FREQUENCY FINE-TUNING OF A SPIN-FLIP CAVITY FOR ANTIHYDROGEN ATOMS

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Abstract

As part of the ASACUSA (*A*tomic *S*pectroscopy *A*nd *C*ollisions *U*sing *S*low *A*ntiprotons) physics program a spin-flip cavity, for measurements of the ground-state hyperfine transition frequency of antihydrogen atoms, is needed. The purpose of the cavity is to excite antihydrogen atoms depending on their polarisation by a microwave field operating at 1.42 GHz. The delicacy of designing such a cavity lies in achieving and maintaining the required properties of this field over a large aperture of 10 cm and for a long period of time (required amplitude stability is 1% over 12 h). This paper presents the frequency fine tuning techniques developed to obtain the desired centre frequency of 1.42 GHz with a Q value below 500 as well as the circuit used for the frequency sweep over a bandwidth of 6 MHz.

INTRODUCTION

The comparison of antimatter to matter provides valuable information regarding charge-parity-time (CPT) symmetry and its possible violation. CPT is conserved in the standard model of particle physics but not necessarily in extensions such as string theory. At CERN's Antiproton Decelerator (AD) spectroscopic measurements of exotic atoms such as antiprotonic helium have already been successfully conducted [1]. In 2010, ASACUSA [2] and, independently, ALPHA [3] successfully produced antihydrogen suitable for spectroscopy.

Within the ASACUSA collaboration, a new experiment is currently being built aiming to measure the ground state hyperfine splitting (GS-HFS) frequency of antihydrogen ($\overline{\mathrm{H}}$) [4]. This splitting is caused by the coupling of the proton (antiproton) and electron (positron) spins to a total spin F. This results in four different states: a singlet state with $F = 0$ and a triplet state with $F = 1$. These states can be divided into one pair of low field seekers [(F,M)=(1,-1) and (F,M)=(1,0)] and one pair of high field seekers [(F,M)=(1,1), and (F,M)=(0,0)] as shown in Fig. 1.

The transition between these states has the characteristic frequency of 1.42 GHz (famous 21 cm line of hydrogen). Since this is very well known in hydrogen [5], its antimatter counterpart — if measured with similar precision — will improve upon the currently most sensitive CPT limit.

The present paper will shortly present the experimental setup, the design of the required spin-flip cavity including first RF measurement results, subsequently focusing on the necessary tuning steps taken to shift the resonance frequency to the desired value. It concludes with an overview of the tuning circuit used for the operation of the cavity within the experimental beam line.

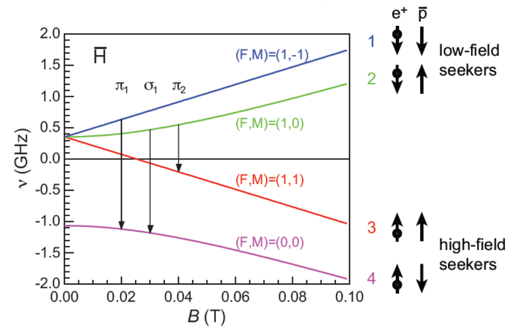

Figure 1: Energies of the four hyperfine states versus an external magnetic field. From [4].

EXPERIMENTAL SETUP

After extraction of the antiproton beam from the AD the antiprotons are cooled further and finally captured in a cusp trap (a pair of anti-Helmholtz coils generating a bottle-like inhomogeneous magnetic field commonly used in plasma physics) where ground state $\overline{\mathrm{H}}$ will be formed [6]. The magnetic field of the trap is such that it allows the extraction of a partially polarized $\overline{\mathrm{H}}$ beam containing more low field seekers than high field seekers [7]. This beam is then projected onto a cavity and from the cavity to a superconducting sextupole magnet with a field of 3 T focusing the beam onto a detector (Fig. 2). If the radio frequency field of the cavity is set to the resonance frequency of 1.42 GHz a spin-flip is induced in the $\overline{\mathrm{H}}$ beam leading to a change in polarization from a low field to a high field seeker state. This causes a deflection instead of a focusing in the sextupole magnet and hence a drop in the count rate at the detector is observed.

THE SPIN-FLIP CAVITY

The rate of $\overline{\mathrm{H}}$ atoms passing through the cavity is in the order of $1-10$ atoms per second over a beam aperture of 10 cm diameter. Since the inhomogeneity of the microwave field broadens the expected resonance line, the requirements on the field distribution and homogeneity inside the cavity are severe. The radio frequency field of the cavity has to provide a purely transverse electromagnetic field (no field components in beam direction) with an inho-

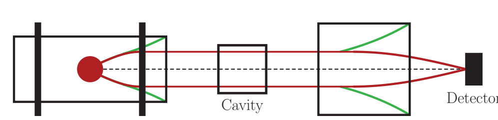

Figure 2: Schematic overview of the experimental setup.

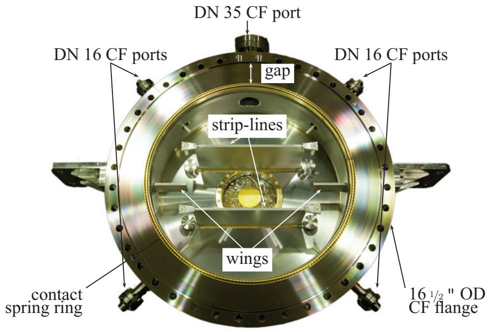

Figure 3: Picture of the open spin-flip cavity with a clearly visible contact spring ring.

mogeneity of not more than ±10% over the whole aperture.

In addition to the oscillating field a static magnetic field must be superimposed to avoid spontaneous spin-flips (Majorana spin-flips) that are induced at transitions from high fields into field free regions. This field has to be variable between 0.1 and 3 G in order to extrapolate the measured ground state hyperfine structure transition frequency back to zero external static magnetic field strength. Due to the sensitivity of the transitions to external magnetic fields, excellent shielding against the earths magnetic field as well as stray fields from the cusp trap (≈ 30 G) and the sextupole (≈ 10 G) is crucial.

For the cavity design, a simple pillbox structure with 320 mm internal diameter and 105 mm internal length, accommodating two strip-lines on top and bottom of the beam aperture, was chosen which proved to be well suited for the application (Fig. 3). It provides a purely transverse field with an inhomogeneity of ±1.5%. The structure was designed to be completely dismountable and suitable for bake out at 300 °C.

The resonator and all components were fabricated from stainless steel 316LN or 316L stainless steel using as far as possible standard vacuum components (Fig. 3). The upstream and downstream part of the cavity is equipped with 16 1/2" OD CF flanges and adapter flanges providing the transition from the cavity to the beamline vacuum chamber[1]. The cavity body is welded on the inner 16 1/2" OD CF blind flange through which a hole of 300 mm diameter is drilled. The strip-lines are screwed onto the front and back of the cavity using silver coated stainless steel screws. Wings are spot welded in three places to the side of the cavity. Four DN 16 CF feedthroughs, equipped with coupling pins, are used around the cavity — two coupling pins for excitation of the desired mode and two for monitoring the excitation.

Such an implementation of the cavity geometry using standard vacuum flanges provides great flexibility for its assembly and facilitates manufacturing considerably. For custom made flanges it would have been a challenge even to get copper gaskets of adequate quality. However, the drawback of standard flanges is the unavoidable gap formed by the copper gasket vacuum seal of the 16 1/2" OD CF end flanges, on the outer rim of the structure, and the edge of the cavity body (Fig. 3). To bridge this gap, which is necessary to prevent the RF wave from propagating into it, specially manufactured spring contact rings (gold plated copper-beryllium) are placed between the end flanges at the welding of the cavity body (Fig. 3). Contact springs of similar material are also used between the strip-lines and the cavity walls to ensure good RF contact between these components[2].

MEASUREMENT RESULTS

To measure the radio frequency properties of the cavity, two antennas connected to a vector network analyzer were used to excite the desired operating mode. With this setup the reflection coefficient (S_{11}) of the resonator as well as the behavior in transmission (S_{12}) could be studied. All measurements have been compared to simulations and showed to be in good agreement.

First RF tests were performed without the spring contact rings to investigate the effect of the gap and compare it to simulation results. It was confirmed that the expected mode pattern changed considerably, caused by propagation of a mixture of modes. Insertion of the contact ring resulted in a mode pattern that was in good agreement with simulation results (Fig. 4). However, a deviation of the measured

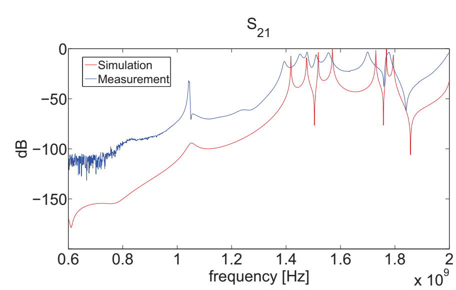

Figure 4: (color) Comparison between the simulated and measured transmission for the spin-flip cavity.

resonance frequency by 26 MHz was observed.

The next step was to optimize the coupling of the RF power into the cavity. This was done by systematic variation of the antenna lengths. It was observed that insertion of the antennas had a considerable influence on the frequency. A summary of the tested antenna lengths, including their effect on the resonance frequency, is given in Table 1. For the optimum coupling antenna length of 12 mm, the resonance frequency was still shifted by roughly 18 MHz.

To compensate for this shift, small metal discs were introduced into the resonator (Fig. 5). In total 8 tuning discs of 1 cm length and 2.5 cm diameter were placed at the end of the strip-lines. This resulted in a resonant frequency

[1] The entrance and exit to the resonator are covered with meshes of 96% transparency for the $\overline{\mathrm{H}}$ atoms to close the resonator RF wise.

[2] A good contact between the strip-lines and the cavity walls is crucial to obtain the desired homogeneity of the oscillating field.

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Table 1: Reflection coefficient (S_{11}) and resonance frequency (F_{res}) of the desired working mode for different antenna lengths (L_a).

L_a [mm]	S_{11} [dB]	F_{res} [GHz]
11	−2.2	1.404
11.5	−5.3	1.403
12	−26.5	1.402
12.5	−5.9	1.401
13	−2.4	1.394

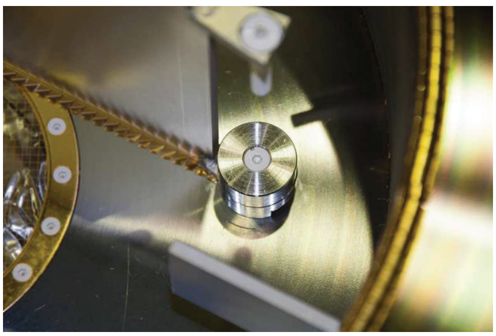

Figure 5: Small metal discs used to detune the cavity to the desired frequency. In total 8 such discs have been used.

of 1.420 GHz — the design frequency value of the desired mode — without affecting the mode geometry (Fig. 6).

The measured unloaded Q-factor of the tuned cavity was determined to be roughly 300. Since no mechanical tuning structures are needed the circuit required for frequency scanning is relatively straight forward.

FREQUENCY SCANNING

During operation of the cavity inside the ASACUSA beam line, it will be necessary to sweep over a frequency bandwidth of 6 MHz. Due to the low Q-factor of the cavity, this can be achieved by implementation of a very simple circuit. It consists of a source, followed by a power amplifier (gain: 40 dB), and a hybrid to excite the desired mode inside the cavity. In total, four antennas are used in the cavity: two for excitation of the RF field and two serve as signal pick-ups. For online monitoring of the frequency and the power inside the cavity, signals of the pick-ups are combined by another hybrid and directly fed to a spectrum analyzer.

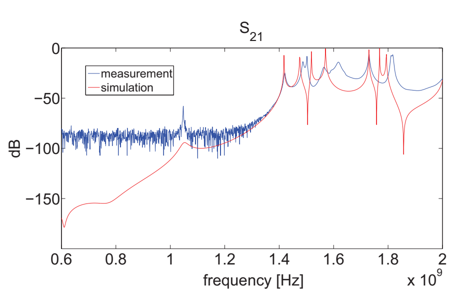

Figure 6: (color) Comparison between the simulated and measured transmission versus frequency for the spin-flip cavity.

CONCLUSIONS AND OUTLOOK

The design of a spin-flip cavity for measurements of antihydrogen atoms has been presented. Measurement results, indicating a resonant frequency 18 MHz lower than the design frequency, showed the necessity of tuning the resonator accordingly. This was carried out by placing stainless steel tuning disks at the bottom of the strip-lines inside the resonator. This increased the resonant frequency to the desired value of 1.420 GHz for the hyperfine transition. The paper concluded with a short overview of the tuning circuit used to excite and monitor the modes, frequencies and power values inside the resonator during operation.

The cavity was first put into the experimental beam line last year, but was not used due to insufficient production rates of ground state antihydrogen. It will be reinstated into the experiment this summer, setting the stage for the first precision measurements of the hyperfine structure of antihydrogen.

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