Pure electron plasmas confined for 90 milliseconds in a stellarator without electron sources or internal objects

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Abstract

We report on the creation and up to 90 millisecond sustainment of pure electron plasmas confined in a stellarator without internal objects. Injection of positrons into such plasmas are expected to lead to the creation of the first electron-positron plasma experiments. These newly created plasmas will also allow a study of pure electron plasmas without the perturbing presence of internal objects. The plasmas were created by thermionic emission of electrons from a heated, biased filament that was retracted in 20 milliseconds. The confinement of these transient plasmas is different from that of steady state plasmas with internal objects and emissive filaments, and is generally shorter, limited by ion buildup. The decay time is increased by lowering the neutral pressure, lowering the electron plasma temperature, or operating with neutrals with high ionization energies (helium). These findings are all consistent with ion accumulation being the cause for the shorter than expected confinement times. The magnetic field strength also moderately increases the decay times. The deleterious effect of ions is not expected to imply a similar deleterious effect when introducing positrons, but it implies that ion accumulation must be avoided also in an electron-positron experiment.

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Introduction

Non-neutral plasmas have been studied for well over 30 years, primarily confined in Penning traps [1–3]. Penning traps are limited to confining particles of one sign of charge. Although nested Penning traps can simultaneously confine both signs of charge [4, 5], they cannot confine many Debye lengths of positive and negative species simultaneously in the same volume [6]. In contrast, purely magnetic confinement configurations such as stellarators and levitated dipoles are capable of simultaneously confining many Debye lengths of positive and negative particles and may be suitable for confining electron-positrons plasmas [7, 8].

To study electron-positron plasmas, one must be able to create a small Debye length plasma without internal objects. The existence of internal objects is incompatible with the creation of electron-positron plasmas: Injected positrons would contact the internal objects and annihilate on a fast time scale ($\tau < 100\mu s$ for conditions envisioned in an electron-positron stellarator, e.g. [7]).

The injection of an energetic electron beam near the last closed flux surface of a stellarator allows creation of pure electron plasmas without internal objects but with a Debye length on the order of the system size and a high electron temperature (on the order of 100 eV) [9] . Experiments in the Columbia Non-neutral Torus (CNT) stellarator have previously demonstrated that pure electron plasmas with a small Debye length and relatively low temperature (< 5 eV) can be routinely created - however, this was in the presence of macroscopic internal objects [10, 11]. This obstacle has now been overcome. It has been determined that for plasmas without internal objects, the confinement time is very sensitive to ionization of background gas. Through a dedicated effort to improve the vacuum conditions, plasmas lasting as long as 90 msec after retraction of the last material object have been created. This letter describes these results.

The CNT experiment

CNT has been in operation since 2004. It is a stellarator whose confining magnetic field is created from four circular coils. The minor radius is 15 cm and the major radius 30 cm. Pure electron plasmas are created in CNT by thermionic emission from heated, negatively biased filaments. A small Debye length is routinely achieved, initially down to 1.5 cm [10, 11], and recently 1.0 cm [12], with typical temperatures of $T_e \approx 4$ eV, densities of $n_e \approx 2 \times 10^{12}$ m^{-3}, and typical central plasma potential of $\phi_p = -200$ V relative to the vacuum chamber and other conducting grounded structures. Thus the Debye length is much smaller than the 15 cm minor radius. It was established early on that the presence of internal structures (ceramic rods) caused significant transport [10, 14], but it was also found that these rods prevented continuous ion accumulation, and that the ion content would therefore reach a steady state value. At low neutral pressures ($p_n < 5 \times 10^{-9}$ Torr) the ion content would be less than 1 % [15]. Confinement times were measured for steady state plasmas by a simple comparison of the source rate (the electron emission current I_e) and the electron charge inventory Q, $\tau = Q/I_e$. During the first year of operation, steady state confinement times up to 20 msec were measured. Confinement was seen to increase with increasing magnetic field (linearly for rod driven transport, stronger than linearly for neutral collision driven transport) and decrease with neutral pressure (linear relationship between transport rate and neutral pressure) [14]. More recently, $\tau = 0.32$ sec was achieved through reduction of the neutral pressure, maximization of the magnetic field strength, and the installation of a flux surface conforming electrostatic boundary [12]. A moveable emitter was installed, capable of full retraction from the magnetic axis to the edge of the magnetic surface in 20 milliseconds [16], ie. much shorter than the best steady state confinement times. Thus, it was expected that the creation of pure electron plasmas without internal objects would be quickly achieved. This, however, turned out to be more complicated than expected. Initial results from retraction experiments were disappointing: There appeared to be no plasma left after retraction, even during operational conditions that favor long confinement times (B-field up to 0.2 T and low neutral pressures $p_n \approx 5 \times 10^{-9}$ Torr) [12].

Ion accumulation cause of fast collapse

The cause for these disappointing results has now been found, and decay times (confinement times) as long as 90 milliseconds have been achieved, Fig. 1. The plasma lifetime without internal objects is much more sensitive to the neutral pressure than the confinement time of plasmas being sustained by emissive filaments held on rods inside the plasma.

This became clear after a fast and reliable non-perturbative external diagnostic for the total plasma charge was developed: The measurements were performed by placing a heated emissive filament a few cm outside the last closed flux surface. The filament was surrounded by an approximately 10 cm diameter grounded copper cylinder open to the plasma, and slightly recessed from the last closed flux surface to prevent it from perturbing the plasma, but intersecting the magnetic field lines on which the filament was emitting, in both directions. This was confirmed by visualizing the magnetic field lines [13]. The filament was connected to a current controlled analog circuit that kept the emission current constant at an absolute value of 20 nA, 5 orders of magnitude below the thermionic emission limit of the filament. Thus, the voltage of the filament was very closely matched to the local space potential. At 20 nA emission current, the electronic circuit would regulate the filament potential with a response time of less than 1 msec. Since the 20 nA current was guided by the magnetic field and collected directly by the surrounding grounded copper cylinder, it did not affect the electron plasma. The voltage of this probe is directly proportional to the central plasma potential, and was calibrated against experiments with plasmas created or diagnosed by internal probes, allowing the central plasma potential to be determined with good accuracy also for these plasmas [17].

The measurements showed that for retraction experiments, the confinement time is strongly affected by the neutral pressure and is shorter than for the plasmas being sustained by an emissive filament held on a ceramic rod. With this knowledge, it was possible to achieve long confinement times through a dedicated effort to lower the neutral pressure in CNT down to 1×10^{-9} Torr). In Figure 1 we present the best result obtained so far, showing that electron plasma gradually disappears with an approximately exponential decay with a time scale of 90 milliseconds, clearly demonstrating that plasma remains after retraction. The confinement times discussed in the following and displayed in Figures 2 and 3 are also measured with this technique.

We have concluded that ion buildup is the cause of the fast decays, based on the following experimental observations: First, a comparison was performed between experiments where the dominant neutral species was nitrogen, to experiments where the dominant neutral species was helium. Figure 2 shows that nitrogen decreases confinement much more than helium at the same pressure does. Given the much larger ionization energy of helium (24.6

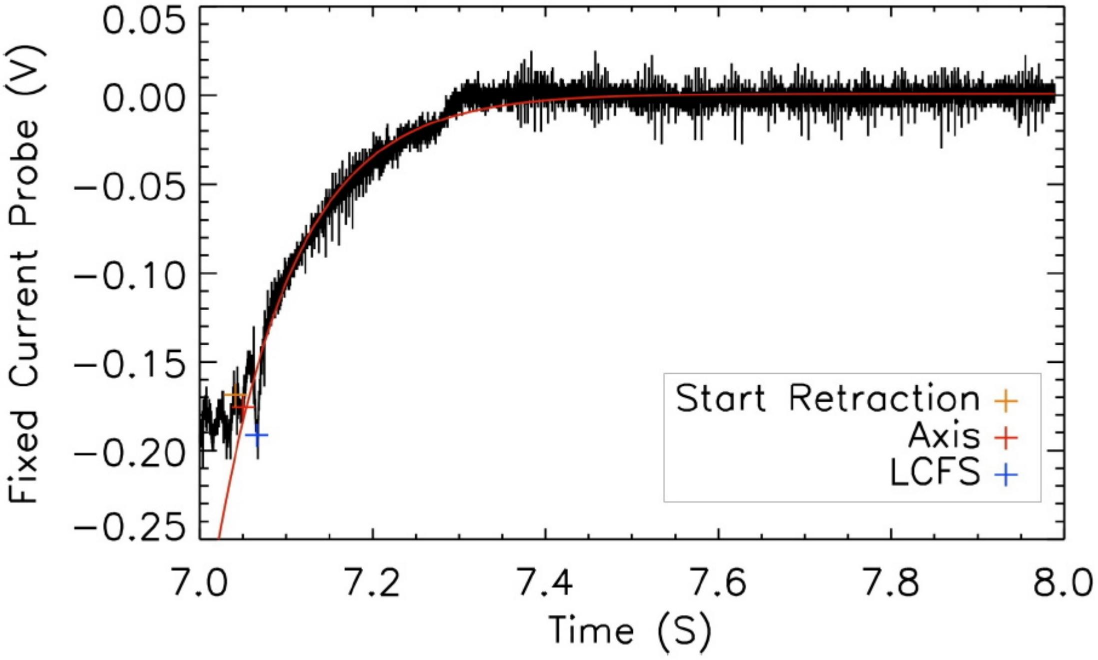

FIG. 1. The decay of plasma charge after retraction of all internal objects is measured for a plasma shot with B=0.055 T, initial plasma potential $\phi_p = -200$ V, and $p_n = 1.8$ nTorr. This decay is well fitted by an exponential decay time of 90 msec. Also marked on the figure are the points in time when retraction begins, when the filament passes through the magnetic axis, and when the filament leaves the last closed flux surfaces (LCFS). The dominant neutral gas was nitrogen.

eV) than oxygen (13.6 eV) or nitrogen (14.5 eV), this indicates that ionization, rather than electron-neutral collisions, is the cause. The two neutral species also scale differently: The decay time decreases with rising helium neutral pressure approximately as $1/p_n$, whereas for nitrogen dominated neutral gas, the decay time decreases more abruptly than $1/p_n$. For the helium dominated gas mixtures, the next most abundant species was nitrogen with partial pressure 3 nTorr, then oxygen at 1 nTorr. For the nitrogen dominated discharges, oxygen was the next most abundant species (at least a factor of 4 smaller). These were measured with a residual gas analyzer (RGA). The magnitude and approximate $1/p_n$ scaling for the confinement time for helium dominated experiments is consistent with measurements of the transport in steady state experiments with helium. The $1/p_n$ scaling is well understood as being electron-neutral collision driven transport and was also observed for nitrogen dominated steady state experiments [10, 14].

Further support for the ionization hypothesis comes from retraction experiments compar-

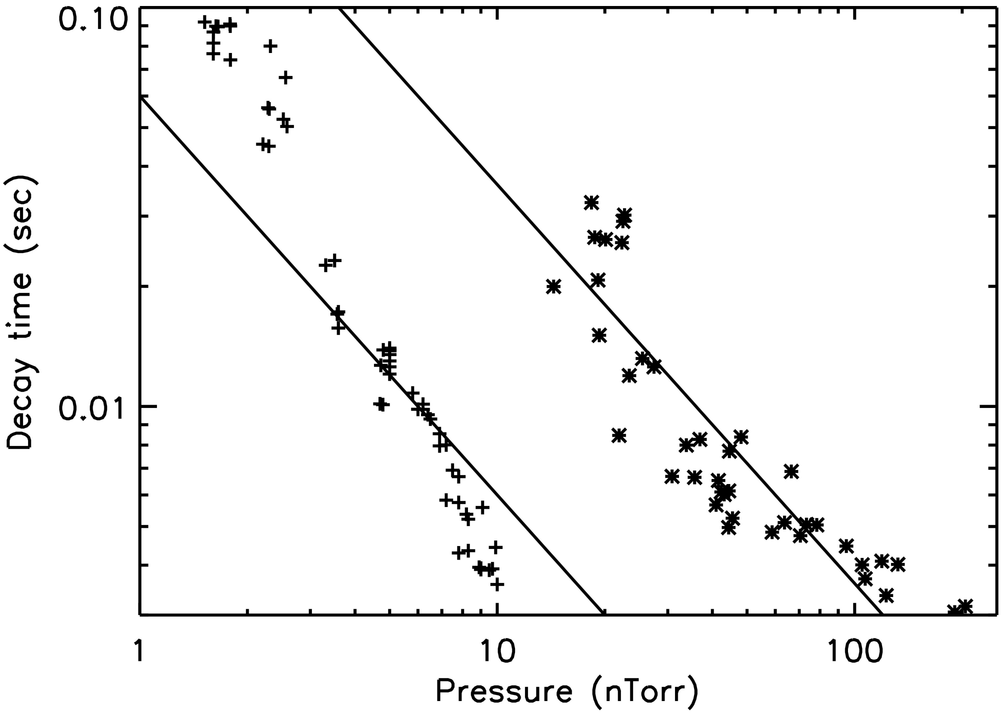

FIG. 2. A comparison of the confinement time as a function of neutral pressure for two sets of experiments - one with the dominant neutral species being nitrogen (+), and another where the dominant neutral species is helium (*). The sweep is performed at B=0.055 T for an initial central plasma potential of $\phi_p = -200$ V. Shown for comparison are two lines representing $1/p_n$ scalings. The point for Figure 1 is included.

ing an electron plasma with a -30 V central plasma potential to one with a -200 V central potential (controlled by setting the emitter bias), Figure 3, clearly showing much longer confinement times for the -30 V plasmas. We interpret this in terms of a lower electron temperature leading to a much lower ionization rate and a much longer confinement time: For a pure electron plasma, the plasma potential is proportional to the charge content, so the initial number of electrons in the shorter lived plasmas starting at $\phi_p = -200$ V is roughly a factor of 7 larger than the $\phi_p = -30$ V plasmas. Nonetheless, the -30 V plasmas last significantly longer. Mobility transport, observed and well understood in Penning traps [18] cannot explain our findings. If mobility transport were the cause, then the initial decay of the -200 V plasma would indeed be fast, but as this plasma decays to -30 V, it should decay just as slowly from there as the plasma that started at -30 V. Instead, a plasma that started at -200 V continues to decay much faster than a plasma that started at -30 V. Mobility transport is in any case not expected to be observed in CNT. Instead of confinement decreasing with increased radial electric field strength (as predicted by mobility transport), theory predicts that confinement should increase with increasing radial electric field strength [19].

The different electron temperatures between the two plasmas are the cause of the difference. In CNT, lower voltage plasmas have lower temperatures (e.g. $T_e = 5.8$ eV at $\phi_p = -400$ V, $T_e = 1.5$ eV at $\phi_p = -100$ V [20]), so the $\phi_p = -30$ V plasmas are cold enough not to ionize the nitrogen atoms and molecules at any appreciable rate, whereas the $\phi_p = -200$ V plasmas decay much more rapidly because they have a significantly higher temperature, and therefore ion birth rate.

The figure also shows that a large magnetic field in general increases the decay time. The confinement improvements at higher fields are rather weak for the $\phi_p = -200$ V plasmas but are clear for the $\phi_p = -30$ V plasmas. For comparison, steady state experiments show the confinement time scaling roughly proportional to $B^{1.5}$ for neutral driven transport, and confinement time scaling roughly proportional to B for rod driven transport (which is usually absent for the retraction experiments) [14]. The lower voltage plasma decay times are roughly the same as the steady state plasma confinement times, again consistent with the overall picture of ion contamination being responsible for the fast decay times.

The ion contamination hypothesis is also consistent with other previously published findings in CNT. In steady state plasmas, an ion density on the order of 10% of the electron density leads to instabilities and decreased confinement in CNT [21]. We therefore believe that the ion contamination causes an instability that destroys confinement rapidly, perhaps by first increasing the electron temperature, or generating a hot tail in the electron distribution function, either of which would then increases the ionization rate [15]. The plasma would be either rapidly neutralized or lost completely due to the increased particle transport caused by the instability [22].

Influence of rods and emissive filaments in the plasma

The mere presence of a rod in the plasma does not cause the confinement to revert to the much longer values seen in steady state plasmas, whether or not the rod holds cold (non-

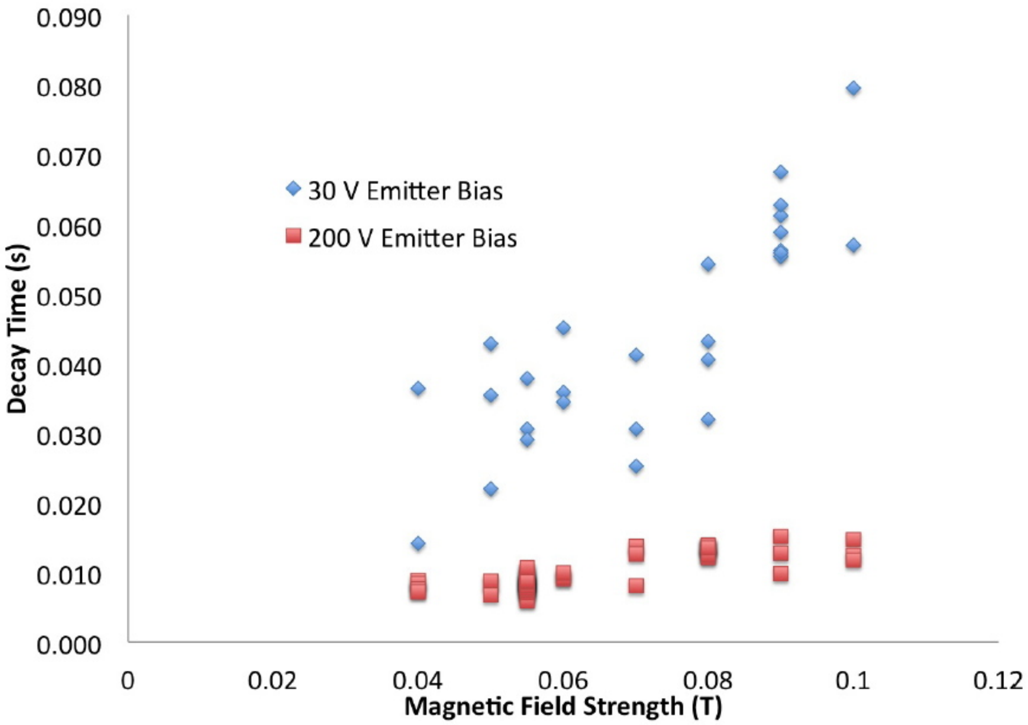

FIG. 3. Plasmas with a lower initial electron content and lower initial temperature last significantly longer than those with higher temperatures and higher initial electron content. Also shown in this figure is the effects on the decay time of varying the B-field. These data were obtained at $p_n = 6$ nTorr.

emissive) filaments. This is somewhat counter to the hypothesis that ion contamination is causing the fast collapse, since rods act as sinks for ions [15]. Interestingly, a rod with an electrically isolated emissive filament *does* increase the confinement time to values consistent with the steady state confinement times. These experiments were done with one stationary rod inserted, and in some cases also with the retractable emitter rod. Thus, we observe that an emissive filament interacts with the plasma and changes plasma confinement even when the filament is not a net source of electrons. A floating emissive filament in CNT will emit and collect an amount equal to the entire electron inventory in only $\tau = V/(v_{th}A) \approx 10$ msec (effective collection area $A \approx 10$ mm^2, $v_{th} \approx 10^6$ m/s, CNT plasma volume $V \approx 100$ liters). It can therefore significantly affect the electron distribution function. In particular, it may suppress the formation of a hot tail in the distribution, which would lead to faster ionization.

Discussion

The creation of small Debye length pure electron plasmas without internal objects lasting for up to 90 msec is an important step towards the creation of an electron-positron (pair) plasma experiment. Now remains two further challenges: The development of an effective positron injection scheme, and the development of a sufficiently large positron source. Numerical simulations show that with a carefully tailored application of bias voltages to external capacitors, positrons can be injected from the outside (open field line) region to the inside (closed flux surface) region of a stellarator in tens of microseconds [24]. A bright source of moderated positrons is already available [25] , and a promising positron accumulation trap concept, capable of holding more than 10^{11} positrons, has been developed [26]. The clearly deleterious effect of adding positively charged ions to the electron plasma appears to be a concern for the lifetime of of a pair plasma. However, the mass symmetry of a pair plasma leads to fundamentally different physics behavior compared to an electron-ion plasma [27]. Gyrokinetic simulations show that a low density pair plasma should be stable [7]. We therefore do not expect a similar crash when positrons are added to an electron plasma. However, our results show that significant ion accumulation should be avoided in a pair plasma experiment.

Note added in proof

An updated plan for the creation of electron-positron plasmas was recently published, to which we refer the reader for more information [28]

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