Development of a charged-particle accumulator using an RF confinement method

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1 Introduction

The ultimate goal of the development of a superconducting radio-frequency charged-particle accumulator is to trap a large number of antiparticles (antiprotons and positrons), and to produce a large quantity of antimatter.

Antihydrogen atoms have recently been produced using Penning traps with magnetic fields of a few tesla [1, 2]. We here propose a method of producing cold antihydrogen in the 1s ground state by simultaneously confining antiprotons and positrons in a radiofrequency Paul trap [3]. The method has the following advantages enabling high-precision laser and microwave spectroscopy experiments,

1. *point-like antihydrogen source*, radiofrequency fields cause positrons and antiprotons with the lowest energies to fall into a millimeter-sized region at the trap center. This point-like region can be easily irradiated by strongly-focused laser beams, thereby achieving the high photon densities needed to efficiently induce radiative recombination and formation of antihydrogen, and deexcitation to its ground state,
2. *Zero magnetic field*, these antihydrogen atoms are unperturbed by the Zeeman effect as they are produced in a zero magnetic field,
3. *Extraction of antihydrogen*, the antihydrogen are emitted from the trap through numerous openings between its electrodes, and can be used to carry out in-flight antihydrogen experiments,
4. *Selectivity of the 1s state, and antiproton/positron recycling*, only ground-state antihydrogen are emitted, as atoms in the higher-lying states are ionized by the strong RF fields near the edges of the trap; antiprotons and positrons emerging from the ionization are recaptured by the trap, cooled, and recycled to form antihydrogen again,
5. *Compact design*, the trap is relatively small ($\sim$ 20 cm diam) as it requires no superconducting magnet.

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2 First successful demonstration of a cryogenic superconducting RF cavity operating at 30-MHz-scale frequencies and MV/m-scale fields.

Figure 1 shows a normal-conducting (copper) model of the linear Paul trap. Antiprotons will be trapped at the center of the four-rod electrods. These electrodes, together with the double-helical coils[*1] placed on both sides, form an *LC* resonator, resonating at 30 MHz.

Based on this copper model, we constructed a superconducting RF test cavity made of high-purity niobium (Figs. 2,3,4) using advanced electron-beam welding, vacuum brazing, and surface cleaning techniques. By placing the cavity in a liquid helium cryostat, cooling it to temperature $T = 4.2$ K, and exciting it with a high-power amplifier, we achieved the nominal RF field needed to trap antiprotons.

To our knowledge, this is the first time a superconducting RF cavity has been operated at the 30-MHz range with such a high field; most previous superconducting cavities work at much higher (200 MHz to several GHz) frequencies. Effects due to multipactoring (i.e., resonant discharge between the

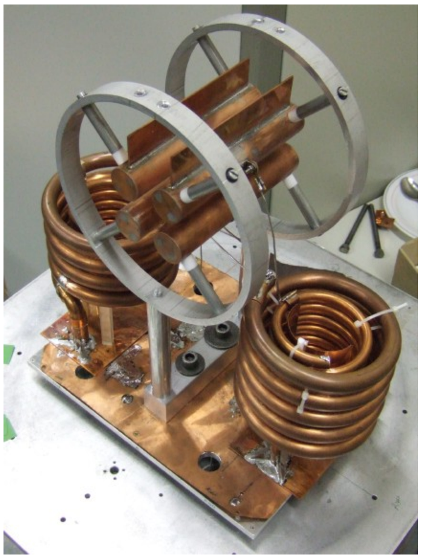

Figure 1 A normal-conducting (copper) model of the linear Paul trap (final version).

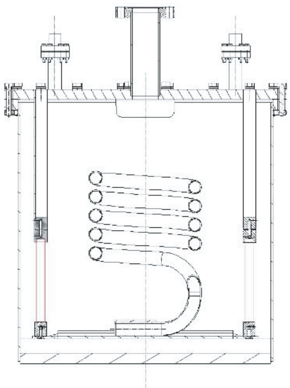

Figure 2 A drawing of the test RF cavity.

Figure 3 Cryogenic superconducting niobium test cavity being cleaned by water jet and assembled in a clean room at CERN.

[*1] The coils are in fact hollow, so that superfluid helium can flow through the coils to cool down the trap system.

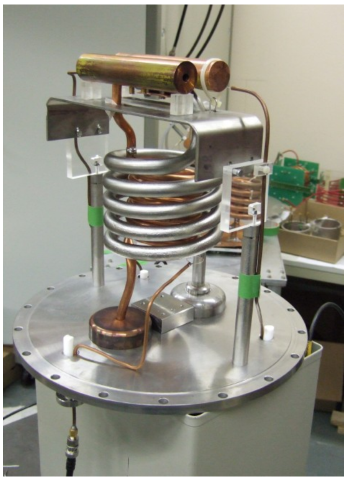

Figure 4 The completed superconducting test cavity, ready to be installed in a helium cryostat for low-temperature, high-power test.

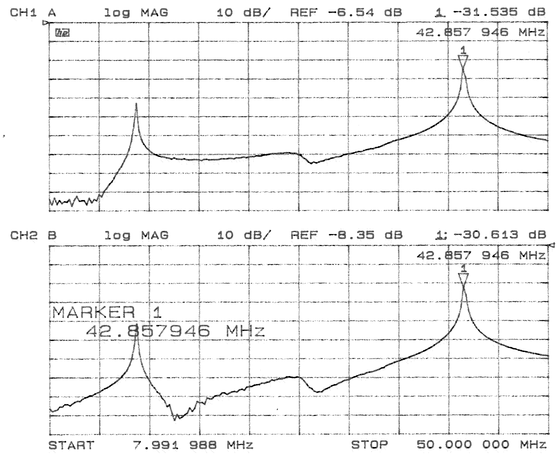

Figure 5 Measurement of Quadrupole resonance and resistive cooling dipole resonance in the test cavity.

cavity surfaces leading to a breakdown of the superconductivity) and microphonic vibrations (caused by liquid helium bubbles vibrating the cavity walls and perturbing the resonance frequency), which could in principle compromise the performance of the cavity, were found to be small. This success validated the basic design of the superconducting Paul trap, and allowed us to proceed to the next step of manufacturing the final trap which will confine antiprotons.

3 Completion of the Paul trap design, and start of manufacture

In 2005, we started to make engineering drawings of the production model of the Paul trap system. We chose a cubic vacuum enclosure of approximately $1 \times 1 \times 1$ m^3, since the flat walls make it easier to interface the trap to the antiproton injector, the positron source, and to the antihydrogen spin analyzer. The result of the stress analysis performed on the 2005 model (Figure 6)however showed that such a design would result in too much wall deformations when evacuated, making it difficult to meet the EU safety standards for large-volume vacuum vessels.

In 2006, we therefore made significant changes to the mechanical design, as shown in Fig. 7. The vacuum enclosure is now a 1-m-diameter cylinder, and the stress analyses verified that the safety standards can be satisfied with this design.

Figures 8 and 9 compare 3-dimensional cross-sectional drawings of the 2005 design (left) and 2006 (right). All technical details have been fixed after careful considerations, simulations, and consultations with CERN experts. Some of these details include a vacuum chamber compatible to a pressure $P < 10^{-12}$ mb, a cryogenic system which cools the traps to 1.8 K, low energy antiproton and positron transport beamlines, and the superconducting RF systems. For example, a mechanical simulation

(Fig. 7) was carried out to determine the optimum construction of the 1-m-diam vacuum chamber, such that the mechanical deformation in each vacuum port when evacuated would be minimized The Paul traps, including all vacuum and cryogenic systems, are now being constructed. We plan to carry out the first tests with particle trapping in 2008, after extensive cryogenic and RF tests.

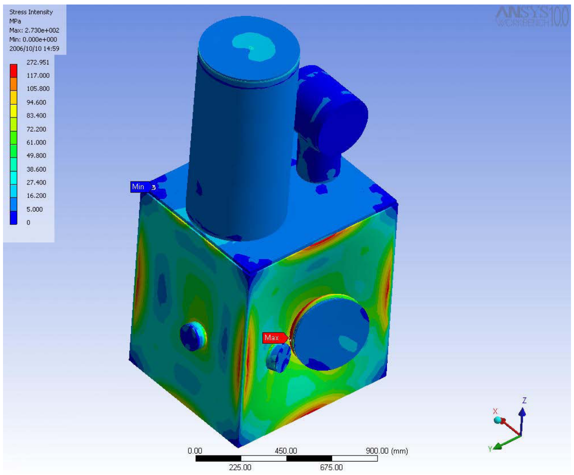

Figure 6 Mechanical stress simulations on the 1-m-cube Paul trap vacuum chamber (version 2005).

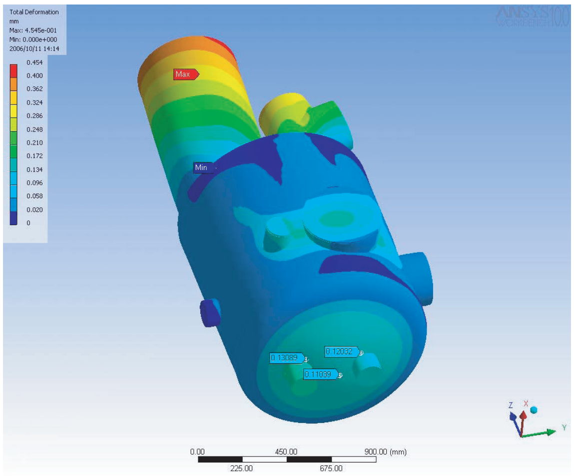

Figure 7 Mechanical stress simulations on the 1-m-diam Paul trap vacuum chamber (version 2006).

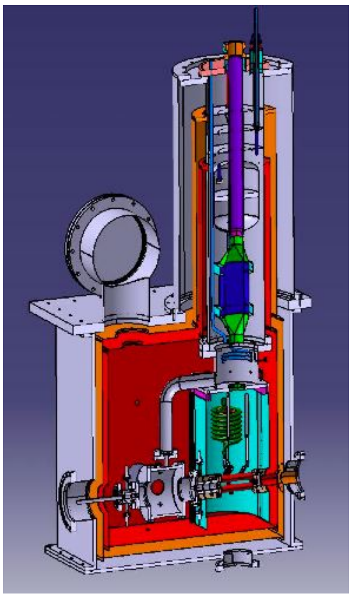

Figure 8 Cutaway view of the RF trap system (version 2005).

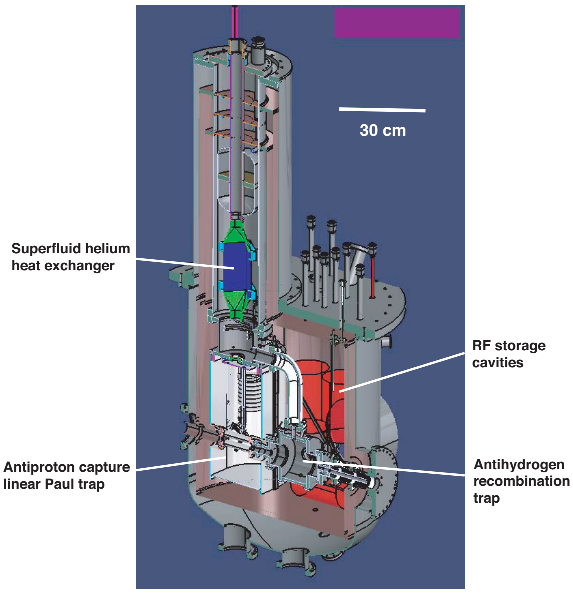

Figure 9 Schematic drawing of two radiofrequency Paul traps now under construction (version 2006).

4 Development of a new superconducting cavity fabrication method

The test superconducting cavity (Fig. 4) was made of pure niobium. Fabricating the intricate hollow coil structure using electron-beam welding however has been very time consuming. Many iterations were needed as we found small vacuum leaks in the coils. We have therefore started to develop an alternative method to make the superconducting cavity based on the niobium sputtering technology. In this method, the mechanical structure (Fig. 10) is made of copper (much easier to machine, weld, etc., as compared to pure niobium, which is very brittle), the parts will be put in a large vacuum chamber (Fig. 11), and niobium will be sputtered on the cavity surface by using an ion source (Fig. 12). The preparation is underway, and the development of this technique is one of the major milestones for 2007.

Figure 10 The radiofrequency cavity made of copper. By sputtering niobium on the inner surface, this cavity will become superconducting at the superfluid helium temperature.

Figure 11 A large vacuum chamber is being prepared to sputter niobium onto the cavity.

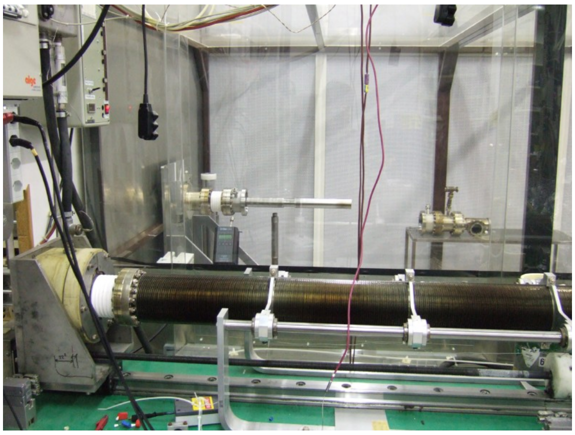

Figure 12 The ion source which we will use to sputter niobium onto the copper electrodes.

5 Development of a power-injection scheme for the spherical RF trap

Figure 13 shows a normal-conducting model of the two-frequency spherical Paul trap used for antihydrogen synthesis. By applying two different frequencies, positrons and antiprotons will be simultaneously trapped at the center of this trap.

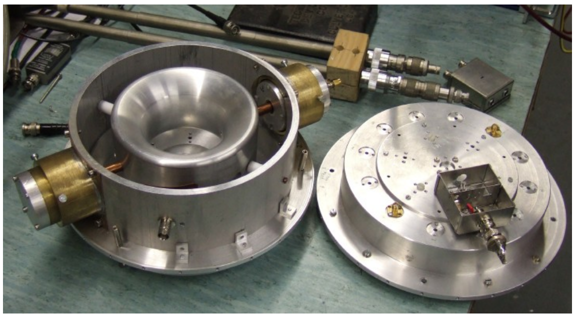

Figure 13 A spherical trap for antihydrogen synthesis (normal-conducting model).

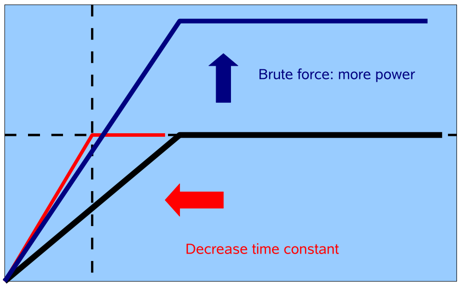

Figure 14 A large power supply would be necessary to achieve fast power injection using the brute-force method. We instead plan to use a fast switch to inject RF power from a storage cavity.

One of the critical issues of Paul traps is how to inject particles from outside of the trap. Once the radiofrequency power is applied to the cavity, the particle-confining potential prevents the particles to escape, but at the same time, the same potential prevents particles to get in to the trap from outside. It would be possible to circumvent this problem if we can switch on the radiofrequency power after a cloud of particles is brought into the cavity. In reality, this is a non-trivial task, especially for positrons (which have large velocities), since it is necessary to fill the cavity with full RF power within 100 ns before they escape.

If we were to use a brute-force method of connecting the cavity to a high-power RF source, a megawatt scale amplifier would be needed to achieve this goal. The large power of the amplifier will be completely wasted after the first 100 ns, since the average power needed to operate the trap is only a few watts. We have instead developed a scheme which uses a storage cavity and a fast diode switch. In this scheme, an RF cavity, similar in RF characteristics to the Paul trap but simpler in construction, is connected to the Paul trap through a PIN diode switch.

Figure 15 shows the PIN-diode switching test results at room temperature (left) and at liquid nitrogen temperature (right), for various bias voltage settings (100, 200, and 800 V). For each oscilloscope screen capture, the upper trace is the RF voltage in the storage cavity while the lower trace is that for the trap cavity. As shown, fast ($<$ 100 ns) injection of the RF power from the storage cavity to the trap

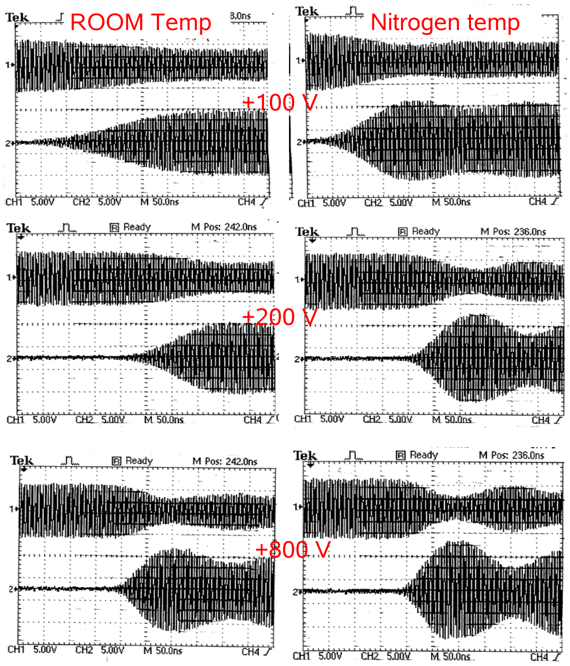

Figure 15　PIN diode switching test results at room temperature (left) and at liquid nitrogen temperature (right), for various bias voltage settings (100, 200, and 800 V). For each oscilloscope screen capture, the upper trace is the RF voltage in the storage cavity while the lower trace is that for the cavity.

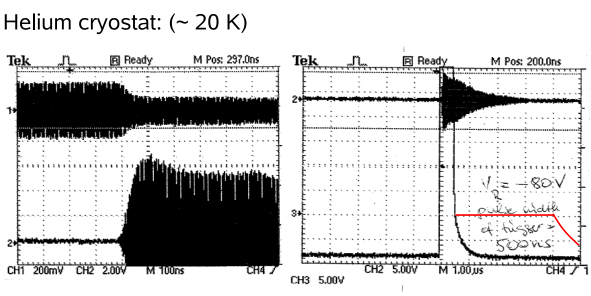

Figure 16　PIN diode switching test result at 20K.

cavity can be realized even at liquid nitrogen temperature (77 K), if sufficient bias voltage is applied to the PIN diode. Note however that there appears a transient ripple (oscillatory behavior of power going back and forth between the two cavities) at low temperature and at high bias voltage.

The same test was conducted at a much lower temperature of 20 K, and the result is shown in Figure 16. The test result is satisfactory, although the carrier lifetime in the PIN diode is much shorter at this temperature (the left panel of Fig. 16); at higher temperatures, carrier lifetimes of several microseconds were observed as indicated by the red curve.

Th oscillatory transient behavior after switching can be compensated by using two diodes instead

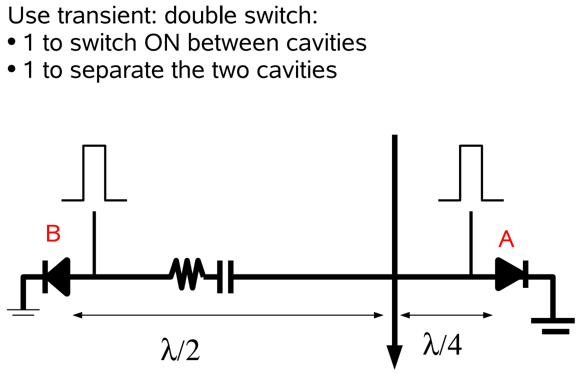

Figure 17 The double-diode switching scheme.

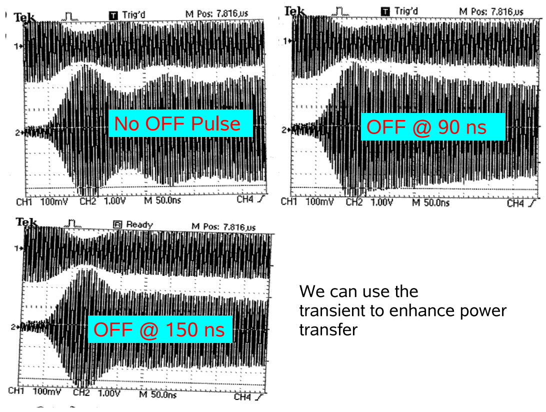

Figure 18 The result of the double-diode switching test. The transient oscillatory behavior can be compensated.

of one, connected as shown in Fig. 17. Here, the first diode is used to connect the two cavities, and the second diode is used, after some delay, to isolate the cavities, preventing the RF power to oscillate between the two. The results of the two-diode test are shown in Fig. 18. As shown, if the delay is properly adjusted (in this case 90 ns), the transient oscillatory behavior can be almost completely eliminated. Note that the tests were conducted by using normal-conducting cavities, which causes the monotonic decrease of the RF power stored in the cavity (see, e.g., top-right panel of Fig. 18). This decay should of course be eliminated in the superconducting cavities, which are under construction.

6 Conclusions

The following table compares the 2006 milestones (as stated in the sow) and the current project status.

2006 Milestones	Status
Test RF Cavity, Construction and Test	Successfully completed
Finalizing the vacuum vessel design.	Design has been completed
Fabrication of the niobium parts for the trap	Pure niobium vs sputtering on copper further R&D needed
Spherical RF trap fast power injection	A scheme has been developed

As shown. we have completed all essential design, test, and development work for the trap, and have in fact started the construction of the outer vacuum vessel. We have however found that making pure-niobium parts, in particular the intricate hollow coil structure, is very time consuming. Many iterations were needed to make them vacuum-leak tight. CERN experts on superconducting cavities have shown in the past that the pure-niobium is a much better solution. This is why we constructed the test cavity using pure niobium. However, since (i) our cavity is mechanically much more complex than the superconducting cavities ever fabricated at CERN or elsewhere, and (ii) our operating frequency is much lower than the CERN accelerator cavities (make the cavities less sensitive to the surface treatment), we have come to conclude that it makes sense to pursue the alternative fabrication technology of niobium sputtering on copper. This additional R&D will be conducted in 2007, while we continue to construct the outer vacuum vessel (the parts unaffected by this extra-R&D decision).

References

[1] M. Amoretti et al., Nature 419 (2002) 456.

[2] G. Gabrielse et al., Phys. Rev. Lett. 89 (2002) 213401.

[3] W. Paul, Rev. Mod. Phys. 62 (1990) 531.