Non-linear Transmission Line (NTL) Study of Electromagnetic (EM) Modes in Capacitive Discharges

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On-line LTP Seminar, 1/25/2022

Ref: Jian-Kai Liu, E. Kawamura, M.A. Lieberman, Yong-Nian Wang, Phys. Plasmas 29, 013058 (2022)

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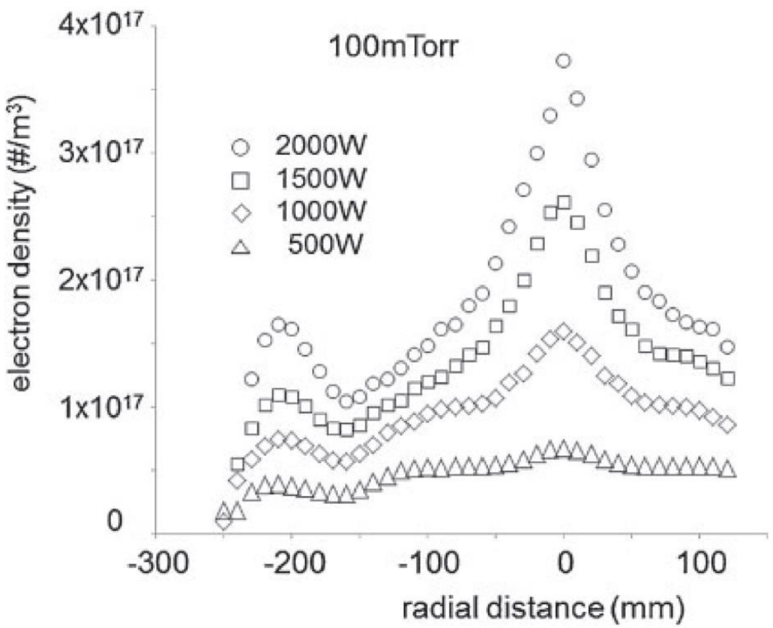
Introduction

Larger area, higher frequency capacitively coupled plasma (CCP) reactors are being used in Si wafer and flat panel processing to maximize production

- When $\lambda >> R$ is no longer satisfied, finite wavelength or standing wave effects can lead to center-high plasma non-uniformity, especially near a spatial resonance
- Harmonics excited in the plasma due to the non-linear sheaths also enhance non-uniformity due to their shorter wavelengths
- These non-linearly excited harmonics can be enhanced by the series resonance



Mid-gap n_e profiles for a 100 mTorr Ar discharge with radius R=26 cm and gap L=2.5 cm, operated at f=60 MHz.

Sawada et al, Japan J. App. Phys. 53, 03DB01 (2014)

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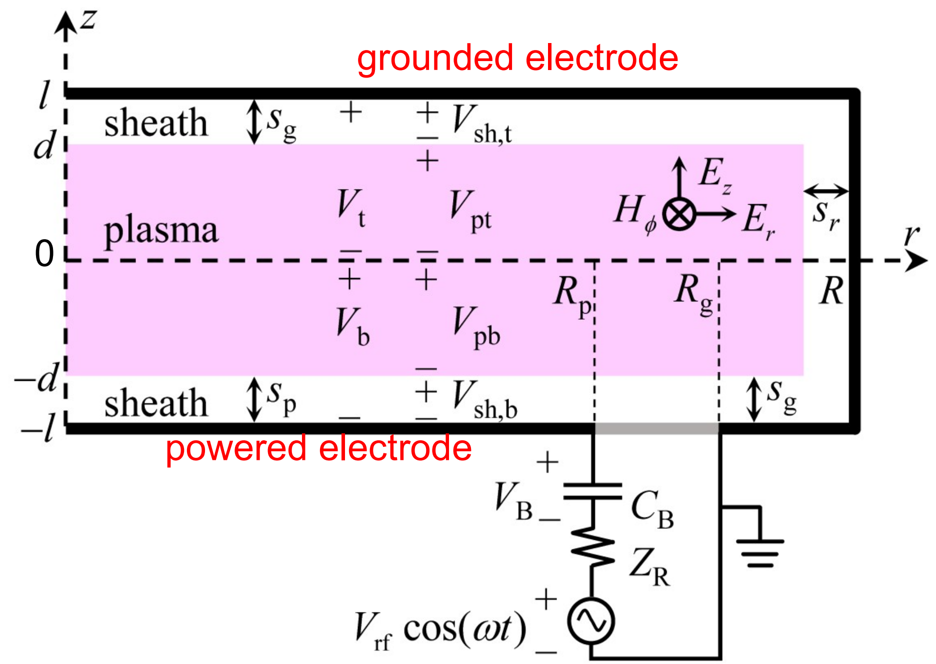
Asymmetric Cylindrical Reactor Geometry

- **Capacitive EM fields are in the transverse magnetic (TM) mode: (E_r, E_z, H_φ)**
- **At low pressure p_g, relative dielectric constant of plasma: $\kappa_p = 1-\omega_p^2/\omega^2 \approx -\omega_p^2/\omega^2$, where $\omega_p=[ne^2/(m\varepsilon_0)]^{1/2}$ and $\omega=2\pi f$ are the plasma and applied radian frequencies**
- **Matching plasma inductance L_p with sheaths' capacitance C_s gives the series resonance: $\omega_{res}=1/(L_pC_s)^{1/2}=\omega_p[(s_g+s_p)/2d]^{1/2}$**



- **R = 25 cm and $2l$ = 5 cm**
- **R_p = 15 cm and R_g = 16 cm**
- **RF voltage source $V_{rf}\cos(\omega t)$**
- **Source resistance Z_R=0.5 Ω**
- **Blocking capacitor C_B**

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Symmetric and Antisymmetric Modes

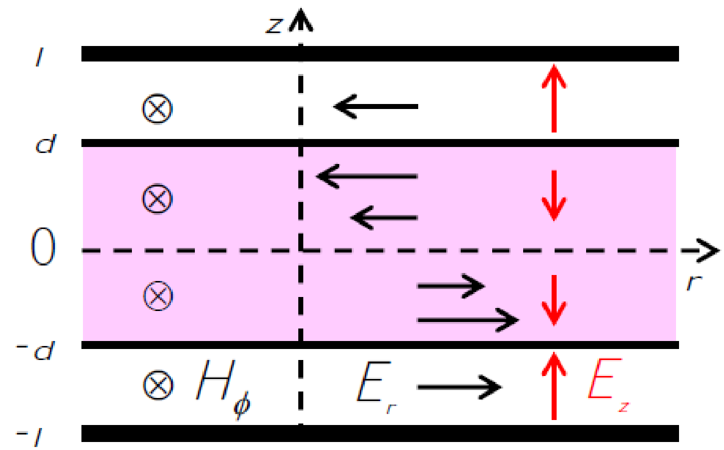
- **Two radially propagating surface wave modes in the plasma:**
  Symmetric: $E_{zs}(z) = E_{zs}(-z)$
  Antisymmetric: $E_{za}(z) = -E_{za}(-z)$

- **At low pressure, the transverse wavenumber $k_t \approx j\,\omega_p/c \equiv j\,\alpha$ =>**
  $E_{zs}(z) \sim \cos(k_t z) \approx \cosh(\alpha z)$ and
  $E_{za}(z) \sim \sin(k_t z) \approx \sinh(\alpha z)$

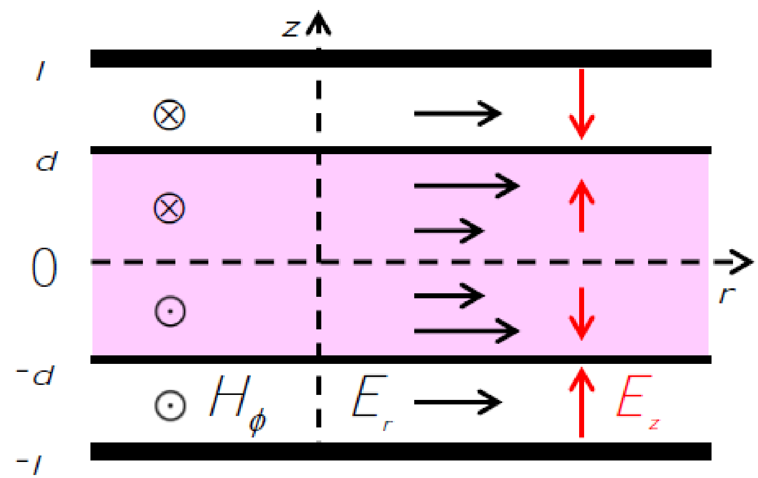
- **Wavelengths of the modes:**
  $\lambda_s \approx \lambda_{vac}\,[(s_p + s_g)/2l]^{1/2}$, $\lambda_{vac} = c/f$
  $\lambda_a \approx \lambda_{vac}(\omega_p/c)[2d\, s_g\, s_p/(s_p+s_g)]^{1/2}$

- **First spatial resonances occur at:**
  $k_s R = (2\pi/\lambda_s)R = \chi_{01}$, $k_a R = (2\pi/\lambda_a)R = \chi_{11}$
  with $\chi_{01} \approx 2.405$, $\chi_{11} \approx 3.832$ the 1st zeroes of $J_0(k_s r)$ and $J_1(k_a r)$

Symmetric Mode:

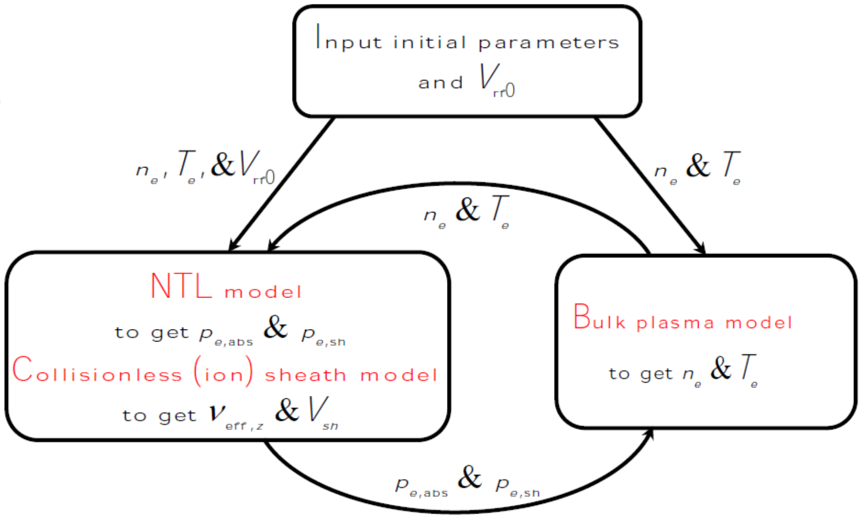


Antisymmetric Mode:



Low pressure Capacitive Discharge Model

- **Analytical axial field solve:**
  $E_z(z,r,t)=(\cosh(\alpha z)/\cosh(\alpha d))E_{zs}(r,t)$
  $+ (\sinh(\alpha z)/\sinh(\alpha d))E_{za}(r,t)$
- **1D radial NTL model: Maxwell's equations and electron momemtum balance equation => set of non-linear PDE's in (r,t) to solve numerically**



- **Analytical collisionless (ion) Child Law sheath model: Finds sheath voltages, sheath widths and an anisotropic effective collision frequency:** $\nu_{eff,z} = \nu_m + \nu_{stoc} + \nu_{ohm,sh}$ $(\nu_{eff,r}=\nu_m)$
- **2D quasi-neutral, ambipolar bulk fluid model obtains** $\langle n_e \rangle$, $\langle T_e \rangle$

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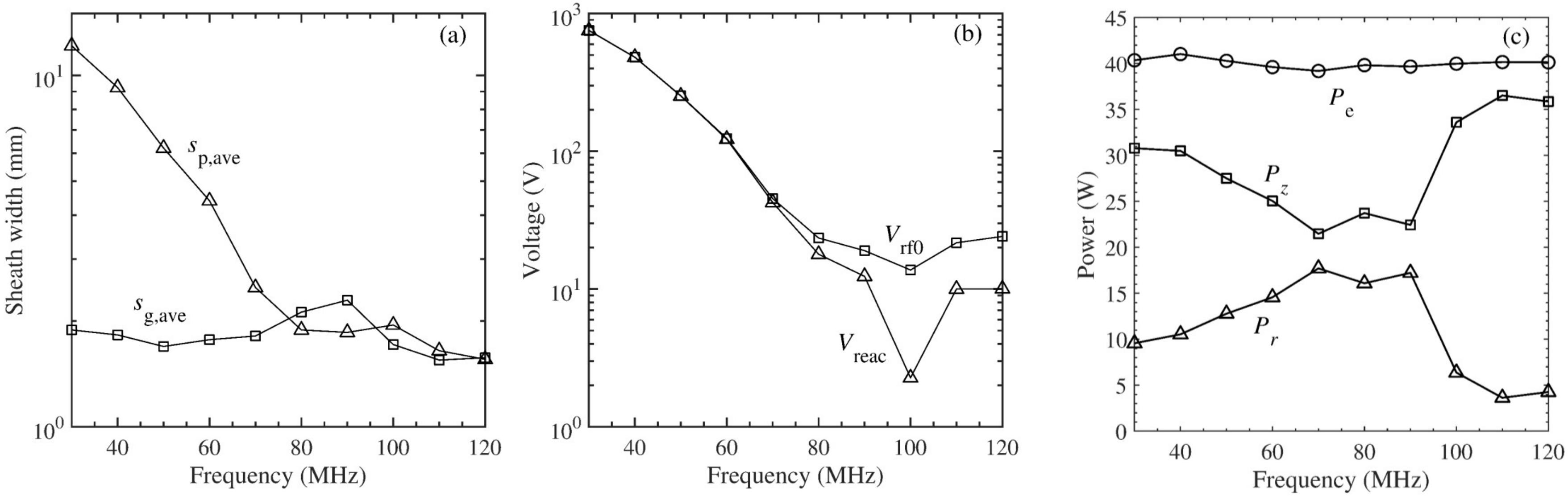
20 mTorr Ar Results for P_e=40 W at f=30-120 MHz



- P_r dominated by anti-sym mode; P_z dominated by sym mode
- Source voltage and s_p tends to decline with increasing f at fixed P_e
- At lowest f, sym mode dominates so that $s_p > s_g$ and $P_r \ll P_z$
- As $f \rightarrow f_{a1}$ ~85 MHz, $s_g > s_p$ and $P_r \rightarrow P_z$, and as $f \rightarrow f_{s1}$~ 100 MHz the source voltage reaches a minimum and $P_z \rightarrow P_e$ and $P_r \rightarrow 0$

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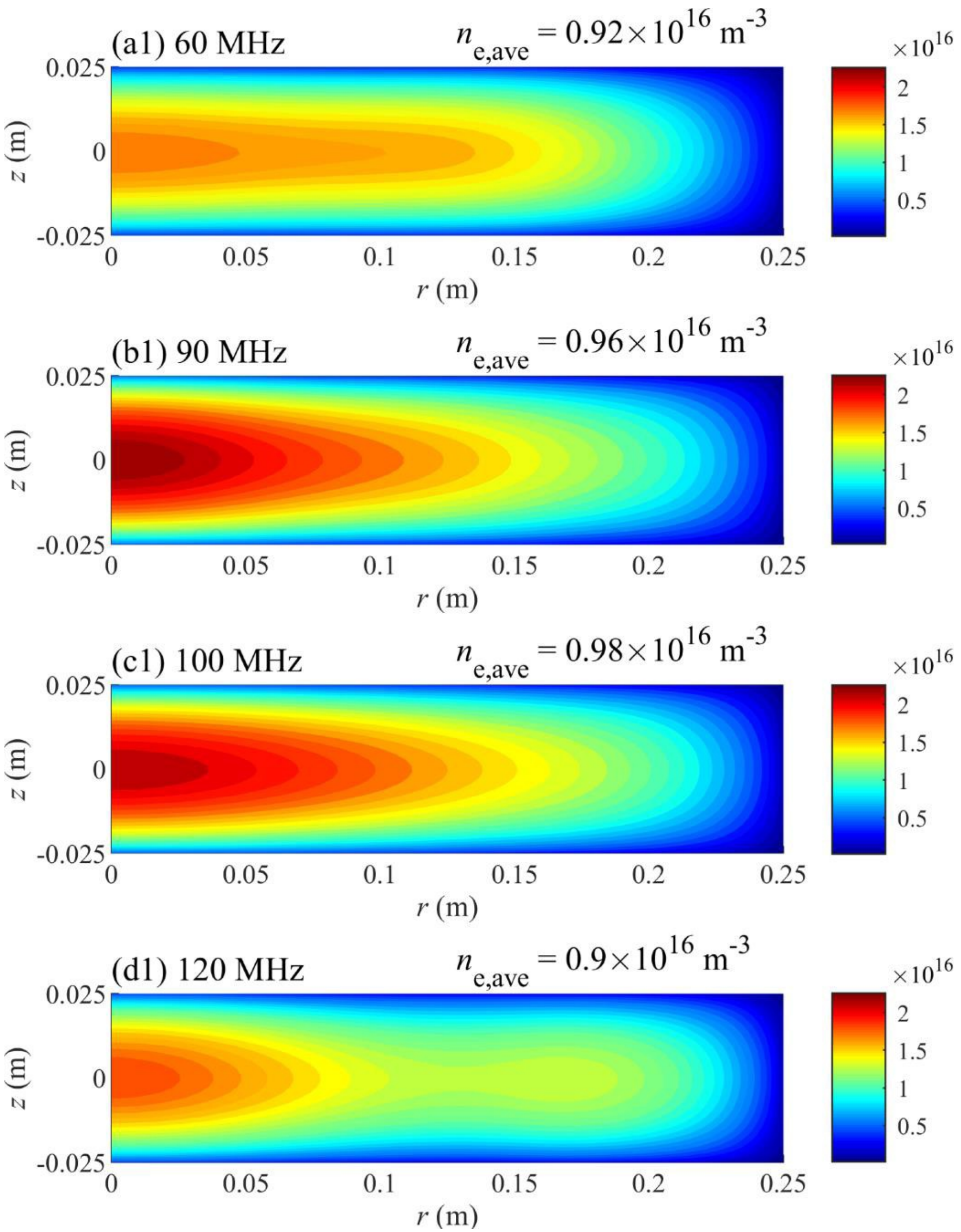
Plasma density at 60, 90, 100 and 120 MHz

- **60 MHz, f < f_{a1}, f_{s1}: center peak due to finite λ effect and non-linear harmonics**
- **90 MHz~f_{a1}, 100 MHz ~ f_{s1}: sharper peaks due to shorter λ at higher f**
- **120 MHz > f_{a1}, f_{s1}: second peak since shorter λ allow secondary maxima of surface waves to appear within reactor**



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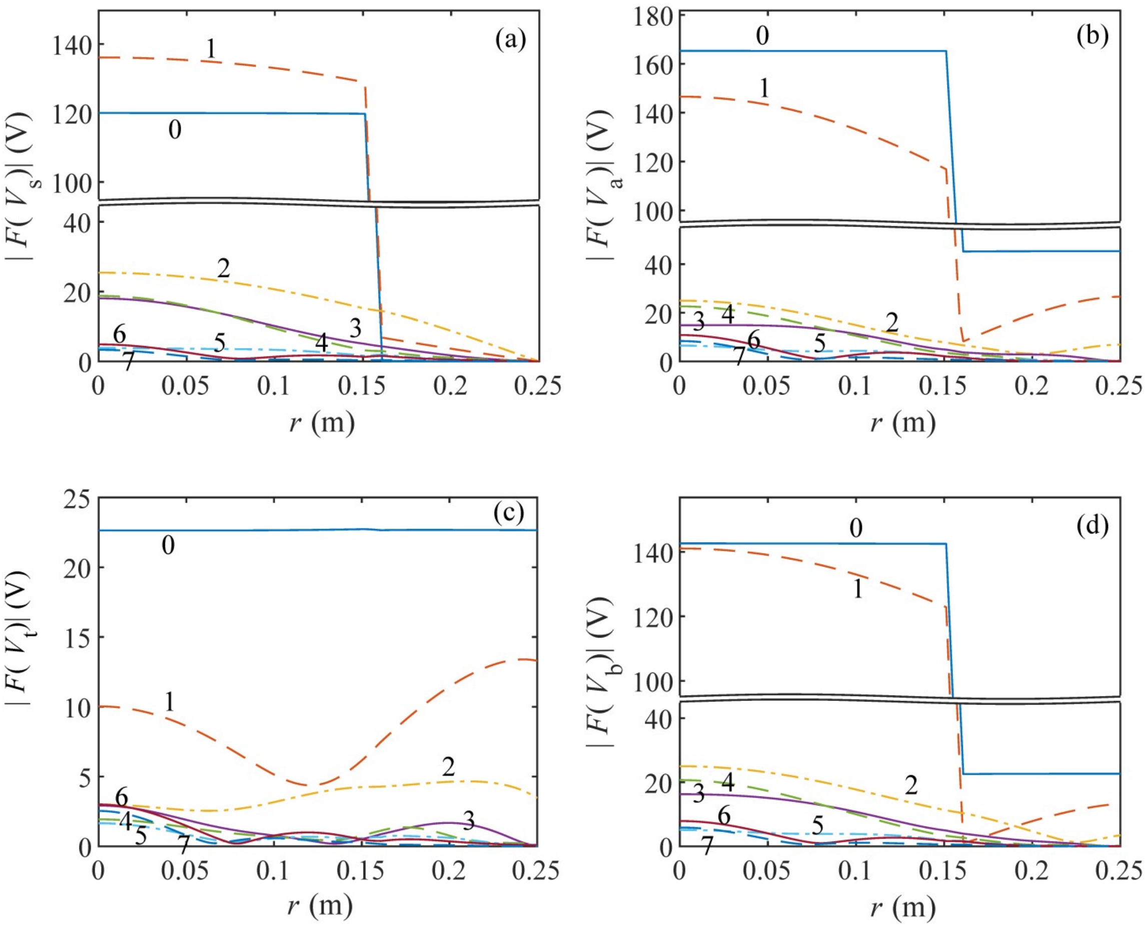
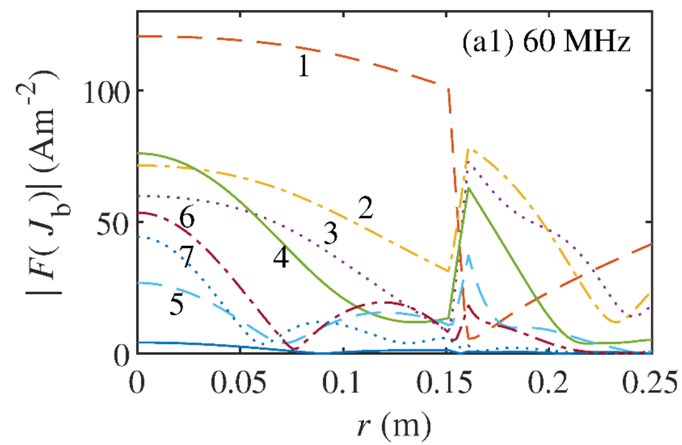
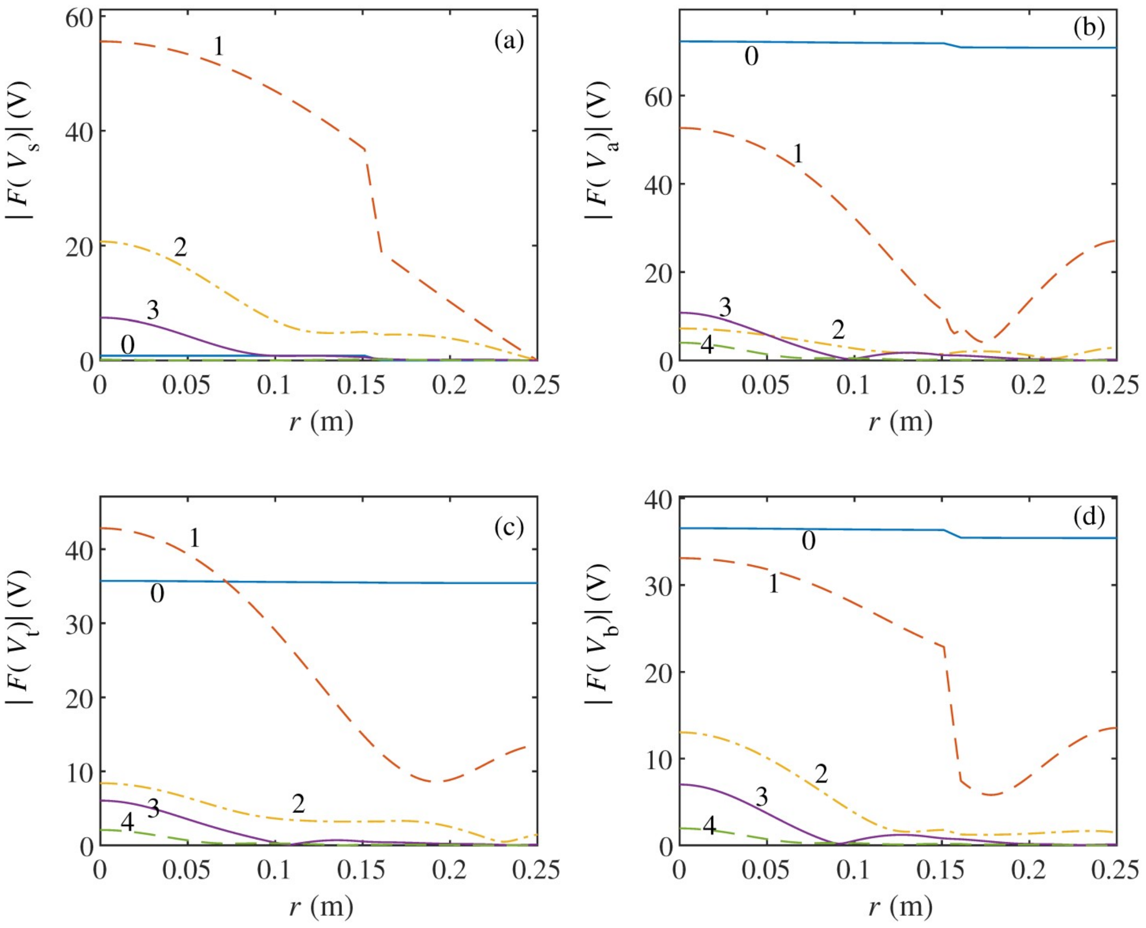
Fourier Transform of Voltages at 60 MHz



- 60 MHz, $f < f_{a1}, f_{s1}$: center-high non-uniformity is enhanced by non-linear harmonics
- f_{res}~400 MHz is between 6th and 7th harmonic



Fourier Transform of Voltages at 90 MHz



- **90 MHz, f ~ f_{a1}: Due to shorter wavelength at higher f, sharper center-high non-uniformity**
- **Fewer harmonics excited due to decreasing V_{rf} with f, and more power going to lower harmonics near their spatial resonances**

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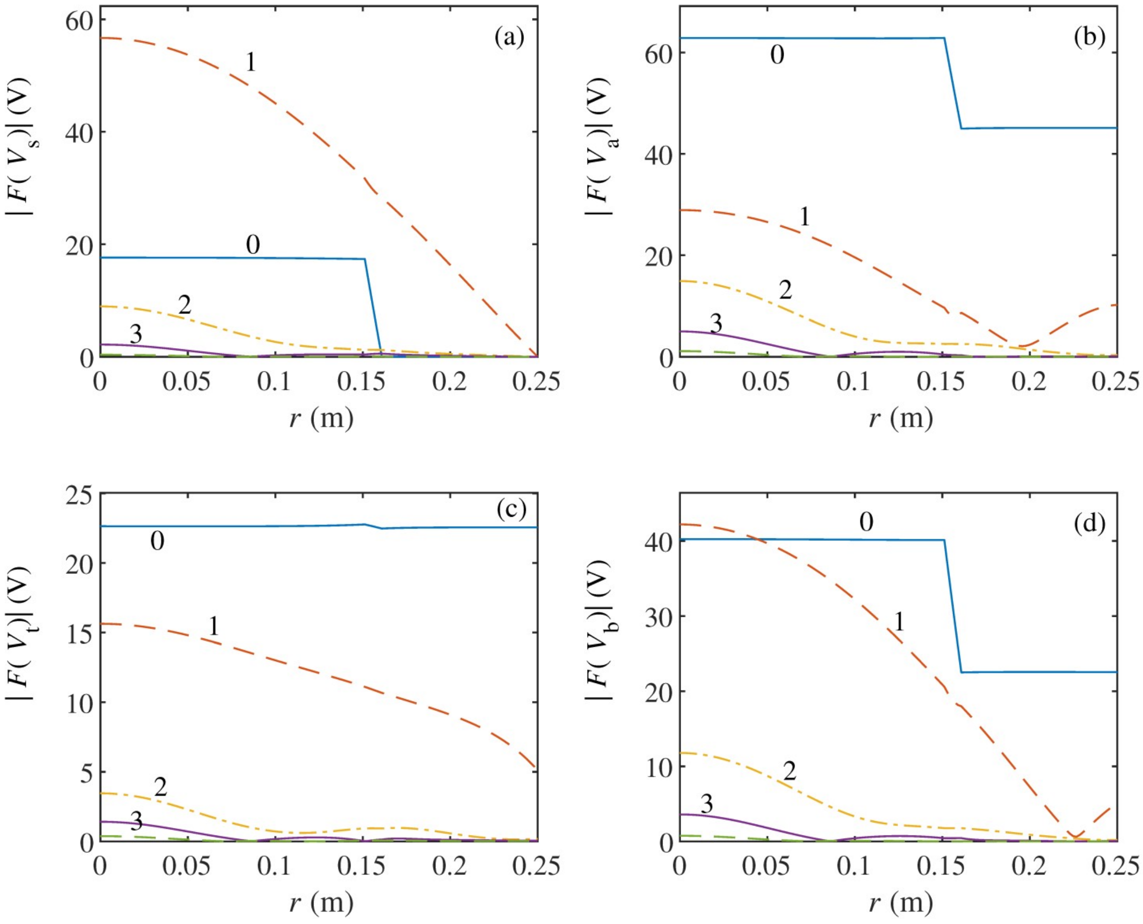
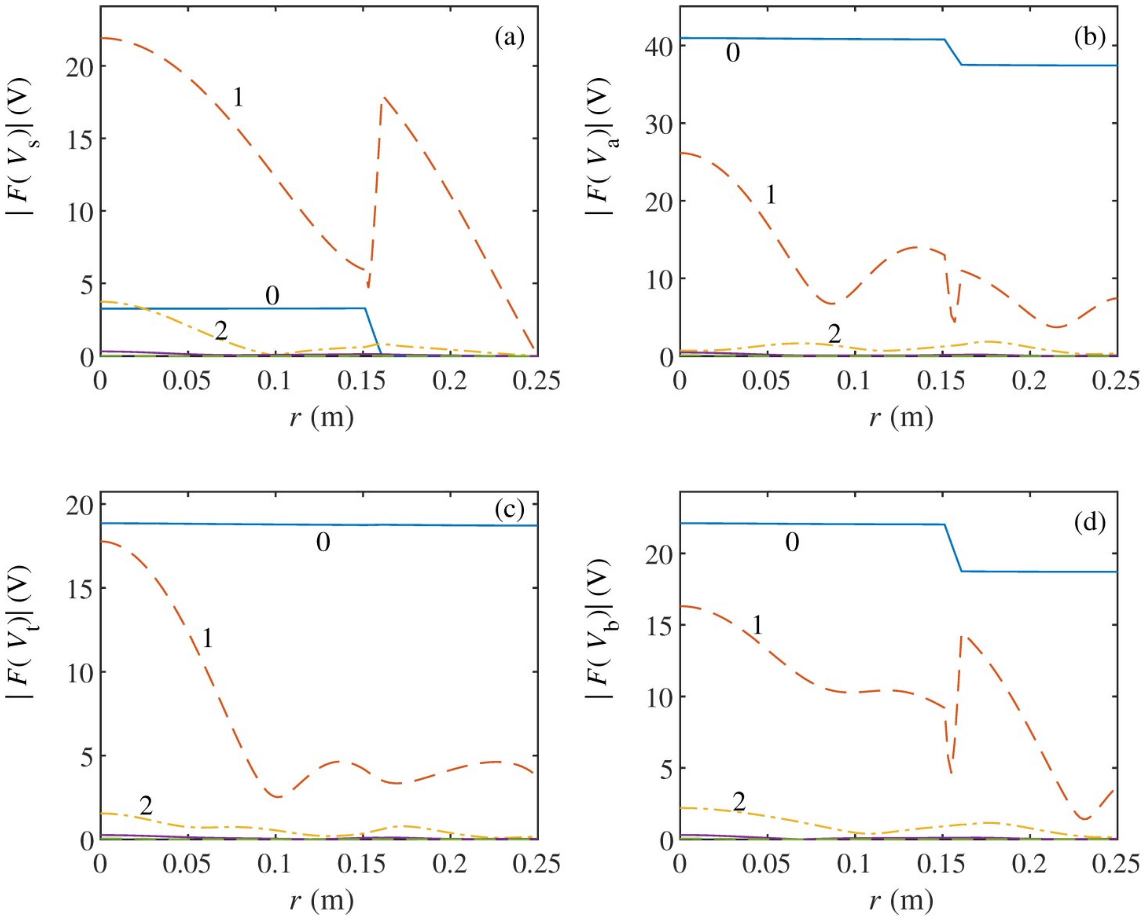
Fourier Transform of Voltages at 100 MHz



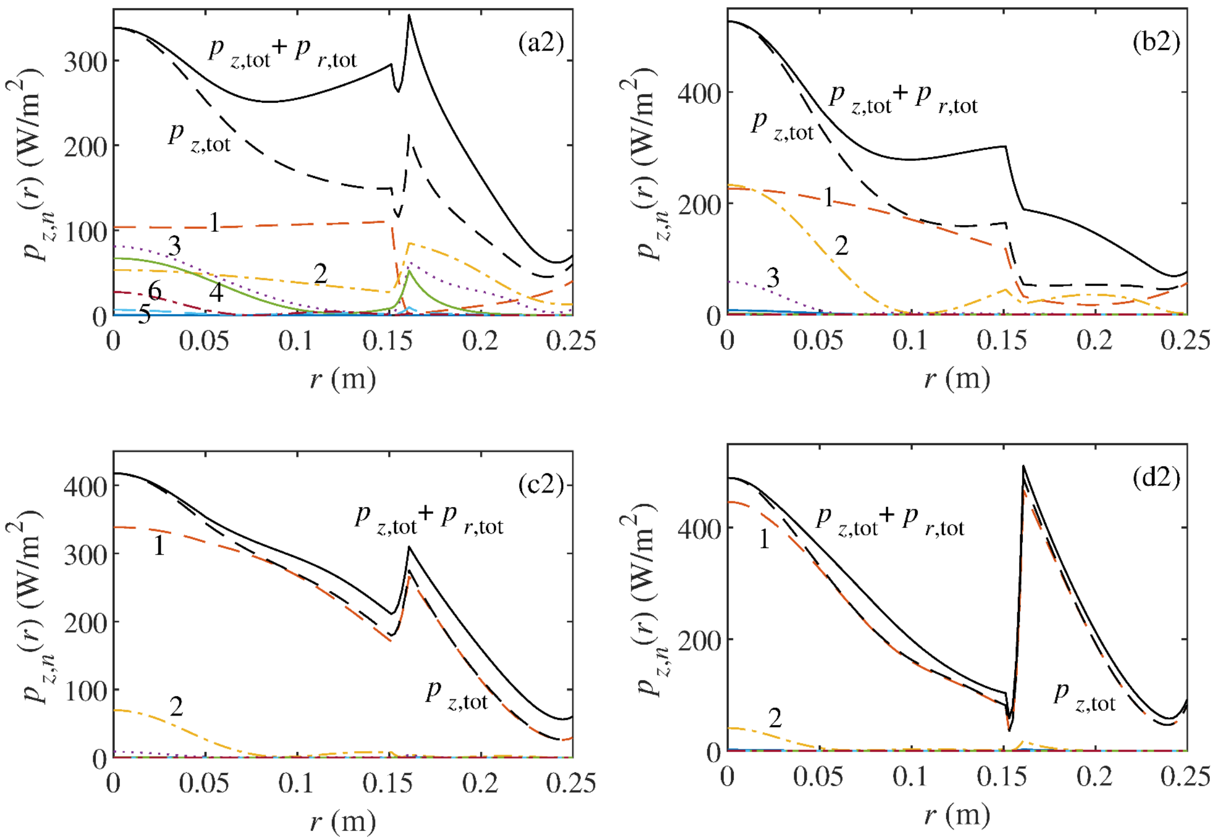
- **100 MHz, f ~ f_{s1} , but still near f_{a1}**
- **Source voltage has minimum at 100 MHz, resulting in few excited harmonics**

Fourier Transform of Voltages at 120 MHz



- **120 MHz, f > f_{s1} , f_{a1}**
- **Observe secondary maxima in 1st harmonic due to shorter wavelengths at higher f**

Electron Power Density at 60, 90, 100 and 120 MHz



- **At 60 MHz significant center-high peak due to numerous higher harmonics**
- **As f increases, less higher harmonics are excited as V_{rf} decreases with f, and more P_e goes to lower harmonics near their spatial resonances**
- **At 120 MHz, see a significant secondary peak due to shorter wavelength**

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Conclusions

- The 1st antisymmetric and symmetric spatial resonances occur at f_{a1}~85 MHz and f_{s1}~100 MHz for a 20 mTorr Ar discharge with $2l$=5 cm, R=25 cm and fixed P_e=40 W
- Due to the different field symmetries, P_r is dominated by the antisymmetric mode while P_z is dominated by the symmetric mode
- At lower f, the symmetric mode dominates so that the sheath widths and voltages at the powered electrode are larger than at the grounded electrode, and $P_r \ll P_z$
- As $f \rightarrow f_{a1}$, $s_g > s_p$ and $P_r \rightarrow P_z$, and as $f \rightarrow f_{s1}$, the source voltage reaches a minimum and $P_z \rightarrow P_e$ and $P_r \rightarrow 0$
- Density shows a sharp center peak due to the standing wave effect, nonlinearly excited harmonics and spatial or series resonances
- For $f > f_{s1}$, the shortened wavelengths allow secondary maxima of the modes to occur within the reactor, causing secondary n_e peaks

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