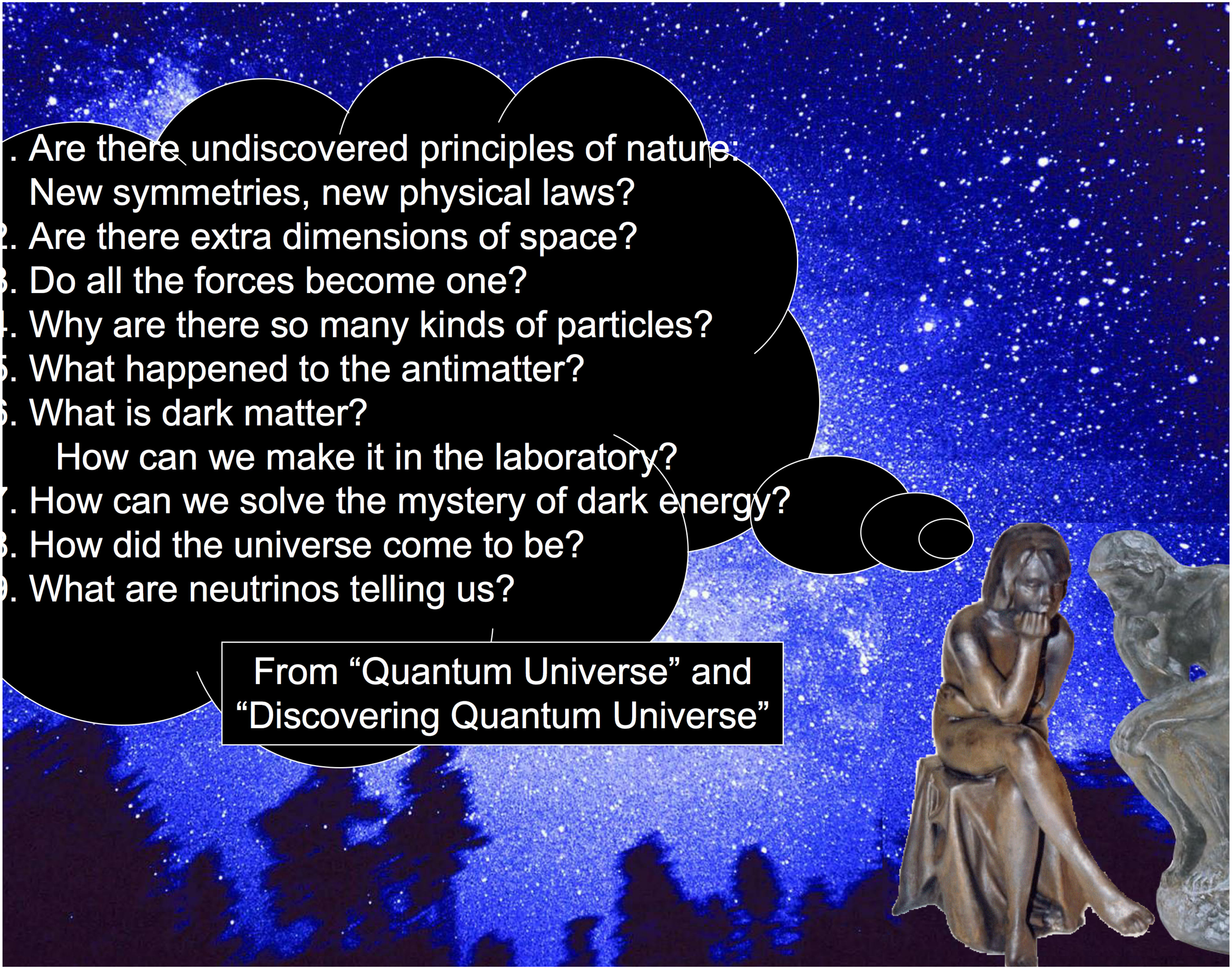
Prospects for the Antimatter Gravity Experiment at Fermilab

Thomas Phillips
Duke University

Outline

1. Motivation (abbreviated)
2. The Antimatter Gravity Experiment (AGE)
   A. Antihydrogen beam
   B. Initial design: transmission-grating interferometer
      - Does not require trapped antihydrogen
      - Monte Carlo results
   C. High-precision design: Raman interferometer
      - Requires trapping & cooling antihydrogen
3. Antihydrogen at Fermilab
   A. Antiproton infrastructure
   B. Future plans
4. History & Prospects for AGE


Are there undiscovered principles of nature:
New symmetries, new physical laws?
Are there extra dimensions of space?
Do all the forces become one?
Why are there so many kinds of particles?
What happened to the antimatter?
What is dark matter?
How can we make it in the laboratory?
How can we solve the mystery of dark energy?
How did the universe come to be?
What are neutrinos telling us?
From “Quantum Universe” and
“Discovering Quantum Universe”

The Antimatter Gravity Experiment

<u>The AGE Collaboration</u>

Duke University
Fermilab
First Point Scientific, Inc
Hbar Technologies, LLC
Illinois Institute of Technology
Kansas State University
Luther College
NASA
Southern Methodist University
Stanford University
University of Arizona
University of Michigan
University of Texas

➤ The goal of the AGE collaboration is to make a direct measurement of the gravitational acceleration of antimatter on the earth.

A Neutral Beam Experiment for Measuring $\bar{g}$

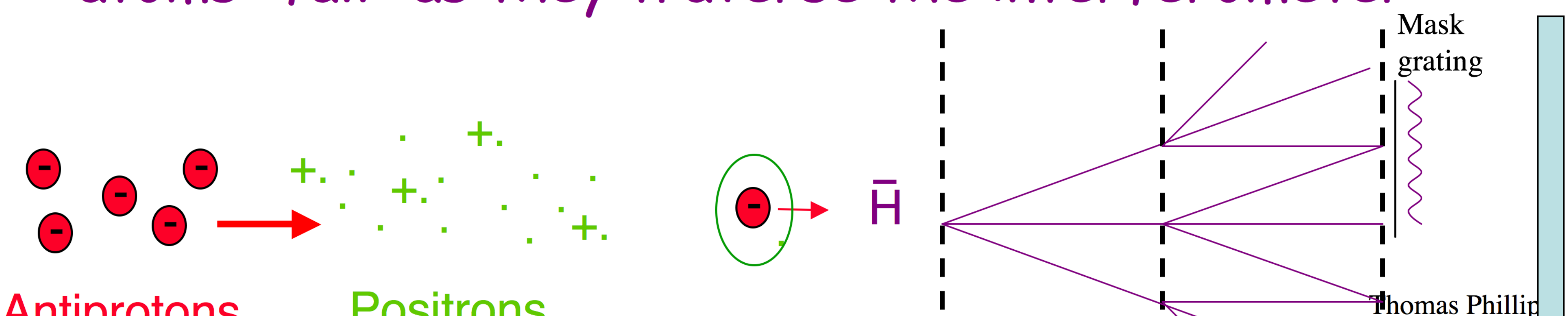
Make a low-velocity antihydrogen beam

- ➢Trap and cool antiprotons
- ➢Trap and cool positrons
- ➢Accelerate antiprotons, direct them through the positron plasma to make a beam of antihydrogen

Direct the beam through a transmission-grating interferometer (Measure velocity with Time of Flight)

Measure $\bar{g}$ by observing the gravitational phase shift

- ➢Interference pattern shifts by the same amount the atoms "fall" as they traverse the interferometer



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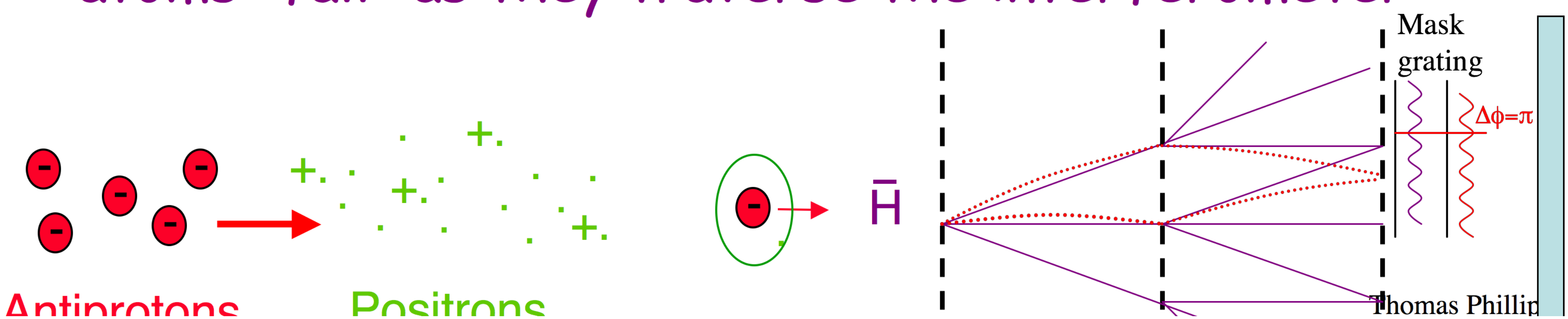
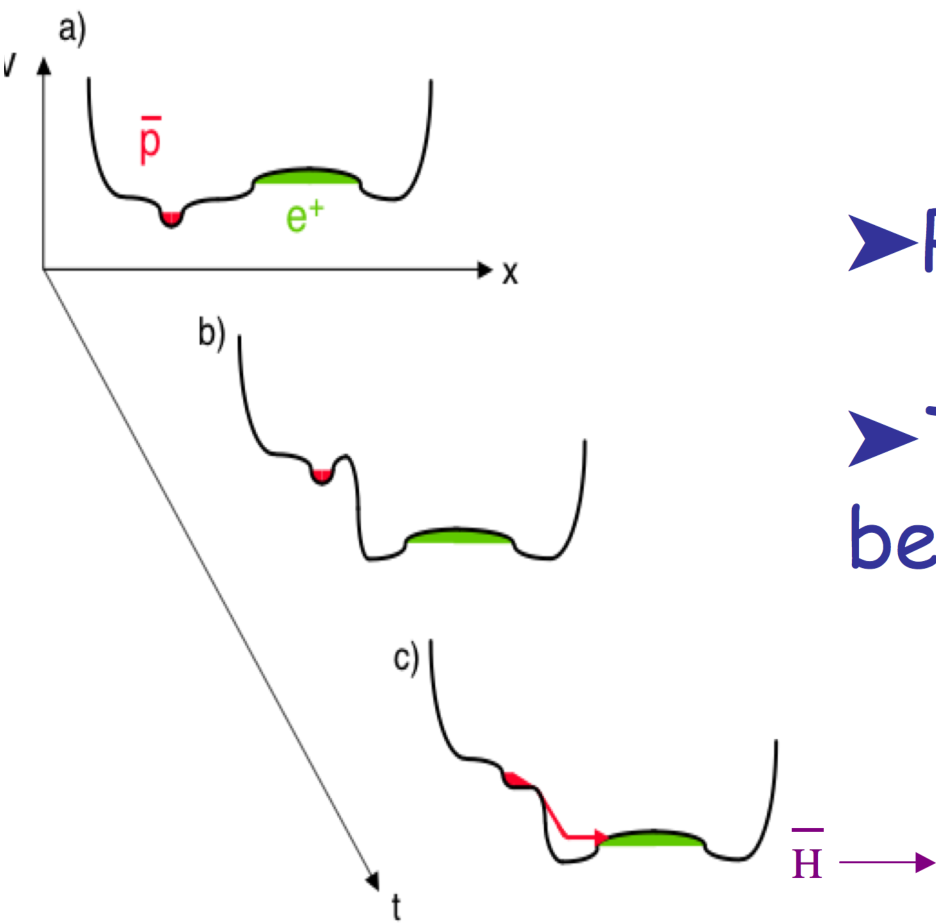


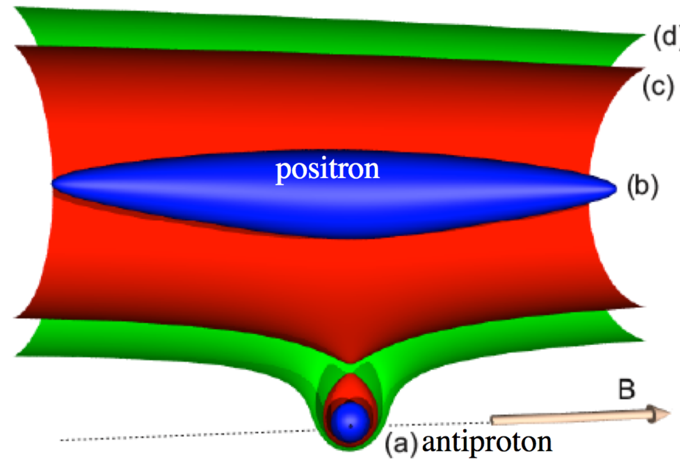
Making Antihydrogen



- ➤Antiprotons in trap are cooled with electrons
  - ➢electrons cool to wall temp by synchrotron radiation
- ➤Positrons in a separate well
- ➤To make antihydrogen beam:
  - ➢accelerate antiprotons thru positrons
  - ➢some make antihydrogen and exit the trap in a beam
    - ➛high 1-pass conversion probability with achievable positron densities

Antihydrogen Production

- Antihydrogen Production
  - Mechanisms:
    - 3-body: $\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$
    - radiative (re)combination
      $\bar{p} + e^+ \rightarrow \bar{H}$ + photon
    - 3-body $\bar{p} + \bar{p} + e^+ \rightarrow \bar{H} + \bar{p}$
  - Rate estimate for first mechanism:



antihydrogen in a strong magnetic fiel

(D.Vrinceanu, 15th International Conference on Atomic Processes in Plasmas, 81 (2007))

$$\Gamma = 6 \times 10^{-13} \left(\frac{4.2}{T} \right)^{\frac{9}{2}} n_e^2 \left[s^{-1} \right]$$

(Glinsky & O'Neil Phys. Fluids **B3** (1991) 1279.)

T in K

n_e in cm^{-3}

For $n_e \geq 10^8 / cm^3$ production rates ~ 45% of $\bar{p}$ converted to $\bar{H}$ per pass through a 10 cm positron plasma at 1 km/s

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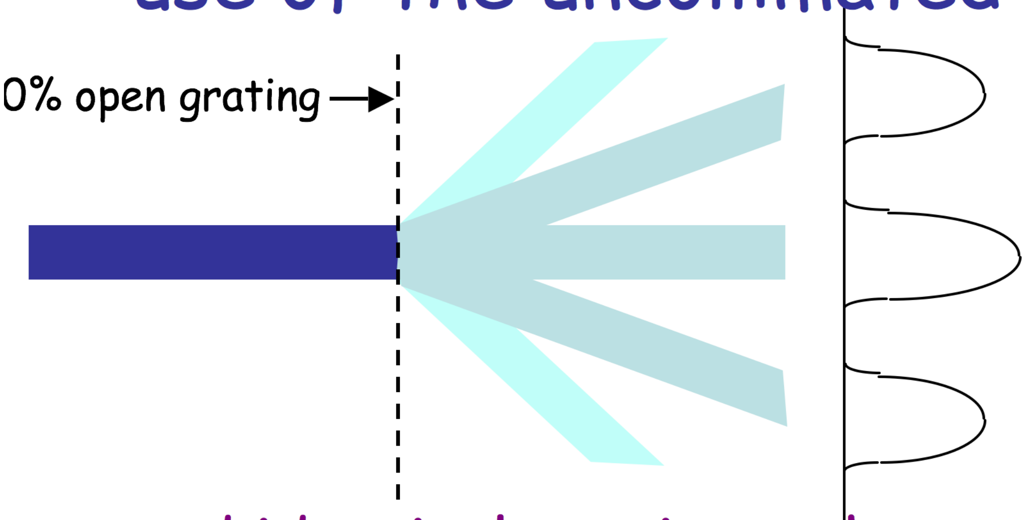
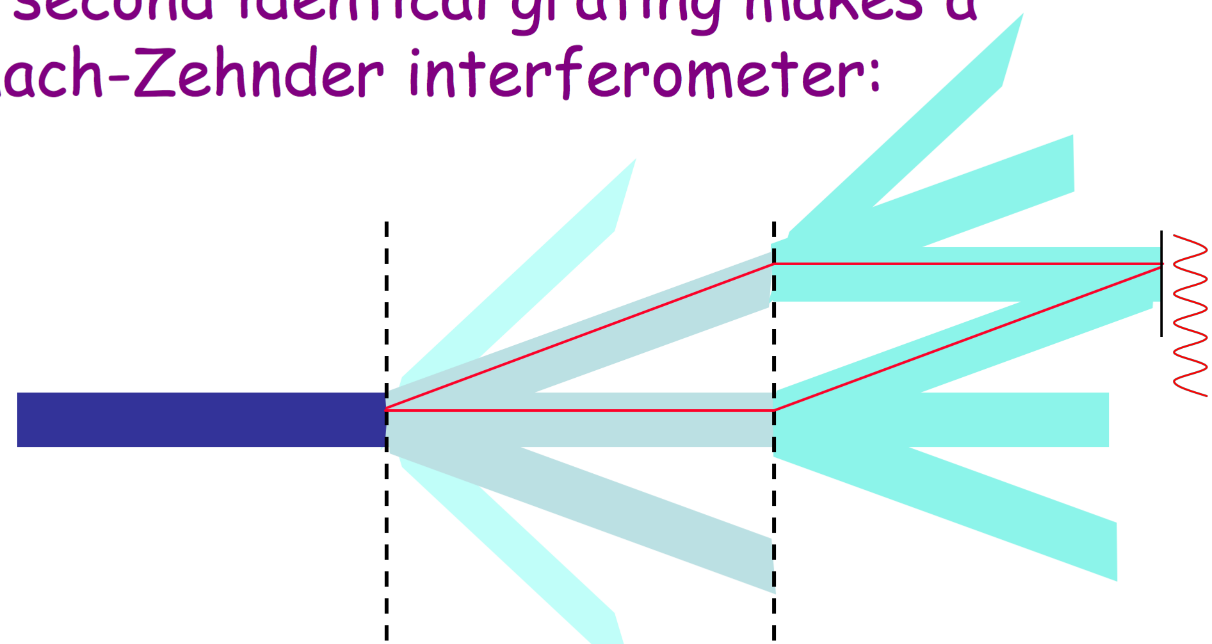
The Atomic Interferometer

This interferometer design can make efficient use of the uncollimated antihydrogen beam.



A single grating splits the beam and makes a diffraction pattern.

. second identical grating makes a
lach-Zehnder interferometer:



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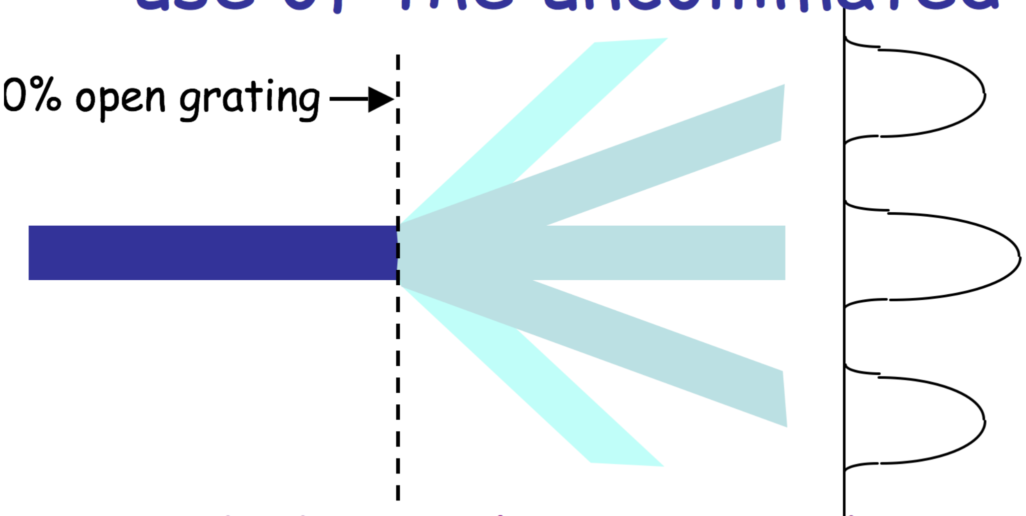

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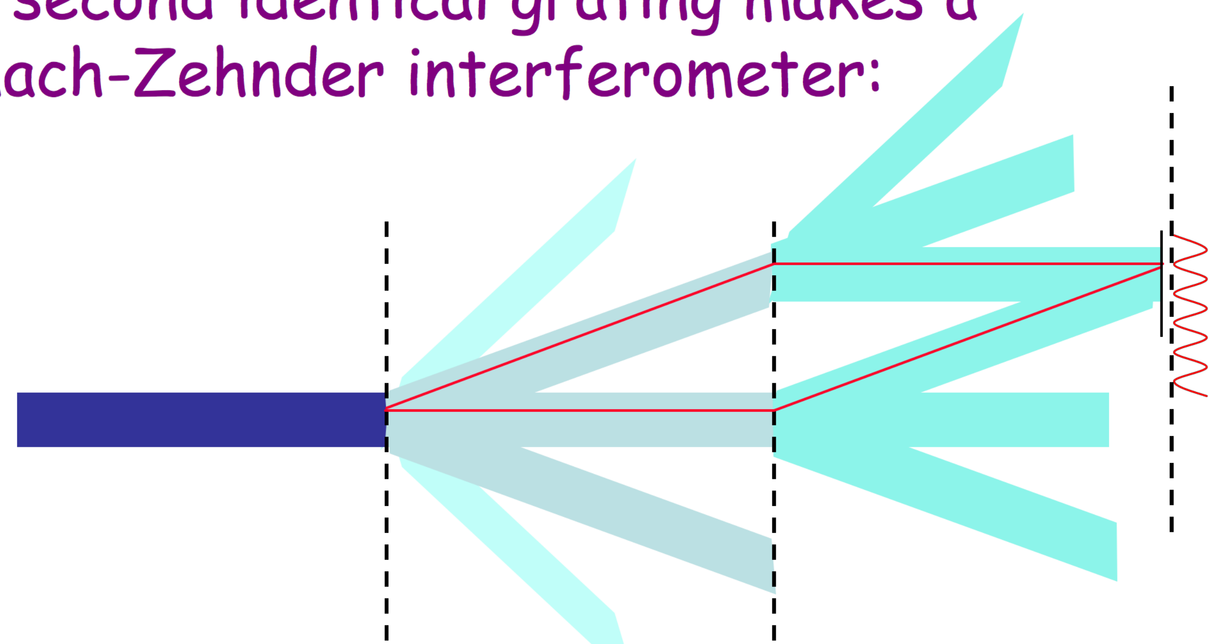

The interference pattern has the same period as th gratings so a third identical grating can be used as a mask to analyze the phase of the pattern.

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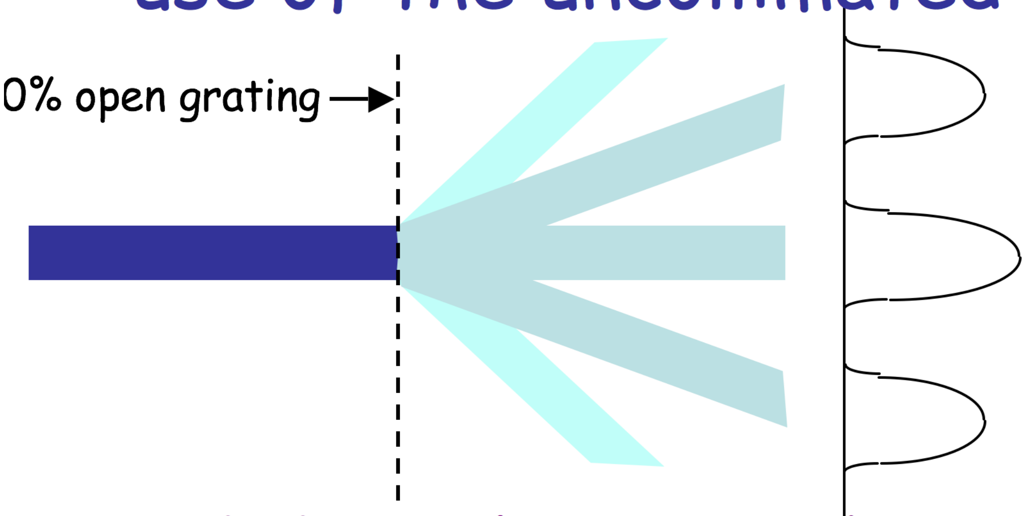

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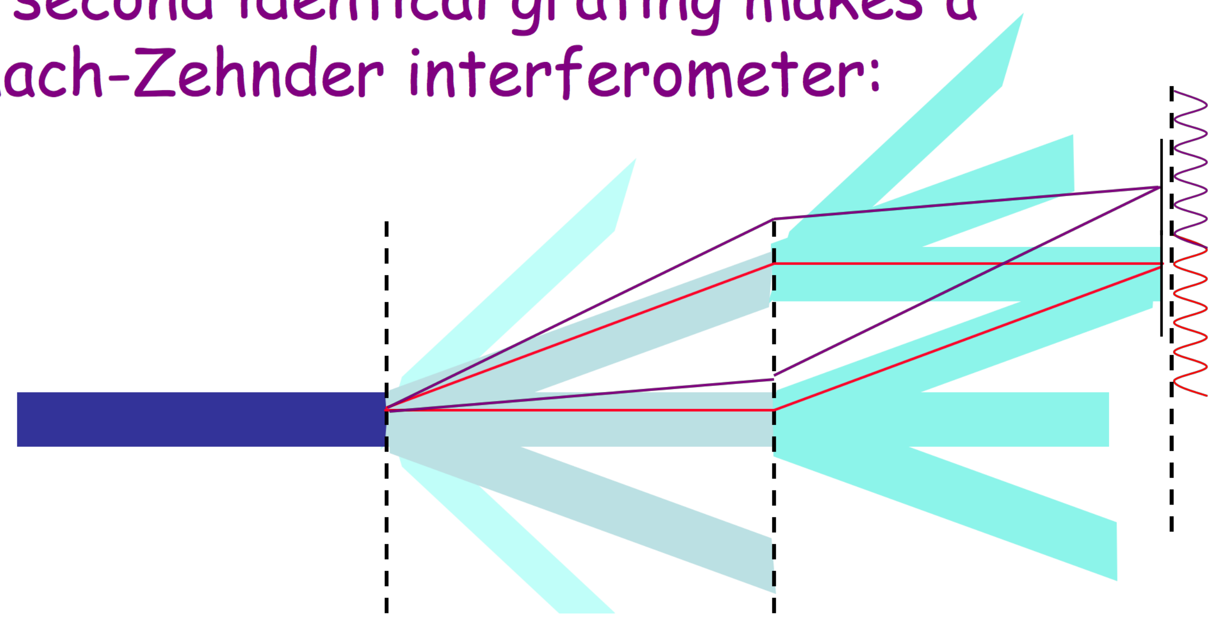

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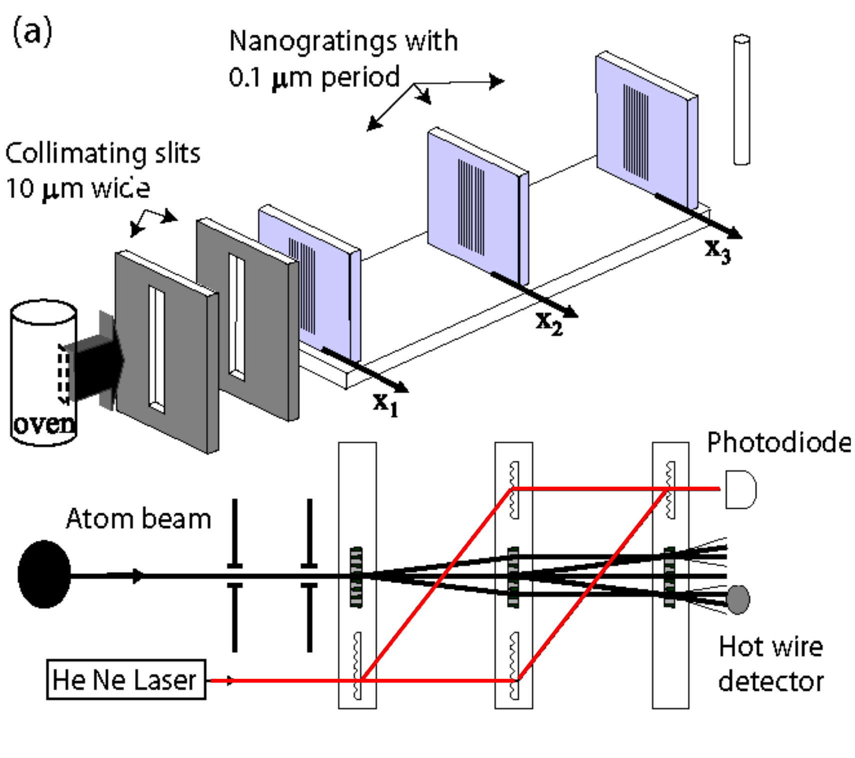
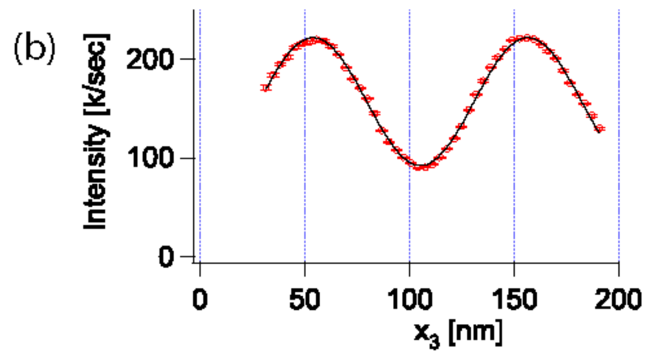
This is a "white light" "extended source" interferometer

Atomic Interferometry Works!

➤Interference has been observed with the MIT/Arizona interferometer using an atomic Sodium beam



ɔmic interferometer using sodium atoms and vacuum transmission gratings

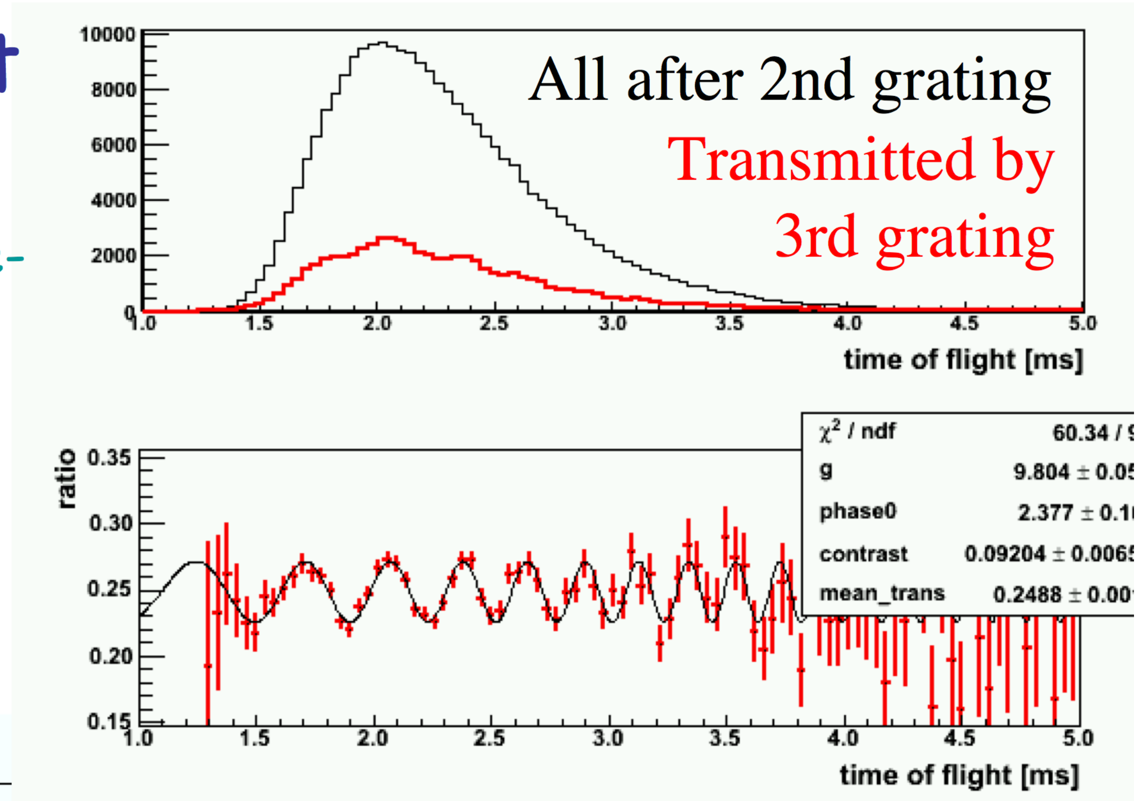


This resolution is an order of magnitude better than we need for the antimatter gravity experiment. If this interferometer were rotated 90°, gravity would cause a phase shift of 200 radians. Ato interferometers (using lasers rather than gratings) have measured g to 1:10¹

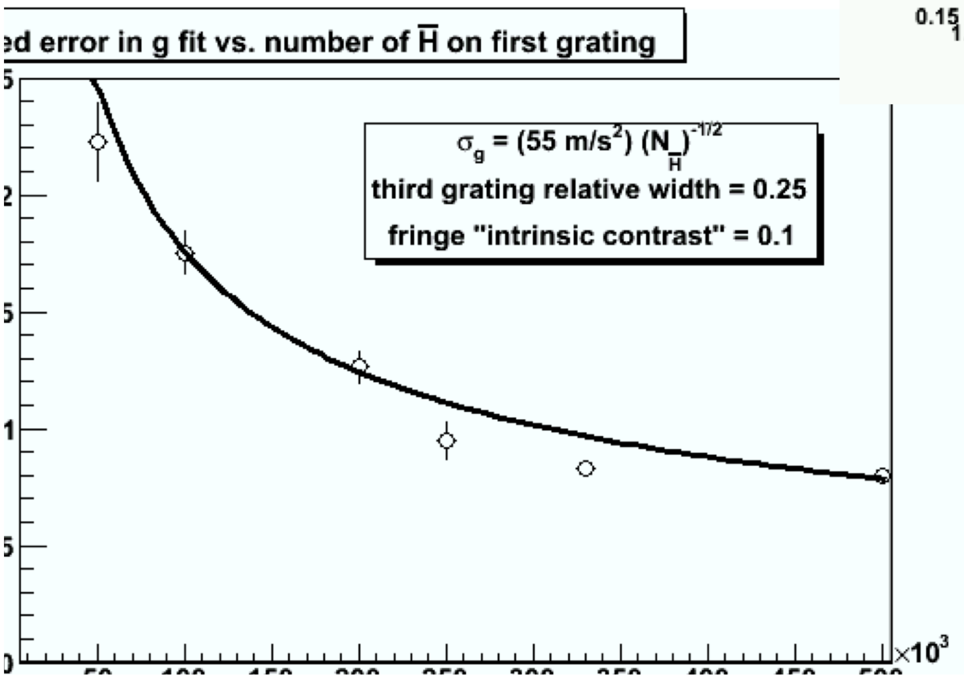
Monte Carlo Results

Simple MC shows what our data will look like.

- Phase shift is a function of time-of-flight: slower particles have larger gravitational phase shift
- Get more transmission when interference peaks line up with gaps in mask



Time of Flight (msec)



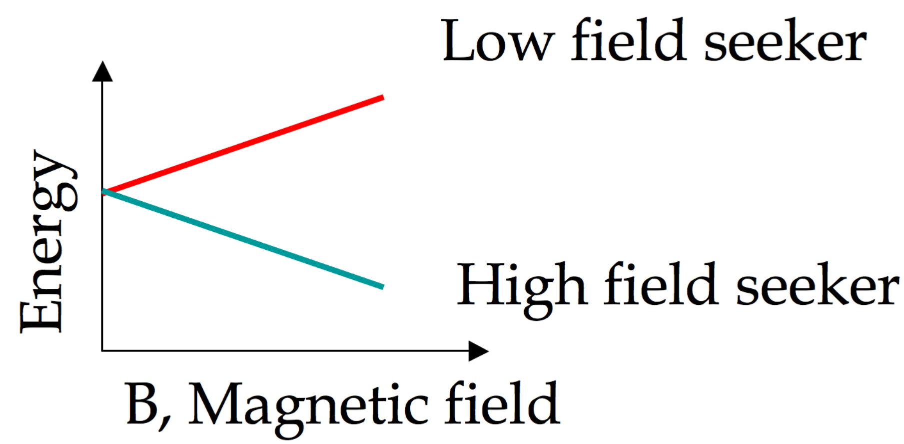
- Half a million antihydrogen will measure $\bar{g}$ to 1% of g.

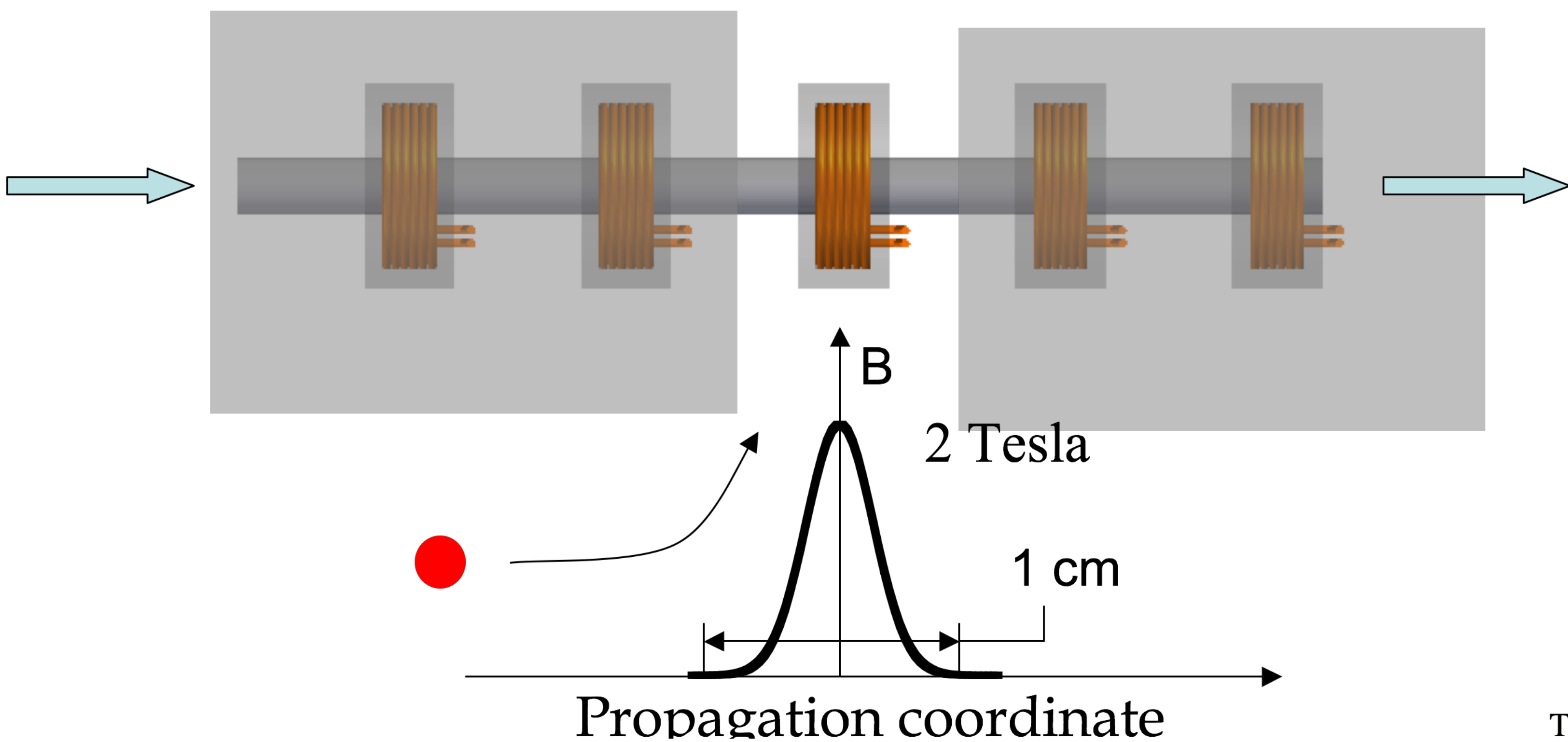
Stopping Antihydrogen

With a Magnetic Hill

Low field seekers are repulsed by magnetic field

Field turned off before atoms exit solenoid





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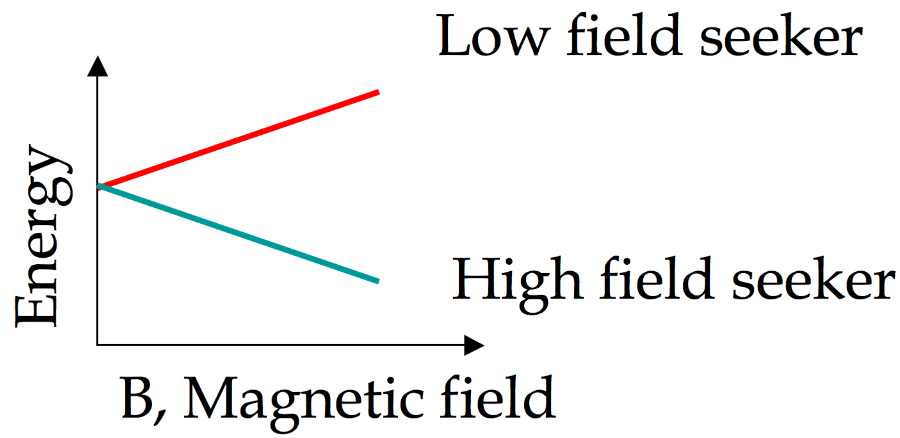

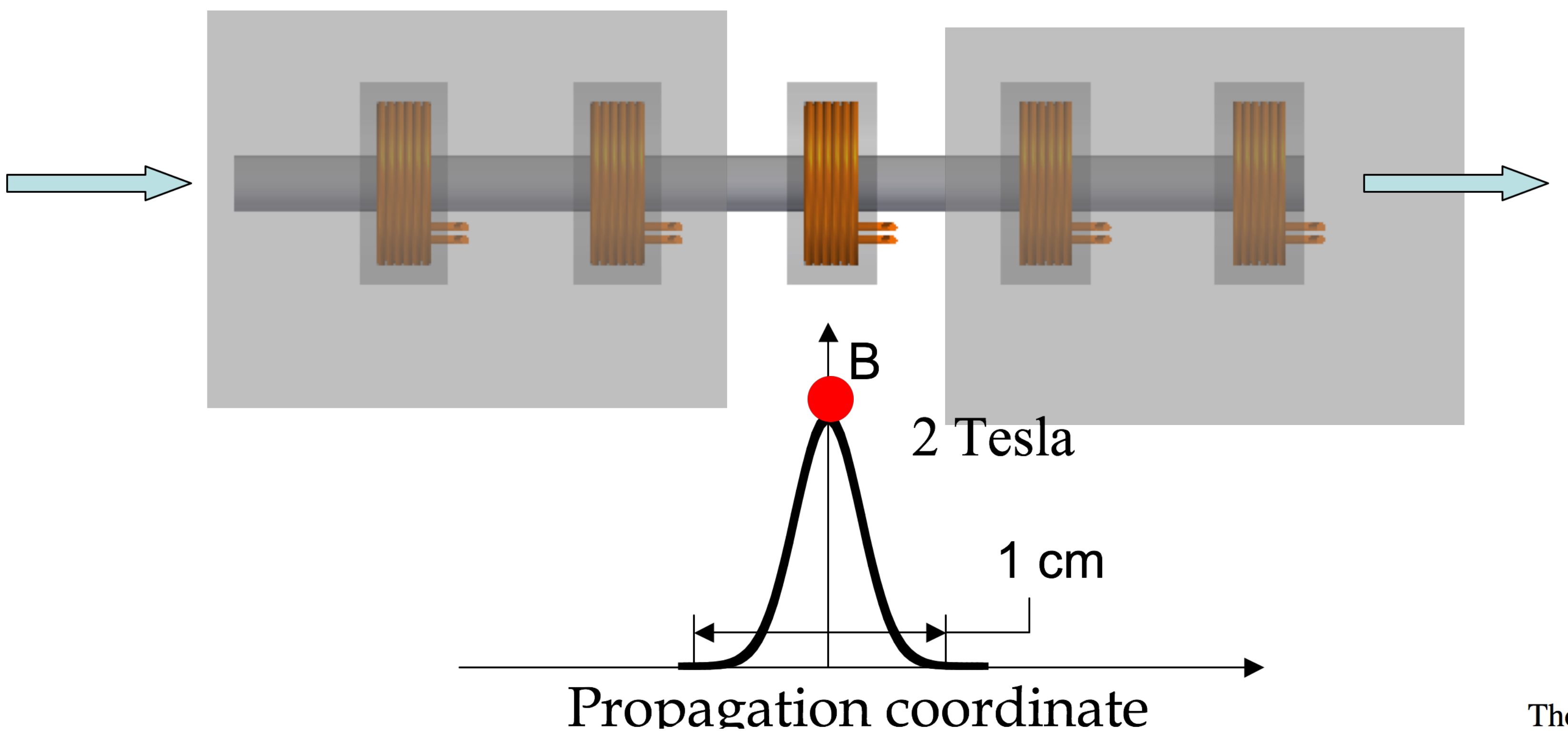

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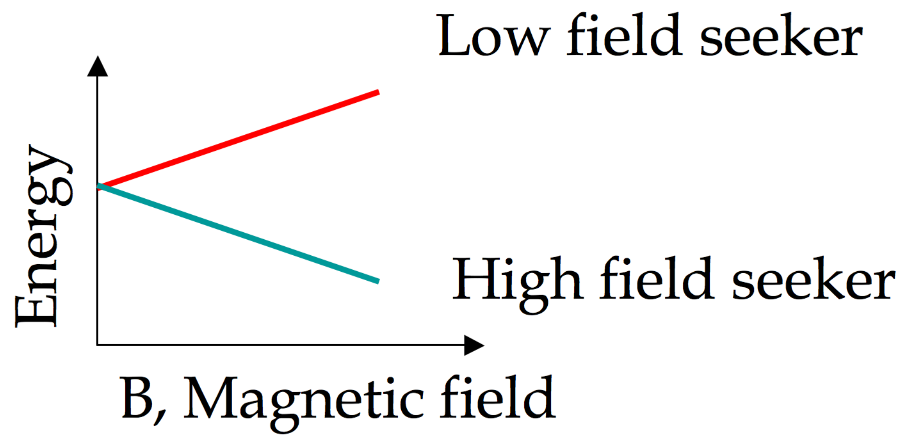

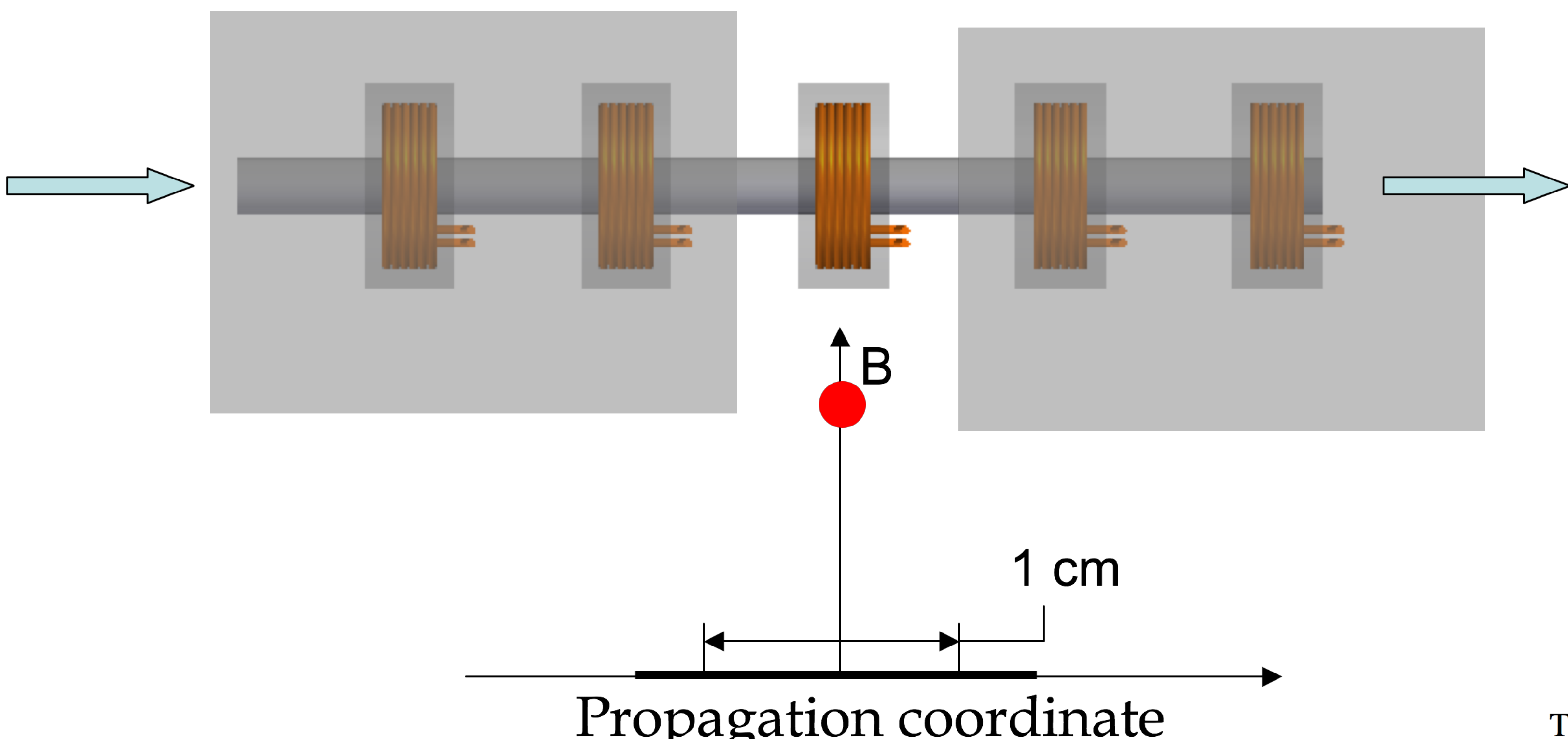

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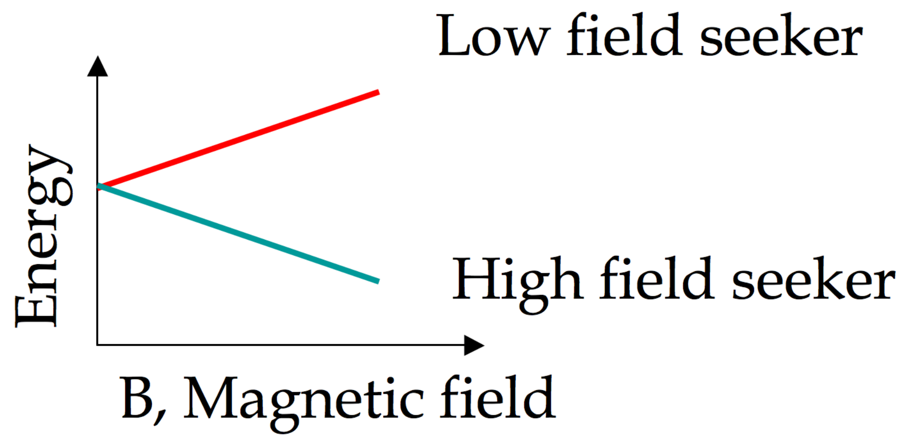

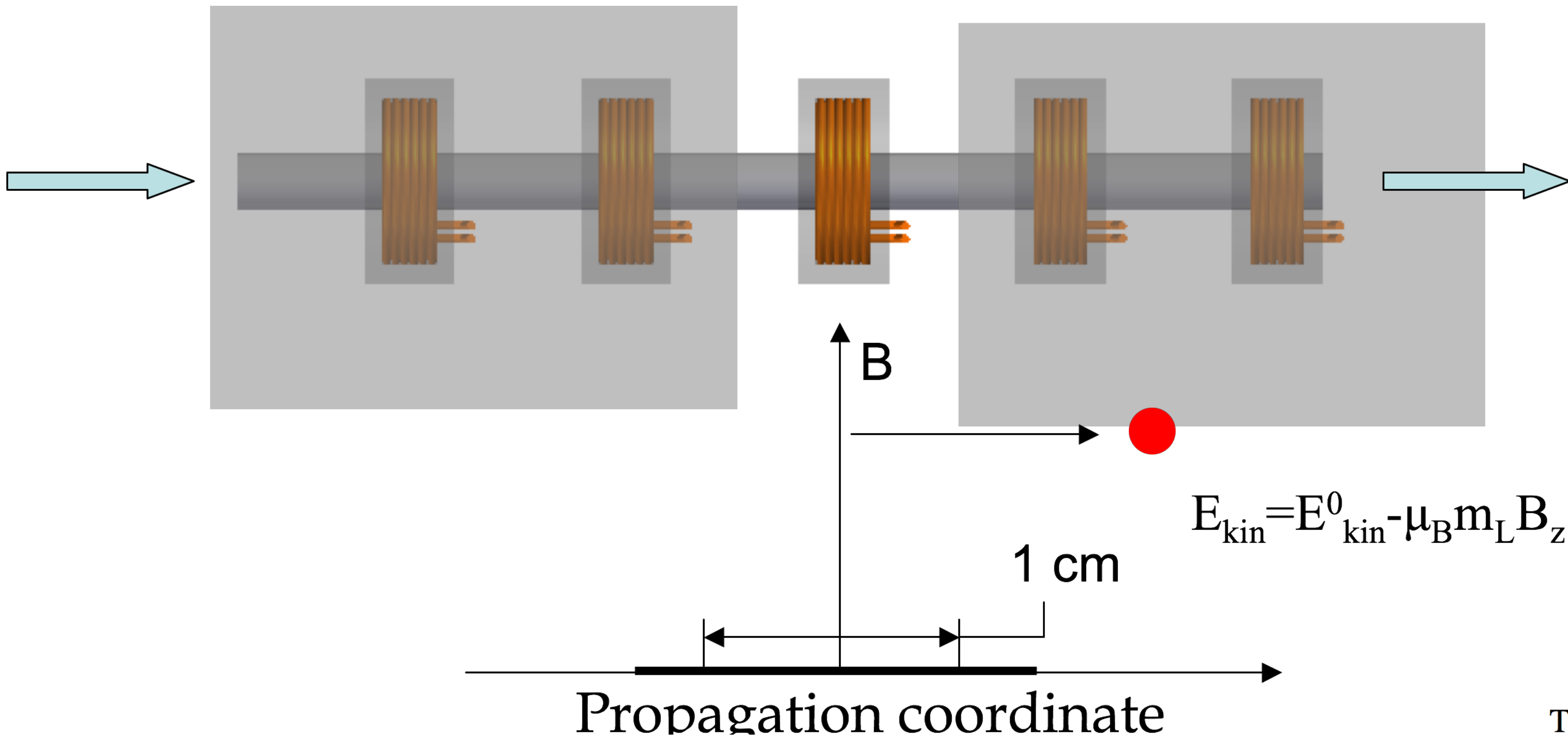

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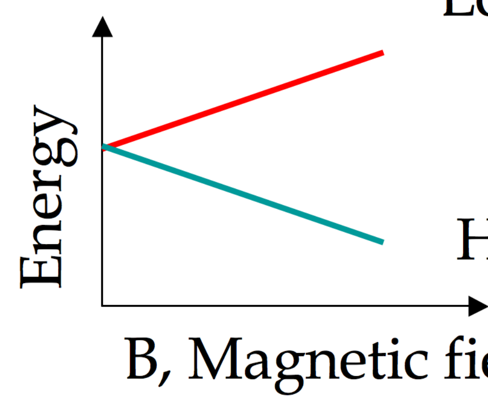

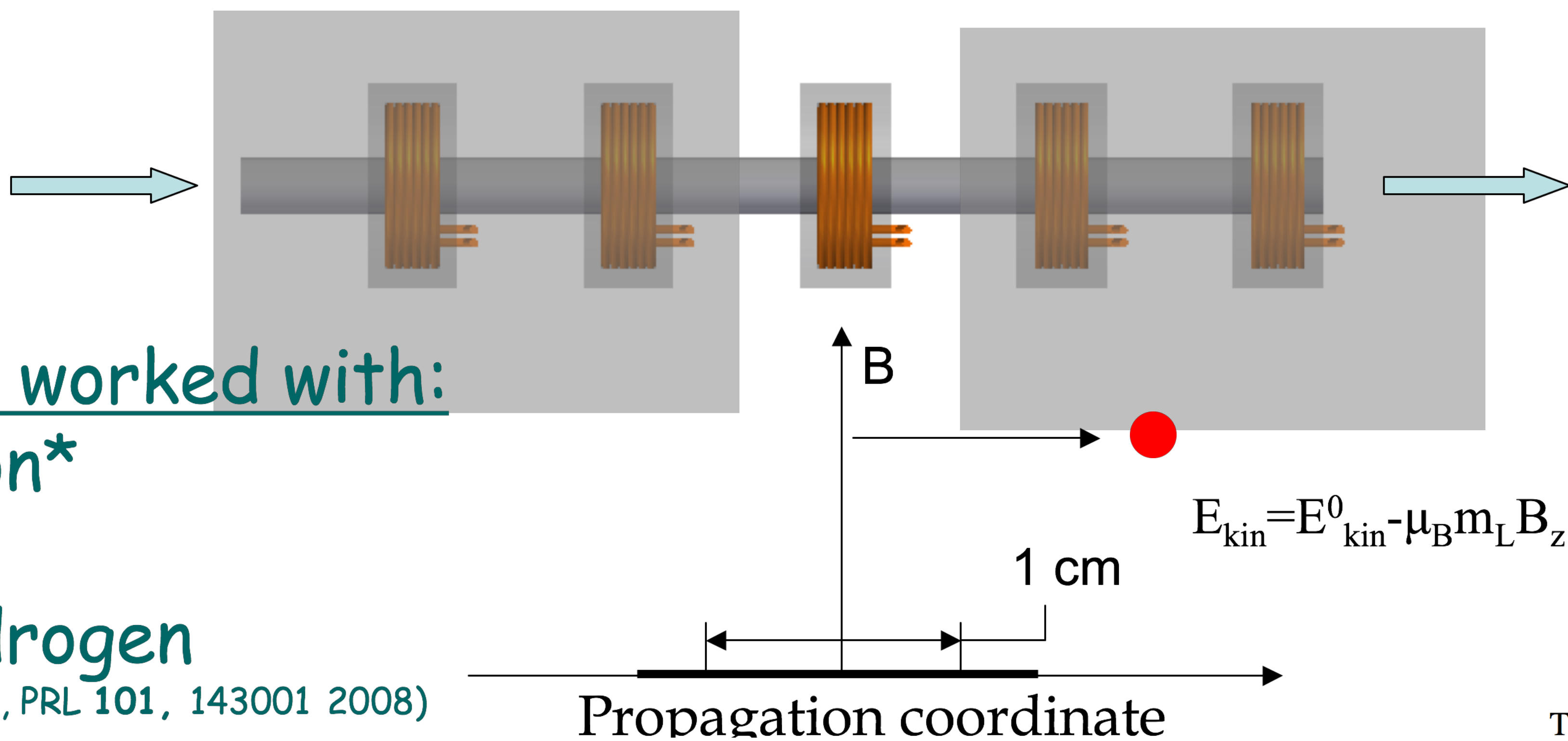

las worked with:

leon*

$)_2$

lydrogen

(lerkt, PRL **101**, 143001 2008)

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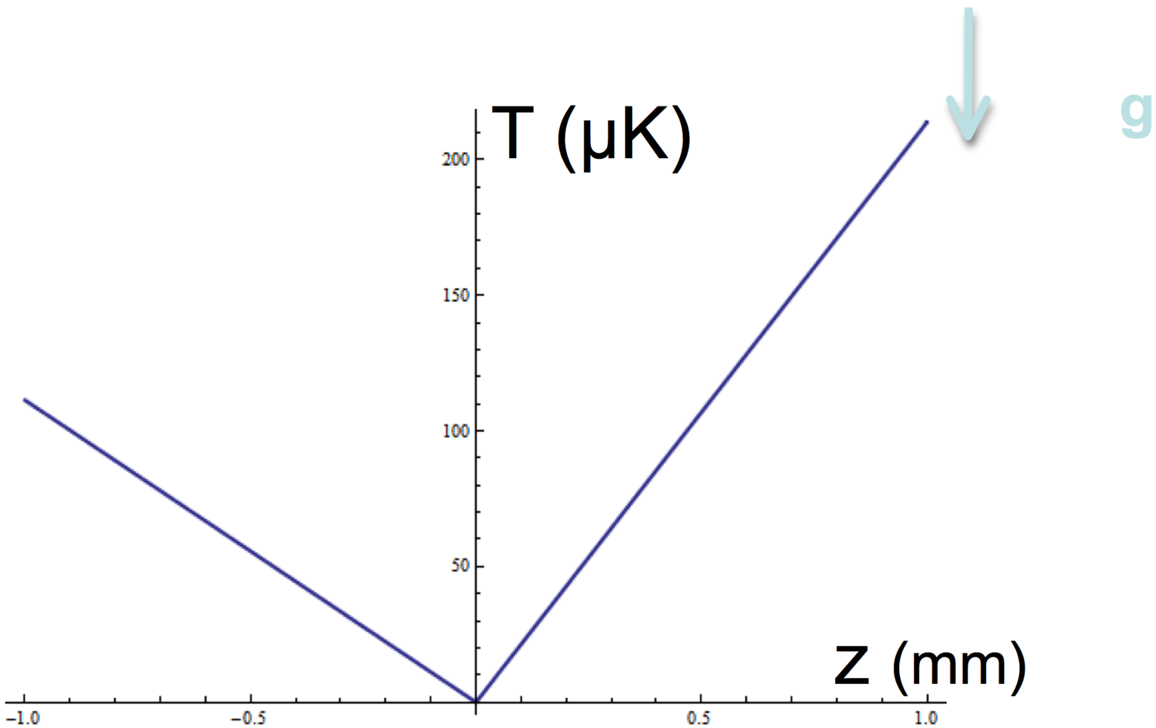
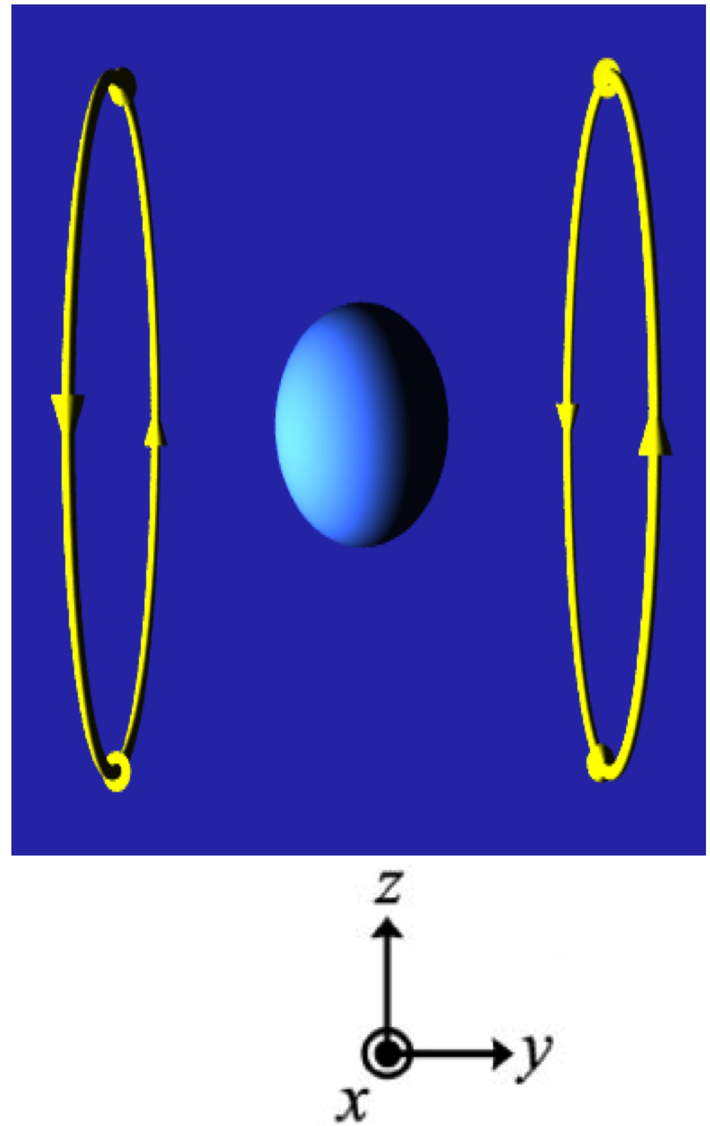
Trapping Antihydrogen

Trap antihydrogen in a magnetic trap with a Quadrupole Potential





$$E = \mu_B \, | \, B \, | + mgz$$

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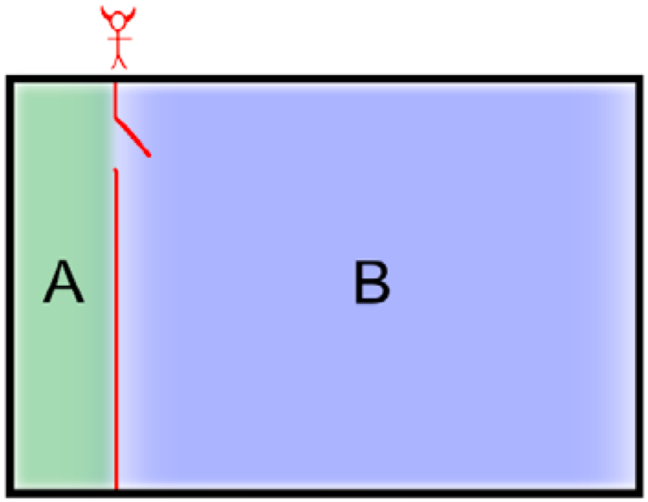
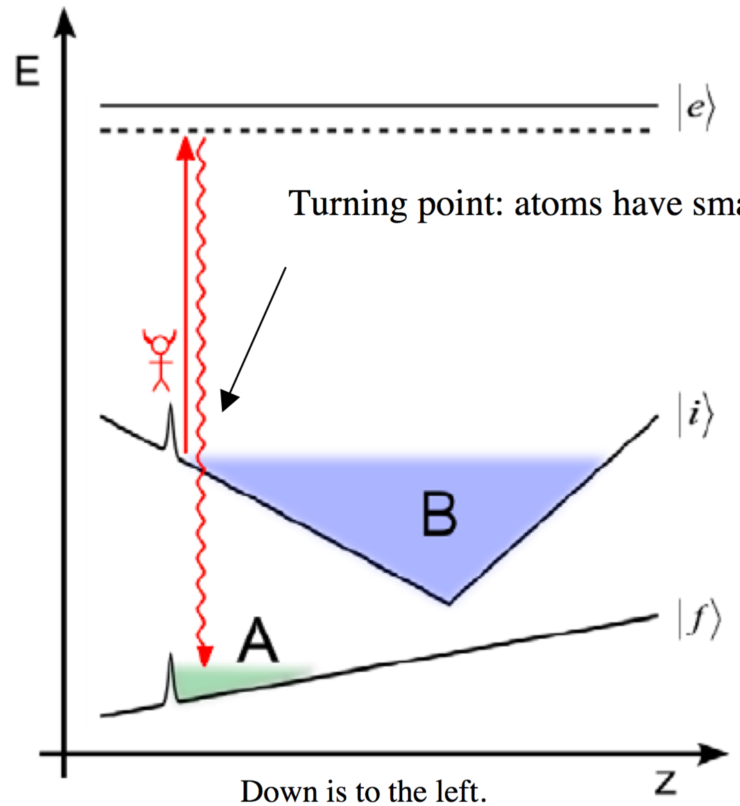
Cooling Antihydrogen





<u>Single-Photon Atomic Cooling:</u> induce an atomic transition when atoms are near their turning point in a trap (minimum kinetic energy). The new state has a smaller magnetic moment, so atom has lower potential energy. It is cooled!

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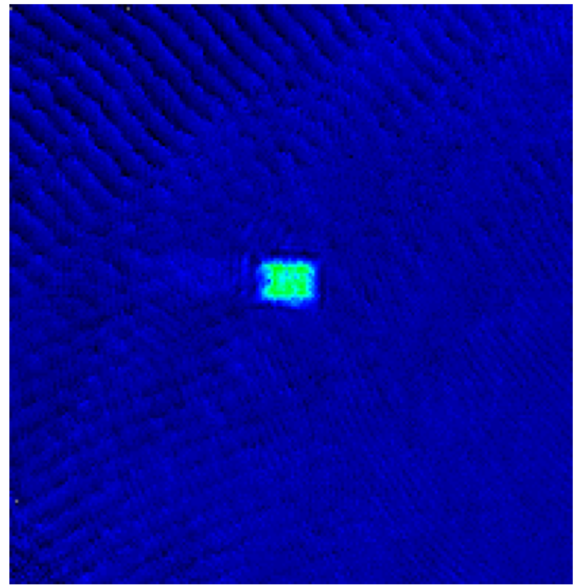
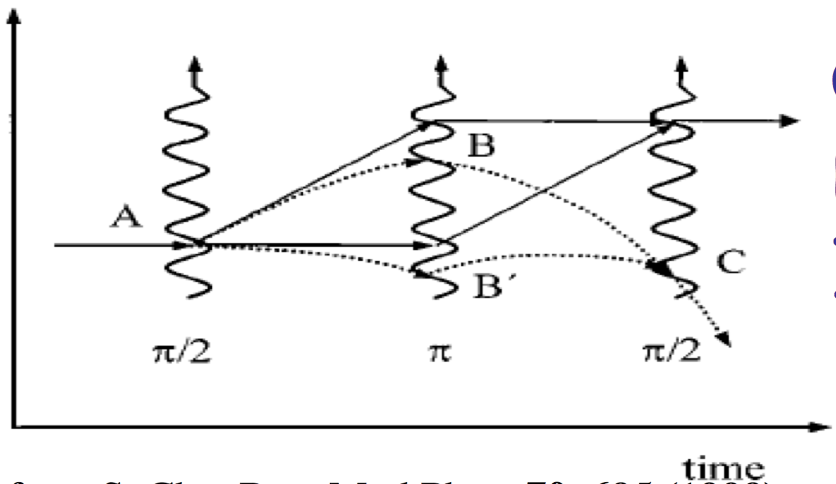


Atoms trapped in an optical bo

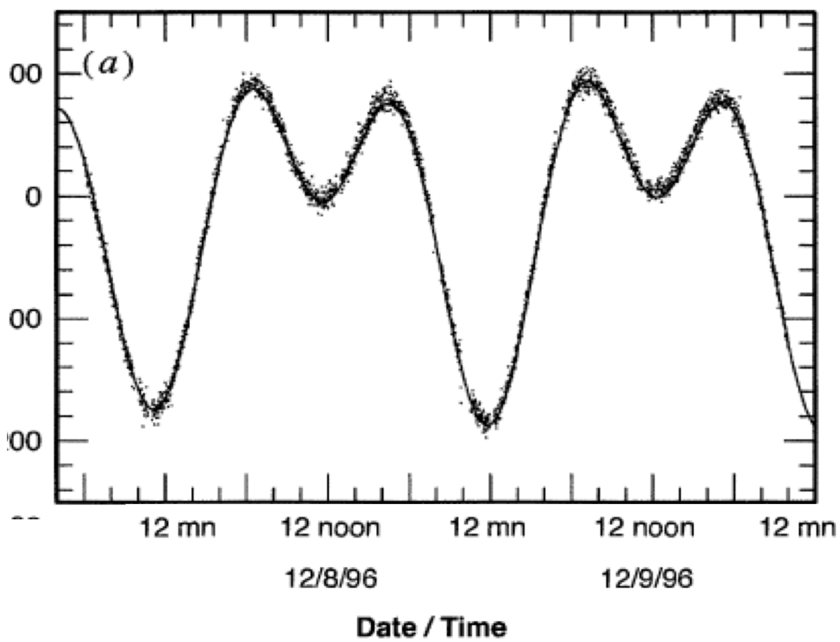
23x increase in phase space density from magnetic trap!

G. Price et al., Phys. Rev. Lett. 100, 093004 (2008)

Raman Interferometer



from S. Chu, Rev. Mod.Phys. **70**, 685 (1998)



A. Peters *et al*. Philos. Trans. R. Soc. London Ser A **355,** 2223.

- High-precision matter-antimatter difference measurement using Raman Interferometer
  - split wave packet with laser
  - reverse split with 2nd pulse
  - recombine with 3rd pulse
  - local g resolution 10^{-10} using Cs atoms
  - hydrogen in development
    - 1000 trapped $\overline{H}$ for $2x10^{-7}$
    - Mark Raizen, AGE collaborator
  - can look for new ultra-weak forces by comparing H, $\overline{H}$

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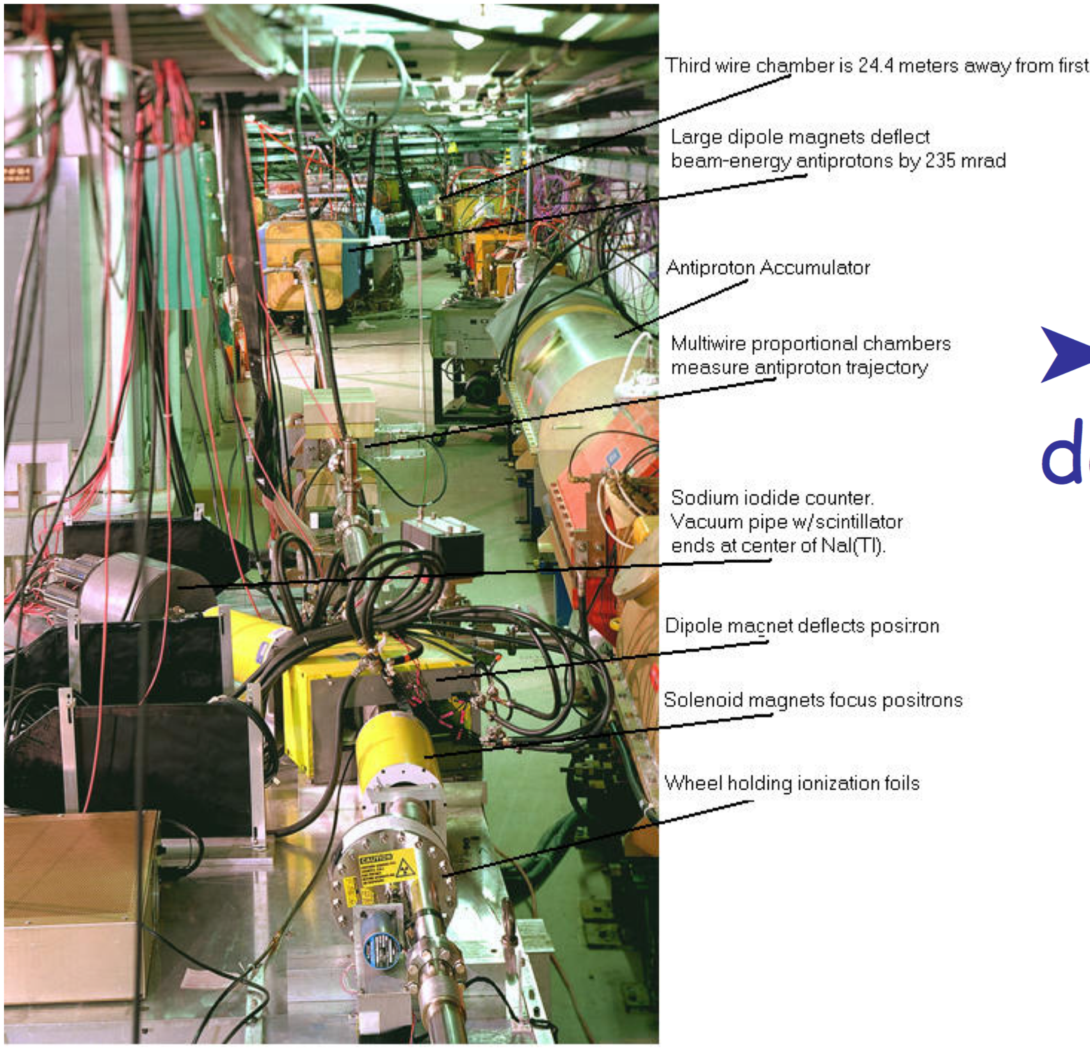
Antihydrogen at Fermilab

➤E862 reported 99 $\bar{H}$ observed in 1996 & 1997

- ➢internal H gas jet target in Antiproton Accumulator beam

➤Relativistic, detected destructively

- ➢not useful for gbar measurement



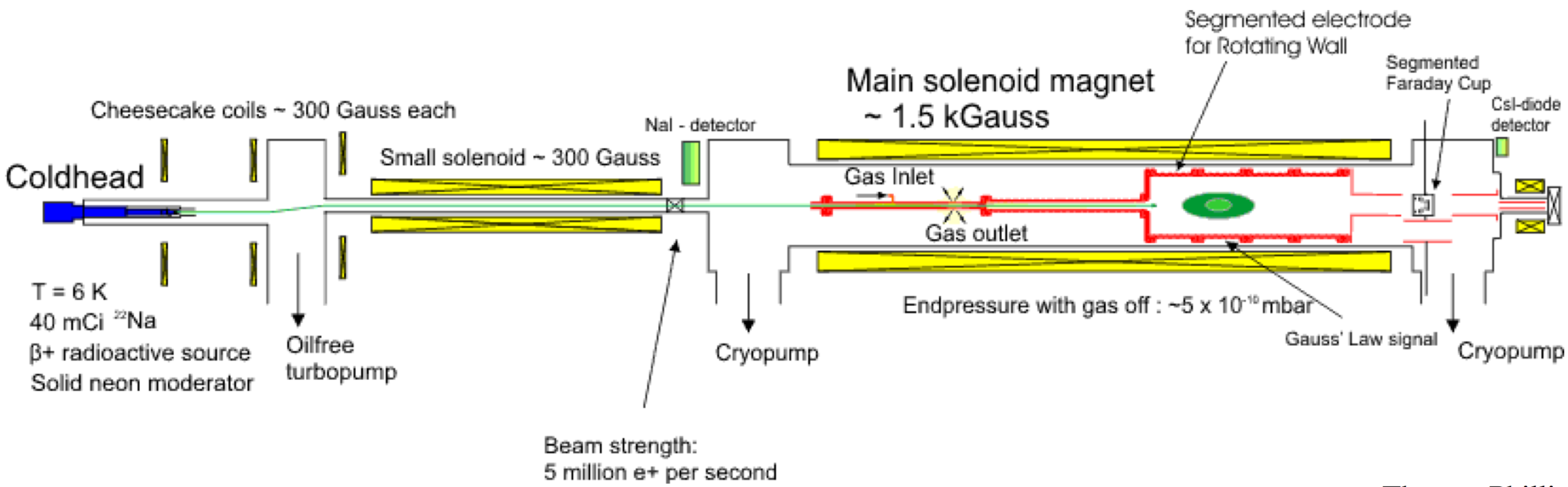
Antihydrogen Ingredients

Making slow antihydrogen requires:

1. positrons
   - can be made or collected from a source
2. antiprotons
   - made at CERN and Fermilab

Positron Source

- ➤Surko Accumulator
- ➤Commercial solution is available
  - ➢up to 10^7 e^+/sec
  - ➢user supplies ^{22}Na
    - ➛up to 150 mCi
  - ➢5-11 month delivery



Antiprotons at Fermilab

Antiprotons are made at Fermilab and CERN

- CERN's AD does not accumulate antiprotons
  - pulses of 3×10^7 antiprotons every 90 s
  - only runs part of year
  - 10^{-3} capture efficiency (3×10^4 per pulse)
- Fermilab can accumulate antiprotons
  - accumulation rate typically exceeds 2×10^{11}/hour
  - ran year-round
  - ~50% capture efficiency possible with deceleration ring
    - 10^5 x higher potential trapping rate than CERN
  - accumulating really helps!
    - antihydrogen production not tied to 90 sec. cycle
    - $\overline{H}$ from charge exchange goes as ($\bar{p}$ density)^2

Bottom line:

Much higher statistics possible at Fermilab

Fermilab Main Injector

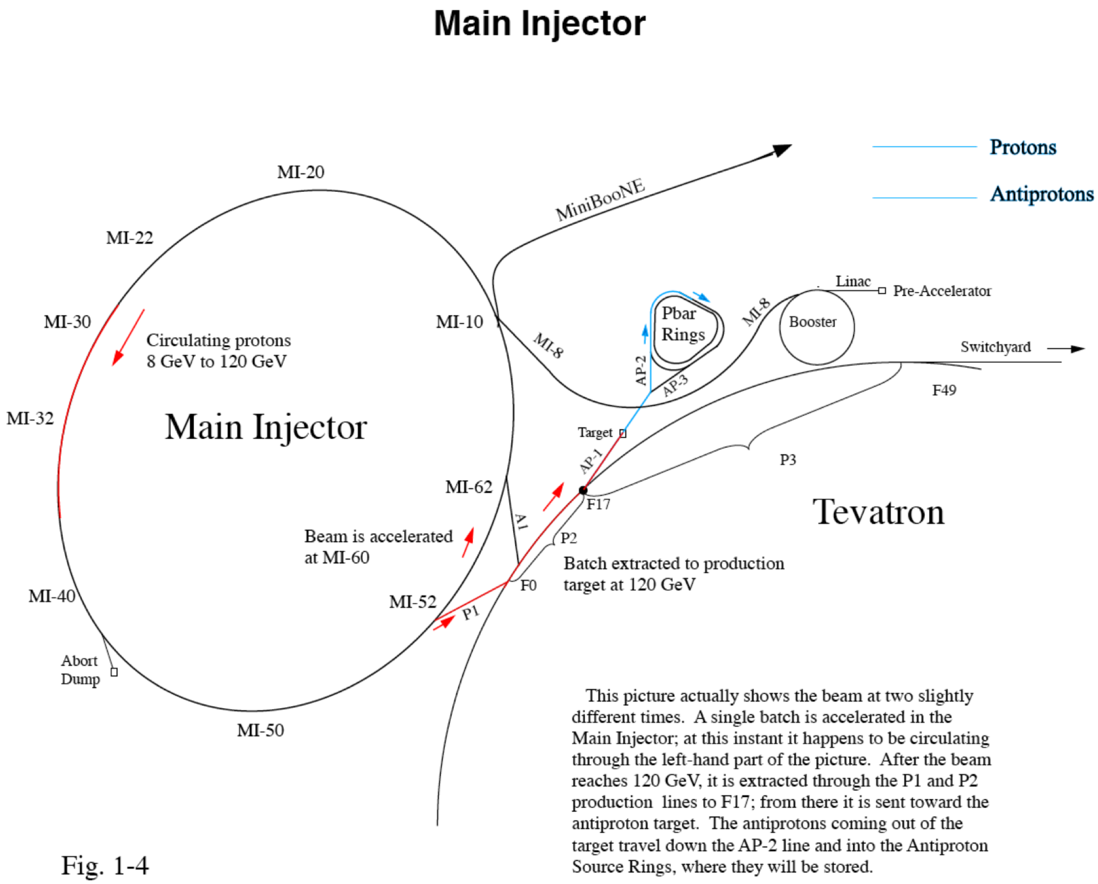
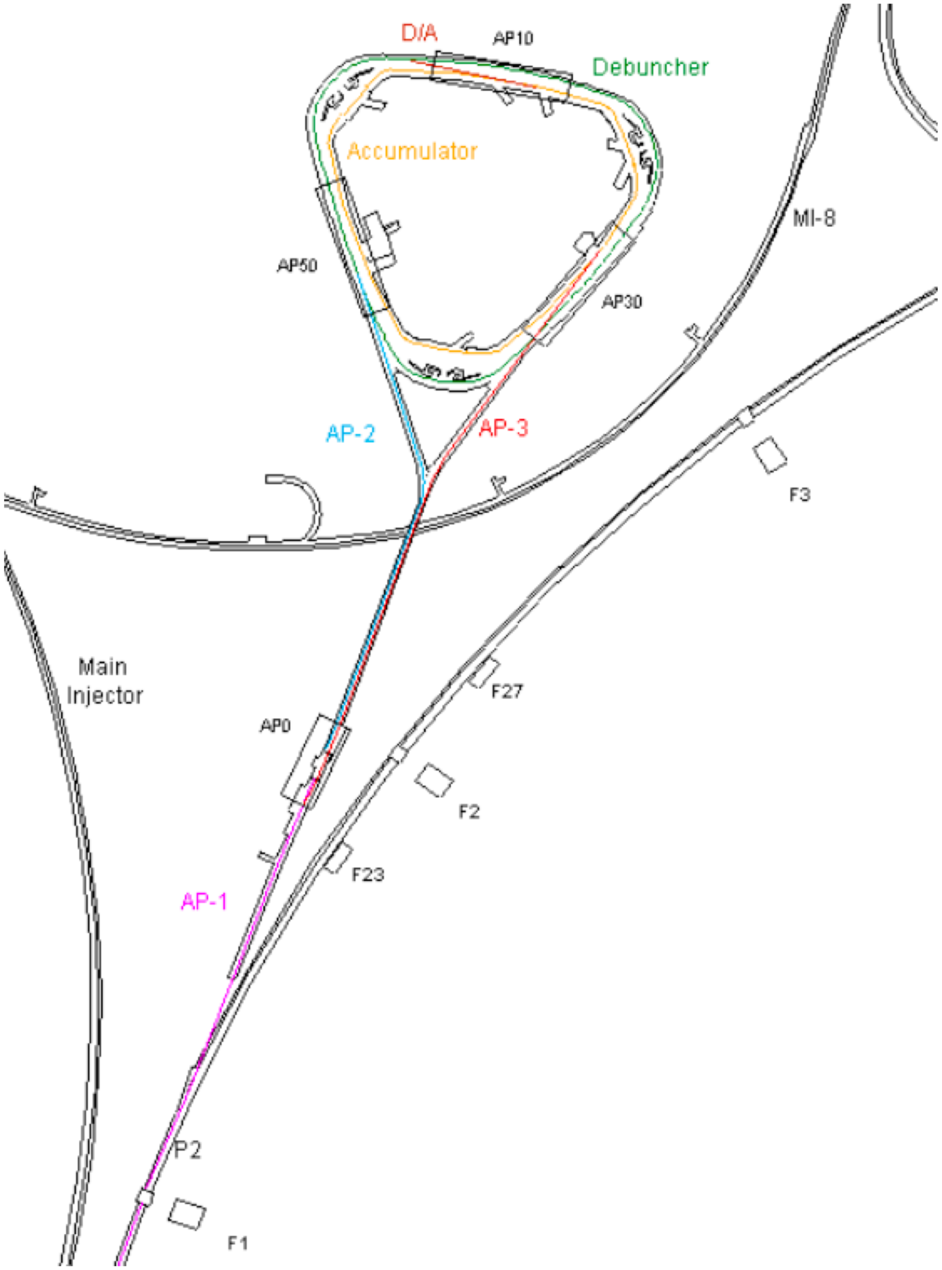


Fig. 1-4
Antiproton Production

- The Main Injector is a 120 GeV storage ring
  - Injection at 8 GeV
  - Protons used for pbar & ν production, Tevatron
  - Can also decelerate protons, antiprotons

Fermilab's Antiproton Source



➤accumulation rate typically exceeds 2×10^{11}/hour

➤accumulation rate decreases with "stack" size, so antiprotons are transferred to the recycler ("stash") for storage and additional cooling

Fermilab Recycler Ring

- ➤Recycler is an 8 GeV fixed-energy (permanent magnet) storage ring used to store & cool pbars
  - ➢Stocastic cooling
  - ➢electron cooling

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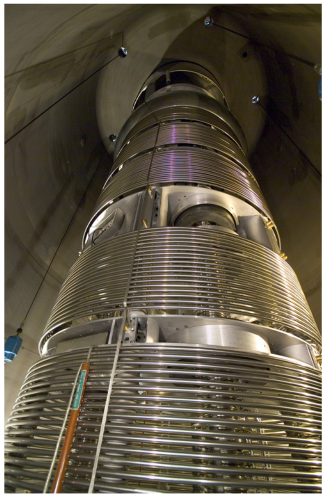
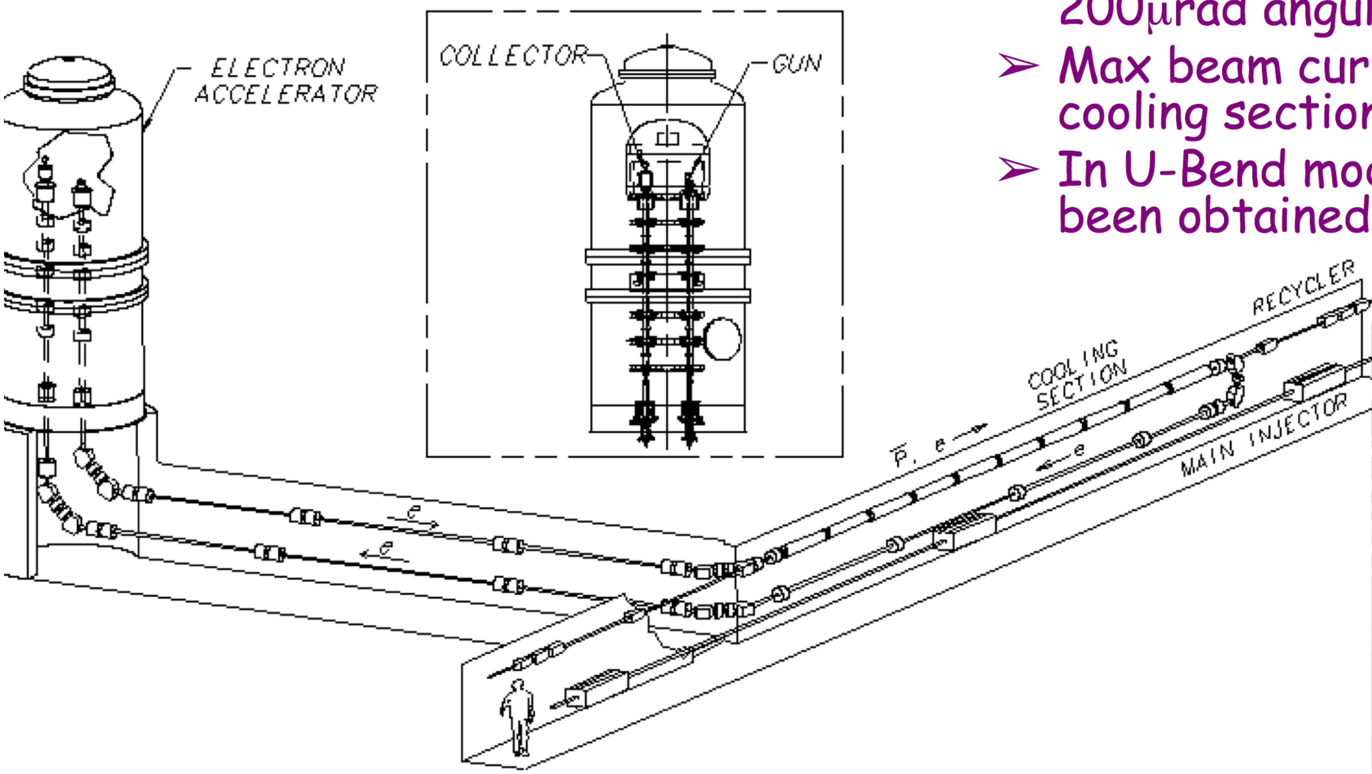
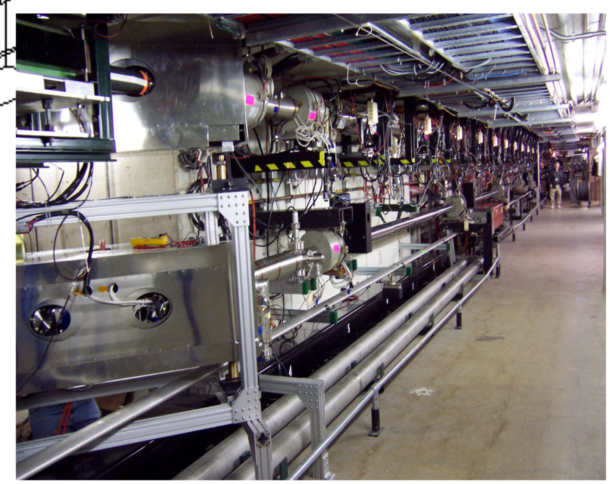
Recycler Electron Cooling



- The maximum antiproton stash size with stochastic cooling only is limited by
  - Stacking Rate in the Debuncher-Accumulator at large stacks
  - Longitudinal cooling in the Recycler
- Longitudinal stochastic cooling of 8 GeV antiprotons in the Recycler is enhanced by Electron Cooling
  - Electron beam: 4.34 MeV – 0.5 Amps DC 200μrad angular spread
  - Max beam current 700 mA Circulated in cooling section
  - In U-Bend mode currents of 1000 mA ha been obtained.





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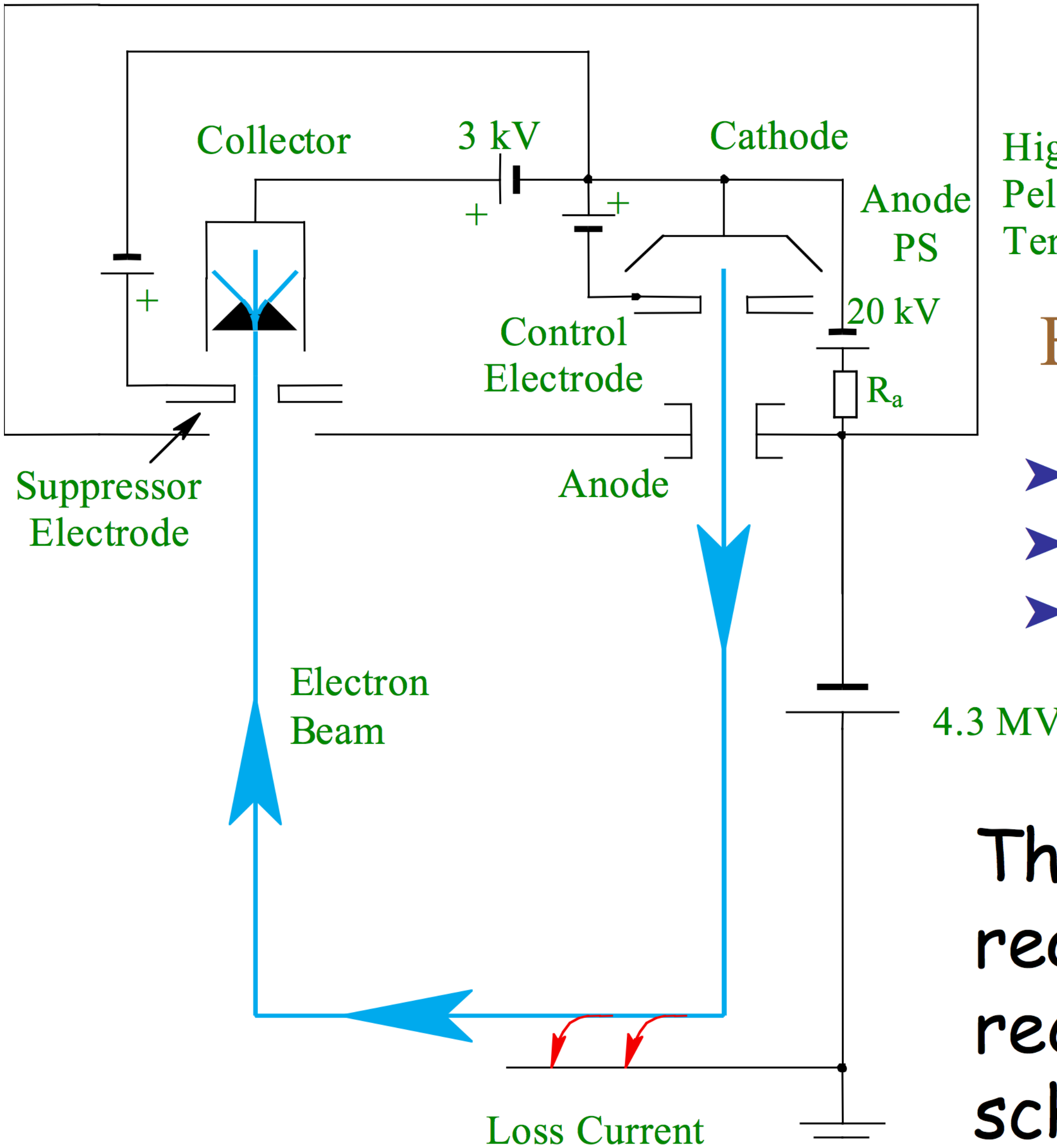
Simplified electrical schematic of the electron beam recirculation system



For I= 0.5 A, ΔI= 5 μA:

- ➤Beam power 2.15 MW
- ➤Current loss power 21.5 W
- ➤Power dissipated in collector 1.6 kW

The beam power of 2 MW requires the energy recovery (recirculation) scheme

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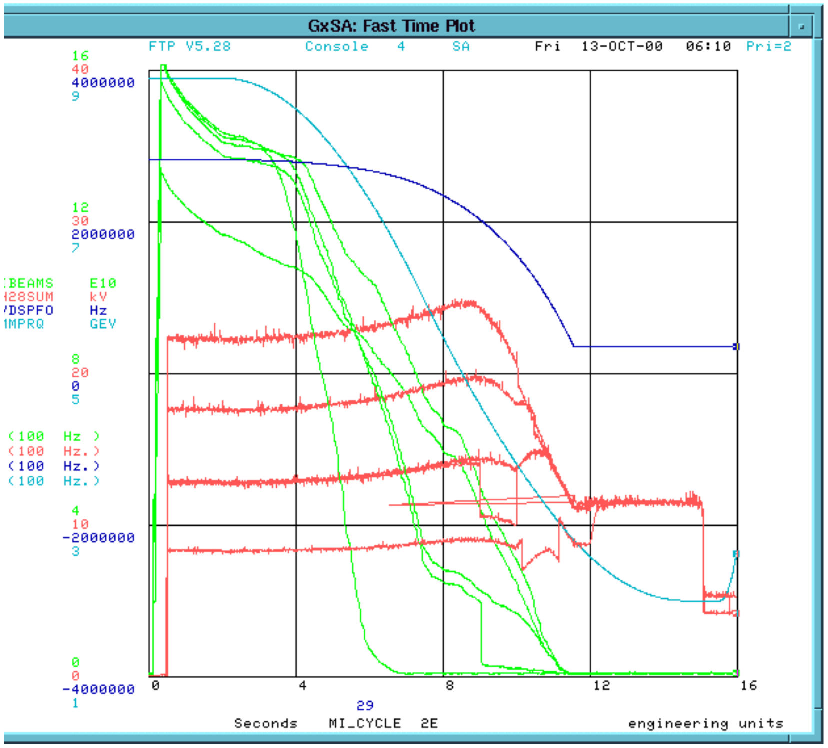
Main Injector Deceleration



- Preliminary deceleration studies done with protons
- A beam momentum of 3GeV/c was achieved without any accelerator hardware modifications. Lower momentum is clearly possible.
- Note the red RF glitches, and accompanying green beam intensity losses.
  - There is a fix for this situation requiring simple LLRF electronics mods.
- Simulations agree well with the experiment.

Bottom line: simple modifications to the Main Injector would allow it to decelerate antiprotons, which could then be transferred to a dedicated low-energy deceleration ring.

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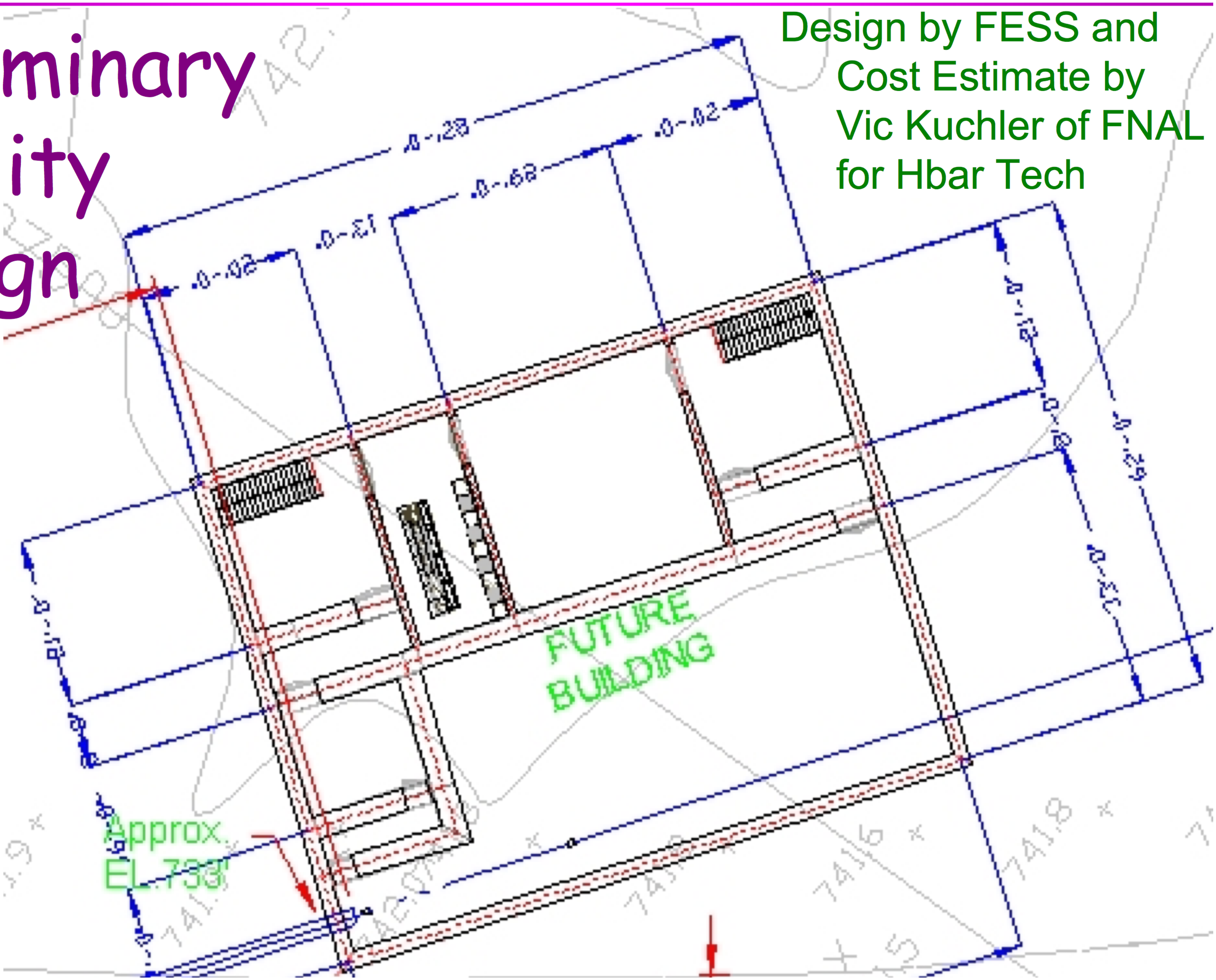
Preliminary Facility Design

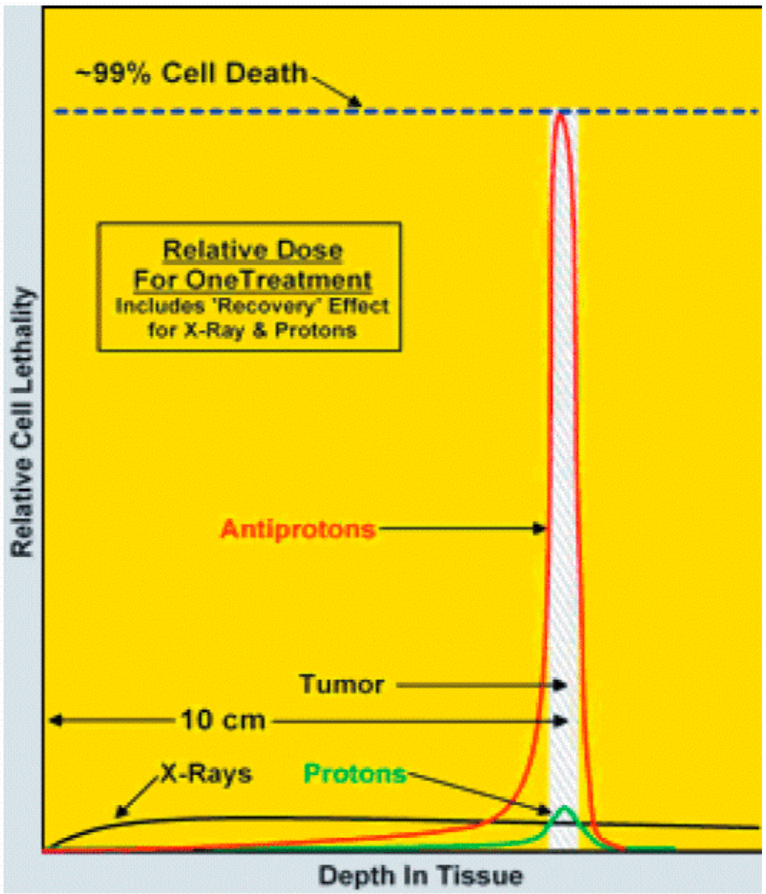
Design by FESS and Cost Estimate by Vic Kuchler of FNAL for Hbar Tech



Stopped Antiprotons at Fermilab

Hbar Tech LLC plans to commercialize antiprotons at Fermilab

- ➢business plan for medical antiprotons
  - ➢cancer therapy
  - ➢PET isotope production
  - ➢non-invasive "surgery"
- ➢Original funding scuttled by financial crisis in 2009
- ➢New funding as soon as January
- ➢Hbar Tech founder built Fermilab's Recycler ring



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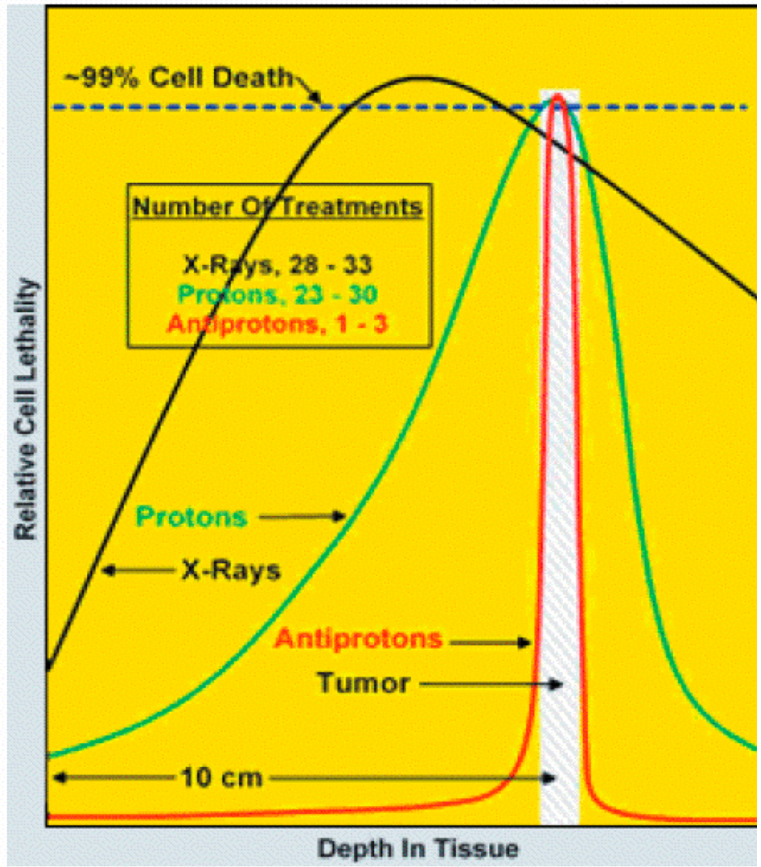
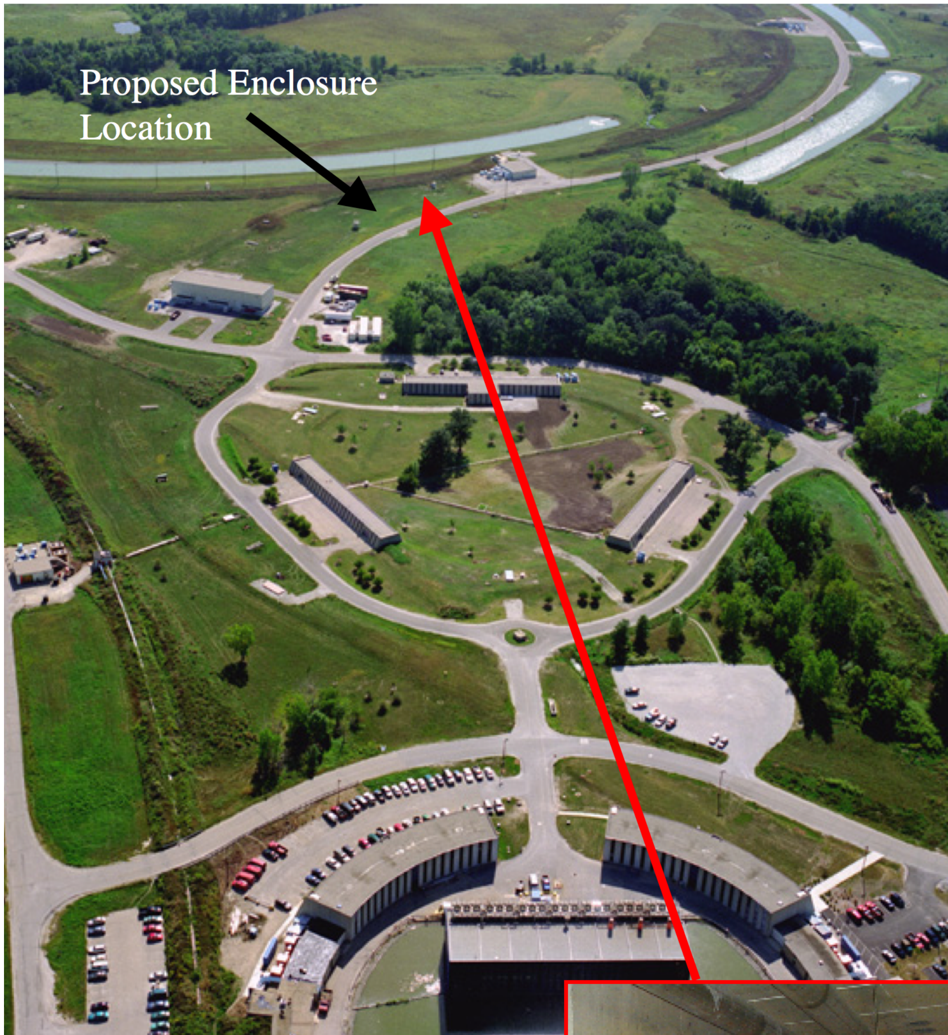
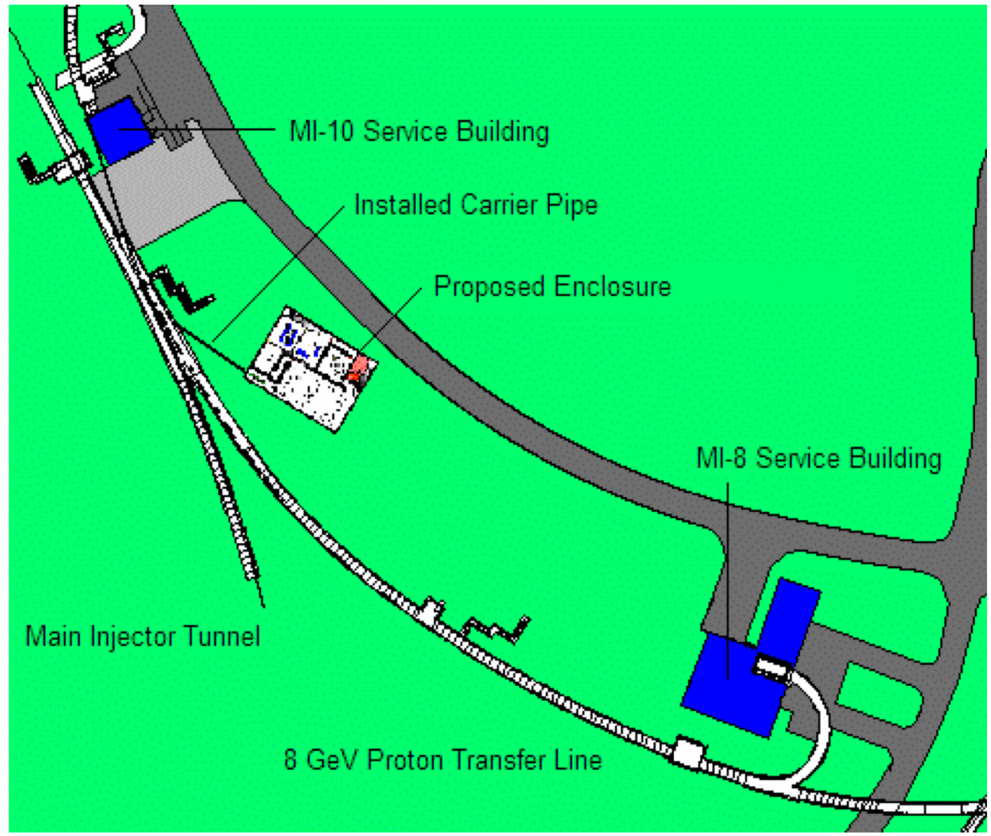


CUMULATIVE TREATMENT COMPARISONS
X-RAY – PROTON - ANTIPROTON

Proposed Facility Location





ransfer line carrier
ipe already installed

Thomas Phillips

Initial Construction

- Transfer line carrier pipe already installed

- Additional construction outside of radiation field
  - ➤Does not require a shutdown to complete

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Outline

1. Motivation (abbreviated)
2. The Antimatter Gravity Experiment
    - A. Antihydrogen beam
    - B. Initial design: transmission-grating interferometer
        - Does not require trapped antihydrogen
        - Monte Carlo results
    - C. High-precision design: Raman interferometer
        - Requires trapping & cooling antihydrogen
3. Antihydrogen at Fermilab
    - A. Antiproton infrastructure
    - B. Future plans
4. History & Prospects for AGE

AGE History

1. AGE sprang from the antiproton working group at Fermilab's 1st Workshop on Physics (2007)
2. Letter of Intent submitted to Fermilab 2008
   - proposed an initial 1% measurement of gbar
     - Fermilab Physics Advisory Committee (PAC) asked for additional theoretical justification for why a 1% measurement might be interesting--they did not find a 1% measurement compelling
   - The PAC asked for additional deceleration studies
   - The PAC asked for additional study of degrader
   - The PAC found the interferometer proposal to be novel, but asked that it be demonstrated with hydrogen

Prototype Interferometer (Hydrogen)

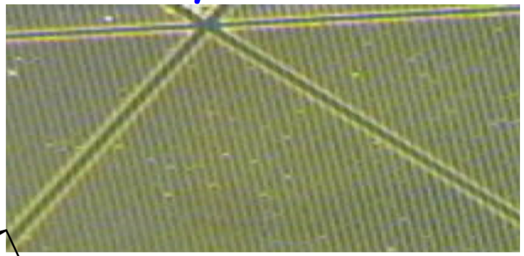
Transmission gratings have a 1 μm period

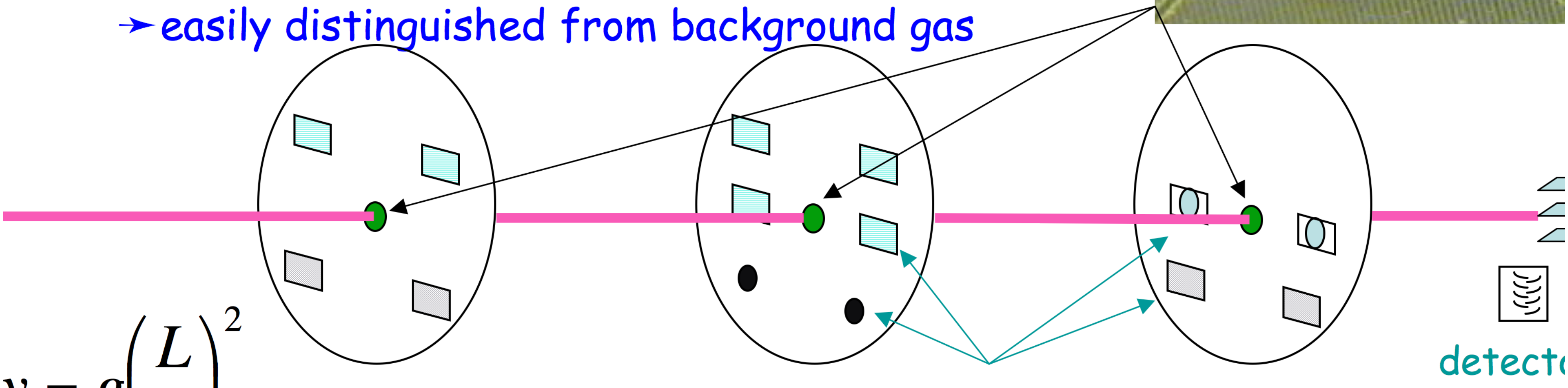
- Courtesy of Max Planck Institute for Extraterrestrial Physics

L = 62 cm between pairs of gratings

Uses a metastable H beam

- easily distinguished from background gas





$$y = g\left(\frac{L}{v}\right)^2$$

avitational deflections: Δy=3.8 μm for v=1000 m/s => $\Delta\phi$=7.5 π radians

Δy=0.4 μm for v=3000 m/s => $\Delta\phi$=0.8 π radians

Δy=0.15 μm for v=5000 m/s => $\Delta\phi$=0.3 π radians

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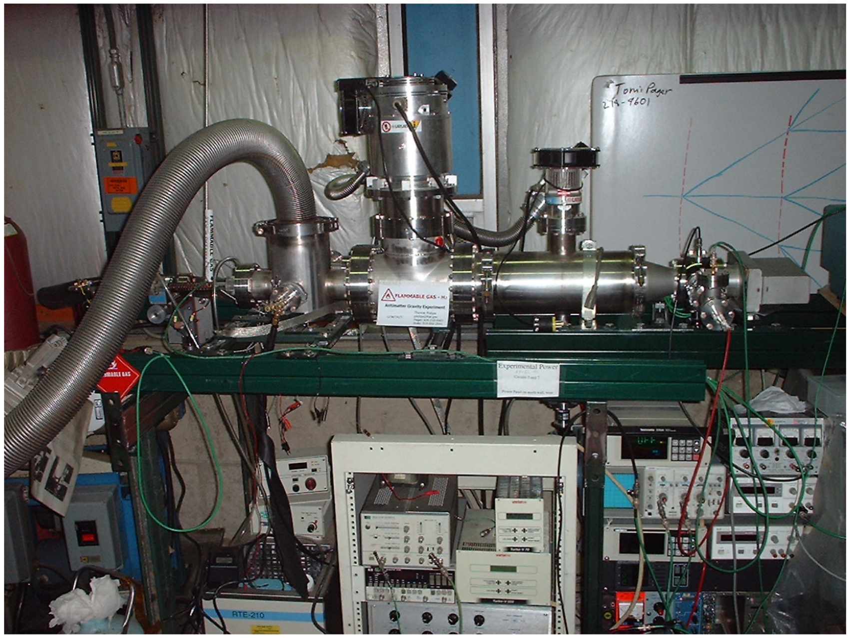
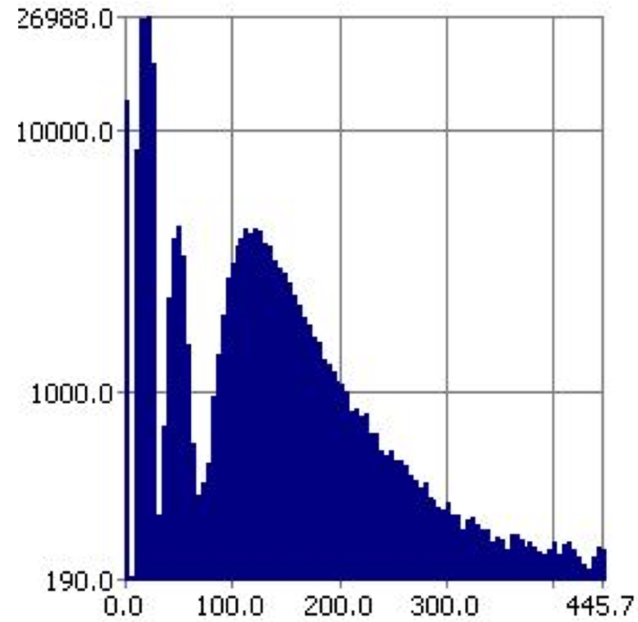
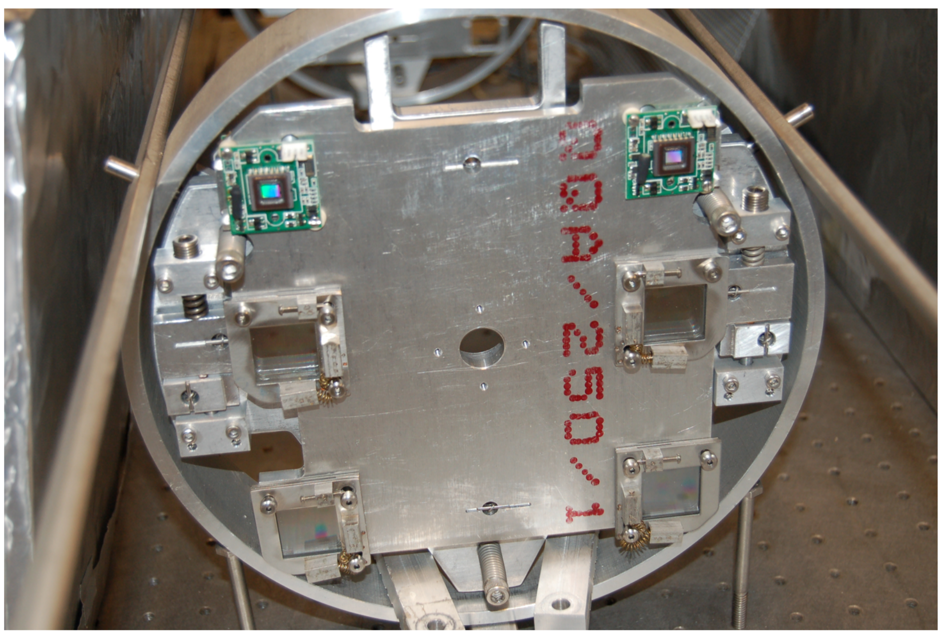


Metastable hydrogen beam is operational



Measured Time of Flight (μsec)



Prototype interferometer under construction.

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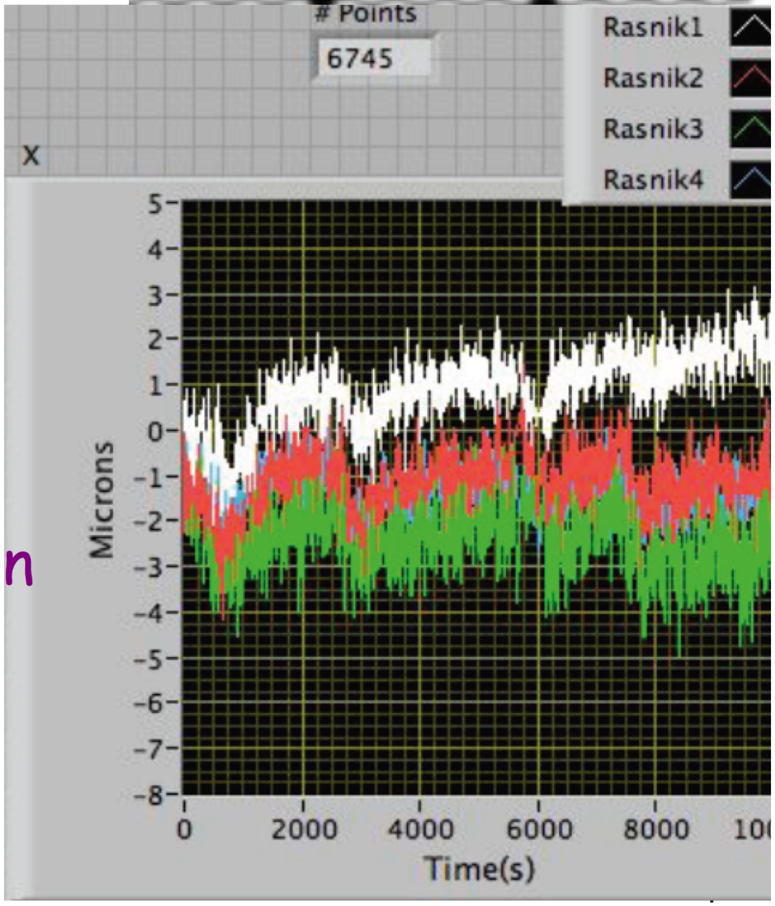
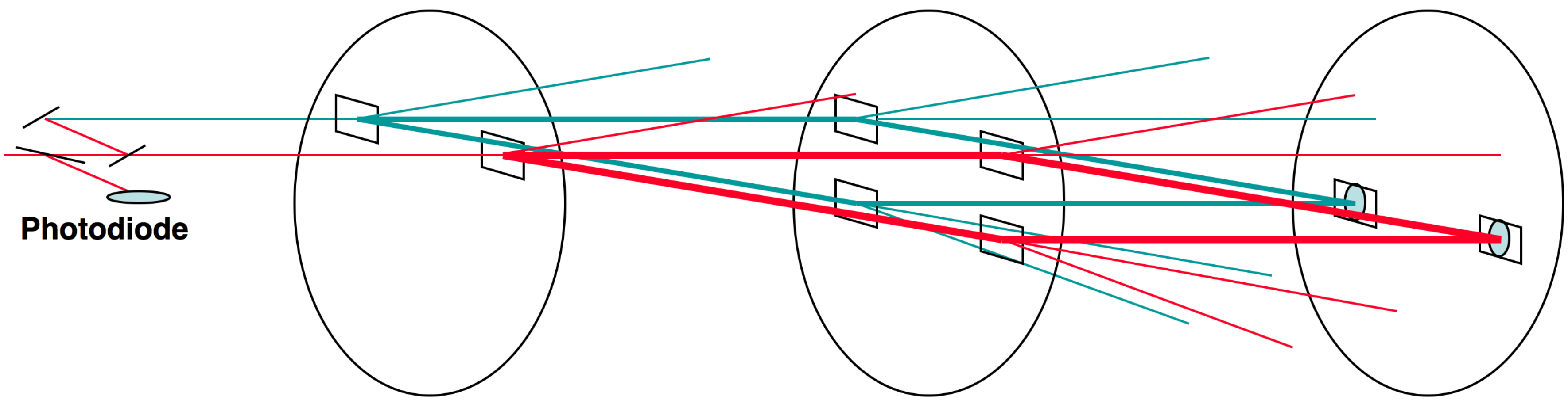
Rasnik Alignment system



- Used for CDF silicon systems
- Screens with 20 micron squares
- Viewed with CCD video camera
- Software analyzes video image
  - Pattern encodes position on screen
  - 0.05 micron relative position resolution
    - (~10000 black <-> white transitions)
- Too slow for phase monitoring

Dual Optical Interferometers

- Same geometry as atomic interferometer
- 5000 line/inch Ronchi gratings
  - Sub-micron resolution
- Side-by-side arrangement measures rotation
- Fast: can measure interferometer phase



AGE History (continued)

Revised Letter of intent submitted in 2009

- proposed a 10^{-7}+ measurement using Raman interferometry
  - The PAC found this compelling
- The PAC recommended the full proposal be deferred until the technique could be demonstrated with matter
  - Fermilab wants to see trapping and cooling H before proposal
  - No resources provided

Collaborator Mark Raizen is working on trapping and cooling hydrogen

- requires a 243 nm laser
  - tried building one using a tapered amplifier (1mW?; not stable)
  - has now purchased a commercial solution (200 mW demonstrated)
    - tunable optically pumped semiconductor laser (OPSL)

No additional resources, so no additional development work is currently being pursued

- Fermilab response was inadequate to get NSF funding

Funding Status

- NSF funding
  - funds trapping of hydrogen at Texas A&M
    - also SGER and ARP (Texas) grants
- Private funding for antiproton facility
  - antiprotons to be used for medical treatments
  - Funding decision as early as this month
    - Funds would be available in January
  - contingent on Fermilab approval
  - business plan calls for building in 1st year
  - deceleration ring in 3rd year
    - stopped antiprotons using degrader until ring complete

Fermilab's Proposed Schedule

- Fermilab's Tevatron just turned off
  - Antiproton source turns off
- Shutdown scheduled for 2012
  - Upgrade for neutrino program
- Accelerator operations resume 2013
- g-2, mu2e planned for >2015
  - current plan repurposes antiproton source for these experiments
    - alternatives exist, might be better.
  - both experiments currently seeking approval

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  - additional resources required

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- Fermilab proposal, approval

Summary

The Antimatter Gravity Expt can directly measure the force between antimatter and the earth with high precision

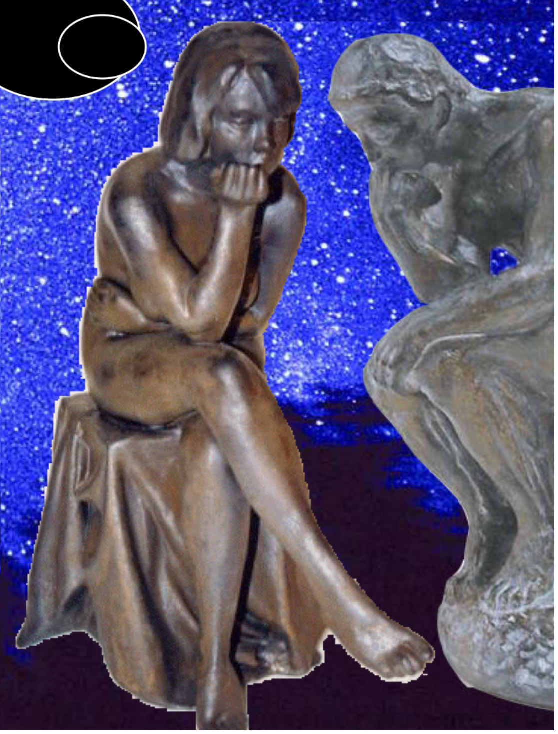
- ➢ The Antimatter Gravity Experiment can be done using proven technologies:
  - ➢ antiproton production, trapping, & cooling
  - ➢ antihydrogen production
  - ➢ atomic interferometry
- ➢ direct test of the equivalence principle for antimatter
- ➢ sensitive to new forces with gravitational-scale couplings
- ➢ Requires new resources to proceed; some possible soon

Regardless of its outcome, AGE will be a classic expt!

Potential to answer some of the biggest questions in physics!

1. Are there undiscovered principles of nature: New symmetries, new physical laws?
2. Are there extra dimensions of space?
3. Do all the forces become one?
4. Why are there so many kinds of particles?
5. What happened to the antimatter?
6. What is dark matter?
   How can we make it in the laboratory?
7. How can we solve the mystery of dark energy?
8. How did the universe come to be?
9. What are neutrinos telling us?

From “Quantum Universe” and “Discovering Quantum Universe”



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