The HAICU Experiment at TRIUMF

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TRIUMF

Science Week
22 July 2024

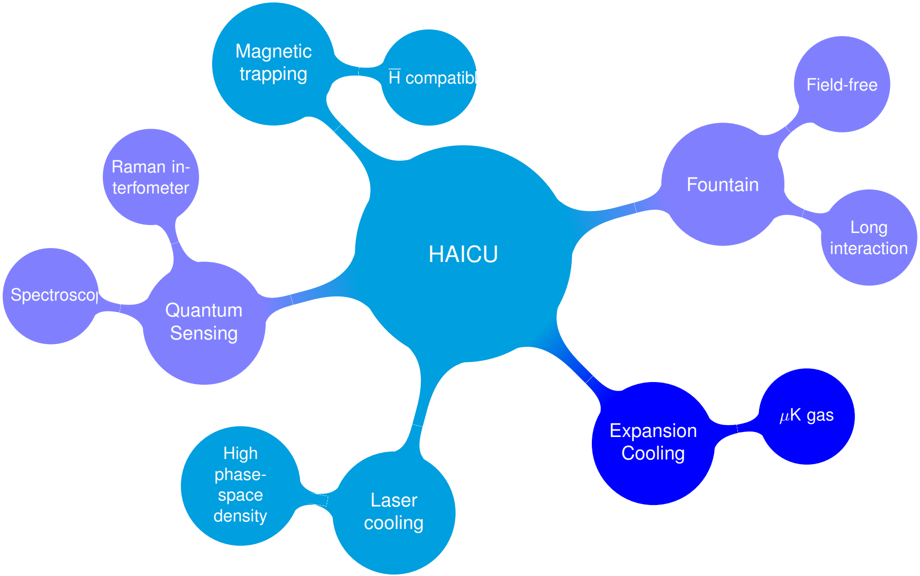
TRIUMF

Hydrogen-Antihydrogen Infrastructure of Canadian Universities

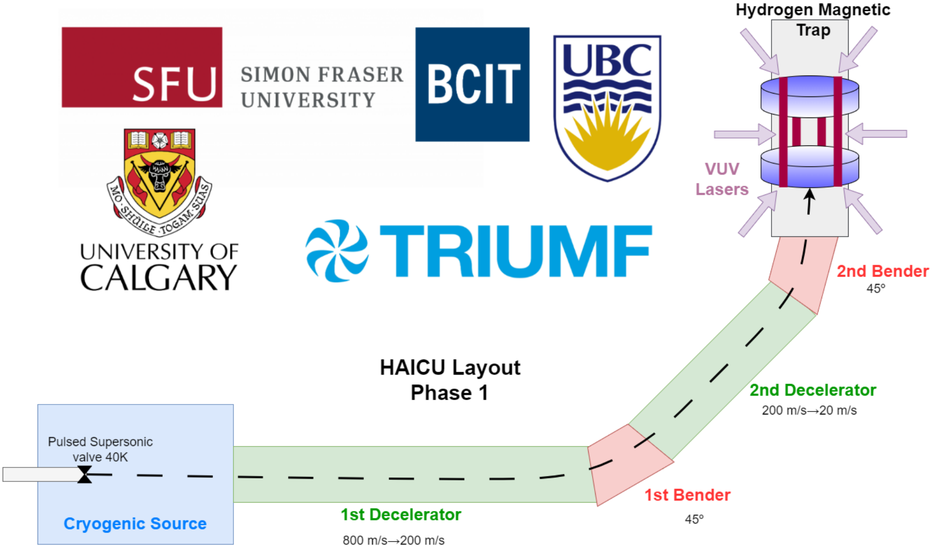
- ✎ Platform to develop quantum sensing techniques on H
- ✎ Pathfinder for next generation of $\overline{\text{H}}$ experiments

- H trapping and detection compatible with ALPHA $\overline{\text{H}}$ at CERN
  - ALPHA = magnetic trapping of $\overline{\text{H}}$ at CERN *The ALPHA antihydrogen trapping apparatus* NIM A **735** (2014)
  - Goal: compare H and $\overline{\text{H}}$ to highest attainable precision
  - spectroscopy *Characterization of the 1S-2S transition in antihydrogen* Nature **557**, 7703 (2018)
  - gravity *Observation of the effect of gravity on the motion of antimatter* Nature **621**, 7980 (2023)

- Reduce main sources of systematic errors in ALPHA ⇒ (Anti-)Atomic fountain
  - Magnetic field gradient (necessary for trapping) ⇒ Field-free region
  - Transit time (line broadening in spectroscopy) ⇒ Long interaction time

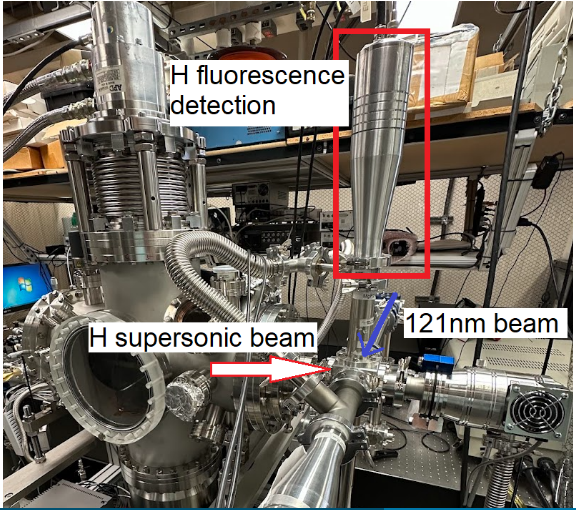

Magnetic trapping
$\overline{\mathrm{H}}$ compatibl
Field-free
Raman in-terfometer
Fountain
HAICU
Long interaction
Spectrosco
Quantum Sensing
Expansion Cooling
μK gas
High phase-space density
Laser cooling

The HAICU experiment at TRIUMF



Hydrogen Source

- Generate H beam with $> 10^{12}$ particles/cm^3 at < 900 m/s velocity



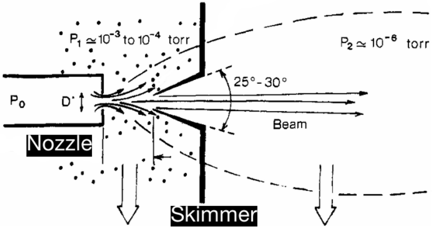
1. H_2 in Ne or He supersonic expansion
2. H generation by molecular dissociation (DC discharge or microwave)

Supersonic H gas: 200K, 90psi, 3kV discharge

R. Akhbari (UBC)

Supersonic Beam

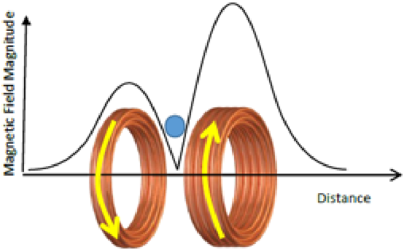
- High-brightness H beam from supersonic nozzle:
  - increase particle flux and narrows the temperature
  - convert a large fraction of the gas's initial enthalpy into translational energy.
- Supersonic transition occurs at nozzle choke point.
- For Mach number $\mathcal{M} \geq 1$ flow rate increases with increasing cross section.
- $P_2 \to 0$ implies $\mathcal{M} \to \infty$, i.e., the initial thermal energy has been converted into translational energy.



J.R. Gardner *Neutral Atom Imaging...* Springer (2018)

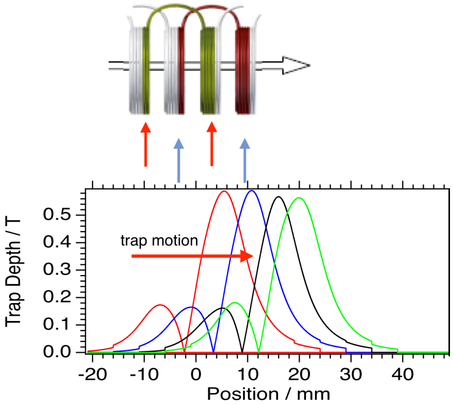
$$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{\gamma/(\gamma-1)} \qquad \gamma = \frac{c_P}{c_V}$$

$$v_{\max} = \sqrt{\frac{2k_B T_1}{m}\frac{\gamma}{\gamma - 1}}$$



Small coil has 8 windings while large coil has 16 windings ⇒ Asymmetric field with minimum

Force on atom $= -\frac{\mathrm{d}U}{\mathrm{d}z} = -\frac{\mathrm{d}U}{\mathrm{d}B}\frac{\mathrm{d}B}{\mathrm{d}z}$
$\frac{\mathrm{d}U}{\mathrm{d}B} \approx \mu_B$ and $\frac{\mathrm{d}B}{\mathrm{d}z} \approx 170$ T/m



Moving Trap by applying 600A current in $5 - 250\mu s$ pulses to anti-Helmholtz coils sequentially.

Design of the Zeeman Decelerator

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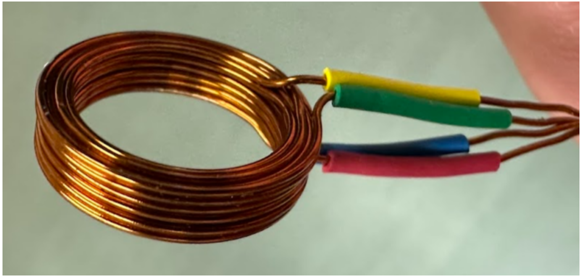
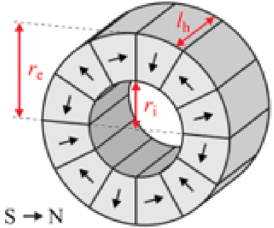
- 1st decelerator: 900 m/s → 350 m/s
  - 370 Anti-Helmholtz coils
  - 12.7 mm ID
  - 24 AWG wire
  - 6.5 mm trap-to-trap spacing
- 2nd decelerator: 350 m/s → 20 m/s
  - 100 Anti-Helmholtz coils
  - 10 mm ID.
  - 26 AWG wire.
  - 5 mm trap-to-trap spacing.



C. Noort (UBC)

Bender Sections

- Blocks carrier gases while acting as a low-pass velocity filter

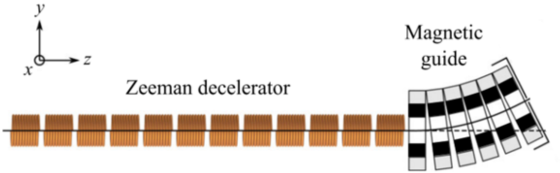


Bender element: hexapole Halback array

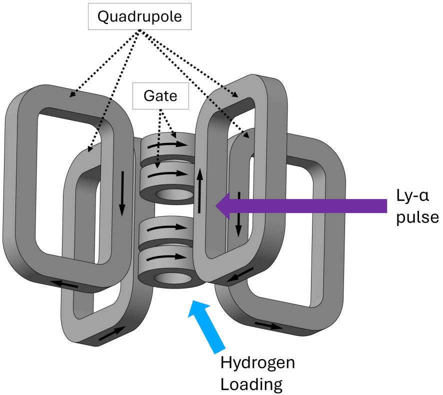
Force on atom $= \frac{mv^2}{R} = \mu_B \frac{\mathrm{d}B}{\mathrm{d}R}$

Max. velocity $\approx$ 360 m/s
for $R = 0.2$ m and $\frac{\mathrm{d}B}{\mathrm{d}R} \approx 100$ T/m

- 1st bender section using Halback array permanent magnets
- 2nd bender will use quadrupole focus

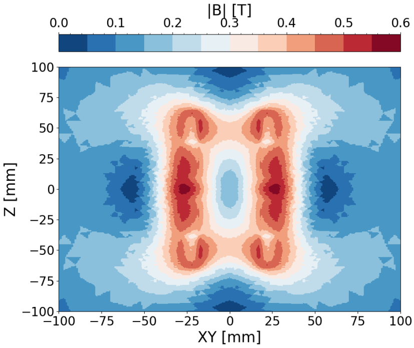


- Ioffe-Pritchard trap
- Water cooled magnets: Bitter coils



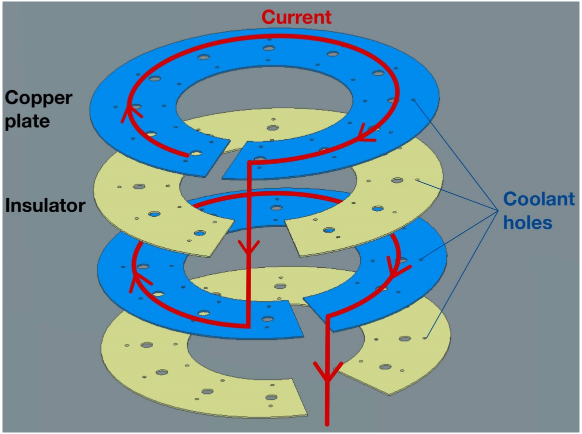
Trap design by Chukman So

- Length = 96 mm, radius is 16.2 mm
- $|B| = 0.15\,\mathrm{T}$ at trap centre, $\Delta B = 0.255\,\mathrm{T}$

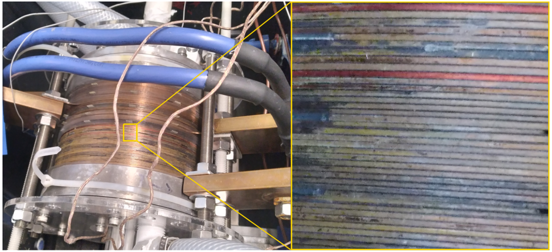


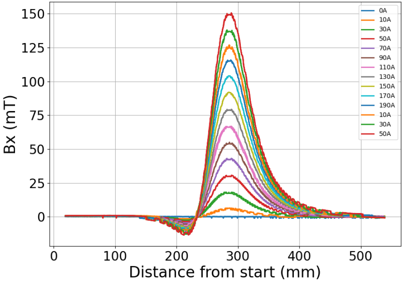
Prototype bitter coil testing

A. Papandreou

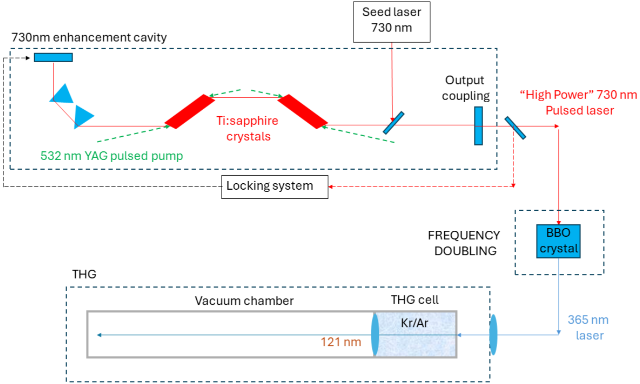


See, for example: IEEE Trans. Plasma Sci. **44** 4 (2016)





1. Generation of strong 730nm light pulse in enhancement cavity
2. Second harmonic (SHG) process to generate one pulse of 365nm light in BBO crystal
3. Third harmonic generation (THG) to generate 121.6nm light in Kr/Ar mixture

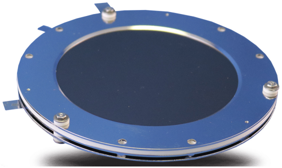


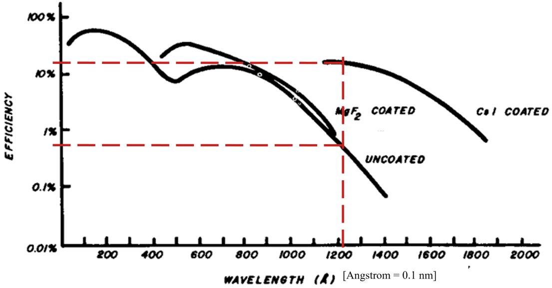
Hyperfine Interactions **228** 77-80 (2014)

Scheme developed by Taka Momose (UBC) and in use at ALPHA@CERN

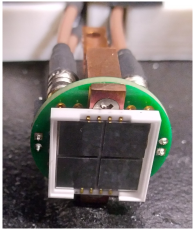
Fluorescence Detection

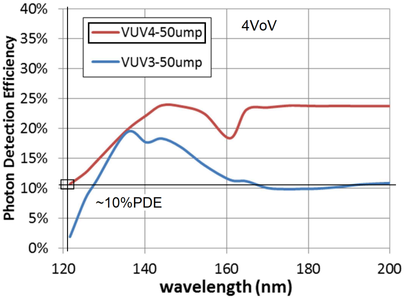
MCP by *Photonis* with CsI coating to enhance VUV sensitivity





Thermoelectric cooled SiPM by *Hamamatsu*: expected $T \sim 213\,\mathrm{K}$





Readout design by P. Margetak, VUV4 from P. Giampa

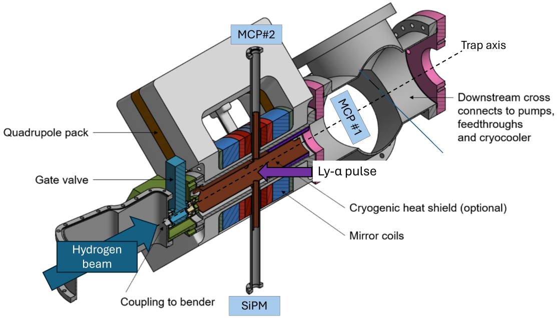
1. H production at cryogenic source
2. Magnetic trap energized, except for *bottom gate*
3. Delivery to magnetic trap via Zeeman decelerator $\approx 6\,\text{ms}$
4. Bottom gate ramp in $\approx 10\,\text{ms}$
5. Lyman-α pulse at 10-50 Hz

   ...

6. 1D laser cooling

   ...

7. 3D laser cooling



HAICU Status

TRIUMF

- 121nm generation is established at UBC
- Optimization of H source at UBC
- Decelerator is being built at UBC
- Bitter coils prototyping at TRIUMF
- Quadrupole assembly at TRIUMF

Quadrupole compression plate manufactured at U. Calgary machine shop

Water cooling testing outside Detector Facility by J. Ewins

Article

Observation of the effect of gravity on the motion of antimatter

https://doi.org/10.1038/s41586-023-06527-1

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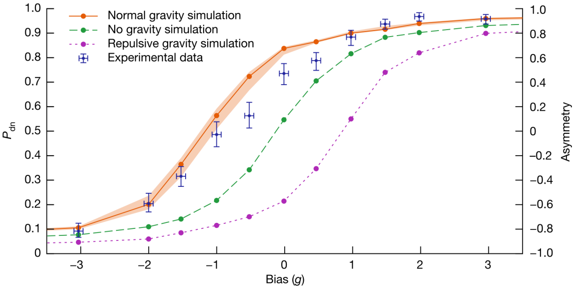
Open access

Check for updates

E. K. Anderson[1], C. J. Baker[2], W. Bertsche[3,4]✉, N. M. Bhatt[2], G. Bonomi[5], A. Capra[6], I. Carli[6], C. L. Cesar[7], M. Charlton[2], A. Christensen[8], R. Collister[6,9], A. Cridland Mathad[2], D. Duque Quiceno[6,9], S. Eriksson[2], A. Evans[6,9], N. Evetts[9], S. Fabbri[3,10], J. Fajans[8]✉, A. Ferwerda[11], T. Friesen[12], M. C. Fujiwara[6], D. R. Gill[6], L. M. Golino[2], M. B. Gomes Gonçalves[2], P. Grandemange[6], P. Granum[1], J. S. Hangst[1]✉, M. E. Hayden[13], D. Hodgkinson[3,8], E. D. Hunter[8], C. A. Isaac[2], A. J. U. Jimenez[6], M. A. Johnson[3,4], J. M. Jones[2], S. A. Jones[14], S. Jonsell[15], A. Khramov[6,9,16], N. Madsen[2], L. Martin[6], N. Massacret[6], D. Maxwell[2], J. T. K. McKenna[1,3], S. Menary[11], T. Momose[6,9,17], M. Mostamand[6,17], P. S. Mullan[2,18], J. Nauta[2], K. Olchanski[6], A. N. Oliveira[1], J. Peszka[2,18], A. Powell[12], C. Ø. Rasmussen[19], F. Robicheaux[20], R. L. Sacramento[7], M. Sameed[3,21], E. Sarid[22,23], J. Schoonwater[2], D. M. Silveira[7], J. Singh[3], G. Smith[6,9], C. So[6], S. Stracka[24], G. Stutter[1,25], T. D. Tharp[26], K. A. Thompson[2], R. I. Thompson[6,12], E. Thorpe-Woods[2], C. Torkzaban[8], M. Urioni[5], P. Woosaree[12] & J. S. Wurtele[8]

$$(-0.75 \pm 0.13\ (\text{stat.+sys.}) \pm 0.16\ (\text{sim.}))\ g$$

$$P_{dn} = \frac{DW}{UP+DW} \qquad \text{Asymmetry} = \frac{UP-DW}{UP+DW} \qquad \text{Bias} = \frac{\mu_B(B_G-B_A)}{m_H(z_G-z_A)}$$



CBC | MENU

NEWS Sections

Science

Scientists drop antimatter to see if it falls

Antimatter is influenced by gravity just like matter, ALPHA-g experiment finds

Emily Chung · CBC News ·
Posted: Sep 27, 2023 8:01 AM PDT | Last Updated: September 27,

Le Monde Se connecter

SCIENCES · PHYSIQUE

Des chercheurs démontrent que l'antimatière ne « tombe » pas vers le haut

Une équipe internationale a observé, pour la première fois, le comportement d'antiatomes en chute libre. La gravité, connue pour attirer les masses de matière ordinaire entre elles, n'est pas répulsive pour l'antimatière.

Par David Larousserie

Publié le 27 septembre 2023 à 17h00, modifié le 28 septembre 2023 à 09h41 · Lecture 4 min.

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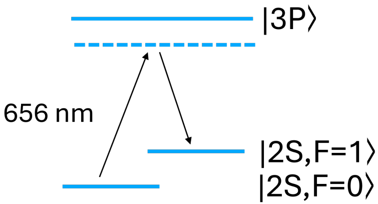
EXPLAINER

Features | Science and Technology

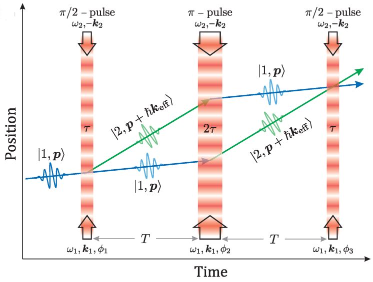
Gravity test: Antimatter falls down, but where did it all go?

From Star Trek to PET scans, antimatter has thrilled and worried humankind. Now, scientists have resolved a key mystery

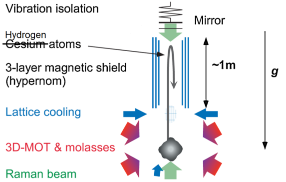


Detection H.F. states: $|2S,F=1\rangle$ vs. $|2S,F=0\rangle$

- H.F. selective $|2S\rangle \rightarrow |2P\rangle$ via μw transition + Ly-α detection
- H.F. selective $|2S\rangle \rightarrow |3P\rangle$ via laser transition + Ly-β detection
- H.F. selective 2S photoionization + Ions collection on MCP
- Detect after deexcitation to ground state



Barrett B. *et al.* 2016. Atoms 4, 3: 19



Adapted from: Phys.Rev.D **80**, 016002 (2009)

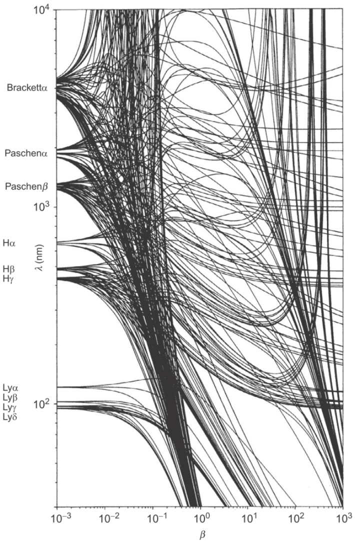
Summary

- HAICU phase 1:
  - Cold hydrogen beam
  - Magnetic trapping
  - Laser cooling
- Long term goal: atom interferometry $\Rightarrow$ Gravimetry
- Critical items are being assembled at TRIUMF and UBC

BCIT: Alex Khramov
Calgary: Tim Friesen
TRIUMF: AC, Jack Ewins, Makoto Fujiwara, Dave Gill, Philip Lu, Giulia Marcoux, Peter Margetak, Lars Martin, Nicolas Massacret, Art Olin, Alexis Papandreou, Chukman So, Giles Wankling and many co-op students...
SFU: Mike Hayden
UBC: Reza Akhbari, Tony Mittertreiner, Takamasa Momose, Colin Noort, Wes Rusinoff

Additional Material

Wavelength spectrum vs. B



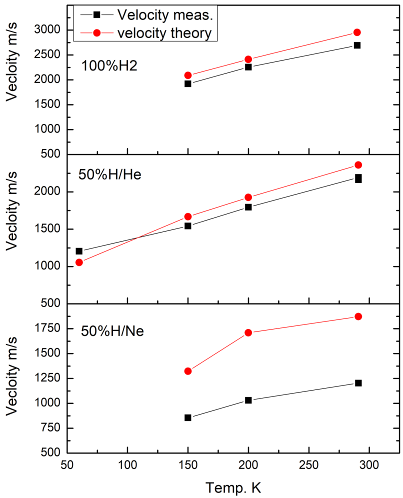
Anand Thirumalai and Jeremy S. Heyl in *Advances in Atomic, Molecular, and Optical Physics*, Volume 63 (2014)

$$\beta = \gamma/2$$

$$\gamma = \frac{\hbar\omega}{2\mathrm{R_y}}$$

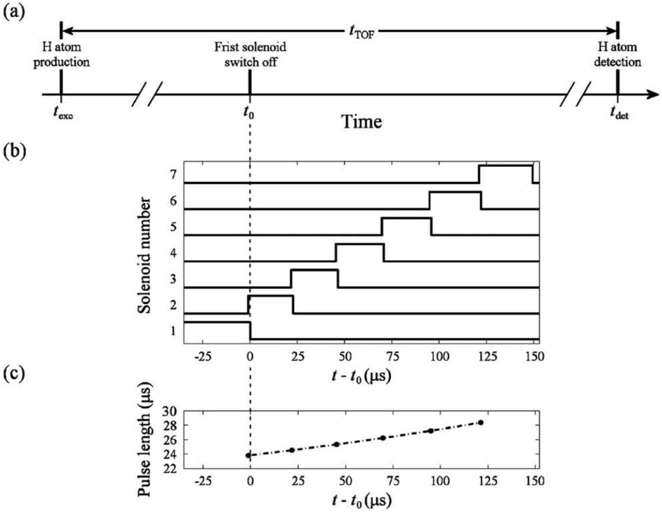
$$\omega = \frac{eB}{m_\mathrm{e}}$$

H Supersonic Source



R. Akhbari (UBC)

PHYSICAL REVIEW A 76, 023412 2007



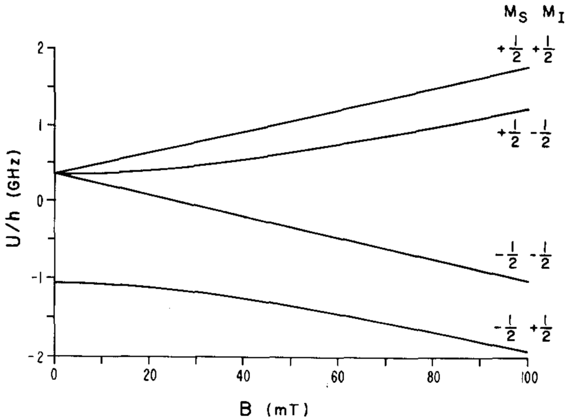
H **magnetic dipole moment** in ground state
$|\boldsymbol{\mu}_\mathrm{H}| \sim \mu_B \approx 6 \times 10^{-11}\,\mathrm{MeV\,T^{-1}}$.

Magnetic field gradient used to trap H: $\nabla B \sim \Delta B \approx 0.3\,\mathrm{T}$
Confinement due to superposition of magnetic fields

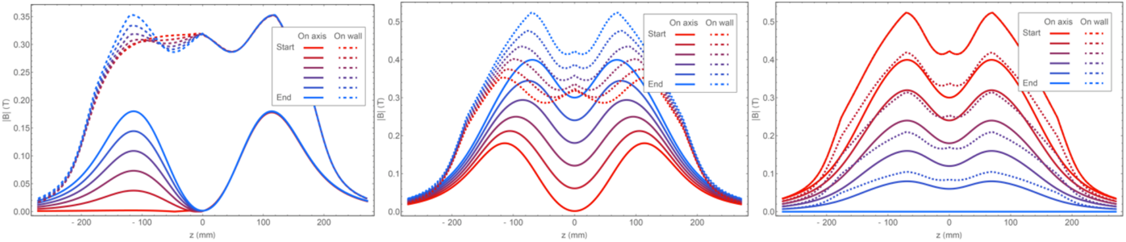
Force on atom $= -\nabla U \qquad U = \mu_B[B_\mathrm{min}(\boldsymbol{x}) - B(\boldsymbol{x})]$

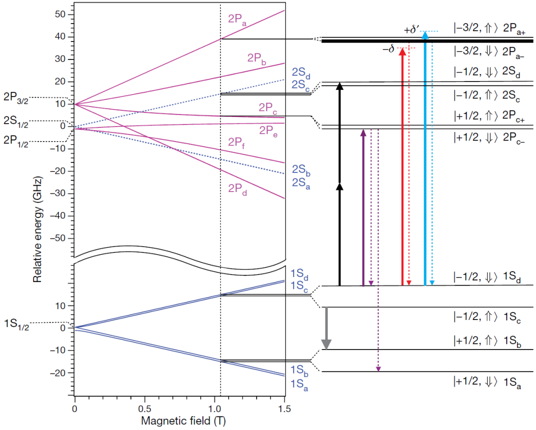
Only $\boldsymbol{\mu}_\mathrm{H}$ anti-parallel to $\boldsymbol{B}$ can be **confined** by U-minimum **low-field seeker**

Am. J. Physics **59** (2) 1991



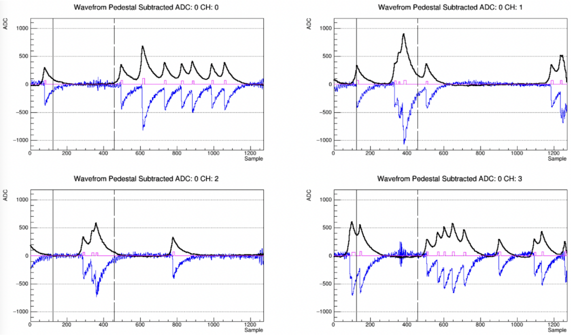
Compression-Cooling Expansion

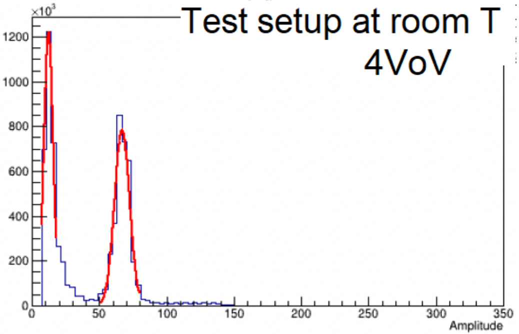




Doppler cooling on $|1S,d\rangle \to |2P_a+\rangle$

SiPM Testing (Dark)





SPE = 66.8, SNR = 8.4

Z. Charlesworth