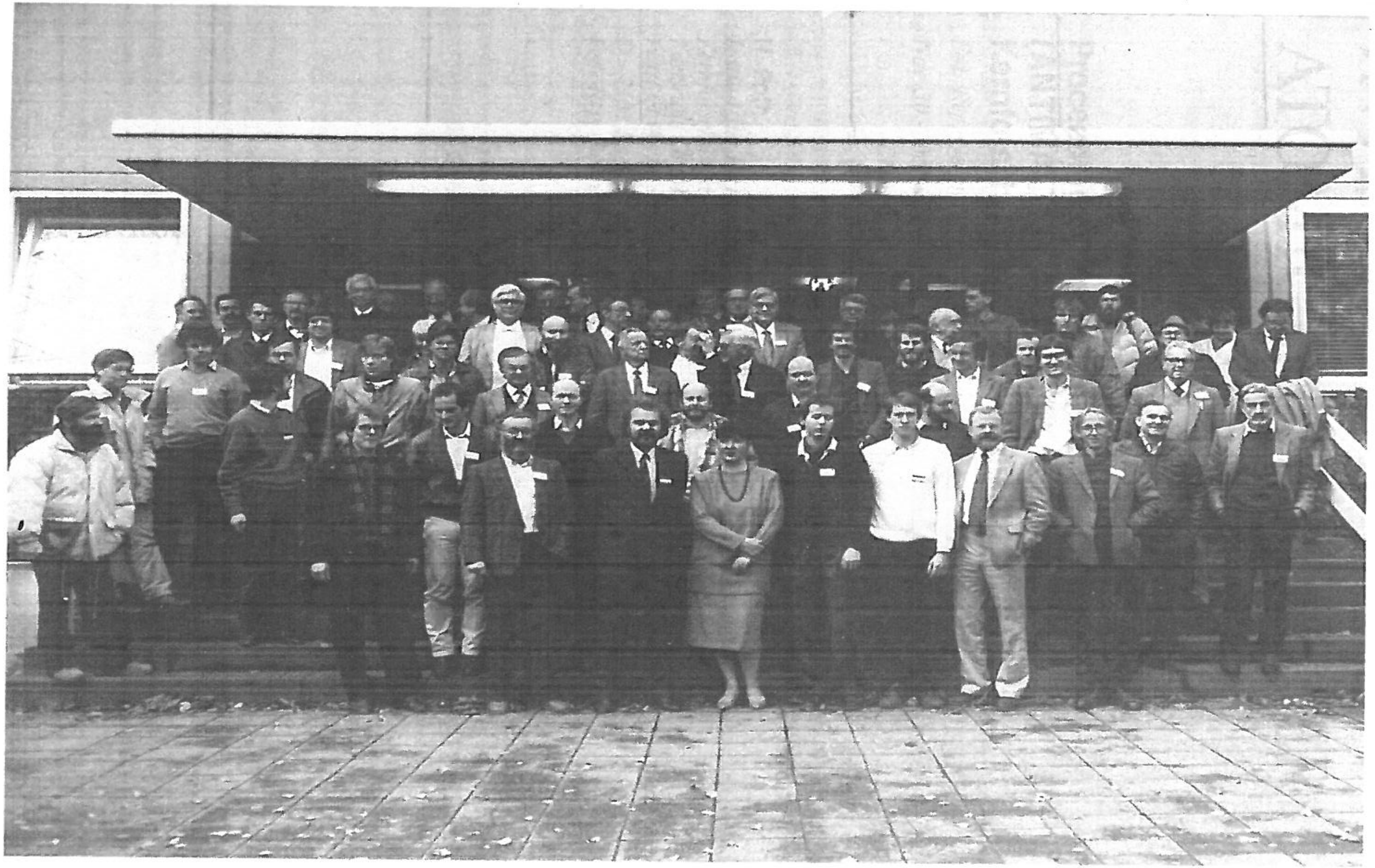
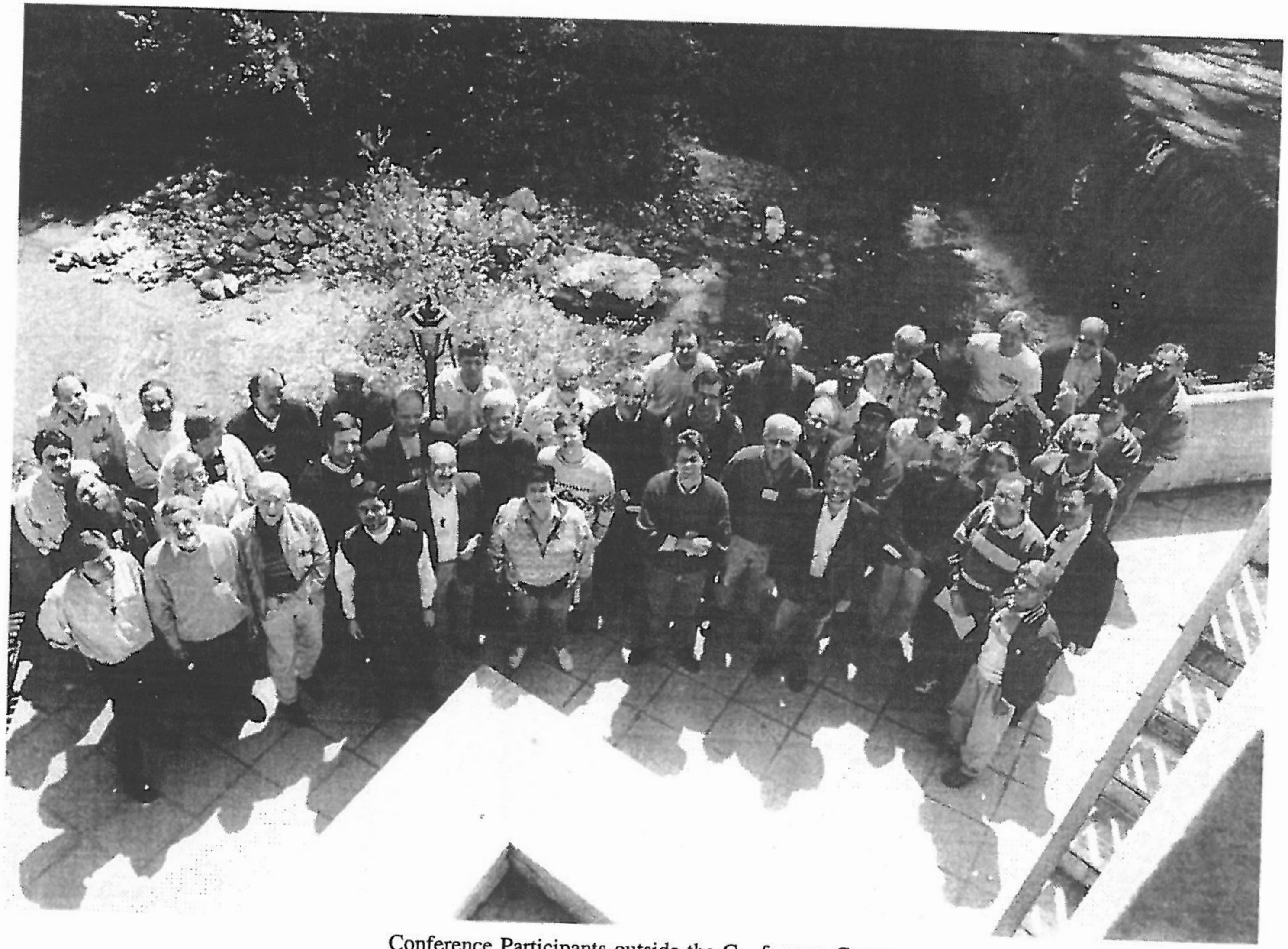
WAG 2013 – Summary Talk

Mike Charlton
Swansea University

Antihydrogen Workshop – Karlsruhe 1987



Antihydrogen Workshop – Sepino 1996



Conference Participants outside the Conference Center

Why antimatter gravity?

- g for matter measured to very high precision
- No direct measurement of antimatter yet
- Test of weak equivalence principle (WEP) for antimatter
- Input for constructing theories of quantum gravity
- Insights to dark matter and dark energy

Courtesy of Klaus Kirch

Gravity on antimatter – what are the options (for now, and mostly “stable” systems)

Positrons

Antiprotons

Antihydrogen positive ion

Photon

Antineutron

Positronium

Muonium

Antihydrogen

Antiprotonic helium

Ballistic free fall

Interferometry

Clocks

Gravity on antimatter – what are the options (for now, and mostly “stable” systems) – minus the no-hopers etc and including (B – L), baryon number minus lepton number.

Ballistic free fall

Interferometry

Clocks

Positrons	(B-L) = 1 (B=0)
Antiprotons	(B-L) = -1 (L=0)
Antihydrogen positive ion	(B-L) = 1
Positronium	(B-L) = 0 (B=0)
Muonium	(B-L) = 0 (B=0, mixed L)
Antihydrogen	(B-L) = 0
Antiprotonic helium	(B-L) = 2

Anti-Ps = Ps … Anti-Mu, not yet observed … Hbar$^+$ is hard to make efficiently

Antihydrogen Workshop – Munich 1992

Summary Comments from Dan Kleppner (Hyp. Int. **76** (1993) 389)
(… a visitor to the world of antihydrogen …)

“If trapped antihydrogen could be cooled to the low temperatures that have already been achieved for ordinary hydrogen, their gravitational scale length would be comparable to the size of the trap. There would be no difficulty deciding whether such atoms settle down or up in the trap.”

“The fact remains, however, that the challenge of creating antihydrogen remains formidable. The situation can be summarized as follows: in the past six years the creation of antihydrogen has advanced from the totally visionary to the merely very difficult. One could hardly ask for more.”

Wise words from Allen Mills from the 1992 Workshop (Hyp. Int. **76** (1993) 233)

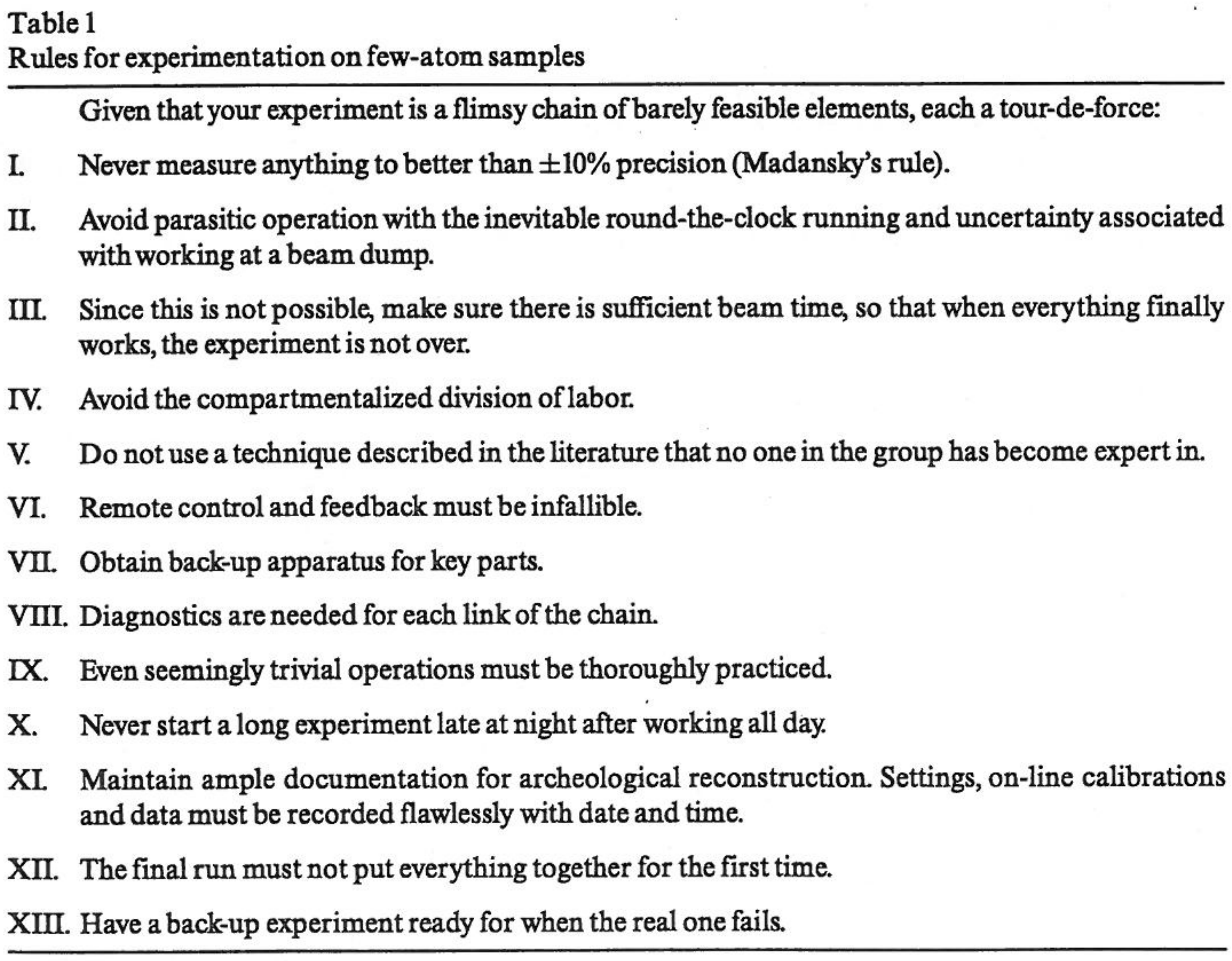


Table 1
Rules for experimentation on few-atom samples

Given that your experiment is a flimsy chain of barely feasible elements, each a tour-de-force:

I. Never measure anything to better than ±10% precision (Madansky's rule).

II. Avoid parasitic operation with the inevitable round-the-clock running and uncertainty associated with working at a beam dump.

III. Since this is not possible, make sure there is sufficient beam time, so that when everything finally works, the experiment is not over.

IV. Avoid the compartmentalized division of labor.

V. Do not use a technique described in the literature that no one in the group has become expert in.

VI. Remote control and feedback must be infallible.

VII. Obtain back-up apparatus for key parts.

VIII. Diagnostics are needed for each link of the chain.

IX. Even seemingly trivial operations must be thoroughly practiced.

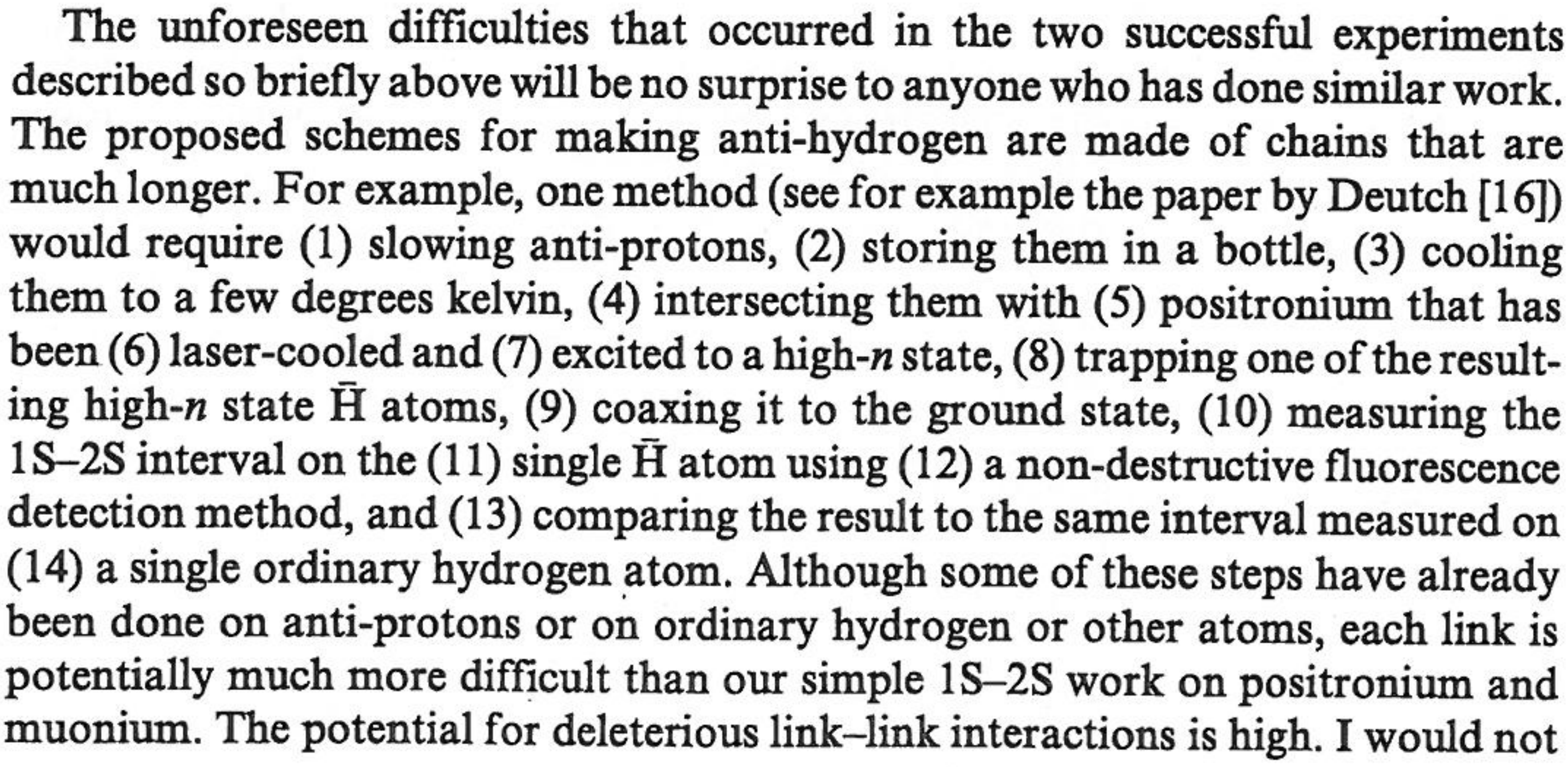
X. Never start a long experiment late at night after working all day.

XI. Maintain ample documentation for archeological reconstruction. Settings, on-line calibrations and data must be recorded flawlessly with date and time.

XII. The final run must not put everything together for the first time.

XIII. Have a back-up experiment ready for when the real one fails.

More Mills-isms from the 1992 Workshop



The unforeseen difficulties that occurred in the two successful experiments described so briefly above will be no surprise to anyone who has done similar work. The proposed schemes for making anti-hydrogen are made of chains that are much longer. For example, one method (see for example the paper by Deutch [16]) would require (1) slowing anti-protons, (2) storing them in a bottle, (3) cooling them to a few degrees kelvin, (4) intersecting them with (5) positronium that has been (6) laser-cooled and (7) excited to a high-*n* state, (8) trapping one of the resulting high-*n* state $\bar{\mathrm{H}}$ atoms, (9) coaxing it to the ground state, (10) measuring the 1S–2S interval on the (11) single $\bar{\mathrm{H}}$ atom using (12) a non-destructive fluorescence detection method, and (13) comparing the result to the same interval measured on (14) a single ordinary hydrogen atom. Although some of these steps have already been done on anti-protons or on ordinary hydrogen or other atoms, each link is potentially much more difficult than our simple 1S–2S work on positronium and muonium. The potential for deleterious link–link interactions is high. I would not

An early ATHENA design

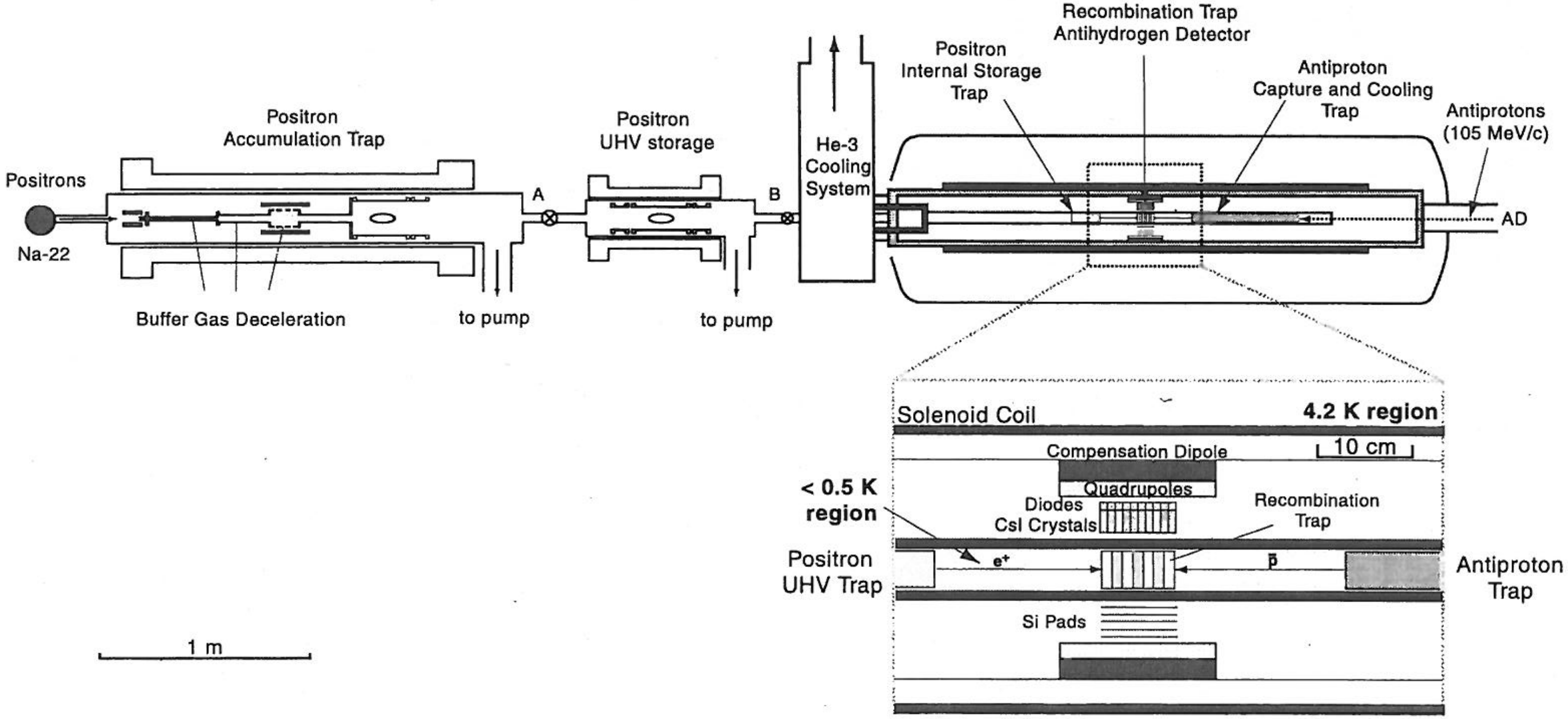
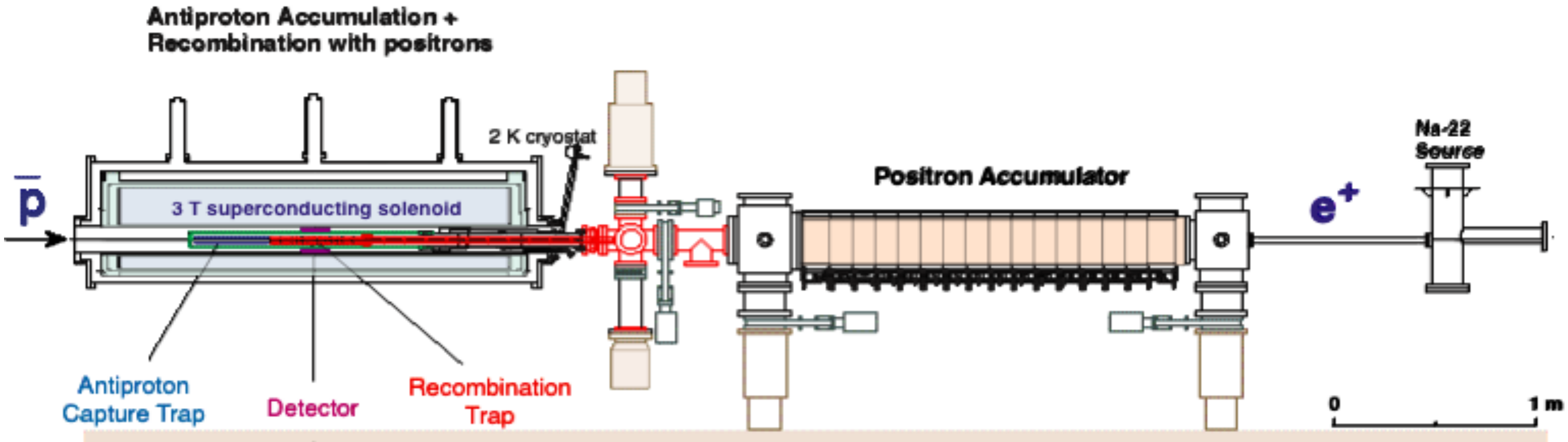
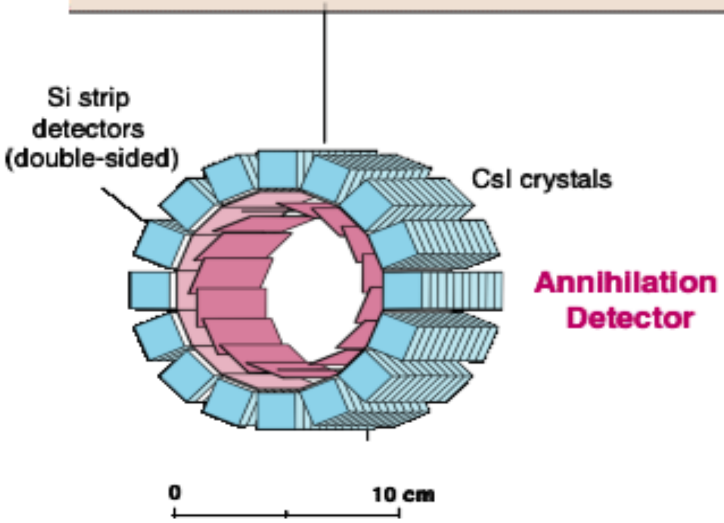


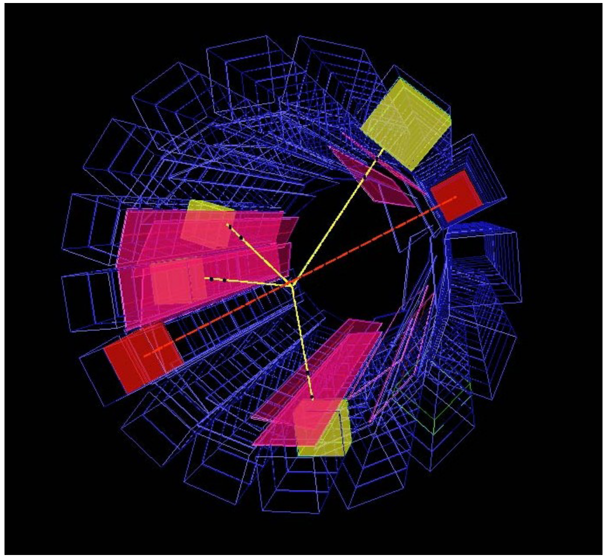
Fig. 1. Overview of the ATHENA apparatus showing the superconducting solenoid with the antiproton capture trap, the positron storage trap, and the recombination trap surrounded by the magnetic gradient trap.

… and what it actually looked like …
well, not quite …

ATHENA / AD-1 : Antihydrogen Production







So what did ATHENA do?

Slow antiprotons: store them in a bottle: cool them to a few degrees Kelvin (well, maybe) …: stack a few AD shots

Store positrons in a buffer gas accumulator: transfer them into an ultra-high vacuum apparatus containing the antiprotons

Build and commission a powerful antihydrogen annihilation detector

Inject antiprotons at around 15-20 eV into the positron cloud: observe antihydrogen annihilation

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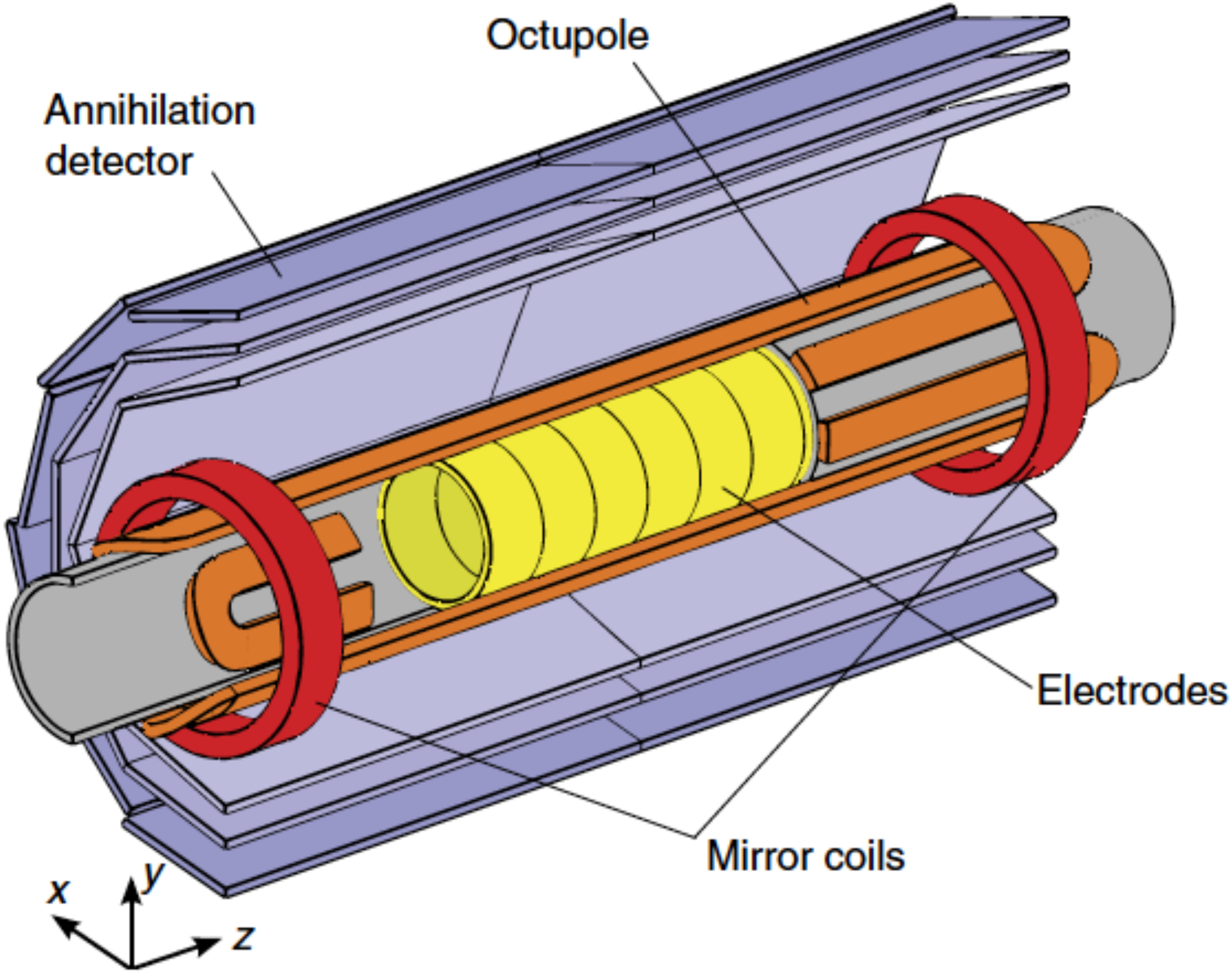
Though much work had been started in previous years, this took about 6 years

And what about ALPHA?



Slow antiprotons: store them in a bottle: cool them to a few degrees Kelvin (well, maybe) ….: stack a few AD shots

Store positrons in a buffer gas accumulator: transfer them into an ultra-high vacuum apparatus containing the antiprotons

Build and commission a powerful antihydrogen (pbar only, actually) annihilation detector

ATHENA-like

Then/and

Superimpose a magnetic minimum neutral atom trap onto the charged particle traps

Careful preparation of charged particle clouds, including temperature diagnostics: compatibility of plasmas and magnetic fields

Develop efficient means of isolating pbar annihilation signals from cosmics (separate rare trapped antihydrogens …)

Devise new ways of mixing positrons and antiprotons to avoid excess energy input and for efficient antihydrogen formation

Demonstrate trapping (by turning the mag. trap off): demonstrate that the antihydrogen can survive in the trap for many seconds; interact with ground state antihydrogen using microwaves …

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This took about 6 years – not including 4 years of learning what not to do to make trapped antihydrogen with ATHENA

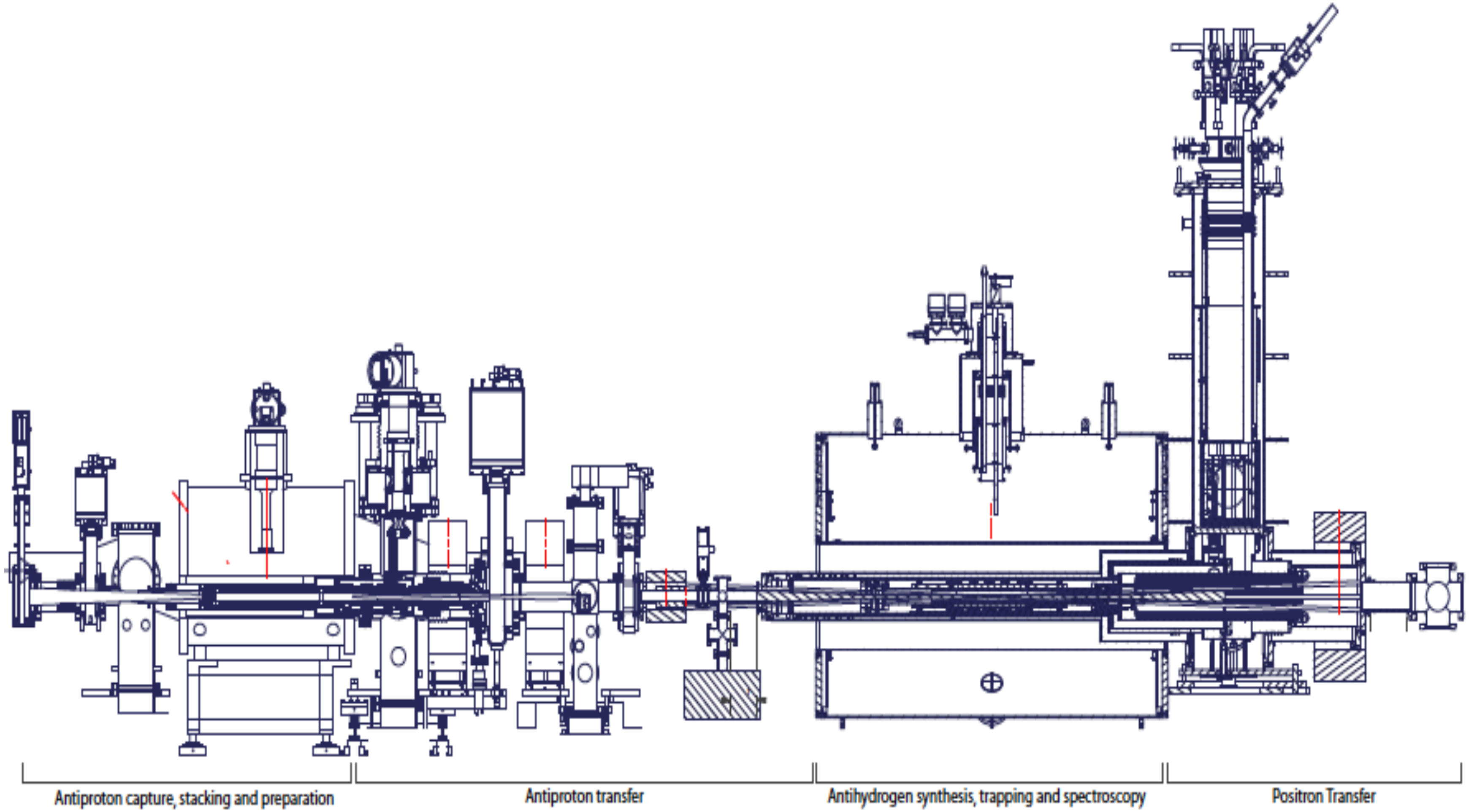
Devise new ways of mixing positrons and antiprotons to avoid excess energy input and for efficient antihydrogen formation

Demonstrate trapping (by turning the mag. trap off): demonstrate that the antihydrogen can survive in the trap for many seconds; interact with ground state antihydrogen using microwaves …

… and we are still not yet close to making a “precision” measurement of the spectrum of antihydrogen, nor of making direct comparisons with hydrogen … this will require a new apparatus …

ALPHA-2

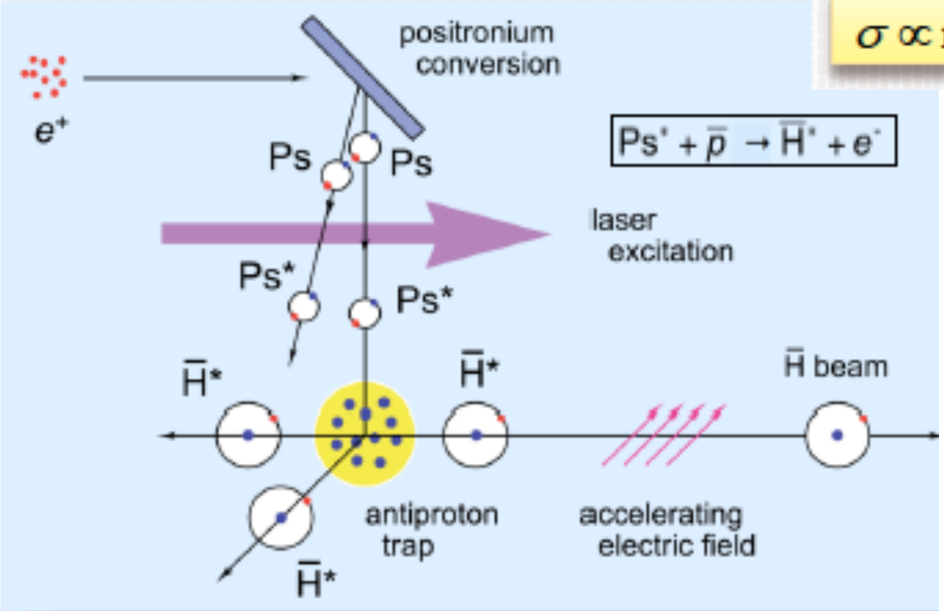
This is under construction/commissioning/testing …


Antiproton capture, stacking and preparation
Antiproton transfer
Antihydrogen synthesis, trapping and spectroscopy
Positron Transfer

Principles of the AEGIS experiment

Courtesy Daniel Krasnicky

$\sigma \propto n^4 \quad \sigma(n_{Ps}=20) \approx 10^{-9}\mathrm{cm}^2$



Antihydrogen at 100mK → $v_H \approx 40$ m/s

So what will AEGIS do? (adapted from Doser et al., Class. Quantum Grav. **29** (2012) 184009)

Slow antiprotons: store them in a bottle: cool them to a fraction of a degree Kelvin

Store positrons in a buffer gas accumulator: transfer them into an ultra-high vacuum apparatus containing the antiprotons

Build and commission a powerful antihydrogen (annihilation) detector with very high spatial resolution

Produce positronium atoms via the interaction of a pulse of positrons with a cooled nano-porous material: laser excite the positronium to a Rydberg state

Form Rydberg antihydrogen via resonant charge exchange collisions of pbars and Rydberg Ps

Form a pulsed beam of antihydrogen via Stark acceleration

Allow the anthydrogen to interact with a two-grating Moiré deflectometer to obtain g by free-fall

Daniel Krasnicky –INFN Geneva

First goal to measure g for Hbar to 1%

Pulsed source of 100 mK antihydrogen with quantum states defined by parent Rydberg Ps atoms

Laser scheme; n=1 to n=3 … 205 nm
n = 3 to n = 20 ish …1650-1700 nm

Cooling of pbars to 100 mK – sympathetic with electrons; possible with laser-cooled negative ions; resistive cooling with a tank circuit strapped to a cold bath

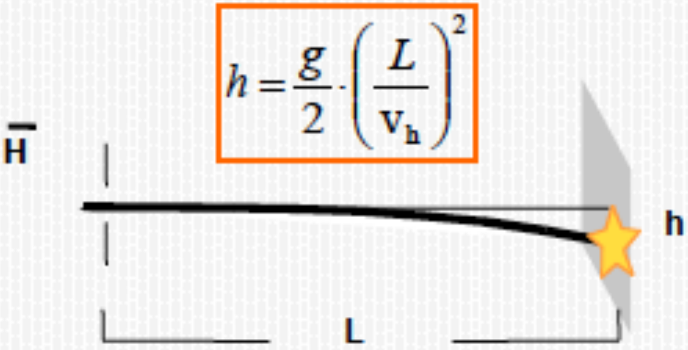
Nuclear emulsion for PSD – 2 micron resolution

1.3 x 10^5 pbars captured per AD shot; mostly cooled to order sub-eV

Proton source for testing

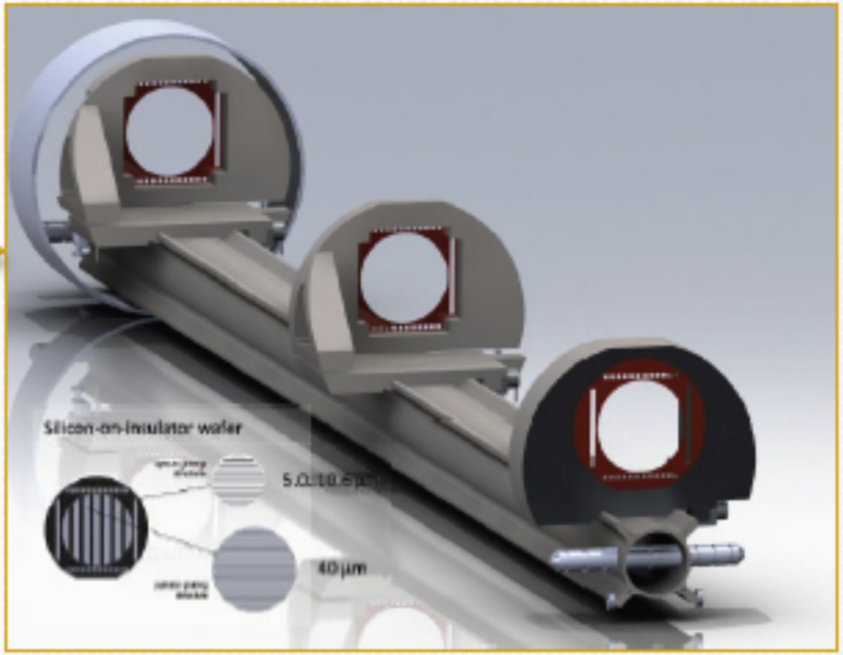
Courtesy Daniel Krasnicky

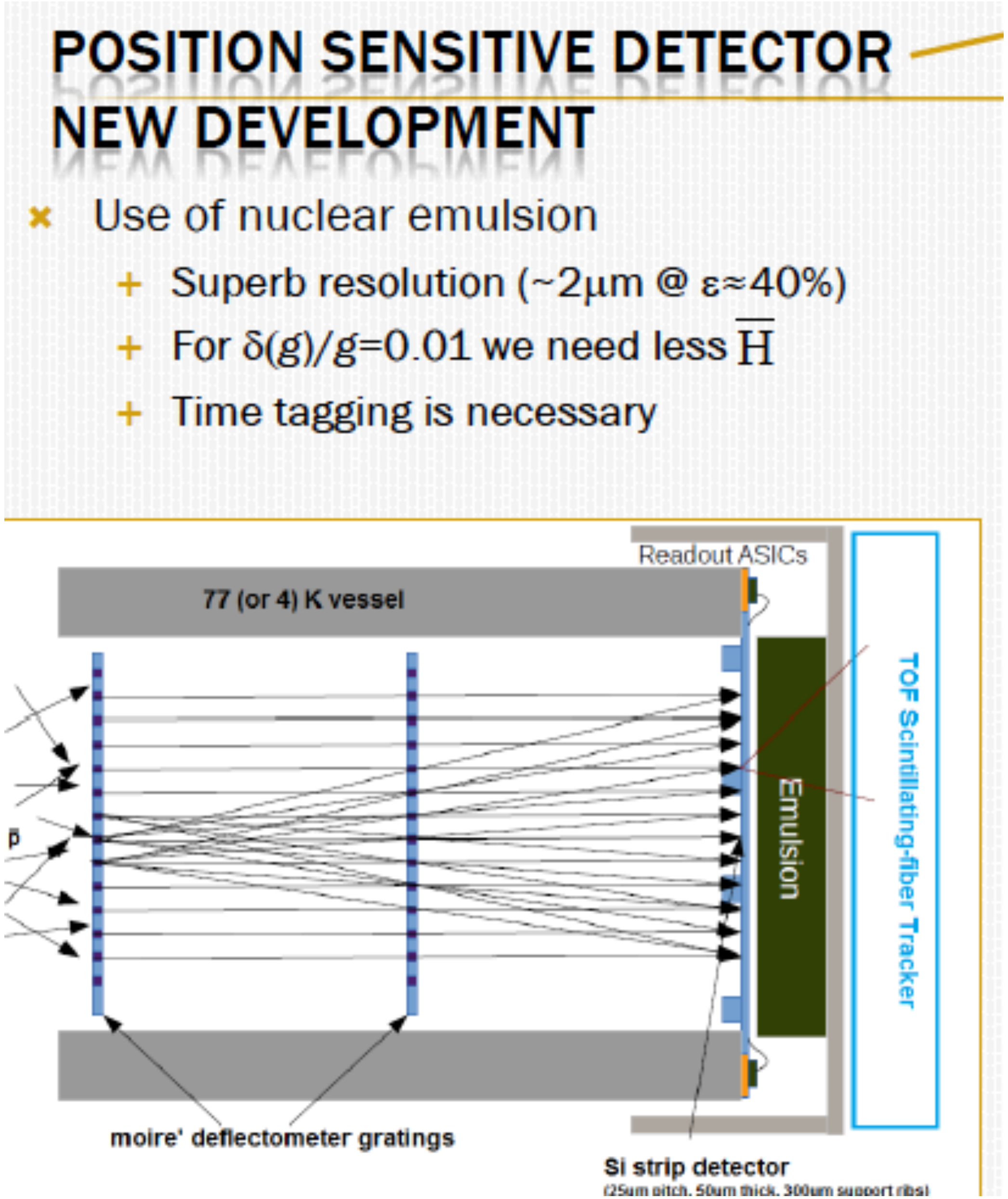
- Horizontal antihydrogen beam @ 500m/s, flight path 1 m
  - Deflection due to gravity h = 20µm


$$h = \frac{g}{2} \cdot \left(\frac{L}{v_h} \right)^2$$

- AEgIS beam will have divergence ≥ 5 °
  - Beam spot size after flight of the order of 20 cm
  - collimation depends on initial $T(\bar{H})$
- AEgIS will use moiré deflectometer
  - A set of horizontal gratings (40µm pitch)
  - Rel. $\delta(g)/g=10^{-4}$ achieved with Argon

M. K. Oberthaler *et al.*, *Phys. Rev. A* 54 (1996) 3165



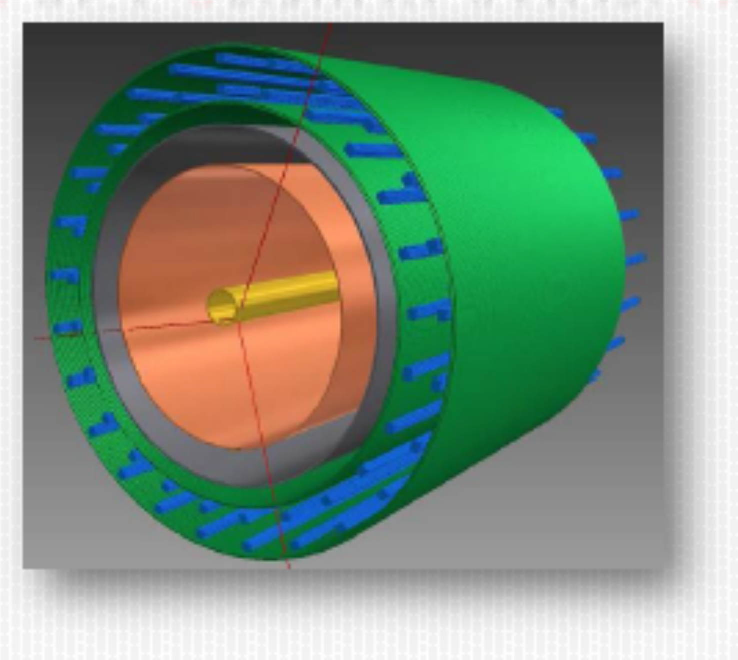


POSITION SENSITIVE DETECTOR NEW DEVELOPMENT

- Use of nuclear emulsion
  - Superb resolution (~2μm @ ε≈40%)
  - For δ(g)/g=0.01 we need less $\overline{\mathrm{H}}$
  - Time tagging is necessary

Courtesy Daniel Krasnicky

Courtesy Daniel Krasnicky



Fibre detector for Hbar detection (pulsed production)

Tomoko Ariga – Bern

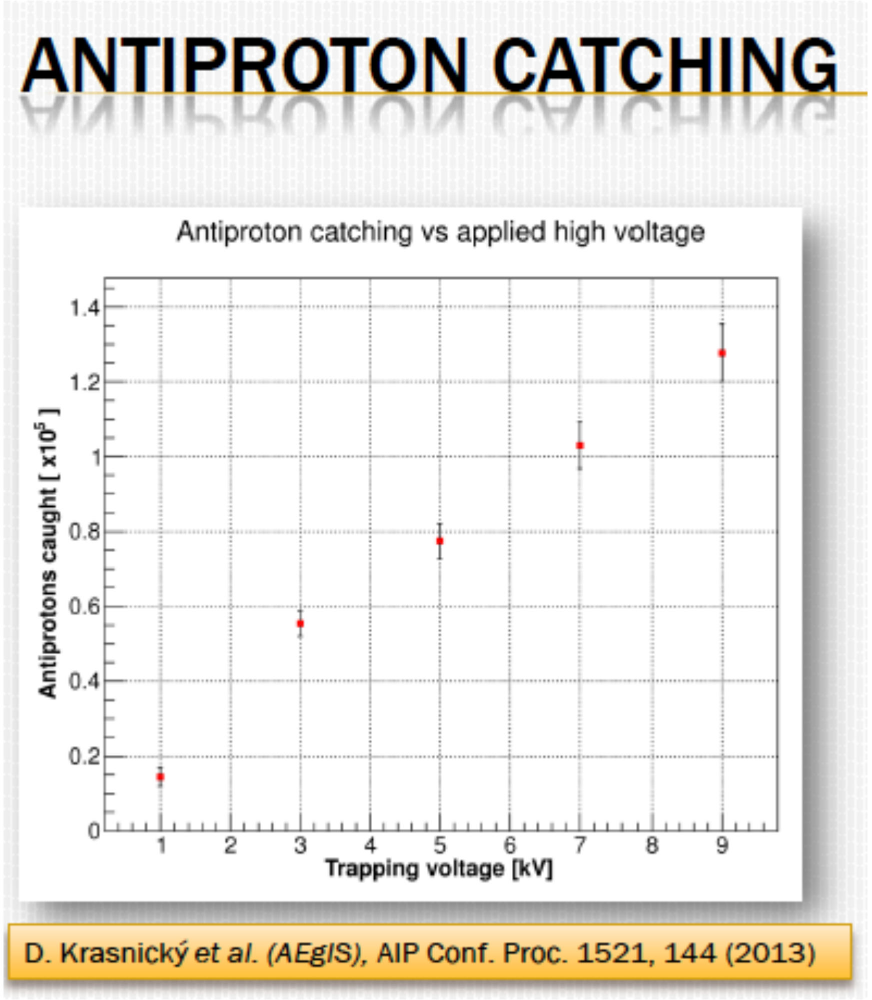
Emulsion detectors 1-2 micron resolution …. Helps to reduce the number of events need to reach 1% precision (< 1000)
AgBr crystals …. 10^{14} channels

Intrinsic resolution about 58 nm

Operation of emulsions in vacuum .. Now OK … Low temperature tests

Beautiful pbar annihilation stars

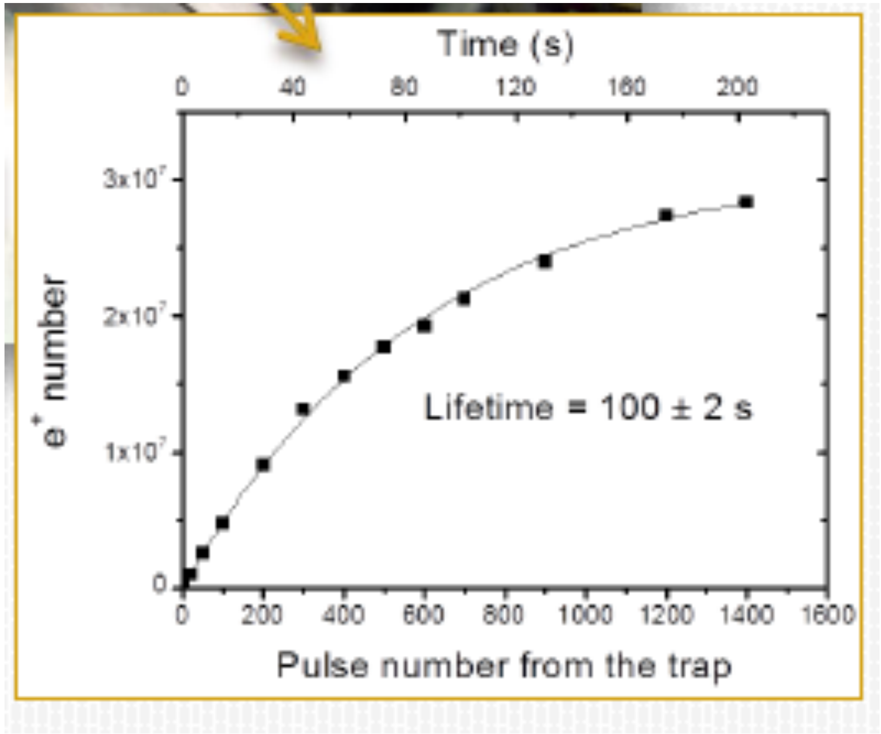
Many impressive technical developments including track-recognition technology



ANTIPROTON CATCHING

D. Krasnický *et al.* (AEgIS), AIP Conf. Proc. 1521, 144 (2013)

Courtesy Daniel Krasnicky



Progress with antiproton and positron capture, laser development and apparatus construction and commissioning

Philippe Bräunig – KIP Heidelberg

…. Moire deflectometry with antiprotons …

Use of arrays of narrow slits to define classical trajectories with decent throughput (30%)

Scan fringe pattern with third grating

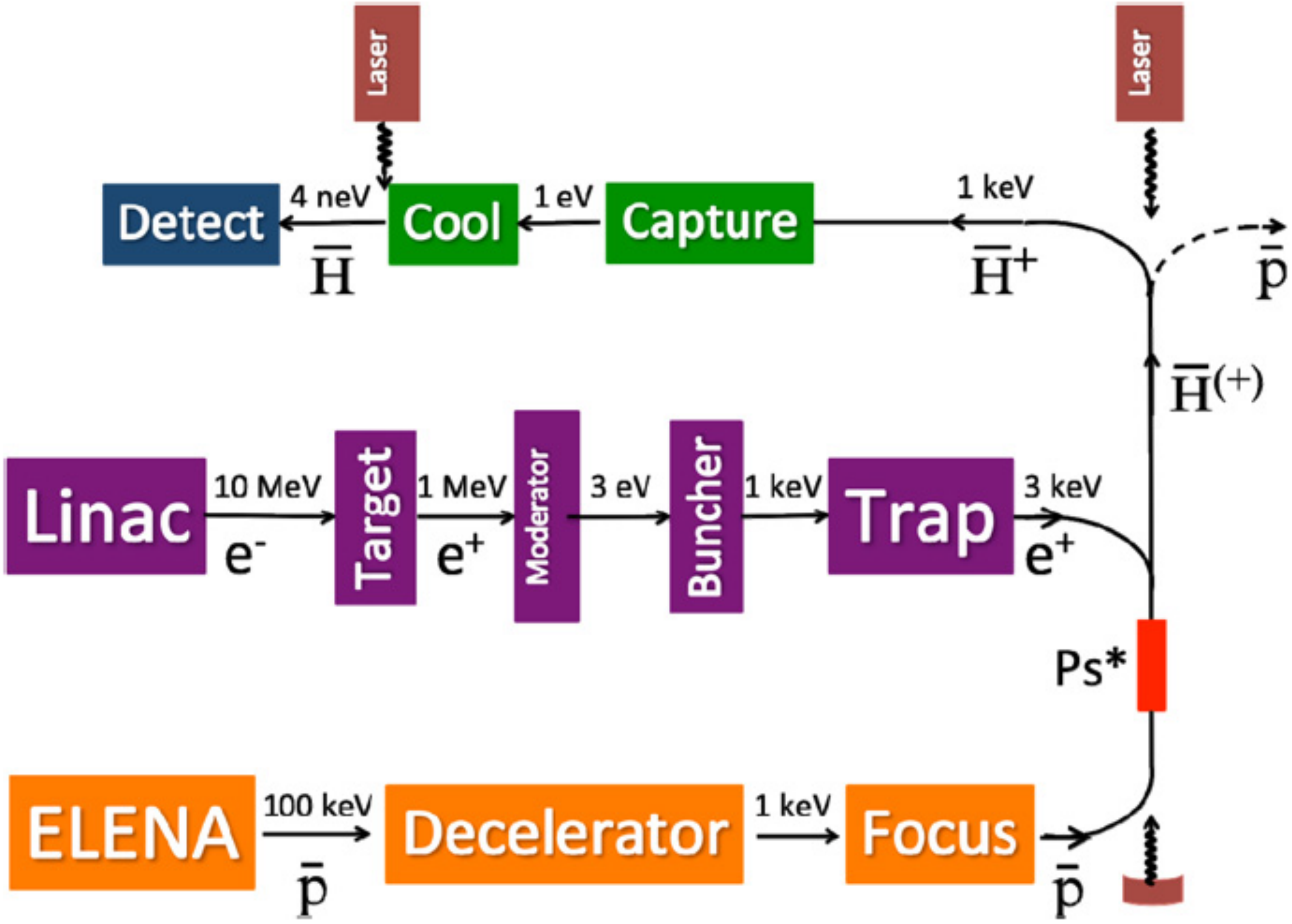
Tests with metastable Ar – develop a system close to the application at the AD. Current performance is deltag/g ~ 10^{-3}

Standard gratings (40 micron pitch) with 25 mm between gratings for antiprotons – using uncaught pbars. Total events about 0.5 antiproton per slit

Analysis reveals correct periodicity of antiproton annihilation positions … use light as a reference to align position of the fringes
Proof of principle experiment.

See a Lorentz force shift! From a few hundred aN force

Principles of the GBAR experiment



So what will GBAR do? (adapted from Perez and Sacquin, Class. Quantum Grav. **29** (2012) 184008)

Intense (10^8-10^9 s^{-1}), accelerator-based positron source coupled to an efficient moderator: store positrons in a high-field accumulator

Ejection of positrons (> 10^{10}) in a narrow (100ns or less) pulse to form dense positronium cloud by collision with a porous silica target: excitation of the positronium to increase interaction cross sections

Use antiprotons from ELENA, decelerated (and possibly trapped); interaction with positronium to form antihydrogen and then its positive ion by successive charge transfer reactions

Capture of the antihydrogen positive ion, followed by sympathetic cooling (in more than one stage) using laser-cooled Be^+ ions to 10 μK

Photodetachment of the excess positron to leave ultra-cold antihydrogen to fall freely

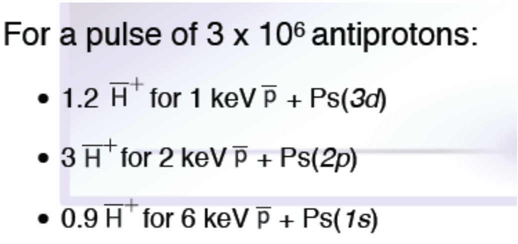
Dirk Peter van der Werf – Swansea

Lots of pbars and positrons needed to get to the antihydrogen ion

99 kV drift tube to slow pbars … as trapping experiments at ISOLDE + (possibly) an electrostatic beam ion trap …

Linac for positron production – in principle more intense than radioactive source based beam; inherently pulsed … then bunched
(18 MeV, 300 Hz, 200 mA peak)

Mutli-ring trap using an electron plasma target to replace buffer gas … 10^{10} e^+



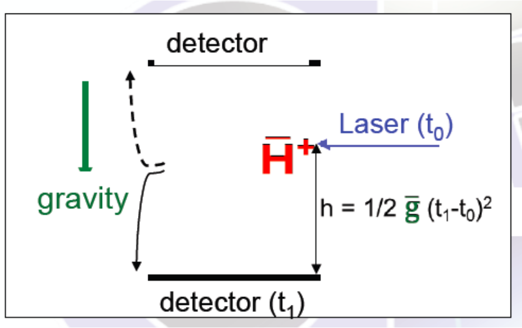
For a pulse of 3×10^6 antiprotons:

- 1.2 $\overline{H}^+$ for 1 keV $\overline{p}$ + Ps(*3d*)
- 3 $\overline{H}^+$ for 2 keV $\overline{p}$ + Ps(*2p*)
- 0.9 $\overline{H}^+$ for 6 keV $\overline{p}$ + Ps(*1s*)

Lasers to excite Ps to aid capture to Hbar

Cooling of Hbar$^+$ … to 10 microK

Photodetachment – recoil manageable



Courtesy of Dirk

Laurent Hilico – LKB

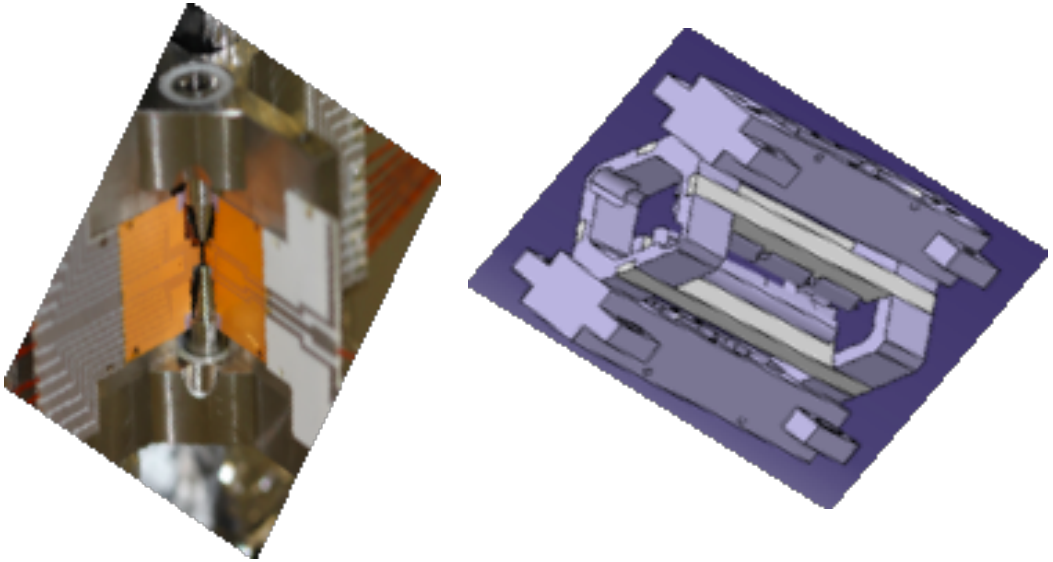
Initial velocity about 1 ms^{-1}

Cooling challenge … ions start at 700,000 K … down to 20 microK

2-step. Sympathetic Doppler cooling in a linear capture trap – 100% capture with a 300 ns bunch. Plan experimental tests with hydrogenic ions (simulations with 500 Be^{+} and 20Hbar^{+} show rapid cooling ~ ms)

Then a high precision trap … just 2 ions involved. First Doppler cooling step … limit about 0.5 mK
Raman side band cooling to get to low temperatures – reduces vibrational energy of the ion pair … cooling time less than 1 s

Mainz group involvement



Joel Fajans – Berkeley

First crude limits on gravitational mass of antihydrogen

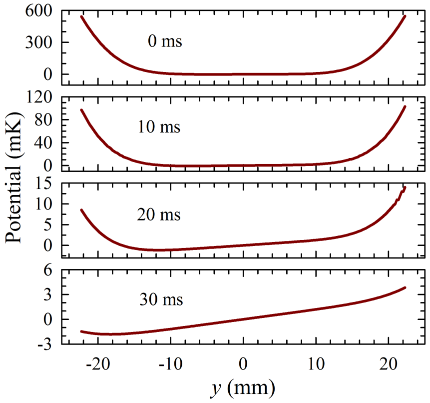
Extension to technique should get to F = 1 ... needs laser cooling to around 10’s of mK (ALPHA starting to prepare for this

Sensitivity arises when the magnetic trap is removed in 10’s of ms

Can gain using a vertical trap … but stuck around F = 1

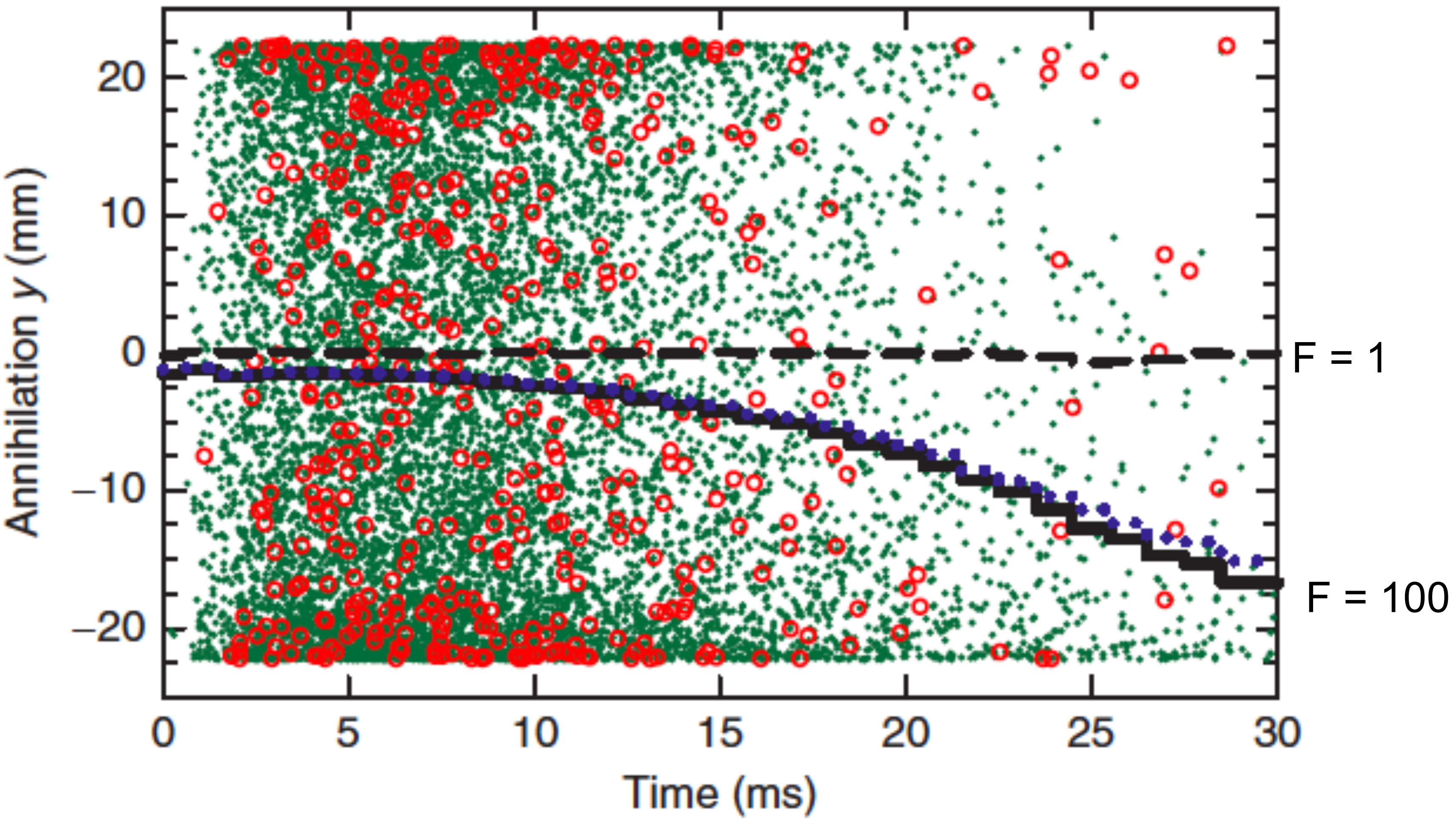
Fountain measurement to 10%

For the future … Interferometer – potential to order ppm



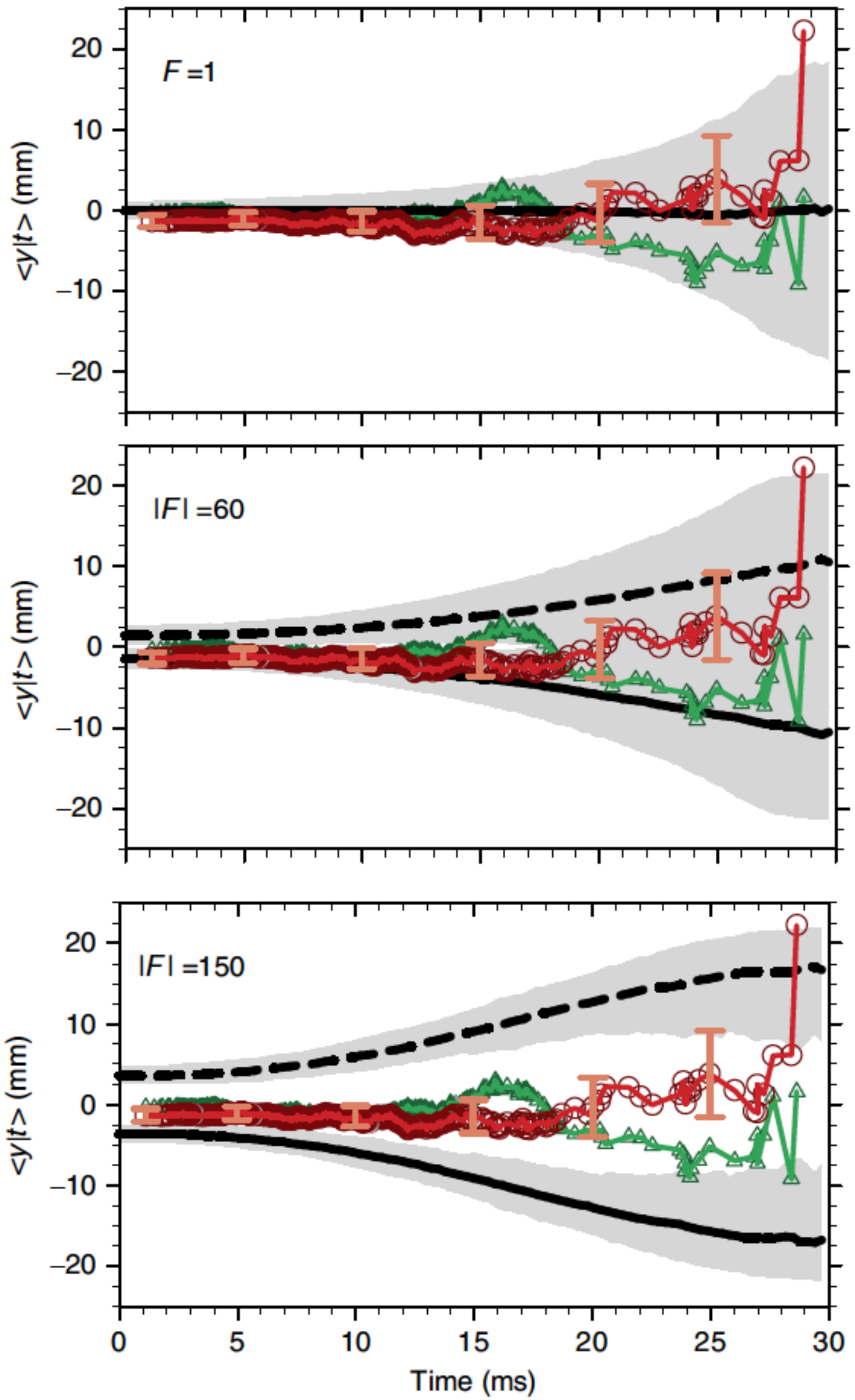
In the meantime … from ALPHA

F = M_g/M, ratio of grav. to inertial mass



Courtesy of Joel Fajans

ALPHA’s reverse cumulative average analysis

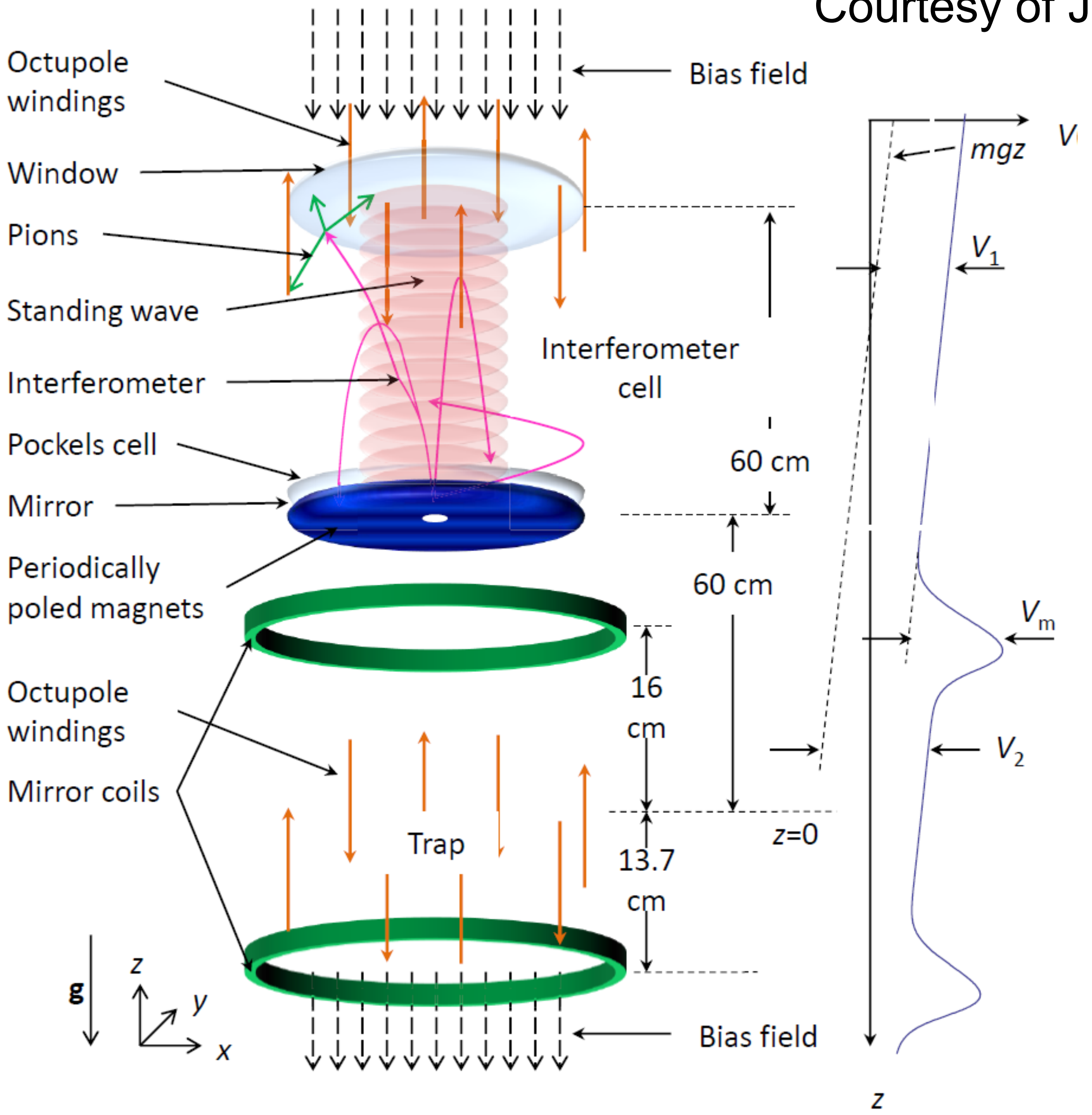


Data
Red: *y*-direction
Green: *x*-direction

Simulations
Dash: “antigravity” at given |F|
Line: gravity at given |F|
Grey bands: 90% confidence limits on simulations

Courtesy of Joel Fajans

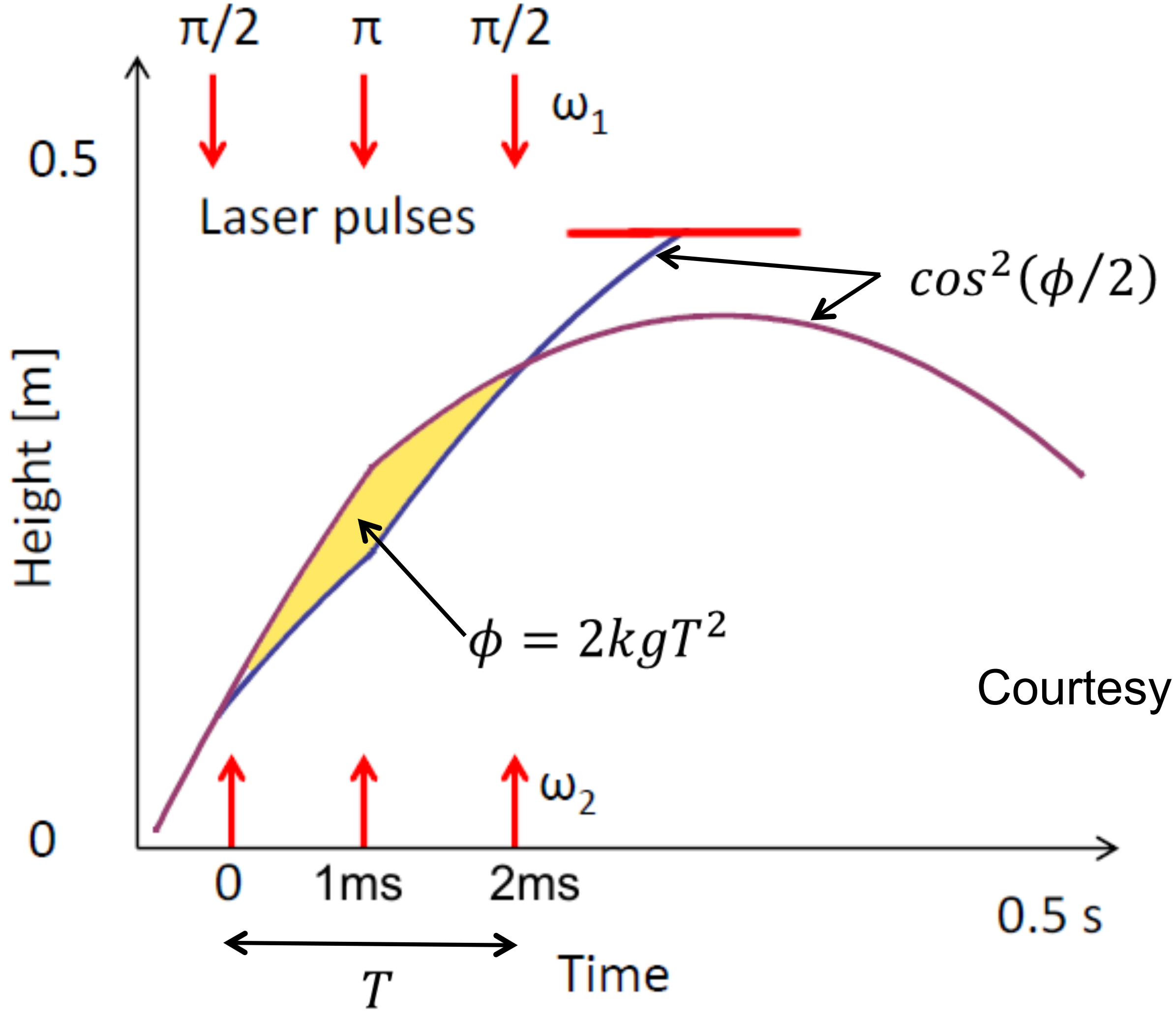
Courtesy of Joel Fajans

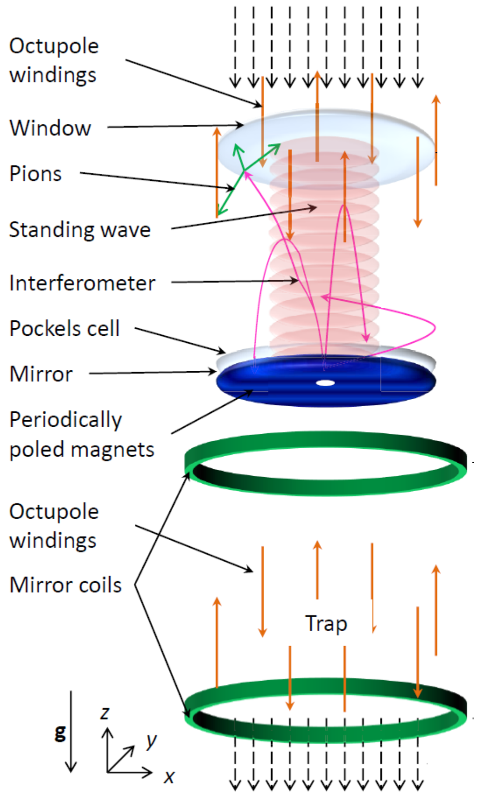


A new proposal … this is another cha££enging experiment

Interferometric Measurement of F

- $^{\pi}/_{2}, \pi, ^{\pi}/_{2}$ laser pulse train.





Courtesy of Joel Fajans

H. Mueller, P Hamilton, A. Zhmoginov, F. Robicheaux, J, Fajans and J.S. Wurtele, Antimatter interferometry for gravity measurements, arXiv:1308.107 (2013).

Christian Bordé – SYRTE Paris

Atomic interferometry using internal state labeling – established since the late 1980’s

Lasers create entangled states which recombine and interfere

Applications to atom and molecules, and different configurations of beams used close the interferometer

2002 – H atom interferometer with short light pulses (Bordé, Hänsch et al)

1S-2S then interferometer between 2S and 15P

Principles of a positronium experiment circa 1987!

A.P. Mills, Jr. / Positron moderation and remoderation techniques 121

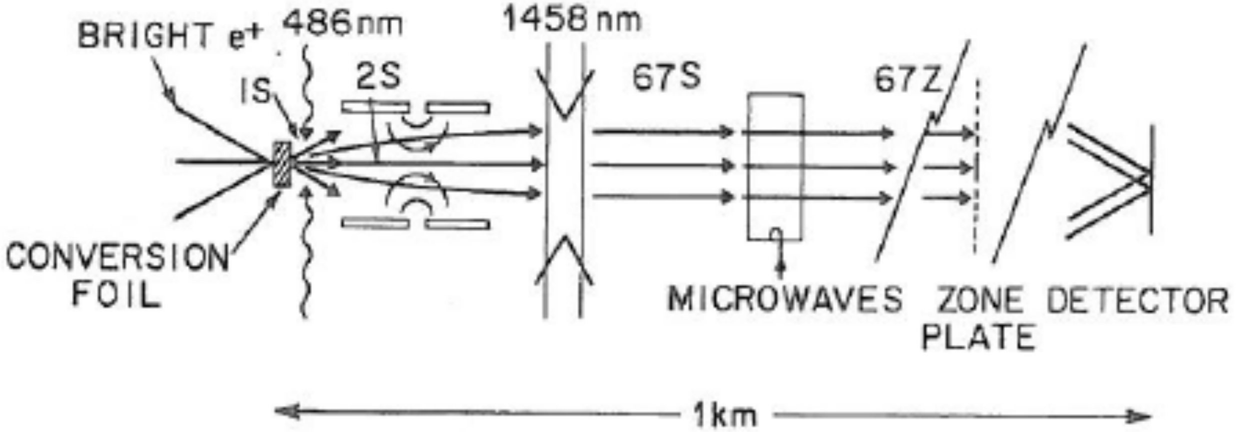


Fig. 22. Go and catch a falling Ps.

Principles of a positronium experiment - update circa 2002!

A.P. Mills Jr., M. Leventhal / Nucl. Instr. and Meth. in Phys. Res. B 192 (2002) 102–106

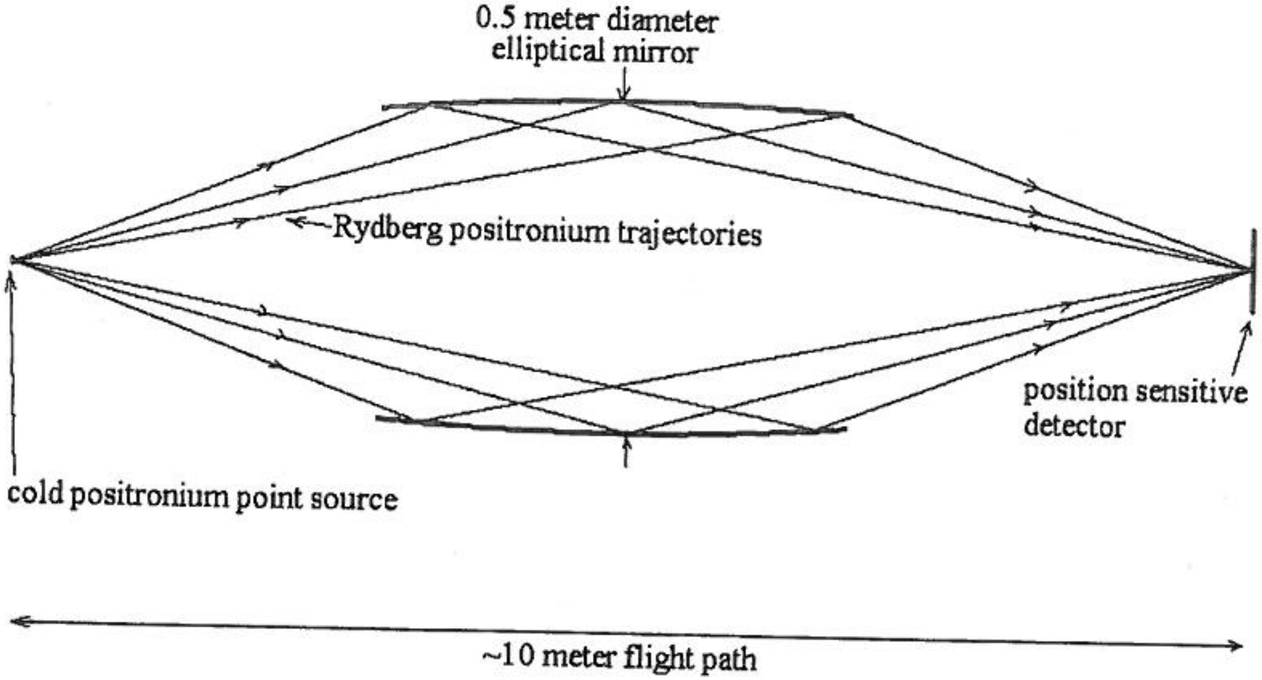
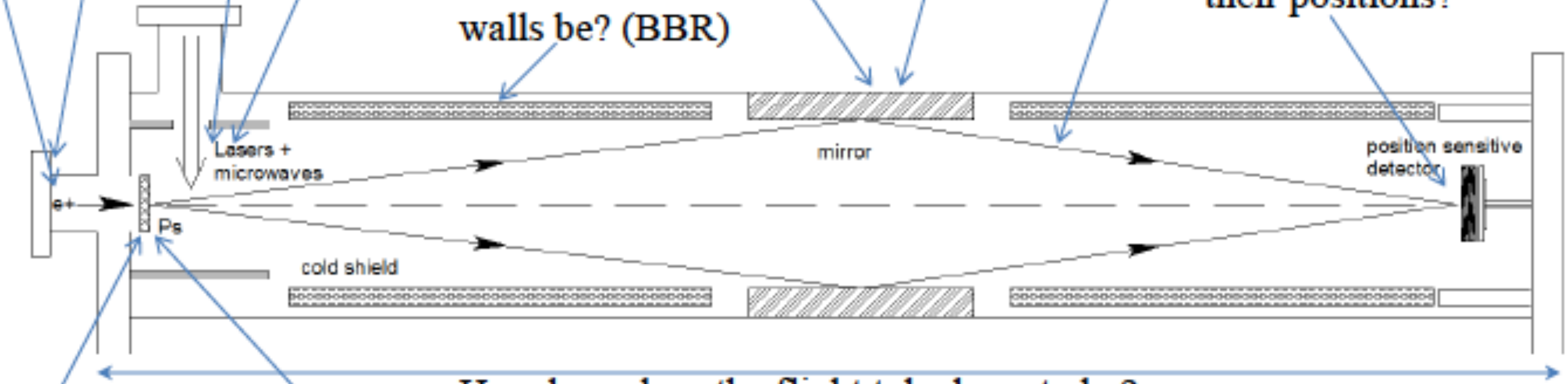


Fig. 1. Experiment to measure the gravitational free fall of $n = 25$ Rydberg positronium.

What might a Ps Rydberg gravity experiment look like?*

Principles of a positronium experiment - update circa 2013!! Courtesy of DB Cassidy



need a point e$^+$ source

Zero or low B field

What n states will be optimal?

How will the circular states be produced?

How does this mirror/lens work?

How cold must the walls be? (BBR)

Will the "atom-optics" work on circular states?

Will patch fields deflect the beam?

Can very slow atoms be detected without perturbing their positions?

How long does the flight tube have to be?

Ps has to be very cold

what Ps converter will work at low temp?

How much will this all cost?

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*Any similarity between the diagram shown here and a real experiment is purely coincidental

So, what will the Ps free-fallers do …

Collect a lot of positrons in a UHV trap and compress them

Create a “point” source (of order microns) of cold positronium atoms

Excite the positronium using a recoil free technique to a Rydberg level: further excite using microwaves into a circular state for enhanced lifetime, and to avoid de-excitation

Allow the positronium to fly for about 1 ms: to possibly include bouncing (via quantum reflection or electrostatic lensing) from an appropriate mirror.

Detect using a position sensitive detector of some sort (field ionization?)

Paolo Crivelli – ETH

1S-2S Spectroscopy, gravitational redshift

Natural linewidth of 1.2 MHz (annihilation-limited) 2 x 486 nm

Theory now about 5x as precise as the Fee/Mills/Chu experimental number

Exploit eccentricity of Earth’s orbit to change gravitational potential and look for transition frequency shifts …

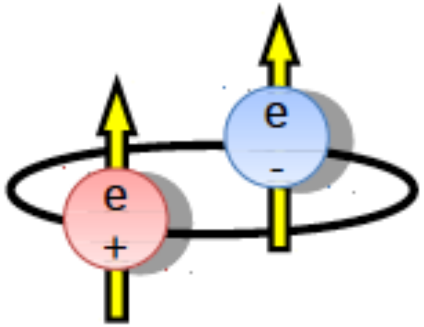
Importance of getting the right Ps source

Long-term stability of laser system (~ kHz short-term and ~MHz per day) and scan +/- 100 MHz

Anticipates statistics down to 0.35 MHz and systematics from 2nd order Doppler effect to 0.4 MHz … leading to 5 x 10^{-10} transition accuracy, but needs to improve by a factor of 5 to start to test redshift

Cryogenic Ps … Ps cooling …???

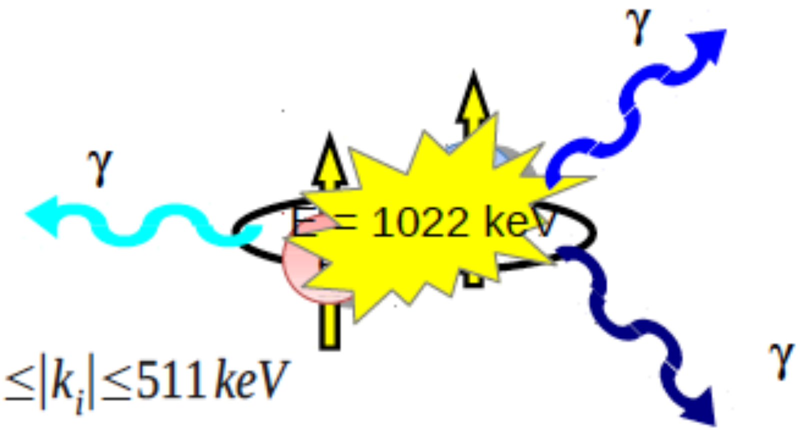
Orthopositronium (o-Ps) triplet spin state $^3S_1$



Theory:

$$\nu^{theory} = 1233607222.2(6) \text{ MHz}$$

K. Pachucki and S. G. Karshenboim,
Phys. Rev. A60, 2792 (1999),
K. Melnikov and A. Yelkhovsky,
Phys. Lett. B458, 143 (1999).



$$0 \le |k_i| \le 511\, keV$$

$$\Gamma^{(0)}_{3\gamma}(n^3S_1) = \frac{2}{9\pi}(\pi^2 - 9)\frac{m_e c^2}{\hbar}\frac{\alpha^6}{n^3}$$

Ore and Powell in 1949

$$\Gamma^{-1} = \tau \approx 142 \text{ ns (in vacuum)}$$

Courtesy of Paolo Crivelli

Experiments:

$$\nu^{a} = 1233607216.4(3.2) \text{ MHz}$$

M. S. Fee et al., Phys. Rev. Lett. 70, 1397 (1993)

$$\nu^{b} = 1233607218.9(10.7) \text{ MHz}$$

S. Chu, A. P. Mills, Jr. and J. Hall, Phys. Rev. Lett. 52, 1689 (1984)

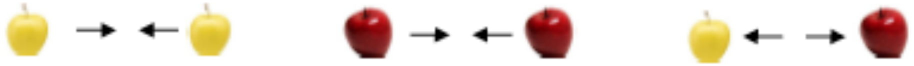
Courtesy of Paolo Crivelli

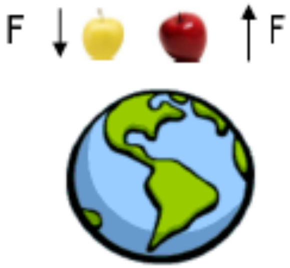
Gravitational Redshift

$$\frac{\Delta\nu}{\nu_0} = \frac{\Delta U}{c^2}$$

$$\frac{\Delta U(r_{\mathrm{max}}) - \Delta U(r_{\mathrm{min}})}{c^2} \simeq 3.2 \times 10^{-10}$$

Assuming antigravity:





$$\nu(r) = \nu_0 \times \begin{cases} \left(1 + \frac{U(r) - U(\infty)}{c^2}\right) & \text{for H} \\ 1 & \text{for Ps} \\ \left(1 - \frac{U(r) - U(\infty)}{c^2}\right) & \text{for } \overline{H} \quad \textit{or Mu} \end{cases}$$

Measurement of 1S-2S Ps, Mu or HBar at a level about 1x10^{-10} => sensitivity to check the shift of antigravity.

Klaus Kirch – PSI

Muonium 2.2 micros lifetime (muon) (2nd generation lepton)

Test gravity

- annual modulation of 1S-2Stransition frequency
- Mach-Zehnder (MZ) 3-grating atom interferometer with a cold atom beam

1S-2S precision of 0.1 ppb needed (40x improvement)

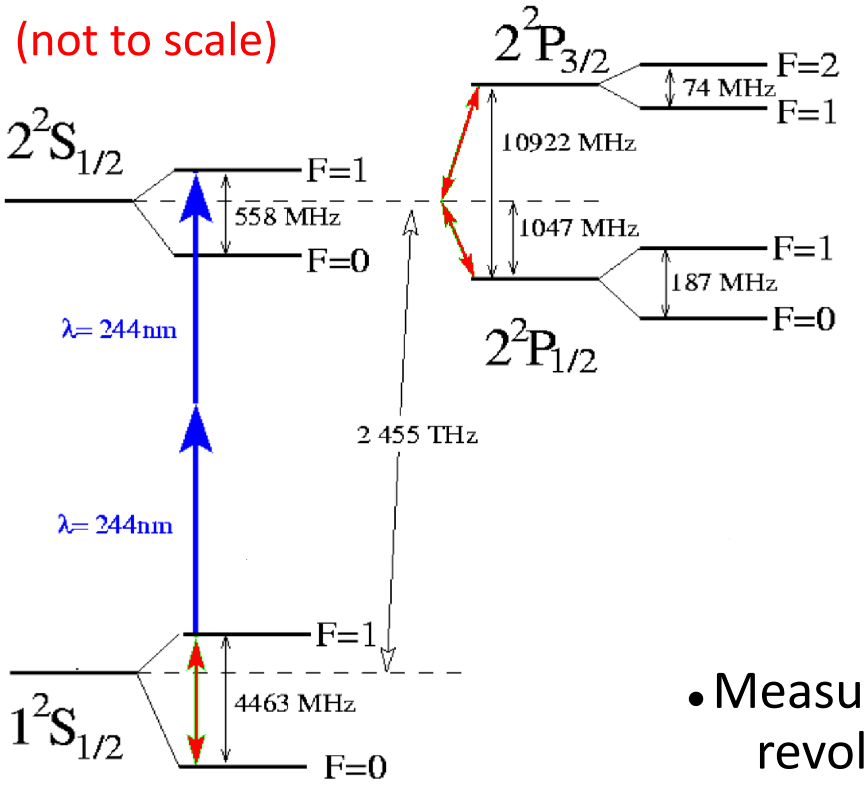
MZ … need 10^5 mono-energetic Mu per second; very stringent requirement on the beam and grating separation ~ 1.4 cm

Ambitious plans to increase muon moderation efficiency – have demonstrated longitudinal compression

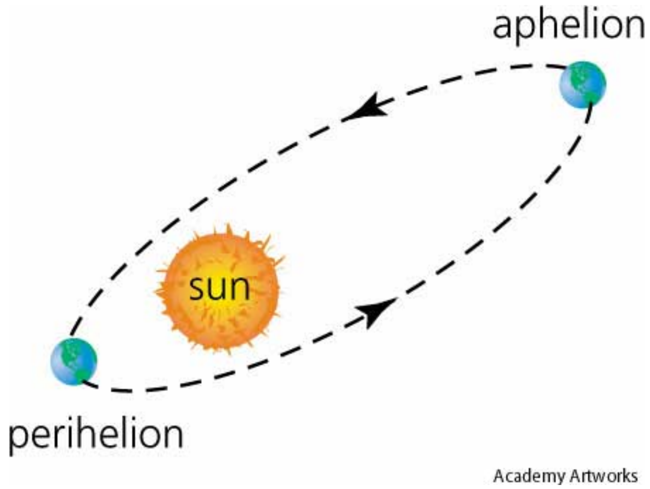
Use low energy beam to form muonium in vacuum ~ 20% at about 100 K

Can improve current 1S-2S by a factor of 10

Mu1S-2S spectroscopy



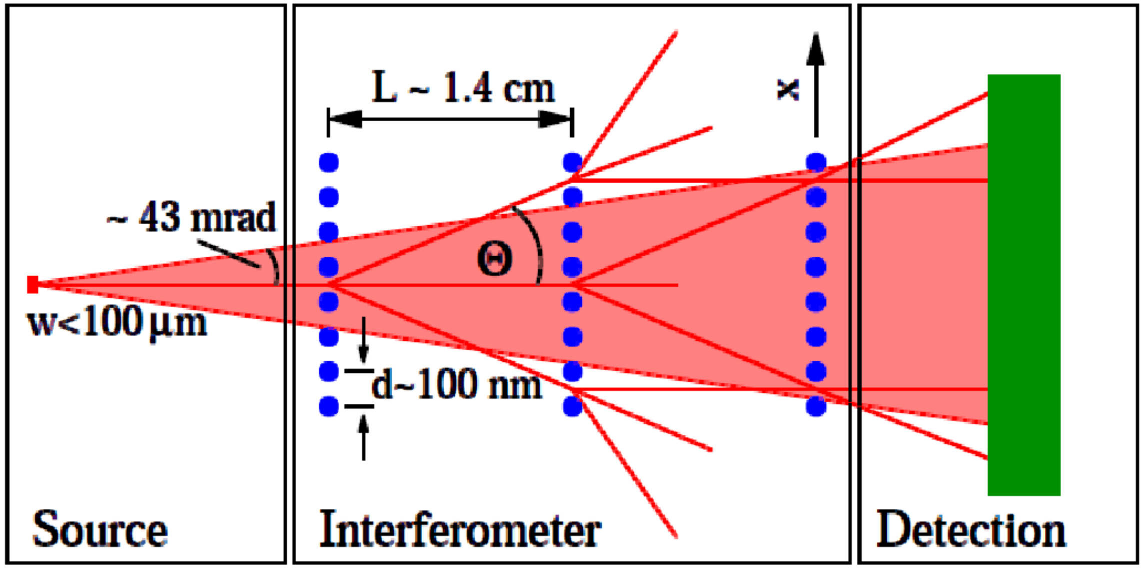
courtesy
K. Jungmann



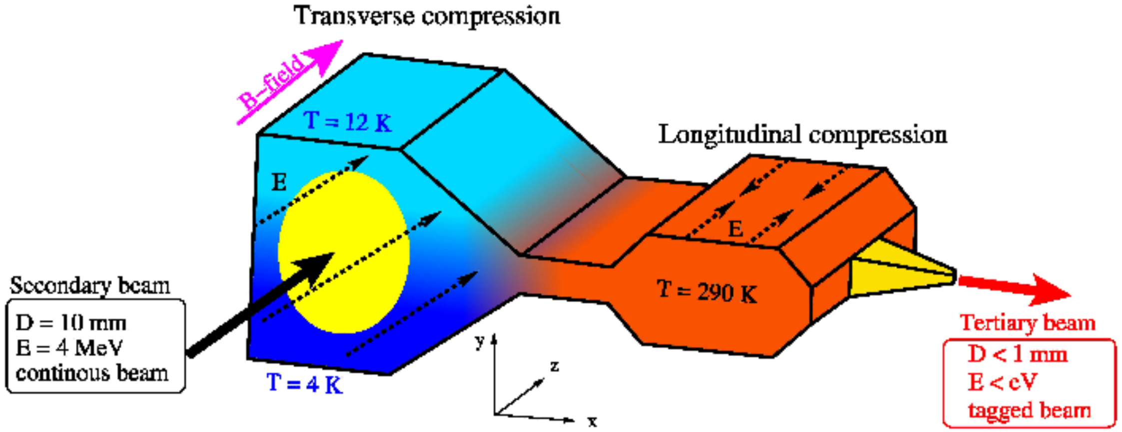
- Measure the gravitational redshift when the earth revolves around the sun (dH = 5 x 10^6 km)
- [dU(r-max)-dU(r-min)]/c ~ 3.2 x 10^{-10}

Courtesy of Klaus Kirch

Mach-Zehnder interferometer

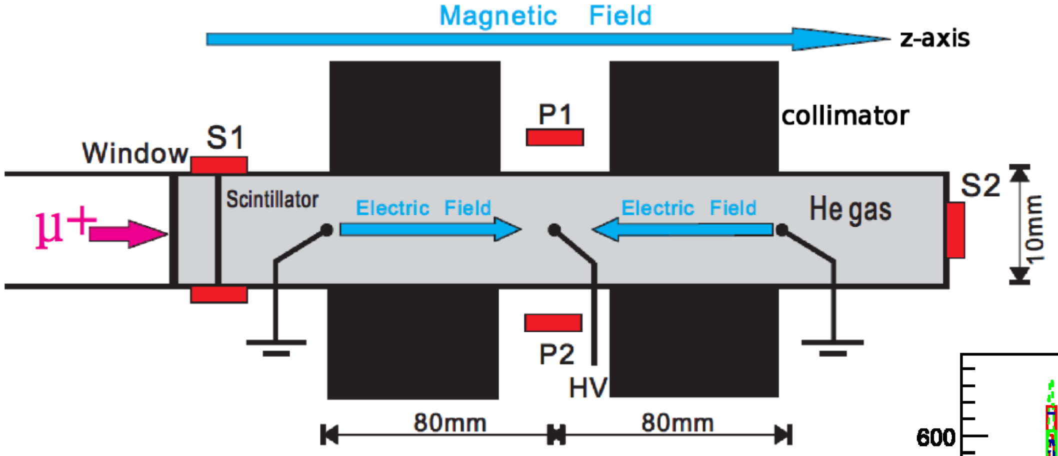


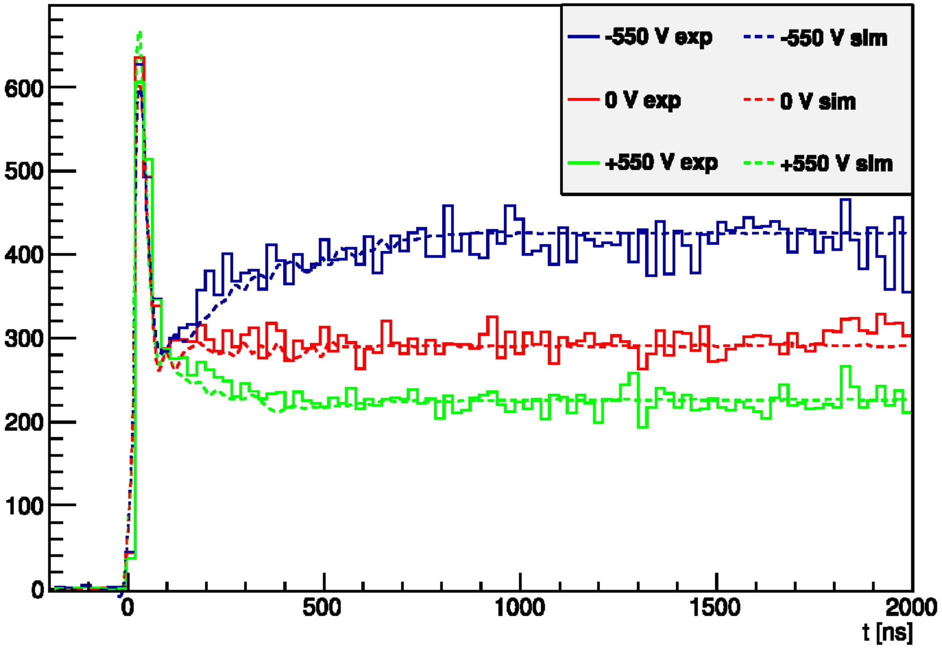
Stringent Mu source requirements – requires developments in slow muon beam intensities



Courtesy of Klaus Kirch

Longitudinal compression





Courtesy of Klaus Kirch

Courtesy of Michael Holzscheiter

Inertial **masses of protons and antiprotons were shown to be equal to 4 x 10^{-8}**
G. Gabrielse et al. ; Phys. Rev. Lett. 63 (1989) 1360

Similar results existed for electrons and positrons for 10 years at lower precision
P.B. Schwinberg, R. S. vanDyck Jr., and H. G. Dehmelt; Phys. Rev. 81A (1981) 119

These experiments are considered precision tests of CPT

But

Assuming CPT is conserved, they provide tests of the weak equivalence principle for a gravitational coupling to the energy of positrons and antiprotons

Why?

The frequencies used to study the inertial mass equalities constitute “local clocks” which are subject to the gravitational redshift, which can be formulated as a test of the weak equivalence principle for their energy content

K. Nordvedt, Phys. Rev. D 11 (1975) 245

Courtesy of Michael Holzscheiter

Matter experiences gravity g, antimatter αg

Frequency difference between matter and antimatter clock

$$(\omega_c - \omega_c)/\omega_c = 3(\alpha - 1)U/c^2$$

U is the Newtonian gravitational potential

G. Gabrielse et al., Phys. Rev. Lett. 82 3198 (1999):

$M_p/M_p = 0.999\ 999\ 999\ 91 \pm 0.000\ 000\ 000\ 09$

$|\alpha - 1| < 1 \times 10^{-6}$

Anna Nobili – Pisa

“Experimental fact” that $m_I = m_g$

Wonderful precision of experiments (torsion balance) of order 10^{-13}

Differential measurements

Susannah Dickerson – Stanford

Composition – antimatter

Direct versus indirect tests, the latter involving couplings to new forces and virtual particles and contribution to mass energy

Coupling of vector force to (B-L), baryon number minus lepton number

Emergence of atom interferometry as a technique to study influence of gravity (apparatus in a 25 foot deep pit! – sounds like the AD Hall).

Atoms temperature of order nK: 2-3 second flight time

Gerry Skinner - Garching

Positrons in ISM in large quantities. Annihilation mostly after positronium formation.

Can use 511 keV lineshape to say something about the environment in which they annihilate – but they travel from their source to get there ….

Positron production mechanisms not yet pinned down
- from radioactive decay, e.g. ^{26}Al – see other gamma-ray lines to back up interpretation

Positrons annihilate after slowing down … limits the energy of creation – lack of evidence for annihilation-in-flight

PAMELA – positron excess in cosmic rays above about 10 GeV

AMS-02 and ground-based instruments (total {e^+ + e^-}) are in support

Pierre Salati - LAPT

Flat Universe, mostly composed of DE and DM; the latter of order 27%

Dark matter is not baryonic! Plethora of DM candidates, for instance WIMPs (weak interactions and gravity only)

Lithium problem – too much lithium-6 … created by WIMP annihilation???

WIMP annihilation can also lead to antiprotons, antideuterons and positrons BUT antiproton flux consistent with secondary processes – conventional astrophysical background. Use as a probe on DM.

Antideuterons – the next challenge (Count me out)

Martin Jankowiak - Heidelberg

Theoretical experimental limits – doesn’t expect “antigravity” at a level of 10^{-7}
- “But it is not a good theory”

General “antigravity” scenarios (as no compelling theory for difference between matter and antimatter)

    Unspecified modification of GR
    5th or 6th forces mediated by scalars/vectors

Uses EP constraints for test masses since atoms “contain” antimatter and different atoms contain different amounts

    Lamb shift, electrostatic self-energy of nucleus – used to deduce limits on antimatter gravity … as the “gravitate universally”

    Further stringent “limits” from antiquarks in the nucleus … ppb

Goldman/Nieto analysis with non-cancellation of vector and scalar forces for antimatter

    Considers coupling via B and L
    Binary pulsar system spin down and radiation of light quanta from extra forces … conventional GR good to 10% … to set limits on antihydrogen gravity – depends upon composition; better than ppm

Savely Karshenboim – MPI Garching

Points out also that might be hints from photons: red shifts/deflections

…. Baffling on deflection of light

Allow m_g/m to vary for matter and antimatter at the same level as we are able to verify deflection of light as it follows from GR …. Precision???

Dirac equation … which is matter/antimatter symmetric – problem if gravitation of positron and electron are not the same

Inertial versus non-inertial systems and energy conservation … forces of inertia

…………. Problem with energy conservation if F not equal to 1

Antigravity and importance of comparisons for H, Hbar and Ps … and measurements of absolute red shifts

Claim of precision for kaons and other “oscillating” mesons

Gabriel Dufour – LKB

Hbar free fall modified close to a surface, Casimir-Polder force (attractive)

V goes as $1/z^4$

Need to be ~ 30 nm from surface; won't noticeably change time-of fall

Reflection from an attractive potential …. "quantum reflection"

Observed in matter …. Atoms/BEC and will get quantum reflection of Hbar from detector surface in GBAR … will be several % in GBAR case

Weaker reflectors of EM field are better reflectors of atoms …behaviour of (decrease in) Casimir-Polder potential

Can we increase it to store antimatter in bottle/pipes etc???? E.g. nano-porous materials … and as a velocity selector for GBAR (only atoms with small vertical velocity) … higher precision for g

Alexei Voronin – Lebedev Physical Institute

Gravity localises particle near a reflecting surface – simplest bound antimatter quantum system

Energy states of order of peV, with spatial size of order 10’s of microns

Gravitational states of UCN bouncing on a mirror – already observed

Hbar states made possible by quantum reflection, which can be very efficient at low enough energies

Annihilation washes out nasty surface chemistry which make matter (e.g. H) studies difficult

Shows how energy/length scale of gravitational state can provide the gravitational mass

C.S. Unnikrishnan – TIFR, Mumbai

WEP for quantum systems – torsion balance etc valid to same precision for quantum systems – nothing special achieved by going to smaller systems

Shapiro delay …. WEP without free-fall Galactic potential, time delays of month …. Neutrinos and photons e.g. SN1987A. Coincidence in arrival time verifies WEP for these particles to better than 0.5% … This is the claim

Shows that these are not true tests of WEP – at core since the particles are ultra-relativistic (KE >>> m_0c^2). Only test of WEP for motional energy.

Getting to the core of WEP … free fall in presence of the rest of the “matter” in the Universe – distant matter dominates; billion times larger than gravitational potential of Earth

Derives Newton’s law from cosmic gravity …. and the equivalence principle

Any particle that obeys N. laws, also obeys EP ….

Ooops!

Direct experiments with slow antimatter are still worthwhile to look for short/intermediate-range interactions

Henri Baumann – Bern

Still use of ballistic gravimeters …with interferometery

Free-falling prism, integral part of the interferometer

Have to damp seismic noise … superspring

20 cm free fall during 0.2 s … compare fringes to Rb/Cs clocks

g with uncertainty of parts in 10^9

Fascinating geophysical applications … and the kilogram

Wolfgang Quint – GSI

FLAIR – Facility for Low Energy Antiproton and Ion Research

Several rings NESR, LSR, USR and HITRAP

USR, 10^7 pbars at 20 keV

HITRAP will deliver 5 keV pbars to experiments

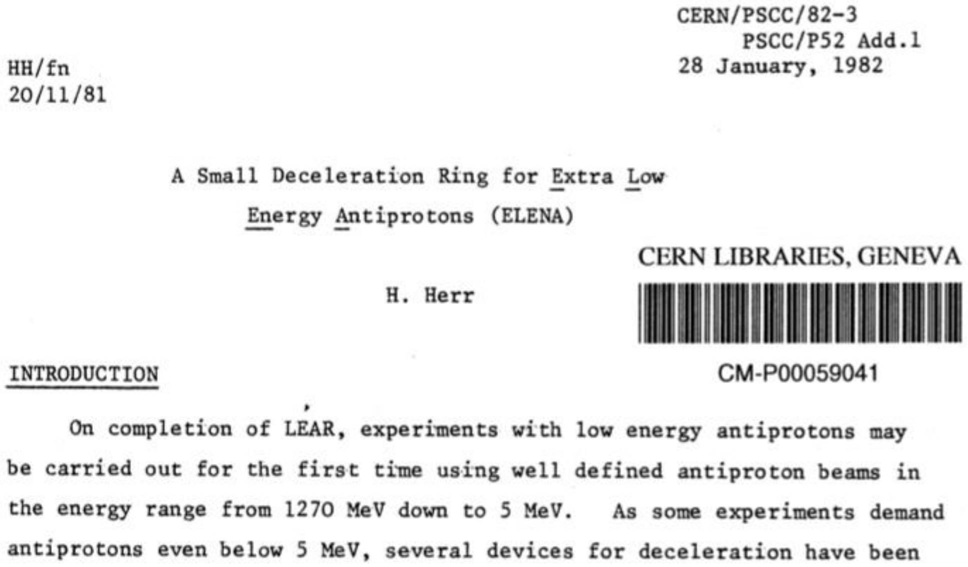
For gravitation – offline “mirror” experiments with matter
storage of 10^8 protons and electrons, fast cooling, sensitive detection

Resistive and feedback cooling – can reach a few 100 mK for a single ion

Sympathetic and evaporative cooling using evaporatively-cooled negative ions

Form neutral hydrogen/antihydrogen beam using a Zeeman slower

New ideas on phase space compression in traps … use the 2-photon 1S-2S transition in hydrogen/antihydrogen



CERN/PSCC/82-3
PSCC/P52 Add.1
28 January, 1982

HH/fn
20/11/81

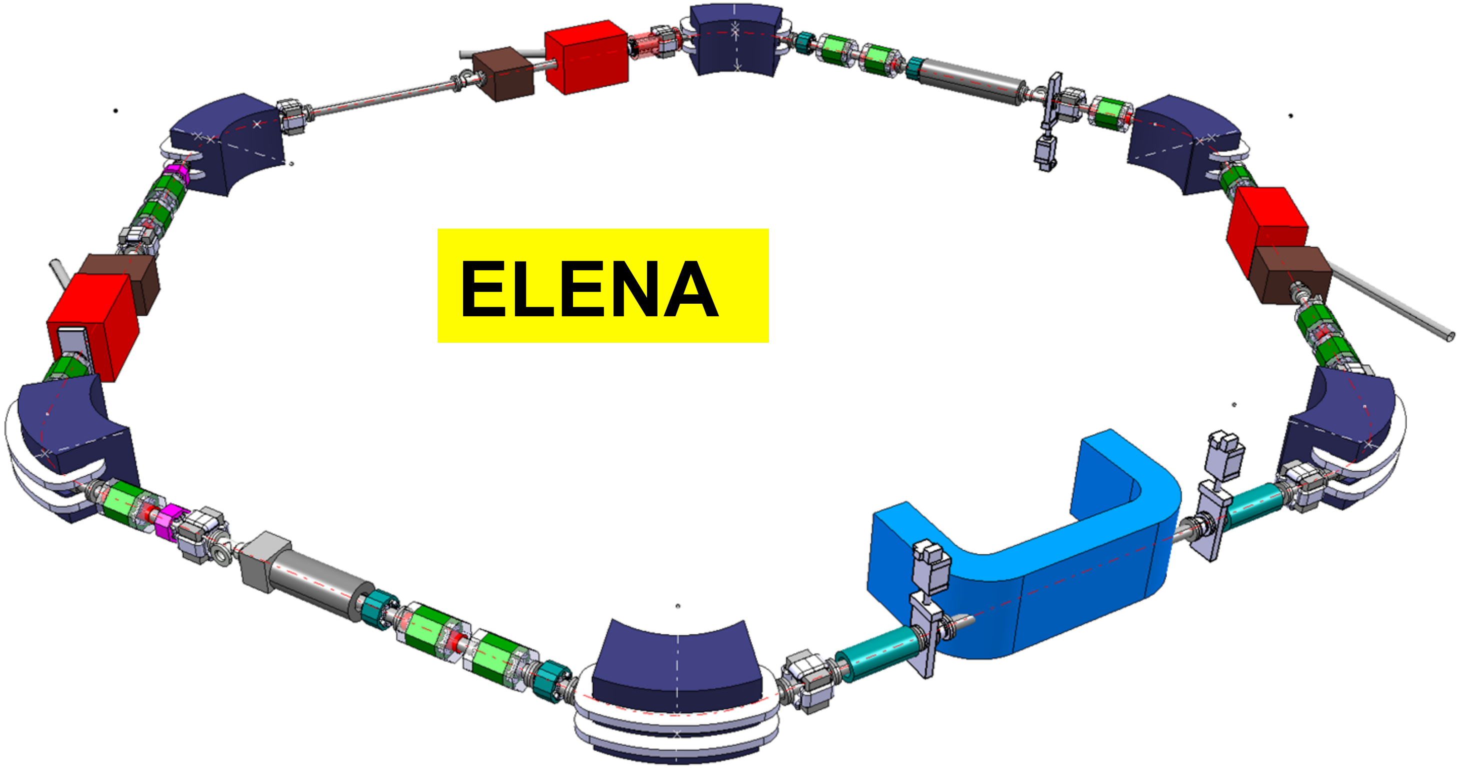
A Small Deceleration Ring for Extra Low Energy Antiprotons (ELENA)

H. Herr

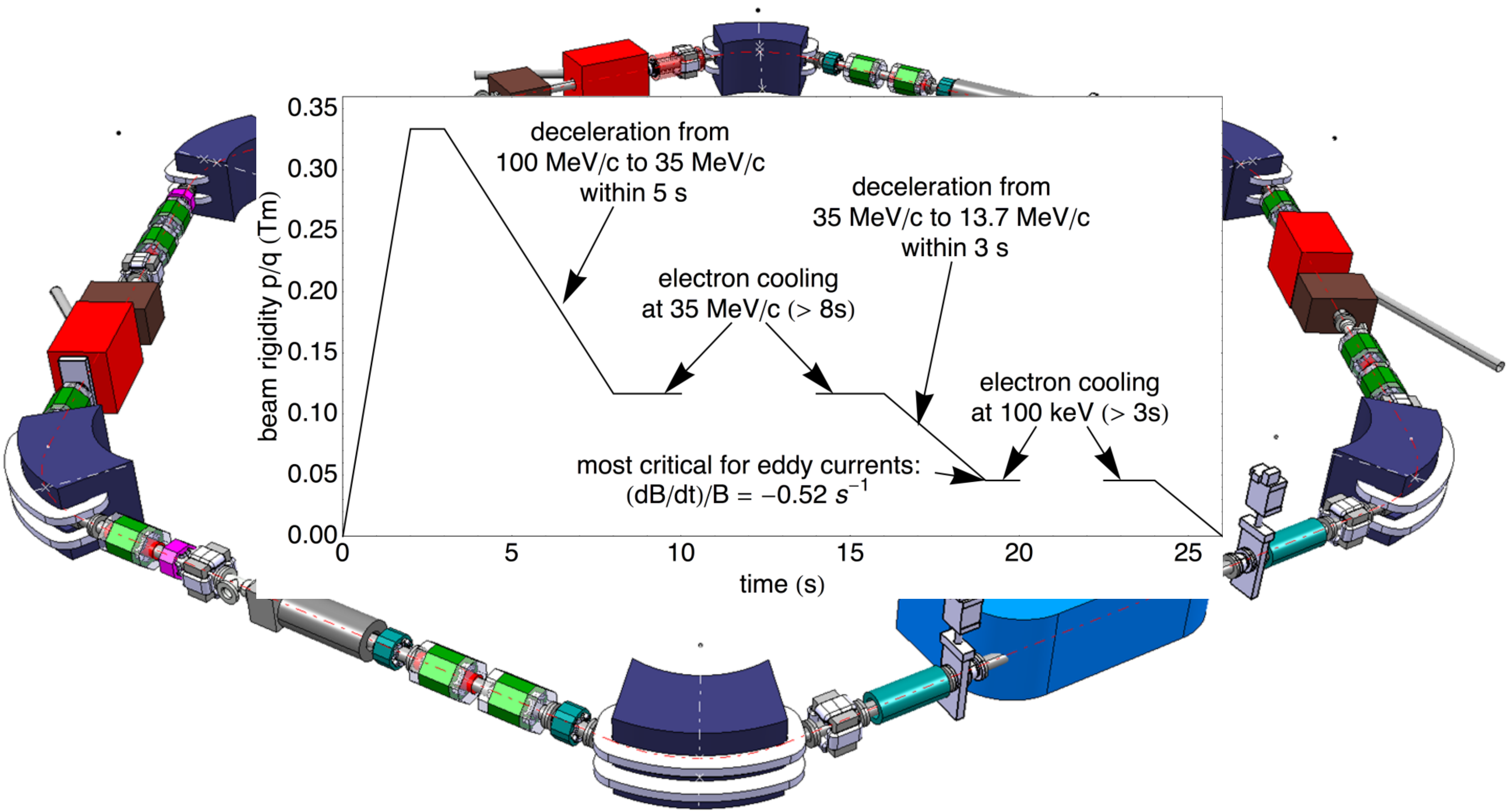
INTRODUCTION

On completion of LEAR, experiments with low energy antiprotons may be carried out for the first time using well defined antiproton beams in the energy range from 1270 MeV down to 5 MeV. As some experiments demand antiprotons even below 5 MeV, several devices for deceleration have been

Material courtesy of C. Carli



Material courtesy of C. Carli



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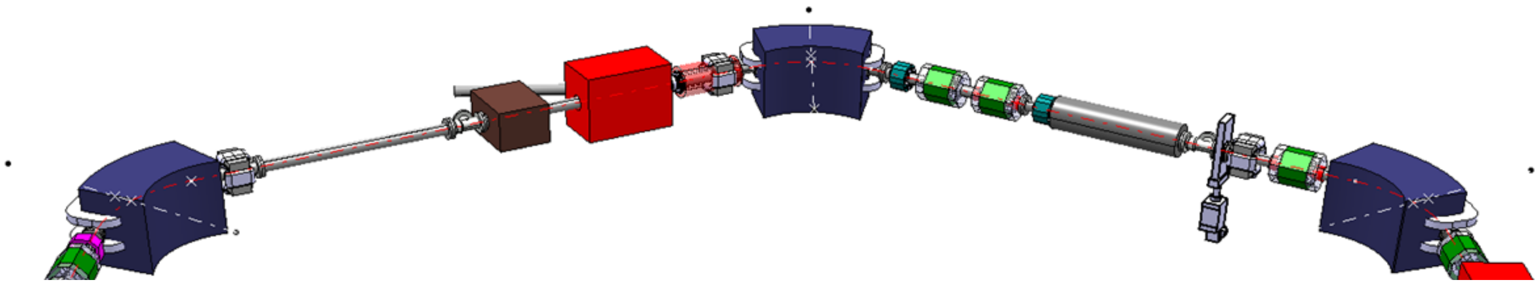
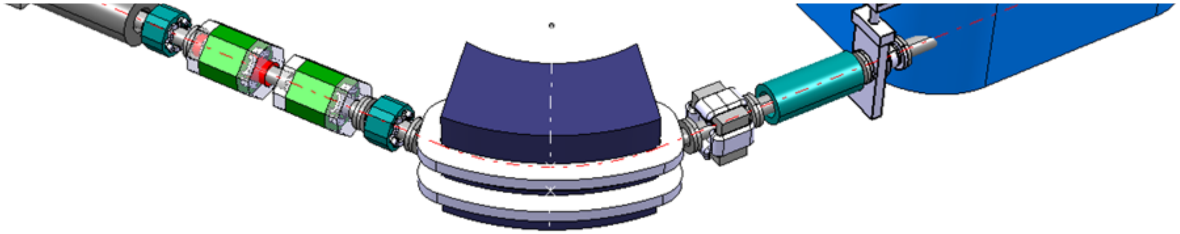


- Aim of ELENA
    - Small synchrotron with electron cooler to further decelerate antiprotons from the AD from 5.3 MeV to 100 keV
    - Improved efficiency of experiments trapping antiprotons by 1 to 2 orders of magnitude and allow for new types of experiments (gravitation with antihydrogen)
    - Will provide beam to several experiments simultaneously (lower intensities)
    - First antiproton physics with ELENA planned in 2017 (2nd half)



Final words from a master

" … is the complicating fact that … standard quantum field theory and general relativity are incompatible as a matter of principle. Either (i) quantum mechanics must be modified, or (ii) general relativity must be modified, or (iii) perhaps both.

In any event this tells us that gravity on antimatter is an important things to measure."

From Holzscheiter, Charlton and Nieto, Phys. Rep. 402 (2004) 1

This text due to Miguel Nieto

Final words from a master

From “Experiments to Measure the Gravitational Acceleration on Antimatter”

Goldman and Nieto, PLB **112** (1982) 437

This is the famous paper where they propose a Witteborn-Fairbank experiment with antiprotons

“A final experimental possibility is to use a facility like LEAR to make antihydrogen.”

… and from me …

To paraphrase Dan Kleppner

“When trapped antihydrogen is cooled to the low temperatures that have already been achieved for ordinary hydrogen, we’ll already know a lot about its gravitational properties.”

“The fact remains, however, that the challenge of measuring gravity on antihydrogen remains formidable. The situation can be summarized as follows: in the past decade the prospect of such experiments has advanced from the totally visionary to the merely very difficult. One could hardly ask for more.”

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… though I am very tempted to.