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Consequences of Long Term Transients in Large Area High Density Plasma Processing: A 3-Dimensional Computational Investigation*

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AGENDA

- Introduction
- Description of 3-dimensional parallel hybrid model
- Consequences of asymmetric pumping
- Pulsed operation of ICPs
- Summary

300MM WAFER PROCESSING: CHALLENGES

- Side-to-side asymmetries in plasma properties become more critical as wafer size increases.

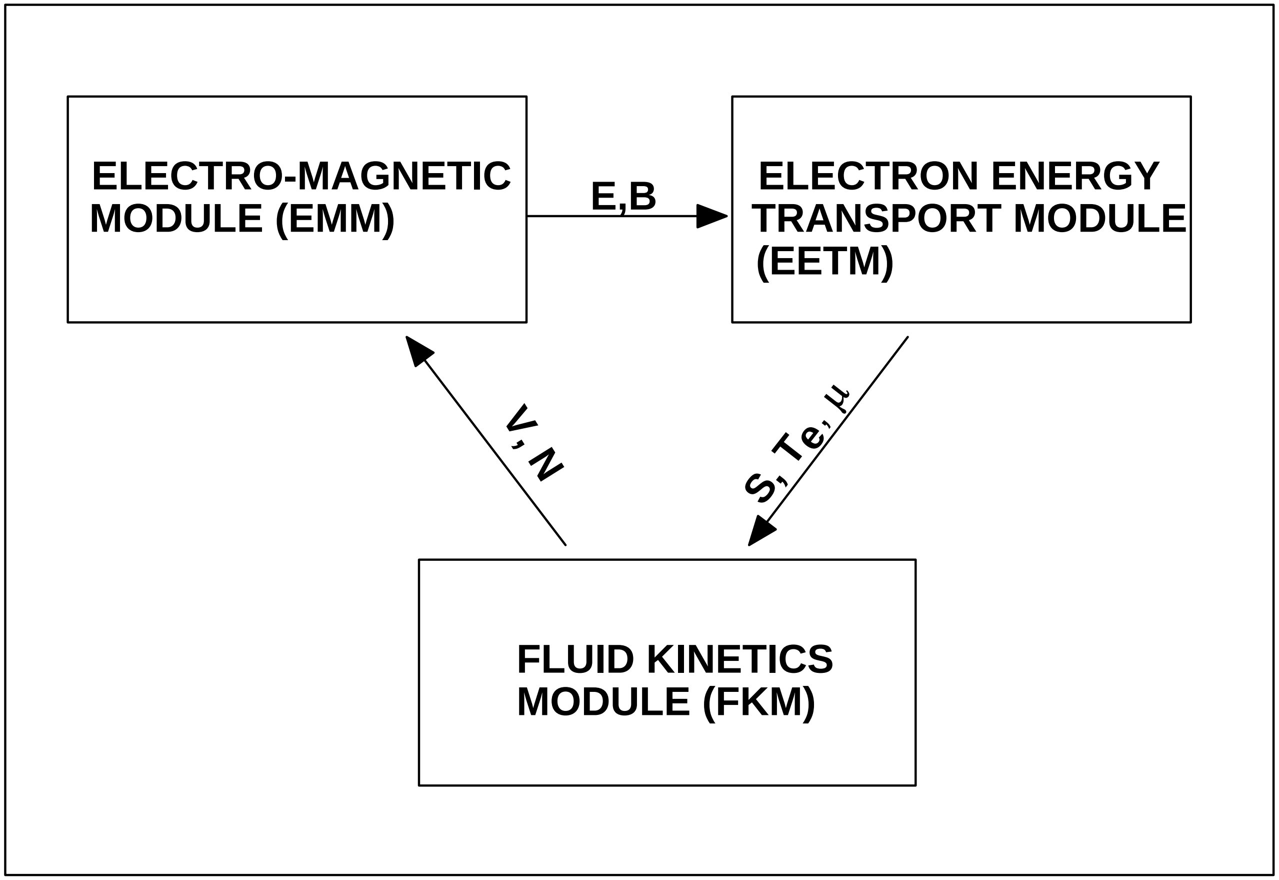
- Side pumping and side gas injection are common in industrial reactors and can lead to asymmetries in species densities, fluxes and temperatures.

- Flow asymmetries become pronounced when feedback through plasma conductivity make the inductive fields and power deposition non-uniform.

- In this work, we investigate the effect of long term transients such as during pulsed operation of ICPs on flow induced asymmetries.

HYBRID PLASMA EQUIPMENT MODEL (HPEM-3D)

- **Hybrid Plasma Equipment Model (HPEM-3D) is a modular simulator to address low temperature plasmas.**



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GOVERNING EQUATIONS IN HPEM-3D

- **Continuity (heavy species) :**

$$\frac{\partial N_i}{\partial t} = \nabla \cdot \left(N_i \vec{v}_i\right) + S_i$$

- **Momentum (heavy species) :**

$$\frac{\partial\left(N_i \vec{v}_i\right)}{\partial t} = \frac{q_i}{m_i} N_i \left(\vec{E}_s + \vec{v}_i \times \vec{B}_s\right) - \frac{1}{m_i} \nabla P_i - \nabla \cdot \left(N_i \vec{v}_i \vec{v}_i\right) - \nabla \cdot \overline{\overline{\tau}}_i + \sum_j N_i N_j k_{ij} \left(\vec{v}_j - \vec{v}_i\right)$$

- **Energy (heavy species) :**

$$\frac{\partial N_i c_v T_i}{\partial t} = \nabla \cdot \kappa_i \nabla T_i - P_i \nabla \cdot \vec{v}_i - \nabla \cdot (\vec{\varphi}_i \varepsilon_i) + \frac{N_i q_i^2}{m_i \nu_i} E_s^2 + \frac{N_i q_i^2 \nu_i}{m_i (\nu_i^2 + \omega^2)} E^2$$

- **Drift-diffusion (electron) :**

$$\frac{\partial n_e}{\partial t} = \nabla \cdot \left(n_e \overline{\overline{\mu}}_e E_s + \overline{\overline{D}}_e \nabla n_e\right) + S_e$$

GOVERNING EQUATIONS IN HPEM-3D

- **Electron energy transport is addressed by solving the electron energy equation coupled with a solution of Boltzmann's equation for transport coefficients.**

- **Electron energy:**

$$\nabla \cdot k\nabla T_e + \nabla \cdot \left(\Gamma T_e\right) = P_{heating} - P_{loss}$$

- **Poisson's equation :**

$$\nabla \cdot \varepsilon\nabla\Phi(t+\Delta t) = \rho(t) + \frac{d\rho(t)}{dt} = \rho(t) + \sum_i q_i \Delta t[-\nabla.\vec{\varphi}_i + S_i]$$

- **Wave equation :**

$$\nabla \cdot \frac{1}{\mu}\nabla E = \frac{\partial^2\left(\varepsilon_0 E\right)}{\partial t^2} + \frac{\partial\left(\overline{\overline{\sigma}}E + J_0\right)}{\partial t}$$

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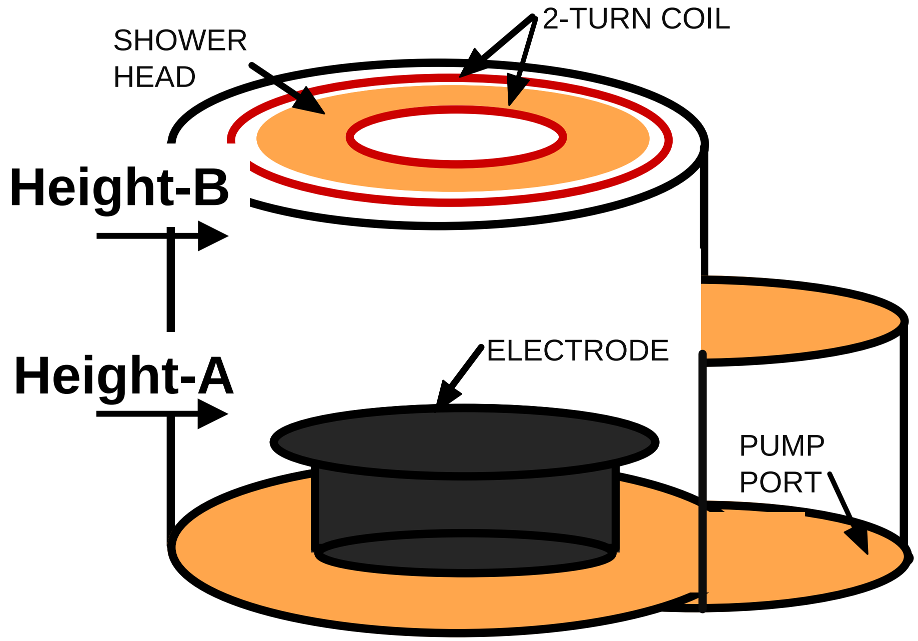
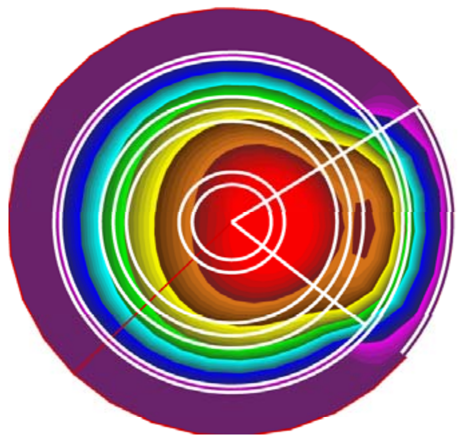
REACTOR GEOMETRY AND SIMULATION CONDITIONS

- **2-turn symmetric coil, showerhead and an asymmetric pump port**
- **Base case conditions:**
- **Power: 600 W, 10 MHz**
- **Flow rate: 160 sccm**
- **Pressure: 5 mTorr**
- **Ar, C_2F_6/CF_4**

Height-A: Densities, Temperatures, Fluxes

Height-B: ICP power, Conductivity, Sources





Top View: Height-A

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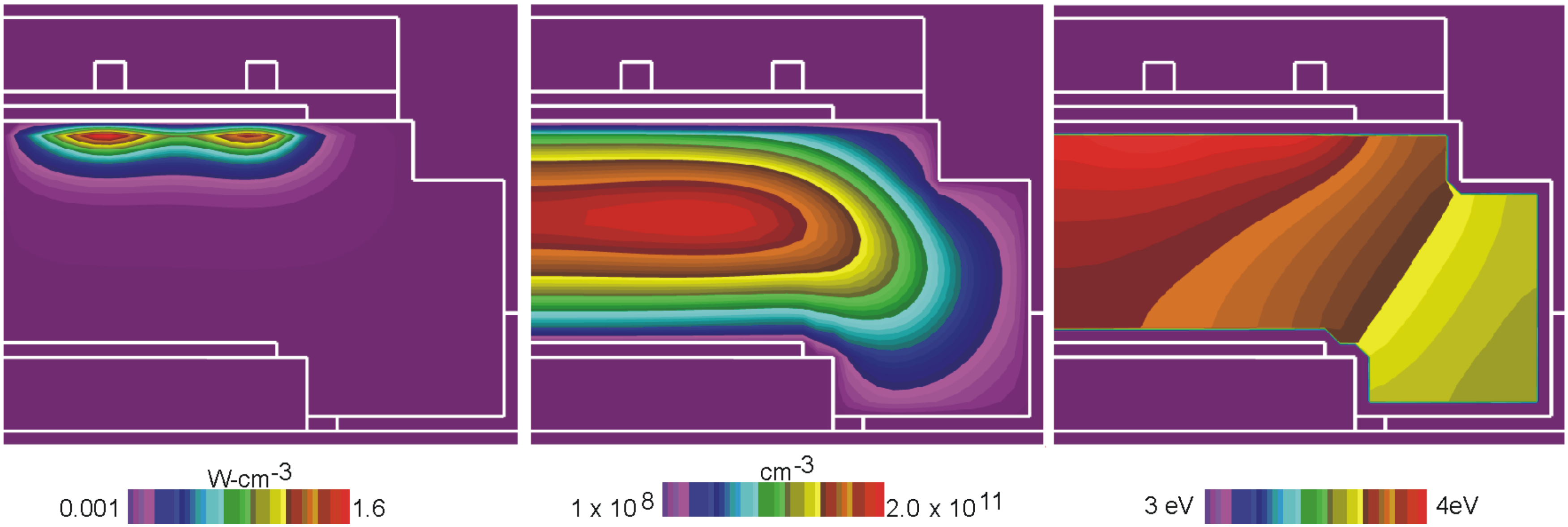
SYMMETRIC CASE: PLASMA PROPERTIES



ICP POWER **[E]** **T_e**

- **Power is deposited beneath the coils within the skin depth.**
- **T_e peaks in the skin depth due to positive power deposition from inductive fields.**
- **Electron density peaks off-center in the bulk of the plasma.**

- **C_2F_6/CF_4 (40/60), 600 W, 5 mTorr, 160 sccm**

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CONTINUOUS WAVE (CW) OPERATION OF ICPS

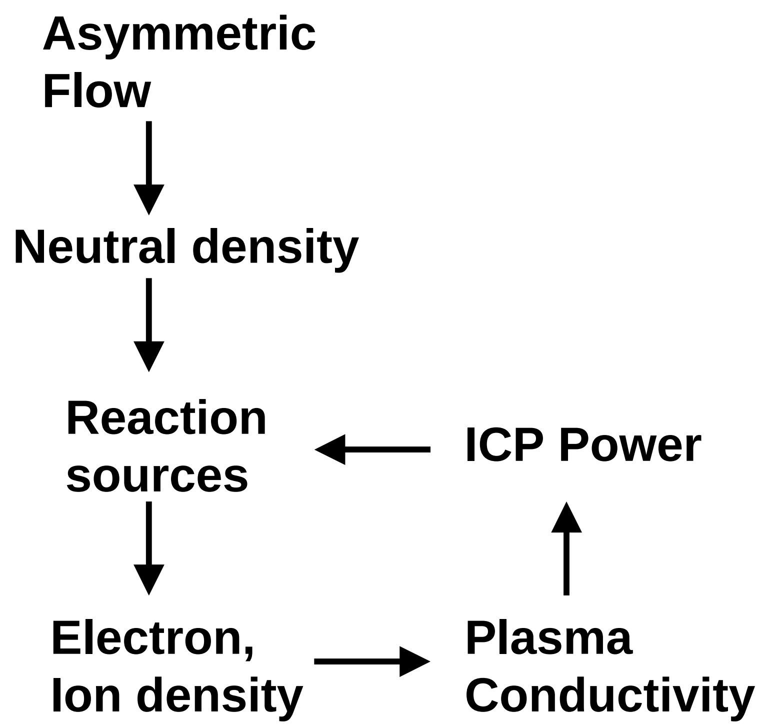
- **Flow induced non-uniformities in reaction sources make ion density non-uniform.**

- **Non-uniform plasma conductivity make the inductive fields and power deposition non-uniform even with symmetric coils.**

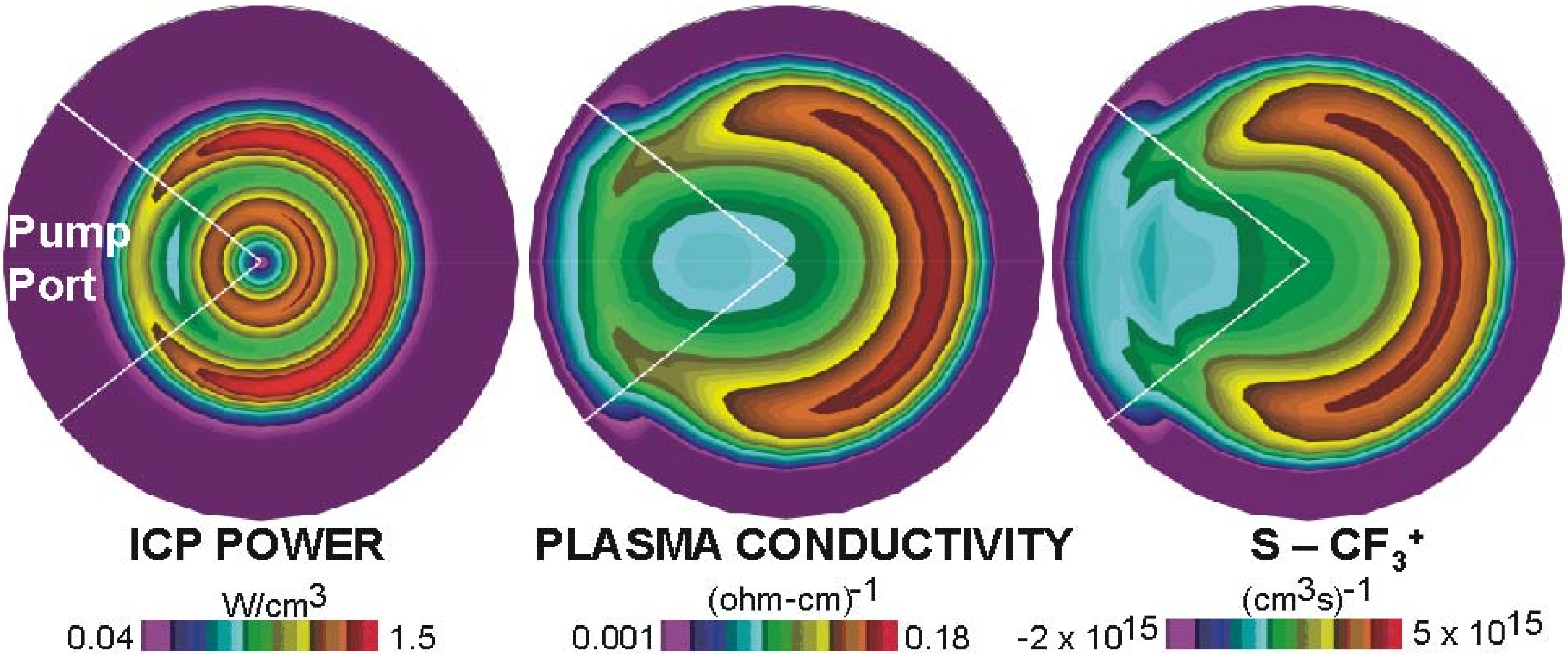
- **Non-uniform power deposition reinforces the asymmetries in reaction sources.**

- **This feedback loop during CW operation strengthens flow induced asymmetries.**

CW Operation



PLASMA CONDUCTIVITY AND POWER DEPOSITION



- **As a result of asymmetric pumping, the plasma conductivity is azimuthally asymmetric even at the plane below the showerhead.**

- **Reaction sources are non-uniform with a maximum away from the pump port.**

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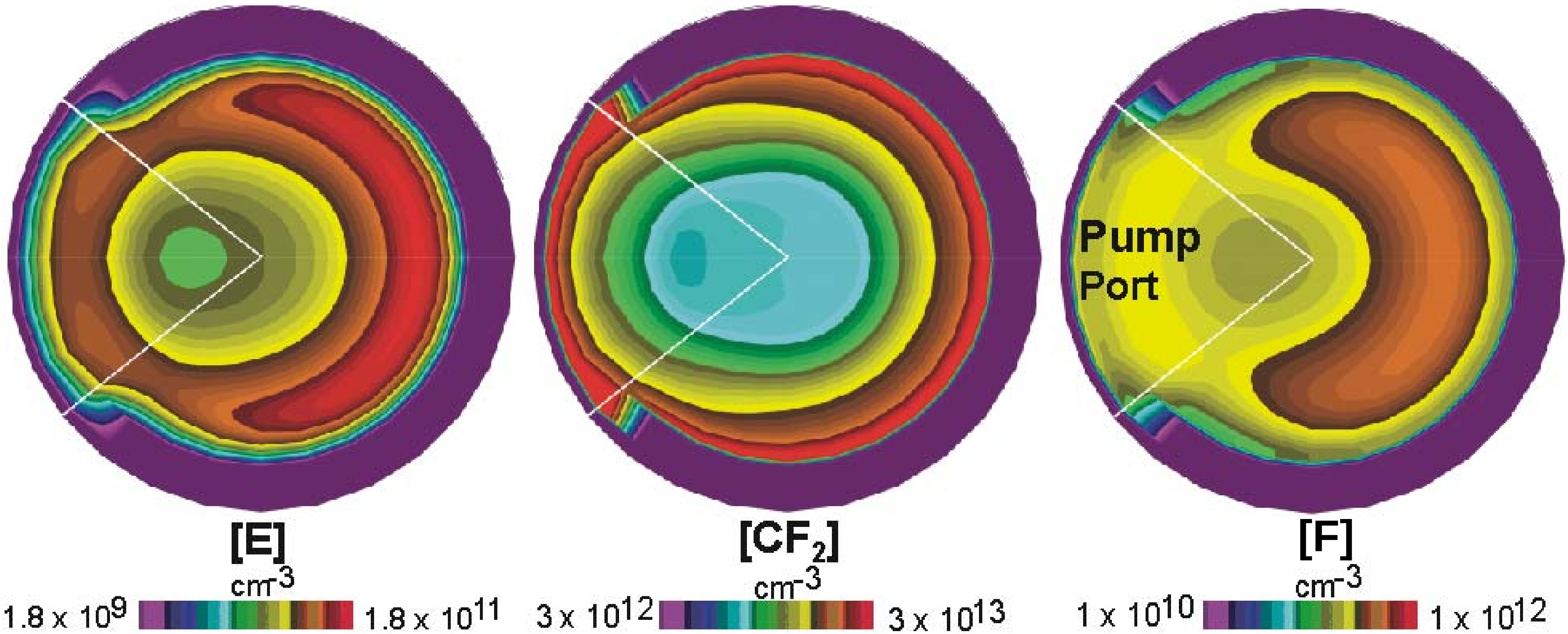
ASYMMETRIC ELECTRON AND RADICAL DENSITIES

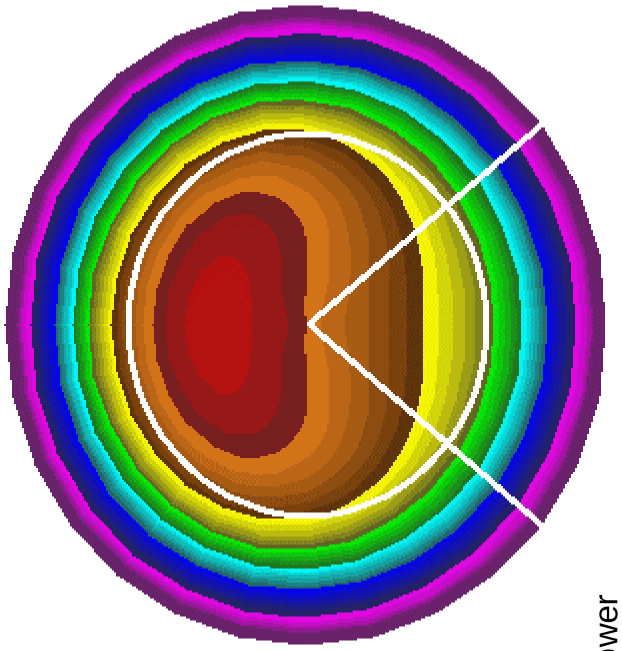


- **Larger reaction sources result in larger ion and radical densities opposite to the pump port.**

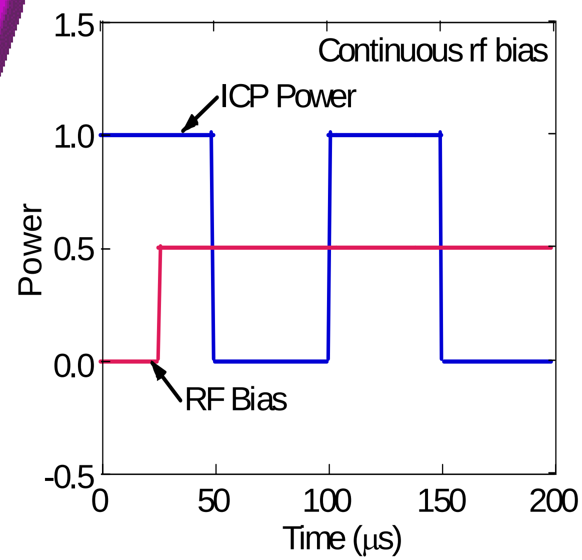
- **Wall recombination results in a virtual asymmetric source of CF_2.**

PULSED OPERATION OF ICPS

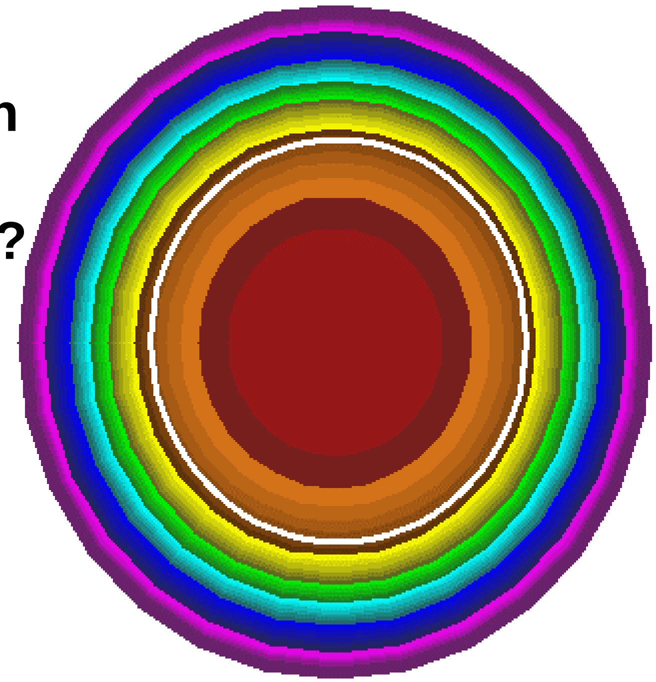
CW Operation of ICP



Can pulsed operation of ICP improve azimuthal uniformity?



Pulsed Operation of ICP



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PULSED INDUCTIVELY COUPLED PLASMAS

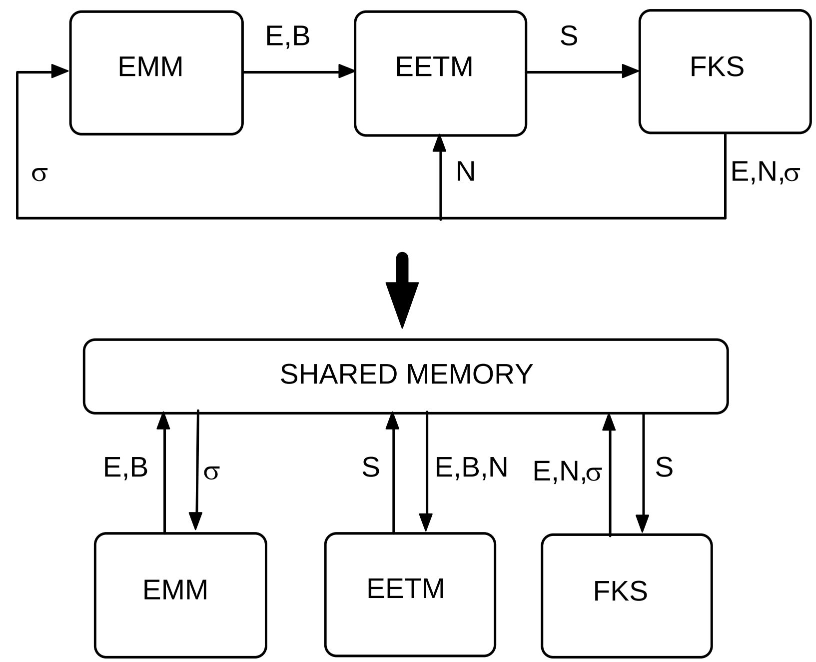
- Pulsed plasmas
    - Plasma etching with better uniformity and anisotropy
    - Improved etch selectivity by modifying the ratio of chemical species
    - Reduce charge buildup on wafers and suppress notching
- Current models for investigating pulsed operation are typically global or 1-dimensional.
- Difficult to resolve long-term transients in multi-dimensional plasma equipment models.
- Moderately parallel algorithms for 2-D and 3-D hybrid models were developed to investigate long term transients.

DESCRIPTION OF PARALLEL HYBRID MODEL

- **The HPEM, a modular simulator, was parallelized by employing a shared memory programming paradigm on a Symmetric Multi-Processor (SMP) machine.**

- **The Electromagnetics, Electron Monte Carlo and Fluid-kinetics Modules are simultaneously executed on three processors.**

- **The variables updated in different modules are immediately made available through shared memory for use by other modules.**



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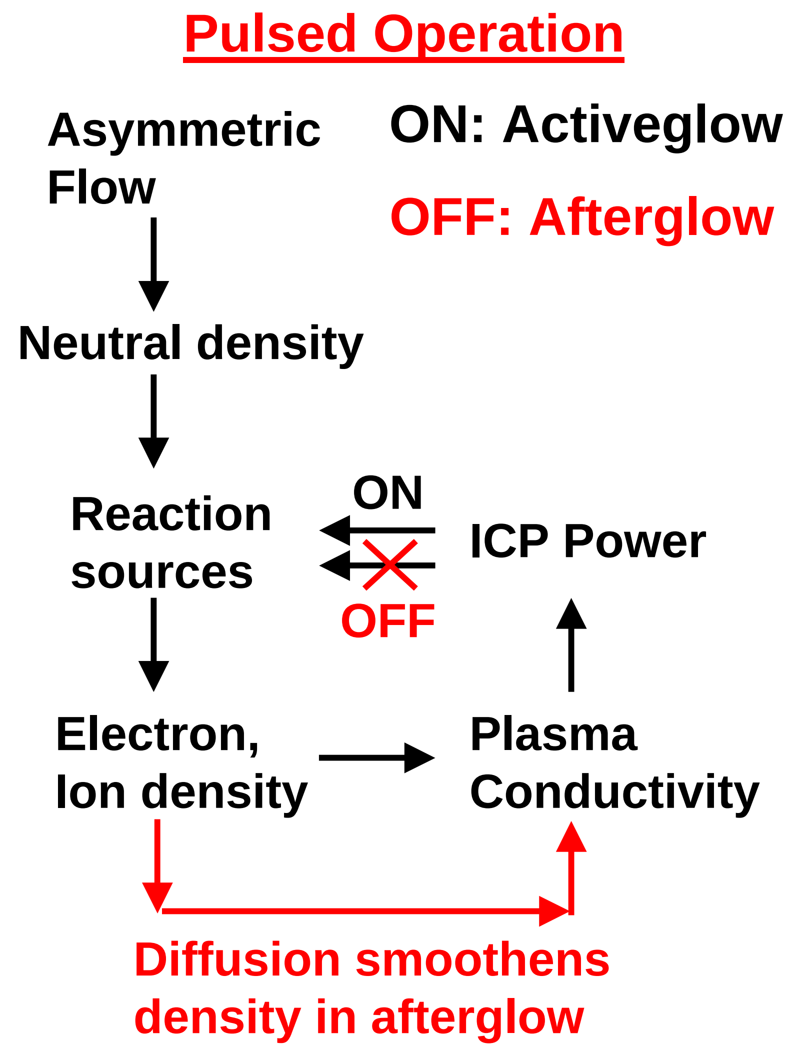
PULSED OPERATION OF ICPS

- Pulsed plasma is a rf discharge in which the ICP power is pulse-square wave modulated.

- Flow asymmetries also become pronounced when feedback through plasma conductivity make power deposition non-uniform.

- Pulsed operation of ICPs may aid in reducing these asymmetries.



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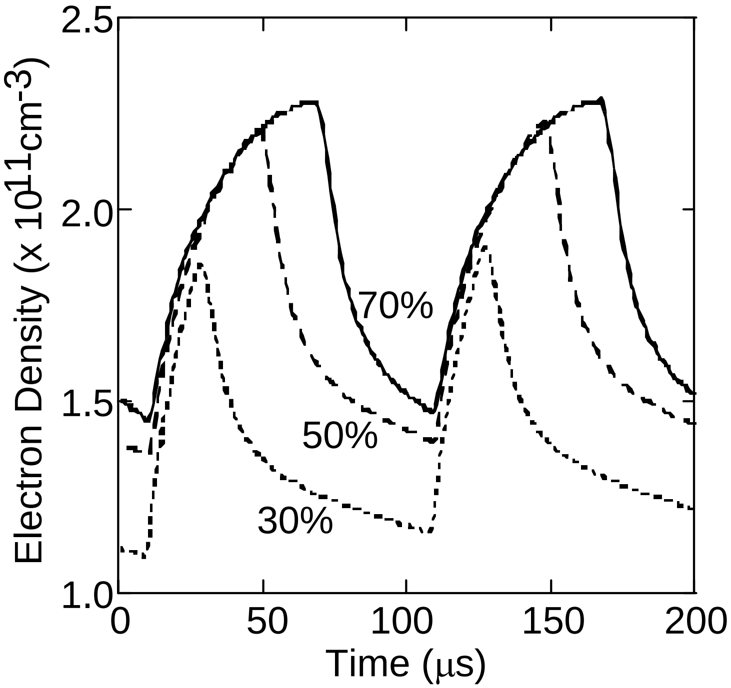
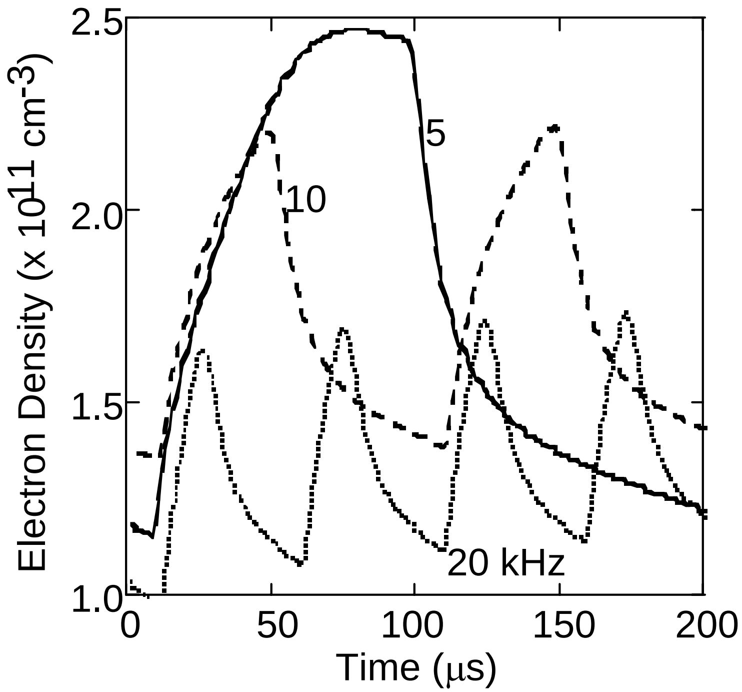
TEMPORAL DYNAMICS OF PULSED PLASMAS



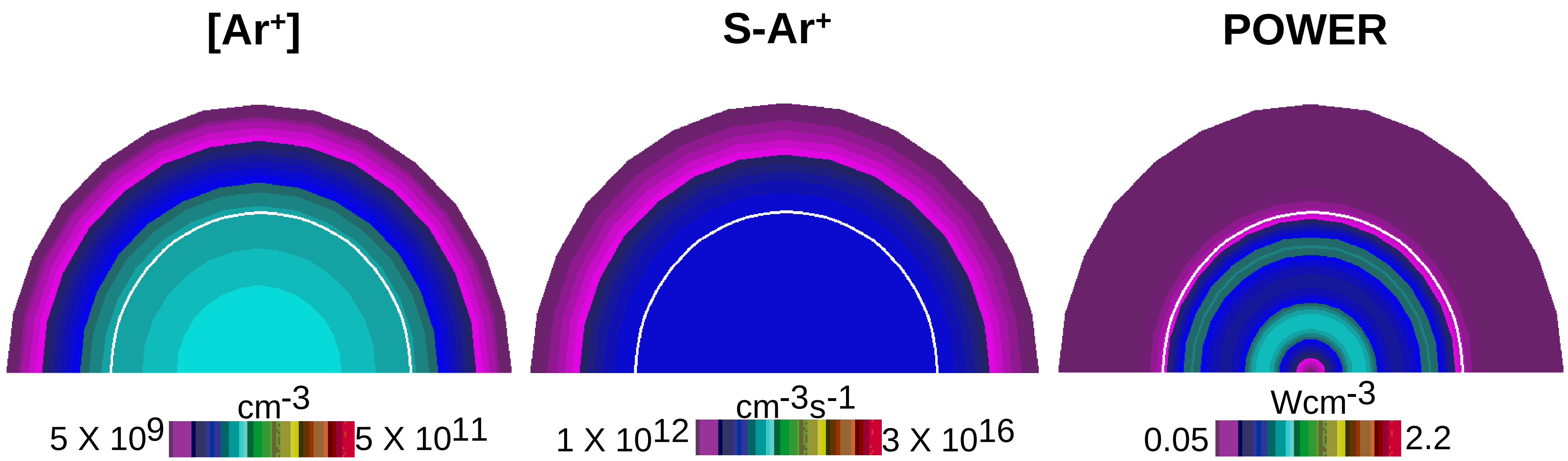


- **As the duty cycle increases, the reactor average electron density in the activeglow increases.**

- **Electron density in the activeglow increases with decrease in 5 KHz as the ICP power is ON for longer duration.**

- **Ar, 600 W, 5 mTorr, 160 sccm, PRF: 10 kHz, 50%**

PULSED ICPS: SYMMETRIC PUMPING



- **Utilizing the plane of symmetry, the simulations need to be performed only for 180^o.**

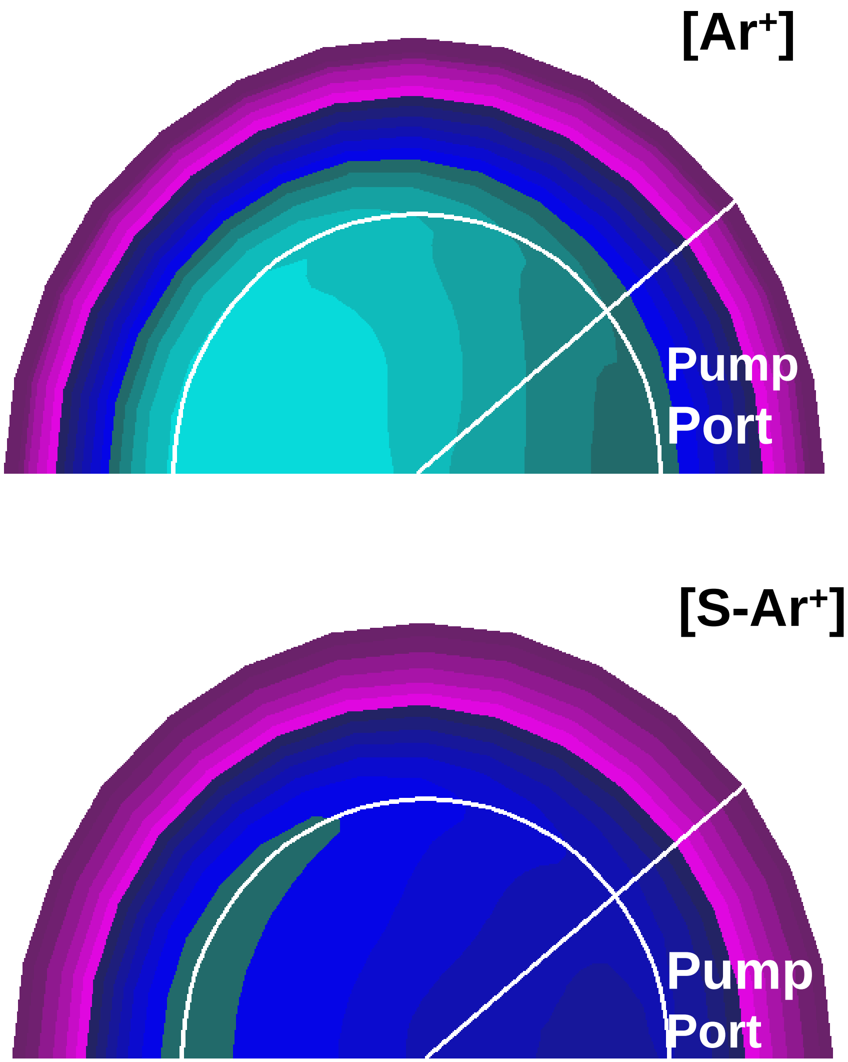
- **With symmetric pumping, the plasma properties are azimuthally symmetric. Ar^+ density peaks in the center of the discharge.**

- **The power deposition is also symmetric.**

Animation slide

PULSED ICPS: ASYMMETRIC PUMPING

- At the wafer plane, density and source function of Ar^+ ions are asymmetric during CW operation.
- By pulsing, asymmetries at the wafer plane are reduced.
- During the afterglow, diffusion smoothens the plasma density profile.
- In pulsed ICPs, feedback between non-uniform densities and power deposition is reduced.



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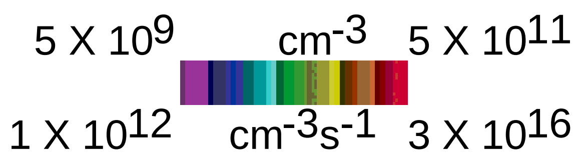

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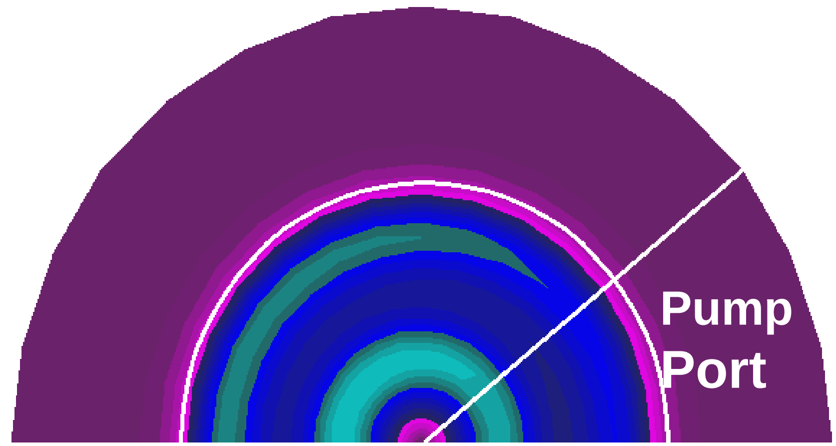
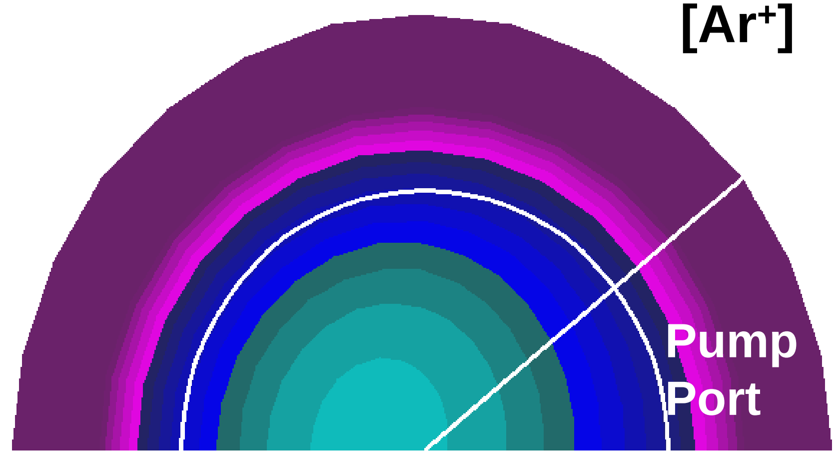
PULSED ICPS: ASYMMETRIC PUMPING

- During CW operation, though the coils are symmetric, ICP power deposition is non uniform.
- ICP power peaks at regions of larger plasma conductivity owing to a larger electron density.
- With 50% duty cycle, ICP power is off during 50% of the pulse period.
- In the absence of non-uniform sources, the plasma becomes more uniform in the afterglow.

ICP POWER



[Ar^+]



Animation slide

3×10^9 cm^{-3} 3×10^{11}

0.05 Wcm^{-3} 2.2

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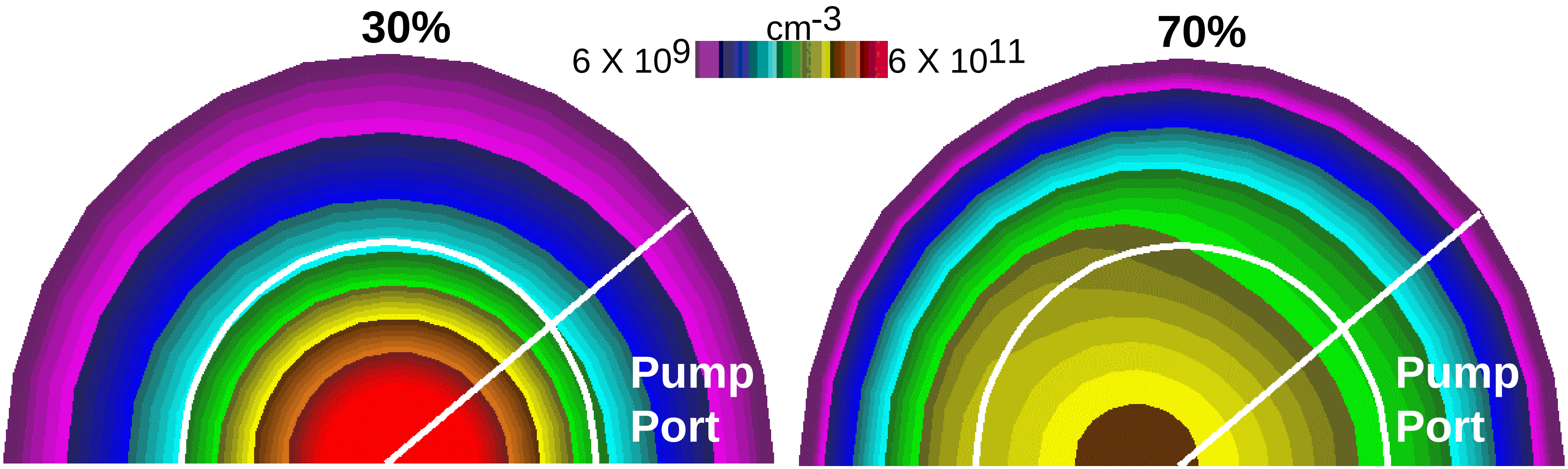
EFFECT OF DUTYCYCLE: Ar^+ DENSITY



- As the duty cycle decreases, the ICP power is OFF for longer duration.
- Hence the reduced feedback and increased diffusion make the time averaged ion density more uniform.
- Radial plasma uniformity is better at a duty cycle of 70% compared to 30%.

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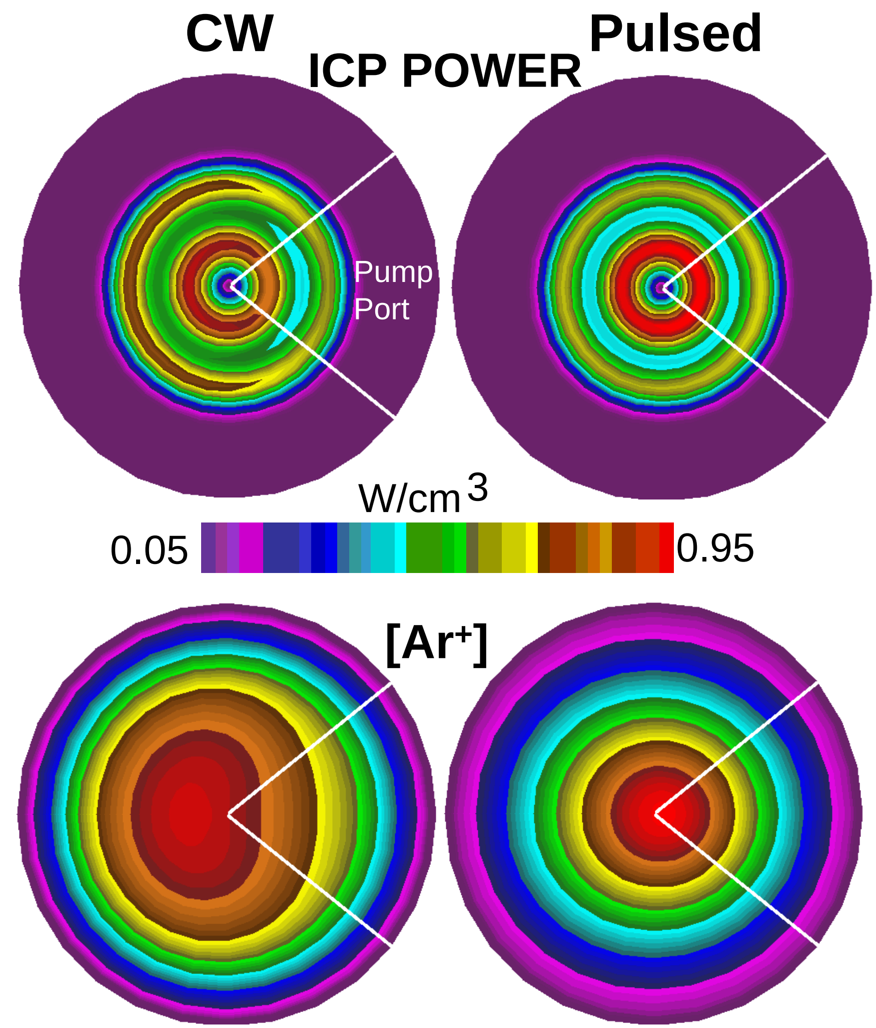
TIME AVERAGED PLASMA PROPERTIES

- **The pulsed operation of ICP makes the power deposition more uniform compared to CW.**
- **On a time average basis, the ion density is more uniform.**
- **The flux of ions impinging the wafer will be more symmetric.**
- **Hence the etch or deposition profiles will be more uniform at different azimuths on the wafer.**



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SUMMARY

- A new 3-D parallel hybrid model was developed to address transients based on moderate computational parallelism.

- Reactor scale asymmetries can result in non-uniform trench evolution during fluorocarbon etching at different azimuthal locations.

- During pulsed operation, diffusion smoothens the plasma density profile in the afterglow, providing a more uniform set of initial conditions for the next power pulse.

- The feedback between non-uniform densities and power deposition is also reduced.

- The flux of ions impinging the wafer will be more symmetric during pulsed operation.