Strong Drive Regime Studies to Improve Antihydrogen Production at the ALPHA experiment at CERN

Celeste Carruth [1], Joel Fajans [1], for the ALPHA collaboration

[1] Physics department, University of California-Berkeley

Introduction

Charge-Parity-Time (CPT) symmetry predicts that antimatter particles should obey the same physical laws that matter particles obey, and that there should be an equal amount of matter and antimatter in the universe [1]; however, we observe a matter-dominated universe. The Antihydrogen Laser Physics Apparatus (ALPHA) experiment studies the discrepancy between theory and observation by trapping antihydrogen and measuring its charge [2] and spectroscopy [3]. We make antihydrogen by combining antiproton and positron plasmas in a Penning-Malmberg trap using a specific combination of electric and magnetic fields. In order to trap a consistent number of atoms each time we capture a beam of antiprotons, we need to have low temperature plasmas with consistent densities and numbers of particles, but the initial densities and numbers of particles vary between different sets of positrons, which negatively affects our trapping rate. We take pictures of our plasmas when they are dumped on a microchannel plate and count the number of particles with a Faraday cup, then use the water bag model to solve for the density and rotation frequency of the plasma.

The strong drive regime is a non-neutral plasma regime driven by a rotating electric field, where the drive frequency synchronizes with the plasma rotation frequency, and this controls the density [4]. For cold plasmas, a specific number of particles, density and on-axis potential give a unique solution to the plasma parameters, so driving in this regime can help us make consistent plasmas. This paper discusses the measurement of the strong drive regime in the ALPHA experiment, and the development of a new method combining the strong drive regime with evaporative cooling to create a plasma with a specific density and number of particles.

Antimatter Sources

The ALPHA experiment is located in the Antiproton Decelerator Hall at CERN. We catch and initially trap the antiprotons from the decelerator in an electron plasma in a deep well with high voltages on both sides, and use the electron plasma to compress and cool the antiproton plasma. The plasma is driven by rotating electric field produced by a six-sector rotating wall electrode, which causes the electrons to cool by emitting cyclotron radiation, and they subsequently cool the antiprotons via coulomb repulsion as the plasma reaches thermal equilibrium. After cooling the antiprotons, the electrons are kicked out of the trap with a short high voltage signal. Positrons are emitted by a radioactive Na-22 source and are cooled via positron capture by nitrogen gas before being delivered to the Penning-Malmberg atom trap, where they are further cooled by emitting cyclotron radiation.

Evaporative Cooling

Before mixing the positrons and antiprotons, they must be cooled as much as possible, and the last cooling step uses the technique of evaporative cooling [3]. Evaporative cooling occurs when the particles are trapped in a potential well inside a 1-3T magnetic field while one side of the potential well is lowered. This allows the hotter particles to fly out while continuing to trap the cooler particles, which then reach a cooler thermal equilibrium. The positron temperatures after this stage are typically 20-30K, while the antiproton temperatures are around 40K.

After cooling the particles, we mix the two species in the magnetic trap to combine and form antihydrogen. The magnetic trap acts on the atom's magnetic dipole moment to prevent if from touching the wall of the trap and annihilating, but in order for it to be effective, the atom's thermal energy must be lower than its magnetic potential energy. Due to the remaining thermal energy of the atoms, the trapping rate is approximately 1 atom out of several thousand atoms [5]; during normal operation we can regularly trap 1-2 atoms per attempt. If the density of the positron plasma changes much or the number of particles suddenly changes, though, we sometimes can't trap antihydrogen until after developing a new set of drive parameters for the positrons, which can take a few hours. The negative effect the variations have on our trapping rate motivated this study for combining evaporative cooling with the strong drive regime.

Operating in the Strong Drive Regime

The strong drive regime is accessible when a non-neutral plasma is driven by a rotating electric field while confined in a potential well inside an axially symmetric magnetic field. Its identifying characteristic is that the drive frequency matches the plasma rotation frequency, which provides a linear relationship between the plasma density and the rotation frequency of the electric field. The rotating electric field is accomplished by applying phase-shifted sinusoidally varying voltages on a six-segmented electrode. Historically the rotating wall frequencies were found experimentally by scanning through a large range of frequencies to find the frequency that produced the desired amount of compression. This is an inefficient method, and only produces desired results when the initial conditions are consistent. The lack of a systematic technique for compressing the plasma has caused us to lose a substantial amount of time while running our experiment, and the strong drive behavior is very useful. Figure 1 shows the linear relationship between the density and the rotating wall frequency for different particle loads, demonstrating the ability for the ALPHA experiment to drive plasmas in the strong drive regime. As we see on the plot, the density is independent of the number of particles. The plasma length we use is about 3cm, confined in a 3T magnetic field inside a potential well with four electrodes set to 100V, driving with the RW electrode at one end. However, currently the upper limit for driving our plasma in this regime is 2 MHz, which limits the maximum density we can achieve.

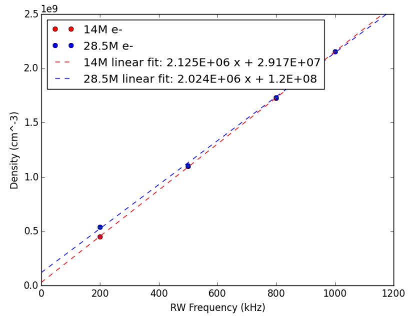

Figure 1: Density vs. Rotating Wall Frequency

Evaporative Cooling and the Strong Drive Regime

Evaporative cooling is a space charge dominated effect. The number of particles in the final stage is dependent on the initial number of particles, the density of the plasma, and the depth of the well. During the evaporative cooling stage, the density decreases as the plasma expands, and the resulting number of particles varies based on the initial density and number of particles. The idea to combine evaporative cooling and the strong drive regime is motivated by the expectation that if the strong drive regime is successful at maintaining a constant density during the evaporative cooling process, the final number of particles would be defined by the well and the density defined by the rotating wall frequency.

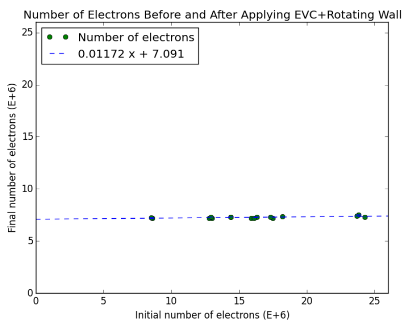

Figure 2: Final vs. Initial Number of Particles

In a normal shallow well, the rotating wall heats up the plasma too much and causes the particles to escape. After testing several different potential well configurations, a well was found that allows us to perform this technique of evaporative cooling in the strong drive regime. The temperature of the plasmas varied from 200-700K, due to unresolved heating issues; however, at this stage, controlling the temperature is less important than the density and number of particles. The number of initial electrons was varied from 8.6M to 24M and the final number varied from 7.2M to 7.5M electrons, as shown in figure 2. We controlled the initial density by applying a 20s rotating wall at different frequencies within the strong drive regime to produce the densities shown in figure 1, and were able to vary the initial density and achieve a relatively consistent output density, shown in figure 3. The small error bars in these plots are calculated by combing in quadrature the line width in the frequency and density analysis plots and the standard deviation of each set of measurements.

These measurements were done with two different particle loads, 14M and 28.5M electrons. Although it was difficult to find this well, we do not need a large number of such wells for our experiment; it is sufficient to just have one well that gives us an acceptable set of initial conditions, and any changes we need in particle load or density can be addressed after applying this technique.

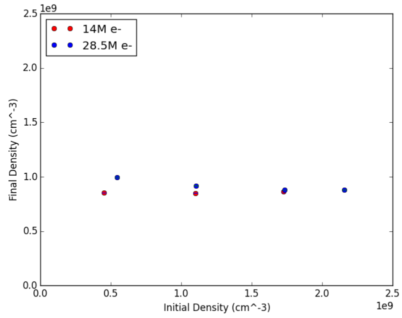

Figure 3: Final vs. Initial Density

Further development and application to ALPHA

The development of the evaporative cooling with strong drive technique was done using electrons, so the next step is to recreate it with our positron plasmas. The advantage to developing with electrons is largely due to the time required by positron studies: the positron accumulator requires 100s to accumulate enough positrons for a plasma. The strong drive regime is already a part of our trapping sequence, and after finishing the positron development, we expect to use the evaporative cooling with strong drive method while trapping antihydrogen this year.

Conclusion

The strong drive regime has already become a useful tool for the plasma manipulations necessary to make antihydrogen, and the development of strong drive regime combined with evaporative cooling techniques shows the potential to create uniquely defined plasmas with consistent parameters regardless of the initial conditions. These tools are expected to contribute to our measurement of the 1S-2S transition of antihydrogen.

References

[1] Schwinger, Julian *The Theory of Quantized Fields I.* Phys. Rev. **82**, 914 (1951)

[2] M. Ahmadi *et al.,* "An improved limit on the charge of antihydrogen from stochastic acceleration" *Nature* **529**, 373 (2016)

[3] C. Amole, *et al*, "The ALPHA Antihydrogen Trapping Apparatus", Nuclear Instruments and Methods in Physics **735**, 319-340, (2014).

[4] J. R. Danielson and C. M. Surko, "Radial compression and torque-balanced steady states of single-component plasmas in Penning-Malmberg traps", Physics of Plasmas **13**, (2006), 055706

[5] C. Amole *et al., Nature* **483**, 439 (2012)

[6] G. B. Andresen *et al., Nature Physics* **7**, 558 (2011))

This research was supported in part by the United States Department of Energy.