17 January 2017

ATRAP Progress

2016 Progress Report by the Antihydrogen TRAP Collaboration (ATRAP)

G. Gabrielse[1], C. Hamley, N. Jones, G. Khatri
K. Marable, M. Marshall, C. Meisenhelder, T. Morrison, E. Tardiff
Department of Physics, Harvard University, Cambridge, MA 02138 USA

M. George, E. Hessels, T. Skinner, C. Storry, M. Weel
Department of Physics and Astronomy, York University, Toronto, Ontario, M3J 1P3, Canada

S.A. Lee, C. Rasor, S.R. Ronald, D. Yost
Department of Physics, Colorado State University, Fort Collins, CI 80526 USA

W. Oelert[2], D. Grzonka, T. Sefzick
Institut für Kernphysik, Forschungszentrum Jülich, Germany

B. Glowacz, M. Zielinski
Institute of Physics, Jagiellonian University, Kraków, Poland

CERN-SPSC-2017-006 / SPSC-SR-204
17/01/2017

[1]spokesperson,gabrielse@physics.harvard.edu
[2]retired

Contents

A. Introduction and Overview

When we launched low energy antiproton and antihydrogen physics at CERN 29 years ago, there was great skepticism that antiprotons 10 orders of magnitude lower in energy than CERN had produced at LEAR could be achieved, that a single antiproton could be trapped and studied for months at a time, and that cold antihydrogen could be produced and trapped for precise spectroscopy. The skepticism was so great that we were initially only allocated 24 hours of beam time.

The skepticism dissipated and a community formed to join us in such experiments only after we completed many demonstrations and gave many lectures about the possibilities. We first demonstrated that antiprotons could be trapped and electron cooled. Exactly 27 years ago we demonstrated that antiprotons (even one at a time) could be kept and studied for months, until we deliberately released them from our trap. About 18 years ago we compared q/m for the antiproton and proton to better than a part in 10^{10} – a feat that was duplicated a couple of years ago. Because of the gravitational red shift, this measurement also demonstrated that the antiproton and proton experience a gravitational acceleration that is the same to within a part per million.

Before LEAR closed, we put antiprotons and positrons into a nested Penning trap – a device we invented for the purpose of creating antihydrogen atoms from trapped plasmas of antiprotons and positrons. Although we did not have the detection capability to demonstrate that antihydrogen formed in this first trial, we did demonstrate that the positrons and antiprotons were interacting in the nested Penning trap, just as was needed to for antihydrogen production. Essentially all the antihydrogen produced even today continues to be in this device.

At this point, even as it shut down LEAR, CERN was persuaded to facilitate the continuation of low energy antiproton and antihydrogen physics by constructing the AD. The collaborations represented now at the AD, or their precursors, were formed. Nearly three decades after we started low energy antiproton and antihydrogen physics, it is very rewarding to see that the low energy antiproton and antihydrogen community at CERN's AD is doing well, and that ELENA seems to be on track to substantially improve all of our scientific productivity.

As the community grew from a handful of us to upwards of 200 physicists, the challenge has grown for our small ATRAP team. While we have not returned to comparing the antiproton and proton q/m ratio for the last 18 years, we would have if we had enough people. We made the first precise comparison of the antiproton and proton magnetic moments a couple of years ago and have slowly been improving our apparatus and methods in pursuit of a much more precise comparison. Meanwhile, another collaboration has formed (with more members than ATRAP) just to improve on what we started.

Meanwhile, there are now several substantial collaborations, all larger than ours, competing on low energy antihydrogen experiments. Antihydrogen is being formed in a nested Penning trap by us and by several collaborations, and is being trapped in a superimposed Ioffe trap by us and antother collaboration, just as we proposed 29 years ago. Another collaboration is pursuing a variant of our demonstrated laser-controlled charge exchange method for producing antihydrogen – the only demonstrated alternative to the nested Pennig trap so far.

As an aside, we suggest to the collaboration that uses a nested Penning trap to produce antihydrogen to make a low energy antihydrogen beam, that they add a Ioffe trap to allow time for the atoms to decay to the ground state. Time varying magnetic fields could be superimposed to coax the trapped atoms out of the trap and into their beam. Or, it may be possible to design a Ioffe trap with a bias field that "leaks" trapped atoms into the beam.

There are now two goals for low energy antihydrogen experiments. The first is to compare antihydrogen and hydrogen at an interesting level of precision using precise laser or microwave spectroscopy to test the most fundamental symmetry of the Standard Model. What is an interesting level of precision? A reasonable requirement is that the comparison and test of this fundamental symmetry should exceed the precision of the sub parts in 10^{10} antiproton and proton q/m comparison that we made 18 years ago.

The second goal is to compare antihydrogen and hydrogen gravity at an interesting level of precision. What is an interesting level of precision? A reasonable requirement is that the comparison exceeds the ppm precision achieved using the graviational red shift of antiproton and proton clocks that was also made 18 years ago.

Given that high precison laser spectroscopy is ATRAP's goal for our trapped antihydrogen, we adopted the following strategy.

1. Our Ioffe trap would have side windows to allow the best possible laser cooling and spectroscopy of trapped antihydrogen atoms. So that all apparatus is as nonmagnetic as possible near where the trapped atoms intersect the laser light, titanium rather than stainless steel would be used. (The side-windows-through-a-Ioffe-trap requirement proved to be very challenging, finally being fully solved only in 2016.)

2. Before we tried any antihydrogen spectroscopy, we would first laser cool our trapped antihydrogen. Producing the required vacuum UV 121 nm light is much more challenging than 243 nm light that can be realized with commercial apparatus. However, we think that cooled atoms are needed to compare antihydrogen and hydrogen at an interesting level of precision.

3. We intend to introduce 243 nm light for 1s - 2s spectroscopy, available to us in a commercial system, only after we have demonstrated laser cooling.

To follow this strategy, ATRAP made essentially a complete apparatus change during the last couple of years. The objective was to move from an apparatus that could produce and trap antihdrogen to an apparatus which could serve as a platform for the laser cooling and the laser spectroscopy of trapped antihydrogen.

The second generation apparatus is larger to facilitate using larger plasmas of antiprotons and positron in the hope that this would help us make more than a few trapped antihydrogen atoms per trial. Our high-inductance, low-current, first generation Ioffe trap (that we used to demonstrated production of 5 trapped ground state antihydrogen atoms per trial) was replaced by a low-inductance, high-current, second generation Ioffe trap. This Ioffe trap also has both radial quadrupole and octupole windings.

Last year we reported that we had successfully enclosed this trap within a titanium enclosure and that we had successfully demonstrated its electrical properties. However, a "cold vacuum leak" had opened only at cryogenic temperatures and disappeared when the apparatus was warmed up to room temperature where we could do conventional vacuum leak checking.

We started 2017 looking for this leak – a very daunting and time consuming procedure given that it takes more than a week to cool the apparatus and more than a week to warm it up. We thought we had a candidate leak last year at this time, but we were never able to convincingly demonstrate any leak it turned out. We were able to show that the immediate vacuum enclosure of the Ioffe trap did not have a leak. The cold leak in the apparatus attached to the Ioffe trap went away only when we replaced essentally everything that attached to it – a tedious and time consuming task since most were custom fabricated of copper or titanium.

While the testing and repair of the vacuum system was underway, we took the opportunity to reconstruct our Penning traps to eliminate some deficiencies in the new way that trap electrodes and insulators had been fabricated and wired to increase the size and number of the electrodes. We also made a substantial improvement in the way that a large number of electrical leads were admitted into the trap vacuum enclosure (separate from the Ioffe trap vacuum).

Finally, we modified the way that positrons were introduced into the vacuum system for the trap. This was done to make it possible to increase the efficiency of the transfer of liquid helium from a storage dewar into the dewars of the trap apparatus.

In parallel, we continued work on the 121 nm laser light system and succeeded in sending this light through the trap apparatus when it was at cryogenic temperatures. We believe that we have about a 1 μW going through the cold trap – enough to cool trapped antihydrogen atoms – but we hope to shortly increase this available power.

The apparatus worked extremely well in the end. A lot of tuning was required, and some remains, given how different the apparatus was from what we had used before. An additional challenge was that none of the young folks at the controls of the experiment had done this before. Nonetheless, the stability of the apparatus and the progress that we were making was very satisfying. We were very sorry to have the beam time end when it did, and we are very much looking forward to the progress that we hope to make in 2017.

Most of the apparatus will stay intact for 2017 so we should be fully ready this year when antiprotons are first available. We are making some small tweaks. An unforeseen consequence of the positron path modification, not yet understood, was that positrons could only be loaded off the central axis of the Penning traps. This problem has yet to be understood and fixed. We also noted that our trap electrodes were heating when we passed 121 nm light through the trapped particles. This is not from the 121 nm light but from the lower light frequency used to do the 4 wave mixing. We plan to eliminate this shortly. In addition, because we hope to succeed in laser cooling trapped antihydrogen this year, we also plan to install our available 243 nm laser system for 1s-2s spectroscopy.

Our priorities for 2017 are

1. Use the new apparatus to try to increase the number of trapped antihydrogen per trial
2. Demonstrate 121 nm laser cooling of trapped antihydrogen
3. Do 1s-2s spectroscopy with the 121 nm cooling laser light
4. Do initial 1s-2s spectroscopy with 243 nm light

This is an ambitious list for one year of 8 hour shifts. It is not likely that we will reach interesting levels of precision during 2017 but we hope to make substantial progress on at least most of these goals.

Finally, although we made the first comparison of the antiproton and proton magnetic moments a couple of years ago, we have no new scientific progress to report. Most of our progress this year was on making antiproton loading more robust and upon improving the infrastructure of an experimental zone which has not before been used for a precision measurement. Magnetic field variations from the AD, and from neighbors who make changes in their magnetic fields without regard for the consequences of others, are and will be substantial challenges. Our trap began behaving strangely when only one particle is trapped and we were not able to tune this away despite a very determined effort to do so. Now we think that the problem may be related to what seems to be a deteriorating gold plating layer on the trap electrodes. We have not encountered this before. We hope to constuct and install an entirely new set of electrodes before taking antiprotons into this experiment in 2017. The goal of this experiment is to make a precise one-particle comparison of the antiproton and proton magnetic moments.

B. Review of Motivations

1. Tests of CPT Invariance

Whether reality is invariant under CPT transformations is fundamentally an experimental question. A primary motivation for this research program is to use precise laser spectroscopy to probe for tiny difference between antihydrogen ($\overline{\mathrm{H}}$) and hydrogen atoms, thereby providing the most sensitive tests of CPT invariance with baryons and leptons.

Experimental tests have made physicists abandon widely held but mistaken assumptions about fundamental symmetries – first that reality is invariant under P transformations and second that reality is invariant under CP transformations. The current assumption, that reality is invariant under CPT, is based in large part upon the success of quantum field theories (QFT) for which there is a CPT theorem if plausible assumptions (like causality, locality and Lorentz invariance) are made. Of course, this argument cannot be universal since gravity does not fit into a QFT.

String theory has no intrinsic CPT invariance except when taken to the limit of a quantum field theory. Theoretical investigations of possible CPT violations have thus been studied in the context of string theory [1, 2]. One widely used parametrization [3] considers standard model extensions that arise if Lorentz violations are not excluded, whether these originate in string theory or elsewhere. Quantitative comparisons of existing CPT tests and possible $\overline{\mathrm{H}}$ measurements [4] were provided.

A reasonable requirement for a CPT test with $\overline{\mathrm{H}}$ and H is that it eventually be more stringent than existing tests with leptons and baryons. Table 1 distinguishes the precision of the CPT test from the measurement precision since these can be very different. The most precise baryon CPT test is the 9×10^{-11} (90 ppt) comparison of the charge-to-mass ratios of the $\overline{\mathrm{p}}$ and p carried out as part of this research program [5]. For that measurement, as for proposed $\overline{\mathrm{H}}$ and H comparisons, the CPT test accuracy is the same as the measurement accuracy, so extremely precise measurements are required to probe CPT invariance at an interesting precision.

Table 1: Comparing the Precise CPT Tests for the Three Species of Particles

	CPT Test Accuracy	Measurement Accuracy	Enhancement Factor
Mesons ($K_0\bar{K}_0$)	2×10^{-18}	2×10^{-3}	10^{15}
Leptons (e^+e^-)	2×10^{-12}	2×10^{-9}	10^{3}
Baryons ($p\bar{p}$)	9×10^{-11}	9×10^{-11}	1

The most accurate direct tests of CPT invariance are represented in Table 1 and Figs. 1-2. The CPT tests with leptons and mesons involve free enhancement factors that make the precision of the CPT test substantially greater than the measurement precision. The most precise lepton CPT test is a 2×10^{-9} comparison of measured magnetic moment anomalies of electron and positron [6], interpreted as a comparison of magnetic moments at 2×10^{-12}. A single meson CPT test is even more precise [7]. The delicately balanced nature of the unique kaon system makes it possible to interpret a measurement precision of only 2×10^{-3} as a comparison of the masses of the K_0 and $\bar{K}_0$ to an astounding 2×10^{-18}. One theoretical suggestion [1] is that quantum gravity could produce a CPT violation which is smaller by about a factor of 10.

2. TRAP/ATRAP Carried Out the Most Precise Symmetry Tests Carried out at the CERN's LEAR and AD

The precise comparisons of antimatter and matter systems, to test the fundamental symmetries of the Standard Model, have been carried out by ATRAP at the AD, and by the TRAP team from

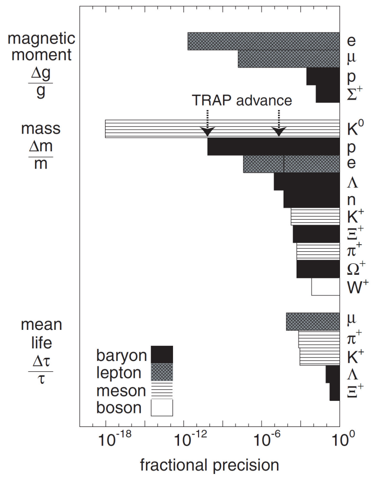

Figure 1: CPT Tests (primarily from the Particle Data Group compilation). Charge-to-mass ratio comparisons are included in "mass" measurements.

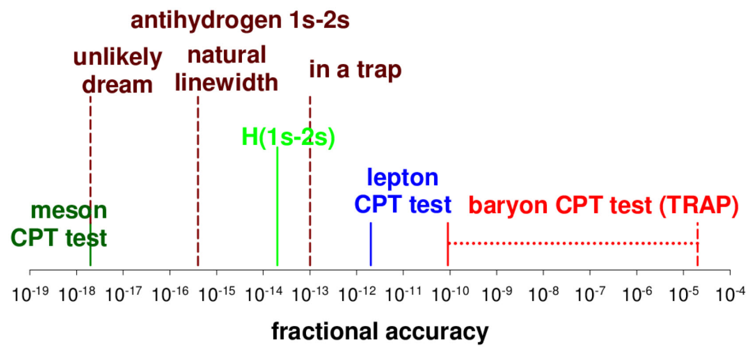

Figure 2: Relevant accuracies for the precise 1s - 2s spectroscopy of antihydrogen are compared to the most stringent tests of CPT invariance carried out with the three types of particles: mesons, leptons and baryons.

which it developed at LEAR.

1. The TRAP comparison of the charge-to-mass ratios of the antiproton and proton to 9 parts in 10^{11} is by far the most precise test of CPT invariance with a baryon system. (This measurement together with an ASACUSA measurement have been interpreted as much less precise and less direct comparisons of the charges and masses of these particles.) More details and the current status will be discussed in a following section.

2. Comparison of antiprotons and proton gravity to 1 part in 10^6 using the gravitational red shift. (This is 10^8 times more precise than a gravitational comparison reported recently at the AD.) More details and the current status will be discussed in a following section.

3. Comparison of the antiproton and proton magnetic moment to 5 parts in 10^6. More details and the current status will be discussed in a following section.

Since much of the focus at the AD is often upon comparisons of antihydrogen and hydrogen, it is worth noting that no scientifically interesting comparisons of antihydrogen and hydrogen have yet been carried out.

3. Antihydrogen Spectroscopy Offers the Prospect of Higher Accuracy CPT Test with Leptons and Baryons

In principle, the comparisons of $\overline{\mathrm{H}}$ and H could make possible a CPT test at the meson precision. The 1s-2s transition has an extremely narrow fractional linewidth of only 5×10^{-16}. With a measurement signal-to-noise ratio of 200, line splitting by this factor would allow a comparison at the kaon precision. There are serious obstacles to attaining this extremely high precision, however, including a small number of available anti-atoms, a 2.4 mK laser cooling limit, a second-order Doppler shift, and possible Zeeman shifts depending on the configuration of the magnetic trap. Nonetheless, even a measurement at an accuracy of 10^{-13}, the level at which the difficulties mentioned may be manageable in the first traps [8], would give a substantially improved CPT test involving leptons and baryons.

The most precise laser spectroscopy of hydrogen attained so far [9] was obtained with a hydrogen beam by a former group in this collaboration. The narrowest observed width is still much wider than the natural linewidth (Fig. 2) but we expect that steady and substantial improvements in accuracy will continue as they have been for many years. If such a narrow line were available for $\overline{\mathrm{H}}$ as well as H, the signal-to-noise ratio would be sufficient to allow the frequencies to be compared to at least 1 part in 10^{13}, a large increase in precision over the current tests involving baryons and leptons. The first use of cold trapped H for 1s-2s spectroscopy [10], in an environment similar in many respects to that we hope to arrange for $\overline{\mathrm{H}}$, comes very close to this linewidth, with substantial improvements expected if laser jitter had been reduced.

The ratio of the 1s-2s transition frequencies determine a ratio of Rydberg constants. In terms of other fundamental constants,

$$\frac{R_\infty(\bar{H})}{R_\infty(H)} = \frac{m[e^+]}{m[e^-]}\left(\frac{q[e^+]}{q[e^-]}\right)^2\left(\frac{q[\bar{p}]}{q[p]}\right)^2\frac{1+m[e^+]/M[\bar{p}]}{1+m[e^-]/M[p]}$$

(assuming the long range Coulomb interaction is the same for $\bar{H}$ and H). The only ratios on the right that have been measured accurately are the electron-to-proton mass ratio and the ratio of the electron and proton charges. This CPT test comparison thus clearly involves fundamental lepton and baryon constants but in a combination which makes it difficult to simply interpret the comparison as a measurement of the electron-to-positron mass ratio, or any other such simple ratio. The comparison of 1s-2s transition frequencies measured for $\overline{\mathrm{H}}$ and H would be a test of CPT invariance that involves the charges and masses of leptons and baryons at an unprecedented precision. Fig. 2 shows how the precision scales for $\overline{\mathrm{H}}$ 1s - 2s spectroscopy (mentioned above) compares favorably with that attained in existing CPT tests with leptons, mesons and baryons.

4. Gravitational Force on Antimatter

A second motivation for experiments which compare cold $\overline{\mathrm{H}}$ and H is the possibility to search for differences in the force of gravity upon antimatter and matter [11]. Making gravitational measurements with neutral $\overline{\mathrm{H}}$ certainly seems much more feasible than using charged $\overline{\mathrm{p}}$, for which the much stronger Coulomb force masks the weak gravitational force. Depending upon how cold is the antihydrogen we eventually achieve, it may be possible to measure the gravitational force on trapped $\overline{\mathrm{H}}$ [12], by adapting methods for measuring the free fall of cold atoms released from a trap [13], perhaps by ionizing H^- with a laser just above threshold, after first sympathetically cooling them to an extremely low temperature in an ion trap [14]. We are intrigued by the possibility of experimental comparisons of the force of gravity upon $\overline{\mathrm{H}}$ and H, and will pursue this direction when the techniques are sufficiently advanced to permit attaining an interesting level of precision.

However, it seems very unlikely that one can attain the precision that we at TRAP attained [15] in comparing the gravitational red shift of an antiproton cyclotron clock with a proton clock [16]. This comparison showed that gravity is the same for a proton and antiproton to 1 part in 10^6.

C. ATRAP Status and Goals

1. ATRAP History and Methods

Especially for the sake of new members to the SPSC, we note that the basic antiproton methods now used by all antihydrogen and antiproton collaborations were developed by the TRAP collaboration which evolved into ATRAP. Antiprotons were slowed in matter and trapped with the sudden application of a potential [17]. The antiprotons were then cooled with electrons to produce antiproton energies about 10^{10} times lower than had previously been produced. Antiproton accumulation (called stacking) was demonstrated soon after [18] and later reported in detail [19]. CERN's Antiproton Decelerator(AD) was built so that the antihydrogen aspirations could be realized. Five collaborations approved by the SPSC are using or planning to use these methods.

The proposal to make cold antihydrogen using cold, trapped antiprotons was laid out by some of us in the TRAP collaboration back in 1987 [20], not long after the first antiprotons were trapped [17]. The production of antihydrogen cold enough to capture in a neutral particle trap for precise laser spectroscopy was proposed at the same time.

2. Dual ATRAP Goals that Remain the Same

From its beginning, ATRAP announced, pursued, and reported to the SPSC each year on two long term goals. These goals were laid out by some of us long ago. They have not changed.

1. Producing cold antihydrogen, trapping cold antihydrogen in its ground state, laser cooling the trapped antihydrogen, and performing precise spectroscopic and gravitational comparisons of trapped antihydrogen and hydrogen.

2. Making precise comparisons of the properties of the antiproton and the proton – their magnetic moments and their charge-to-mass ratios in particular.

In subsequent sections we discuss the ATRAP antiproton beam line that was built with two ports to make it possible to purse both goals simultaneously. Almost all of the available antiprotons go to the antihydrogen experiments. However, a small fraction of the antiprotons can be skimmed off as often as once per day, or as seldom as once per month, as needed.

3. Status and Immediate Objectives of Antiproton-to-Proton Comparisons

a. Magnetic Moments

Preparations for the ATRAP antiproton magnetic moment measurement were carried out at Harvard. In 2010, the first observations of self-excitation and feedback cooling of a single trapped proton were reported [21]. In 2012 the first one-particle measurement of the proton magnetic moment was reported [22].

In 2013, ATRAP reported the first one-particle measurement of the antiproton magnetic moment, the only such measurement so far, achieving a 680 times more precise measurement than had been realized with any other method. Our report on this measurement [23] was widely celebrated.

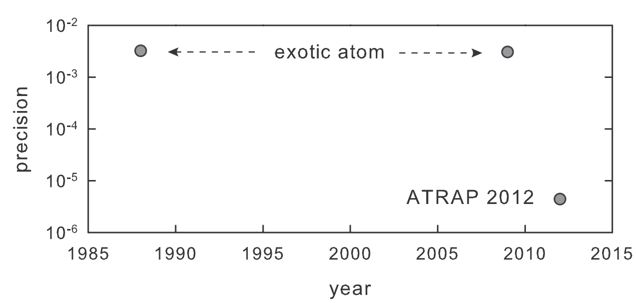

Figure 3: ATRAP made the first one-particle measurement of the antiproton magnetic moment [23]. The comparison of the antiproton was 680 times more precise than any comparison reported before or since.

Great additional improvements in precision, perhaps as much as 1000 to 10,000, may be possible with the use of quantum methods. A demonstration experiment that made use of one trapped antiproton demonstrated that individual spin flips of a single antiproton could be observed [24].

Examples of improvements made include a magnetic field that is now much more spatially uniform. This field should also be much more stable in time due to better decoupling from the fluctuating pressure of the helium recovery system at the AD. The shielding that our self-shielding solenoid provides against fluctuations in the ambient field in the AD hall is now much higher than for our earlier measurements. Greatly improved diagnostics compared to what we used for our 2013 measurement now make it possible for us to optimize our antiproton loading and electron cooling much more efficiently. Fiber detectors that are not needed for these antiproton measurements have been removed to give us a larger experimental volume.

b. Charge-to-Mass Ratios

As illustrated in Fig. 4, a series of three comparisons of the charge-to-mass ratios of the antiproton and proton were carried out at LEAR [18, 5, 15]. These measurements reduced the uncertainty in the measured mass ratio by nearly a factor of a million. The measurements were made by the TRAP collaboration, that later expanded to become ATRAP. (The measured value was later shifted by a small fraction of an error bar without changing the uncertainty [25].) To complete these measurements, TRAP developed methods to slow, capture and cool antiprotons [26]. These are the antiproton methods that have since made all of the AD antihydrogen experiments and competing antiproton measurements possible.

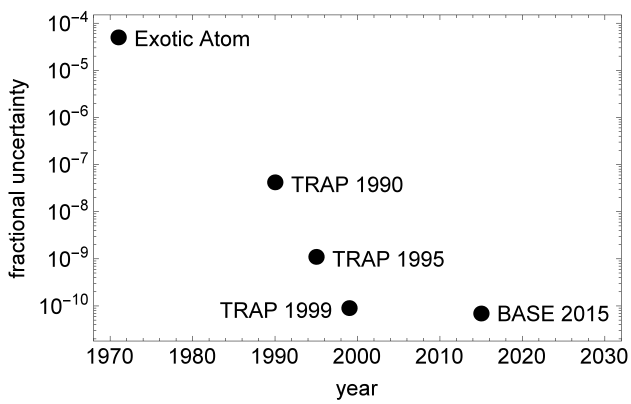

Figure 4: The 1999 comparison of the charge-to-mass ratios of the antiproton and proton performed by TRAP [15] was confirmed in 2015 by BASE [27] at essentially the same uncertainty. (The quoted uncertainties were about 20% smaller.).

Our most precise comparison of the charge-to-mass ratios of the antiproton and proton showed that these have the opposite sign with the same magnitude to 9 parts in 10^{11}. This is by far the most sensitive test of CPT invariance for a baryon system. Most of this final measurement was done with one antiproton just two weeks before LEAR closed. About 16 years later, BASE [27] has just confirmed our TRAP measurement [15] at essentially the same precision. (The reported uncertainty is about 20% smaller than reported in 1999.) Congratulations to BASE for their measurement.

ATRAP plans to do such measurements in the same traps used for antiproton magnetic moment measurements, when time permits. However, the magnetic moment measurements have the highest priority given that they have so far been measured much less precisely than the charge-to-mass ratios.

4. Status and Immediate Objectives of the Antihydrogen Program

ATRAP has reported the observation of 5 trapped, ground state antihydrogen atoms per trial [28]. A 2013 report discusses how electric fields were used to avoid mirror-trapped antiprotons

[29]. The 5 atoms per trial is more antihydrogen per trial than has otherwise been realized, but more trapped atoms per trial are needed. We believe that we have developed the methods to make this possible once our second generation Ioffe trap and the associated Penning traps are fully operational.

The next objective (once antiprotons are again available) is to demonstrate three dimensional laser cooling of trapped antihydrogen atoms. Doing this most effectively requires Lyman alpha radiation at 121 nm, and also a Penning-Ioffe trap which has sideports (perpendicular to the magnetic field direction) to admit the 121 nm into the trap.

a. Coherent Lyman Alpha Radiation for Cooling

A considerable challenge to realizing laser cooling of trapped antihydrogen atoms was that as 2015 began we were very disappointed to find that there was no source of 121 nm light available for ATRAP's use at CERN. Insofar as we had trapped enough antihydrogen to observe such cooling, we were counting upon having collaborators bring to CERN a CW Lyman alpha source that was in preparation for many years (as was often been reported to the SPSC). However, it emerged early in 2015 that the research priorities of these collaborators had changed and that neither their source nor a copy would be coming to CERN.

This had a big impact upon the 2015 activities in ATRAP. Before deciding who was going to provide the badly needed Lyman alpha source, we decided to re-evaluate the possibilities. Roughly speaking, we need about a nW of 121 nm radiation to cool trapped antihydrogen in minutes. To get this power at the trapped atoms likely requires at least ten time more power on the laser table given nearly a factor of two loss in any window, lens or mirror and the need to steer the light through a cryogenic apparatus with small apertures.

We had long preferred to use a CW source, believing that it would be best suited for antihydrogen spectroscopy as well as for cooling. The first CW demonstration [30] using 4-wave mixing in Hg gas had produced 20 nW at 121 nm, and an expected "increase by several orders of magnitude" was mentioned. However, some 12 years later [31], the most recent implementation of the CW source produced only 0.3 nW of 121 nm light. (This report suggested that more power should be available "at full power" but this was not attempted to avoid damage to fiber laser and a doubling crystal that otherwise could not be prevented.) A fraction of a nW would not suffice.

ATRAP remains committed to developing a CW Lyman alpha source. We believe that we can and will produce a lot more CW power than has been realized so far, and we are now in the process of building up such a system. However, we did not believe that we could start from scratch in 2015 and do so within a year. We plan to implement this in the future.

The result was that we decided to go ahead with a pulsed source of Lyman alpha for our first antihydrogen cooling experiments. The system now operating at CERN was designed to produce 30 μW of 121 nm light in 30 ns pulses arriving at 30 Hertz. We start with 730 nm light, double this to 365 nm, and then produce 121 nm light by tripling within a Kr-Ar gas cell [32]. We currently have about $1 \mu W$ passing through the trap via the side windows.

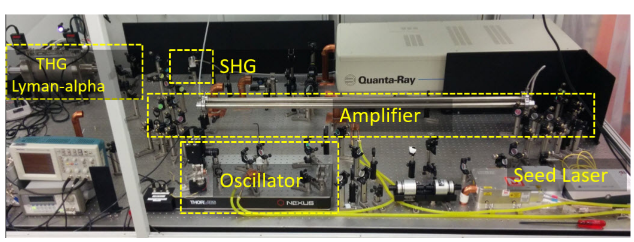

Figure 5: The ATRAP pulsed Lyman alpha (121 nm) system that is now operating in the ATRAP laser cabin.

Although more optimization remains to be done, we note that this power compares very favorably to earlier realizations (both in 1993) of pulsed, coherent radiation at 121 nm. An Amsterdam group realized 130 nW [33] and a NIST group realized 150 nW [34]. Moreover, 1000 nW is a great deal more than the 20 nW and 0.3 nW realized with the mentioned CW productions. And, 1000 nW is already a potentially useful amount of power for cooling trapped antihydrogen.

b. Superimposed Ioffe and Penning Traps

Our first generation Ioffe trap was the first to have the needed optical access into a antihydrogen trap perpendicular its symmetry axis, but the technology of this trap prevented it from being used for more than a trial or two during an 8 hour beam shift. Our second generation trap is designed to be used repeatedly during a beam shift, as well having sideports. In 2014 we were able to demonstrate this first low-inductance, high-field Ioffe trap with side windows. It behaved as designed and is a very big step forward for ATRAP. The trap can be turned on in less than a minute, can be turned off on the order of ten milliseconds, and can be operated many times during a shift.

Three features distinguish the ATRAP, low-inductance Ioffe trap from all others.

1. The side windows will make it possible to laser-cool trapped antihydrogen atoms with the highest possible efficiency.

2. The trap can be operated as either a quadrupole or an octupole Ioffe trap.

3. The apparatus uses substantially less iedid helium than systems at the AD with comparable scope.

The apparatus is now operating extremely well as summarized in the overview.

c. 243 nm Laser Light for 1S - 2S Spectroscopy

We have a operating laser system that produces 243 nm light as needed for 1s - 2s spectroscopy. This system remains at Harvard, and has not yet been moved to CERN, because we think that laser cooling is the first priority. The optics for sending laser light from our laser table to the trap apparatus, and for guiding the light through the cryogenic trap and its vacuum system, is a separate light path from the 121 nm path. This system should be moved to CERN before beam time in 2017.

D. Manpower

The ATRAP collaboration at the AD, and the TRAP collaboration at LEAR from which it developed, have both always been small compared to the collaborations with which they have competed at LEAR and the AD.

Over the years we have demonstrated that a small team can compete effectively. Our small teams developed and demonstrated the cold antiproton methods upon which the current AD collaborations rely, as has been mentioned. As summarized earlier, the precise CERN comparisons of antimatter and matter systems have been carried out by the small TRAP and ATRAP teams.

While effective for precision measurements, the small size of our collaboration does reduce the rate at which we can build new apparatus, and does make it difficult to build and/or develop apparatus during antiproton beam time. With a larger team, for example, we likely would have been able to recover more quickly from the failure of the Ioffe trap vacuum enclosure.

A new group recently joined our collaboration to take over some of the detector maintenance for which our Juelich collaborators have been responsible. Detector upgrades are being discussed.

And, as mentioned, another new group has joined is in developing our pulsed Lyman alpha source. In addition, our spokesperson is changing laboratories in part because the relocation should make it possible to have more manpower for the ATRAP experiments.

E. ATRAP Apparatus Overview

To allow the simultaneous pursuit of ATRAP's dual goals, as discussed above, the ATRAP beamline was built with two ports. The precision antiproton measurement require antiprotons

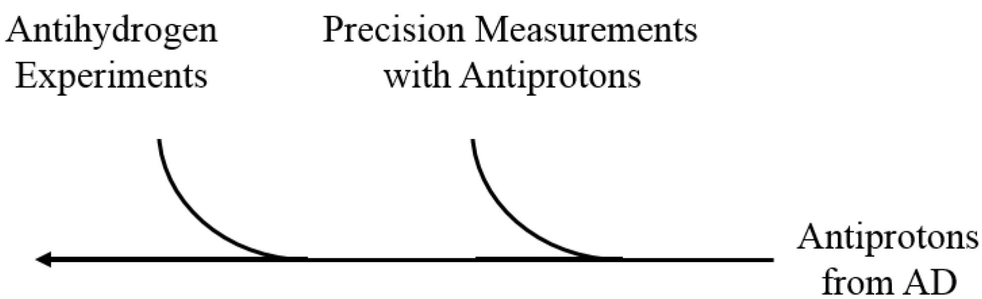

Figure 6: The ATRAP beamline has two antiproton ports – one for antihydrogen experiments and the second for antiproton experiments.

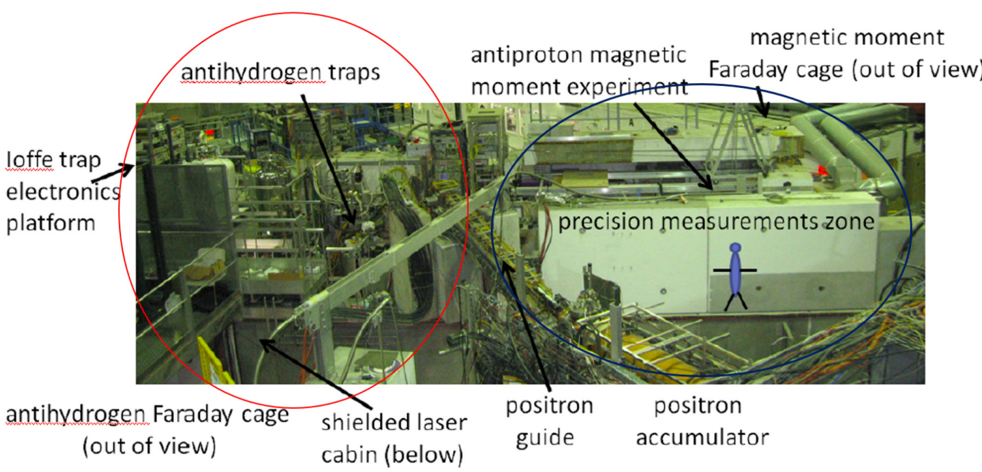

Figure 7: Photograph of the ATRAP beamline with two antiproton ports – one for antihydrogen experiments and the second for antiproton experiments.

much less frequently since we have demonstrated that antiprotons can be stored for such measurement for weeks and even months at a time without reloading. Most of the antiprotons thus are used for antihydrogen experiments.

The ATRAP experimental area is divided into three experimental zones which are radiation controlled. A top view of these areas is represented in Fig. 8. Antiprotons are available for precise antiproton experiments in zone 1. The most sensitive control and detection electronics for this zone are in an adjacent Faraday cage – both within the red dotted lines in the figure. Antiprotons are available for antihydrogen experiments in zone 2. The most sensitive control and detection electronics for this zone are also in an adjacent Faraday cage – both within the blue dotted lines in the figure. The positrons needed to make antihydrogen are produced in zone 3, within the green

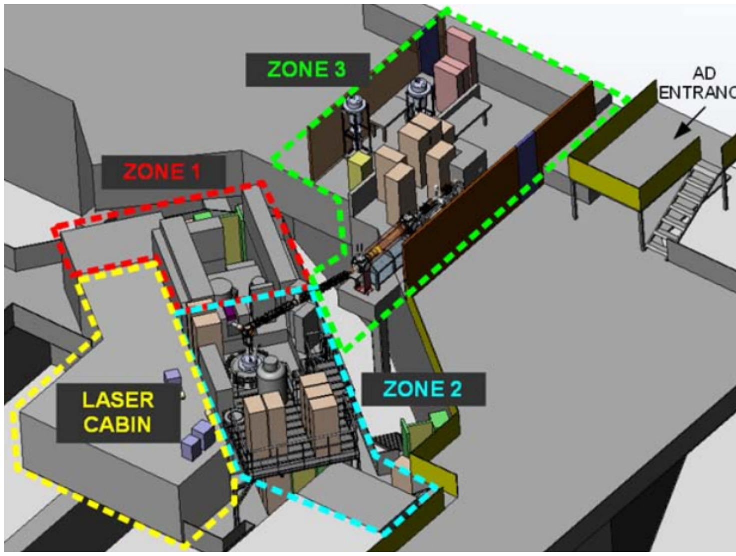

Figure 8: Top representation of the three ATRAP experimental areas. Antiprotons are available for precise antiproton experiments (zone 1) and for antihydrogen experiments (zone 2). The positrons needed to make antihydrogen are produced in third area (zone 3).

dotted lines in the figure. The lasers needed for antihydrogen production are located in a third Faraday cage, labeled as "laser cabin" within the dotted yellow lines in the figure.

1. Zone 1: For Precise Comparisons of Antiprotons and Protons

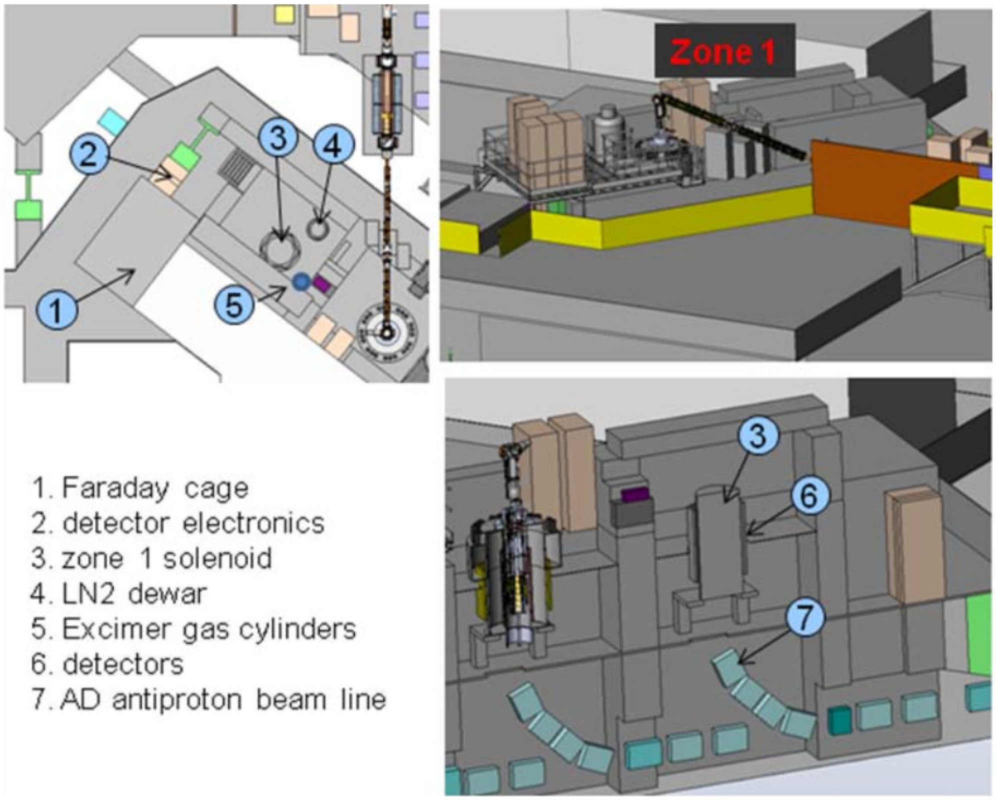

Figure 9: Precise comparisons of antiprotons and protons take place in ATRAP zone 1.

2. Zone 2: Antihydrogen

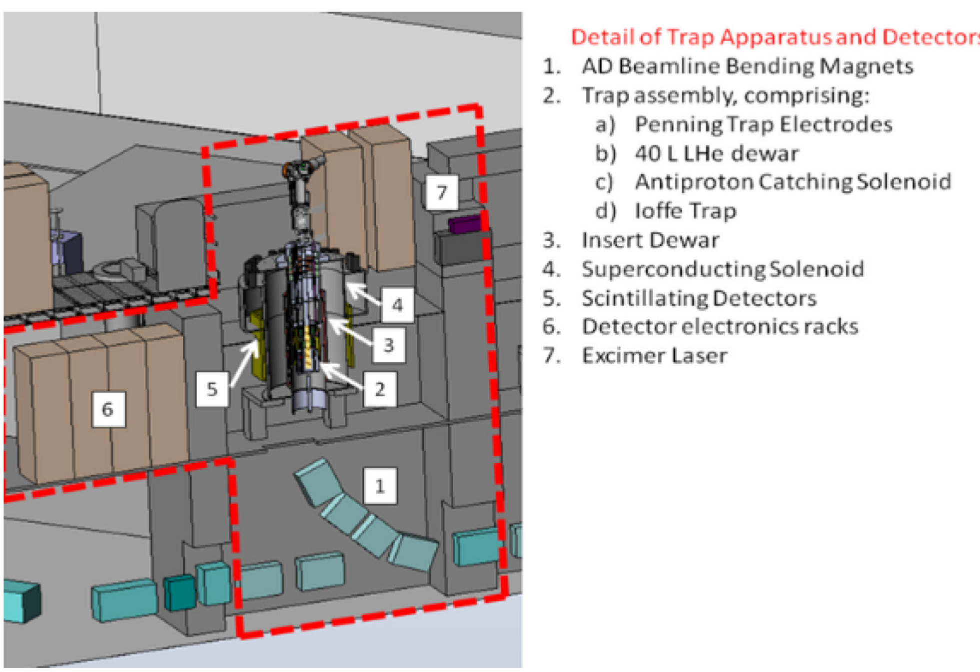

Figure 10: Antidhyrogen production and studies take place in ATRAP zone 2.

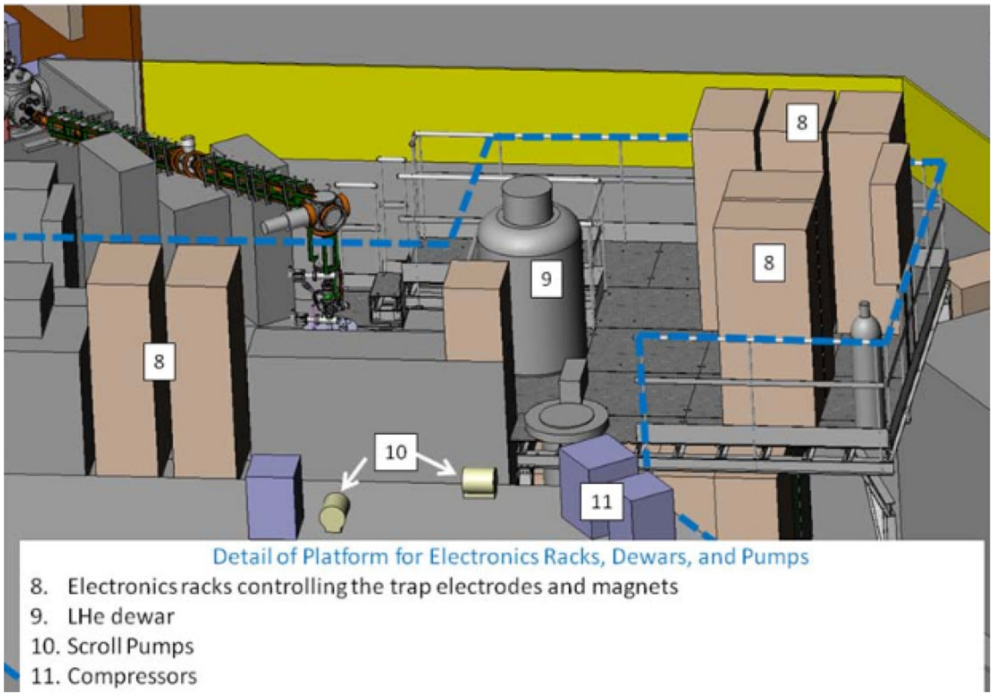

Figure 11: The antihydrogen production area (ATRAP zone 2) includes a platform on which supporting electronics and cryogen dewars are stored.

3. Zone 3: Positron Production for Antihydrogen

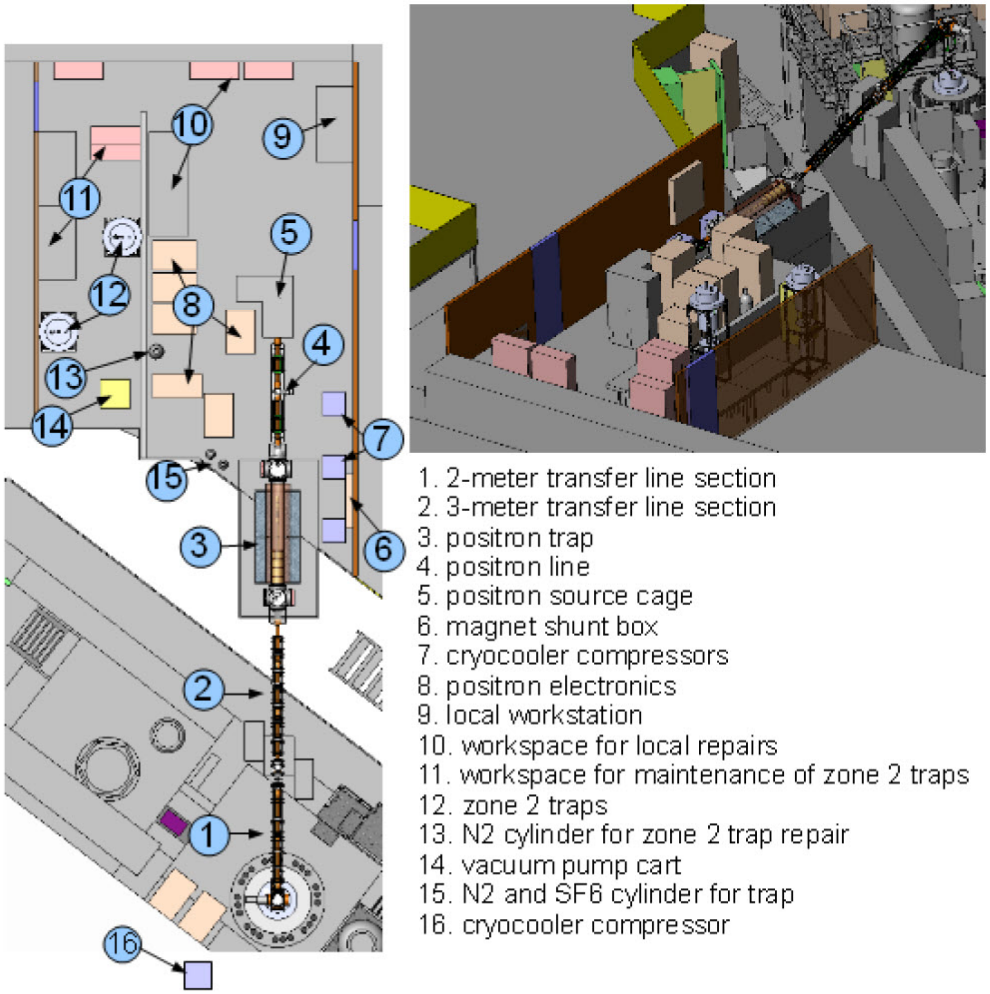

Figure 12: Positron production for antihydrogen production takes place in ATRAP zone 3.

4. Laser Faraday Cage

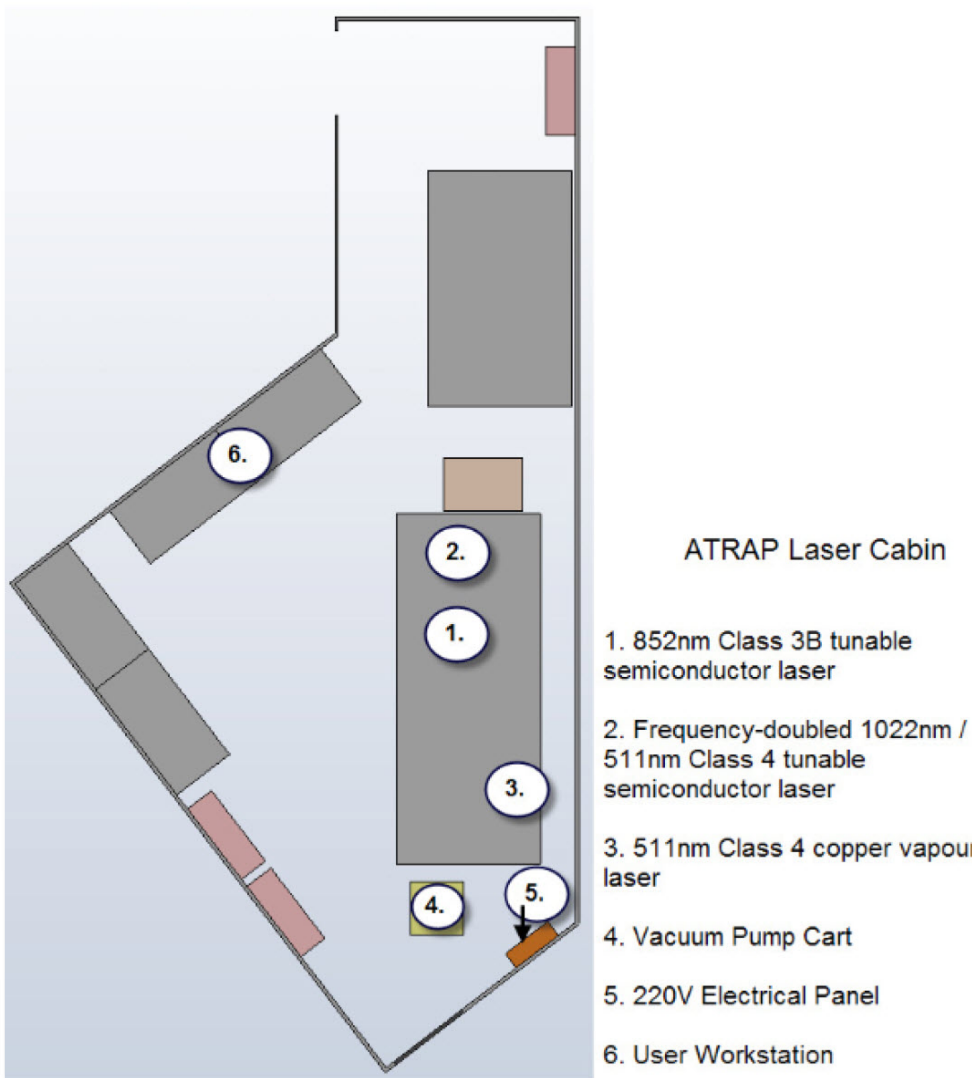

Figure 13: A third Faraday cage contains two laser tables. Our initial laser configuration shown has just been updated to accomodate the pulsed Lyman alpha source described and pictured in the text.

The additional laser systems that are critical for the future objectives of ATRAP have been described earlier.

F. Not the Usual CERN Experiment

Especially for the sake of new SPSC members, it is important to note that the low-energy, high precision antihydrogen research differs substantially from the normal high energy particle and nuclear physics experiments that are practiced so successfully at CERN. Most CERN experiments are carefully crafted so that with a large number of particles delivered to an interaction region over some years, a signal of a particular interaction or particle will be established (or not) at a desired and predictable level of statistical accuracy.

Antihydrogen experiments, like most highly accurate low-energy experiments, are very different. Most of the experimental time is spent in inventing new techniques and methods that make it possible to see a signal at all. A long sequence of short experiments require very precise control and preparation, but the result of one short experiment helps decide what short experiments will follow it. Longer term time schedules are thus less predictable than is normal for CERN high energy experiments. Once a signal is found, the accuracy attained is rarely statistical, being generally limited by systematic uncertainties.

Many other examples can be given for extremely precise measurements being realized after considerable time and effort. One is that the extremely accurate hydrogen spectroscopy experiments by a former ATRAP collaborator who was recognized with the 2005 Nobel prize [35]. The recent electron magnetic moment measurement and the fine structure constant measurement made recently by another in our collaboration is another example [36].

In the past, some on the SPSC committee have had difficulty understanding the difference between the high energy experiments that they are involved in at CERN, and this low energy antihydrogen research program. They have wanted time lines which show clearly and precisely what accuracy antihydrogen spectroscopy will be attained with what number of antiprotons delivered from the AD. It is important to realize that we spend most of our time at ATRAP inventing and refining new methods which eventually should make it possible to see and use an antihydrogen spectroscopy signal.

In some ways the situation is similar to the situation which pertained when the original TRAP Collaboration (PS196) proposed to accumulate antiprotons at an energy 10^{10} times lower than the lowest storage energy in the Low Energy Antiproton Ring, and to listen to the radio signal of a single antiproton as a way of the comparing antiproton and proton 45,000 time more accurately than had been done before. Despite the experience and expertise of the original collaboration, techniques demonstrated with matter particles had to be adapted for the very different circumstances under which antimatter particles were available. Most of the TRAP time and effort went into developing, demonstrating and improving apparatus and techniques, rather than into accumulating statistics with a fixed apparatus. There was some risk insofar as much had yet to be invented, but after a decade of concentrated effort by a small team, the ambitious goal was met and even substantially exceeded.

References

[1] J. Ellis, N. E. Mavaromatos, and D. V. Nanopoulos, Phys. Lett. B **293**, 142 (1992).

[2] V. A. Kostelecký and R. Potting, Nucl. Phys. **B359**, 545 (1991).

[3] D. Colladay and V. A. Kostelecký, Phys. Rev. D **55**, 6760 (1997).

[4] R. Bluhm, V. A. Kostelecký, and N. Russell, Phys. Rev. Lett. **82**, 2254 (1999).

[5] G. Gabrielse, D. Phillips, W. Quint, H. Kalinowsky, G. Rouleau, and W. Jhe, Phys. Rev. Lett. **74**, 3544 (1995).

[6] R. S. Van Dyck, Jr., P. B. Schwinberg, and H. G. Dehmelt, Phys. Rev. Lett. **59**, 26 (1987).

[7] R. Carosi, P. Clarke, D. Coward, D. Cundy, N. Doble, L. Gatignon, V. Gibson, P. Grafström, R. Hagelberg, G. Kessler, and et al., Phys. Lett. B **237**, 303 (1990).

[8] C. Zimmermann and T. Hänsch, Hyperfine Interact. **76**, 47 (1993).

[9] C. Parthey, A. Matveev, J. Alnis, B. Bernhardt, A. Beyer, R. Holzwarth, A. Maistrou, R. Pohl, K. Predehl, T. Udem, T. Wilken, N. Kolachevsky, M. Abgrall, D. Rovera, C. Salomon, P. Laurent, and T. W. Hänsch, Phys. Rev. Lett. **107**, 203001 (2011).

[10] C. L. Cesar, D. G. Fried, T. C. Killian, A. D. Polcyn, J. C. Sandberg, I. A. Yu, T. J. Greytak, D. Kleppner, and J. M. Doyle, Phys. Rev. Lett. **77**, 255 (1996).

[11] R. J. Hughes, Hyperfine Interact. **76**, 3 (1993).

[12] G. Gabrielse, Hyperfine Interact. **44**, 349 (1988).

[13] P. D. Lett, R. N. Watts, C. I. Westbrook, W. D. Phillips, P. L. Gould, and H. J. Metcalf, Phys. Rev. Lett. **61**, 169 (1988).

[14] J. Walz and T. Hänsch, Gen. Rel. Grav. **36**, 561 (2004).

[15] G. Gabrielse, A. Khabbaz, D. S. Hall, C. Heimann, H. Kalinowsky, and W. Jhe, Phys. Rev. Lett. **82**, 3198 (1999).

[16] R. J. Hughes and M. H. Holzscheiter, Phys. Rev. Lett. **66**, 854 (1991).

[17] G. Gabrielse, X. Fei, K. Helmerson, S. L. Rolston, R. L. Tjoelker, T. A. Trainor, H. Kalinowsky, J. Haas, and W. Kells, Phys. Rev. Lett. **57**, 2504 (1986).

[18] G. Gabrielse, X. Fei, L. A. Orozco, R. L. Tjoelker, J. Haas, H. Kalinowsky, T. A. Trainor, and W. Kells, Phys. Rev. Lett. **65**, 1317 (1990).

[19] G. Gabrielse, N. S. Bowden, P. Oxley, A. Speck, C. H. Storry, J. N. Tan, M. Wessels, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, J. Walz, H. Pittner, and E. A. Hessels, Phys. Lett. B **548**, 140 (2002).

[20] G. Gabrielse, in *Fundamental Symmetries*, edited by P. Bloch, P. Pavlopoulos, and R. Klapisch (Plenum, New York, 1987), pp. 59–75.

[21] N. Guise, J. DiSciacca, and G. Gabrielse, Phys. Rev. Lett. **104**, 143001 (2010).

[22] J. DiSciacca and G. Gabrielse, Phys. Rev. Lett. **108**, 153001 (2012).

[23] J. DiSciacca and et al., Phys. Rev. Lett. **110**, 130801 (2013).

[24] J. DiSciacca, M. Marshall, K. Marable, and G. Gabrielse, Phys. Rev. Lett. **110**, 140406 (2013).

[25] G. Gabrielse, Int. J. Mass Spectrom. **251**, 273 (2006).

[26] G. Gabrielse, Adv. At. Mol. Opt. Phys. **45**, 1 (2001).

[27] S. Ulmer and *et al.* (BASE Collaboration), Nature **524**, (2015).

[28] G. Gabrielse, R. Kalra, W. S. Kolthammer, R. McConnell, P. Richerme, D. Grzonka, W. Oelert, T. Sefzick, M. Zielinski, D. Fitzakerley, M. C. George, E. A. Hessels, C. H. Storry, M. Weel, A. Müllers, and J. Walz, Phys. Rev. Lett. **108**, 113002 (2012).

[29] P. Richerme, G. Gabrielse, S. Ettenauer, R. Kalra, E. Tardiff, D. Fitzakerley, M. George, E. Hessels, C. Storry, M. W. ahd A. Mullers, and J. Walz, **87**, 023422 (2013).

[30] J. Walz, A. Pahl, K. Eikema, and T. Hänsch, Nucl. Phys. A **692**, 163c (2001).

[31] D. K. K. Scheid and J. Walz, Appl. Phys. B (2013).

[32] R. Hilbig and R. Wallenstein, IEEE J. of Quant. Elect. **QE-17**, 1566 (1981).

[33] I. D. Setija, H. G. C. Werij, O. J. Luiten, M. W. Reynolds, T. W. Hijmans, and J. T. M. Walraven, Phys. Rev. Lett. **70**, 2257 (1993).

[34] W. Phillips, S. L. Rolston, P. D. Lett, T. MeIrath, N. Vansteenk, and C. I. Westbrook, Hyper. Int. **76**, 265 (1993).

[35] M. Niering, R. Holzwarth, J. Reichert, P. Pokasov, T. Udem, M. Weitz, T. W. Hänsch, P. Lemonde, G. Santarelli, M. Abgrall, P. Laurent, C. Salomon, and A. Clairon, Phys. Rev. Lett. **84**, 5496 (2000).

[36] D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev. Lett. **100**, 120801 (2008).