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

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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

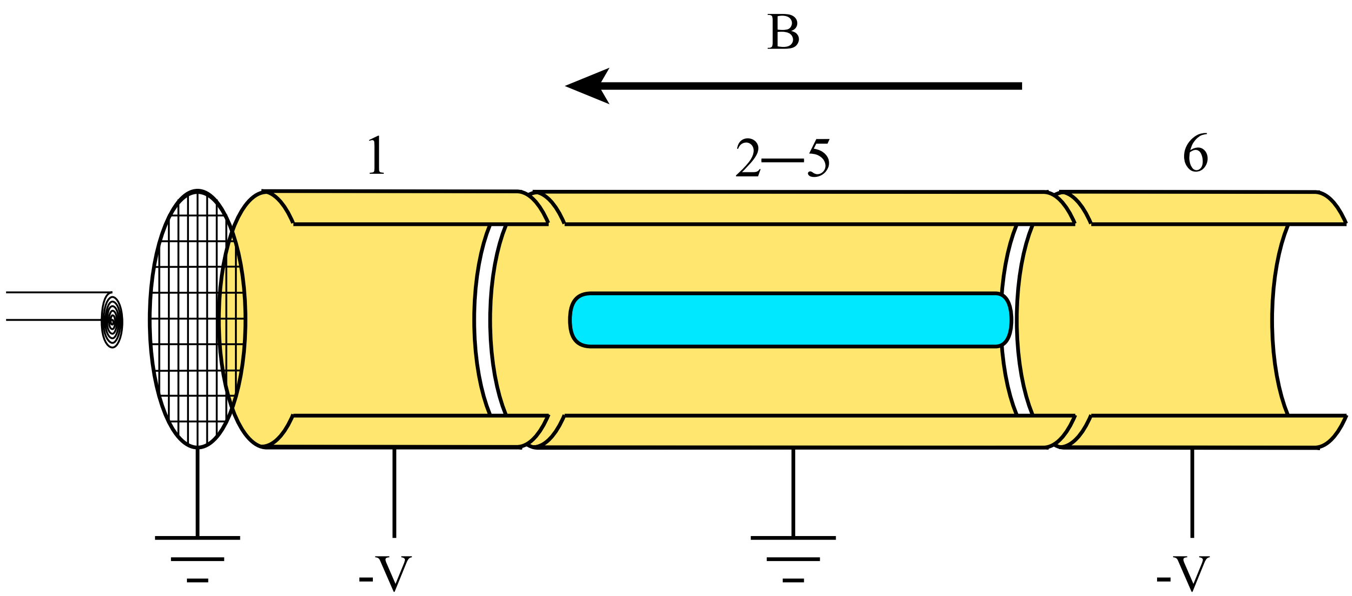
Non-neutral plasma physics is important for describing

- 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

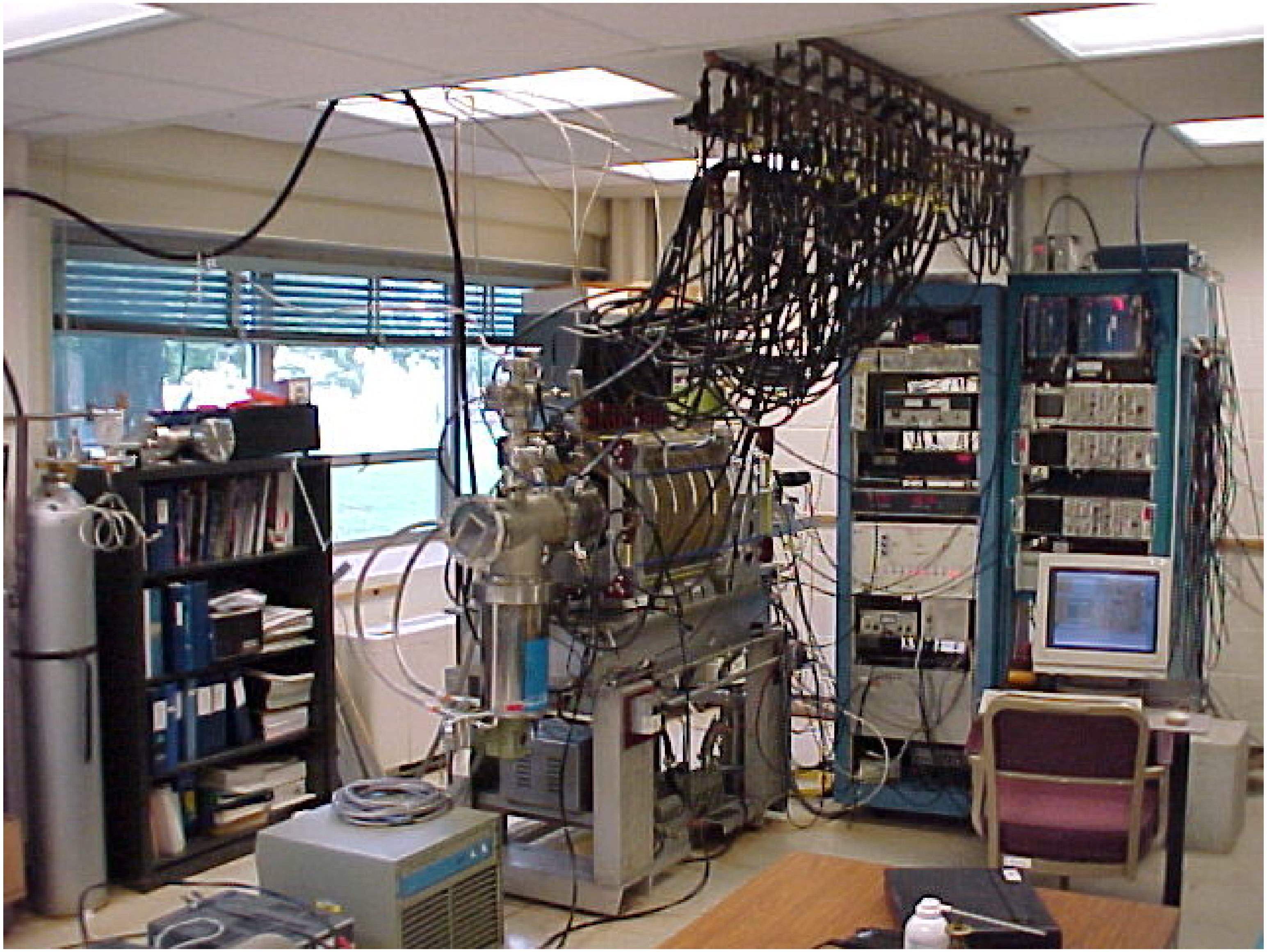
- Atomic clocks,
- Positron and antiproton recombination,
- Modeling inviscid 2-D fluids,
- Studies of the basic processes of transport across magnetic fields.

Malmberg-Penning Trap Geometry

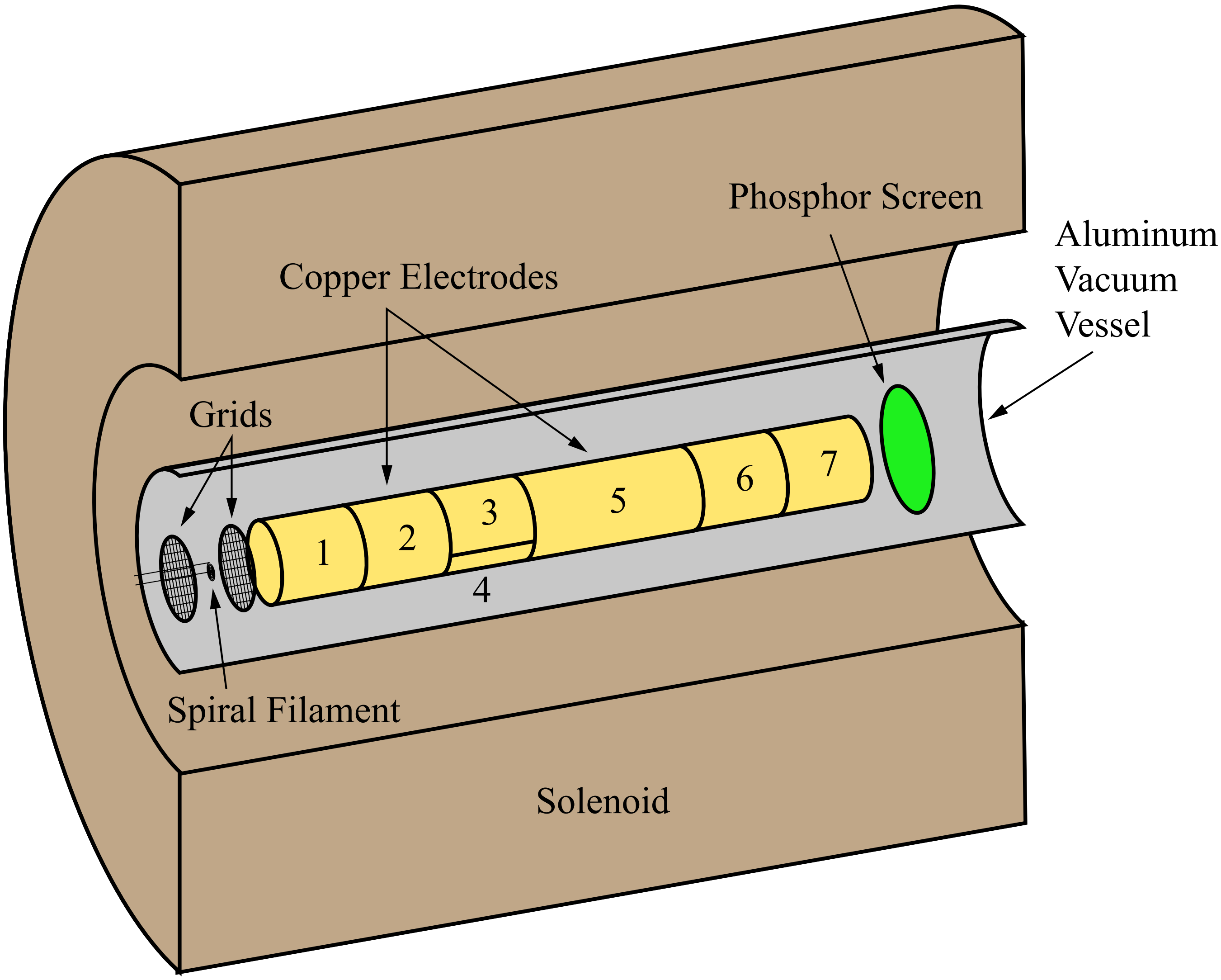


- Malmberg-Penning traps are cylindrically symmetric.
- A uniform, axial magnetic field confines particles radially.
- Non-adjacent cylindrical electrodes are biased to confine particles axially.
- Malmberg-Penning traps confine particles with the same charge sign (e.g., $^{24}Mg^{+}$ and $^{24}Mg^{2+}$).

EDG facility



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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Malmberg-Penning Trap Confinement

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

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

$\Rightarrow$ 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:

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

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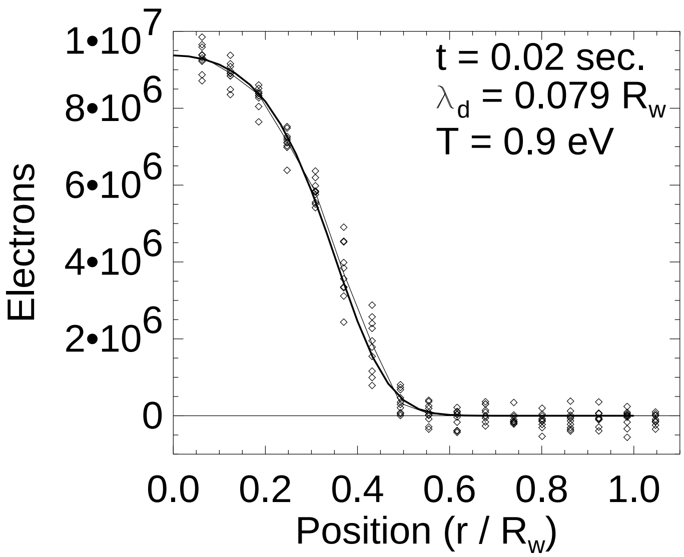
Theoretical Prediction

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

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

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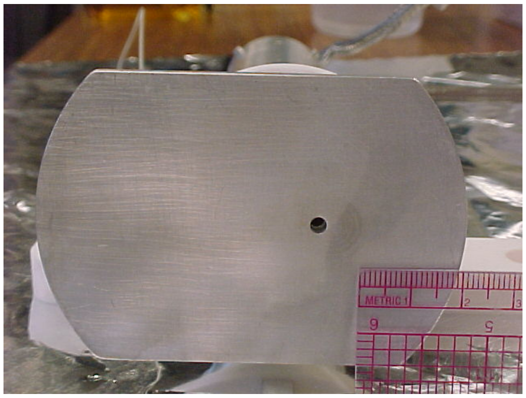
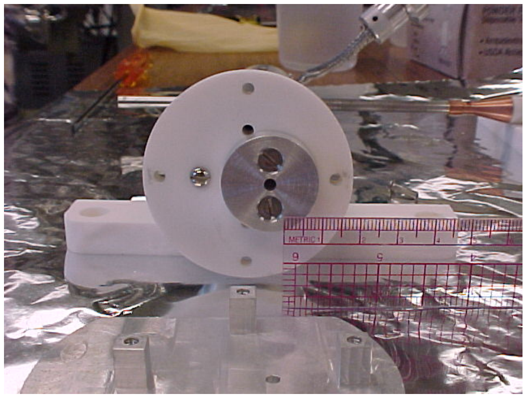
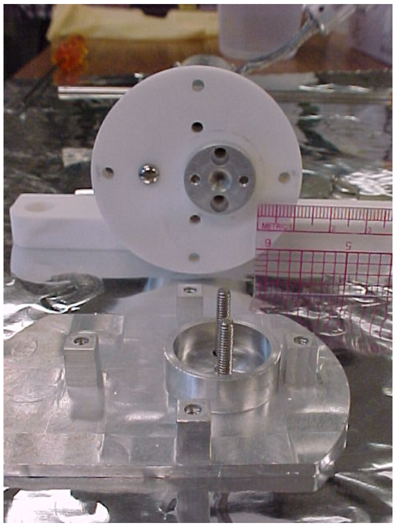
Radially-Scanning Faraday Cup Density Diagnostic Electrodes



(a) Total collector.



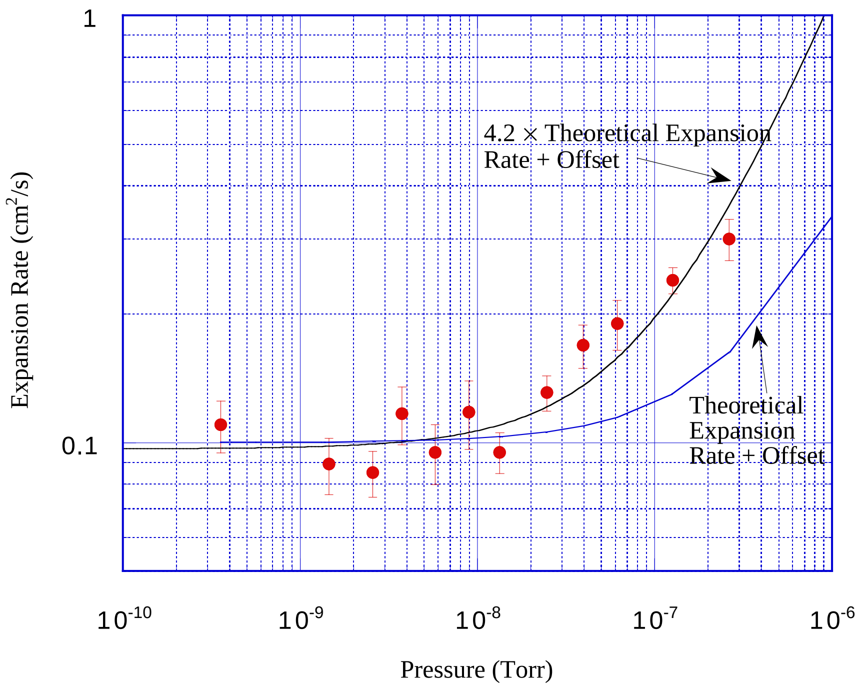
(b) Capacitive shield.



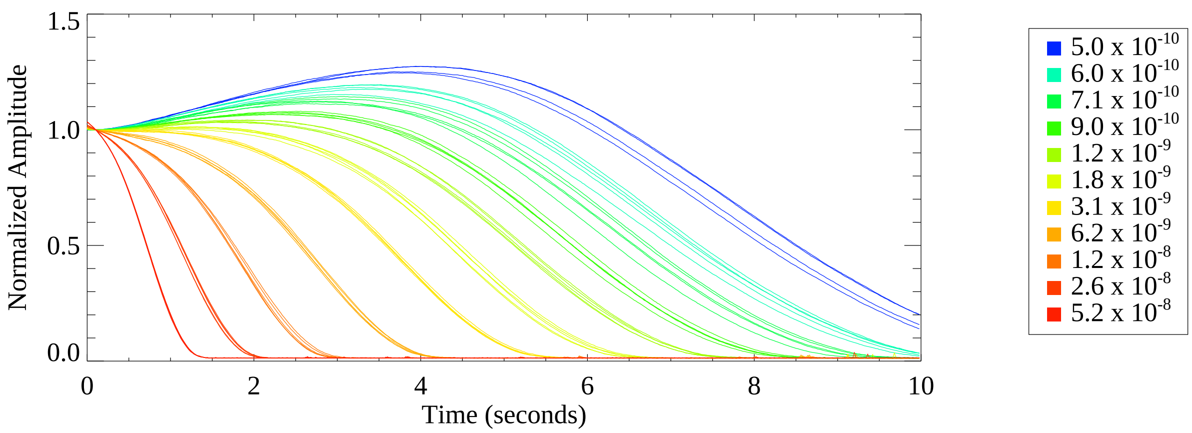
(c) Local collector.

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

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.

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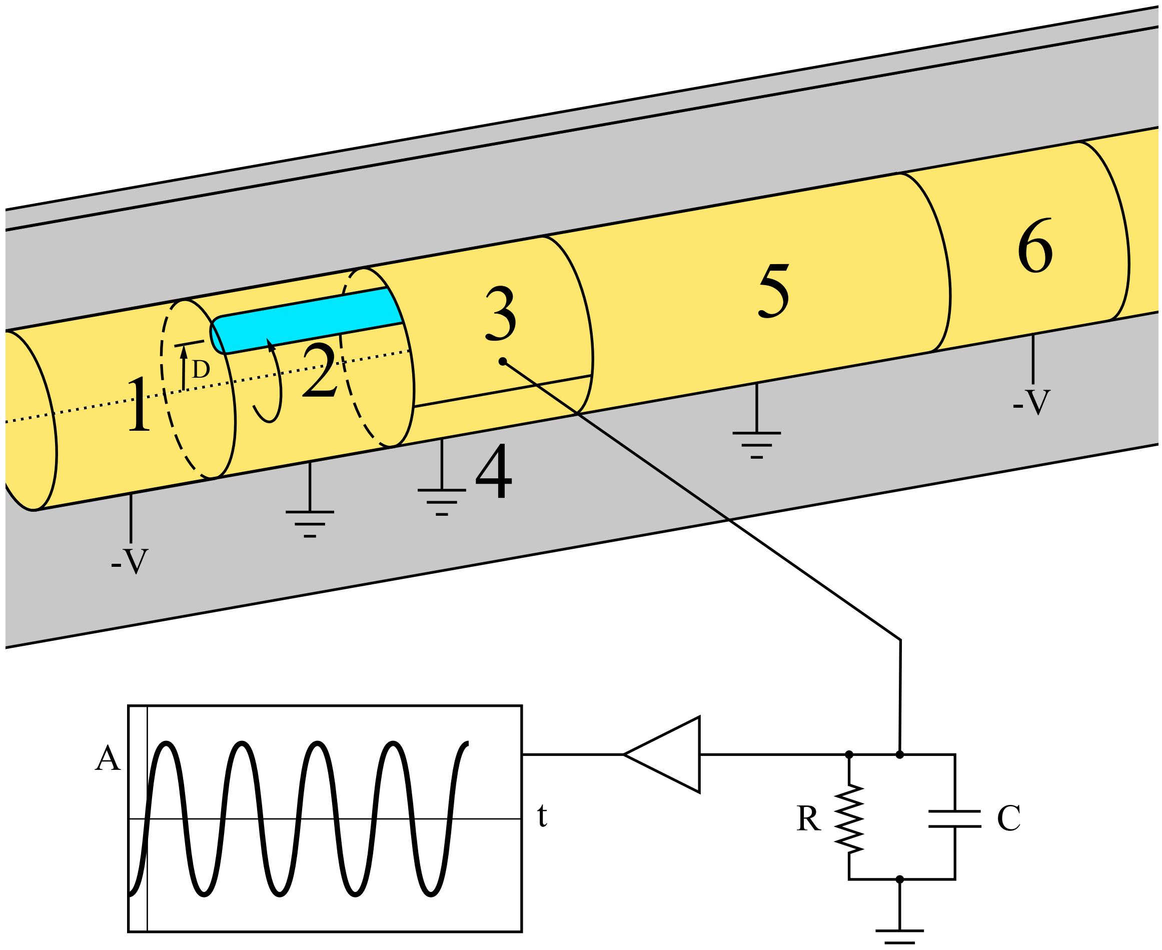
Schematic of $m = 1$ Diocotron Mode Diagnostic



- 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.

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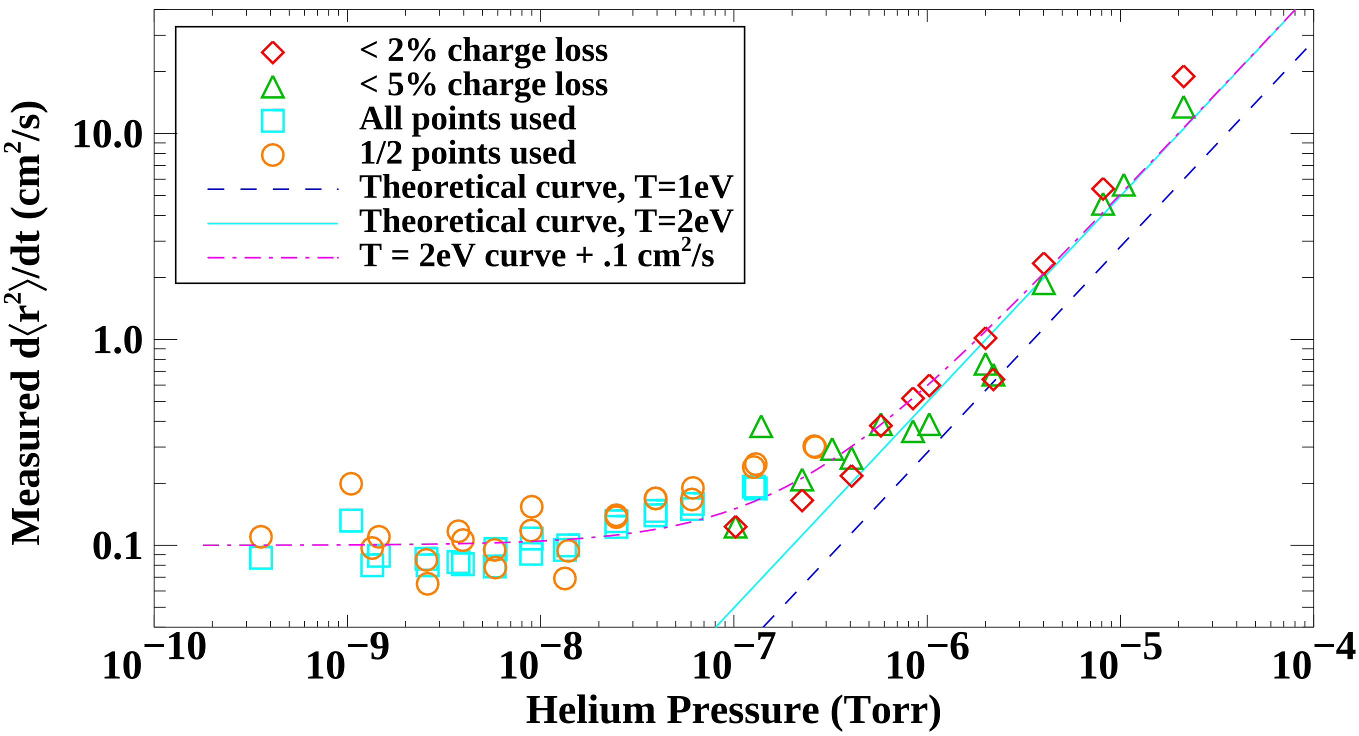
Expansion Rate Scaling with Pressure (large filament, 610 G)



- 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.

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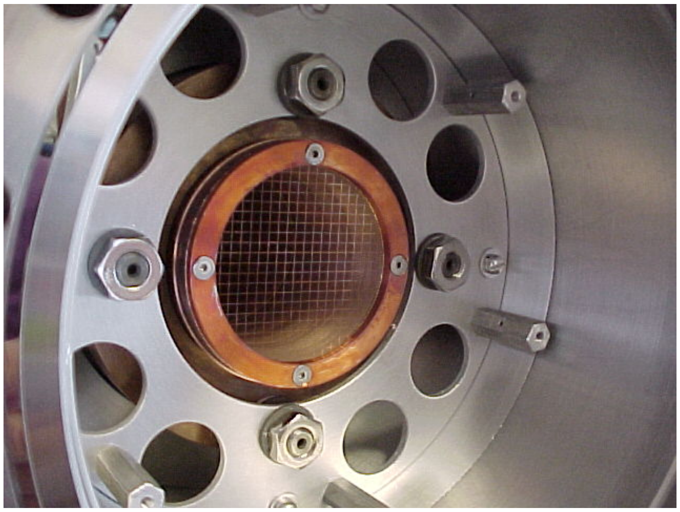
Phosphor-Screen Density Diagnostic

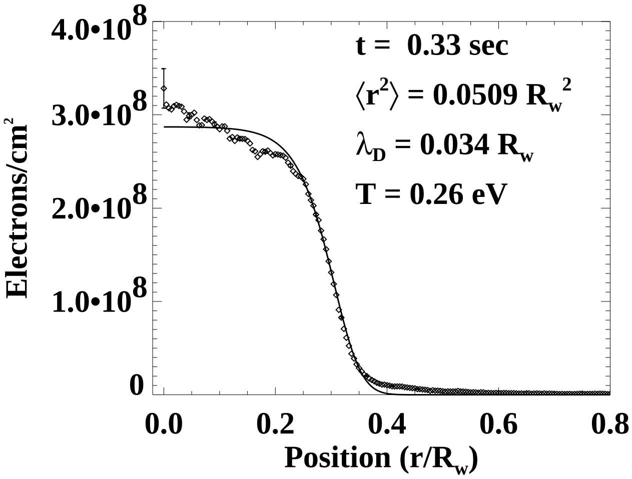


- A biased, aluminum-coated, P43 phosphor screen produces an image of the entire, axially integrated plasma when the plasma strikes it.

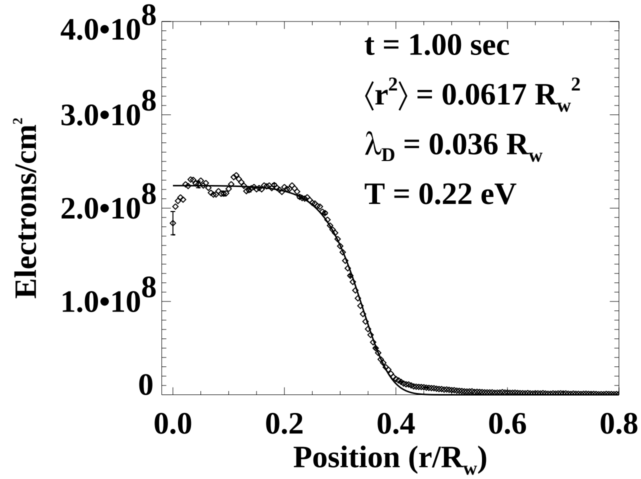
- A copper grid is clamped to the last, grounded trap electrode to give a more radially uniform accelerating electric field.

- A PULNiX TM-1010 CCD camera with an ITT NE6010 intensifier records the glowing image for later analysis.

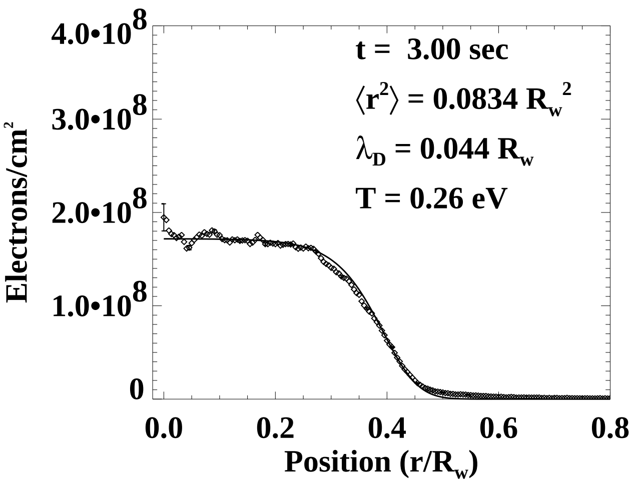
Density Profile Evolution in EDG



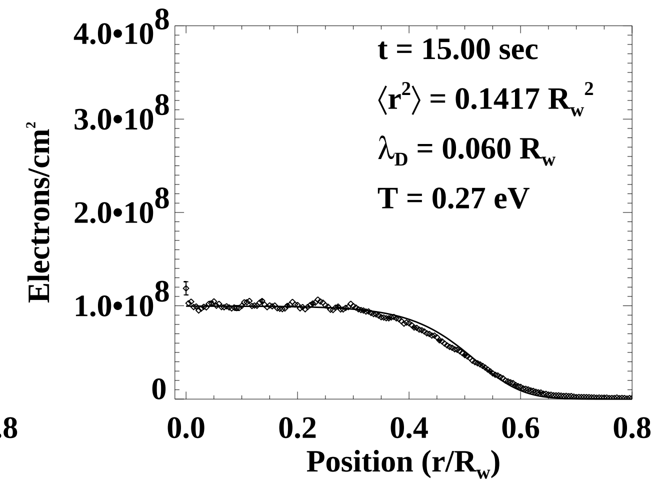
(a) 1/3 s.



(b) 1 s.



(c) 3 s.

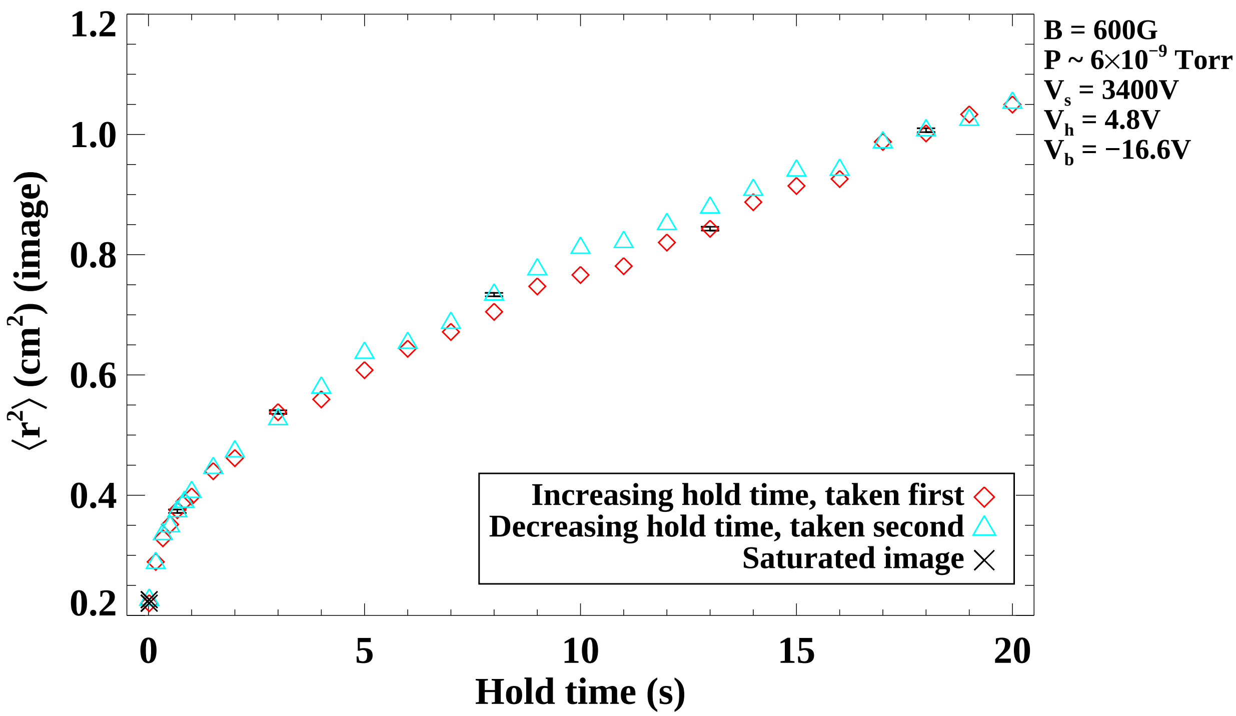


(d) 15 s.

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.

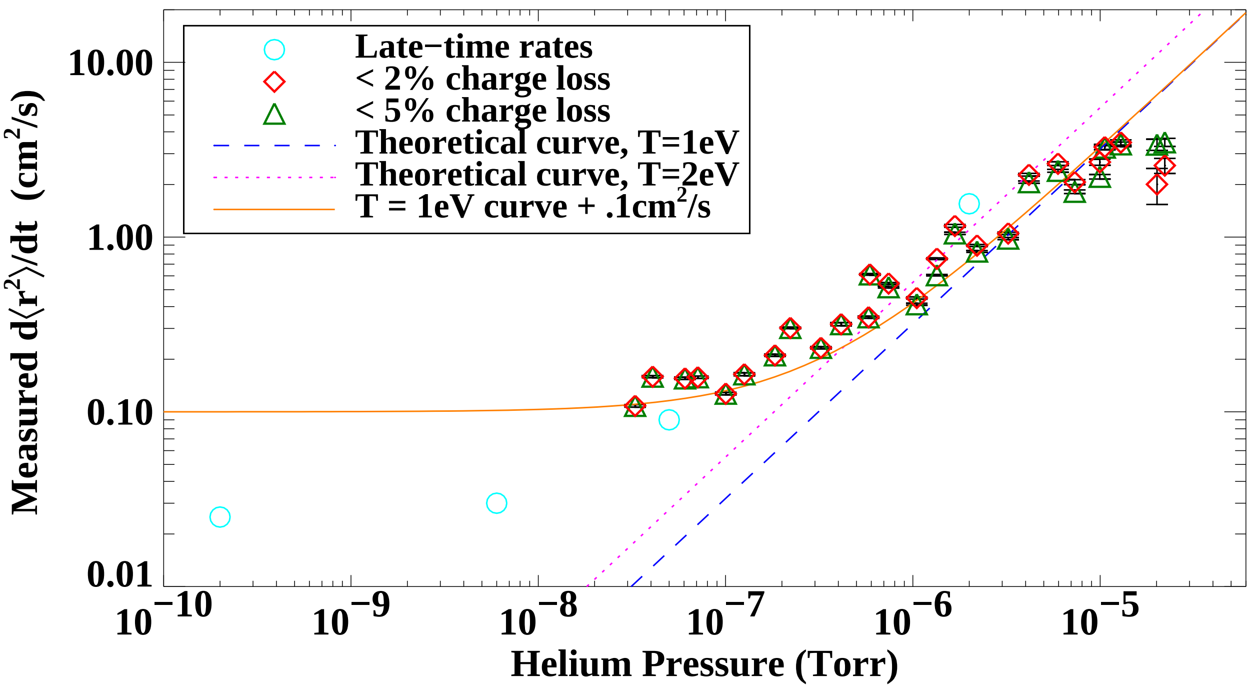
Plasma Expansion After 1 second ($P = 6 \times 10^{-9}$ Torr)



- 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.

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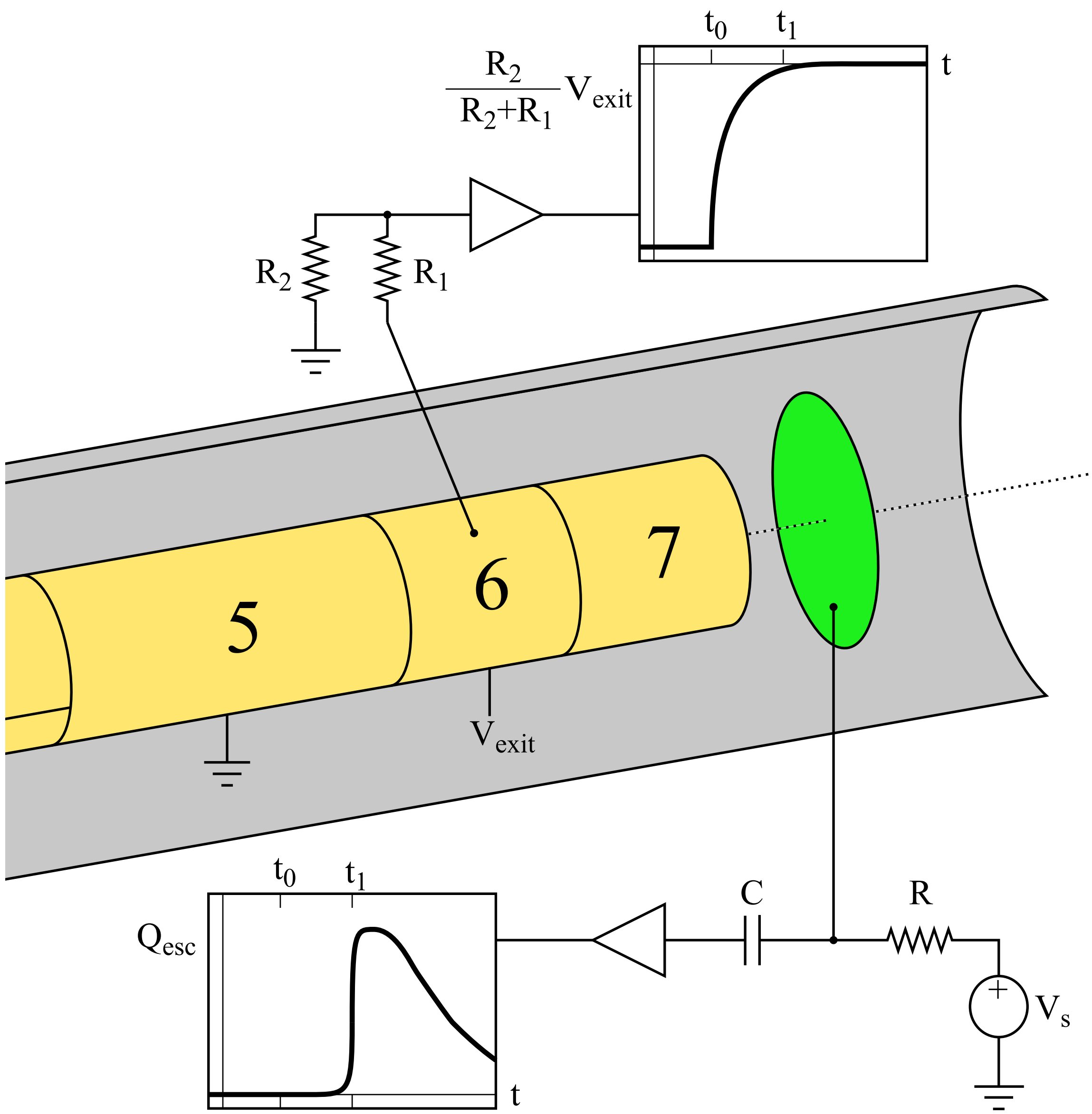
$T_\parallel$ Diagnostic Setup



- 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.

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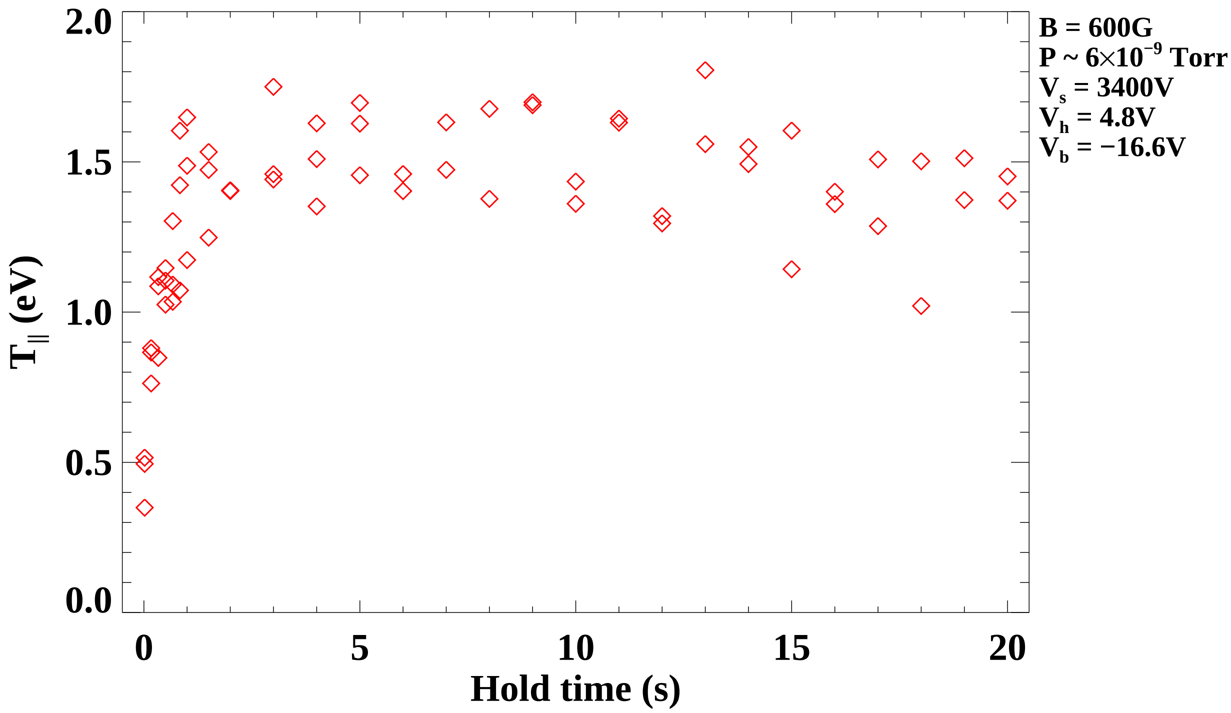
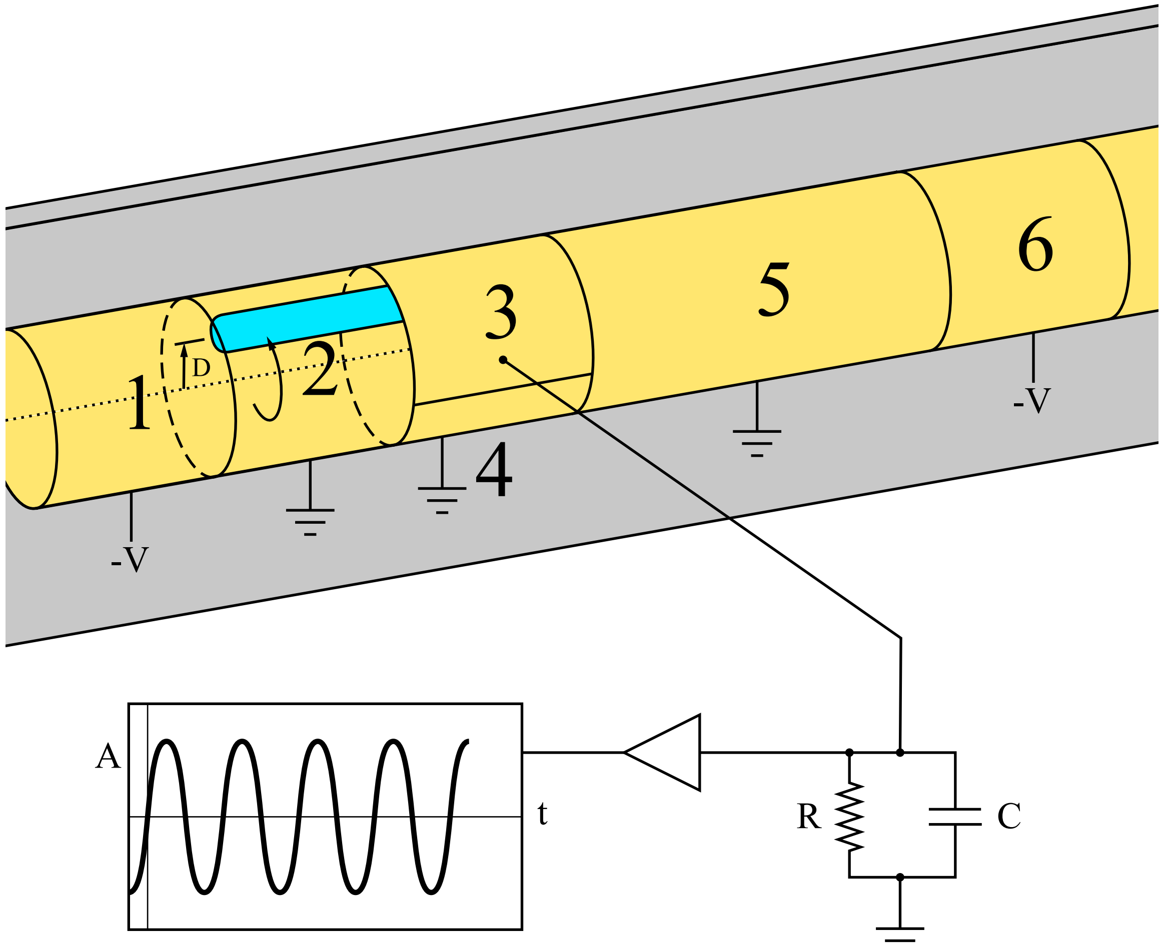
On-Axis Temperature Diagnostic Data (small filament, P$= 6 \times 10^{-9}$ Torr)



- 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.

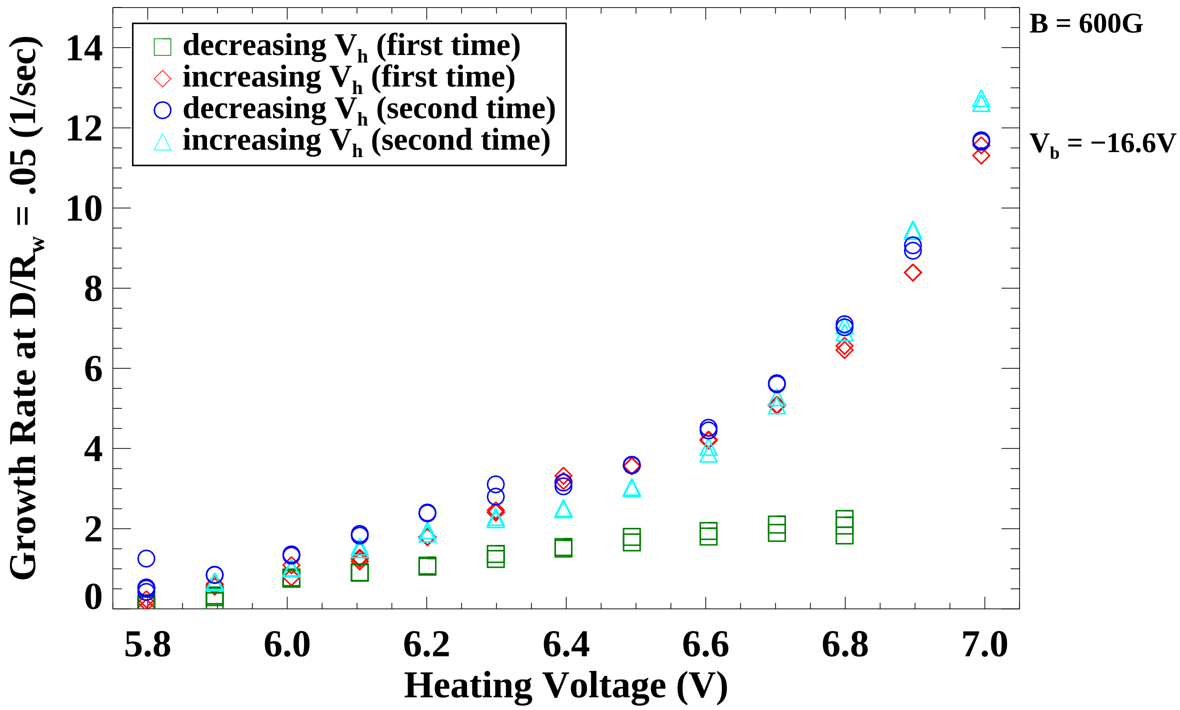
Schematic of $m = 1$ Diocotron Mode Diagnostic



- 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.

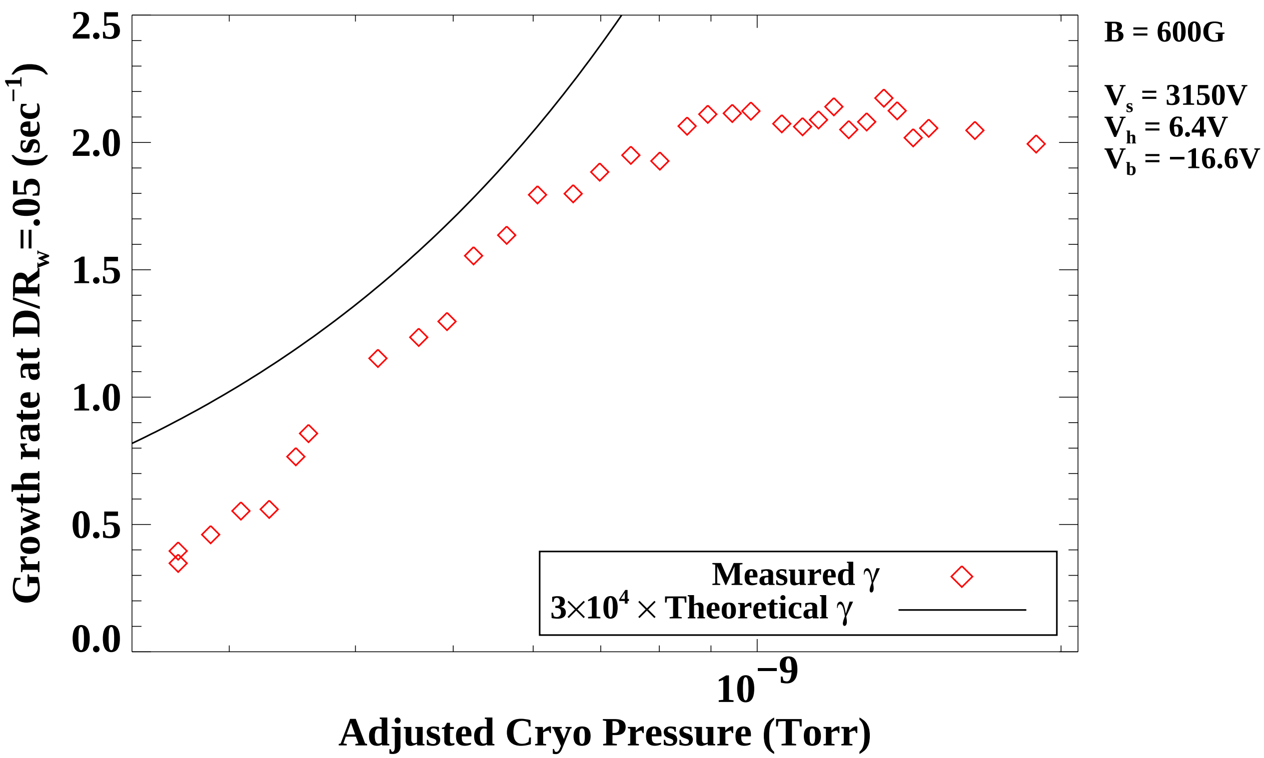
Diocotron Mode Sensitivity to Filament Heating Voltage



- 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).

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.

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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,

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

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is available at

http://w3.pppl.gov/~kmorriso/storage/k.presentation.2.pdf