

*An Antihydrogen
Interferometer for Measuring
Antimatter Gravity*

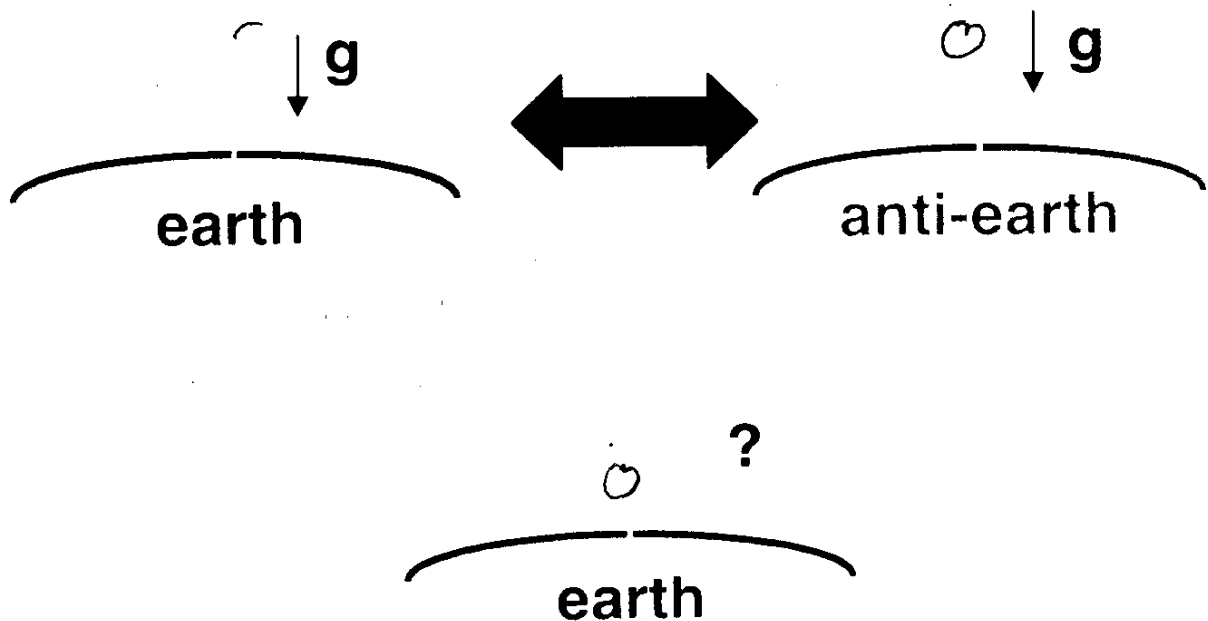
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Pbar 2000
August 2000

Physics Motivation

\bar{g} has never been measured!

CPT:



CPT does not address how an antiapple falls on the earth.

CPT theorem assumes flat spacetime.

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Do we really understand gravity?

General Relativity

- Is a classical theory
- Is not renomalizable
- Cosmological constant is unexplained
- Strong field limit confirmed, but weak field limit violated:

Galactic Rotation Curves:Missing Mass?

- Missing mass helped to find Neptune
- Incorrectly predicted Vulcan to explain Mercury's orbit
- Modified Newtonian Dynamics (MOND)
The new Kepler's laws?

Superstring gravity theories, etc., generally include equivalence principle violations (but not necessarily measureable)

Search for a New Force

Any difference observed between the acceleration of matter and antimatter could indicate a new force that couples to baryon number

- Precision beyond 10^{-6} is new territory
- Larger difference may be possible, depending upon assumptions

Measuring Anit-g

Antimatter candidates for measuring \bar{g} :

charged:	e^+	\bar{p}	
neutral:	\bar{n}	\bar{H}	Ps

Attempts to measure charged antimatter
failed (EM forces too strong)

Suggested methods for measuring \bar{H}
generally require trapping \bar{H}

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 through positron plasma

Direct the beam through a transmission-grating interferometer

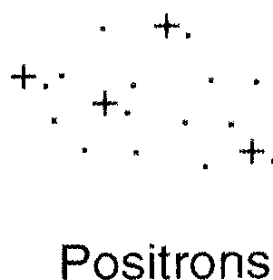
Measure \bar{g} by observing the gravitational phase shift

- Interference pattern shifts by the same amount that the atoms fall

Can get $\frac{\Delta\bar{g}}{\bar{g}} < 0.01$ with 10^5 – 10^6 $\bar{\text{H}}$

Making Antihydrogen

Ingredients:



Collect antiprotons in a trap. Add electrons to cool to 4 degrees K. Collect positrons in an adjacent trap.



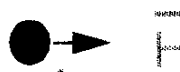
Then raise potential of \bar{p} ...



...and drop barrier:



\bar{p} acquires an e^+ and exits.



Antihydrogen Production Rate

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

T in degrees K

n_e in cm^{-3}

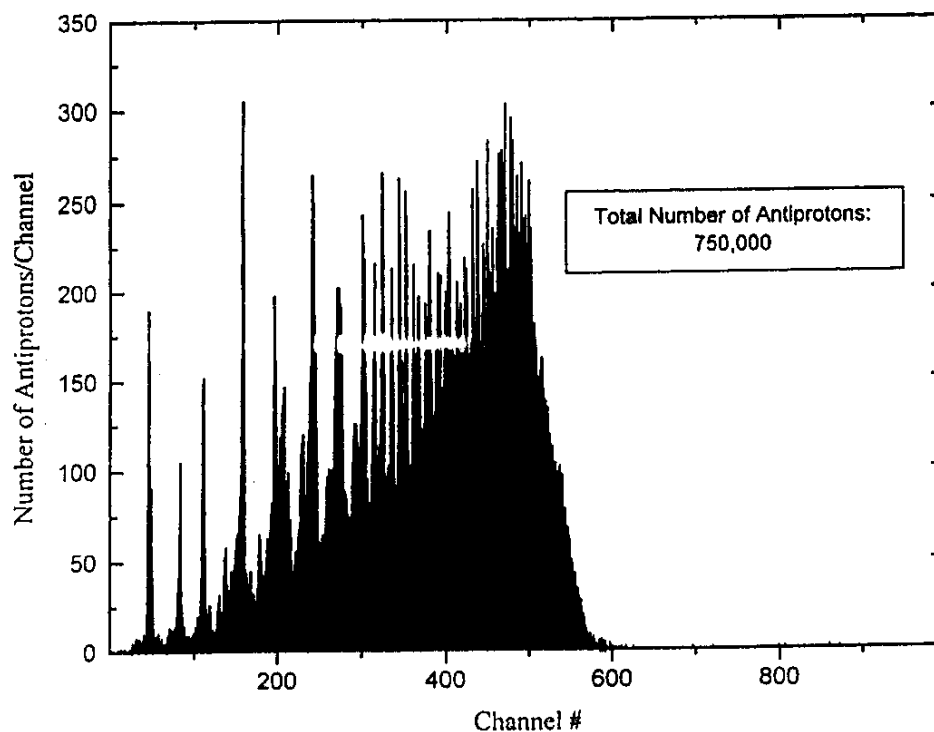
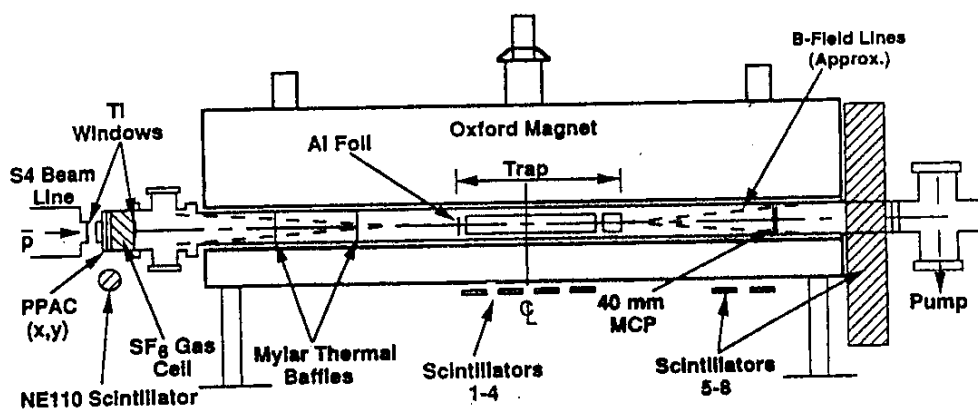
For $n_e \geq 10^8 / cm^3$ and a 10cm long positron plasma, each antiproton has >0.6% chance to become antihydrogen.

High rate means this could be tested with matter.

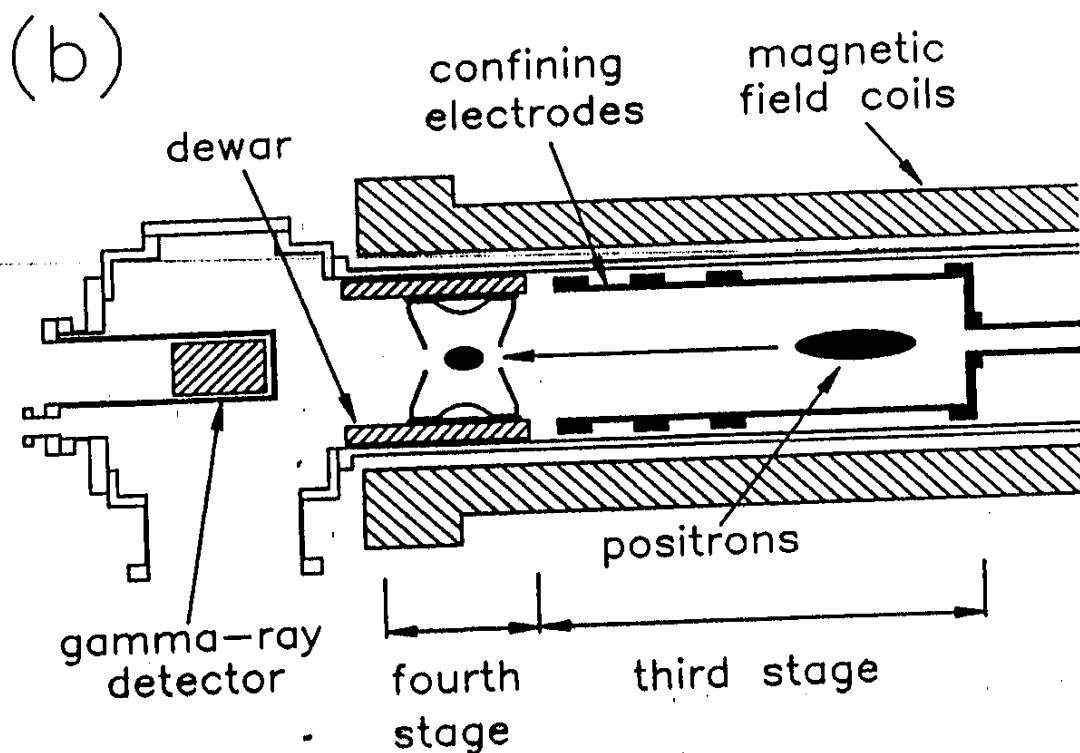
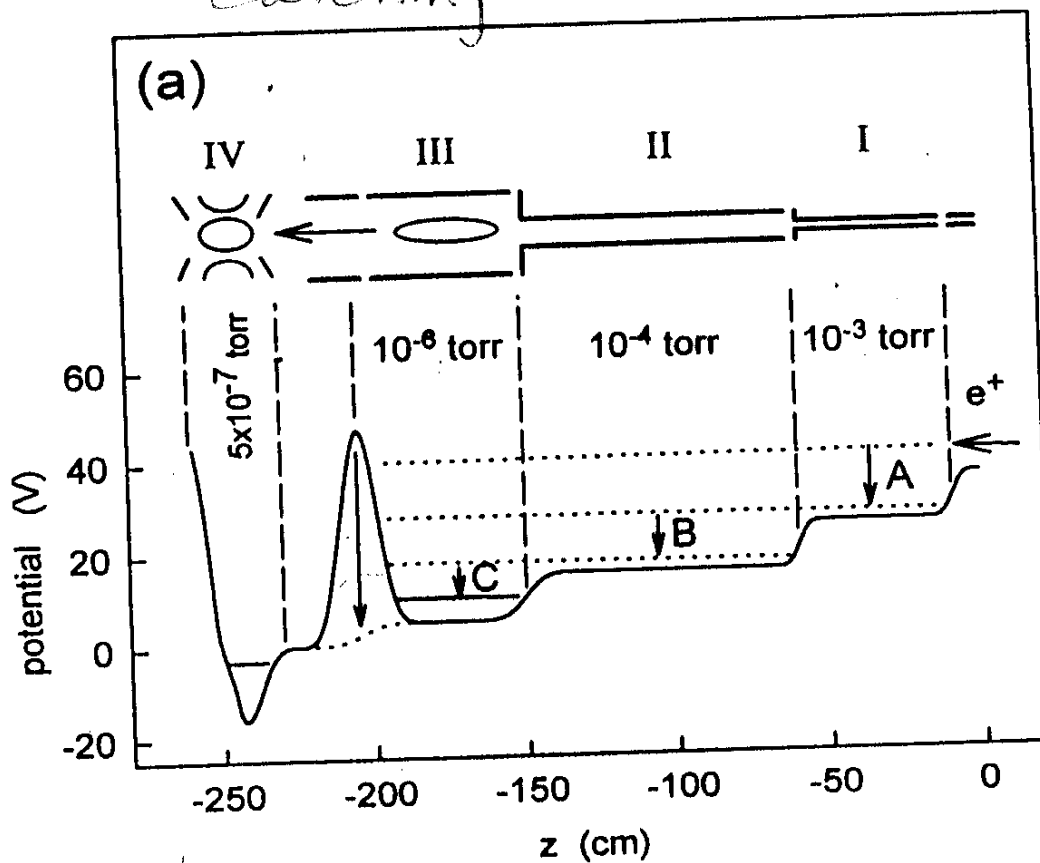
Could use a laser to enhance rate, and to select a low-lying n state.

Collecting Antiprotons

The PS200 Catching Trap at LEAR



Catching Positrons



Positron Plasmas

Because positrons are difficult to obtain in large numbers, they must be contained in devices with very long confinement times. At present, the only feasible way of doing this is to accumulate them in a Penning trap.

Pure Positron Plasmas

At present, we are able to accumulate up to 100 million positrons in our Penning trap, and to store them for up to half an hour. The clouds of positrons, which are at room temperature, are typically 5 to 20 cm long and about 2 cm in diameter. 10^8
 $5\text{ cm}^3 - 60\text{ cm}^3$

Electron-Positron Beam-Plasma System

The simplest experimental approach to the study of electron-positron plasmas is to create a beam-plasma system by transmitting an electron beam through a positron plasma stored in a Penning trap. This has the advantage that it is not necessary to confine both species at the same time. We have conducted the first experiment of this type using a low-energy electron beam and have observed several fundamental plasma physics phenomena, including two-stream and transit-time instabilities.

Stationary Electron-Positron Plasmas

The long-term goal of the program is to study electron-positron plasmas in which the two species are stationary relative to each other. This cannot be accomplished in Penning traps, which can confine only one sign of charge. One of the methods we are considering is the RF trap or Paul trap.

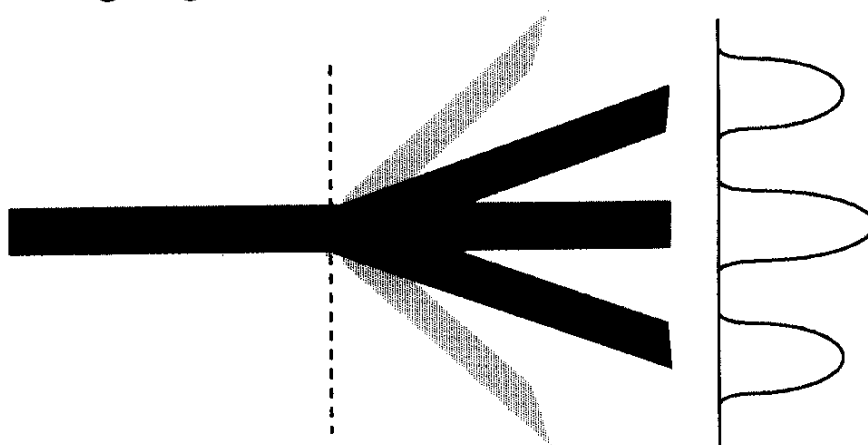
Papers about positron plasma experiments

Group members working on positron plasmas are: Rod Greaves, Chris Kurz, and Steven Gilbert.

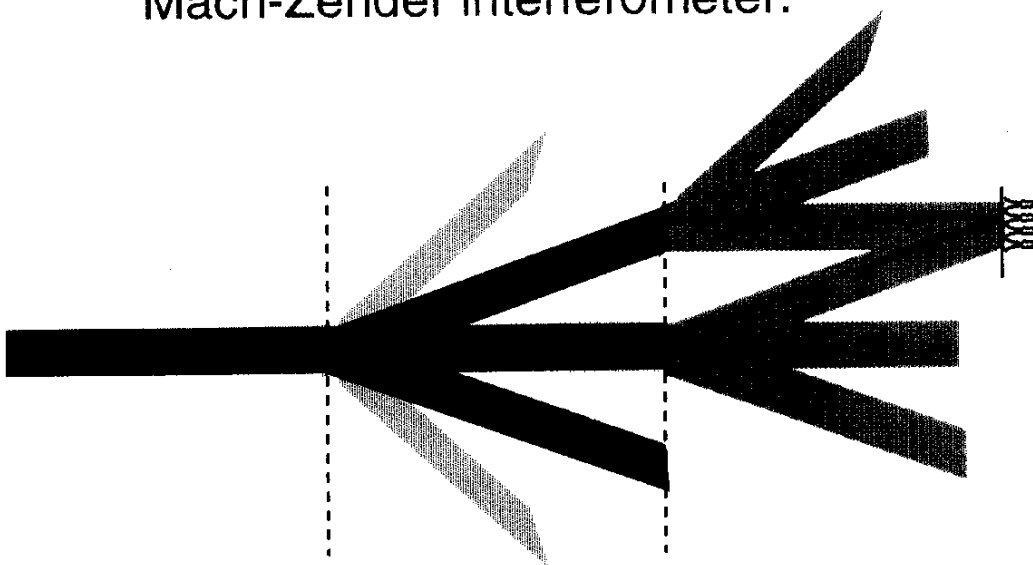
Updated November 21, 1995

A Remarkable Interferometer

A single grating makes a diffraction pattern:

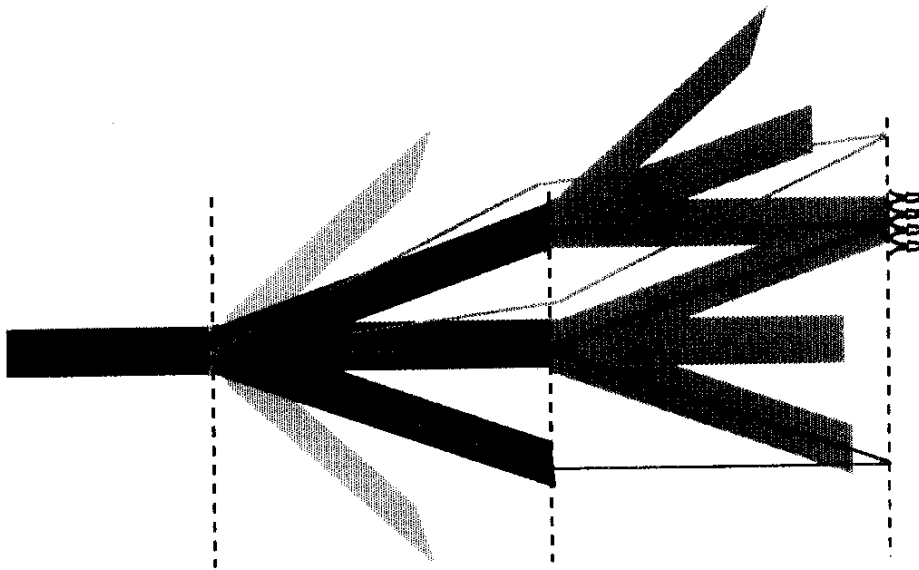


A second identical grating makes a
Mach-Zender interferometer:



“White Light”, Extended Source

The location of the interference pattern is independent of wavelength and source location.



The spacing of the interference peaks is equal to the grating period D , so a third identical grating can be used to analyze the position of the pattern. The 3rd grating can be moved, and the transmitted intensity is measured as a function of position.

Atom Interferometry Works

David Pritchard's group at MIT routinely operates an atom interferometer.

Uses Na at 1000 m/s

- wavelength much shorter than H
- collimates beam and gets separated beams in the interferometer
- about 12% of beam in interference pattern
- can measure phase to 0.1 radian with 4000 atoms in interference pattern
this corresponds to a position measurement of 6nm

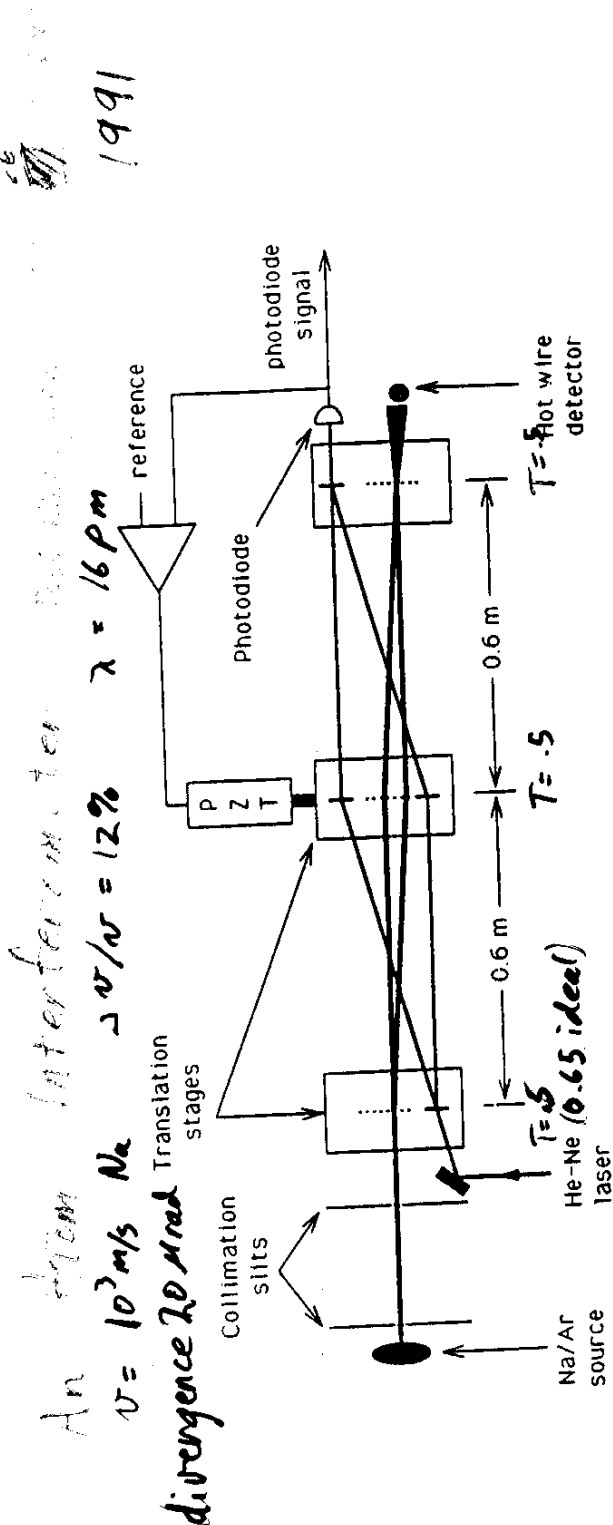


FIG. 1. A schematic of our interferometer showing the active vibration isolation system. Not to scale. The 0.4-μm-period gratings are indicated by a vertical dashed line, and the 3.3-μm-period optical gratings by a vertical solid line.

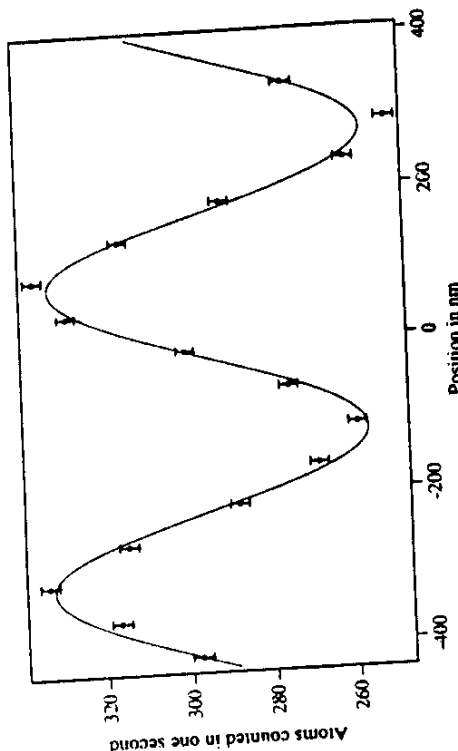
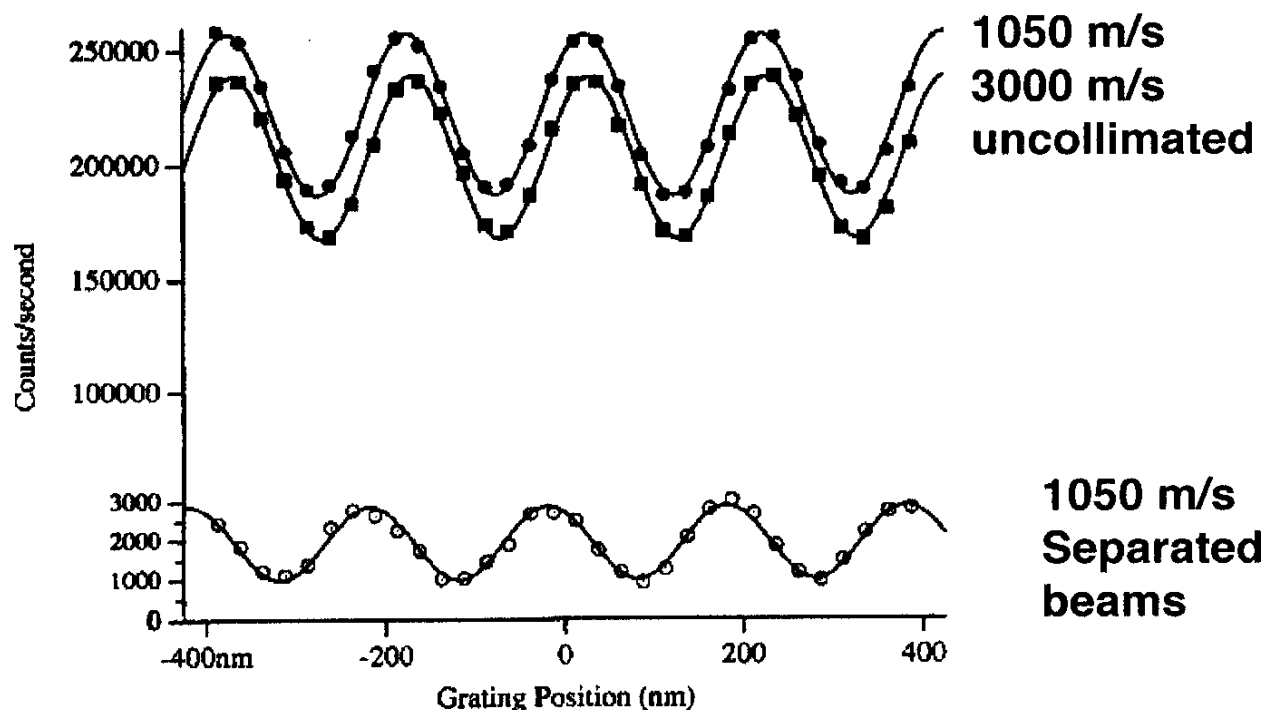


FIG. 4. Interference signal from 400 s of data (~23 s per point). Background hot-wire noise of 40 counts/s subtracted. The solid line is a least-squares fit by a sine function with 400-nm period. Error bars are 1 standard deviation assuming Poissonian noise, and slightly underestimate the noise because of the super-Poissonian character of the hot-wire background.

Sodium Interferometer

High contrast has been observed with the MIT interferometer using an atomic Sodium beam



Atom Interferometry: Dispersive Index of Refraction and Rotation Induced Phase Shifts for Matter-Waves
Troy Douglas Hammond, Ph.D. Thesis, MIT, February 1997.

Getting Started with Hydrogen

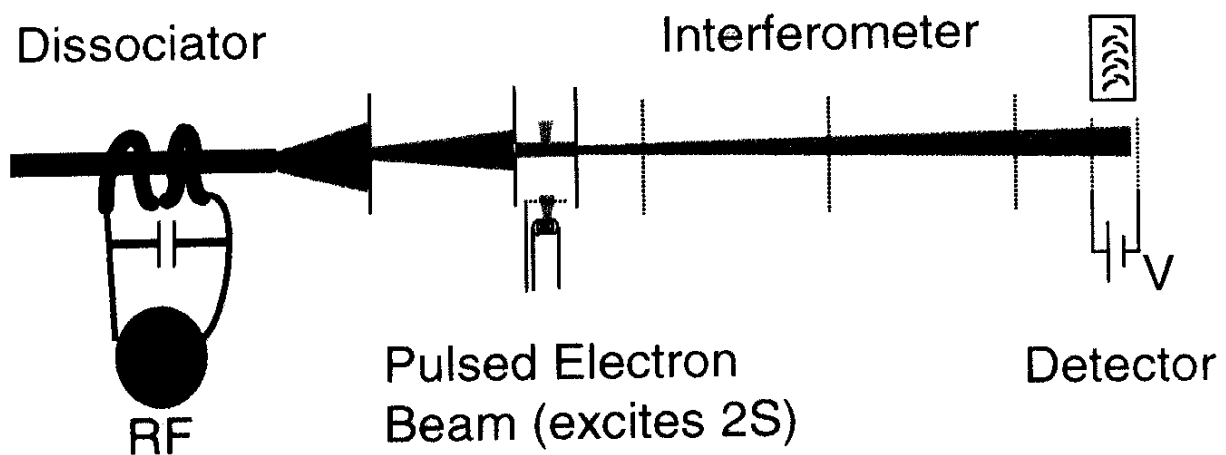
Desirable to develop interferometer with a hydrogen beam

- No accelerator required to make antiprotons
- Can optimize measurement with an easily produced and controlled beam
- Eventually want a matter-antimatter differential measurement

Beam requirements:

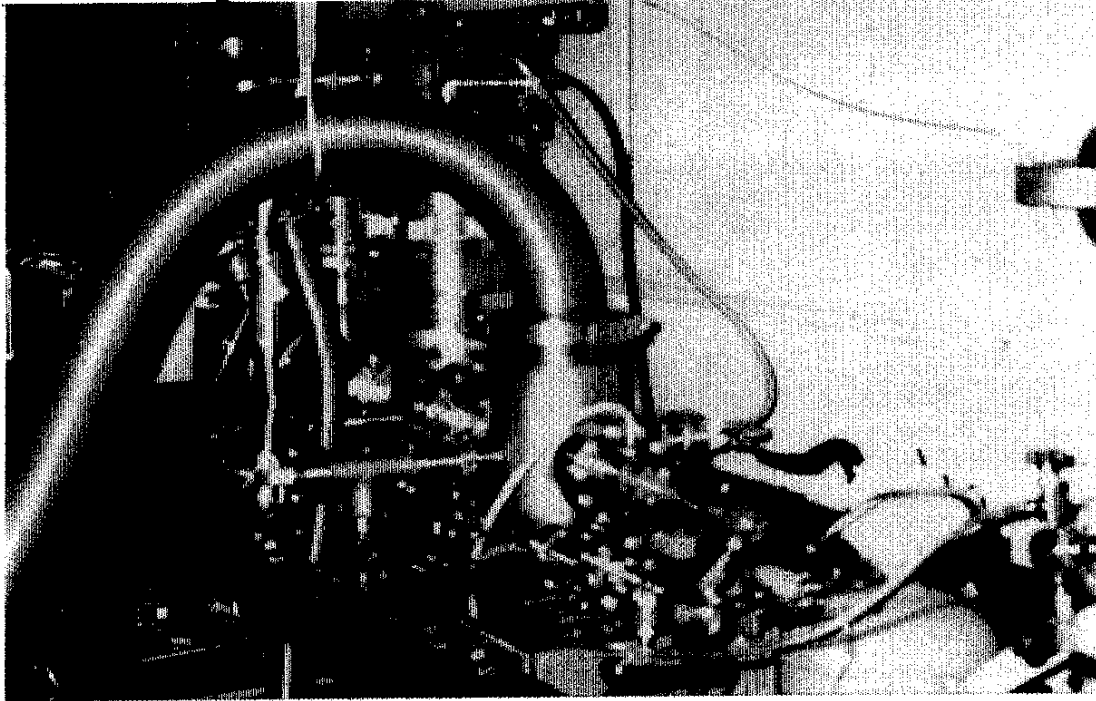
- atomic hydrogen
- about 1000 m/s
- small velocity spread and/or time-of-flight
- detectable
- Use metastable (2s) state
 - Quench with E field; observe Lyman α
 - Pulse for time-of-flight

Atomic Hydrogen Beam for Gravity Measurement



- Dissociate H_2 to produce atomic hydrogen
- Pass through cold nozzle to get right velocity
- Skim and collimate to produce beam
- Excite 2S with pulsed electron gun
- Pass through transmission-grating interferometer
- Quench 2S and observe Lyman α photons to measure transmission (interference pattern) and time-of-flight

Hydrogen Dissociator



Hydrogen gas is dissociated with RF

- Pulsed valve for hydrogen

- Reduces gas load

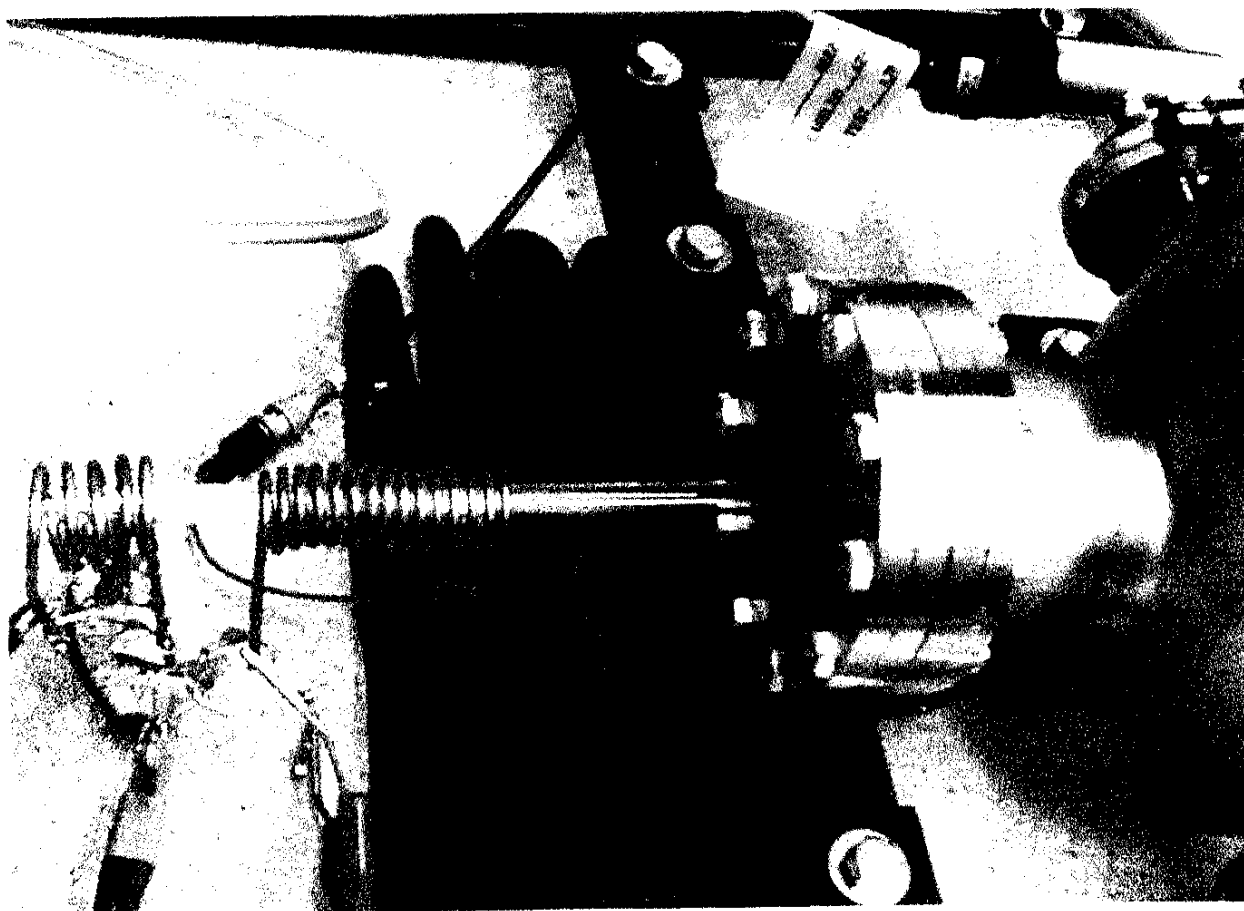
- Dissociation tube is water cooled

Roots blower pump on nozzle chamber

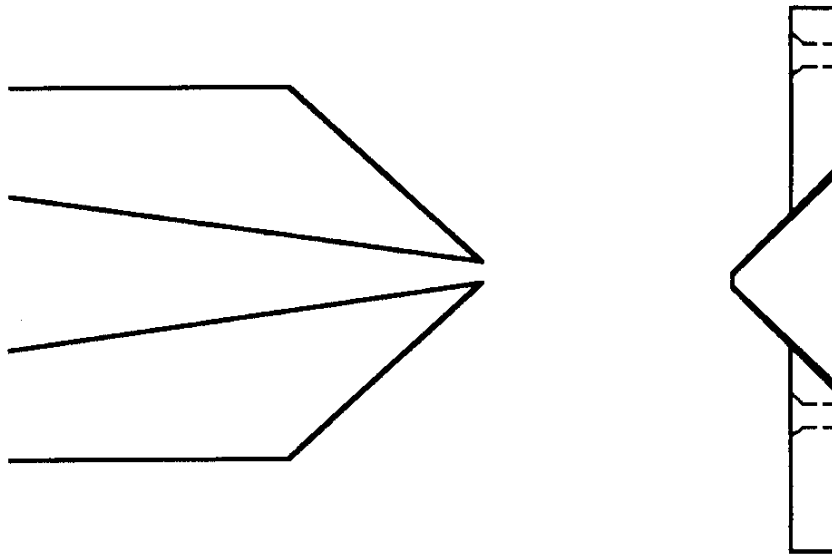
- Needed for high gas load

Nozzle cooled with liquid nitrogen

Hydrogen Plasma



Supersonic Nozzle



Cooled with liquid nitrogen

Gives non-thermal velocity distribution

–Compresses longitudinal velocity

Skimmer extracts core of beam

Collimator in next chamber reduces angular divergence

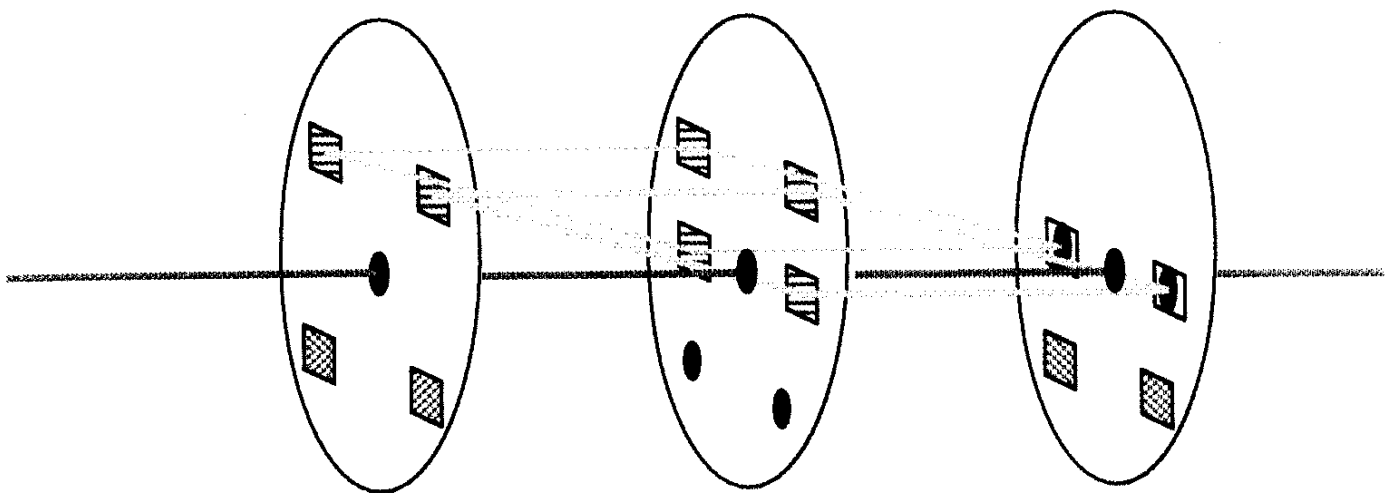
Same design is used in TUNL polarized source.

Hydrogen Interferometer

Based upon MIT Design

Transmission gratings can have a larger period

Less sensitive to vibration, misalignment



Atomic Transmission gratings mounted on floating aluminum plates along with Rasnik grids and optical gratings for alignment.

Floating aluminum plates are mounted on fixed plates with piezoelectric positioners.

Fixed plates are mounted in a 10" pipe.

Vacuum Transmission Gratings

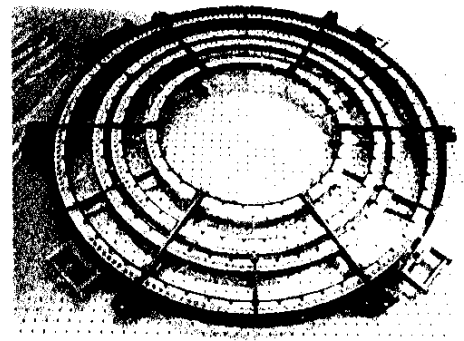


Atomic gratings from Max-Planck-Institut für
extraterrestrische Physik

- Spares from Chandra X-ray telescope low-
energy transmission grating

- 1 micron period

- Large area: 1.5 cm diameter



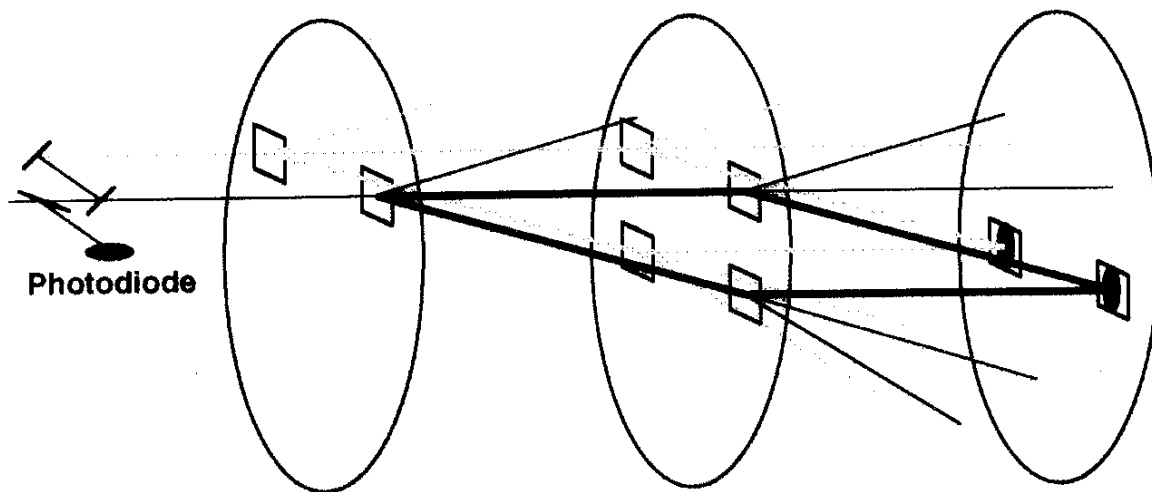
Dual Optical Interferometers

Same geometry as atomic interferometer

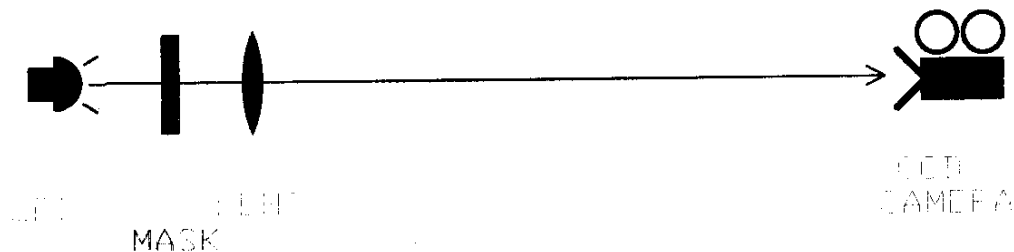
5000 line/inch Ronchi gratings

Sub-micron resolution

Side-by-side arrangement measures rotation



Rasnik Alignment system



- Being 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

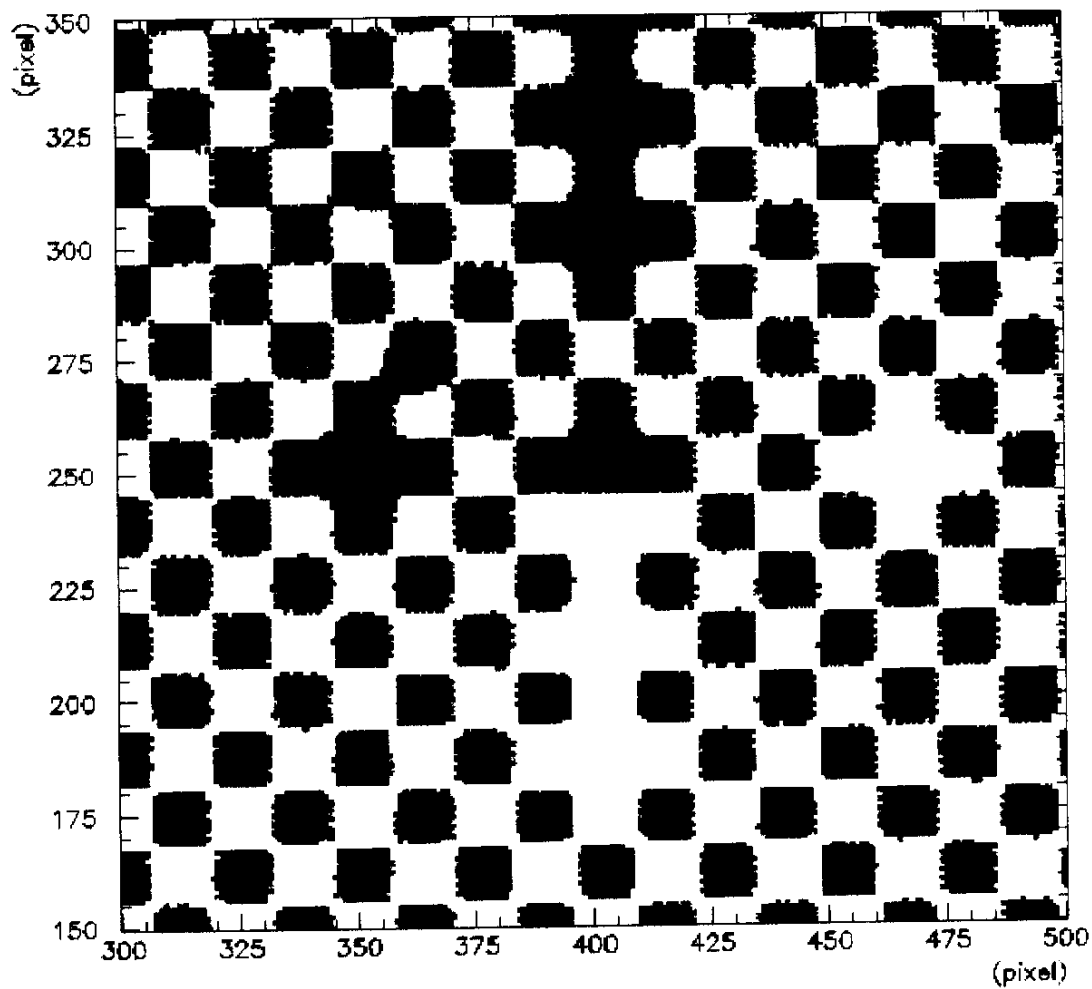


Figure 2: Portion of an actual image taken by one of the Rasnik systems. The full image is 768×512 pixels (10 times the area shown). Each square is about 13 pixels wide.

The Window of Opportunity

The cost of some other gravity experiments:

- Gravity Probe B: ~\$560 M
- LIGO:

The Antimatter Gravity Interferometer

Experiment is **CHEAP**, but only because the accelerator for making \bar{p} already exists.

The window of opportunity for making this measurement at a bargain-basement cost closes when accelerators are no longer making antiprotons for other purposes.

The Public Loves Antimatter

CERN had a tremendous response when they announced making a few antihydrogen atoms

Many believe antimatter is only science fiction

Many also believe that antimatter will fall up

This experiment would have great PR value regardless of the result