NONLINEAR ELECTROMAGNETICS MODEL OF AN ASYMMETRICALLY DRIVEN CAPACITIVE DISCHARGE

M.A. Lieberman

Department of Electrical Engineering and Computer Sciences
University of California
Berkeley, CA 94720

Collaborators:
E. Kawamura and A.J. Lichtenberg, UC Berkeley
De-Qi Wen and You-Nian Wang, Dalian University of Technology

Publication: Phys. Plasmas **24** 083517 (2017)

Partially supported by DOE Office of Fusion Energy Science

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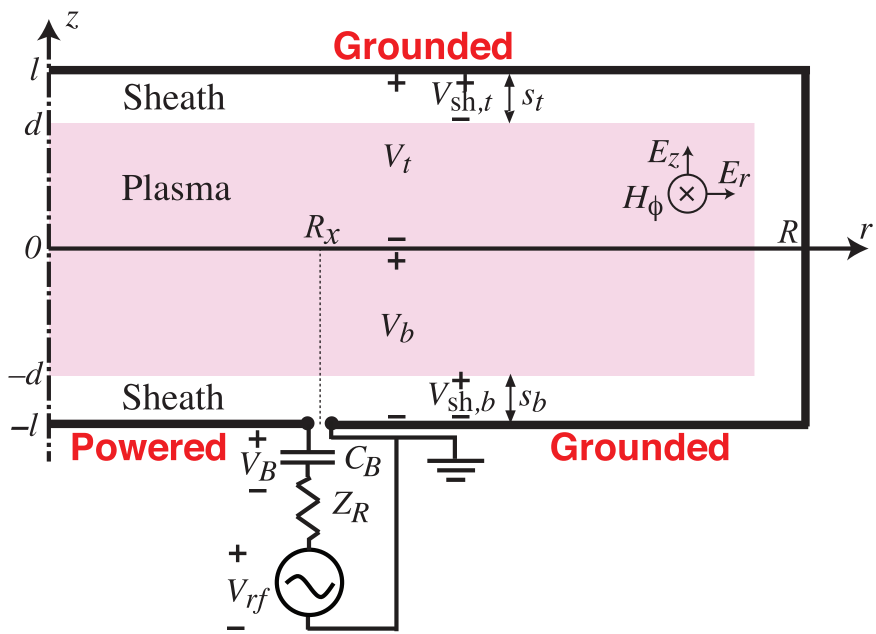
SYSTEM CONFIGURATION

- Cylindrical discharge radius R and gap $2l$
- Driven axisymmetrically by high frequency source at radius $R_x < R$
- Maximum sheath width $s_{\max} \ll l \ll R$



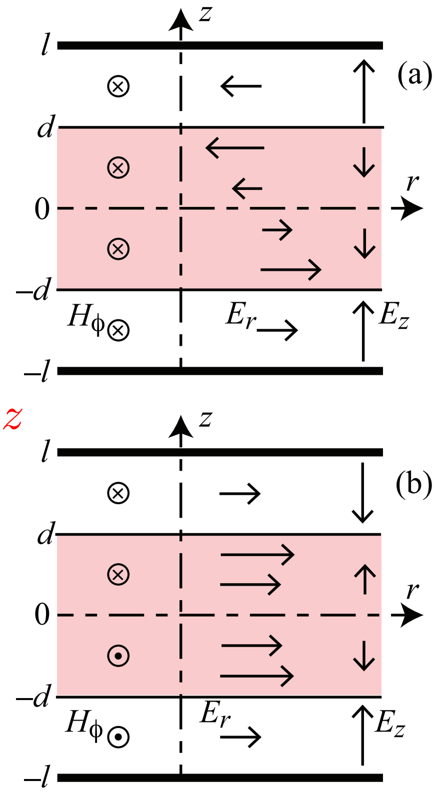
- Uniform density plasma n_{e0}
- Child law sheaths: $s_{t,b}(r, t)$

ELECTROMAGNETICS AND SPATIAL RESONANCE

- Transverse magnetic (TM) mode structure $(H_\phi,\ E_r,\ E_z)$
- Top electrode/bulk plasma/bottom electrode sandwich forms a 3-electrode system in which two radially-propagating TM wave modes exist
- Symmetric mode (a): $E_{zs} = A(r,t)\cosh\alpha z$
- Antisymmetric mode (b): $E_{za} = B(r,t)\sinh\alpha z$
- Low pressure $(\nu \ll \omega) \Longrightarrow$

  $\alpha = \omega_{pe}/c =$ plasma axial decay constant,
  $\omega_{pe} =$ plasma frequency, $c =$ speed of light
- Radial (quarter-wave) resonance; e.g.,

$$\omega_{\rm sw} = \left(\frac{\bar{s}}{l}\right)^{1/2} \frac{2.405\,c}{R}$$

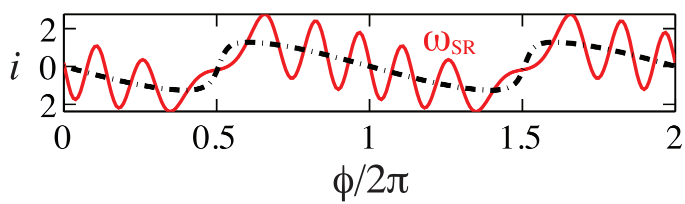


NONLINEAR SHEATHS AND SERIES RESONANCE

- Sinusoidal rf driving source: $V_{\rm rf} = V_{\rm rf0}\cos\phi$; $(\phi = \omega t)$
- Sheath motions $s_{t,b}(r,t)$ vary nonlinearly with the voltage across the sheath
- Child law sheath nonlinearity: $s(r,t) \propto V_{sh}^{2/3}(r,t)$
- Nonlinearity generates driving frequency harmonics 2ω, 3ω, ...

- Series resonance (capacitive sheaths + inductive plasma) near the Nth harmonic:

$$\omega_{\rm SR} = \left(\frac{\bar{s}}{l}\right)^{1/2} \omega_{pe} \approx N\omega$$



SOLUTION PROCEDURE

- Maxwell's equations + Newton's laws for TM modes in the plasma:

$$\text{symmetric mode: } E_{zs} = A(r,t)\cosh\alpha z$$

$$\text{antisymmetric mode: } E_{za} = B(r,t)\sinh\alpha z$$

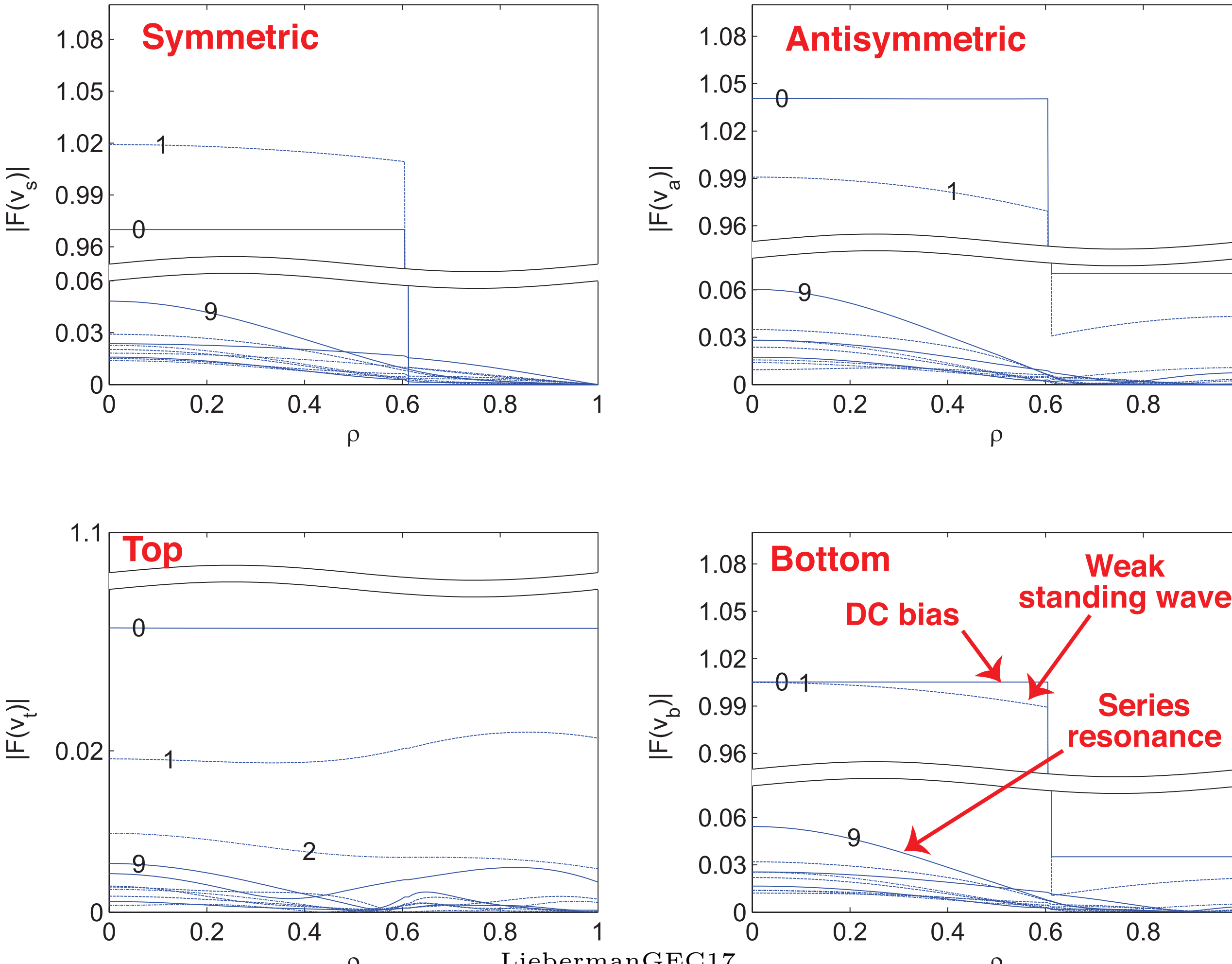
- Self-consistent (nonlinear) rf Child law in the sheaths:

  $\Longrightarrow$ Set of nonlinear pde's in (r,t), solved numerically

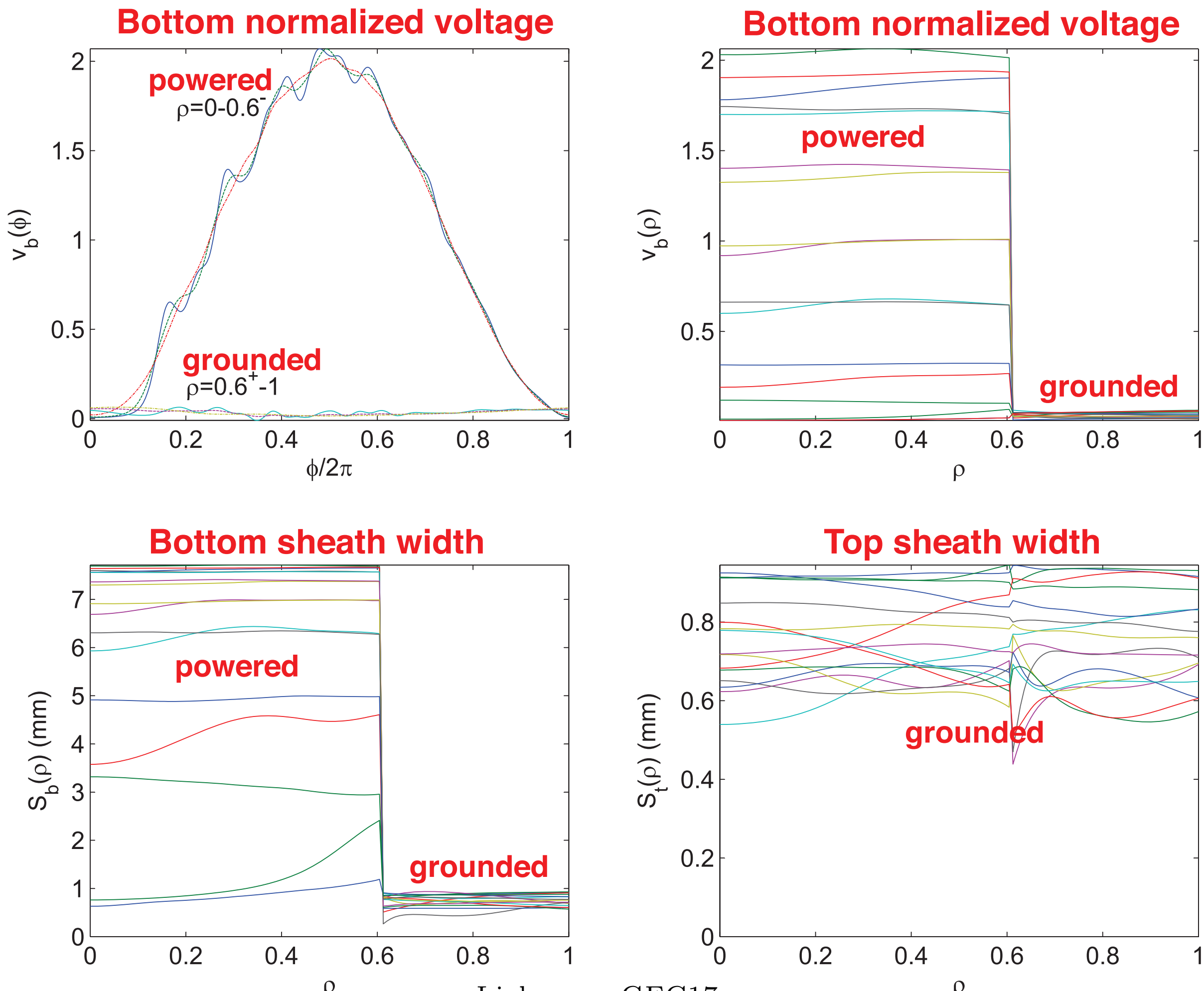
- Typical commercial system parameters:
  $p = 10$ mTorr chlorine
  discharge radius $R = 25$ cm, gap $2l = 5$ cm,
  powered electrode radius $R_x = 15$ cm
  $n_{e0} \approx 2\times 10^{16}$ m^{-3} (electron power ≈ 200 W)
  $T_e = 3.2$ V, source resistance $Z_R = 0.5\ \Omega$
  (self-consistent fluid code $\Rightarrow V_{\rm rf0}$ and T_e for the specified n_{e0})

- Mainly examine 30 MHz ($V_{\rm rf0} = 560$ V)
  Also compare 30 and 60 MHz power depositions

30 MHZ NORMALIZED FOURIER VOLTAGES VS $\rho = r/R$

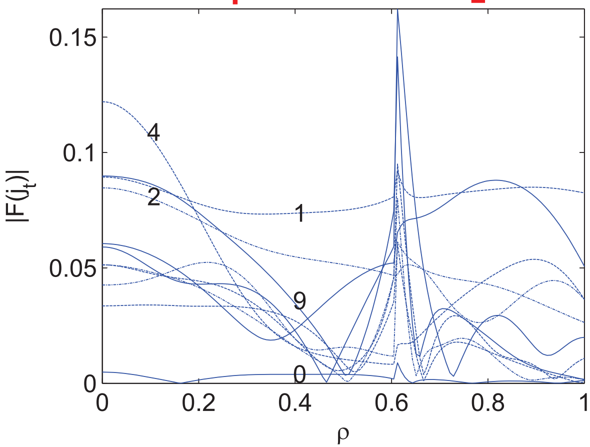


30 MHZ VOLTAGES AND SHEATH WIDTHS

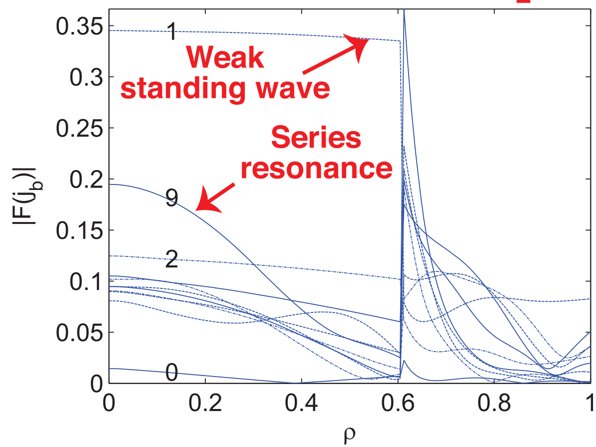


30 MHZ CURRENT DENSITIES, POWER, V_{disch} AND I_{disch}

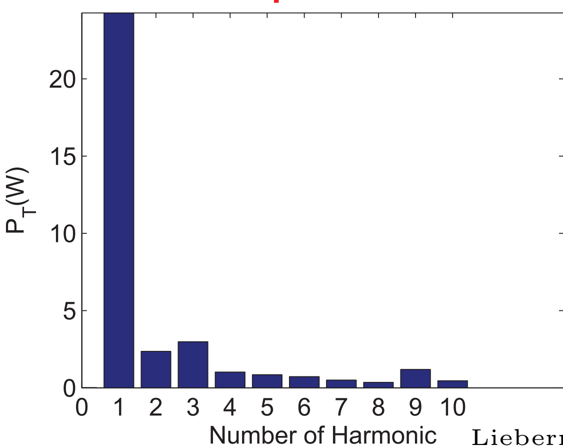
Top normalized J_z



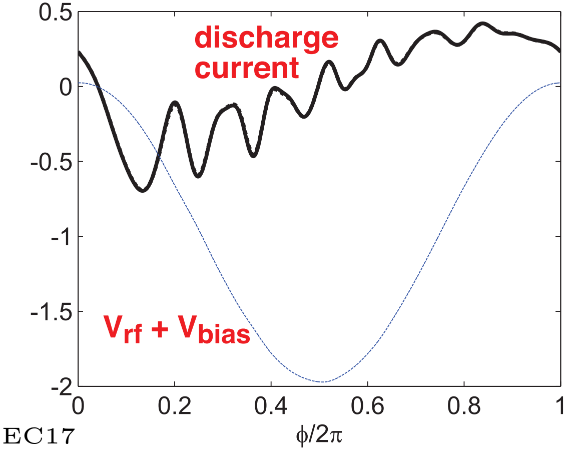
Bottom normalized J_z



Electron power absorbed

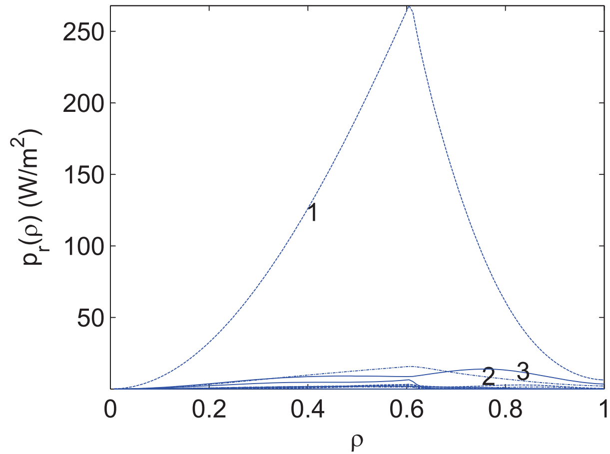


Normalized voltage and current

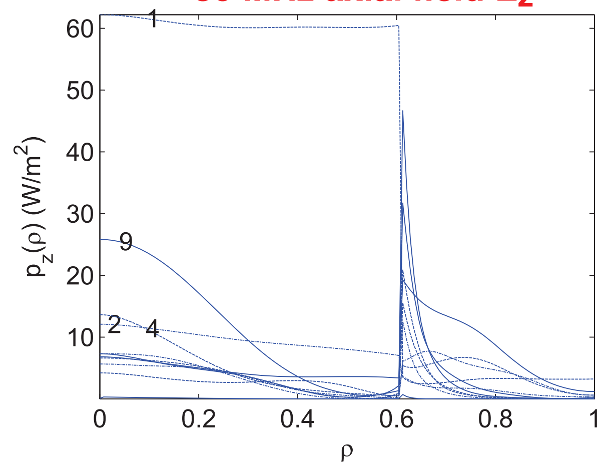


30 AND 60 MHZ POWERS/UNIT AREA

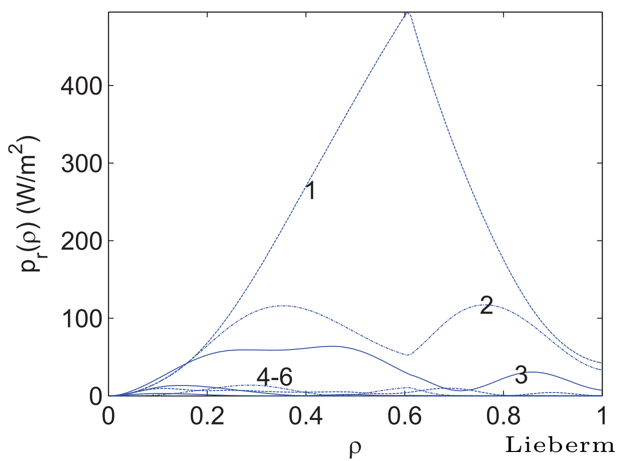
30 MHz radial field E_r



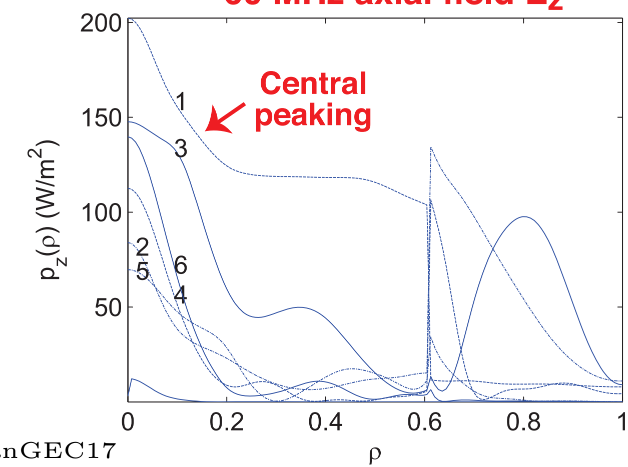
30 MHz axial field E_z



60 MHz radial field E_r



60 MHz axial field E_z



CONCLUSIONS

- We developed and numerically solved a nonlinear electromagnetics model of an asymmetrically driven rf capacitive discharge, incorporating symmetric and antisymmetric radially propagating waves.
- The series resonance-enhanced harmonics of the driving frequency can couple strongly to the standing wave spatial resonances.
- At 60 MHz, there is significant center-peaking of the higher harmonic fields and the electron power/area (seen experimentally: GEC abstract SR3-00007).
- These phenomena may be responsible for the center-peaked plasma densities seen experimentally in high frequency capacitive discharges (e.g., Sawada et al, JJAP, 2014).

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