NONLINEARITY AND WAVES IN CAPACITIVE DISCHARGES

M.A. Lieberman

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

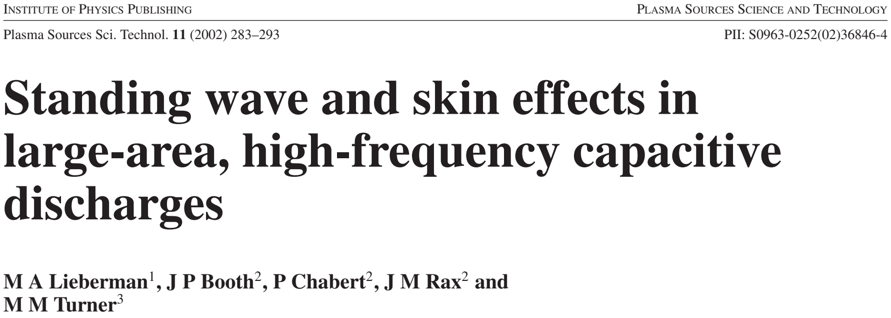
Collaborators:
E. Kawamura and A.J. Lichtenberg, UC Berkeley
Pascal Chabert, Ecole Polytechnique
De-Qi Wen, Kai Zhao, and You-Nian Wang, Dalian University of Technology

Download this talk:

http://www.eecs.berkeley.edu/∼lieber

MOTIVATION

- Radial uniformity in high frequency capacitive discharges



Institute of Physics Publishing — Plasma Sources Science and Technology

Plasma Sources Sci. Technol. **11** (2002) 283–293 — PII: S0963-0252(02)36846-4

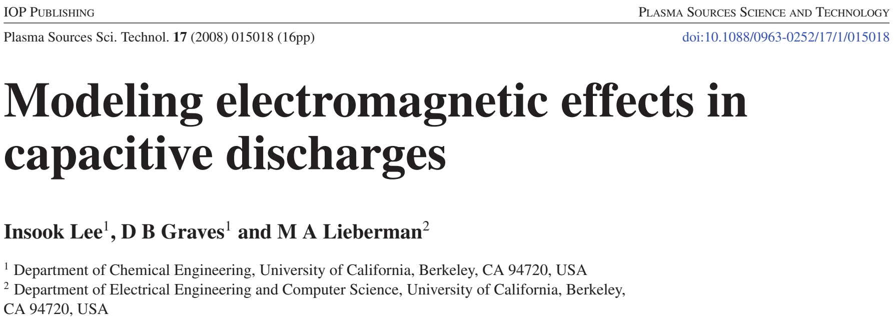
Standing wave and skin effects in large-area, high-frequency capacitive discharges

M A Lieberman[1], J P Booth[2], P Chabert[2], J M Rax[2] and M M Turner[3]

- Linear analytical electromagnetics model showed
  - Standing wave effect $\Longrightarrow$ center-high power deposition
  - Skin effect $\Longrightarrow$ center-low power deposition

MOTIVATION

- 2D fluid simulations with linear electromagnetics showed the same



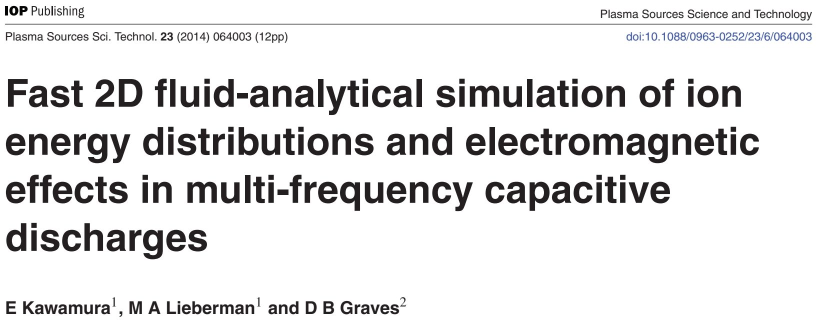
IOP Publishing | Plasma Sources Science and Technology

Plasma Sources Sci. Technol. **17** (2008) 015018 (16pp) | doi:10.1088/0963-0252/17/1/015018

Modeling electromagnetic effects in capacitive discharges

Insook Lee[1], D B Graves[1] and M A Lieberman[2]

[1] Department of Chemical Engineering, University of California, Berkeley, CA 94720, USA
[2] Department of Electrical Engineering and Computer Science, University of California, Berkeley, CA 94720, USA



IOP Publishing | Plasma Sources Science and Technology

Plasma Sources Sci. Technol. **23** (2014) 064003 (12pp) | doi:10.1088/0963-0252/23/6/064003

Fast 2D fluid-analytical simulation of ion energy distributions and electromagnetic effects in multi-frequency capacitive discharges

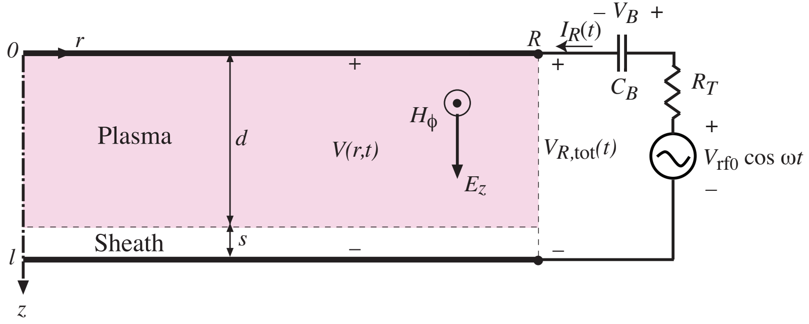
E Kawamura[1], M A Lieberman[1] and D B Graves[2]

- But experiments sometimes showed very sharply peaked central plasma nonuniformity

CENTRAL PLASMA NONUNIFORMITY

- Asymmetric argon capacitive discharge (2.5 cm gap, driven at 60 MHz), showing $n_e(r)$
  (Sawada et al, JJAP, 2014)

- Investigate coupling of nonlinearly-generated series-resonance enhanced harmonics of driving frequency to standing waves using a single-sheath radial transmission line model



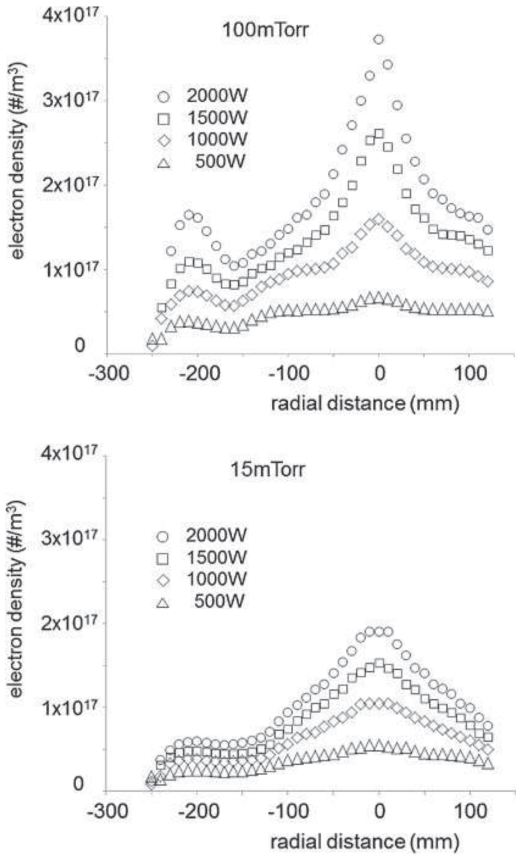


Fig. 3. Experimentally measured electron density profiles along the test-bench A reactor midgap for argon plasma driven at 60 MHz. Top: 100 mTorr. Bottom: 15 mTorr.

TRANSMISSION LINE MODEL RESULTS

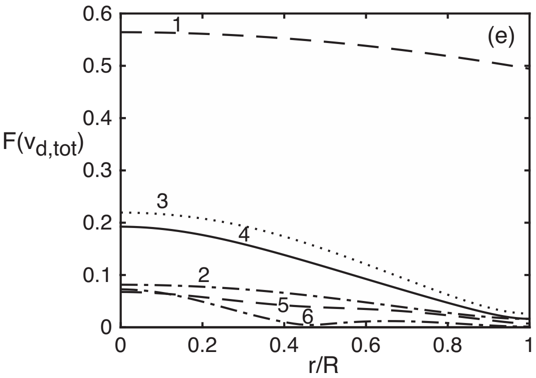
- Series resonances

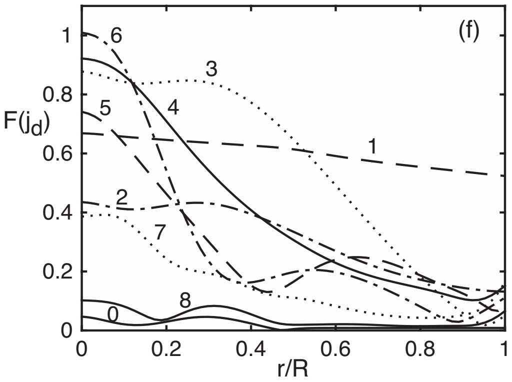
$$\omega_{\mathrm{SR}} = N\omega = \left(\frac{s}{d}\right)^{1/2}\omega_{pe}$$

- Standing wave resonances

$$\omega_{\mathrm{wave}} = M\omega = \left(\frac{s}{d}\right)^{1/2}\frac{\chi_{01}c}{R}$$

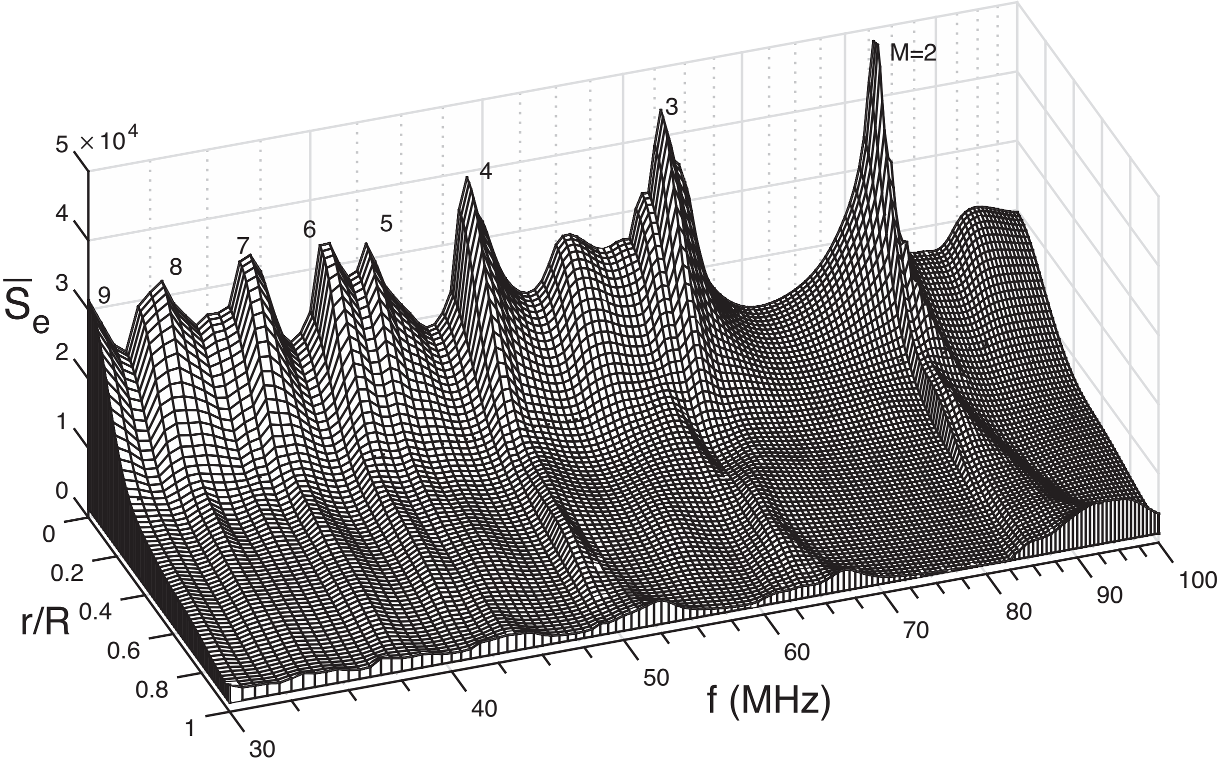
- Example
  10 mTorr argon driven at 60 MHz and 500 V through 0.5 Ω,
  15 cm radius, 2 cm gap, $n_e = 2\times10^{16}$ m^{-3}





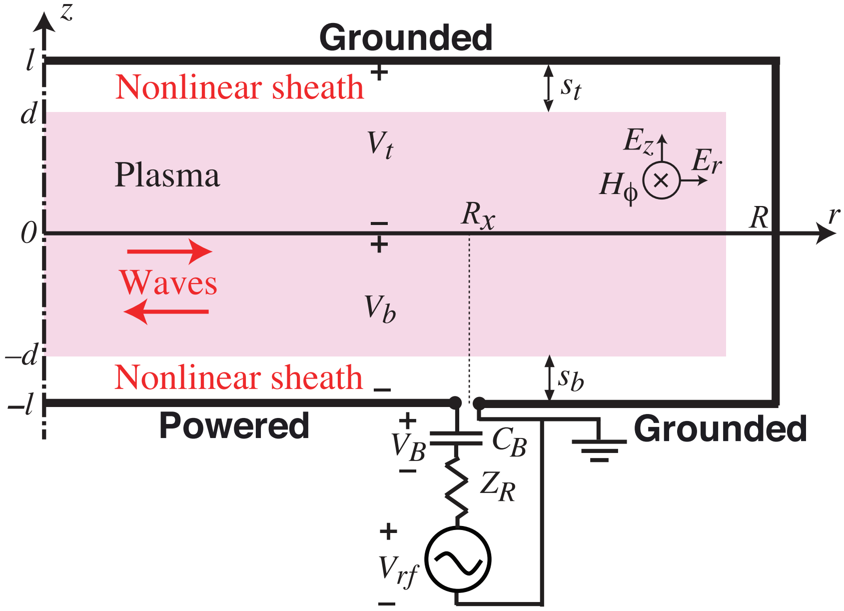
DISCHARGE ELECTRON POWER/AREA

- 10 mTorr argon discharge driven through 0.5 Ω, 15 cm radius, 2 cm gap
- Voltage rescaled as $\omega^2 V_{\rm rf} = {\rm const}$ to keep $n_e = 2\times10^{16}$ m^{-3}



ASYMMETRICALLY-DRIVEN DISCHARGE

- Motivation: uniformity and controllability of large area, high frequency capacitive discharges for thin film processing
- Cylindrical discharge radius R and gap $2l$
- Driven axisymmetrically at radius R_x by high frequency source $V_{\rm rf}$



Coupling of Child law sheath nonlinearities to waves

LiebermanAKT19

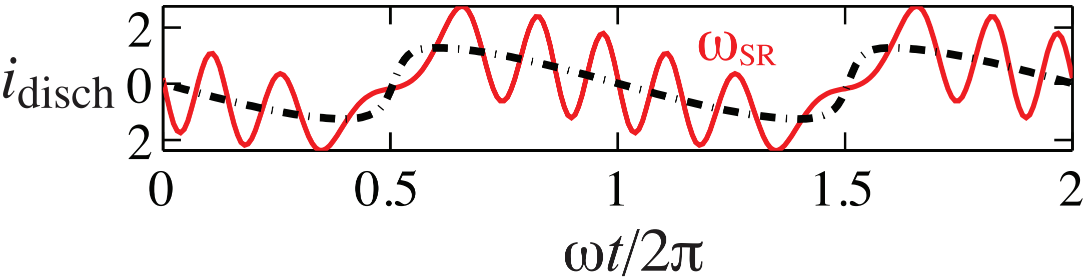
NONLINEAR SHEATHS AND SERIES RESONANCE

- Sinusoidal rf driving source: $V_{\mathrm{rf}} = V_{\mathrm{rf0}} \cos \omega t$
- Child law sheaths strongly nonlinear: $V_{sh} \propto Q_{sh}^4$
- Sheath nonlinearity generates harmonics 2ω, 3ω, ...

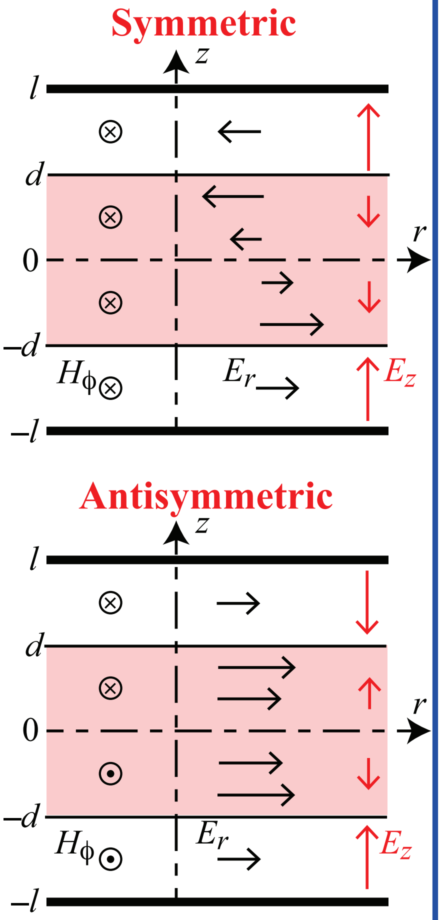
- Series resonance (capacitive sheaths + inductive plasma) near the Nth harmonic:

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

$\bar{s}$ = mean sheath width; ω_{pe} = plasma frequency



ELECTROMAGNETICS AND SPATIAL RESONANCE



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

  $(\alpha =$ inverse plasma skin depth$)$
- Radial (spatial) resonance near Mth driving frequency harmonic; e.g., for antisymmetric mode

$$M\omega \approx \omega_a = 3.83\,\omega_{pe}\frac{\sqrt{\bar{s}d}}{R}$$

THEORETICAL MODEL SOLUTION AND DISCHARGE PARAMETERS

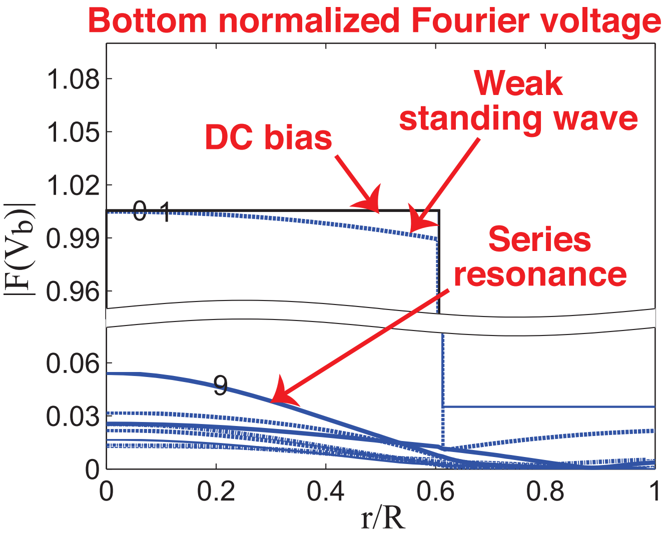
- Maxwell's equations + Newton's laws
  for symmetric and antisymmetric modes in the plasma
- Self-consistent (nonlinear) rf Child law in the sheaths

$\Longrightarrow$ 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
  electron power $P_e \approx 200$ W $(n_{e0} \approx 2 \times 10^{16}\ \mathrm{m}^{-3})$

- Example of 30 MHz ($V_{\mathrm{rf0}} = 560$ V)
  Compare 30 and 60 MHz powers

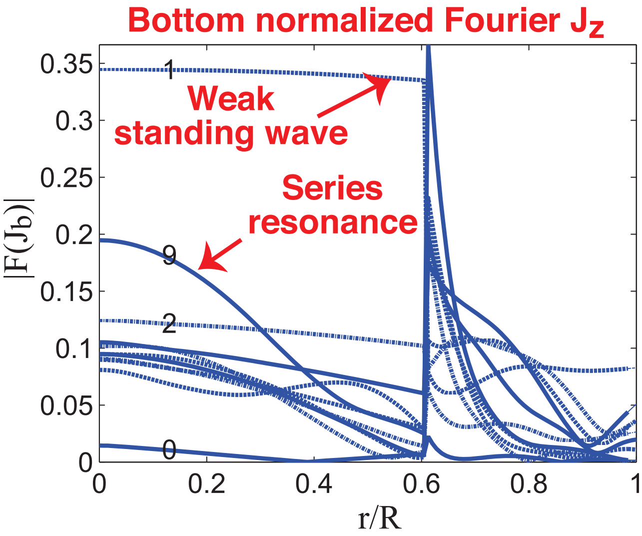
30 MHz VOLTAGE AND CURRENT HARMONICS


Bottom normalized Fourier voltage

Weak standing wave

DC bias

Series resonance


Bottom normalized Fourier J_z

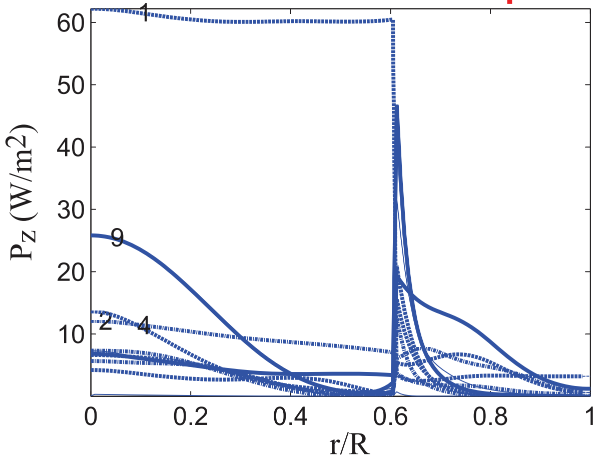
Weak standing wave

Series resonance

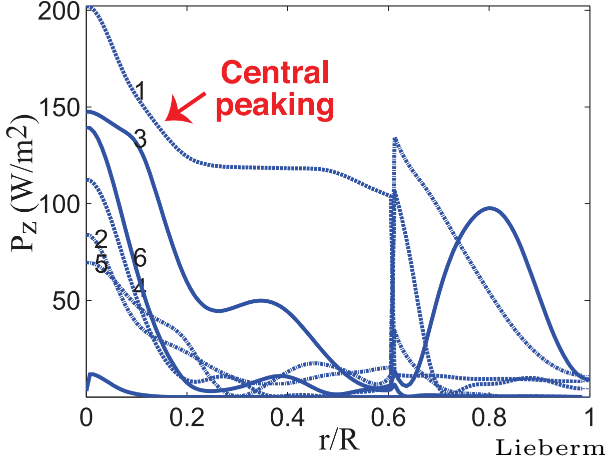
- Weak 1st harmonic standing wave
- Significant 9th harmonic series resonance

30 AND 60 MHz POWER HARMONICS

30 MHz-driven axial field power

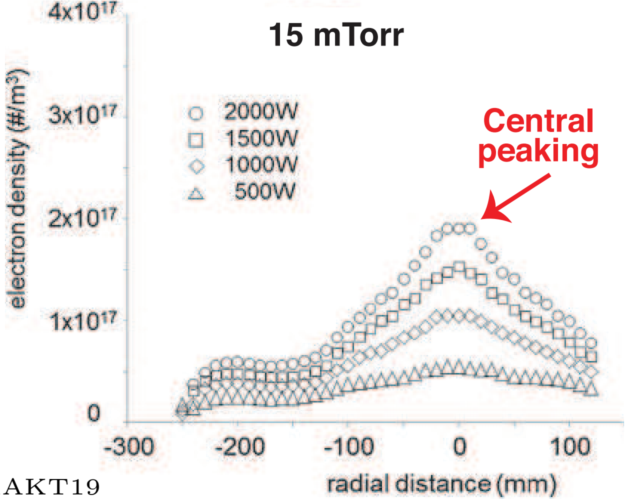


60 MHz-driven axial field power



Central peaking

Measurements of $n_e(r)$ (2.5 cm gap, driven at 60 MHz), showing central peaking (Sawada et al, JJAP, 2014)



15 mTorr

Central peaking

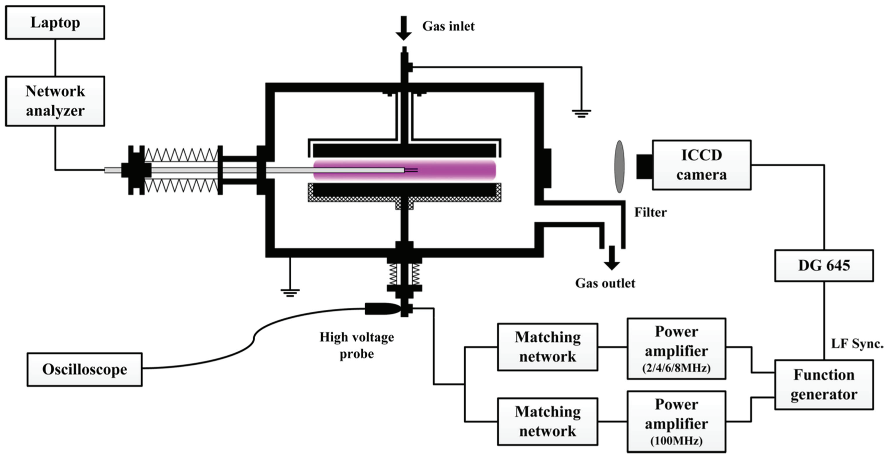
EXPERIMENTAL RESULTS

PHYSICAL REVIEW LETTERS **122,** 185002 (2019)

Observation of Nonlinear Standing Waves Excited by Plasma-Series-Resonance-Enhanced Harmonics in Capacitive Discharges

Kai Zhao,[1,2,*] De-Qi Wen,[1,*] Yong-Xin Liu,[1,†] Michael A. Lieberman,[3]
Demetre J. Economou,[2] and You-Nian Wang[1,‡]

Plasma Sources Sci. Technol. **27** (2018) 055017 K Zhao *et al*



- 28 cm diameter argon plasma CCP reactor
- 21 cm diameter plates with 3 cm gap
- $B_\phi(r)$ measured with a B-dot probe (2–200 MHz)

EXPERIMENTAL RESULTS (FREQUENCY)

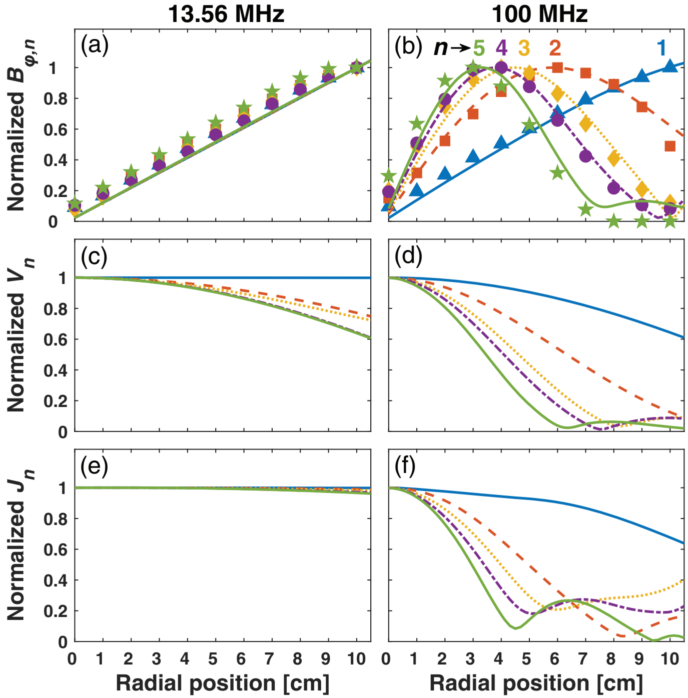


FIG. 1. Experimental data (points) and simulation predictions (lines) for discharges driven at 13.56 MHz (left) and 100 MHz (right) at 3 Pa, for a fixed power of 80 W: radial distributions of the harmonic magnetic field $B_{\varphi,n}$ (a),(b), the harmonic voltage V_n (c),(d), and the harmonic current J_n (e),(f). All harmonic amplitudes ($n = 1$–5) are normalized to the radial maxima [$B_{\varphi,n,\max}$, $V_{n,\max}$, and $J_{n,\max}$ (see Table I)] to obtain a clearer view of the harmonic structures.

EXPERIMENTAL RESULTS (PRESSURE)

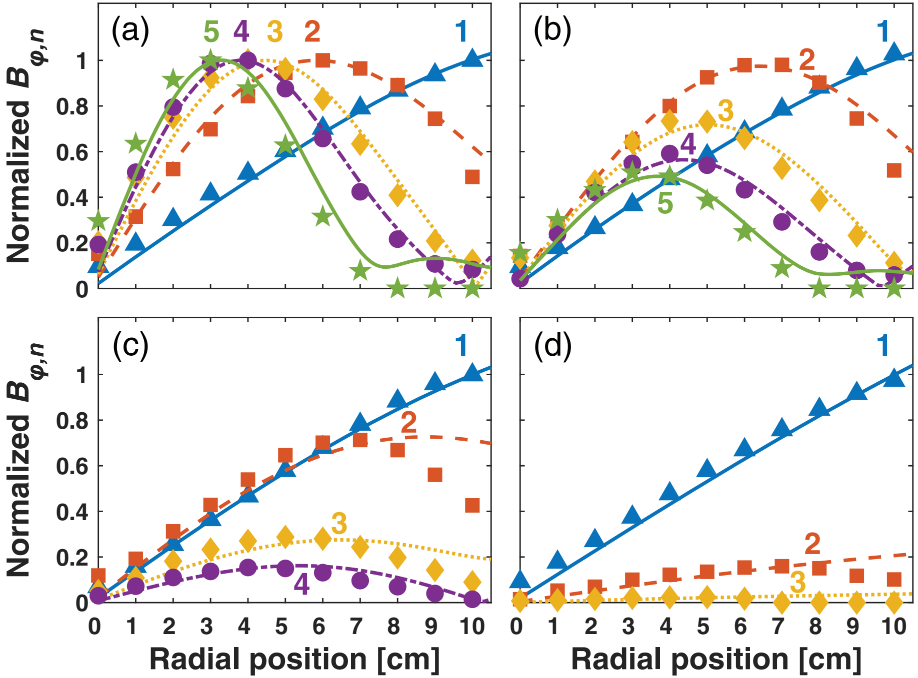
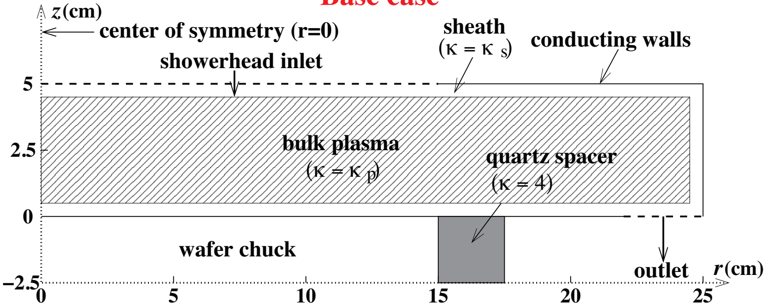


FIG. 4. Experimental data (points) and simulation predictions (lines) of the radial distributions of $B_{\varphi,n}$ at different pressures: (a) 3 Pa, (b) 8 Pa, (c) 20 Pa, and (d) 50 Pa. All harmonic magnetic field amplitudes were normalized to the maxima at 3 Pa. Other conditions were $\omega/2\pi = 100$ MHz and power = 80 W.

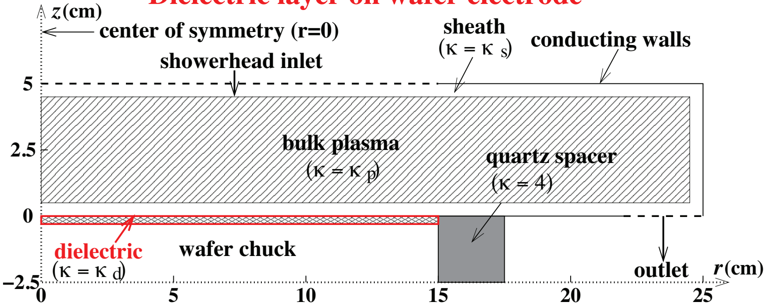
SUPPRESSING NONLINEARLY-DRIVEN INHOMOGENEITIES BY DIELECTRIC LAYER

- 2D fluid simulations without/with dielectric layer

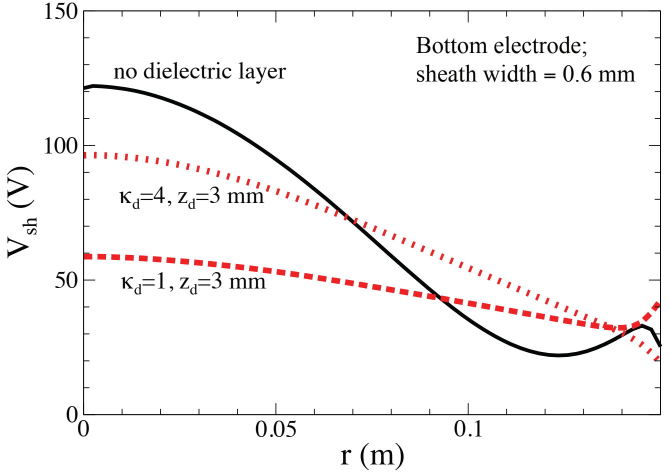
Base case



Dielectric layer on wafer electrode



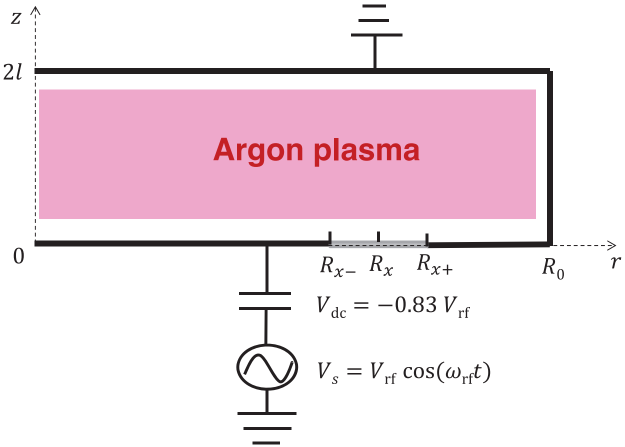
300 W Cl_2 CCP driven at 100 MHz

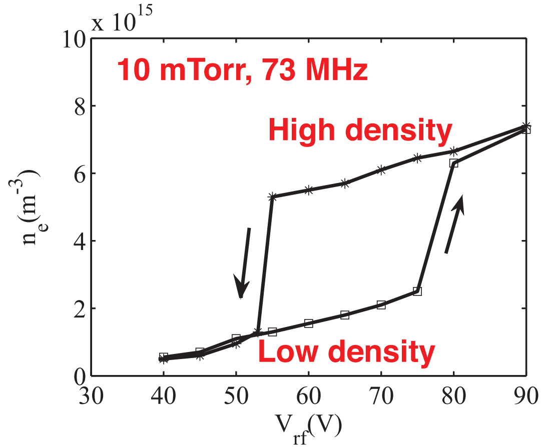


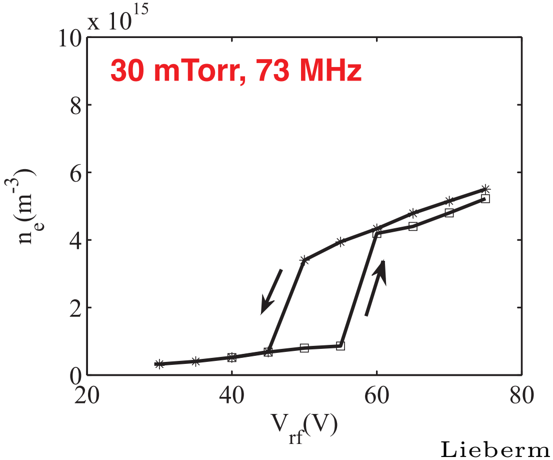
- Adding dielectric layer increases "effective" sheath width ⇒ increases radial wavelength ⇒ increases uniformity

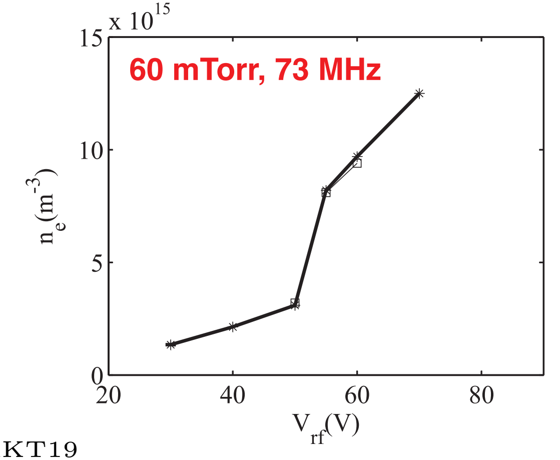
2D PIC SIMULATIONS OF HYSTERESIS

- High driving frequencies and low pressures ⇒ discharge hysteresis

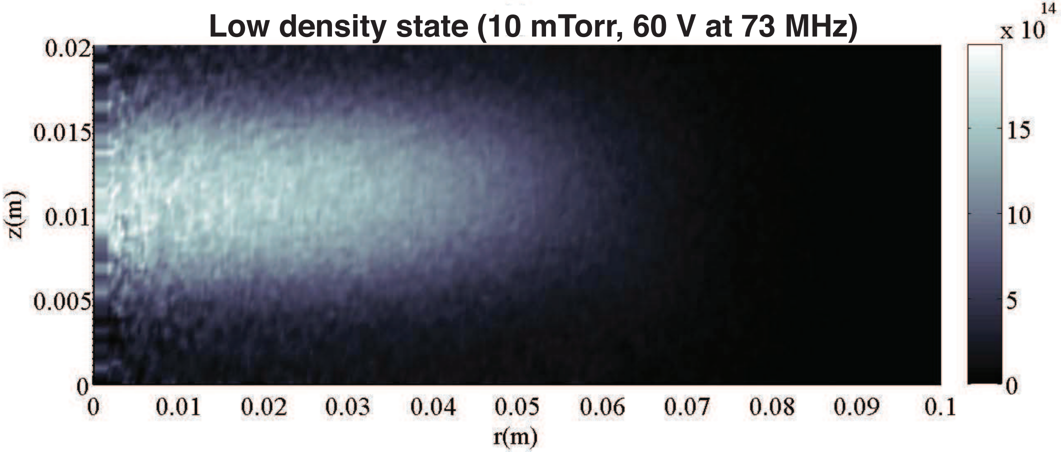


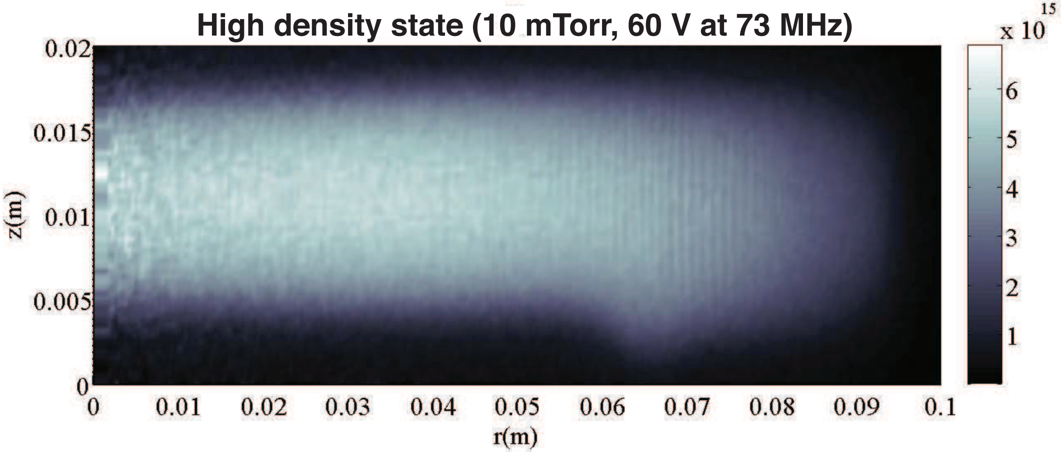






HYSTERESIS DENSITIES n_e

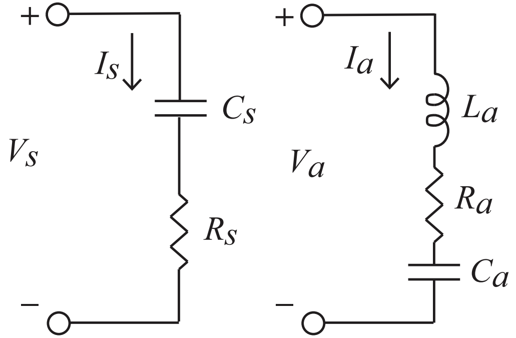

Low density state (10 mTorr, 60 V at 73 MHz)


High density state (10 mTorr, 60 V at 73 MHz)

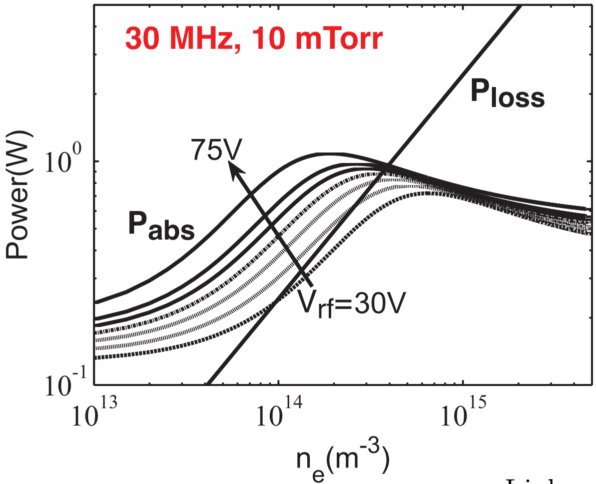
HYSTERESIS CIRCUIT MODEL

- Symmetric mode not spatially resonant
- Antisymmetric mode has radial (spatial) resonance

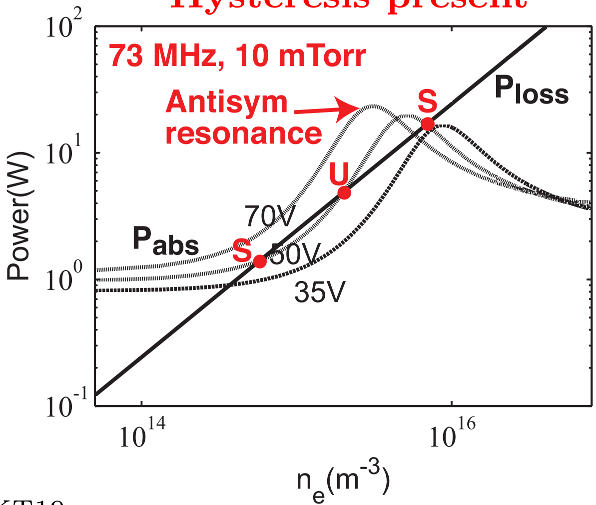
Symmetric mode **Antisymmetric mode**



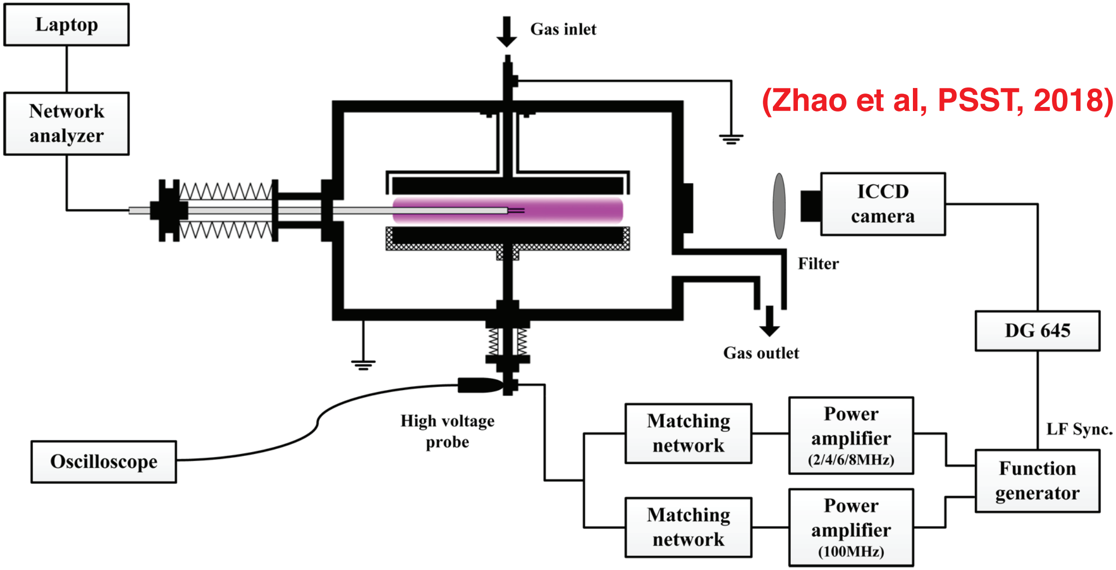
No hysteresis



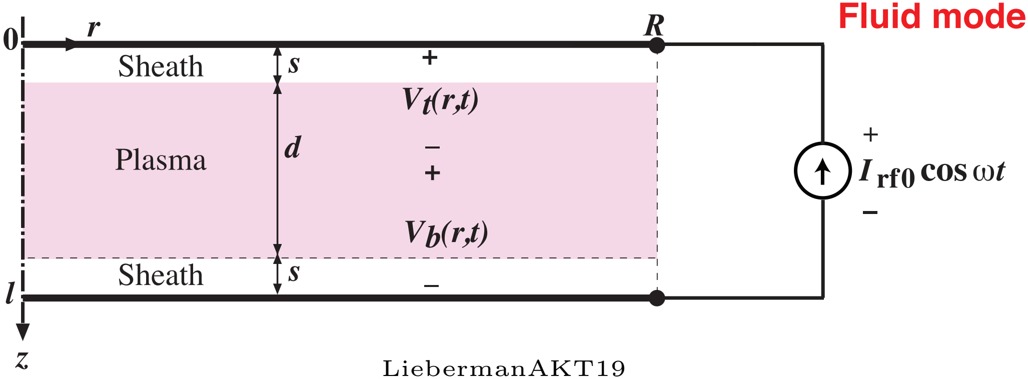
Hysteresis present



SYMMETRIC DISCHARGE SYMMETRICALLY EXCITED

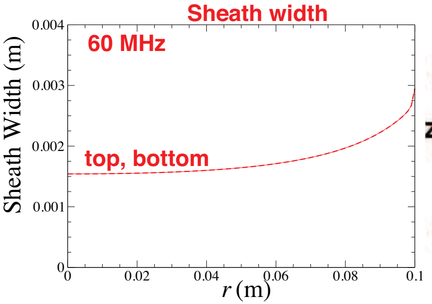


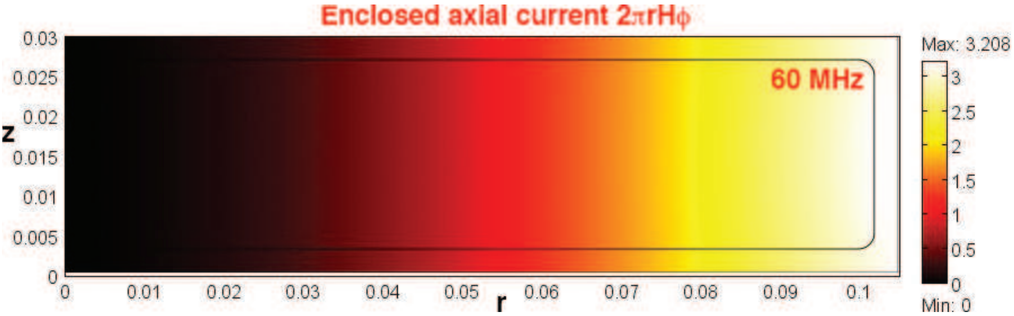
(Zhao et al, PSST, 2018)

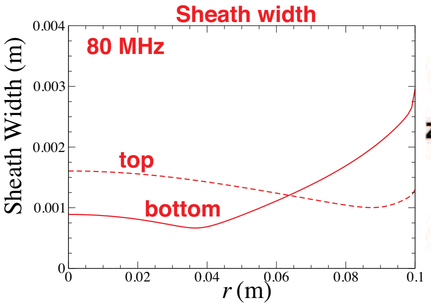


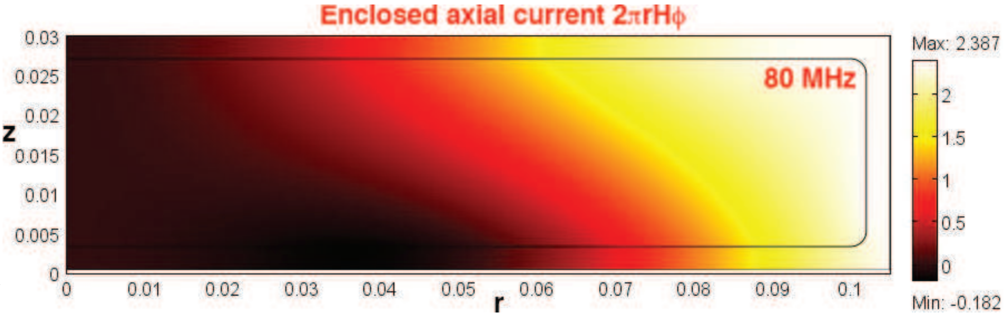
Fluid model

FLUID SIMULATIONS







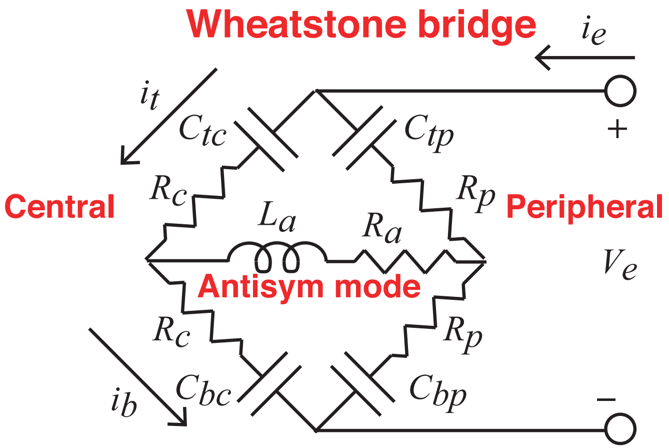


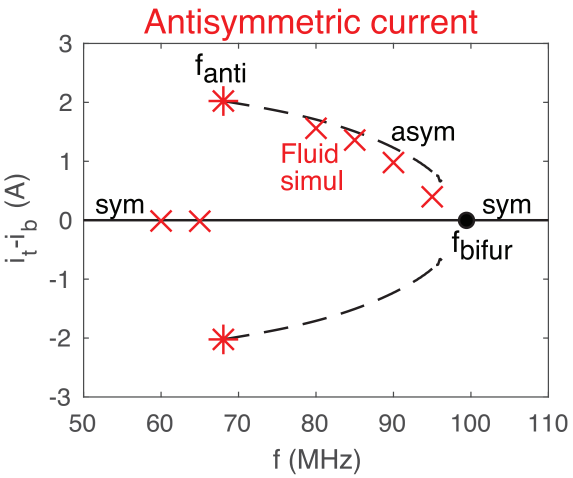
- Sheath nonlinearity coupled to antisymmetric wave resonance

$\Longrightarrow$ **Symmetry-breaking**

WHEATSTONE BRIDGE MODEL

- Central and peripheral regions connect to each other through the radial fields of the antisymmetric mode





- Classic reverse pitchfork bifurcation as frequency decreases

CONCLUSION

Accounting for sheath nonlinearities and radially-propagating EM wave modes can be critical for achieving good uniformity and control of high frequency, large area CCP's

REFERENCES

[1] De-Qi Wen, E. Kawamura, M.A. Lieberman, A.J. Lichtenberg, and You-Nian Wang, "Nonlinear series resonance and standing waves in dual-frequency capacitive discharges," *Plasma Sources Sci. Technol.* **26,** 015007 (2017).

[2] De-Qi Wen, E. Kawamura, M.A. Lieberman, A.J. Lichtenberg, and You-Nian Wang, "A nonlinear electromagnetics model of an asymmetrically-driven, low pressure capacitive discharge," *Phys. Plasmas* **24,** 083517 (2017).

[3] E. Kawamura, De-Qi Wen, M.A. Lieberman and A.J. Lichtenberg, "Effect of a dielectric layer on plasma uniformity in high frequency electronegative capacitive discharges," *J. Vac. Sci. Technol. A* **35,** 05C311 (2017).

[4] De-Qi Wen, E. Kawamura, M.A. Lieberman, A.J. Lichtenberg and You-Nian Wang, "Two-dimensional particle-in-cell simulations of standing waves and wave-induced hysteresis in asymmetric capacitive discharges," *J. Phys. D: Appl. Phys.* **50,** 495201 (2017).

[5] Kai Zhao, Yong-Xin Liu, E. Kawamura, De-Qi Wen, M. A. Lieberman, and You-Nian Wang, "Experimental investigation of standing wave effect in dual-frequency capacitively coupled argon discharges: role of low frequency source," *Plasma Sources Sci. Technol.*, in press (2018).

[6] E. Kawamura, M.A. Lieberman and A.J. Lichtenberg, "Symmetry breaking in high frequency, symmetric capacitively coupled plasmas," *Phys. Plasmas* **25** 093517 (2018).

[7] Kai Zhao, De-Qi Wen, Yong-Xin Liu, M.A. Lieberman, D.J. Economou and You-Nian Wang, "Observation of Nonlinear Standing Waves Excited by Plasma Series Resonance-Enhanced Harmonics in Capacitive Discharges," *Phys. Rev. Lett.* **122,** 185012 (2019).