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Experiment on Electron Confinement in a Strong Magnetic Quadrupole Superposed with an Electric Octupole

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Introduction

Combination of a magnetic quadrupole (cusp) with an electric octupole (MCEO) has been experimentally proved to form a trap of non-neutral electron plasma[1,2). These previous experiments were carried out at the magnetic field strength less than 0.05 T, which was too low to study behaviours of trapped electrons under cyclotron radiation cooling. A new trap with a super-conducting quadrupole magnet has been completed recently for further study. Experiments using this trap are first performed on electron confinement in a warm bore to establish the control of particle accumulation in the trap and also to clarify dynamics of electrons trapped in a high magnetic field such as particle diffusion across the magnetic field and cooling by cyclotron radiation. Then, the experiment will proceed to trap ions in an electric self-field induced by confined electrons. Through these experiments it is expected to explore the possibility of antihydrogen synthesis from cold positrons and antiprotons in this field configuration. If cold antihydrogen atoms are synthesised, they come out as a focused spin-polarised beam from the trap[3).

Here is the demand for the future application that antiprotons loaded into the trap should be cooled by preloaded positrons under cyclotron radiation cooling via. Coulomb collisions with each other. The confinement time of the positrons has to exceed this cooling time. This report describes a preliminary experiment concerning the confinement of electrons in the new trap instead of positrons. It is experimentally demonstrated that the confined electron plasma keeps itself isolated from the surrounding wall for much longer than the cooling time estimated under a necessary condition.

Cusp-trap

The super-conducting quadrupole magnet with the bore radius of 16 cm generates ~3.5 T at 15 cm from the plane of symmetry, i.e., midplane, on the axis and its maximum field gradient is 35 T/m. The spatial distribution of the field gradient enables the extraction of a focused spin-polarised beam of antihydrogen atoms in the ground state when they are synthesised. Figure 1 shows magnetic field lines inside an aluminium vacuum tube of the inner diameter of 13 cm and also the arrangement of electrodes producing an electric octupole. The centre of the magnetic cusp coincides with that of the octupole at the midplane on the axis. The dimensions of the electrodes and the voltage allocation on them are optimised so as to make a wide region of octupole in the space enclosed by the electrodes, *i.e.*, $|z|<4.6$ cm and *r*<4.6 cm. Another set of electrodes, which are noted as ion reflectors in Fig.1, are set to repel ions back to the trap region when they are loaded. In the present experiment, these reflectors are biased equal to those of their nearest octupole electrodes. The system is evacuated with a turbo-molecular pump down to the vacuum pressure of 2×10^{-7} Pa.

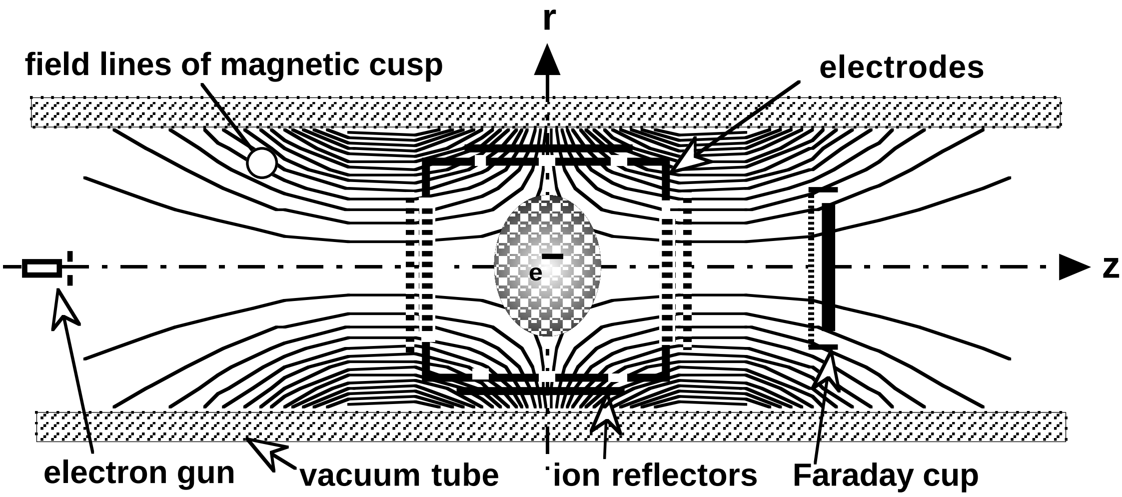

Fig.1 Cross-sectional view of the experimental setup. Field lines of the cusp and the positioning of the electrodes are shown. Pulsed electron beams are injected from the left side and the Faraday cup is on the other side.

Injection, confinement and dump of electrons

Electron beams are produced with a tiny electron gun set outside the trap on the axis (Fig.1). A burst of pulsed electron beams, each of which has the pulse width of 40 μs and the current of about 10 μA, are injected into the trap along the axis. Synchronously to each beam pulse, the potential on the injection side is made shallower to introduce the beam into the trap as shown in Fig.2(a). Electrons are thus stacked and then confined, where the octupole electric field blocks electron leakage along magnetic field lines. In this stage, the combination of the magnetic cusp and the electric octupole forms an MCEO trap for non-neutral electron plasma (Fig.2(b)). At an elapsed time, the electrons are dumped out of the trap by changing the potential distribution (Fig.2(c)). A half of the dumped electrons are collected with the Faraday cup that is installed on the other side to the electron gun (Fig.1).

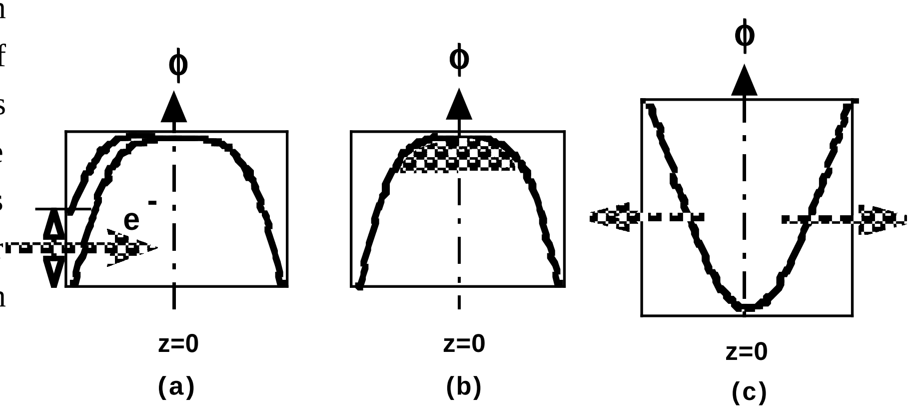

Fig.2 Electric potential distributions, ϕ, along the axis, z, at (a) electron injection, (b) confinement and (c) dump.

Time evolution of confined electron number

The trapped electrons are localized around the centre of the trap in a quite earlier phase after the injection, and then they change their spatial distribution towards an equilibrium one. The field strength near the centre is not so strong to withstand the expansion of trapped electrons due to their space charge, so that the equilibrium density distribution becomes like a paraboloid. This evolution had been observed in the previous experiment[2)]. In practical cases, the periphery of the trapped electrons is not sharply bounded and may be diffusive. Such an ensemble of electrons gradually expands across the magnetic field lines, being caused either by collisions with the residual molecules or by fluctuations in the plasma. Finally, the outward tail of the plasma touches the electrodes and its particle loss becomes faster. Therefore, the time evolution in the totally confined electron number, N, strongly reflects the global behaviour of the trapped electrons.

Figure 3 shows examples of the decay of N for different initially stacked numbers of electrons, N_0. Here, the magnetic field at the radial inner surface of the electrodes is B_E=0.7 T and the well depth of the octupole potential is 33.7 V. In the case of N_0=2.9x10^7, N is nearly constant until the time t_c~ 300 s and then begins to decay. This turning time t_c becomes shorter as N_0 increases, e.g., t_c ~160 s for N_0=7.6x10^7. Such a flatness of N with time means that the plasma is confined without touching the electrode surfaces, so that there is no particle loss. However, the plasma is gradually expanding and it contacts with the electrode wall at t~t_c . Velocity shear of a non-neutral plasma becomes larger with higher plasma density in this trap and internal fluctuations may come out, because the magnetic field is highly non-uniform. The observed shortening of t_c with N_0 may be caused by the enhancement of plasma diffusion with the fluctuations.

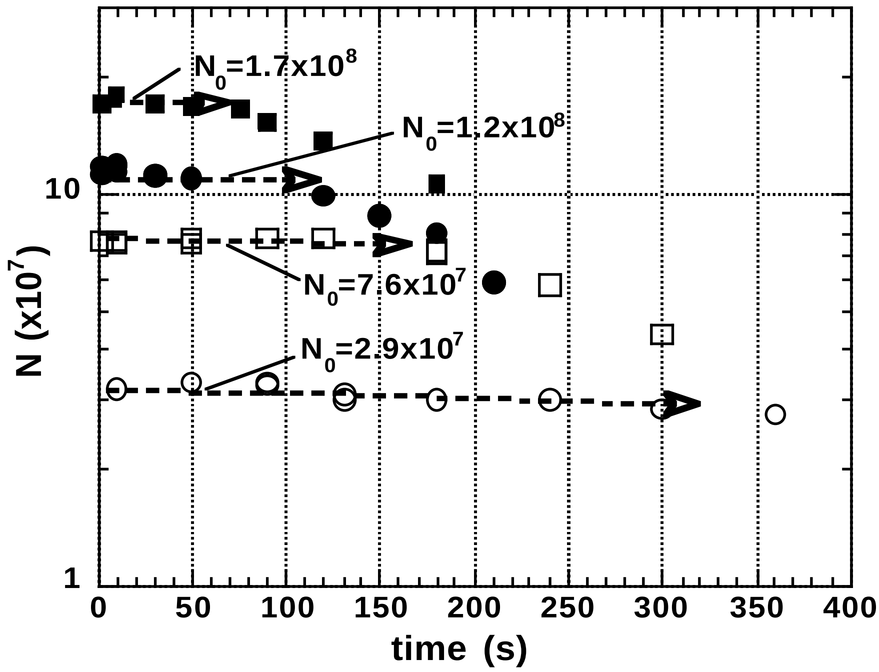

Fig.3 Time variation in N for different initial values N_0
Time durations of nearly constant N are shown by arrows.

Electron (positron) cooling of protons (antiprotons)

When antiprotons are injected into the cold positrons which are being confined in MCEO trap, both of the particles gets colder by the cyclotron radiation of the positrons. The cooling time should be sufficiently shorter than a realizable confinement time. In the other words, the cooling time has to be much shorter than the turning time t_c explained above. Here is roughly estimated the time variation in the temperature of protons, T_p, and also that of the electron temperature T_e using parameters as the volume of electron plasma V_e and the loaded number of protons N_p .

We shall consider the case such that $T_e(0)$=1 meV, N_0=7x10^7, $T_p(0)$=2 eV, N_p=1x10^6, V_e=14 cm^3 and the magnetic field of 0.7 T that is an effective strength for cyclotorn cooling in the new MCEO trap. The cooling rate of electrons by cyclotron radiation is assumed to obey the scaling expressed as 6/B^2[T][4], A result obtained by numerically solving the equipartition equation is shown in Fig.4. The electron temperature T_e rises up by the proton loading while T_p quickly goes down. Both T_e and T_p reach an equi-temperature within 0.2 s and then they fall down continuously. This result suggests that the time length necessary for cooling both of the particle is shorter than 100 s. On the other hand, experimentally obtained turning time for N_0=7.6x10^7 is t_c ~160 s, which is sufficiently longer than the cooling time. Therefore, it may be said that the confinement of electrons in the CMEO trap can satisfies an essential demand needed for the future application to antihydrogen synthesis.

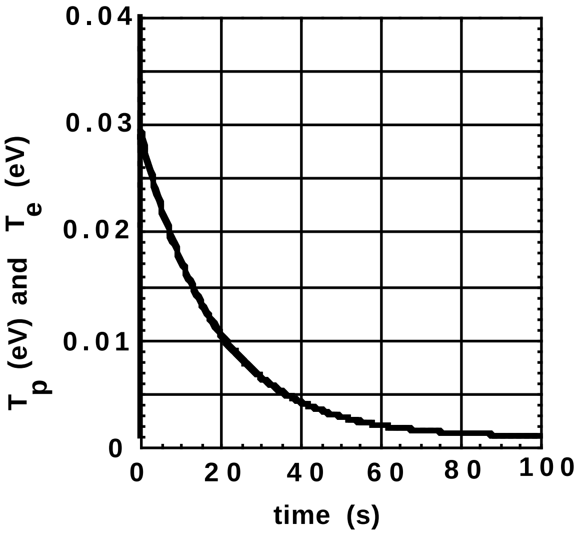

Fig.4 T_p (t) and T_e (t) after loading 1x10^6 protons of 2 eV into 7x107 electrons of 1 meV.

References

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