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Microwave-plasma interactions studied via mode diagnostics in ALPHA

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Abstract The goal of the ALPHA experiment is the production, trapping and spectroscopy of antihydrogen. A direct comparison of the ground state hyperfine spectra in hydrogen and antihydrogen has the potential to be a high-precision test of CPT symmetry. We present a novel method for measuring the strength of a microwave field for hyperfine spectroscopy in a Penning trap. This method incorporates a non-destructive plasma diagnostic system based on electrostatic modes within an electron plasma. We also show how this technique can be used to measure the cyclotron resonance of the electron plasma, which can potentially serve as a non-destructive measurement of plasma temperature.

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1 Introduction

Antihydrogen is a promising candidate for high-precision tests of the CPT theorem. It is the simplest pure anti-atomic system and its matter counterpart, hydrogen, is one of the best studied systems in physics. In 2010, the ALPHA collaboration observed 38 annihilation events consistent with the release of trapped antihydrogen from a magnetic trap [1]. The demonstration of antihydrogen trapping is a major milestone towards high precision study of antihydrogen. The first such study that will be pursued by ALPHA will be of the hyperfine levels of antihydrogen's ground state, for which the hyperfine constant is known to 1.4 parts in 10^{12} in hydrogen [2].

The core of the ALPHA apparatus is a Penning-Malmberg trap for the confinement of charged particles such as electrons, positrons, and antiprotons. The Penning trap consists of a series of cylindrical electrodes inside a uniform 1 Tesla magnetic field. Voltages applied to the electrodes create a potential well along the trap axis and the magnetic field provides radial confinement. Superimposed on the Penning trap is a magnetic neutral atom trap for the trapping of antihydrogen. The ALPHA apparatus was designed as an antihydrogen trap first and foremost and was not optimized for microwave spectroscopy. For microwaves injected into

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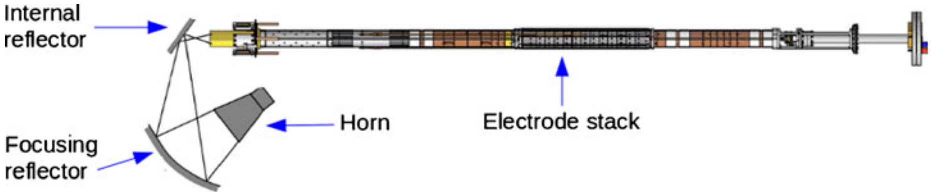

Fig. 1 Sketch of the microwave injection set-up. The horn is connected to an Agilent 8257D synthesizer, capable of producing signals up to 32 GHz at up to 25 dBm in power

the Penning trap, the electrode structure can result in complicated standing wave patterns, potentially reducing the microwave field strength severely. Furthermore, microwaves are currently injected from outside the main apparatus and directed down the trap bore by a pair of mirrors (see Fig. 1), potentially introducing additional losses. The strength of the field, which determines the rate of spin flip transitions, is a critical parameter when working with few anti-atoms.

This paper will introduce a novel method to measure the strength of a microwave field in a Penning trap using an electron plasma. The microwave-plasma interactions are studied using a non-destructive plasma mode diagnostic system developed for this purpose. In addition, we will outline how the system can be used to measure the electron cyclotron resonance. From the central frequency of the cyclotron resonance we can obtain an accurate determination of the axial magnetic field strength. The width of the resonance can also serve as a measure of the electron plasma temperature.

2 Electron plasma as a power meter

To measure the microwave field seen by antihydrogen atoms in the magnetic trap, we load an electron plasma into the antihydrogen trapping region. The electrons precess around the axial magnetic field, B, at the cyclotron frequency given by $f_c = eB/2\pi m$, where e is the elementary charge and m is the electron mass. Microwaves incident on the plasma at the electron cyclotron frequency, 28 GHz at 1 T, will excite the cyclotron motion of the electrons. After a microwave pulse, the kinetic energy will re-distribute between three translational degrees of freedom via collisions, increasing the plasma temperature. The stronger the microwave field in the trap, the greater the temperature increase. The challenge is then to measure the temperature change of the plasma due to the microwave pulse before the plasma cools significantly via cyclotron radiation (with a cooling time constant of approximately 4 s). To measure the temperature change of the plasma we have implemented a non-destructive method based on a temperature dependent electrostatic mode of the electron plasma.

2.1 Electrostatic modes of non-neutral plasmas

Single component plasmas in a harmonic confining potential and at temperatures close to absolute zero form spheroids of constant charge density [3]. These spheroidal plasmas have internal oscillation modes at frequencies that can be calculated analytically [4]. The low-order plasma mode frequencies are related to the number density, n, and aspect ratio, $\alpha = L/2r$, where L is the axial length of the plasma and r its radius. The theory has been confirmed experimentally on laser cooled ion plasmas [5, 6] and cold electron plasmas [7] and has been used as a diagnostic of density and aspect ratio [8].

The second order mode, the quadrupole mode, is an oscillation of the aspect ratio of the plasma. The analytic theory assumes a cold fluid but an approximate treatment of temperature effects has been proposed and shown to agree well with experiment [8, 9]. For a change in temperature of ΔT a corresponding change in the quadrupole frequency is predicted:

$$(\omega_2')^2 - (\omega_2)^2 = 20\left(3 - \frac{\alpha^2}{2}\frac{\omega_p^2}{(\omega_2^c)^2}\frac{\partial^2 f(\alpha)}{\partial\alpha^2}\right)\frac{k_B \Delta T}{mL^2}, \tag{1}$$

where ω_2 and ω_2' are the quadrupole frequencies before and after the pulse, respectively. The cold fluid result is given by ω_2^c, $\omega_p = \sqrt{\frac{ne^2}{m\epsilon_0}}$ is the plasma frequency and $f(\alpha) = 2Q_1[\alpha(\alpha^2-1)^{-1/2}]/(\alpha^2-1)$. We can linearize (1) by assuming $\omega_2' \approx \omega_2$ so that $(\omega_2')^2 - (\omega_2)^2 = (\omega_2' + \omega_2)(\omega_2' - \omega_2) \approx 2\omega_2\Delta\omega_2$. This approximation is valid for the temperature range of interest (<2,000K) as $\omega_2 \approx 26.7$ MHz and $\Delta\omega_2$ is on the order of 10 kHz. The quadrupole frequency shift is therefore expected to be of the form $\Delta\omega_2 = \beta\Delta T$.

2.2 The experimental set-up

An electron plasma is placed in an approximately harmonic potential well spanning three electrodes. The quadrupole mode is excited by applying a 1 μs Gaussian modulated pulse, near the frequency of the mode, to one of the end electrodes. The oscillation of the plasma induces a signal on an electrode centered on the plasma. This signal is amplified, filtered, and digitized before applying a fast Fourier transform to determine the frequency. The electron plasma used for these measurements consisted of 7×10^7 electrons in a long thin column with an aspect ratio of 27. This type of measurement could potentially be used as a non-destructive measurement of the aspect-ratio, density and temperature. For the purpose of measuring the microwave field amplitude in our trap, we focus on the quadrupole mode and its use as a temperature measurement. The system developed here can also be used to track both the first order, or dipole, mode and the quadrupole mode in real time and serve as a qualitative diagnostic of plasma changes.

3 Results

3.1 Quadrupole mode calibration

In order for the mode theory to hold, certain conditions must be satisfied [4]: (1) The confining potential must be harmonic, (2) the plasma must be small compared to the electrode radius so that image charge effects are negligible, and (3) the plasma density must be approximately uniform throughout the plasma. Rather than assume the theory holds and attempt to use (1) directly, we calibrate the change quadrupole frequency to the change in plasma temperature as measured

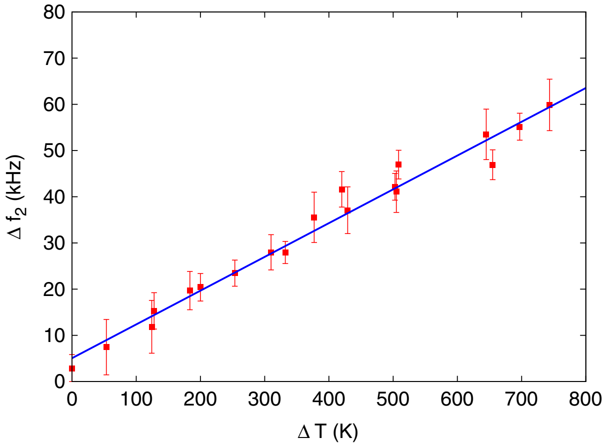

Fig. 2 Change in quadrupole mode frequency as a function of the plasma temperature. The blue line is a linear fit to the data

by a destructive temperature diagnostic dump. The destructive temperature measurement is realized by lowering one side of the confining potential and releasing the electrons onto a micro-channel plate (MCP). Assuming that the plasma was in thermal equilibrium, the particles that escape first will be from the exponential tail of a Boltzmann distribution. By fitting the high energy tail we can determine the plasma temperature [10].

The calibration was produced by monitoring the quadrupole mode as the plasma was heated to a steady state by applying a radio-frequency drive on a nearby electrode at the dipole mode frequency (approximately 16 MHz). For each drive amplitude the final temperature was measured using the MCP. The initial temperature is taken to be the average starting temperature of 107 K as measured by the MCP. The resulting experimental calibration is shown in Fig. 2.

The quadrupole frequency shift is linear with respect to temperature, as expected. We emphasize that this calibration is experimentally determined and independent of the theory. From this calibration, the temperature change of the plasma can be measured using the quadrupole mode. Using single particle equations of motion, the temperature change of the plasma can be related to the microwave power in the antihydrogen trapping region. With an input of 0.32 W of microwave radiation at 28.23 GHz, we measured 1.1 mW in the trapping region, a 24.5 dB loss. We view this measurement as accurate to within a factor of 2. While there are large losses, this result is encouraging as the input power required to drive positron spin flips in antihydrogen is within practical limits. In addition, the quadrupole mode frequency can be used to troubleshoot and optimize the microwave injection.

3.2 Cyclotron resonance

The proportional response of the quadrupole mode to the absorbed power also allows the electron cyclotron line-shape to be measured. A large electron plasma is loaded into a three electrode well as before and the quadrupole mode frequency is measured every 1.2 seconds. A series of 1 μs microwave pulses are applied, at incremental frequencies, near the cyclotron resonance. After each pulse the plasma is allowed to cool back to equilibrium. Figure 3a shows the resulting cyclotron

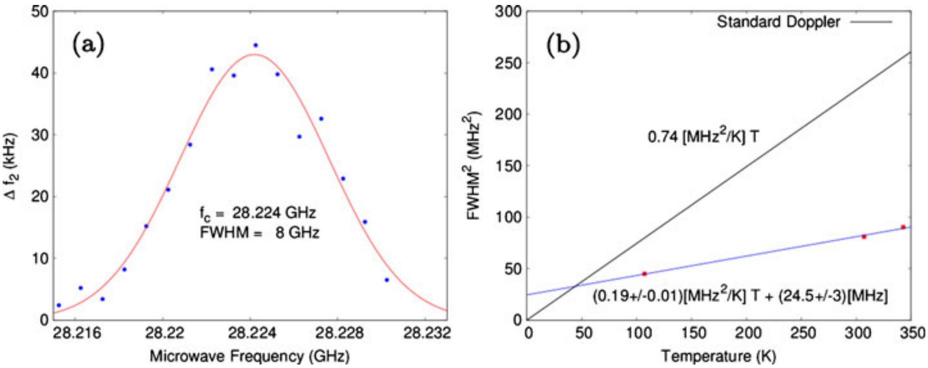

Fig. 3 (**a**) The quadrupole mode response plotted as a function of microwave frequency. The central frequency corresponds to a B-field magnitude of 1.0934 T. The width of the cyclotron line-shape is a function of plasma temperature (**b**) and may serve as a non-destructive measure of plasma temperature

line-shape. The magnitude of the solenoidal field can be calculated from the central frequency (recall $f_c = eB/2\pi m$) to an absolute precision of approximately one Gauss, or a relative precision of 1 part in 10^4. Accurate measurements of the magnetic field in the antihydrogen trapping region are critical since the magnitude determines the energy of the positron spin flip transitions.

The width of the cyclotron line-shape may also serve as a measure of the plasma temperature. Doppler broadening is expected to dominate the width of the line, with a potential contribution from magnetic field inhomogeneities. Typically, when discussing Doppler broadening, the motion of the absorber in all three dimensions contributes to the Doppler width. In ALPHA's case, electrons are absorbing cyclotron radiation and only the motion along the axial magnetic field contributes to the Doppler width. If we assume the microwaves propagate as plane waves down the trap, parallel to the magnetic field, then the standard expression for the Doppler width applies:

$$\mathrm{FWHM} = \sqrt{\frac{8kT\ln 2}{mc^2}}\, f_c, \tag{2}$$

where FWHM is the full width at half max. If the waves are incident on the plasma at an angle θ then the Doppler width is smaller by a factor of $\cos\theta$. It may also be possible that the microwaves are incoming at a distribution of angles, in which case an average over the angles must be taken.

To measure the resonance width versus temperature the plasma is heated by driving the dipole mode constantly to reach a steady-state temperature. The line-shape is then mapped out to find the width. Preliminary results at three temperatures are shown in Fig. 3b.

We see a linear trend as expected, however the slope deviates substantially from the $\theta = 0$ expectation and we find a non-zero intercept. The observed slope is consistent with microwaves incident on the plasma at $\theta = 60°$ with respect to the trap axis. The difference in slope may also be due to a reduction in width due to standing waves. The non-zero intercept may be explained, in part, by additional broadening from magnetic field inhomogeneities.

4 Conclusion

We have implemented a novel method for measuring the amplitude of a microwave field in a Penning trap. A quadrupole mode diagnostic system has been developed to measure temperature changes of an electron plasma. This system can also be used to track plasma changes in real-time and monitor interactions between the microwave field and an electron plasma. The amplitude of the microwave field in the antihydrogen trapping region of the ALPHA trap has been measured and shown to be sufficient for initial hyperfine spectroscopy experiments. We also demonstrated how this system can be used to map out the cyclotron line-shape, providing an accurate measure of the axial magnetic field. Although further investigation is required, preliminary results suggest that the width of the cyclotron resonance may be useful as a non-destructive diagnostic of plasma temperature.

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