ASACUSA

Atomic Spectroscopy And Collisions Using Slow Antiprotons

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ASACUSA

Atomic Spectroscopy And Collisions Using Slow Antiprotons

Goal

Test CPT (matter-antimatter symmetry) to the highest-possible precision -

How ?

‘Weigh’ the antiproton (proton mass = antiproton mass?)

Use the **antiprotonic helium atom** as our ‘scale’ - so far -

Collaborating institutes and funding

	Tokyo RIKEN	MEXT, Japan RIKEN
	Aarhus	Danish natural science foundation, ISA
	RMKI Debrecen	OMFB TeT OTKA
CERN	CERN	

MoU to be signed

Part 1

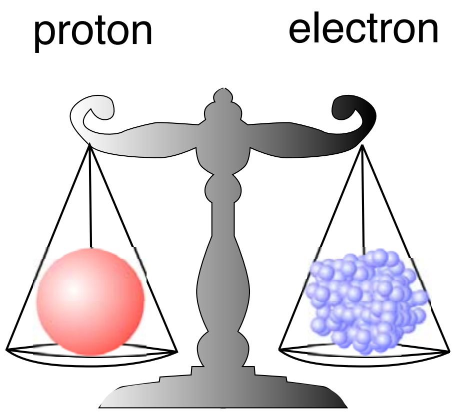
ASACUSA 2000 - 2004

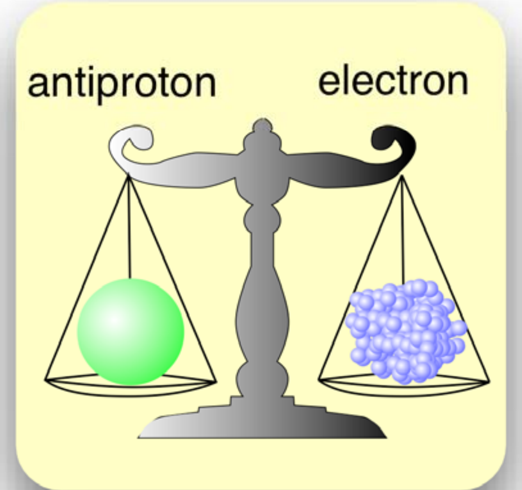
CPT 'theorem'

- CPT 'theorem' -
  Physics laws unchanged by the simultaneous exchange of
  C(particle↔ antiparticle), P(left↔right), T(future↔past)
- If CPT is OK, **particle mass = antiparticle mass**
- Extensions of the standard model accommodate CPT violation.
- CPT violation, if discovered, has a profound impact on the basic understanding of nature (but the magnitude must be very small)
- CPT must be experimentally tested to the highest-possible precision
- ASACUSA compares **proton mass vs antiproton mass**

The best baryonic CPT test

Weighing the antiproton



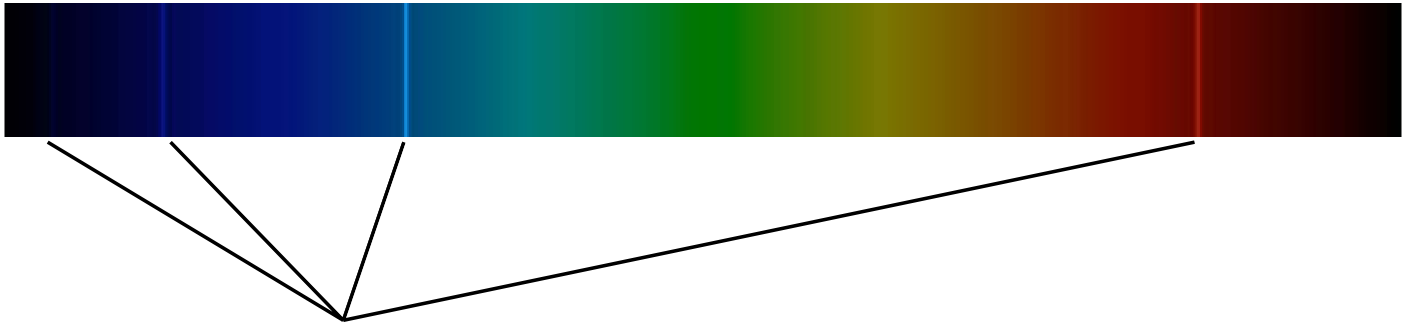


- proton-electron mass ratio is known to high precision

m_p/m_e = 1836.15267261 ± 0.00000085 (4.6 x 10^{-10})

- ASACUSA measures antiproton-electron mass ratio, (and then compares it with the proton-electron ratio) but how?

Hydrogen spectrum and electron mass



Famous Balmer lines of hydrogen

The photon frequency is

$$\nu(n, n') = Rc\left(\frac{1}{n^2} - \frac{1}{n'^2}\right)$$

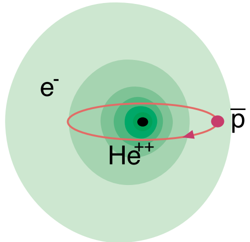
$$R = \frac{m_e e^4}{8c\epsilon_0^2 h^3}$$

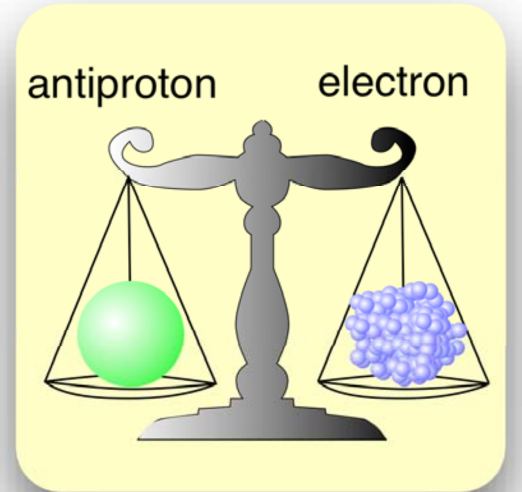
where R is the Rydberg constant.

Antiprotonic helium

For antiprotonic helium $(\bar{p} + e^- + \alpha)$,

$$\nu(n, n') = Rc \frac{M_{\bar{p}}}{m_e} Z^2_{\text{eff}} \left(\frac{1}{n^2} - \frac{1}{n'^2} \right)$$



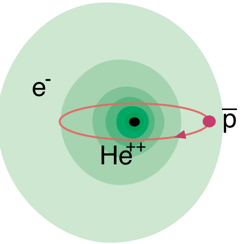


Z^2_{eff}: helium charge, shielded by electron (calculated by theory)

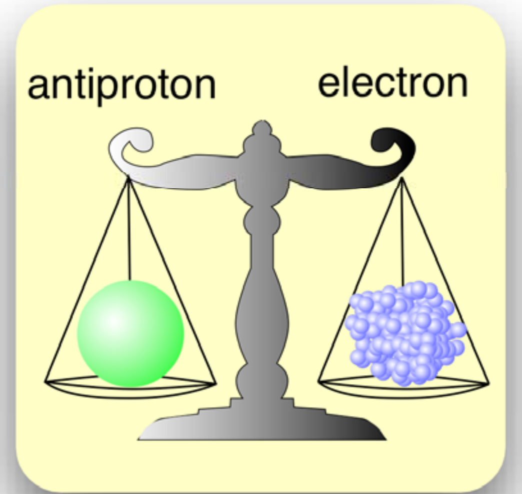
- **Rc** is known to an astounding precision of 6.6×10^{-12}.
- By measuring ν, antiproton mass can be determined.

(to be more precise)

For antiprotonic helium $(\bar{p} + e^- + \alpha)$,



$$\nu(n, \ell; n', \ell') = Rc\frac{M^*_{\bar{p}}}{m_e} Z^2_{\text{eff}} \frac{Q^2_{\bar{p}}}{e^2}\left(\frac{1}{n^2} - \frac{1}{n'^2}\right)$$



$Z^2_{\text{eff}}(n, \ell; n', \ell')$: state-dependent helium charge, shielded by electron (calculated by 3-body QED)

- By measuring ν, and by combining it with $Q_{\bar{p}}/M_{\bar{p}}$ measured by the TRAP group (at LEAR), antiproton mass and charge can be determined (PDG)

Q/M by TRAP @ LEAR

TRAP III (Phys.Rev.Lett. **82** (1999) 3198)

$$\frac{Q_{\bar{p}}/M_{\bar{p}}}{Q_p/M_p} + 1 = 0.9(9) \times 10^{-10}$$

Note: A polarization force shifts the H^- ion's cyclotron frequency (Nature **430**, 58 (2004)); a corrected value is $1.6(9) \times 10^{-10}$

Best baryonic CPT limit

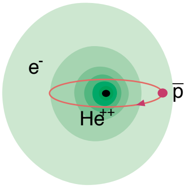
- **Antiproton 'weighed' to 10^{-8}** precision using the antiprotonic helium laser spectroscopy - the **best** (baryonic) CPT limit.

From The Review of Particle Physics (2004)

$$|m_p - m_{\overline{p}}|/m_p$$

A test of *CPT* invariance. Note that the comparison of the $\overline{p}$ and p charge-to-mass ratio, given in the next data block, is much better determined.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<1.0 \times 10^{-8}$	90	[1] HORI	03	SPEC	$\overline{p} e^{-}$ ^{4}He and $\overline{p} e^{-}$ ^{3}He
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<6 \times 10^{-8}$	90	[1] HORI	01	SPEC	$\overline{p} e^{-}$ He atom
$<5 \times 10^{-7}$		[2] TORII	99	SPEC	$\overline{p} e^{-}$ He atom

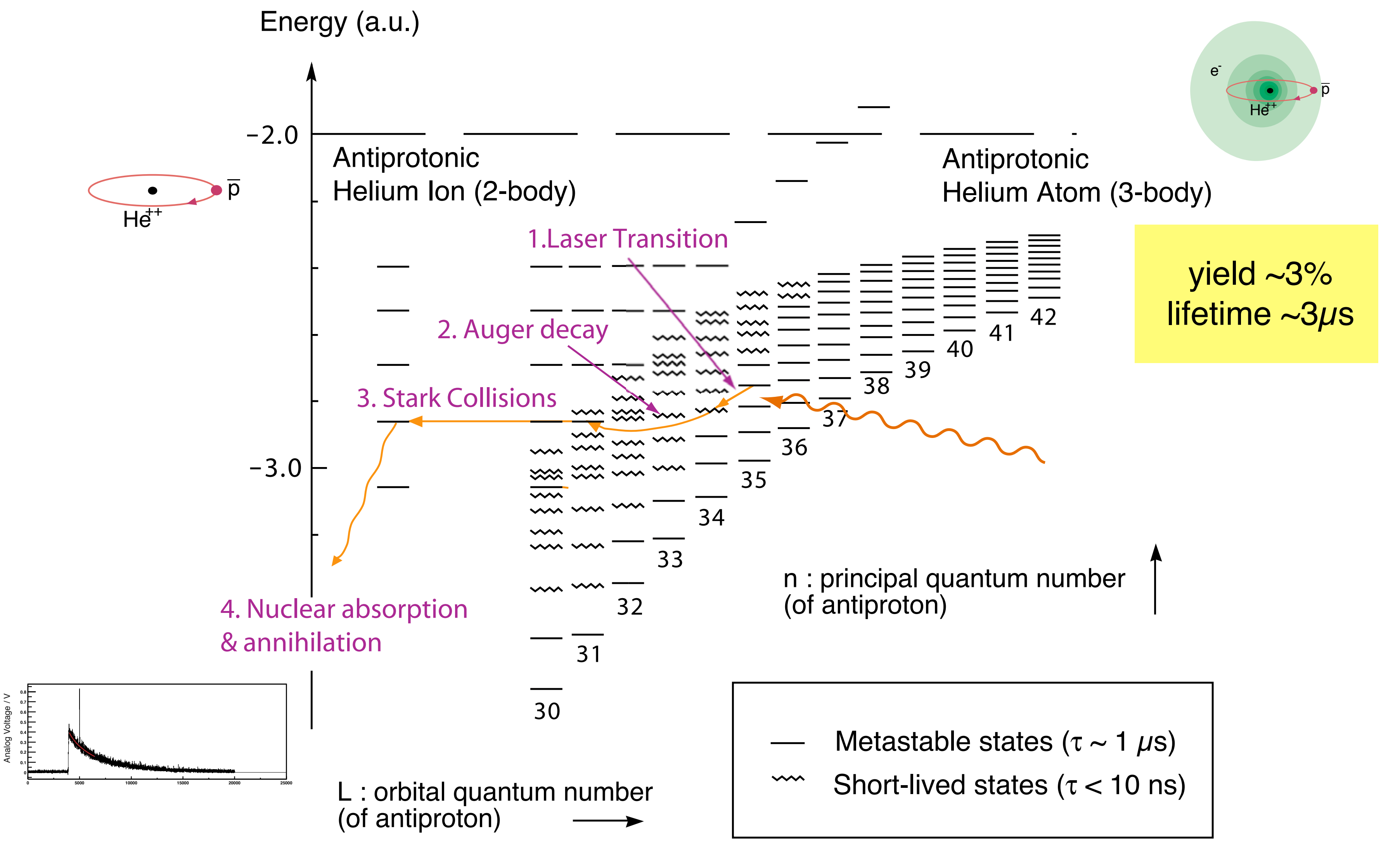


Antiprotonic helium

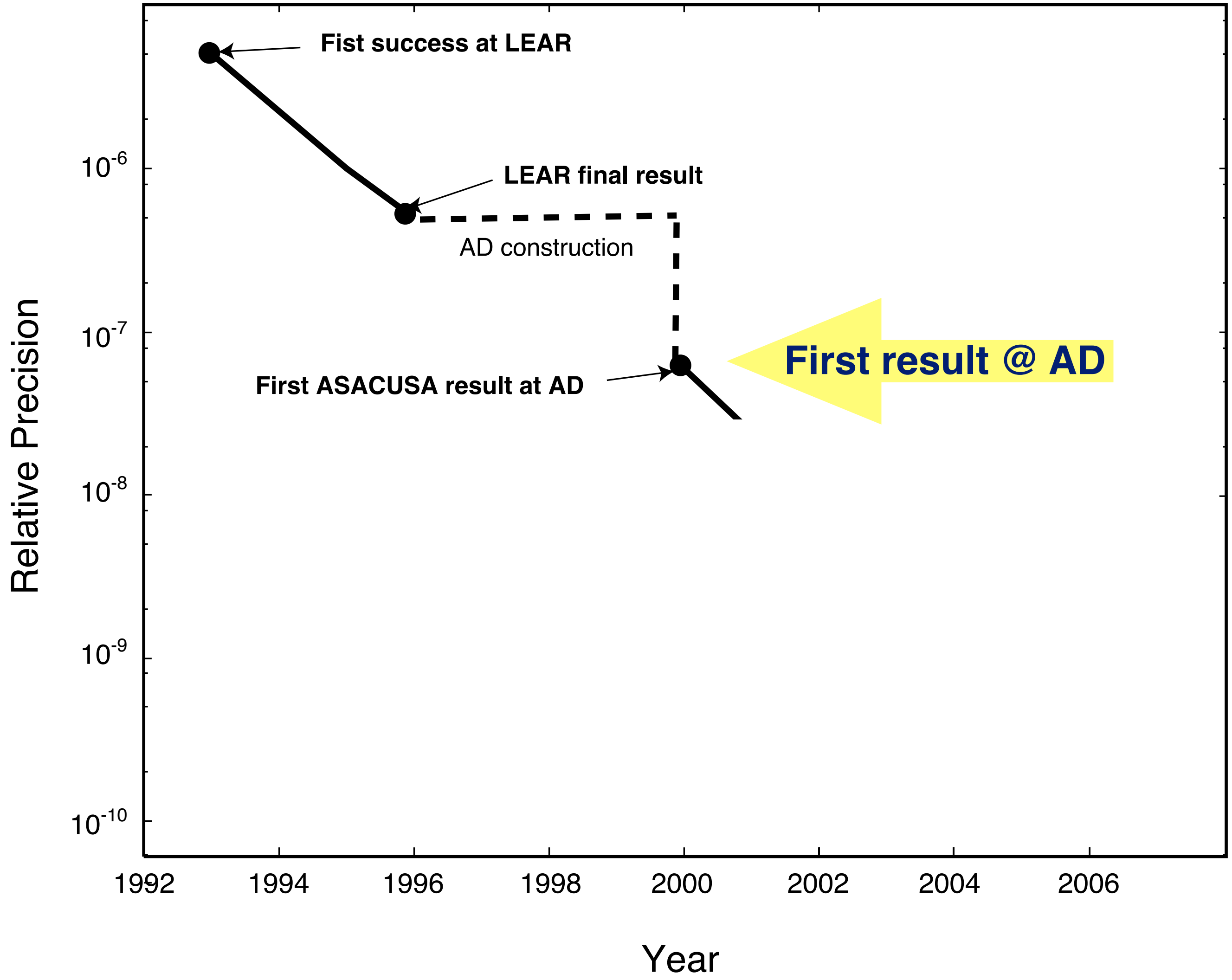
antiprotonic helium vs antihydrogen

	antiprotonic helium atom	Antihydrogen
System	3-body	2-body
Theory	Difficult, accuracy ~ppb?	not needed if H and HBar are compared
Production	Easy, can be abundantly produced	demonstrated, but not so many in the ground state yet?
Cold?	Yes, < 10 K	???
Ultimate precision	$10^{-10 \sim 12}$	$10^{-14 \sim 18}$
Outlook	Will continue to provide the best baryonic CPT test for some more time	Future hopeful

Antiprotonic helium - a closer look



Weighing the antiproton, progress



60 ppb

using 5 MeV beam
(ASACUSA phase 1)

NOTE

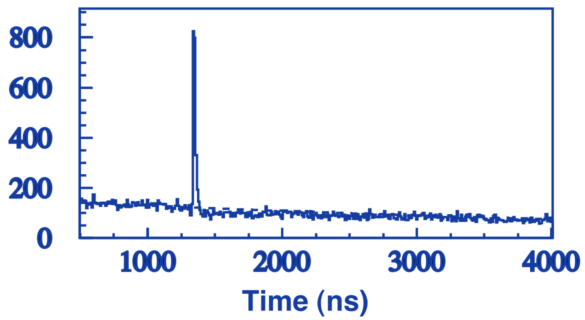
Every x10 improvement

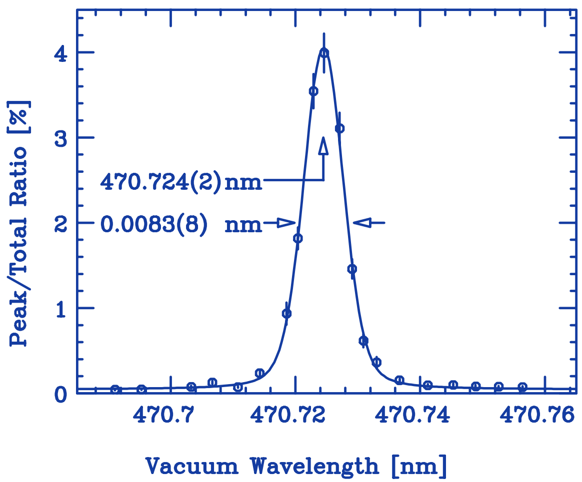
requires new developments

from LEAR (500 ppb)

to ASACUSA phase 1 (60 ppb)

LEAR offered slow extraction

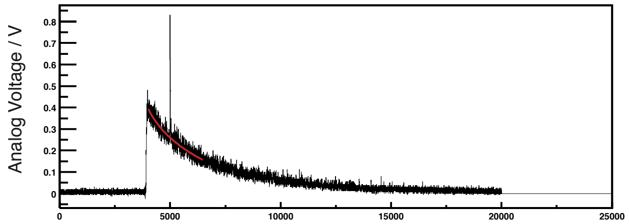


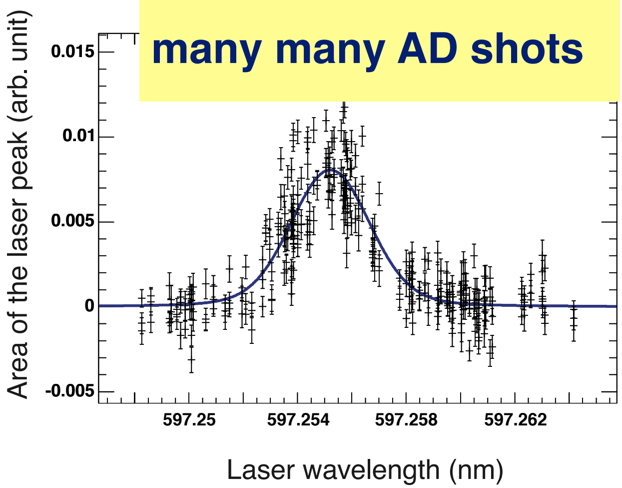


- LEAR - slow extraction, event by event counting
- good event identification
- 1 atom, 1 laser shot, ~ 300 Hz
- rapid frequency scan so as to minimize (average out) systematic errors

AD - fast extraction

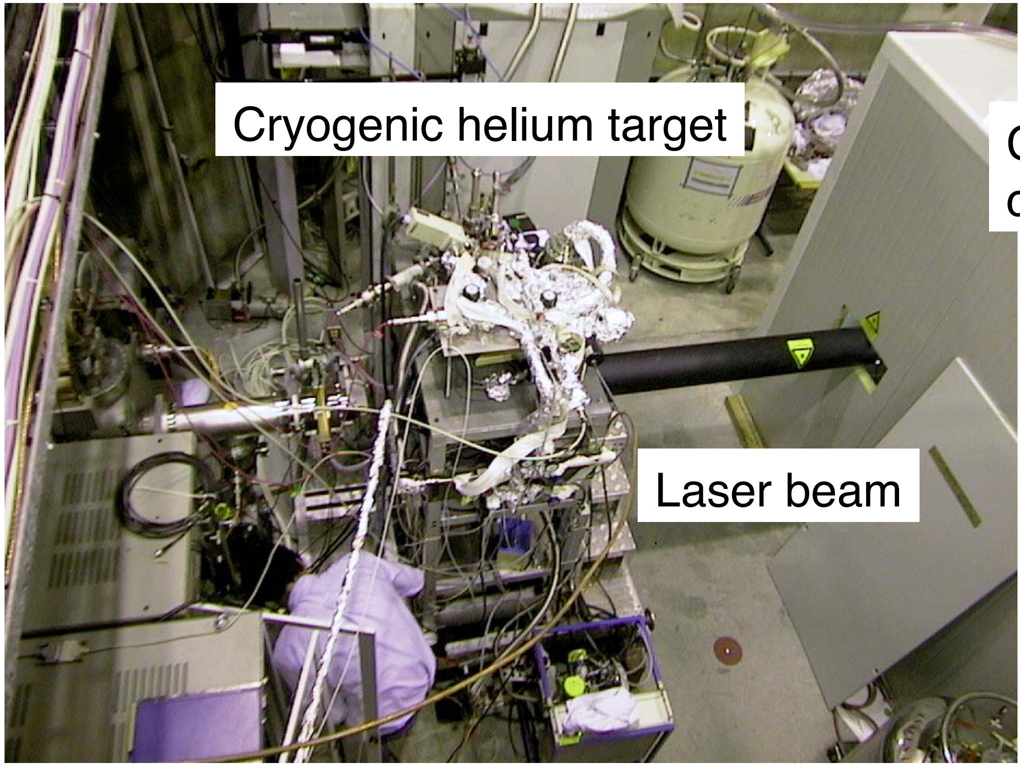
Measured in a single AD shot

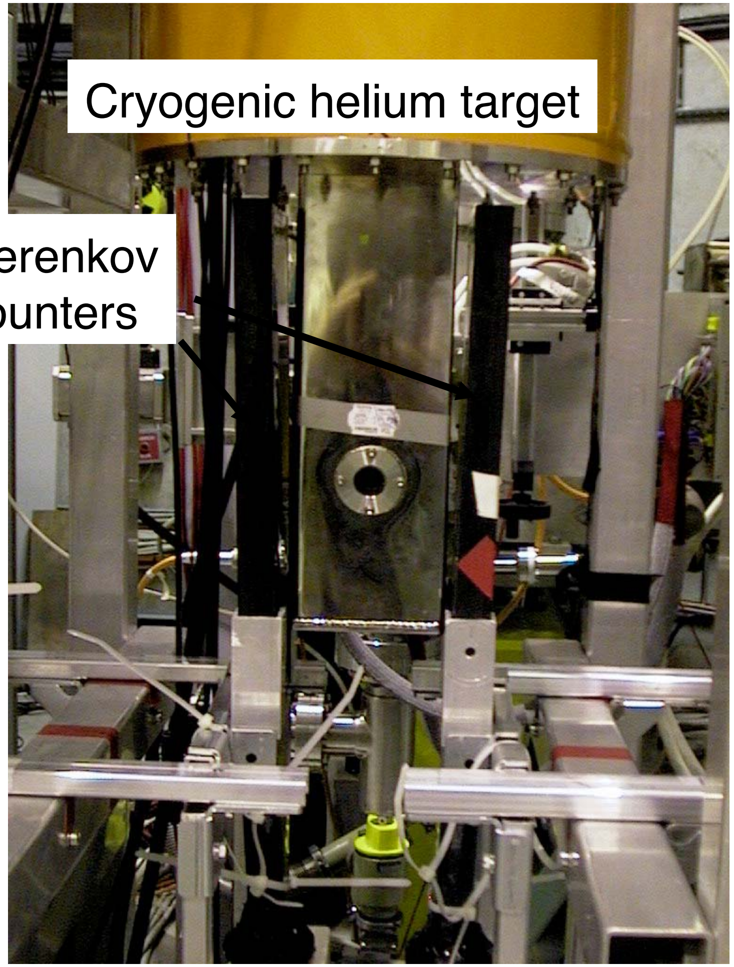




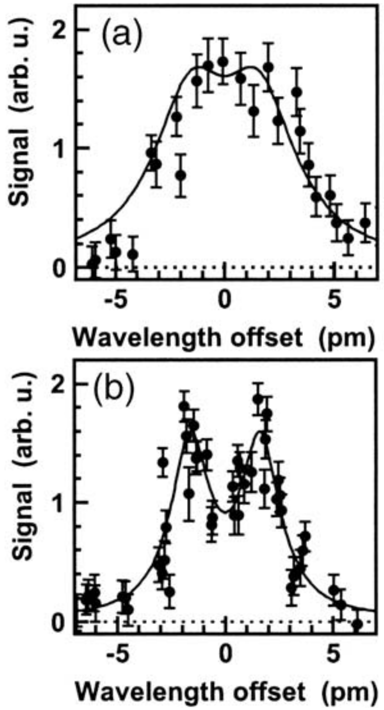
- AD - fast extraction, 3×10^{7} pbar, 10^{6} atoms, 1 laser pulse
- Each laser-frequency point ↔ 1 AD shot
- Good control of systematics over ~8 hours is crucial
  - target condition
  - laser shot-to-shot power stability, frequency stability
  - antiproton beam intensity, position

Phase 1 (5 MeV beam)





Pulsed laser system

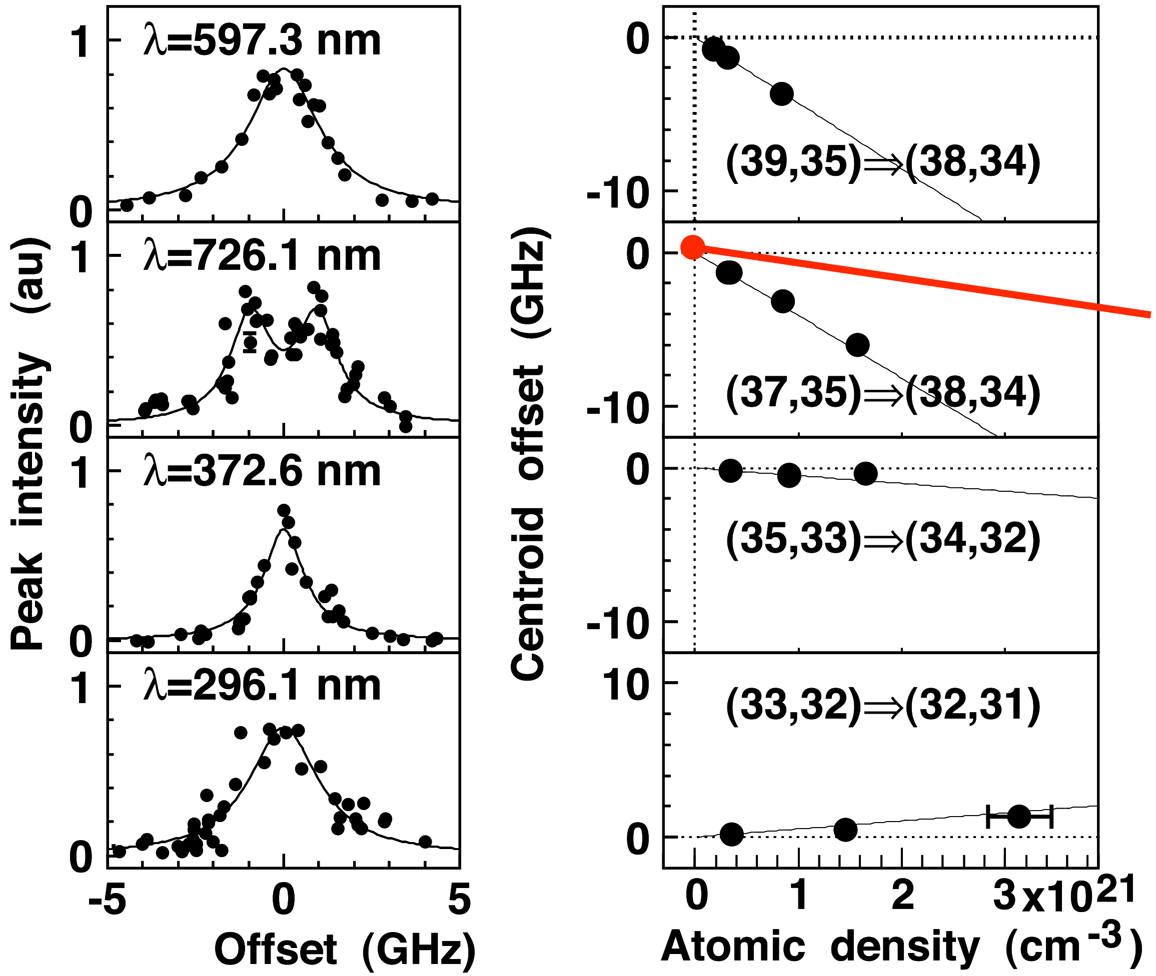


LEAR

AD

hyperfine structure can be resolved (more later)

Collisional frequency shift correction



Antiprotons stopped in dense (~1bar, 0.5K) target, zero-density extrapolation needed

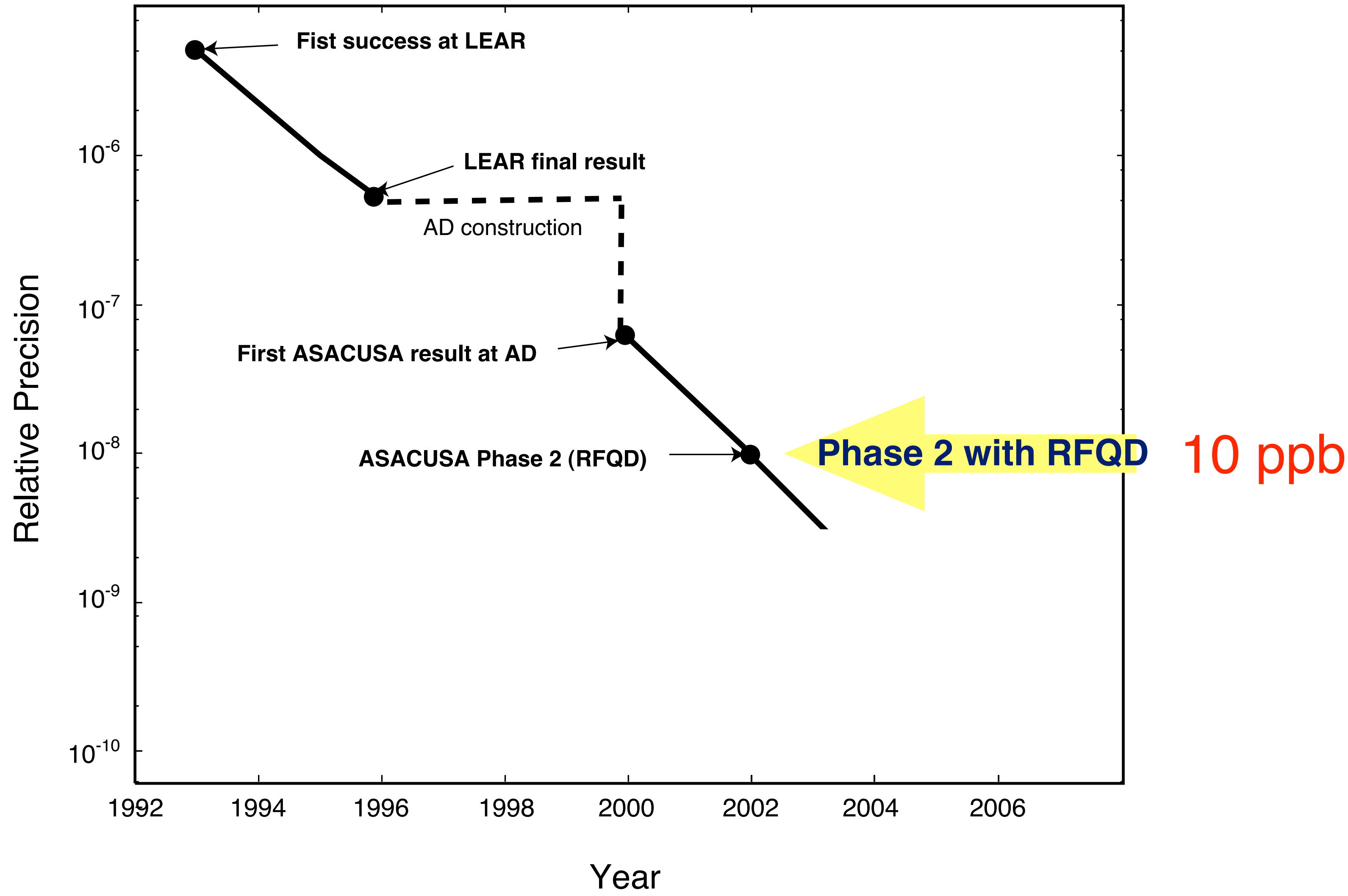
↓

60 ppb

from ASACUSA phase 1 (60 ppb)

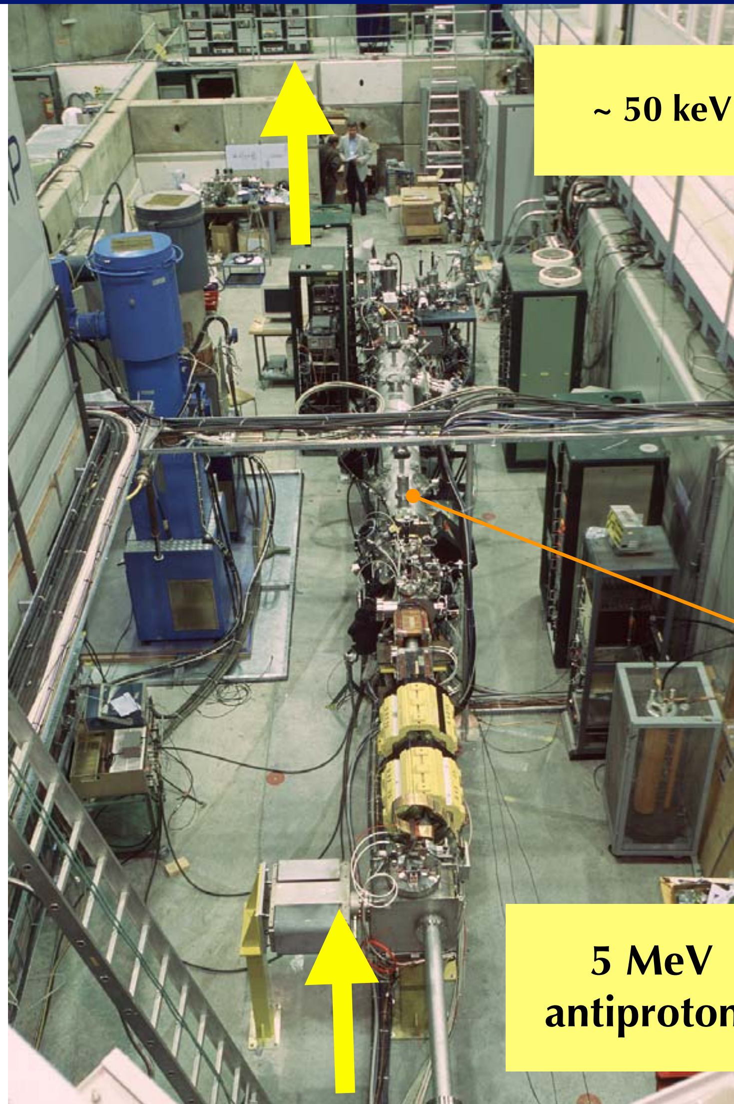
to ASACUSA phase 2 (10 ppb)

RFQD is essential



RFQD - an inverse linear accelerator

- RFQD (radio-frequency quadrupole decelerator) is an ‘inverse accelerator’
- Antiprotons can be decelerated from 5 MeV 50 keV
- With the 50 keV beam, antiprotonic helium can be produced in a ‘near-vacuum’ condition



Beam energy & target density

	Method	Beam Energy	Typical target density	Physics output
Phase 1	AD direct	5 MeV	$10^{21}cm^{-3}$	$\bar{p}$He - 60 ppb $\bar{p}$He HFS interaction with H_2/D_2
Phase 2	RFQD	<100 keV	10^{16}-$10^{18}cm^{-3}$	$\bar{p}$He - 10 ppb dE/dx to <10 keV

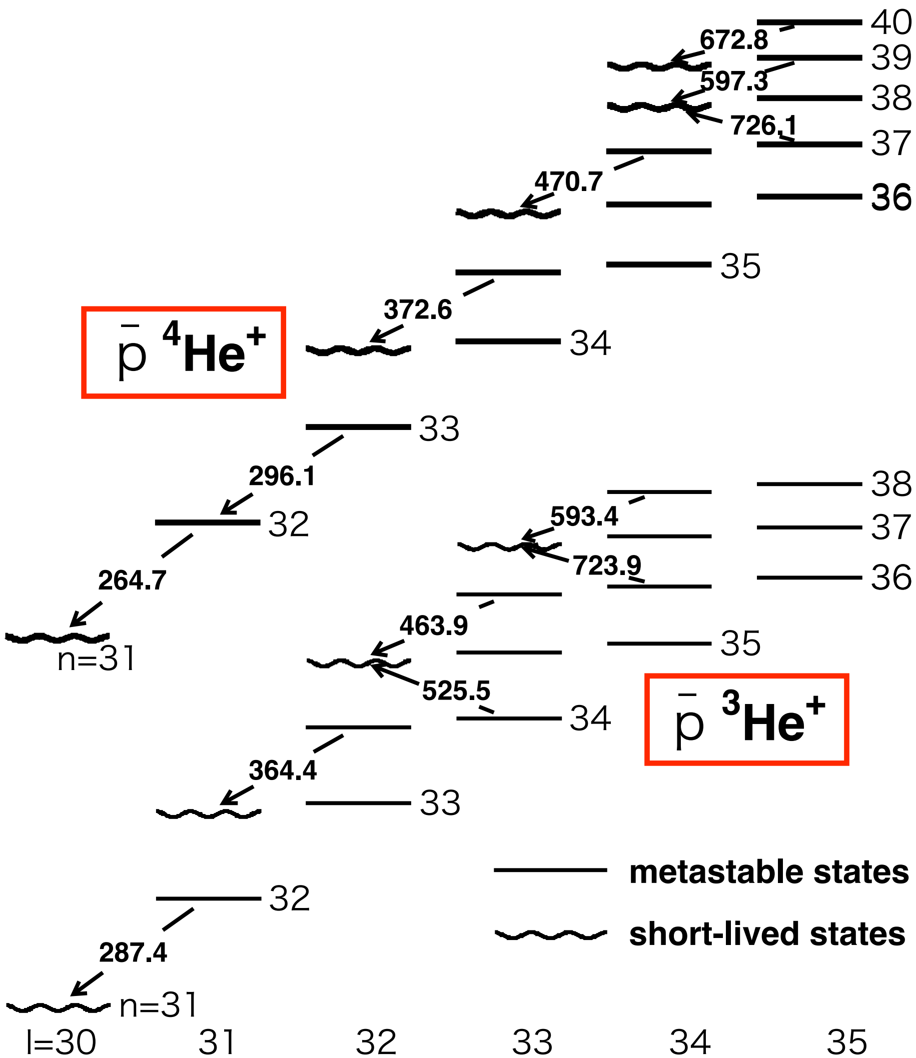
5 orders of magnitude

RFQD eliminates collisional effects

	Phase 1	Phase 2	Notes
Natural width	0.1 - 100000 MHz	←	
Collisional Shift	~~~500 MHz~~	<1 MHz	Shift is state dependent, difficult systematics
Collision width	~~~500 MHz~~	~1 MHz	
Doppler width	~500 MHz	←	Peak center can be determined to ~1/100 of the width
Laser band width (beaware of chirp)	800 ~2000 MHz	←	
Calibration	10 - 60 MHz	←	
Achieved precision	60 ppb	10 ppb	

for a typical transition, 5 MHz ↔ 10 ppb

13 transitions were measured



and the results were compared with

3-body QED theoretical calculations

Theory - non-relativistic H

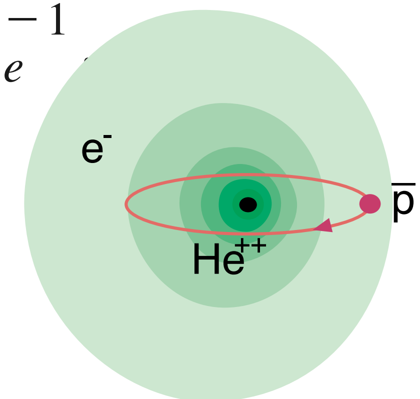
antiproton

electron

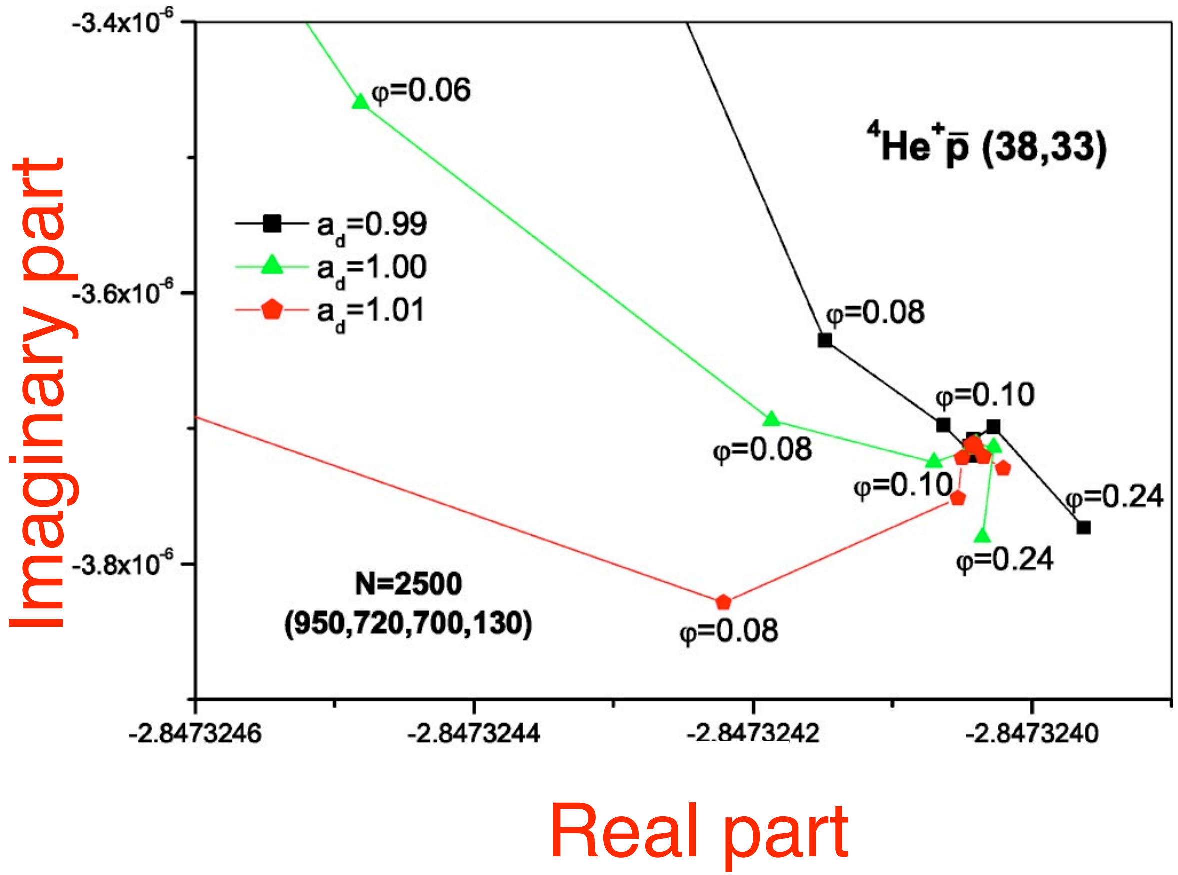
$$H = T + V$$

$$= -\frac{1}{2\mu_1}\nabla_{\mathbf{R}}^2 - \frac{1}{2\mu_2}\nabla_{\mathbf{r}}^2 - \frac{1}{M_{\mathrm{He}}}\nabla_{\mathbf{R}}\cdot\nabla_{\mathbf{r}} - \frac{2}{R} - \frac{2}{r} + \frac{1}{|\mathbf{R}-\mathbf{r}|},$$

$$\mu_1^{-1} = M_{\mathrm{He}}^{-1} + M_X^{-1}, \quad \mu_2^{-1} = M_{\mathrm{He}}^{-1} + m_e^{-1}$$



Complex coordinate rotation method



- not true bound states
- careful treatment of Auger decay is needed
- complex eigen values calculated by using the "complex coordinate rotation" method

add relativistic correction (~100 ppm)

$$H = T + V$$

$$= -\frac{1}{2\mu_1}\nabla^2_{\mathbf{R}} - \frac{1}{2\mu_2}\nabla^2_{\mathbf{r}} - \frac{1}{M_{\mathrm{He}}}\nabla_{\mathbf{R}}\cdot\nabla_{\mathbf{r}} - \frac{2}{R} - \frac{2}{r} + \frac{1}{|\mathbf{R}-\mathbf{r}|},$$

$$\mu_1^{-1} = M_{\mathrm{He}}^{-1} + M_X^{-1}, \quad \mu_2^{-1} = M_{\mathrm{He}}^{-1} + m_e^{-1},$$

$$E_{rc} = \alpha^2 \left\langle -\frac{\mathbf{p}_e^4}{8m_e^3} + \frac{4\pi}{8m_e^2}[Z_{\mathrm{He}}\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}\delta(\mathbf{r}_{\bar{p}})] \right\rangle.$$

add self energy (~15 ppm)

$$H = T + V$$

$$= -\frac{1}{2\mu_1}\nabla_{\mathbf{R}}^2 - \frac{1}{2\mu_2}\nabla_{\mathbf{r}}^2 - \frac{1}{M_{\mathrm{He}}}\nabla_{\mathbf{R}}\cdot\nabla_{\mathbf{r}} - \frac{2}{R} - \frac{2}{r} + \frac{1}{|\mathbf{R}-\mathbf{r}|},$$

$$\mu_1^{-1} = M_{\mathrm{He}}^{-1} + M_X^{-1}, \quad \mu_2^{-1} = M_{\mathrm{He}}^{-1} + m_e^{-1},$$

$$E_{rc} = \alpha^2 \left\langle -\frac{\mathbf{p}_e^4}{8m_e^3} + \frac{4\pi}{8m_e^2}[Z_{\mathrm{He}}\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}\delta(\mathbf{r}_{\bar{p}})]\right\rangle.$$

$$E_{se} = \frac{4\alpha^3}{3m_e^2}\left[\ln\frac{1}{\alpha^2} - \ln\frac{k_0}{R_\infty} + \frac{5}{6} - \frac{3}{8}\right]\langle Z_{\mathrm{He}}\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}\delta(\mathbf{r}_{\bar{p}})\rangle$$

$$+ \frac{4\alpha^4}{3m_e^2}\left[3\pi\left(\frac{139}{128} - \frac{1}{2}\ln 2\right)\right]\langle Z_{\mathrm{He}}^2\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}^2\delta(\mathbf{r}_{\bar{p}})\rangle$$

$$- \frac{4\alpha^5}{3m_e^2}\left[\frac{3}{4}\right]\langle Z_{\mathrm{He}}^3 \ln^2(Z_{\mathrm{He}}\alpha)^{-2}\delta(\mathbf{r}_{\mathrm{He}})$$

$$+ Z_{\bar{p}}^3 \ln^2(Z_{\bar{p}}\alpha)^{-2}\delta(\mathbf{r}_{\bar{p}})\rangle,$$

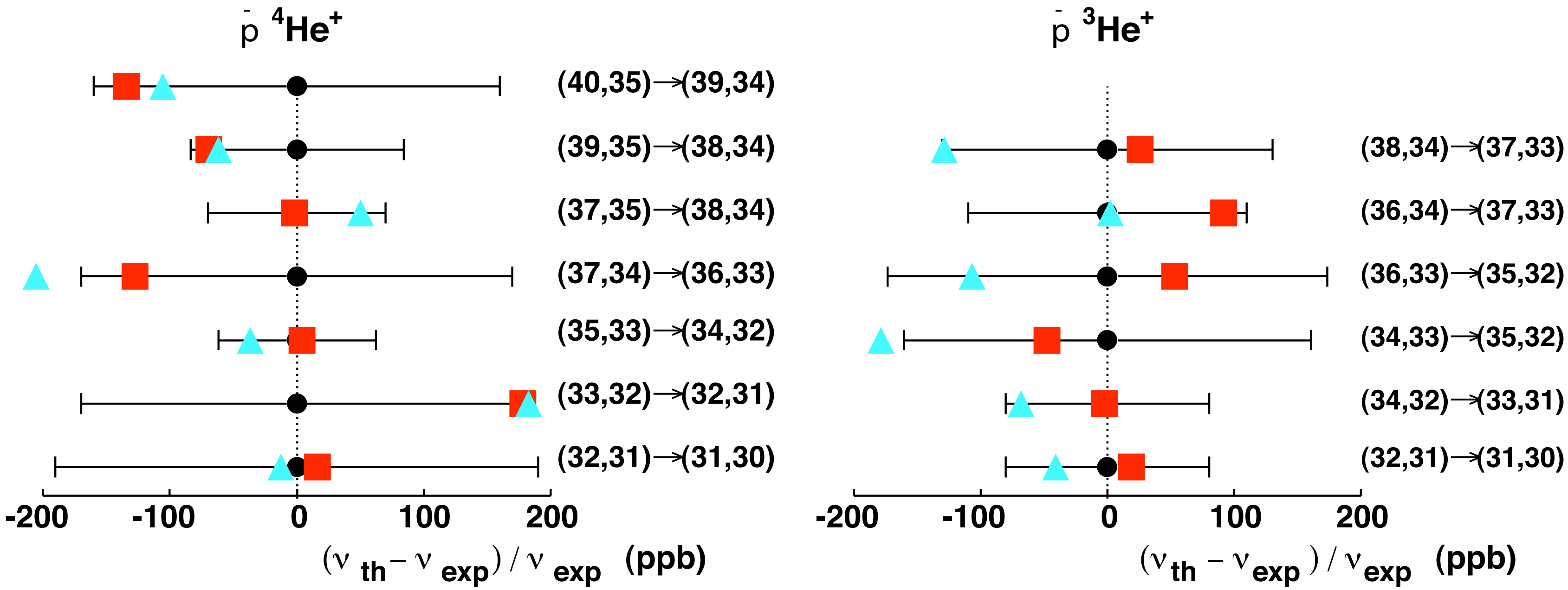
Breakdown of various contributions

(37,34) → (38,33) example (Korobov)

E_{nr}	$=$	$420\,158\,166(20)$
E_{rc}	$=$	$-43\,753(30)$
$E_{rc\text{-}QED}$	$=$	360
E_{se}	$=$	$5\,929(5)$
E_{vp}	$=$	-189
E_{kin}	$=$	-4
E_{ret}	$=$	-65
E_{fsc}	$=$	4
E_{total}	$=$	$420\,120\,448(40)$ MHz

~ 2 ppb - 100 ppb, depending on the Auger lifetime

Theory vs Experiment



Two theory calculations (▲and■) compared with experiment ●

▲and■ differ up to about 100 ppb

In order to improve, we must

- Reduce the experimental error bar by an order of magnitude
  - One of the two theoretical calculations turn may turn out to be wrong
- Urge theorists to work harder

Part 2

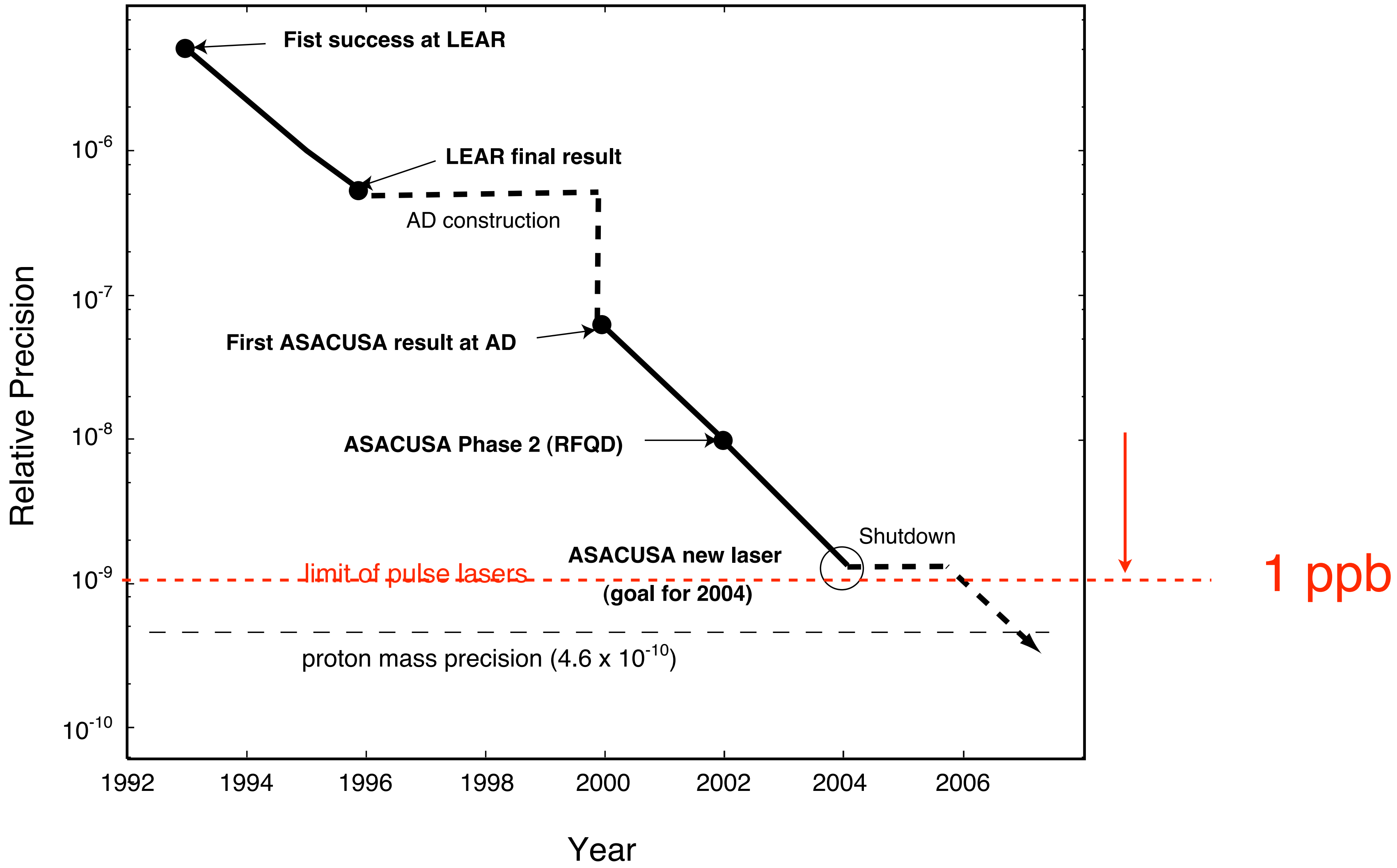
ASACUSA FUTURE

Physics Goals	Measurements		Method	Status & Outlook	
CPT tests: high-precision determination of antiproton mass, charge, magnetic moment and magnetic structure using various spectroscopic methods	**3-body system**	Antiprotonic helium **atom** laser & microwave spectroscopy	**RFQD**+low-density target	New high-precision laser system. Two-photon spectroscopy will enable ultimate accuracy.	Proton mass is known to 0.46 ppb. The goal is to measure antiproton mass to a similar precision.
	2-body systems	Antiprotonic helium **ion** laser spectroscopy	**RFQD**+low-density target	Free from theoretical ambiguities.	
		Antihydrogen ground-state **HFS** microwave spectroscopy	**RFQD** + Paul trap + Two-tone Paul trap (point source of cold antihydrogen)	Superconducting Paul traps being developed first Hbar production test in 2006.	The magnetic properties of antiproton poorly known. The goal is to compare the magnetic structure of proton and antiproton.
			RFQD + Penning trap + cusp trap (possible source of polarized antiydrogen beam)	Cusp trap being developed. Proton + electron test to be done in Japan in 2004-2005.	
	Auxiliary measurements	Collisional behavior of very low energy antiprotons	**RFQD** + gas/solid targets 100 eV beam extracted from Penning trap	Ready to start measurements in 2006. Potential "users" of the extracted beam	

from ASACUSA 2002 (10 ppb)

to 1 ppb

going to sub-ppb



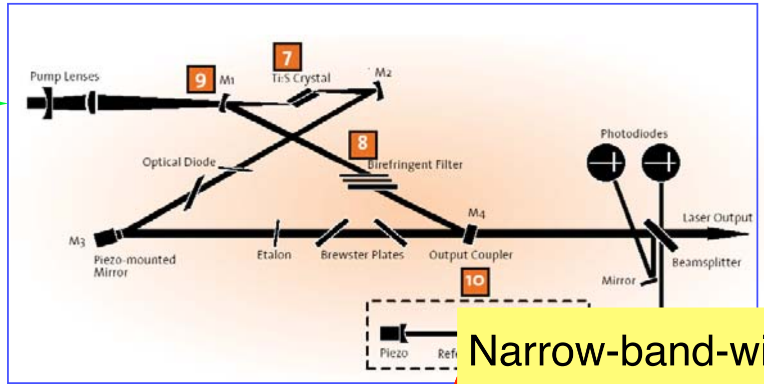
We need a new laser system

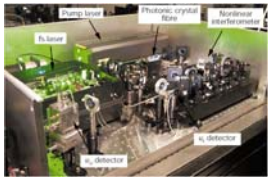
	Phase 1	Phase 2	New Laser
Natural width	0.1 - 100000 MHz	←	←
Collisional Shift	~~~500 MHz~~	<1 MHz	←
Collision width	~~~500 MHz~~	~1 MHz	
Doppler width	~500 MHz	←	Split by ~1/100
Laser band width beaware of chirp	~~800~2000 MHz~~	←	< 20 MHz (pulse amplified CW)
Calibration	~~10 - 60 MHz~~	←	~0 (frequency comb)
Achieved precision	60 ppb	10 ppb	work in progress

New Laser System

Verdi (CW-Nd:YAG)

MBR-110 (CW Ti:S)





Narrow-band-width CW laser locked to the freq. comb

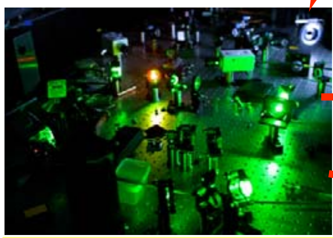
Frequency Comb: calibration with atomic clock precision

Frequency lock/scan unit

Chirp compensation / measurement essential

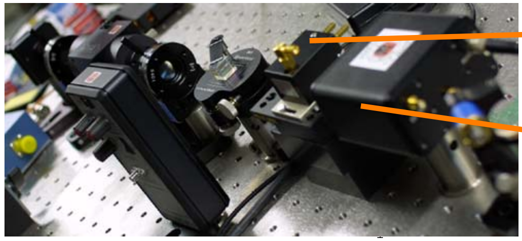
(Photodiode + log amp + digital oscilloscope)

Infinity (Pulsed Nd:YAG)



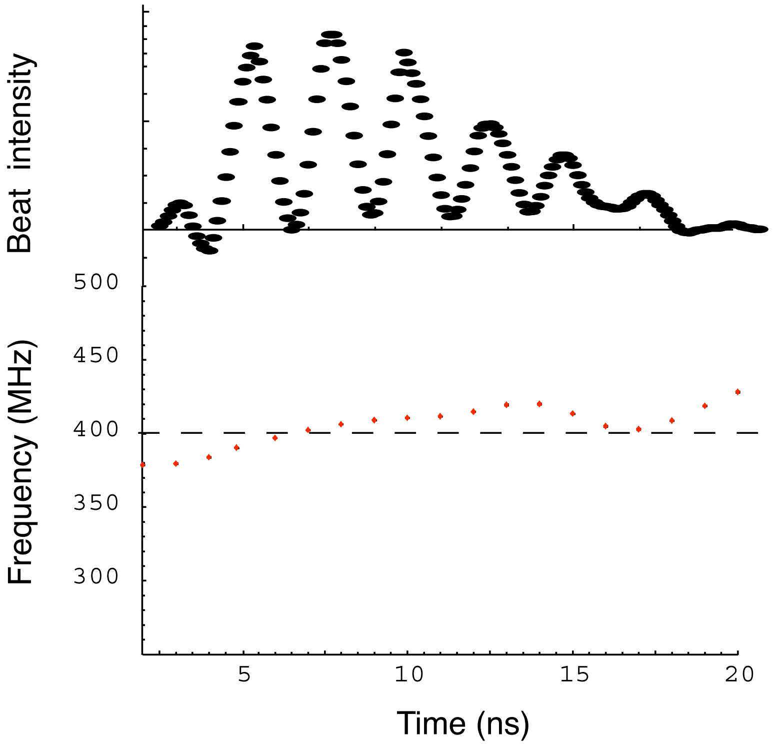
Pulse amplification: narrow-band high-power

Chirp measurement



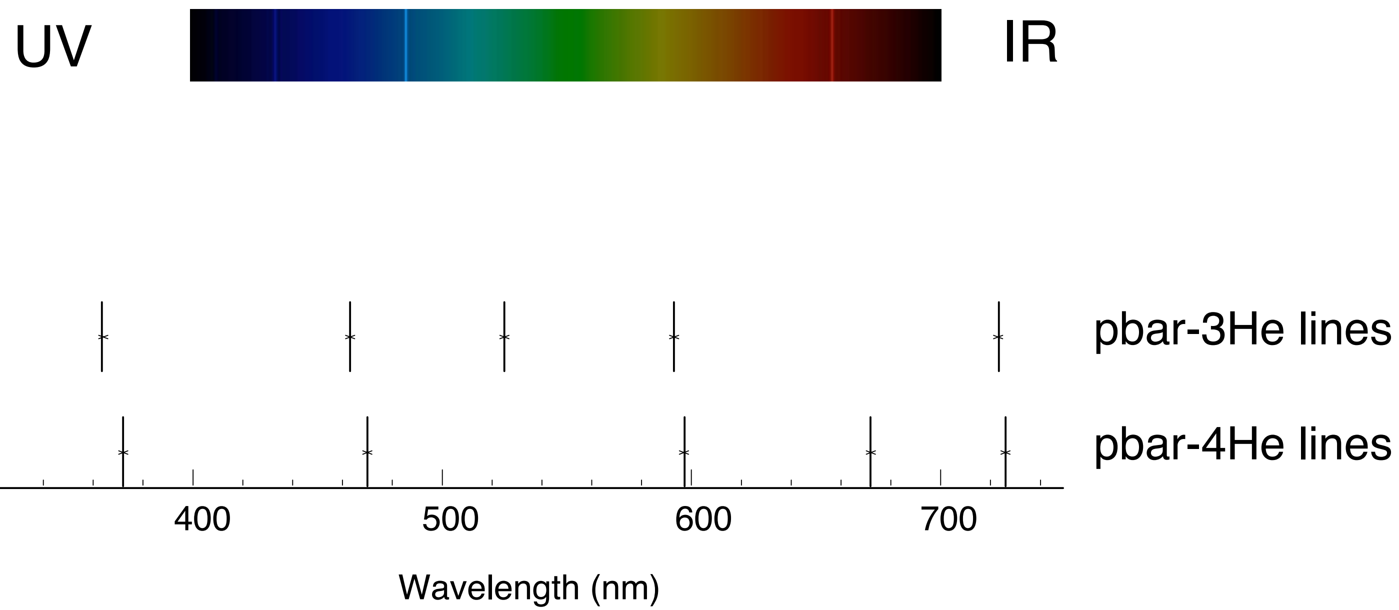
Acousto-optic modulator
Shifts CW laser by +400 MHz

Measure “beat note” of
the shifted CW laser and and
pulsed laser



Most of these methods are not new; e.g., chirp measurement/ compensation was done by Jungmann et al. for muonium 1s-2s, but doing this at AD for many different colors is still a challenge

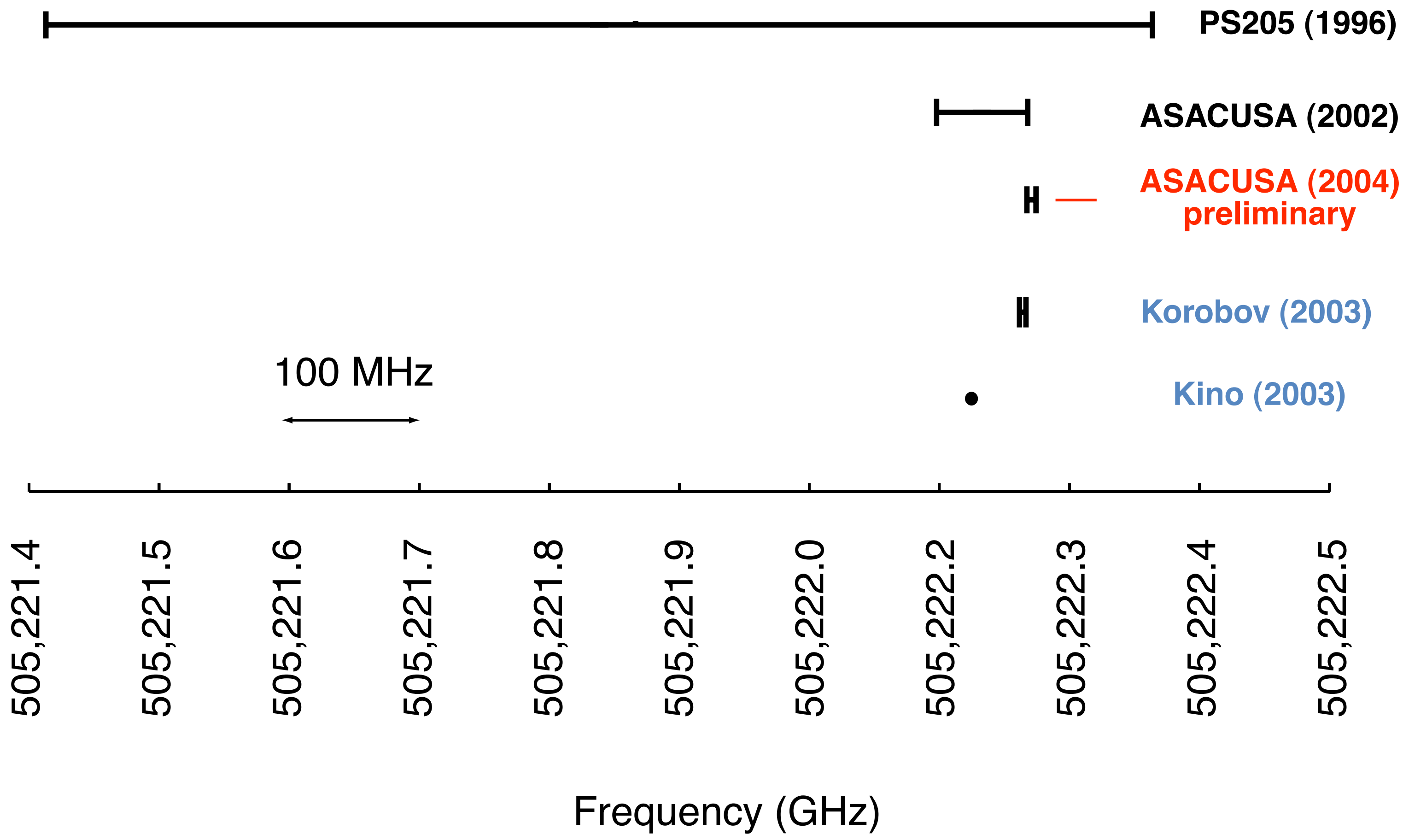
wavelengths of the resonance lines



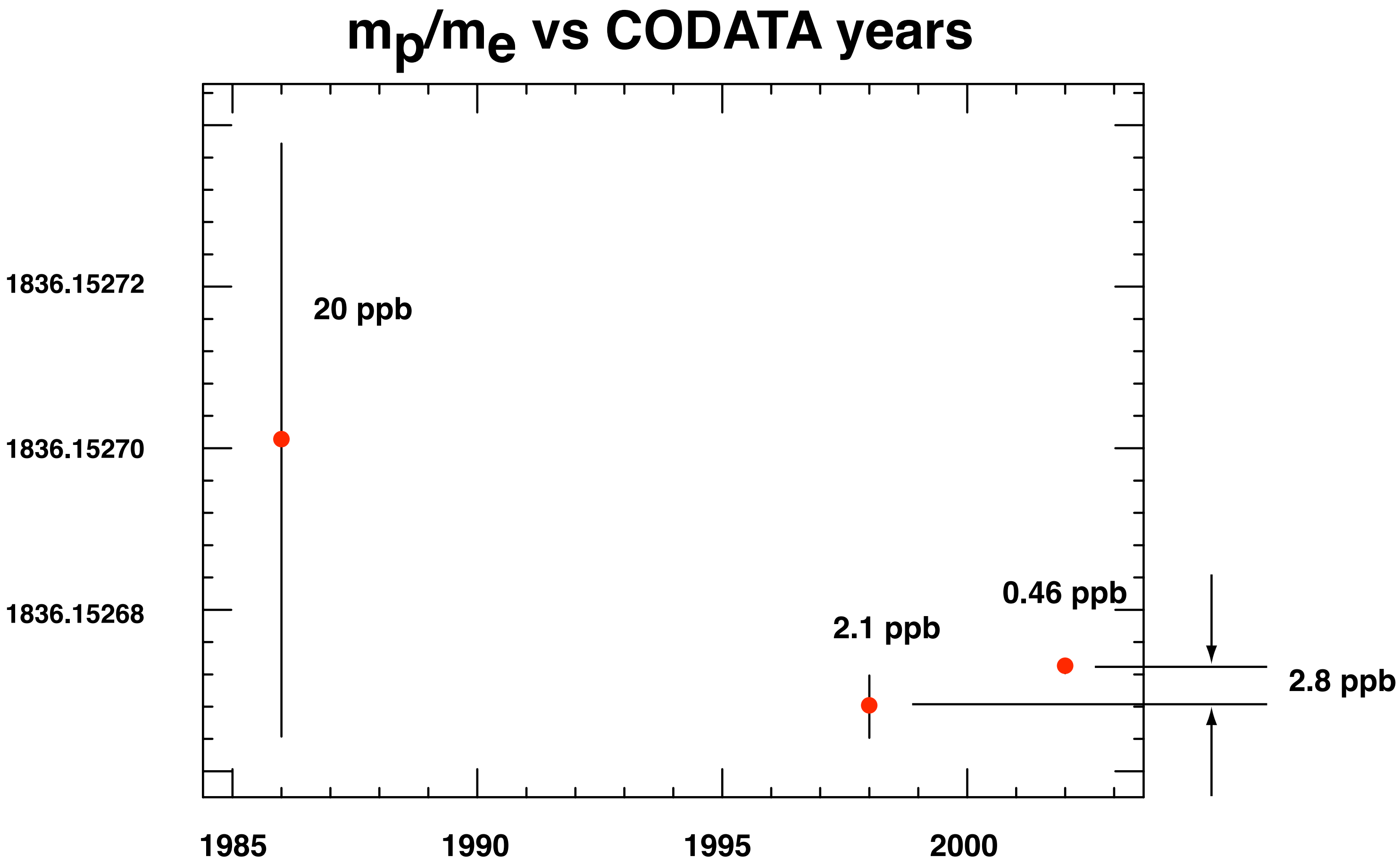
it is nontrivial to achieve highest accuracy for these many transitions

Preview of the 2004 result

593-nm (505,222 GHz) resonance in helium3

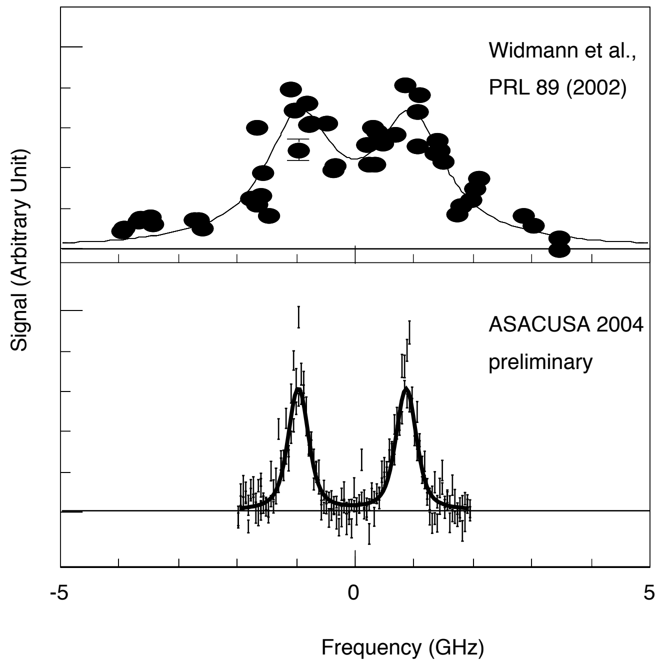


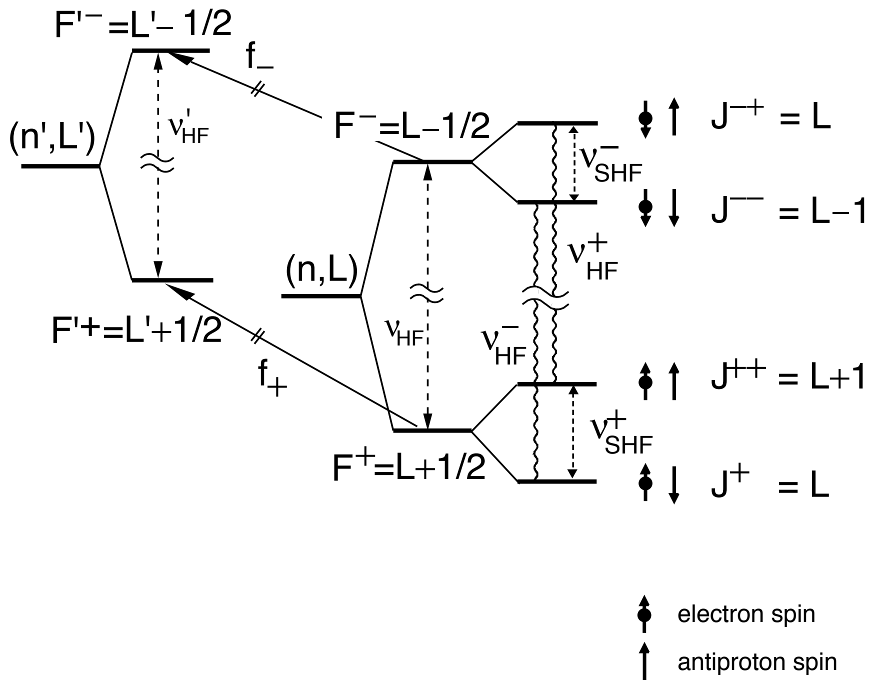
Meanwhile the proton mass has moved



note: alpha mass/proton mass known to 0.13 ppb

HFS → magnetic moment





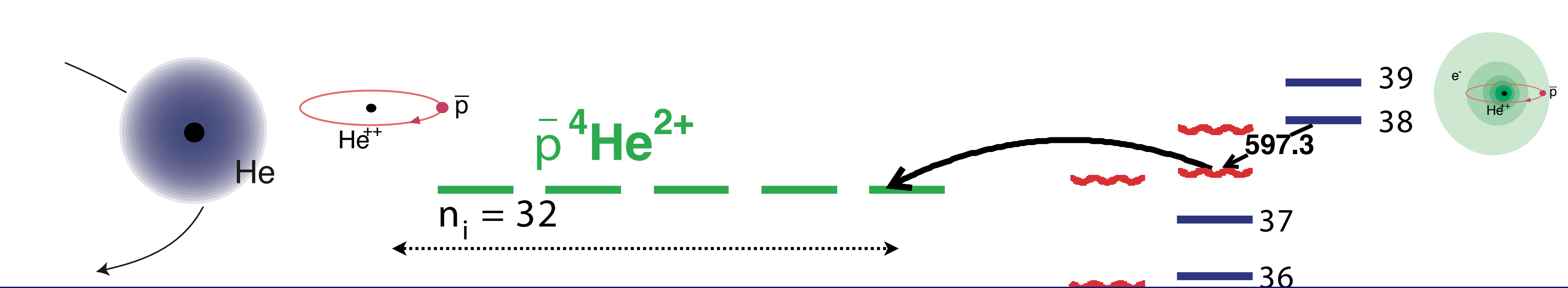
- HFS measurement, 726-nm laser + 13GHz microwave, so far limited by laser
- with the new laser, accuracy improvement possible
- antiproton μ known only to 0.3%, ASACUSA 2001 was 1.6%
- In 2006 we will measure antiproton μ to << 0.1%

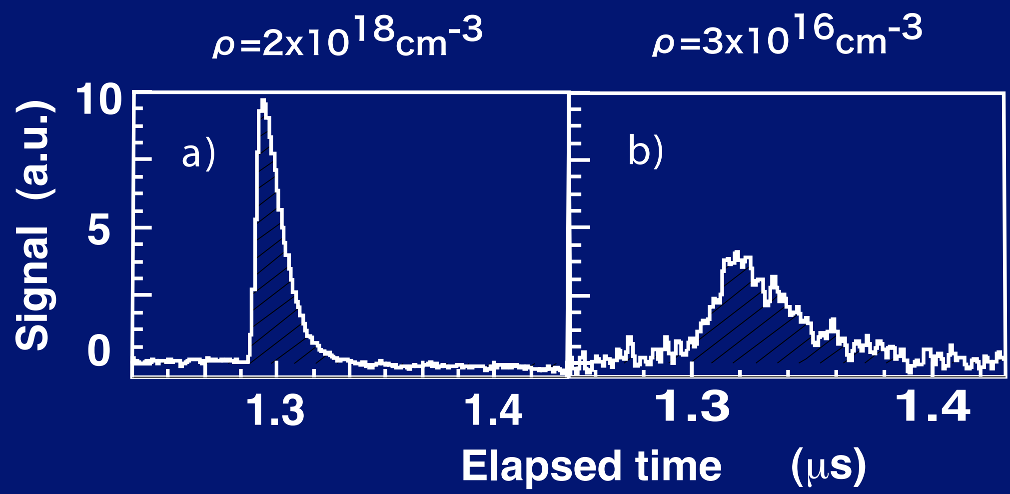
Physics Goals	Measurements		Method	Status & Outlook	
CPT tests: high-precision determination of antiproton mass, charge, magnetic moment and magnetic structure using various spectroscopic methods	**3-body system**	Antiprotonic helium **atom** laser & microwave spectroscopy	**RFQD**+low-density target	New high-precision laser system. Two-photon spectroscopy will enable ultimate accuracy.	Proton mass is known to 0.46 ppb. The goal is to measure antiproton mass to a similar precision.
	2-body systems	Antiprotonic helium **ion** laser spectroscopy	**RFQD**+low-density target	Free from theoretical ambiguities.	
		Antihydrogen ground-state **HFS** microwave spectroscopy	**RFQD** + Paul trap + Two-tone Paul trap (point source of cold antihydrogen)	Superconducting Paul traps being developed first Hbar production test in 2006.	The magnetic properties of antiproton poorly known. The goal is to compare the magnetic structure of proton and antiproton.
			RFQD + Penning trap + cusp trap (possible source of polarized antiydrogen beam)	Cusp trap being developed. Proton + electron test to be done in Japan in 2004-2005.	
	Auxiliary measurements	Collisional behavior of very low energy antiprotons	**RFQD** + gas/solid targets 100 eV beam extracted from Penning trap	Ready to start measurements in 2006. Potential “users” of the extracted beam	

difficulties with the 3-body calculations

- Reduce the experimental error bar by an order of magnitude
  - One of the two theoretical calculations turn may turn out to be wrong
- Urge theorists to work harder
- Try 2-body system(s)

at very low density, Stark rate is reduced





The first observation of cold, long-lived antiprotonic helium ions

- Change of the decay slope of the laser "spike" is due to the prolongation of antiprotonic helium ION lifetime (Stark rate is reduced)

Laser spectroscopy of antiprotonic helium ions

- Antiprotonic helium ion:
  - Almost pure classical Bohr atom. No relativistic correction, no QED, no strong interaction, no hyperfine; practically no theoretical error
  - Already cold (guaranteed to be thermalized to <10 K - parent is a thermalized 3-body atom)
  - In a well-defined circular orbit (n, l) = (N, N-1)
  - Lifetime long enough for laser spectroscopy

plan was to try this already in 2004
but had to be deferred due to PS-AD failures

Physics Goals	Measurements		Method	Status & Outlook	
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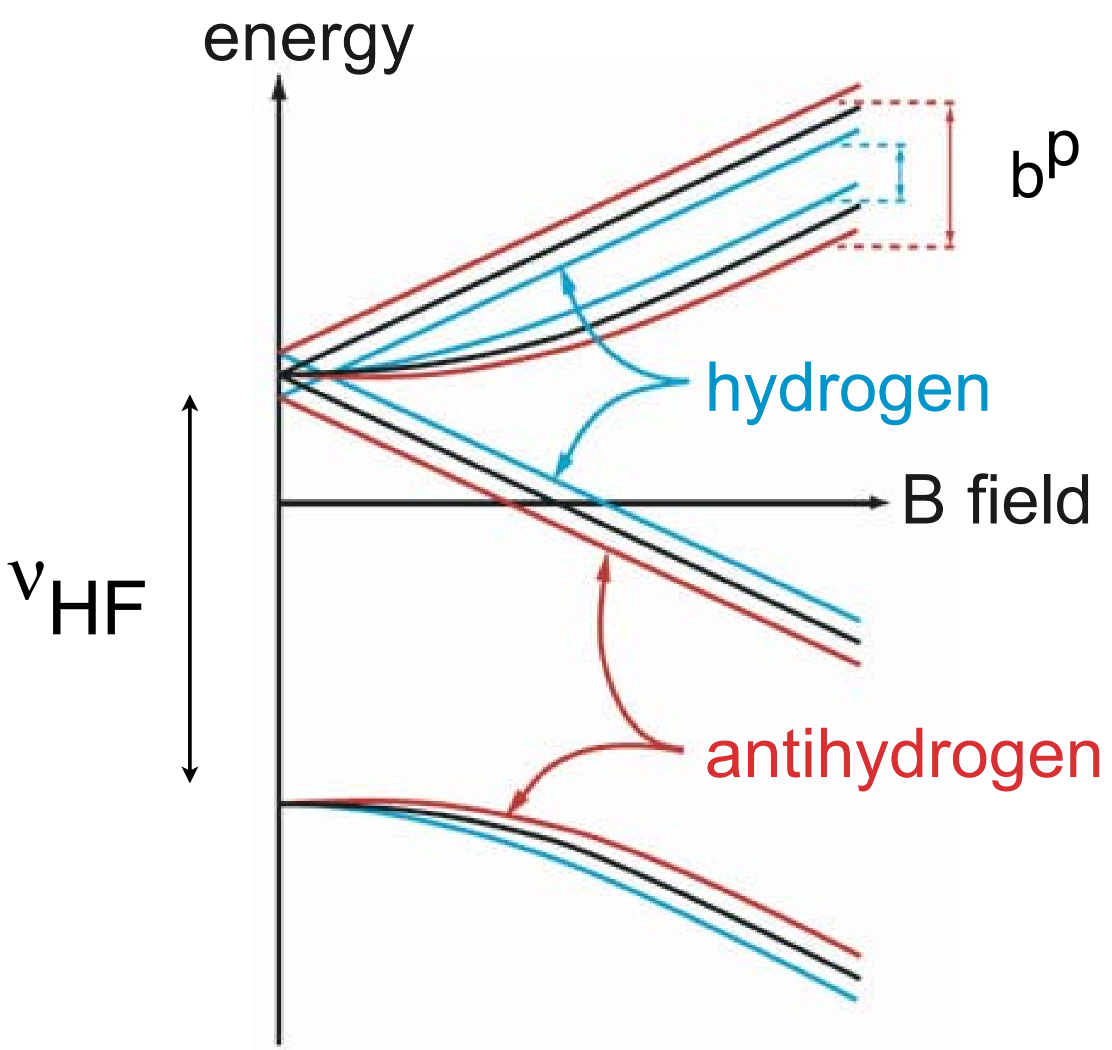
Why yet another antihydrogen experiment?

	GSHFS	1s-2s
method	beam + microwave	atom trapping + 2-photon transition
sensitivity to CPTV	can directly probe "b"	in free H, no CPTV sensitivity

$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu$$
$$- \tfrac{1}{2} H^e_{\mu\nu} \sigma^{\mu\nu} + i c^e_{\mu\nu} \gamma^\mu D^\nu + i d^e_{\mu\nu} \gamma_5 \gamma^\mu D^\nu)\psi = 0 .$$

Breit-Rabi diagram



μ_p and R_M

GS-HFS

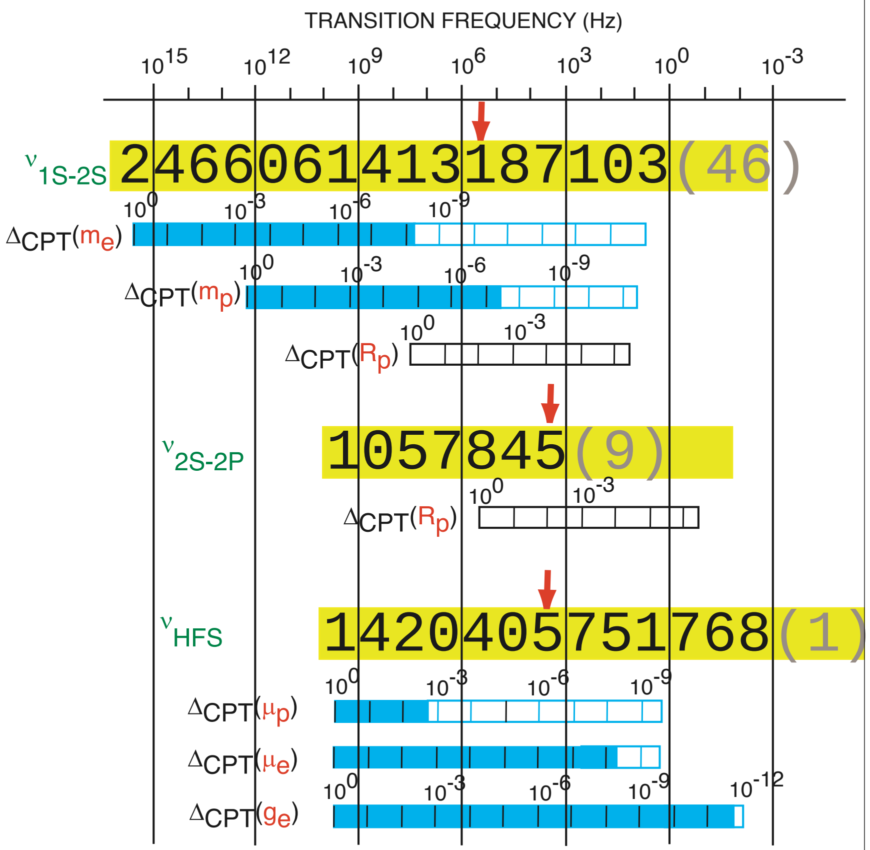
- Proton magnetic moment μ_p
- μ_e
- Proton magnetic radius R_M

Theory

- R_p and R_M

$$\nu_{HF} = \frac{16}{3}\left(\frac{M_p}{M_p+m_e}\right)^3 \frac{m_e}{M_p}\frac{\mu_p}{\mu_N}\alpha^2 Ry$$

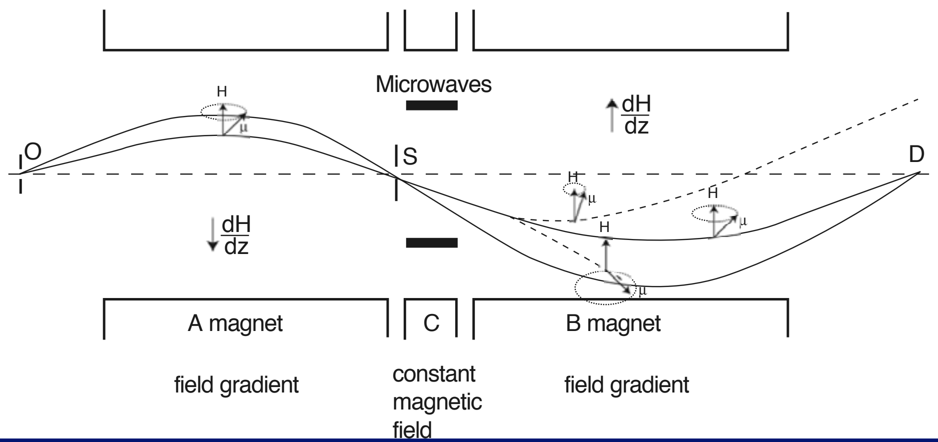
$$\Delta\nu(\text{Zemach}) = \nu_F \frac{2Z\alpha m_e}{\pi^2}\int\frac{d^3p}{p^4}\left[\frac{G_E(p^2)G_M(p^2)}{1+\kappa}-1\right]$$



History of Hydrogen HFS

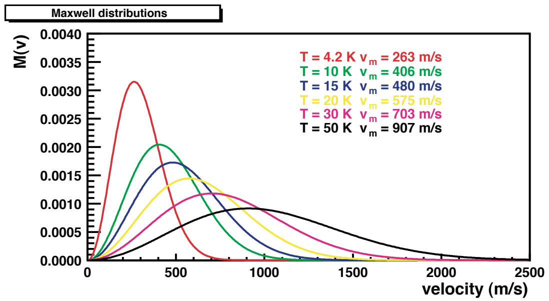
1936	Simple atomic beams	~ 5 %	
1947	Atomic beams plus microwave resonance	4×10^{-6}	discovery of **anomalous magnetic moment** of e^-
1950		4×10^{-8}	
1960-70	Hydrogen maser	6×10^{-13}	**not possible for antimatter**

Molecular Beam Resonance Setup, I.I. Rabi et al., Phys. Rev. 55, 526 (1923)



N.B. HFS spectroscopy of trapped antihydrogen does not necessarily lead to high precision due to the inhomogeneous magnetic field inside the trap

focus - resonate - analyze

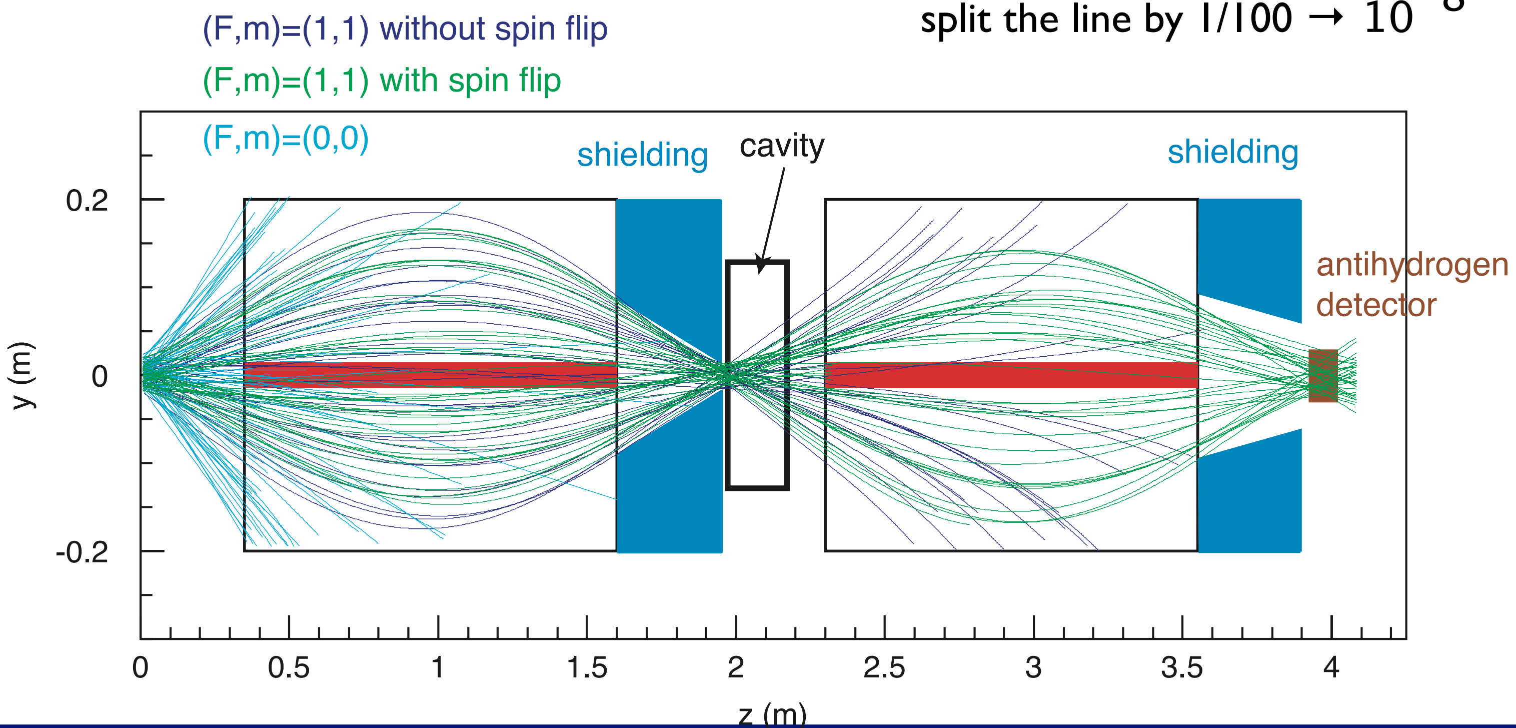


Assumed: 15 K source, 1.2T on the pole

Acceptance is 10^{-4}

Resonance curve width ~ 2 kHz, 2 ppm

split the line by 1/100 → 10^{-8}



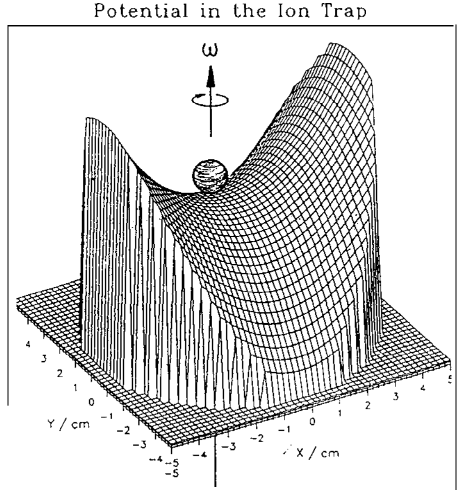
How to make a point source

- atomic-beam geometry works best if the source is point like
- antihydrogen source size prodcued in nested Penning trap ~ $1cm^3$ - too large
- limited access (optical & extraction)
- why not some other methods?

RF (Paul) Trap

- High-frequency RF (Paul) trap
  - Paul traps used for high-precision atom studies, but not usually to store a large number of particles
  - Try to catch, cool, and store a large number of protons, electrons, antiprotons, positrons in Paul traps
  - Needs high frequency, high field, use superconducting technology

Potential in the Ion Trap



Linear Paul trap, Q-mass, RFQD

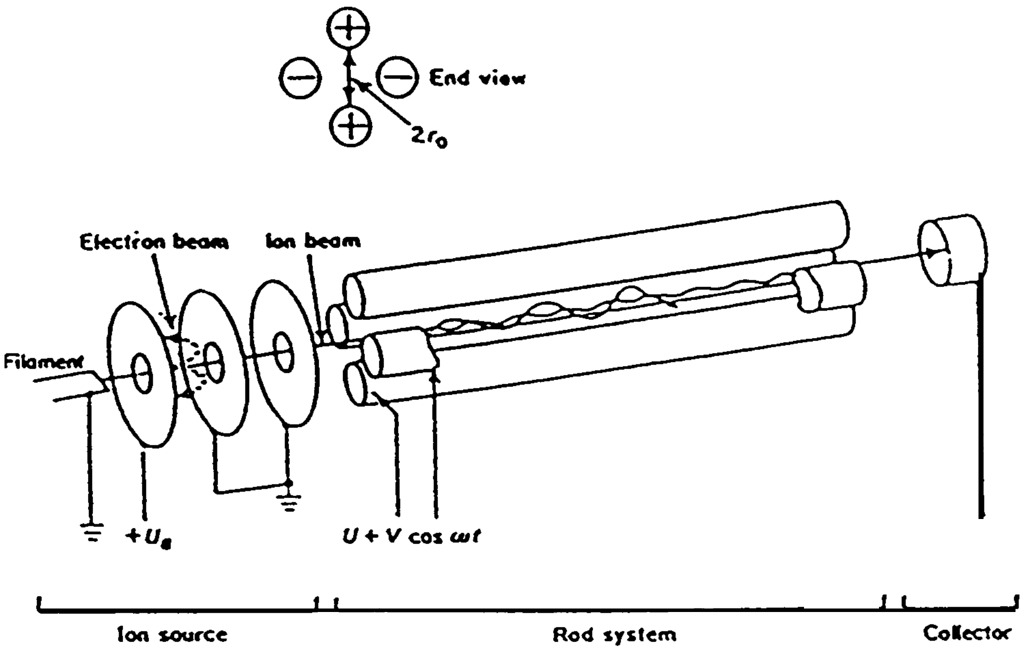
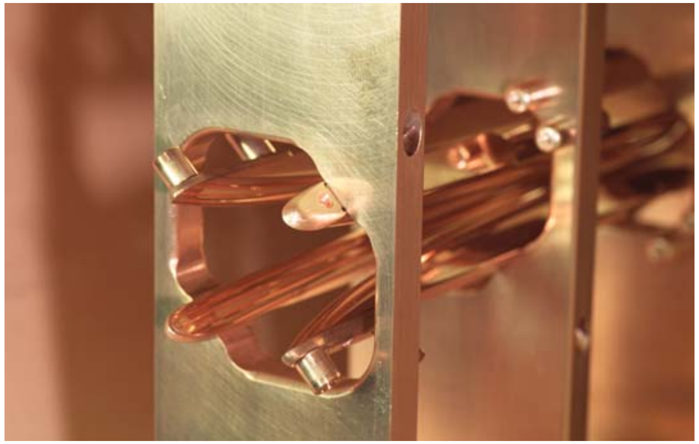


Figure 4. Schematic view of the quadrupole mass spectrometer or mass filter.



why not apply the RFQD technology to antimatter trapping?

Particle cooling in the trap is the key

- RFQD has no beam cooling
- No magnetic field → synchrotron cooling is not effective
- We use resistive cooling (dump energy in an external register)
- This requires careful optimization of the cavity L & C

Cooling considerations

≡ Resistive cooling damps the center-of-motion of the particle cloud.
✳Effectively damps the secular and micro-motions simultaneously.
✳Diminishes the particle excursion = size of the cloud.

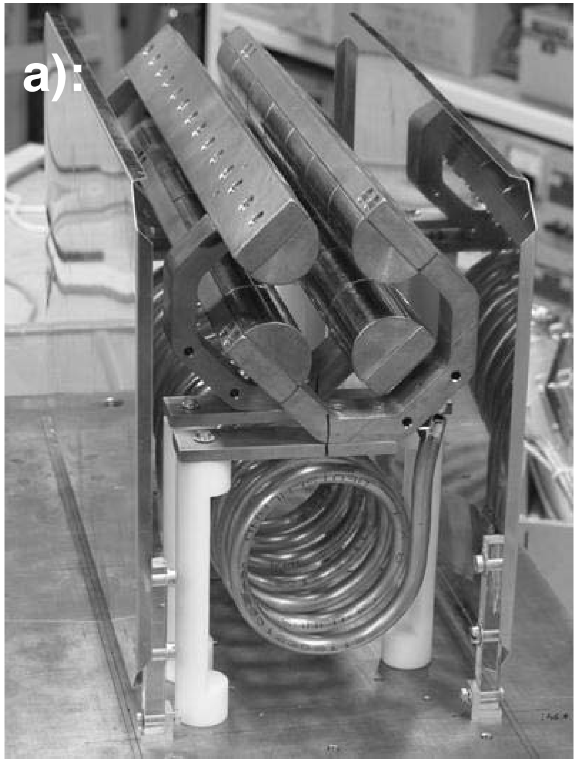
≡ Speed of cooling is independent of particle number.
Inversely proportional to C and d.
Inversely proportional to the square root of the Pseudopotential.

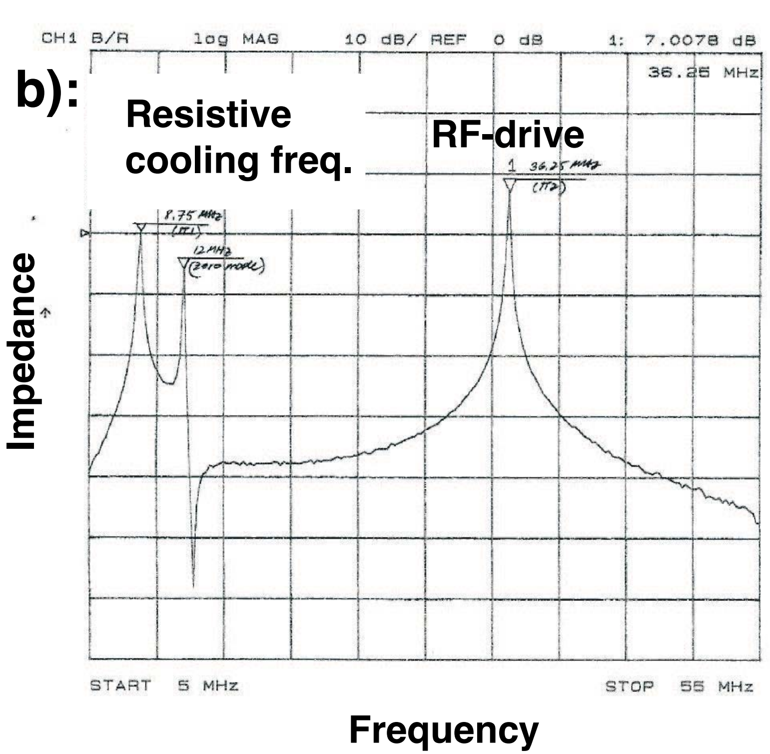
$$\tau_{\text{cool}} = g\frac{8\sqrt{2}mr_0^2\omega(1+s)^2C_{\text{elec}}}{q(1-s)^2Q} = \frac{16\sqrt{2me\Theta}r_0(1+s)^2C_{\text{elec}}}{q^2(1-s)^2Q}.$$

≡ Resistive cooling stops when space-charge effects become dominant (the bottom of the harmonic potential becomes flat) and the particles do not move with a definite "secular frequency" any more.
✳ They begin to move chaotically, like the particles in a gas.
✳ The edges of this gas cloud is heated by the radiofrequency.
✳ Particles near the cloud center are Debye-screened from RF.
✳ The heating strength depends on the distance from the trap center.
✳ The size of the cloud = surface temperature depends on N.

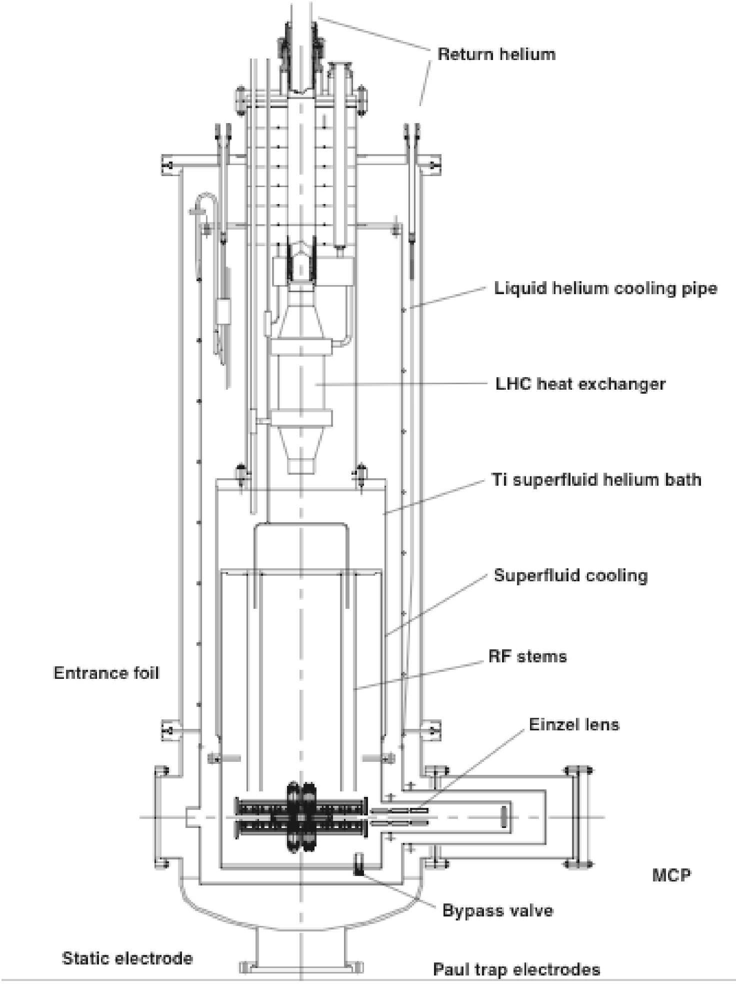
$$T = \frac{1}{k_B}\left(\frac{9meN^2(2\omega_r^2+\omega_z^2)}{128\pi^2}\right)^{1/3} \qquad \lambda = \sqrt{\frac{k_BT}{m(2\omega_r^2+\omega_z^2)}}.$$

Paul trap R&D in progress



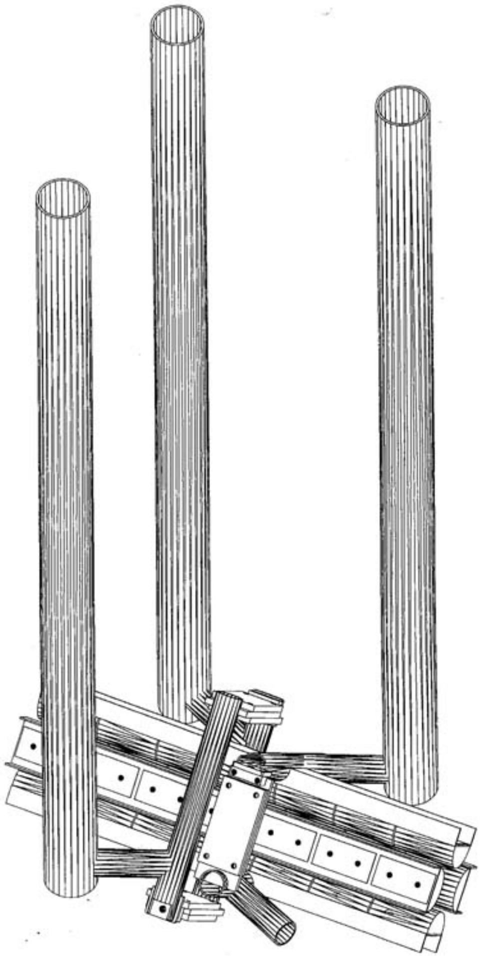


Superconducting Linear Paul Trap



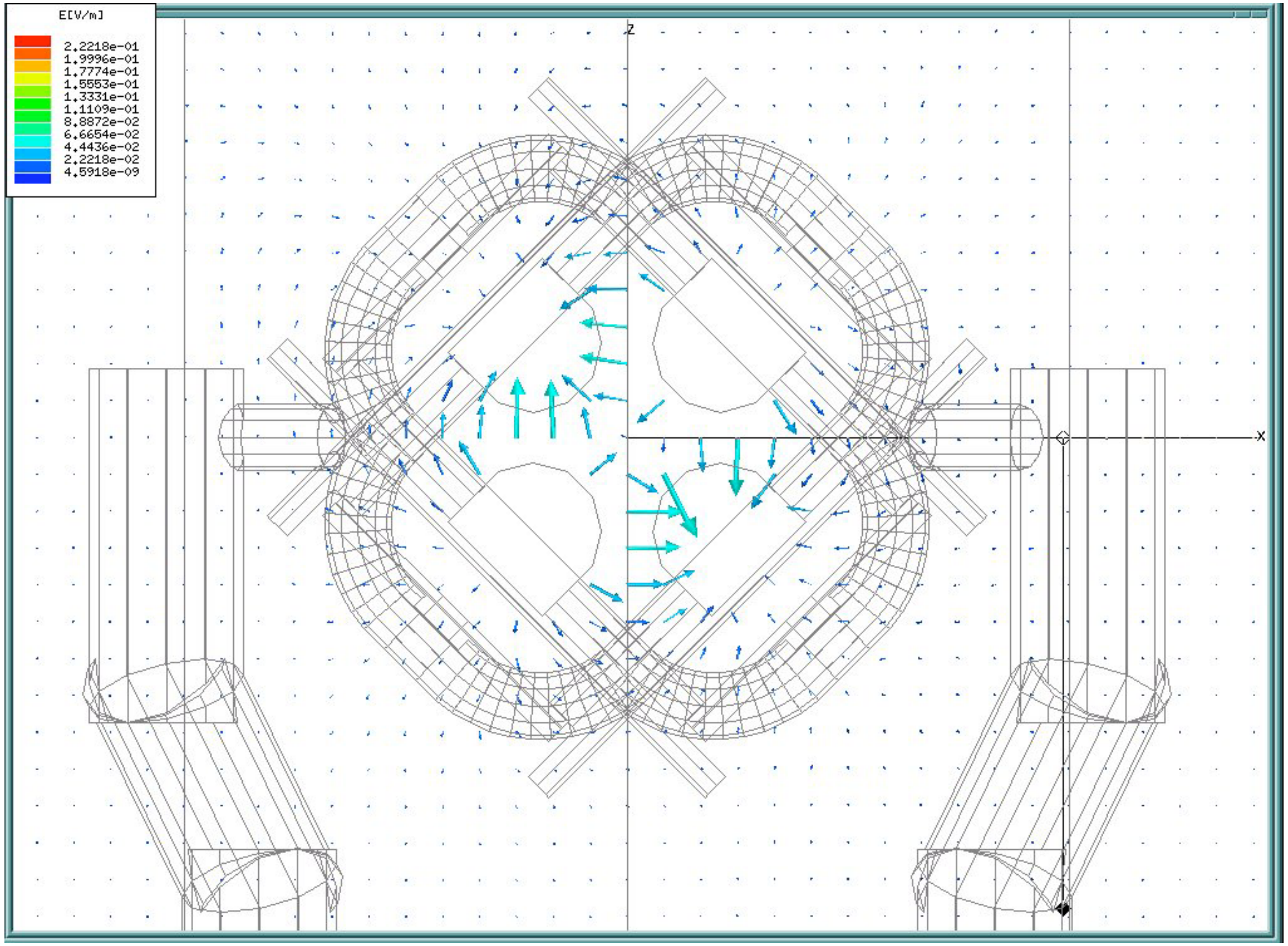
- Engineering Drawing being completed
- This model will be tested using protons
- Cooling to superfluid 1.6 K to avoid microphonics (no bubbles).
- Inductive RF feedthrough (3cm diam, center cooled).
- Two pickups to observe quadrupole and dipole resonances.
- 0.7 micron-thick biaxially-oriented monomar entrance window.

Some specifications

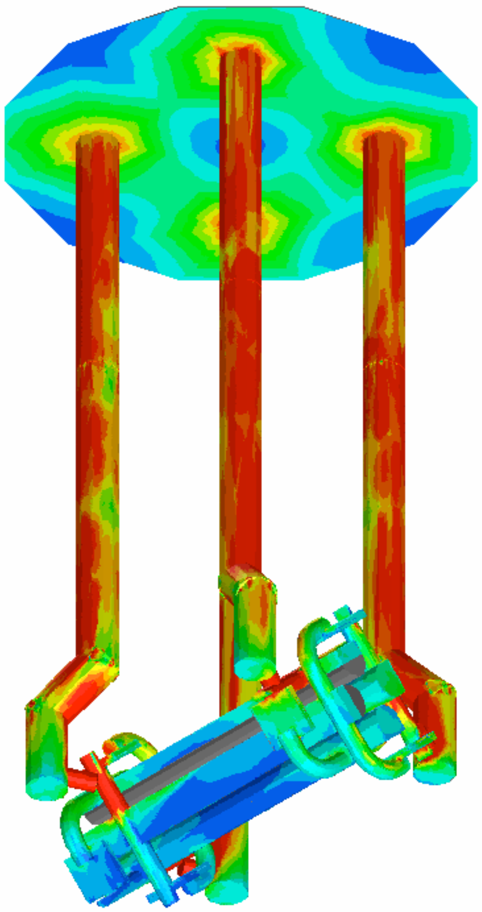


Radius:	3 cm
Length:	15 cm
RF drive:	30 MHz
Fluctuations:	+/- 10 kHz
Maximum voltage:	60 kV
Electrode capacitance:	15 pF
Dipole cooling capacitance:	300 pF
End ring electrodes voltage:	6 kV
Pseudopotential:	4.5 kV
q-value:	0.85
Secular frequency:	11.4 MHz
(Anti)protons trapped:	1 million per shot?
(Anti)proton density:	4 million / mm^3
Cloud diameter:	40 micron
RF heating at surface:	200 K
Q-value of cooling:	10^5
Cooling time constant:	10 seconds

Detailed RF simulations done



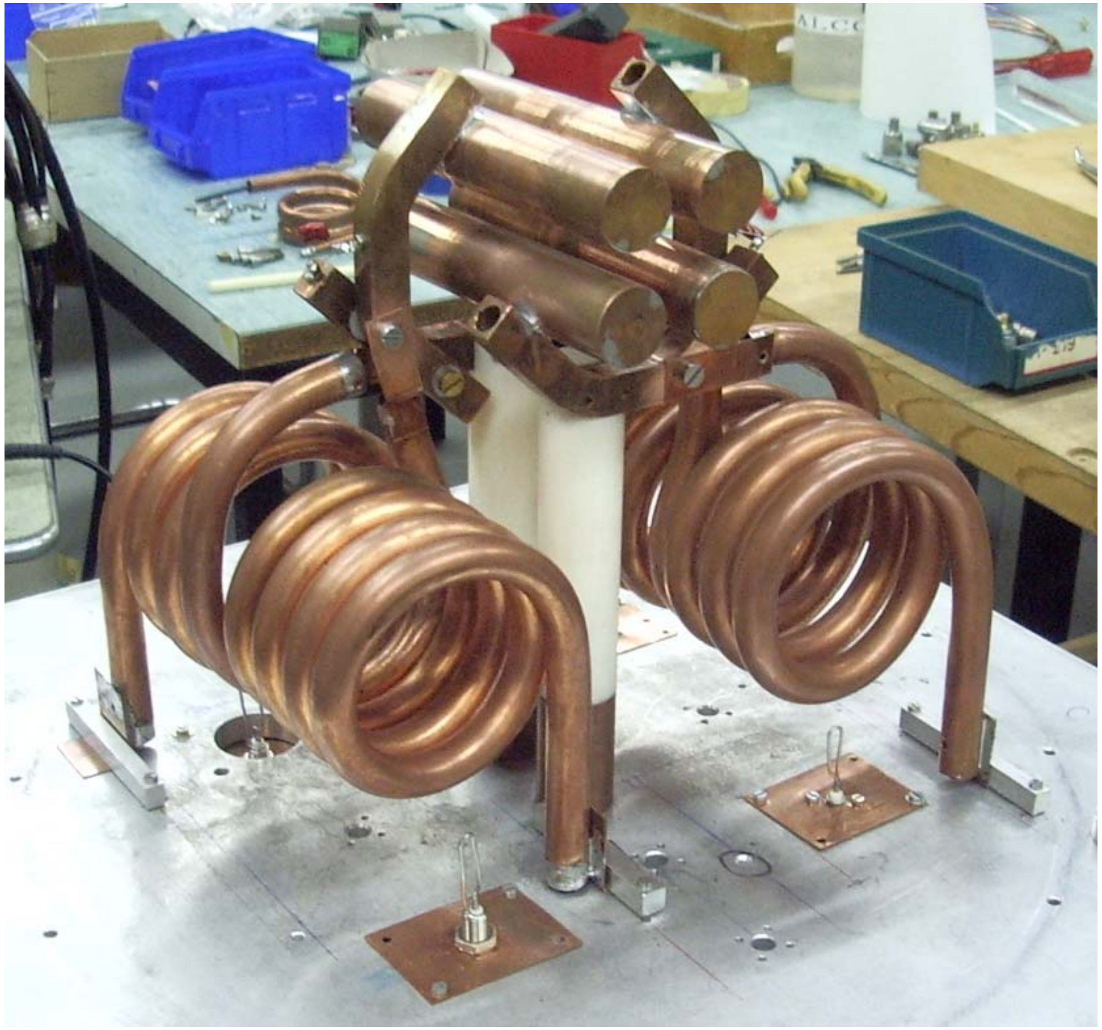
Cooling (cryogenic) calculations



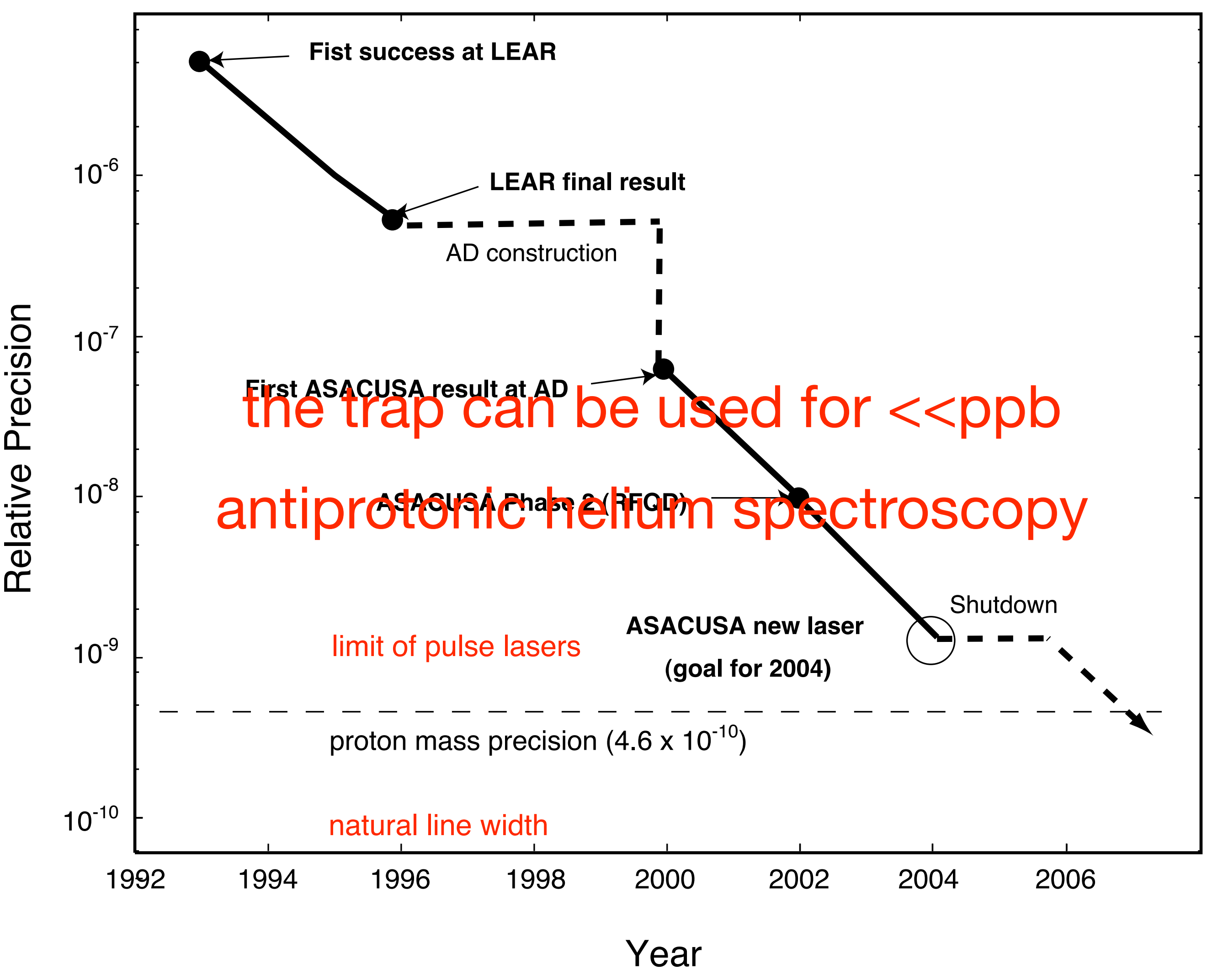
- Cool by flowing superfluid helium through stems.
- Simulation shows 0.5-1 W heat dissipation per stem.

Copper model (version 3)

Copper model version 5



Larger L (inductance) required for efficient resistive cooling - now use coils (but must reduce microphonics)



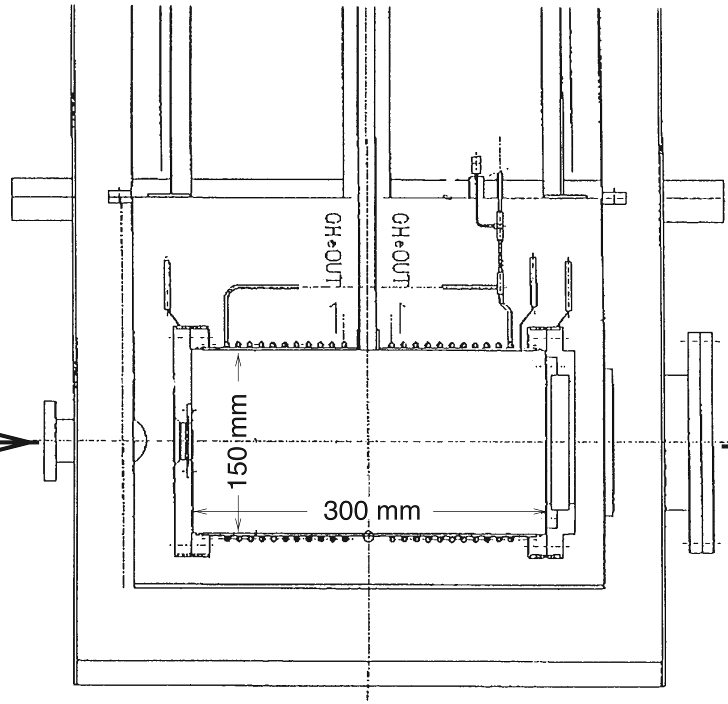
Fist success at LEAR
LEAR final result
AD construction
First ASACUSA result at AD
ASACUSA Phase 2 (RFQD)
ASACUSA new laser
(goal for 2004)
Shutdown
limit of pulse lasers
proton mass precision (4.6 x 10-10)
natural line width
Relative Precision
10-6
10-7
10-8
10-9
10-10
1992
1994
1996
1998
2000
2002
2004
2006
Year
the trap can be used for <<ppb
antiprotonic helium spectroscopy

to reach << ppb

- Eliminate Doppler width (~500 MHz) using two-photon transitions
- Eventually, the use of pulsed laser has to be abandoned (chirp < 1MHz is difficult)

pulsed laser is unavoidable now

Antiproton beam
from RFQD
90 keV
spread 10 keV,
100 π mm•mrad



Laser beam
5 mJ, 5ns pulse typical
expanded to d=50-100 mm
(i.e., 50-100 kW/cm^2)

Outer quartz window
d = 120 mm, t = 5 mm

1.5µm Mylar window

Inner quartz window
d = 100 mm, t = 15 mm

Helium gas target,
10 K, 1 Torr, typical

antiprotonic helium in a Paul trap

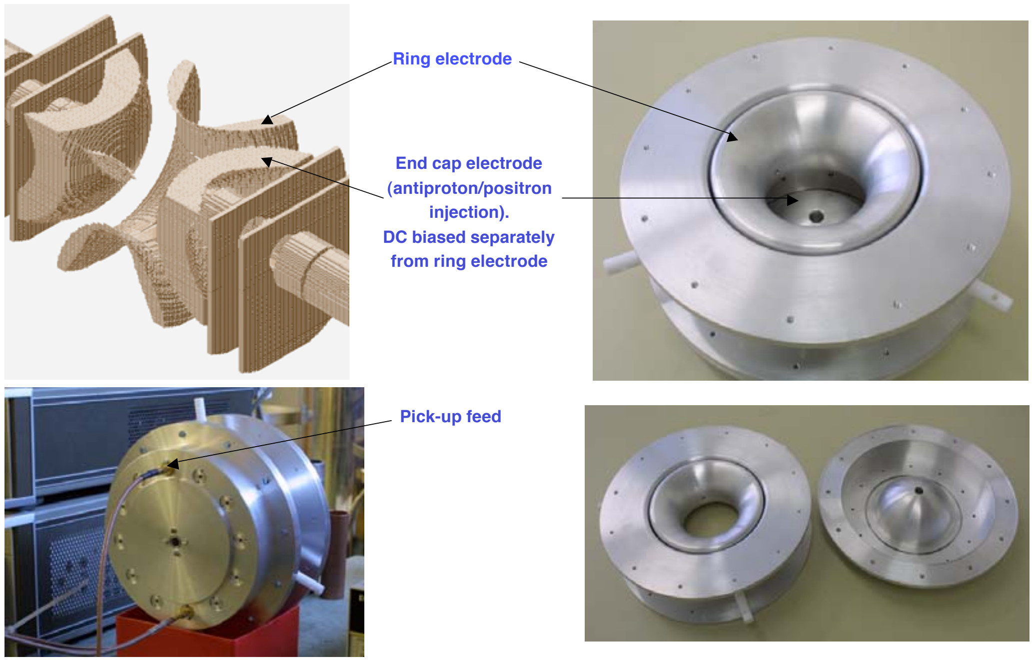
- with antiprotons compressed in the Paul trap (filled with dilute helium gas), antiprotonic helium atoms can be produced in a tiny volume
- then, CW-laser 2-photon spectroscopy will become possible
- natural line width ~ 160 kHz ~ 0.16 ppb, split the line by 1/100 → 10^{-12} will be possible

back to antihydrogen

how to make antihydrogen in a Paul trap?

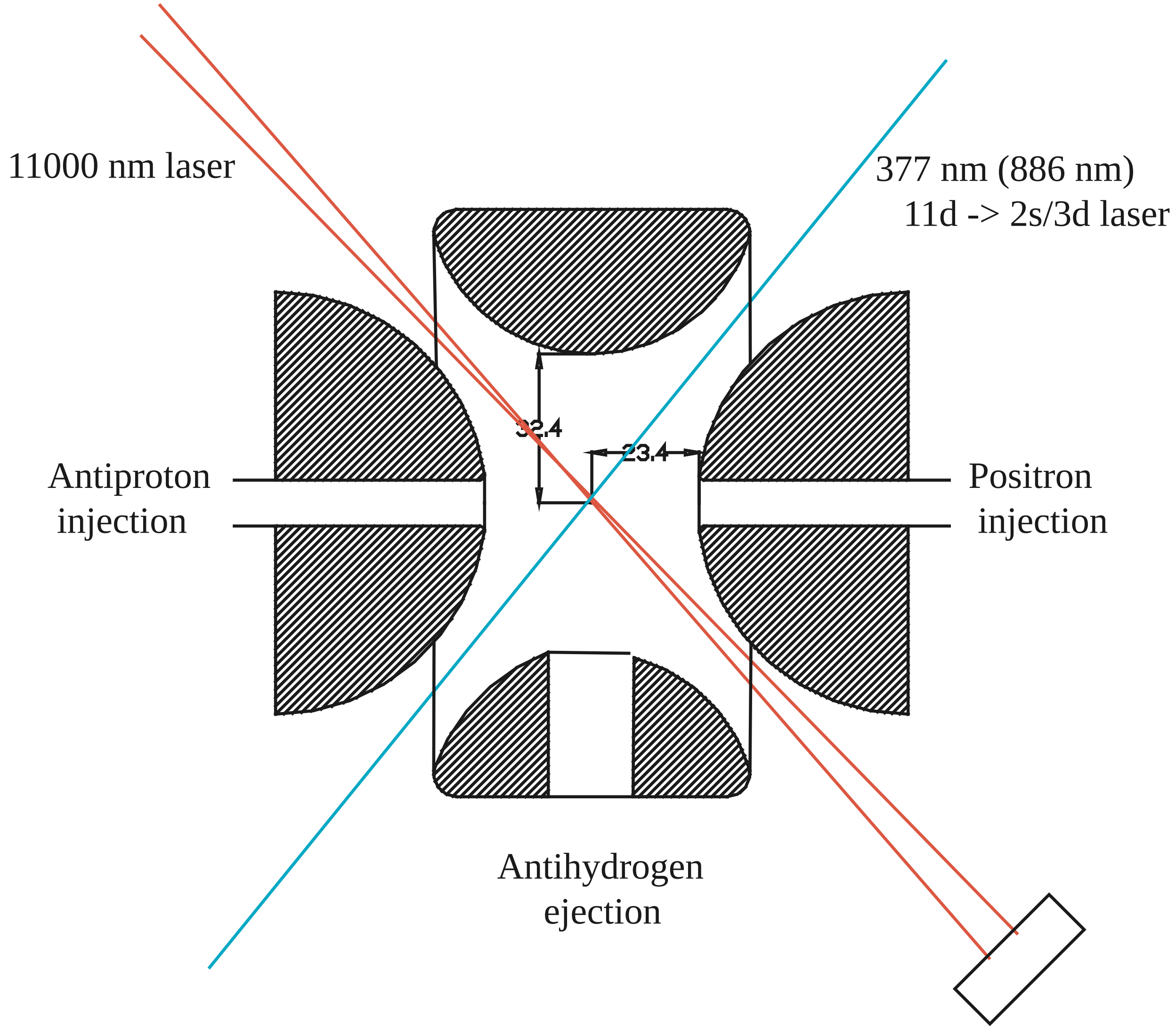
Innovative two-tone trap

Antihydrogen production trap

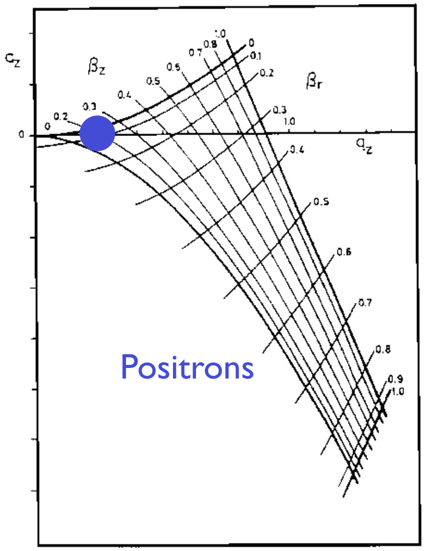


- **two-frequency trap (3GHz to confine positrons, 2MHz for antiprotons)**
- **RF characterization done, mechanical & cryogenic implications studied**

Two tone trap + laser

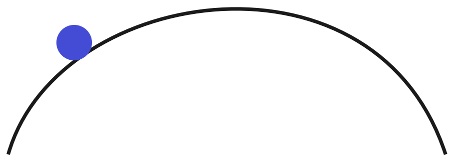


e^+ in the two-tone trap

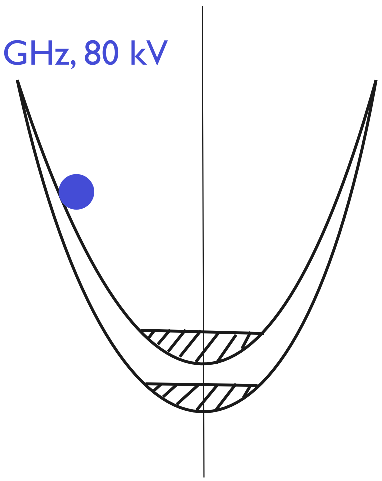


Positron q-value:	0.15
Positron oscillatory a-value:	+/- 1.7×10^{-4}
Positron pseudopotential:	2100-2200 V
Positron secular motions:	78+/-0.4, 156+/-0.5 MHz
Number of positrons trapped:	10000
Positron density:	5×10^{8} / cm^3
Positron cloud diameter:	300 micron
Temperature at cloud surface:	50 K

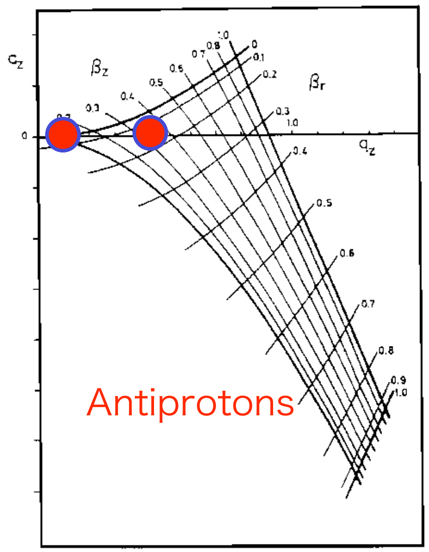
RF=1 MHz, 40 V



RF=3 GHz, 80 kV



Pbar in the 2-tone trap



Antiproton q-values: 0.37, $8\text{x}10^{-5}$

Antiproton pseudopotential: 3 V, 1.2 V

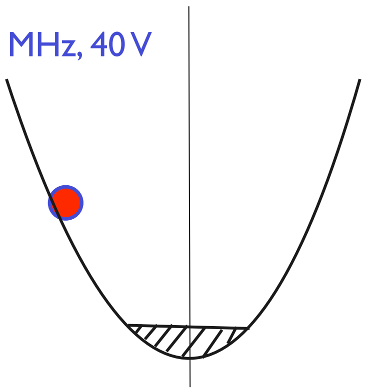
Number of antiprotons trapped: 10000

Antiproton density: $7\text{x}10^{5}$ / cm^{3}

Antiproton cloud diameter: 3 mm

Temperature at cloud surface: 50 K

RF=1 MHz, 40 V



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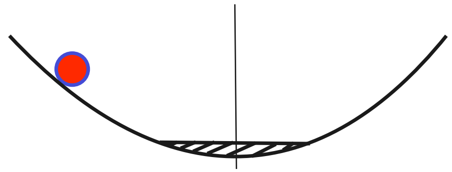
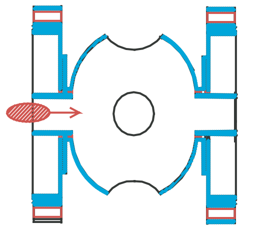
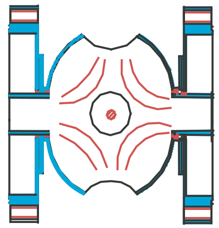


Antihydrogen production in the two-tone trap

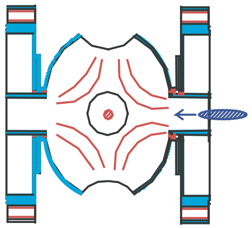
1): Antiproton injection



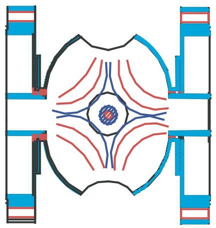
2): Antiproton trapping by 7 MHz RF field



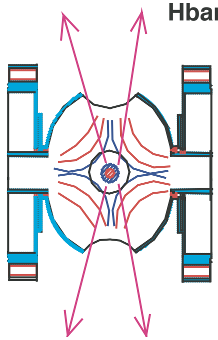
3): Positron injection



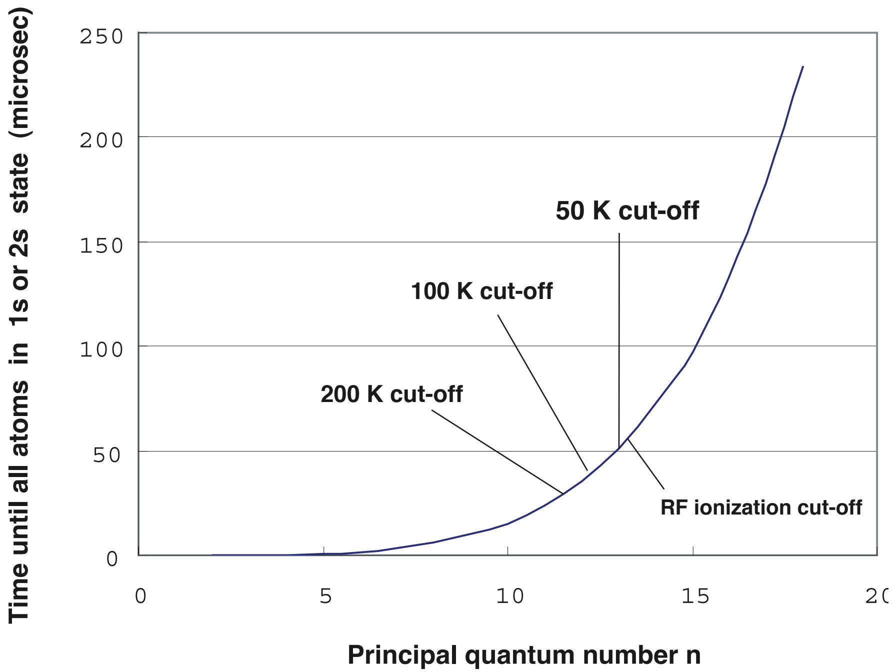
4): Positron trapping by 3 GHz RF field



Hbar beam

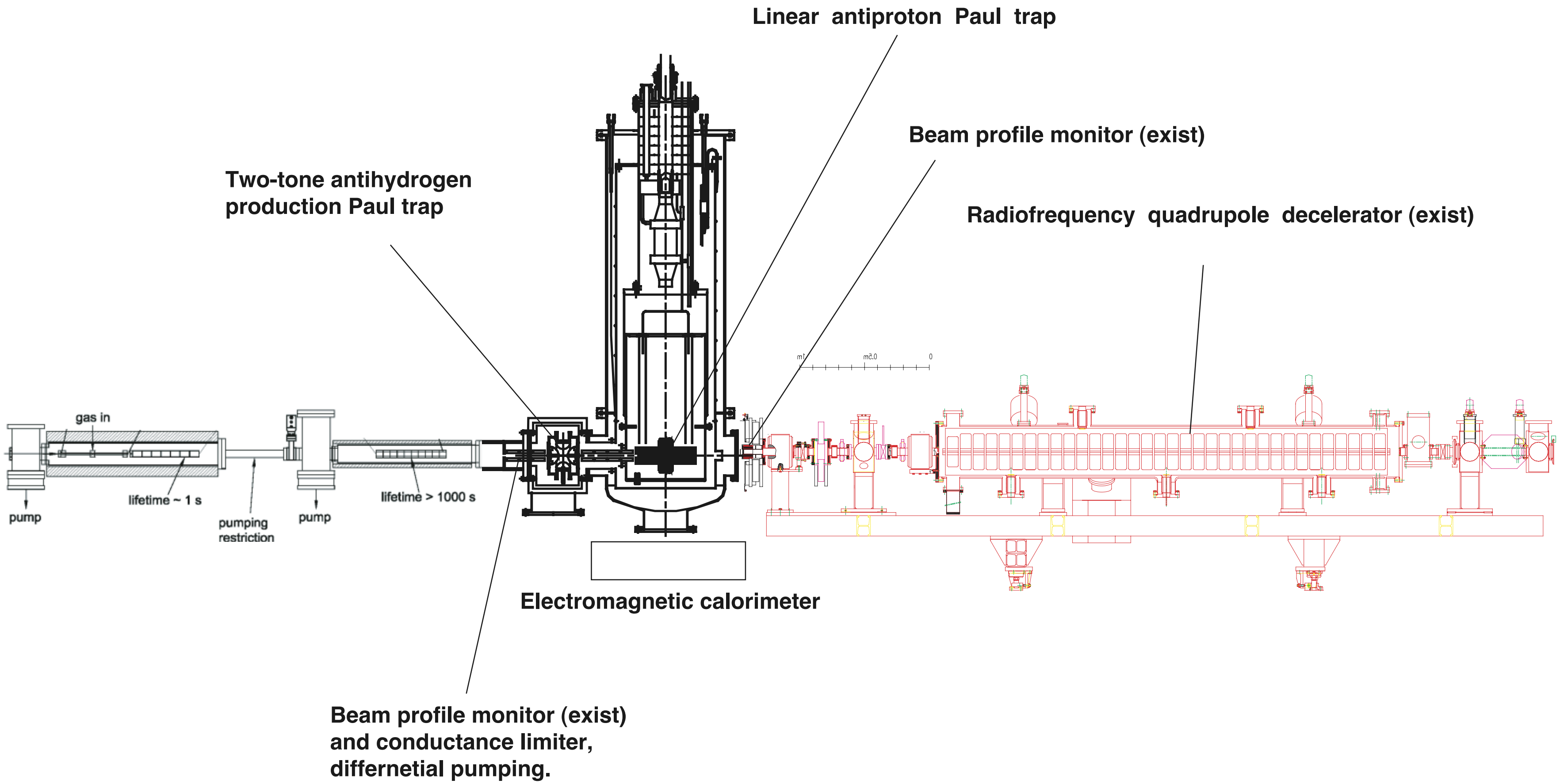


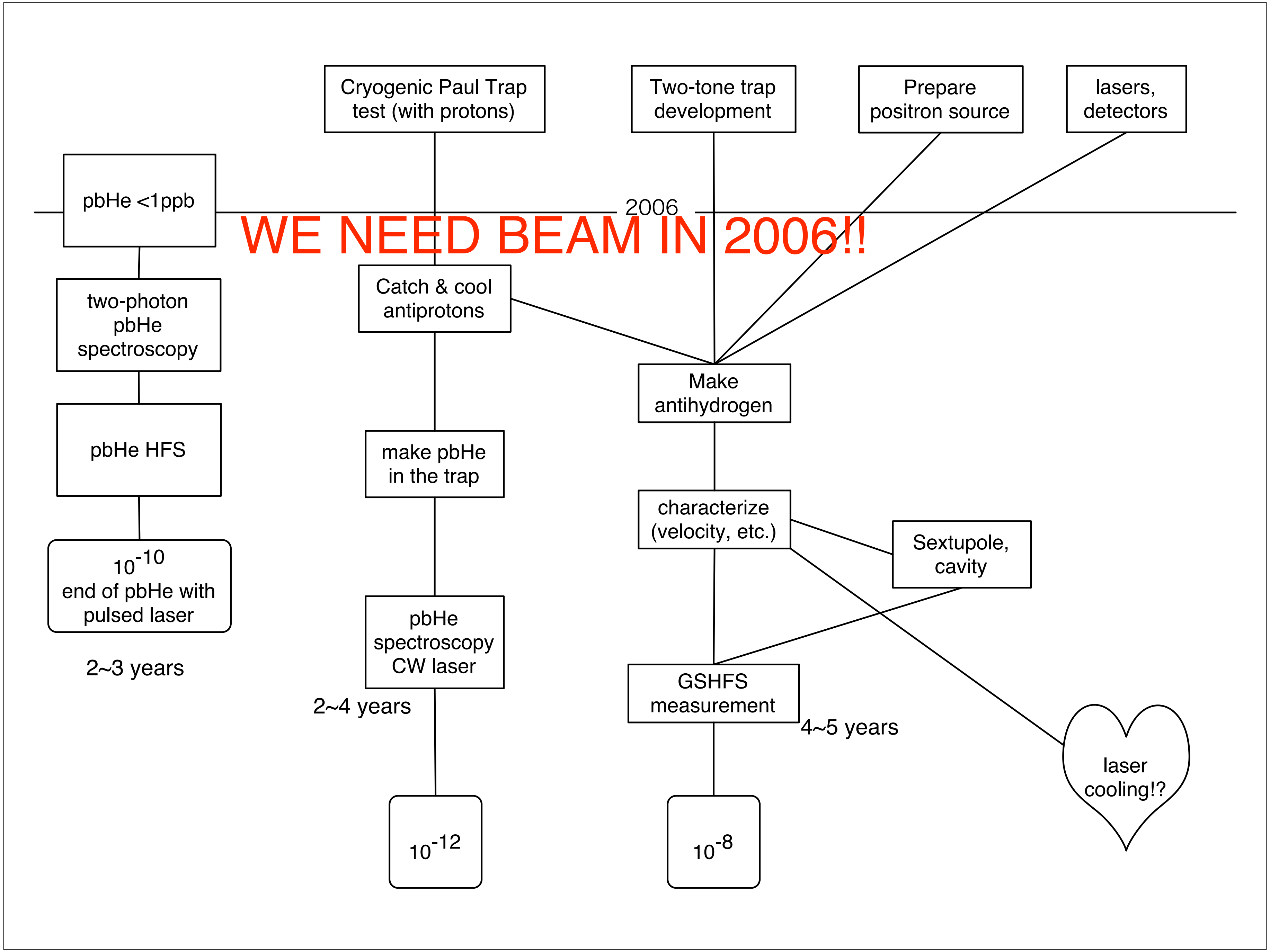
5): Antihydrogen production and extraction



Only ground-state (or 2s) antihydrogen are emitted

A possible setup





Cryogenic Paul Trap test (with protons)
Two-tone trap development
Prepare positron source
lasers, detectors
pbHe <1ppb
2006
WE NEED BEAM IN 2006!!
two-photon pbHe spectroscopy
Catch & cool antiprotons
Make antihydrogen
pbHe HFS
make pbHe in the trap
characterize (velocity, etc.)
Sextupole, cavity
10^{-10} end of pbHe with pulsed laser
pbHe spectroscopy CW laser
GSHFS measurement
2~3 years
2~4 years
4~5 years
laser cooling!?
10^{-12}
10^{-8}

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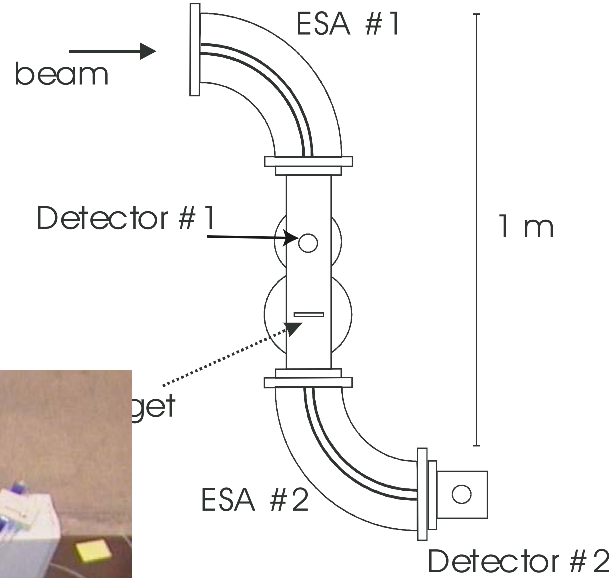
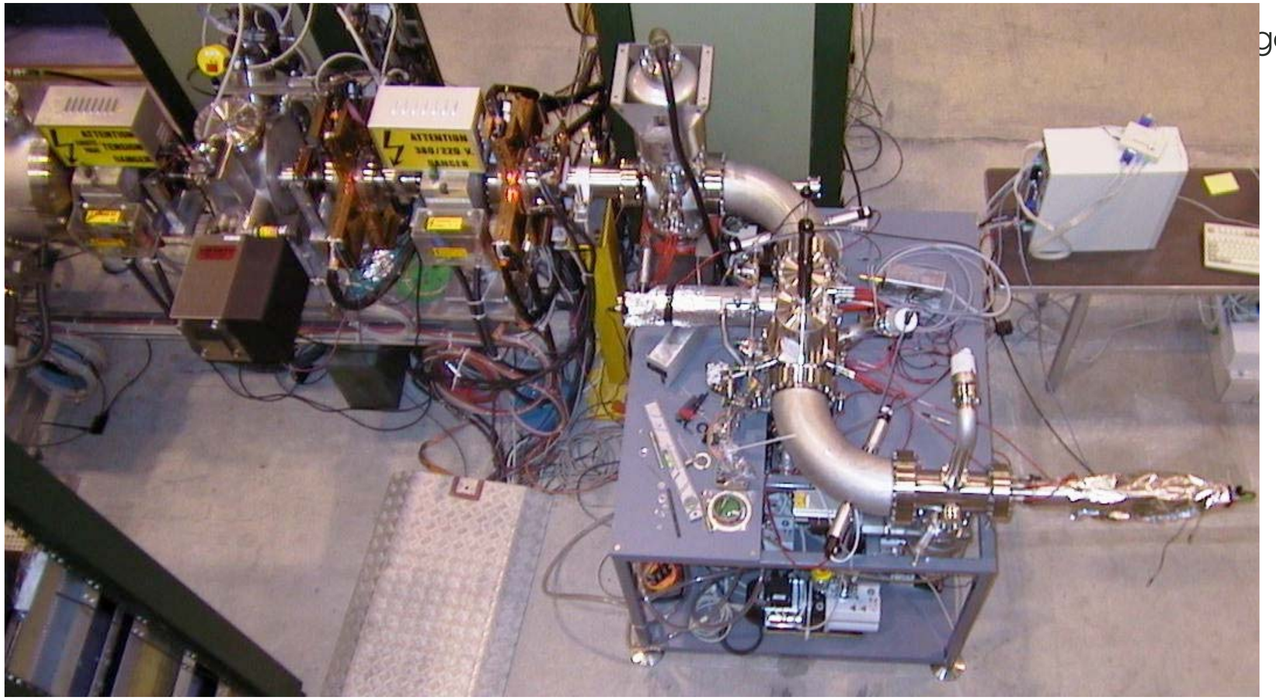
Potential “users” of the extracted beam</td></tr>
</table>

Antiproton dE/dx measured to ~ keV

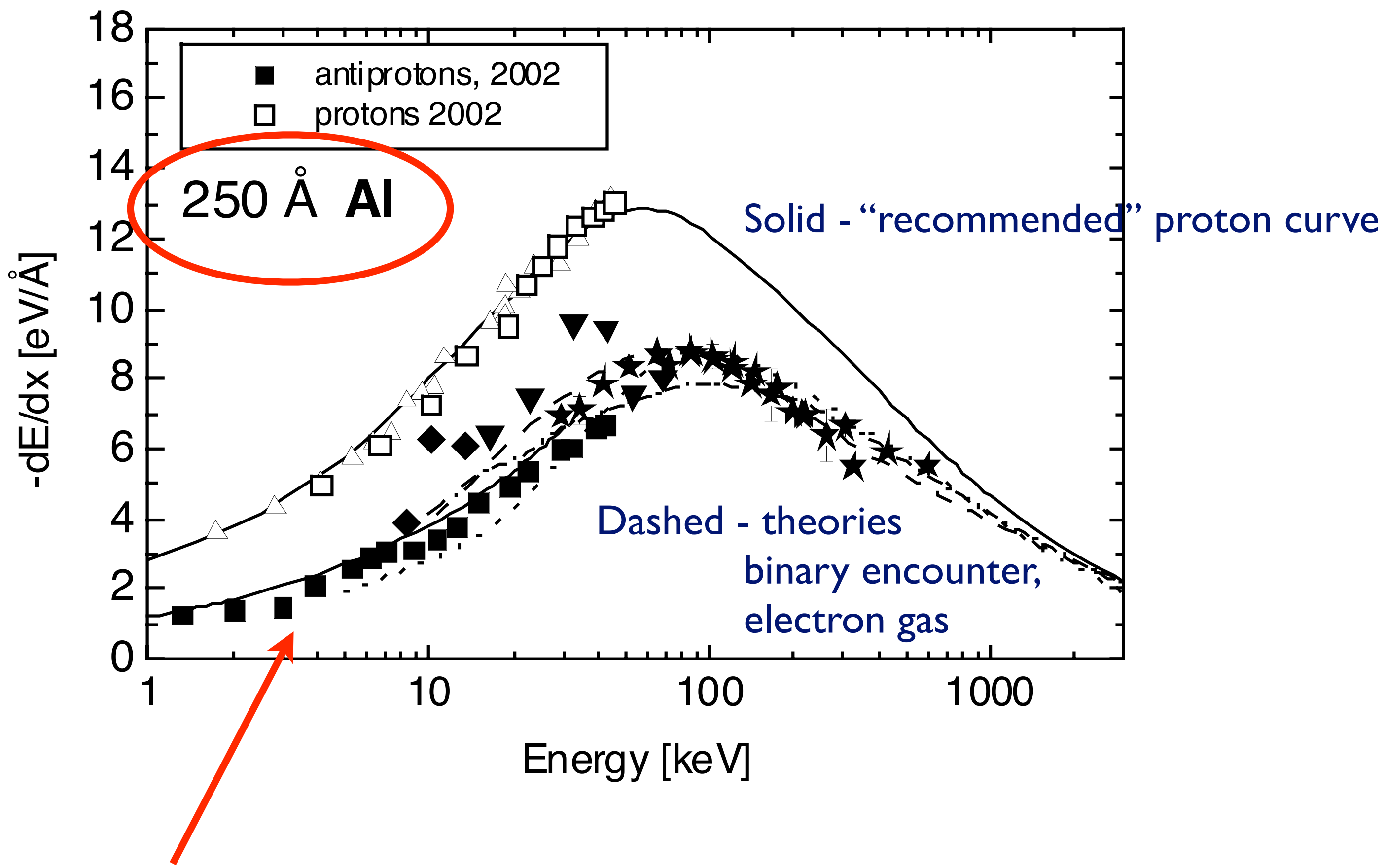
From RFQD





Electrostatic Analyzer (ESA)

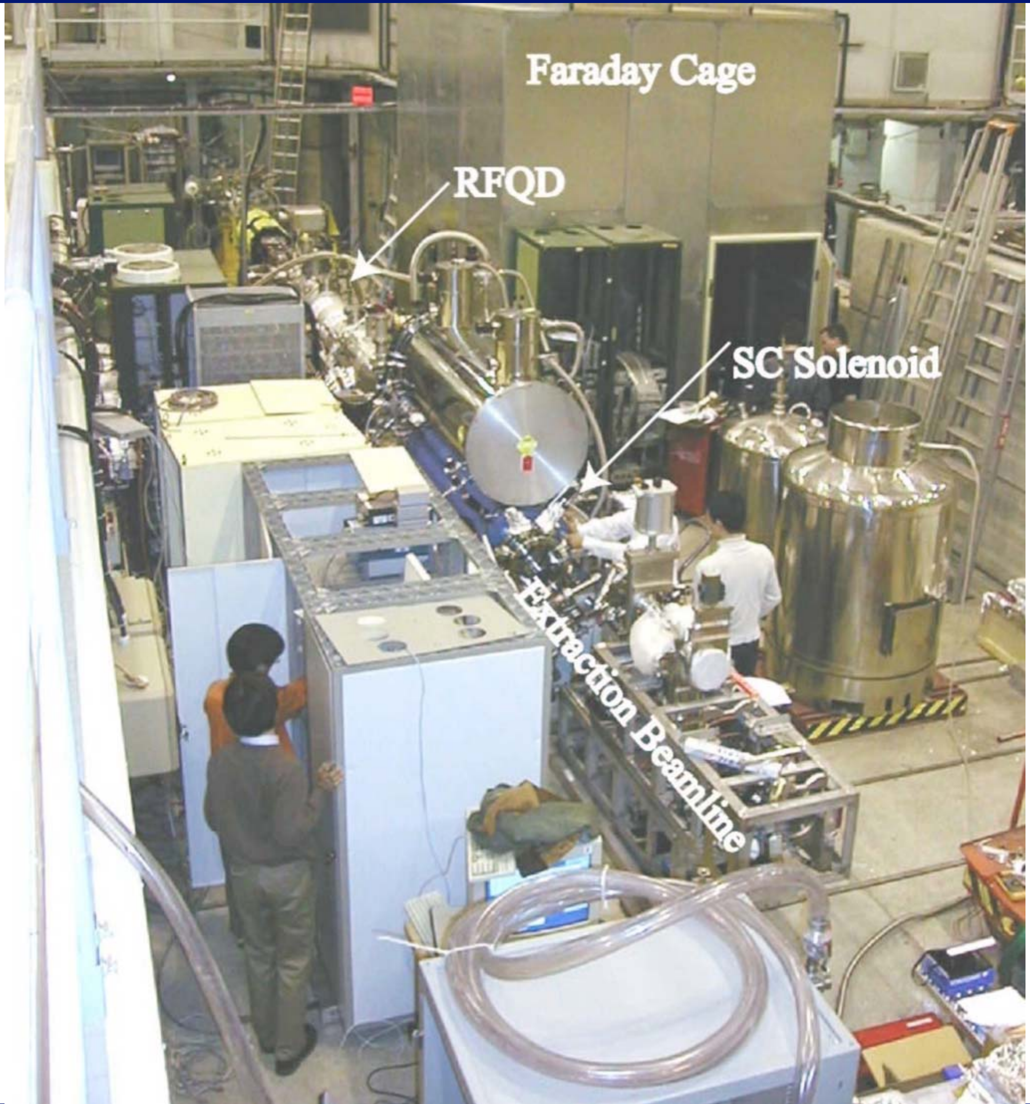
Antiproton dE/dx measured to ~ keV



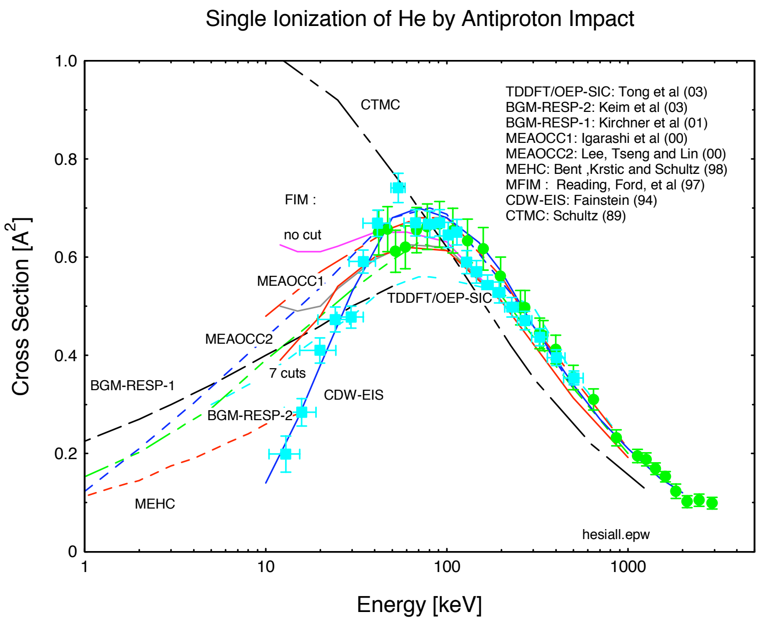
- Velocity proportionality at low energy (expected from electron gas model) evident in metal foils

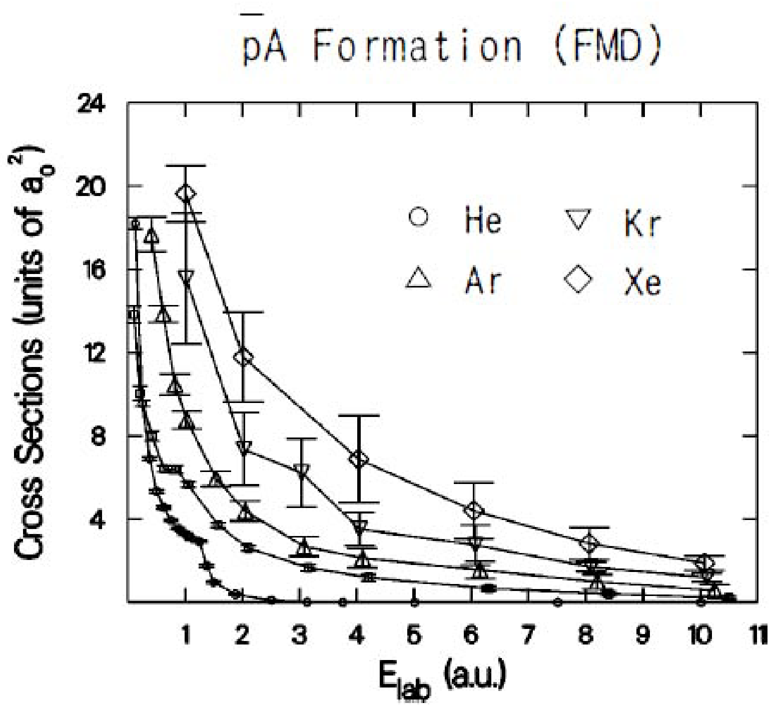
Phase 3 (use TRAP, <100 eV)

- Recently succeeded to extract a large number of antiprotons from the trap
- details by Y. Yamazaki



Ionization, antiprotonic atom formation





In the ASACUSA original proposal, but were deferred,
waiting for the phase-3 beam development

“phase 3 beam”

- some experiments planned for FLAIR (slow extraction) may already be explored at AD

Summary

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<tr><th>Physics Goals</th><th colspan="2">Measurements</th><th>Method</th><th colspan="2">Status & Outlook</th></tr>
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Physics Goals	Measurements		Method	Status & Outlook	
CPT tests: high-precision determination of antiproton mass, charge, magnetic moment and magnetic structure using various spectroscopic methods	**3-body system**	Antiprotonic helium **atom** laser & microwave spectroscopy	**RFQD**+low-density target	New high-precision laser system. Two-photon spectroscopy will enable ultimate accuracy.	Proton mass is known to 0.46 ppb. The goal is to measure antiproton mass to a similar precision.
	2-body systems	Antiprotonic helium **ion** laser spectroscopy	**RFQD**+low-density target	Free from theoretical ambiguities.	
		Antihydrogen ground-state **HFS** microwave spectroscopy	**RFQD** + Paul trap + Two-tone Paul trap (point source of cold antihydrogen)	Superconducting Paul traps being developed first Hbar production test in 2006.	The magnetic properties of antiproton poorly known. The goal is to compare the magnetic structure of proton and antiproton.
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ASACUSA has a comprehensive program
promising future