A new frontier in laboratory plasma- and astrophysics: electron-positron plasmas

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The visible universe is predominantly in the plasma state. On Earth, plasmas are less common, but they find many applications in industry and are also studied with the goal of providing an abundant energy source for mankind through fusion energy. The behaviour of plasmas studied thus far, in particular those for which the interaction with an external magnetic field is substantial, is very complex. The complexity manifests itself first and foremost as a host of different wave types, many of which are generically unstable and evolve into turbulence or violent instabilities. This complexity and the instability of these waves stems to a large degree from effects that can be traced back to the difference in mass between the positively and the negatively charged species, the ions and the electrons.

In contrast to conventional ion-electron plasmas, electron-positron (pair) plasmas consist of charged particles with exactly equal mass. This symmetry results in unique behaviour of pair plasmas, a topic that has been intensively studied theoretically and numerically for decades, but experimental studies are only just starting. These studies are not only driven by curiosity: Strongly magnetized electron-positron plasmas are believed to exist ubiquitously in pulsar magnetospheres and active galaxies in the universe, and the entire universe is believed to have been a matter-antimatter symmetric plasma in its earliest epochs after the Big Bang.

We describe here efforts to create and study electron-positron pair plasmas on Earth. This is now possible due to novel approaches and techniques in plasma, beam, and laser physics. We describe the differences and similarities of the several distinct approaches currently being pursued, and discuss the unique physics insights that can be gained by these studies.

Introduction

Plasma physics describes the most abundant state of observable matter in the universe; it had significant successes and today is at the heart of diverse scientific and industrial applications. Yet there is an experimentally nearly unexplored class of plasmas overlapping with the field of antimatter physics, namely pair plasmas (plasmas consisting of two classes of particles with opposite sign of the charge, but equal mass). It was recognized more than 30 years ago that the physics of pair plasmas is truly unique[1], and around the same time, it was proposed that magnetized electron-positron plasmas can be presumed to exist around pulsars[2]. The gamma ray flux around neutron stars and active galactic nuclei is so large that copious pair production can occur as the gamma radiation interacts with matter. Pair plasmas appear, for example, in the relativistic jets that are observed around these objects. That some relativistic jets are in fact dominated by pair plasma has been concluded based on observations[3,4], and these findings have attracted significant attention. The ability to study and manipulate pair plasmas in the laboratory will open an entirely new avenue for understanding the astrophysical phenomena that involve electron-positron plasmas. However, we have not yet been successful in making an electron-positron plasma on Earth.

In the following, we will give an introduction into the physics of pair plasmas and describe the various schemes currently pursued towards making them in a laboratory. For astrophysical pair plasmas, we refer to a recent review[5]. The plan of this paper is as follows: In an introductory section, we refer to some of the physics which makes a pair plasma to a unique object for studies in a laboratory. In a second section, we line out a plan to create confined electron-positron plasmas in some detail. We conclude by a comparison to other approaches to the pair plasma challenge.

Unique behaviour in general

A primary difference between regular plasmas and electron-positron plasmas is the lack of coupling between density fluctuations and electrostatic potential fluctuations. This is easily illustrated by considering the basic physics of the ion acoustic wave, one of the best known and most fundamental waves in a conventional plasma consisting of electrons and ions. The wave is driven by the combination of the electron pressure and the ion mass. We take a positive pressure perturbation in a plasma with equal temperature of both components ($T_e = T_i$) as the initial condition for the problem (Fig. 1), and ignore collisions. Due to their much lower mass, electrons escape much quicker from the high-pressure region than ions. In doing so, they leave behind the ions, and there is some charge separation. The electrons continue to escape until at some point they are pulled back by the electric field resulting from the positive space charge by the surplus of ions. The ions accelerate in this self-generated electric field. They overshoot due to their inertia, and a wave is born: the ion acoustic wave. This is illustrated in Fig. 1. This is a wave whose coherence is held together not by collisions (which for the vast majority of laboratory and astrophysical plasmas can be ignored) but instead by the collective electric field spontaneously generated by the plasma through the process sketched out above. Now consider the same pressure perturbation in an equal-temperature electron-positron plasma ($T_e = T_p$). Here, no electric field develops: the two species escape a high-pressure region at the same rate since they have the same mass and the same thermal speed. With no electric field and negligible amounts of collisions, no coherent wave appears. Instead the plasma simply relaxes and eliminates the pressure perturbation through free-streaming of the particles.

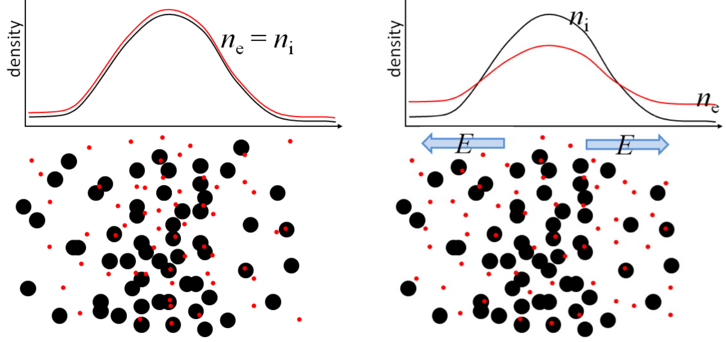

Fig. 1: Creation of an ion acoustic wave from a density perturbation in a conventional (electron-ion) plasma. As the electrons flow out of the region of increased density more quickly than the ions, an electric field is produced. The ions collectively accelerate in this self-produced field, which leads to an ion density wave. In an electron-positron plasma, this type of wave is predicted to be absent.

Unique stability against micro-instabilities (turbulence)

Remarkably, the above-mentioned result can be generalized to include a much wider class of wave phenomena, turbulence and instabilities, which are ubiquitous in conventional plasmas. Recently, it has been shown analytically for the case of a pair plasma in a dipole trap, complete microstability should be expected.[6,7] The situation is best summed up with a quote from Helander's paper[6]: *In summary, it has been found that the electrostatic instabilities causing turbulence and transport in magnetically confined electron-ion plasmas are largely absent in low-density electron-positron plasmas*.

Many (electron-ion) plasmas, in the laboratory as well as in astrophysical settings, are 'magnetized': They interact with an external magnetic field, and the radius of the cyclotron motion that particles undergo around the field lines ('Larmor radius', ρ) is much smaller than the typical length scale of the plasma. The same is true for many astrophysical plasmas. A magnetized plasma is anisotropic, because the plasma can flow rather freely along the magnetic field, but only drifts much more slowly across the magnetic field. This is the fundamental reason why a plasma can be confined efficiently by toroidal magnetic topologies. This anisotropy leads to complex and often non-linear behaviour. A wealth of research exists for magnetized plasmas, and tremendous progress has been made in the last few decades, but even with today's sophisticated codes and theories, experiments and astrophysical observations still offer surprises. We do not yet have the power to quantitatively predict plasma behaviour in many situations where it would be highly desirable (Fig. 2). Fundamental to fusion and many astrophysical plasmas is the occurrence of micro-turbulence – that is, fluctuations of plasma parameters (density, temperature, etc.) on spatial scales comparable to or smaller than the ion Larmor radius ρ_i. The turbulence changes the macroscopic behaviour of the plasma strongly, since it allows transport of particles, momentum, and energy across the magnetic field at rates orders of magnitude higher than what is predicted from single-particle orbits and the binary interactions of particles (classical and neoclassical transport). This has been known in fusion energy for about half a century ("anomalous transport") and it is being recognized more and more that such collective electrostatic or electromagnetic processes also play a major role in many astrophysical settings.

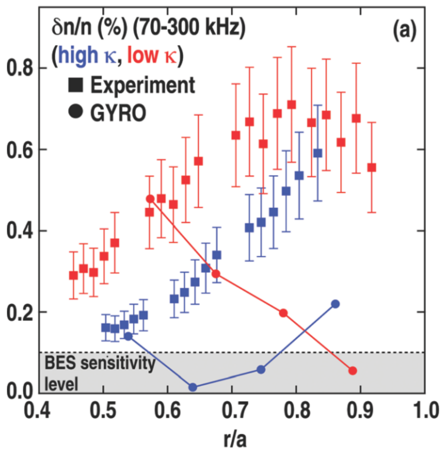

Fig. 2: Fluctuation of the electron number density in a typical fusion plasma (density variation in % vs. normalized toroidal magnetic flux), measured at the DIII-D Tokamak (squares), and comparison to predictions from a gyrokinetic modelling code (circles). Different values of κ denote plasmas with a more (1.8) or less (1.2) elongated, elliptical shape of the plasma cross section.[8]

In a magnetized electron-positron plasma, although it shares the anisotropic features of a magnetized electron-ion plasma, turbulence is predicted to be practically absent, and cross-field transport processes are hence very slow.[1,6,7] If this were indeed verified experimentally, it will be the first time that a magnetically confined quasi-neutral plasma is free of anomalous transport. This will be a strong test of our predictive abilities in magnetic confinement fusion research, and, whether verified or falsified, it could have a profound impact on our understanding of a number of astrophysical phenomena, where we otherwise would invoke turbulent processes to explain the rapid rates of transport and/or dissipation that are observed (e.g. the rate of accretion in accretion disks and angular momentum transport, or the rate of magnetic reconnection in a whole range of astrophysical and laboratory plasmas).

Therefore, experiments with this type of plasma will become important benchmarks for predicting the behaviour of any type of plasma, conventional or pair plasma, astrophysical or laboratory plasma.

Timeliness of electron-positron plasma studies

Electron-positron plasma studies are particularly timely because of recent innovations in antimatter physics. Experimental methods in this area are rapidly progressing, fuelled by dramatic advances in particle beam technologies. These innovations are opening opportunities for novel research in interdisciplinary fields. At the Antiproton Decelerator (AD) facility of CERN[9], the formation of a large number of antihydrogen atoms was achieved in 2002[10,11]. Further studies are in progress aiming for the stringent test of the CPT symmetry. The intense antiproton beam from AD has also made it possible to study "exotic" atoms that consist of matter and antimatter.[12] In the history of research in antimatter sciences, many fundamental ideas and key techniques were adopted from plasma physics.[13,14] These include electromagnetic trapping configurations for charged (and even neutral) particles, diagnostic techniques using collective modes, and manipulation techniques for confined charged particles.[13] Although plasma physics contributed a lot to antimatter physics, there is still a large unexplored field of antimatter plasma physics, where collective phenomena of many-body systems play an essential role. It is here that studies of electron-positron plasmas can play an important role.

Magnetic confinement in levitated dipoles and stellarators: similarities and differences

A device for the confinement of a pair plasma must be able to confine particles with both signs of charge. Although excellent confinement of either positrons or electrons can be achieved in a Penning-Malmberg trap, this configuration cannot simultaneously confine both positively and negatively charged particles with a spatial overlap beyond the Debye length.[15,16,17,18,19] And, while pair plasma confinement in a magnetic mirror device has been proposed[20,21], this approach suffers from a loss-cone instability. With regard to Paul traps, heating of the particles due to coupling with the radiofrequency fields that forms the trapping potential must be overcome. While both the combination of a magnetic mirror and a Penning trap and a Penning/Paul trap can be used to study pair plasmas[22], the resulting plasmas will likely be in other than equilibrium states.

In contrast to conventional linear configurations, where axial confinement is realized by plugging electro-static fields, toroidal configurations have no open ends. Therefore, in principle, toroidal geometries can confine charged particles of both signs together, as a plasma, at any degree of non-neutrality. Focus will at first be on a magnetic dipole as confinement device. The idea of dipole confinement itself dates back to early fusion studies in 1960s.[23] Besides its application to fusion science, the dipole field is one of the most fundamental magnetic configurations found in the Universe. Motivated by satellite observations of high-pressure flowing plasmas in the Jovian magnetosphere[24], the dipole confinement concept has attracted a renewed interest these days. In a laboratory, use of a levitated coil to produce the dipole field is essential for the experiment, as otherwise mechanical support structures would impair the magnetic confinement and cause unacceptable particle losses. Two experiments, the Ring Trap 1 (RT-1, Fig. 3) of The University of Tokyo[25] and the Levitated Dipole Experiment (LDX) of MIT[26], have achieved high-performance plasma confinement in levitated dipole configurations.

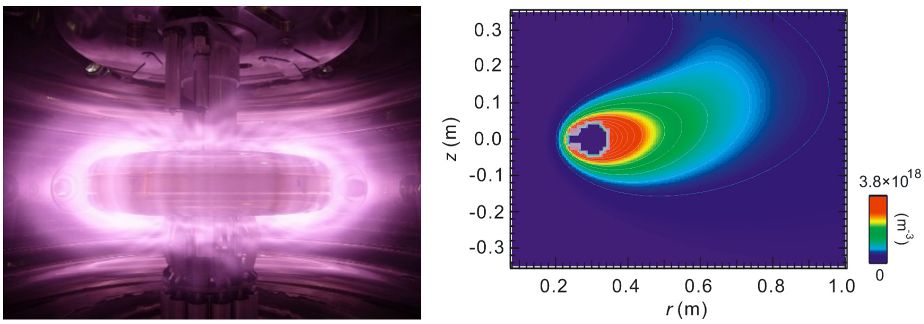

Fig. 3: A plasma confined in RT-1, a laboratory "artificial magnetosphere" generated by a superconducting (SC) levitated dipole coil (lhs), and an example for a self-organized peaked density profile of a plasma in RT-1 (rhs)[25,27]

A dipole magnetic field is characterized by its strongly inhomogeneous field strength. As observed in planetary magnetospheres and experiments in RT-1 and LDX, charged particles in an inhomogeneous dipole field exhibit interesting self-organization and complex nonlinear dynamics.[28] The strong compressibility of the dipole field provides a remarkable stability of plasmas even with a strong pressure gradient. Contrary to common sense, diffusion in such plasmas leads to a plasma density profile strongly peaked towards the dipole magnet.[28] These unique self-organization and inward-transport processes play important roles in penetration of solar wind particles and structure formation in magnetospheres.[29] Moreover, we can use such properties of the dipole field for scientific applications. Strong heating effects caused by the inward particle diffusion are suitable for burning advanced fusion fuels for future power production[30], as intensively studied in RT-1 and LDX.

Confinement of non-neutral plasmas has been studied at RT-1, where levitated dipole experiments started in 2006 after intensive technical development.[31] In pure electron plasma experiments, detailed measurements of the internal potential structure and electrostatic fluctuations revealed a remarkable self-organization process of dipole non-neutral plasmas[27]. After turbulence-induced "inward-diffusion" transported the injected electrons into a strong field region, a rigid-rotating equilibrium state is spontaneously generated in the dipole field. This relaxed state is so robust that of the order of 10^{10} electrons were stably trapped for more than 300 s, which is a world record for confinement of a non-neutral plasma in a toroidal geometry.

Besides the levitated dipole, another successful trapping configuration for toroidal non-neutral plasmas is a stellarator.[32] The stellarator is one of the promising magnetic configurations for nuclear fusion power production, and one in which closed magnetic surfaces are generated solely by external current coils. The Columbia Non-neutral Torus (CNT)[33] was designed and operated for the purpose of studying pure electron plasmas in a stellarator, with the ultimate goal of paving the way for the creation of an electron-positron plasma. In CNT, stable equilibrium and relatively long confinement (more than 90 ms, which is much longer than time scales of most plasma phenomena)[34] of an electron plasma were demonstrated. The stellarator has a large advantage of device simplicity, as the confinement configuration can be generated by mechanically supported coils. This is in marked contrast to the levitated dipole experiment. The stellarator is also a highly complementary magnetic confinement device to a levitated dipole for the purposes of understanding the basic plasma physics behaviour. These differences are listed in the table below:

stellarator	**levitated dipole**
steady state	steady state on typical plasma timescales
fusion relevance	astrophysical relevance
negligible flux expansion	strong flux expansion
magnetic flux surfaces	each B-field line closes after one pass
long B-field connection lengths	short B-field connection lengths
parallel force balance counteracts instabilities	parallel force balance does not counteract instabilities
drift orbit confinement requires optimization	drift orbits always confined (axisymmetry)
indefinite operation	levitation requires cooling/warming cycles
many 3D coils	2-3 planar coils (floating, lifting, charging)
permanently attached current leads	detachable current leads OR inductive charging
requires positron pulses for fueling	possibility for steady state fueling

Target parameters and feasibility study of the magnetically confined pair plasma experiments

The APEX project aims to create electron-positron plasmas in the levitated dipole device APEX-D. As explained in one of the following paragraphs, in order to observe self-generated collective behaviour of the charged particles the Debye length λ_D of the charged particles must be smaller than the spatial scale length of the plasma. We therefore aim to create electron-positron pair-plasmas with a number density range of 10^7 cm^{-3} and a typical temperature $k_B T = 1$ eV. This corresponds to a Debye length λ_D of around 0.2 cm, much smaller than the plasma size.

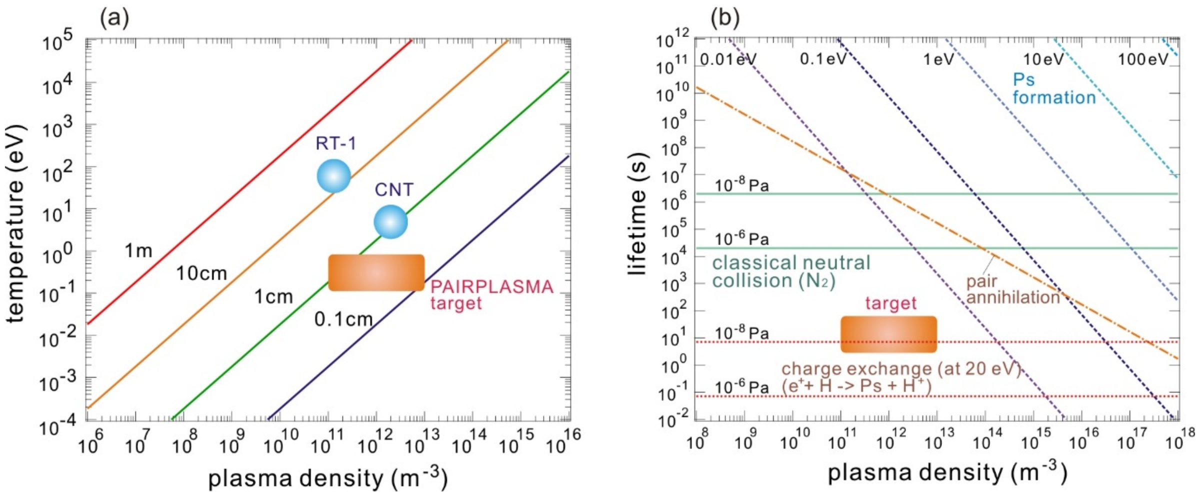

Fig. 5 a.) Target parameters. b.) Lifetimes of positrons and electron-positron clouds set by direct annihilation, direct Ps formation, neutral collisions, and charge-exchange formation of Ps.[22,35].

These parameters are shown in Fig. 5(a) in comparison with the results of pure electron plasma experiments in RT-1 (a levitated dipole)[27] and CNT (a stellarator)[34]. The target density range is comparable to the electron densities realized in the previous experiments, indicating that this aim is realistic in view of the confinement performance of the trapping configuration. The confinement region volume of APEX-D will be approximately 2.5 liters, which is much smaller than those of the previous two experiments (1000 liters for RT-1 and 100 liters for CNT). Thus, the small Debye length criterion can be satisfied with a smaller number of charged particles[16]; effective injection of 10^{10} positrons in APEX-D will be needed (along with the same number of electrons).

Annihilation of positrons is not ruling out long confinement

Before considering the accumulation and injection methods for positrons it is worth noting that recombination effects neither impede the production nor the study of long-lived electron-positron plasmas for realistically achievable parameters.[22] These considerations are summarized in Fig. 5(b) for magnetically confined pair plasmas. The cross section for direct annihilation of positrons with electrons is quite small, and this loss channel is effectively negligible, as is positronium formation. Another relevant effect is the interaction with the neutral background gas of the vacuum chamber. Classical neutral effects are negligible, but Ps formation by charge exchange collisions[35] could limit the positron lifetime, as shown in the figure, unless UHV conditions (10^{-10} mbar or 10^{-8} Pa) are achieved. Under UHV conditions, the shortest expected lifetime is on the order of minutes, which is much longer than the time scales of most of plasma phenomena and would be a record long confinement time for a quasi-neutral plasma.

The importance of a small Debye length

Collective plasma behavior is expected when the Debye length is smaller than the size of the plasma.[36,37,38,39] This has not yet been achieved on Earth for a cloud of simultaneously confined electrons and the positrons. Such collective behavior is of great importance in regular electron-ion plasma. Of interest in this regard, numerous theoretical and numerical studies of pair plasmas show that they behave very differently from regular plasmas regarding such collective dynamics (e.g., "micro-instabilities"), which are examples of self-generated collective plasma behaviour.[6,40,41,42] A more comprehensive discussion of Debye-length physics can be found in Ref. 43.

Self-generated electrostatically driven dynamics lead to drift-wave type turbulence. The same drivers are strong candidates for causing a whole host of other complex phenomena, such as the anomalously fast rate of magnetic reconnection, the larger than expected rate of inward transport in accretion disks, and the larger than expected rates of outward transport in fusion experiments. Such phenomena occur if the electric field, or the electrostatic potential, is large enough that it substantially affects the motion of many plasma particles. This is generally true if $e\varphi / k_B T$ is not much smaller than unity, with φ the electric potential. A requirement is therefore that the absolutely largest conceivable potential that can be created by a plasma satisfies $e\varphi_{max}/k_B T > 1$.

The maximal space charge that a plasma with density *n* can create results if one species entirely leaves the other species behind. In this case, the space charge electrostatic potential can be estimated from Poisson's equation. We assume for simplicity a spherical plasma with radius *L* and constant density of the remaining species, which is singly charged:

$$\varepsilon_0 \nabla^2 \varphi = en \quad \Leftrightarrow \quad \varepsilon_0 \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \frac{\partial \phi}{\partial r}) = en \quad \Rightarrow \quad |\varphi_{\max}| = \frac{1}{6\varepsilon_0} enL^2$$

Combining this with our requirement above we get:

$$\frac{e}{k_B T}\frac{enL^2}{6\varepsilon_0} > 1 \Leftrightarrow L^2 > 6\frac{\varepsilon_0 k_B T}{ne^2} \Leftrightarrow L^2 > 6\lambda_D^2 \Leftrightarrow \lambda_D < \frac{L}{\sqrt{6}}$$

That is, the Debye length should be small relative to the plasma size, otherwise the charge cloud is too thin or too hot for electrostatic dynamics to play a role. If one resorts to a more realistic model, in which one sort of particles is separating from the other not entirely, then a stricter upper bound on the Debye length is results. Most textbooks require $\lambda_D << L$ without specifying what that exactly means. We take it to mean

$$\lambda_D < \frac{L}{10}.$$

Laser-produced electron-positron plasmas and the importance of the plasma skin depth

We now compare the target properties for magnetically confined electron-positron pair plasmas to an alternative experimental approach, namely production of a pair plasma by laser-based techniques. The laser-produced electron-positron plasmas described in Ref. 44 are highly complementary to the magnetically confined plasmas just described, and which will have a small Debye length but a long plasma skin depth, $L_s = c/\omega_p$. At the expected densities of 10^6 cm^{-3}, L_s will be of order 5 m, whereas the plasmas will be of order 10 cm. For the laser-produced plasmas, the opposite is true: the skin depth is smaller than the plasma size, whereas the Debye length is larger than the plasma. The skin depth is the characteristic size a charged cloud must have to significantly affect externally launched electromagnetic radiation. An electromagnetic wave is reflected from an unmagnetized plasma if the plasma frequency exceeds the electromagnetic wave frequency, $\omega_p > \omega$. However, the wave fields will still penetrate a distance $L_s = c/\omega_p$. If L_s , the skin depth, is significantly greater than *L* (the plasma size) then the plasma is not large and dense enough to reflect the wave, nor will it substantially be able to change the amplitude or the phase of the wave. Thus, to study how a plasma affects the propagation of an electromagnetic wave, the skin depth must be small. And indeed, just as electrostatic turbulence is uniquely different in small Debye-length pair plasmas compared to otherwise equivalent electron-ion plasmas, electromagnetic wave propagation is uniquely different in small-skin-depth pair plasmas compared to otherwise equivalent electron-ion plasmas. This is illustrated in the figure below[43], which shows the propagation characteristics of waves in electron-ion and pair plasmas:

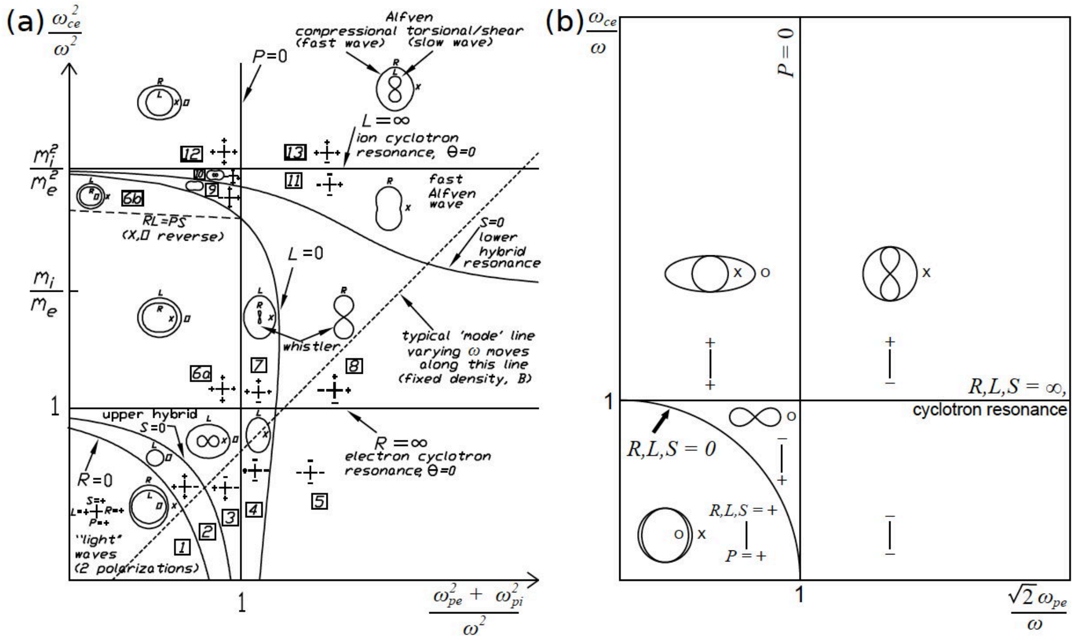

Fig. 6: Electron-positron plasmas (b) have strongly simplified wave propagation characteristics compared to those of electron-ion plasmas (a). Figure taken from Ref.s 44 (a), 43 (b).

Summarizing, the laser-produced pair plasmas can be used to study how pair plasmas interact with electromagnetic radiation, and how relativistic effects change the dynamics of the pair plasma, whereas the magnetically confined low-temperature plasmas can be used to study how pair plasmas are confined, and how they create and are affected by electrostatic dynamics, including generation of turbulence and any associated anomalous transport of particles and energy.

Summary

In summary, we have highlighted some of the unique properties pair plasmas are expected to show in laboratory experiments. Due to the availability of intense sources for positrons, based on nuclear reactions[46] or intense lasers[45,47], steps towards the experimental study of electron-positron plasmas are making rapid progress. Pair plasmas with quite different properties are expected to emerge from the experiments currently in planning, and we have delineated their complementarity. Also, pair plasmas composed of anions and cations of the same species have attracted some interest.[48,49] Due to the much higher mass of the particles they are less attractive for studying magnetized plasmas, though.

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