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3-Dimensional Modeling of Pulsed Inductively Coupled Plasmas: A Method to Improve Uniformity*

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AGENDA

- **Motivation**
- **Description of the model**
- **Consequences of asymmetric pumping**
- **3-Dimensional modeling of pulsed Ar and Cl_2 plasmas**
  - **Effect of Duty cycle**
  - **Effect of PRF**
- **Conclusions**

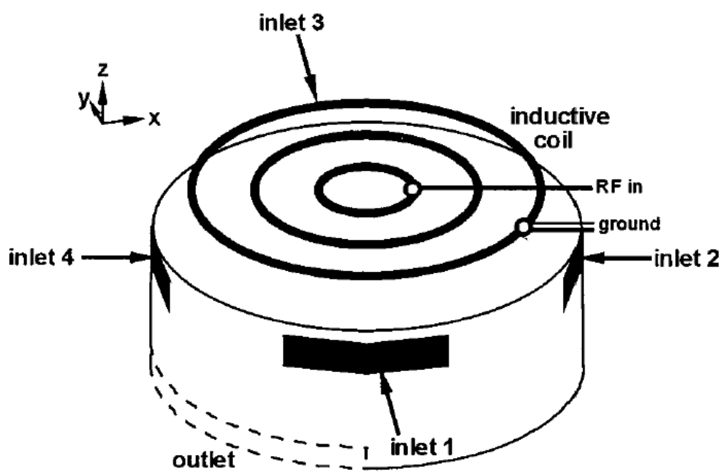
300MM WAFER PROCESSING: CHALLENGES

- 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, the impact of 3-d plasma transport and the effect of transients on uniformity were investigated.

3-D MODELING OF CW PLASMAS

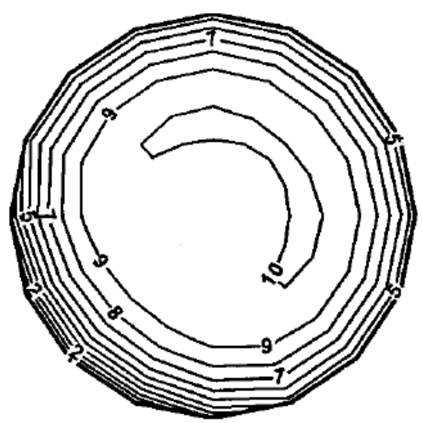
- **A 3-d finite element fluid model has been employed by Panagopoulos et. al.[1] for investigating azimuthal reactor asymmetries.**

3-d reactor geometry[1]

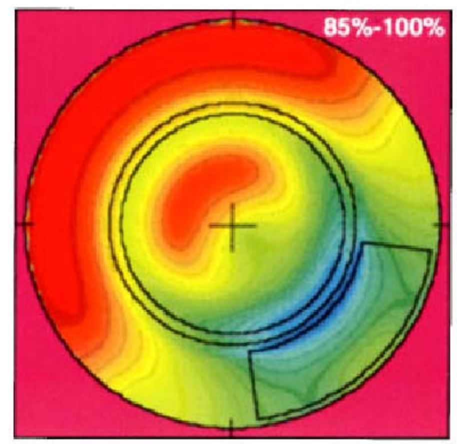


Cl density at the wafer plane[1, 2]

Ref. 1



Ref. 2

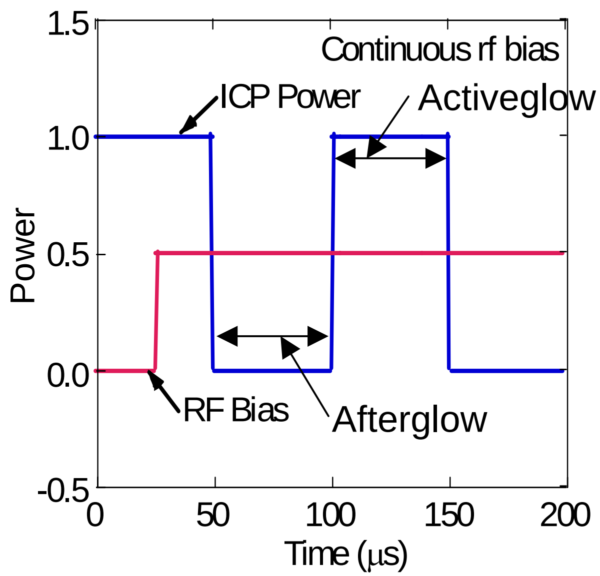


[1]Panagopoulos et. al., J. Appl. Phys., 91(5), 2687 (2002)
[2]Kushner, J. Appl. Phys., 82(11), 5312 (1997)

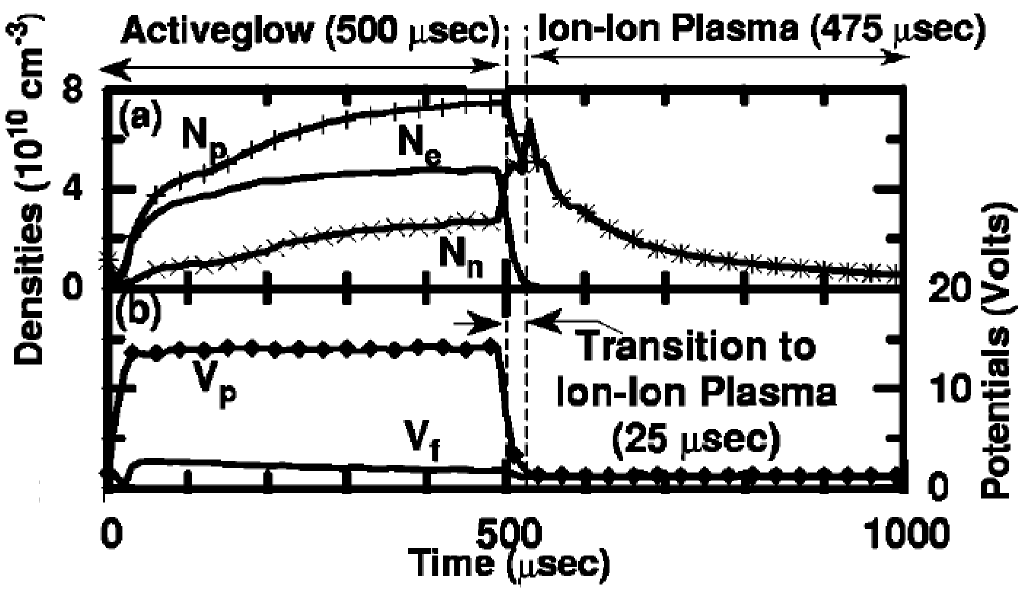
MOTIVATION: PULSED PLASMAS

- 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, 1-dimensional or 2-dimensional.
- Difficult to resolve long-term transients in multi-dimensional plasma equipment models.
- Moderately parallel algorithms for 3-dimensional hybrid models were developed to investigate long term transients.

PULSED PLASMAS



Power modulation



Plasma properties in Cl_2*

PRF: 10 kHz (Pulse period 100 μs)

Duty Cycle: 50%

- **Pulsed plasma is a rf discharge in which the carrier frequency is pulse-square wave modulated.**

***S. K. Kanakasabapathy et al, Appl. Phys.Lett., Vol. 79, 1769 (2001)**

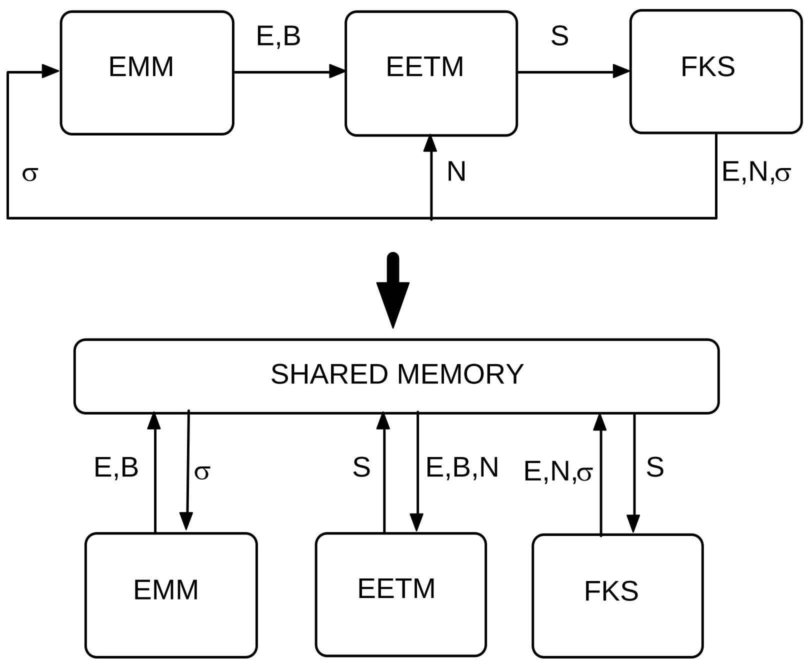
DESCRIPTION OF PARALLEL HYBRID MODEL

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

- The Electromagnetics, Electron Energy Transport and Fluid-kinetics Modules are simultaneously executed on three processors.

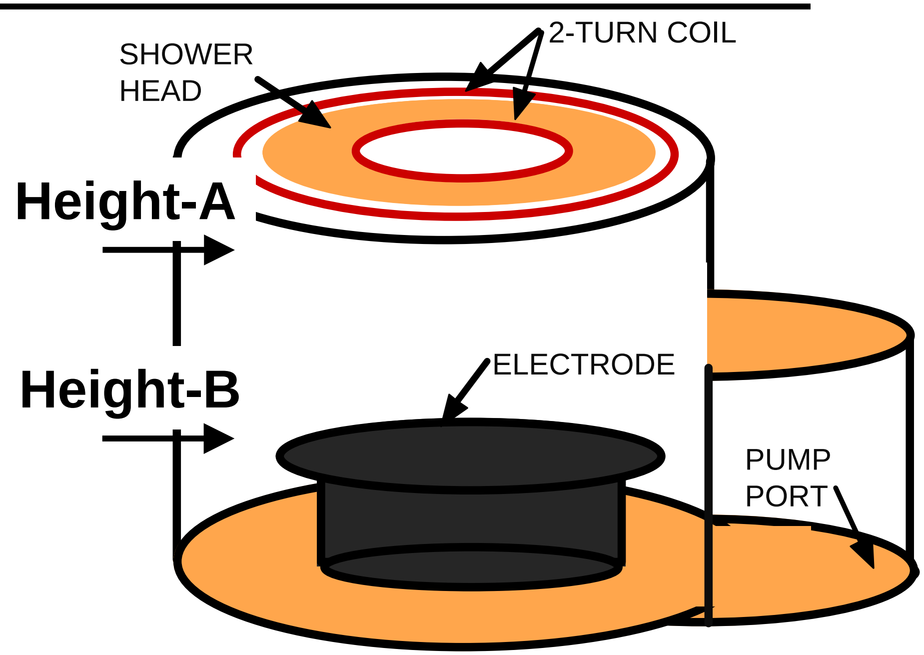
- The variables updated in different modules are immediately made available through shared memory for use by other modules.

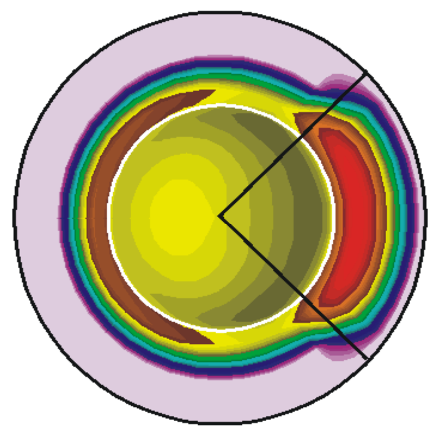
- Dynamic load balancing is implemented to equalize the load on different processors.



REACTOR GEOMETRY AND SIMULATION CONDITIONS

- 2-turn symmetric coil, showerhead and an asymmetric pump port
- Base case conditions:
- Power: 500 W, 10 MHz
- Flow rate: 150 sccm
- Pressure: 10 mTorr
- PRF: 10 kHz
- Duty cycle: 50%
- Ar, Cl_2



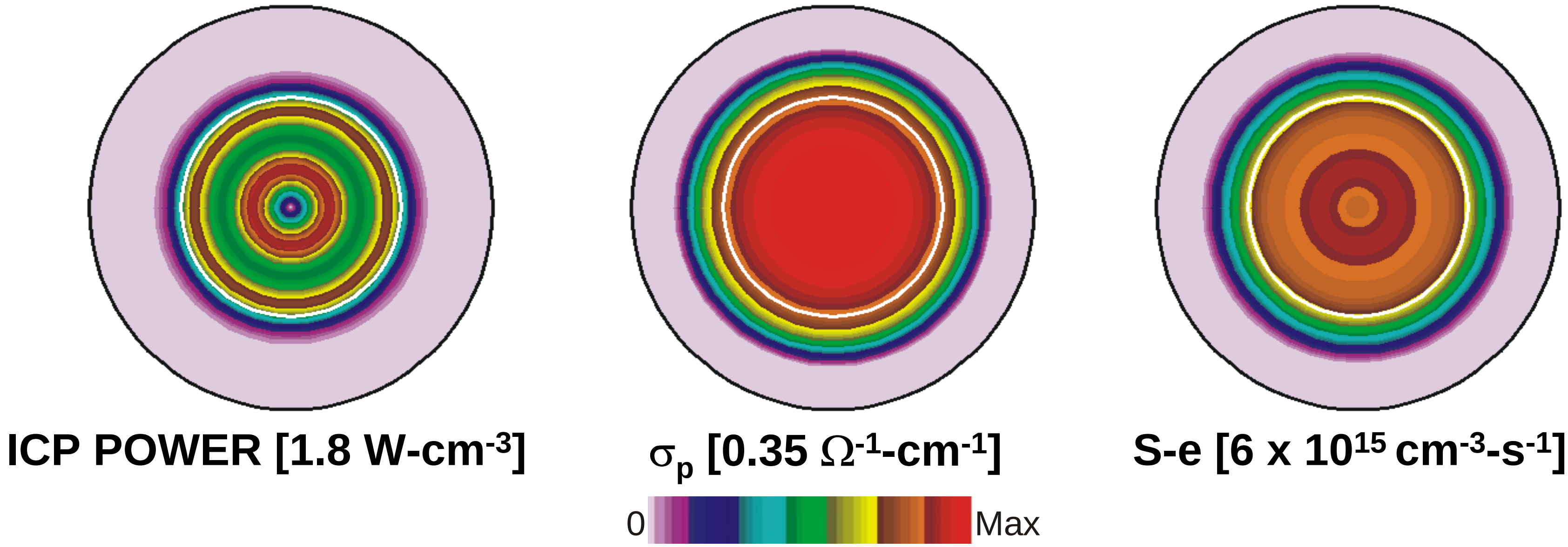


Top View: Height-B

Height-A: ICP power, Conductivity, Sources

Height-B: Densities, Temperatures, Fluxes

SYMMETRIC CASE: PLASMA PROPERTIES



- **Plasma properties are azimuthally symmetric.**
- **n_e and plasma conductivity peaks in the center of the reactor.**
- **Electron impact sources peak off-axis at location of maximum power deposition.**

• Ar, 500 W, 10 mTorr, 150 sccm

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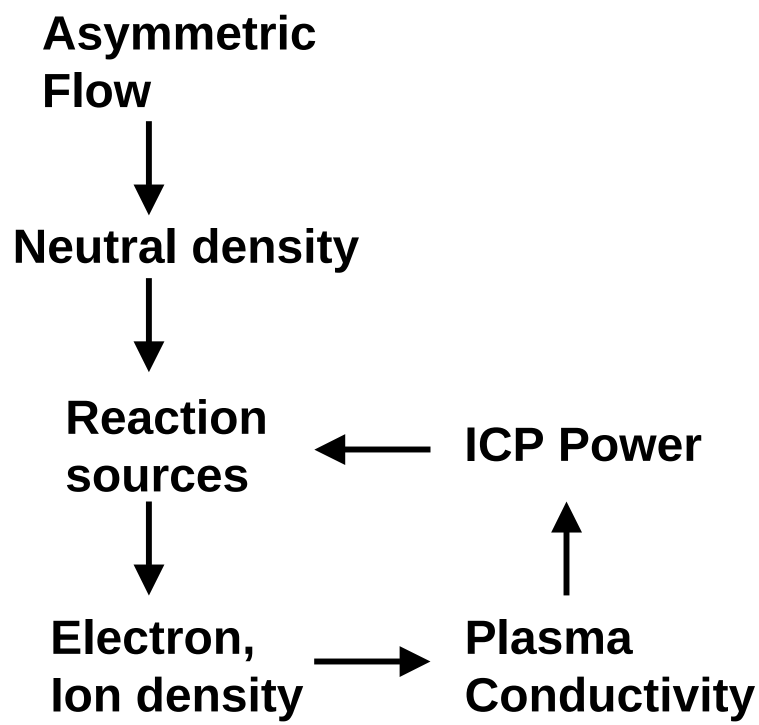
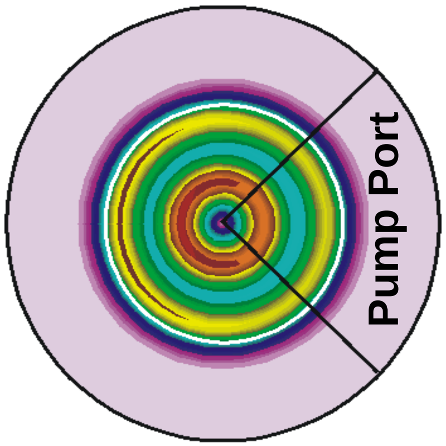
CONTINUOUS WAVE (CW) OPERATION OF ICPS

- Flow induced non-uniformities in reaction sources make ion density non-uniform.
- Non-uniform plasma conductivity makes power deposition non-uniform.
- Non-uniform power deposition reinforces the asymmetries in reaction sources.
- This feedback loop during CW operation strengthens flow induced asymmetries.

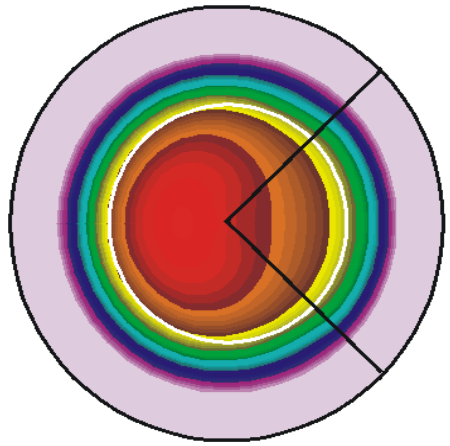
CW Operation



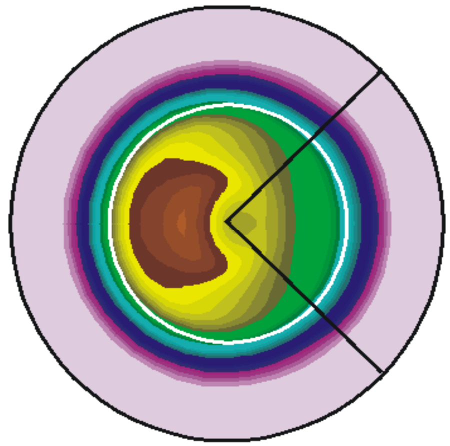
EFFECT OF ASYMMETRIC PUMPING: Below Dielectric



ICP POWER [2.0 W-cm^{-3}]



σ_p [0.50 Ω^{-1}-cm^{-1}]



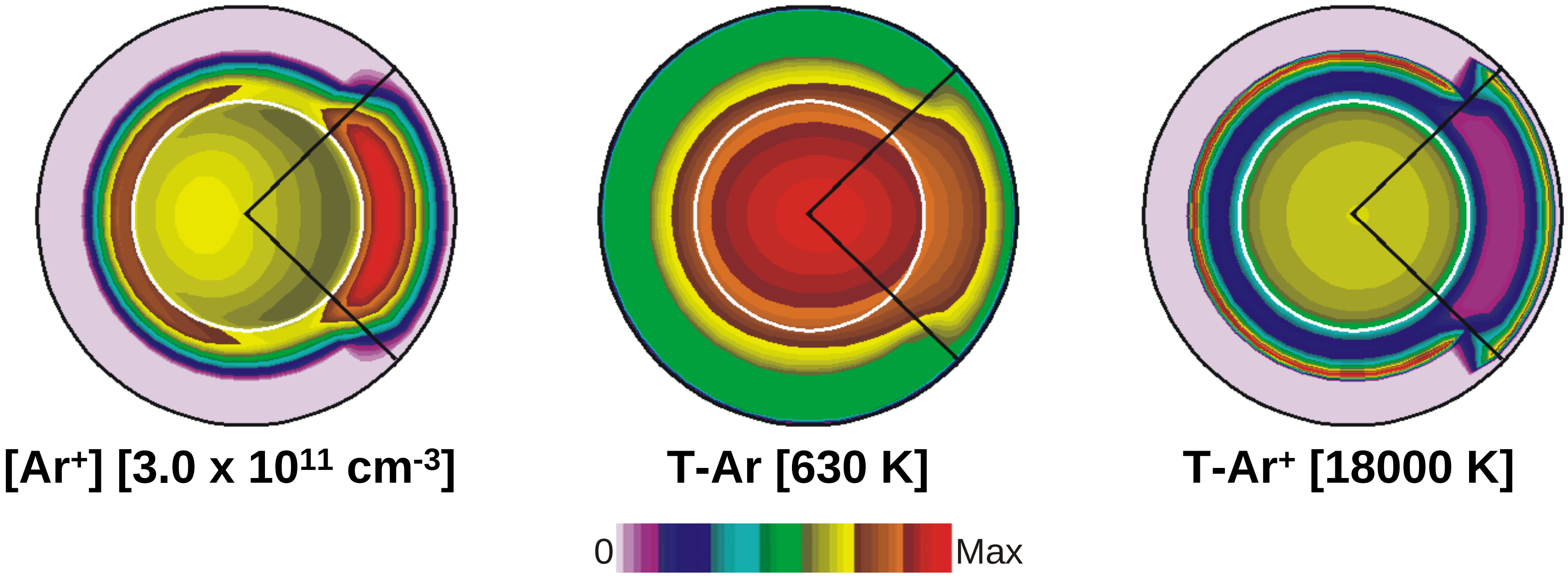
S-e [12 x 10^{15} cm^{-3}-s^{-1}]

- σ_p is azimuthally asymmetric below the dielectric due to non-uniform n_e.

- Non-uniform power deposition makes reaction sources asymmetric.

• Ar, 500 W, 10 mTorr, 150 sccm

EFFECT OF ASYMMETRIC PUMPING: Above Wafer



- [Ar^+] peaks near the pump port due to the absence of a wall at the side of the pumping.
- T-Ar and T-Ar^+ peak slightly off center to the side of pumping.
- T-Ar^+ is higher near the walls owing to sheath heating.

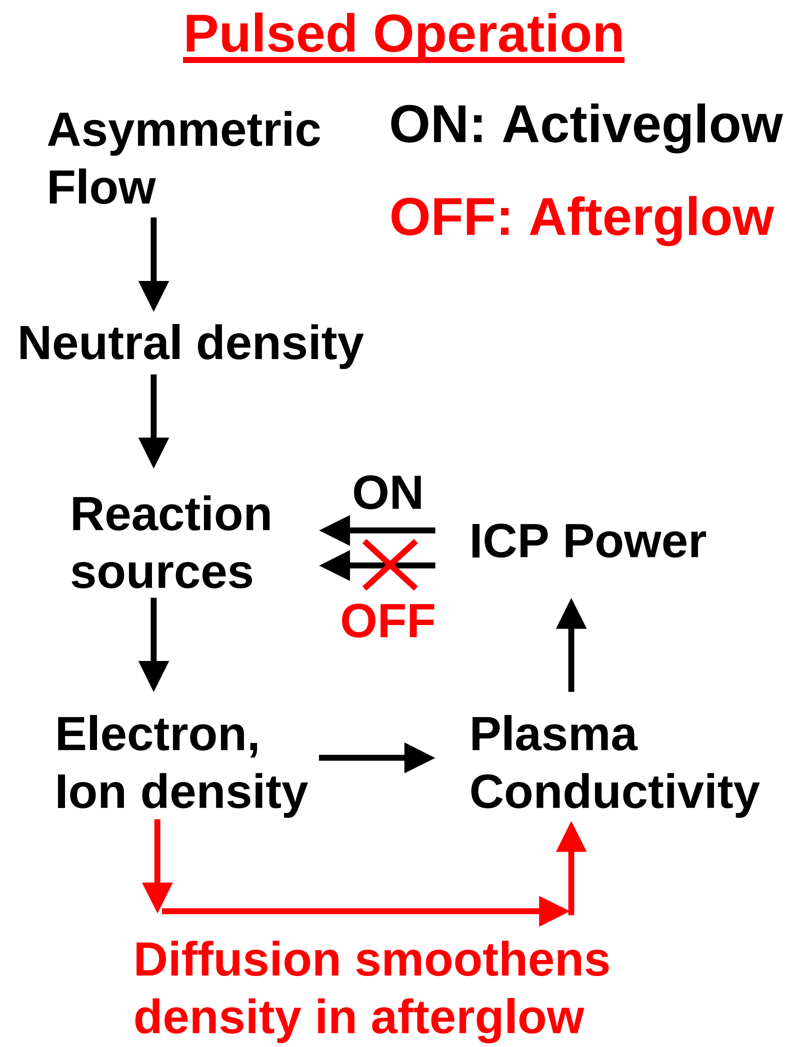
• Ar, 500 W, 10 mTorr, 150 sccm

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.

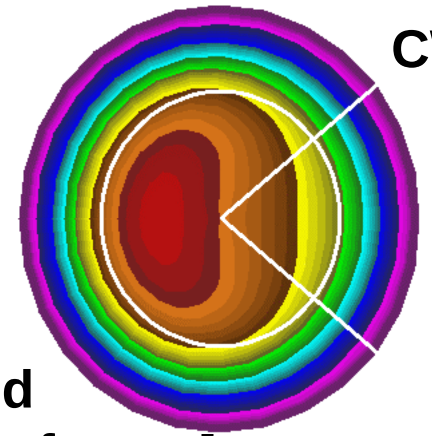
- Pulsed operation of ICPs may aid in reducing these asymmetries.



PULSED OPERATION OF ICPS

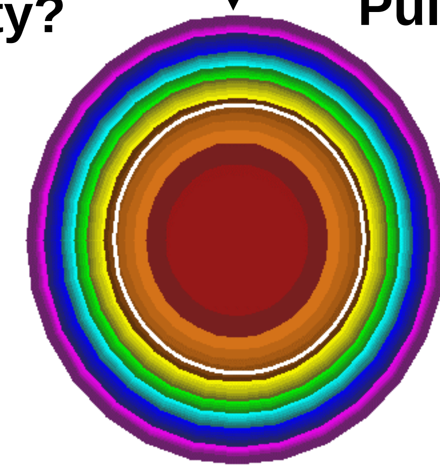
- To check our premise, ICP is first operated in CW mode to attain a steady state.
- CW operation results in asymmetries in species densities.
- CW operation is then followed by a series of pulses.
- Results for time averaged plasma properties for each pulse following CW operation will be shown.

CW ICP

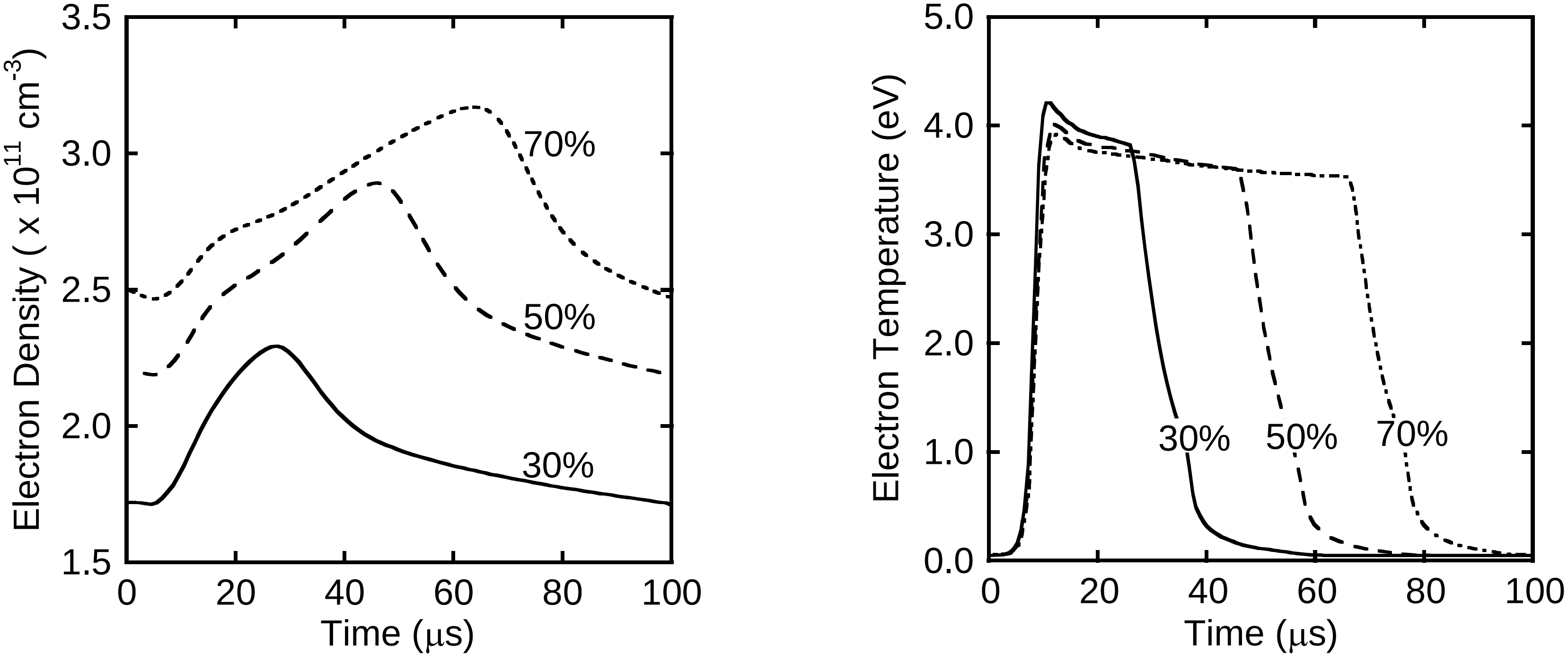


Can pulsed operation of ICP improve azimuthal uniformity?

Pulsed ICP



DYNAMICS OF PULSED PLASMAS: Ar

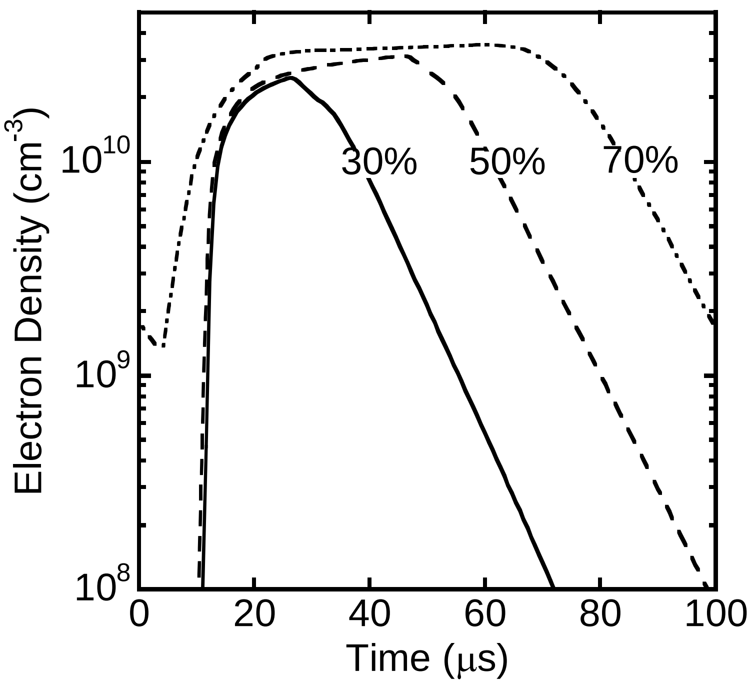


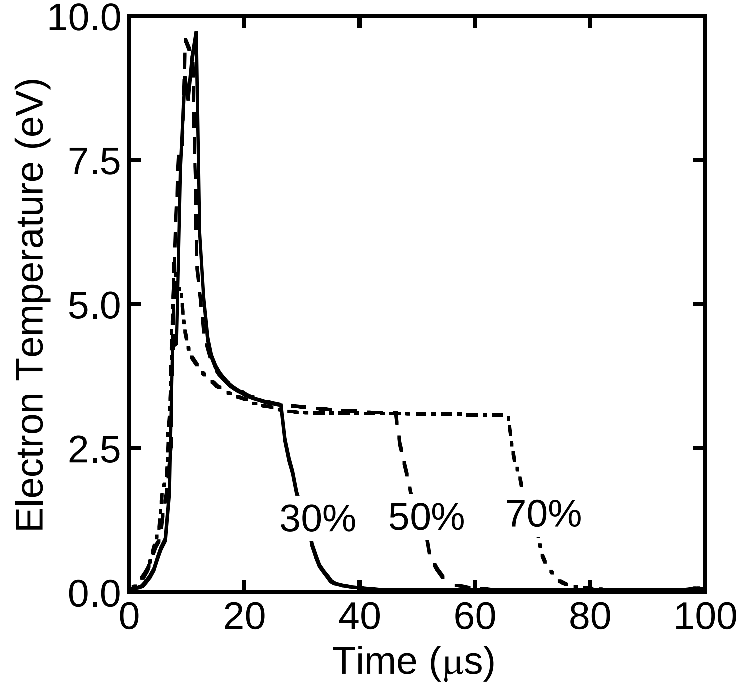
- **As the duty cycle increases, the reactor average electron density in the activeglow increases.**

- **When the power is turned off, T_e falls rapidly as electrons cool by inelastic collisions.**

- **Ar, 500 W, 10 mTorr, 50 sccm, PRF: 10 kHz, 50%**

DYNAMICS OF PULSED PLASMAS: Cl_2





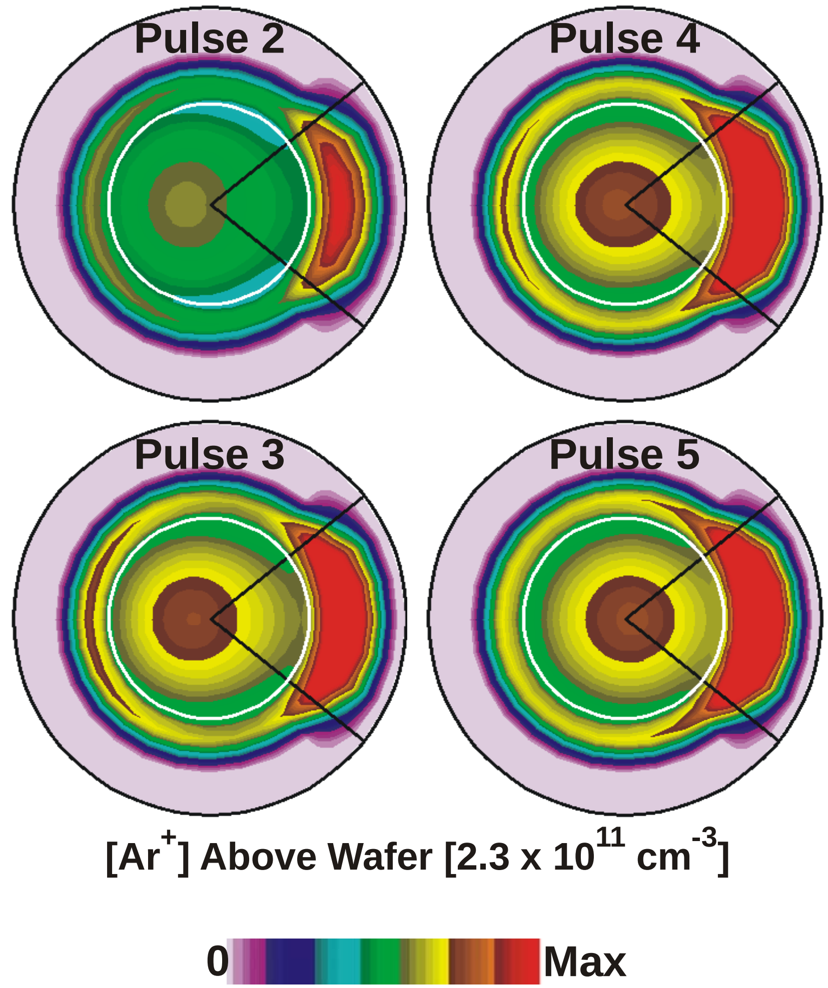
- **When power is terminated at the end of the activeglow, T_e thermalizes within 15 μs.**

- **The resulting increase in dissociative attachment produced a rapid decrease in n_e.**

• Cl_2, 300 W, 10 mTorr, 150 sccm, PRF: 10 kHz, 50%

PULSED ICPS WITH ASYMMETRIC PUMPING

- During CW operation, [Ar^+] is offset to the side opposite to the pump port.
- [Ar^+] shifts to the center of the reactor over a period of several pulses.
- Uniformity is improved as the positive feedback is reduced.
- Diffusion during the afterglow mitigates the non-uniformities.



- Ar, 500 W, 10 mTorr, 50 sccm, PRF: 10 kHz, 50%

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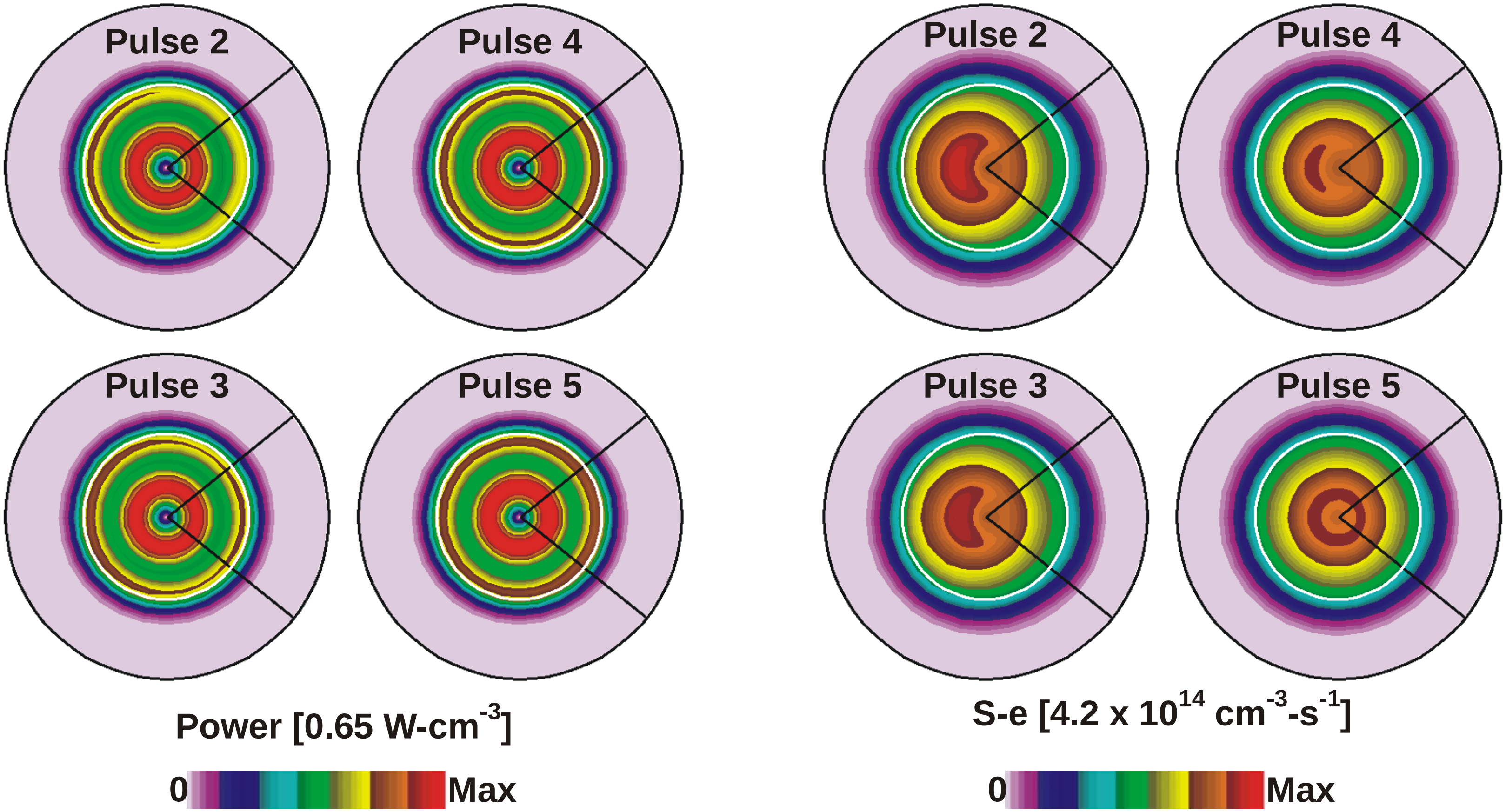
PULSED ICPS WITH ASYMMETRIC PUMPING

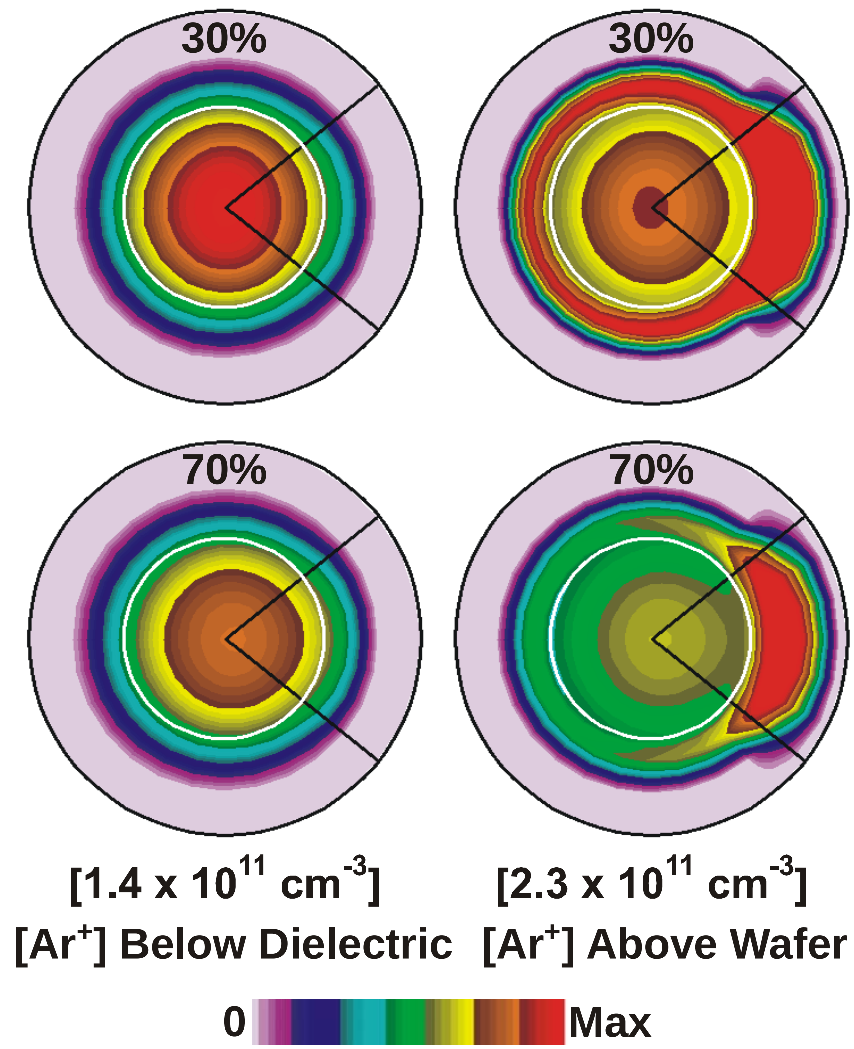


- **Through several pulses, the sources and power deposition become more uniform as the positive feedback through plasma conductivity is lessened.**

- **Ar, 500 W, 10 mTorr, 50 sccm, PRF: 10 kHz, 50%**

EFFECT OF DUTY CYCLE

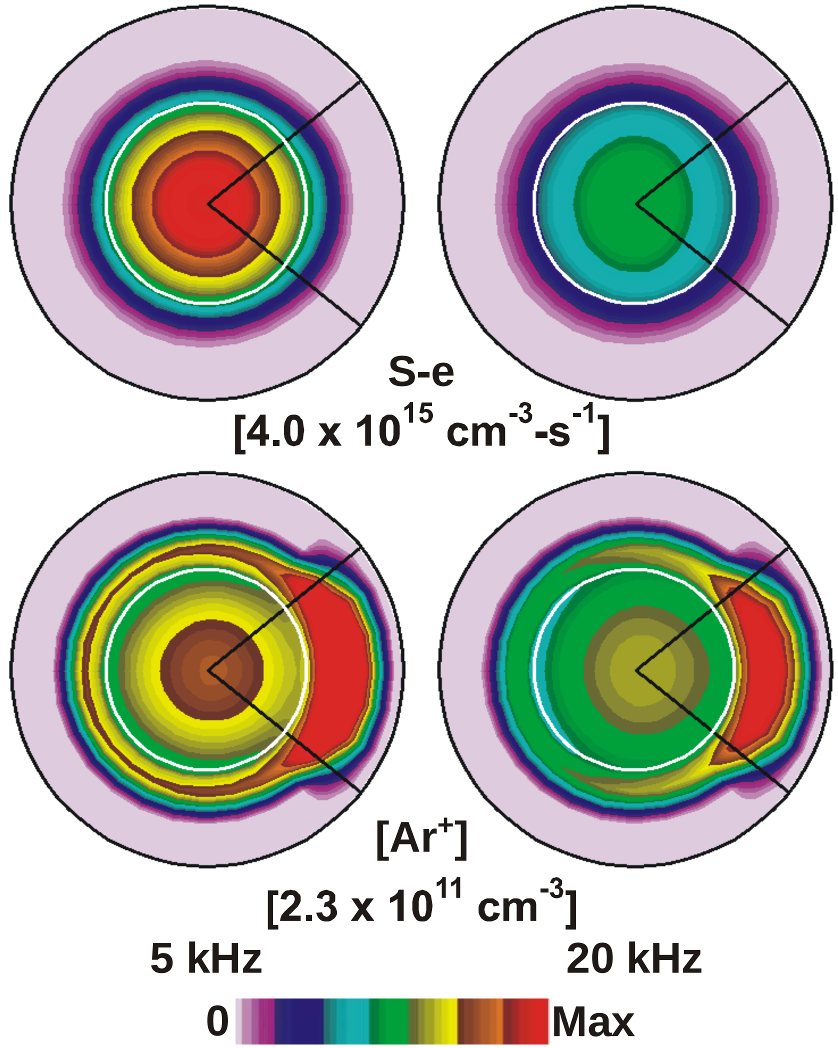
- As the duty cycle is decreased, afterglow is extended.
- Non-uniform sources are absent and mitigating diffusion is active for a longer duration.
- Also, positive feedback during the power pulse occurs for a shorter duration.
- Asymmetries in [Ar^+] decrease as the duty cycle is reduced from 70% to 30%.



- Ar, 500 W, 10 mTorr, 50 sccm, PRF: 10 KHz

EFFECT OF PRF

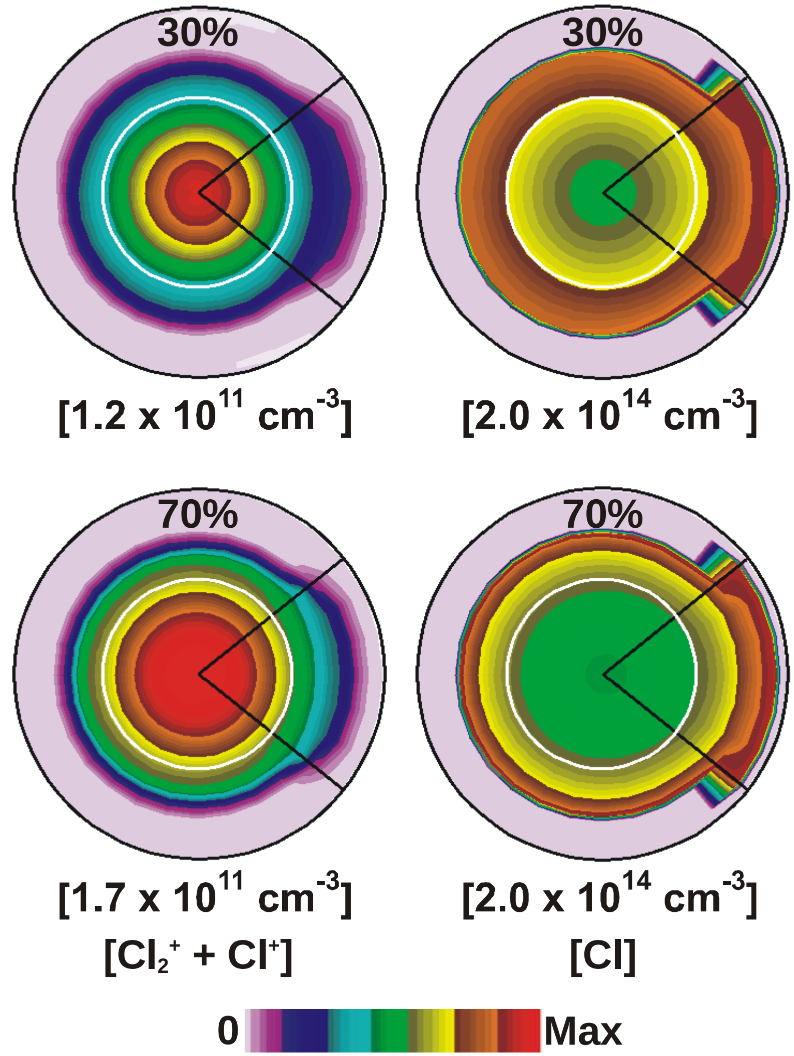
- As the PRF is decreased from 20 kHz to 5 kHz, afterglow is increased from 25 to 100 μs.
- Smaller PRFs also increase the activeglow.
- Longer activeglow reinforces non-uniformities.
- Longer afterglow reduces them.
- At 50%, this tradeoff is in favor of afterglow, hence better uniformity is attained at lower PRF.



• Ar, 500 W, 10 mTorr, 50 sccm, 50%

PULSED Cl_2 ICPS WITH ASYMMETRIC PUMPING

- Attachment dominates electron loss during the afterglow which results in residual electrons generally being more uniform.
- Any degree of pulsing which significantly depletes the electrons during the afterglow will break the positive feedback.
- For 30% duty cycle, the electrons are depleted significantly in the afterglow and this results in better azimuthal uniformity.



- Cl_2, 300 W, 10 mTorr, 150 sccm, PRF: 10 kHz

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CONCLUSIONS

- CW operation of ICPs with asymmetric pumping results in azimuthally asymmetric species densities, fluxes and temperatures.

- 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.

- Uniformity is generally improved at lower duty cycles and PRFs.