MWP 1.00009

MODELING AND SIMULATION OF ELECTROMAGNETIC EFFECTS IN CAPACITIVE DISCHARGES

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STANDING WAVES AND SKIN EFFECTS

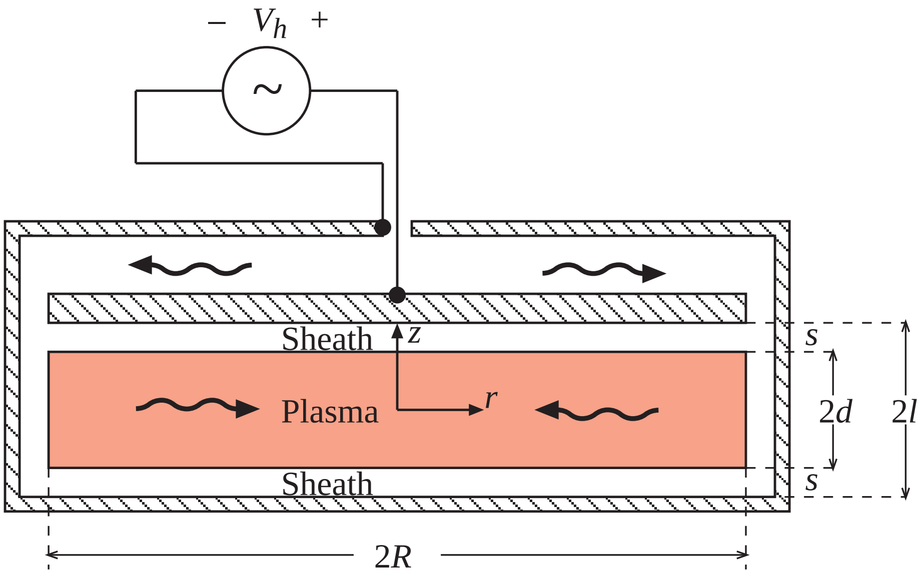
- High frequency and large area ⇒ standing wave effects

- High frequency ⇒ high density ⇒ skin effects

1. M.A. Lieberman, J.P. Booth, P. Chabert, J.M. Rax, and M.M. Turner, *Plasma Sources Sci. Technol.* **11**, 283, 2002
2. P. Chabert, *J. Phys. D: Appl. Phys.* **40**, R63, 2007
3. Insook Lee, D.B. Graves, and M.A. Lieberman, "Modeling of electromagnetic effects in capacitive discharges," submitted to *Plasma Sources Sci. Technology*, 2007

CYLINDRICAL CAPACITIVE DISCHARGE

Consider only the high frequency source

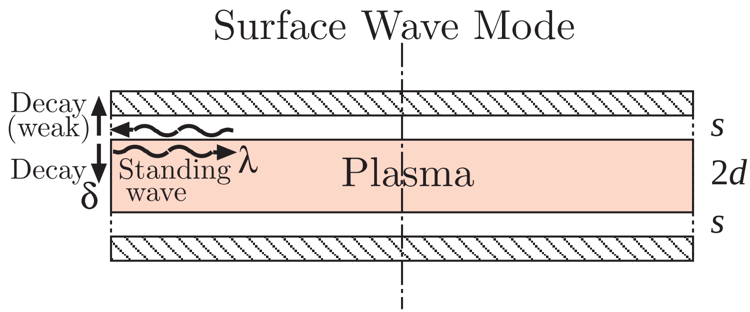


Fields cannot pass through metal plates

(1) V_s excites radially outward wave in top vacuum gap
(2) Outward wave excites radially inward wave in plasma

SURFACE WAVE MODE

- Power enters the plasma via a *surface wave mode:*



- Radial wavelength for surface wave (low density limit):

$$\lambda \approx \frac{\lambda_0}{\sqrt{1 + d/s}} \sim \frac{\lambda_0}{3}$$

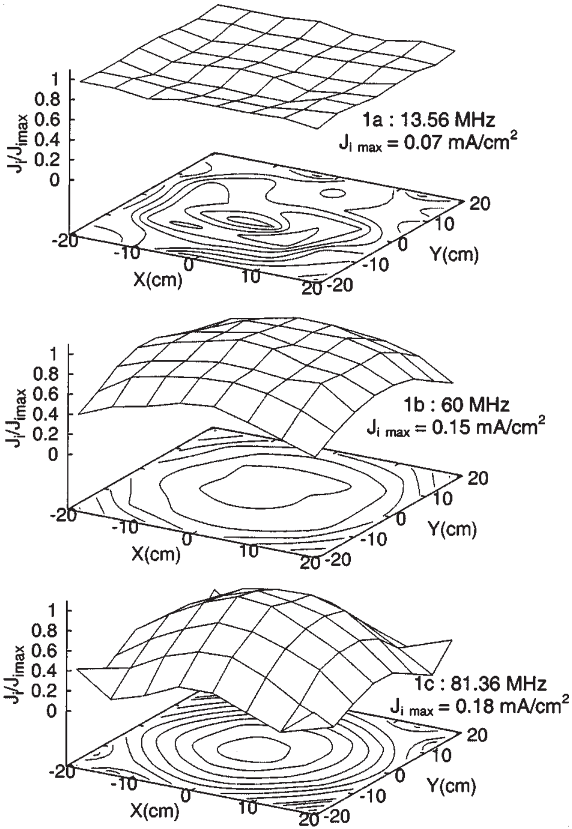
with $\lambda_0 = c/f$ the free space wavelength

- Axial skin depth for surface wave:

$$\delta \sim \frac{c}{\omega_p}$$

- There are also *evanescent modes* leading to edge effects near $r = R$

EXPERIMENTAL RESULTS FOR STANDING WAVES



20×20 cm discharge
$p = 150$ mTorr
50 W rf power

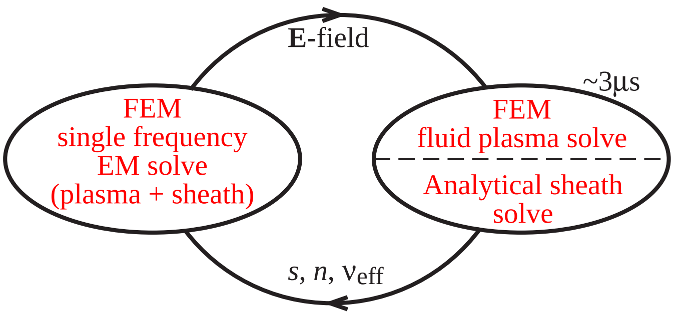
The standing wave effect is seen at 60 MHz and is more pronounced at 81.36 MHz

(A. Perret, P. Chabert, J-P Booth, J. Jolly, J. Guillon and Ph. Auvray, *Appl. Phys. Lett.* **83**, 243, 2003)

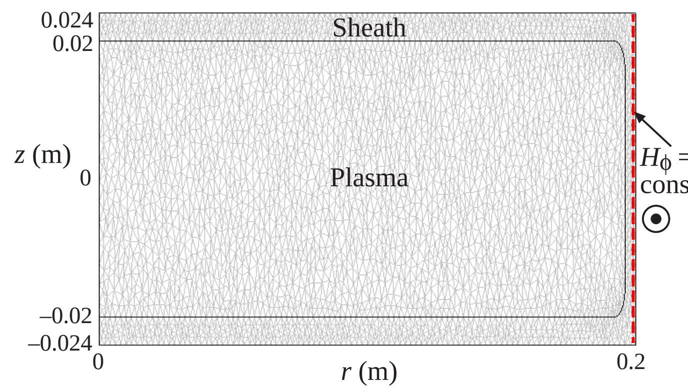
FINITE ELEMENT METHOD (FEM), 2D EM SOLUTIONS

(with Insook Lee and D.B. Graves)

- Arbitrary (asymmetric) discharge geometries and materials
- Transition from global to local power balance
- Distinguish edge effects (electrostatic) versus EM effects
- Series resonance stop band



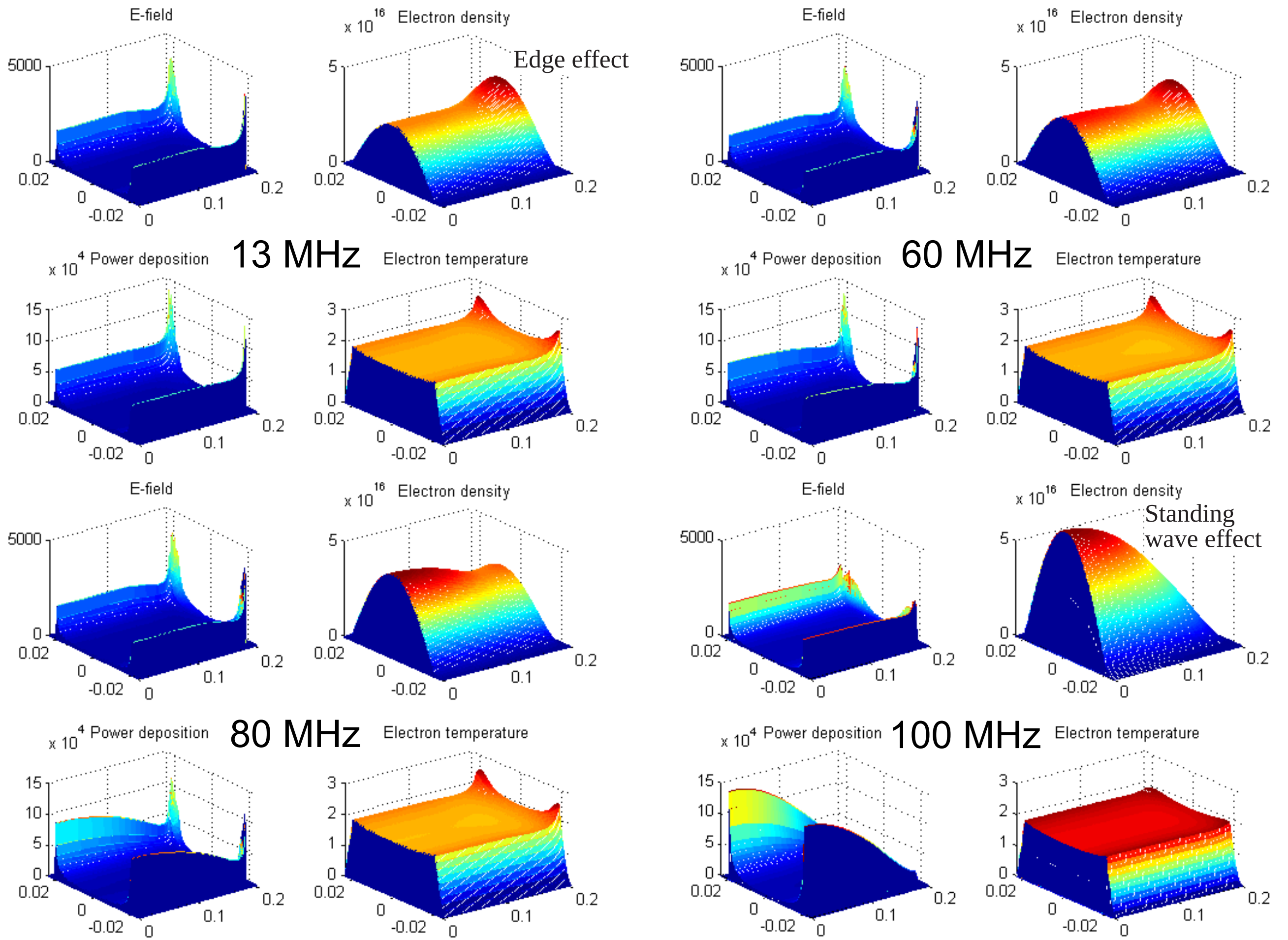
Solution Procedure



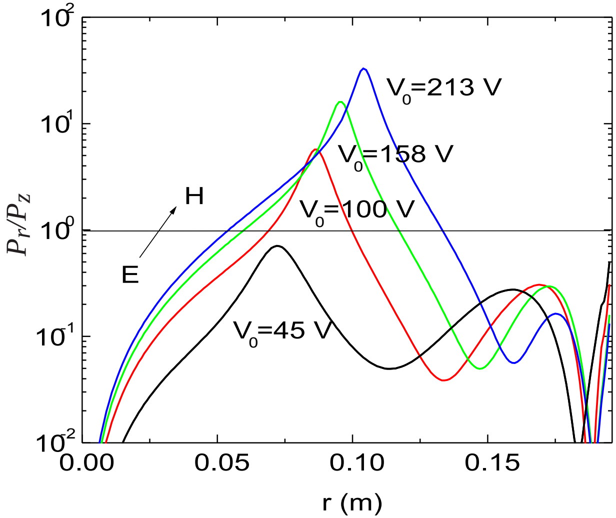
FEM Mesh (6252 elements)

(Analytical model: collisional Child law, variable sheath width, stochastic and ohmic heating in the sheath)

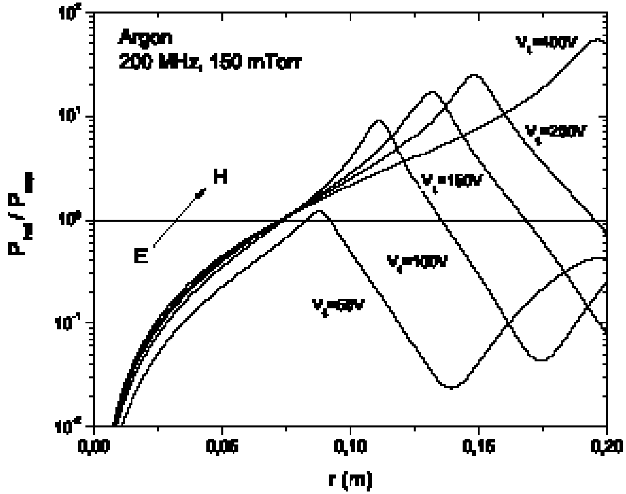
STANDING WAVES — 40 W, 150 mTORR



SKIN EFFECTS — 150 mTORR



FEM model
(with Insook Lee and D.B. Graves)



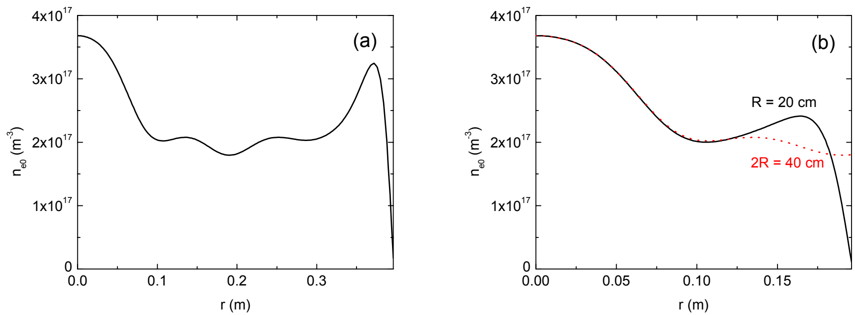
Transmission line model
(P. Chabert et al, *Plasma Sources Sci. Technol.* **15,** S130, 2006)

- Transmission line model: collisionless sheaths, no edge effects, purely local power deposition

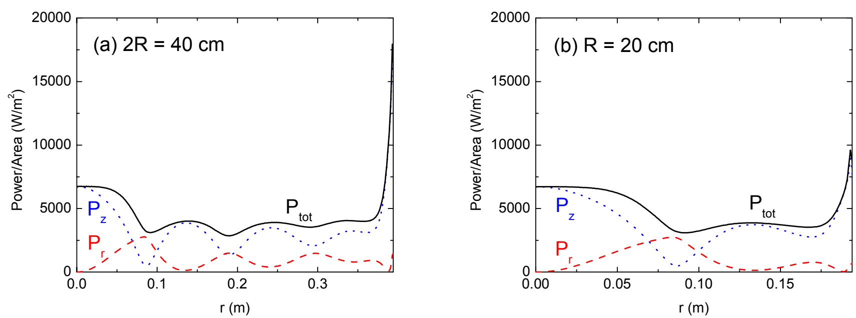
In both cases spatial E to H transitions are seen

COMPARE 20 CM AND 40 CM RADIUS REACTORS

(150 mTorr, 200 MHz, $V_{\rm rf} = 100$ V on-axis)



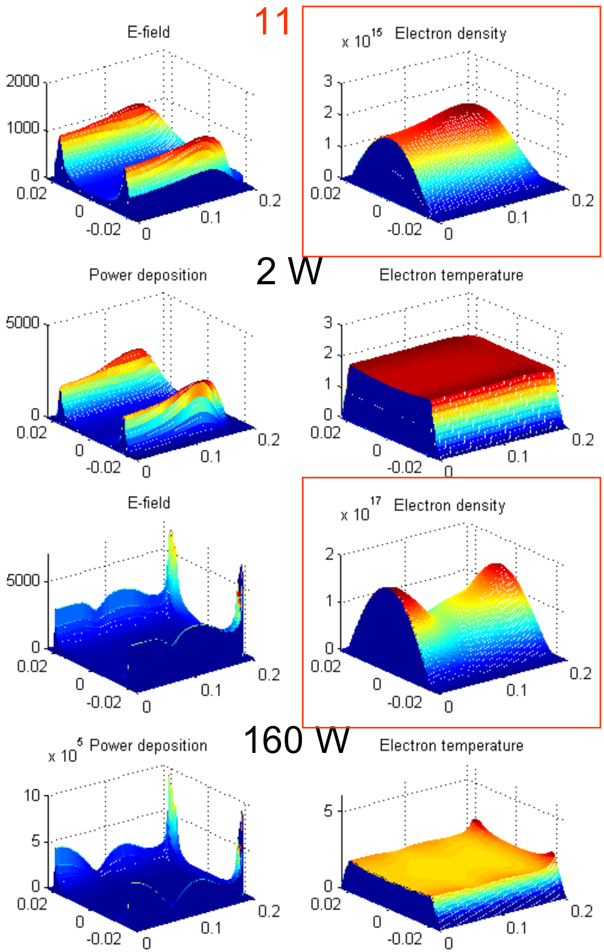
Radial plasma profile for (a) 40 and (b) 20 cm radius reactors

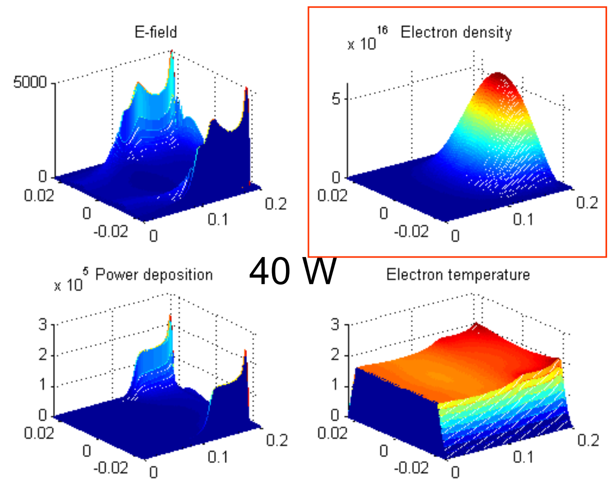


Radial P_r and axial P_z power deposition versus radius r, and their sum

- Edge effect for 20 cm radius reactor, and wave effects, are apparent

SERIES RESONANCE — 200 MHz, 150 mTORR





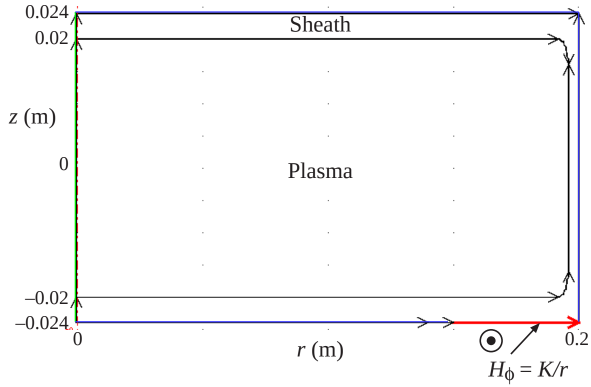
Surface wave does not propagate for 40 W case:

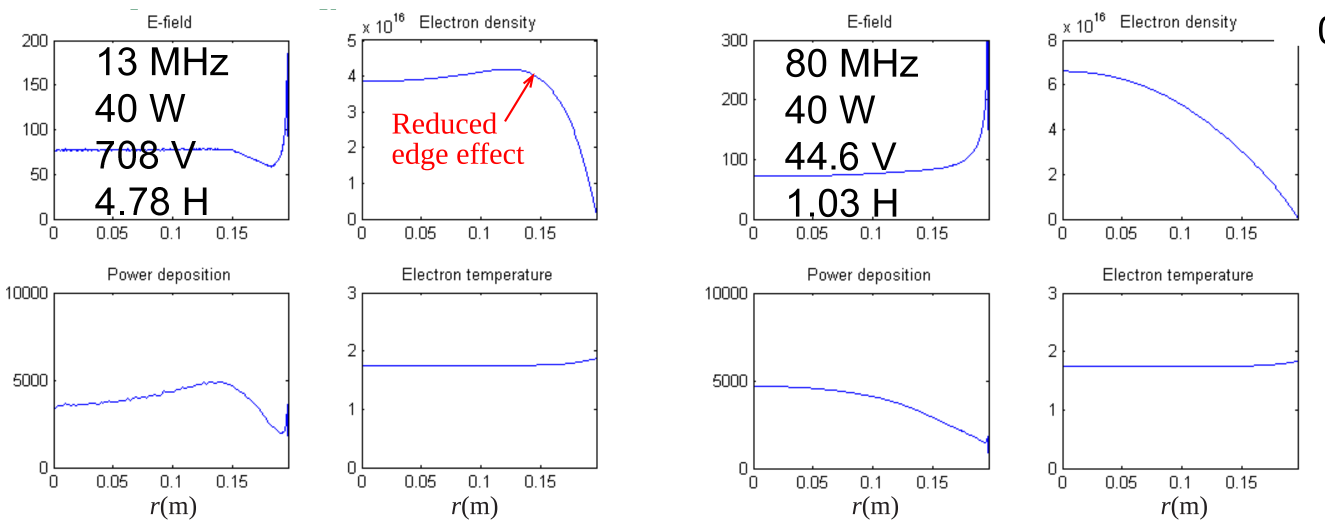
$$\omega_{\rm res} \lesssim \omega \lesssim \omega_p$$

$\omega_{\rm res}$ = series resonance frequency

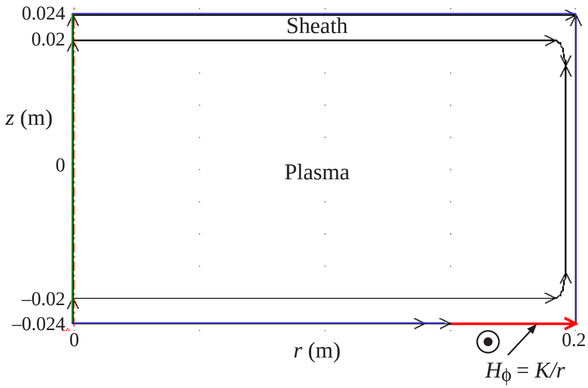
ω_p = plasma frequency

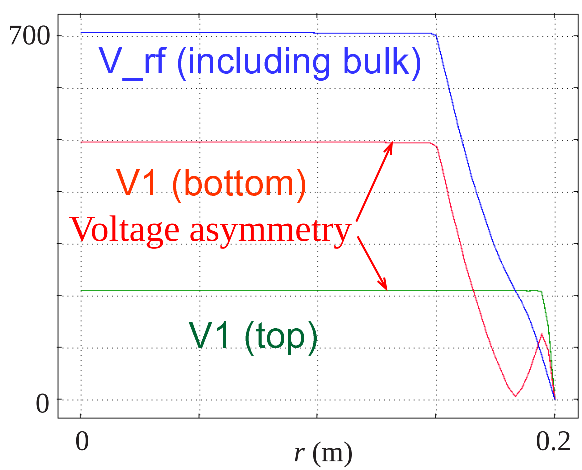
ASYMMETRIC (BOTTOM) EXCITATION — 150 mTORR

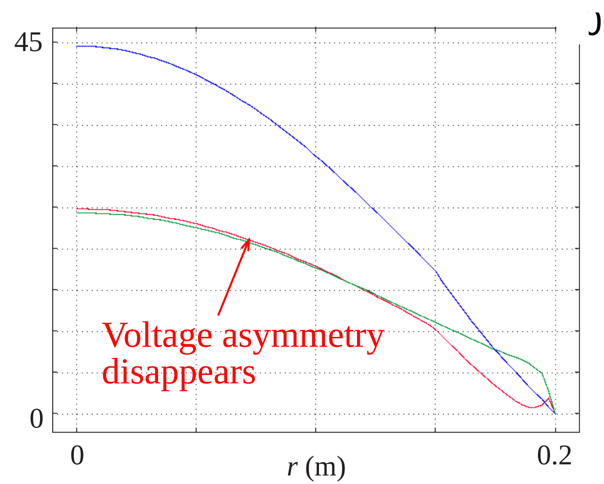




ASYMMETRIC VOLTAGE WAVEFORMS







CONCLUSIONS

- A 2-D axisymmetric model and finite element method (FEM) simulation strategy was developed to determine radial plasma uniformity in large-area, high frequency capacitive discharges
- Electromagnetic effects and electrostatic edge effects are well captured by the simulations
- The use of a FEM-based simulation allows for irregular and complex geometries, as well as fluid flow, heat and mass transfer, and chemical kinetics, although we do not include most of these effects here

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