Electron Plasma Expansion due to Background Gas in the Electron Diffusion Gauge Experiment [1]

K. Morrison, S. F. Paul, and R. C. Davidson

Princeton Plasma Physics Laboratory

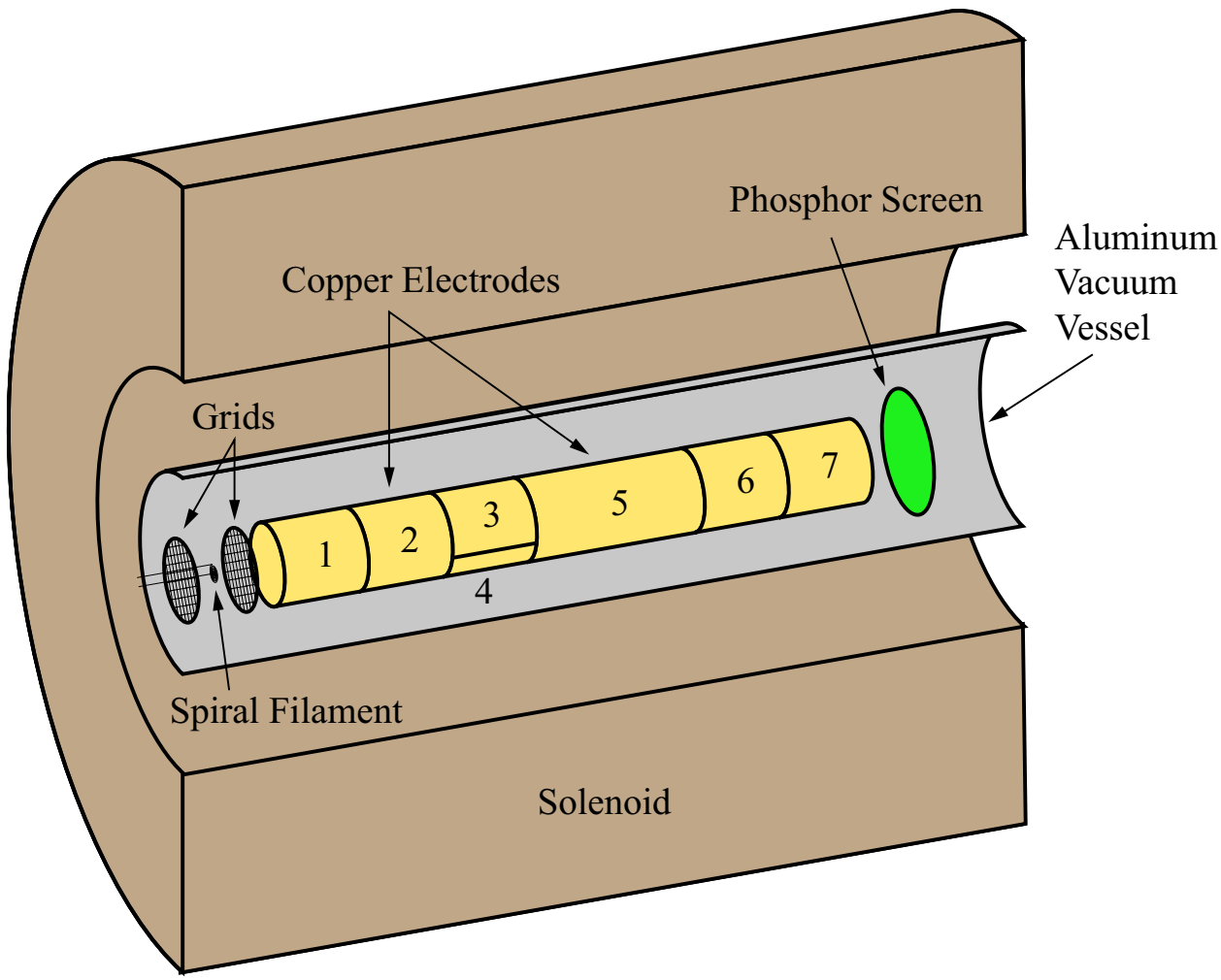
[1] Research supported by the Office of Naval Research.

Abstract

The expansion of the Electron Diffusion Gauge (EDG) electron plasma due to collisions with background neutral gas atoms is observed. Measurements of the expansion rates made with the new, 2-D density diagnostic suggest that the rates measured previously were observed during the plasmas' relaxation to thermal quasi-equilibrium. If this is so, it is even more remarkable that they agree above $P \approx 2 \times 10^{-7}$ Torr with the classical fluid estimate that assumes quasi-equilibrium. The minimum expansion rates measured previously are attributed to the relaxation of the density profiles, and the rates determined from the plasmas' post-relaxation expansion are considered to represent the asymmetry-induced expansion rates in EDG.

The on-axis plasma temperature, measured by recording the number of electrons that escape the trap as a function of confining electrode voltage, increases by ~ 1 eV in the first second of evolution at low pressures. The temperatures inferred from fitting the measured density profile with the thermal quasi-equilibrium profile are relatively constant over the course of the evolution, however. That the profiles appear to fit the measured density profiles so well where the plasma is not in thermal quasi-equilibrium indicates that inferring the temperature in this manner is not a reliable diagnostic of the plasma temperature.

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. Parallel temperature on axis (destructive measurement),
4. Amplitude waveform of the $m = 1$ Diocotron mode (non-destructive measurement).

Phosphor-Screen 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.

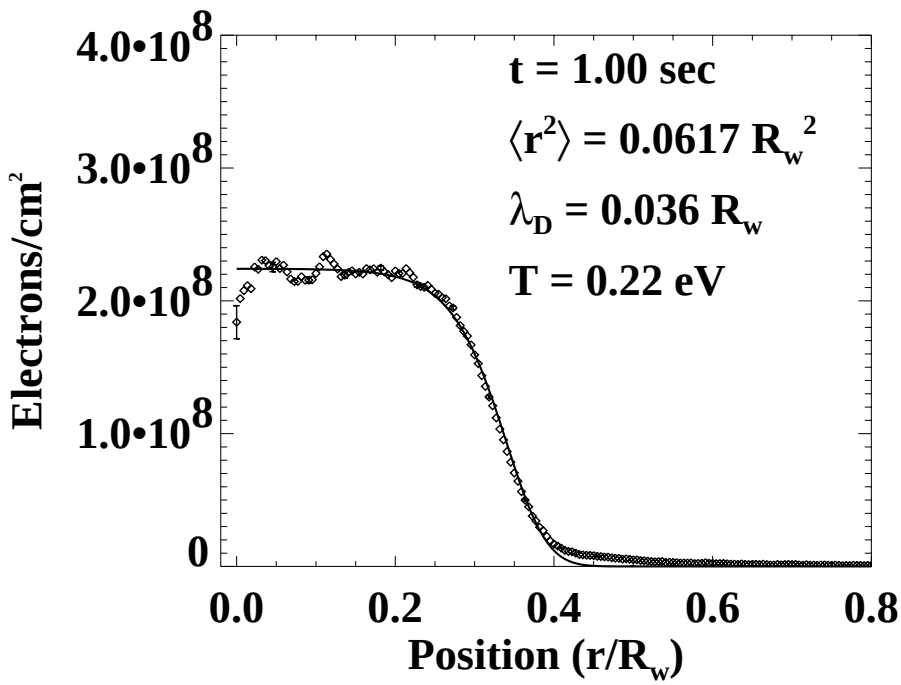
Plasma Parameters

P	$=$	1×10^{-10} – 1×10^{-5} Torr
T	$=$	1 eV
B	$=$	600 G
N	$=$	5×10^{8} electrons
L_{plasma}	$=$	15 cm
$R_P(t=0)$	$=$	0.87 cm (sm. fil.) and 1.27 cm (large fil.)
$n(r=0)$	$=$	1.15×10^{7} /cm^3
N_L	$=$	3.3×10^{7} /cm
v_T	$=$	4.2×10^{7} cm/s
$\omega_p/2\pi$	$=$	30 MHz
$\omega_c/2\pi$	$=$	1.7 GHz
$\omega_r/2\pi$	$=$	280 kHz
$\omega_b/2\pi$	$=$	1.4 MHz
$\omega_D/2\pi$	$=$	40 kHz
ν_{en}	$=$	0.15 – 1.5×10^{4} Hz
ρ_L	$=$	0.04 mm
λ_D	$=$	2.1 cm
$R_{\text{coll. hole}}$	$=$	1.6 mm
R_w	$=$	2.54 cm

Theoretical Profile

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

Fluid Theory predicts expanding Quasi-Equilibrium Profiles.



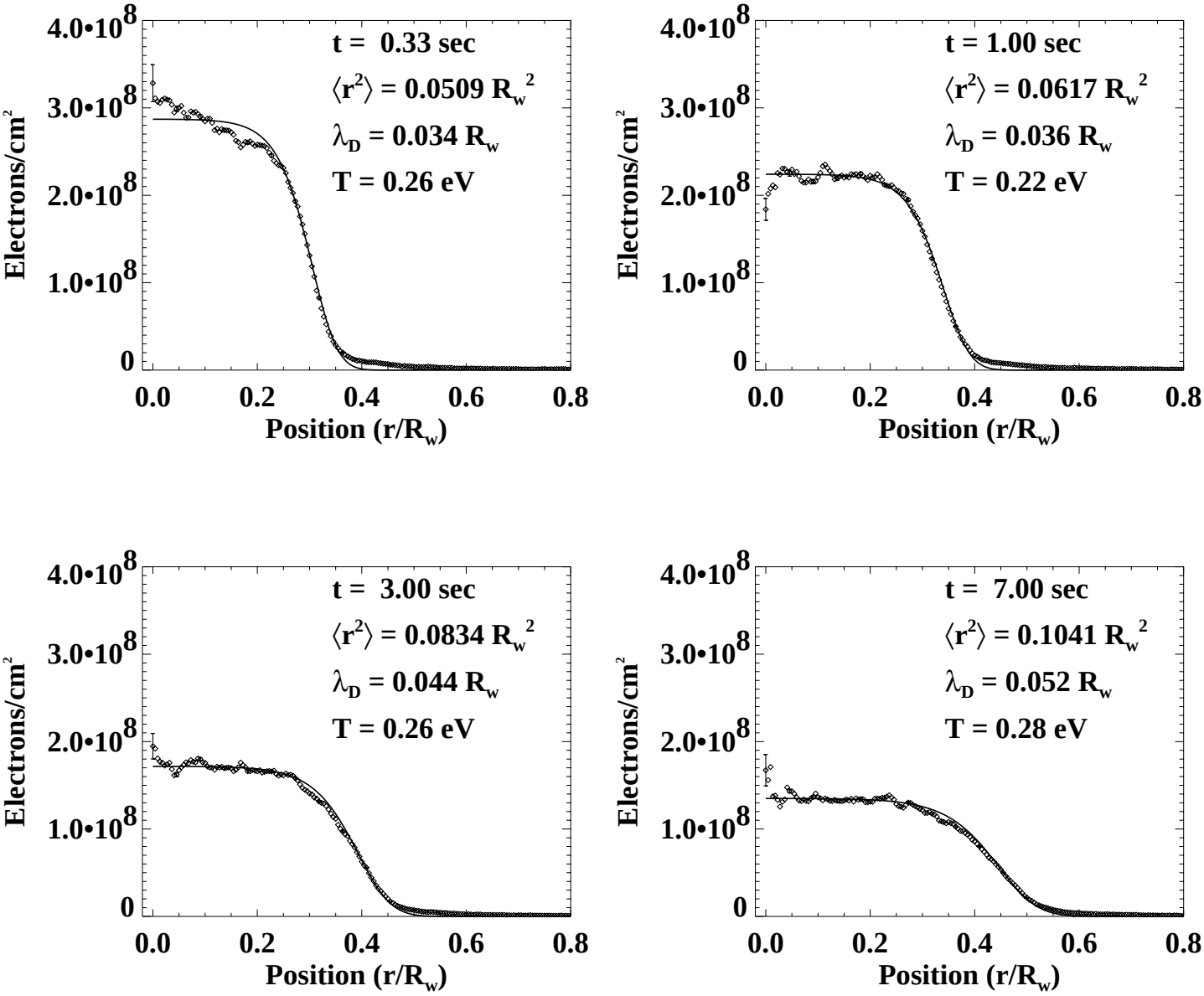
For isothermal electrons [Davidson and Moore 1996]:

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

subject to

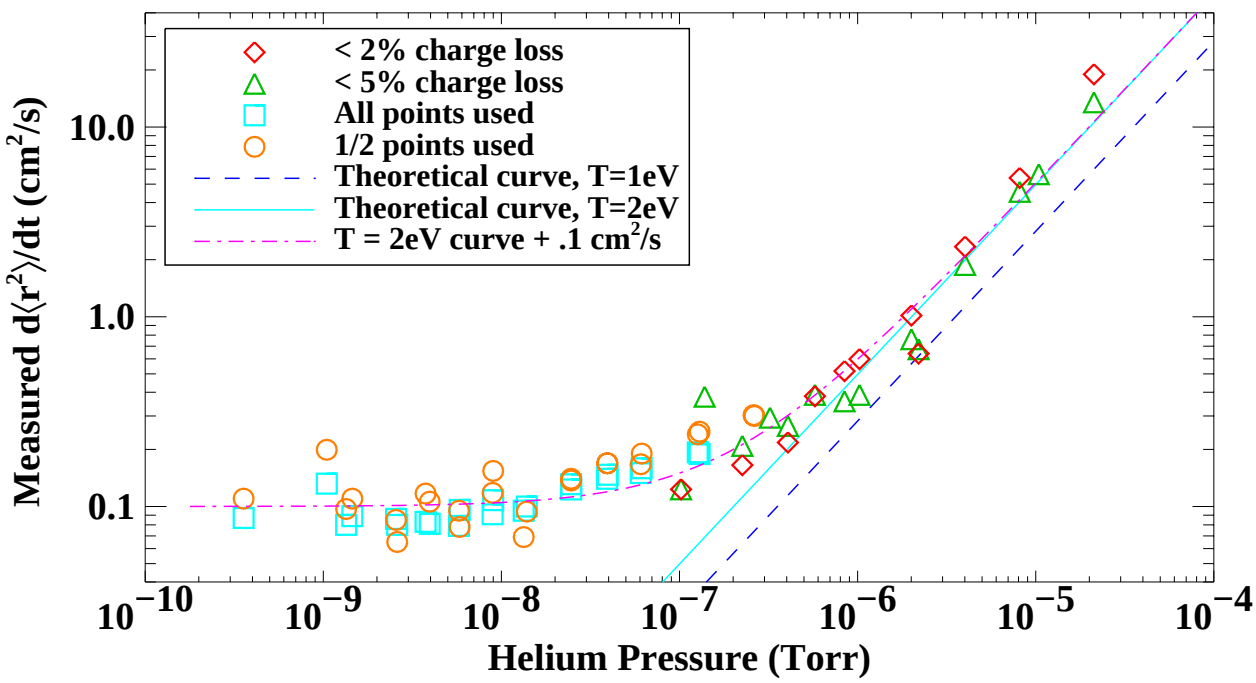
$$\frac{d}{dt}\langle r_\circ^2\rangle = \frac{2N_L e^2 \nu_{\rm en}}{m(\nu_{en}^2 + \omega_{ce}^2)}\left(1 + \frac{2T}{N_L e^2}\right).$$

Density Profile Evolution in EDG



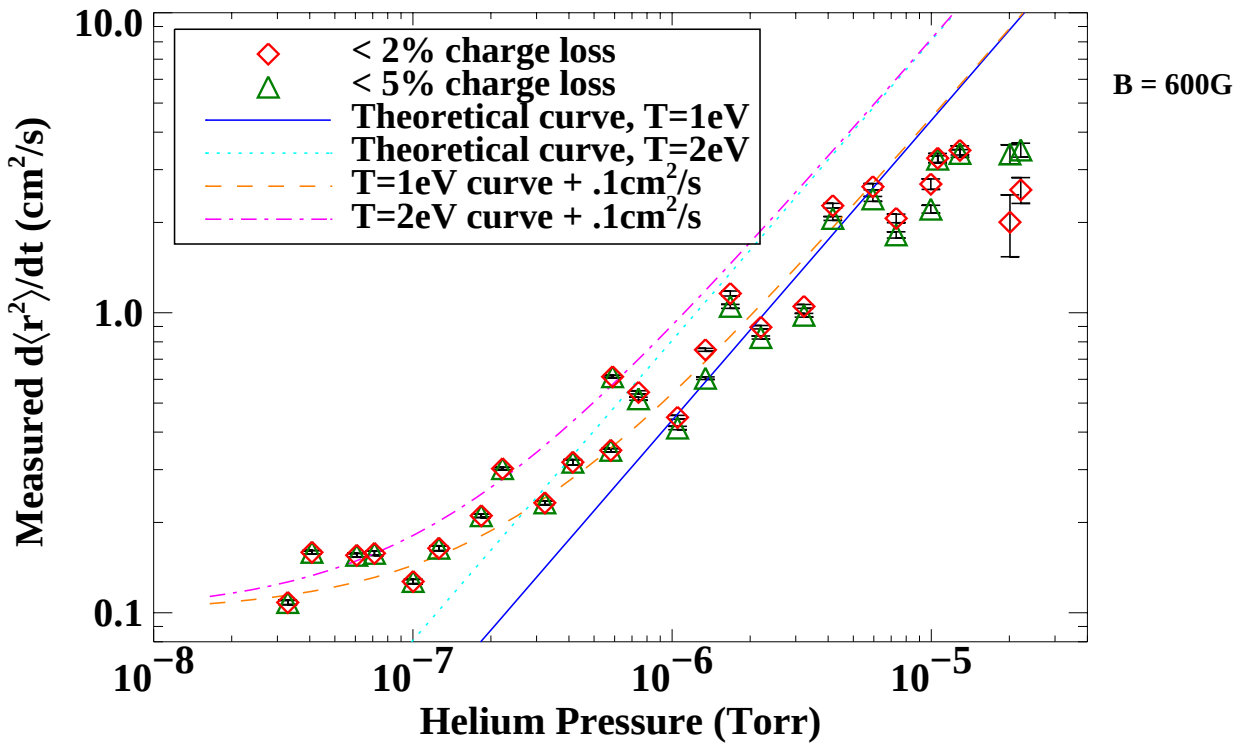
- Quasi-equilibrium profiles fit the data well.
- Collisions with neutral background gas atoms break the conservation of canonical angular momentum and allow expansion of the electron column.

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



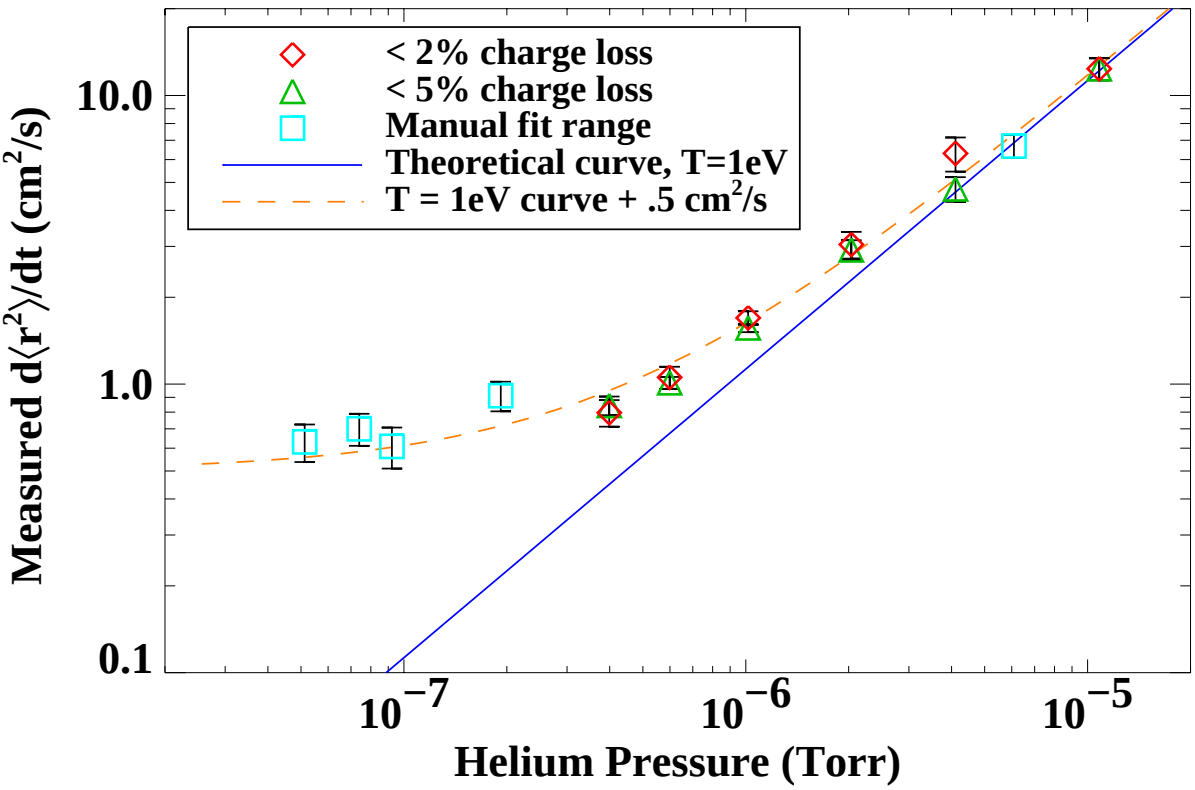
- The plasma's expansion rate should scale linearly with pressure for plasmas expanding in quasi-equilibrium.
- This scaling is readily seen from the equation for the expansion rate, $\frac{d}{dt}\langle r_\circ^2\rangle$, since $\nu_{en} \propto P$ and $\omega_{ce} \gg \nu_{en}$.
- The measured expansion 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)



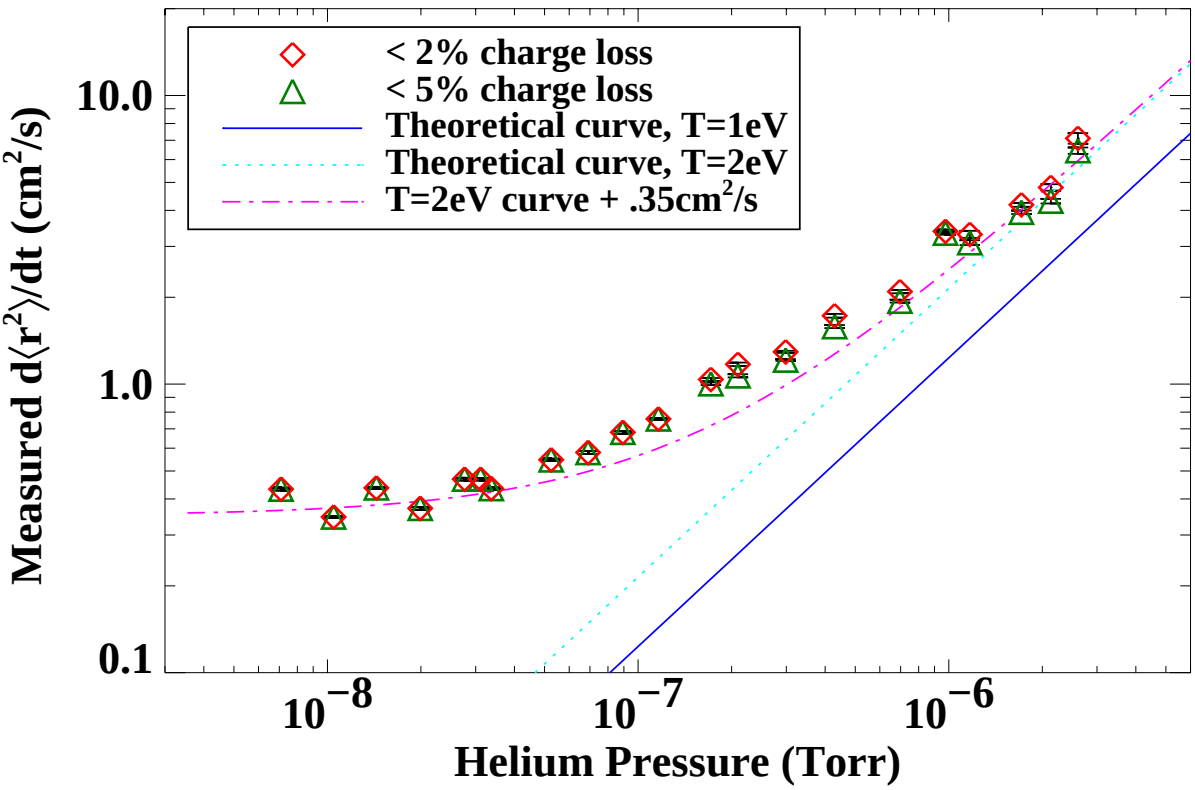
- The linear dependence with pressure is also exhibited by smaller plasmas (from a smaller filament with a .25 inch radius).
- This data indicates that plasma-wall interactions have a negligible impact on the expansion rate scaling measured.

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



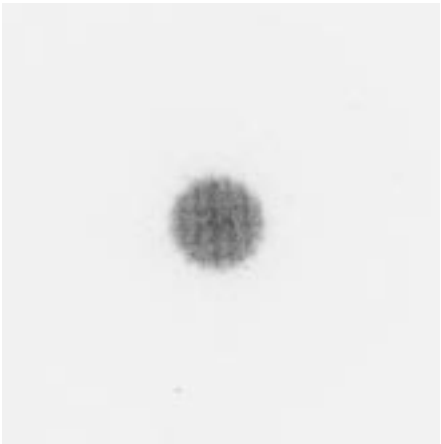
- The linear dependence with pressure is obtained at $B = 300$ G for pressures above 3×10^{-7} Torr.
- The theoretical expansion rate computed for $T = 1$ eV agrees with the expansion rates measured.

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

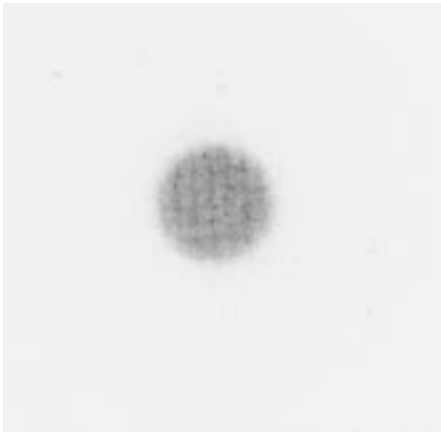


- The small filament data agree with the large filament data better at B=300G than at B=600G, due to the faster, more measurable expansion of the plasma.
- The small filament data have line densities and temperatures very similar to those of the large filament data, and the absolute expansion rates measured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

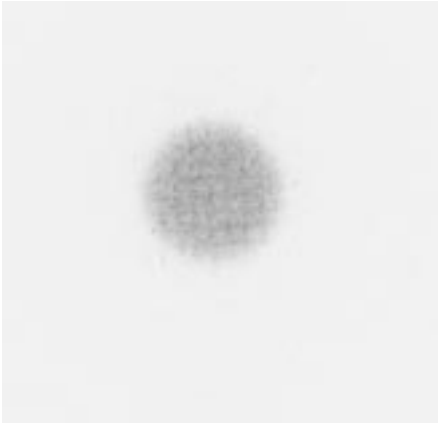
Density Diagnostic Images



(a) t = 1/6 s.



(b) t = 1 s.

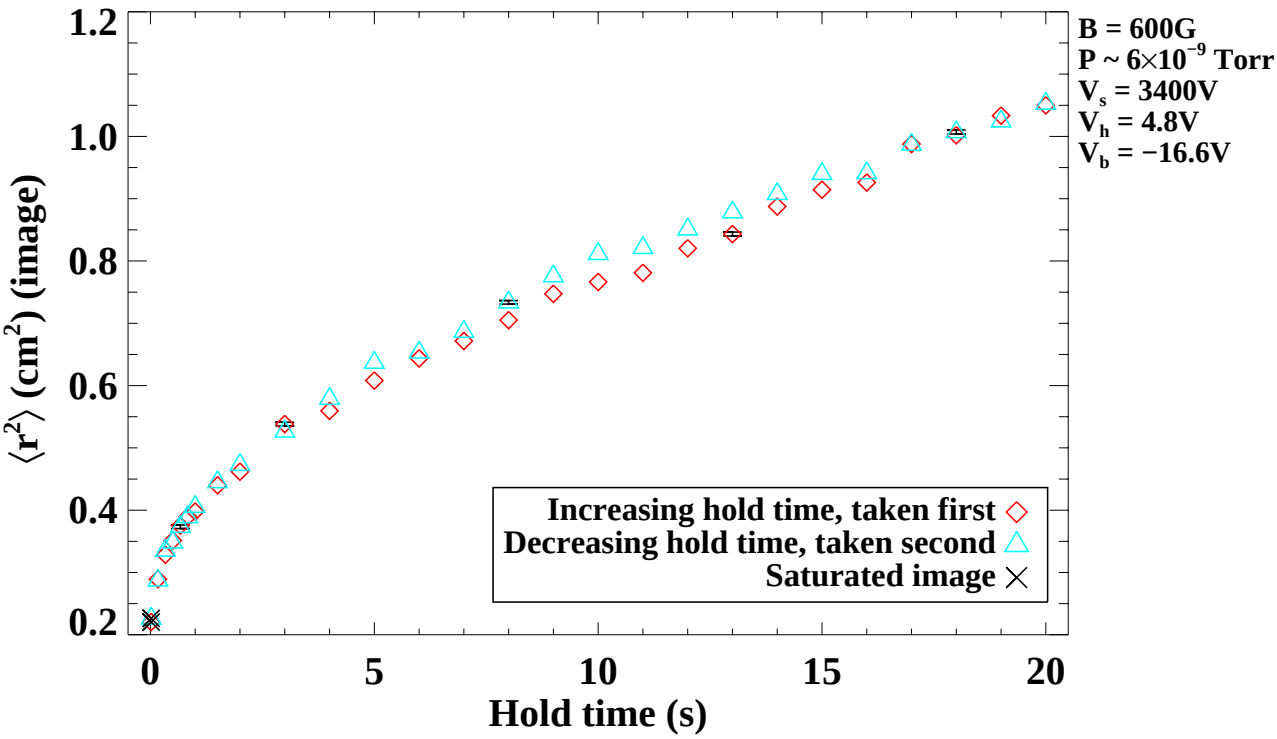


(c) t = 3 s.

(d) t = 15 s.

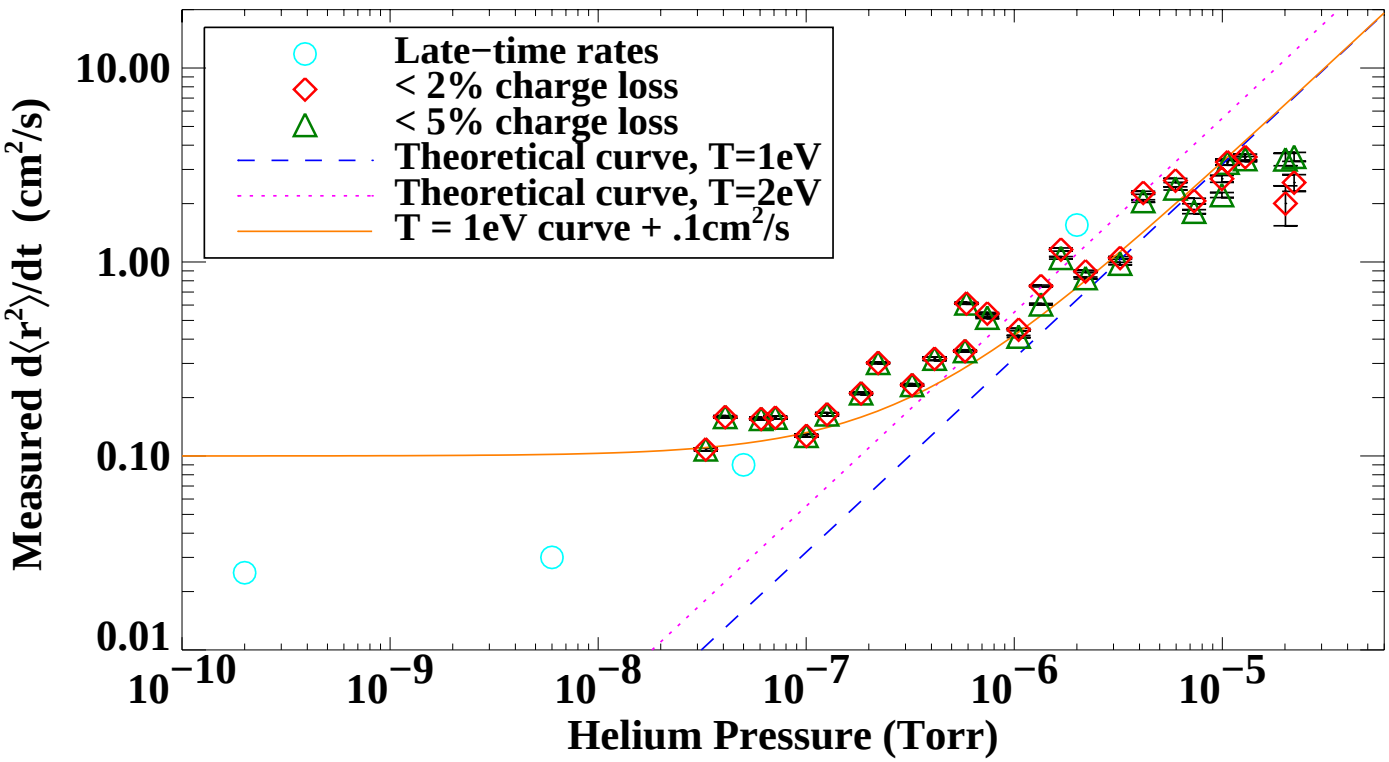
- Data taken with the new, phosphor-screen density diagnostic give axially integrated 2-D density profiles.
- The radial density profile may be estimated by averaging the data values azimuthally around the centroid of the image.

Plasma Expansion After 1 second (P= 6×10^{-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 quasi-equilibrium.
- The initial expansion (t $<$ 3 s.) is the same at several pressures below P $= 2\times10^{-7}$ Torr, and the rate agrees with that measured previously.

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

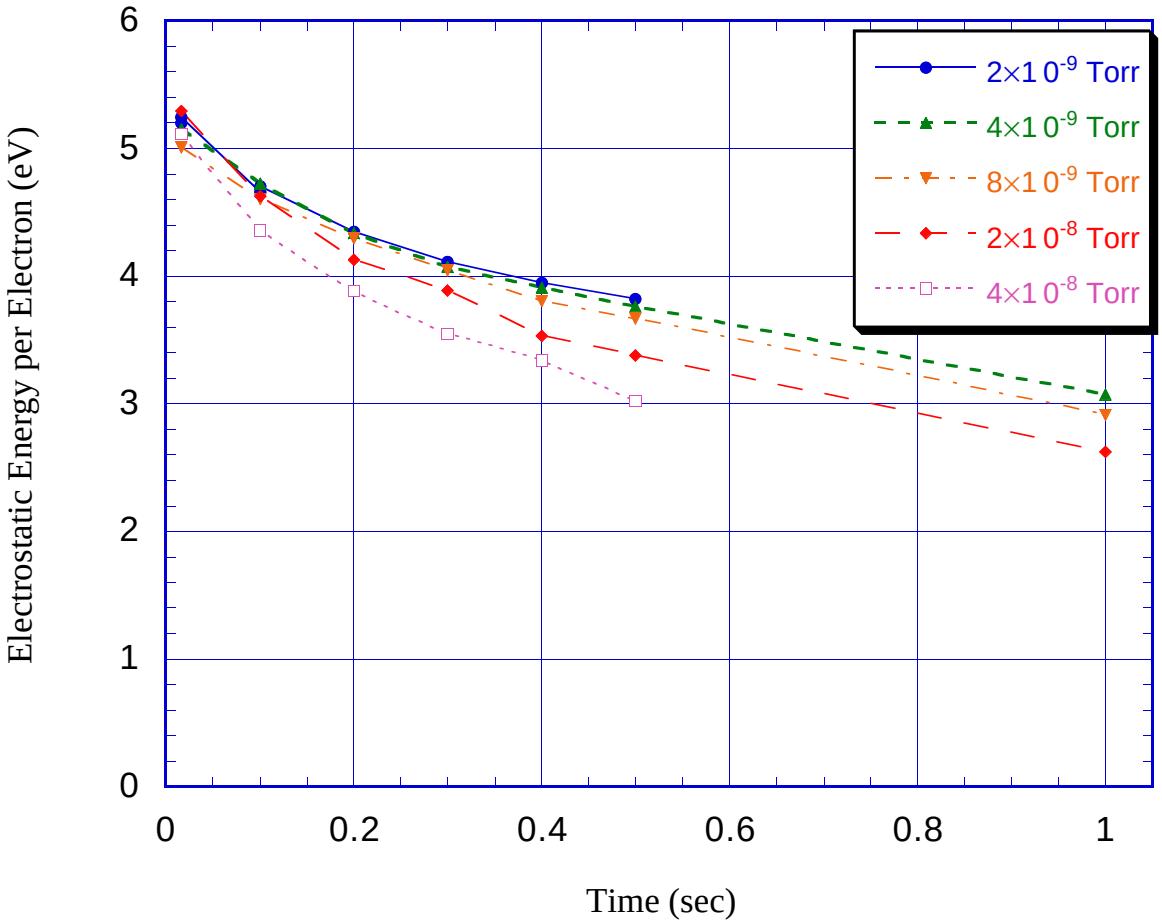


- The circles denote the new expansion rates computed by excluding the initial plasma relaxation.
- The expansion rates still level off at the lowest pressures, indicating that asymmetry-induced expansion is affecting the measurements.

Expansion Rate Scaling Results

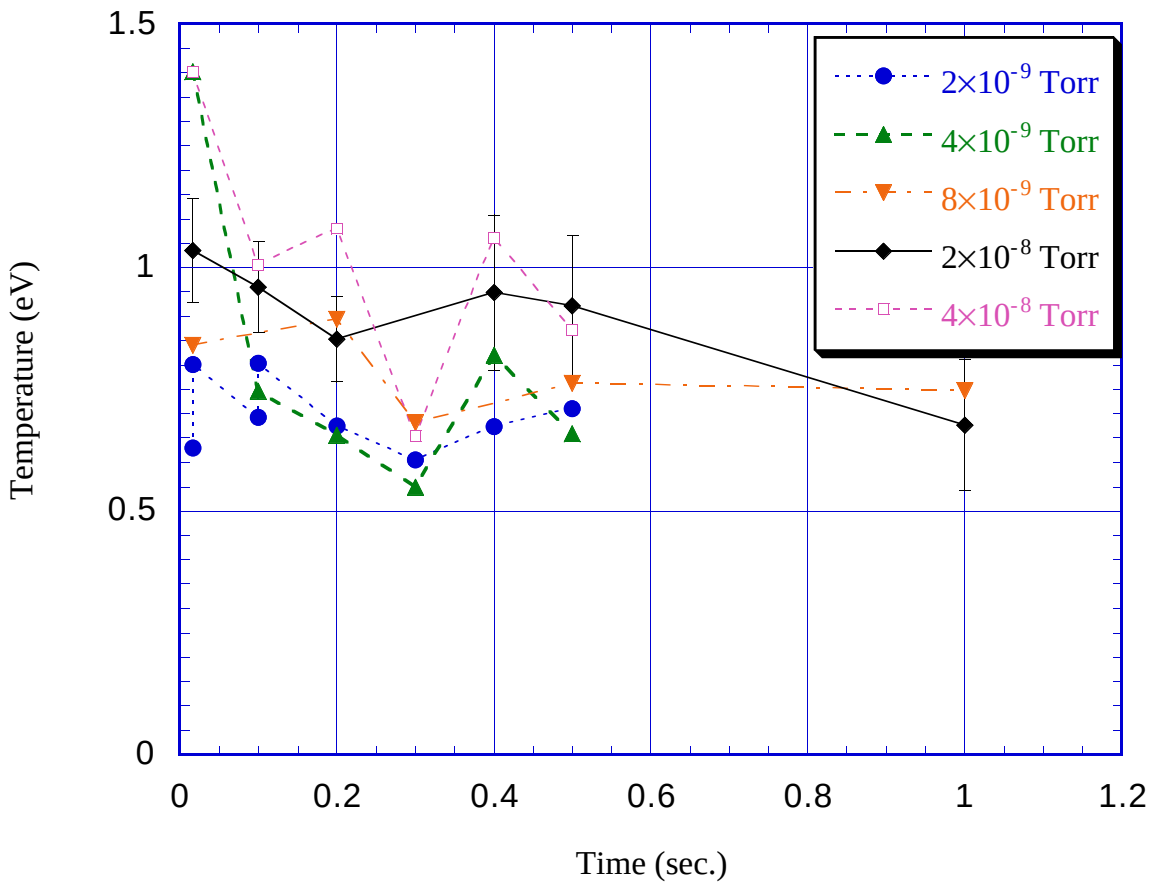
- The observations show that the plasma's expansion rate behaves consistently with the predictions of the theoretical model at higher pressures, even for plasmas that are not strictly in thermal quasi-equilibrium.
- We have verified a linear dependence of plasma expansion on neutral background gas pressure 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's expansion.

Electrostatic Potential Energy at Lower Pressures (large filament)



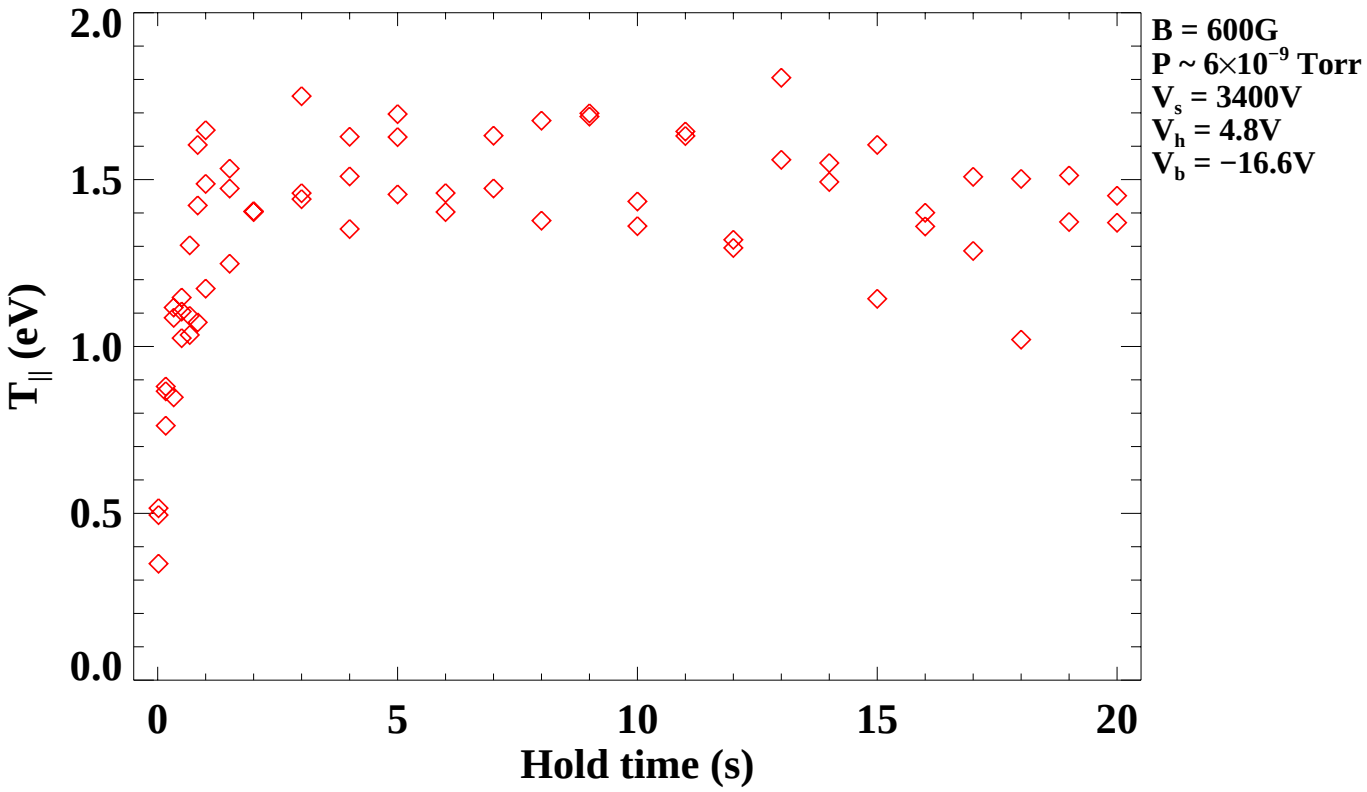
- The electrostatic potential energy of the column decreases as the plasma expands.
- Collisions with helium atoms in the EDG range of temperatures ($T < 4$ eV) are too elastic to dissipate any of this energy.

Inferred Perpendicular Temperature at Lower Pressures (large filament)



- The electron temperatures inferred from fitting the density profiles suggested that the plasma electrons are losing kinetic energy.
- Energy balance indicated that inelastic collisions with trace background gases must be the sink for the decreasing electrostatic energy.

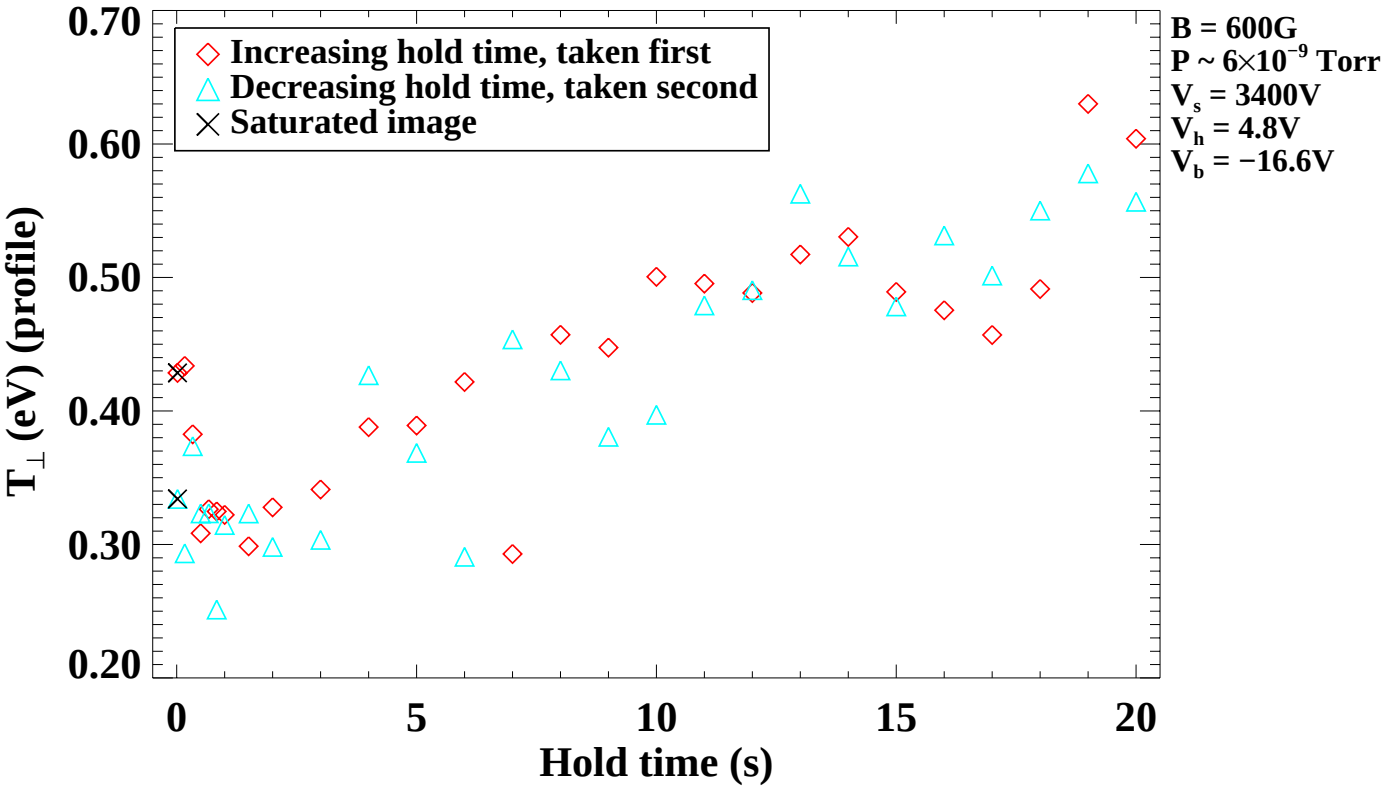
On-Axis Temperature Diagnostic Data (small filament, P=6×10^{-9} Torr)



- The measured parallel temperature does not increase while the plasma is expanding under the influence of electron-neutral collisions (t $>$ 3 sec.), but clearly increases while the plasma is relaxing to thermal equilibrium (t $<$ 3 sec.).

- The parallel temperature evolution for t $<$ 1 sec. does not agree with the perpendicular temperatures inferred previously.

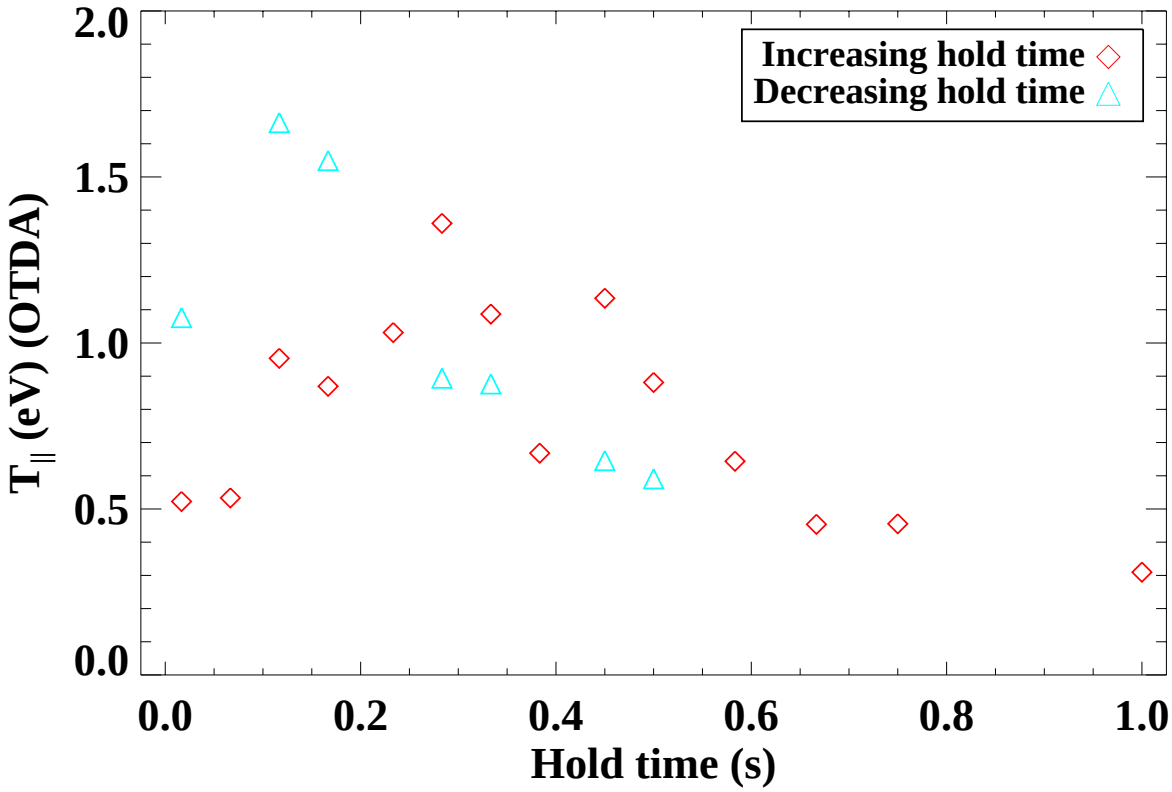
Inferred Temperature Data (small filament, P=6×10^{-9} Torr)



- The temperatures inferred from fitting the phosphor-screen-diagnostic density profiles with quasi-equilibrium profiles change very little during both phases of expansion.

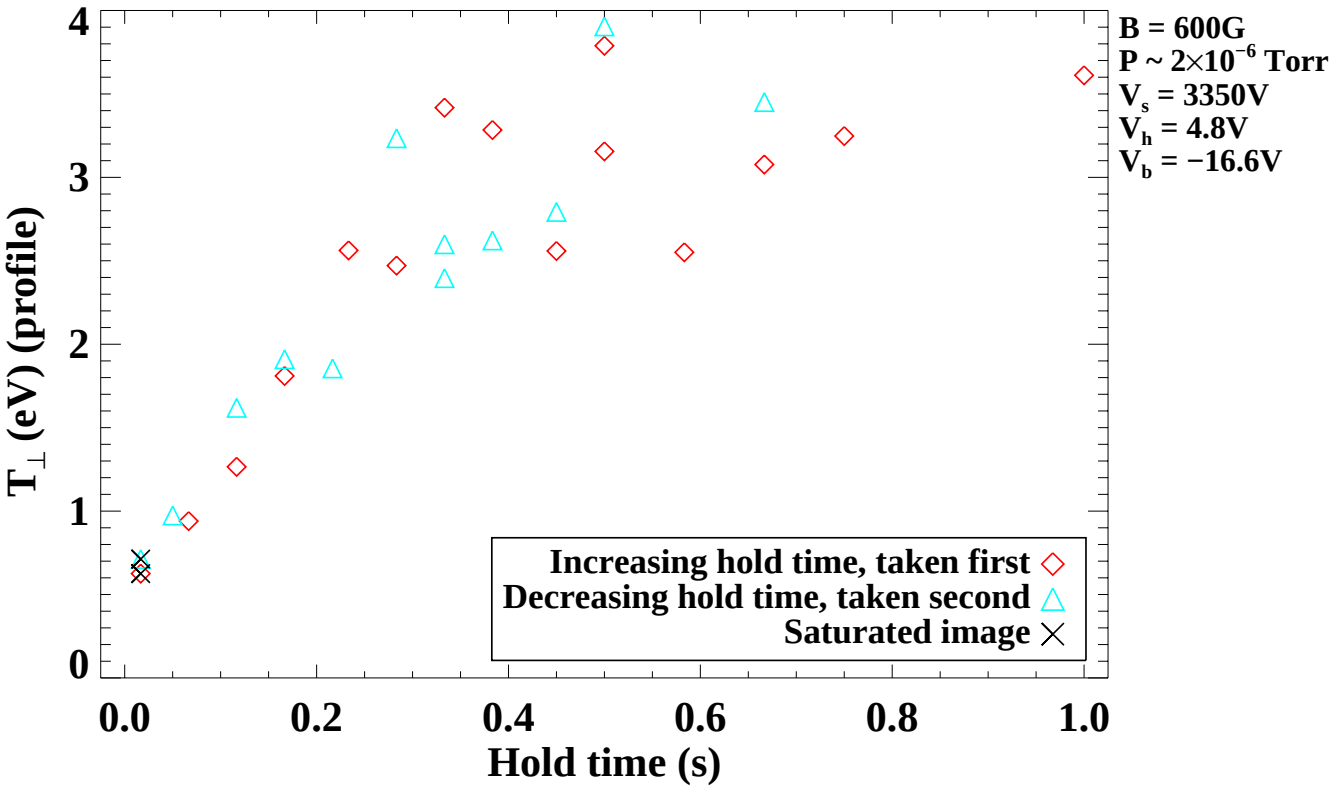
- The quasi-equilibrium profiles fit the measured density profiles well, even when the plasma is expanding quickly.

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 should have a sizeable temperature gradient, may be in contact with the trap wall, and is not in quasi-equilibrium; the temperatures inferred are not expected to be representative of the true temperature profile in the plasma.

Summary

- The plasmas' expansion rate dependence on background gas pressure is in good agreement with theoretical predictions for plasmas formed with both large and small filaments at pressures above $\sim 3 \times 10^{-7}$ Torr.

- The measured, on-axis parallel temperature evolution and mean-square radius evolution suggest that the EDG plasma takes a few seconds to reach thermal quasi-equilibrium.

- The expansion rate due to electron-neutral collisions at low pressures has been observed to be lower than previously though by using a new, phosphor-screen density diagnostic.

The poster

Electron Plasma Expansion due to Background Gas in the Electron Diffusion Gauge Experiment

by

K. Morrison, S. F. Paul, and R. C. Davidson

is available at

http://w3.pppl.gov/∼kmorriso/storage/k.dpp2003.poster.1.pdf