Simultaneous confinement of low-energy electrons and positrons in a compact magnetic mirror trap

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Abstract

More than $10^7$ electrons and $10^5$ positrons with energy less than a few eV were confined simultaneously for the first time in a compact magnetic mirror trap with plugging potentials. The exponential decay time constant of the confined positrons exceeded 70 ms at the beginning of the simultaneous confinement. Particle simulations in the early stages of the mixing process were also conducted. The results obtained in the experiments and simulations suggested that an improved setup would make it possible to investigate the unexplored field of low-energy electron–positron plasmas experimentally.

1. Introduction

High-energy electron–positron plasmas are expected to play important roles in astrophysical objects such as pulsar magnetospheres, black holes, and so on [1]. Thus, high-energy electron–positron plasmas have been studied theoretically for many years, which also stimulated experimental studies of electron–positron plasmas. About forty years ago, the use of a high-energy electron beam impinging on a high-Z material target for pair creations of high-energy electrons and positrons to be confined in a magnetic mirror device was proposed [2]. In addition, high-energy positrons emitted from radioactive nuclei ($^{19}$Ne) were confined in a magnetic mirror [3]. Unfortunately, trials to confine high-energy electron–positron plasmas have not been successful so far. Meanwhile, the production of electron–positron jets with high-intensity lasers has become an active area of research [4] and it was reported recently that high-density ($\sim 1.8 \times 10^{16} \text{ cm}^{-3}$) electron–positron pair plasmas were created with a high-intensity laser [5]. Although these plasmas had short time scales, they led to further investigations on high-energy density electron–positron plasmas in laboratories.

On the other hand, a confined low-energy electron–positron plasma is expected to have different energies ($\leq 10$ eV), densities ($\leq 10^7 \text{ cm}^{-3}$) and time scales ($\geq 10$ ms). Various techniques have been pursued to obtain a large number of low-energy positrons. For examples, metal moderators (Cu, W, Ni, etc.) of single and polycrystals and rare gas (Ne, Ar, Kr, Xe) solid moderators have been investigated with various geometries [6]. A nitrogen buffer gas cooling made it possible to accumulate a large number of low-energy positrons in a Penning–Malmberg trap [7, 8]. Today, more than $10^8$ low-energy positrons, which behave as a non-neutral plasma, are routinely accumulated with the use of $\sim 50$ mCi $^{22}$Na radio isotope (RI) source, a solid Ne moderator [9], $N_2$ buffer gas and rotating electric fields [10–12]. Similar positron accumulators are used for the production of anti-hydrogen atoms in the Antiproton Decelerator at CERN. They are also used for atomic physics research [13, 14]. However, the simultaneous confinement of low-energy electrons and positrons has not yet been realized.

In the case of ordinary electron–ion plasmas, different masses of components result in complicated dispersion relations and the rich phenomena observed so far. For a pair plasma that has equal masses of positive and negative charged particles, the dispersion relation becomes simpler. However, much theoretical research suggests that unique features can be observed in pair plasmas [15–24]. Nevertheless, experimental studies have
been limited to the observations of electrostatic oscillations in a positron plasma; electron beam interaction [25], and streaming pair fullerene ion plasmas [26–28]. Therefore, experimental studies with a confined electron–positron plasma will be important for the further understanding of pair plasmas. In fact there are projects that have tried to confine low-energy electron–positron plasmas with a magnetic dipole field [29] and a stellarator [30].

Here, the simultaneous confinement of low-energy (approximately a few eV) electrons and positrons in a compact magnetic mirror trap is reported. Although the mixture of these electrons and positrons was not regarded as an electron–positron plasma, this is a first step for experimental investigations on confined electron–positron plasmas.

2. Experiments

2.1. Experimental setup

The experimental setup is composed of a low-energy positron accumulator and a compact magnetic mirror trap. The details of the low-energy positron accumulator have been reported previously [31] and it is the device similar to that developed by the UCSD group [7–9] except for the intensity of the RI source. In short, ~5 mCi $^{22}$Na with a solid Ne moderator and a $N_2$ buffer gas cooling system were used to accumulate ~2 × 10^6 positrons in 120 s by applying a rotational electric field. The accumulator provided a few eV positron pulse with a pulse width less than 10 μs. A retractable electron gun was also installed at the end of the positron accumulator.

A schematic diagram of the compact magnetic mirror trap is shown in figure 1(a), which is connected to the positron accumulator through the gate valve (GV). The base pressure is better than $3 \times 10^{-10}$ Torr. Two pairs of coils are used to provide the magnetic field and the field strength on the axis of symmetry is plotted in figure 1(b). The inner coils provide the magnetic mirror field with a mirror ratio $R$ slightly larger than 5, which means that the volume of loss cones in the velocity space is less than 10%. The magnetic field provided by the outer coils guides electrons and positrons into the magnetic mirror trap when they are injected from the accumulator, and also guides them to a multi-channel plate (MCP $\phi \sim 40$ mm) with a Faraday cup for measurements. Since the field strength at the MCP is about 120 G, it covers the radial extent of $\phi \sim 30$ mm at the center of the magnetic mirror. Therefore, the number of trapped particles measured with the MCP is underestimated when trapped particles exist outside this region. Also, two NaI scintillators with a photomultiplier (PM) are placed at the gate valve (PM1) and the center of the confinement region (PM2).
In the past, a similar magnetic mirror trap was used to accumulate positrons aimed at the confinement of electron–positron plasmas [32]. With the use of a 600 μCi $^{22}$Na R1 source and a $W$ moderator, continuous low-energy positrons were injected along the magnetic field into a magnetic mirror. Since the application of 100 W cyclotron resonance heating was necessary for the accumulation of axially injected positrons, the confined $10^4$ positrons were heated up to $\sim$9 keV.

The unique feature of the present compact magnetic mirror trap is that it contains ten ring electrodes (U1-U5, and D1-D5) inside the magnetic mirror and four cylindrical electrodes (U6, U7, D6 and D7) outside the magnetic mirror. The ring electrodes have an inner diameter of 80 mm and an axial length of 14 mm, except for U1 and D1, which have a length of 25 mm. The cylindrical electrodes have an inner diameter of 56 mm and an axial length of 90 mm. The potentials on these electrodes are controlled synchronously with a time constant of 1 μs, except U6, which has a time constant of 0.3 μs for catching a positron pulse. Various potentials provided by these electrodes enable catching and confining an injected positron pulse without cyclotron resonance heating. It also means that a pulse injection of low-energy positrons is the key for avoiding the application of cyclotron resonance heating for accumulating positrons in a magnetic mirror.

The basic confinement properties of this compact magnetic mirror trap were tested with electrons and reported in our previous paper [33]. The confinement time (or the exponential decay time constant) $\tau_c$ was about 140 s for $\sim 10^8$ electrons with a harmonic potential inside the magnetic mirror. When the electrodes were grounded for the magnetic mirror confinement, the number of electrons decreased from $10^8$ to $2 \times 10^7$ within a few ms due to the space potential of the electrons. Then, trapped electrons decreased exponentially with $\tau_c \sim 40$ ms in a simple magnetic mirror confinement. When plugging potentials were applied to cylindrical electrodes U6 and D6 (or U7 and D7), the confinement became a kind of electrostatic confinement and $\tau_c$ became longer than a few hundred ms. Although the confinement time of $\sim 40$ ms in the magnetic mirror was not long, axial electrostatic oscillations in the few MHz range were observed with $2 \times 10^7$ electrons. These results suggested that this compact magnetic mirror could potentially be used to confine electron–positron plasmas if a similar number of positrons could be confined in the device.

2.2. Experimental results

At first, positrons were confined in a similar manner to the previous experiments with electrons except that the magnetic field strength was about twice. Shown in figure 2(a) is the number of positrons as a function of time confined in a harmonic potential inside a magnetic mirror. The exponential decay time constant is about 58 s, which is less than half compared with that of electrons. This is partly because the vacuum pressure goes up to $2 \times 10^{-9}$ Torr when the GV is opened for 2 s to inject a positron pulse. It takes more than 30 s to recover the base pressure. It is also plausible that the injected positron pulse was not aligned well along the axis of symmetry.

Also shown in figure 2(b) is the number of positrons confined in a magnetic mirror after 5 s confinement in a harmonic potential inside a magnetic mirror. The confinement time is more than 100 ms, which is longer than that of electrons measured previously. It is thought that the space charge is reduced due to the smaller number of trapped positrons.

For the simultaneous confinement of electrons and positrons, the experimental procedure becomes as follows. Firstly, electrons are injected for 5 s with GV opened and confined in the potential denoted by the dashed line in figure 1(c). The vacuum pressure goes up to $\sim 1 \times 10^{-8}$ Torr. Then, the potential is changed to the solid line depicted in the same figure to inject a positron pulse. In fact, it was found that the catching potential should not be a harmonic one, but a flat one, to maximize the number of trapped positrons. This is probably because the bounce time of positrons becomes longer for a flat potential. When $\sim 2 \times 10^6$ positrons are injected, the potential on U6 is grounded and put back to a positive one (the solid arrow in figure 1(c)) to confine
positrons. About 18 ms later, the potential inside the magnetic mirror is grounded for the mixing of electrons and positrons, as shown in figure 1(d). During the confinement with the plugging potentials for both electrons and positrons, electrons accumulate at the positive plugging potentials through collisions with background neutrals (mostly N\textsubscript{2}). After a certain holding time, the confined positrons are extracted with the potential shown in figure 1(e) to measure the number of positrons at the MCP. Although, a few mV signal of positrons can be measured without the MCP, it is used to improve the signal-to-noise ratio. An independent measurement can be performed to measure the number of electrons confined inside the magnetic mirror with the potential (dotted line) shown in figure 1(f). It is also possible to measure independently the number of electrons accumulated in one of the positive potentials made by the electrode D6 with a potential shown by the solid line in figure 1(f). Subtracting the former signal from the latter one, the number of electrons accumulated in a positive potential can be deduced. Assuming that the same amount of electrons are accumulated in the positive potential made by the electrode U6, the total number of electrons can be estimated.

In figures 3(a) and (b), the output signals of PM1 and PM2, are plotted as a function of time for the simultaneous confinement of electrons and positrons with the plugging potentials. Red signals are background without injecting a positron pulse. (c) The number of positrons (solid circles) and electrons (red squares) extracted to the MCP, where \( t = 0\) ms corresponds to the start of mixing with plugging potentials. Red triangles are the estimated total electron number with those accumulated in the positive plugging potentials. Shown in (d), (e) and (f) are the similar data sets when electrons are confined with plugging potentials, while positrons are confined with a quasi-magnetic mirror.

![Figure 3](image-url)

Figure 3. The output signals of PM1 and PM2 are shown in (a) and (b), respectively, for the simultaneous confinement of electrons and positrons with the plugging potentials. Red signals are background without injecting a positron pulse. (c) The number of positrons (solid circles) and electrons (red squares) extracted to the MCP, where \( t = 0\) ms corresponds to the start of mixing with plugging potentials. Red triangles are the estimated total electron number with those accumulated in the positive plugging potentials. Shown in (d), (e) and (f) are the similar data sets when electrons are confined with plugging potentials, while positrons are confined with a quasi-magnetic mirror.
3. Simulations

Simulations with a particle-in-cell (PIC) code Warp [34] were also conducted to understand the initial stages of the mixing process. Warp has been used to predict and study various non-neutral plasma experiments and phenomena [35–39]. As a matter of course, the electrodes inside the vacuum chamber and the magnetic mirror field shown in figures 1(a) and (b) are included in the simulations. Although simulations are performed with various parameters, the results presented here correspond to the experimental procedure with the plugging potentials shown in figure 1. Other results will be reported elsewhere.

At first, $2 \times 10^7$ electrons in a harmonic potential and $10^7$ positrons in a flat potential near thermal equilibrium are prepared inside the magnetic mirror, as shown in figure 1(c). Here, $10^4$ macroparticles were used for both electrons and positrons with different weights of 2000 and 10, respectively. The time step was $5 \times 10^{-11}$ s to resolve the cyclotron motion at a maximum field of about 1500 G. After the electrons and positrons were prepared, the harmonic potential for the electrons was flattened in accordance with the experimental procedure, i.e. electrodes inside the magnetic mirror were grounded linearly in 1 μs. This potential variation starts at $t = 0.05$ μs and finishes at 1.05 μs. Then, the calculation continued until 10 μs, for which a calculation time of more than 5 d was necessary with a single core processor. Unfortunately, a long calculation time prevents us from investigating phenomena like diocotron oscillations and curvature drifts, which have long time scales of milliseconds. On the other hand, the short simulation time of 10 μs makes sense in that collisions can be ignored, since the collisions between charged particles and those with background $N_2$ buffer gas are not included in the PIC simulations presented here.

Shown in figures 4(a1)–(a4) are the potentials on the axis of symmetry with the space potential of confined charged particles. Also, shown in figures 4(b1)–(b4) are the macroparticle distributions for both electrons and positrons projected on the x–z plane. The macroparticle distributions of electrons projected on the phase space $z$–$v_z$ are shown in figures 4(c1)–(c4) and those for positrons are shown in figures 4(d1)–(d4). The color scales are normalized by the peak value of each figure. Each column in figure 4 corresponds to the time $t = 0, 1, 2$ and 5 μs from the start of mixing. At the beginning, most of the electrons are localized in the harmonic potential and positrons occupy the left half space ($z < 0$) inside the magnetic mirror, as seen in figure 4(b1). When the potentials on electrodes inside the magnetic mirror approach 0 V at $t = 1$ μs, the electrons expand towards

Shown in figure 3(c) are the number of electrons (red squares) and positrons (solid circles) as a function of holding time during the mixing with plugging potentials. In figure 3(c), $t = 0$ ms corresponds to the start of mixing and positrons with plugging potentials. Also shown by red triangles are the estimated total electron number with those accumulated in the positive plugging potentials, which is almost constant at $\sim 2.5 \times 10^7$. It is observed that $\tau_e$ of positrons is about 76 ms up to $t \sim 40$ ms from the beginning of simultaneous confinement. Then, the annihilation of positrons is enhanced and $\tau_e$ becomes $\sim 13$ ms. Meanwhile, $\tau_e$ of electrons stays at $\sim 30$ ms. Since the enhancement of the annihilation signal after $t = 60$ ms is not observed at PM1 but observed only at PM2, a simple speculation is that an off-axis injection of positrons resulted in the enhancement of the radial diffusion of positrons through a diocotron instability inside the magnetic mirror. Unfortunately, the reason for the observed instability in the simultaneous confinement with plugging potentials is unknown, which should be investigated in future experiments.

Although the radial profiles of trapped charged particles were not measured in the experiments, rough estimates of the density and Debye length of an electron cloud are possible by assuming the uniform cylindrical distribution of an electron column with a diameter of $\sim 30$ mm (which is measurable with the MCP) and an axial length of 60 cm (between plug potentials for electrons), which gives the minimum density of $\sim 5 \times 10^4$ cm$^{-3}$ at $t = 0$ ms. The corresponding Debye length is about 3.3 cm for 1 eV. This rough estimation suggests that the confined electrons behave as a plasma in the axial direction. However, it is marginal in the radial direction.

Shown in figures 3(d), (e) and (f) are the similar data set for another example of simultaneous confinement. In this case, electrons are confined with plugging potentials at U7 and D7, while positrons are confined with a quasi-magnetic mirror by grounding the potential at D6. The timing sequence is almost the same in figures 3(d) and (e). The positrons are injected at $t = 10$ ms and the mixing starts at $t \sim 28$ ms until the positrons are extracted to the MCP at $t \sim 93$ ms. In this case, a large number of positron annihilations are also observed right after the positron injection. However, there is no enhancement of positron annihilation during the mixing duration of 65 ms. The number of confined positrons is decreased due to the magnetic mirror confinement on the MCP side, and it decays exponentially with the reduced $\tau_e \sim 27$ ms, as denoted by solid circles in figure 3(f), where $t = 0$ ms corresponds to the start of mixing. This means that a certain number of positrons are confined by positive plugging potentials in the simultaneous confinement with plugging potentials. The number of electrons confined by a plugging potential decreases exponentially with $\tau_e \sim 38$ ms.
$z < 0$, as seen in figure 4(c2). Trapped charged particles move in a clockwise direction in the projected phase space $z - v_z$, which is schematically shown by red arrows in figure 4(c4). In addition, the expanded electrons occupy the region surrounded by a certain magnetic flux surface inside the magnetic mirror (figure 4(b2)). The red dashed lines in figure 4(b4) represent a magnetic flux surface calculated from the magnetic field in figure 1(b). In fact, this axial adiabatic expansion of electrons results in a lower axial electron temperature at $t = 2 \mu$s, which is favorable for magnetic mirror confinement. It is also confirmed in figure 4(c3) that only a fraction of electrons escapes from the magnetic mirror and reflected back at the negative plugging potentials. This means that most of the electrons are confined by the magnetic mirror. Since there are many more electrons than positrons, a negative space potential is created inside the magnetic mirror, as seen in figure 4(a4). The vertical axis in figure 4(a4) is magnified ten times to see the space potential of about $-0.3$ V.

The advantage of simulation studies on the present magnetic mirror confinement is that it is easy to understand the particle distributions in the velocity space. In figures 5(a1)–(a4), the macroparticle distributions of electrons projected on the $v_x$–$v_z$ plane are shown and those of positrons are shown in figures 5(b1)–(b4). Each column in figure 5 also corresponds to the time $t = 0, 1, 2$ and $5 \mu$s from the start of mixing. White dashed lines in figures 5(a4) and (b4) represent the loss cone boundaries with a loss cone angle of about $26.6^\circ$ for $R \sim 5$. It should be noted that the vertical scale is half the horizontal one. In the case of electrons, it is clearly seen that the axial temperature decreases by grounding the harmonic potential at the beginning and that only a small amount of electrons are left inside the loss cones. Then electrons start axial oscillations, whose frequency depends on the
energy of trapped electrons. On the other hand, the distribution of positrons in the velocity space stays almost the same, except for the slight axial oscillations at the beginning. Compared with the distribution of electrons in figure 5(a4), that of positrons extends in a much wider velocity region, as in figure 5(b4). It is thought that positrons are trapped not only by the magnetic mirror field but also with the plugging potentials. Although the space potential of $-0.3 \text{ V}$ created by excess electrons can confine positrons with velocity less than $\sim 0.3 \times 10^6 \text{ m s}^{-1}$, it is seen in figure 5(b4) that the space potential has little effect on the confinement of positrons in the simulation with experimental parameters.

The results of the simulation suggest that a larger number of positrons should be accumulated in the harmonic potential inside the magnetic mirror to confine more positrons in a magnetic mirror without plugging potentials.

4. Prospects of low-energy electron–positron plasmas in a magnetic mirror

The mixtures of electrons and positrons reported here are not regarded as electron–positron plasmas because the diameter of the charged cloud is comparable to the estimated Debye length. However, it is thought that further improvements will lead to experimental studies on low-energy electron–positron plasmas in a magnetic mirror trap. Firstly, the stronger magnetic mirror field of a few T with a superconducting magnet will improve the confinement of positrons in a harmonic potential inside the magnetic mirror and enable the stacking of many pulses of positrons. A 50 mCi $^{22}$Na RI source, instead of $\sim 5$ mCi in this report, will also improve the positron accumulation, which will reach more than $10^8$ positrons in a harmonic potential inside a magnetic mirror. The density of positrons will increase accordingly. Since it was demonstrated that the application of the rotational electric field to a non-neutral plasma in a magnetic field gradient resulted in an increase in the density by radial compression [40], the technique will make the confinement time even longer and improve the reproducibility of the experiments. In addition, the initial loss of injected positrons will be suppressed. Furthermore, it is thought that the temperature of the charged particles becomes less than 0.1 eV through cyclotron radiation due to the strong magnetic field. On the whole, it is thought that the Debye length will be less than 1/10th of the present value.

In addition, the extra vacuum chamber for the retractable electron gun between the positron accumulator and the compact magnetic mirror will reduce the harmful effect of the $N_2$ buffer gas in the compact magnetic mirror. A longer confinement time with a strong magnetic field and a rotational electric field will be also helpful for the system to recover the base pressure of $\sim 10^{-10} \text{ Torr}$ after injecting a positron pulse. When the base pressure is recovered before mixing electrons and positrons, the particle loss from a magnetic mirror will not be dominated by the collisions between charged particles and $N_2$; the collisions between charged particles will be important. Since the collision frequency is proportional to the density, it is thought that the collisions between...
trapped charged particles will limit the highest density for the magnetic mirror confinement. In fact, a simple estimation suggested that the density of $\sim 10^6$ cm$^{-3}$ at 0.1 eV resulted in the collision frequency of $\sim 100$ Hz [41]. For the purpose of increasing the density more by reducing the collision frequency, heating up electrons and positrons may work. Then a density of $\sim 10^7$ cm$^{-3}$ at 1 eV may be possible with $\sim 100$ Hz collision frequency.

5. Summary

The simultaneous confinement of $10^6$ electrons and $10^5$ positrons with energies less than a few eV was demonstrated experimentally in a compact magnetic mirror trap with plugging potentials. It was confirmed that the confinement time in the early phase of the mixing process exceeded 70 ms for positrons. In addition, it was observed that an instability resulted in the radial diffusion of positrons inside the magnetic mirror.

PIC simulations for the mixing process with the experimental configurations were also performed. It was inferred that preparing more positrons in the harmonic potential is necessary to confine more positrons inside a magnetic mirror without plugging potentials.

The use of a stronger magnetic field with a superconducting magnet will be necessary to realize the experimental study of electron–positron plasmas in a compact magnetic mirror trap.

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References

[1] Goldreich P and Julian W H 1969 Pulser electrodynamics Astrophys. J 157 869
[2] Begelman M C, Blandford R D and Rees M J 1984 Theory of extragalactic radio sources Rev. Mod. Phys. 56 255
[3] Sakai J and Kawata T 1980 Waves in an ultra-relativistic electron–positron plasma J. Phys. Soc. Japan 49 747
[4] Tsytomchuk V and Wharton C B 1978 Laboratory electron–positron plasma—A new research object Comm. Plasma Phys. Control. Fusion 4 91
[5] Gibson G, Jordan W C and Lauer E J 1963 Particle behavior in static, axially symmetric, magnetic mirror and cusp geometries Phys. Fluids 6 116
[6] Chen H et al 2015 Scaling the yield of laser-driven electron-positron jets to laboratory astrophysical applications Phys. Rev. Lett. 114 215001
[7] Sarri G et al 2015 Generation of neutral and high-density electron–positron pair plasmas in the laboratory Nat. Commun. 6 6747
[8] Schultz P and Lynn K G 1988 Interaction of positron beams with surfaces, thin films, and interfaces Rev. Mod. Phys. 60 701
[9] Surko C M, Leventhal M and Passner A 1989 Positron plasma in the laboratory Phys. Rev. Lett. 62 901
[10] Murphy T J and Surko C M 1992 Positron trapping in an electrostatic well by inelastic collisions with nitrogen molecules Phys. Rev. A 46 5696
[11] Greaves R G and Surko C M 1996 Solid neon moderator for positron-trapping experiments Can. J. Phys. 74 445
[12] Huang X-P, Anderegg F, Hollmann E M, Driscoll C F and O’Neill T M 1997 Steady-state confinement of non-neutral plasmas by rotating electric fields Phys. Rev. Lett. 78 875
[13] Anderegg F, Hollmann E M and Driscoll C F 1998 Rotating field confinement of pure electron plasmas using trivelpiece–gould modes Phys. Rev. Lett. 81 4875
[14] Greaves R G and Surko C M 2000 Inward transport and compression of a positron plasma by a rotating electric field Phys. Rev. Lett. 85 1883
[15] Greaves R G and Surko C M 1997 Antimatter plasmas and antihydrogen Phys. Plasmas 4 1528
[16] Surko C M and Greaves R G 2004 Emerging science and technology of antimatter plasmas and trap–based beams Phys. Plasmas 11 2333
[17] Danielson J R, Dubin D H, Greaves R G and Surko C M 2015 Plasmas and trap-based techniques for science with positrons Rev. Mod. Phys. 87 247
[18] Iwamoto N 1993 Collective modes in nonrelativistic electron–positron plasmas Phys. Rev. E 47 6704
[19] Zank G P and Greaves R G 1995 Linear and nonlinear modes in nonrelativistic electron-positron plasmas Phys. Rev. E 51 6079
[20] Verdun M W and Melrose D B 2008 Wave dispersion in a counterstreaming, cold, magnetized, electron–positron plasma Phys. Rev. E 77 046403
[21] Moslem W M 2011 Langmuir rogue waves in electron–positron plasmas Phys. Plasmas 18 032301
[22] Shukla P K, Eliasson B and Stenflo L 2011 Electromagnetic solitary pulses in a magnetized electron–positron plasma Phys. Rev. E 84 037401
[23] Jao C-S and Hau L-N 2012 Formation of electrostatic solitons and hole structures in pair plasmas Phys. Rev. E 86 056401
[24] Saberian E and Esfandyari-Kalejahi A 2013 Langmuir oscillations in a nonextensive electron–positron plasma Phys. Rev. E 87 053112
[25] Jao C-S and Hau L-N 2014 Electrostatic solitary waves and hole structures generated by bump-on-tail instability in electron–positron plasmas Phys. Rev. E 89 033104
[26] Helander P 2014 Microstability of magnetically confined electron–positron plasmas Phys. Rev. Lett. 113 135003
[27] Chatterjee D and Misra A P 2015 Nonlinear landau damping and modulation of electrostatic waves in a nonextensive electron-positron-pair plasma Phys. Rev. E 92 063110
[28] Greaves R G and Surko C M 1995 An electron–positron beam–plasma experiment Phys. Rev. Lett. 75 3846
[29] Ooshara W, Date D and Hatakeyama R 2003 Electrostatic waves in a paired fullerene–ion plasma Phys. Rev. Lett. 95 175003
[27] Oohara W and Hatakeyama R 2007 Basic studies of the generation and collective motion of pair-ion plasmas Phys. Plasmas 14 050704
[28] Oohara W, Kuwabara Y and Hatakeyama R 2007 Collective mode properties in a paired fullerene-ion plasma Phys. Rev. E 75 056403
[29] Saitoh H, Stanja J, Stenson E V, Hengenhahn U, Niemann H, Sunn Pedersen T, Stoneking M R, Piochacz C and Hungenschmidt C 2015 Efficient injection of an intense positron beam into a dipole magnetic field New J. Phys. 17 103038
[30] Sunn Pedersen T, Danielsen J R, Hungenschmidt C, Marx G, Sarasola X, Schauer F, Schweikhard L and Surko C.M 2012 Plans for the creation and studies of electron-positron plasmas in a stellarator New J. Phys. 14 035010
[31] Higaki H, Kaga C, Nagayasu K, Okamoto H, Nagata Y, Kanai Y and Yamazaki Y 2015 A low energy positron accumulator for the plasma confinement in a compact magnetic mirror trap Non-Neutral Plasma Physics IX (AIP Conf. Proc. 1668) ed Y Soga, A Sanpei and H Himura (Melville, NY: AIP) 040005
[32] Boehmer H, Adams M and Rynn N 1995 Positron trapping in a magnetic mirror configuration Phys. Plasmas 2 4369
[33] Higaki H, Sakurai S, Ito K and Okamoto H 2012 Nonneutral electron plasmas confined in a compact magnetic mirror trap Appl. Phys. Express 5 106001
[34] Friedman A, Grote D P and Haber I 1992 Three-dimensional particle simulation of heavy-ion fusion beams Phys. Fluids B 4 2203
[35] Peinetti F, Peano F, Coppa G and Wurtle J 2006 Particle-in-cell method for parallel dynamics in magnetized electron plasmas: study of high-amplitude BGK modes J. Comput. Phys. 218 102
[36] Gomberoff K, Fajans J, Wurtle J, Friedman A, Grote D P, Cohen R H and Vay J-L 2007 Simulation studies of non-neutral plasma equilibria in an electrostatic trap with a magnetic mirror Phys. Plasmas 14 052107
[37] Gomberoff K, Fajans J, Friedman A, Grote D P, Vay J-L and Wurtle J 2007 Simulations of plasma confinement in an antihydrogen trap Phys. Plasmas. 14 102111
[38] Higaki H, Fukata K, Ito K, Okamoto H and Gomberoff K 2010 Density and potential profiles of non-neutral electron plasmas in a magnetic mirror field Phys. Rev. E 81 016401
[39] Takeuchi H, Fukushima K, Ito K, Moriya K, Okamoto H and Sugimoto H 2012 Experimental study of resonance crossing with a Paul trap Phys. Rev. Accel. Beams 15 074201
[40] Saitoh H, Mohri A, Enomoto Y, Kanai Y and Yamazaki Y 2008 Radial compression of a non-neutral plasma in a cusp trap for antihydrogen synthesis Phys. Rev. A 77 051403(R)
[41] Higaki H 2005 On the possibility of non-neutral antiproton plasmas and antiproton-positron plasmas Physics with Ultra Slow Antiproton Beams (AIP Conf. Proc. 793) ed Y Yamazaki and M Wada (Melville, NY: AIP) 351