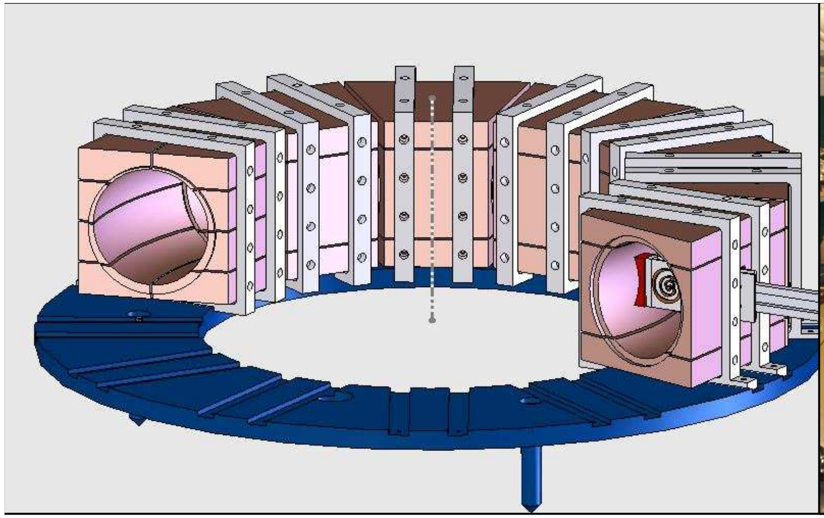

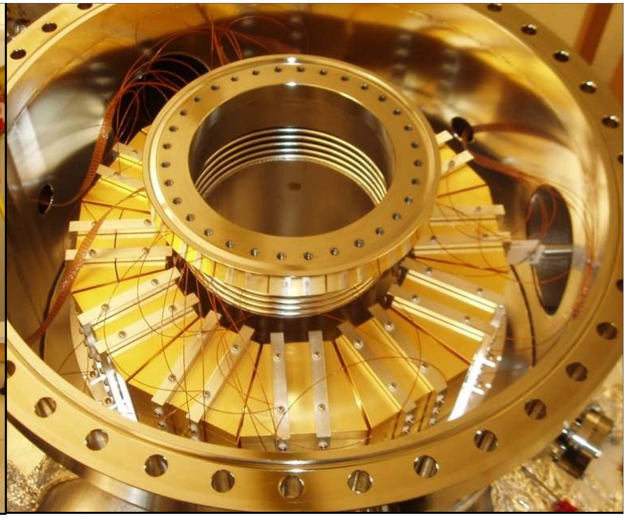

Experimental Realization of Nearly Steady-State Toroidal Electron Plasmas

Matthew R. Stoneking
Lawrence University
Appleton, Wisconsin

APS-DPP ’08, Invited Talk UI1 1

LAWRENCE UNIVERSITY
APPLETON, WISCONSIN

Acknowledgements

- Joan Marler (Post-doctoral Fellow 2005-2007)
    - Present address: University of Aarhus, Denmark
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    - Present address: California Institute of Tech.
- Jason Smoniewski (LU undergraduate ’09)
    - Undergraduate poster session: JP6 10
- National Science Foundation / Dept. of Energy
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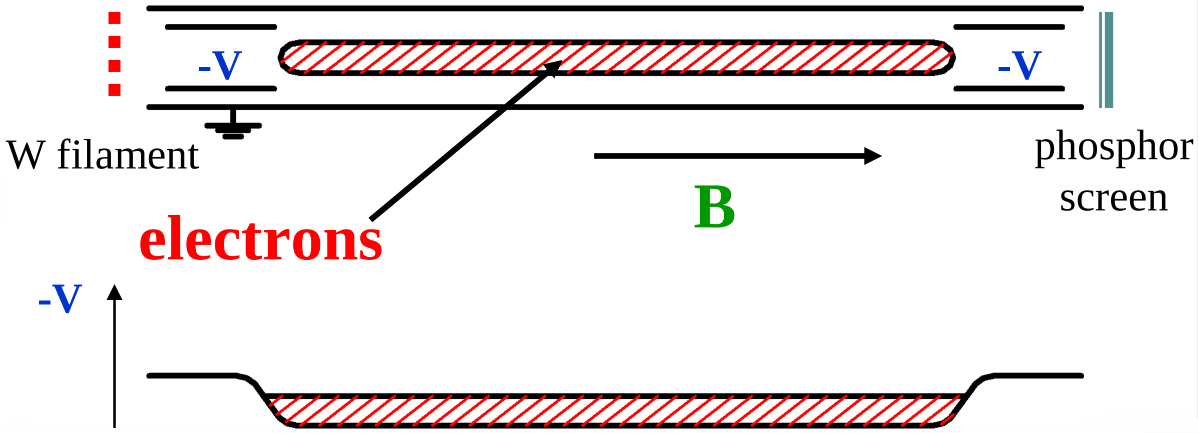
Take Home Points

- *Theoretical Predictions:* Electron plasmas can be confined in a purely toroidal magnetic field.
  - Stable, maximum energy state equilibria exist and rely on the poloidal *ExB* rotation acting as an effective rotational transform [1,2].
  - Magnetic pumping transport limits ultimate confinement time [3].
- *Experimental Results:* A new experiment (Lawrence Non-neutral Torus II) has demonstrated long-lived (>1 s) toroidal electron plasmas that approach the predicted maximum lifetime [4].

[1] Daugherty and Levy, *Phys. Fluids* **10**, 155 (1967)
[2] O'Neil and Smith, *Phys. Plasmas* **1**, 2430 (1994)
[3] Crooks and O'Neil, *Phys. Plasmas* **3**, 2533 (1996)
[4] Marler and Stoneking, *Phys. Rev. Lett* **100,** 155001 (2008).

Non-neutral Plasmas: *The Penning-Malmberg Trap*

- Non-neutral plasmas: *electron plasmas, ion plasmas, positron plasmas.*
- Experimental “wind-tunnel” tests of plasma and (2D-) neutral fluid theory.
- Applications/connections: *neutral antimatter production, frequency standards, quantum computation*
- Confinement theorem: T.M. O’Neil, Phys.Fluids **23**, 2216 (1980)
- Penning-Malmberg trap: J.H. Malmberg and C.F. Driscoll, Phys. Rev. Lett. **44**, 654 (1980)



Dynamic equilibrium:
azimuthal **E**x**B** flow due to space charge provides inward **J**x**B** force to balance outward electrostatic force.

Toroidal Electron Plasmas

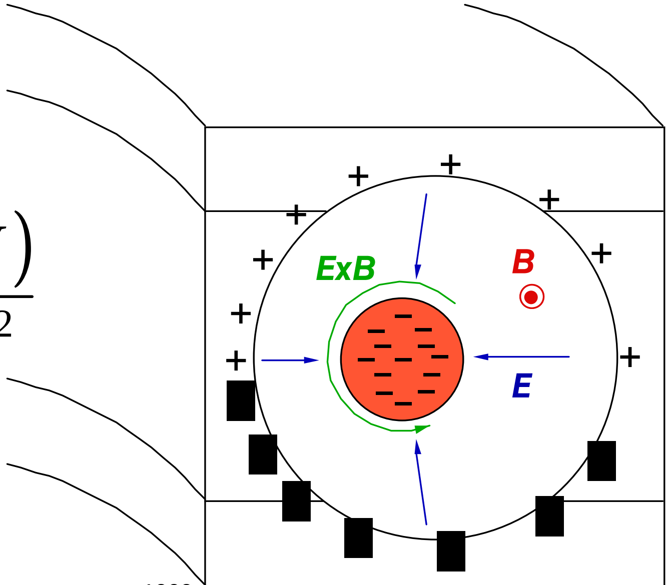
- Interest in toroidal electron plasmas pre-dates much of the work in Penning-Malmberg traps.
  - **Theory:** JD Daugherty and RH Levy, Phys. Fluids **10**, 155 (1967)
  - **Exp't:** JD Daugherty, JE Eninger, and GS Janes, Phys. Fluids **12**, 2677 (1969).
- Contemporary/recent experiments that investigate non-neutral plasmas in toroidal geometry:
  - Columbia Non-neutral Torus, New York: stellerator field
  - Compact Helical System, Japan: stellerator field
  - Proto-RT, Japan: (levitated) dipole field
  - Smartex-C, India: pulsed purely toroidal field … partial torus
  - Lawrence Non-neutral Torus II, Wisconsin: DC purely toroidal field

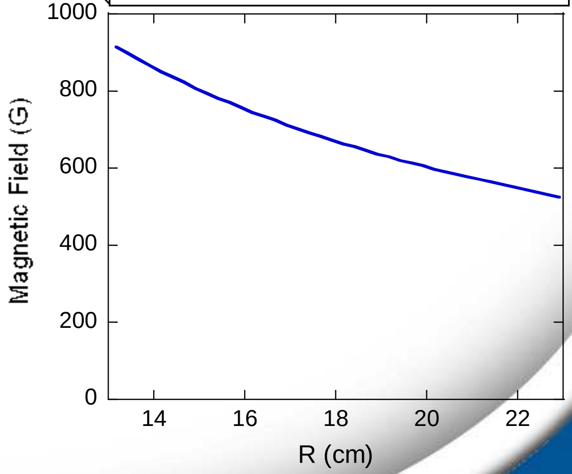
Physics Issues for Toroidal Electron Plasmas

- Equilibrium & Stability
- Dynamics
- Limitations on confinement

Equilibrium & Stability

- Daugherty-Levy Eq. [1]: $\nabla^2 V = \dfrac{ef(V)}{\varepsilon_o R^2}$
- Poloidal ExB rotation acts as an effective rotational transform.
- No banana orbits.
- Criteria for closed orbits: $e\phi_{plasma} > kT$
- Maximum energy state is stable because kinetic energy is constrained by invariants [2].



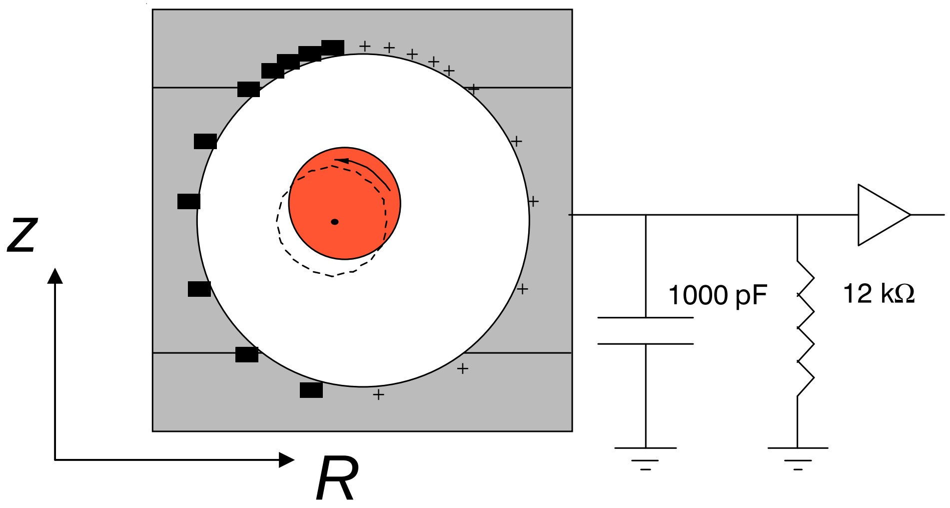


[1] Daugherty and Levy, *Phys. Fluids* **10**, 155 (1967)
[2] O'Neil and Smith, *Phys. Plasmas* **1**, 2430 (1994)

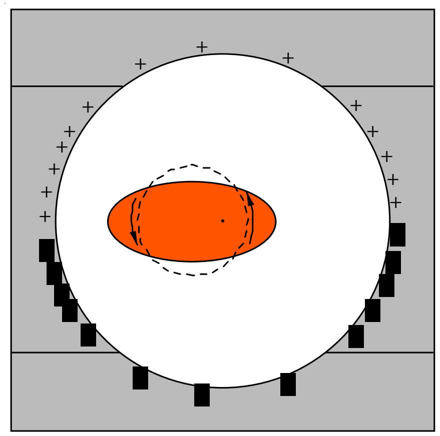
Dynamics (& Diagnostics):

Diocotron Modes ($k_{||} = 0$)

m=1 Mode



m=2 Mode



Theory for cylinder:

$$f_1 = \frac{Q}{4\pi^2 \varepsilon_o L B b^2}\left(\frac{1}{1-\left(A_1/b\right)^2}\right)$$

- Measure trapped charge.

Theory for cylinder:

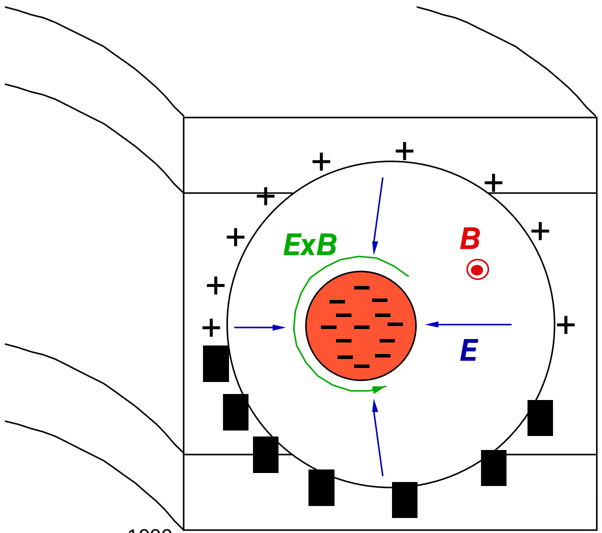
$$f_2 \approx \frac{ne}{4\pi\varepsilon_o B} = f_{ExB}$$

- Measure density.

- Toroidal effects?

Limits on Confinement: *Magnetic Pumping Transport*

S.M. Crooks and T.M. O'Neil, Phys. Plasmas **3**, 2533 (1996)



Adiabatic invariants/constants of the motion:

Magnetic moment

Angular momentum

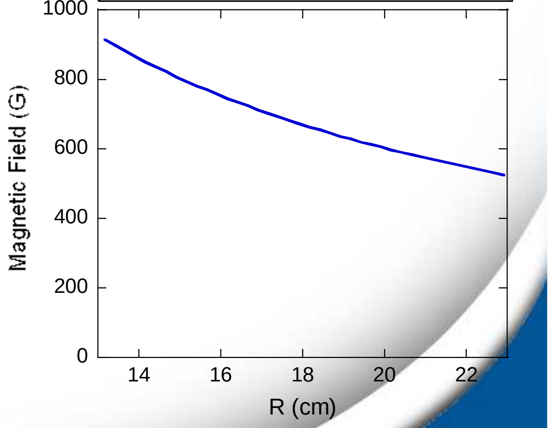
For each fluid element:

$$T_\perp = \left\langle \frac{1}{2} m v_\perp^2 \right\rangle = \frac{\langle \mu \rangle B_o R_o}{R}$$

$$T_\perp R = \text{constant}$$

$$\frac{1}{2} T_\| = \left\langle \frac{1}{2} m v_\|^2 \right\rangle = \frac{\langle L_z^2 \rangle}{2mR^2}$$

$$T_\| R^2 = \text{constant}$$



- $\tilde{T}_\| = 2\tilde{T}_\perp$
- Collisional equilibration leads to heating.
- Energy source: electrostatic (space-charge) potential energy.

→Plasma expands …. TRANSPORT.

Scaling analysis:

$$\boxed{\tau_{mp} \approx 0.02 R_o(\text{cm})^2 \sqrt{T(\text{eV})}}$$

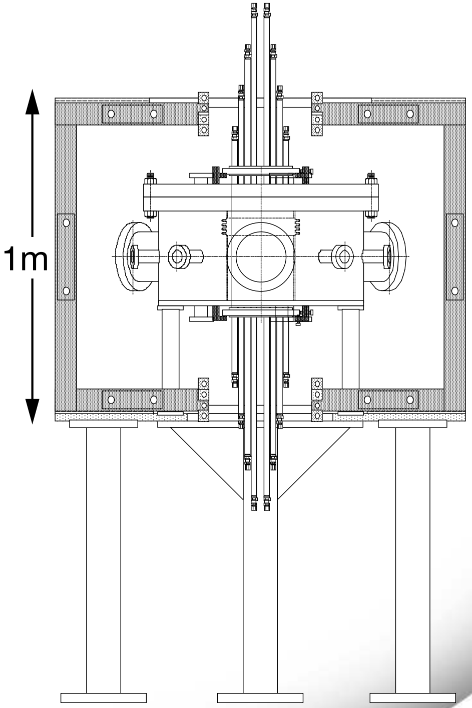
Independent of *B*, *n*, *a*!!

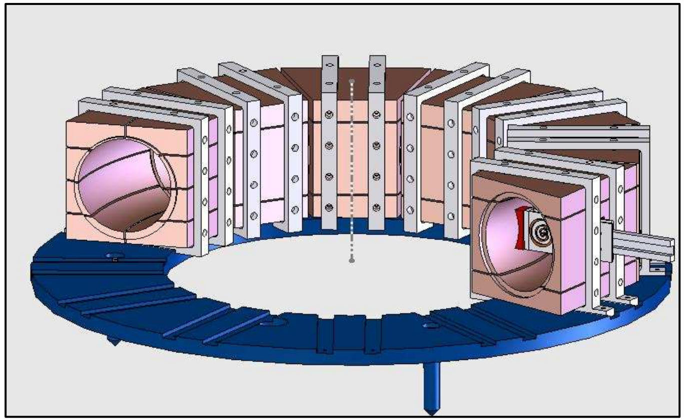
$$\tau_{mp} \approx 6\,\text{s}$$

For R_o = 17.4 cm, T=1 eV

Lawrence Non-neutral Torus II

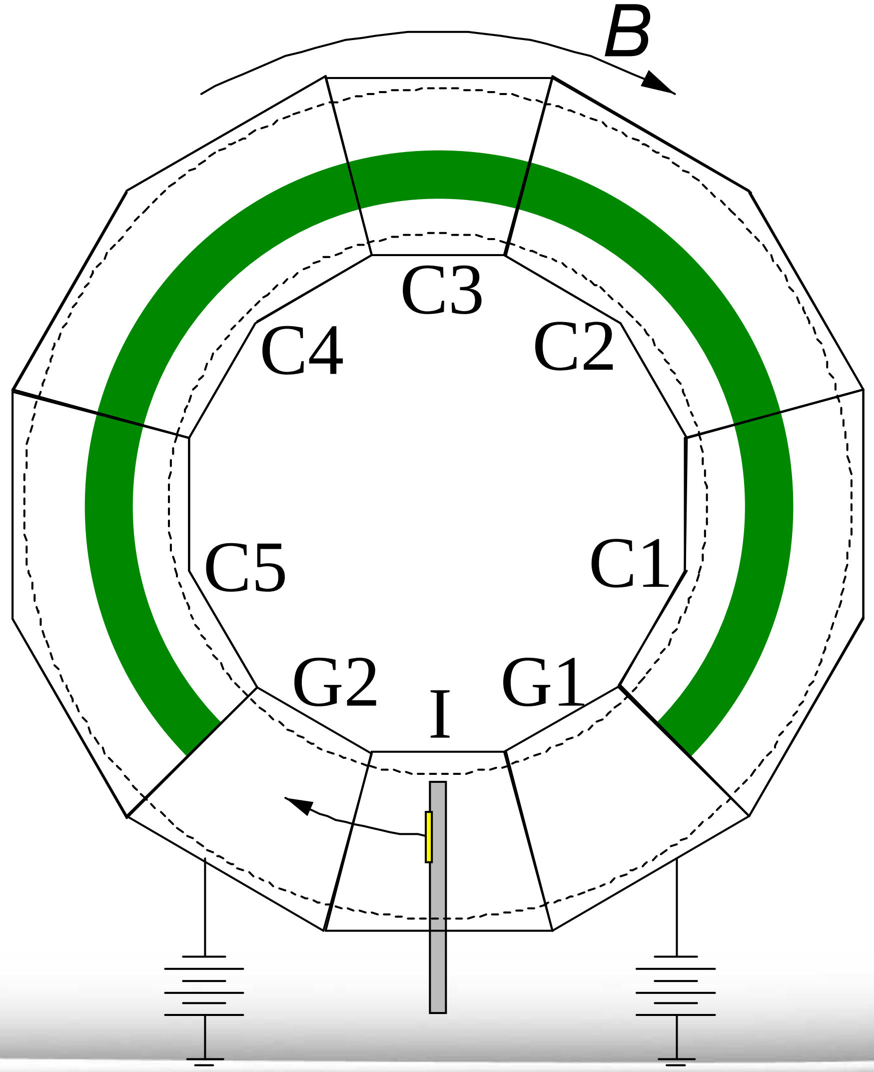
- Vacuum ~10^{-9} Torr
- Magnetic field ~ 700 G
- Field symmetry / boundary conditions
- Flexible wall diagnostics and control
- Fully toroidal… eventually

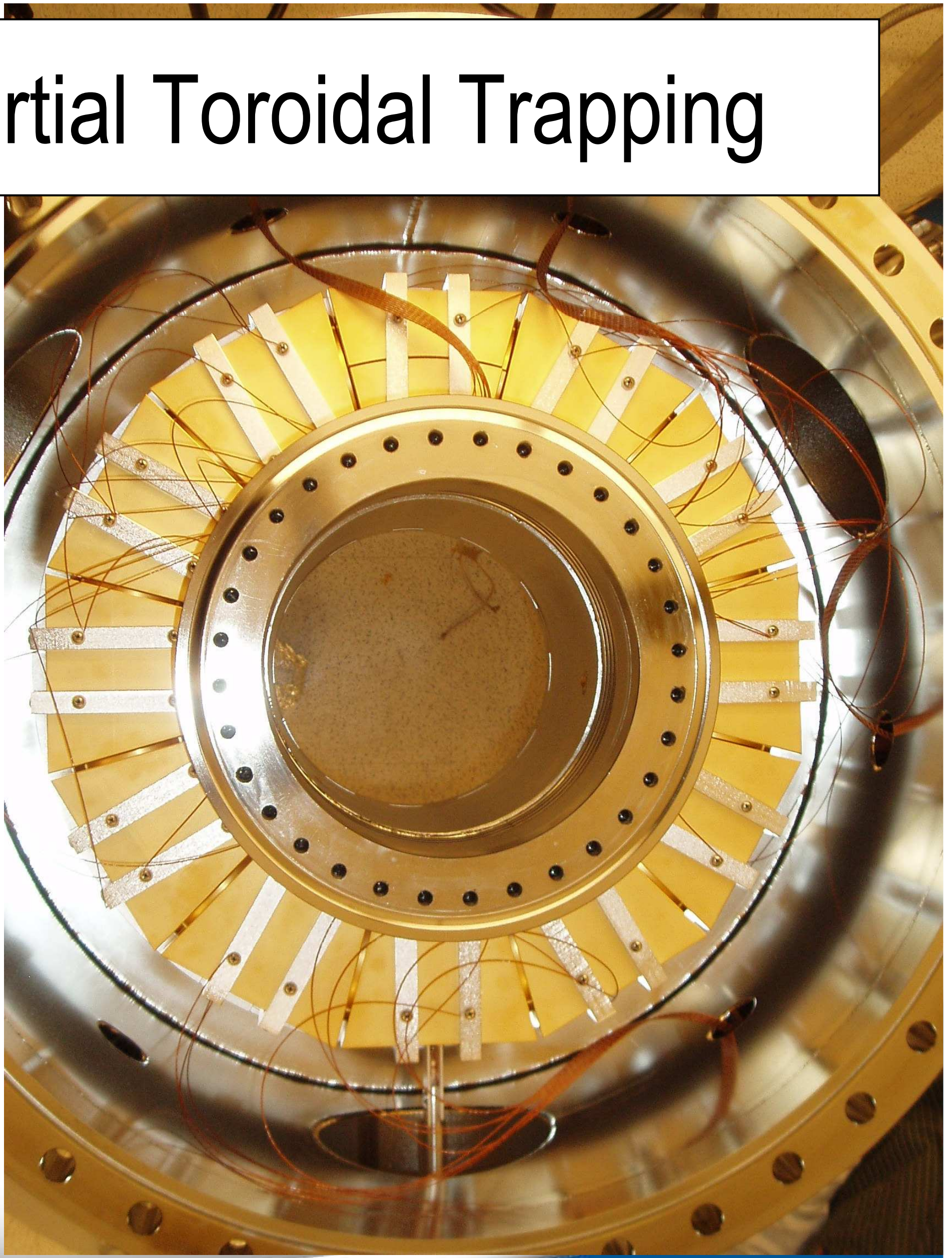




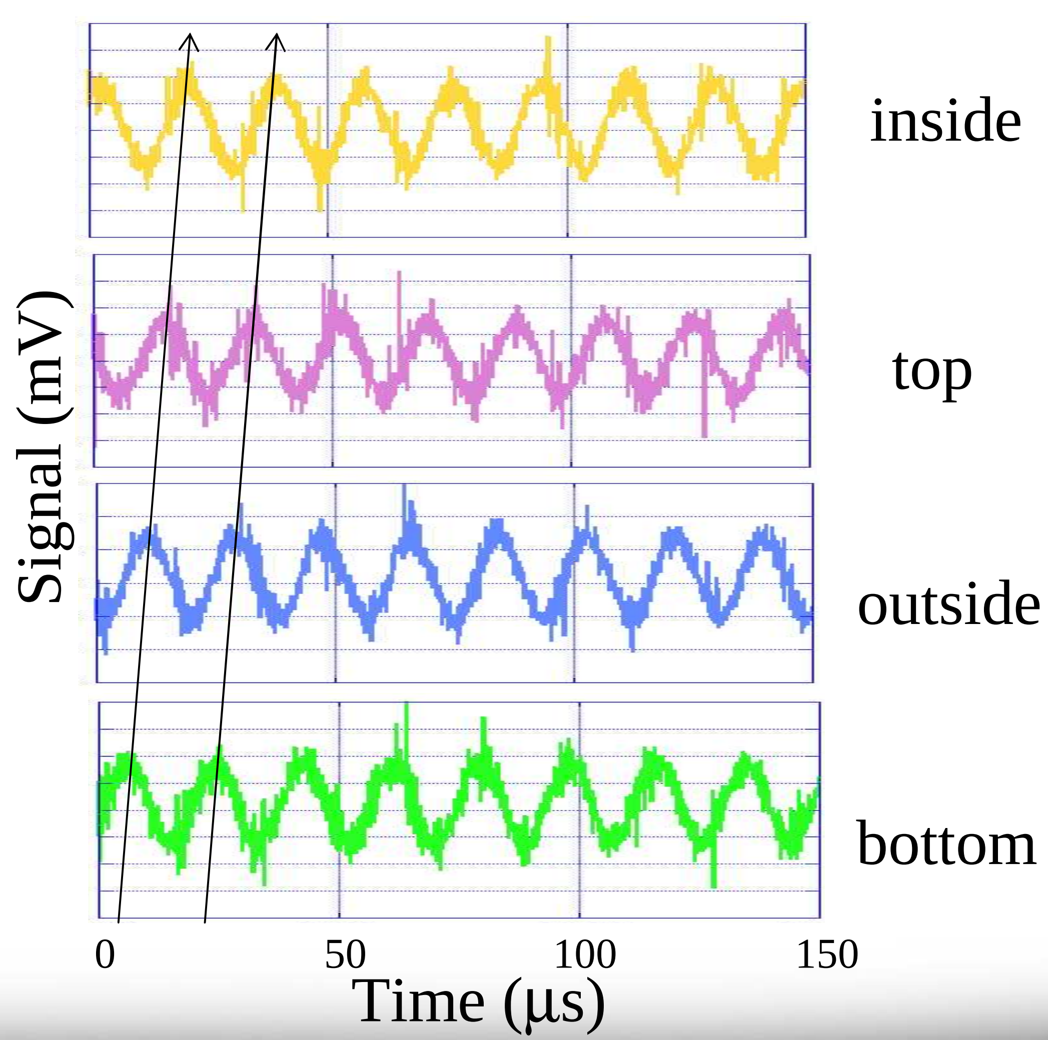
- Plasma major radius: 17.4 cm
- Plasma minor radius: ~1.3 cm
- Length: 82 cm (270 degrees)
  109 cm (360 degrees)

Internal Electrodes and Partial Toroidal Trapping





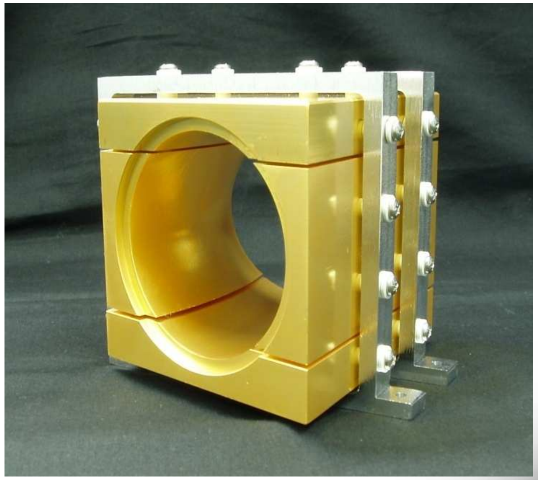
Observation of *m*=1 Diocotron Mode



$$f_1 = \frac{Q}{4\pi^2\varepsilon_o L b^2}\left(\frac{1}{B}\right) \approx 50\,\mathrm{kHz}$$

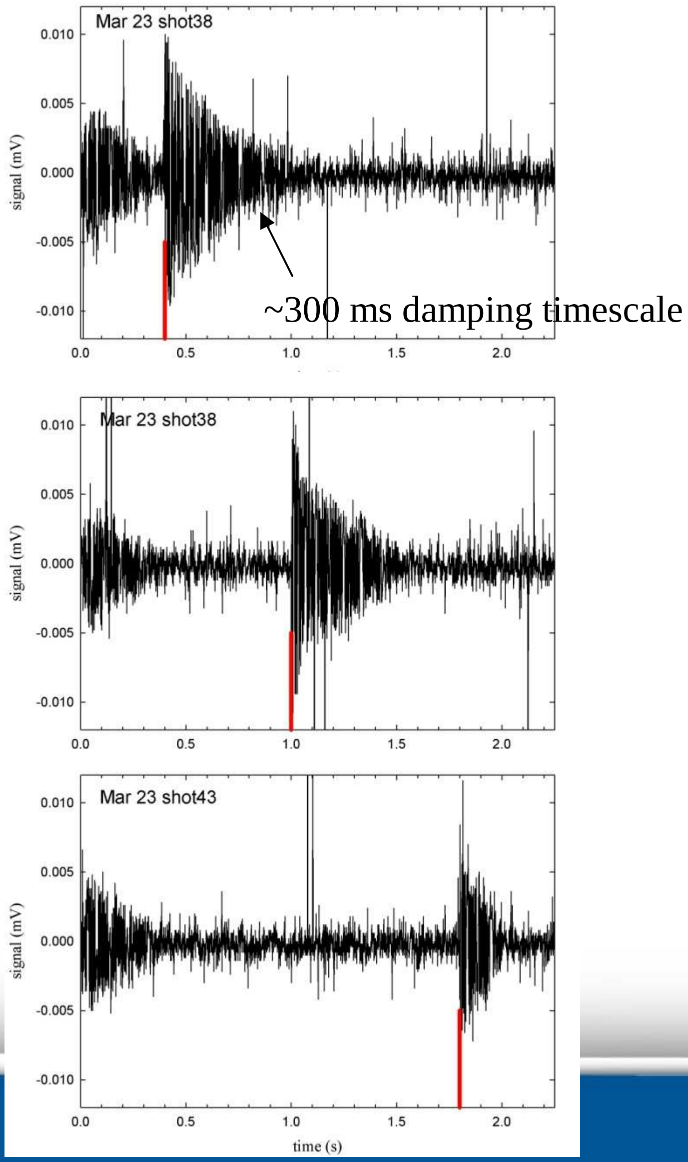
$$Q \approx 1.5\,\mathrm{nC}$$

$$\mathrm{N} \approx 10^{10}\ \text{electrons}$$



Marler and Stoneking, *PRL* **100**, 155001 (2008)

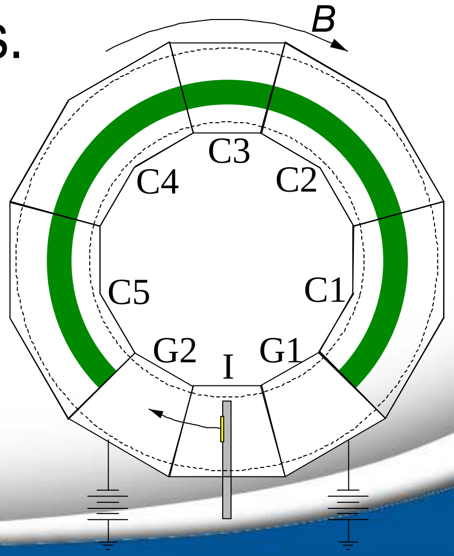
Measuring Confinement Time



- *m*=1 mode frequency → charge

$$f_1 = \frac{Q}{4\pi^2 \varepsilon_o L b^2}\left(\frac{1}{B}\right)$$

- Launch (C5) with a 5 cycle, near-resonant tone burst.
- Mode damps on ~300 ms timescale.
- Frequency is measured (C2) after the tone burst ceases.

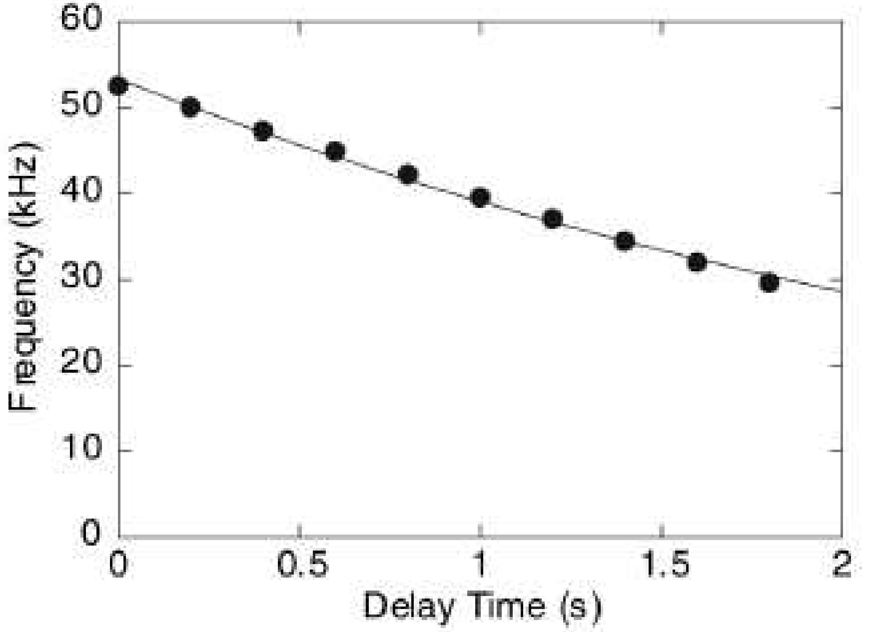


Marler and Stoneking, PRL **100**, 155001 (2008)

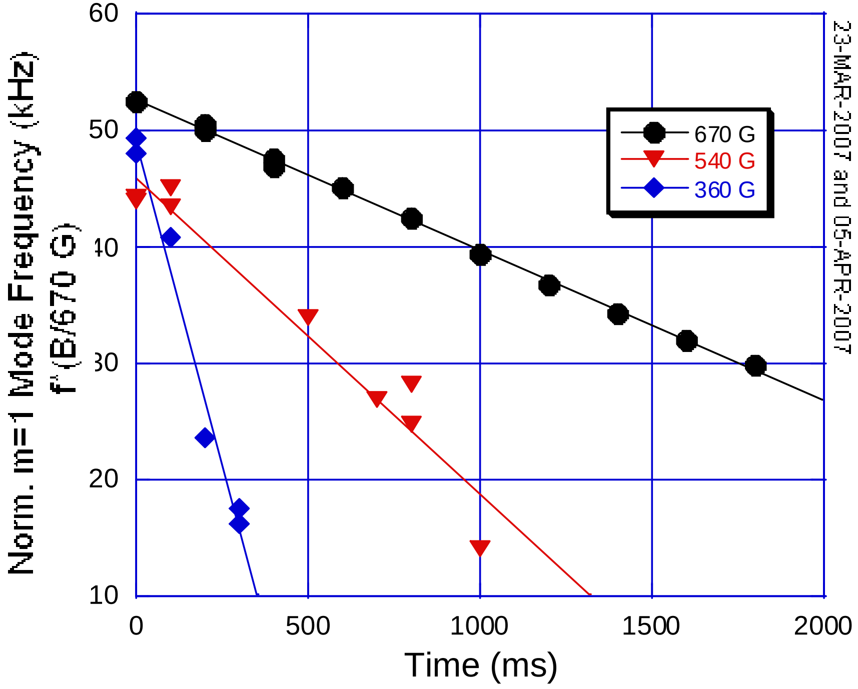
Confinement Time

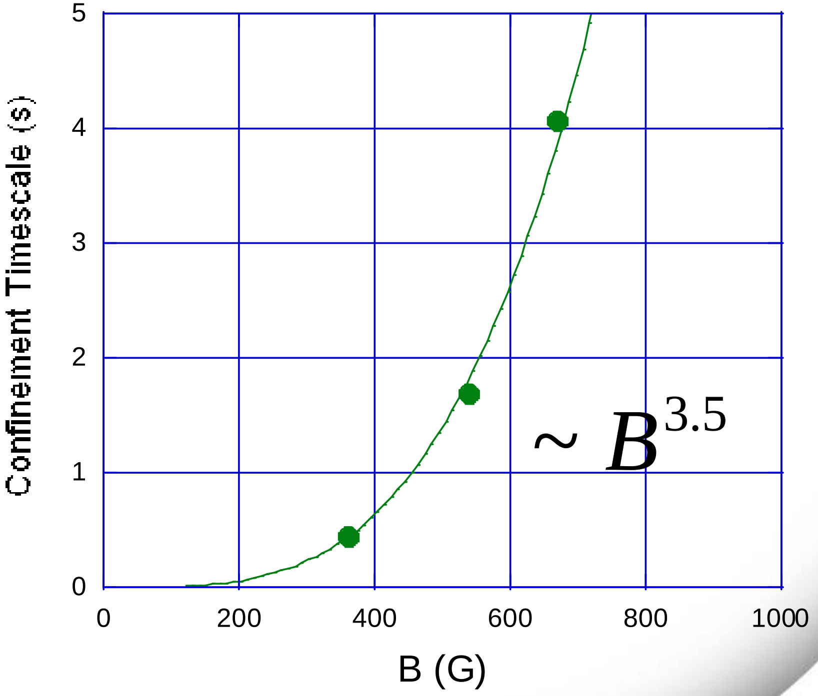
- Frequency decays on ~3 s timescale → charge confinement time.
- ~100X improvement over previous experiments.
- Magnetic pumping transport timescale:

  ~ 6 s (for *T* ~ *1* eV)



Confinement Scales Strongly with Magnetic Field





Not yet dominated by magnetic pumping transport.

Equilibrium Modeling

- Daugherty-Levy Eq.

$$\nabla^2 V = \frac{ef(V)}{\varepsilon_o R^2}$$

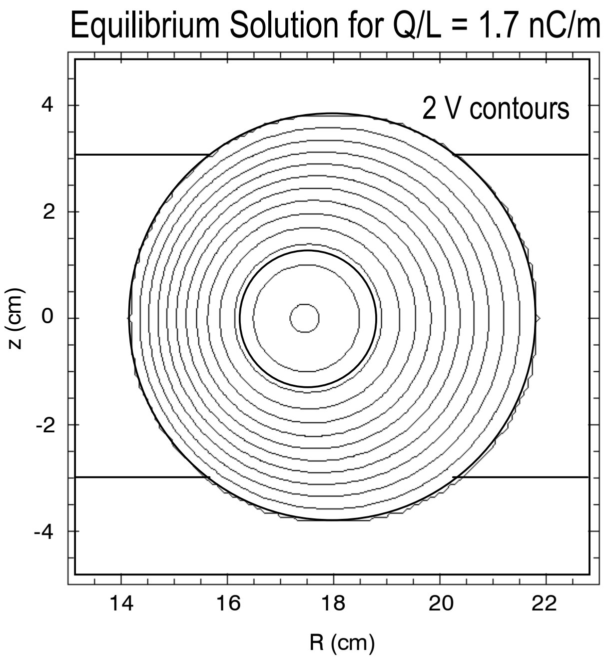
- Experimental constraints
  - *m*=1 diocotron mode frequency

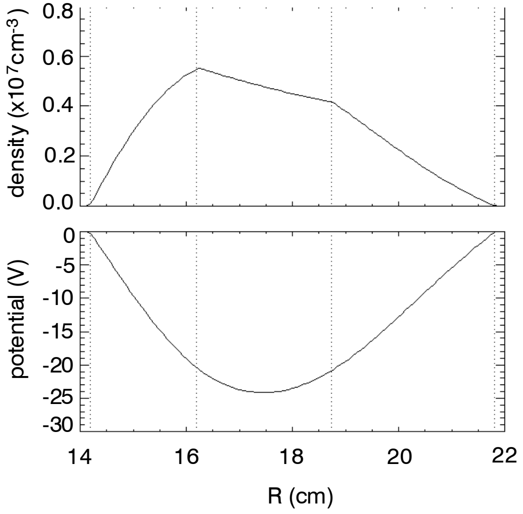
$$f_1 \approx 50\,\mathrm{kHz} \longrightarrow \frac{Q}{L} \approx 1.7\,\mathrm{nC/m}$$

  - Central potential on filament

$$V_0 \geq -27\,\mathrm{V}$$

- Equilibrium solution:
  - Density ~ **0.5 x 10^7 cm^{-3}**
  - Central potential -23V



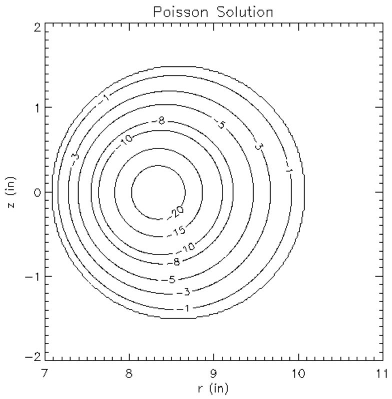


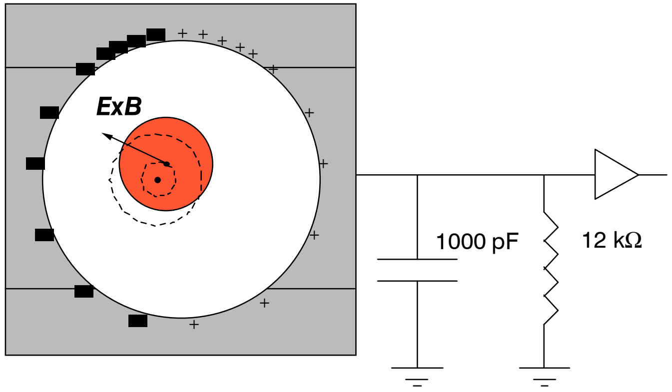
3 second confinement time is ~10^5 ExB rotations.

Simulating the *m*=1 Mode

Solve **Poisson's equation** in toroidal geometry for a *uniform density* plasma with specified position and radius.

Compute $\mathbf{E}_\rho$ and $\mathbf{E}_z$ from the potential solution.



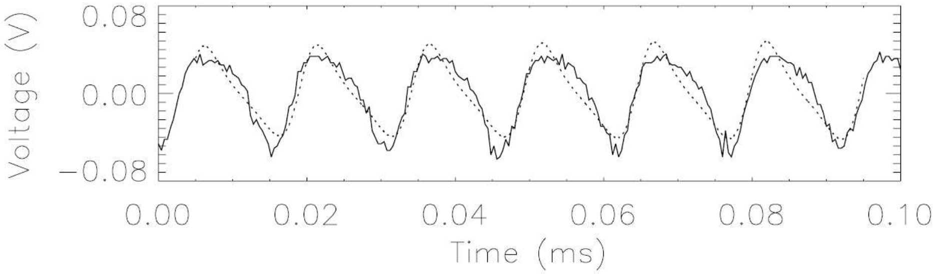


Integrate **E** along the surface of the electrode sections to obtain the charge on the wall probe.

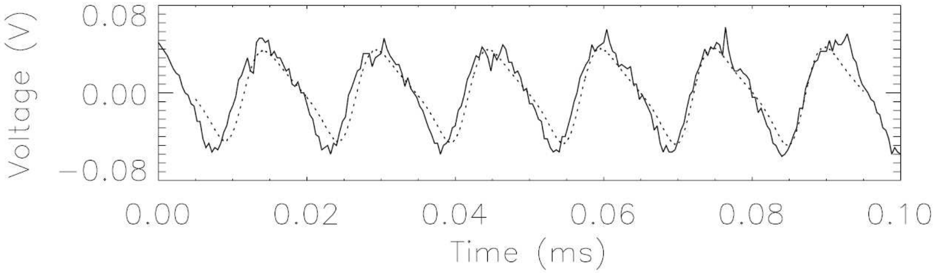
Calculate the **E** x **B** drift at plasma center and update the position and radius of the plasma

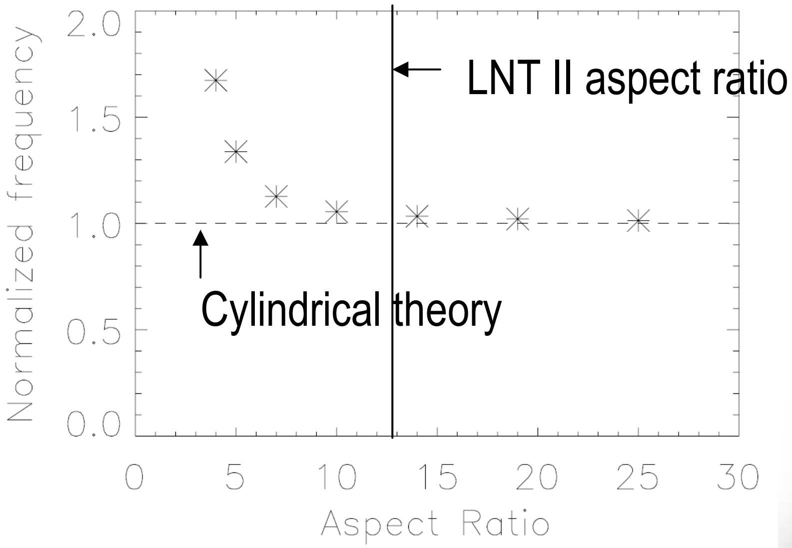
Simulation Results Compared to Data

Top Electrode Signal



Bottom Electrode Signal





LNT II aspect ratio

Cylindrical theory

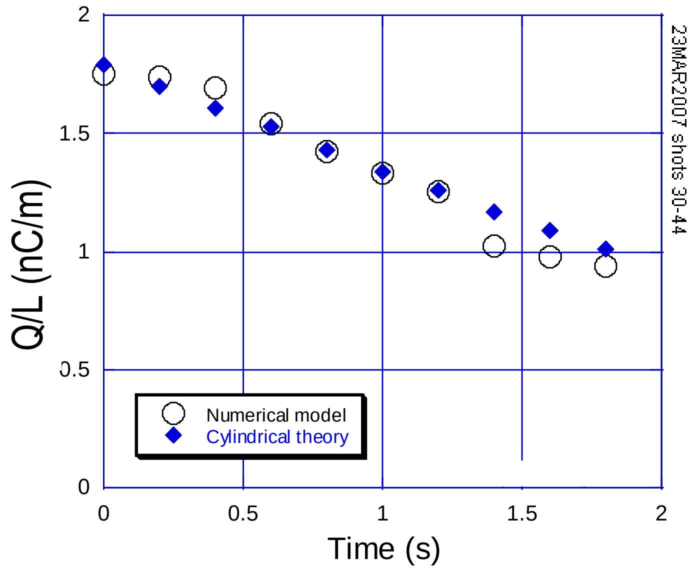
Signal characteristics used to determine simulation input parameters:

- frequency
- ratio of second harmonic power to fundamental power

Extracting Plasma Parameters using Simulations

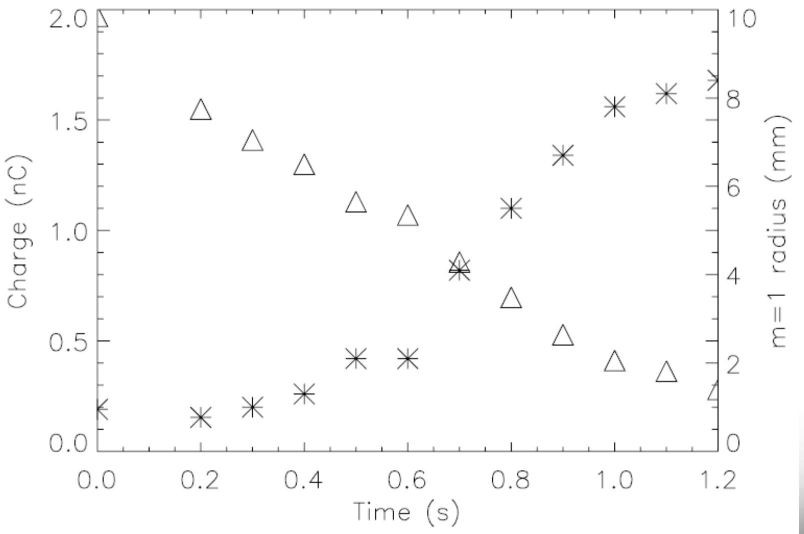
Near-resonant tone burst

- Excites small amplitude (< 1mm) mode
- Maximizes confinement time.



Fixed frequency (55 kHz) tone burst

- Drives mode to larger amplitude
- Incomplete autoresonance [1,2]
- Accelerates charge loss.

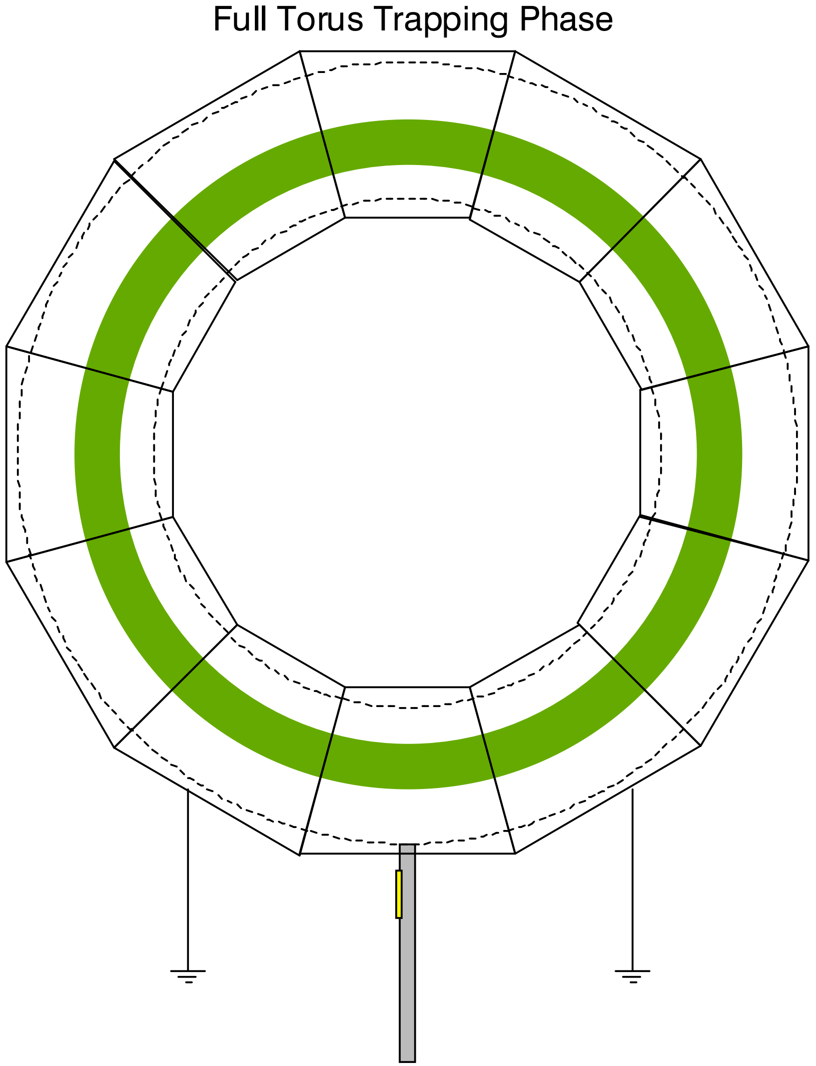


$$f_1 = \frac{Q}{4\pi^2 \varepsilon_o L B b^2}\left(\frac{1}{1-(A_1/b)^2}\right)$$

[1] J. Fajans, E. Gilson, and L. Friedland, *Phys. Rev. Lett.* **82**, 4444 (1999).
[2] J.R. Danielson, T.M. Weber, C.M. Surko, *Phys. Plasmas* **13,** 123502 (2006).

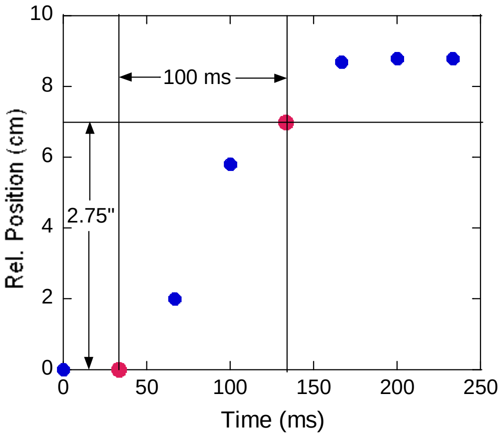
B.N. Ha, J.P. Marler, and M.R. Stoneking submitted to *Phys. Plasmas* (2008).

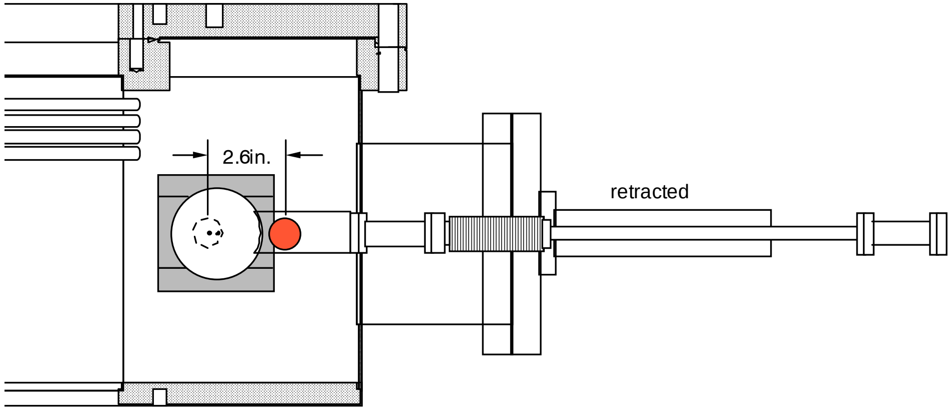
Future Work: *Fully Toroidal Trapping*

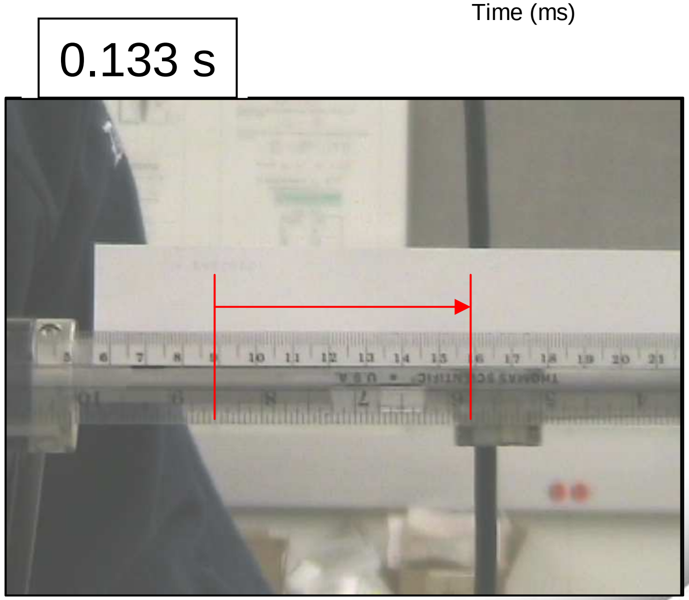


Pneumatic Filament Retraction System

- •Filament mounted on a welded bellows feedthru
- •Solenoid activated pneumatic switch drives retraction
- •Retraction time ~ 0.1 seconds



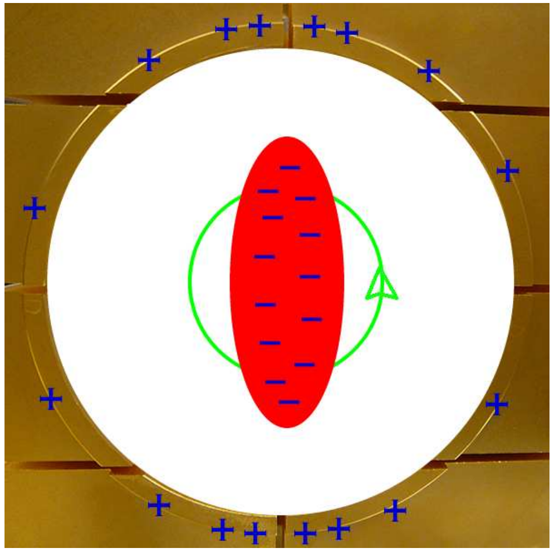




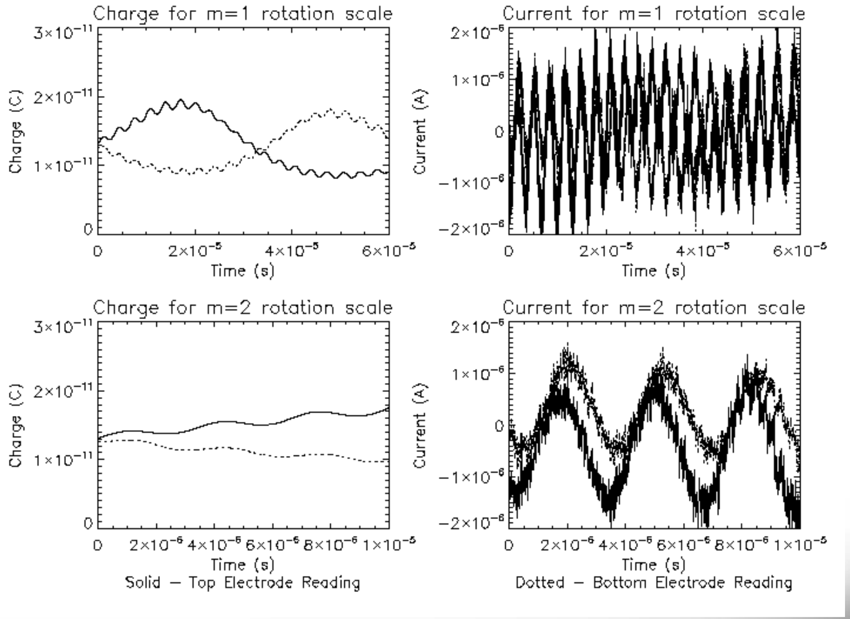
Future Work:

Launch, detect, and model the m=2 diocotron mode

- Frequency of the *m*=2 mode yields information on *density*.
- Coupled with total charge measurement from *m*=1 mode frequency, can get measurement of *transport.*



Simulation results with *m=1* and *m=2* mode



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