Measuring Plasma Expansion on the Electron Diffusion Gauge Experiment [1]

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Abstract

The expansion of the Electron Diffusion Gauge (EDG) pure-electron plasma due to collisions with background neutral gas atoms is observed in order to develop an accurate way to measure gas pressure in Ultra-High Vacuum devices. The EDG is a cylindrically-symmetric, Malmberg-Penning trap, and has diagnostics to measure the axially integrated, 2-D density profile, the plasma's total charge, the on-axis electron temperature, and (non-destructively) the evolution of the $m = 1$ diocotron mode. The measured expansion rate at higher pressures is found to be in agreement with the classical fluid estimate

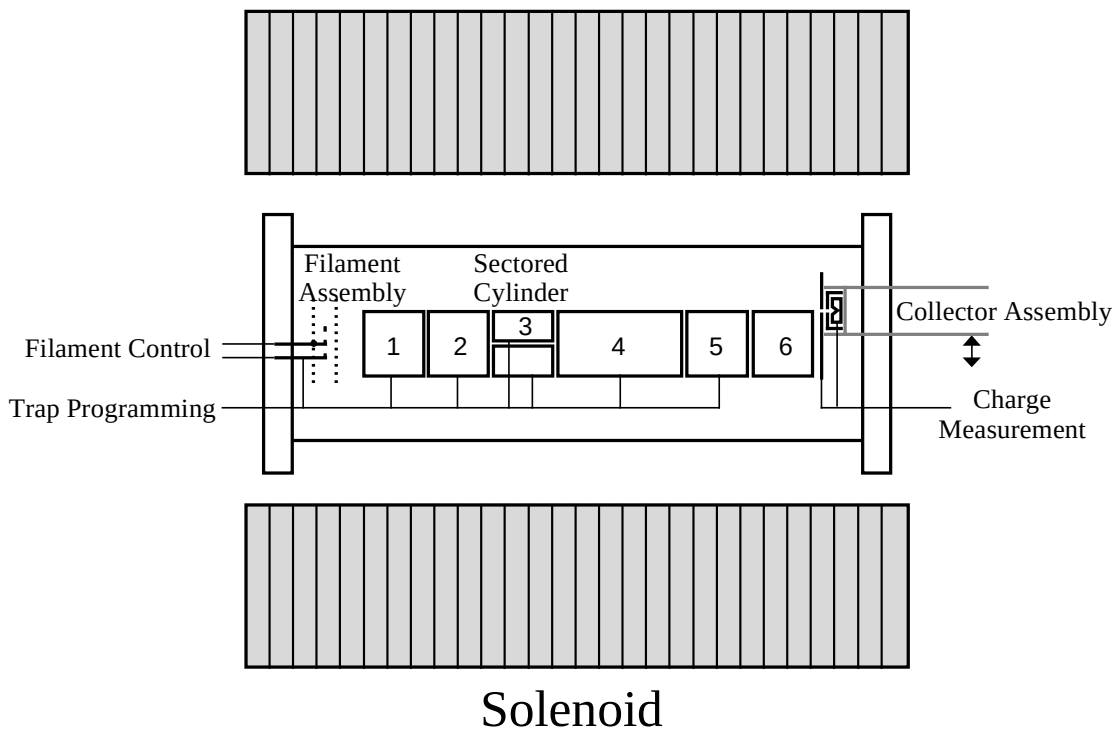
$$\frac{d}{dt}\langle r^2 \rangle = \frac{2N_L e^2 \nu_{\mathrm{en}}}{m\omega_c^2}\left(1 + \frac{2T}{N_L e^2}\right),$$

where N_L is the plasma line density, T is the homogeneous plasma temperature (in eV), ω_c is the electron cyclotron frequency, and ν_{en} is the electron-neutral atom collision frequency. Measurements made with the new, 2-D density diagnostic are compared to those made previously with the radially-movable electron collector, and the dependence of the diocotron mode growth rate on the plasma source conditions is also explored. New data from the on-axis temperature diagnostic (OTDA) is presented.

Outline

- EDG Device Diagnostics
- Plasma Parameters
- Theoretical Profile and Evolution
- Plasma Expansion Rate Scaling with Pressure
- Comparison of Inferred Temperatures and On-Axis Temperature Measurements
- $m = 1$ Diocotron Mode Growth Rate Sensitivity to Filament Conditions
- Research Plans
- Summary

Schematic of the EDG device



EDG has diagnostics to measure the

1. Total charge in the trap (destructive measurement),
2. Axially integrated density profile (destructive measurement),
3. On-axis plasma temperature (destructive measurement),
4. Amplitude waveform of the $m = 1$ Diocotron mode (non-destructive measurement).

Phosphor-Screen-Type Density Diagnostic

- An aluminum-coated, P43 phosphor screen produces an image of the entire, axially integrated plasma when the plasma is released from the trap.
- A copper grid is clamped to the last, grounded trap electrode to give a more radially uniform accelerating electric field.

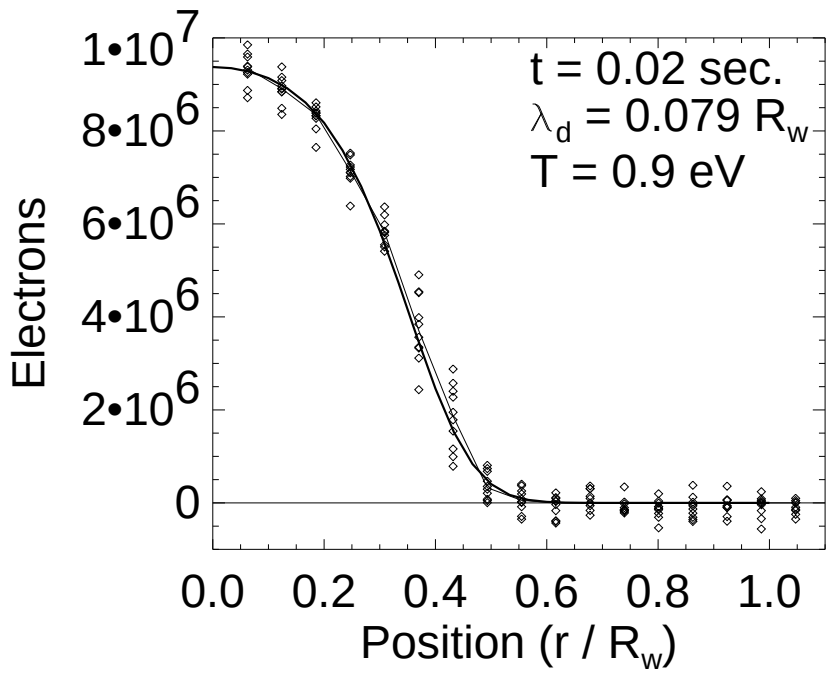
Plasma Parameters

P	$=$	1×10^{-10} – 1×10^{-5} Torr
T	$=$	1 – 4 eV
B	$=$	300 – 800 G
$n(r=0)$	$\approx$	10^7 /cm^3
L_{plasma}	$=$	15 cm
$\omega_c/2\pi$	$=$	.56 – 2.2 GHz
t_c	$=$	1.7 – .45 ns
$\omega_r/2\pi$	$=$	180 – 720 kHz
t_r	$=$	1.4 – 5.6 μs
v_T	$=$	4 – 8 $\times$ 10^7 cm/s
$\omega_{\text{bounce}}/2\pi$	$=$	2.8 – 5.6 MHz
$\omega_p/2\pi$	$\approx$	30 MHz
N_L	$\approx$	3 $\times$ 10^7 /cm
$\omega_\infty/2\pi$	$=$	27 - 107 kHz
ν_{en}	$=$	.06 – 1500 /s
t_{coll}	$=$	.67 ms – 17 s
ρ_L	$=$	.03 – .2 mm
λ_D	$=$	2 – 5 mm
$R_{\text{coll. hole}}$	$=$	1.6 mm
$R_P(t=0)$	$=$	1.27 cm (large fil.) and .95 cm (sm. fil.)
R_W	$=$	2.54 cm
$\phi_\circ$	$=$	-147 V
ϕ_{plasma}	$\approx$	-15 V

Theoretical Profile

Due to collisions between plasma electrons and neutral background gas atoms,

Fluid Theory predicts expanding Quasi-Equilibrium Profiles.



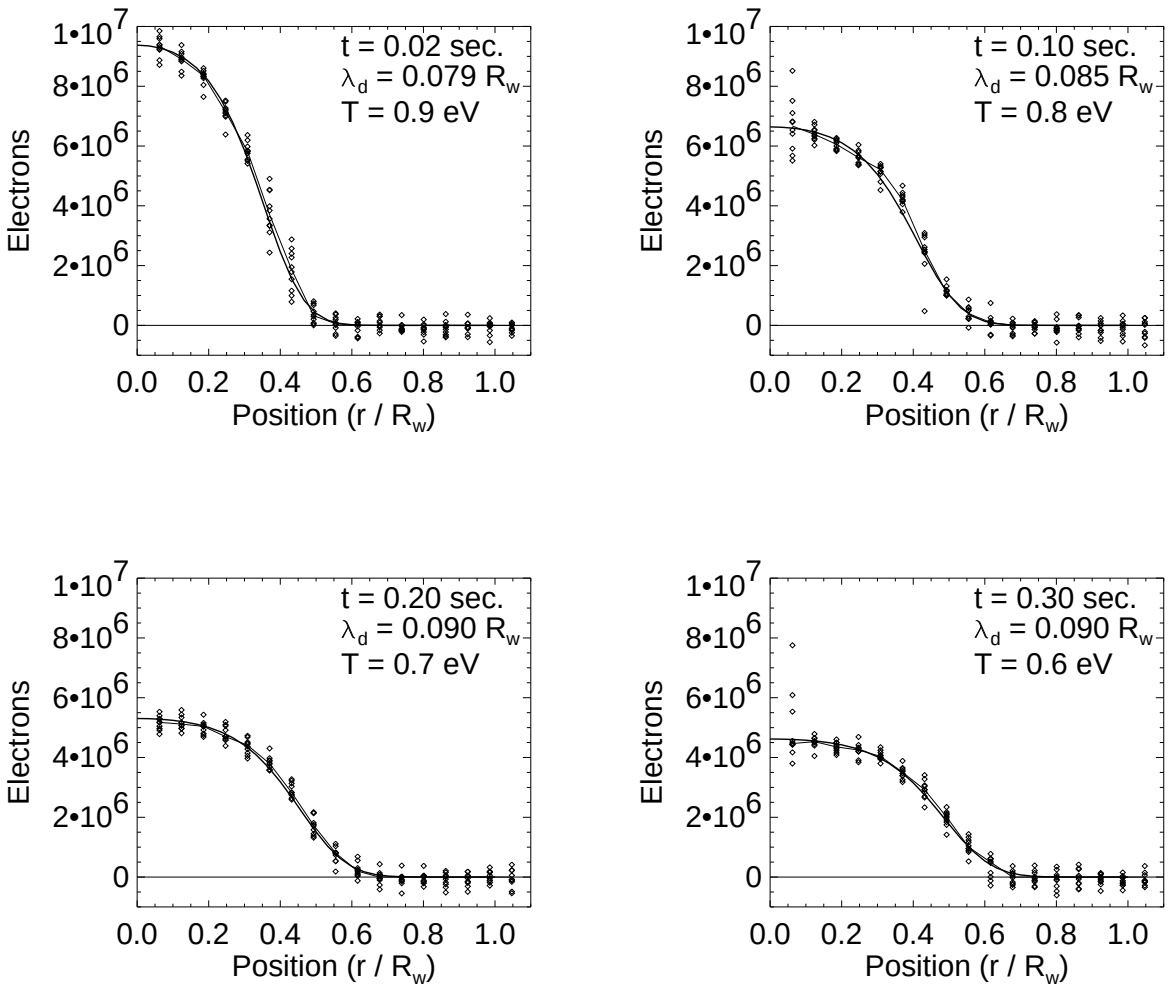
For isothermal electrons [Davidson and Moore 1996]:

$$n(r,t) = \hat{n}(t)\,\exp\left\{\frac{e\phi(r,t) - e\hat{\phi}(t)}{T} - \frac{r^2}{r_\circ^2(t)}\left(1 + \frac{Ne^2}{2T}\right)\right\},$$

subject to

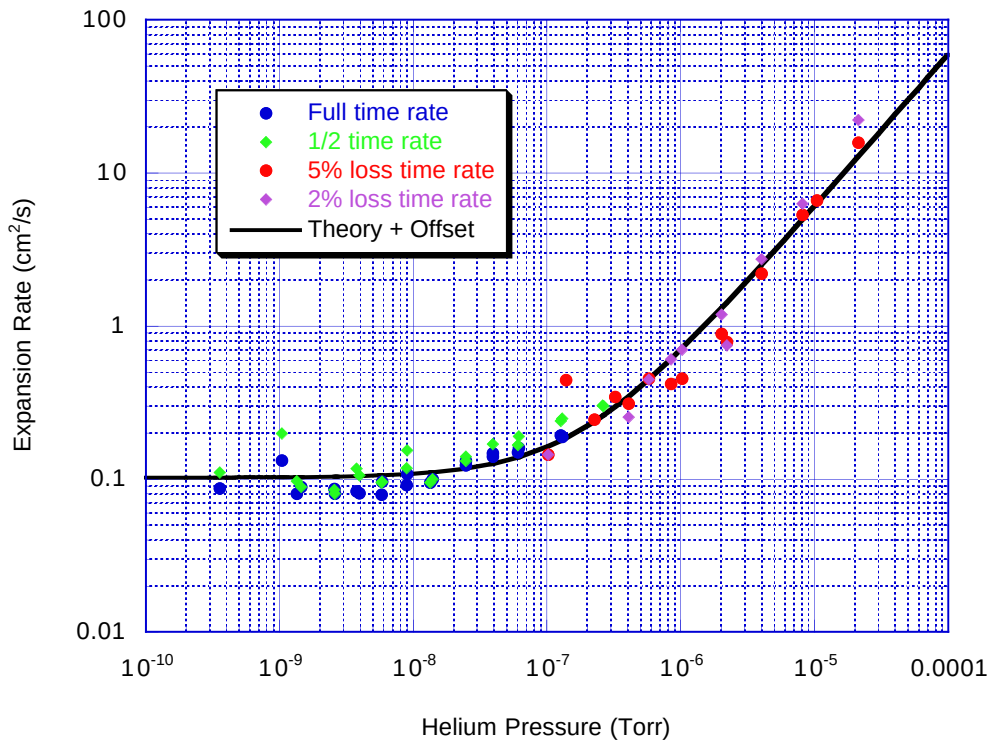
$$\frac{d}{dt}\langle r_\circ^2\rangle = \frac{2N_L e^2 \nu_{\rm en}}{m(\nu_{en}^2 + \omega_{ce}^2)}\left(1 + \frac{2T}{N_L e^2}\right).$$

Density Profile Evolution in EDG



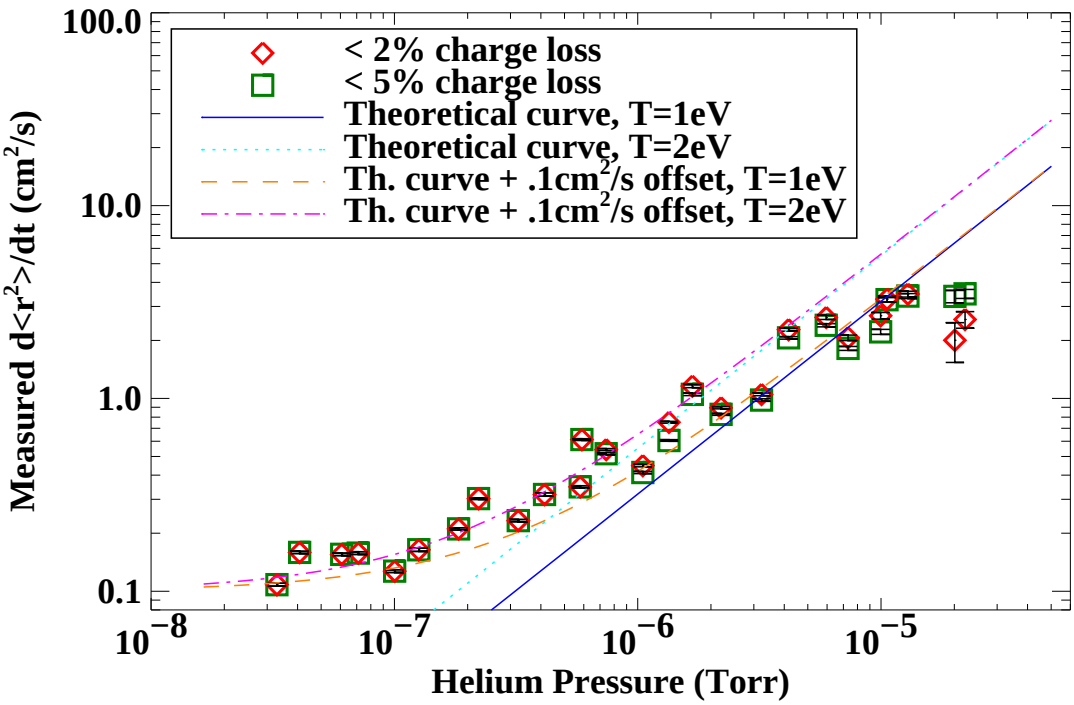
- Quasi-equilibrium profiles fit the data well.
- Collisions with neutral background gas atoms break the conservation of canonical angular momentum and allow expansion of the electron column.

Expansion Rate Scaling with Pressure (large filament, 610 G)



- The plasma's expansion rate should scale linearly with pressure for plasmas expanding in quasi-equilibrium.
- This scaling is readily seen from the equation for the expansion rate, $\frac{d}{dt}\langle r_\circ^2\rangle$, since $\nu_{en} \propto P$ and $\omega_{ce} \gg \nu_{en}$.
- The measured expansion rate at lower pressures is dominated by a process we suspect is the relaxation of the plasma to global thermal equilibrium, but shows linear behavior at higher pressures where the electron-neutral collisions dominate.

Expansion Rate Scaling with Pressure (small filament, 600 G)

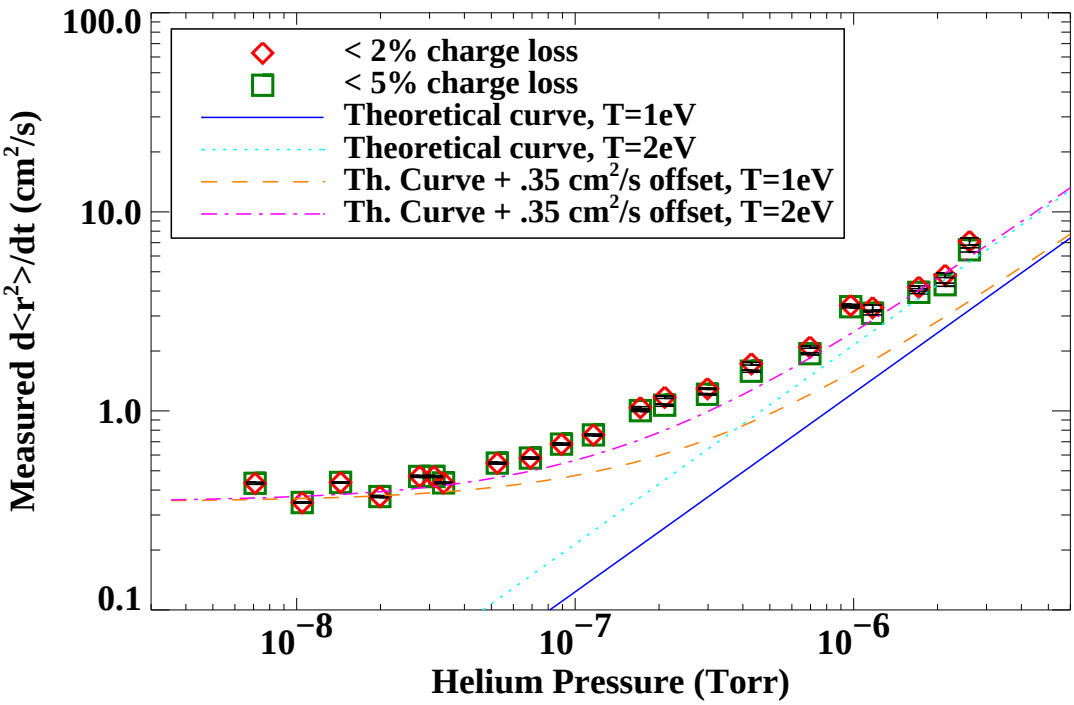


- The linear dependence with pressure is also exhibited by smaller plasmas (from a small filament with .25 inch radius).
- This data indicates that plasma-wall interactions have negligible impact on the expansion rate scaling measured.

- The linear dependence with pressure is obtained at $B = 300$ G for pressures above 3×10^{-7} Torr.

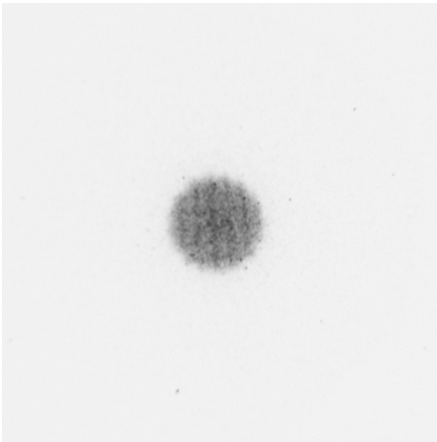
- The theoretical expansion rate computed for $T = 1.5$ eV agrees with the expansion rates measured before 2% of the total plasma charge is lost.

Expansion Rate Scaling with Pressure (small filament, 300 G)

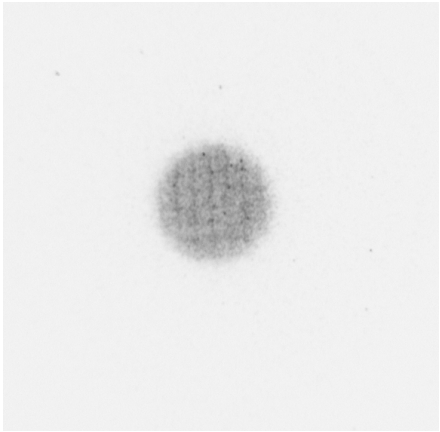


- The small filament data agree with the large filament data better at B=300G than at B=600G, due to the faster, more measurable expansion of the plasma.
- The small filament data have line densities and temperatures very similar to those of the large filament data, and the absolute expansion rates measured at the same magnetic field are close.

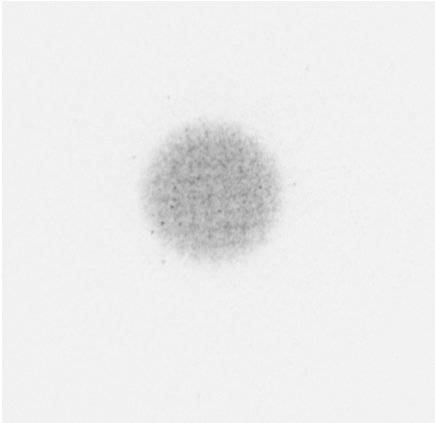
Density Diagnostic Images



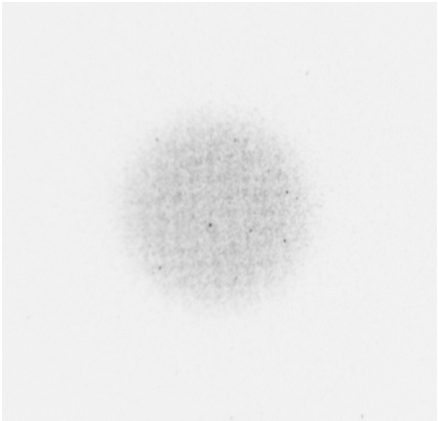
(a) Trapped for 1/6 s.



(b) Trapped for 1 s.



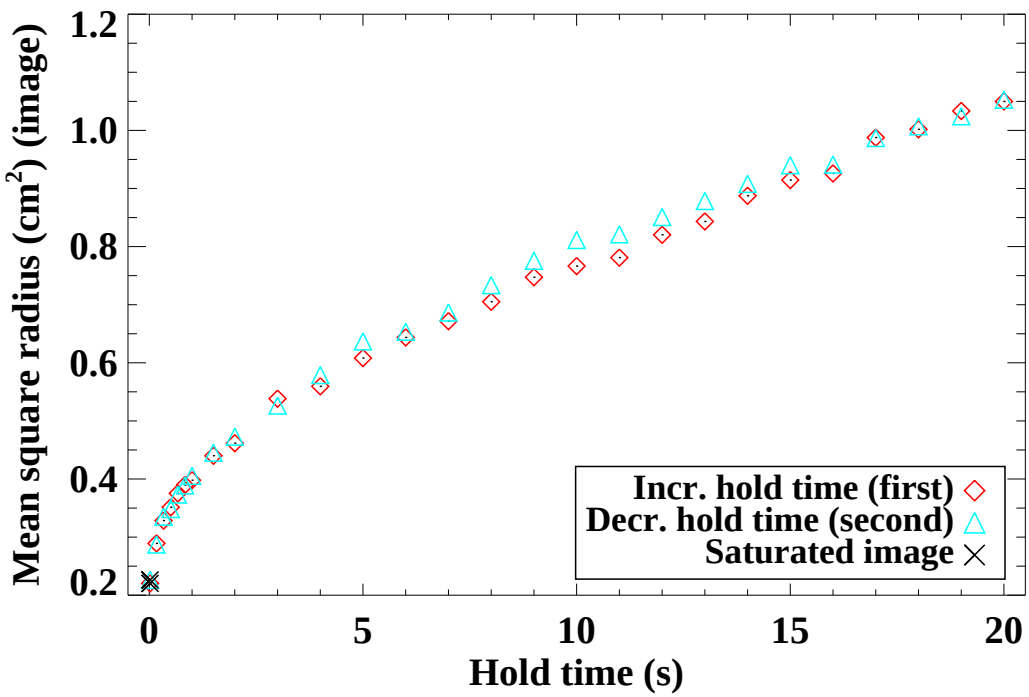
(c) Trapped for 3 s.



(d) Trapped for 15 s.

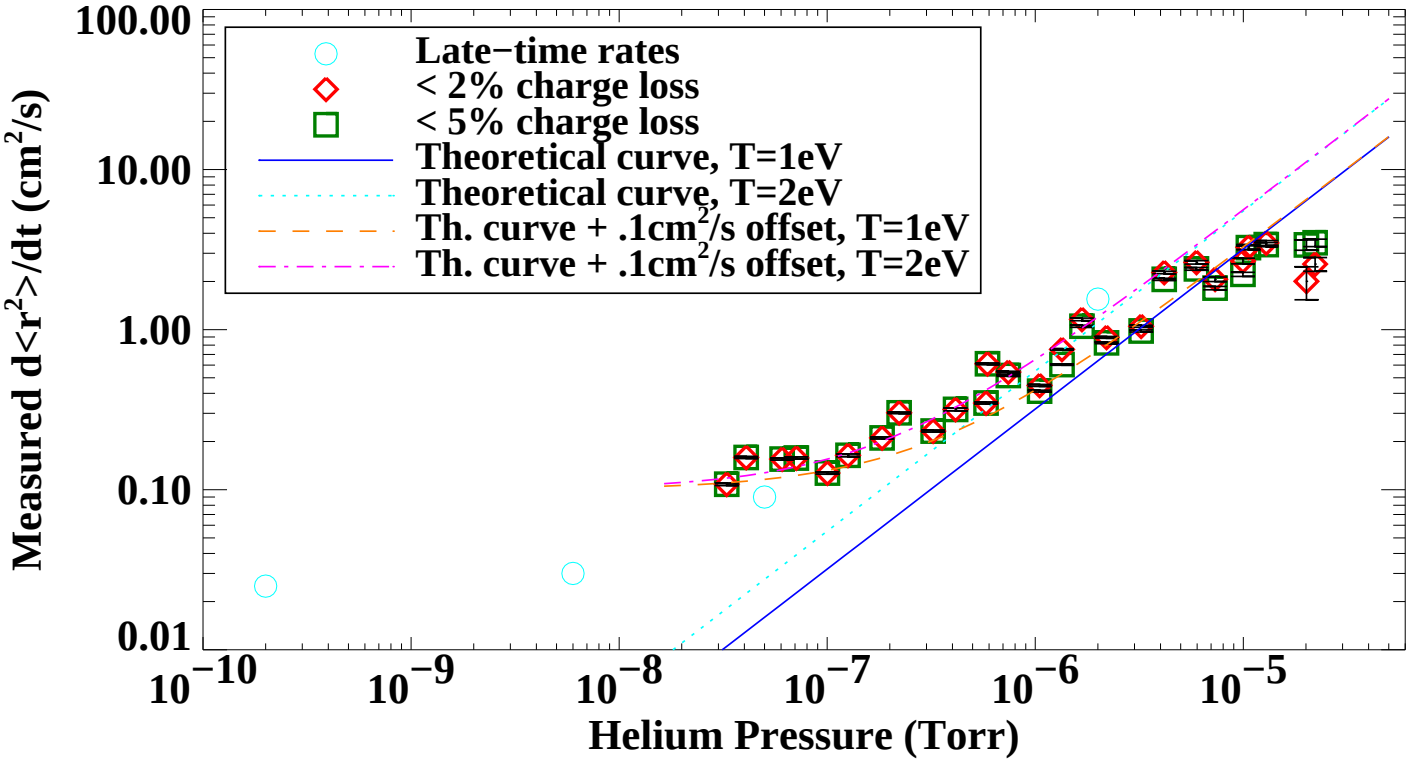
- Data taken with the new, phosphor-screen-type density diagnostic give axially integrated 2-D density profiles.
- The radial density profile may be estimated by averaging the data values azimuthally around the centroid of the image.

Plasma Expansion After 1 second (P= 5×10^{-9} Torr)



- Data taken with the new density diagnostic suggests that the plasma expansion measured previously occurred during relaxation of the plasma to global thermal equilibrium.
- The initial expansion (t $<$ 3 s.) is the same at several pressures below P $= 2 \times 10^{-7}$ Torr, and the rate agrees with that measured previously.

Late-time Expansion Rates (small filament, 600 G)

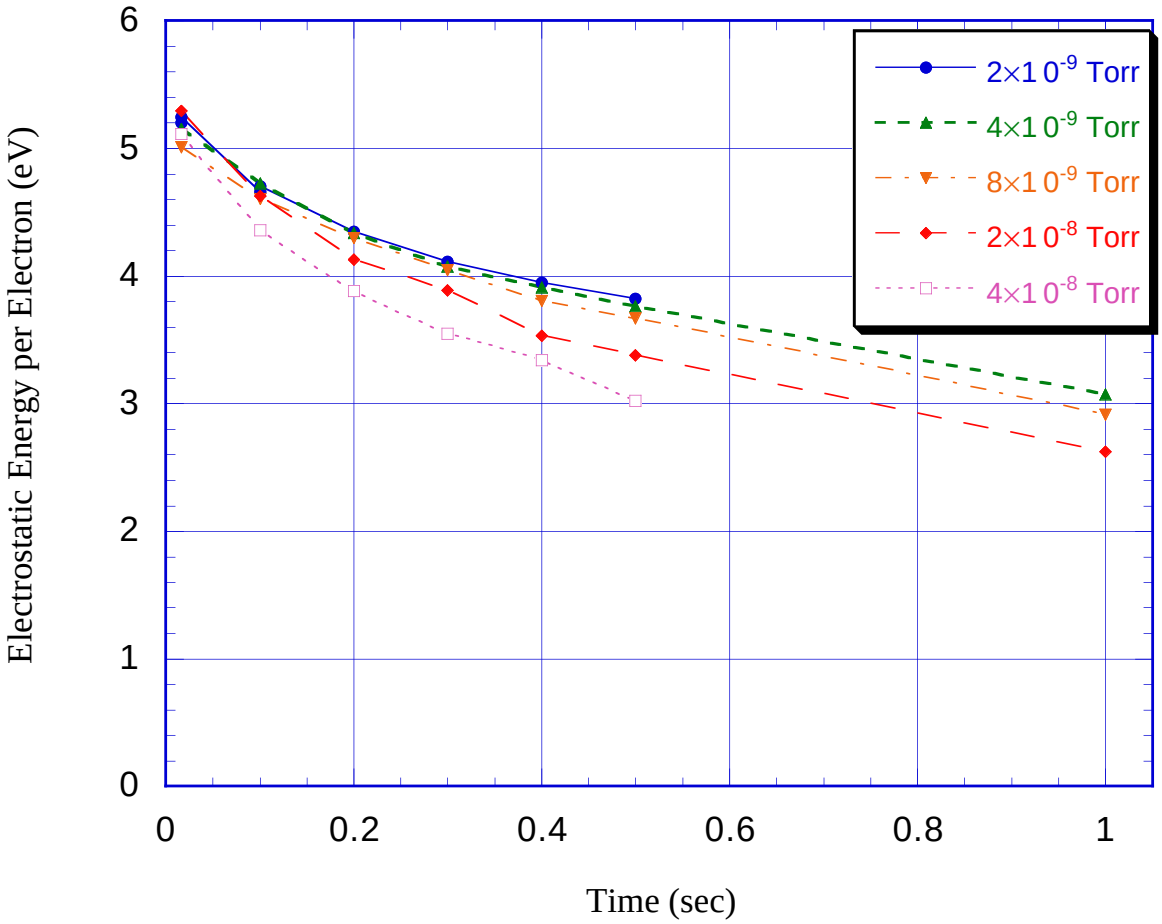


- The circles denote the new expansion rates computed by excluding the initial plasma relaxation.
- The expansion rates still level off at the lowest pressures, indicating that asymmetry-induced expansion is affecting the measurements.

Expansion Rate Scaling Results

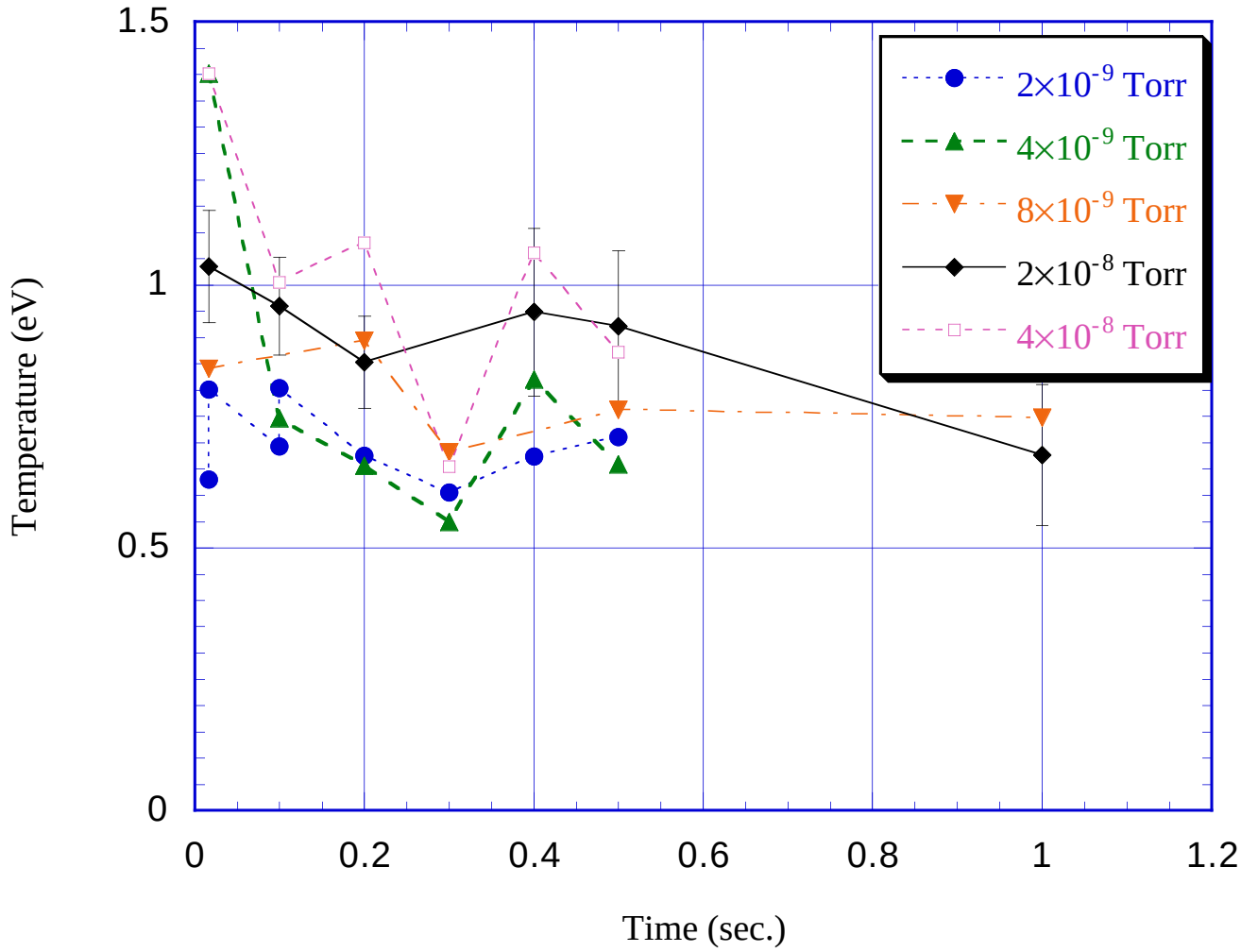
- The observations show that the plasma's expansion rate behaves consistently with the predictions of the theoretical model at higher pressures even for plasmas that are not strictly in thermal equilibrium.
- We have verified a linear dependence of plasma expansion on neutral background gas pressure for plasma *profiles*, not just for central density decay.
- The agreement between the data and the theory at higher pressures also suggests that temperature gradients might not be very important to the plasma dynamics.

Electrostatic Potential Energy at Lower Pressures (large filament)



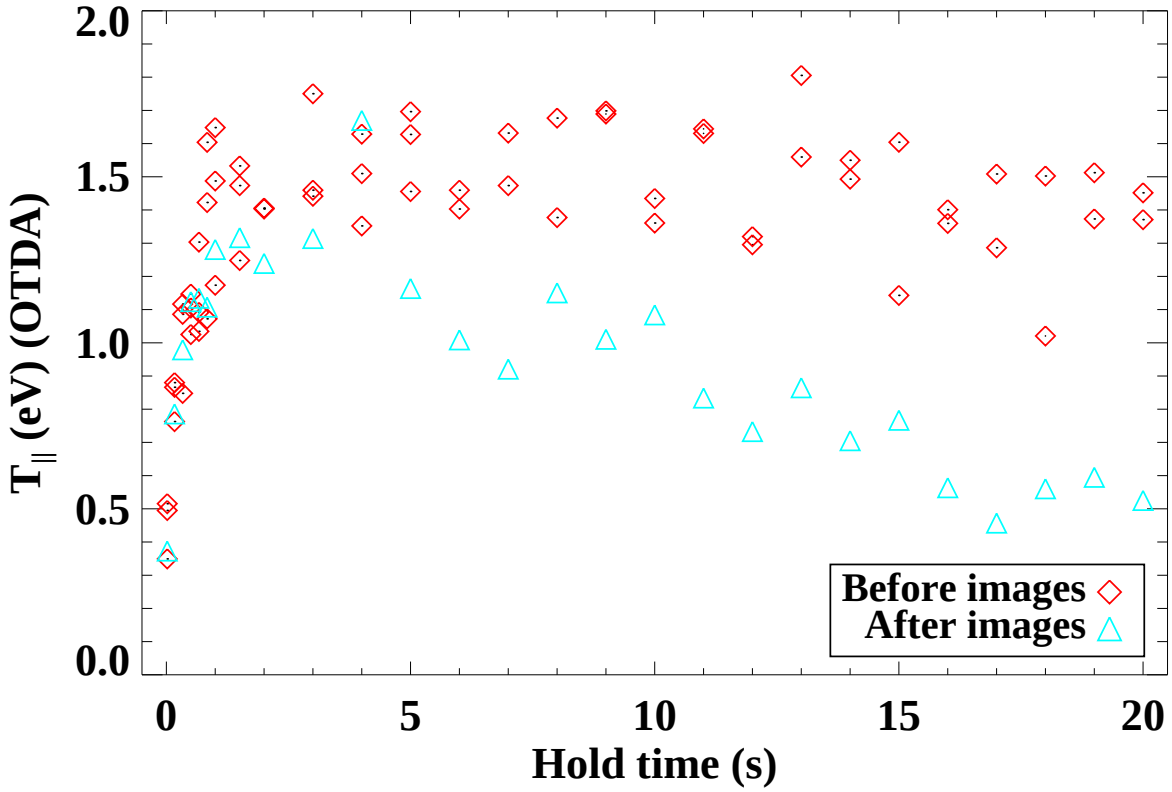
- The electrostatic potential energy of the column decreases as the plasma expands.
- Collisions with helium atoms in the EDG range of temperatures (< 4 eV) are too elastic to accept any of this energy.

Inferred Parallel Temperature at Lower Pressures (large filament)



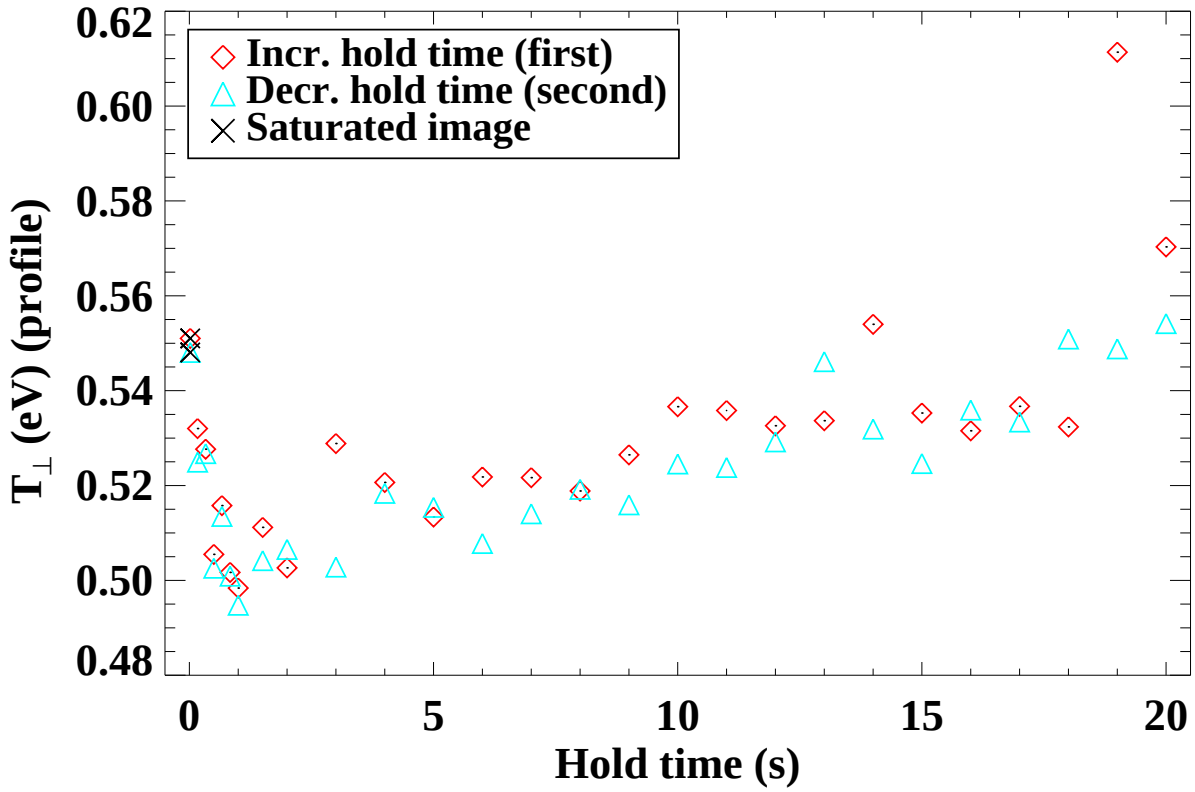
- The electron temperatures inferred from fitting the density profile suggested that energy is leaving the plasma.
- Energy balance indicated that inelastic collisions with trace background gases must be the sink for the decreasing electrostatic energy.

On-Axis Temperature Diagnostic Data (small filament, P=6×10^{-9} Torr)



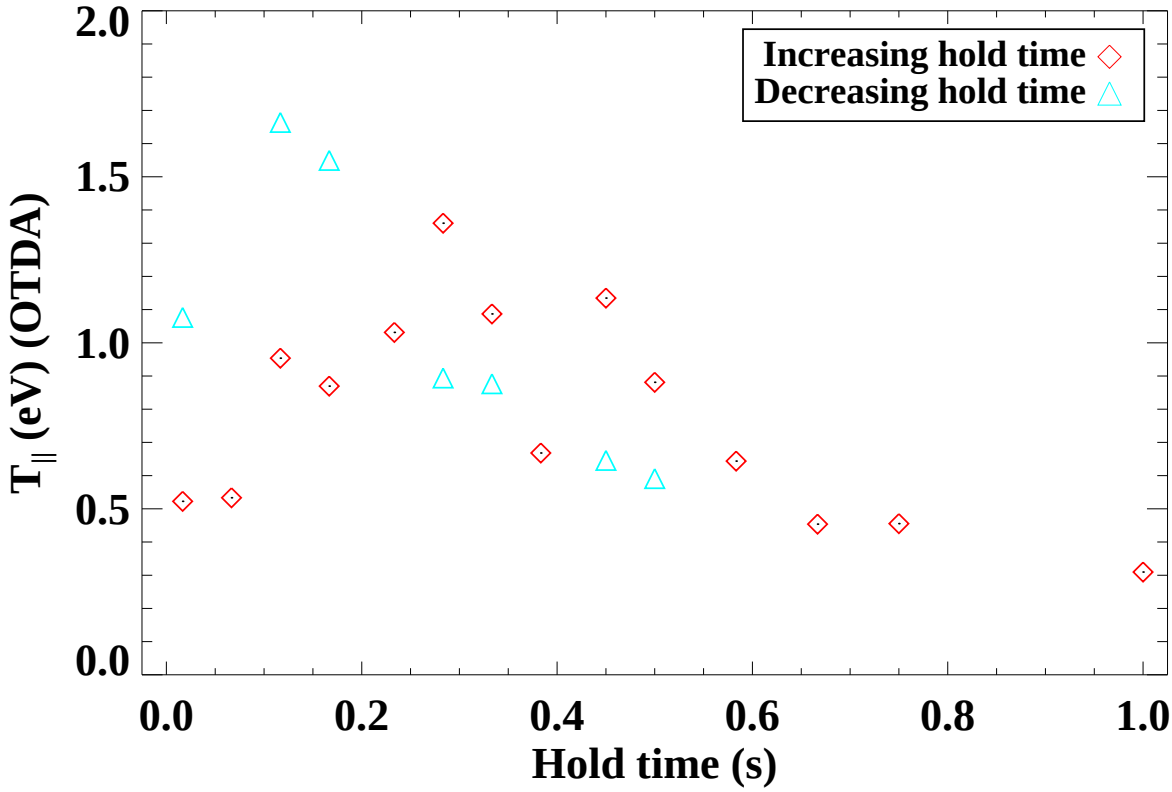
- The parallel temperature measured does not increase while the plasma is expanding under the influence of electron-neutral collisions (t > 3 s.), but increases while the plasma is relaxing to thermal equilibrium
- The measured temperature evolution does not agree with the inferred temperatures measured previously.

Inferred Temperature Data (small filament, P=6×10^{-9} Torr)



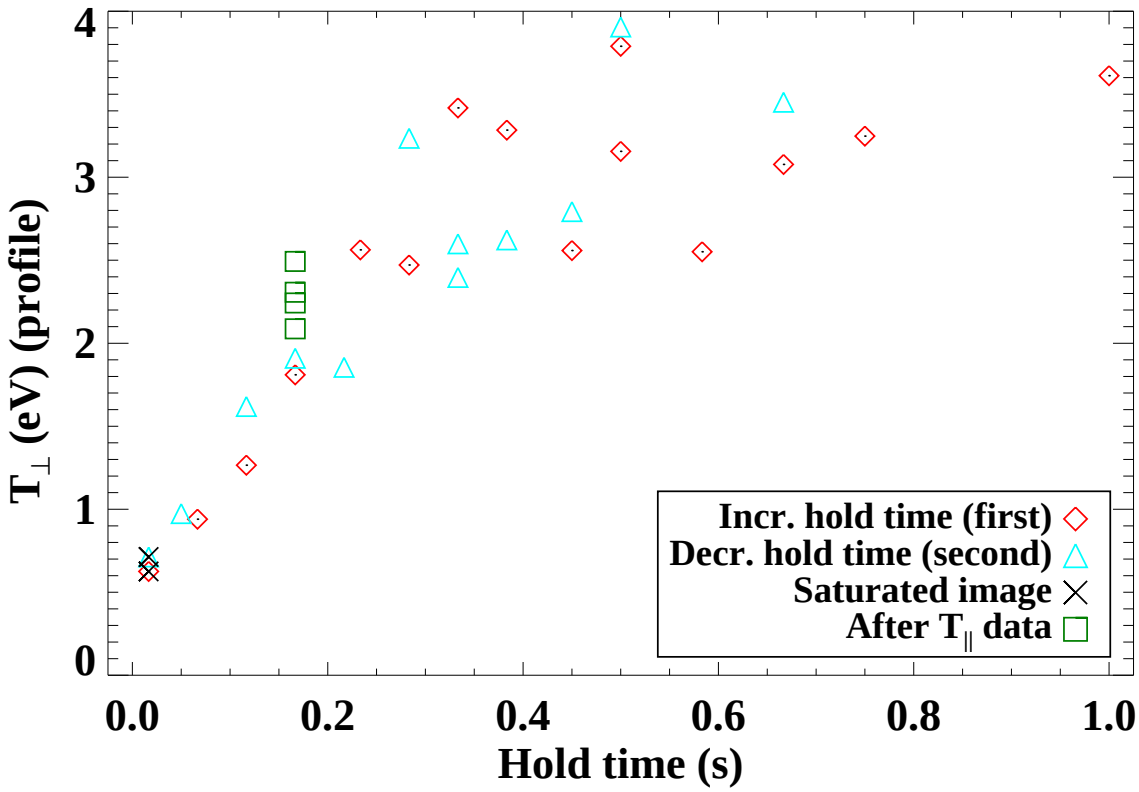
- The temperatures inferred from fitting the measured density profiles with quasi-equilibrium profiles change very little during both phases of expansion.
- The quasi-equilibrium profiles fit the density profiles well, even when the plasma is expanding quickly.

On-Axis Temperature Diagnostic Data (small filament, P=2×10^{-6} Torr)



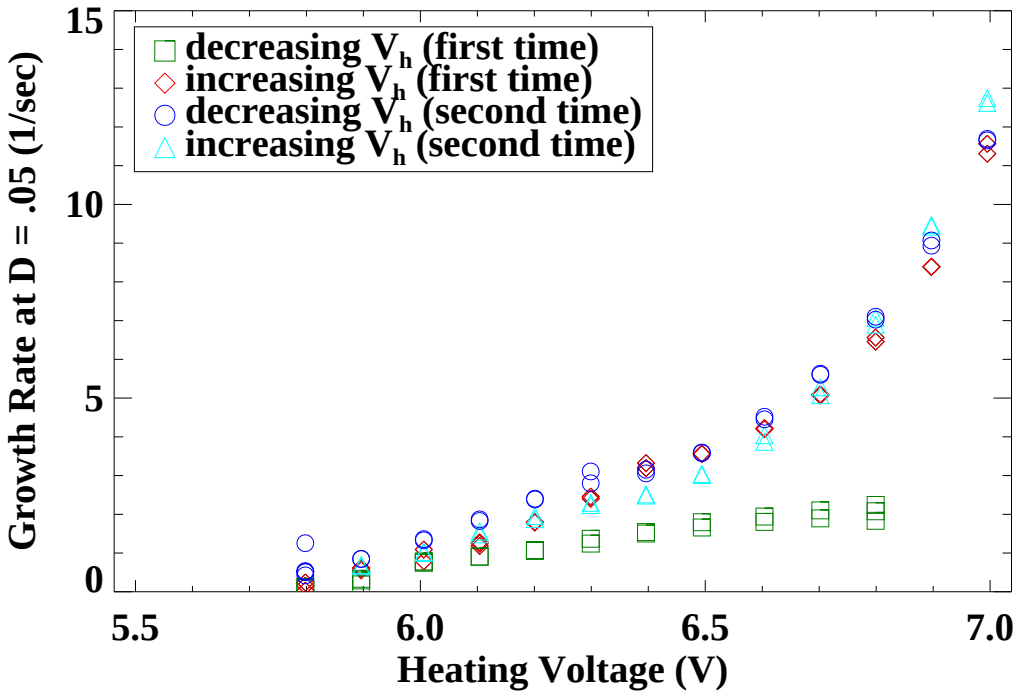
- At higher pressure, the plasma touches the trap wall quickly (here, ~ 0.4 s.).
- The measured temperature again rises quickly, but drops once the plasma begins to interact with the wall.

Inferred Temperature Data (small filament, P=2×10^{-6} Torr)



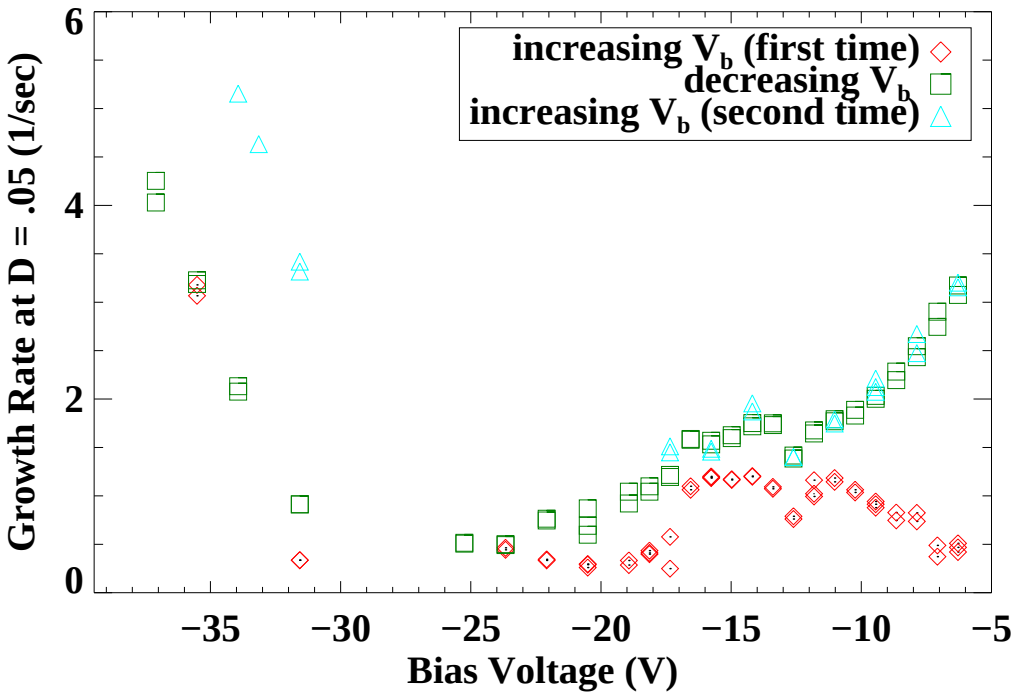
- The profile broadens rapidly at higher pressure, implying a higher perpendicular temperature.
- At these pressures, the plasma must have a sizeable temperature gradient and is not in quasi-equilibrium.

Diocotron Mode Sensitivity to Filament Heating Voltage



- The growth rate of the $m = 1$ diocotron mode increases with filament heating voltage (V_b = -16.6V). This behavior is observed at several different values of bias voltage.
- During the course of this scan, the vessel pressure increased, explaining why the data taken first (the green squares, P$\sim 1 \times 10^{-10}$ Torr) differ from the rest of the data (P$\sim 8 \times 10^{-10}$ Torr).
- Changes in the heating voltage produce only modest changes in the plasma density, so we suspect that this is a profile shape or temperature effect.

Diocotron Mode Sensitivity to Filament Bias Voltage



- The growth rate of the $m = 1$ diocotron mode exhibits a complicated behavior with filament bias voltage ($V_h = 6V$). This behavior is observed at several different values of heating voltage.
- Again, during the course of this scan, the vessel pressure increased. The data taken first (red diamonds) is lower than the data taken later.
- Changes in the bias voltage produces large changes in the plasma density, which we attribute most of the growth rate behavior to.

Research Plans

1. Observe the initial evolution of the density profile to thermal equilibrium and see how it compares to theory.
2. Compare the temperature and density profile evolution of plasmas in thermal equilibrium to see what we can learn about the plasma expansion.
3. Explain why the diocotron mode growth rate is primarily affected by filament heating voltage, and how it is affected by background gas pressure.

Summary

- The plasmas' expansion rate dependence on background gas pressure is in good agreement with theoretical predictions at pressures above $\sim 3 \times 10^{-7}$ Torr for plasmas formed with both large and small filaments.
- The expansion rate due to electron-neutral collisions at low pressures has been observed using a new, phosphor-screen-type density diagnostic.
- The growth rate of the $m = 1$ diocotron mode is very sensitive to filament conditions, which must be accounted for when measuring its dependence on background gas pressure.

The poster

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is available at

http://w3.pppl.gov/∼kmorriso/storage/k.APR03.poster.1.pdf