The Effects of Neutral Gas Pressure and Electron Temperature on the Dynamics of the Electron Diffusion Gauge Experiment Electron Plasma

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

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Outline

- EDG Device
- Measurements of Plasma Expansion
- On-axis Electron Temperature Measurements
- $m = 1$ Diocotron Mode Evolution Measurements

Studying Non-neutral Plasmas

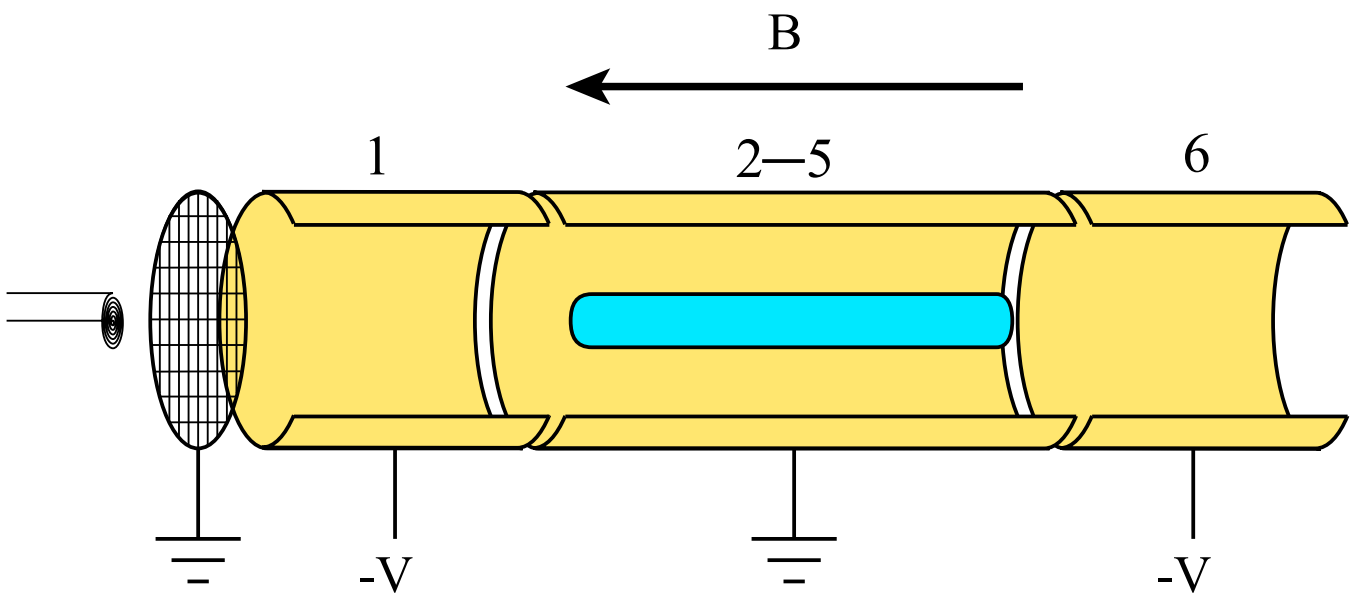
Non-neutral plasma physics is important for describing

- Intense charged particle beams in accelerators,
- Generation of coherent radiation (e.g., in Free Electron Lasers),
- Intense currents in high-voltage diodes.

Non-neutral plasmas similar to EDG's have been used in

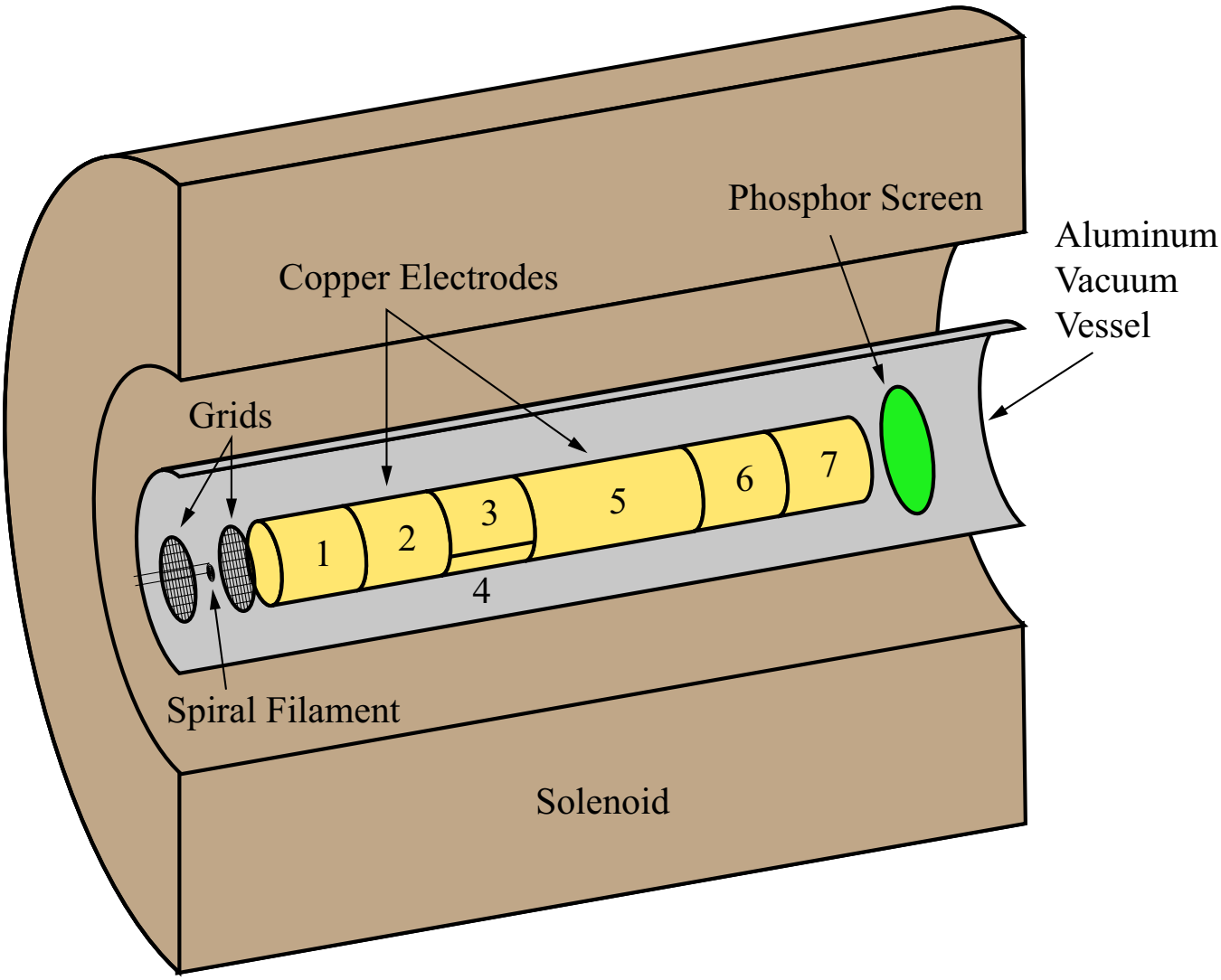
- Atomic clocks,
- Antihydrogen production experiments,
- Modeling inviscid 2-D fluids,
- Studies of the basic processes of transport across magnetic fields.

Malmberg-Penning Trap Geometry



- Malmberg-Penning traps are cylindrically symmetric.
- A uniform, axial magnetic field confines particles radially.
- Non-adjacent cylindrical electrodes are biased to confine particles axially.
- Malmberg-Penning traps confine particles with the same charge sign (e.g., $^{24}Mg^{+}$ and $^{24}Mg^{2+}$).

Schematic of the EDG device



EDG has diagnostics to destructively measure:

1. Total number of electrons in the trap;
2. Axially-integrated density profile;
3. Parallel temperature on axis;

and non-destructively measure:

4. Amplitude waveform of the $m = 1$ diocotron mode.

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Typical Plasma Parameters

Background gas pressure	P	$=$	1×10^{-10} – 1×10^{-5} Torr
Temperature	T	$=$	1 eV
Magnetic field	B	$=$	600 G
Total charge trapped	N	$=$	5×10^{8} electrons
Electron density (on axis)	$n(r=0)$	$=$	1.15×10^{7} /cm^3
Plasma potential (on axis)	$\phi(r=0)$	$\approx$	-15 V
Electron gyroradius	ρ_L	$=$	0.04 mm
Debye length	λ_D	$=$	0.21 cm
Plasma radius (initial)	$R_P(t=0)$	$=$	0.87 cm (small filament)
			1.27 cm (large filament)
Electrode inner radius	R_w	$=$	2.54 cm
Plasma length	L_p	$=$	15 cm
Electron gyrofrequency	$\omega_c/2\pi$	$=$	1.7 GHz
Plasma frequency	$\omega_p/2\pi$	$=$	30 MHz
Axial bounce frequency	$\omega_b/2\pi$	$=$	1.4 MHz
Plasma rotation frequency	$\omega_r/2\pi$	$=$	290 kHz
$m=1$ Diocotron mode frequency	$\omega_D/2\pi$	$=$	40 kHz
Electron-electron collision frequency	ν_{ee}	$=$	200 Hz
Electron-neutral collision frequency	ν_{en}	$=$	0.15 – 1.5×10^{4} Hz

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Malmberg-Penning Trap Confinement

For an ideal trap with a perfectly uniform magnetic field and perfectly symmetric electric fields,

$$\frac{d}{dt}L_z = 0$$

$$\begin{aligned} L_z = \sum_j p_j r_j &= \sum_j \left[m_j v_{\phi j} + \frac{q_j}{c} A_\phi(r_j) \right] r_j \\ &= \sum_j \left[m_j \cancelto{0}{v_{\phi j}} r_j + \frac{q_j}{c}\frac{B_0}{2}\, r_j^2 \right] \\ L_z &\approx \frac{qB_0}{2c} \sum_{j=1}^{N} r_j^2 \equiv \frac{qB_0}{2c} N \langle r^2 \rangle \end{aligned}$$

$\Rightarrow$ In the absence of external influences, the plasma is extremely well-confined.

Imperfections in the trap fields or collisions with background gas can effectively torque the plasma, allowing it to expand:

$$\Delta L_z \approx \frac{qB_0}{2c}\, \Delta\left(\sum_j r_j^2 \right)$$

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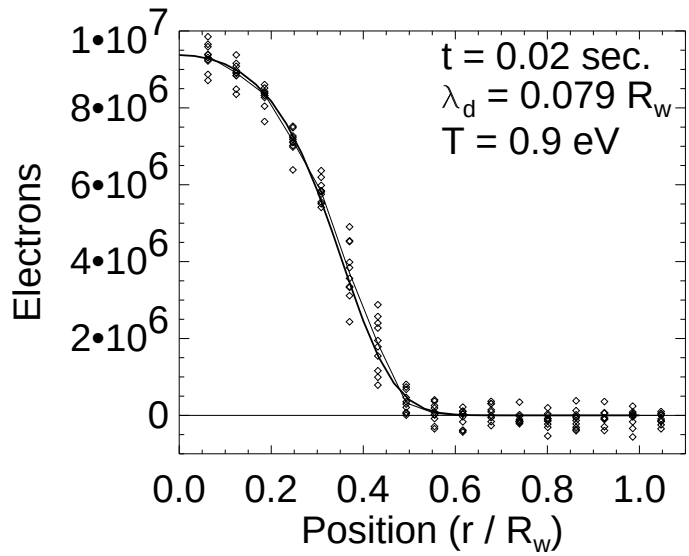
Thermal Quasi-Equilibrium

A fluid model predicts expanding quasi-equilibrium density profiles for plasmas experiencing elastic collisions with the background gas.



Radial electron density profile. [Chao, 1999]

The thermal quasi-equilibrium density profile [for $T \neq T(r)$] is

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

where

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

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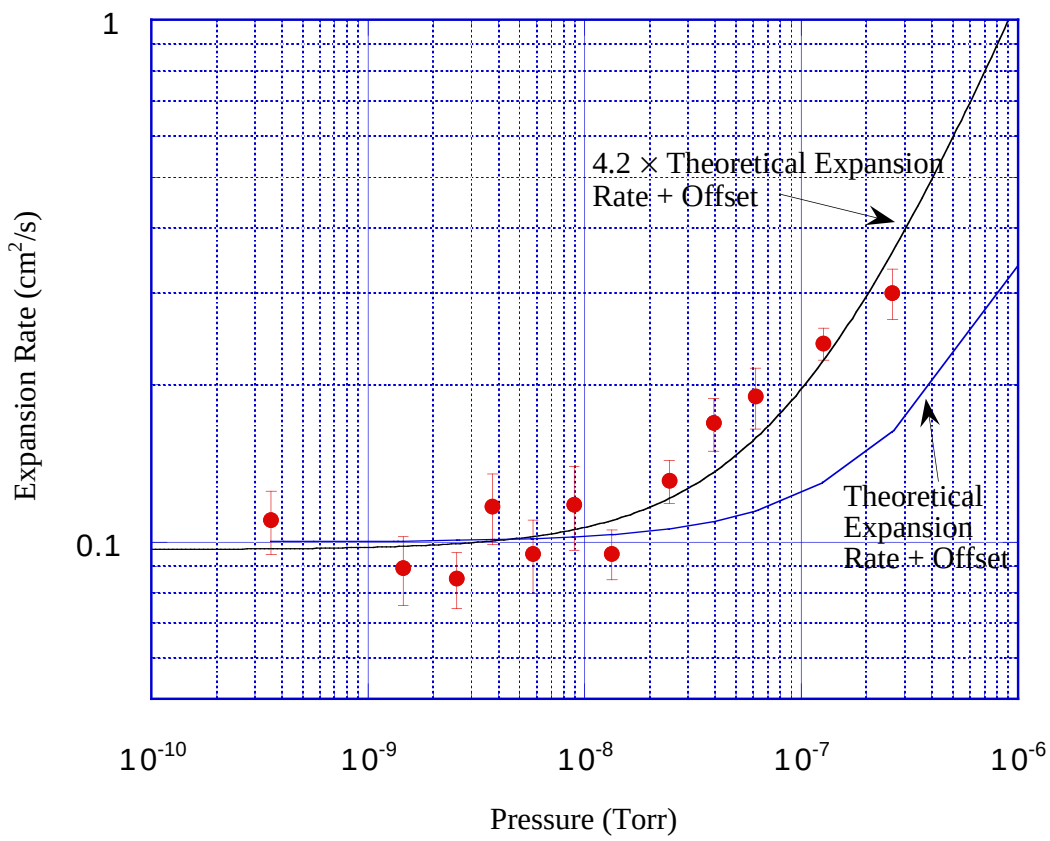
Expansion Rate Scaling with Pressure Measured Previously



$\frac{d}{dt}\langle r^2 \rangle$ vs. background gas pressure. [Chao, 1999]

- The plasma's expansion rate should scale linearly with pressure for plasmas expanding in quasi-equilibrium.
- This scaling is readily seen from the expansion rate equation, since $\dfrac{d}{dt}\langle r_0^2 \rangle \propto \nu_{en}$ and $\nu_{en} \propto P$.
- The measured expansion rate at lower pressures was thought to be dominated by asymmetry-induced plasma expansion.

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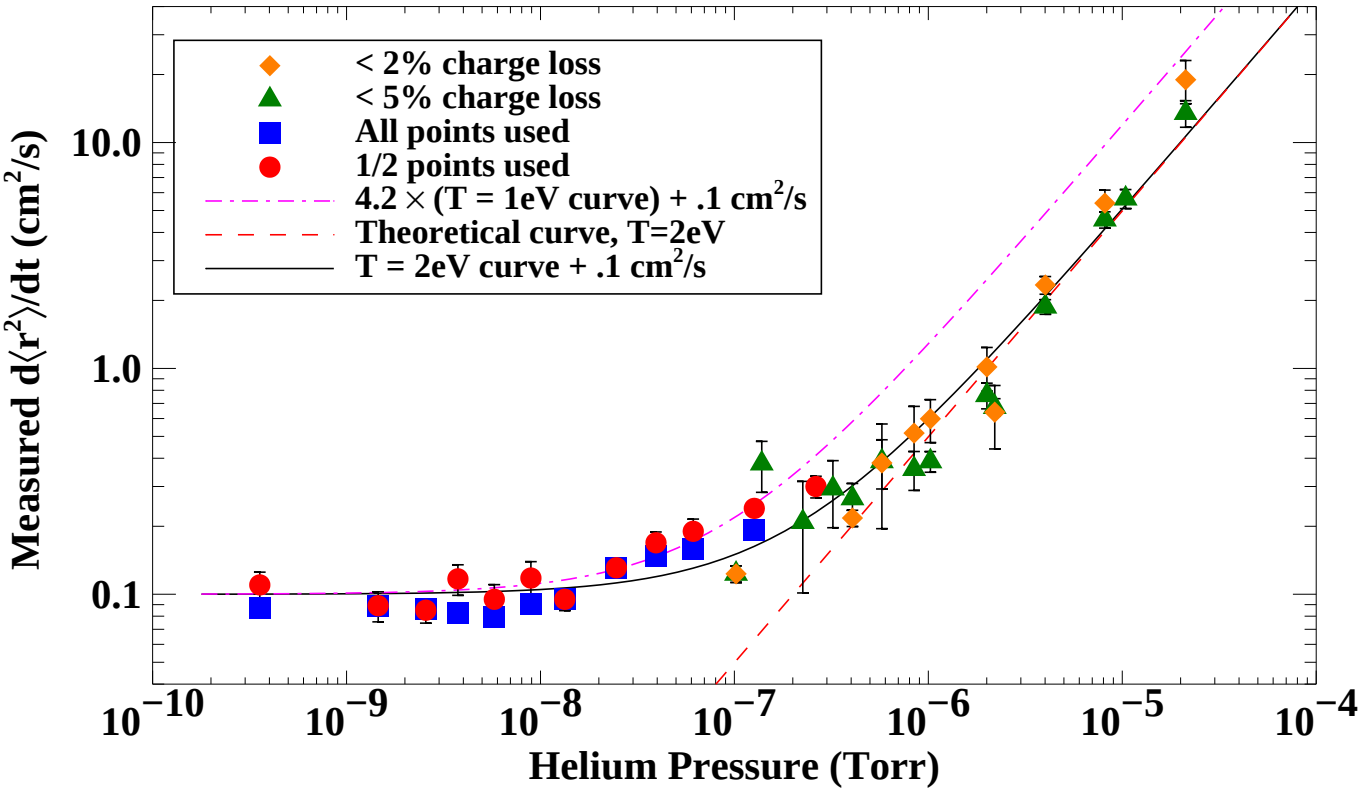
Expansion Rate Scaling with Pressure



- An approximately linear dependence is seen at higher pressures than those tested previously.

- The expansion rate data expand at a rate consistent with the model for a temperature of $T = 2$ eV, which agrees with the temperatures inferred from the density profiles.

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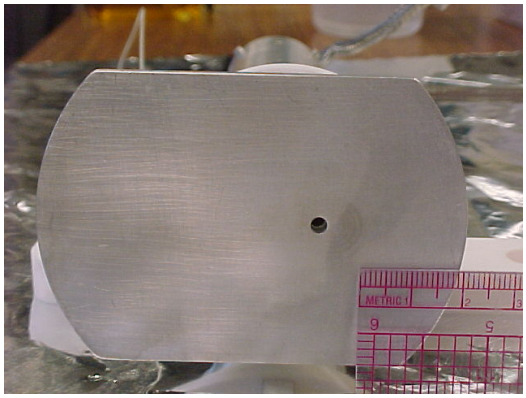
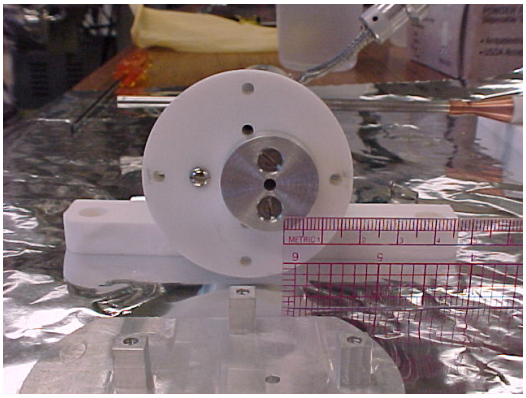
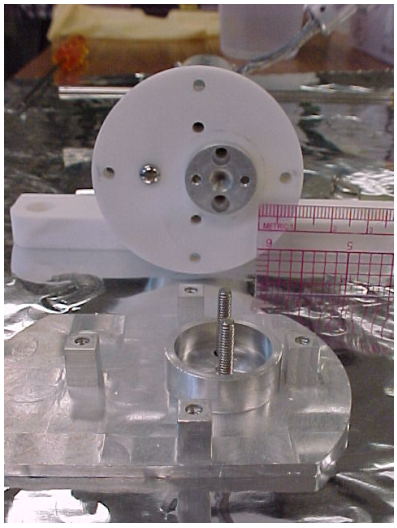
Radially-Scanning Faraday Cup Density Diagnostic Electrodes



(a) Total collector.



(b) Capacitive shield.



(c) Local collector.

- The local collector collects electrons from magnetic field lines that pass through the 1/8"-diameter holes in the total collector and capacitive shield.

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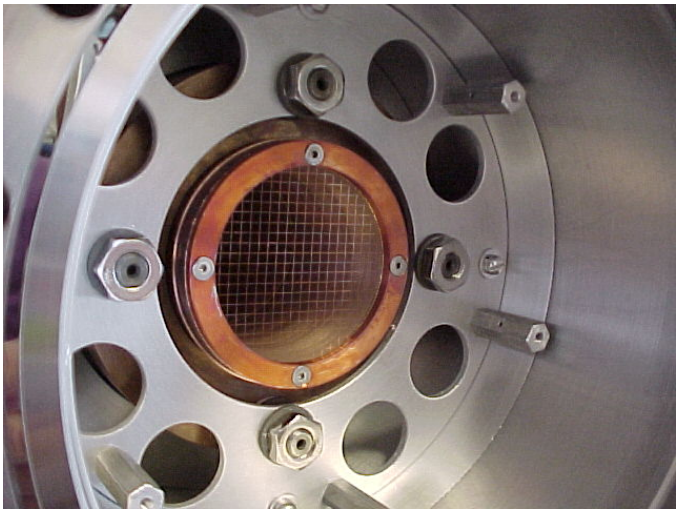
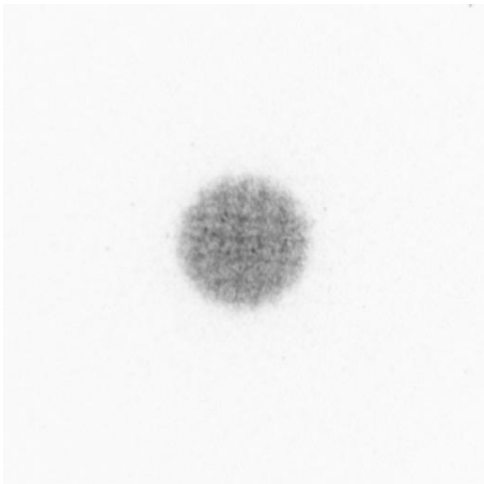
Phosphor-Screen Density Diagnostic

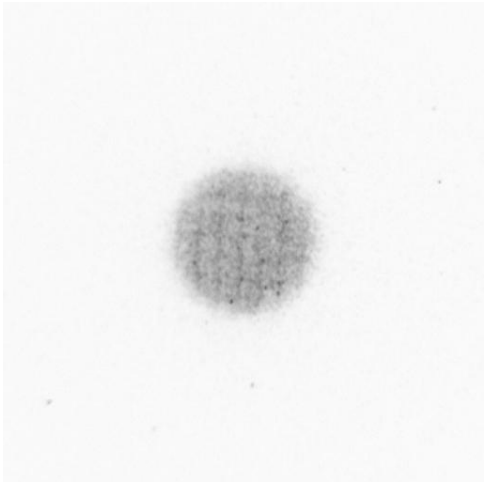


- A biased, aluminum-coated, P43 phosphor screen produces an image of the entire, axially integrated plasma when the plasma strikes it.
- A copper grid is clamped to the last, grounded trap electrode to give a more radially uniform accelerating electric field.
- A PULNiX TM-1010 CCD camera with an ITT NE6010 intensifier records the glowing image for later analysis.

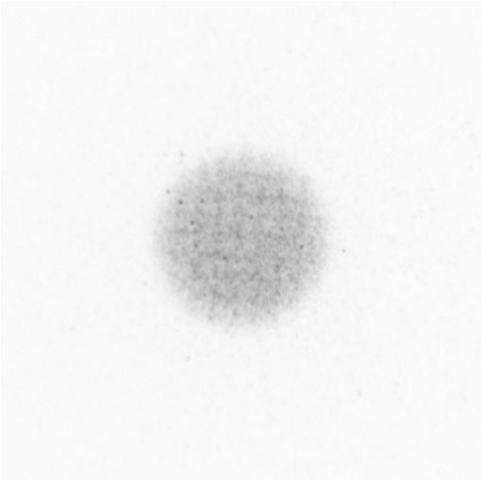
Density Diagnostic Images



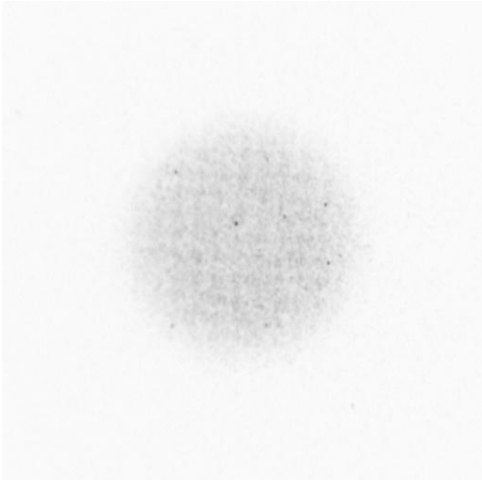
(a) Trapped for 1/3 s.



(b) Trapped for 1 s.



(c) Trapped for 3 s.



(d) Trapped for 15 s.

Raw images of plasmas expanding at $P \sim 6 \times 10^{-9}$ Torr.

- The images clearly show that the plasma is expanding.
- The plasmas are azimuthally symmetric.

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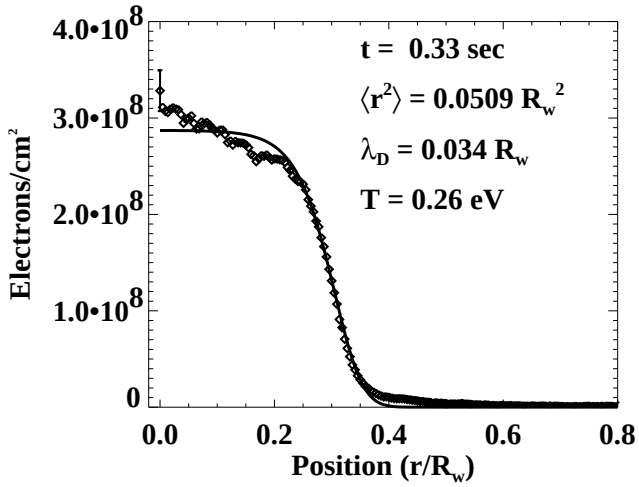
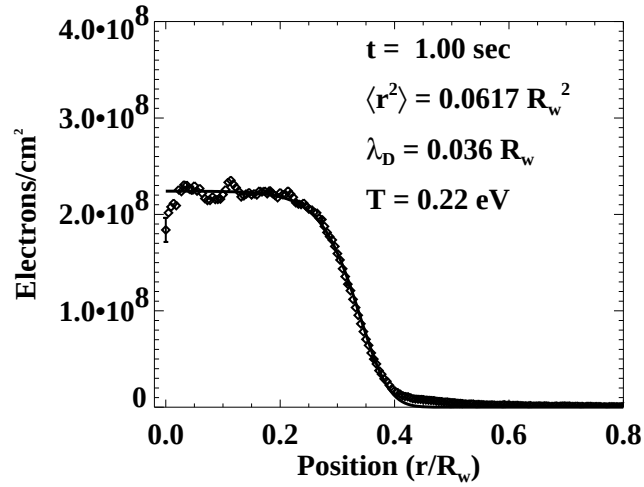
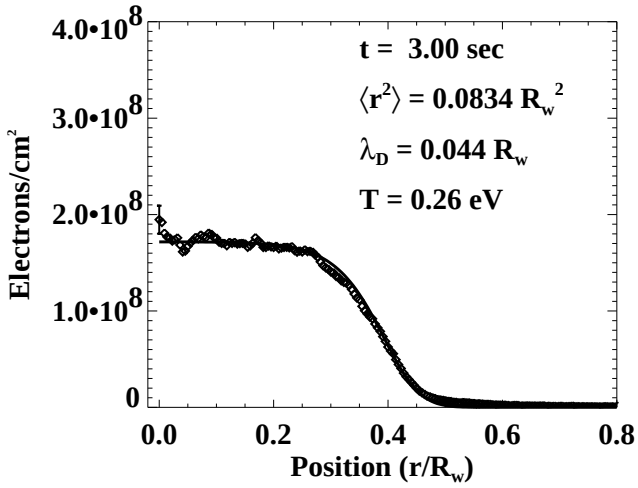
Density Profile Evolution in EDG



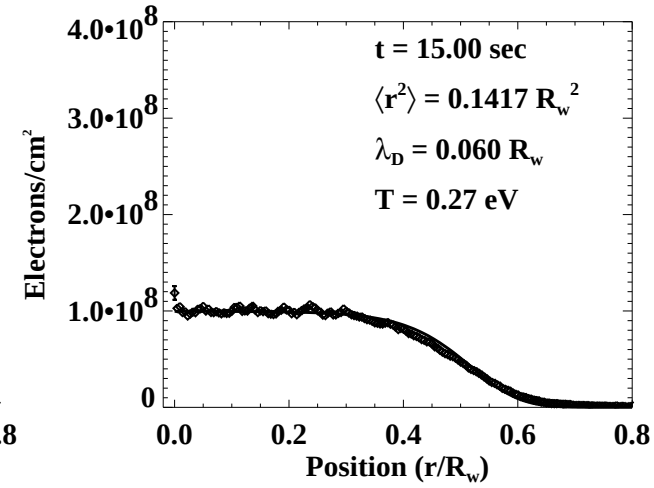
(a) 1/3 s.



(b) 1 s.



(c) 3 s.



(d) 15 s.

Evolution of density profiles at $P \sim 6 \times 10^{-9}$ Torr

- The thermal quasi-equilibrium density profiles agree very well with the new density profile measurements.

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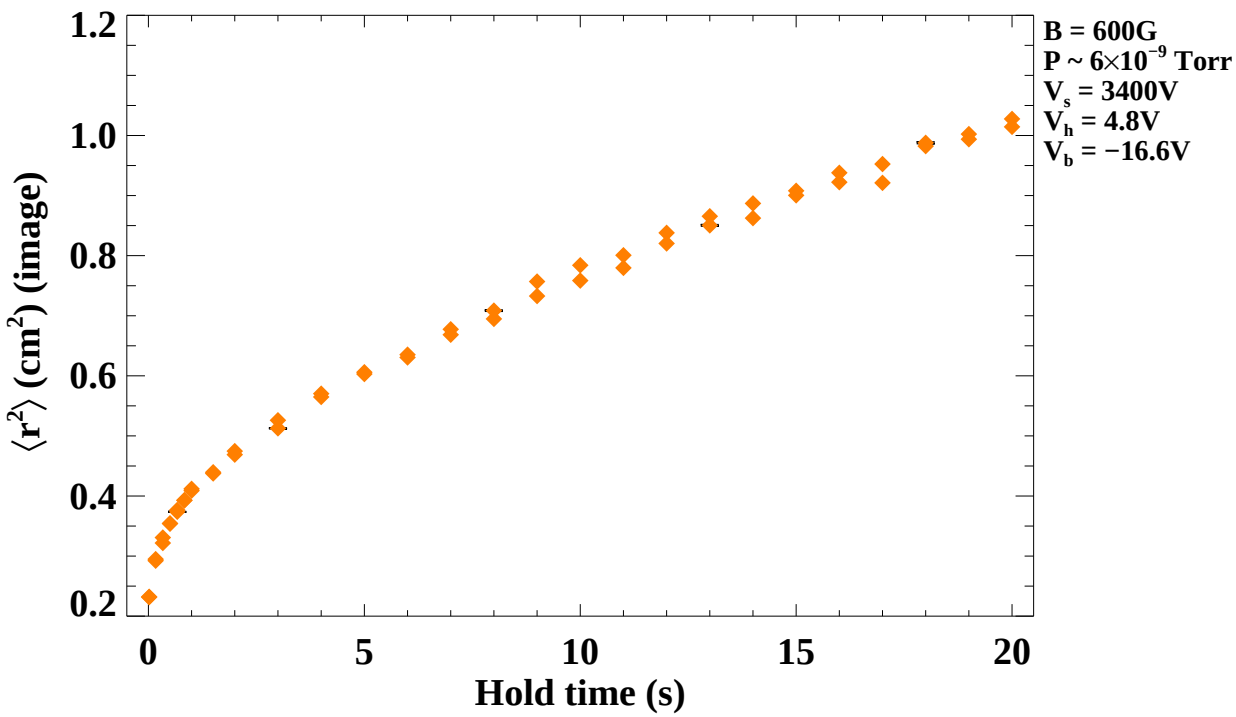
Relaxation to Thermal Quasi-Equilibrium



Mean-square radius evolution at $P = 6 \times 10^{-9}$ Torr

- Data taken with the new density diagnostic suggests that the plasma expansion measured previously occurred during a relaxation of the plasma to the thermal quasi-equilibrium state.

- The initial expansion (t $<$ 2 s.) is the same at several pressures below P $= 2 \times 10^{-7}$ Torr, and the rate agrees with that measured previously.

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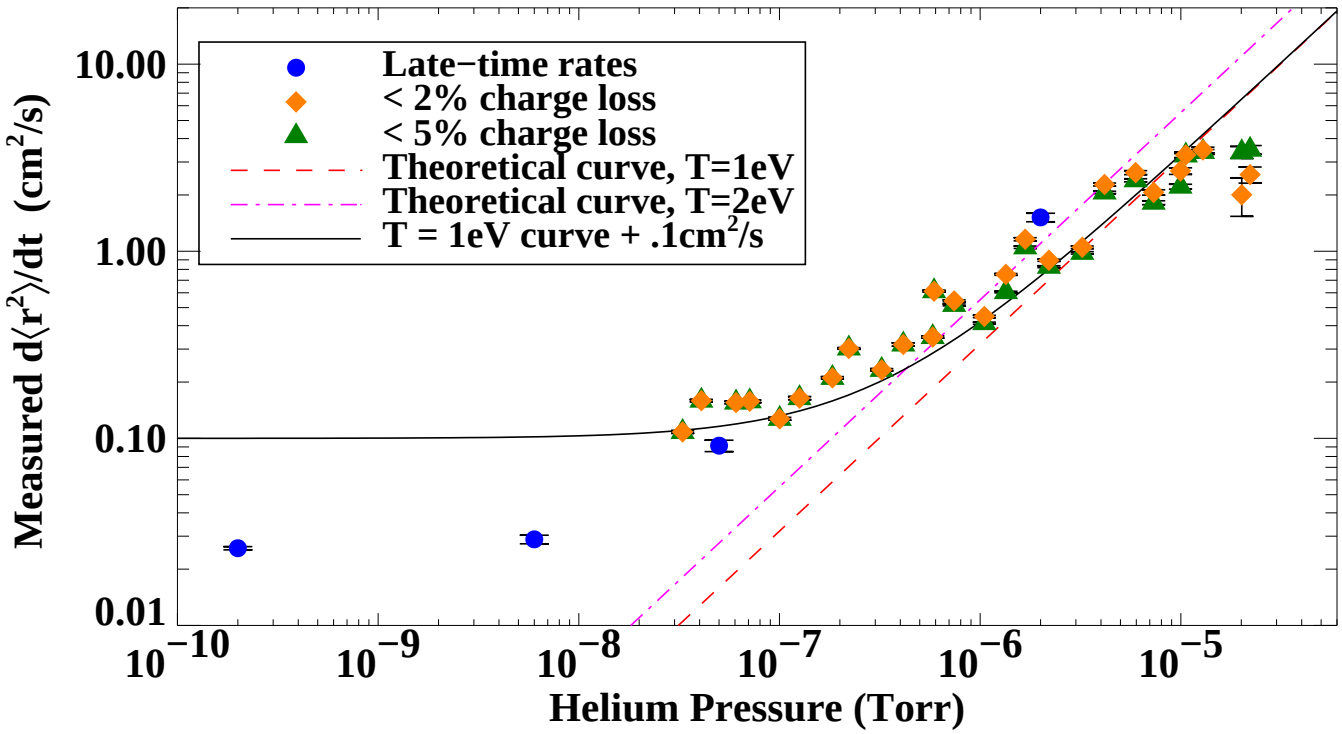
Late-time Expansion Rates



Plasma expansion rate measured vs. pressure for small filament plasmas.

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

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Plasma Expansion Measurements Results

- The plasma's expansion rate is consistent with the predictions of the theoretical model at higher pressures.
- We have verified a linear dependence of plasma expansion on neutral background gas pressure for plasma *profiles*, not just for central density decay.
- The plasma takes several seconds to relax to a thermal quasi-equilibrium state.

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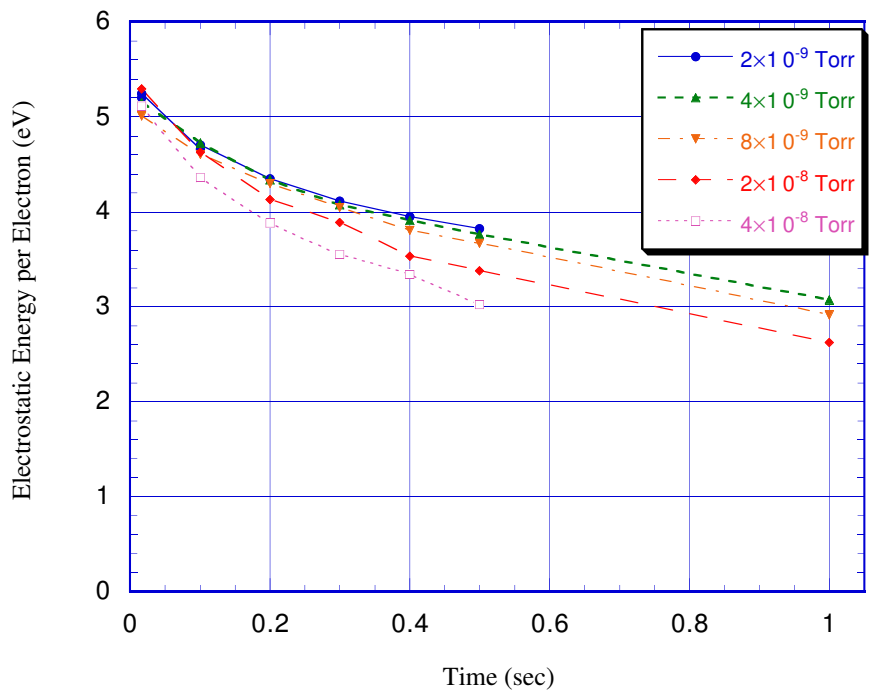
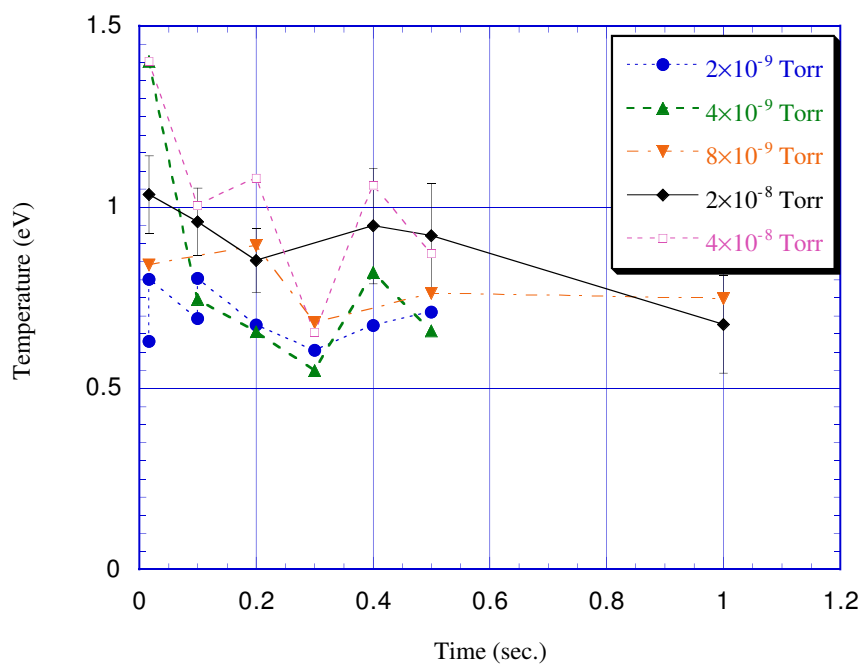
Initial Energy Evolution



(a) Electrostatic potential energy. (Chao, 1999)



(b) Inferred perpendicular temperature. (Chao, 1999)

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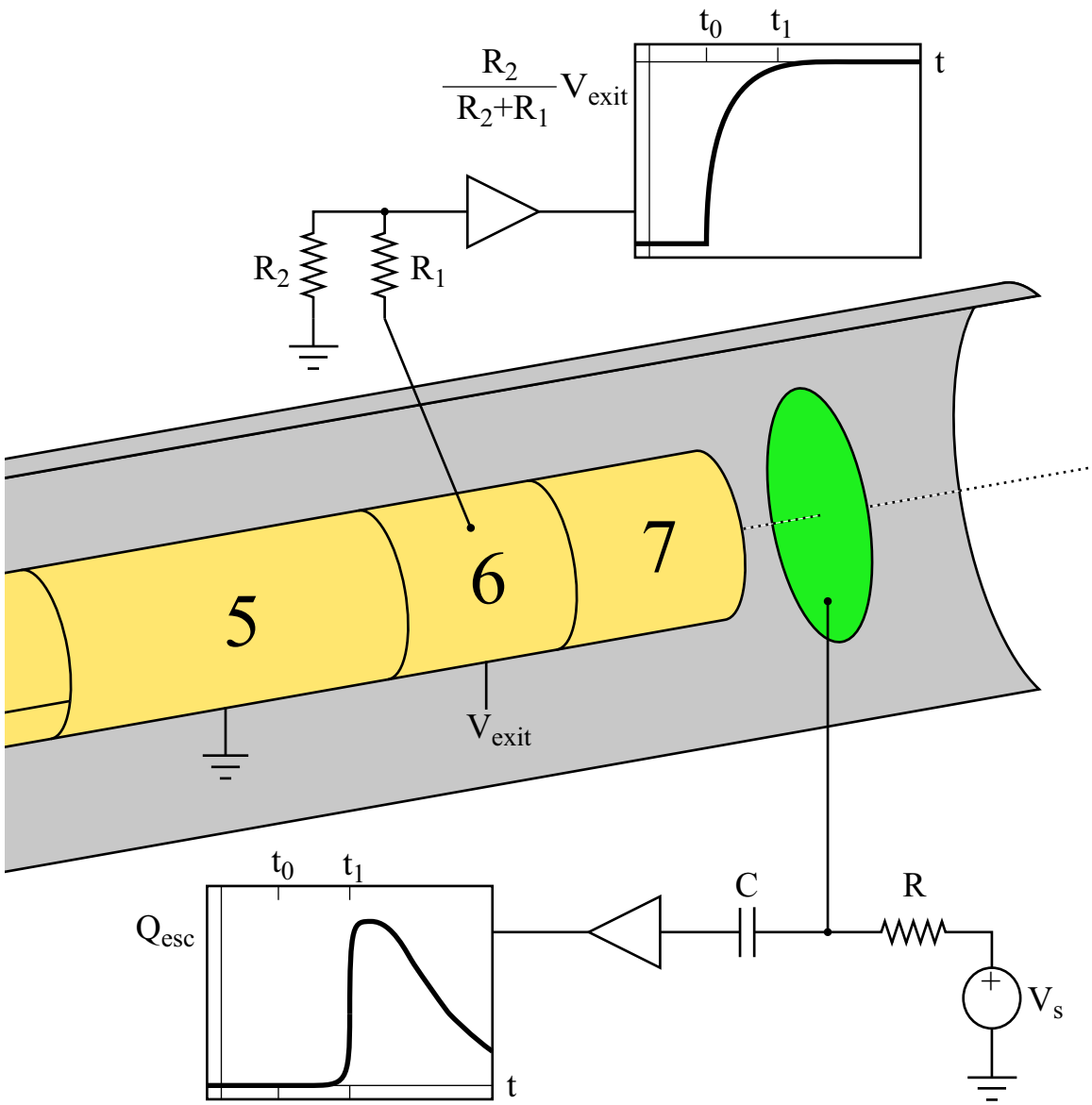
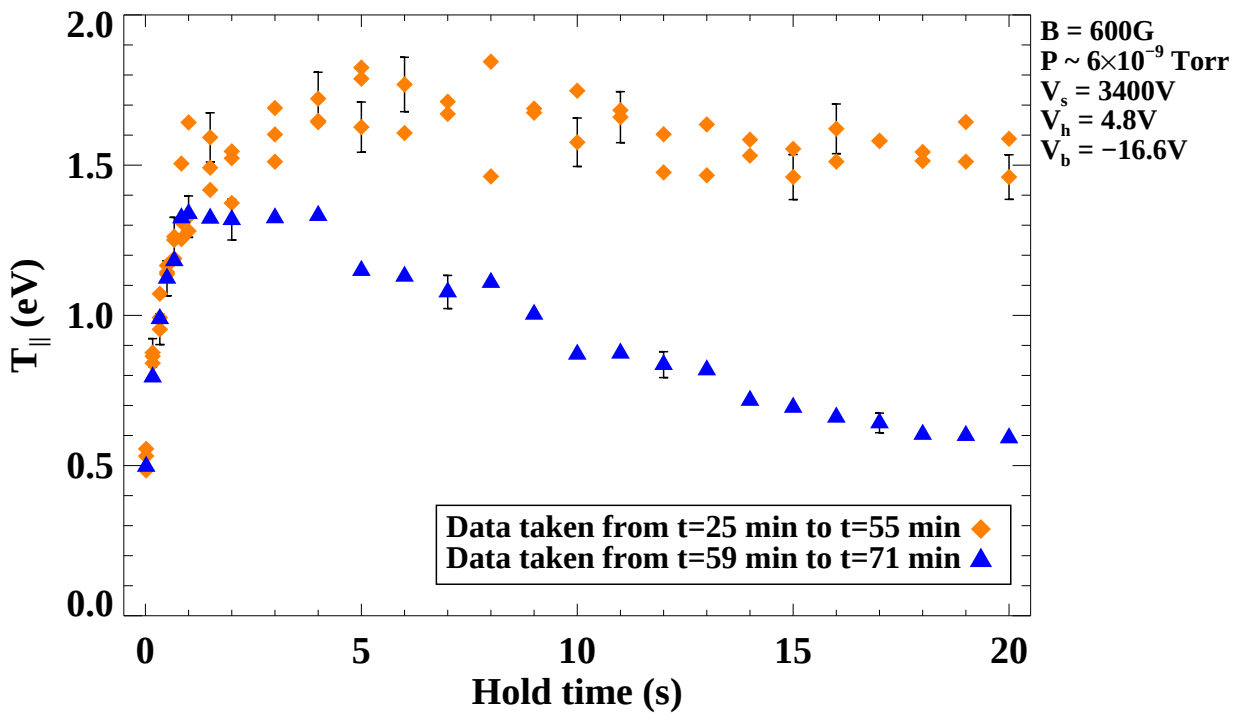
$T_{\parallel}$ Diagnostic Setup



- The change in the confining voltage on electrode 6 during the plasma's release is slowed to resolve the electron energy distribution at $r \approx 0$.
- An amplifier is coupled to the phosphor screen to measure the number of electrons that have escaped as a function of time.

$T_{\parallel}$ Data



On-axis parallel temperature evolution measured at $P = 6 \times 10^{-9}$ Torr

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

- The difference in the two evolutions is thought to be due to the different amounts of gas desorbed from the trap surfaces.

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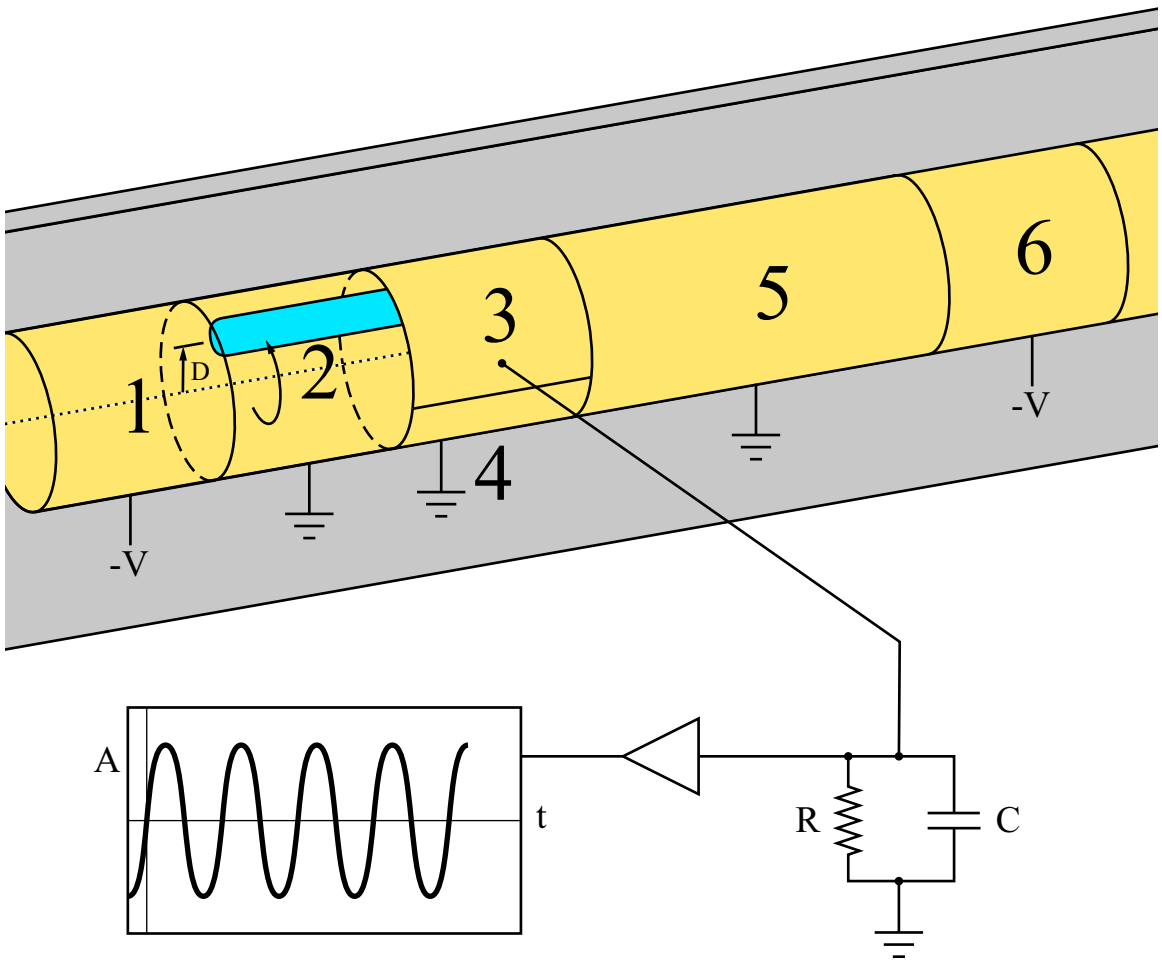
Schematic of the $m = 1$ Diocotron Mode Diagnostic



- The $m = 1$ diocotron mode has $k_z \approx 0$, and is analogous to a radial displacement of the plasma.

- An azimuthally-discontinuous electrode segment draws current when the charged plasma passes by, and this current is measured to record the mode evolution.

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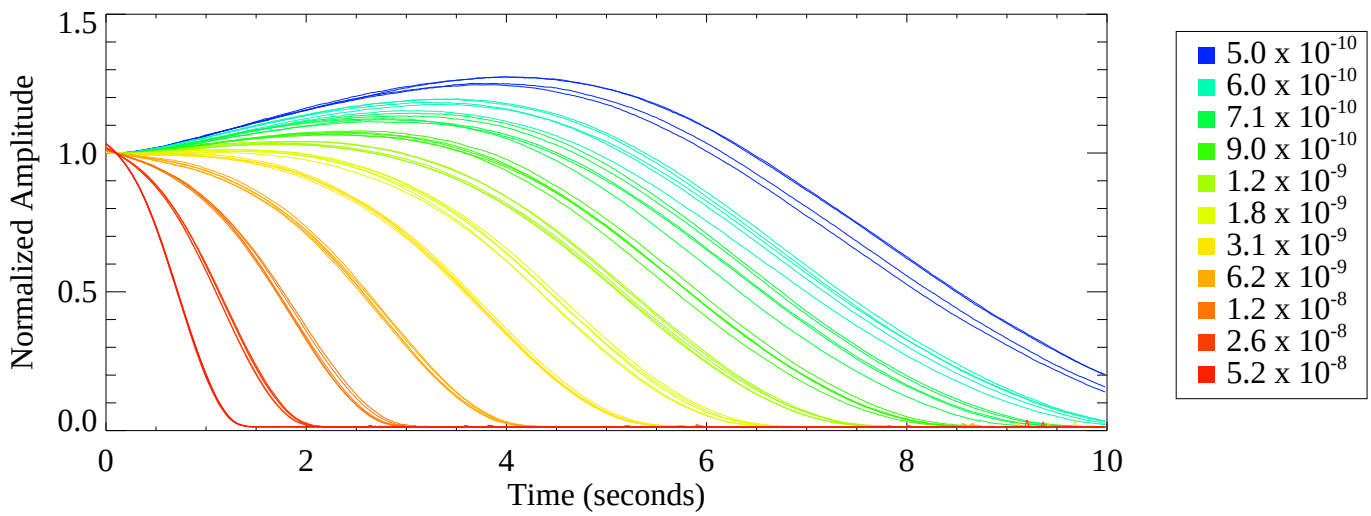
Diocotron Mode Evolution Measured Previously



(a) Amplitude evolution of the $m = 1$ diocotron mode.

Amplitude evolution of the $m = 1$ diocotron mode. [Chao,1999]

- The diocotron mode was observed to damp more strongly with increased background gas pressure.
- Differences in pressure as small as $\Delta P \approx 5 \times 10^{-10}$ Torr have been observed with this technique.

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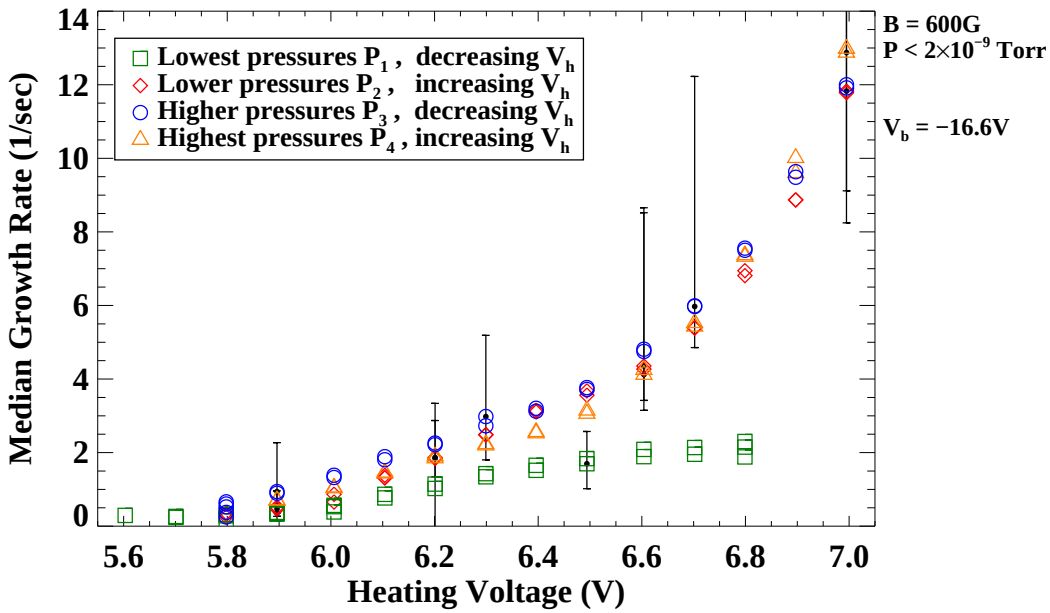
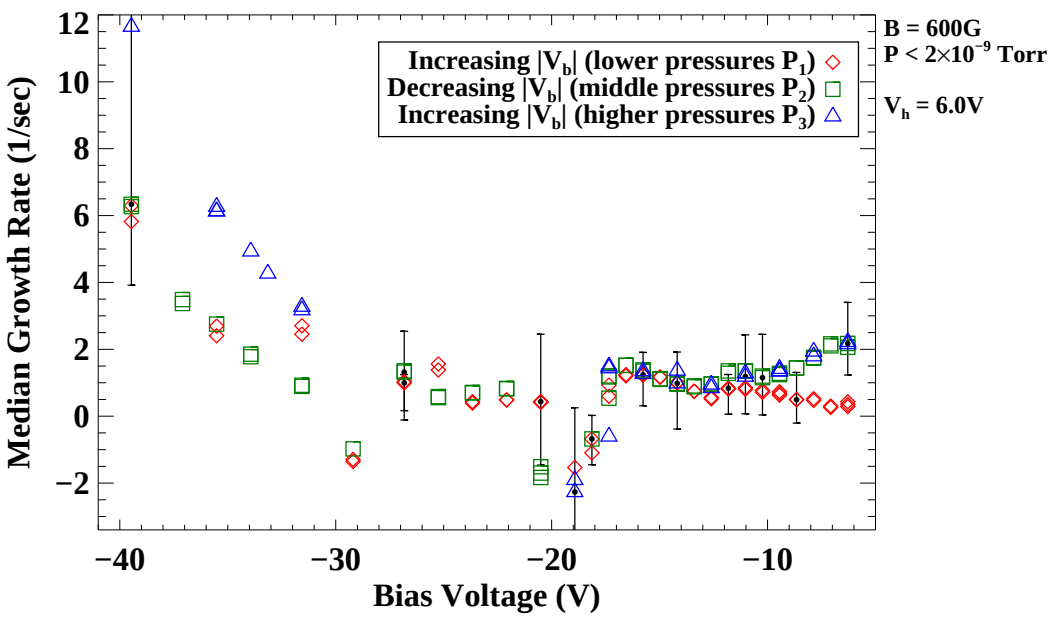
Diocotron Mode Sensitivity to Filament Voltages



(a) Median Growth Rate vs. Filament Heating Voltage



(b) Median Growth Rate vs. Filament Bias Voltage

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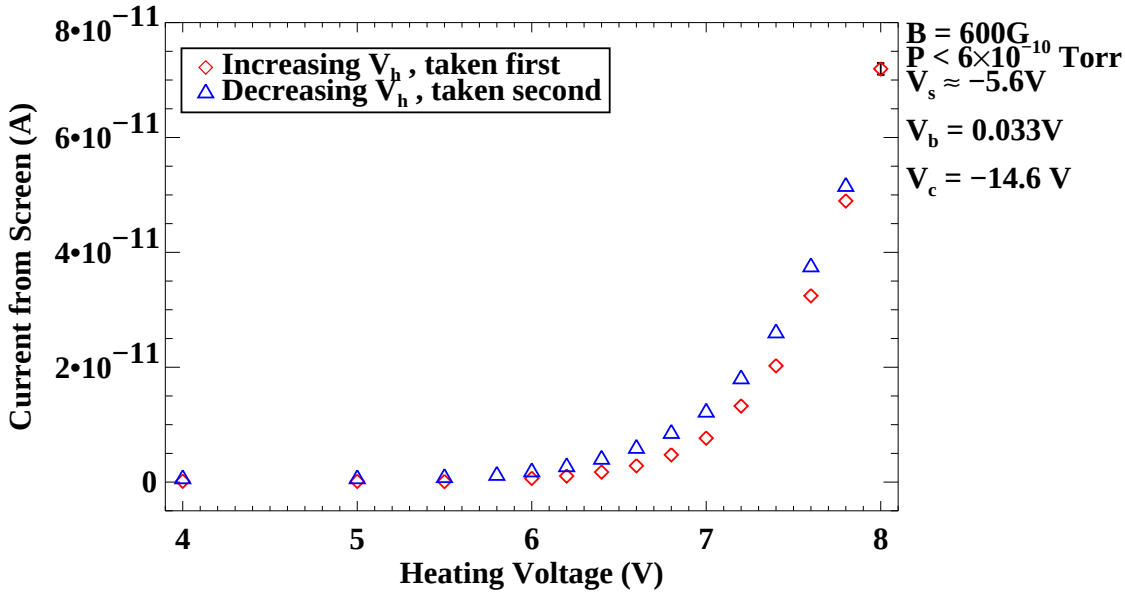
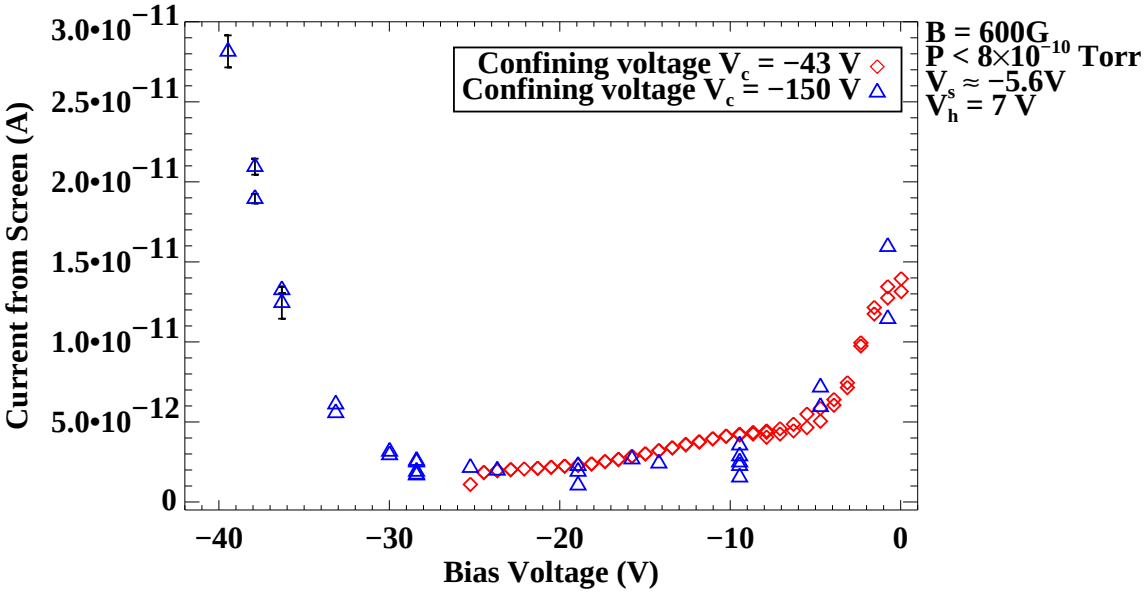
Ion Current Dependence on Filament Voltages



(a) Ion current vs. Filament Heating Voltage



(b) Ion current vs. Filament Bias Voltage

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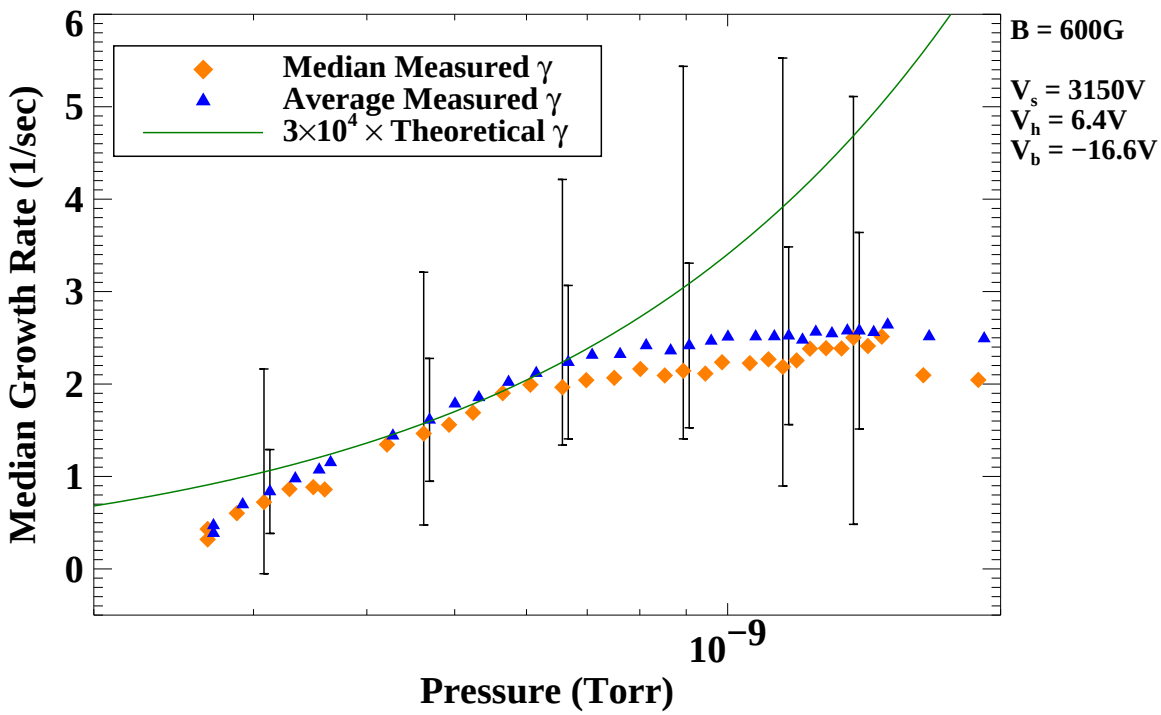
Diocotron Mode Sensitivity to Pressure



- The changing background pressure at filament conditions where the mode is clearly growing produces a different pressure dependence than before.

- Differences in mode growth are evident for changes in pressure as small as $\Delta P \approx 2 \times 10^{-10}$ Torr.

- The growth rate is relatively constant from $P \sim 1 \times 10^{-9}$ Torr to $P \sim 1 \times 10^{-8}$ Torr for the data we've taken.

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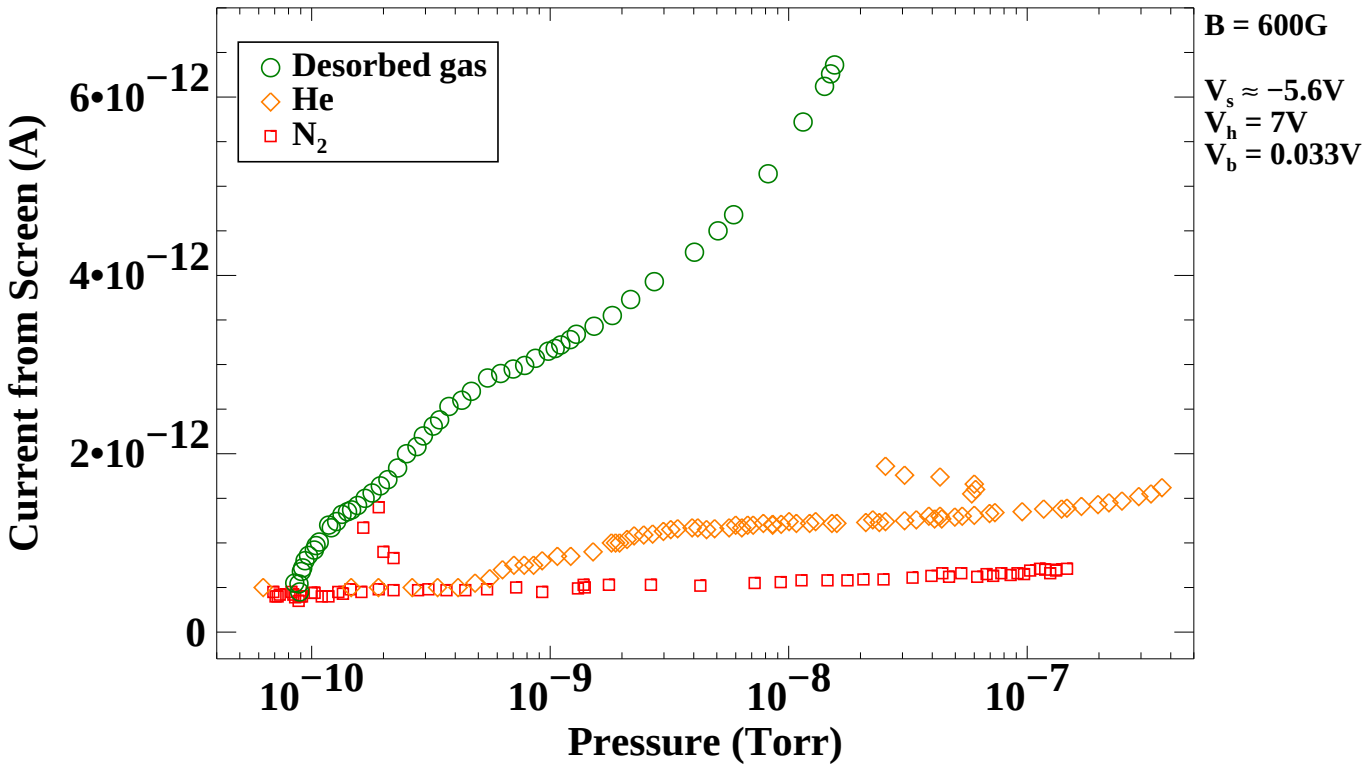
Ion Current Dependence on Pressure



- "Transiting" ions can be created by electron impact with background gas molecules, in which case both the number of ions and the mode growth rate should be proportional to the background gas pressure.

- These measurements show that the ion production mechanism is much less efficient for helium or nitrogen gas than it is for the gas desorbed from the trap surfaces.

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Summary

- The extended plasma expansion rate data shows that the rate's dependence on background gas pressure is consistent with the predictions of a fluid model at pressures above $\sim 3 \times 10^{-7}$ Torr.
- The on-axis parallel temperature evolution and mean-square radius evolution measured with the new temperature and density diagnostics suggest that the EDG plasma takes a few seconds to reach thermal quasi-equilibrium.
- The measurements of the temperature and mean-square radius evolution at late times indicate that the plasma is indeed losing energy then, presumably through inelastic collisions with trace background gases.
- The diocotron mode growth rate at high filament heating voltages is observed to be more sensitive to filament conditions and background pressure than the Ions flowing into the trap from the filament assembly are suspected to be the cause of the mode growth and to be responsible for the mode's pressure and filament voltage dependences.

This presentation,

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by

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

is available at

http://w3.pppl.gov/∼kmorriso/storage/k.fpoe.talk.2.pdf

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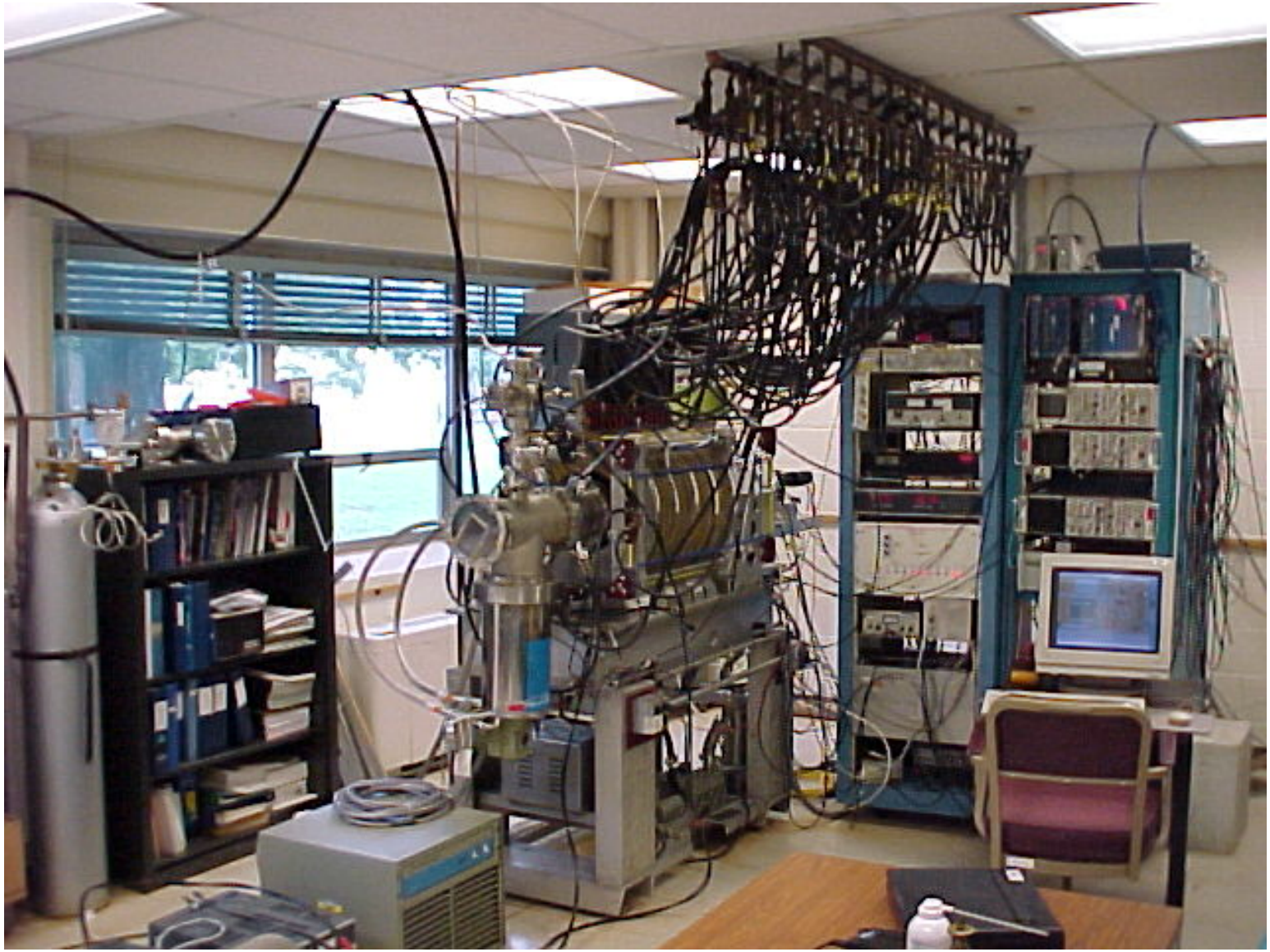
EDG facility



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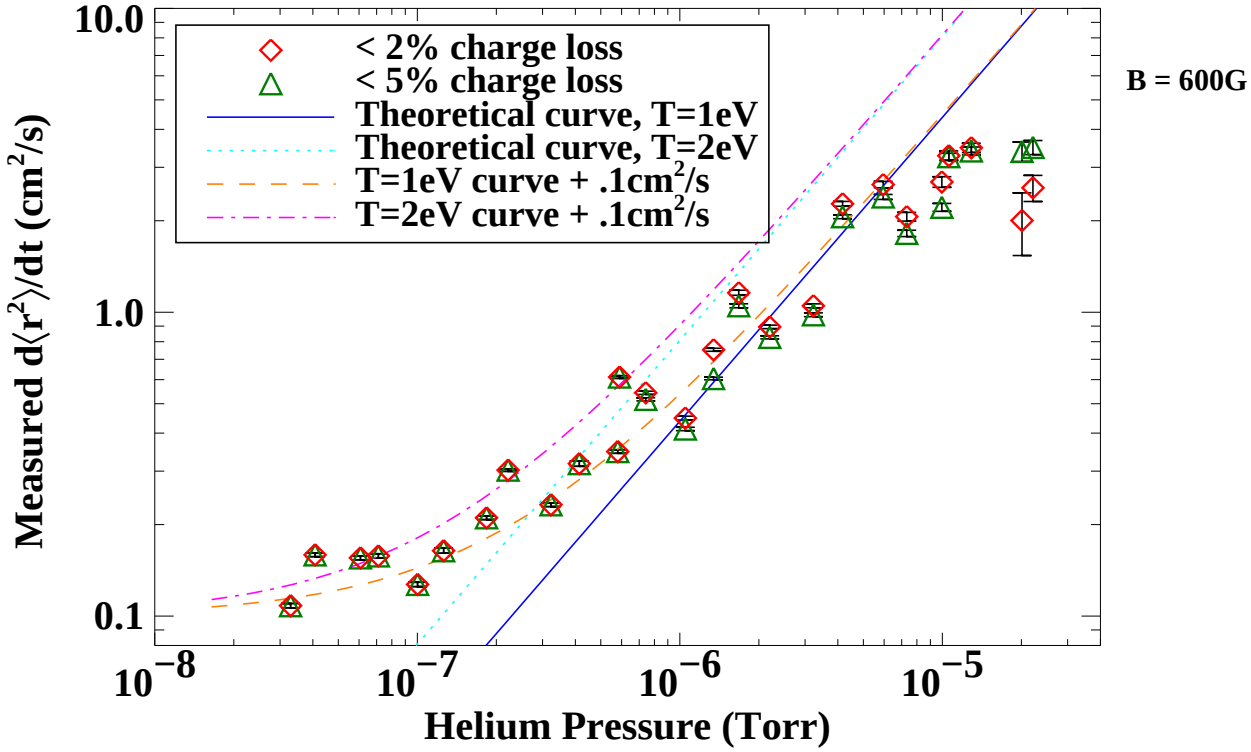
Expansion Rate Scaling with Pressure (small filament, 600 G)



- The approximately linear dependence with pressure is also exhibited by smaller plasmas (made with a 0.25-inch-radius filament).

- This data indicates that plasma-wall interactions have a negligible impact on the expansion rate scaling measured.

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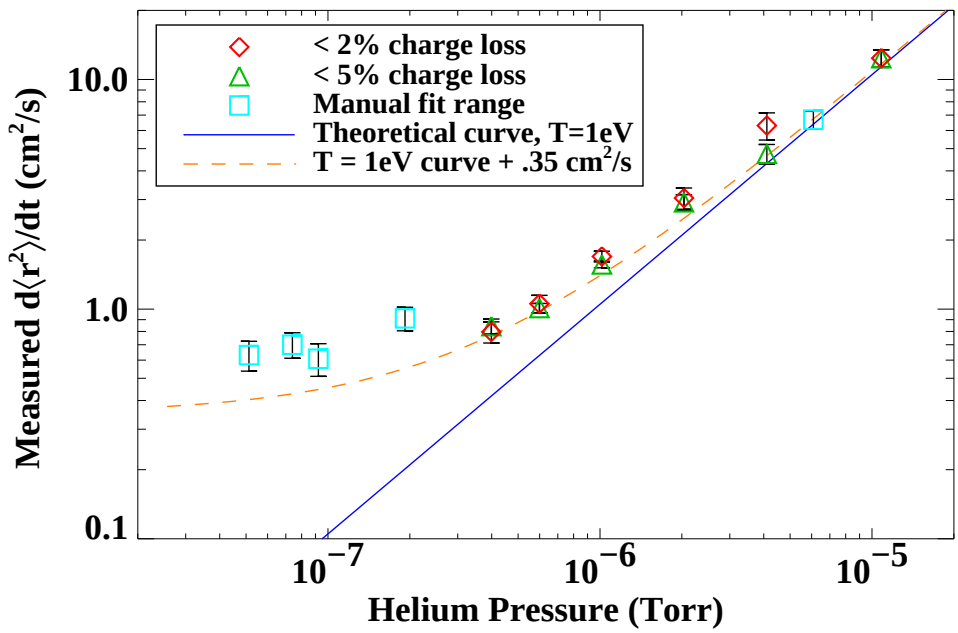
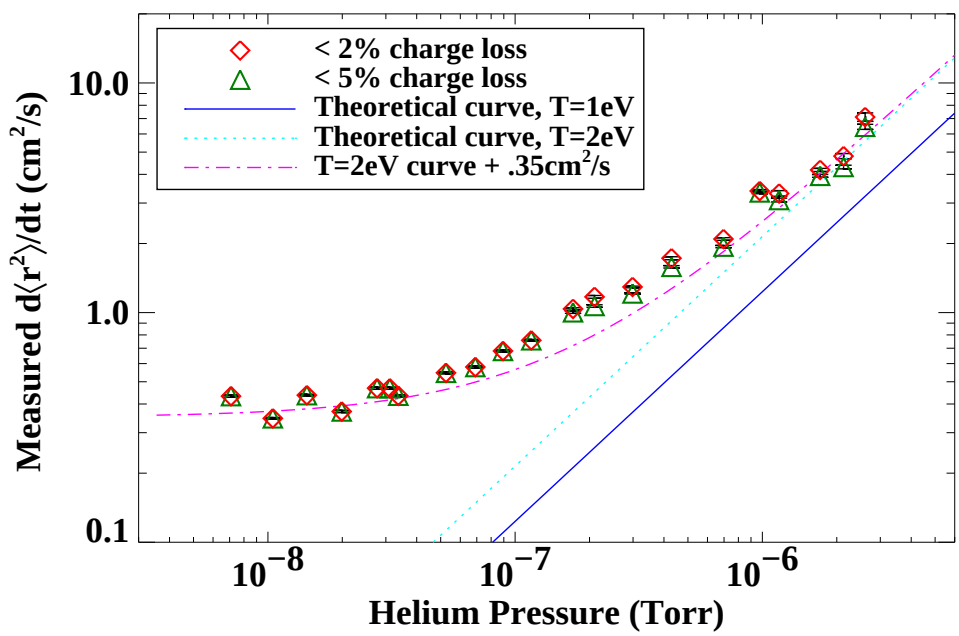
Expansion Rate Scaling with Pressure (300 G)



(a) Large filament.



(b) Small filament.

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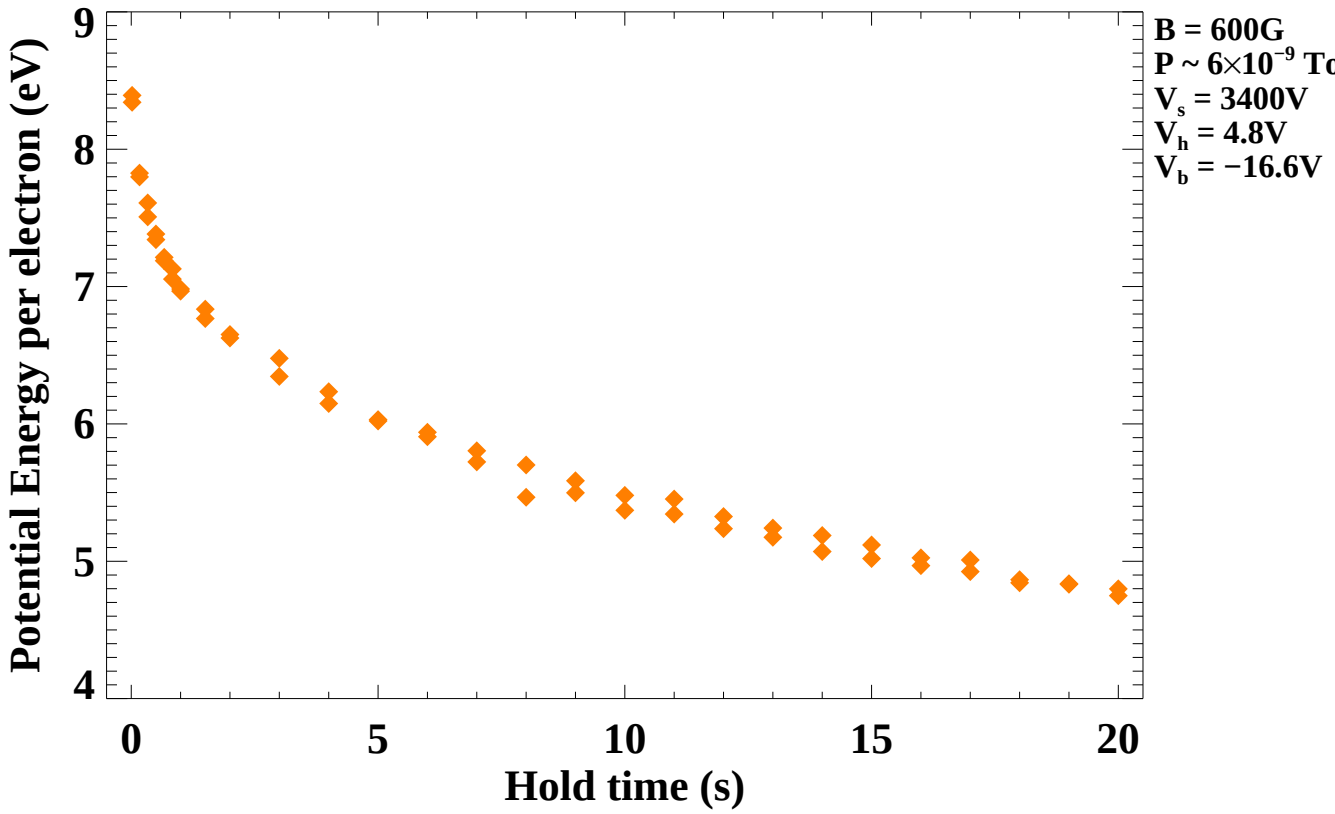

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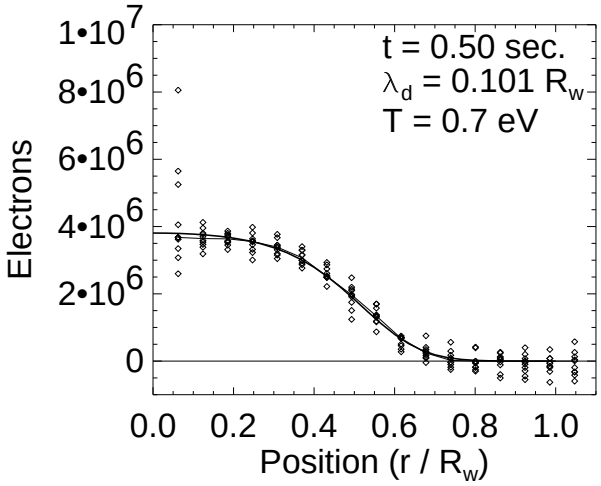
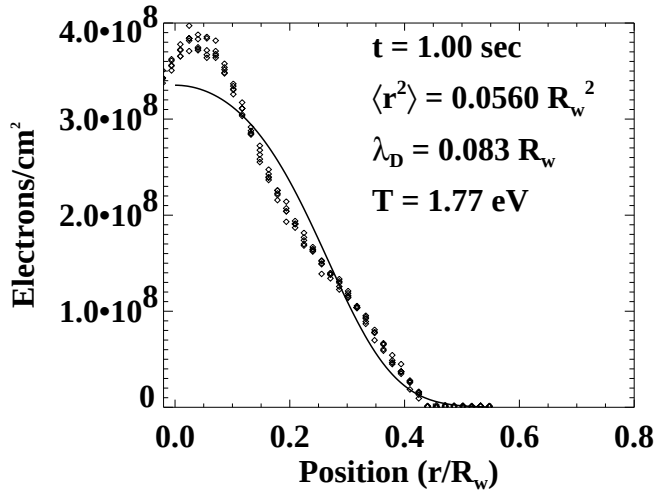
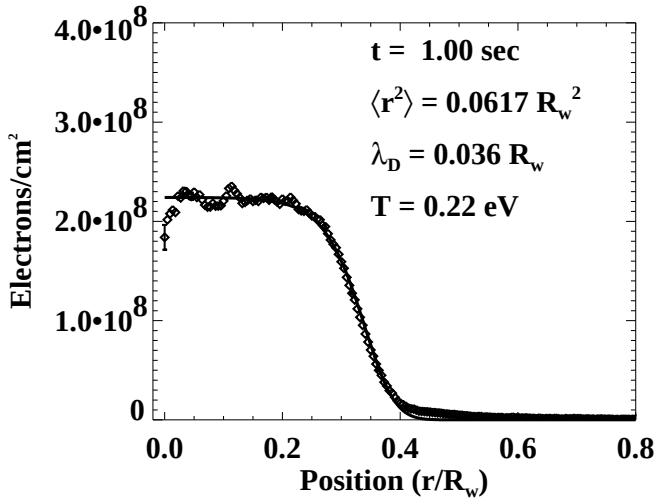
Comparison of density profiles



(a) Faraday-cup-derived profile (large filament).



(b) Faraday-cup-derived profile (small filament).



(c) Image-derived profile.

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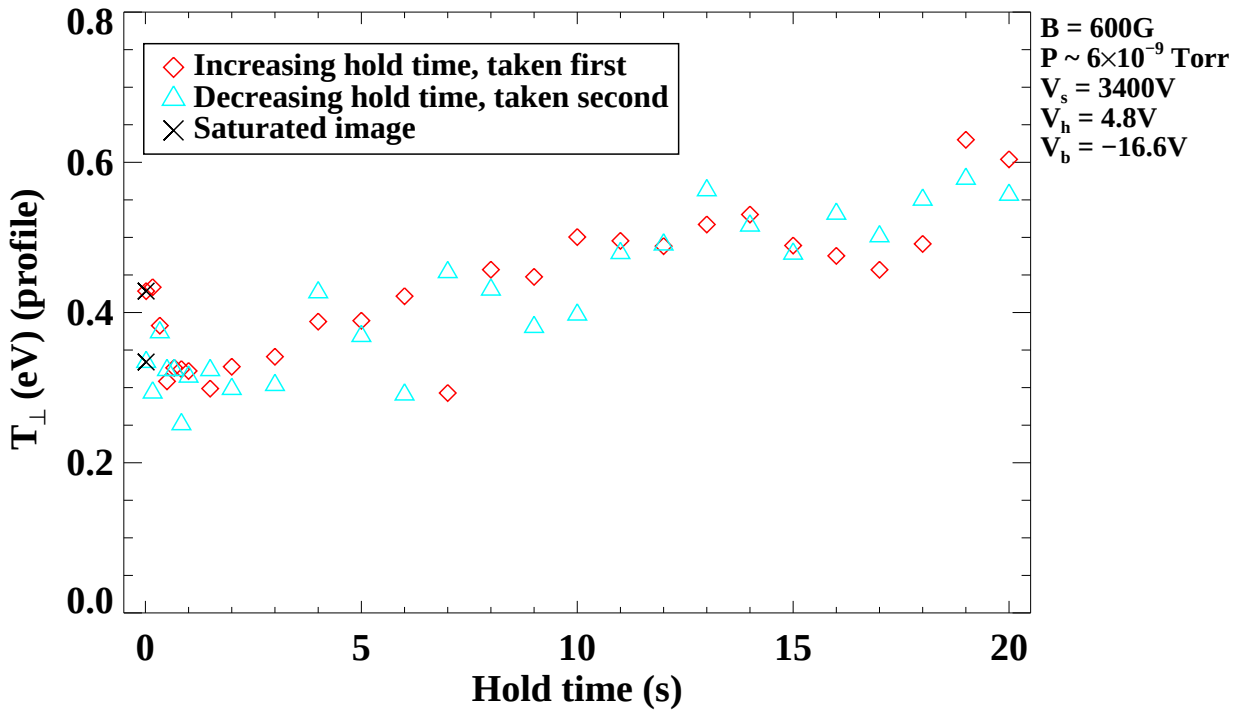
Inferred Temperature Data (small filament, P=6×10^{-9} Torr)



- 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.

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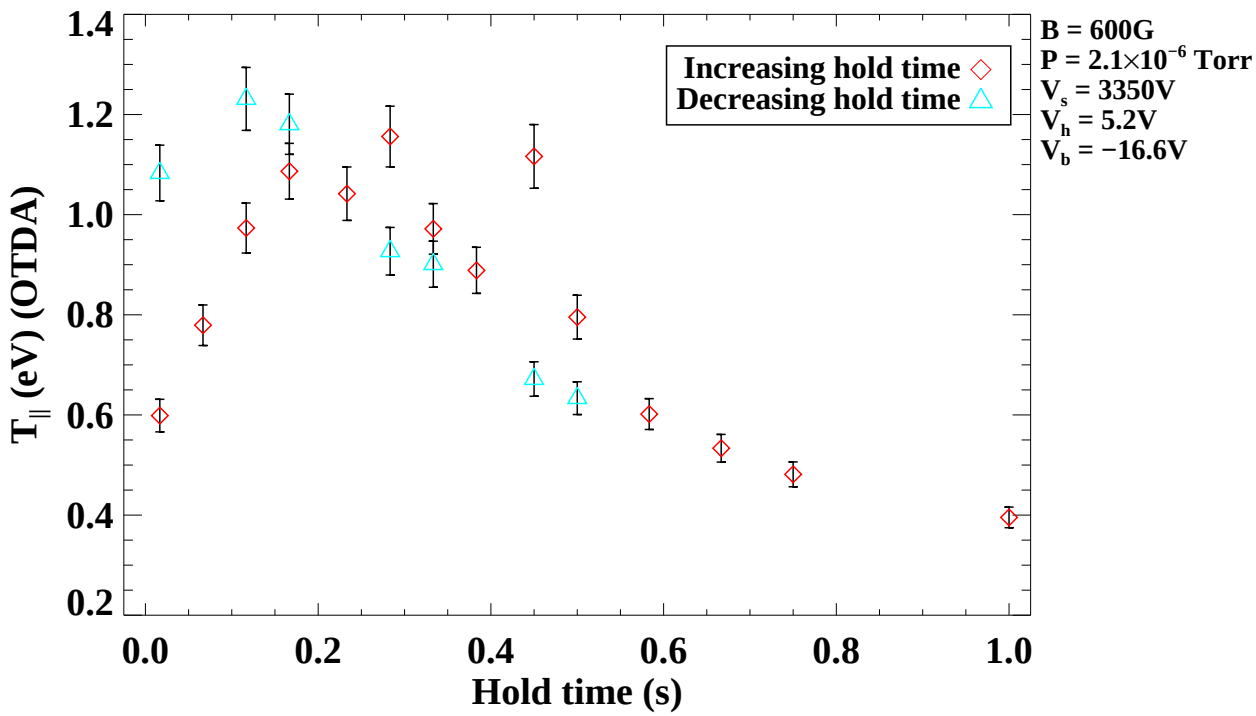
On-Axis Temperature Diagnostic Data (small filament, P=2×10^{-6} Torr)



- At higher pressure, the plasma reaches 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.

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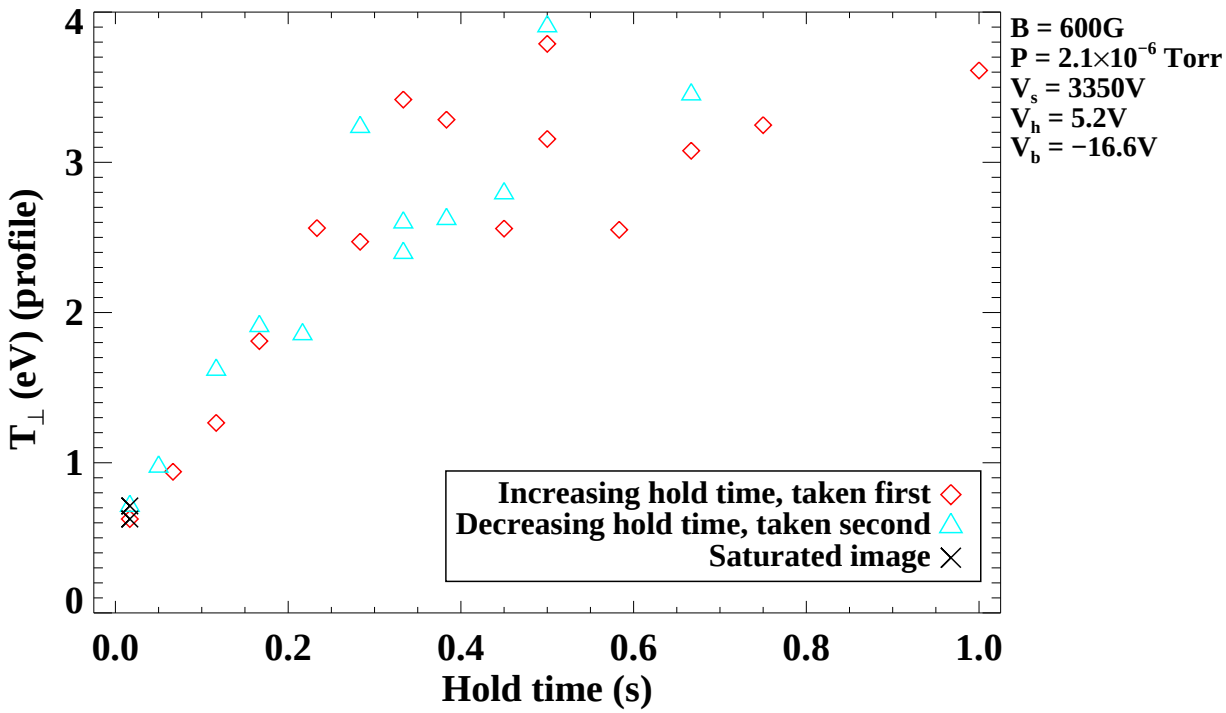
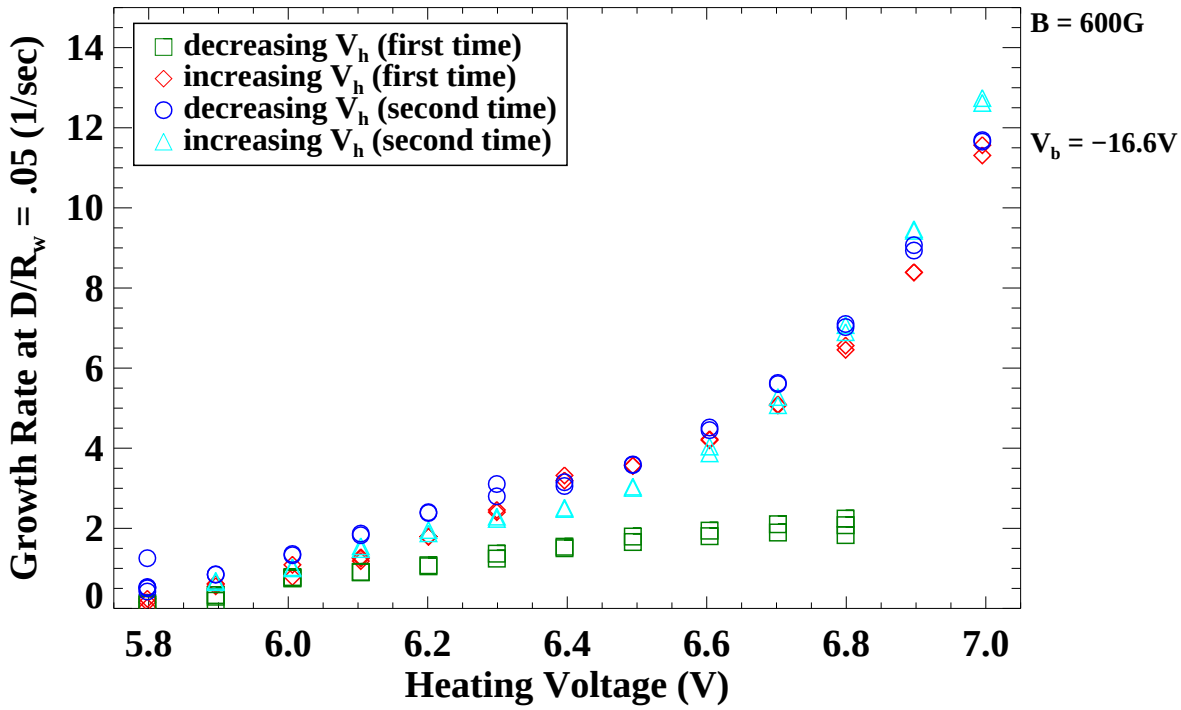
Inferred Temperature Data (small filament, P=2×10^{-6} Torr)



- 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.

Diocotron Mode Sensitivity to Filament Heating Voltage



- The growth rate of the $m = 1$ diocotron mode increases with filament heating voltage (at V_b = -16.6V). This behavior is observed at several different bias voltages.

- During the course of this scan, the vessel pressure increased; the data denoted by the green squares was taken first (when P$\sim 1 \times 10^{-10}$ Torr) and the rest of the data was taking at somewhat higher pressures (P$\sim 8 \times 10^{-10}$ Torr).

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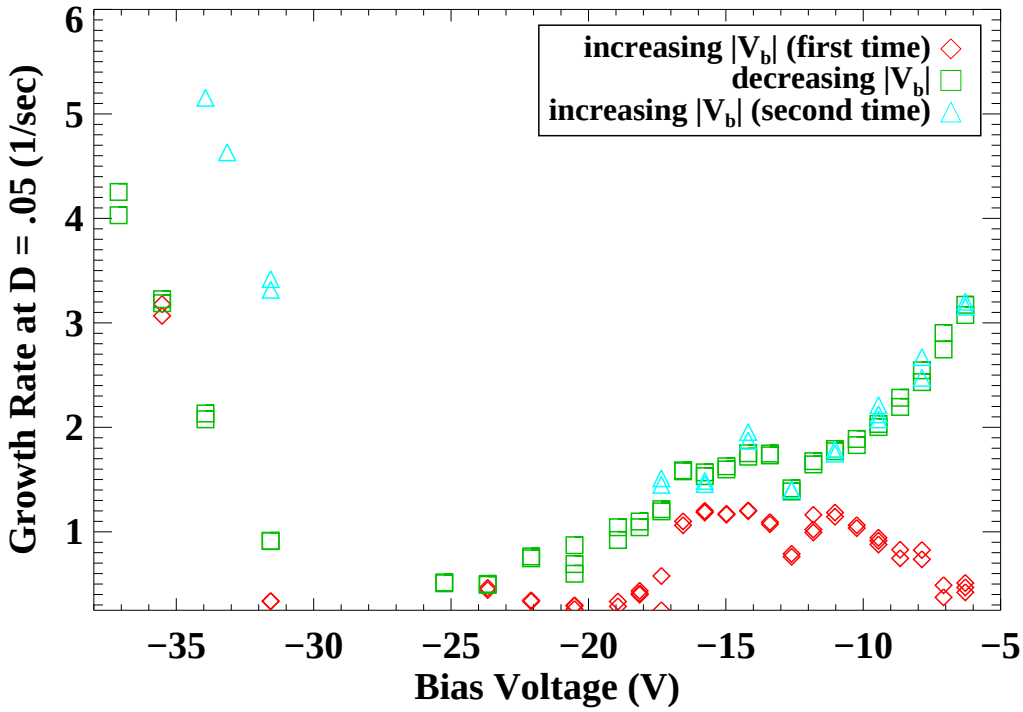
Diocotron Mode Sensitivity to Filament Bias Voltage



- The growth rate of the $m = 1$ diocotron mode exhibits a complex dependence on filament bias voltage ($V_h = 6V$). Similar behavior is observed at several different values of heating voltage.

- Again, during the course of this scan, the background pressure increased. The growth rates for mode evolutions early in the dataset (red diamonds) are lower than those for the subsequent data.

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