The Positron Trap — A New Tool for Plasma Physics

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ABSTRACT

We discuss the possibility of using electrostatic trapping techniques to produce a collection of $\sim 10^{10}$ positrons in the form of a single-component, positron plasma with density $n \sim 10^7$ cm^{-3}, temperature ~ 0.2 eV, and particle containment time $\gtrsim 10^2$ sec. Possible uses of such a positron plasma are briefly discussed. They include the injection of bursts of positrons into a tokamak fusion plasma to study the transport of electron-mass charged particles in plasma and investigation of the uniques properties of an equal-mass plasma, such as evolution of the electron-positron beam-plasma instability.

I. Introduction

At a time when positrons continue to play an ever-increasing role in our understanding of the physical world, it is of interest to consider storing slow positrons and the possible uses of the resulting positron plasma. For a collection of classical particles, the criterion for collective behavior in $n\lambda_D^3 > 1$ and $L/\lambda_D >> 1$, where n is the positron density, L the smallest dimension of the system, and $\lambda_D = (kT/4\pi ne^2)^{1/2}$ is the Debye length in cgs units with T the positron-plasma temperature and n the density. A few numbers illustrate that such densities are plausible: If we choose L = 10 cm and T = 1 eV, then for $n \sim 10^6$ cm^{-3}, $\lambda_D = 1$ cm, $L/\lambda_D = 10$ and $n\lambda_D^3 = 10^6$.

Single-component electron plasmas of these densities are now produced routinely using techniques developed recently by the group at the University of California at San Diego.[1,2] For example, in a room-temperature apparatus they achieve densities $n_e \sim 10^8$ cm^{-3}, with temperatures $T_e \sim 0.5$ eV and plasma lifetimes $\gtrsim$300s.

The analogous positron plasma could have a number of interesting applications. For example, perhaps the simplest plasma experiment would be to study the interaction of the positron plasma with an electron beam. The electron beam would act as a means of excitation of positron plasma. It could also serve as a probe of the (non-linear) beam-plasma interaction in that measurement of the fluctuations and changes in the velocity distribution of the exiting beam can yield detailed information about the interaction of the beam with the plasma. Other consequences of an electron-positron plasma have been discussed by Wharton and Tsytovich.[3]

An interesting application of the positron trap described here would be to study the containment and transport of electron-mass charged particles in magnetically-confined fusion plasmas (e.g., a tokamak plasma). In magnetic fusion physics, one of the outstanding problems is the fact that the transport of electrons is much more rapid (e.g., by factors $\gtrsim 10^2$) than one would expect on the basis of classical Coulomb collisions. The electron heat transport is the most significant energy loss mechanism for such plasmas, and, to a large extent, it is likely to determine the criterion for ignition and useful fusion energy output. A positron trap could be used to store positrons from a radioactive source in the time (~5 minutes) between tokamak discharges. During the discharge, the positrons would be converted to a neutral positronium beam and injected into the tokamak plasma, where the positronium would be ionized. The positrons, thus injected and thermalized in times $\lesssim 100$ μs, would then be transported out of the

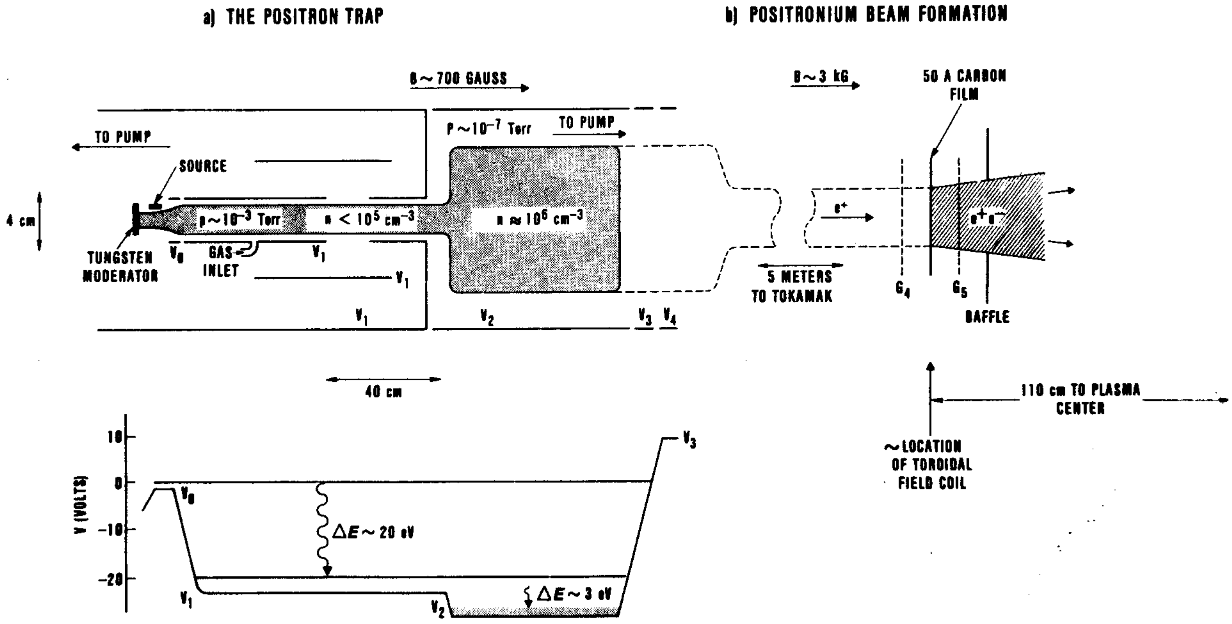

Fig. 1. Conceptual design of an apparatus for positron containment and the formation of a neutral positronium beam: (a) Positrons from a radioactive source (^{58}Co) are moderated in energy by a Tungsten crystal, and drift along the magnetic field into a potential well. Collisions in a high-pressure region ($p \sim 10^{-3}$ torr) provide sufficient energy loss to trap them between guard rings at voltages V_0 and V_3 in one round trip through the trap. Subsequent inelastic collisions trap them in the lower pressure region ($p \sim 10^{-7}$ torr) at potential V_2 in times <1 sec. In this low-pressure region, the containment time is expected to be $>10^2$ sec. (b) During tokamak discharge, the positrons in the trap are accelerated to ~ 1 keV by adjusting the voltages V_3 and V_4. Then the positrons travel to near the tokamak plasma (~ 100 cm from the plasma center), where they impinge on a 50 A carbon foil to form a positronium beam. The resulting burst of positronium atoms consists of a total of about 10^5 atoms with energies ranging from 10 to 10^3 eV in a time $\lesssim 10$ μsec.

plasma on the time-scale for electron transport (~30 – 100 ms). This transport time can be measured directly by the annihilation gamma rays emitted when the positrons strike a limiter. Such an experiment would provide the first direct measure of the transport of electron-mass particles in a tokamak plasma.

The remainder of this article is organized in the following way. In Sec. II we discuss the design of a containment device suitable for efficiently trapping positrons from a continuous positron source (which might be a radioactive source or an accelerator beam stop), and we also describe questions the properties of such a plasma. In Sec. III we describe questions the tokamak experiment might address. Finally, we conclude with some remarks about other possible applications of an efficient positron trap and the resulting positron plasma.

II. The Positron Trap

It is now well established that a uniform, linear magnetic field B ~ 1 kG with electrostatic potentials at the ends can contain a single-component electron plasma for times $\tau_e \gtrsim 10^2$ sec.[1,2] At high neutral gas pressures P, the containment time τ_e is proportional to 1/P and is limited by the combined effects of the radial space charge of the single-component plasma and the cross-field mobility due to electron-molecule scattering. At lowest pressures, τ_e is independent of P. While the limiting mechanism in this regime is not understood, τ_e is large and reproducible in a given geometry and magnetic field. The central point of this article is that such a trapping device will be useful to contain slow positrons, provided we can identify a suitable energy-loss mechanism to efficiently deposit positrons in the trap without disturbing the containment properties of the device.

The conceptual design of such a device is shown in Fig. 1. A ^{58}Co radioactive source emits positrons having a broad spectrum of energies up to 470 keV with a branching ratio for positron production of ~1/7. Thus, for example, a 7 Ci source will produce ~4×10^{10} positrons/sec. A key to this containment scheme is the production of slow positrons with energies ~1 eV. Fortunately, it is known that reflection of energetic positrons emitted by ^{58}Co source from a single-crystal Tungsten surface yields "slow" positrons[4] having energies of 2.5 ± 1 eV with an efficiency ~2×10^{-3}. For the 7 Ci source, this results in a total flux of 8×10^7 slow positrons per second.

As shown in Fig. 1, the slow positrons then enter a trap similar to that used[1] by Driscoll and Malmberg to contain single-component electron plasmas with a magnetic field (B ~ 10^3 Gauss) and guard rings at the ends to apply electrostatic potentials. An energy-loss mechanism is required to trap the continuous flow of positrons from the source. The trap in Fig. 1 shows two such stages: first a section with pressure $\sim 10^{-3}$ torr is used to initially trap the positrons; and then a deeper potential well at ~10–7 torr is used to hold the positrons for long periods -- comparable, for example, to times ~5 minutes between tokamak discharges. A more realistic apparatus would include intermediate stages to minimize the radial diffusion (by minimizing the time spent in the high-pressure regions) and to simplify the problems associated with differential pumping. Voltages on the cylindrical electrodes shown in Fig. 1 determine the electrostatic potentials in the different stages.

The gas species and pressure in the high-pressure region must be chosen so that positrons will be trapped in one transmit through the trap. Elastic scattering and the potential barrier establishing by V_0, could be used to contain the positrons for a number of bounces $N \sim \dfrac{V_1}{E - V_0} \sim 10$, where E is the energy of the injected positrons. Then electronic excitation (e.g., the inelastic cross section for positrons in Ar gas is $\sim 3 \times 10^{-16}\ \mathrm{cm}^2$) can provide the required energy loss. In this case, there will be a loss due to positronium formation[5] of ~2/3. Energy loss via vibrational excitation of molecules would be ideal, since then, the positron energy is below the positronium-formation threshold. However the cross sections for vibrational excitation of molecules are poorly known, and one can probably only count on[6] $\sigma_v \geq 10^{-17}\ \mathrm{cm}^2$. Thus vibrational excitation as an energy loss mechanism will probably be useful only after the first stage (e.g., in the 10^{-7} torr region shown in Fig. 1).

The working gas might be a mixture of Ar and N_2, although in an actual experiment a variety of gases and gas mixtures could be tried relatively easily. The voltage V_2 would be adjusted to inhibit positronium formation in the low-pressure region after the first inelastic collision. For the case of *electrons* in He gas, the lifetime in a low pressure region such as that shown in Fig. 1 is the order of 300s.[1] For the positron case, the efficiency of the trap is estimated to be $\geq 20\%$, thus the total number of positrons trapped in 300 sec from a 7 Ci source is expected to exceed $\sim 5 \times 10^9$. Radial expansion will lead to a plasma diameter ~20 cm, thus the volume plasma will be $\sim 3 \times 10^4\ \mathrm{cm}^{-3}$. Such a plasma might be compressed electrostatically in the longitudinal direction by an order of magnitude and radially by a factor of more than two (by a suitably arranged magnetic field) resulting in a plasma density $\sim 10^7\ \mathrm{cm}^{-3}$. The positrons are likely to cool via vibrational excitation of the gas molecules of energies $T \sim 0.3 - 0.5$ eV.[2] For a density $\sim 10^6\ \mathrm{cm}^{-3}$, the Debye wavelength will be

$\lambda_D \sim 0.5$ cm, which is much less than the dimensions of the column of positrons. Thus the positrons will behave collectively as a plasma.

III. Measurement of Transport in a Tokamak Plasma

A. Design of an Experiment

During a tokamak discharge, we envision that the positrons from the trap would be accelerated to ~1 keV. They are then transported to the tokamak in a 3 kG guiding field (Fig. 1b) and made to impinge on a 50Å thick carbon foil, supported by a grid, where they form positronium (e^+e^-) at energies ~20 – 100 eV (see Fig. 2).[7] The neutral positronium will penetrate the tokamak plasma and be inonized. The deposition profile of the positrons with plasma is shown in Fig. 3.

The positrons will thermalize with the bulk plasma electrons within 1 μsec of injection. Due to motion of the positrons along the magnetic field lines and to the sheared magnetic field in the tokamak, the profile shown in Fig. 3 will also become symmetric about the magnetic axis on a time-scale of the order of 1 μsec.

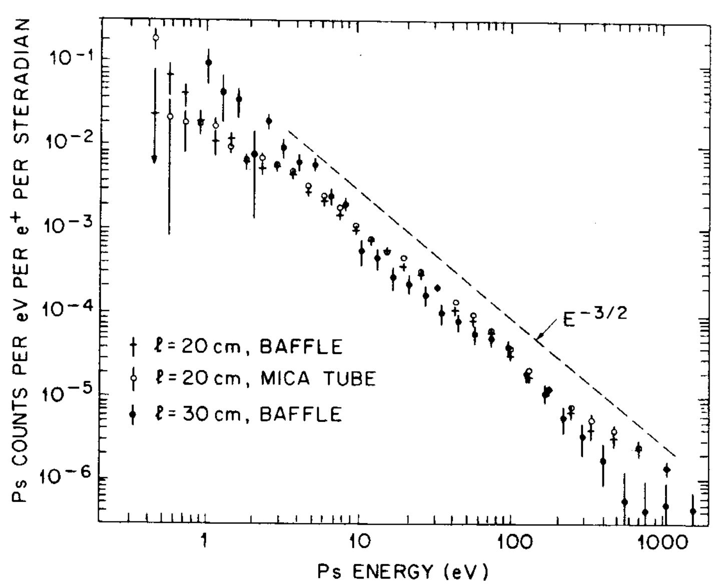

Fig. 2. Flux and energy distribution of positronium atoms produced by 1 keV positrons impinging on a 50Å carbon foil (from Ref. 7).

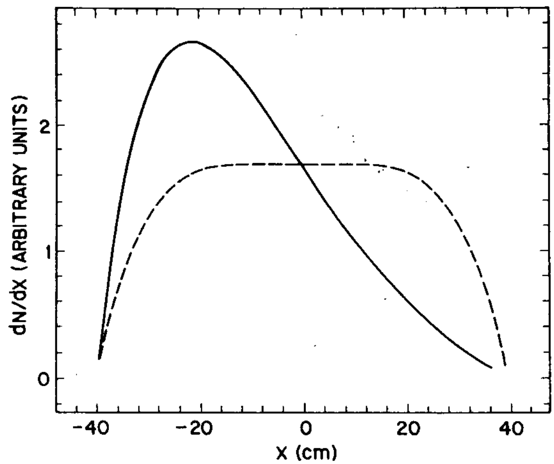

Fig. 3. Deposition profile of the positrons in the plasma as a function of distance from the plasma center. The solid curve assumes the positrons do not move after ionization. The dashed curve is the profile expected when the positrons average poloidally over a magnetic flux surface (in a time $\lesssim 1$ μsec). The positronium source (i.e., the carbon foil) is located at $x = -110$ cm. This calculation includes all positronium atoms emitted from the foil with energies >20 eV and takes into account the finite lifetime of the positronium. The cross-section is assumed to be $\sigma = 2 \times 10^{-16}$ cm^2: At 20 eV, σ is dominated by charge exchange, (i.e., $H^+ + (e^+e^-) \rightarrow H + e^+$), whole at energies ~ 100 eV, ionization of the positronium by the plasma ions dominates.[8] We have also assumed $Z_{eff} = 2$, $\bar{n} = 2 \times 10^{13}$ cm^{-3} and a plasma with a parabolic density profile between $x = \pm 40$ cm.

The efficiency of the process (positrons) $\rightarrow$ (positronium) $\rightarrow$ (positrons in the plasma) is estimated to be $\sim 10^{-5}$, where the dominant loss mechanisms are the positronium conversion efficiency in the carbon foil ($\sim 10^{-4}$) and the 140 nsec lifetime of the positronium traveling the estimated 1 m distance from the foil to the plasma center. Approximately 10^4 positrons would be deposited in the plasma in a time <1 msec.

The transport of positrons out of the plasma can be measured by monitoring the positron flux to the limiter. This is accomplished by measuring the 511 keV γ radiation produced when a positron annihilates with an electron at the limiter. Since the positron lifetime for annihilation in a plasma of density $2 \sim 10^{13}$ cm^{-3} plasma is ~ 10 sec and the diffusion tine to the limiter is $\sim 10^2$ msec, most of the positrons will impinge on the limiter. It is known from previous experiments that positrons with energies $\lesssim 100$ eV, impinging on a "dirty" metal plate, have a high probability ($\gtrsim 50\%$) of producing annihilation radiation, with the remainder of the positrons forming positronium atoms.[9] Thus the time between the deposition of the positron burst in the plasma and the arrival of the 511 keV annihilation radiation will be a measure of the cross-filed, positron transport rate.

The limiter and γ–ray detector system, prototypes of which are shown in Figs. 4 and 5, are designed to maximize the detector efficiency while protecting the detector from excessive heat loads. It is estimated that such a limiter/detector system can have an overall efficiency $\sim 10^{-1} - 10^{-2}$. Thus we expect $> 10^2$ γ–ray counts per tokamak discharge. This signal will arrive within a few particle containment times (i.e., $\sim 10^2$ msec) after the positrons are injected into the plasma.

B. Some Details on the Limiter and Detector System

The limiter surface which contacts the plasma must be a low Z, low sputtering material with excellent vacuum properties and have a high melting temperature and a high thermal conductivity. In addition, the limiter must be of sufficient thickness to provide the required thermal inertia to the high front-face temperatures. Shown in Figs. 4 and 5 are possible designs of such a limiter. The scintillators are positioned as close as possible to the limiter surfaces in

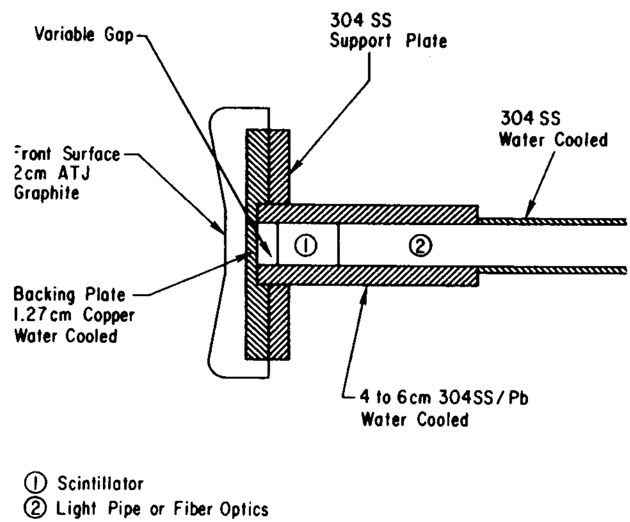

Fig. 4. A "rail" limiter with a scintillator for detecting the 511 keV annihilation radiation. The light pipe (or fiber optics) transmits the scintillator signal to a magnetically-shielded photomultiplier located in a low field region outside of the vacuum vessel.

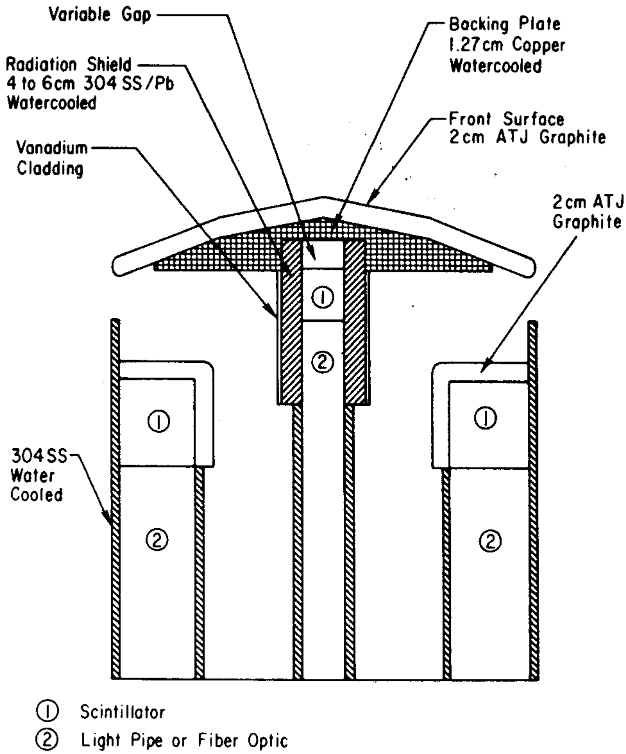

Fig. 5. A "scoop" limiter with three scintillator light pipe systems for detecting separately the 511 keV annihilation radiation at the center of the limiter and at each of the port edges. Additional detector systems could be positioned to view the vanadium neutralizer surfaces and the emission along the limiter surface.

water-cooled radiation shields. Optimal light pipes transmit the scintillator light from the high magnetic field region to a magnetically-shielded photomultiplier in a low-field region outside of the vacuum vessel. The scintillator material is NaI ($T\ell$), which is chosen for its high photopeak efficiency at 511 keV, although other scintillators could also be considered.

For clean, low Z_{eff} discharges in plasmas which are not too low in density, there is expected to be no 511 keV background radiation. For example, for such discharges in the PLT tokamak, a detector volume 10^3 cm^3 located near the device was limited only by the cosmic-ray background.[10]

In some discharges, plasma-produced runaway electrons at MeV energies may present a special problem due to the large fluxes of hard x-rays and the annihilation radiation from pair production at the limiter. This effect of runaway electrons can be reduced by using a special runaway scrape-off limiter, located on the large major radius side of the plasma and slightly outshifted from the edge magnetic surface of the plasma. The energetic runaway electrons will be preferentially scraped off by this limiter, since their drift surfaces are outshifted from the magnetic surfaces, and runaway electrons are not expected to be observed at the top and bottom limiters.

C. Possible Physics Payoff of Such an Experiment

The distribution of arrival times of the γ—ray signal depends on both the diffusion and convection of the positrons and the initial positron deposition profile. It is expected that the deposition profile can be determined by the varying plasma density, the positronium beam energy, and the vertical angle of injection of the positrons. Thus, *the experiment described here provides a direct measure of the positron transport* rate. The radial profile of positron particle transport can be determined by varying the vertical angle or the positronium beam injection energy.

A fundamental issue in fusion physics is the transport of electrons in tokamak plasmas. It is well known that the electron thermal conductivity is large compared to that expected from Coulomb collisions.[11] However there are no direct measurements of electron particle transport. The positron transport measurements will undoubtedly shed light on this issue. Whether the electron and the positron transport coefficients are identical is, to our knowledge, an unanswered theoretical question. It will probably depend on which specific transport mechanism is dominant.

Variations of the positron transport experiment described above could be used to measure a variety of quantities of interest. For example, the positron "scrape-off" length at the plasma edge can be measured, either by varying the radial position of the detector/limiter relative to a fixed limiter or by measuring the annihilation rate along a limiter whose surface is at an angle to the toroidal direction. The net positron transport to the detector/limiter is given by the absolute intensity of the γ—ray signal.

Changes in transport during neutral-beam injection or magnetothydrodynamic (MHD) activity could be studied by suitable timing of the injection of the positron burst. For example, the effects of high β (i.e., high plasma pressure relative to B^2) and "fish-bone" (which is a kind of MHD activity particularly important for neutral beam heating) on the particle transport would be of interest.[12] The MHD-enhanced transport near rational magnetic surfaces could also be studied. Poloidal asymmetries in the transport to different limiters (e.g., top and bottom) could be studied by the use of two limiter/detector systems.

The positron velocity distribution in the plasma could be measured (at least in principle) by the angular spread in the γ–rays emitted during annihilation events from the bulk plasma. Finally, the spatial distribution of the positrons as a function of time could be measured directly by studying the bulk plasma annihilation events using a detector array and co-incidence techniques. However the anticipated count rates and the experimental tokamak geometry indicate that these last two experiments will be difficult.

IV. Concluding Remarks

We have described a device to produce a collection of $\sim 10^{10}$ positrons with a temperature $\sim$0.5 eV and a containment time $> 10^2$s. We have also discussed one potential use of this device which is to study the transport of electron-mass charged particles in a tokamak fusion plasma.

If such a positron plasma is achieved, it is likely to be of use to study interesting features of the equal-mass, electron-positron plasma which could be obtained by adding electrons. Many of the interesting features of such a plasma require the two species to have equal temperature and densities.[3] Since the addition of electrons to the positron plasma is likely to degrade the containment time dramatically, experiments on such a compensated plasma will necessarily have to be pulsed in nature. In this case, the geometry of a double-plasma device would be convenient.[13] As we point out in the introduction, one relatively simple plasma experiment which might be carried out on a steady-state positron plasma would be to inject an electron beam to study the electron/positron beam-plasma instability. For example, the effects of "clump" and "hole" phenomena[14] are expected to be most pronounced for this case of equal masses. These effects lead to the growth of large-amplitude fluctuations at drift velocities well below the threshold for the usual (linear) ion-acoustic instability.

It is quite likely that there will be other uses of the positron trap described here. If this scheme is successful, a low-temperature, high-field version of the positron trap is a logical extension, based on the recent work of Malmberg et. al.[15] In the pure-electron plasma case, plasmas of densities $\sim 10^{10}$ cm^{-3} with temperature $< 10^\circ$K have been achieved. Other potential uses of the positron trap include study of the annihilation linewidth of the positrons in laboratory and fusion plasmas to model astrophysical processes and use of the trap as a source of intense positron bursts for atomic and solid-state physics experiments.

V. Acknowledgements

It is a pleasure to acknowledge the advice and encouragement of J. H. Malberg, C. F. Driscoll and W. D. White regarding the design of the positron trap based on their experience with the electron trapping techniques which they pioneered. We wish to thank B. L. Brown and O. R. Wood, II for useful discussions, and R. E. Olson for calculating the positronium ionization and charge-exchange cross sections relevant to the tokamak experiment.

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Published by

World Scientific Publishing Co. Pte. Ltd.
P. O. Box 128, Farrer Road, Singapore 9128

Library of Congress Cataloging-in-Publication data is available.

POSITRON STUDIES OF SOLIDS, SURFACES, AND ATOMS

ISBN 9971-978-44-X

Printed in Singapore by Kim Hup Lee Printing Co Pte Ltd.