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A Method of Positron Plasma Formation Using Electron LINAC

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Trapped non-neutral positron plasmas have been utilized as cold positron sources to suit various experiments such as annihilation, positronium production, synthesis of antihydrogen, production of pair plasma and cooling of highly charged ions. Here is reported a basic experiment using pulsed electron beams to simulate a new accumulation method of intermittent positron beams, which are produced through photon-positron conversion of gamma rays generated with an electron linac. This method is suitable for experiments to evade positron annihilation since the operation can be performed thoroughly in high vacuum environment.

Accumulation of cyclic pulsed positron beams

We shall consider positron accumulation in a Penning trap characterised as harmonic potential well(HPW), of which the well depth and the axial length are V_w and $2L$, respectively. In the early stage of the accumulation, the charge of trapped positrons is too small to deform the trap field. Positrons with mass m and charge e take bounce oscillations in the trap with the period $\tau_H = L\sqrt{m/(2eV_w)}/2\pi$ or the frequency $f_H = 1/\tau_H$. To capture the whole of an injected beam in the trap region, its pulse width τ_b should be shorter than τ_H, i.e., $\tau_b < \tau_H$. A longer and shallower well is necessary for beams of larger τ_b .

The potential barrier on the injection side is lowered by δV_w in the time of beam injection and then returned back to the normal potential. Here, $e\delta V_w$ should be set larger than the spread in the beam energy. To realise perfect catching of incident beams, decrease in their beam energies in the interval of injection $\tau_{inj} = 1/f_{inj}$ is required to be larger than $e\delta V_w$. There are some candidates to damp the beam energy, such as Coulomb collisions with preloaded electrons, attachment of a resistive wall and time-control of the well depth.

As the accumulation proceeds, the trapped positrons behave as a non-neutral plasma, when the spatial distribution of the potential is deformed due to the charge of accumulated positrons. The duration in which an injected beam returns back to the incident position, τ_r, may be different from τ_H. In this case, the requirement for the perfect beam catching is written by $\tau_b < \tau_r$. To achieve the accumulation of a large number of positrons, a deep potential well is required for trapping them, while the effective well depth should be kept shallow to hold the requirement $\tau_b < \tau_r$. Here, Automatic or preset control of $V_w(N)$ corresponding to the accumulated positron number N will become necessary .

Experimental simulation using pulsed electron beams

To simulate the accumulation of pulsed positron beams, experiments on pulsed electron beam injection were carried out using a multi-ring trap (MRT), which is composed of axially aligned 31 electrodes of 9 cm inner diameter and a superconducting solenoid generating the uniform magnetic field of 1.5 T over 60 cm, as shown in Fig.1(a). [1]

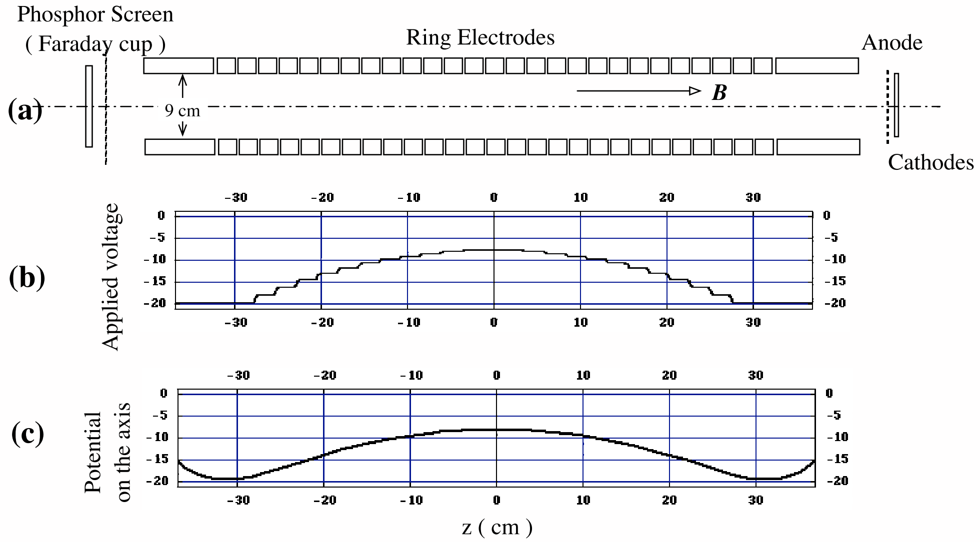

Figure 1: (a) Schematic view of alignment of ring electrodes of the MRT. (b) Allocation of voltages applied on electrodes. (c) Produced potential on the axis.

An axially 58 cm long harmonic potential well (HPW) was formed (Fig1(c)), into which pulsed electron beams were injected in 100 Hz repetition. A single pulsed beam was a bundle of 20 beam strings extracted from 20 tiny cathodes connected in parallel. The edge potential of the well was changed synchronously to every incidence of beam, as illustrated in Fig.2. Each beam had the pulse width of 300 ns, the energy spread of 1.4 eV and 2×10^6 electrons.

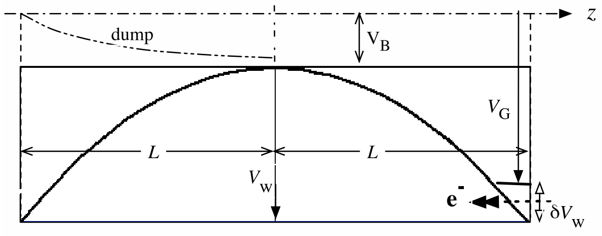

Figure 2: Potential control of the MRT. Potentials at beam injection, holding and dump are depicted.

- Single pulse injection -

A single beam pulse was injected into the trap, where $V_w = 10\,\text{V}$, $\delta V_w = 1.4\,\text{V}$ and the gate open time was 400 ns, The trapped electron number N was measured by dumping the electrons

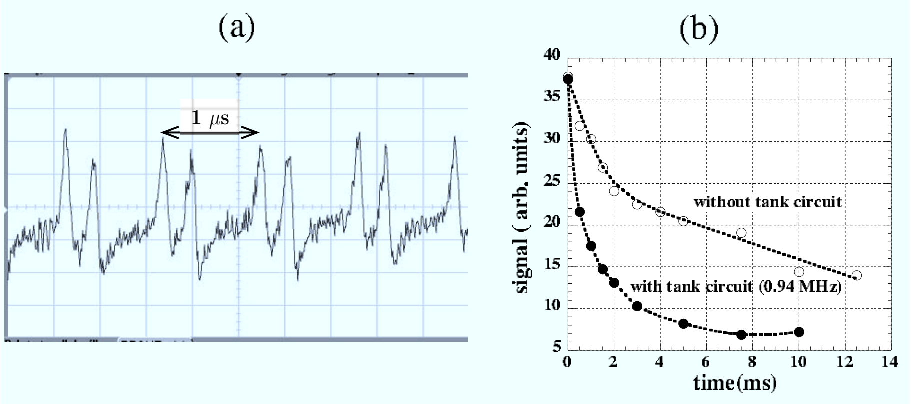

Figure 3: (a) Detected signal of the bounce oscillation. (b) Damping of the oscillations for the cases without and with the tank-circuit.

onto the Faraday cup (see Fig.1). The electrons of a single beam were thoroughly caught and oscillated at the bounce frequency $f_H = 940$ kHz. Figure 3(a) shows the oscillation signal taken 4.5 μs after the injection and its amplitude decayed as shown in Fig.3(b). The oscillation continued for a fairly long time, during which a transition from the bounce motion of the injected beam blob to an oscillation of a trapped electron cloud, like the electrostatic mode (1,0), probably occurred.

When a tank-circuit, which resonated at f_H with Q$\sim$ 50, was connected to one of the electrodes, the decay of the oscillation became drastically faster as shown in Fig.2(b). Although the coupling between the electrode and the electrons was weak, there was seen a clear effect on the damping. More faster damping is expected if more electrodes are used to get better coupling. This result shows that so-called 'resistive wall' effectively works to decrease incident beam energy.

- Multiple injection -

Pulsed electron beams were injected in the repetition of 100 Hz, where the external potential configuration was the same as noted above. Here, the ratio of the stacked electron number by the n-th injection, ΔN_j, to the electron number of the incident beam, N_b, i.e., $\Delta N_j/N_b$, was taken as a measure to see the stepwise increment in trapped electron number at each injection.

When the beams were injected without installing the tank-circuit, the ratio $\Delta N_j/N_b$ lay under 20% and the total number N increased slowly as $\sim 4\times 10^5$/pulse. If an injected beam cannot sufficiently decrease its energy within the repetition period τ_{inj}, a fraction of the beam electrons leak out of the trap at the next opening of the gate potential. Whence the attainable accumulation efficiency remains below 100%. In the above case, the energy distribution of the injected beam was nearly flat with the spread width of 1.4 eV($\sim \delta V_w$). The result shows that electrons with energies above 0.3 eV were not damped to be trapped in τ_{inj} and lost.

In order to verify if the accumulation was improved by decreasing the energies of beam electrons after trapped, the potential well was externally deepened with time. In this operation, trapped electrons decreased their potential energies, that is equivalent to the energy decay by damping.

The well depth was ramped by linearly decreasing at the rate $dV_B/dt = 100\,\text{V/s}$ (see Fig.2). The other parameters were the same as previously noted. Figure 4 shows the obtained results. The ratio $\Delta N_j/N_b$ was about 70% at the early stage and then gradually increased by repeating the injection. In the experimental condition that $\delta V_w = 1.4$V, the ramping step in one cycle was 1V and the energy spread of the incident beams was nearly flat, the estimated ratio coincides with the observed 70%. The observed increase in $\Delta N_j/N_b$ in the later phase shows that damping was enhanced through interactions between a newly injected electrons and those trapped in advance. After 30 repetitions, the ratio reached 100% and N became 1.5×10^8.

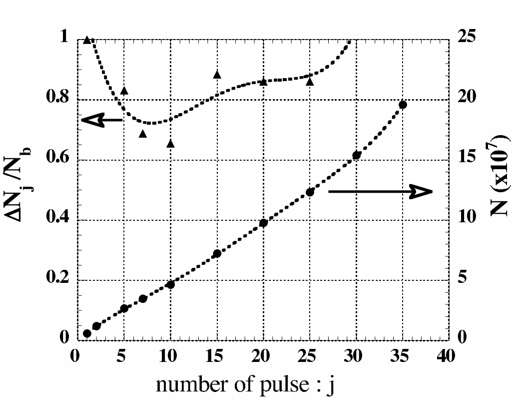

Figure 4: Left ordinate: $\Delta N_j/N_b$ at j-th injection, where ΔN_j is the stacked electron number by the jth injection and N_b is the electron number of the incident beam. Right ordinate: total number N stacked with the repetition.

Experiments described here suggest how to accumulate a large number of positrons in a harmonic trap by the use of an electron linac.

We can propose a method that adopts the following means ;

- Use of a strong magnetic field to increase the Brillouin density limit and to enable fast cyclotron cooling of trapped positrons.
- Control of the well depth to keep the bounce period long enough to catch injected beam as well as to enable the confinement of a large number of positrons.
- Preload of electrons to induce Coulomb collisional damping at the early stage.
- Additive enhancement of damping with an effective resistive wall.

References

[1] J. Aoki, Y. Kiwamoto and Y. Kawai, Phys. Plasmas **13**, 102109 (2006).