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"Noisy" emission of a slowly released single component plasma

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Abstract

A single component plasma confined in a Penning–Malmberg trap may be released in a controlled manner by regulating the rate at which one of the confining (gate) potentials is dropped. A close inspection of the emission profiles of such plasmas has revealed fluctuations far beyond those that might be expected from counting statistics, with additional features becoming prominent when the gate is lowered slowly. The exact mechanism behind the observed emission characteristics are not known at this time and we show here some details and consider possible explanations. We also demonstrate a quick and simple method to measure the plasma collision frequency.

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Keywords: Positron; Trap; Plasma

Single component electron and ion plasmas have been extensively studied because of their relevance to a wide variety of topics in plasma and atomic physics. Many of the techniques developed to study and manipulate such plasmas [1–3] are now routinely used, along with positron moderation [4] and trapping [5,6] methods, to create pure positron plasmas in Penning–Malmberg (PM) traps. The motivation for doing so is primarily to facilitate the storage and manipulation of positrons and not for basic plasma research.

Nevertheless, in order to take advantage of the large body of work that has been done regarding various techniques developed to manipulate electron plasmas it is necessary to produce well characterized positron plasmas. This requires knowledge of basic plasma parameters such as density, temperature, space charge potential and so on. It was in the course of measuring such properties that we observed some unexpected effects in the manner in which positrons left the PM trap when the gate was lowered slowly.

The experiments we describe here were carried out with the UCR positron accumulator, a schematic of which is shown in Fig. 1 [7]. The positron beam was generated using a 30 mCi ^{22}Na source and a solid neon moderator [4]. Positrons were then captured in a two-stage Surko-type buffer gas trap [5] that delivered pulses containing approximately 10^5 positrons to a separate UHV accumulation section (base pressure $\sim 5 \times 10^{-11}$ Torr) at 10 Hz. The trap and accumulator were both within 400 G solenoids. The accumulator potential structure was such that before release the plasma was contained in a well 10 V deep. The final electrode of the accumulation region was azimuthally segmented into eight sections to allow the application of a rotating electric field. This 'rotating wall' generates a torque on the plasma, which results in inward transport and thence compression [8,9]. The shot to shot variation from the positron accumulator was low (<2%) and, the lifetime was long (>1000 s), and we do not believe that the observations reported are due to device idiosyncrasies [10]. The use of a rotating wall meant that cooling gas had to be introduced into the accumulator. Approximately 2×10^{-8} Torr of CF_4 was used, which was the limiting factor on the lifetime. The rotating wall effectively negated any losses due to transport effects.

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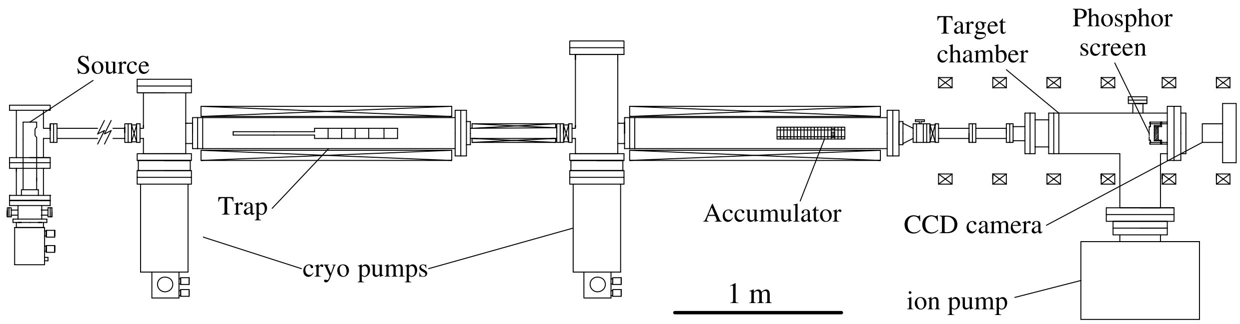

Fig. 1. A schematic of the positron accumulator layout. A slow positron beam was generated in the source chamber, and positrons were stopped in the nitrogen gas filled trap section. Every 100 ms a pulse of positrons was sent to the accumulator where more than 9×10^7 positrons could be accumulated. A scale bar of 1 m is shown, and the entire apparatus is approximately 9.5 m in length.

Since they must be generated from low current beams, positron plasmas, unlike electron plasmas, are formed by accumulation over time. When the space charge potential of a plasma thus formed becomes equal to the confining electrostatic potential, no further filling is possible, and we refer to this situation (where the plasma self-charge reduces the effective potential barrier to zero for at least some of the plasma) as the space charge limit. This condition is of relevance to the formation of high-density plasmas [11], to the confinement of two charge species in a nested trap (as has been used, for example, to create antihydrogen [12,13]) and to the formation of a narrow or pulsed beam by controlled release of a pre-formed plasma [14]. Observation of the annihilation radiation produced in a positron plasma dump is a straightforward way to obtain time resolved particle flux information. This is especially useful for the work described here since we can efficiently observe very low particle fluxes that, for example, might be impossible to distinguish from amplifier noise in a charge collection device such as a Faraday cup. Furthermore, detection of in situ annihilation radiation facilitates non-destructive monitoring of particle losses by annihilation or cross field transport [15].

Once the desired number of positrons had been accumulated the plasmas were held for several seconds to allow them to equilibrate. Then they were released at various rates by controlling the voltage on the final (gate) electrode. All electrodes in the accumulator were copper rings with a 2.54 cm inner diameter. By reducing the potential on the last of these rings the positrons were released. The escaping positrons then travelled along the magnetic field lines and annihilated about 60 cm downstream from the trap region. A plastic scintillator attached to a 56DUVP photomultiplier was used to detect the resulting annihilation radiation. Fig. 2 shows the (direct coupled) detector anode signal voltage as a function of the gate potential for two typical plasma dumps with different gate ramp rates. Both the gate time constant (τ_{gate}) and the detector integration time constant (τ_{det}) were defined by simple RC circuits, and are quoted in the appropriate figures. In the data shown both the detector and gate time constants were adjusted so as to provide a constant ratio $\tau_{gate}/\tau_{det} = 5000$. Prior to collecting the data checks were made to ensure that no information was lost by the choice of time constants. For most of the data shown here the plasmas consisted of $\sim 1 \times 10^7$ positrons. In all cases the plasma radial distributions (measured using a phosphor screen and a CCD camera) by were well approximated by a 2-dimensional Gaussian distribution with a full width at half maximum (FWHM) of around 3 mm (in a 500 G magnetic field). This was somewhat reduced (~20%) for the slowest dumps [16].

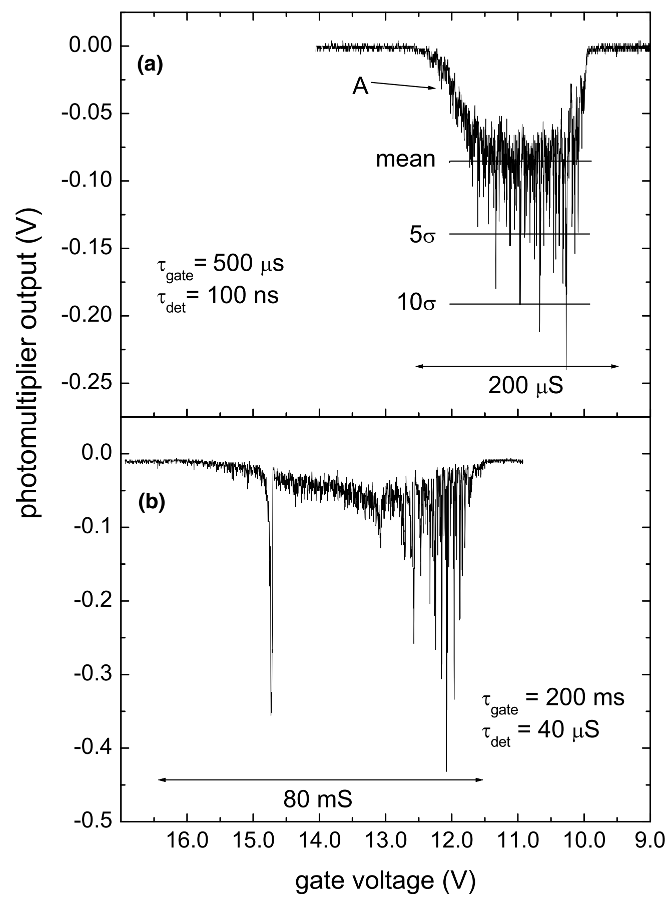

Fig. 2. (a) Emission profiles for plasmas released quickly (a) and slowly (b). The gate time constant is shown in the appropriate figure, as is the total time taken for emission to occur.

The sharp peak seen at the beginning of Fig. 2(b) appears only when the gate time constant is around 10 ms or higher, and it appears to be due to resonant heating or the excitation of large amplitude modes by the rotating wall drive. If the drive is switched off during the dump, this peak does not appear, although the rest of the profile is largely unaffected. For all of the data shown here the rotating wall was not switched off before the dump.

At first sight the emission profiles seem almost chaotic, but they do in fact exhibit a remarkable reproducibility for given loading/dumping parameters. Fig. 3 shows an expanded section of two pairs of traces from separate shots with identical loading parameters. These data are raw oscillograms and have not been manipulated in any way. Although the two traces in each pair (a) and (b) are not identical, they do exhibit many similarities, which suggest that the responsible mechanisms are neither random nor chaotic.

Fig. 4 is a three-dimensional construction of many slow plasma release profiles, showing the detector anode voltage (z-axis) as a function of both the rotating wall drive frequency and the gate voltage. The time constant of the gate for these profiles was 0.8 s. The diagonal, frequency dependent, band labelled (A) corresponds to the resonant peak. We note also that a second harmonic is starting to appear, which we have labelled (B). Reducing the rotating wall drive amplitude by almost an order of magnitude reduced this peak height by less than a factor of two, indicating that the resonance is either non-linear or saturated. Features that are essentially independent of the rotating wall frequency are labelled (C).

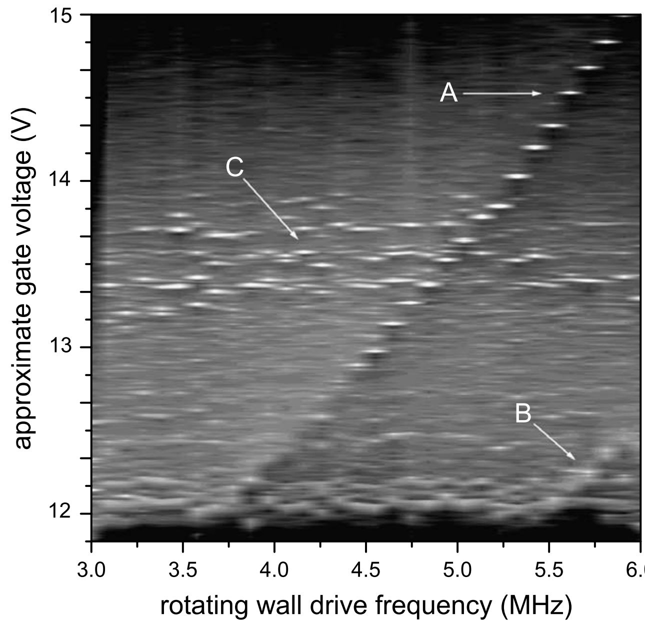

Fig. 4. Construction of many emission profiles, showing the dependence of the resonant component on the rotating wall drive frequency. The data were taken in 0.1 MHz steps. The vertical scale should actually be slightly (5%) nonlinear because of the exponential time variation of the gate voltage. As in Fig. 3, $\tau_{gate} = 800$ ms and $\tau_{det} = 160$ μs for these data.

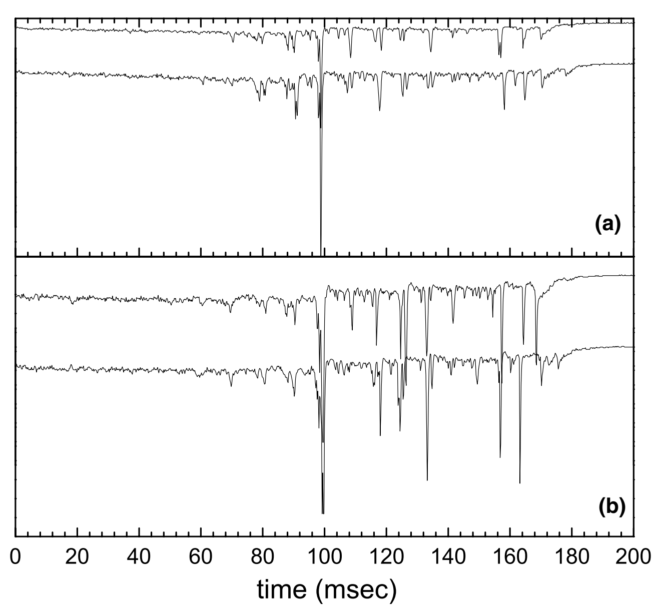

Fig. 3. Demonstration of the reproducibility of the emission profiles. Two pairs of oscillograms are shown for different density plasmas of approximately 5×10^7 cm^{-3} (a) and 9×10^7 cm^{-3} (b). Each has nominally identical loading and release parameters which included a rotating wall drive frequency of 4.8 MHz and amplitude of 180 mV pk–pk. The time constant for the gate voltage was 0.8 s, and the detector integration time was 160 μs. The vertical scale is the photomultiplier output (in arbitrary units), and the traces in each pair have been displaced for clarity.

The structures that occur for both fast and slow dumps are very similar in form. They have in common the fact that the seemingly erratic parts do not appear until some fraction of the plasma has been released. In the cylindrical geometry of PM traps the confining potential has a minimum value on axis, while the axial space charge potential has its maximum value. Thus, when the gate is lowered slowly, particle emission always occurs from the central region of the plasma first. Therefore we may deduce that, at least initially, it is hollow plasmas that give rise to the emission profiles we observe.

Such hollow density profiles in electron plasmas are known to result in the formation of instabilities [17]. In fact they are often deliberately created in order to study various plasma dynamics [18], in particular diocotron waves [19]. Thus, it is tempting to ascribe the plasma dynamics we have observed to diocotron instabilities, however the continuous release of particles complicates the matter considerably.

Studies of diocotron waves are usually accomplished by forming a hollow radial density profile and then observing the 2-dimensional evolution of that profile destructively by dumping the plasmas, a process which must therefore be done many times. In this case we may well form a hollow profile to begin with, but as particles are released the evolution of the radial profile is unlikely to follow the same path as a simple diocotron wave. Furthermore, diocotron waves usually develop on a ms time scale (for parameters similar to those here), whereas we see large fluctuations in the escape rate over much shorter time scales. Also, diocotron wave frequencies depend on the plasma frequency, and we would therefore expect to see variations in the non-resonant emission with the rotating wall drive frequency (which changes the plasma density) if it were caused by such waves. The peaks labelled (C) in Fig. 4 show very little change, even though the density variation over this rotating wall frequency range is approximately a factor of two. The insensitivity to the plasma density of the responsible mechanism is also apparent if one compares Fig. 3(a) and (b), in which similar profiles are seen for almost a factor of two change in density at a fixed rotating wall frequency.

The reproducibility of the emission profiles as shown in Fig. 3 seems to suggest that the behaviour of the plasmas is in fact well defined. There are some initial plasma states that could affect the escape profiles [20], but since the plasmas are quiescent before release it seems more likely that instabilities develop after some of the particles are emitted.

For the first few particles to be released the space charge potential hardly changes at all and may be considered to be constant. Similarly, the loss of a small number of particles does not generally lead to plasma instabilities, and so the particle emission is described by the energetics. This idea is the basis of the standard method used to measure (parallel) plasma temperatures, developed by Eggleston and co-workers [21], in which the emission as a function of the confining potential is simply determined by the shape of a Maxwell–Boltzmann distribution. That is, if the confining potential barrier is ϕ the rate at which particles are emitted depends on ϕ as,

$$N(\phi) \propto \mathrm{erfc}\left[\sqrt{\frac{q\phi}{kT}}\right], \tag{1}$$

where erfc is the complementary error function, q is the charge on the particles, k is Boltzmann's constant and T is the parallel plasma temperature. This expression describes the particle emission as a function of the effective confining barrier and has been used to determine the parallel plasma temperature (using just the first 1% of positrons emitted) for various different release rates in Fig. 5(a). As is evident from the figure, essentially the same temperature was obtained from the fastest gates, until the gate is lowered too slowly, and erroneous values for the temperature are obtained. We believe that this is due to collisional repopulation of the hot tail of the distribution. For a nearly stationary gate potential, after the highest energy particles have been released no more emission is possible and so the emission profile follows the MB distribution as the gate is slowly lowered. However, if the gate potential is reduced so slowly that it may be considered to be stationary for a time comparable to or longer than the interval between particle collisions the original distribution will be reformed (with some slight cooling) and particles will again be able to leave. Thus, the point at which the measured temperature starts to diverge from the "correct' value obtained with appropriate gate ramp rates can be used to estimate the inter-particle collision rate. One can also see that the fitting errors start to increase as the emission profile starts to deviate from that shown in Eq. (1). The original purpose in collecting these data was simply to measure the plasma temperature and hence the data set is not optimised to extract this information. We are able here to make only an estimate, by way of a demonstration of the technique. The condition for which collisional repopulation of the distribution is likely to occur may be written as

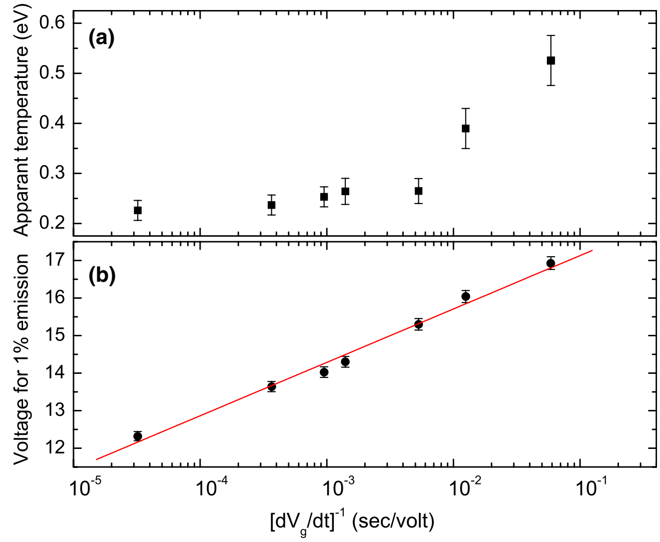

Fig. 5. The apparent plasma temperature (a) and the gate voltage for which 1% of particles have been released (b) for the various gate lowering rates. Because the gate was lowered using an RC time constant, the actual value of $\mathrm{d}V/\mathrm{d}t$ was numerically evaluated for the emission period. The change in $\mathrm{d}V/\mathrm{d}t$ during the first 1% emission was negligible. The straight line in (b) is a linear fit using a linearized X scale.

$$\frac{\mathrm{d}V_g}{\mathrm{d}t} > \frac{kT}{T_{col}}, \tag{2}$$

where V_g is the gate voltage and T_{col} is the time between collisions. From Fig. 5 we can only say that the temperature measurement diverges from the constant value at some point in the (inverse) gate reduction rate between 0.0053 and 0.0125 s/V, which for a plasma temperature of 0.22 eV implies that the collision time must be between 1.2 and 2.8 ms. Obviously, greater accuracy could be obtained with additional data points.

As explained by Hyatt et al. [22], a theory developed by Ichimaru and Rosenbluth [23] to calculate the collision frequency of magnetized plasmas may be adapted for the regime $\lambda_D \gg r_c \gg b$ (where λ_D is the Debye length, r_c is the cyclotron radius and b is the classical distance of closest approach) simply by replacing the Debye length with the Larmor radius in the Coulomb logarithm. The collision frequency v_{col} is then given by

$$v_{col} = \frac{8\sqrt{\pi}}{15} nb\bar{u}\log(\Lambda), \tag{3}$$

where n is the plasma density, $\bar{u}$ is the average thermal velocity, b is the classical distance of closest approach and $\Lambda = r_c/b$.

For a plasma temperature of 0.22 eV the collision frequency given by Eq. (3) is $738\ \mathrm{s}^{-1}$, corresponding to a time between collsions of (T_{coll}) of 1.4 ms, which is consistent with our results. Even with a more complete dataset this methodology is probably less accurate than the techniques developed by Malmberg and co-workers to measure T_{col} [24–26] and is more useful in circumstances when a quick estimate is sufficient.

Fig. 5(b) shows the gate voltage by which the first 1% of the positrons have been emitted for the different gate ramp rates. It is curious that particle emission occurs for ever higher gate voltages as the ramp rate decreases even when the temperature data indicate that there are no collisions on the time scale of the release.

To conclude, we have observed a "noisy" emission from a slowly released plasma, the origin of which is presently unknown. It seems that the large variations in the emission profile are due to some process that may be a diocotron-like mode, perhaps driven by the continuous release of particles. However, the time scale of the mechanism, as well as the relative insensitivity to density are not consistent with a simple diocotron wave. More information could be obtained by releasing the plasma in the same manner as has been done here, but halting the release and quickly dumping and imaging the plasma at various stages in the process. We note that when slow dumps are imaged the (integrated) radial distribution always looks like a Gaussian that is slightly narrower than the corresponding fast dump.

We do not believe that the rotating wall is driving this process, whatever it may be, since essentially the same effects are seen when it is switched off a few seconds before the plasma is released. However, the rotating wall is critical to obtain long lifetimes and small plasmas and so it was always on during the accumulation phase. It is possible that some long-lived effect occurs that remains even after the drive is switched off for a few seconds before dumping.

Similarly, we do not know exactly why the plasma begins to escape at increasingly higher potential barriers as the gate ramp rate is reduced, even when the measured parallel temperature does not increase. Any mechanism that allows particles to escape at an energy higher than one would expect from Eq. (1) (such as collisional repopulation of a depleted thermal distribution) ought to make the temperature seem higher unless it only affects the space charge potential. Thus, we can only conclude that many interactions with a potential barrier somehow allows the charge distribution to shift so as to increase the space charge potential without affecting the temperature. The observation that this seems to increase logarithmically with time at a rate that does not increase even when there are interparticle collisions may serve as a clue to the nature of this mechanism.

As pure speculation, we could imagine that particles scatter repeatedly from the potential barrier prior to release in such a way that positrons accumulate on the axis and the local space charge potential is increased. Alternatively, as the plasma is held close to the space charge limit (as determined by the lowered gate potential) the plasma may stretch out at the ends, forming narrow extensions where the space charge is locally enhanced, and the degree to which this happens could then depend on how long this configuration is maintained. However, further investigation is required to properly understand how such processes might happen. We point out though that erroneous measurements of the space charge potential may occur if the barrier is lowered too slowly, even though this may not be apparent from an inspection of the integrated emission profile or from temperature measurements.

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