NONLINEARITY AND WAVES IN CAPACITIVE DISCHARGES

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MOTIVATION

- Ensure uniformity and controllability of large area, high frequency capacitive plasma discharges used for thin film processing

  Large area ⇒ 3m × 3m glass substrates
  High frequency ⇒ high density, low sheath voltage silicon wafers

- For these conditions, a linear electromagnetics model showed a significant standing wave effect

⟹ center-high, gradually-varying radial power deposition profile

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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]

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]

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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]

HIGHLY-PEAKED PLASMA NONUNIFORMITY

- But experiments often showed very sharply peaked density
- Asymmetric argon capacitive discharge (2.5 cm gap, driven at 60 MHz), showing $n_e(r) \Longrightarrow$ (Sawada et al, JJAP, 2014)
- Could sheath nonlinearities generate driving frequency harmonics responsible for these sharp peaks?
- Investigate coupling of nonlinearly-generated harmonics of the driving frequency to the standing waves using a radial transmission line model

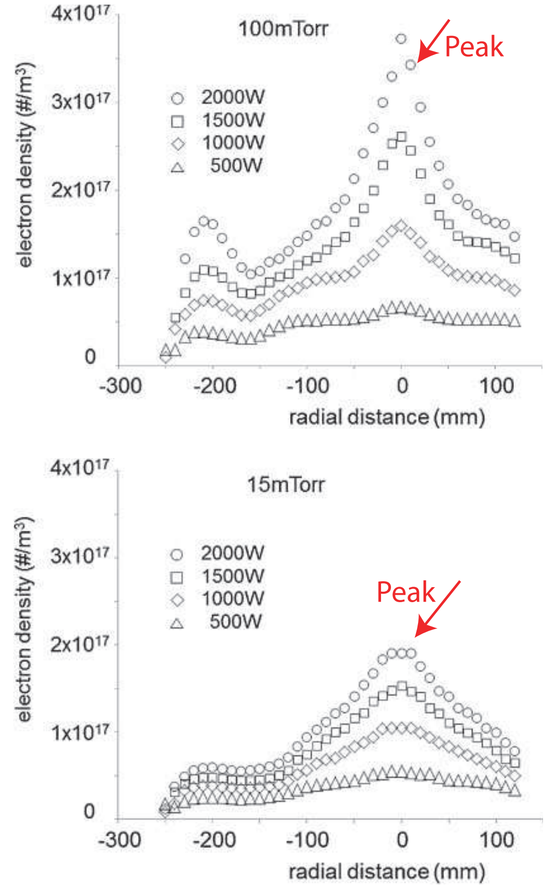


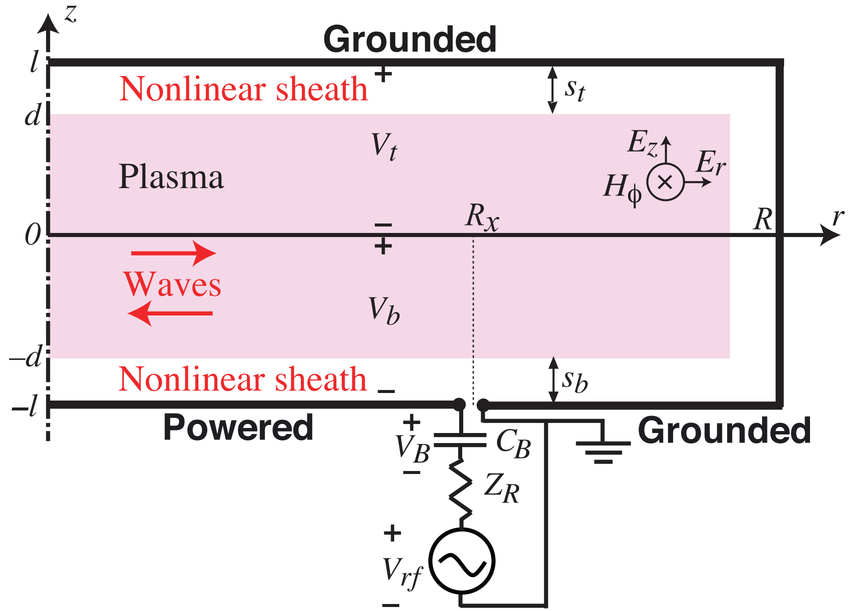
Fig. 3. Experimentally measured electron density profiles along the test-bench A reactor midgap for argon plasma driven at 60 MHz. Top: 100 mTorr. Bottom: 15 mTorr.

DISCHARGE UNIFORMITY:

COUPLING OF SHEATH NONLINEARITIES TO EM PLASMA WAVES

ASYMMETRICALLY-DRIVEN DISCHARGE

- Cylindrical discharge radius R and gap $2l$
- Driven axisymmetrically at radius R_x by high frequency source $V_{\rm rf}$



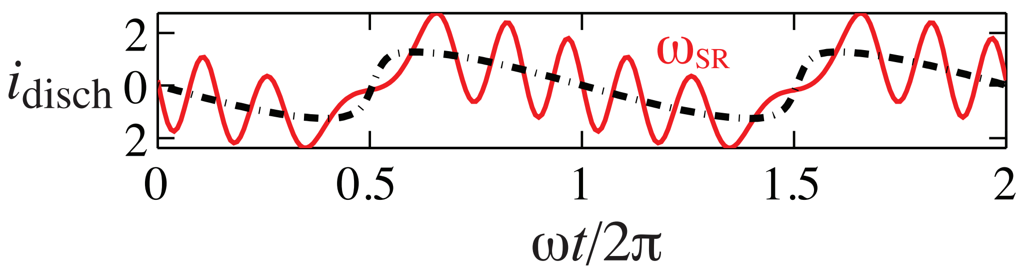
Sheath nonlinearities couple to bulk plasma ⇒ resonances

NONLINEAR SHEATHS AND SERIES RESONANCE

- Sinusoidal rf driving source: $V_{\rm rf} = V_{\rm rf0}\cos\omega t$
- Sheaths are strongly nonlinear; for Child law: $V_{sh} \propto Q_{sh}^4$
- Sheath nonlinearity generates harmonics 2ω, 3ω, ...
- Series resonance (capacitive sheaths + inductive plasma) near the Nth harmonic:

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

($\bar{s}$ = mean sheath width; ω_{pe} = plasma frequency; l = half-gap width)



(Dash-dot – smooth w/o harmonics; red – oscillations with harmonics)

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_ϕ, E_r, E_z) exist
- Symmetric mode: $E_{zs} = A(r,t)\cosh\alpha z$
- Antisymmetric mode: $E_{za} = B(r,t)\sinh\alpha z$

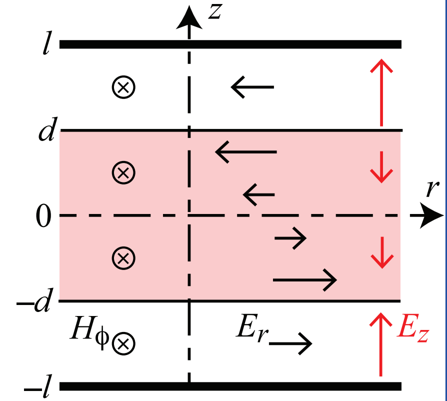
  (α = inverse plasma skin depth)
- Radial (spatial) resonance near Mth driving frequency harmonic; e.g., for 1st antisymmetric mode

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

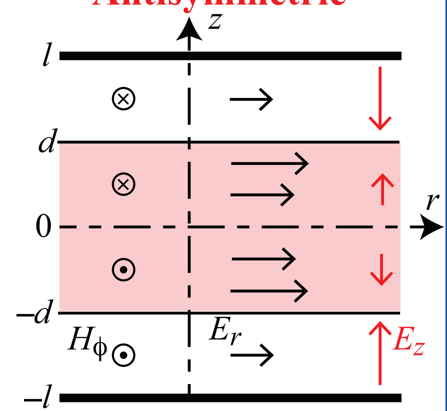
($\bar{s}$ = mean sheath width; ω_{pe} = plasma frequency;

d = half-bulk width; R = discharge radius)

Symmetric

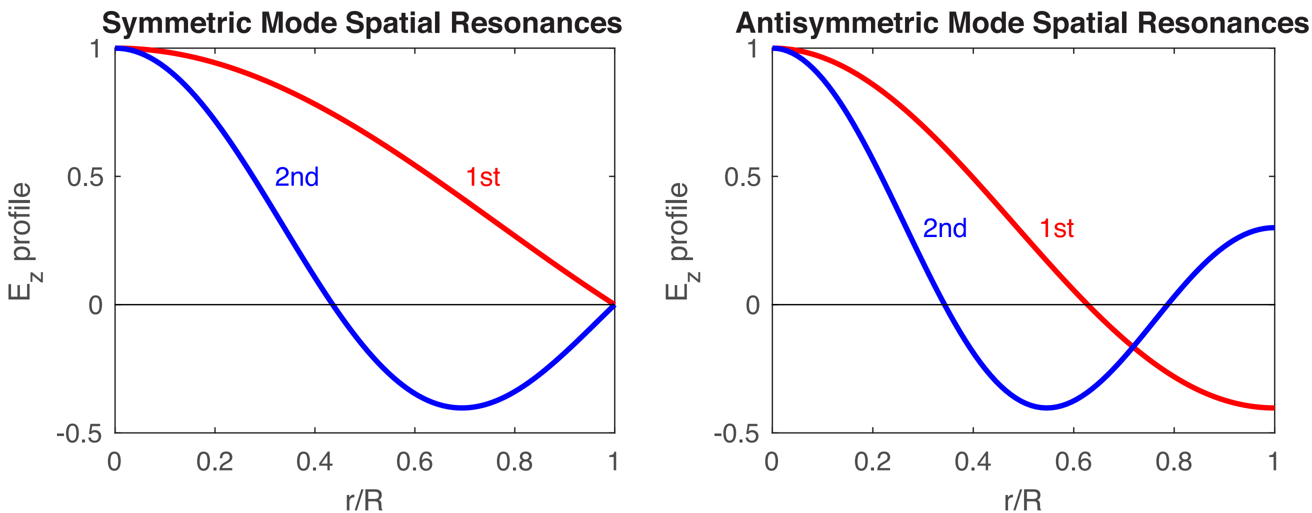


Antisymmetric



UNIFORMLY-EXCITED SPATIAL RESONANCES

- For uniform (in r) excitations of the spatial resonances, the radial variations of $E_z(r)$ are Bessel functions



- For nonuniform radial excitations, these spatial resonance curves become distorted

MODEL SOLUTION AND DISCHARGE PARAMETERS

(De-Qi Wen et al, PoP, 2017)

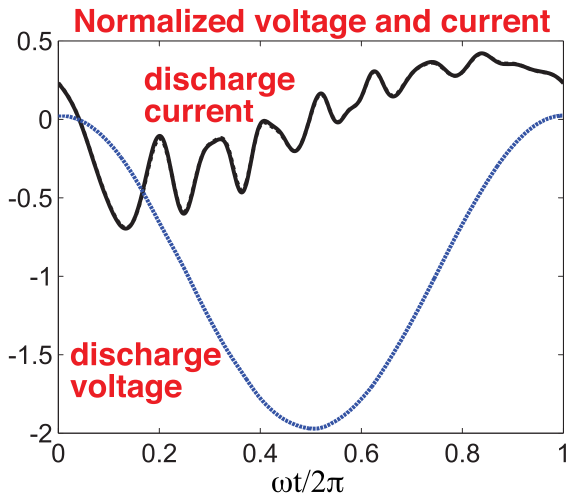
- Maxwell's equations + Newton's laws for symmetric and antisymmetric modes at low pressure
- Initial assumption of uniform density plasma slab
- Self-consistent (nonlinear) rf Child law in the radially-varying sheaths

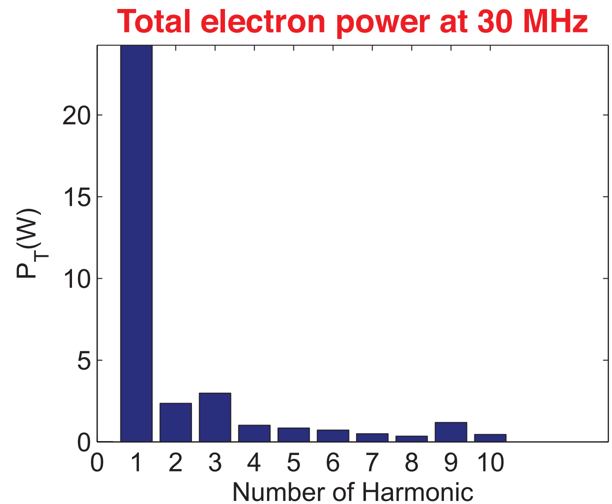
  $\Longrightarrow$ Set of nonlinear pde's in (r, t), solved numerically

- Typical commercial system parameters:
  – $p = 10$ mTorr chlorine
  – discharge radius $R = 25$ cm, gap $2l = 5$ cm,
  – powered electrode radius $R_x = 15$ cm
  – total source power $P \approx 200$ W ($n_{e0} \approx 2 \times 10^{16}$ m^{-3})

- Examples of 30 MHz ($V_{\mathrm{rf0}} = 560$ V) and 60 MHz ($V_{\mathrm{rf0}} = 160$ V)
  Compare 30 and 60 MHz electron powers

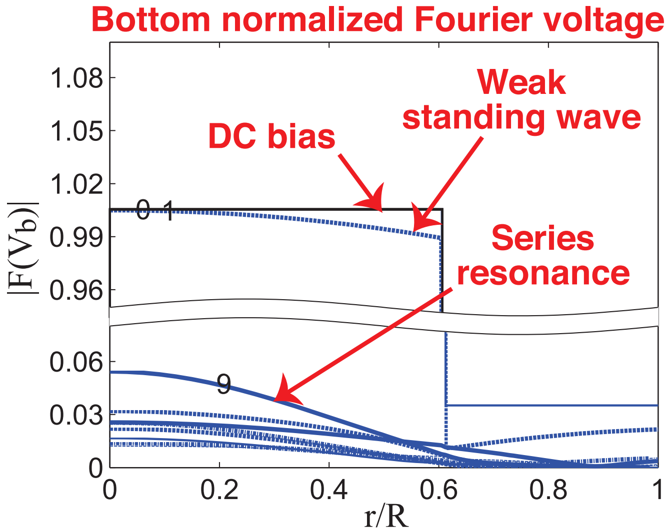
30 MHZ V_{disch}, I_{disch}, AND ELECTRON POWER

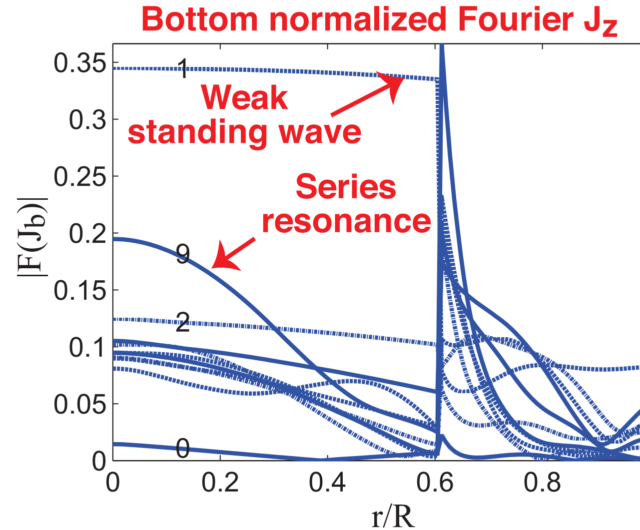




- The discharge current shows a strong 9th harmonic oscillation (near the series resonance frequency)
- The total electron power in the harmonics is fairly small
- However, the radial profiles . . .

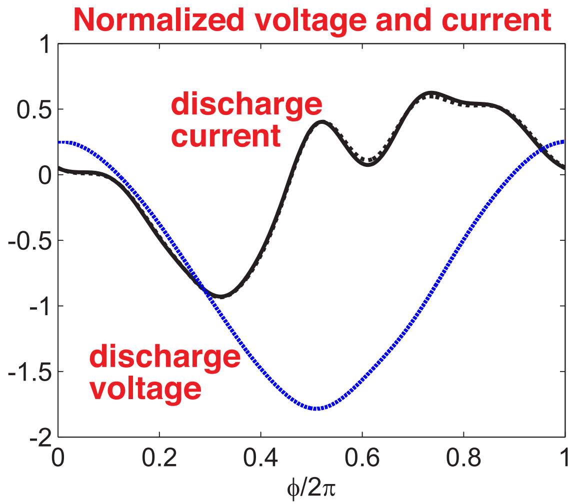
30 MHz VOLTAGE AND CURRENT HARMONICS

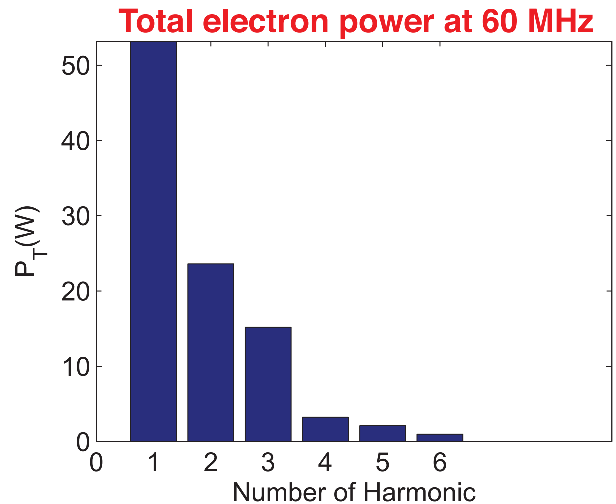




- Weak 1st harmonic standing wave
- Significant 9th harmonic series resonance current

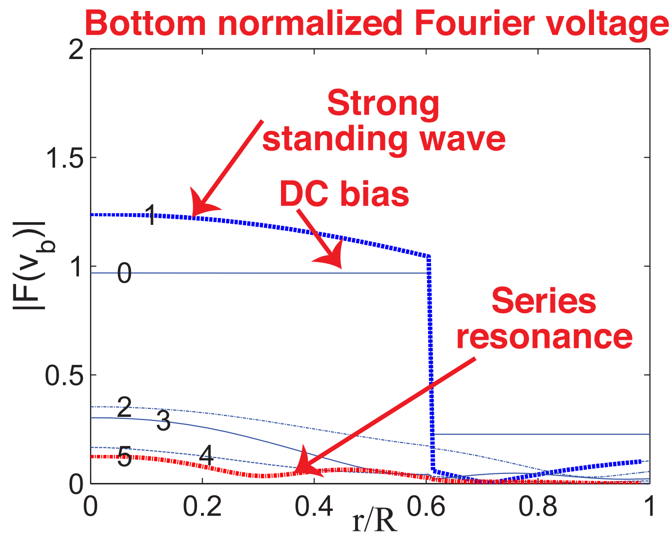
60 MHZ V_{disch}, I_{disch}, AND ELECTRON POWER

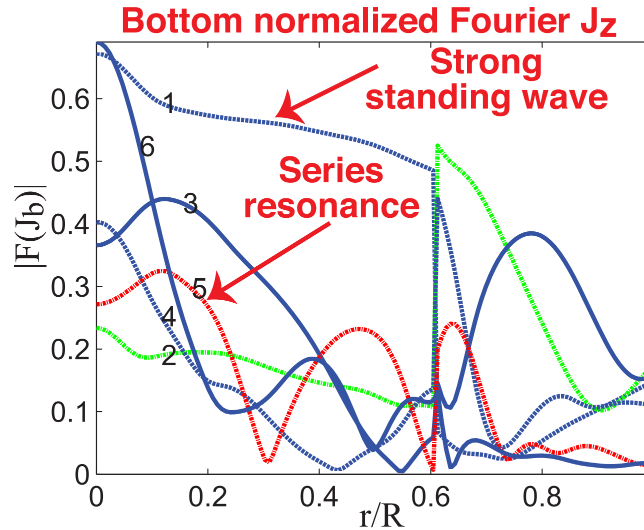




- The discharge current shows strong 4th–6th harmonic oscillations (near the series resonance frequency)
- There are also strong 2nd and 3rd harmonic powers
- The total electron power in the harmonics is roughly equal to the fundamental power

60 MHz VOLTAGE AND CURRENT HARMONICS

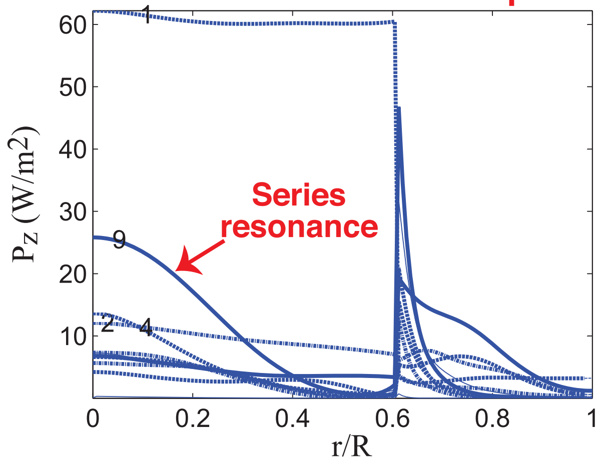




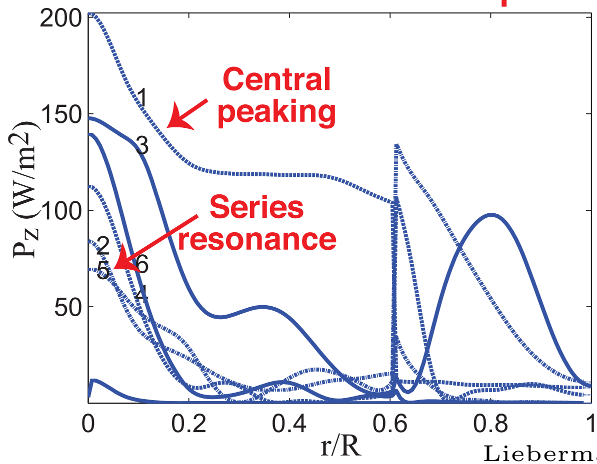
- Strong 1st harmonic standing wave
- Large 4th–6th harmonic series resonance currents near $r = 0$
- Note: radial power profile $P_z(r) \propto J_z^2(r)$ ...

30 AND 60 MHz POWER HARMONICS

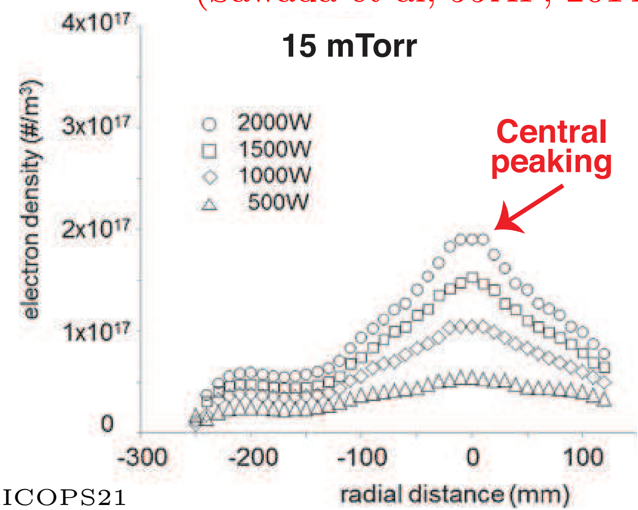
30 MHz-driven axial field power



60 MHz-driven axial field power



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



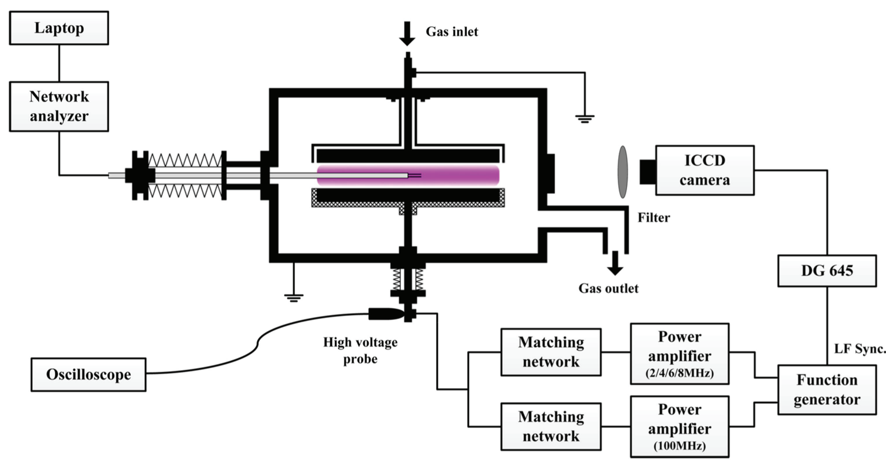
EXPERIMENTAL RESULTS

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)

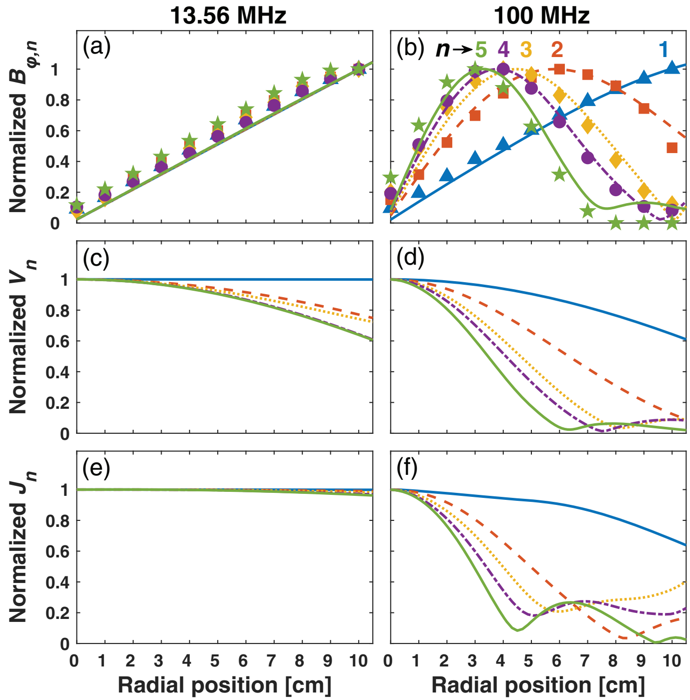


FIG. 1. Experimental data (points) and simulation predictions (lines) for discharges driven at 13.56 MHz (left) and 100 MHz (right) at 3 Pa, for a fixed power of 80 W: radial distributions of the harmonic magnetic field $B_{\varphi,n}$ (a),(b), the harmonic voltage V_n (c),(d), and the harmonic current 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)

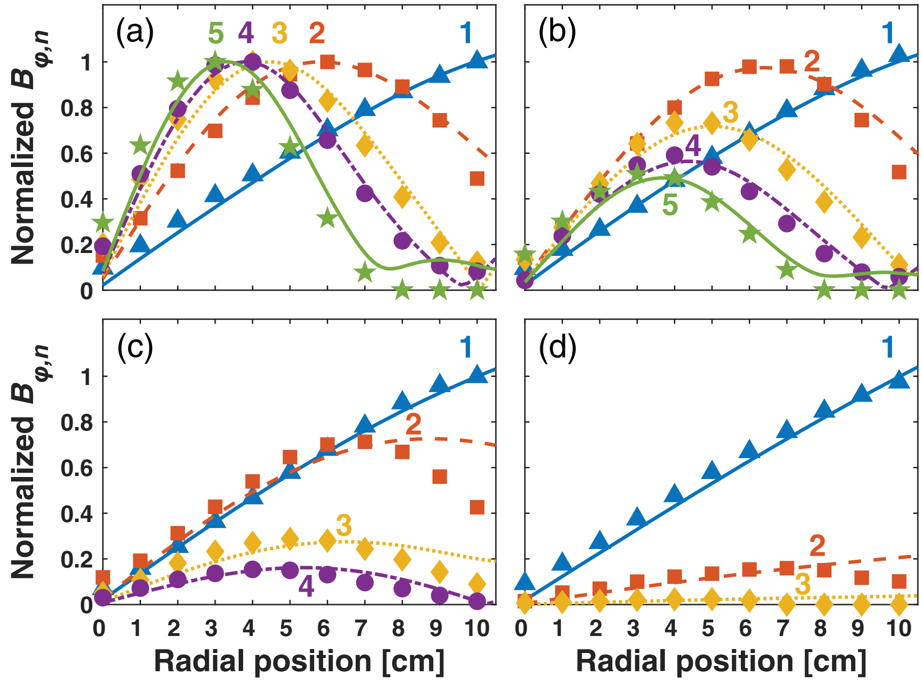
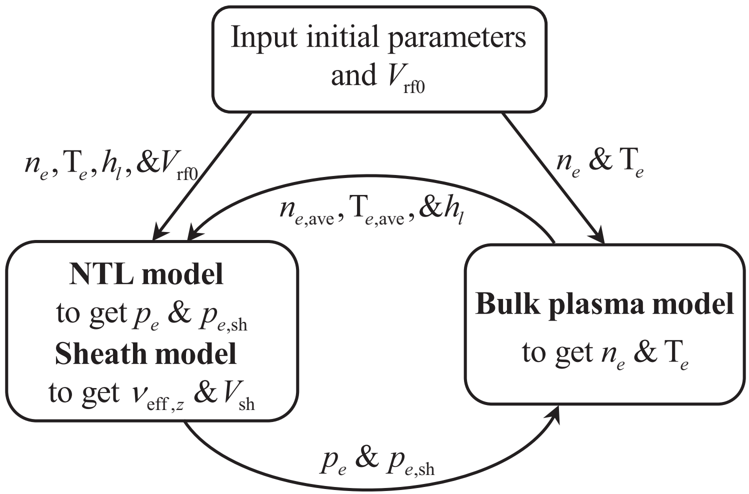


FIG. 4. Experimental data (points) and simulation predictions (lines) of the radial distributions of $B_{\varphi,n}$ at different pressures: (a) 3 Pa, (b) 8 Pa, (c) 20 Pa, and (d) 50 Pa. All harmonic magnetic field amplitudes were normalized to the maxima at 3 Pa. Other conditions were $\omega/2\pi =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

FLUID PLASMA MODEL AND HIGH PRESSURES

(Jian-Kai Liu et al, PSST, 2021)

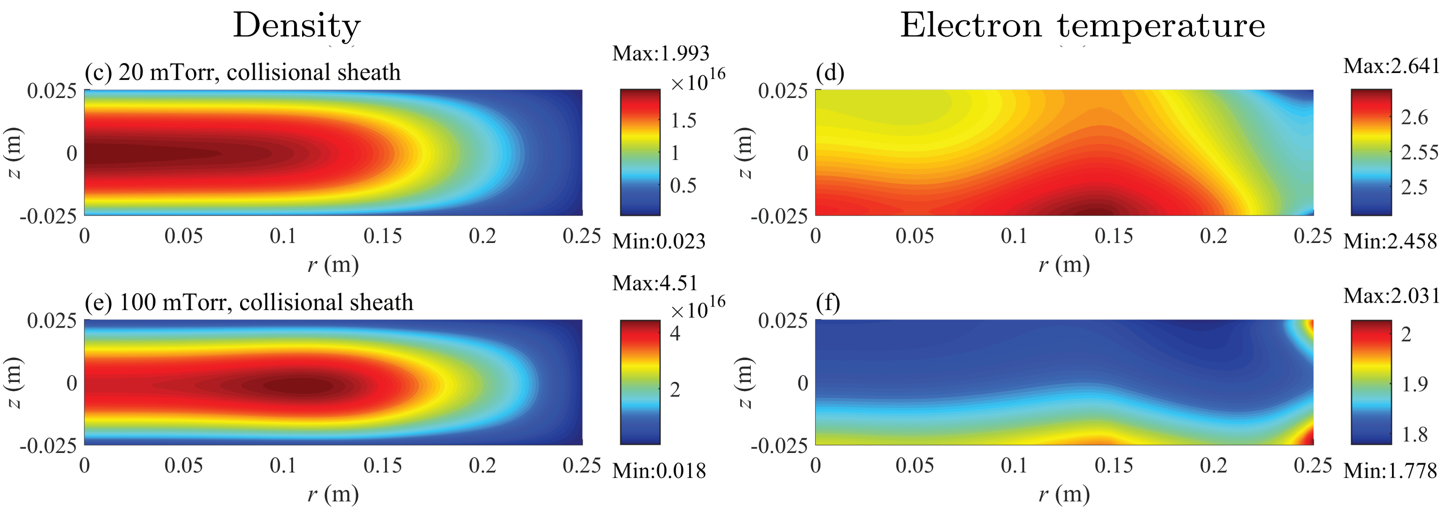
- Couple nonlinear transmission line (NTL) model to spatially-varying bulk plasma fluid model



- Use collisional Child law at higher pressures

HIGH PRESSURE EFFECTS

- Argon discharge, 60 MHz driving frequency, 40 W electron power

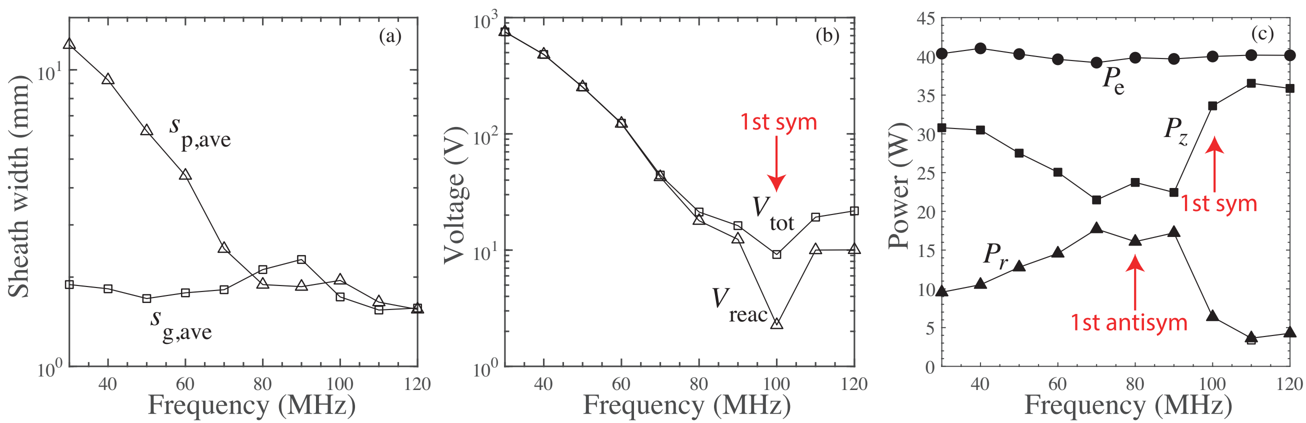


- As pressure increases, the nonlinear harmonics damp out, and the enhancement of on-axis power deposition becomes less significant
- Electrostatic edge effects increase the density near the powered electrode edge
- These pressure effects also seen in experiments

FREQUENCY VARIATIONS

(Jian-Kai Liu, work in progress)

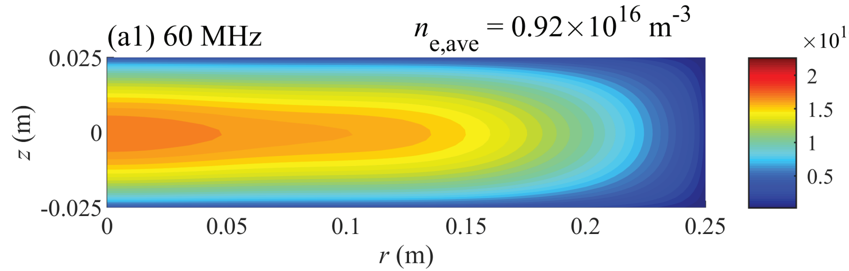
- With increasing driving frequency,
  - the powered sheath width $s_{\mathrm{p,ave}}$ decreases to near $s_{\mathrm{g,ave}}$
  - the discharge voltage V_{tot} decreases to a few 10's of volts
- Near 80 MHz, the driving frequency becomes equal to the 1st antisymmetric mode radial resonance $(P_r \to P_z)$
- Near 100 MHz,the driving frequency becomes equal to the 1st symmetric mode radial resonance $(V_{\mathrm{reac}} \to 0,\ P_r \ll P_z)$



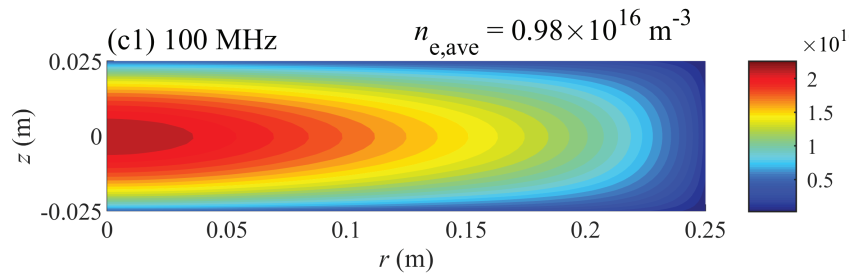
(Argon pressure = 20 mTorr, electron power P_e = 40 W)

DENSITY VARIATION WITH FREQUENCY

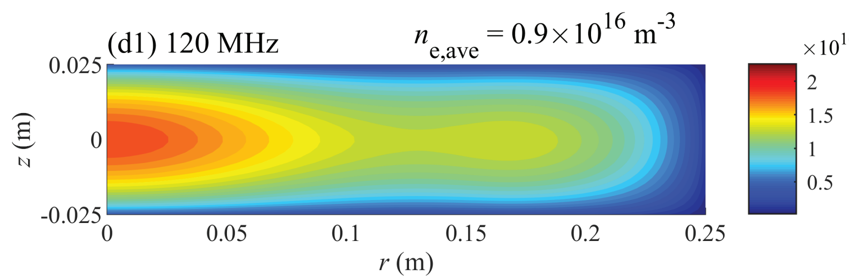
Far from driving frequency resonance $\Longrightarrow$



Near symmetric mode resonance $\Longrightarrow$



Higher frequency shows strong edge heating $\Longrightarrow$

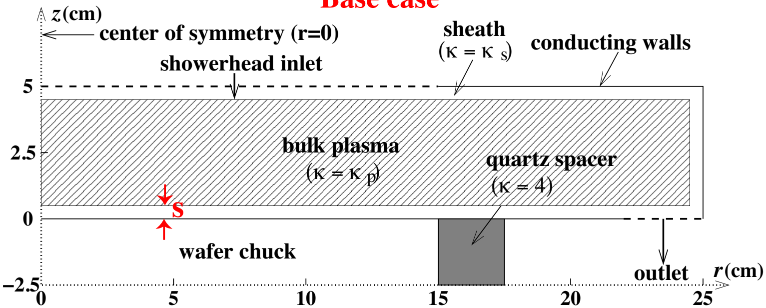


ADD DIELECTRIC LAYER TO POWERED ELECTRODE

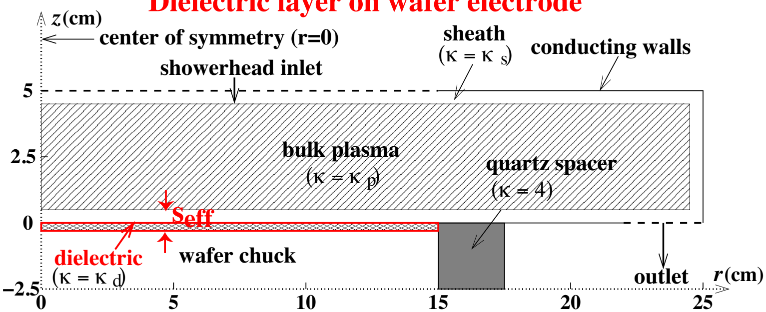
(E. Kawamura et al, JVSTA, 2017)

- Radial wavelength $\propto \sqrt{\text{sheath width}}$
  $\Rightarrow$ a dielectric layer increases the "effective" sheath width

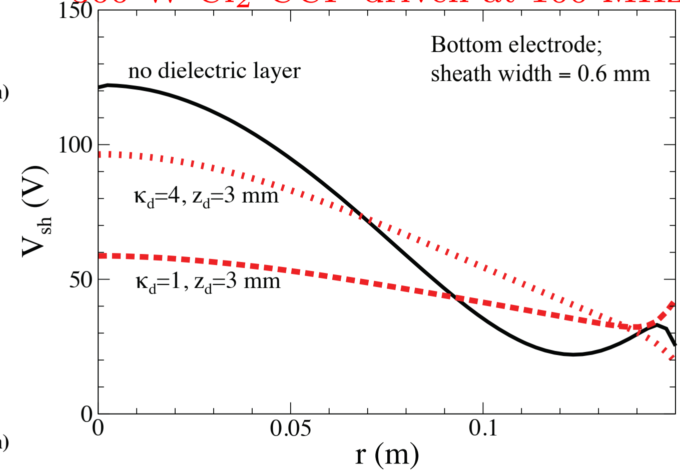
Base case



Dielectric layer on wafer electrode



300 W Cl_2 CCP driven at 100 MHz



- Dielectric layer increases radial wavelength $\Rightarrow$ improves uniformity

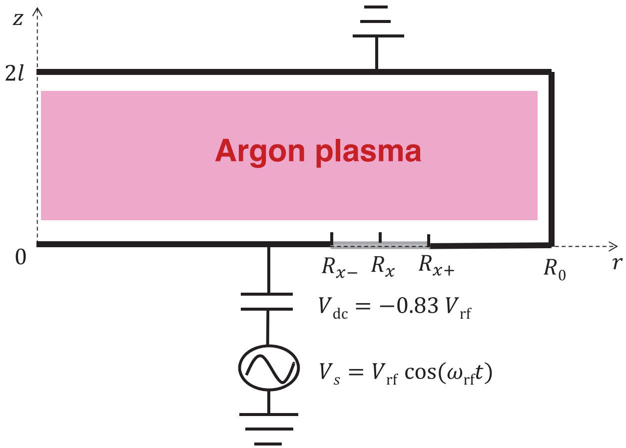
DISCHARGE CONTROLLABILITY:

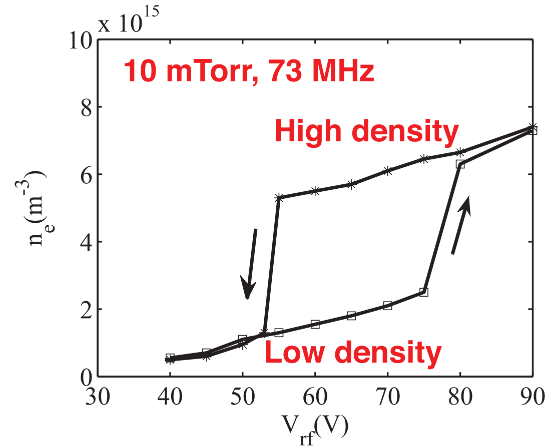
RADIAL WAVE RESONANCES $\Rightarrow$ HYSTERESIS
$\Rightarrow$ MULTIPLE EQUILIBRIUM STATES

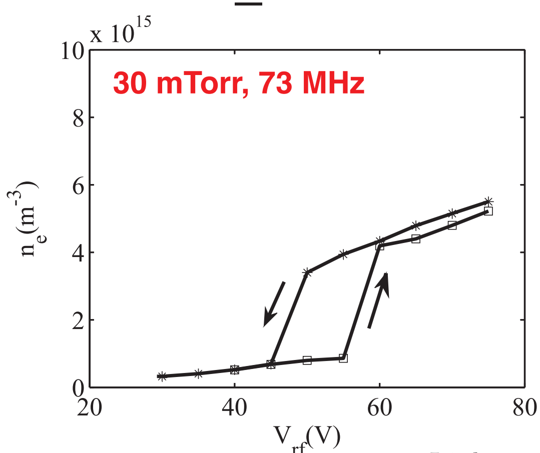
2D PIC SIMULATIONS OF HYSTERESIS

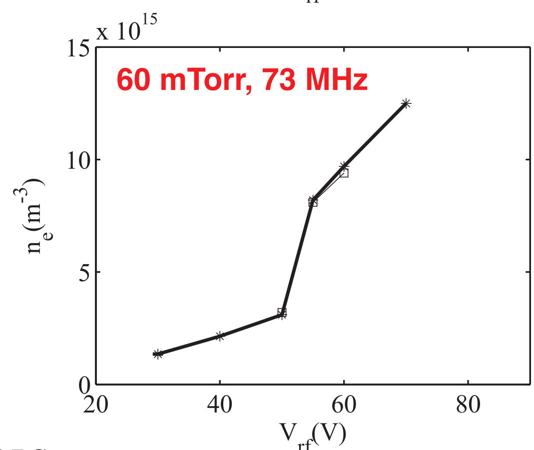
(De-Qi Wen et al, JPD, 2017)

- High driving frequencies and low pressures ⇒ discharge hysteresis

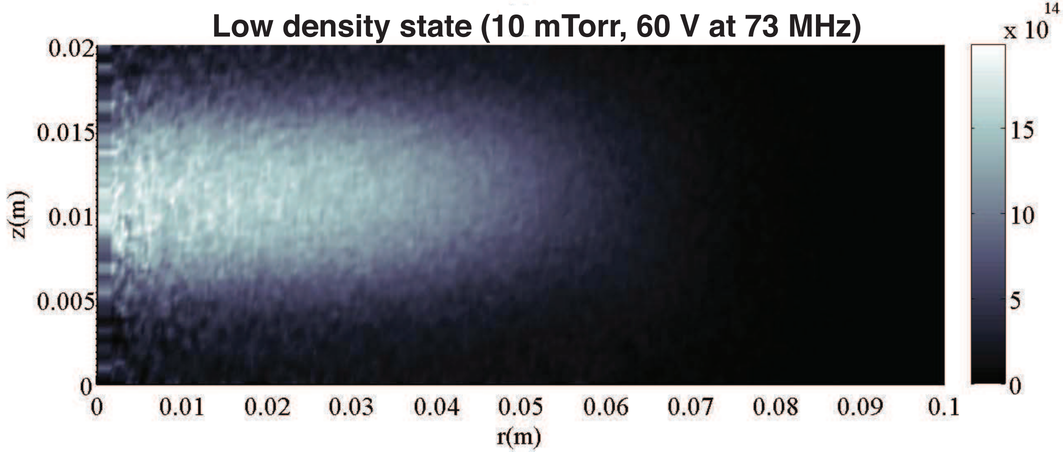


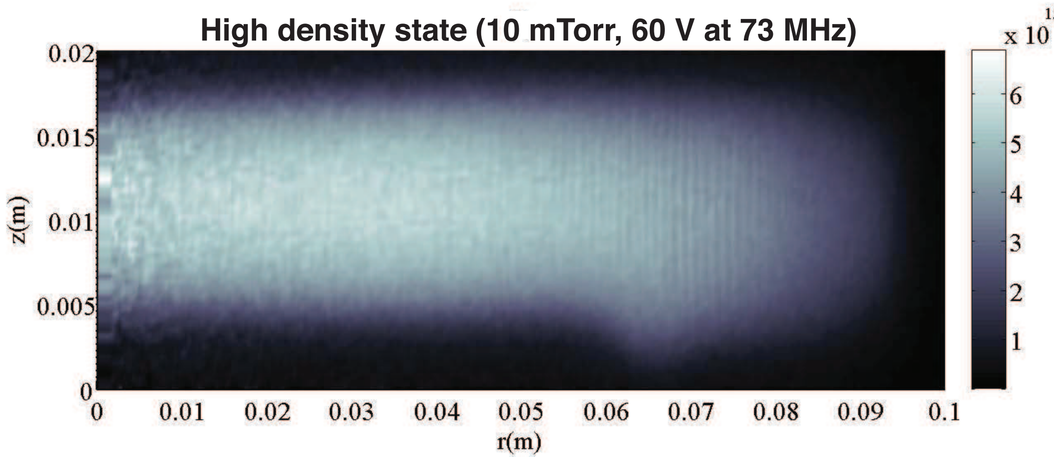






HYSTERESIS DENSITIES n_e

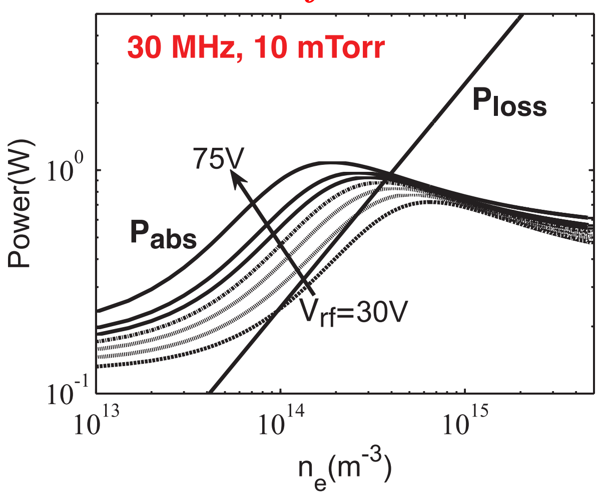




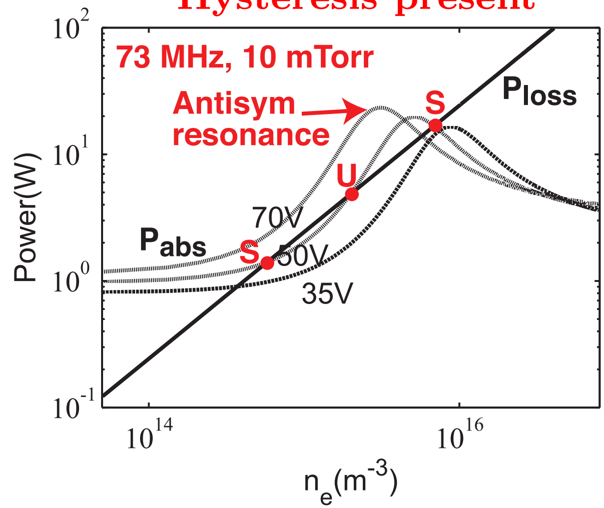
HYSTERESIS MODEL

- Symmetric mode not spatially resonant
- Antisymmetric mode has radial (spatial) resonance
- Plot power absorbed and power lost versus density intersection(s) $\Longrightarrow$ discharge equilibrium

No hysteresis



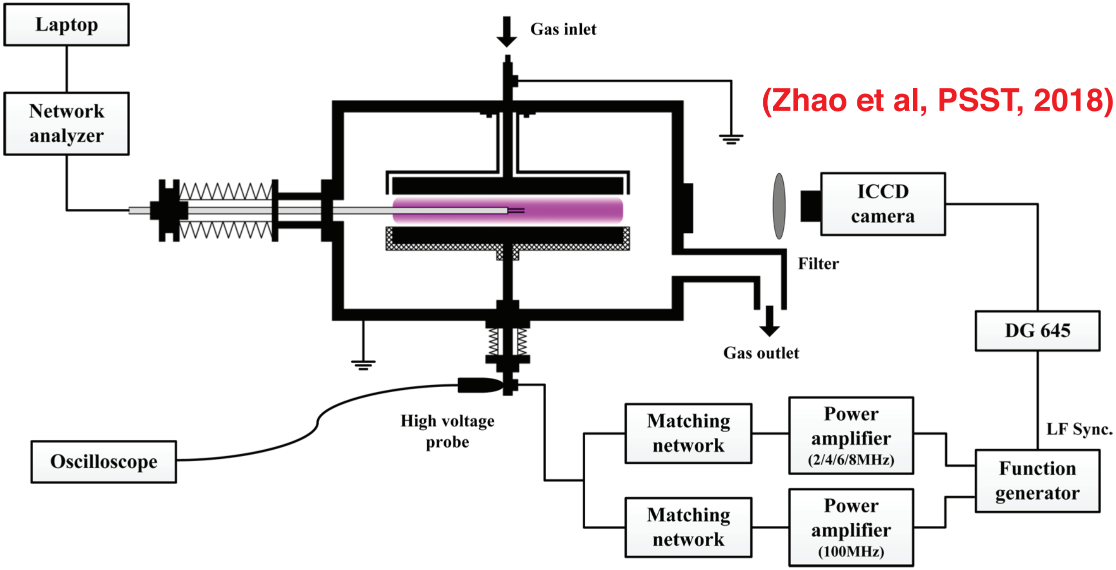
Hysteresis present



DISCHARGE CONTROLLABILITY:

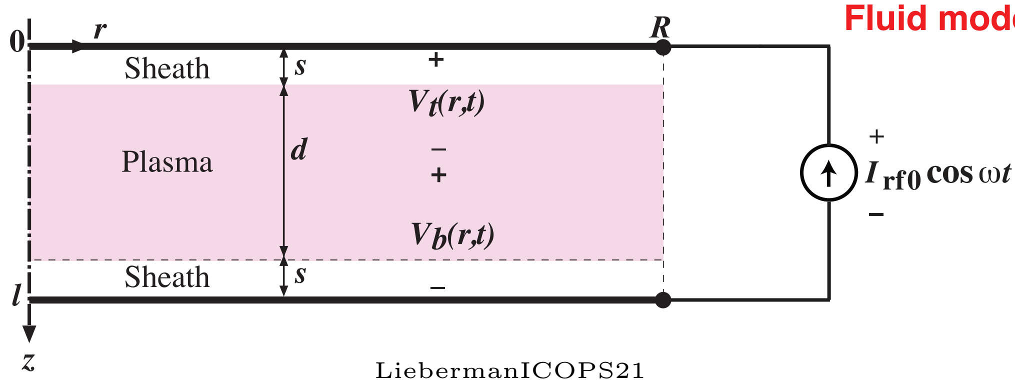
RADIAL RESONANCES $\Rightarrow$ SYMMETRY-BREAKING
$\Rightarrow$ MULTIPLE EQUILIBRIUM STATES

SYMMETRIC DISCHARGE SYMMETRICALLY EXCITED



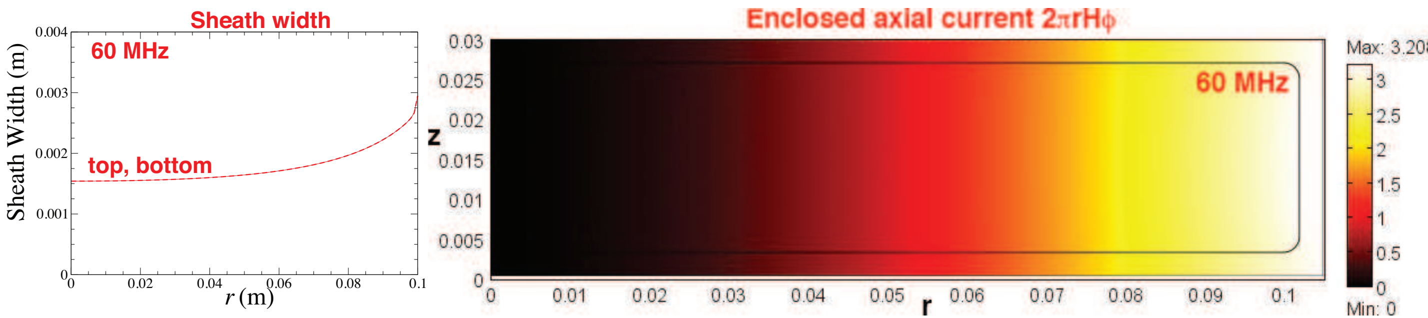
(Zhao et al, PSST, 2018)

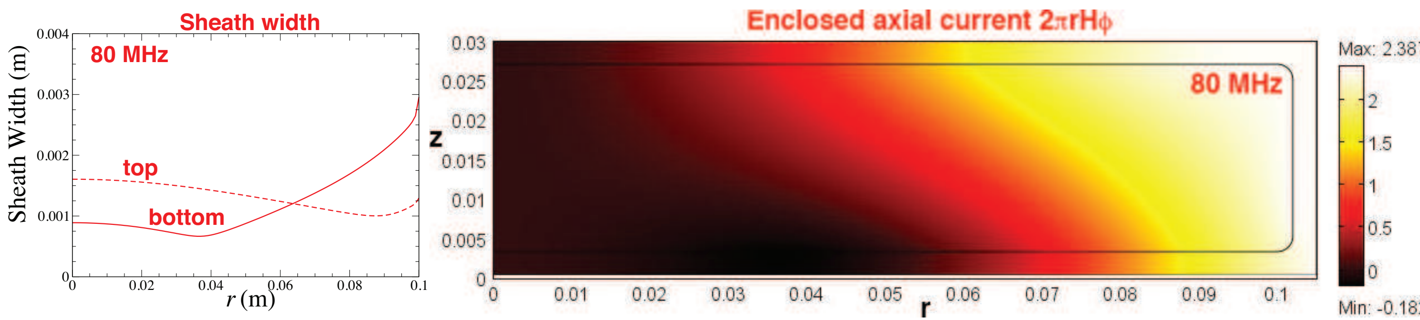
Fluid model



FLUID SIMULATIONS

(E. Kawamura et al, PoP, 2018)





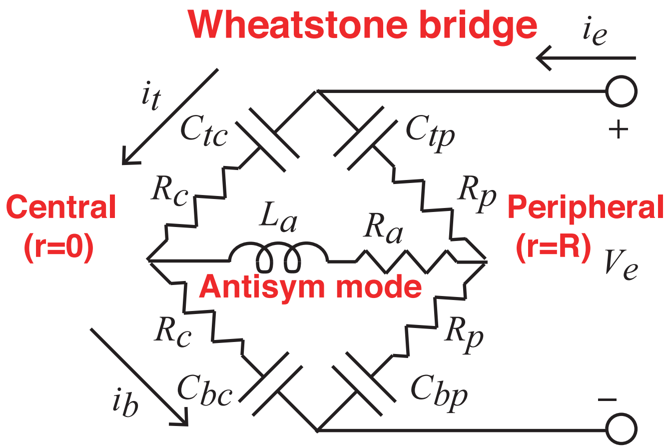
- Sheath nonlinearity coupled to antisymmetric mode resonance

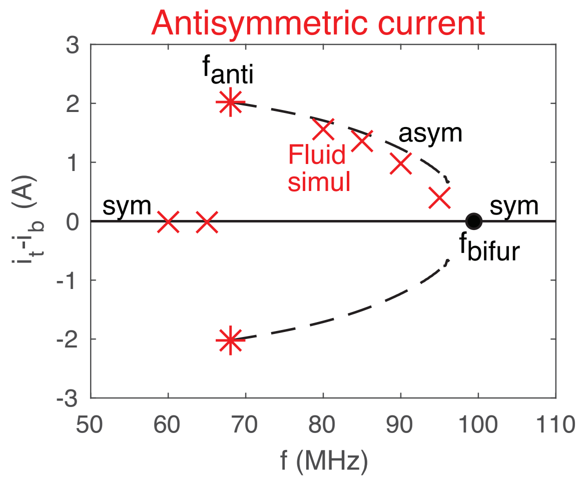
$\Longrightarrow$ **Symmetry-breaking**

- Discharge can be in two states:
  top sheath > bottom sheath, or bottom sheath > top sheath at $r = 0$

WHEATSTONE BRIDGE MODEL

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





- Due to the sheath capacitance nonlinearity
$\Longrightarrow$ classic pitchfork bifurcation as frequency is varied

CONCLUSIONS

- Large area and/or high frequency capacitive rf discharges are used extensively for thin film processing
- In these discharges, sheath nonlinearities can couple to radially-propagating EM wave modes, producing strong resonance effects
- Understanding these effects can be critical for achieving good uniformity and control of the processing environment

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