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Characterization and Simulation of a VHF Remote Plasma Source

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Problem Statement

- A newly introduced, capacitively coupled, VHF remote plasma source has demonstrated unique functionality, warranting improved understanding
- Empirically derived evaluation imposes practical limits to comprehensive characterization
- Discretized simulation methods have been used previously to optimize the mechanical and electrical performance of the plasma source
- Multi-physics simulation methods are now being used to characterize the *plasma* performance of the device

Objective

- Generate and validate multi-physics simulation tools which allow for a complete characterization of the plasma

Unique simulation challenges, relative to typical CCP reactors

- Operation at VHF (60 MHz) frequency
- Non-traditional, curvilinear geometry
- Asymmetric electrode structure
- Broad operating space
- Remote application – need to predict downstream effects

Background

- A Remote Plasma Source (RPS) is a plasma-generating device (source) which is installed remotely from the process chamber
- An RPS can introduce a desirable stream of radicals to the substrate, while minimizing damage from higher energy ions and photons which are prevalent in the active discharge
- The archetypal RPS is an inductively coupled plasma (ICP) chamber, often toroidal in design
- Conventional applications for remote plasma sources include: chamber clean, process chamber exhaust abatement, stripping, or ashing processes
- In recent years, RPS technologies are demonstrating advantage in a wider scope of applications: radical generation for direct processing, low energy processing, and augmentation or replacement of in-situ sources
- Previous papers:

  - S. Polak, D. Carter, "Measurement and Simulation of a VHF Remote Plasma Source," in Society of Vacuum Coaters TechCon, Chicago, IL, 2014
  - D. Carter, et al. "Plasma Generation and Delivery From a VHF Remote Source," in Society of Vacuum Coaters TechCon, Providence, RI, 2013.
  - S. Polak, et al. "Remote Plasma Source Mechanical Analysis Methodology," in AVS International Symposium and Exhibition, Tampa, 2012.

Previous Simulations

Previously, a variety of discretized (finite-element, finite-volume) simulations were used to enhance the structural reliability of the device, and optimize the performance of heat and mass transfer

- Computational fluid dynamics (CFD) was used to assess and optimize feed-gas delivery in the chamber, to promote rapid pressure equalization and azimuthal symmetry (Figure p1)
- Coupled, thermal-structural finite-element models were used to predict the fracture-mechanics thresholds for defects in critical ceramic components (Figure p2), leading to enhanced manufacturing and inspection methods

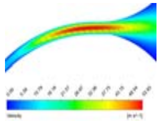


Figure p1: CFD analysis of feed-gas distribution manifold channels

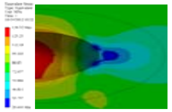


Figure p2: Fracture mechanics modeling of known defects

Empirical Plasma Measurement

Langmuir Probe:

- Scientific Systems SmartProbe®
- Inserted axially into the output section of plasma source
- Measurements from 3.8 to 30.5 cm spacing to powered electrode
  - 4.5 cm increments
- Argon
  - Flow: 50 sccm
  - Pressure: 0.1, 0.5, and 1.0 torr
  - Power: 50-200 W

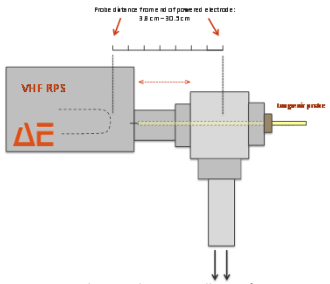


Figure m1: Schematic showing installation of translatable Langmuir probe within the remote plasma source and downstream tubulature

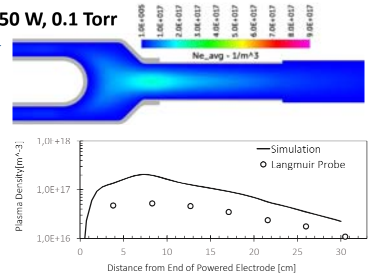
Plasma Simulations

Argon, 50 sccm, 50-150 W, 0.1 – 1.0 Torr, all transient CCP simulation results at ~2 seconds

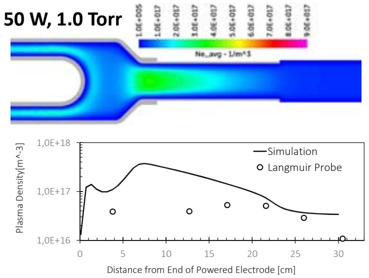
Power

Pressure

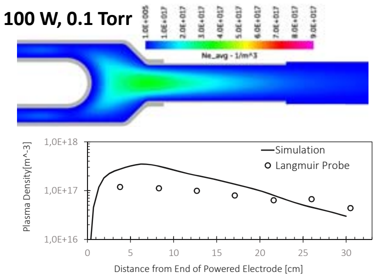
50 W, 0.1 Torr



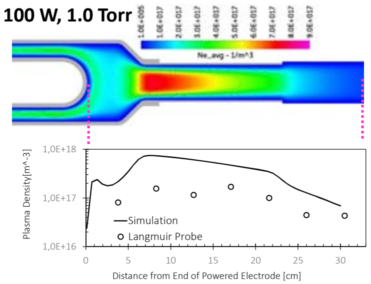
50 W, 1.0 Torr



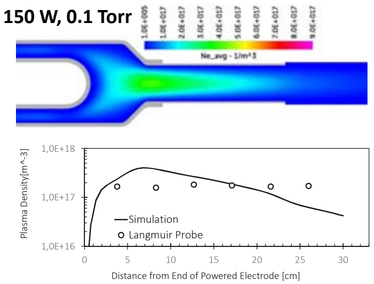
100 W, 0.1 Torr



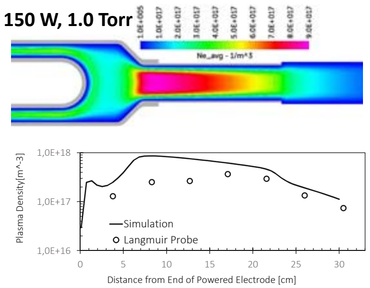
100 W, 1.0 Torr



150 W, 0.1 Torr



150 W, 1.0 Torr



CFD-ACE+ Multi-Physics Solver

Coupled Physics for Plasma Simulation:

- Fluid Dynamics
- Heat Transfer
- Chemistry
- Electromagnetic
- Plasma
- Boltzmann / Kinetics

Plasma Equations:

- Poisson's equation is solved sequentially with charged species transport equations and surface charge

$$\nabla \cdot \varepsilon \nabla \varphi = 0 \qquad \frac{\partial}{\partial t} \cdot N_i + \nabla(\Gamma_i) = S_i \qquad \frac{\partial}{\partial t} \cdot \rho + \sum_i \nabla(\Gamma_i q_i) = 0$$

- Neutral transport equations are addressed
- The electron energy equation is solved for electron temperature, considering power deposition and collisional losses

$$\frac{3}{2} \cdot \frac{\partial}{\partial t} \cdot (n_e T_e) + \nabla\left(\frac{5}{2} T_e \Gamma_e - \chi \nabla T_e\right) = P - n_e \sum_r N_r K_r$$

Electron Energy Density (EEDF) Look-Up Tables

- The dependence of electron reaction and transport coefficients on the non-Maxwellian EEDF is accounted for using lookup tables.
- Lookup tables are created from the numerical solution of the Boltzmann equation to create tabulated data that is imported into the multidimensional simulation:
- Reaction rate constant ®, diffusion coefficient (D), and mobility of electrons are calculated from the EEDF

n_e	E	T_e	R_1 (Fwd)	R_2 (Bwd)	…	R_N (Fwd)	R_N (Bwd)	μ_e	D_e
(m^{-3})	V/m	eV	$(m^3 s^{-1})$	$(m^3 s^{-1})$		$(m^3 s^{-1})$	$(m^3 s^{-1})$	$(m^2 s^{-1} V^{-1})$	$(m^2 s^{-1})$

Conclusions

- Plasma density magnitude and its relationship with power correlate well to empirical data
- Plasma density gradients (relationship with position) show a disparity with empirical data, and warrant further study
- The simulations are accurately predicting the relationship between plasma density and power, as well as plasma density and pressure

Future Work

- Continue to refine the simulations for Argon:
  - Achieve better correlation to empirical data, especially plasma distribution and position accuracy
  - Enhance computing efficiency and reduce solve time
  - Understand the impact of various simulation options
    - Heat transfer & Stochastic heating
    - Lossy dielectric layers
    - Reactor-circuit coupling
    - Ion momentum
- Explore other feed-gas chemistries, including H2, O2, and NF3.
- Perform H2 radical output/delivery optimization, parametric study
- Use plasma simulation to optimize the geometry of future RPS designs