NONLINEAR ELECTROMAGNETICS MODEL OF AN ASYMMETRICALLY DRIVEN CAPACITIVE DISCHARGE

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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 $s_{\text{max}} \ll l \ll R$

\[ \text{Powered} \quad \overset{+}{V_{rf}} \quad \underset{-}{V_{rf}} \quad \text{Sheath} \quad \overset{+}{V_{sh,t}} \quad \overset{+}{V_{sh,b}} \quad \text{Grounded} \]

- Uniform density plasma $n_{e0}$
- Child law sheaths: $s_{t,b}(r, t)$
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 \((\nu \ll \omega) \Rightarrow \alpha = \frac{\omega_{pe}}{c} = \text{plasma axial decay constant,}\)
\(\omega_{pe} = \text{plasma frequency, } c = \text{speed of light}\)

Radial (quarter-wave) resonance; e.g.,
\[\omega_{SW} = \left(\frac{\bar{s}}{l}\right)^{1/2} \frac{2.405 \, c}{R}\]
NONLINEAR SHEATHS AND SERIES RESONANCE

• Sinusoidal rf driving source: \( V_{\text{rf}} = V_{\text{rf}0} \cos \phi; (\phi = \omega t) \)

• Sheath motions \( s_{t,b}(r,t) \) vary nonlinearily 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 \( 2\omega, 3\omega, \ldots \)

• Series resonance (capacitive sheaths + inductive plasma) near the \( N \)th harmonic:

\[
\omega_{\text{SR}} = \left( \frac{s}{l} \right)^{1/2} \omega_{pe} \approx N\omega
\]
SOLUTION PROCEDURE

- Maxwell’s equations + Newton’s laws for TM modes in the plasma:
  
  symmetric mode: \( E_{zs} = A(r, t) \cosh \alpha z \)
  
  antisymmetric mode: \( E_{za} = B(r, t) \sinh \alpha z \)

- Self-consistent (nonlinear) rf Child law in the sheaths:
  
  \[ \Rightarrow \text{Set of nonlinear pde’s in } (r, t), \text{ solved numerically} \]

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

- Mainly examine 30 MHz (\( V_{rf0} = 560 \text{ V} \))
  
  Also compare 30 and 60 MHz power depositions
30 MHZ NORMALIZED FOURIER VOLTAGES VS $\rho = r/R$

Symmetric

Antisymmetric

Top

Bottom

DC bias

Weak standing wave

Series resonance
30 MHZ VOLTAGES AND SHEATH WIDTHS

Bottom normalized voltage

- Powered $\rho=0.6^\circ\cdot1$
- Grounded $\rho=0.6^\circ\cdot1$

Bottom sheath width

- Powered $\rho=0.6^\circ\cdot1$
- Grounded $\rho=0.6^\circ\cdot1$

Top sheath width

- Powered $\rho=0.6^\circ\cdot1$
- Grounded $\rho=0.6^\circ\cdot1$
30 MHz CURRENT DENSITIES, POWER, $V_{\text{disch}}$ AND $I_{\text{disch}}$

**Top normalized $J_z$**

**Bottom normalized $J_z$**

Electron power absorbed

Normalized voltage and current

- Weak standing wave
- Series resonance
- $V_{\text{rf}} + V_{\text{bias}}$
30 AND 60 MHZ POWERS/UNIT AREA

30 MHz radial field $E_r$

60 MHz radial field $E_r$

30 MHz axial field $E_z$

60 MHz axial field $E_z$

Central peaking
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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