Lossless Positron Injection into a Magnetic Dipole Trap

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The high-efficiency injection of a low-energy positron beam into the confinement volume of a magnetic dipole has been demonstrated experimentally. This was accomplished by tailoring the three-dimensional guiding-center drift orbits of positrons via optimization of electrostatic potentials applied to electrodes at the edge of the trap, thereby producing localized and essentially lossless cross-field particle transport by means of the $E \times B$ drift. The experimental findings are reproduced and elucidated by numerical simulations, enabling a comprehensive understanding of the process. These results answer key questions and establish methods for use in upcoming experiments to create an electron-positron plasma in a levitated dipole device.

The nucleation and trapping of small-Debye-length electron-positron plasmas would enable novel laboratory studies of pair plasmas, which dominated the early universe during the lepton epoch (1 to 10 s after the Big Bang), are still found in astrophysical settings, and are predicted to have properties significantly different from those of standard electron-ion plasmas [1–6]. A fundamental challenge is the development of a scheme that allows efficient injection and subsequent confinement of both species. Injection and trapping of particles with a single sign of charge is well established in linear traps, which are used, for example, in the mass determination of unstable nuclei [7], in solvation studies of ionic species in water clusters [8], and in precision measurements of antimatter [9]. While linear traps can contain positrons and electrons simultaneously [10, 11], this has not yet been demonstrated with both species achieving plasma densities in the same volume. Toroidal traps with closed magnetic field lines, such as the stellarator [12, 13] and the levitated dipole [14–16], more readily confine positive and negative charges simultaneously, but injection from outside these devices is inhibited by the same physics that traps particles inside: electron-ion plasmas are typically ionized within the confinement region. Inward transport into a dipole due to turbulent interactions at high particle densities has been demonstrated for an electron beam [17]; however, typical particle densities of positron beams are well below the threshold for such collective interactions [18]. Additionally, the relatively small margin between the available flux of positrons and the amount needed to nucleate a plasma [19] necessitates that manipulation techniques for positrons strictly minimize losses. Therefore, electron-positron plasma experiments involving toroidal devices [19–21] require that efficient injection methods be developed and verified.

Earlier numerical studies indicated that $E \times B$ drifts can transport particles into and out of a stellarator [22]. Experimental demonstration of positron injection into a prototype dipole trap was recently achieved with 38% efficiency, as was subsequent trapping [23]. We now report essentially lossless injection into that same device (Fig. 1), with a detailed analysis based on numerical simulations of both these and earlier experiments. This is a significant step towards studies of confined electron-
positional plasmas, which we seek to realize by accumulating orders of magnitude more positrons into pulses [24], then injecting these (and electrons) into a levitated dipole trap [25].

As shown in Fig. 1a, the confining magnetic field is generated by a neodymium permanent magnet (0.6 T at its poles), housed in a copper case and mounted with its dipole moment oriented vertically [23]. The outer wall, which has been divided into eight lower sections (1/8 each) and two upper sections (1/8 and 7/8), acts as a limiter, determining the size of the confinement region. (In a levitated dipole trap, the confinement region comprises closed field lines not touching any material objects; in the prototype trap, it comprises field lines intersecting only the magnet.) Low-energy charged particle motion in the trap is well described by guiding center theory [26, 27].

The center of the cyclotron orbit moves back and forth along the magnetic field with the effective potential energy \( U = q \phi + \mu B \), where \( \mu \equiv m v_{\perp}^2 / (2B) \) is an adiabatic invariant (with \( q, m \) and \( v_\perp \) being particle charge, mass, and velocity perpendicular to the magnetic field \( B \); \( \phi \) being the electrostatic potential; and \( B = |B| \)). Additionally, the guiding center drifts across the magnetic field at the rate \( v_{\phi, \perp} = B \times \nabla U / (qB^2) + mv_{\perp}^2 B \times \nabla B / (qB^3) \). Confined orbits consist of periodic motion at three well-separated times scales: cyclotron orbits, magnetic mirroring, and slower toroidal drift around the magnet — i.e., 80 MHz - 4 GHz, 1-10 MHz, and 1-100 kHz, respectively, for 5-eV positrons in a grounded trap (\( \phi = 0 \)).

The challenge is to transport particles onto these trapped orbit from an external source; this is accomplished by tailoring \( U(r) \) via optimization of \( \phi(r) \) (where \( r \) is spatial position).

The NEutron-induced POsitron source MUniCh (NEPOMUC), operated at the Research Neutron Source Heinz Maier-Leibnitz (FRM II), produces a nearly monoenergetic, high-brightness beam with an energy of \( \sim 5 \) eV, a temperature of \( \sim 2 \) eV, a spatial extent of \( \sim 3 \) mm (FWHM), and a typical flux of \( \sim 2 \times 10^7 \) positrons/s (3 pA) [28-30]. A magnetic guiding field (5 mT) transports the positrons to the dipole trap, installed at the open beam port and mated to the beam line by a set of Helmholtz coils. Positrons enter the experiment from above, along field lines connecting to the top of the magnet; the magnet’s axis is parallel to but not coaxial with the Helmholtz coils. On either side of these field lines are rectangular plates biased to \( \pm V_{E \times B} \), creating an electric field mainly in the \( y \) direction; this leads to the positrons drifting across the magnetic field into the confinement region (as shown in Fig. 1b), due to the \( E \times B \) drift (the contribution to \( v_{\phi, \perp} \) from \( B \times \nabla \phi \)). A third plate, grounded and installed above the magnet, perpendicular to the \( E \times B \) plates, shields the far side of the trap from the injection potential. A 1-cmx1-cm target probe (stainless steel) can be inserted in the equatorial plane of the trap on the opposite side from the injection region, so as to determine the fraction of the beam that has been successfully injected into the confinement region and trapped for a half toroidal transit. The current to the target probe is measured with a charge-integrating amplifier and compared to the full beam current. The \( \gamma \)-radiation from positrons annihilating on the target is measured with a collimated scintillation detector (BGO). Further details can be found in the Supplemental Material [31].

A number of experimental parameters can be varied in order to optimize the injection of positrons into the trap. These include the bias used to produce the cross-field drift \( V_{E \times B} \), the biases applied to the magnet case \( V_{mag} \) and the wall electrodes \( V_{top1}, V_{top2}, \) and \( V_{rw1} \) through \( V_{res} \); see Fig. 1a), and the currents in the steering coils \( (I_r, I_B) \) that adjust the position of the beam right before it enters the main chamber of the experiment. Together these constitute a many-dimensional parameter space, which can be investigated via series of scans, such as the ones shown in Fig. 2a-b. Using this approach, we found conditions that result in the entire positron beam reaching the target probe. This occurs when \( V_{top1}, V_{rw1}, \) and \( V_{mag} \) are set to positive biases greater than the beam energy, the rest of the outer electrode is grounded, and the appropriate \( I_r, I_B, \) and \( V_{E \times B} \) are determined via pa-

![FIG. 2. 2D scans such as these in \( I_r, V_{E \times B} \) were used to experimentally optimize injection conditions into the dipole trap. When biases are applied to electrodes rw1 and top1, and the rest of the wall was grounded (a), high-efficiency injection — up to 100% — is achieved over a large region of the parameter space; this is not possible when all wall electrodes are biased (b). Single-particle simulations have been used to generate a “synthetic diagnostic” that produces good agreement with experiments (c,d). In all panels, the color scale indicates the fraction of the beam that reaches the target probe.](image-url)
(b) -10.0

lossless injection can still be achieved.

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is severely restricted (Fig. 4). Biasing top2 (instead of

ances for high injection efficiencies are found only when

sufficient bias is applied to the top1 and rw1 electrodes.

When either or both of those electrodes is grounded, not

sufficient bias is applied to the top1 and rw1 electrodes.

FIG. 3. Spatial profile measurements are shown for lossless

scintillator (× and +, left axis; “probe out” value subtracted)

and positron flux (solid symbols, right axis; measured with

the charge-integrating amplifier) are each plotted as a func-

tion of target probe position and are in good agreement, as are

synthetic profile measurements from simulations (open sym-

bols). The black line and grey area indicate the average and

standard deviation of measurements of total beam flux im-

mediately upstream of the experiment; these and the vertical

scatter of identical symbols illustrate typical uncertainties.

parameter scans. If instead the entire outer electrode is

biased, the optimization procedure yields a maximum ef-

ciency of ∼ 40% (Fig. 2b), reproducing our earlier work
done with an unsegmented outer electrode [23]. Measure-

ments at different target probe positions indicate where

in the confinement region injected positrons are located
(Fig. 3); these are by nature integrated spatial profiles,

example derivatives of which are plotted in the Supple-

mental Information [31]. Systematic studies of how the
different injection parameters can be used to influence

the mean, width, and height of these profiles have been
done and will be detailed in a separate publication.

Because the peak in Fig. 2a is wide in both $V_{E\times B}$ and

$I_r$, we expect to be able to find efficient injection condi-
tions for beams with larger energy spreads and/or larger

spatial spreads. (The optimal setting of $V_{E\times B}$ is closely

related to the energy of the injected beam; positrons with

more kinetic energy, which move faster along the mag-

netic field lines and therefore spend less time between

the parallel plates, require more $E \times B$ bias to be drifted

by the same amount.) Significantly, these large toler-

ances for high injection efficiencies are found only when

sufficient bias is applied to the top1 and rw1 electrodes.

When either or both of those electrodes is grounded, not

only is the peak injection efficiency lower, but the re-

gion of parameter space in which injection is achievable

is severely restricted (Fig. 4). Biasing top2 (instead of

grounding it) also reduces the tolerances in parameter

space, though this is a comparatively mild effect, and

lossless injection can still be achieved.

So as to enable analyses of loss channels and their eli-

mination, as well as separate examination of the injection

and toroidal drift processes, simulations of the positron

trajectories have been done both with the SIMION soft-

ware package [32, 33] and with AlGeoJ, a home-grown

particle mover that implements a modified leapfrog algo-

rithm in Java [34]. Initial conditions can be generated

as random draws from energy and spatial distributions

matching those measured for the positron beam [30].

Synthetic diagnostics of the simulations produce both

current and count “data” that can then be compared to

experimental measurements, with the initial position of

the beam center as an adjustable parameter. Further de-

tails can be found in the Supplemental Material [31], as

well as in other publications [33, 34]. Injection efficiencies

are reproduced in simulations using voltage and current

settings identical to those used in the experiments.

Individual inspection of particle trajectories illumi-

nates the physics behind the optimal parameter settings

that result in lossless injection into the trap and subse-

quent toroidal transport to the target probe. Positrons

are clearly on trapped particle orbits as they drift around

the magnet and are particularly well-confined when wall

biases are localized to the injection area (Fig. 5a). Simu-

lations of our earlier experiments [23, 33] revealed the two

primary loss channels that limited injection in that con-

figuration to ∼ 40%. First, there was a large loss cone

for particles that did not have sufficient perpendicular
velocity to magnetically mirror before hitting the negatively biased magnet case (~ 40%). Second, enhanced outward transport during the first half toroidal transit resulted in further losses (~ 20%), as shown in Fig. 5b.

Particles are injected into a range of orbits (different radii from the magnet, different energies), due to the beam’s finite spatial and energy spreads, resulting in different rates of toroidal drift (e.g., a particle with the same velocity vector at a smaller radius in a grounded dipole trap goes around more slowly than one at a larger radius, as shown in Fig. 5c). Thus, a particle bunch will spread out within a few toroidal orbits around the magnet. (Note that although particles are lost after a single orbit if \( V_{E \times B} \) is applied steady state, switching off \( V_{E \times B} \) after injection results in trapped particles with confinement times of hundreds [23] to tens of thousands [33, 35] of toroidal transits.)

As mentioned previously, injection that is both lossless and robust across the parameter space is achievable in the prototype trap when both \( r_{w1} \) and \( \text{top}_1 \) are biased. To illustrate why this is, we examine a different plane in the parameter space for injection with \( \text{top}_1 \) and \( \text{top}_2 \) set to the same bias and, more significantly, \( r_{w1} \) grounded. In this case, injection is possible only for small islands in the parameter space (Fig. 6a) with lower efficiency than when \( r_{w1} \) is biased (Fig. 6b). The simulated diagnostic (Fig. 6c) reproduces the key features of the experimental results, and particle trajectories (Fig. 6d) demonstrate that successful injection does not necessarily occur via a single magnetic mirroring event (trajectory 0) but can also follow multiple mirroring events that alternate with electrostatic reflection off the outer wall (trajectories 1, 2). When \( r_{w1} \) is grounded, trajectories that would otherwise have reflected off a biased \( r_{w1} \) to become trapped in the confinement region do not do so; tracking of particle “hit locations” confirms that annihilation on \( r_{w1} \) is indeed a primary loss channel [34].

All of the following are desirable: that injection efficiency be maximized, that the injection region be localized (to enable stacking of pulses, e.g.), and that the “sweet spot” in parameter space be large (to accommodate beams’ spatial and energy spreads, as well as to give more options in terms of which beam settings can be used). There was no guarantee that these conditions could all be met simultaneously, but indeed this is the case. Therefore, \( E \times B \) drift injection is a viable approach that can be incorporated into the design for the levitated dipole experiment [25]. There will be some key differ-
ences from the prototype device (e.g., magnetic field lines of the confinement region will not intersect the magnet), for which the details of the injection scheme will need to be adjusted accordingly; simulations that can reproduce the experimental results in the prototype trap constitute a powerful tool for engineering efficient injection into the levitated trap. Finally, upcoming experiments will extend drift injection — used to date with a steady-state positron beam — for use with one or more pulses of positrons accumulated beforehand in linear traps [24], so as to achieve orders of magnitude more confined positrons in the dipole trap. Although the experiments reported here are in the single-particle regime, the technique can be expected to work well up to densities at which collective behavior of the positrons screens out the injection potentials — that is, near to the goal of achieving plasma densities [18, 22].

In summary, we have shown that a low-density, low-energy positron beam can be injected with ~100% efficiency into the confinement region of a magnetic dipole field. This was done by strategically tailoring the effective potential energy \( U = \phi B + \mu B \) to produce the desired guiding center drifts for realistic beam properties. This finding is essential for plans to produce a confined electron-positron plasma in a laboratory magnetosphere [19–21]. As a further perspective, applying our scheme to trap molecular ions can be conceived; here, it could be used to study cation-anion reactions at low temperatures, which are only accessible with great effort otherwise [36].

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