White Paper for the *Frontiers of Plasma Science Panel*

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Title: **Creation and Study of Electron-Positron ("Pair") Plasmas**

Corresponding Author: Clifford M. Surko

- Institution: University of California, San Diego
- Email: csurko@ucsd.edu

Co-Authors: Thomas Sunn Pedersen; Max Planck Institute for Plasma Physics

2tspe@ipp.mpg.de
Creation and Study of Electron-Positron ("Pair") Plasmas

Cliff Surko,1 University of California, San Diego, and Thomas Sunn Pedersen,2 Max Planck Institute for Plasma Physics, Greifswald, Germany

INTRODUCTION AND CONTEXT. In a seminal paper, Tsytovich and Wharton outlined the unique properties that could be expected for an electron-positron (so called "pair") plasma, consisting of plasma particles with equal masses, equal temperatures and opposite signs of charge [1]. In such plasmas, three-wave coupling vanishes identically, and so parametric processes (e.g., Raman and Brillouin) are absent. Electromagnetic waves in such plasmas are linearly (as opposed to circularly) polarized, and nonlinear Landau damping is stronger by the ion/electron mass ratio, as compared with the behavior expected in an ordinary electron-ion plasma. Ion acoustic waves are expected to be heavily damped, and solitary-wave behavior is expected to be prominent. Since the Tsytovich work, similar effects have been predicted for the astrophysically relevant case of relativistic pair plasmas, such as those expected at the poles of neutron stars.

RESEARCH FRONTIER AND SCIENTIFIC CHALLENGES. In spite of extensive theoretical work on pair plasmas (> 1000 papers), they have not yet been studied in the laboratory. Progress in the accumulation and manipulation of antimatter made over the past two decades (for a review, see [2]) is now at the cusp of making possible precision studies of pair plasmas. We suggest that this is an important new plasma-physics frontier area worthy of support.

The focus here is on approaches that utilize low-energy positrons confined in an electromagnetic trap. Not discussed is an alternative approach that utilizes electron-positron pairs produced by high intensity lasers [3, 4]. The methodology described here is more amenable to fixing precise plasma conditions (e.g., equal densities and equal temperatures) and achieving small Debye lengths, in turn permitting study of plasma phenomena with precision on relatively long time scales [2].

A potentially seminal line of investigation will be to test theoretical predictions as a function of the positron/electron density ratio R. For example, three-wave coupling decreases and then vanishes as this ratio is varied through the condition R = 1, as should the Faraday rotation of electromagnetic radiation. Of interest also is confinement in a neutral, pure lepton plasma (i.e., with correspondingly small gyroradii of both signs of charge carriers). The dynamics of electron and/or positron vortices could also be studied in the Penning/Paul configuration described below.

There are an enormous number of challenges. Available positron sources are weak. Long-time confinement of such a unique object as an equal-mass lepton plasma is uncertain; and densities, at least initially, will be relatively low. Further, given that one charge carrier is antiparticle, many of the standard diagnostic techniques cannot be used.

TECHNICAL APPROACH AND REQUIREMENTS. A number of possible trapping schemes have been proposed for pair-plasma studies, including confinement in stellarators [5], magnetic mirrors [6], levitated magnetic dipoles [7], and in Penning-Paul (combination) traps [8, 9]. In fact, low-density pair plasmas in toroidal geometries, such as the dipole, are predicted to have unique stability properties [10]. Nevertheless each

1Corresponding author, csurko@ucsd.edu; 2tspe@ipp.mpg.de.
approach has its potential advantages and disadvantages. For brevity, we discuss briefly here two possible approaches: the levitated dipole trap (LDT) and the Penning-Paul trap (PPT). Relativistic pair-plasma phenomena (of keen astrophysical interest) can potentially be studied in dipoles and in mirrors, due to their good confinement of hot particles; the challenge there will be to assemble sufficiently large numbers of positrons to produce a small Debye length at relativistic temperatures.

**Positron Sources.** One requirement is to assemble a sufficient number of cool positrons \(N_p\) so that the plasma is several Debye lengths in all dimensions. For the PPT experiment, \(N_p \geq 10^9\); while for the LDT, \(N_p > 10^{10}\), assuming both plasmas have temperatures \(T \leq 0.5\) eV. The former number can be obtained using a radioisotope source and buffer-gas trap, while the larger requirement can be fulfilled at a reactor-based positron facility such as those at N. Carolina State University and in Munich [11, 12].

**Levitated-Dipole Confinement.** Levitated dipole traps have demonstrated confinement times of \(\geq 300\) s for electron plasmas [13] and seconds for confinement of high-energy electrons neutralized by colder ions [14]. They are expected to exhibit good confinement for partially or fully neutralized plasmas. Positrons can be introduced using pulsed E x B plates [15] or via bursts of positronium atoms that will subsequently be laser ionized in situ [15]. Following the design of a similar stellarator experiment [15, 16], parameters would be \(V \sim 5 \times 10^{-3} \text{ m}^3\), \(n \geq 10^{12} \text{ m}^{-3}\), and \(T \sim 0.5\) eV. An electron plasma of similar characteristics would be introduced. Plasma density information is available from the flux of 511 keV annihilation gamma rays, while Doppler broadening can provide temperature information. Annihilation from a pellet shot through the plasma can provide information about the plasma density profile. Initial wave studies will be conducted with pick-up loops and antennas exterior to the plasma [6].

**Penning-Paul Confinement.** A long cylindrical positron plasma would be loaded in a conventional Penning trap, in \(B \sim 0.1 - 5.0\) T [8, 9]. Then \(rf\) would be applied in localized regions at each end of the plasma (i.e., inside the dc end gates), and electrons added, now both confined in the direction along \(B\) by the \(rf\) Paul-trap fields. Nominal parameters are given in Ref. [9]: a cylindrical volume \(\sim 10^{-2}\) m in diameter by \(0.3\) m long, \(n \sim 10^{13} \text{ m}^{-3}\) and \(T \leq 0.5\) eV. The \(rf\) potential well would be \(\sim 5\) eV at \(100\) MHz. The plasma would be cooled using a \(\text{CO}_2\) buffer gas. Density and temperature would be measured by dumping the plasma onto a collector or phosphor screen, and wave studies will be done by exciting and monitoring electrical pickup using close-fitting electrodes.

**RESEARCH IMPACTS. Plasma Physics:** In one sense, pair plasmas represent a unique plasma state with many novel properties, many of them nonlinear. In another sense, they are arguably the simplest possible neutral plasma, one in which the ion has no internal structure and where only a single charge to mass ratio is present. If successful, pair plasma studies can be expected to lead to many new fundamental insights into plasma behavior. **Related Disciplines:** Pair plasmas are of keen interest in astrophysics, and many of the novel phenomena predicted are common to relativistic and nonrelativistic plasmas. **Societal Benefits:** Physics with antimatter is of considerable interest to the lay public thus providing a vehicle to increase the lay public’s interest and literacy in science.