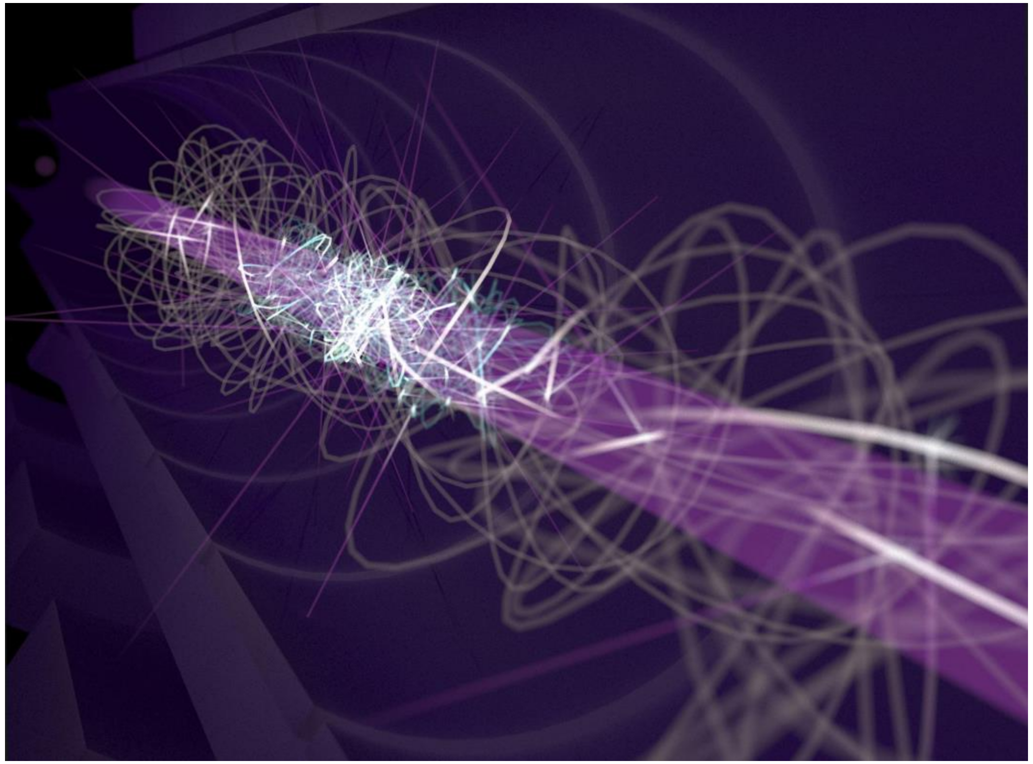
11 March 2024

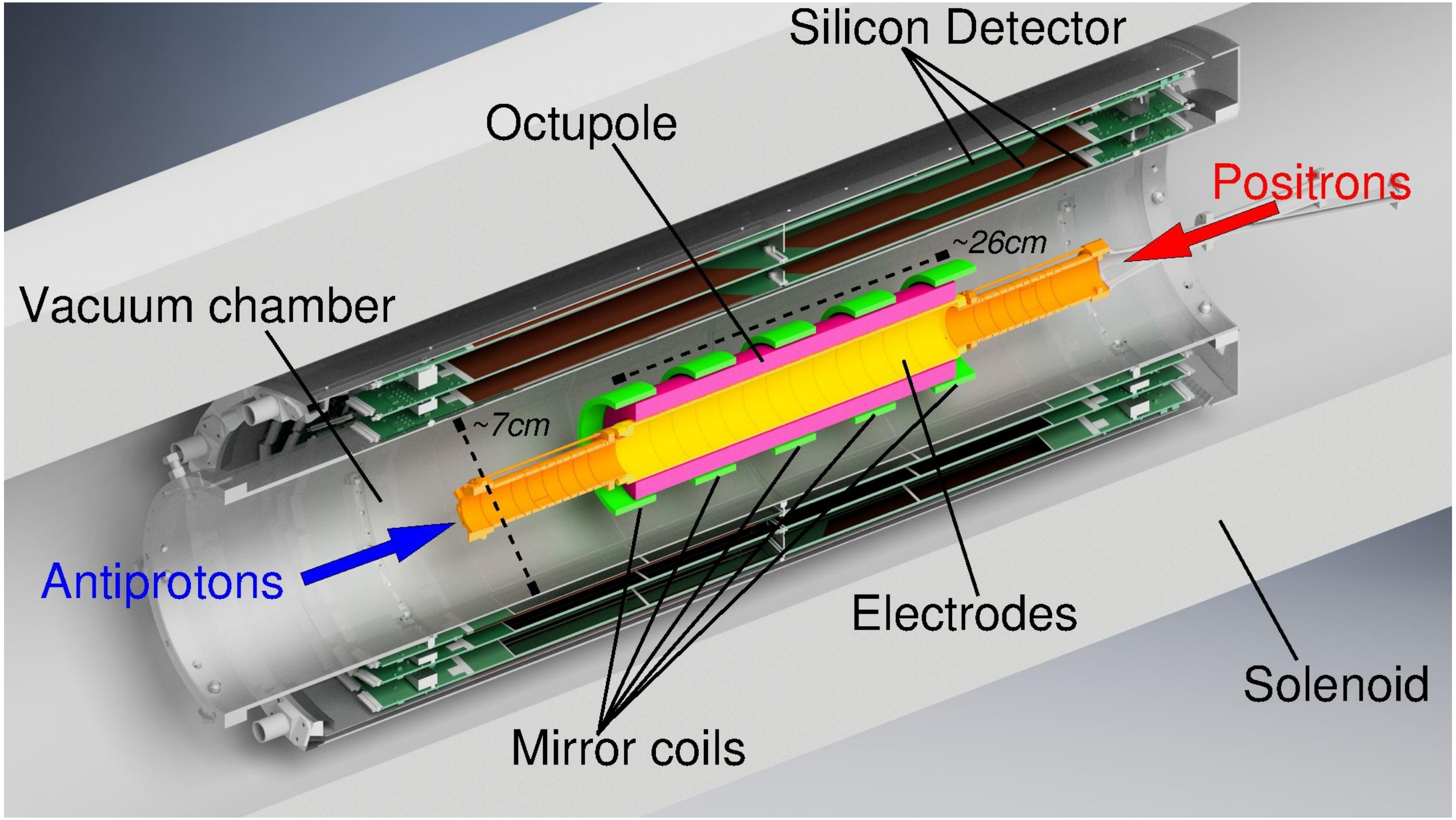
TRIUMF Quantum Workshop



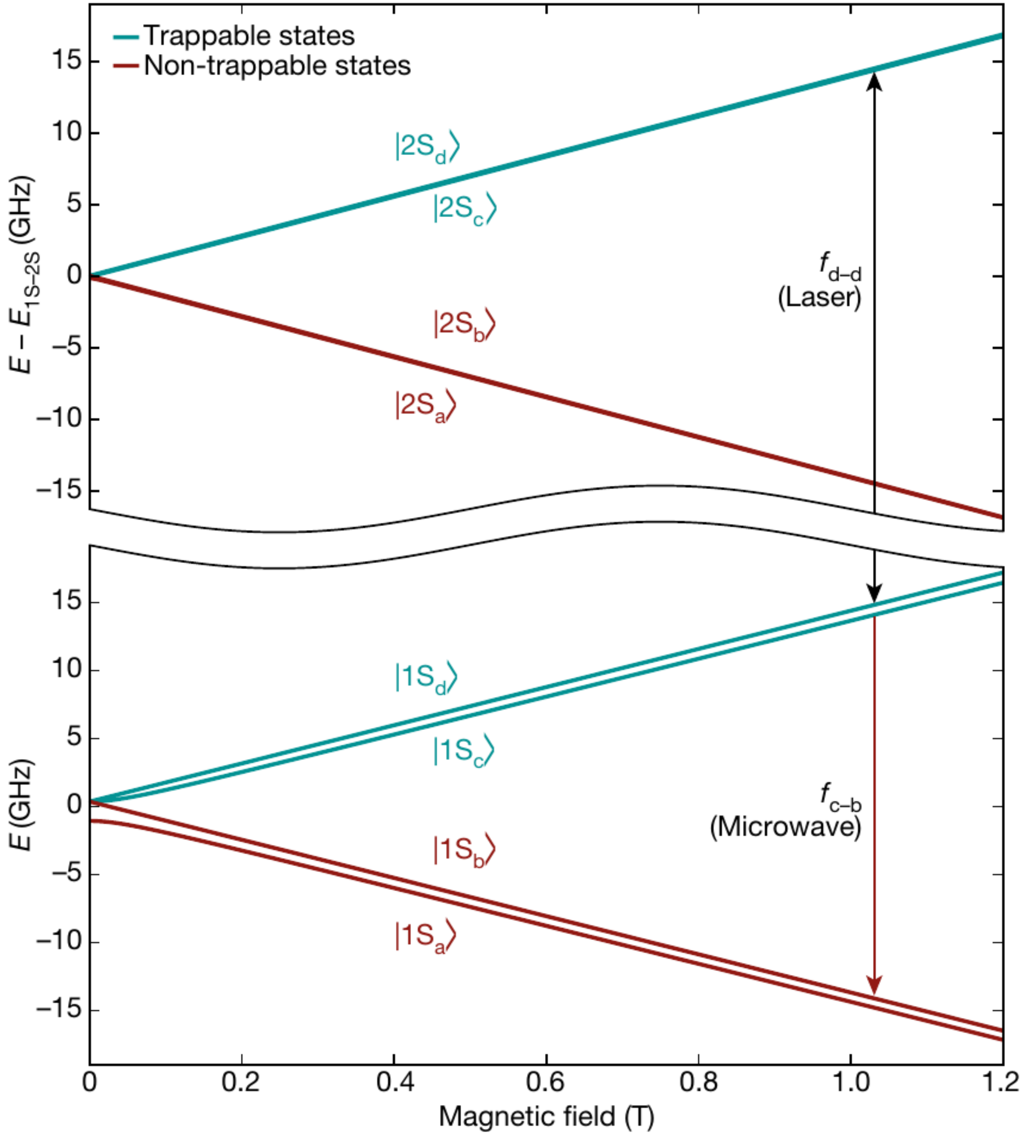
ALPHA Program

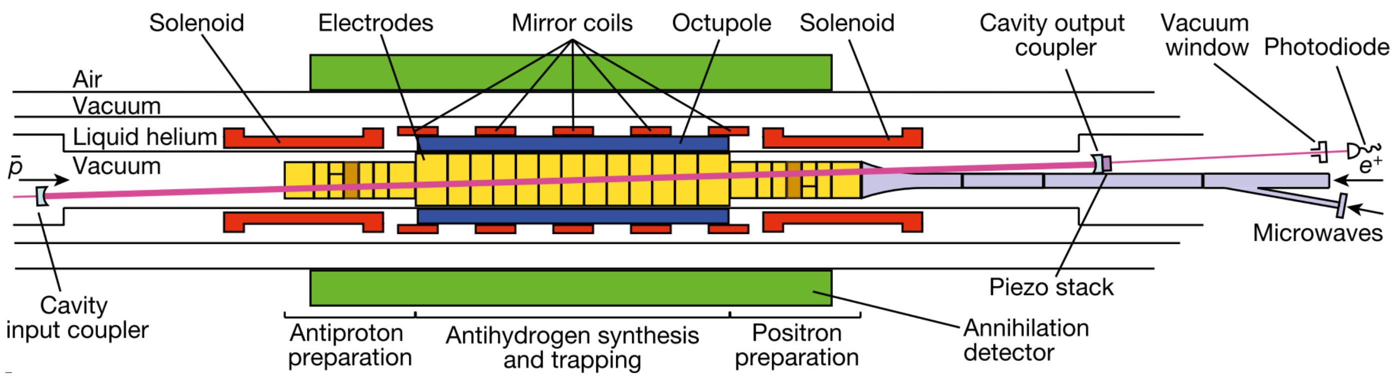
- Study fundamental symmetries
  - precision measurements pave the way to New Physics
- CPT symmetry:
  - implies that atomic spectra of hydrogen and antihydrogen are identical
- Einstein's Equivalence Principle
  - Matter and Antimatter fall with same with the same acceleration
- Ultimate precision with quantum sensors

ALPHA-2 @ CERN


Silicon Detector
Octupole
Positrons
~26cm
Vacuum chamber
~7cm
Antiprotons
Electrodes
Solenoid
Mirror coils

Precision Measurement





- Measurement in Antihydrogen: 1S-2S 2×10^{-12} @ 1T
  Nature 541, 506 (2017), Nature 557, 71 (2018)
- Hydrogen: 4×10^{-15} (beam)
  PRL 107, 203001 (2011)

Example: Fundamental Constants

$$E_{nlj} = R_\infty\left(-\frac{1}{n^2} + f_{nlj}\left(\alpha, \frac{m_p}{m_e}, \ldots\right) + \delta_{l0}\frac{c_{NS}}{n^3} r_P^2\right)$$

- Measurement of 2S-4P in hydrogen 4×10^{-12} *Science* **358**,79-85(2017).
- Combined with 1S-2S yields Rydberg constant at 10^{-12} level and proton charge radius ~1%

Main Limitations due to Broadening Effects

1. Availability of antiatoms: $\frac{1}{\sqrt{N}}$

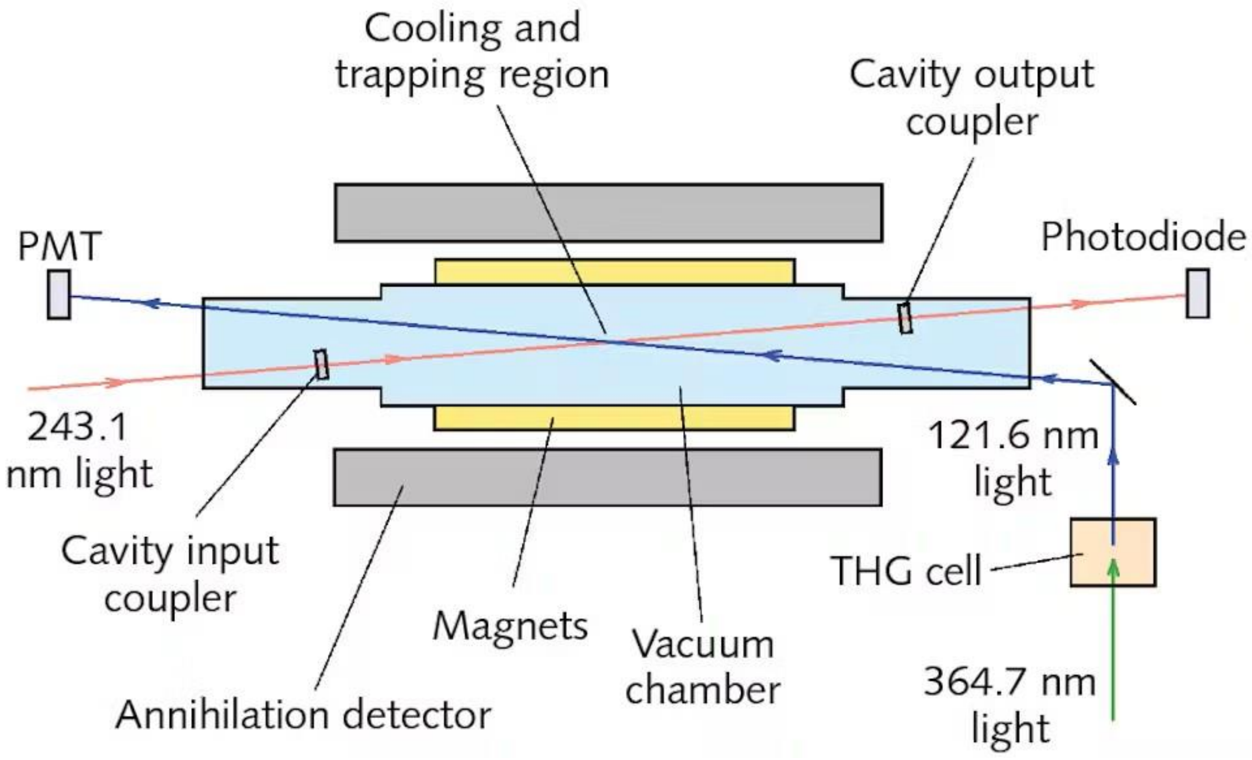
2. Finite temperature, e.g., transit-time broadening: linear with (transverse) velocity

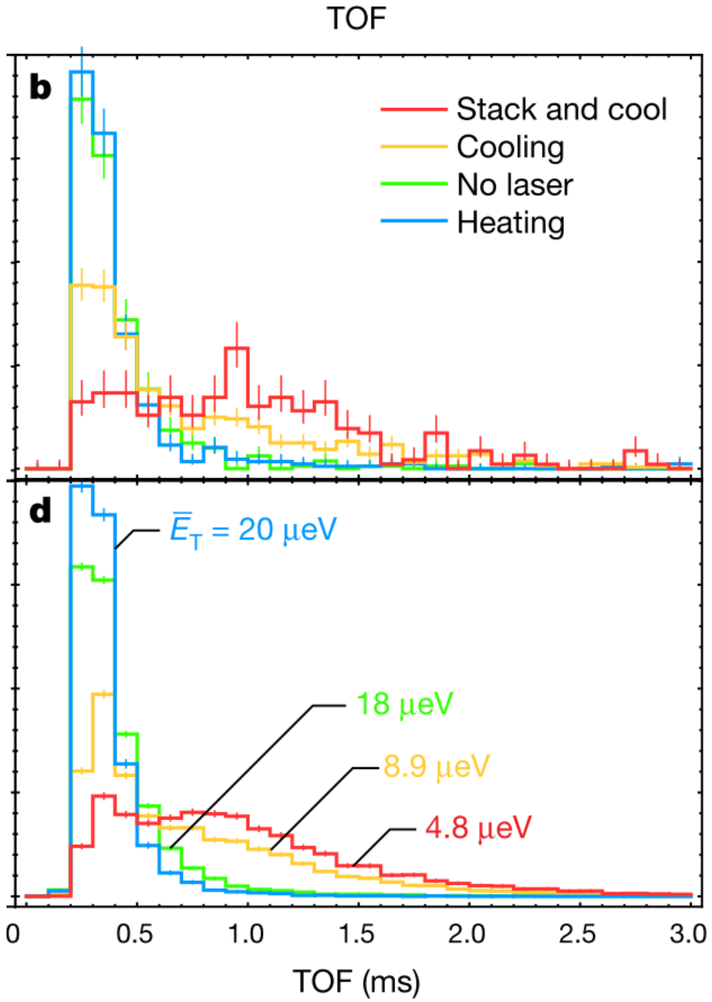
3. Zeeman shift: ~kHz/B

- Improvement required to exploit the full potential of quantum sensors!

Laser Cooling of Antihydrogen – ALPHA-2

Cooling transition: 1S,d → 2P,a





Pulsed 121 nm laser: ~nJ in ~20ns at 10Hz

Radial Energy reduced by factor of ~4

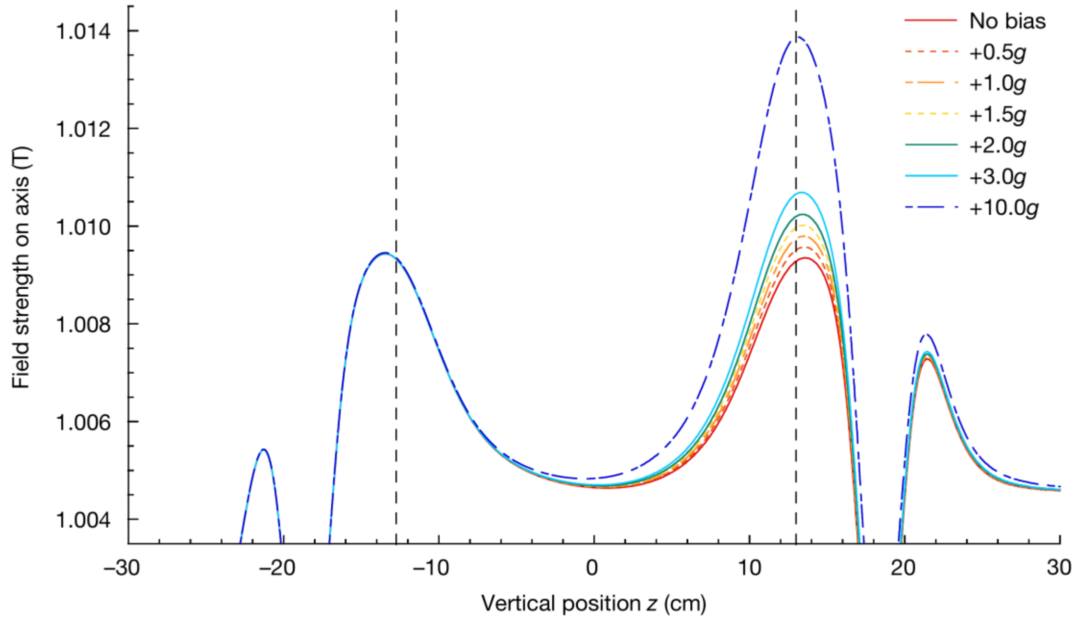
Cooling increase the **Time-Of-Flight** (annihilation) to wall

Manipulation of (Anti)Hydrogen – ALPHA-g

Article

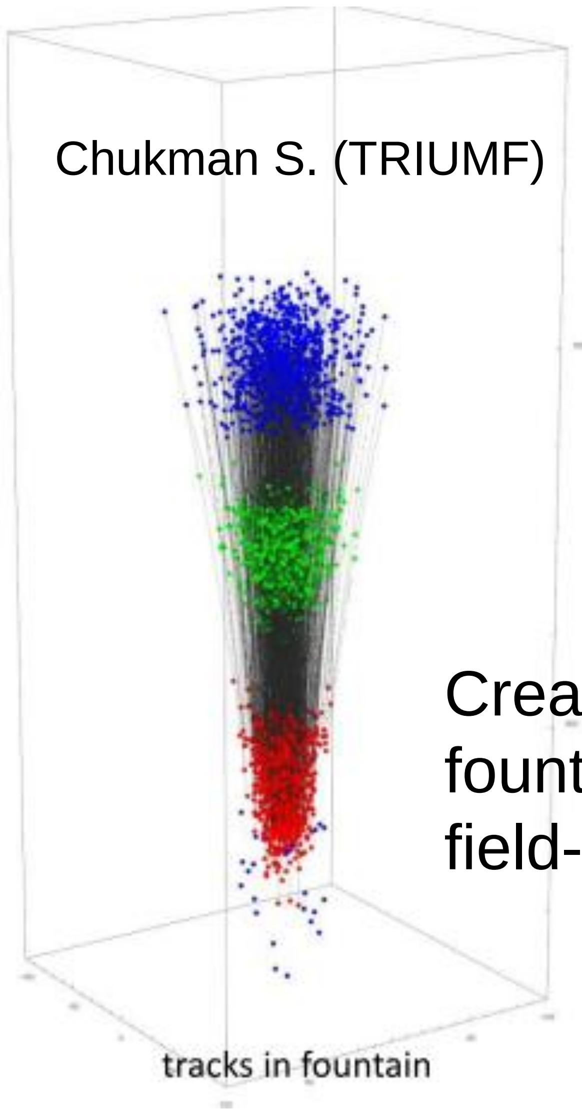
Observation of the effect of gravity on the motion of antimatter

Nature **621**, 28 September 2023



- Magnetic field gradients to push antihydrogen F ~ ∇B

Chukman S. (TRIUMF)



Create atomic fountain in field-free region

HAICU Phased Approached

- Wall-free trapping of antihydrogen
- Fluorescence detection
- Laser cooling

- Cool below Doppler limit with “Adiabatic Expansion Cooling”
- Hydrogen Fountain

Quantum sensing with Hydrogen: e.g. Interferometer

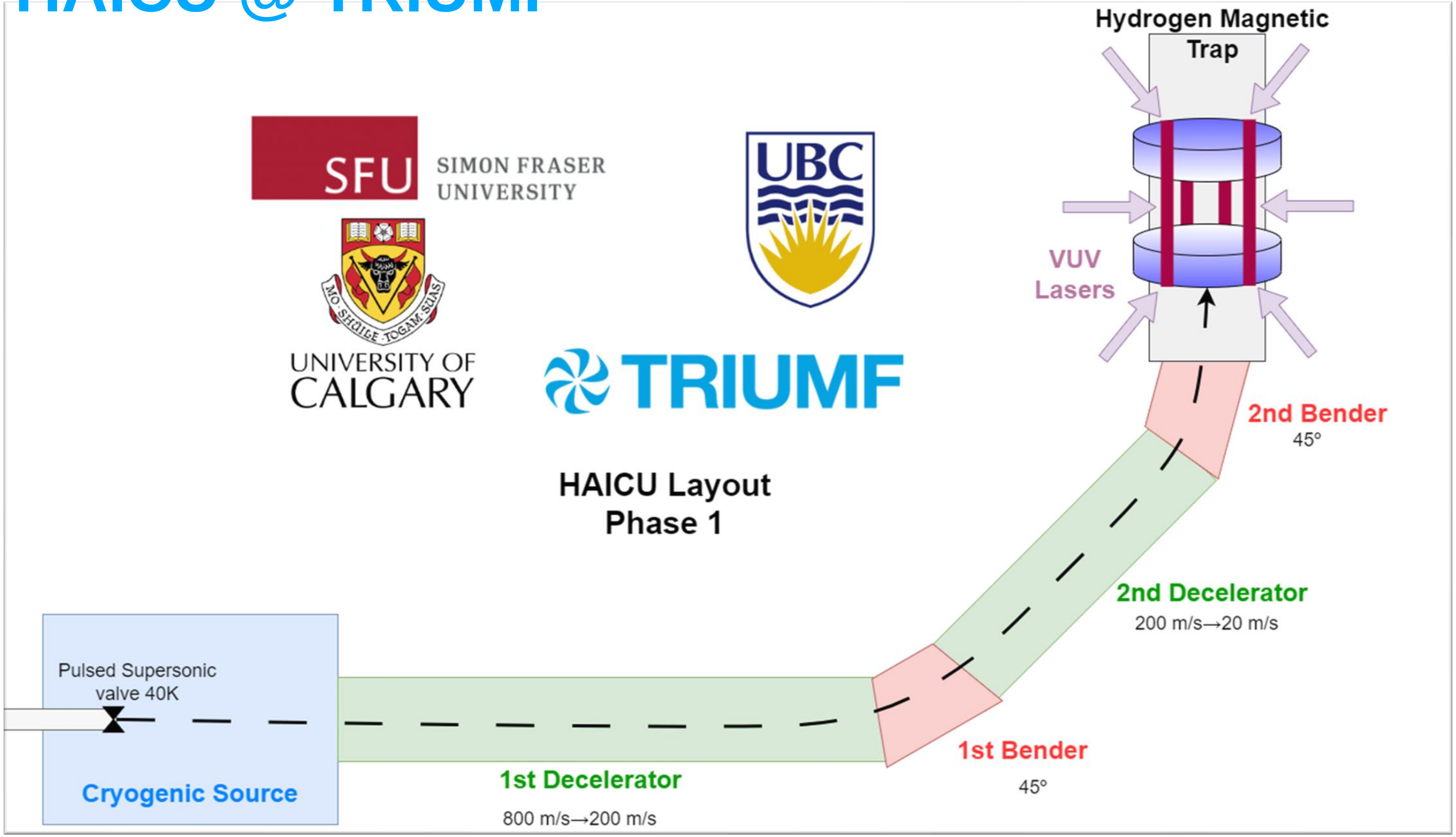
Drawing board

Develop techniques in hydrogen compatible with ALPHA setup at CERN:

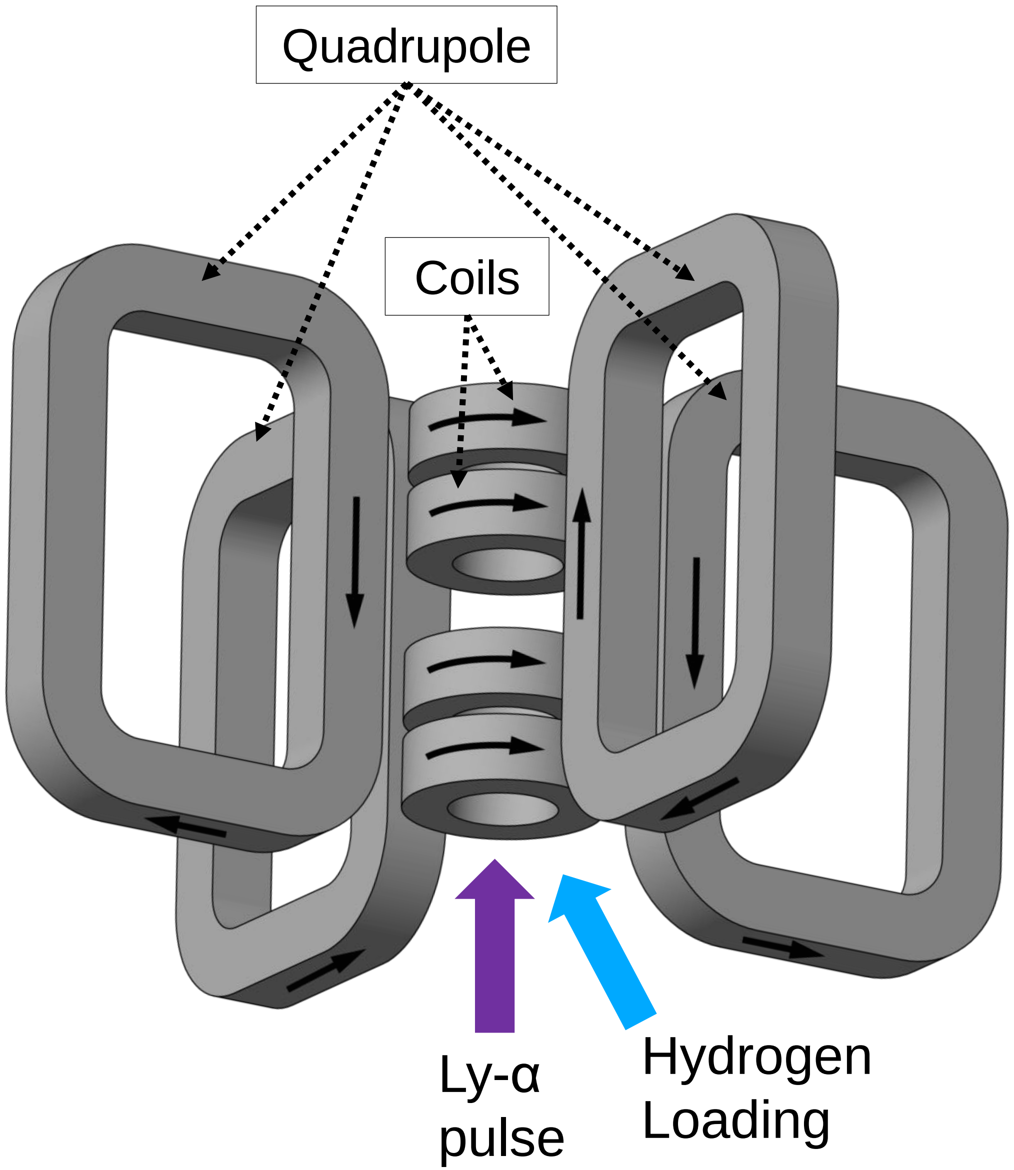
Cold (anti)hydrogen and move it to field-free region

Establish quantum protocols to make precision measurements in (anti)hydrogen

HAICU @ TRIUMF

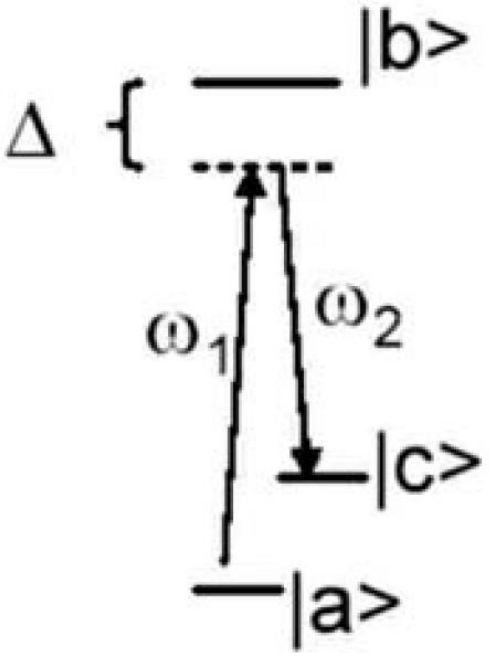


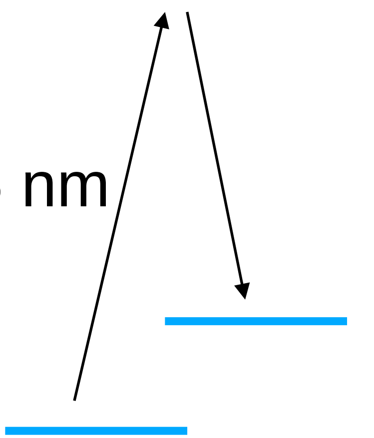
HAICU Hydrogen Trap (current design)

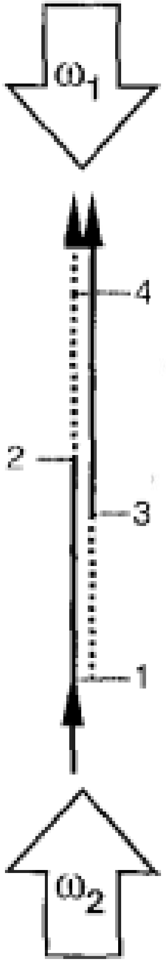


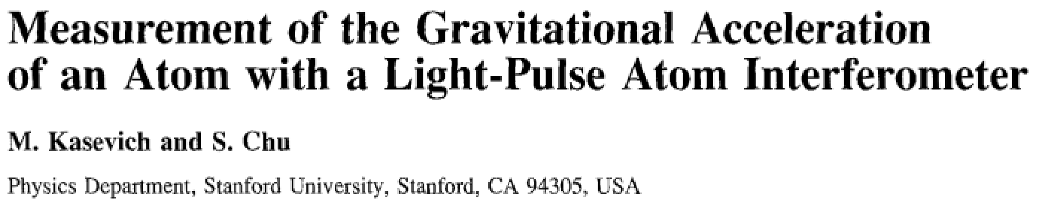
- Ioffe-Pritchard Trap (same as ALPHA but with quadrupole)
- Normal conducting magnets
  - Bitter coils (current flows through sheets of conductors)
- |B| = 0.15 T at trap centre
- Max |B| = 0.376 T

Raman Interferometry





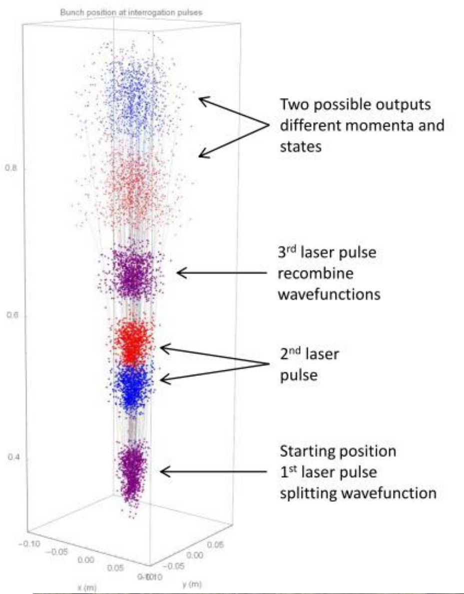




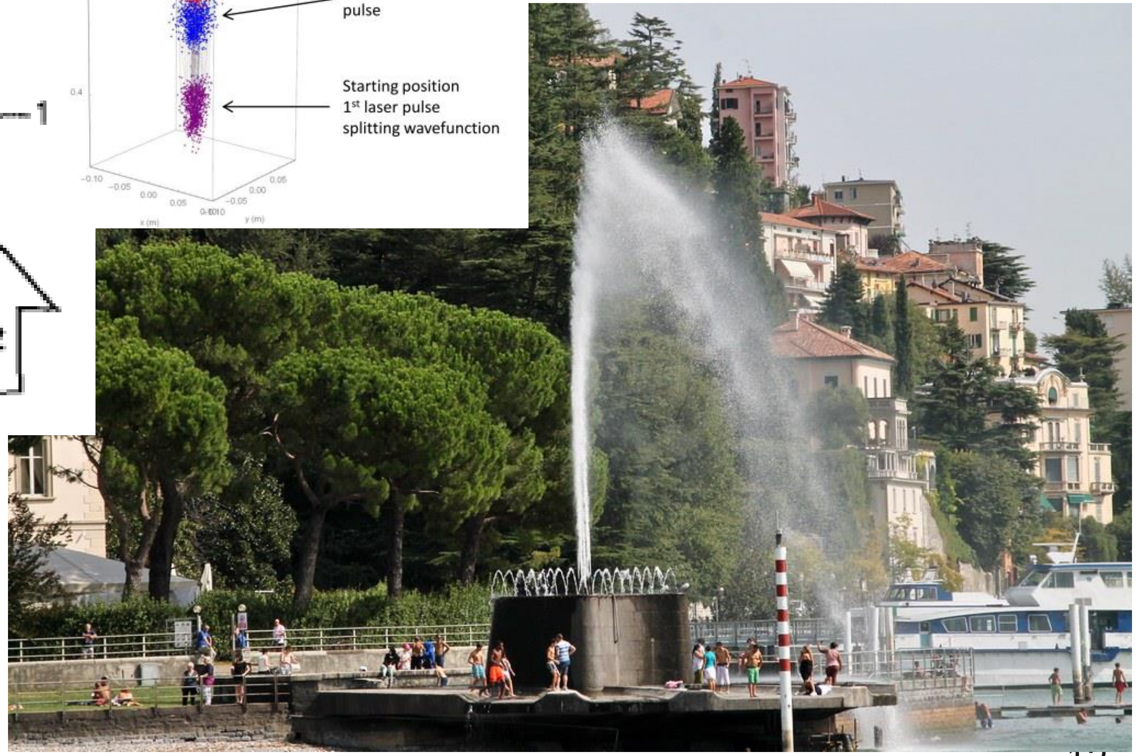
Measurement of the Gravitational Acceleration of an Atom with a Light-Pulse Atom Interferometer

M. Kasevich and S. Chu

Physics Department, Stanford University, Stanford, CA 94305, USA

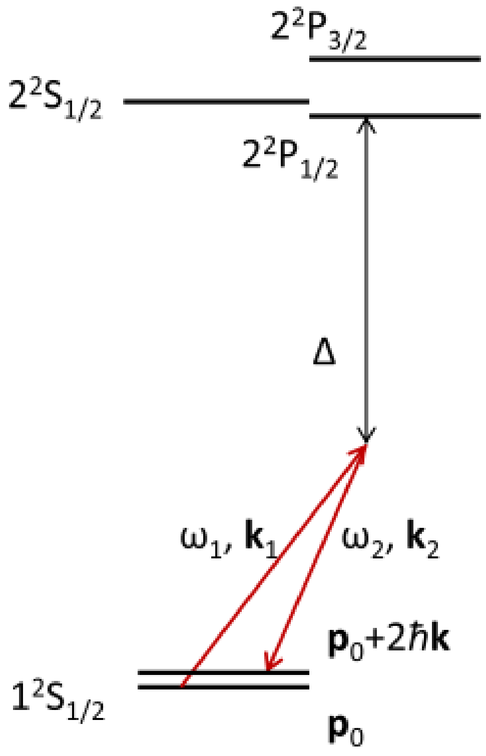


Atomic Gravimeter



Momentum kick ~2ħk
No spontaneous emission
2S metastable state HFS ~177MHz @ 0T

Another Antihydrogen AI Proposal



Bragg transition in (anti)hydrogen

PRL **112,** 121102 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

Antimatter Interferometry for Gravity Measurements

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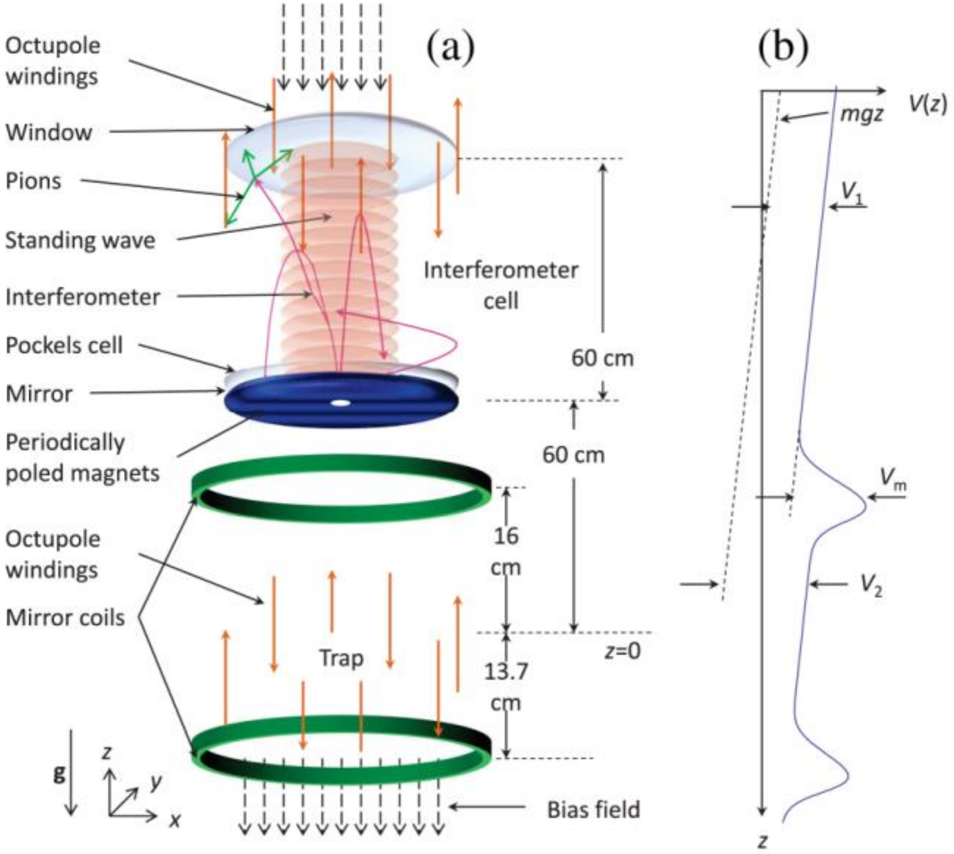
(Received 12 August 2013; published 25 March 2014)



Summary

- Antihydrogen is a tool to search for New Physics (ALPHA)
- High-precision measurements using quantum technologies

- Develop techniques in hydrogen to push the quantum initiative at TRIUMF

Thank you
Merci

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REVIEWS OF MODERN PHYSICS, VOLUME 89, JULY–SEPTEMBER 2017

Quantum sensing

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(published 25 July 2017)

Current ALPHA → (I) Use of a quantum object to measure a physical quantity (classical or quantum). The quantum object is characterized by quantized energy levels. Specific examples include electronic, magnetic or vibrational states of superconducting or spin qubits, neutral atoms, or trapped ions.

HAICU project → (II) Use of quantum coherence (i.e., wavelike spatial or temporal superposition states) to measure a physical quantity.

Future! → (III) Use of quantum entanglement to improve the sensitivity or precision of a measurement, beyond what is possible classically.

✓ (1) The quantum system has discrete, resolvable energy levels. Specifically, we assume it to be a two-level system (or an ensemble of two-level systems) with a lower energy state $|0\rangle$ and an upper energy state $|1\rangle$ that are separated by a transition energy $E = \hbar\omega_0$ (see Fig. 1).[1]

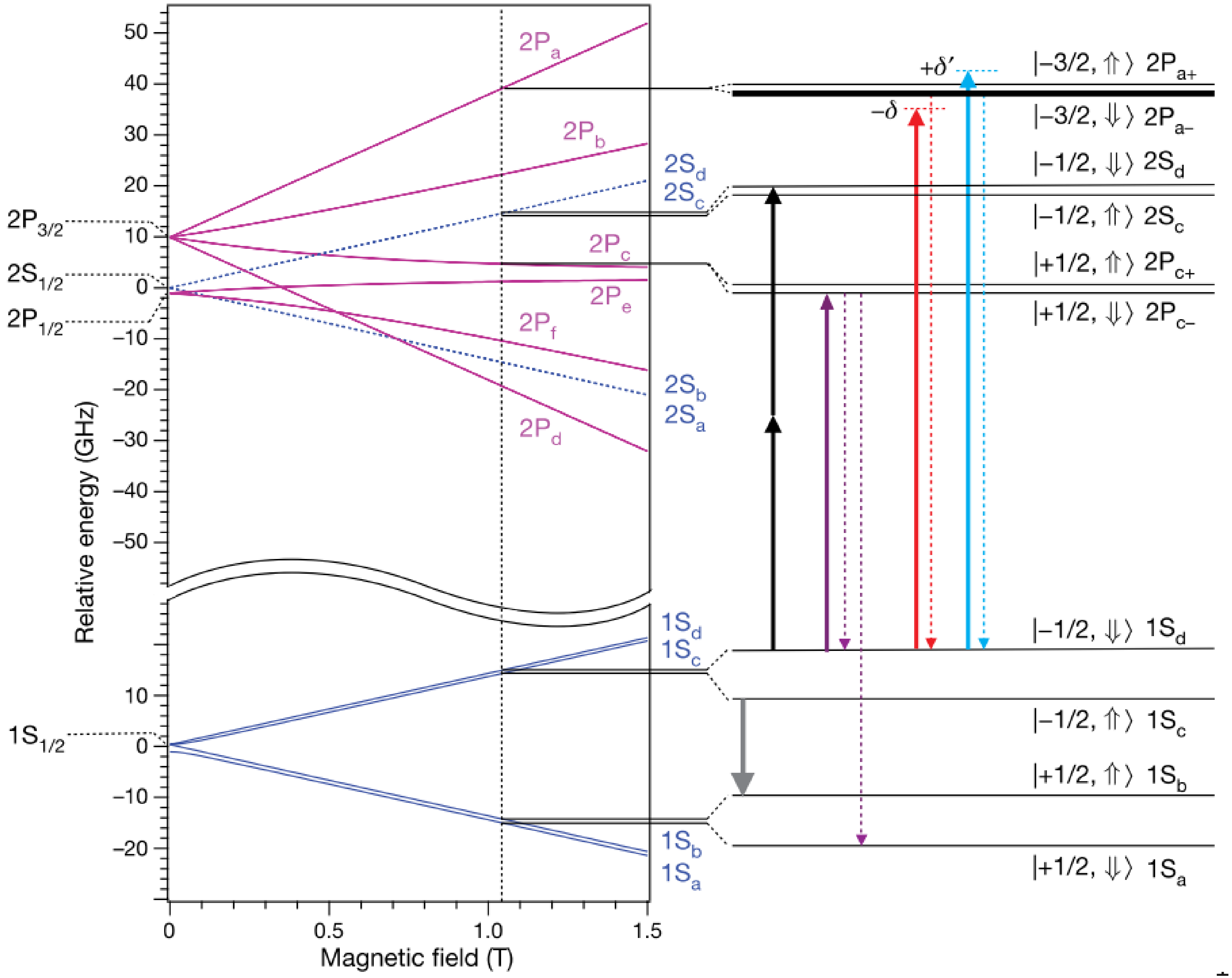
✓ (2) It must be possible to initialize the quantum system into a well-known state and to read out its state.

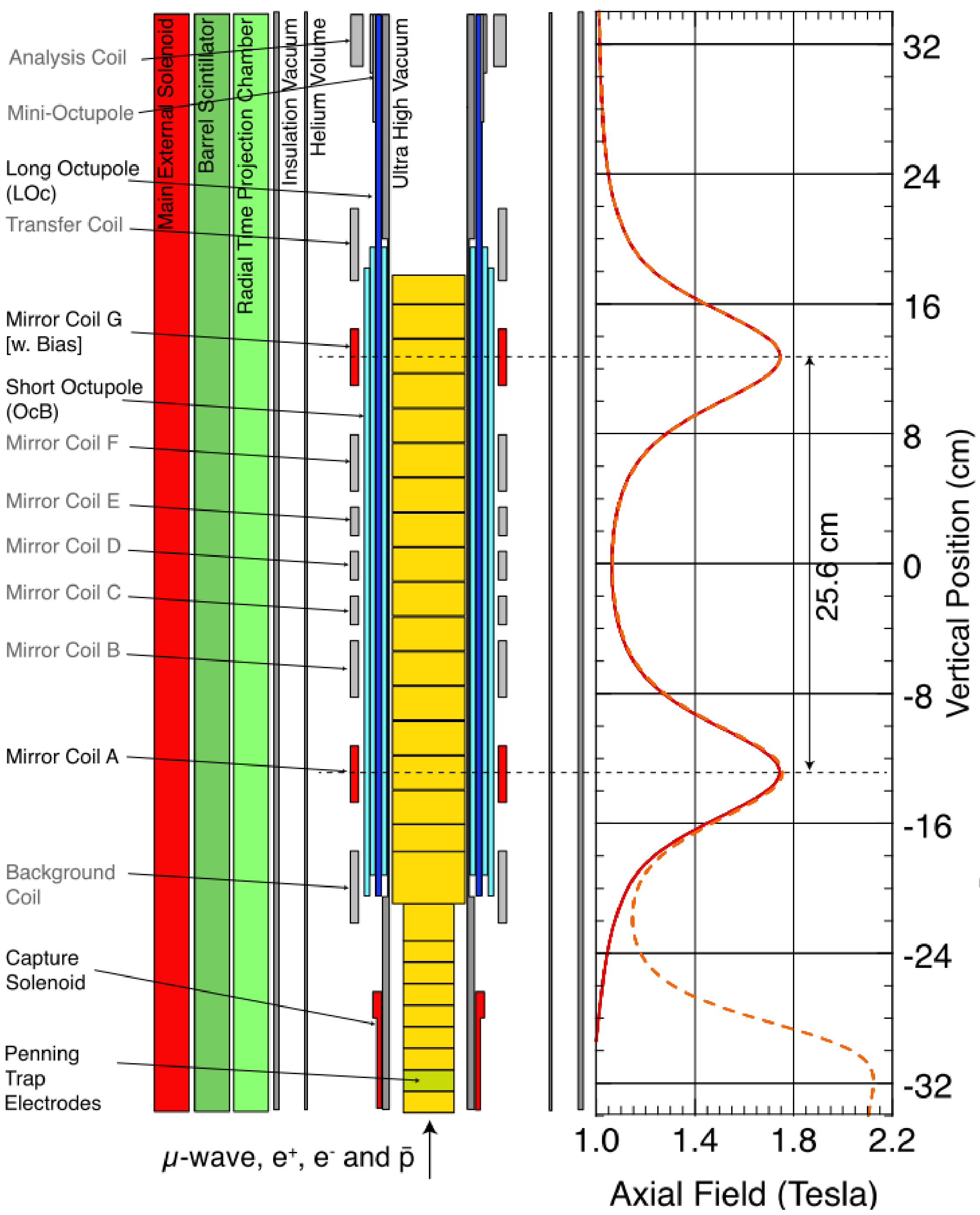
✓ (3) The quantum system can be coherently manipulated, typically by time-dependent fields. This condition is not strictly required for all protocols; examples that fall outside of this criterion are continuous-wave spectroscopy or relaxation rate measurements.

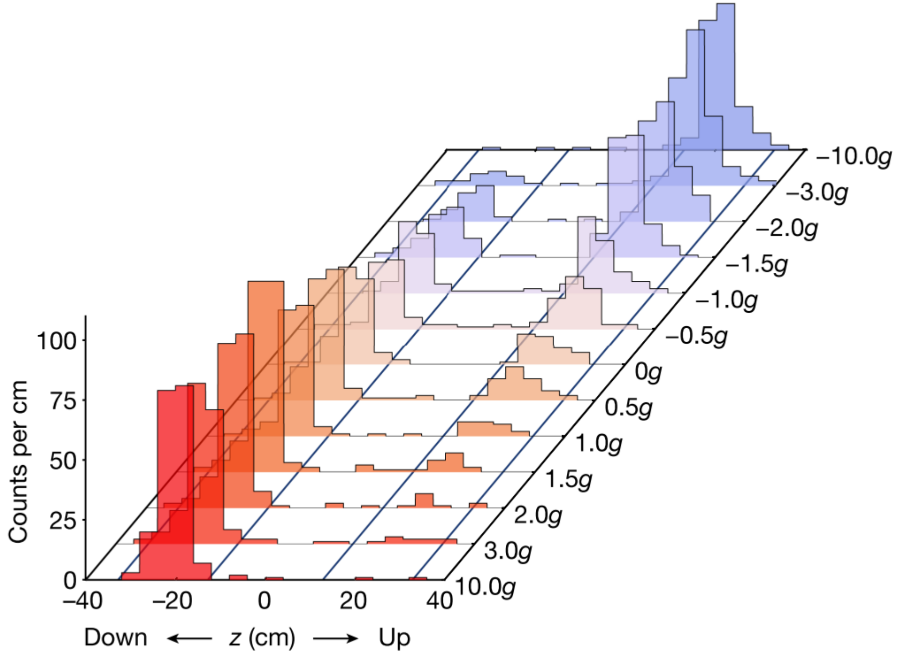
✓ (4) The quantum system interacts with a relevant physical quantity $V(t)$, such as an electric or magnetic field. The interaction is quantified by a coupling or transduction parameter of the form $\gamma = \partial^q E/\partial V^q$ which relates changes in the transition energy E to changes in the external parameter V. In most situations the coupling is either linear ($q = 1$) or quadratic ($q = 2$). The interaction with V leads to a shift of the quantum system's energy levels or to transitions between energy levels (see Fig. 1).

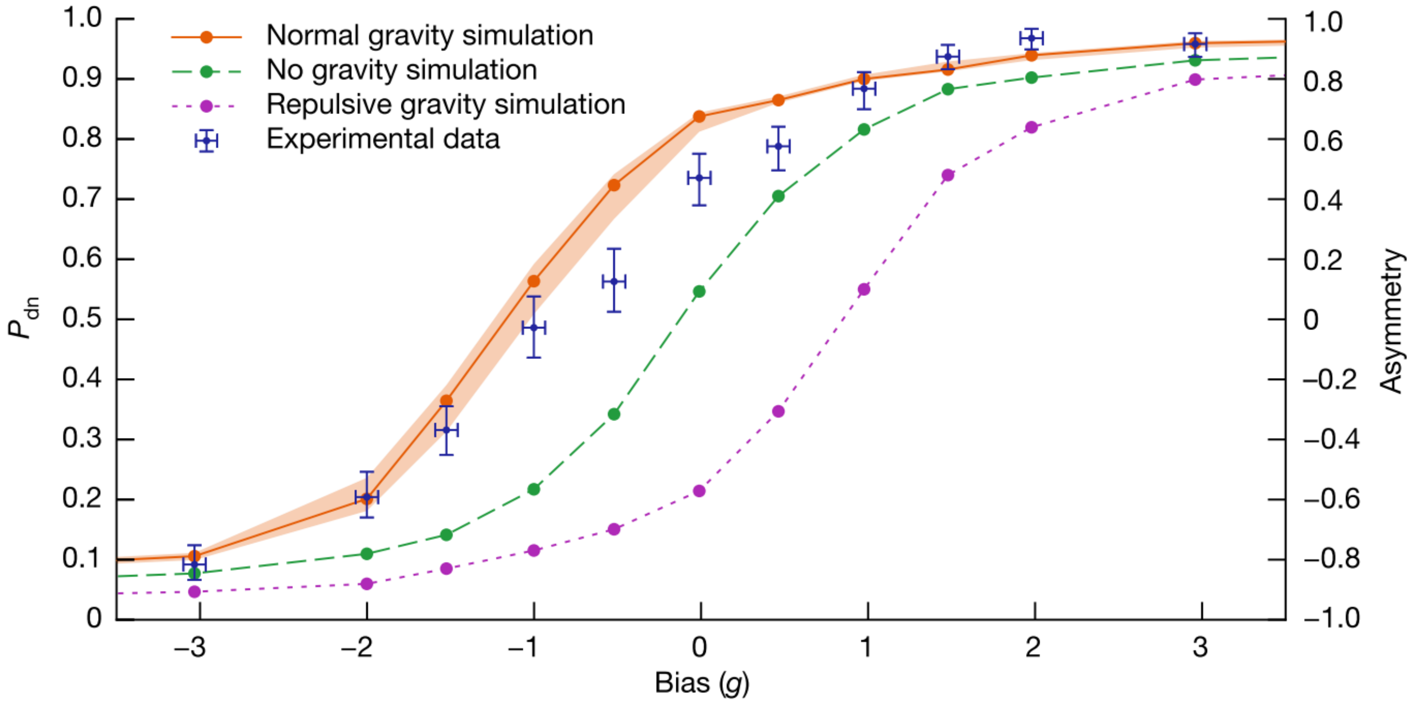
Laser Cooling

Nature 592 (2021)




Analysis Coil
Mini-Octupole
Long Octupole (LOc)
Transfer Coil
Mirror Coil G [w. Bias]
Short Octupole (OcB)
Mirror Coil F
Mirror Coil E
Mirror Coil D
Mirror Coil C
Mirror Coil B
Mirror Coil A
Background Coil
Capture Solenoid
Penning Trap Electrodes
Main External Solenoid
Barrel Scintillator
Radial Time Projection Chamber
Insulation Vacuum
Helium Volume
Ultra High Vacuum
μ-wave, e⁺, e⁻ and p̄
25.6 cm
Vertical Position (cm)
Axial Field (Tesla)
32
24
16
8
0
-8
-16
-24
-32
1.0
1.4
1.8
2.2


Counts per cm
100
75
50
25
0
−40
−20
0
20
40
Down ⟵ z (cm) ⟶ Up
−10.0g
−3.0g
−2.0g
−1.5g
−1.0g
−0.5g
0g
0.5g
1.0g
1.5g
2.0g
3.0g
10.0g


Normal gravity simulation
No gravity simulation
Repulsive gravity simulation
Experimental data
P_{dn}
Asymmetry
Bias (g)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−3
−2
−1
0
1
2
3
1.0
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1.0