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SIMULATION OF TRANSIENTS IN PLASMA PROCESSING REACTORS USING MODERATE PARALLELISM*

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AGENDA

- Introduction
- Description of the model
- Validation
- Properties of pulsed plasmas
    - Argon
    - Ar/Cl_2
- Conclusions

INTRODUCTION

- **Transient phenomena are often encountered in plasma processing**
  - **Pulsed operation of plasmas**
  - **Study startup and shutdown**
  - **Recipe changes**
- **Pulsed plasmas**
  - **Damage free plasma etching with better uniformity and anisotropy**
  - **Additional control knobs : Duty cycle and Pulse repetition frequency**
  - **Reduce charge buildup on wafer and suppress notching**
- **Difficult to resolve in multi-dimensional plasma equipment models**
- **Moderately parallel algorithms for hybrid models were developed to investigate the long-term transients.**

HYBRID PLASMA EQUIPMENT MODEL (HPEM)

- HPEM iterates modules to converged solution.

- Electromagnetics Module
  - Maxwell's equations are solved in frequency domain

- Electron-Energy Transport Module
  - Electron impact source functions and transport coefficients
  - Monte Carlo Simulation is used to generate spatially dependent EEDs

- Fluid Kinetics Module
  - Fluid transport equations for species densities, fluxes and temperature
  - Poisson's equation for time dependent electric potential
  - Ions and Neutrals : Continuity, Momentum and Energy equation
  - Electrons : Drift-diffusion equation

- Modeling truly time dependent phenomena is difficult using an modular iterative scheme

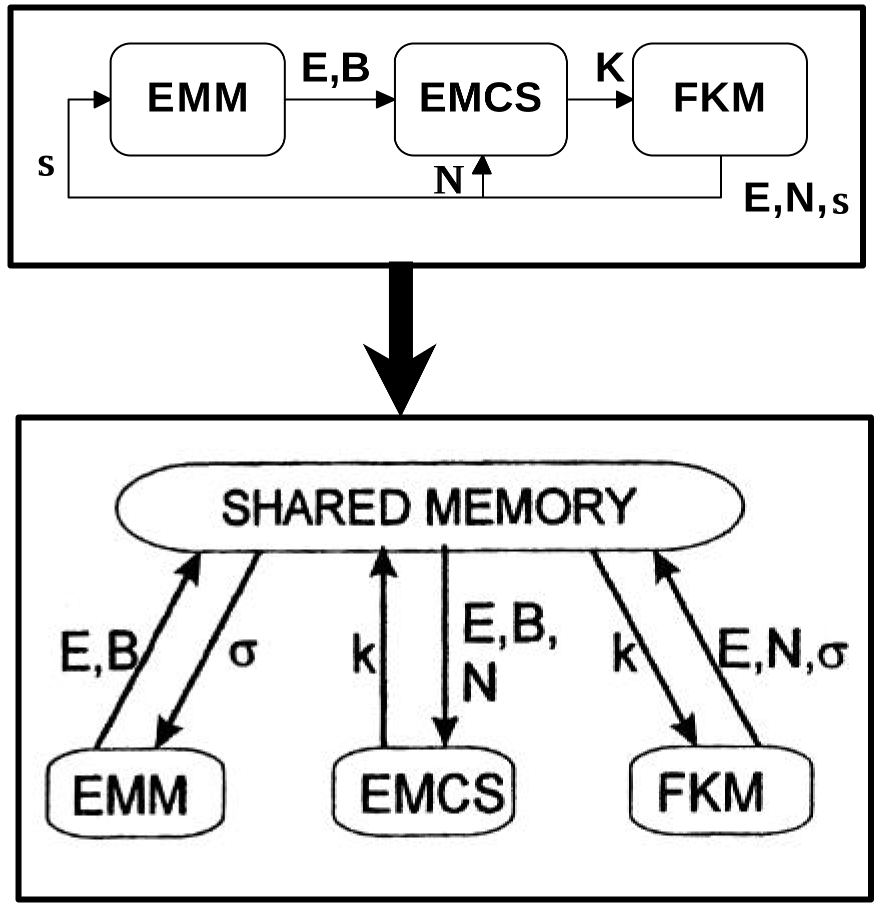
DESCRIPTION OF THE PARALLEL HYBRID MODEL

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

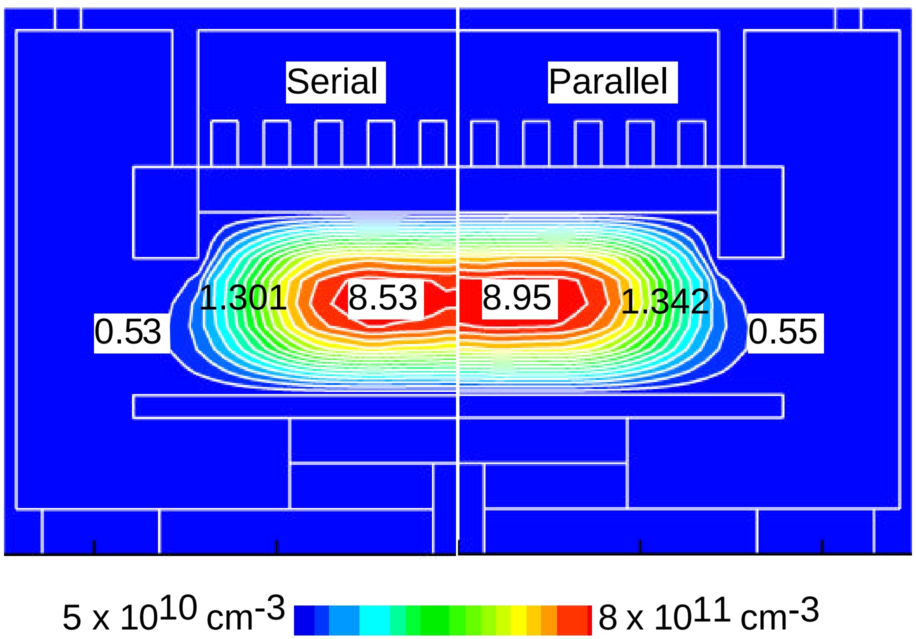
- Dynamic load balancing is implemented to equal the tasks on different processors.



VALIDATION OF THE MODEL : NUMERICS

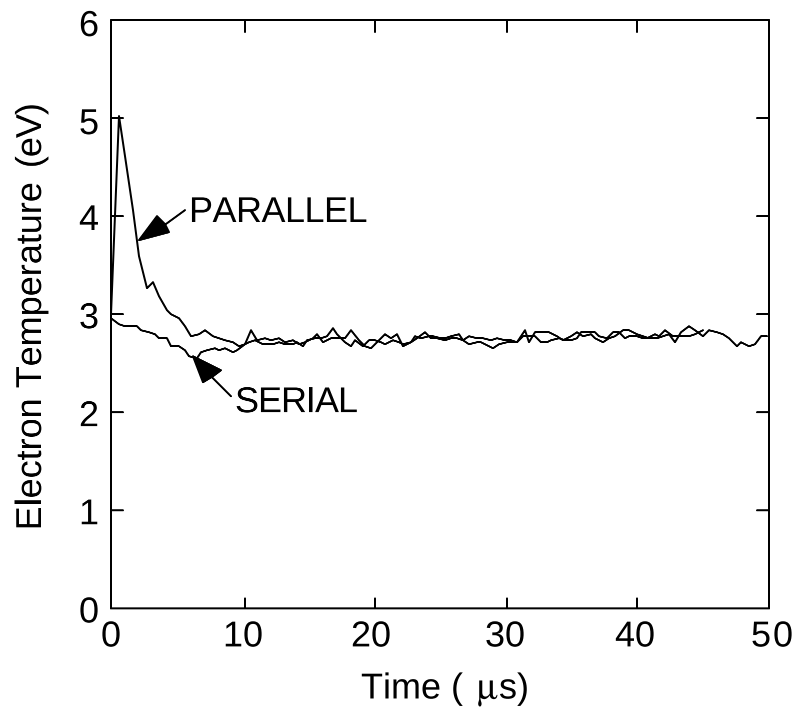
- **Parallel and serial execution gives similar results for steady state conditions in Ar plasma.**

- **Electron Density**
- **3-5% difference in the estimated electron density**



- **Ar, 20 mTorr, 300 W, GECRC**

- **Electron Temperature (T_e)**
- **The steady state T_e is same in parallel and serial execution.**



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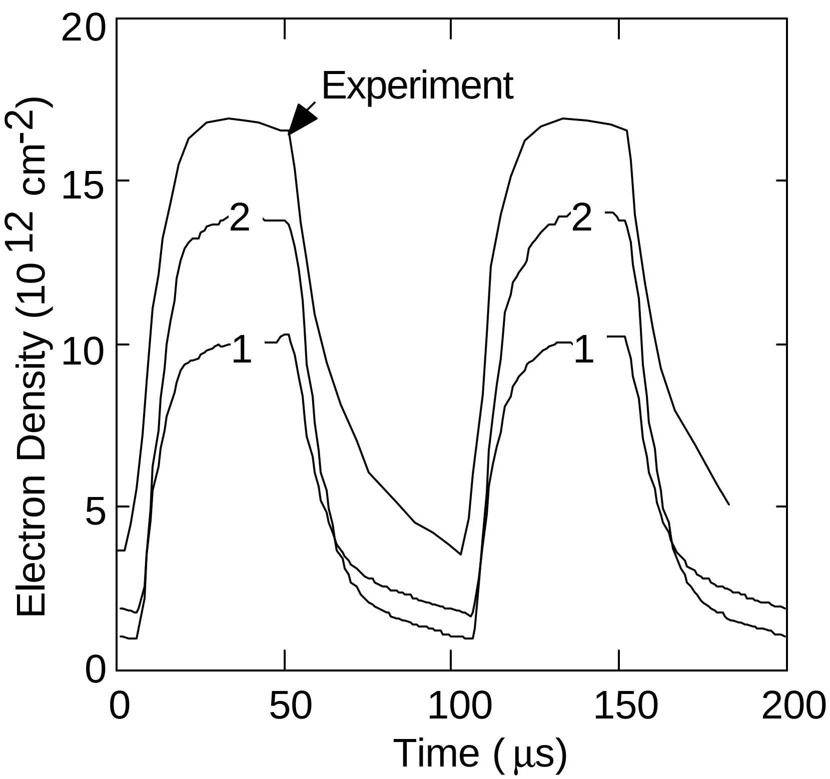
VALIDATION OF THE MODEL : PHYSICS

- Model results compare well with experiments*

- Simulations (1 and 2) show similar trends as in experiments

- Rates of avalanche and decay at leading edge and interpulse periods are well captured

- Quantitative agreement in column densities depends on physics model ("1" and "2")
  - "1" : Low degree of radiation trapping of Ar (4s) and Ar (4p)
  - "2" : High degree of radiation trapping of Ar (4s) and Ar (4p)

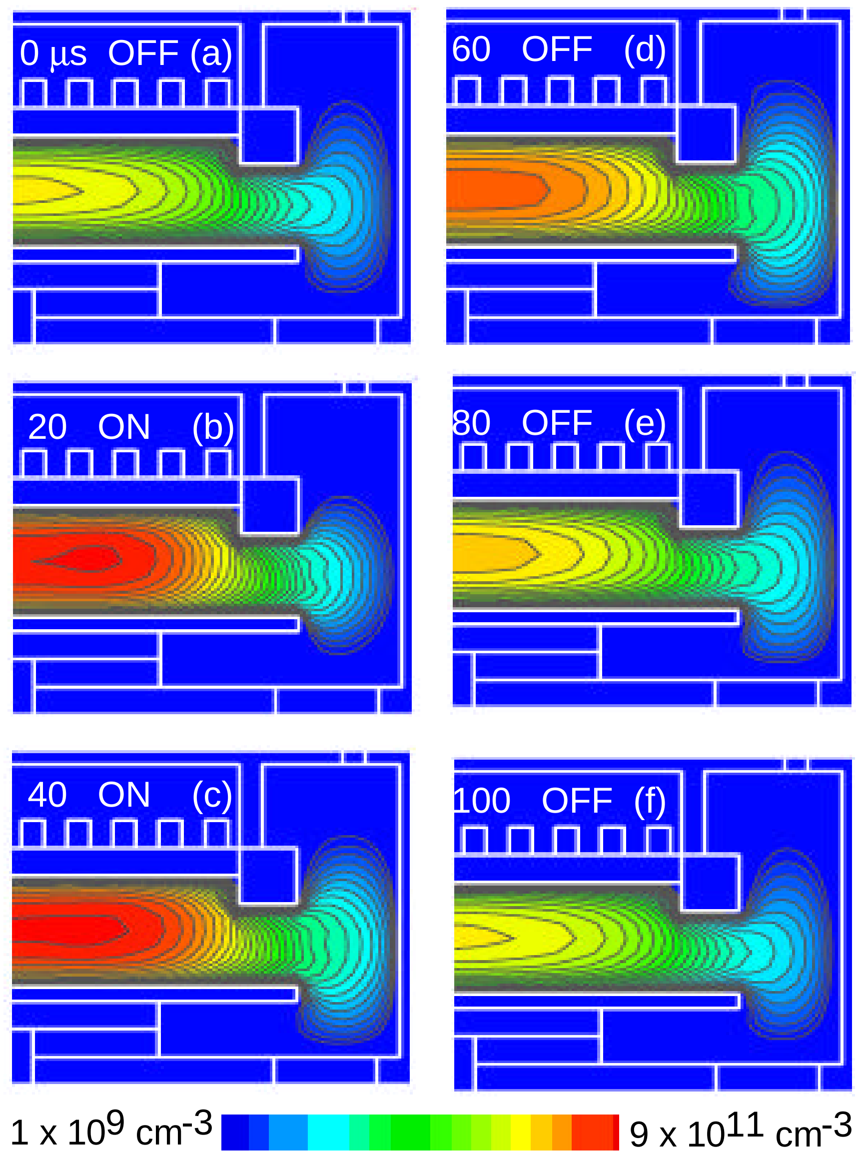


- Ar, 20 mTorr, 300 W, 10kHz/50%

  * G. A. Hebner and C. B. Fleddermann, J. Appl. Phys. 82, 2814 (1997)

2-D DYNAMICS IN ARGON : ELECTRON DENSITY [e]

- **The peak [e] migrates to below the coils during "power-on" where the source is maximum**
- **At steady state , [e] becomes more uniform.**
- **As the power is turned off, in the early afterglow ambipolar losses dominate over generation of electrons.**
- **Rate of electron decay decreases in the late afterglow.**
- **Faster decay of [e] in the center than at the walls due to shorter diffusion length**
- **Ar, 20 mTorr, 300 W, 10kHz/50%**



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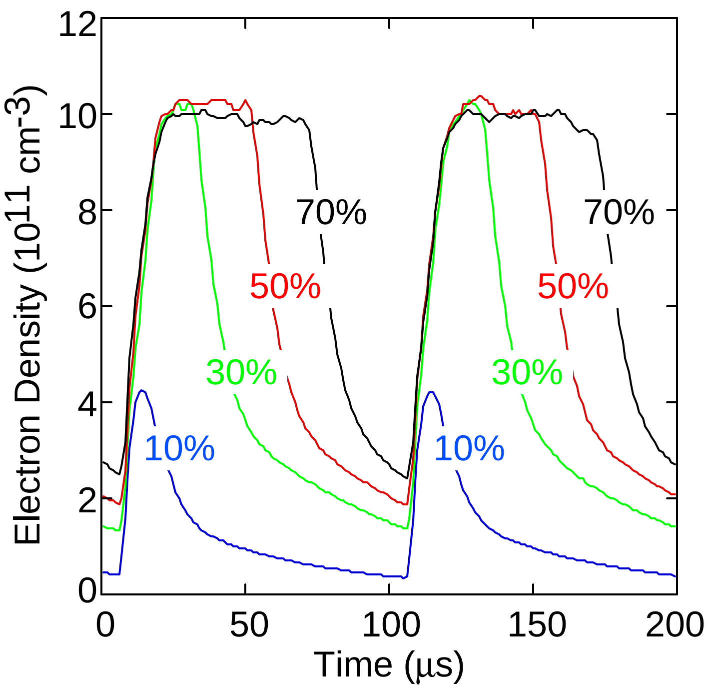
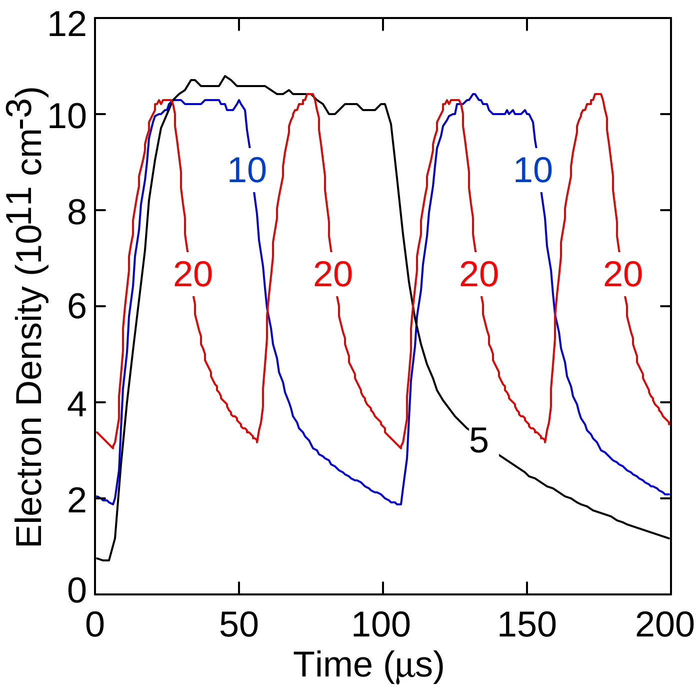
EFFECT OF DUTY CYCLE AND PULSE REPETITION FREQUENCY (PRF)

- **EFFECT OF DUTY CYCLE**
- **Decay time for electron density ([e]) was longer than the off-period**
- **Rise time is about 25 ms**
- **Higher duty cycle resulted in a constant [e]**



- **EFFECT OF PRF**
- **Peak [e] is same for all cases**
- **Higher PRF resulted in higher time averaged [e]**
- **Lower PRF resulted in lower [e] in the late afterglow**



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2-D DYNAMICS IN Ar/Cl_2 : Cl^- DENSITY [Cl^-]

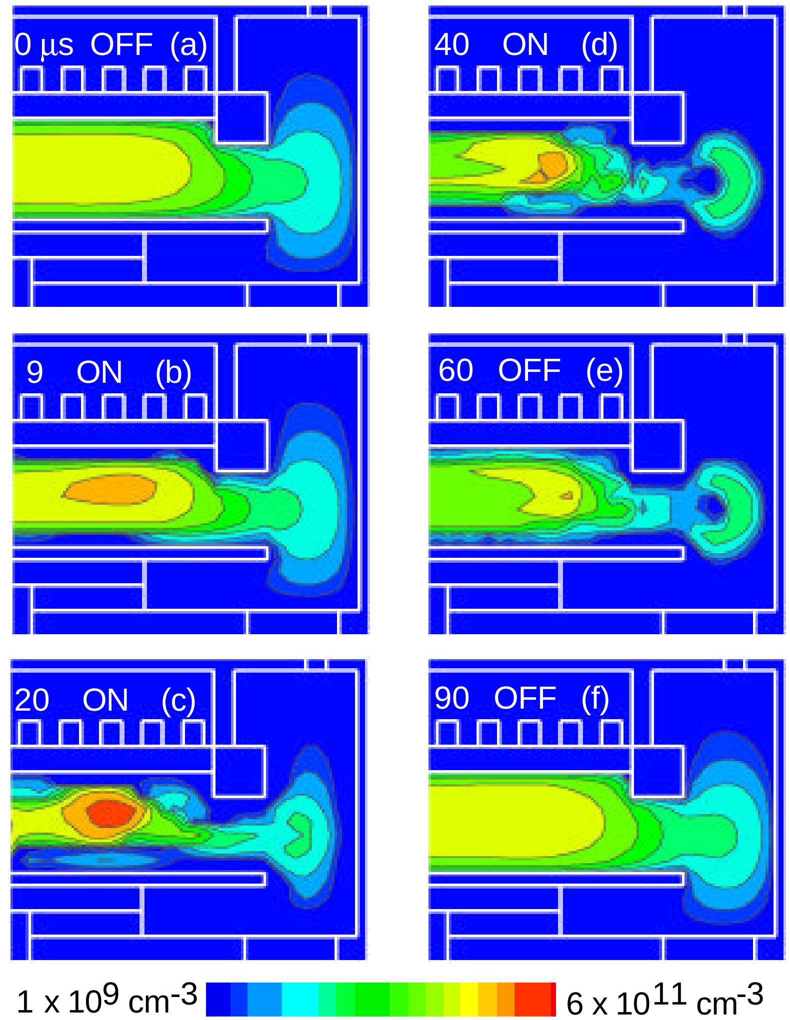
- When the pulse begins, the plasma potential peaks thereby "compressing" the [Cl^-]

- At steady state, [Cl^-] "rebounds" as the plasma potential decreases.

- Due to inertia, [Cl^-] does not respond to changes in plasma potential immediately.

- When the plasma is turned off, the [Cl^-] increases due to a higher rate of dissociative attachment at low T_e.

- Later, the plasma potential falls and [Cl^-] spreads.



- Ar/Cl_2 = 80/20, 20 mTorr, 300 W, 10 kHz/50%

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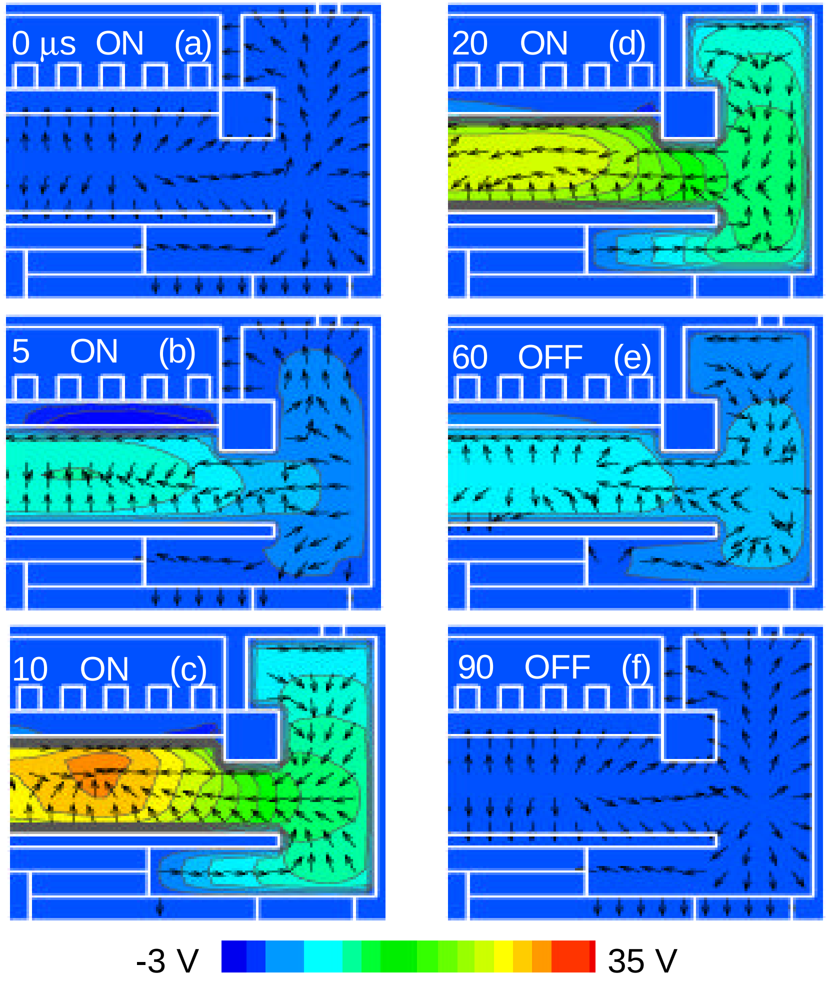
Ar/Cl_2 : PLASMA POTENTIAL AND Cl^- FLUX VECTORS

- **As the pulse begins, the peak plasma potential migrates to under the coils.**
- **As the steady state is reached, the peak plasma potential moves towards the center.**
- **Cl^- flux vectors point towards the peak plasma potential when plasma potential is large.**
- **It takes about 25 ms for the ions to move from periphery to the center.**
- **When the plasma is turned off, Cl^- flux vectors reverse, pointing towards boundaries.**



- **Ar/Cl_2 = 80/20, 20 mTorr, 300 W, 10 kHz/50%**

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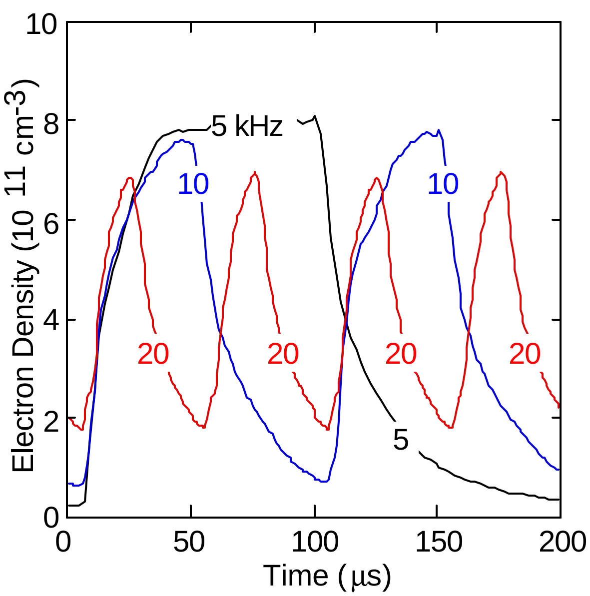
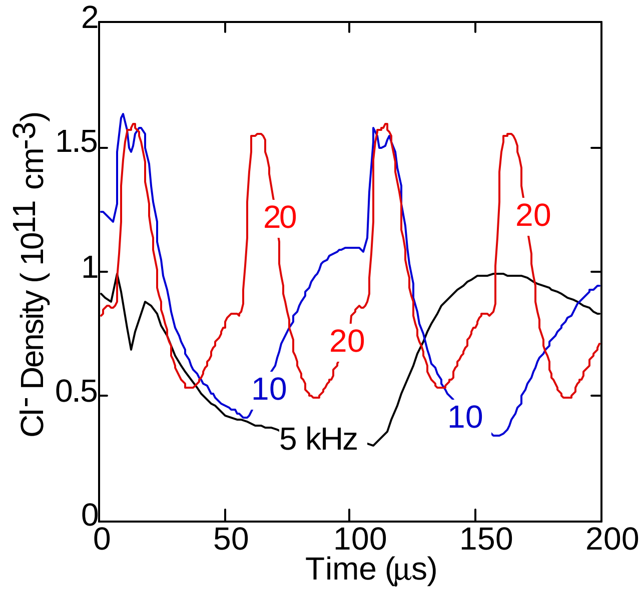
EFFECT OF PULSE REPETITION FREQUENCY (PRF)

- Electron density (at center)
- Non-monotonic behavior in peak [e] is also observed in experiments.
- Lower PRF results in higher rate of dissociation due to higher T_e
- Decay rate is similar for all PRFs



- Cl^- density [Cl^-] (at center)
- During plasma turn on, Cl^- ions move to the center
- [Cl^-] then decreases due to ion-ion recombination.
- When power is removed, [Cl^-] increases and then decreases.



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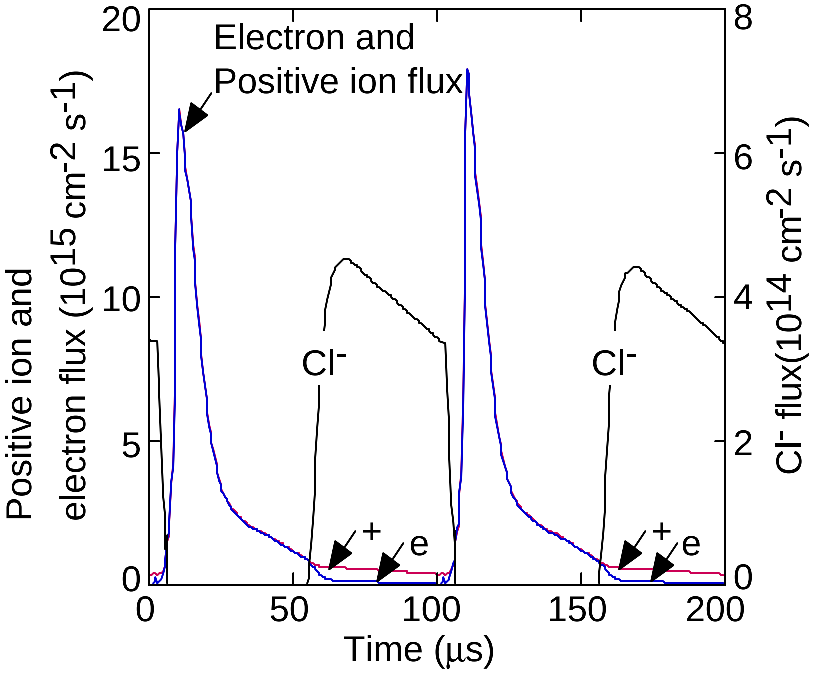
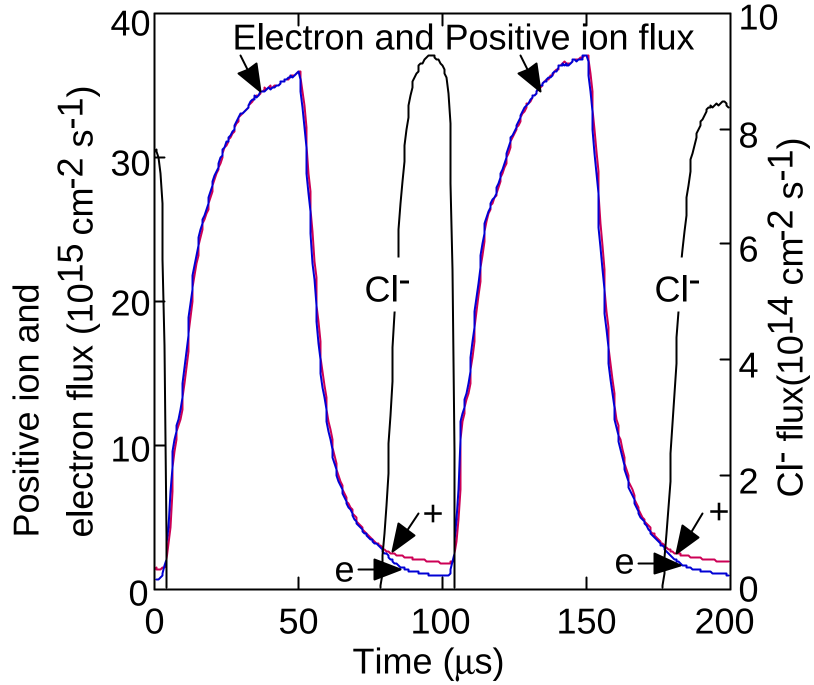
EFFECT OF DUTY CYCLE ON FLUXES TO SUBSTRATE

- **Flux to substrate can be controlled by varying duty cycle.**
- **As duty cycle increases, the flux to the substrate increases**
- **For 10%, plasma potential decays away in 40 ms after the turn off.**
- **For 50%, plasma potential decays away in 25 ms after the turn off.**



- **DUTY CYCLE : 10%**



- **DUTY CYCLE : 50%**

- **Ar/Cl_2 = 80/20, 20 mTorr, 300 W, 10 kHz**

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CONCLUSIONS

- **A new 2-D hybrid model was proposed to address transients based on moderate parallelism.**
- **Plasma transport, neutral fluid transport, and electromagnetics are simultaneously computed on separate processors.**
- **Computational studies were performed for pulsed operation of Ar and Ar/Cl_2 ICPs.**
- **In argon plasmas, the peak in electron temperature during the turn-on phase is nearly twice the steady state value.**
- **In electronegative plasmas, electron-ion plasma in the activeglow becomes ion-ion plasma in the afterglow.**
- **Negative ions do not respond immediately to plasma potential changes.**
- **Present study can be extended to investigate the effect of pulsed ECRs and charge buildup in fine features during etching.**