Achieving ultra high vacuum conditions in SMARTEX-C: control of instabilities and improved confinement

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Abstract. Small Aspect Ratio Toroidal Experiments in a C-shaped trap (SMARTEX-C) attempts to confine electrons in a toroidal trap using static electric and magnetic field. Confinement of these electrons is largely limited by charge losses due to the presence of background neutrals and by short pulsed magnetic field. Ions formed due to electron impact ionization of background neutrals lead to instabilities that are ultimately observed to limit the confinement. Lowering the amount of neutrals in the trap is therefore of paramount importance. Prior to electron injection, the trap is pumped down to base pressures of the order of $2 \pm 1 \times 10^{-8}$ mbar. However, as one turns on the electron source (tungsten filament emitting thermionically) pressure in the system increases to $\sim 1 \times 10^{-7}$ mbar. Partial pressure analysis of the vacuum system indicates predominant presence of H₂ during filament operation. Replacing the copper current-leads for electron source with stainless steel-304 led to reduction of H₂ outgassing. Additionally, viton seals have been replaced with Aluminum wire-seals that allow baking at elevated temperatures and further reduce out-gassing. All these measures have led to an improvement in the base pressure to $7 \pm 1 \times 10^{-9}$ mbar even during filament operation. Confinement of electron plasmas in the trap has thus significantly improved.

1. Introduction
Electron plasmas confined in a uniform magnetic field (in cylindrical chamber) have become an important part of fluid dynamics research [1] and its distinct feature of confinement [2], equilibria [3], transport and Kelvin-Helmholtz instability makes it exciting branch of plasma physics. Such traps have demonstrated confinement for hours and even days [4] when operated at pressures $\sim 1.33 \times 10^{-10}$ mbar. The successful confinement under under ultra-high vacuum (UHV) conditions follows from conservation of angular momentum of a collection of like charges; presence of neutrals in the trap leads to an external torque and hence causes rapid collisional losses [2].

In contrast, poor confinement ($\sim 100\,\mu$s) of electron plasmas observed in in non-uniform magnetic field, such as toroidal geometries, [5-7] were attributed primarily to toroidal effects namely, curvature and and $\nabla B$ drifts. However, with efficient injection of electrons along field lines especially in C-shaped traps [8,9], confinement of toroidal electron plasma has significantly improved; strong $E \times B$ drifts are seen to compete and overcome the toroidal drifts. Lifetimes of the order of few milliseconds were successfully reported in SMARTEX-C. At this stage the
lifetime in SMARTEX-C was largely thought to be limited due to a short pulse magnetic field. However, in recent times, even in the presence of a steady state B field of 10 ms, SMARTEX-C demonstrated only a limited improvement in confinement [10].

The limited confinement of plasma in SMARTEX-C is now determined by losses that are dominated by instabilities, primarily driven by ions. Ion resonance instability [11, 12, 13] occurs when a small number of ions trapped in the electron potential well oscillate with a frequency close to that of the diocotron frequency. This drives the diocotron mode unstable. The presence of ions results from electron impact ionization of the residual gas in the trap. Growth rates of the instability are accordingly observed to get effected by the energy of injected electrons and the ionization cross-section of the residual gas [14].

Any further improvement in confinement in SMARTEX-C is therefore crucially dependent on controlling ion driven instabilities. In other words, it underlines the requirement of UHV in SMARTEX-C. In this paper we present our efforts towards up-gradation of vacuum conditions that allow operations in SMARTEX-C at base pressures of the order of $\sim 1 \times 10^{-9}$ mbar. Section 2 explains the trap and its limitations including residual gas analysis of the trap under vacuum. Several measures taken to improve the vacuum are discussed in section 3. The improved vacuum condition in SMARTEX-C along with the significant improvement obtained in confinement are reported in the concluding section.

2. SMARTEX-C Trap and its operation

![Figure 1](image)

**Figure 1.** Left: Trap geometry and arrangement of electrodes, Right: Typical pulses of (a) diagnostics signal from midplane capacitive probe across $1 \times 10^3 \Omega$ (b) magnetic field (solid), injector grid (dash-dot) bias, collector grid (dash) bias.

SMARTEX-C attempts to confine electrons in a C-shaped toroidal trap using static axial electric and toroidal magnetic field. The device, geometry of electrodes and diagnostic are shown in figure 1 (left). The plasma chamber is a torus with rectangular cross-section. Trap is pumped down to $1 \times 10^{-8}$ mbar. Injector grid and collector grid are kept $270^\circ$ apart from each other. Vessel wall and inner wall are held at ground potential. A single circular filament of diameter 10 cm is placed on a poloidal section, which emits electrons thermionically parallel to B field. A 100-200 Gauss toroidal pulsed magnetic field is generated for $\sim 10$ ms. As it reaches a steady state, electrons are injected by switching the injector grid to ground for a brief period of 60 $\mu$s (inject mode). This is followed by the hold mode when the injector grid is turned “off” (reverts to negative bias) and the electrons are confined between two negatively biased grids. Capacitive probe diagnostics kept flush with inner wall responds to electrostatic activity in the plasma and therefore provides an order of
magnitude estimate of the confinement time [14]. The trap is operated in an “inject-hold-dump” mechanism akin to a cylindrical penning trap [1] and is described in detail in [13].

2.1. Vacuum-System
The trap volume is \(~ 50 l\). Prior to electron injection the trap is evacuated to base pressures of \(1 \times 10^{-8} \text{ mbar}\) by a 500 L s\(^{-1}\) Turbo Molecular Pumping (TMP) backed by rotary pump (30 m\(^3\)/h). The conduction of the pumping port limits the effective pumping speed to 2591 s\(^{-1}\). All the ports and flanges of the vessel are vacuum-sealed. The pump down is followed by a bake-out of chamber up to 150\(^\circ\)C for 48 - 60 h. Pressure is monitored by Bayard-Alpert ionization gauge. After a cycle of pump down and bake out ultimate base pressure obtained in the device is of the order of \(2 \pm 1 \times 10^{-8} \text{ mbar}\). However, pressure rises during filament operation up to \(1 \times 10^{-7} \text{ mbar}\).

2.2. Poor vacuum conditions: Reasons, analysis and effect on plasma confinement

![Figure 2. Left: (a) Diocotron modes reaching peak amplitude at 1 ms and decay in oscillation amplitude driven by collisional losses and ion-resonance instability limiting the confinement of electron plasma. (b) Inset graph shows zoomed diocotron oscillations for the period of 2.0 - 2.1 ms. Right: Diagnostics signal at \(3 \times 10^{-7} \text{ mbar}\) pressure, faster growth rate of instability due to higher pressure.](image)

The high operating pressures in SMARTEX-C restricts the lifetime of the plasma. At \(1 \times 10^{-7} \text{ mbar}\) the trapped electron plasma shows coherent periodic oscillations as shown in figure 2(left (a)). These are the familiar diocotron oscillations [1] albeit with toroidal signatures (figure 2(left (b))) [8]. The amplitude of oscillations grow and then saturates before decaying. The unstable non linear mode is primarily responsible for the loss of charges. As discussed earlier, the mode is driven unstable by ions whose oscillating frequencies are close to the diocotron frequency (\(\sim 100 \text{ kHz}\) for \(n_e = 5 \times 10^{6} \text{ cm}^{-3}\)). The presence of ions can be traced to the existing high operating pressures in the trap at \(1 \times 10^{-7} \text{ mbar}\) fractional ionization due to electron (300 eV) impact ionization of H\(_2\) can be estimated to be \(0.69 \times 10^{-2}\). This fractional ionization goes down by one order if, one reduces the operating pressure from \(1 \times 10^{-7} \text{ mbar}\) to \(1 \times 10^{-8} \text{ mbar}\). The effect on confinement can be seen from figure 2(right), where operating pressure is \(3 \times 10^{-7} \text{ mbar}\). \(1/e\) decay of peak amplitude can be used to estimate the confinement time of the plasma. Higher pressures evidently lead to rapid onset of the instability and shorter confinement time.

Several factors that effect the gas load in SMARTEX-C and eventually the confinement are discussed below.
2.2.1. Gas Load due to real and virtual leaks: All the ports of SMARTEX-C are vacuum sealed using aluminum wire seals or copper gaskets. Top and bottom flange of the vacuum vessel due to their large sizes were however sealed with high vacuum Viton O-rings and had leak rates of the order of $1 \times 10^{-9}$ mbar s$^{-1}$. Outgassing rate and permeation rate of these Viton O-rings contributed to the virtual leak and increased the total gas load by an order of magnitude. These O-rings also limited the baking of the vacuum vessel to $150 - 175^\circ$C. Theroretical estimation of total gas load due to real and virtual leaks is $3.5 \times 10^{-7}$ mbar L s$^{-1}$. After two-three baking cycles, these O-rings were vulnerable to leaks further increasing the gas load.

2.2.2. Higher neutral pressure during filament operation: Once the heating of the filament is turned on, the pressure in the trap slowly increases from $2 \times 10^{-8}$ mbar to $3 \pm 1 \times 10^{-7}$ mbar. Thereafter it reduces but steadies at $1 \times 10^{-7}$ mbar. The electron injection and confinement is carried out at these pressures. The unwanted gas load evidently results from higher outgassing from vessel walls and other in-vacuum components at high temperature. Efforts were therefore initiated to diagnose and identify the source of this gas load at elevated temperatures.

![Figure 3](image1.png) **Figure 3.** Left: Partial pressure analysis at base pressure before baking system (in green) and after baking at $175^\circ$C for 48 - 72 h condition (in blue) in Viton sealed vacuum system, Right: Partial pressure analysis at base pressure (in blue) and filament operation condition (in red) in Viton sealed vacuum system.

![Figure 4](image2.png) **Figure 4.** Copper strips used as injection leads for tungsten filaments

A Residual Gas Analyser (RGA) was used and mass spectrum of background neutrals in the trap was acquired during various stages of pump down. When system is exposed to atmosphere for prolonged time and injector assembly is newly assembled consisting of new tungsten filament and alumina bushes, it takes 24 to 48 hours of pump down for pressures to reach $1 \times 10^{-7}$ mbar. Mass spectrum shows higher amount of water vapor pressure at this stage. A complete baking cycle at $150^\circ$C for 72 h and simultaneous operation of the filament source reduces water vapor from the system by an order of magnitude as evident from RGA spectrum in figure 3 (left). Total pressure of the system is reduced to $1.5 \times 10^{-8}$ mbar.

When the filament is heated to 2800 K with a dc current of 20 A, it expectedly raises the...
temperature of injector assembly and surrounding vessel wall through radiation. RGA spectrum (figure right) now reveals the dominant presence of Hydrogen.

There are two likely sources; high outgassing of H\textsubscript{2} from copper strips that act as current leads to the filament (figure 4) and/or outgassing of the Stainless Steel vessel at elevated temperature. The latter indicated occurrence of an insufficient baking of the vacuum vessel. Increase in N\textsubscript{2}, CO and CO\textsubscript{2} in RGA spectrum during filament operation could also be due to high permeation rate of Viton O-rings, used to seal the top and bottom flanges of the vacuum vessel.

3. Measures to attain UHV

In view of the analysis presented in the previous section several measures were taken to reduce the neutral pressures: (1) Viton O-rings were replaced with Aluminum wire seal (2) ETP copper strips were replaced with SS 304 strips and (3) Baking was carried out at higher temperatures of 250 - 275°C for prolonged duration.

Smooth, parallel flanges with three-delta finish were fabricated to obtain sealing with wire seals. To obtain a leak rate better than 1 \times 10^{-10}\text{mbar} L s^{-1}, 3 mm thick circular Al wire seals of diameter ~ 512 mm were prepared. Viton O-rings were replaced with Aluminum wire seal. Necessary torque $T$, required to tighten the bolts (having diameter $D$) of wire-seal flange (having radius $R$) for a specific leak rate can be given by, $T = \frac{2 \pi R F D}{K N}$ where, $K$ is the constant dependant on accuracy of threads, smoothness and lubrication, $F$ is the sealing force required per unit length and $N$ is the number of bolts. All quantities are in SI. As reported in [15], to attain specific leak rate of 1 \times 10^{-10} mbar L s^{-1} a sealing force of 250–270 kN m^{-1} is required. Theoretically, 40 N m should be enough to tighten the wire seal flange of 526 mm diameter having 36 bolts of M10 standard.

The wire seal flanges were leak tested up to 1 \times 10^{-9} \text{mbar L s}^{-1}. Wire seals also made it possible to bake the system at 250–275°C for 48–72h. Permeation through Viton O-rings was also reduced. Theroretical estimation of total gas load resulting from vessel, trap components and sealants reduced from 2.5 \times 10^{-6} to 3.5 \times 10^{-7} \text{mbar L s}^{-1} after taking measures.

![Figure 5](image)

**Figure 5.** Left: Partial pressure analysis at base pressure before baking system (in green) and after baking at 250°C for 48 - 72 h condition (in blue) in Wire-sealed vacuum system, Right: Partial pressure analysis at base pressure (in blue) and filament operation condition (in red) in Wire-sealed vacuum system.

Additionally presence of hydrogen significantly reduced on replacing copper current leads with SS leads. RGA spectrum under improved condition reveals that outgassing of Hydrogen is absent during filament operation (figure [5] right). High temperature baking also resulted in very low partial pressure of water vapor as seen in RGA spectrum of baked system (figure [5]
Replacement of Viton O-rings with Al wire-seals has removed the CO and CO$_2$ from the vacuum system.

4. Results
Measures reported in the previous section result in lower base pressure of $4 \pm 0.2 \times 10^{-9}$ mbar. Significantly the pressures during filament operation also remained as low as $6 \pm 1 \times 10^{-9}$ mbar.

Controlled and reproducible experiments are possible at pressures as low as $8 \pm 1 \times 10^{-9}$ mbar. The improved vacuum conditions eventually leads to successful control of the diocotron instability and considerable increase in the confinement time as described below.

Electrons were injected at a background pressure of $2 \times 10^{-8}$ mbar. Diocotron oscillations as seen from wall probe is shown in figure 6. The oscillations are linear (small amplitude) and growth is largely arrested till 3 ms. Beyond this period, the oscillations grow slowly and are seen to last longer than the duration of the steady-state magnetic field. The confinement time is well beyond 20 ms. At $6 \times 10^{-9}$ mbar and a B field of 30 ms a further improvement upto 70 ms has been obtained. Controlled ultra-high vacuum conditions resulting in slow growth-rate of ion-resonance instability therefore marks a significant improvement in lifetime of toroidal electron plasmas in SMARTEX-C and lifetimes well beyond 100 ms can be expected with an extended B field.

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