NONLINEAR STANDING WAVE EXCITATION BY SERIES-RESONANCE ENHANCED HARMONICS IN LOW PRESSURE CAPACITIVE DISCHARGES

M.A. Lieberman

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

Collaborators:
E. Kawamura, A.J. Lichtenberg, UC Berkeley
A. Marakhtanov, Lam Research Corporation

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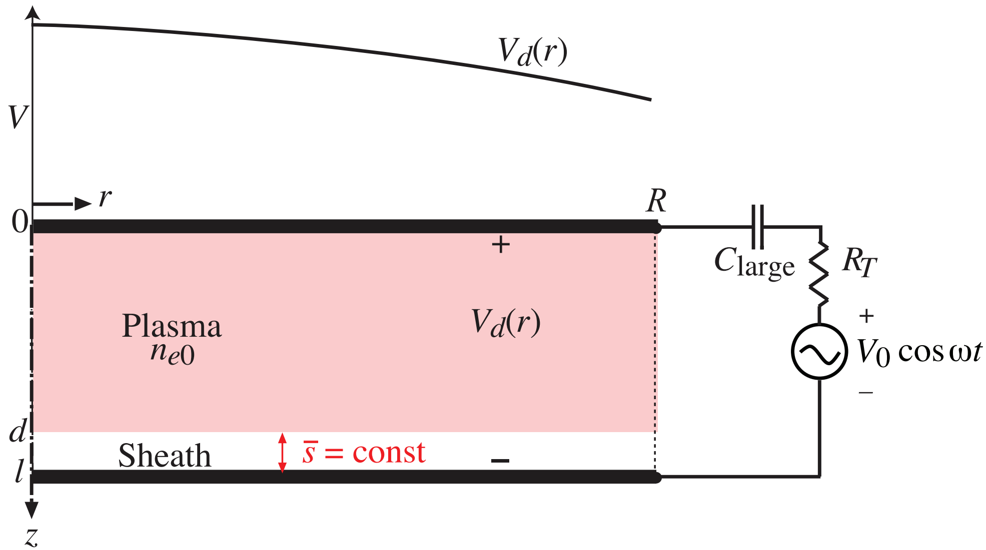
INTRODUCTION — STANDING WAVES

(Lieberman et al, PSST, 2002)

- Cylindrical discharge driven at outer radius
- Linear sheath model (constant sheath width $\bar{s}$)
- Electromagnetic fields



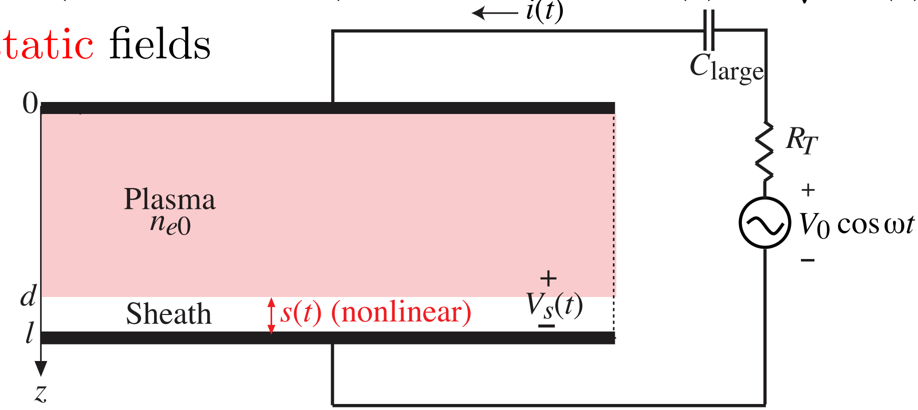
- Spatial (quarter-wave) resonance

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

INTRODUCTION — NONLINEAR SERIES RESONANCE

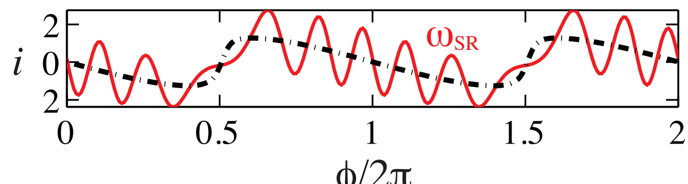
(Mussenbrock and Brinkmann, APL, 2006; Lieberman et al, PoP, 2008)

- Voltage-driven, asymmetric (single sheath) discharge
- Nonlinear (homogeneous) sheath model $\bar{s}(t) \propto \sqrt{V_s(t)}$
- Electrostatic fields

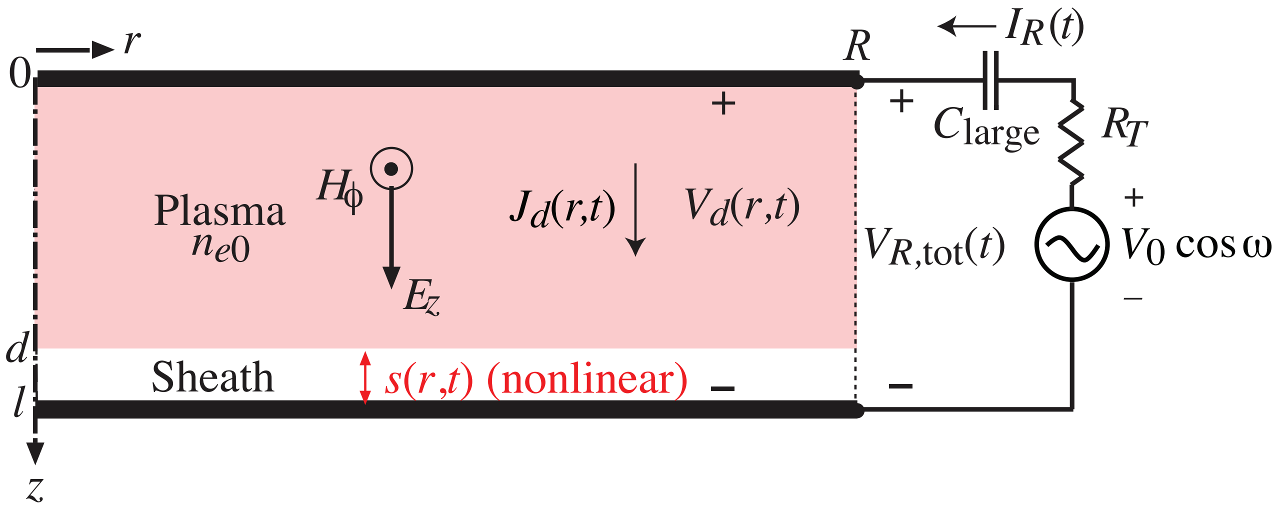


- Series resonance (capacitive sheath + inductive plasma)

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



SERIES RESONANCE ENHANCED STANDING WAVES



- Nonlinear radially-varying sheath + electromagnetic fields
- Low density regime ($E_z \gg E_r$) with ordering

$$\boxed{s \ll l \ll \delta_p,\ R}$$

with $\delta_p = c/\omega_p$ the collisionless skin depth

MODEL EQUATIONS AND BASE CASE

$$\frac{\partial \Sigma}{\partial t} = J_d - J_{i0} + J_{e0}\mathrm{e}^{-\Sigma^2/2en_e\epsilon_0 \mathrm{T}_e}, \quad \Sigma > 0, \qquad \text{(sheath charge)}$$

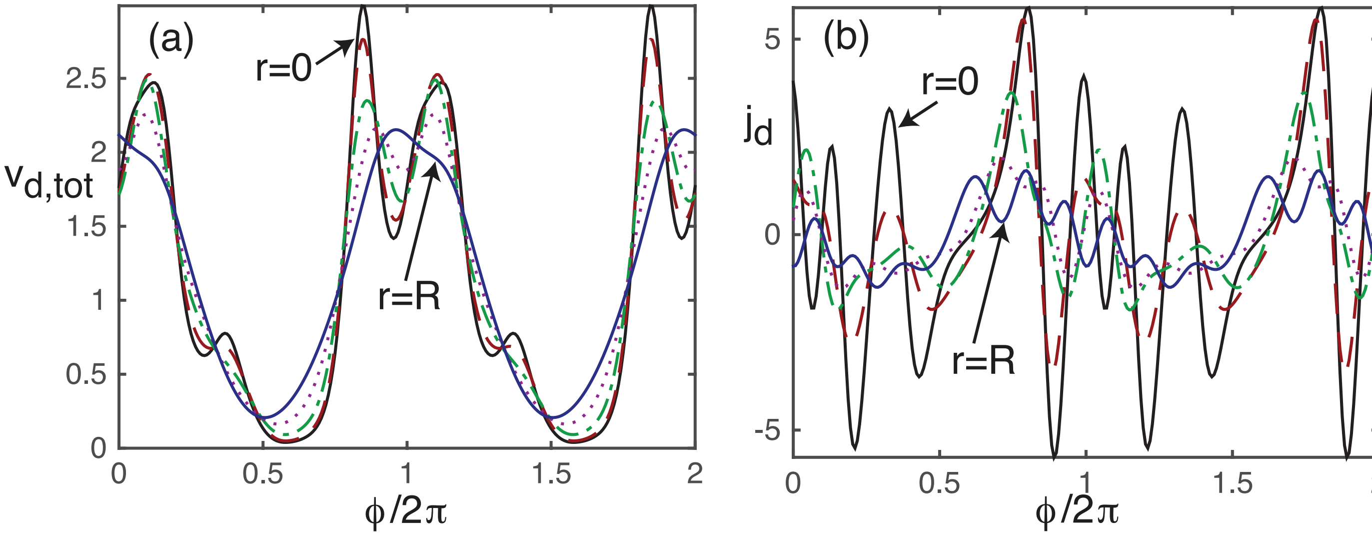
$$\frac{\partial J_d}{\partial t} = \frac{e^2 n_e}{md}(V_d - V_{\mathrm{dc}}) - \frac{e}{2\epsilon_0 md}\Sigma^2 - \nu J_d, \qquad \text{(axial current density)}$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V_d}{\partial r}\right) = \mu_0 l \frac{\partial J_d}{\partial t}, \qquad \text{(radial transmission line voltage)}$$

$\Sigma = en_e s(r,t)$, $\nu =$ collision frequency, $V_{\mathrm{dc}} =$ bias voltage

- Solve for $V_d(r,t)$, $J_d(r,t)$, $s(r,t)$, and V_{dc}
- BASE CASE:
  $l = 2$ cm, $R = 15$ cm conducting electrodes
  10 mT argon, $n_e = 2 \times 10^{16}$ m^{-3}, $\mathrm{T}_e = 3$ V
  $V_0 = 500$ V, $f = 60$ MHz, $R_T = 0.5\ \Omega$

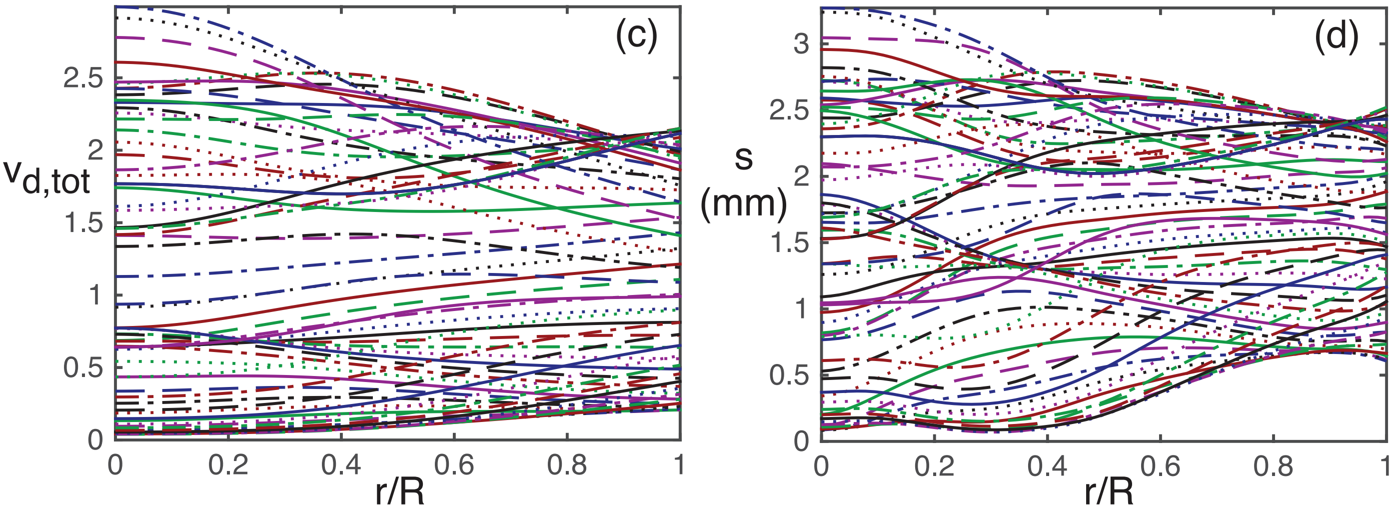
BASE CASE DISCHARGE VOLTAGE AND CURRENT



- Normalized discharge voltage has weak harmonic content at $r = R$; stronger at $r = 0$
- Voltage at $r = R$ can be greater than at $r = 0$
- Normalized discharge current density shows strong harmonics; series resonance oscillations at $r = R$; strong at $r = 0$

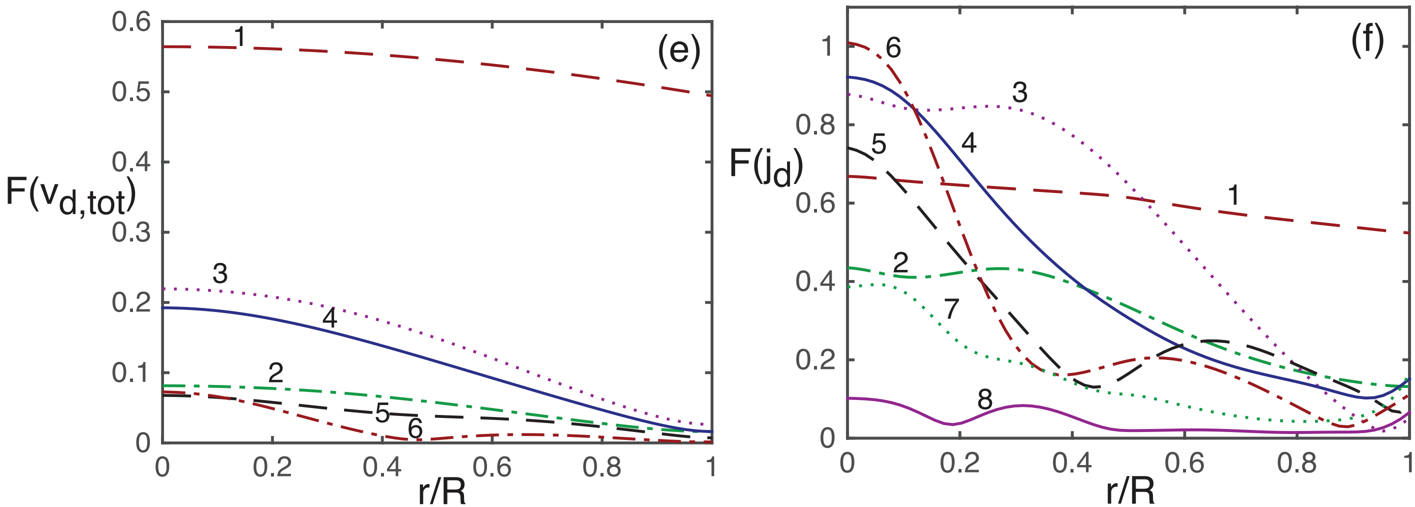
BASE CASE VOLTAGE AND SHEATH MOTION

(65 times within an rf cycle)



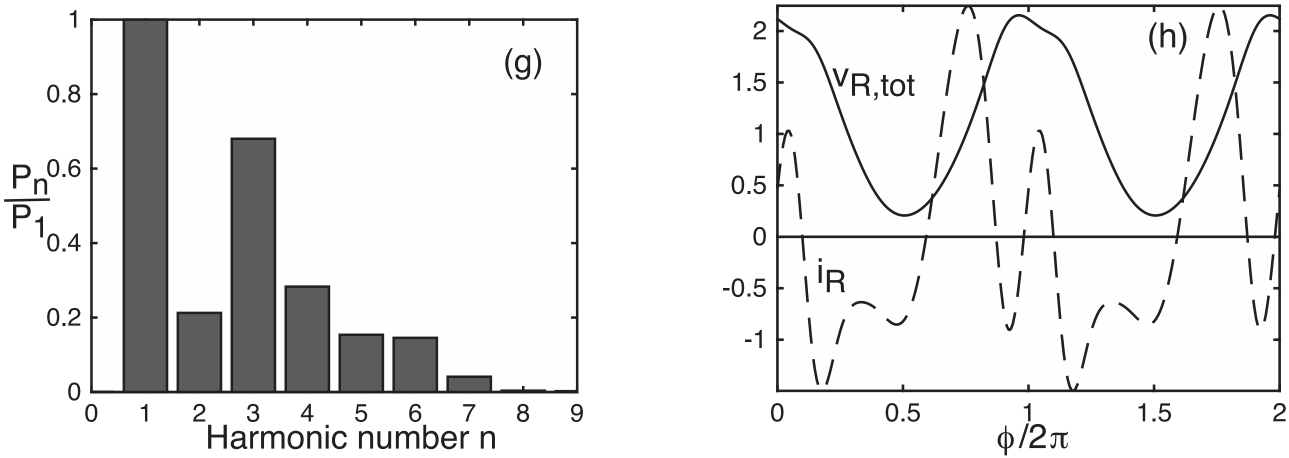
- Maximum discharge voltage is higher at $r = 0$ than at $r = R$
- Minimum sheath width at $r = 0$ is smaller than at $r = R$
  $\Rightarrow$ electrons collected near $r = 0$, ions collected near $r = R$
- Maximum sheath width at $r = 0$ is larger than at $r = R$
- Sheath motion shows series resonance oscillations; strong at $r = 0$

BASE CASE FOURIER TRANSFORMS OF V AND J



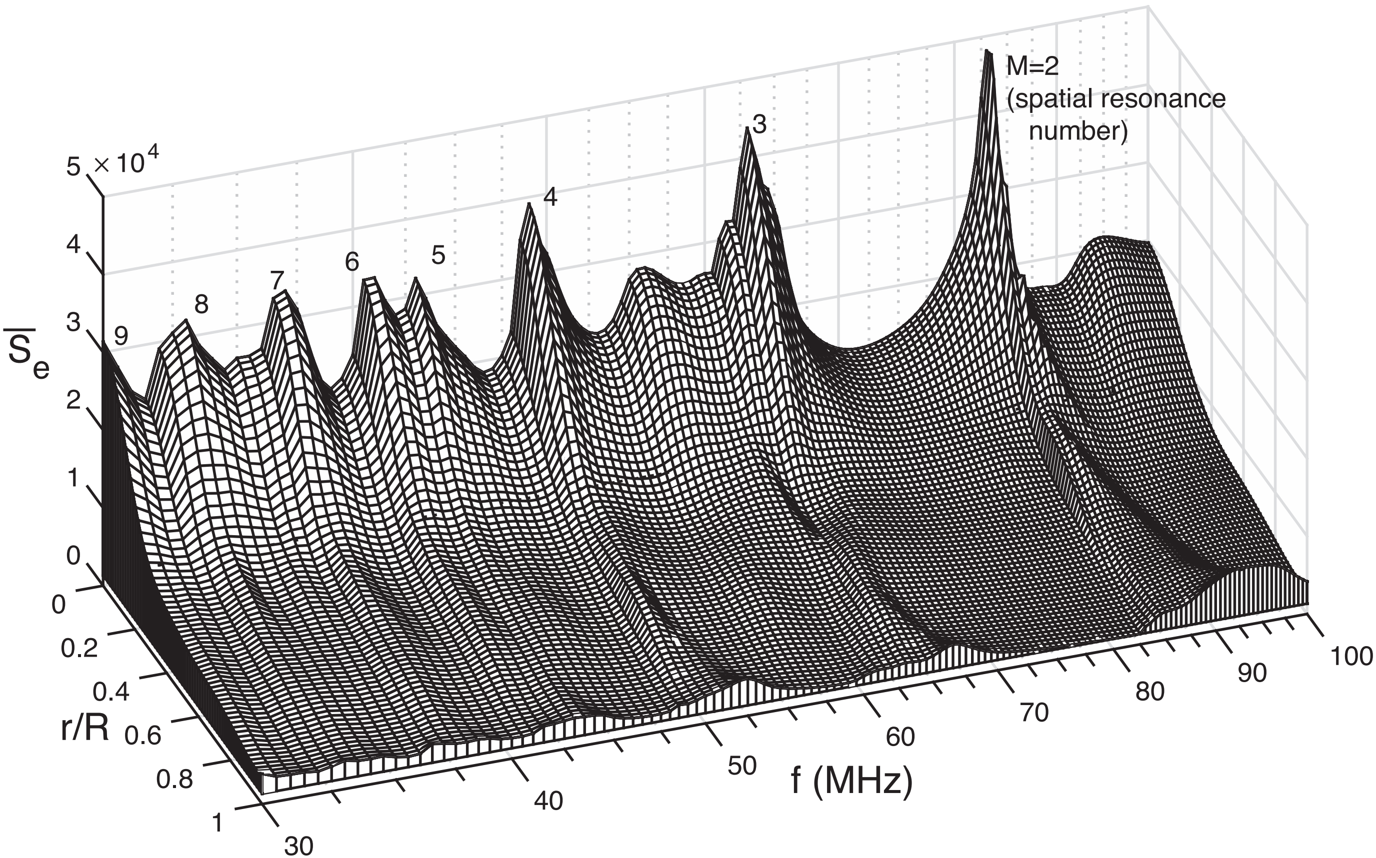
- Fundamental voltage and current show a weak standing wave
- Voltage shows significant 3rd and 4th harmonics
- Discharge current shows strong central ($r = 0$) 3–6 harmonics
  - — $J \propto \omega CV$ (capacitive sheath)
  - — Series resonance enhancement (sheath resonates with plasma)

BASE CASE TOTAL POWER AND EXCITATION V-I



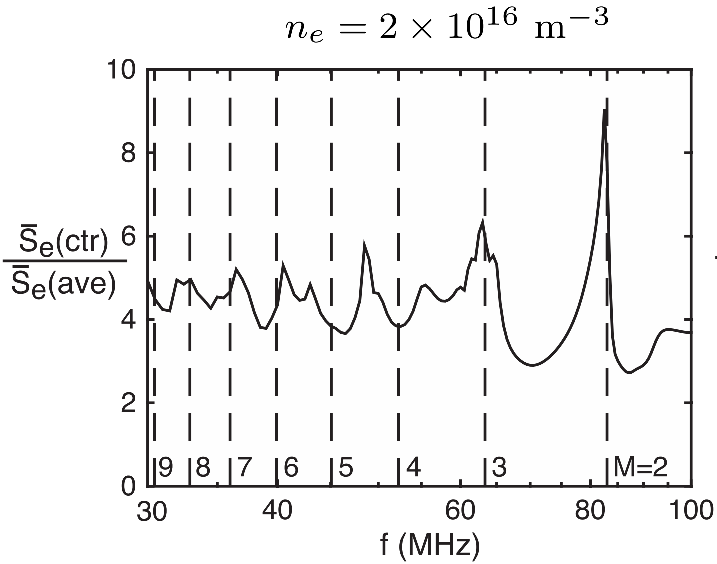
- Total electron power has strong 3rd and 4th harmonics
- Excitation voltage is nearly sinusoidal with a dc bias
- Excitation current has strong harmonic content

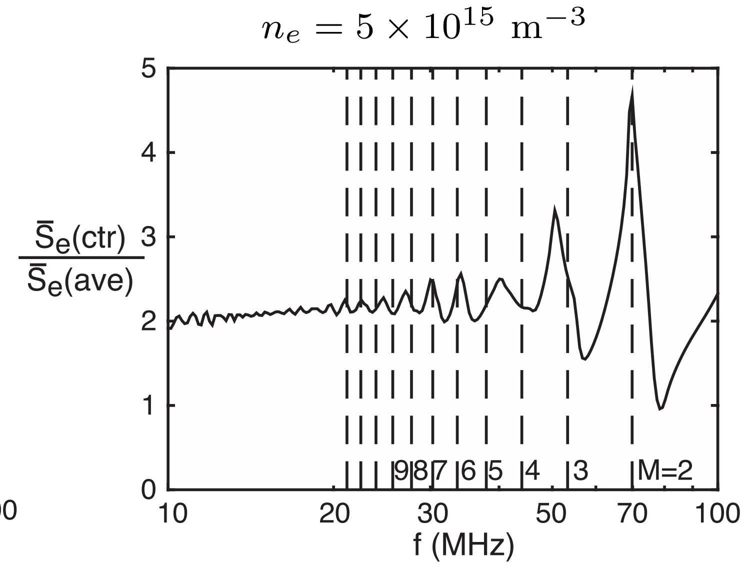
POWER/AREA VS FREQUENCY AND RADIUS



- Strong spatial resonance effects seen near $M\omega = \omega_{\text{SW}}$

CENTER-TO-AVERAGE POWER/AREA





- Dashed vertical lines are the spatial resonances
- Even at lower frequencies there is a significant center-peaking of the electron power/area

CONCLUSIONS

- We developed and numerically solved a nonlinear radial transmission line model of an asymmetrically driven rf capacitive discharge.
- We found that the series resonance-enhanced harmonics of the driving frequency coupled strongly to the standing wave spatial resonances.
- We found significant center-peaking of the electron power/area, even at low excitation frequencies.
- These phenomena may be responsible for the center-peaked plasma density seen experimentally in high frequency capacitive discharges (e.g., Sawada et al, JJAP, 2014).

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