

The Effects of Ambient Neutral Gas Molecules on the Evolution of the EDG Pure Electron Plasma.

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Research supported by the Office of Naval Research,
and in part by the Department of Energy.

Outline

- EDG Device
- Measurements of Plasma Expansion
- Inferred Temperatures and On-Axis Temperature Measurements
- Measurements of the $m = 1$ Diocotron Mode Evolution

Studying Non-neutral Plasmas

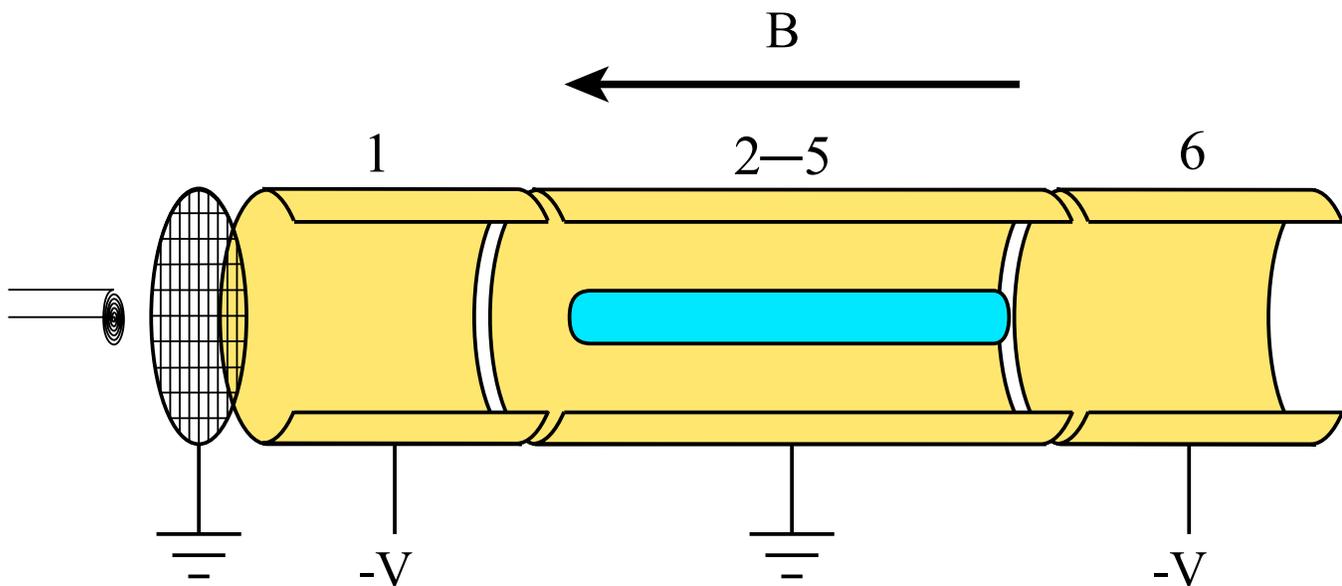
Non-neutral plasma physics is important for describing

- 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

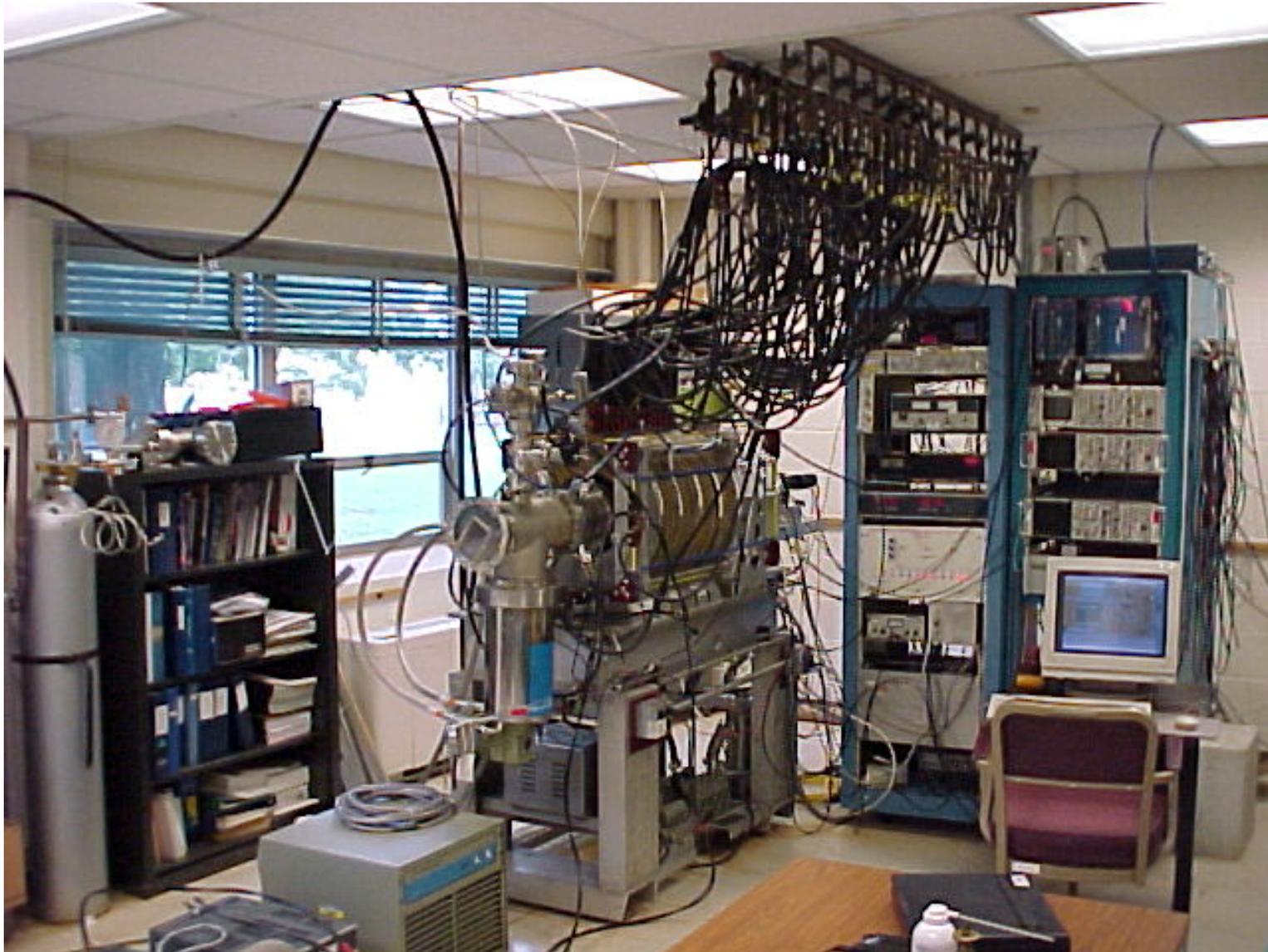
- Atomic clocks,
- Positron and antiproton recombination,
- Modeling inviscid 2-D fluids,
- Studies of the basic processes of transport across magnetic fields.

Malmberg-Penning Trap Geometry

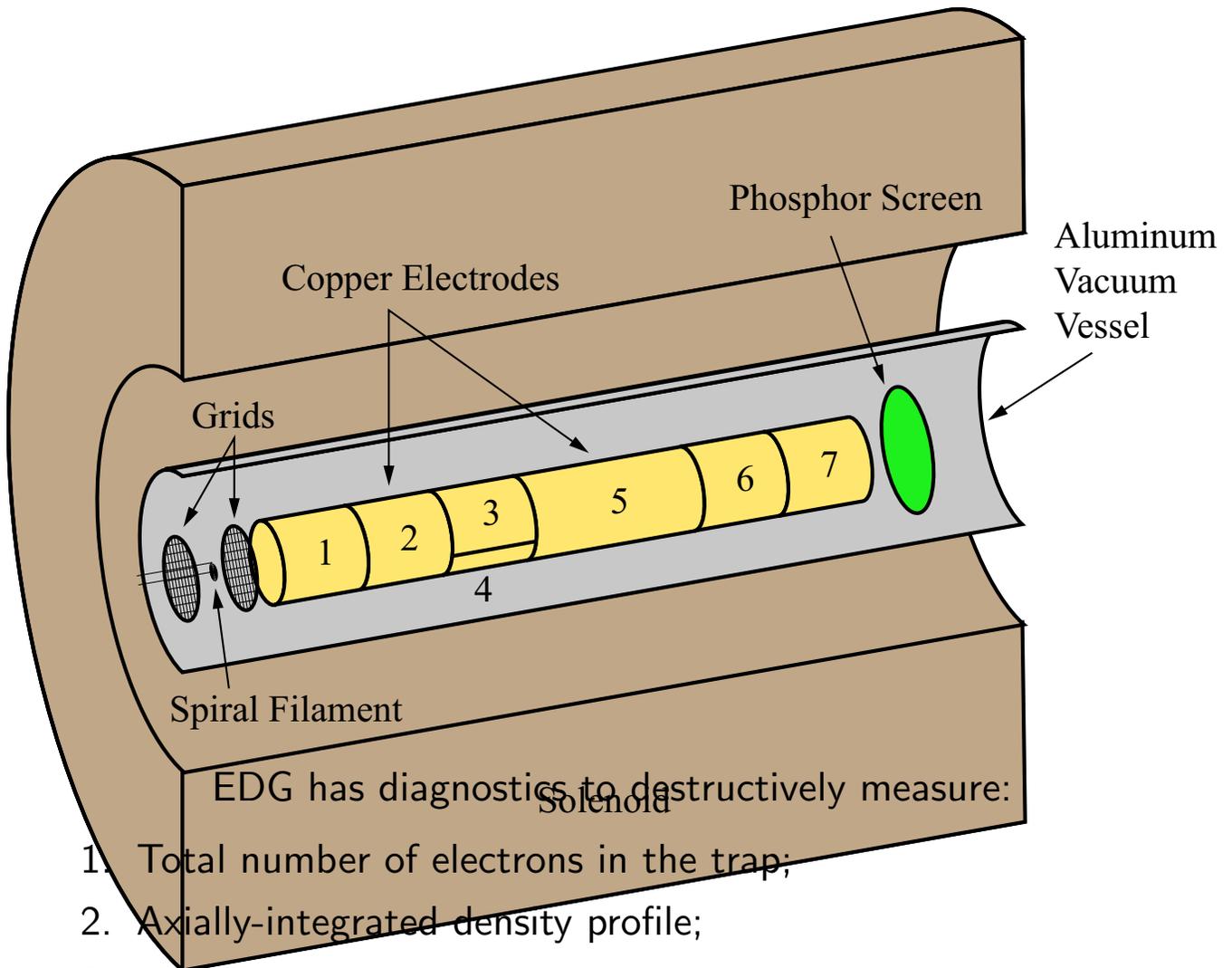


- Malmberg-Penning traps are cylindrically symmetric.
- A uniform, axial magnetic field confines particles radially.
- Non-adjacent cylindrical electrodes are biased to confine particles axially.
- Malmberg-Penning traps confine particles with the same charge sign (e.g., $^{24}\text{Mg}^+$ and $^{24}\text{Mg}^{2+}$)

EDG facility



Schematic of the EDG device



and non-destructively measure:

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

Typical Plasma Parameters

P	=	$1 \times 10^{-10} - 1 \times 10^{-5}$ 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}	=	$0.15 - 1.5 \times 10^4$ Hz
ρ_L	=	0.04 mm
λ_D	=	2.1 cm
$R_{\text{coll. hole}}$	=	1.6 mm
R_w	=	2.54 cm

Malmberg-Penning Trap Confinement

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

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

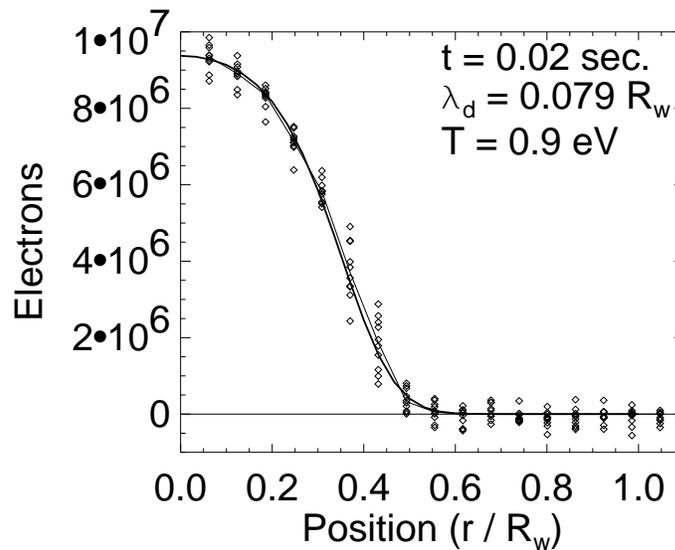
⇒ In the absence of external influences, the plasma is extremely well-confined.

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

$$\Delta P_\phi \approx \frac{q B_0}{2c} \Delta \left(\sum_j r_j^2 \right)$$

Theoretical Prediction

Fluid Theory predicts expanding Quasi-Equilibrium Profiles.



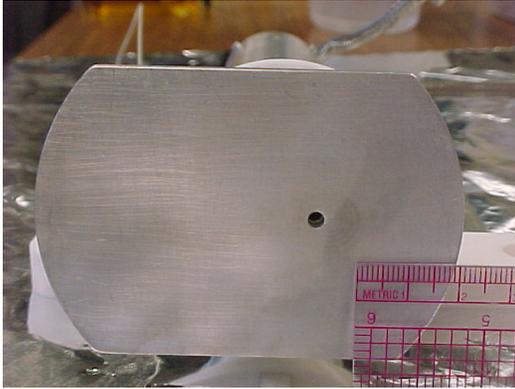
For isothermal electrons [Davidson and Moore 1996],

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

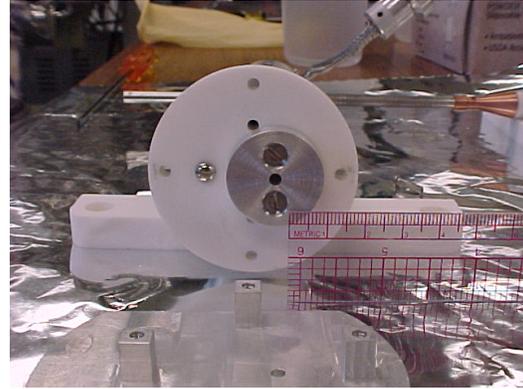
where

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

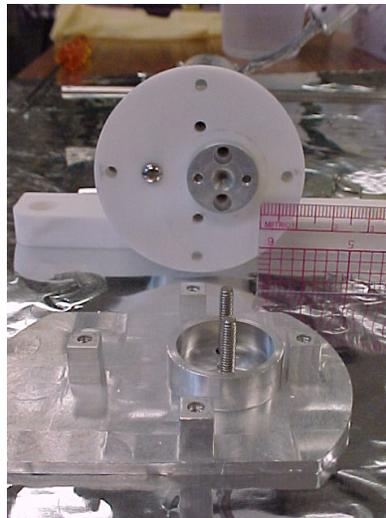
Radially-Scanning Faraday Cup Density Diagnostic Electrodes



(a) Total collector.



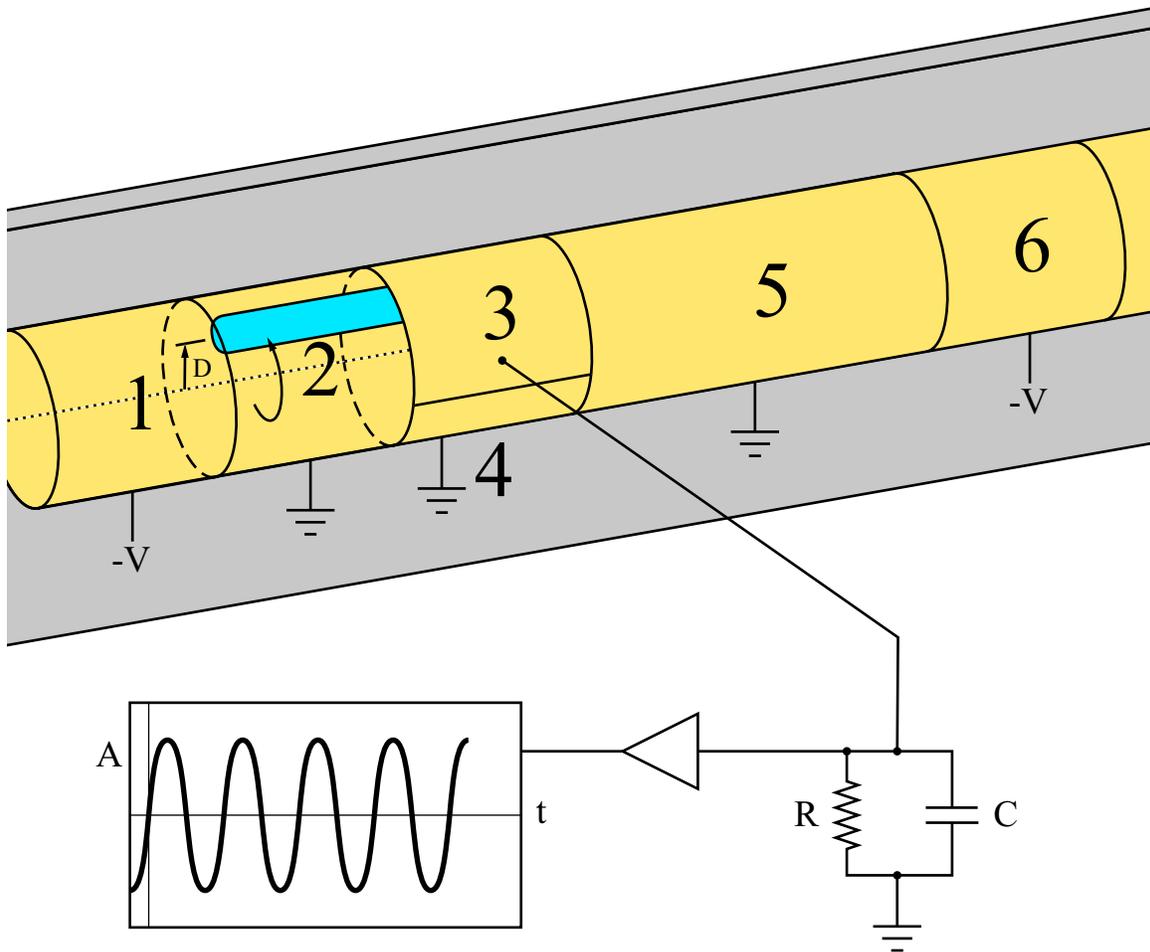
(b) Capacitive shield.



(c) Local collector.

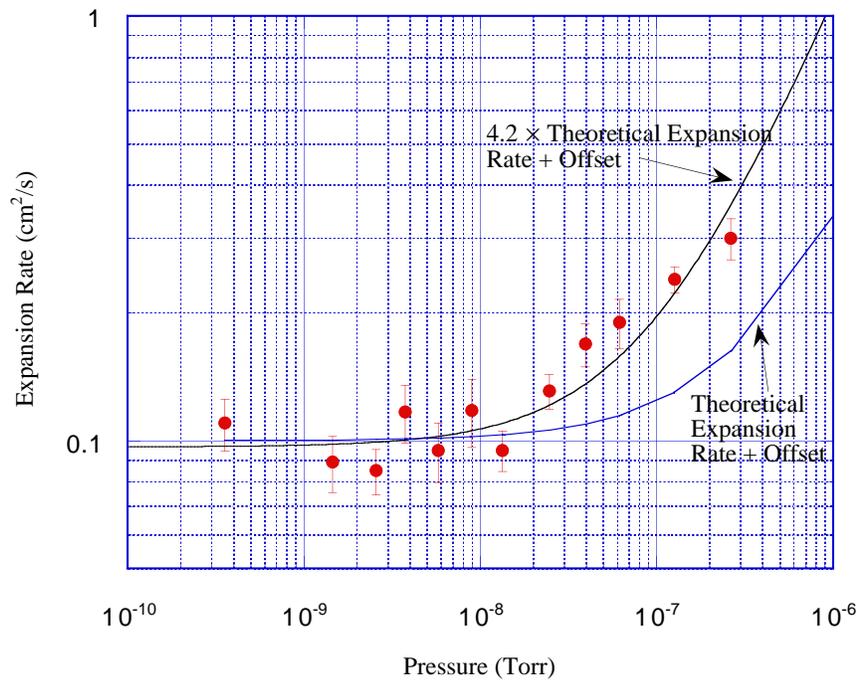
- The local collector collects electrons from magnetic field lines that pass through the 1/8"-diameter holes in the total collector and capacitive shield.

Schematic of $m = 1$ Diocotron Mode Diagnostic

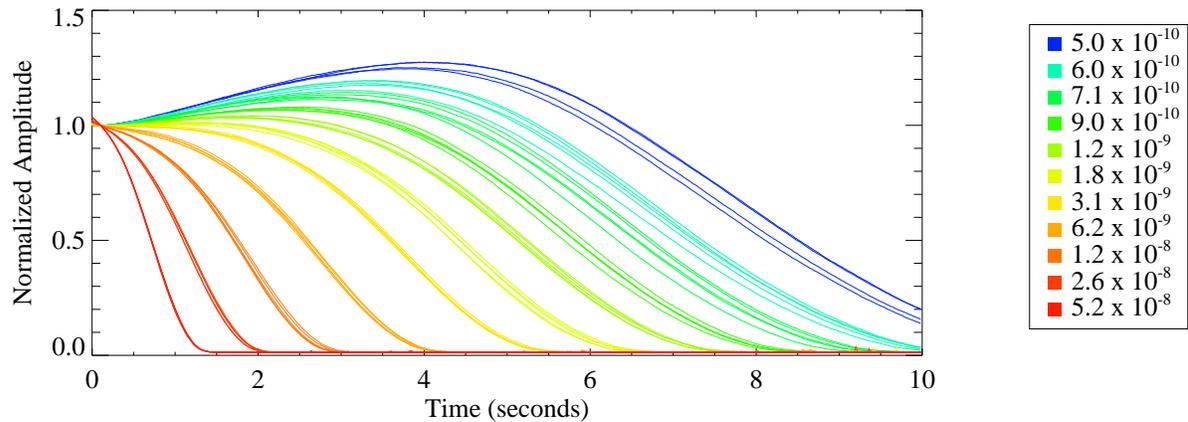


- The $m = 1$ diocotron mode has $k_z \approx 0$, and is analogous to a radial displacement of the plasma.
- An azimuthally-discontinuous electrode segment draws current when the charged plasma passes by, and this current is measured to record the mode evolution.

Preliminary results from EDG

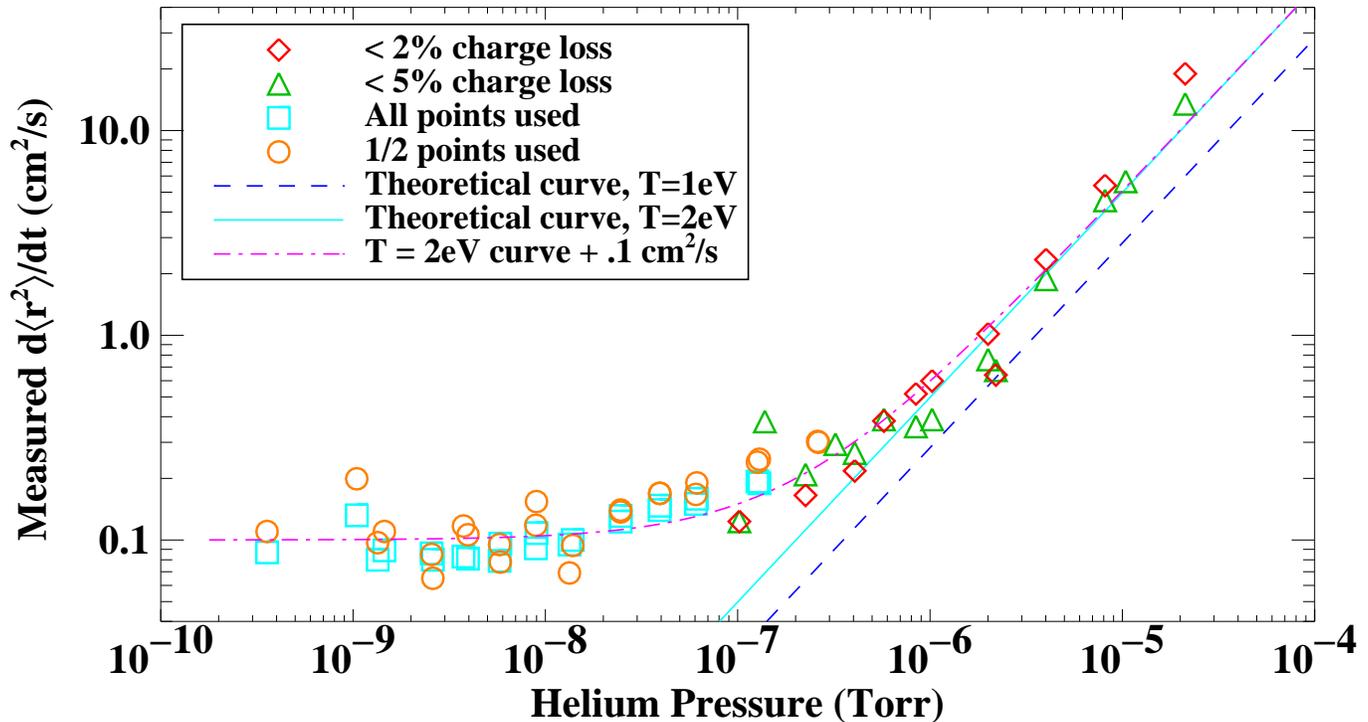


(a) Change in $\frac{d\langle r^2 \rangle}{dt}$ with background gas pressure.



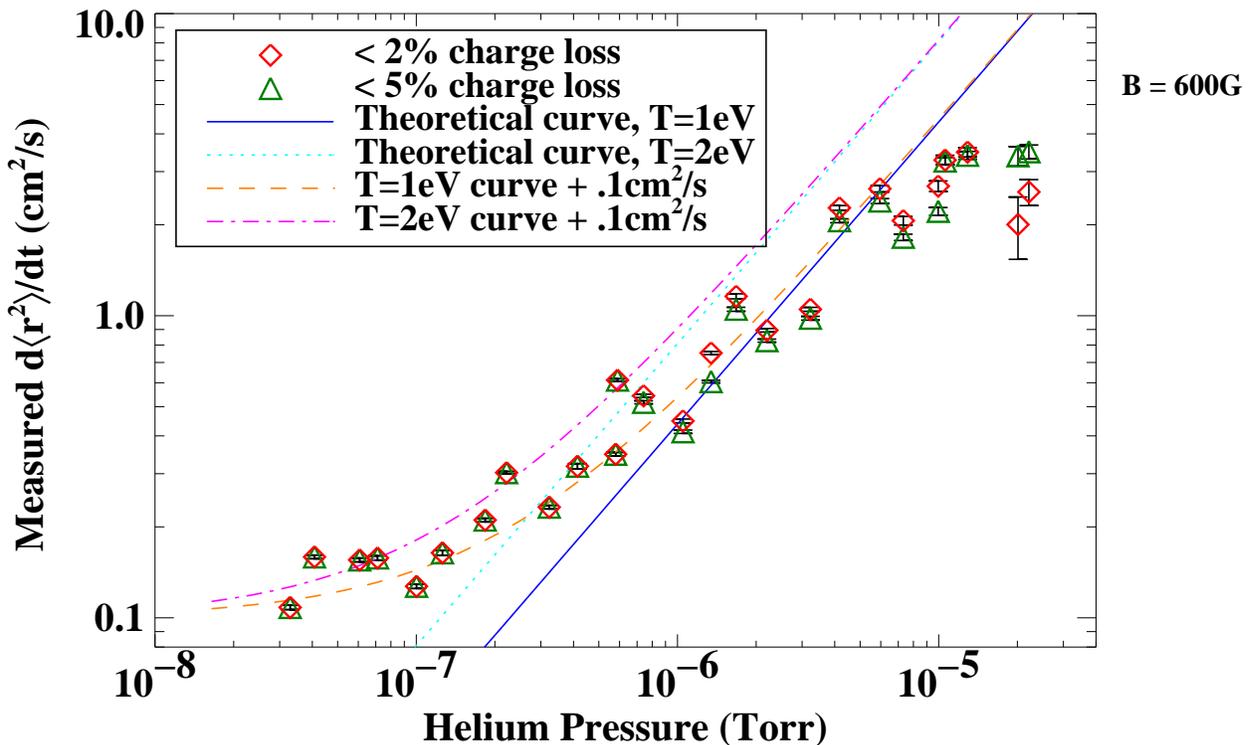
(b) Amplitude evolution of the $m = 1$ diocotron mode.

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



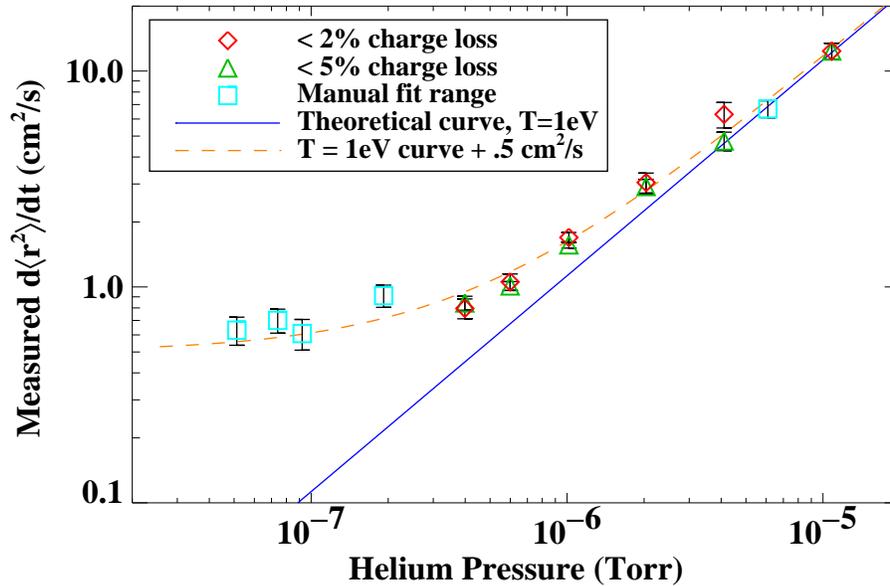
- The plasma's expansion rate should scale linearly with pressure for plasmas expanding in quasi-equilibrium.
- An approximately linear dependence is seen at higher pressures than those tested previously.
- The measured expansion rate at lower pressures is dominated by a different process, which we expect is the relaxation of the plasma to global thermal quasi-equilibrium.

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

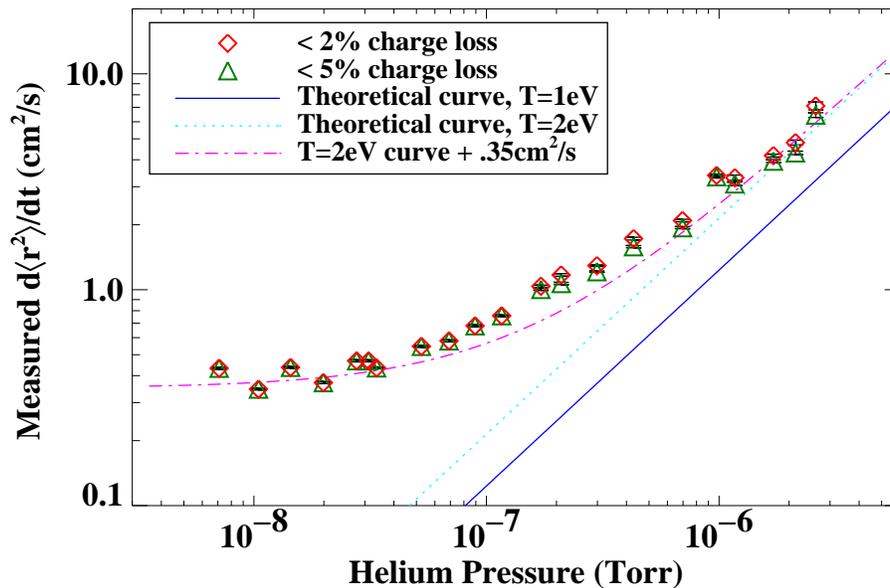


- The approximately linear dependence with pressure is also exhibited by smaller plasmas (made with a 0.25-inch-radius filament).
- This data indicates that plasma-wall interactions have a negligible impact on the expansion rate scaling measured.

Expansion Rate Scaling with Pressure (300 G)

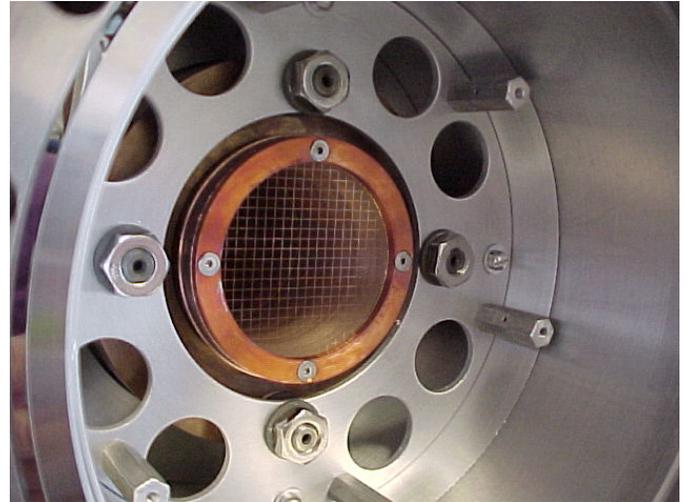
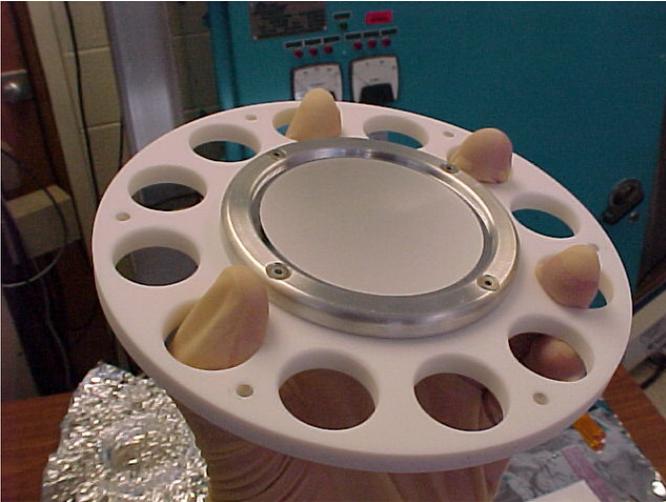


(a) Large filament.



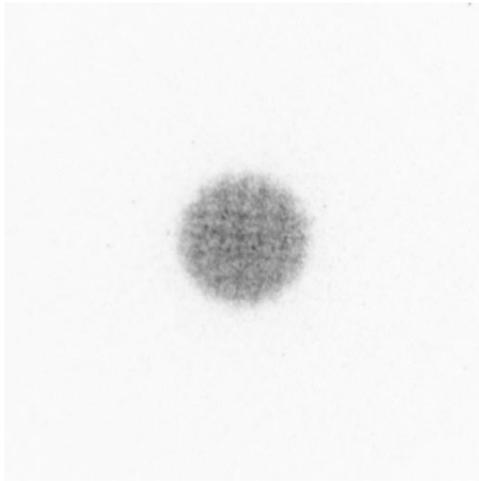
(b) Small filament.

Phosphor-Screen Density Diagnostic

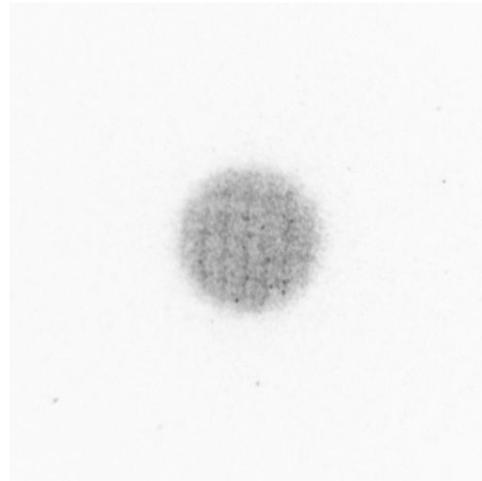


- A biased, aluminum-coated, P43 phosphor screen produces an image of the entire, axially integrated plasma when the plasma strikes it.
- A copper grid is clamped to the last, grounded trap electrode to give a more radially uniform accelerating electric field.
- A PULNiX TM-1010 CCD camera with an ITT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

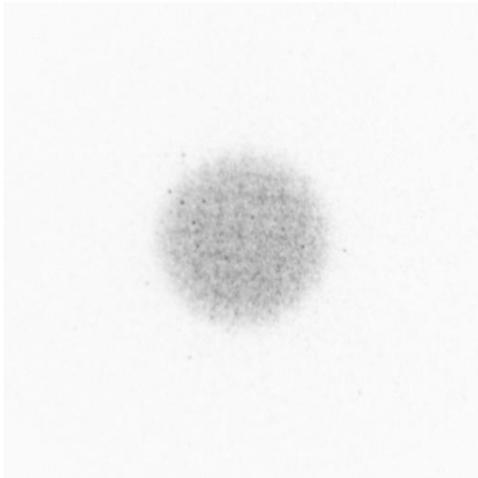
Density Diagnostic Images



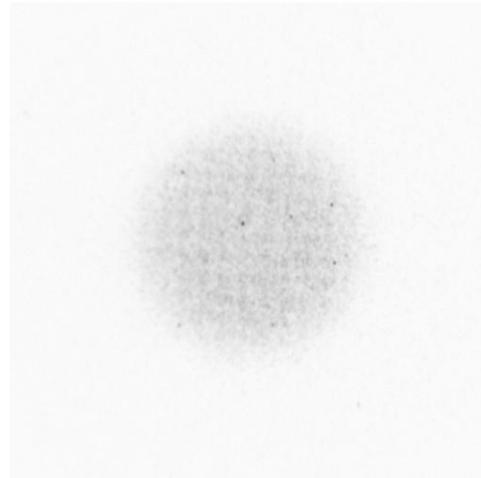
(a) Trapped for 1/3 s.



(b) Trapped for 1 s.



(c) Trapped for 3 s.

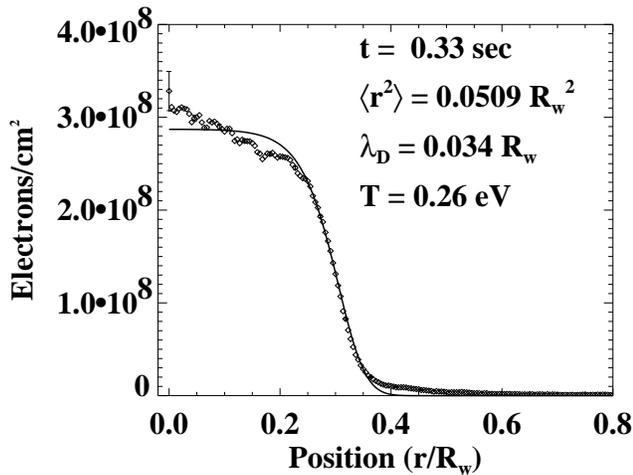


(d) Trapped for 15 s.

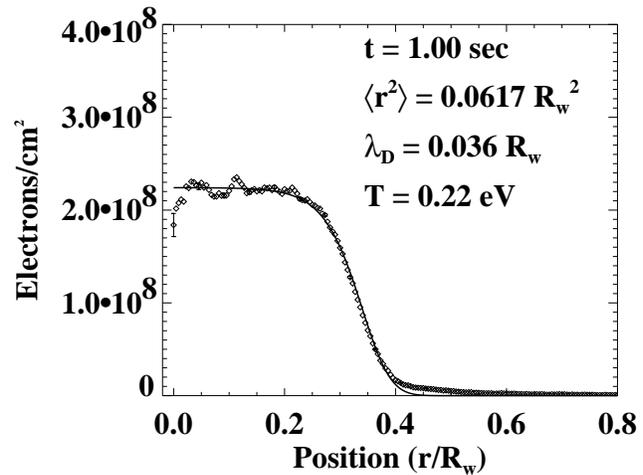
Raw images of expanding plasmas at $P \sim 6 \times 10^{-9}$ Torr.

- The hatched pattern in the images is due to focussing by the copper grid.
- The pattern is readily removed with a simple FFT mask.

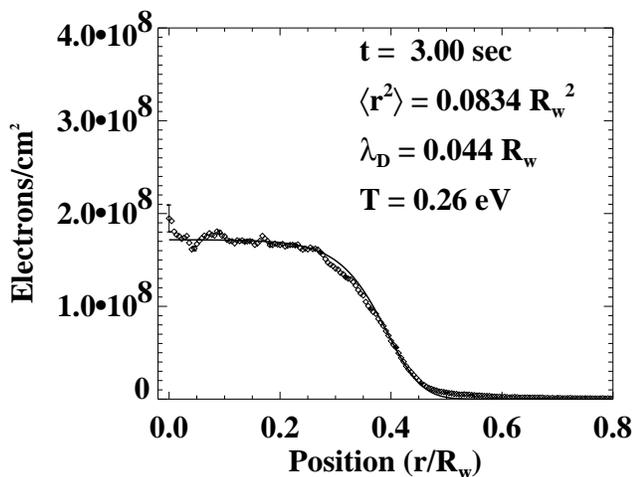
Density Profile Evolution in EDG



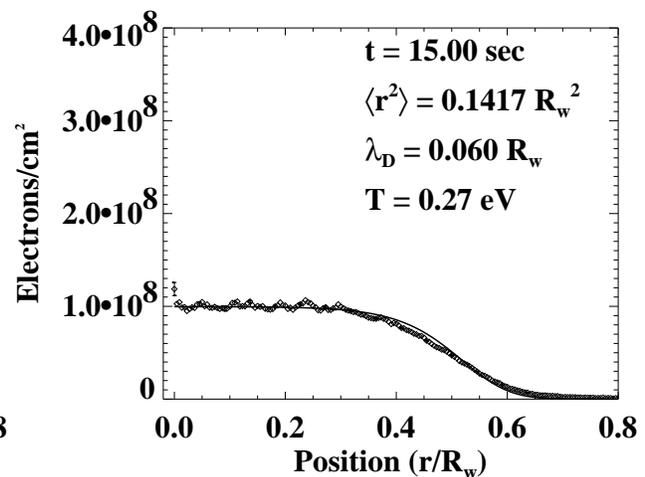
(a) 1/3 s.



(b) 1 s.



(c) 3 s.

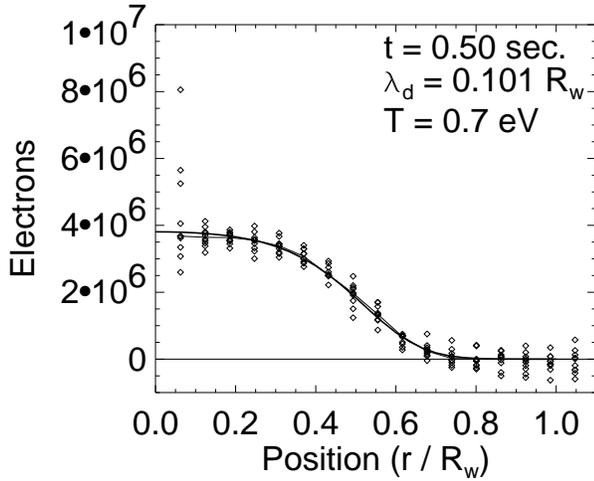


(d) 15 s.

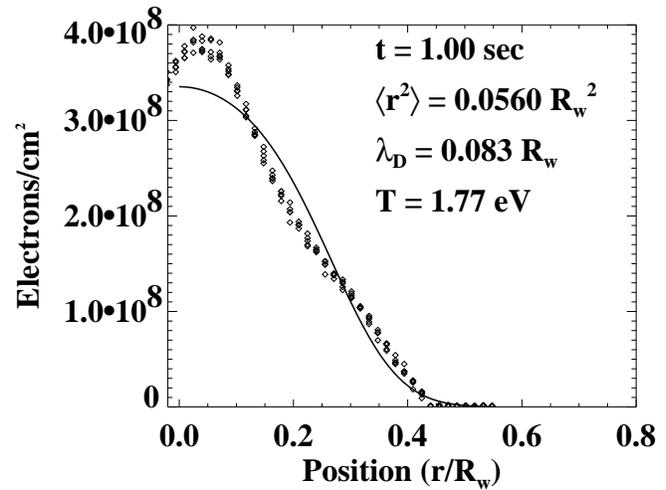
Evolution of density profiles at $P \sim 6 \times 10^{-9}$ Torr.

- The radial density profile is estimated by averaging the data values azimuthally around the centroid of the image.

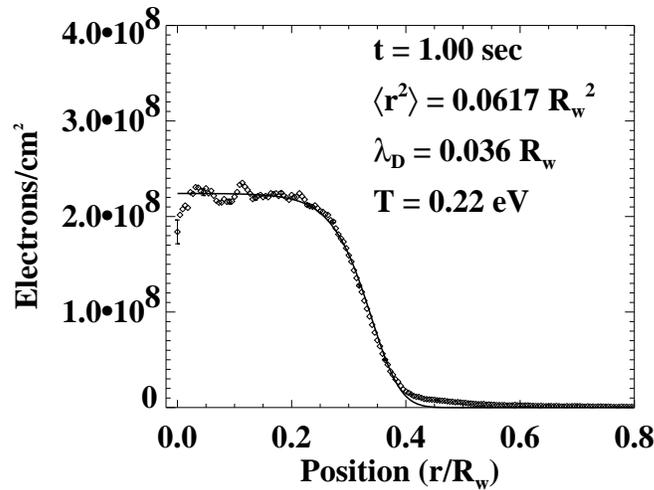
Comparison of density profiles.



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

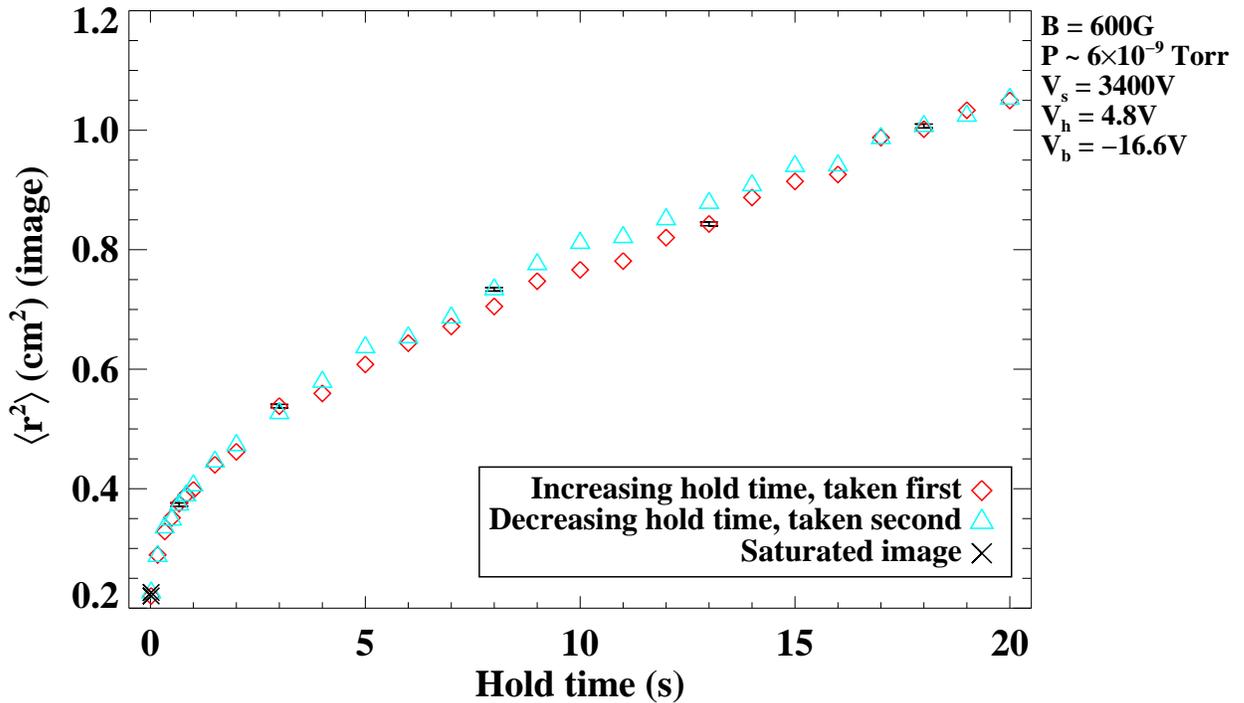


(b) Faraday-cup-derived profile (small filament).



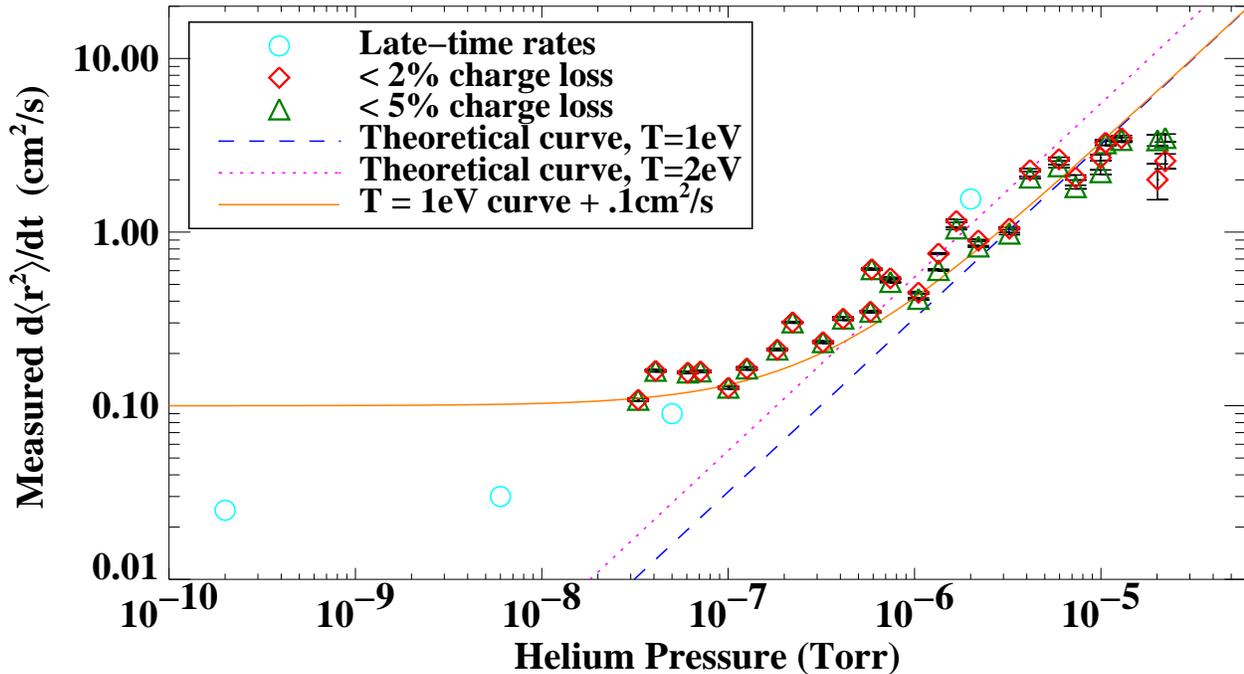
(c) Image-derived profile.

Plasma Expansion After 1 second ($P = 6 \times 10^{-9}$ 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 $P = 2 \times 10^{-7}$ Torr, and the rate agrees with that measured previously.

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

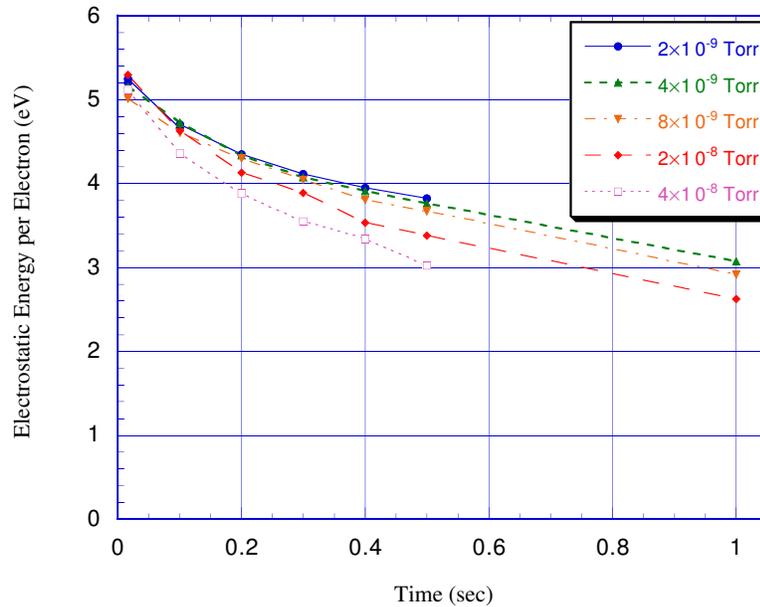


- The circles denote the new expansion rates computed by excluding the initial plasma relaxation (where possible).
- The expansion rates still level off at the lowest pressures, indicating that asymmetry-induced expansion is affecting the measurements.

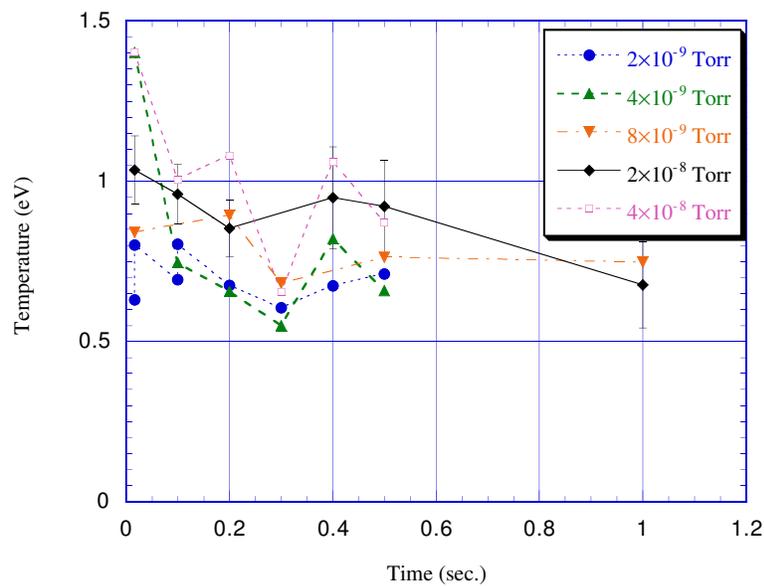
Expansion Rate Scaling Results

- 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 during the plasma's expansion.

Previous Energy Evolution (large filament)

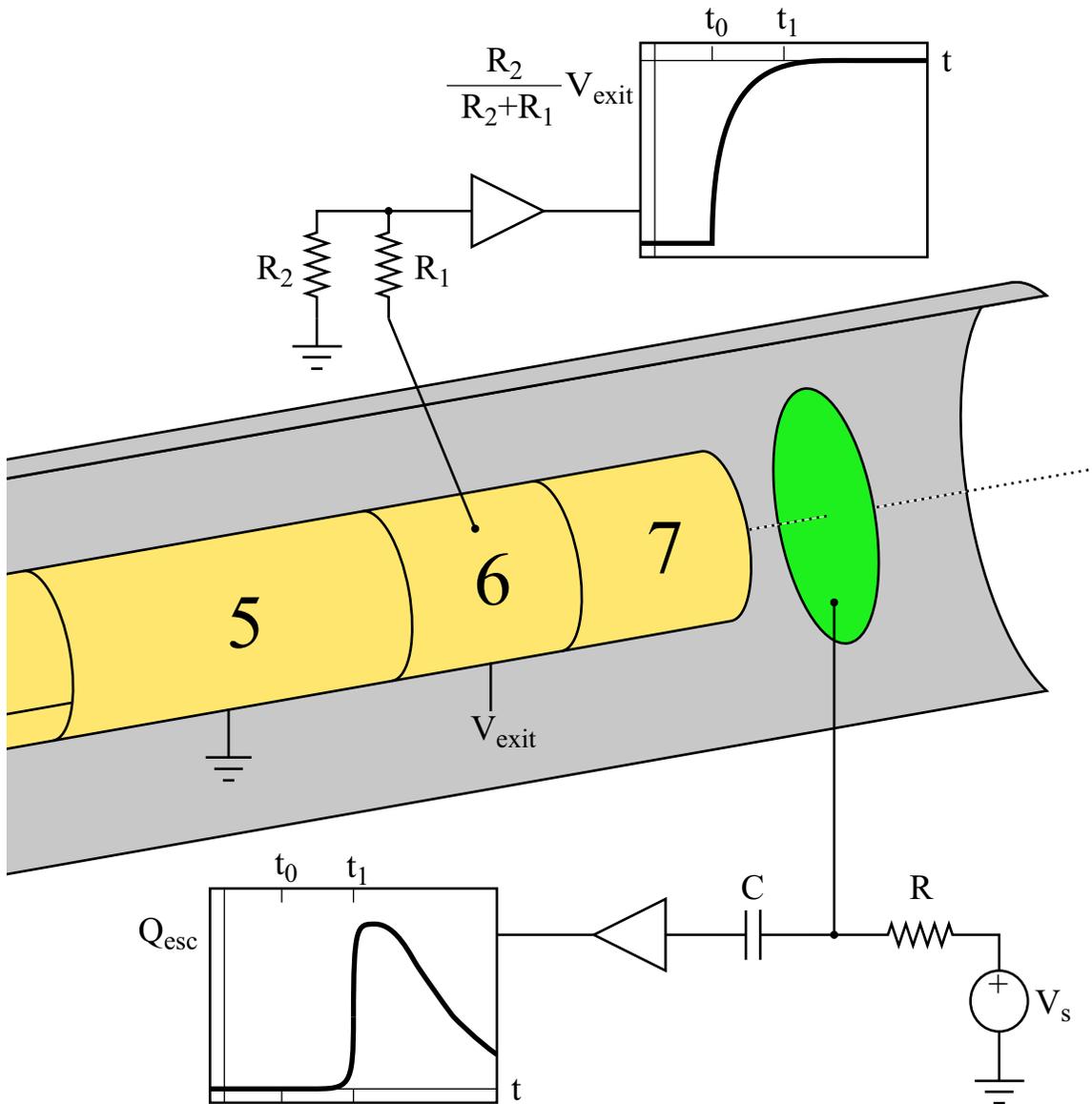


(a) Electrostatic potential energy.



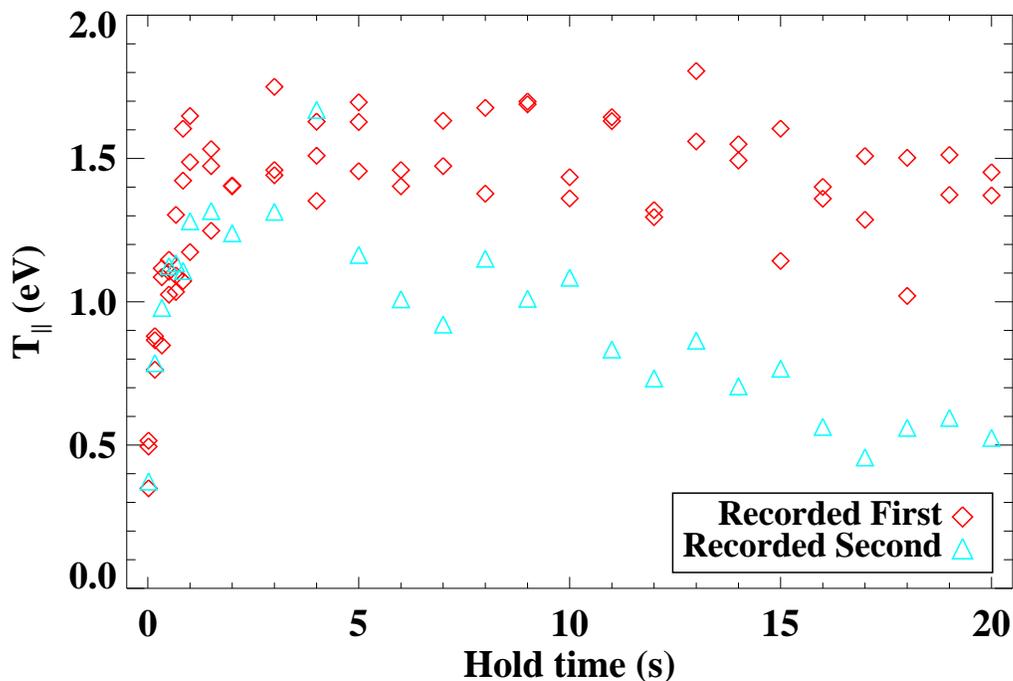
(b) Inferred perpendicular temperature.

T_{\parallel} Diagnostic Setup



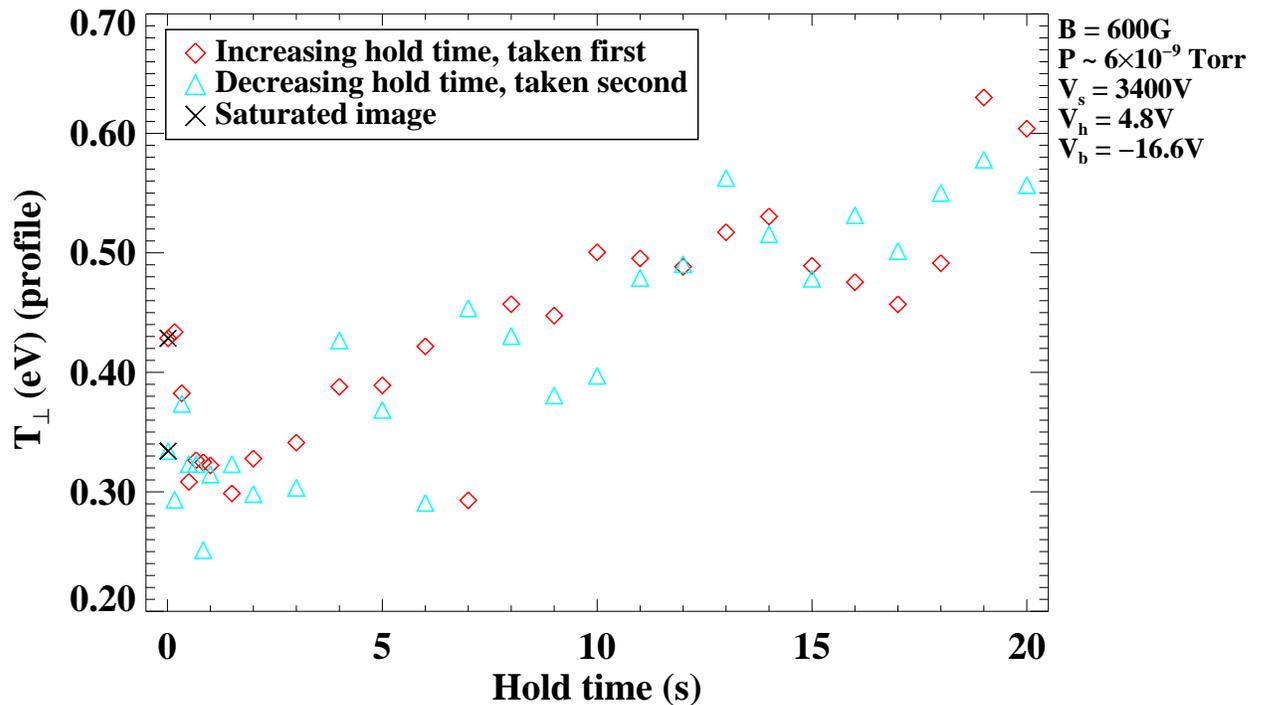
- The change in the confining voltage on electrode 6 during the plasma's release is slowed to resolve the electron energy distribution at $r \approx 0$.
- An amplifier is coupled to the phosphor screen to measure the number of electrons that have escaped as a function of time.

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



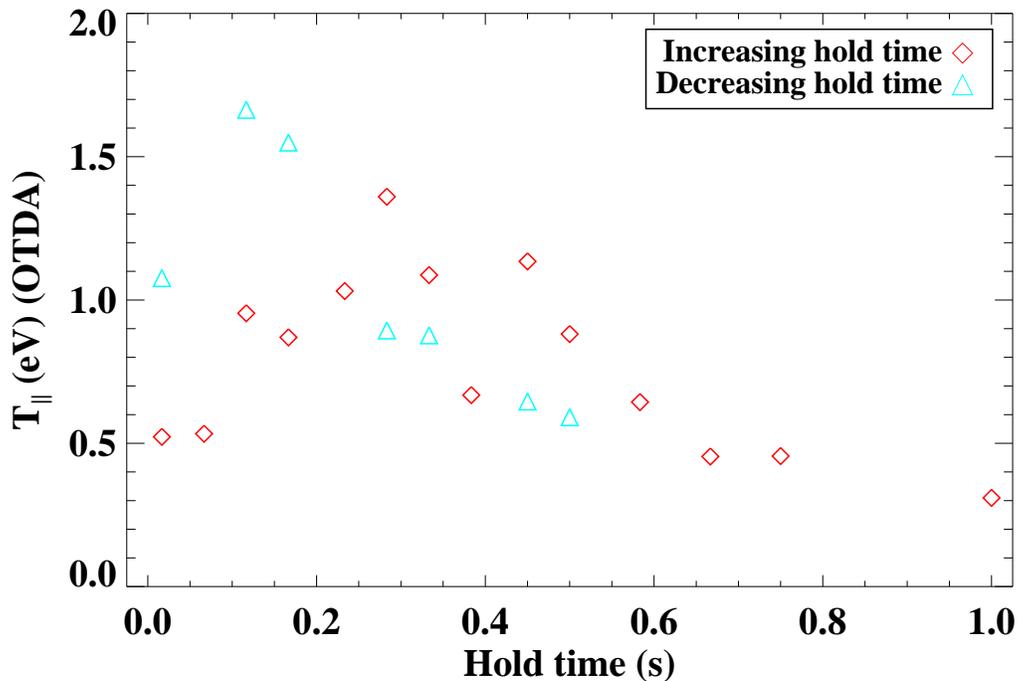
- The measured parallel temperature does not increase while the plasma is expanding under the influence of trap asymmetries ($t > 3$ sec.), but clearly increases while the plasma is relaxing to thermal equilibrium ($t < 3$ sec.).
- The parallel temperature evolution for $t < 1$ sec. is different from with the perpendicular temperatures inferred previously.

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



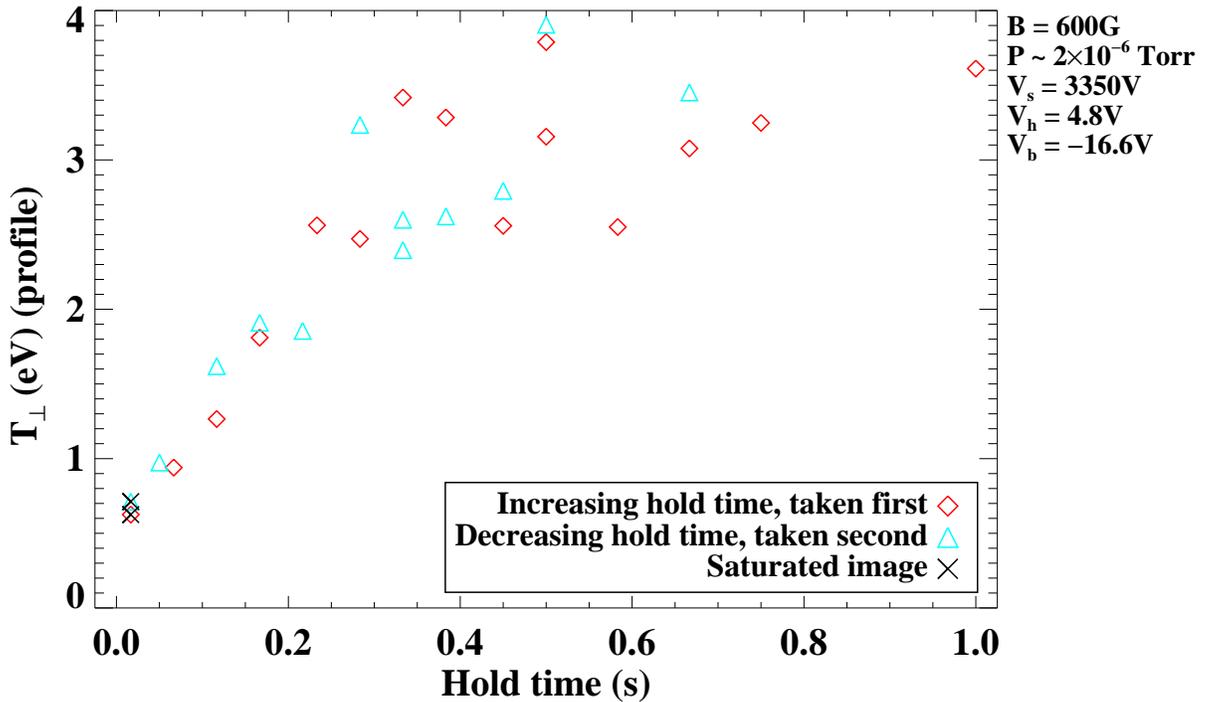
- The temperatures inferred from fitting the phosphor-screen-diagnostic density profiles with quasi-equilibrium profiles change very little during both phases of expansion.
- The quasi-equilibrium profiles fit the measured density profiles well, even when the plasma is expanding quickly.

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



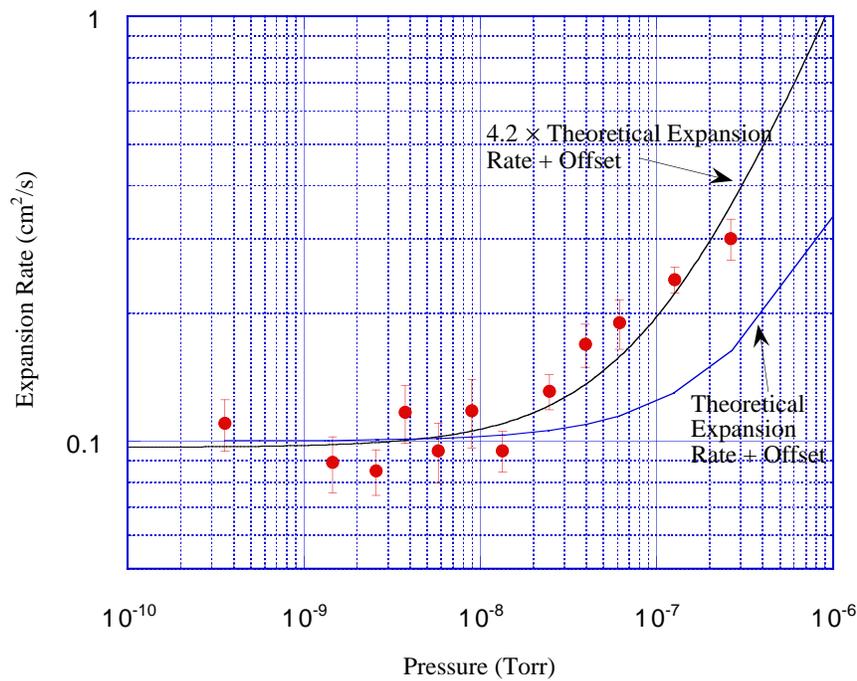
- At higher pressure, the plasma reaches the trap wall quickly (here, ~ 0.4 s.).
- The measured temperature again rises quickly, but drops once the plasma begins to interact with the wall.

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

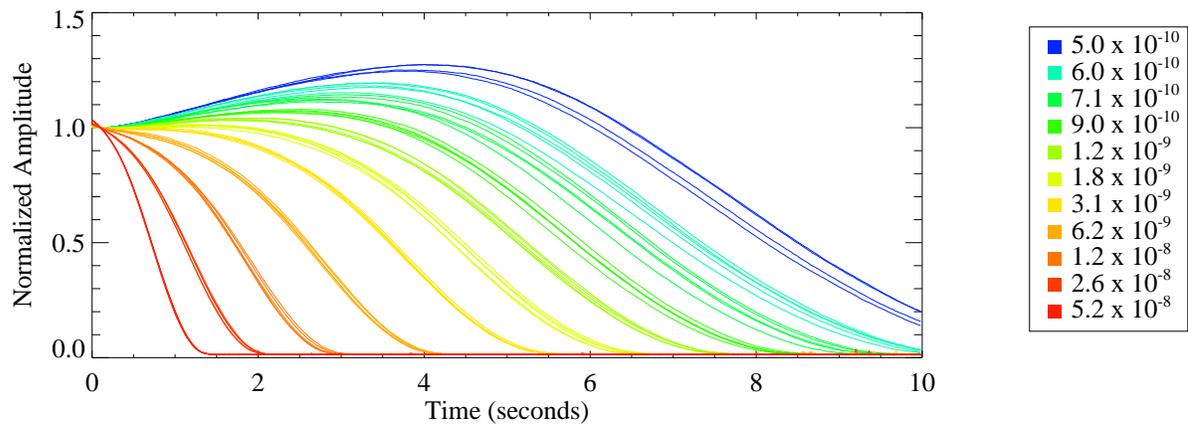


- The profile broadens rapidly at higher pressure, implying a higher perpendicular temperature.
- At these pressures, the plasma should have a sizeable temperature gradient, may be in contact with the trap wall, and is not in quasi-equilibrium; the temperatures inferred are not expected to be representative of the true temperature profile in the plasma.

Preliminary results from EDG

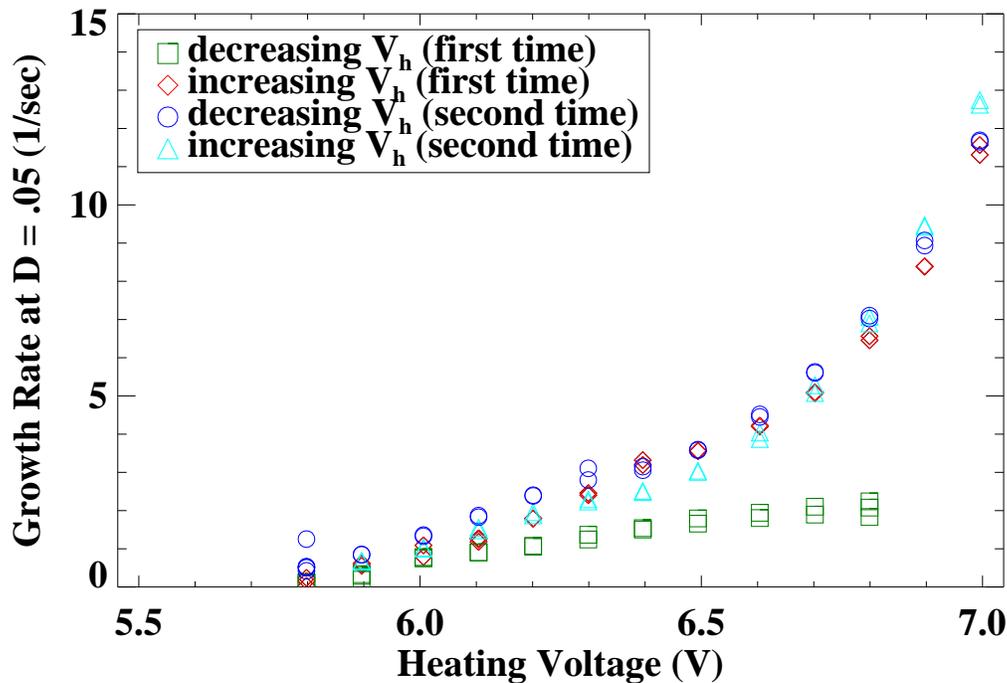


(a) Change in $\frac{d\langle r^2 \rangle}{dt}$ with background gas pressure.



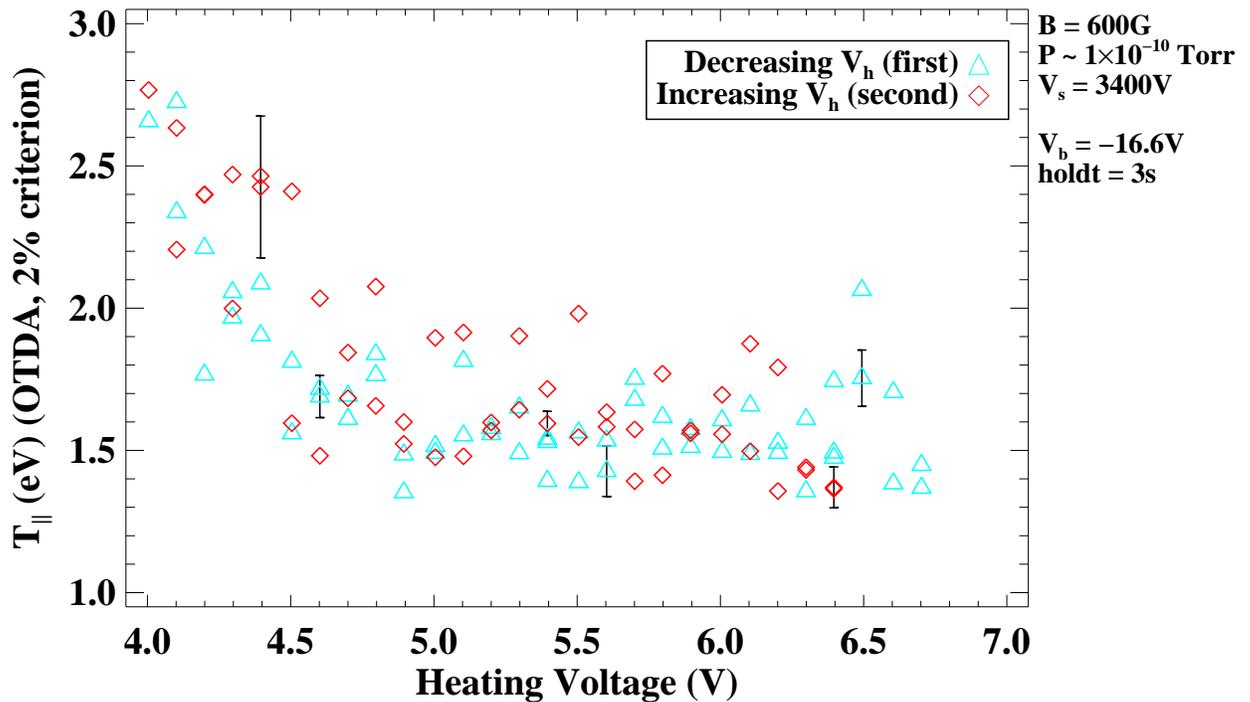
(b) Amplitude evolution of the $m = 1$ diocotron mode.

Diocotron Mode Sensitivity to Filament Heating Voltage



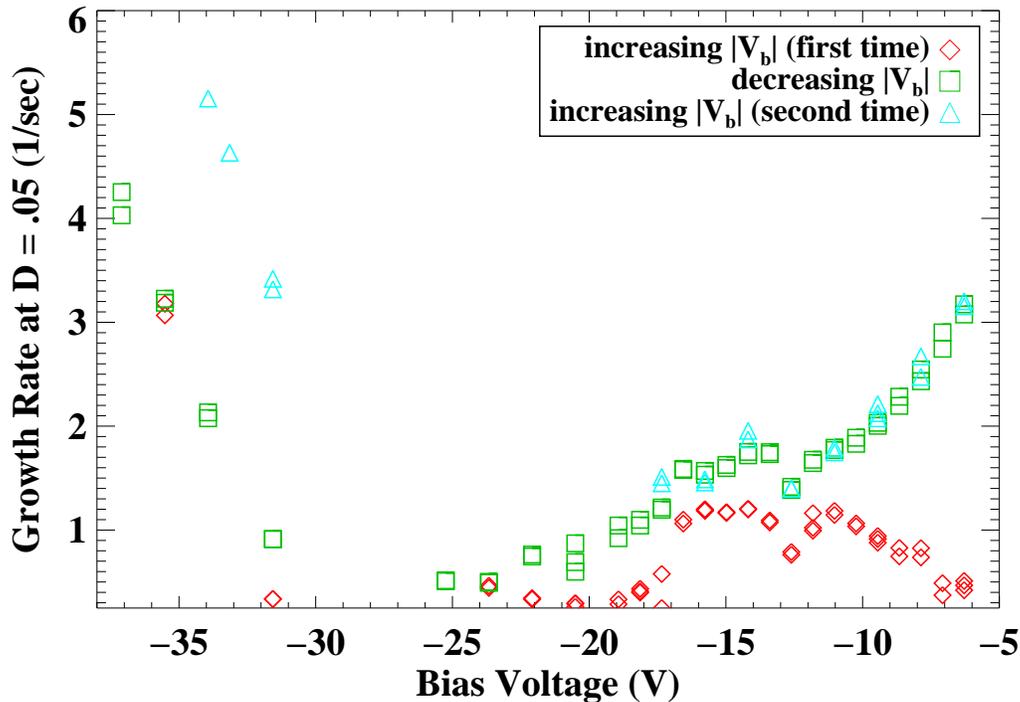
- The growth rate of the $m = 1$ diocotron mode increases with filament heating voltage ($V_b = -16.6V$). This behavior is observed at several different bias voltages.
- The vessel pressure increased during this scan, suggesting an explanation for the difference between the data taken first (the green squares, $P \sim 1 \times 10^{-10}$ Torr) and the rest of the data ($P \sim 8 \times 10^{-10}$ Torr).

Measured T_{\parallel} vs. Filament Heating Voltage



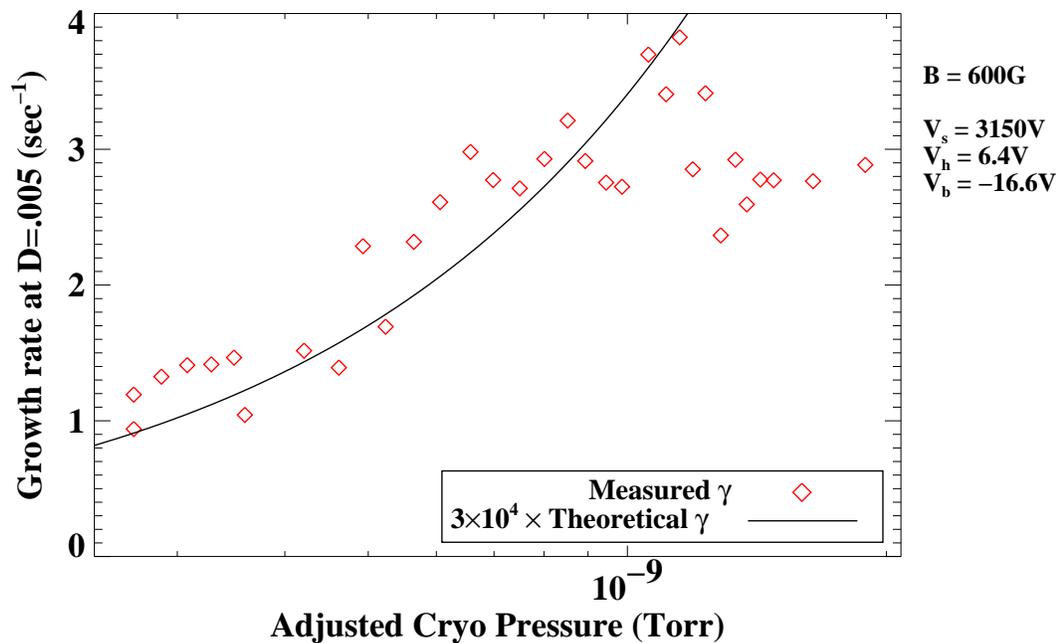
- Changes in the heating voltage do not have a clear effect on the measured temperature.
- Recently, it has been predicted by Kabantsev that ions created near the filament could cause diocotron mode growth.

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 measured early in the dataset (red diamonds) are lower than those computed for the subsequent data.

Diocotron Mode Sensitivity to Pressure



- 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 $P \sim 1 \times 10^{-10}$ Torr to $P \sim 1 \times 10^{-8}$ Torr for the data we've taken.

Summary

- The plasmas' expansion rate dependence on background gas pressure is consistent 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 quasi-thermal-equilibrium.
- The diocotron mode growth rate is sensitive to filament conditions as well as background pressure (to differences as small as $\Delta P \approx 2 \times 10^{-10}$ Torr).

This presentation,
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is available at

<http://w3.pppl.gov/~kmorriso/storage/k.presentation.1.pdf>