Unprecedented confinement time of electron plasmas with a purely toroidal magnetic field in SMARTEX-C

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Confinement time of electron plasmas trapped using a purely toroidal magnetic field has been extended to $\sim 100 \text{ s}$ in a small aspect ratio ($R_0/a \sim 1.59$, $R_0$ and $a$ are device major and minor radius, respectively), partial torus. It surpasses the previous record by nearly two orders of magnitude. Lifetime is estimated from the frequency scaling of the linear diocotron mode launched from sections of the wall, that are also used for mode diagnostics. Confinement improves enormously with reduction in neutral pressure in the presence of a steady state magnetic field. In addition, confinement is seen to be independent of the magnetic field, a distinguishing feature of Magnetic Pumping Transport (MPT) theory. Since MPT predicts an upper limit to confinement comparisons have been made between our experiments and MPT estimates.

The excellent confinement of electron plasmas in cylindrical traps had unleashed a plethora of laboratory investigations into their rich collective dynamics in the latter half of previous century [1–3]. This impacted a large number of fundamental studies relevant to diverse fields ranging from atomic physics to incompressible fluid dynamics. In contrast, the behaviour and applications of such single species plasmas confined in other geometries and magnetic field topologies remained rather unexplored due to their unknown confinement properties. Historically though, experiments in toroidal electron plasmas, preceded cylindrical plasmas and several applications had also been proposed. These included, for example, formation of a deep potential well by an electron cloud trapped in toroidal geometry as a source of highly stripped ions [4], heavy ion particle accelerator [5], electrostatic thermonuclear fusion reactor [6, 7], or as a shielding mechanism for space vehicles from solar radiation [8]. Besides these, confinement of non-neutral plasma in toroidal geometry and investigating the effects of arbitrary degree of non-neutrality under controlled conditions [9] was also expected to aid the understanding of transport in neutral plasmas which are of profound interest to the fusion community. In recent times, much of the motivation and interest in toroidal traps seem to follow from the possibility of creating electron-positron pair plasmas [10, 11] due to the expected lack of instabilities in such plasmas and in view of their relevance to astrophysical objects. In addition to this, just like cylindrical electron plasmas in homogeneous magnetic field have served as excellent test-beds for carrying out incompressible fluid dynamics experiments [12, 13], toroidal electron plasma in the presence of an in-homogeneous magnetic field may mimic compressible fluids and has remained an attractive proposition for some time [14] that certainly merits further investigation.

Undoubtedly, the minimum underlying requirement for achieving any of the stated objectives with toroidal non-neutral plasmas, is a long time confinement. Theoretically, in the presence of a purely toroidal B field, such plasmas are supposed to be in stable equilibrium [15, 16]. However, unlike cylindrical plasmas in uniform magnetic field which are governed by robust confinement theorem [17], plasmas trapped with a purely toroidal B field are thought to be fundamentally limited in their confinement properties due to MPT. Proposed by O’Neil and Crooks [18], this radial transport arises due to $E \times B$ drifts of the plasma in a spatially inhomogeneous toroidal B field. The flux rates, as derived in the limit of large aspect ratio, suggest a transport time scale [19] that is dependent on major radius $R_0$ and electron temperature $T_e$. Experimentally, a few early initiatives in toroidal traps reported successful trapping to varying degree and successfully demonstrated steady state confinement of a few hundred microseconds [20–23] overcoming the single particle drifts. Renewed interest in toroidal traps in the late 90’s and early 2000s, led to a major turnaround. Two of the new traps with purely toroidal magnetic field, were converted into partial torus in order to combine the technique and advantages of cylindrical traps with toroidal geometry. Among them were LNT-I [21] which was a large aspect ratio device and SMARTEX-C [25], a small aspect ratio trap. While significant improvement in trapping ranging from few to 10s of ms were achieved, yet, till early 2006, the best confinement times reported remained orders of magnitude less than those predicted by MPT theory. Finally, in 2009, with improved operating scenarios like enhanced vacuum, higher magnetic field and a higher degree of symmetry LNT-II successfully confined toroidal electron plasma in a steady state for 3s [19, 26, 27]. They argued that the confinement time approached the limit set by MPT (for the trap major radius of 17.4 cm and assumed temperature of 1 eV), although no direct evidence of MPT was observed. Results from SMARTEX-C followed, whose reported confinement time (2.14±0.1 s) was also very close to their theoretically predicted time scales [25]. Its worth mentioning here that no such theoretical limitations are known to apply to plasmas trapped in other B field topologies like in Stellators or, say, in a torus with levitated dipole magnetic
field. Attempts to confine such plasmas on nested flux surfaces in a Stellarator though has been limited to \( \sim 90 \text{ ms} \) due to ion dynamics. Experiments with a levitated dipole \[25] magnet have however triumphed in extending the confinement to \( \sim 300 \text{ s} \) and has been by far the most promising. It may thus appear that low temperature electron plasmas trapped with purely toroidal \( B \) field are fundamentally constrained and will perhaps never be able to achieve the goals of long time confinement and thermal equilibrium like their cylindrical counterparts and/or other contemporary traps with alternate \( B \) field topologies.

This letter reports an improvement in the confinement of pure electron plasma by nearly two orders of magnitude in an upgraded SMARTEX-C, where plasma remains in a steady state equilibrium for nearly 100 ± 20 s at 200 Gauss. This is the highest reported time from a trap with purely toroidal \( B \) field. Comparisons of experimental results with predictions based on MPT are interesting and have been revisited.

![Figure 1: Schematic diagram of SMARTEX-C device](image)

SMARTEX-C is a partial (C-shaped) toroidal trap with aspect ratio of \( R_0/a \sim 1.59 \), trapping electron plasma in an angular arc of \( \Phi \sim 315^\circ \). The electrode arrangement as shown in Fig. 1 allows us to operate the trap in a “inject-hold-dump” cycle \[25\], as is typically carried out in cylindrical Penning-Malmberg traps. The electrons emitted thermionically are injected for a brief period (\( \sim 60 \mu \text{s} \)) into the arc by turning the injector grid bias positive with respect to the (tungsten) filament. As the grid turns negative, the injection stops. The electrons injected at \( \sim 250 \text{ eV} \parallel \text{energy} \) are held between negatively biased end-electrodes and radially confined with a purely toroidal \( B \) field. A sufficient number of these electrons gives them a collective \( E \times B \) drift that helps to overcome the single particle drifts, thus forming a plasma. It may be noted that presence of neutrals contaminates a pure electron plasma primarily affecting its confinement. In our earlier experiments pressures of \( \sim 4 \times 10^{-9} \text{ mbar} \) were reported from a gauge placed close to the pumping port. As the confinement time has been observed to be highly sensitive to neutrals, pressure measurements were re-calibrated accurately with a nude Bayard-Alpert gauge located close to the trapping arc; the measured pressure in such cases was found to be higher by a factor \( \sim 4 \) (1.5 \( \pm \) 0.1 \( \times \) \( 10^{-8} \text{ mbar} \)). To improve the vacuum a Non-Evaporable Getter (NEG) pump was installed on a port close to the trapping arc. Background pressures in the trapping arc now improved to 5.0 \( \pm \) 1.0 \( \times \) \( 10^{-9} \text{ mbar} \). In earlier experiments thermal loading of toroidal field (TF) coils (AWG-8, 20 turns) limited the steady state \( B \) field (\( \sim 380 \text{ Gauss} \)) to 4 s with a droop of \( \sim 35\% \). The confinement time was found to be sensitive to the droop rather than the strength of the magnetic field. The limited operation to 4 s also made any estimation of long time confinement unreliable. Upgraded TF is now generated out of an AWG-2 silver-plated, 24 turns copper cable. A maximum of 900 Gauss could therefore be generated for \( 3 - 4 \text{ s} \) with \( < 5\% \) droop. Whereas, a nearly steady state \( B \) field for \( \sim 40 \text{ s} \) could be generated at 100 – 200 Gauss with droop \( < 0.1\% \). The latter has given us the best and most reliable estimates of confinement time in SMARTEX-C. Principal diagnostics of the trap are capacitive probes \[31] which are essentially parts of wall insulated from the rest of it and are located at various toroidal and poloidal locations. These wall probes are utilized to monitor image currents that can be interpreted to obtain information about any electrostatic activity in the plasma \[32\]. Additionally, if the plasma is quiescent, these probes have been used to excite normal modes, namely the diocotron modes that are ubiquitously present in such single species plasma. Under linear approximations, the frequency of \( m = 1 \) mode, which represents the azimuthal rotation of a displaced charge cloud, is a good estimate of the charge content. In cylindrical machines, such modes have been therefore used as a non-destructive diagnostics to estimate the total stored charge. In toroidal machines, if the mode is linear, the total charge content \( Q \) can be obtained from mode frequency (\( m = 1 \)) using \( f_D = Q/4\pi^2\epsilon_0 L_p R_w^2 B \), where \( Q \) is total stored charge, \( L_p \) plasma length, \( R_w \) wall radius and \( B \) is toroidal magnetic field. The frequency evolution can therefore provide us with an estimation of confinement time \[25\]. Note that in toroidal electron plasmas, shift in equilibrium position, if any, has to be accounted for and \( B \) field at equilibrium position has to be used. However estimation of lifetime from the time evolution of frequencies is unaffected by this shift as it only scales the exponential function by a factor.

In a typical experiment, a natural diocotron mode appears soon after injection but quickly damps in less than one-fourth of a second resulting in a quiescent plasma
Such a quiescent plasma in stable equilibrium has been achieved through a series of measures leading to control of various instabilities [28]. With instabilities arrested, charge loss rate reduces and lifetime increases. However, in such a quiescent plasma with no electrostatic activity, wall probes fail to detect any image current and signatures of plasma dynamics. In such a scenario the presence of plasma can be detected by launching the diocotron mode externally. A small electric field perturbation is applied to the equilibrium plasma using a pair of oppositely located wall probes at a toroidal location [28]. While the applied perturbation may contain a chirp of frequency within a few kHz, the linear $m = 1$ mode is excited with a frequency that is proportional to the charge content in the plasma at the instant of launch. The launched mode at $5 \times 10^2$ Gauss at different instants after injection are shown in Figure 2 (b)-(d). Several “injection-hold-launch” cycles have been repeated keeping all other operational parameters same. In each cycle the mode is triggered at a different instant of time to construct the time evolution of mode frequency. The e-folding time of the charge evolution, suggesting a confinement time, has been obtained through a linear least square fit to a natural log of the measured frequencies. Multiple shots have been acquired at each instant to verify the shot-to-shot reproducibility and error in confinement time is obtained from goodness of fit. Earlier experiments in SMARTEX-C had reported [28] a confinement time of $2.14 \pm 0.1$ s at 380 Gauss. The confinement seemed to be severely limited by droop $\sim 35\%$ in the B field. Pressures in the trapping region (following calibration) were of the order of $1.5 \pm 0.5 \times 10^{-8}$ mbar. Experiments with an upgraded TF coil (droop $<5\%$) were carried out at B fields between 525 Gauss and 900 Gauss (Fig. 3). The difference in initial frequencies at different B fields in Fig. 3 merits discussion. Soon after injection, the frequency of the spontaneously triggered diocotron mode is observed to follow the $1/B$ scaling, suggesting that initially injected charge is nearly same for all B fields. However, the damping of the mode and the rearrangement of the cloud that follows injection seem to be dependent on B field, involving different time scales. The charge left in the quiescent plasma is also different for different B fields. Admittedly, the dynamics and charge loss during the rearrangement is presently not well understood. However, after the initial dynamics, as the plasma becomes stable and quiescent, the loss of charge appears exponential in nature. Also, the confinement time, although showed marginal improvement ($\sim 5.2 - 6.2$ s), was interestingly, independent of B field. Currents were therefore lowered and experiments were conducted at reduced magnetic field of 100 and 200 Gauss. The droop in B field could therefore be further reduced to $< 0.1\%$. More importantly, due to less Joule heating of TF coils, the duration of B field could be increased to 40 s. Further, to push the limits of confinement, pressures in the trapping region were lowered by a factor of $\sim 4 (5.0 \pm 1.0 \times 10^{-9}$ mbar) by turning on the NEG pump. The significant improvement in confinement is visible from Fig. 4. At 100 Gauss the confinement time is $109.4 \pm 9.3$ s and at 200 Gauss it is $102.8 \pm 18.9$ s, with goodness of fit $\sim 95\%$. In addition to this being the highest confinement time with a purely toroidal B field, the independence of the lifetime with
respect to B is being reported for the first time. The
dependence of B is a distinguishing characteristic of the
Magnetic Pumping Transport theory. MPT is thought
to fundamentally limit the confinement in toroidal traps
due to the presence of an in-homogeneous B field, causing
a gradual radial expansion of the plasma. Confinement
time $\tau$ following dimensional analysis is given as [19]
\[
\tau = \frac{an_{av}}{2\Gamma_r},
\]
where $\Gamma_r$ is the flux rate derived by Crooks and O'Neil
[18],
\[
\Gamma_r = \frac{1}{2} \nu_{\parallel\perp} n(r) \frac{T_{eq}}{-e\Phi/\partial r} \left( \frac{r}{R_0} \right)^2,
\]
where $n_{av}$ is volume averaged electron density, $\partial \Phi/\partial r \sim 4\pi nea$, $T_{eq} = (T_{\parallel} + 2T_{\perp})/3$ and $\nu_{\parallel\perp}$ is the rate at which
electron-electron collisions equilibrate perpendicular and
parallel temperatures. If one assumes $\nu_{\parallel\perp}$ to be given
by Spitzer rate of energy equipartition $\nu_{ee}$ [33], $n_{av} \sim n$, and $T_{\parallel} \approx T_{\perp} = T$, then Eq. (1) becomes
\[
\tau_1 \approx \frac{0.623}{\ln \Lambda_1} R_0^2 \sqrt{T},
\]
where $\ln \Lambda_1 = \log(\lambda_D/b)$ is Coulomb logarithm, $\lambda_D$ is
Debye length, and $b = e^2/kT$ is the distance of closest
approach. If we use Eq. (3) the estimate of temperature
would be $\sim 475$ eV for a plasma confinement of 100 s
($R_0 = 13.5$ cm). Well-confined pure electron plasmas are
typically assumed to be 1 to few tens of eV. Even if we
were to consider $T$ of few tens of eV, the unprecedented
confinement time at lower pressures breaches the theo-
retical limits estimated from Eq. (3), fairly convincingly.
This discrepancy thus warrants a closer scrutiny of the
radial particle flux used to derive Eq. (3). It is possible
that $\nu_{\parallel\perp}$ is not equal to $\nu_{ee}$, especially for plasmas with
temperature anisotropy ($T_{\parallel} \neq T_{\perp}$). If instead, we use
for $\nu_{\parallel\perp}$, the prediction given by modified Ichimaru and
Rosenbluth formula [31, 32] and confirmed experimentally
[33, 34], then the revised confinement time is given by,
\[
\tau_2 \approx \frac{2.2}{\ln \Lambda_2} R_0^2 \sqrt{T}
\]
where $\ln \Lambda_2 = \log(r_c/b) + 0.75$, $r_c$ is thermal cyclotron
radius, and this yields $T = 17$ eV. Note that, for weak
magnetization ($r_c \gg b$), the magnetic field dependence of
the transport is expected to be very weak, as also seen
from our experiment. It is thus shown that 100 s con-
finement can be explained within the present framework
of MPT considering the temperature anisotropy related
collisional equilibration rates.

In conclusion, recent experiments in SMARTEX-C
have led us to confine pure electron plasmas with a purely
toroidal magnetic field for approximately 100 s. Control
of instabilities followed by improved operating parameters
have led to such unprecedented confinement time. The
lifetime appears to be independent of B field, sug-
gesting magnetic pumping like transport. Availability
of accurate temperature measurement will lead to better
understanding of underlying transport mechanism.

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