REAL TIME CONTROL OF PLASMA TOOLS DURING RECIPE CHANGES AND TRANSIENTS*

Mark J. Kushner
University of Illinois
Department of Electrical and Computer Engineering
Urbana, IL 61801

Shahid Rauf
Motorola
Austin, TX

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AGENDA

- Introduction to modeling of RTC for plasma tools
- Description of the Virtual Plasma Equipment Model
- Control strategies through transients
  - Impurity injection
  - Actinometry as a sensor
  - Recipe changes
- Concluding Remarks

REAL TIME CONTROL OF PLASMA TOOLS

- **Strategies are being developed for control of plasma tools with the goals of producing improvements in both real-time and run-to-run performance using increasingly more sophisticated diagnostics.**

  - **Krogh et al have demonstrated multivariable real-time-control of PECVD of silicon nitride using multi-species mass spectroscopy.**

  - **Khargonekar et al have investigated control of RIE using response-surface based controllers with OES and interferometry as sensors.**

  - **Lee and Maynard demonstrated the use of multi-wavelength ellipsometry for real-time-control using patterned wafers.**

- **In this paper, two topics in RTC will be addressed in the context of controlling transients in plasma tools.**

  - **Can first principles modeling be used to optimally select sensors?**
  - **Demonstration of advanced control strategies using gain scheduling.**

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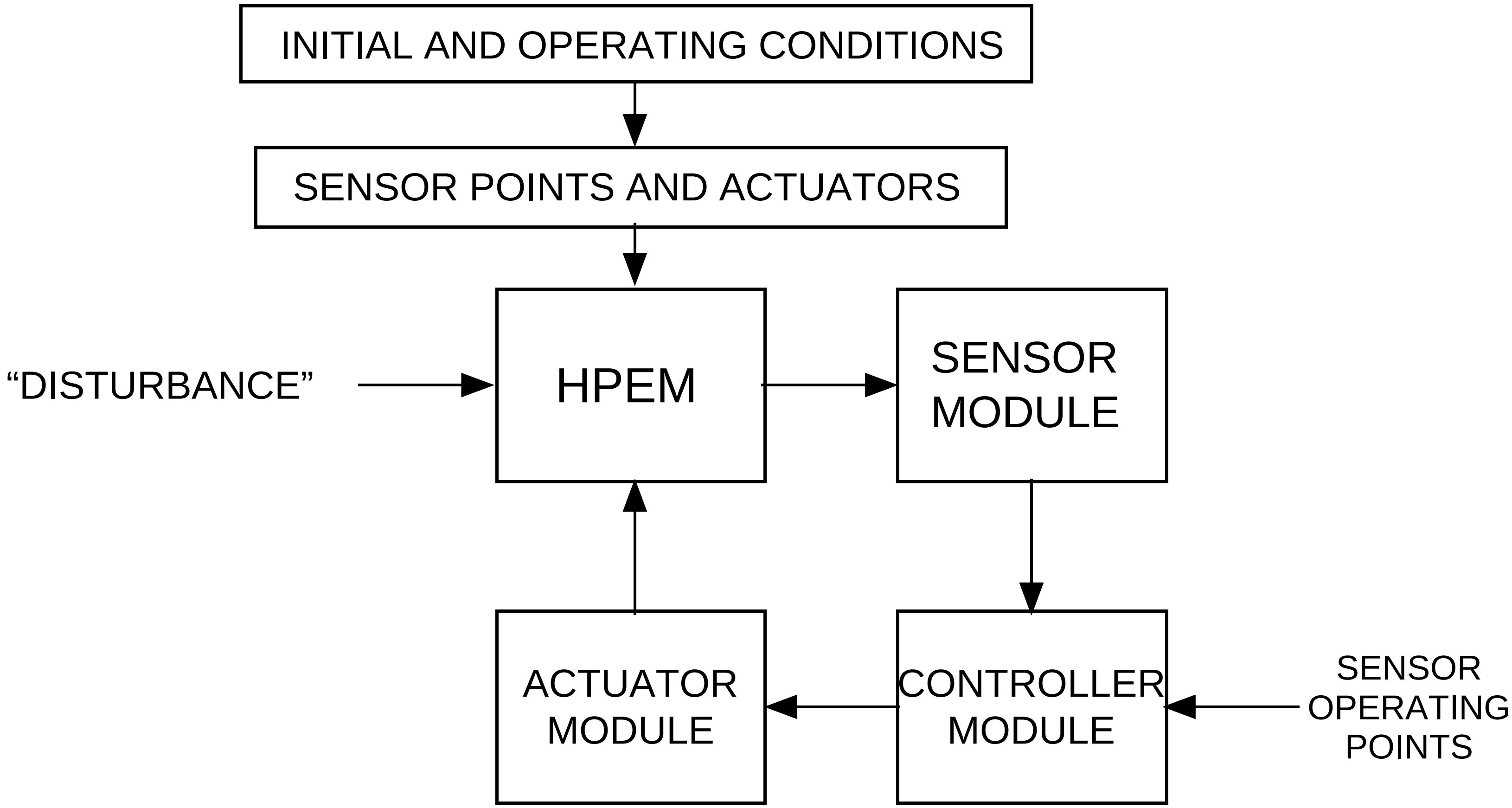
VIRTUAL PLASMA EQUIPMENT MODEL (VPEM)

- The Virtual Plasma Equipment Model (VPEM) is a “shell” which supplies sensors, controllers and actuators to the HPEM.



SENSORS AND ACTUATORS IN THE VPEM

- **The VPEM has been equipped with a variety of sensors and actuators.**
- **Sensors:**
  - **Spatially averaged densities**
  - **Densities at points**
  - **Optical emission through ports**
  - **Electrical sensors (I-V)**
  - **Actinometry**
  - **Mass spectroscopy**
  - **Fluxes to surfaces**
  - **Bias power**
  - **Langmuir probe**
  - **Pressure**
- **Actuators:**
  - **Pressure**
  - **Inductive power**
  - **Coil currents**
  - **Power supply frequency**
  - **Flow rate/mole fractions**
  - **Bias power**
  - **Electrode voltage**

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RESPONSE SURFACE BASED CONTROLLERS

- **The response surface is developed by performing a "S-DOE" (statistical design of experiments) using the commercial software package "E-CHIP".**

- **The response surface is constructed in the following manner:**
  - **Sensors, actuators and parameter are specified.**
  - **Using E-CHIP, a statistical model is specified, a set of "experimental" points are selected; and simulations run for those parameters.**
  - **A response surface is constructed from successive runs of the HPEM, and least mean square (LMS) polynomial coefficients are computed. In the case of a 2 sensor-2 actuator control scheme**

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{bmatrix} x_2^1 \\ x_2^2 \end{bmatrix} + \begin{bmatrix} d_1 \\ d_2 \end{bmatrix} x_1 x_2$$

- **We assume that small perturbations do not significantly alter the response surface, and linearize the system.**

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RESPONSE SURFACE BASED CONTROLLERS

- **The changes in sensor outputs resulting from small changes in actuator settings are then**

$$\begin{bmatrix} dy_1 \\ dy_2 \end{bmatrix} = \begin{bmatrix} b_{11} + 2c_{11}x_1 + d_1x_2 & b_{12} + 2c_{12}x_2 + d_1x_1 \\ b_{21} + 2c_{21}x_1 + d_2x_2 & b_{22} + 2c_{22}x_2 + d_2x_1 \end{bmatrix} \begin{bmatrix} dx_1 \\ dx_2 \end{bmatrix} = A \begin{bmatrix} dx_1 \\ dx_2 \end{bmatrix}.$$

- **Taking the inverse,**

$$\begin{bmatrix} dx_1 \\ dx_2 \end{bmatrix} = A^{-1} \begin{bmatrix} dy_1 \\ dy_2 \end{bmatrix}.$$

- **To restore the system from a perturbed condition (y_1',y_2') to desired a desired condition (y_1,y_2) the actuators are changed by**

$$\begin{bmatrix} dx_1 \\ dx_2 \end{bmatrix} = gA^{-1} \begin{bmatrix} \left(y_1 - y_1'\right) \\ \left(y_2 - y_2'\right) \end{bmatrix}$$

where g is a specified gain.

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PID CONTROLLER

- A Proportional-Integral-Differential (PID) controller has been implemented in the VPEM.

- **Proportional:**

$$\Delta A = A \cdot g \cdot \frac{\Delta S}{S}, \quad \Delta S = \left(S_o - S\right) = Error\, Signal$$

- **PID**

$$A = g \cdot \left(\frac{\Delta S}{S} + \frac{1}{t_i} \int \frac{\Delta S}{S} dt + t_d \left(\frac{\Delta S / S}{dt} \right) \right) + A_o$$

where:

$\Delta S, S, S_o$	**Error, current value and set point of sensor**	g	**Gain of Controller**
$\Delta A, A, A_o$	**Change, current value and set point of actuator**	t_d, t_i	**Differential and integral time constants**

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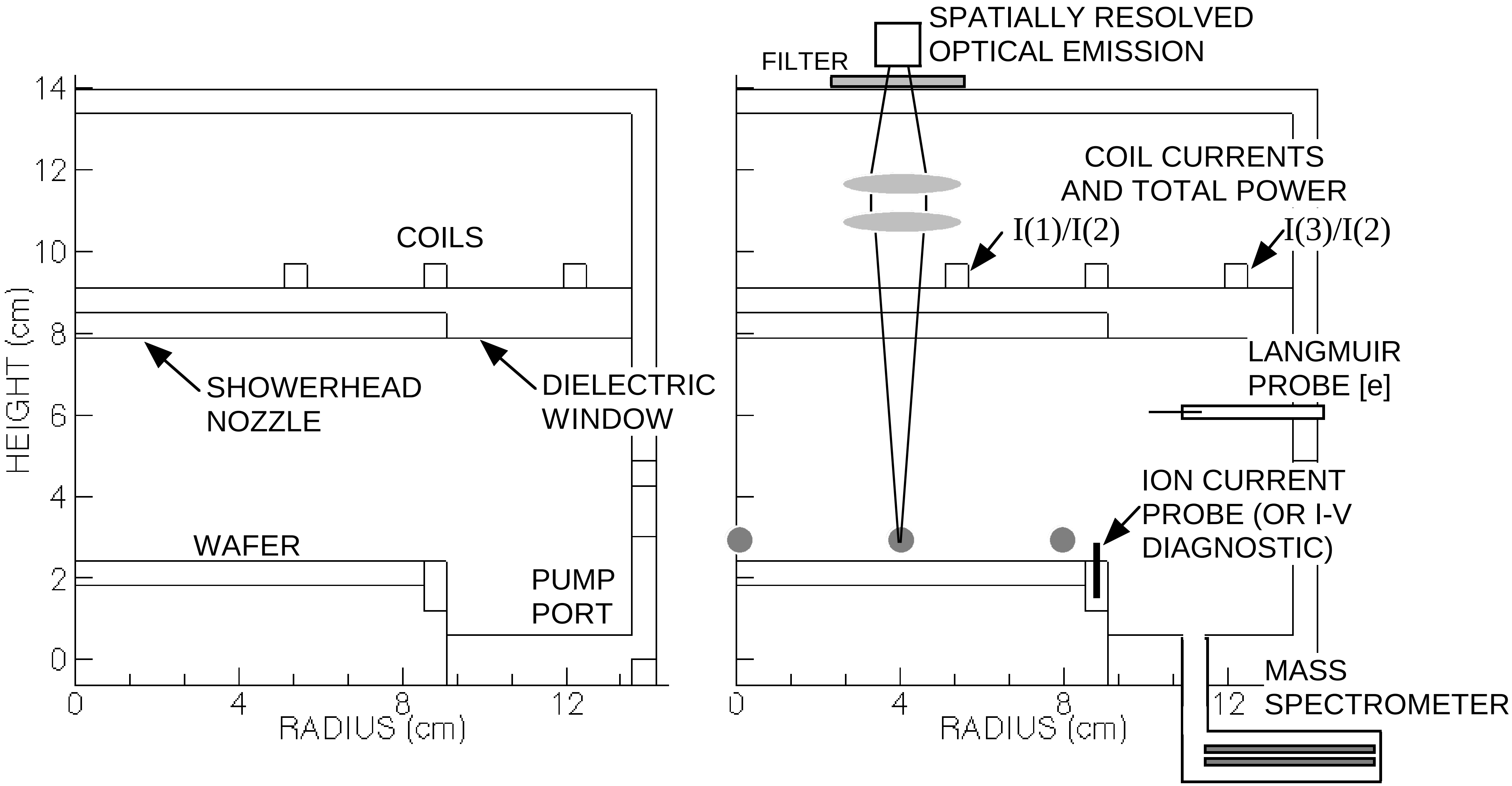
ICP PLASMA TOOL: GEOMETRY, SENSORS, ACTUATORS

- An Inductively Coupled Plasma (ICP) reactor will be used to demonstrate control strategies during transients and recipe changes.
- Sensors: Optical emission, mass spectroscopy, ion current, electron density
  Actuators: Coils currents, power deposition, pressure



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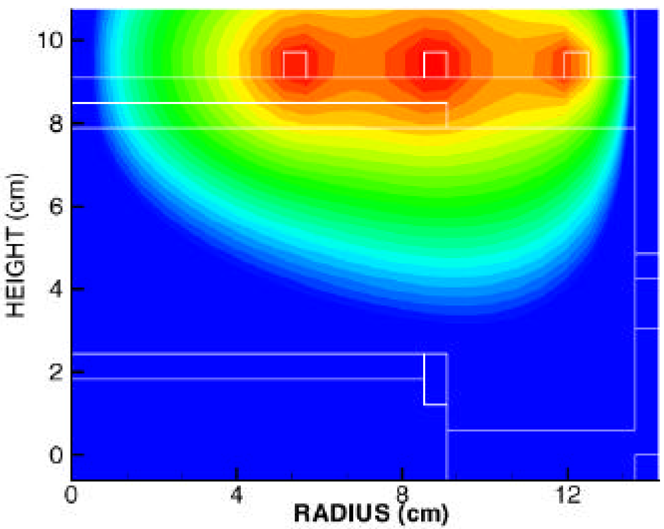
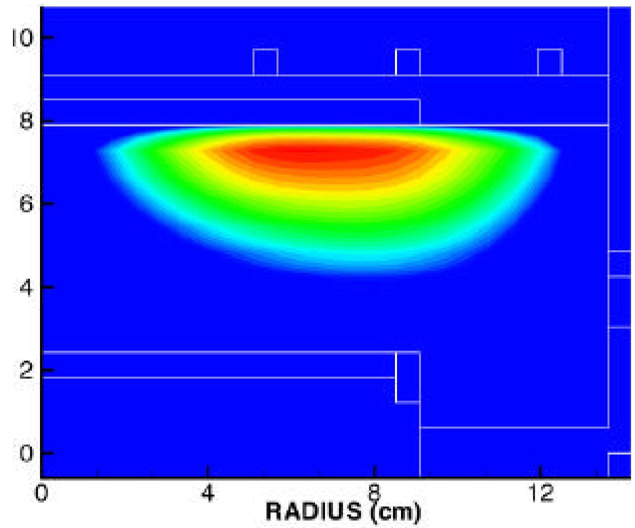
TYPICAL ICP DENSITIES

- Electric Field (8.8 V/cm)

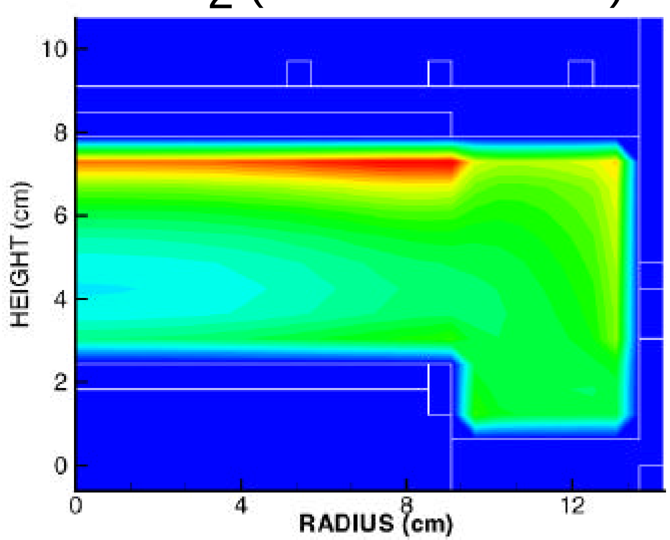


- Power (0.5 W/cm^3)

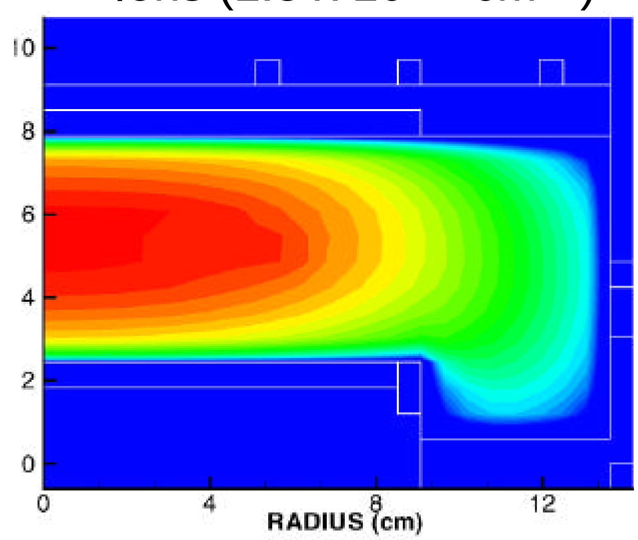


- Ar/Cl_2 = 98/2, 10 mTorr, 200 W, 250 sccm

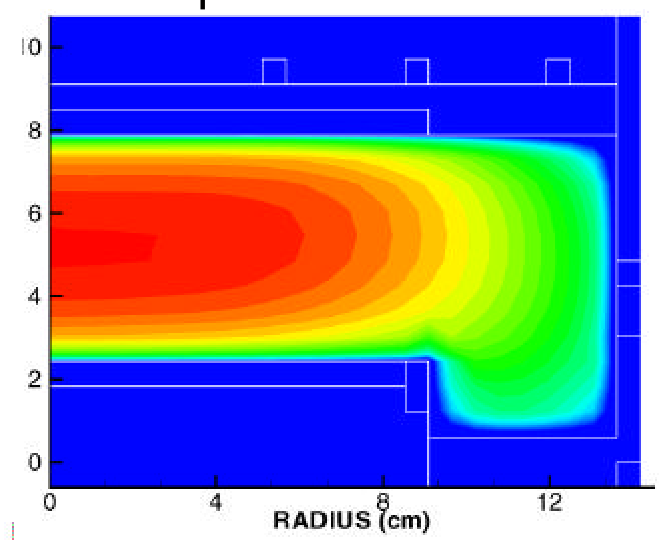
- Cl_2 (6.9 x 10^{11} cm^{-3})



- Ions (1.8 x 10^{11} cm^{-3})



- Optical Emission



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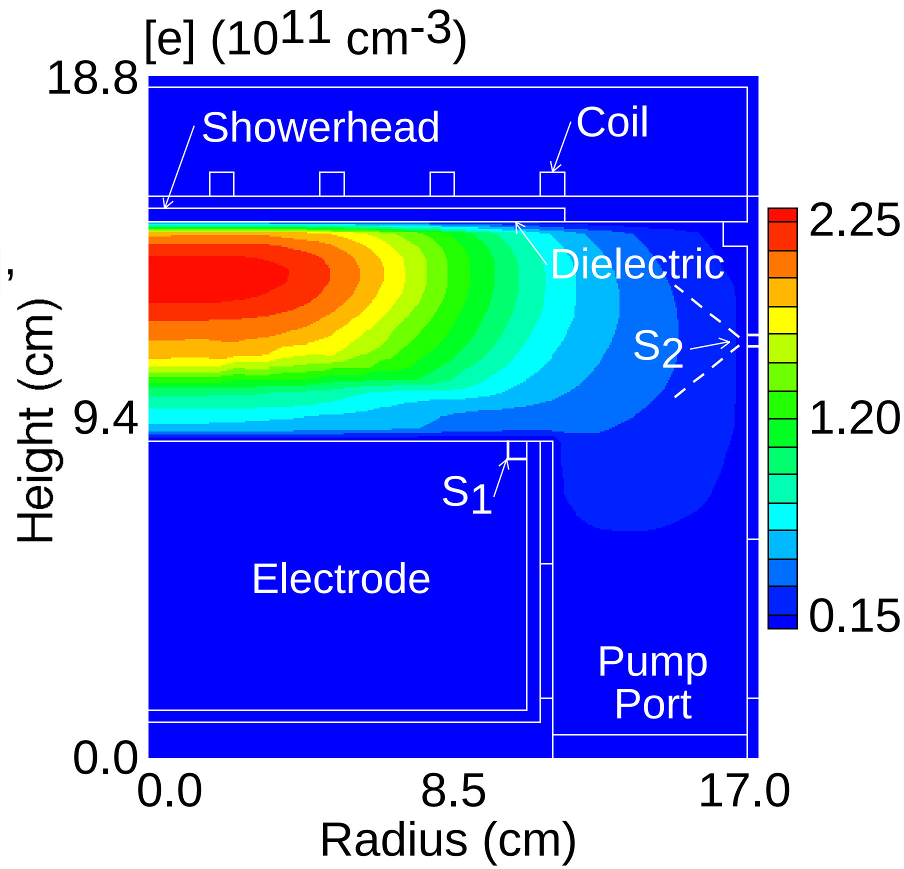
CONTROL OF FACTORS THAT EFFECT ETCH RATE

- Etch rate in Cl_2 chemistries is a function of:
  1. Ion flux to substrate,
  2. Cl flux to substrate,
  3. Ion energy.

- We consider polysilicon etching in an ICP reactor.

- Sensors:
  - Total ion flux at S_1 (e.g., Sobolewski, APL 72, 1146 (1998)],
  - Cl^* density using OES from S_2.

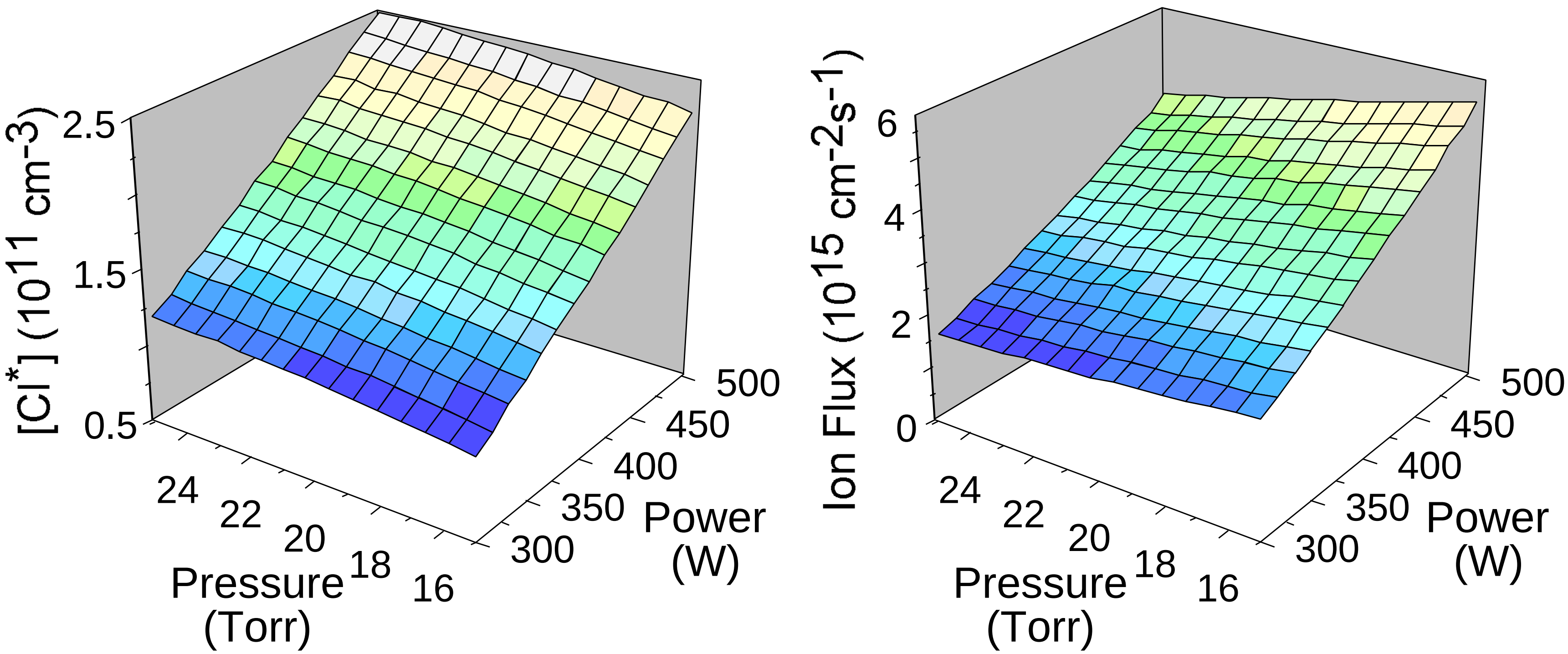
- Actuators:
  - Inductive power (300-500 W),
  - Pressure (15-25 mTorr).



- Ar/Cl_2 = 70/30, 150 sccm, no rf bias.

RESPONSE SURFACES

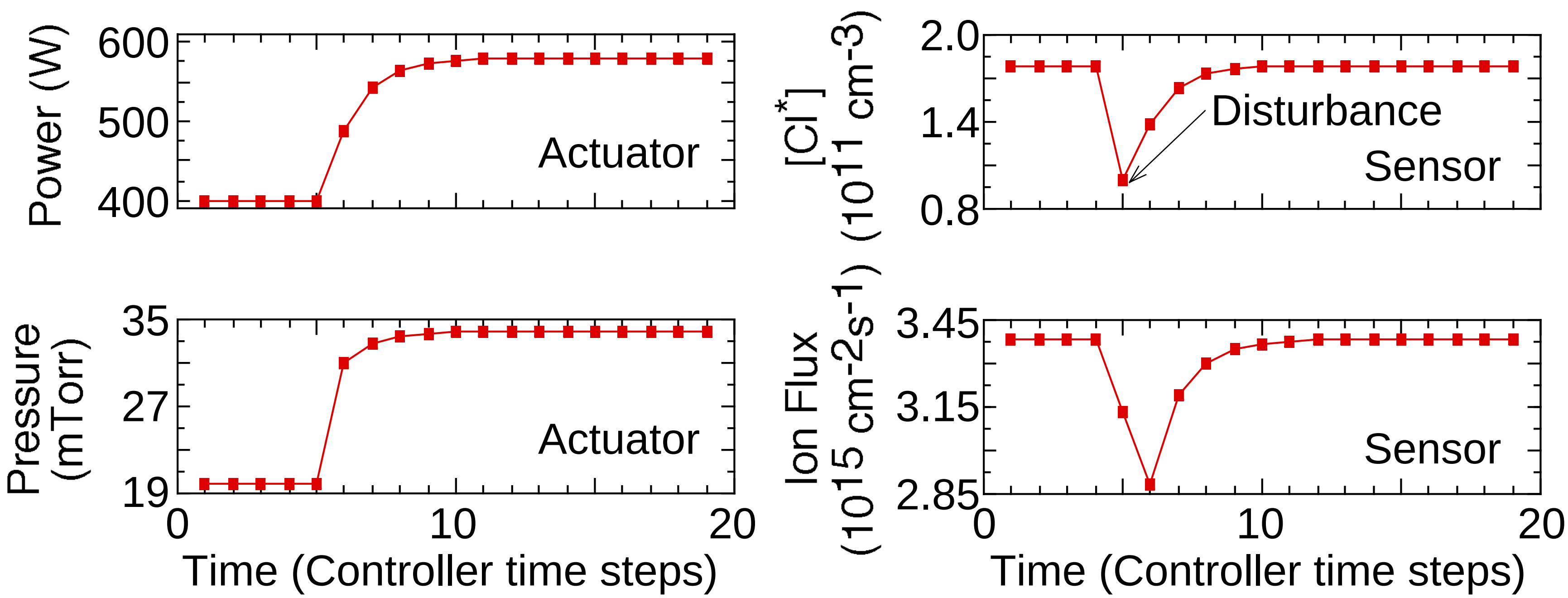
- Increase in power deposition causes more ionization and excitation, which enhances the Cl^* density and total ion flux to the substrate.
- Cl^* density increases slightly with pressure because the number of Cl that can be excited is larger.
- Since the plasma is more collisional at higher pressures, ion velocity and hence ion flux is smaller.



- Ar/Cl_2 = 70/30, 150 sccm, no rf bias.

CONTROL OF CHANGE IN WALL CONDITIONS

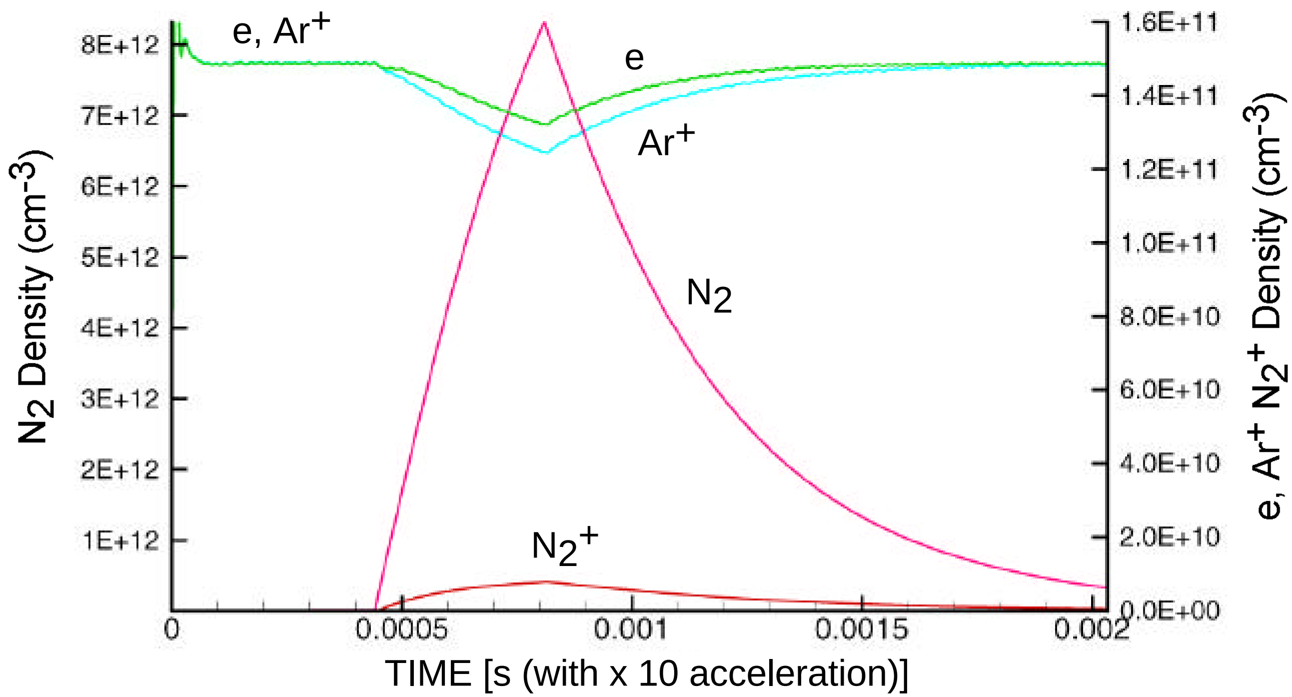
- At T=5, we artificially increase the Cl→Cl_2 sticking coefficient at the wall to simulate a change in wall conditions.
- This decreases the Cl^* density because of enhanced loss of Cl at the walls and decreases ion flux to substrate because the gas becomes more electro-negative.
- The RS based controller increases the pressure and power until the sensors return to their original values.



ICP Ar PLASMA TOOL WITH N_2 INJECTION

- The Mass Flow Controller (MFC) in an ICP plasma tool (Ar, 10 mTorr) malfunctions and injects a pulse of N_2 (25 sccm)

- Due to the large inelastic electron impact cross sections of N_2, the electron and ion densities decrease.



- Ar, 10 mTorr, 250 sccm, 200 W

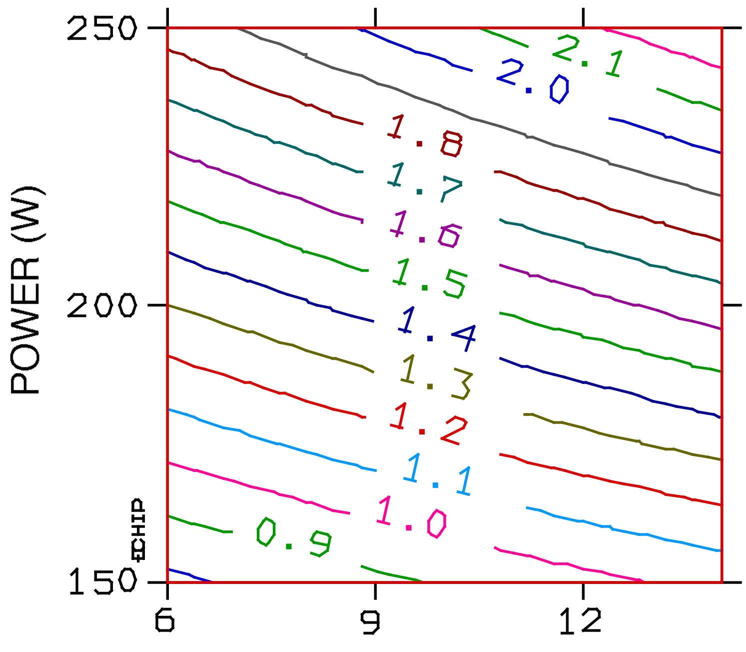
SENSORS-ACTUATORS FOR CONTROL OF GAS INJECTION

- Since etch rate depends on the total rate of radical production and ion bombardment on the wafer, choose electron density and ion flux as sensors.

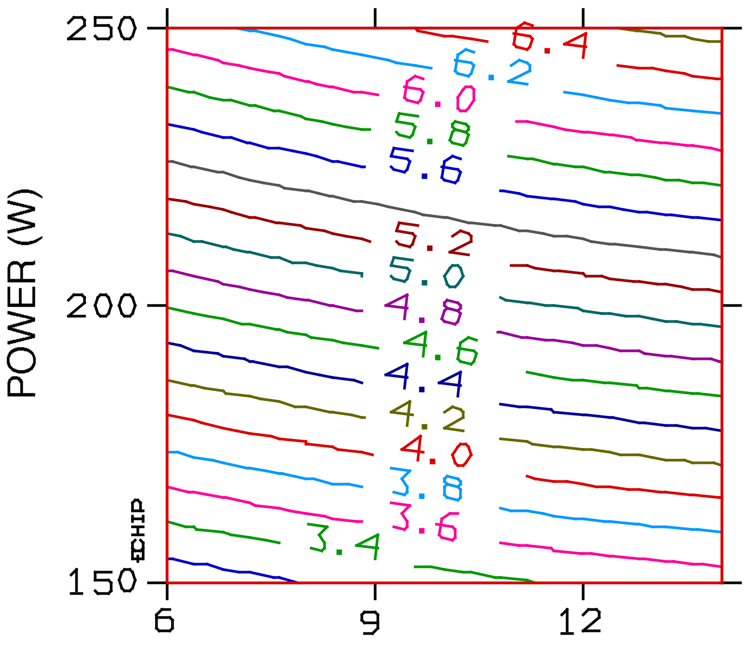
- Since radical production scales with electron density and ion flux with pressure, choose power and pressure as actuators.

- Response surfaces obtained from DOE. Note weaker dependence on pressure implying need for lower gain.

ELECTRON DENSITY ($10^{11} cm^{-3}$)



ION FLUX TO WAFER (10^{18} s^{-1})



- Ar, 10 mTorr, 250 sccm

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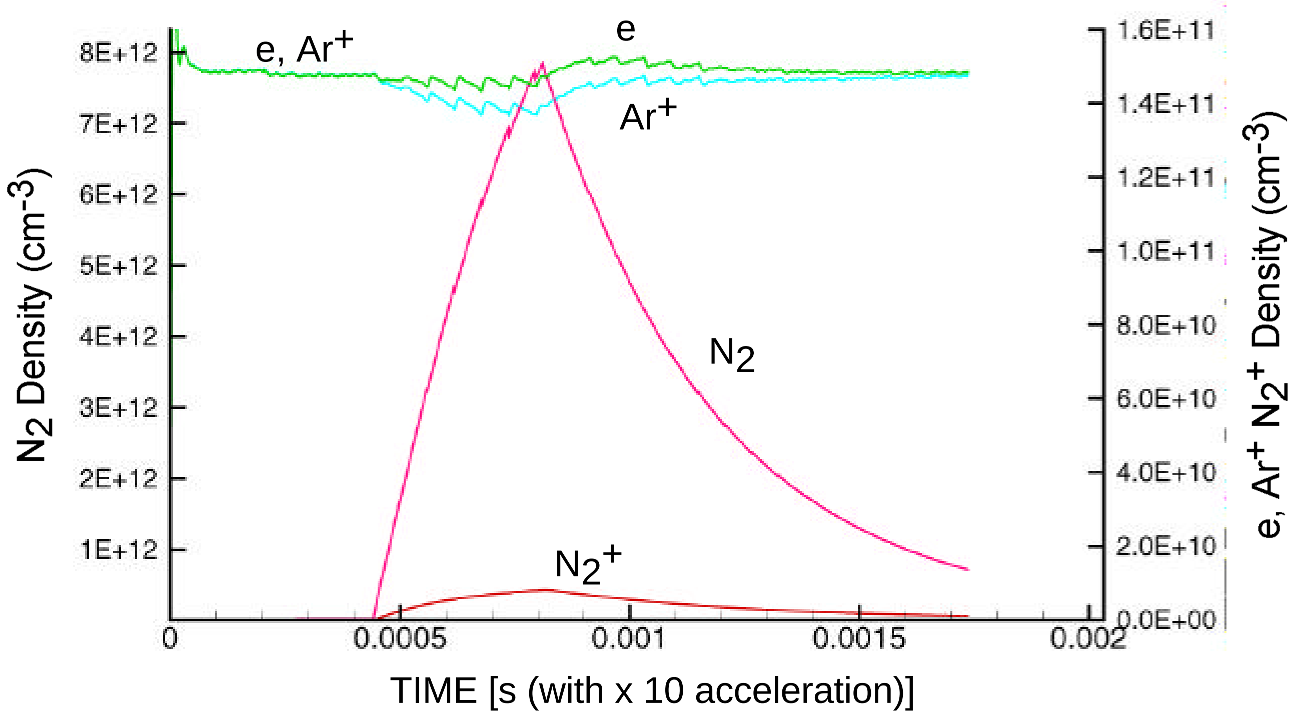
ICP Ar PLASMA TOOL: N_2 INJECTION w/CONTROL

- The electron (and ion) densities are only moderately well regulated against the perturbation by N_2 injection.
- The response surface was formulated using pure Ar, whereas the characteristics of the perturbed system differ significantly.
- As the N_2 density increases as the “pulse” moves through the reactor, larger actuator adjustments “in the future” are required than the controller suggests.



- Ar, 10 mTorr, 250 sccm, 200 W

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ICP Ar PLASMA TOOL: N_2 INJECTION w/CONTROL (cont.)

- When the N_2 density increases, the controller underpredicts changes in actuator settings since the "future" conditions are always "worse". When the N_2 density decreases, the controller overpredicts changes since future conditions are "better".

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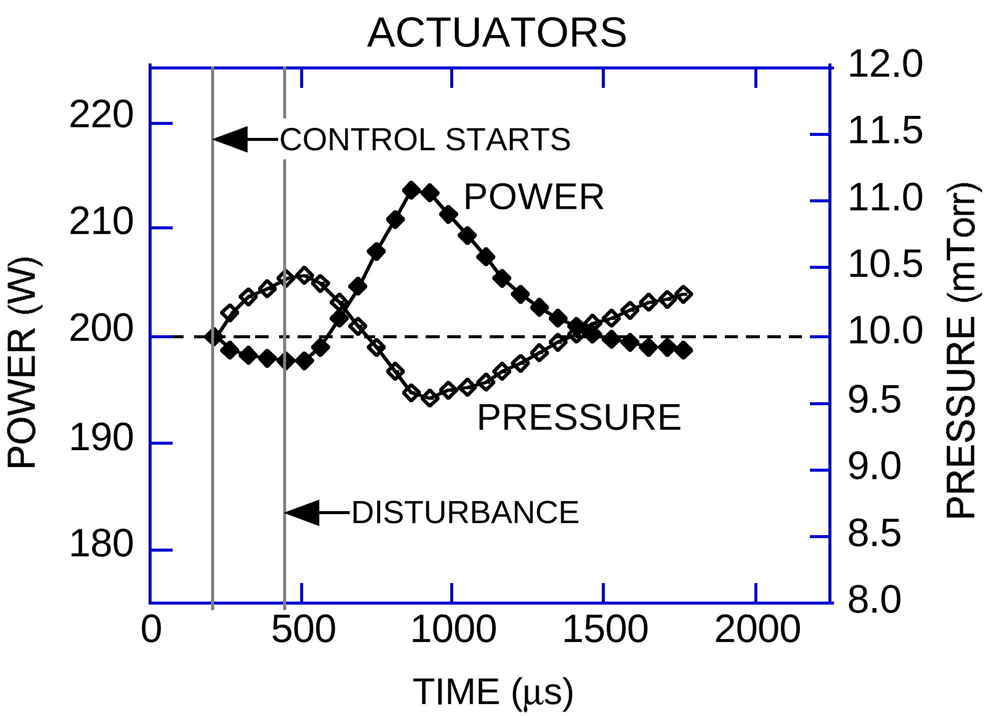
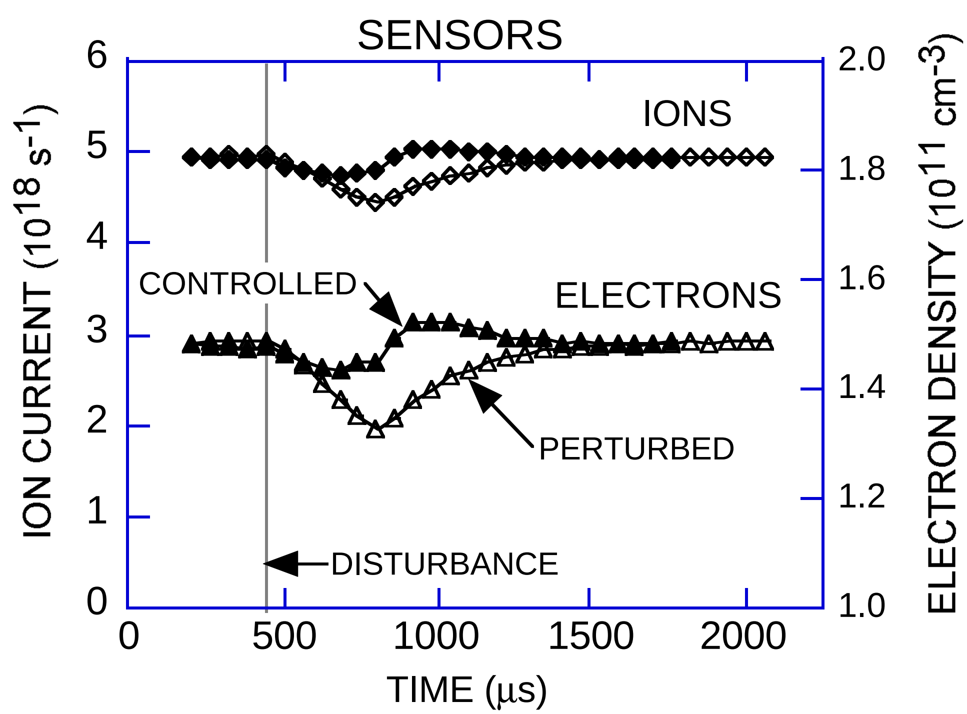
- To address these issues, the controller requires knowledge of the "physics" of the disturbance or must cycle at a high enough frequency to negate poor knowledge of the future.





- Ar, 10 mTorr, 250 sccm, 200 W

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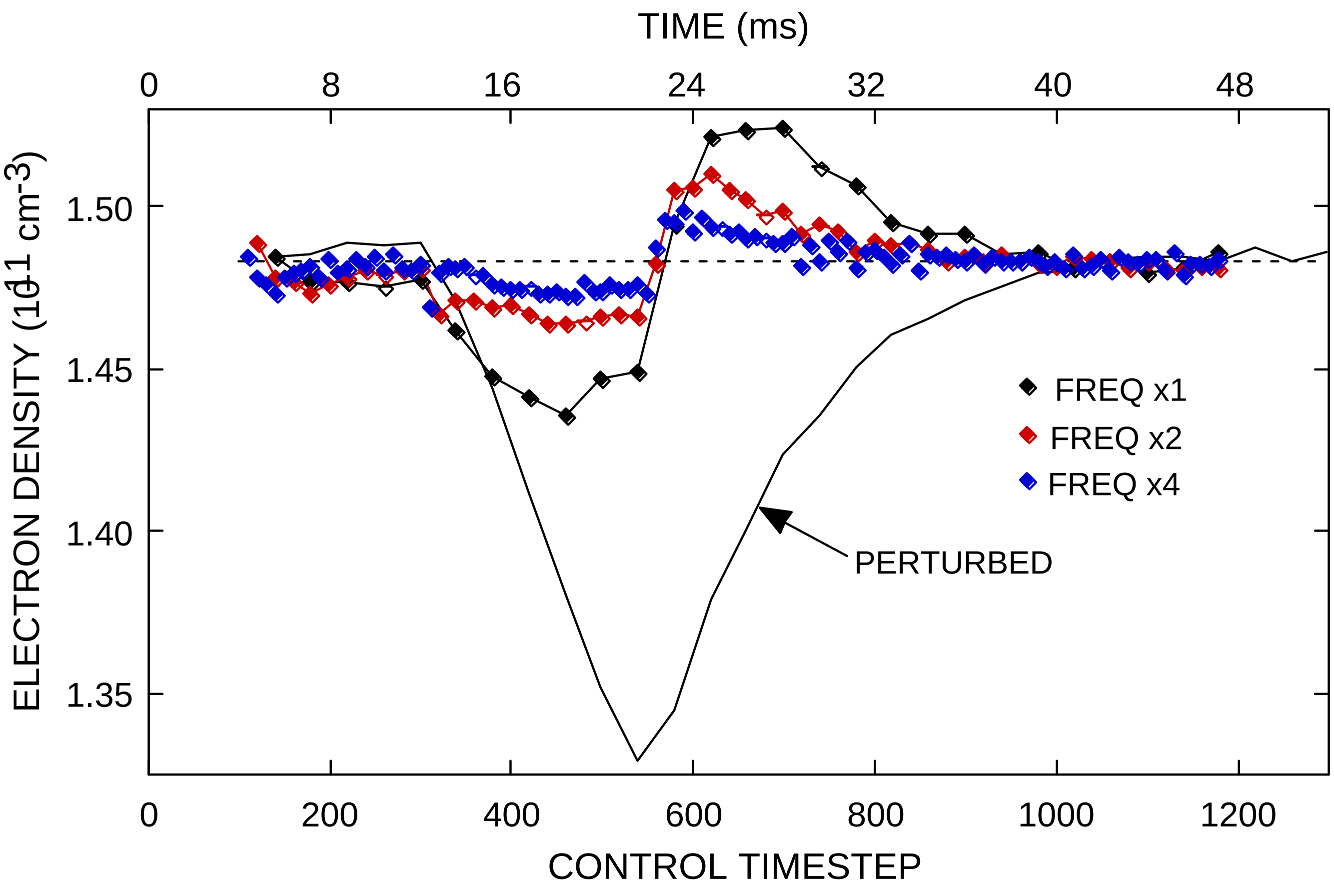
TRANSIENTS: CONTROLLER FREQUENCY

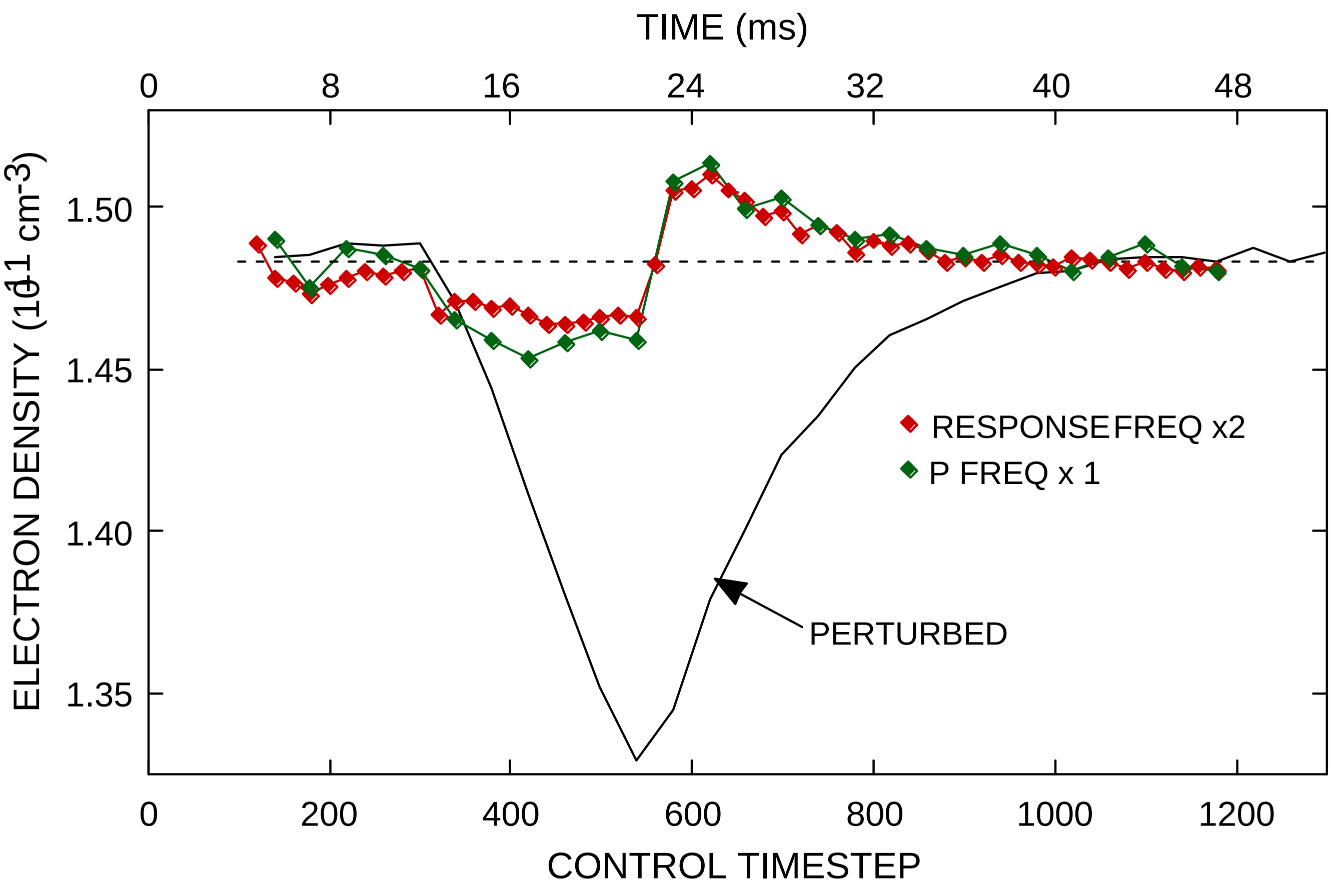
- **With no apriori knowledge of the "physics" of the transient, one strategy is to increase the frequency of the controller so that lack of knowledge of future (or present) conditions is less of an issue.**



- **Ar w/N_2, 10 mTorr, 250 sccm, 200 W**

TRANSIENTS: PROPORTIONAL CONTROLLER

- **Given the uncertainty and possible misguidance of response surface controllers during "unknown" transients, simplier PID controllers may fare better.**
- **A "slower" proportional controller with high gain is competitive.**



- **Ar w/N_2, 10 mTorr, 250 sccm, 200 W**
- **P-controller gain = 0.75**

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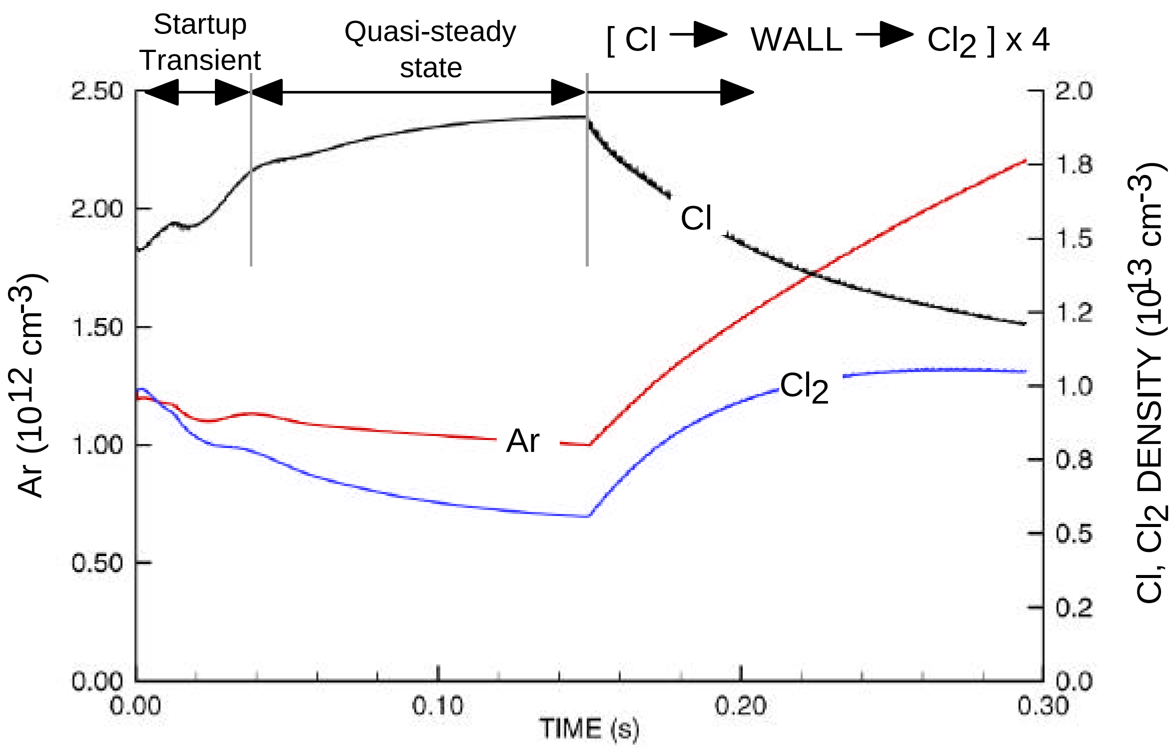
CHOICE OF SENSOR FOR TRANSIENTS: ACTINOMETRY

- **The proper choice of sensor is critical to controlling through transients.**
- **Sensors which are adequate for perturbations to the steady state may fail during a transient.**
- **Example: Impulsively change the coefficient for Cl ® Cl_2 on walls while keeping the input flow rate and pressure constant.**



- **Sensor: Actinometry of Cl*: S = [Cl*]/[Ar**]**
- **The decrease in outflow resulting from more recombination increases the Ar density.**
- **10 mTorr, 120 sccm, Cl_2/Ar = 95/5, 500 W**

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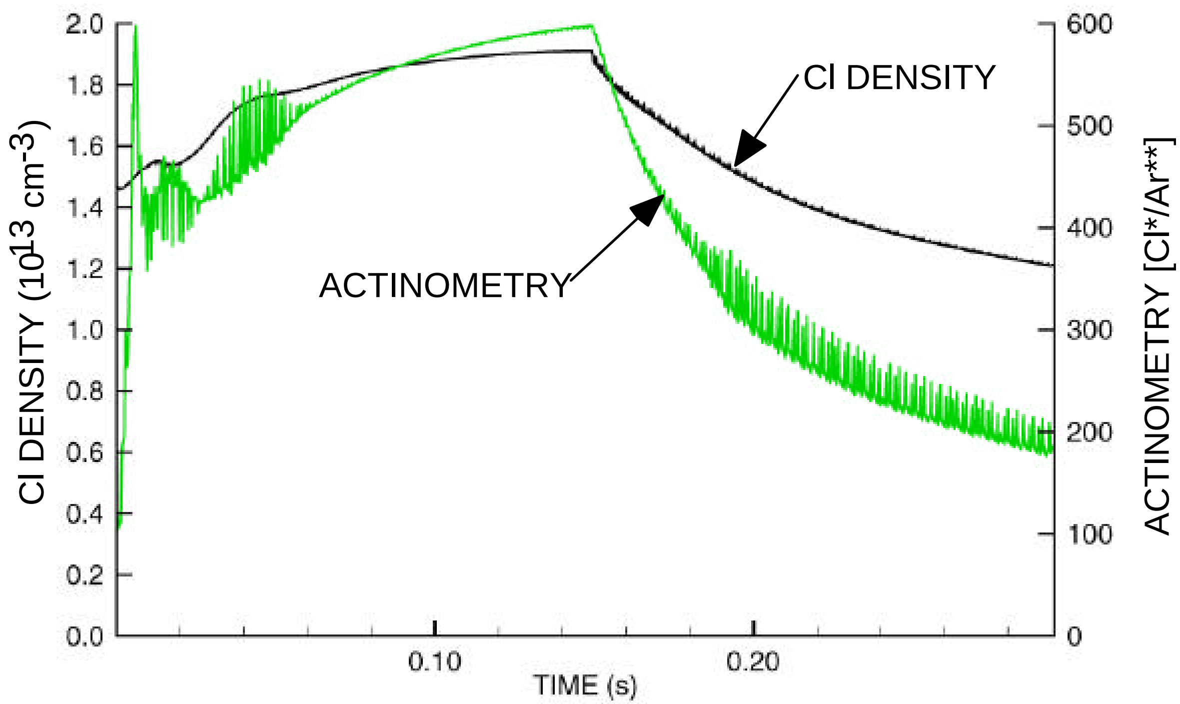
CHOICE OF SENSOR FOR TRANSIENTS: ACTINOMETRY

- **As a result of the absolute increase in Ar density (and Ar* signal) resulting from the change in mole fractions, the actinometry signal *decreases* relative to the actual Cl density.**



- **Transients which change the mole fraction of the reference will complicate use of actinometry.**

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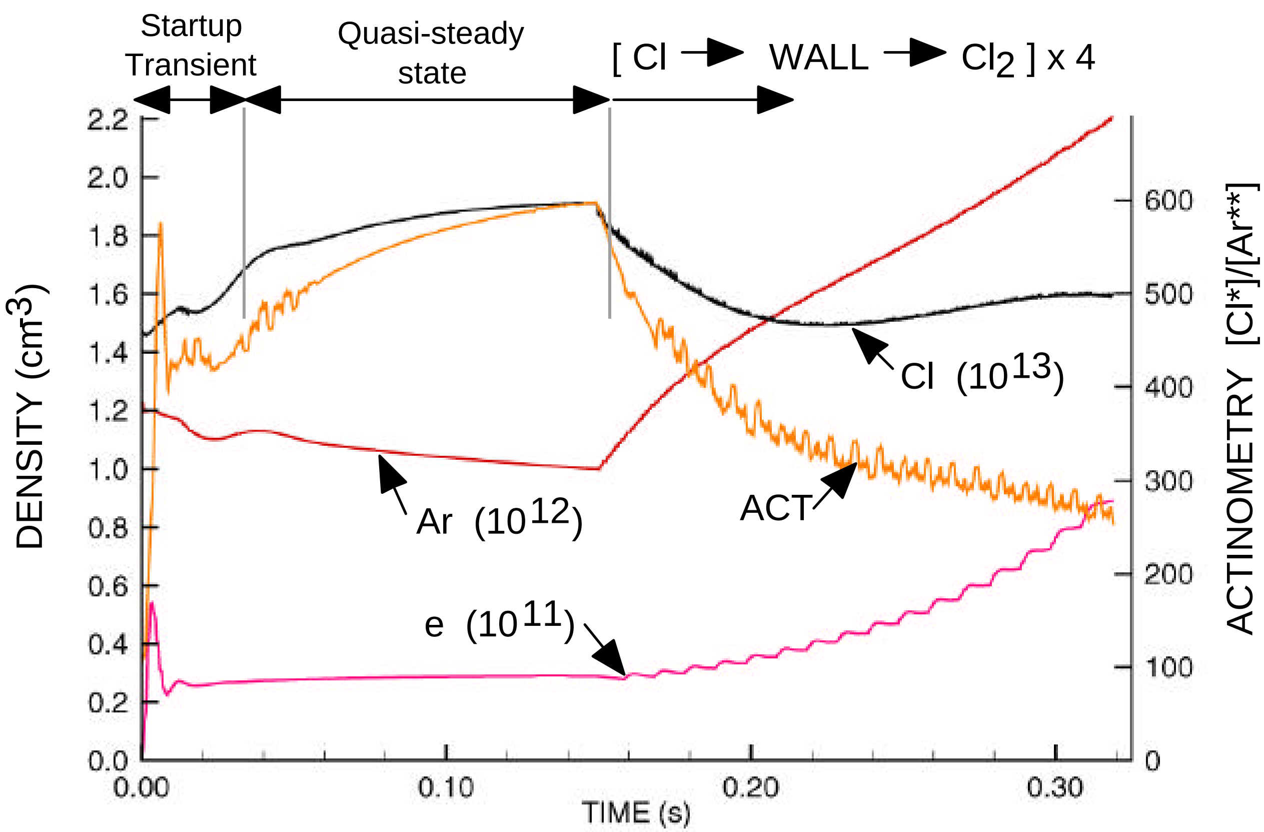
CHOICE OF SENSOR FOR TRANSIENTS: ACTINOMETRY

- **The response of the system is to increase power to recoup the actinometry signal which, during the transient, produces an unstable excursion in power and gas heating.**



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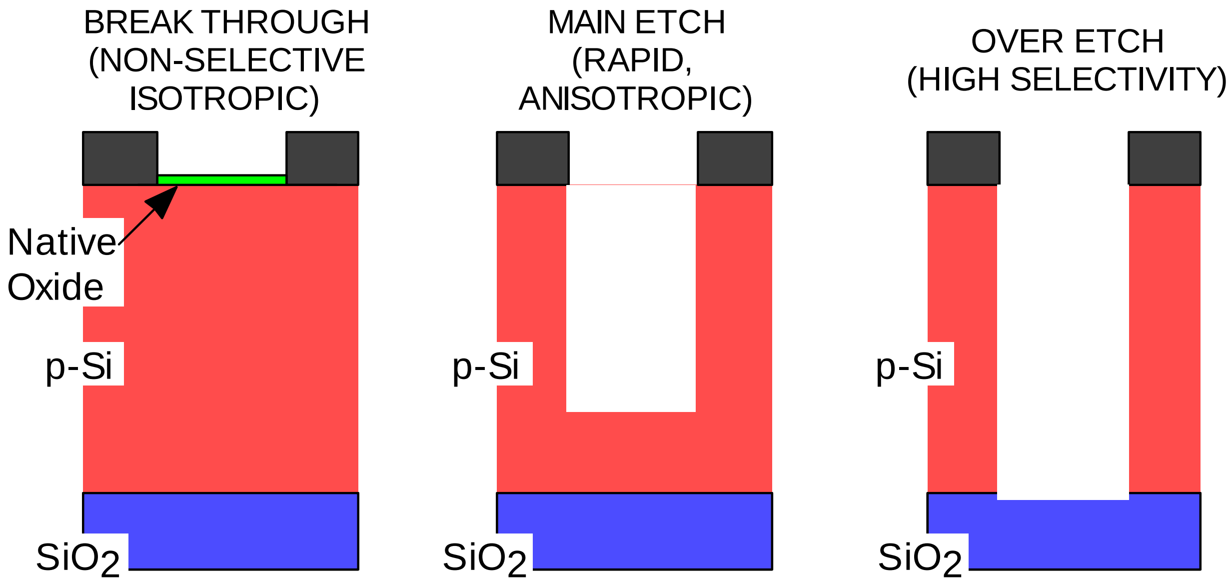
RECIPE CHANGES AND IMPACT ON CONTROL

- **During a plasma etching process, it is not unusual for there to be 2-4 "recipe" changes.**
- **Recipe changes are different values of, for example, power, pressure, flow rate or gas mixture to address beginning, middle and end of the etch.**

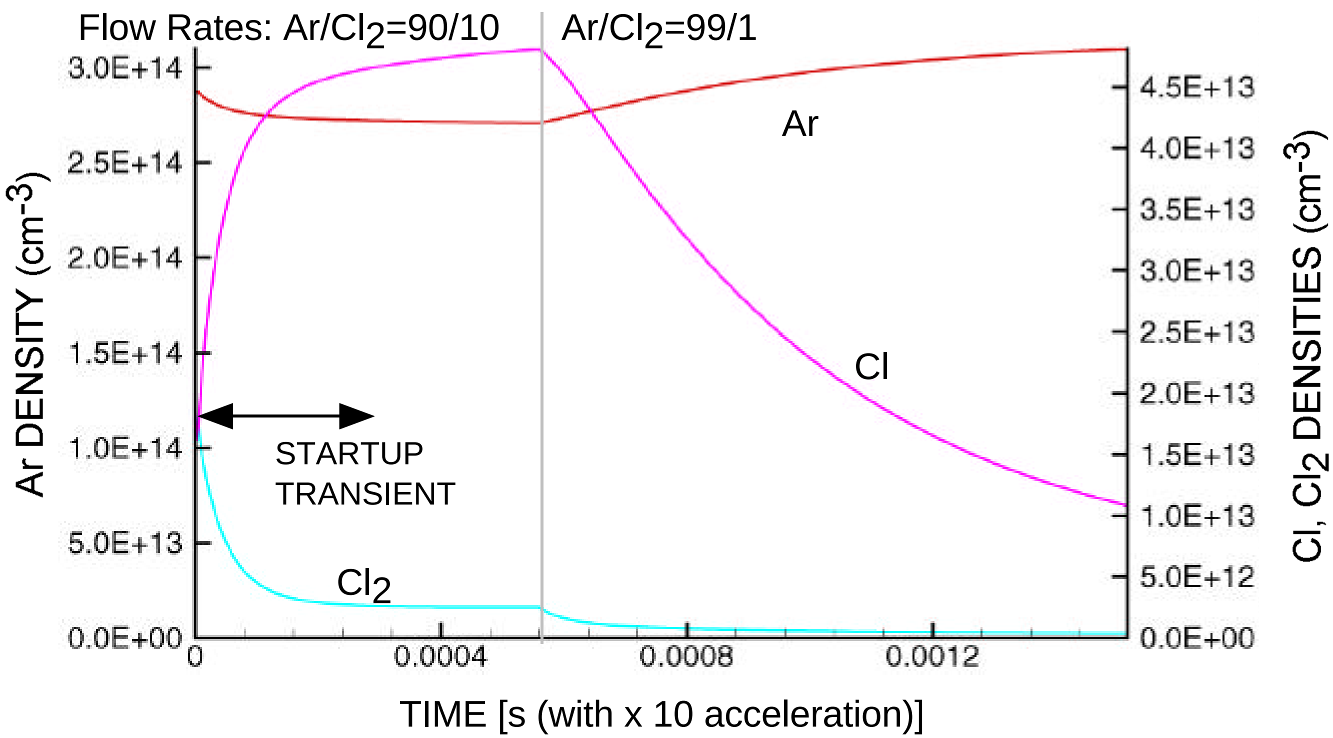


- **Changes in recipes may produce unanticipated changes in plasma parameters such as uniformity or rate which may need to be controlled.**

RECIPE CHANGE: Ar/Cl_2 p-Si ETCH TOOL

- An ICP reactor undergoes a recipe change during which the input flow rate changes from Ar/Cl_2 = 90/10 to 99/1. "Clearing" through the reactor produces an intermediate term transient which will be "controlled".

- Electron impact processes deplete Cl_2, produce radicals, ions and excited states which radiate.



$e + Cl_2 > Cl + Cl$

$e + Cl_2 > Cl_2^+ + 2e$

$e + Cl_2 > Cl^- + Cl$

$e + Cl > Cl^+ + 2e$

$e + Cl > Cl^* + e$

$e + Cl^* > Cl^+ + 2e$

$e + Ar > Ar^+ + 2e$

$e + Ar > Ar^* + e$

- 10 mTorr, 250 sccm, 200 W

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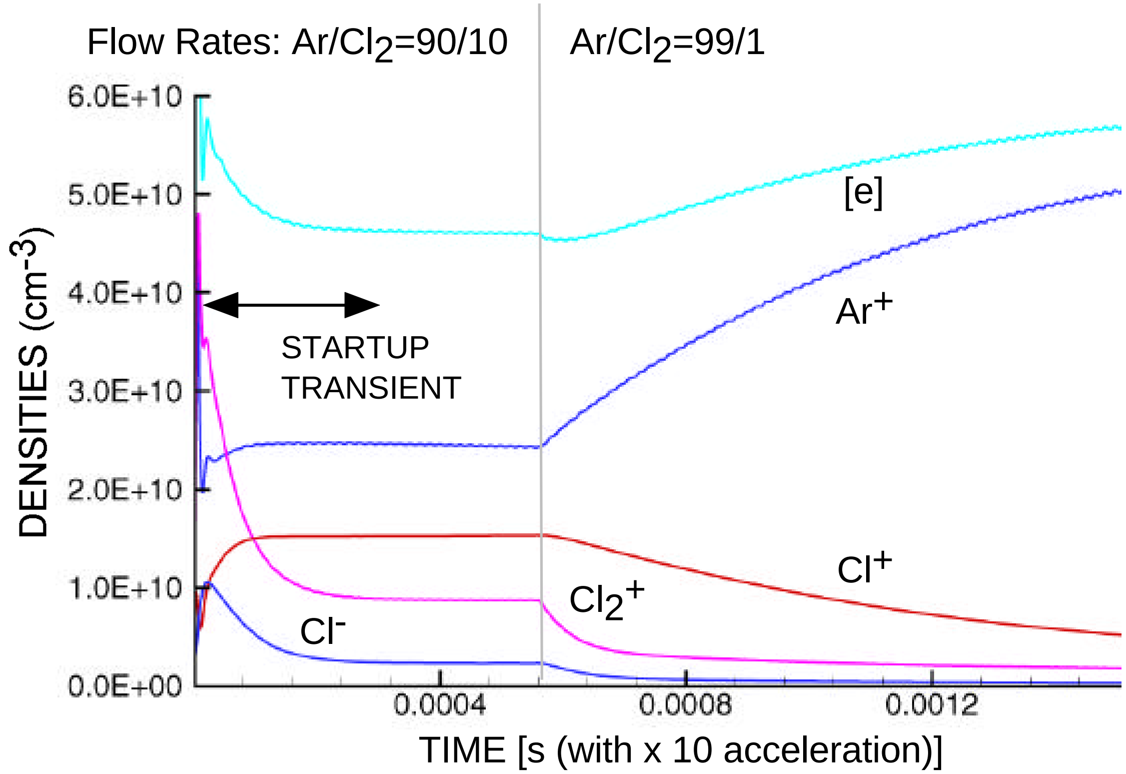
RECIPE CHANGE: Ar/Cl   p-Si ETCH TOOL (cont.)

- Although the power deposition remains constant through the recipe change, the decreasing Cl_2 produces a decrease in electron loss rates and power transfer.
- As a consequence, total electron and ion densities increase (which one may want to control...)



- 10 mTorr, 250 sccm, 200 W

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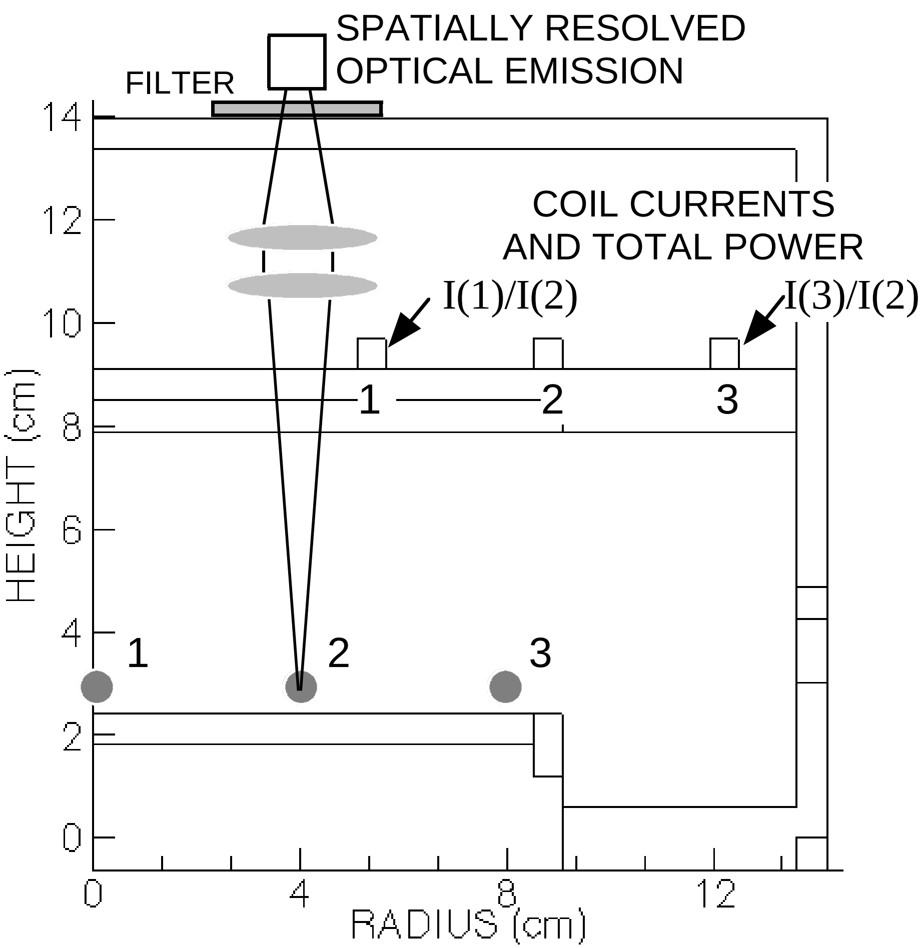
RECIPE CHANGE: CONTROL OF UNIFORMITY

- Goal: Control uniformity of etching before and after recipe change. Prior studies have shown a close correlation between Cl* emission and local etch rate.

- Sensors: Optical emission S(1)/S(2), S(3)/S(2)
  Actuators: Coils currents I(1)/I(2), I(3)/I(2)

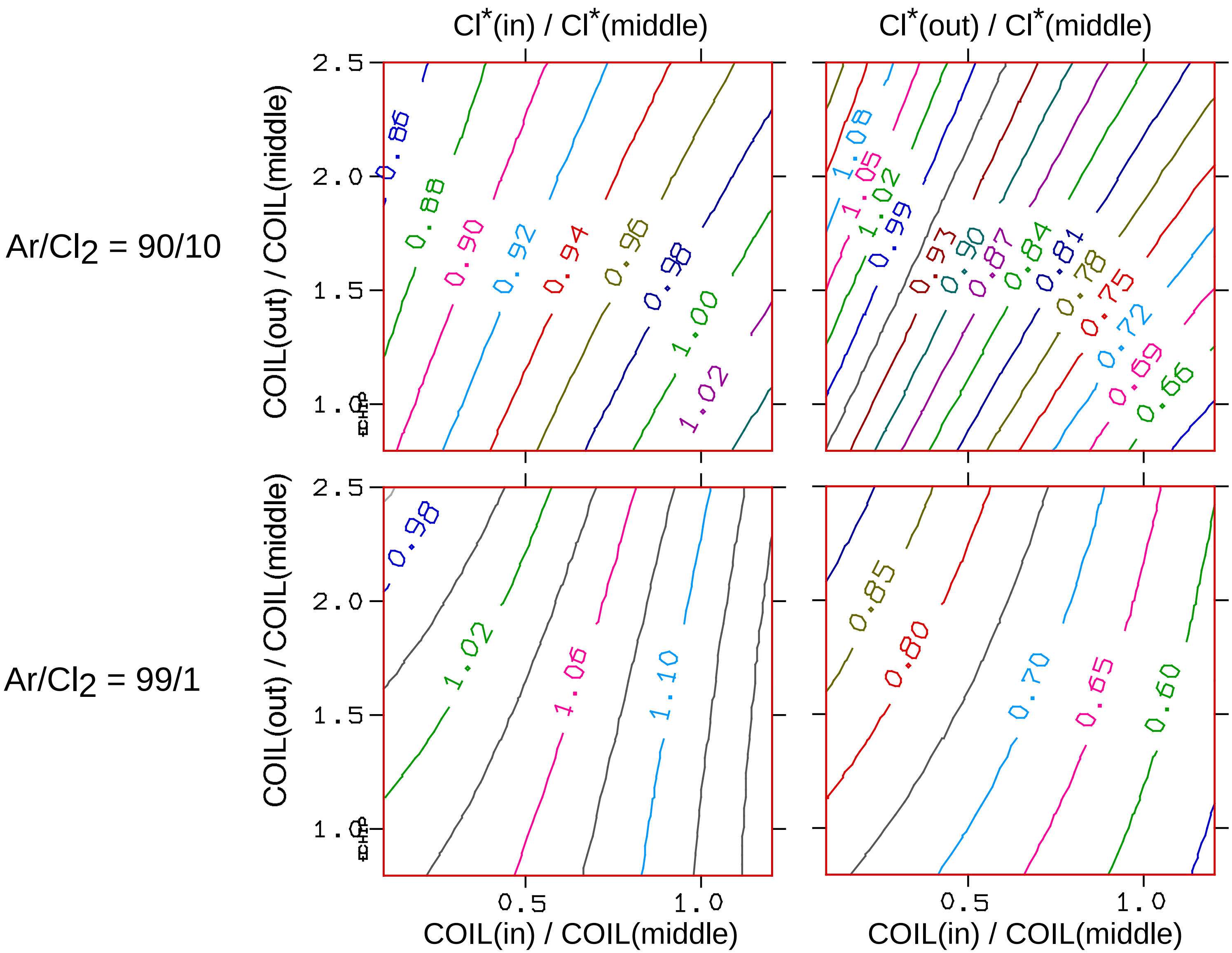


- During the recipe change, the chlorine density changes from 10% to 1%, with there being commensurate changes in plasma properties.

- In the absence of additional information, one must choose a chlorine density at which the response surface is developed and coefficients for the controller are derived.

RESPONSE SURFACES vs Ar/Cl_2 RATIO

- Response surfaces for uniformity of Cl* critically depend on the Ar/Cl_2 ratio.



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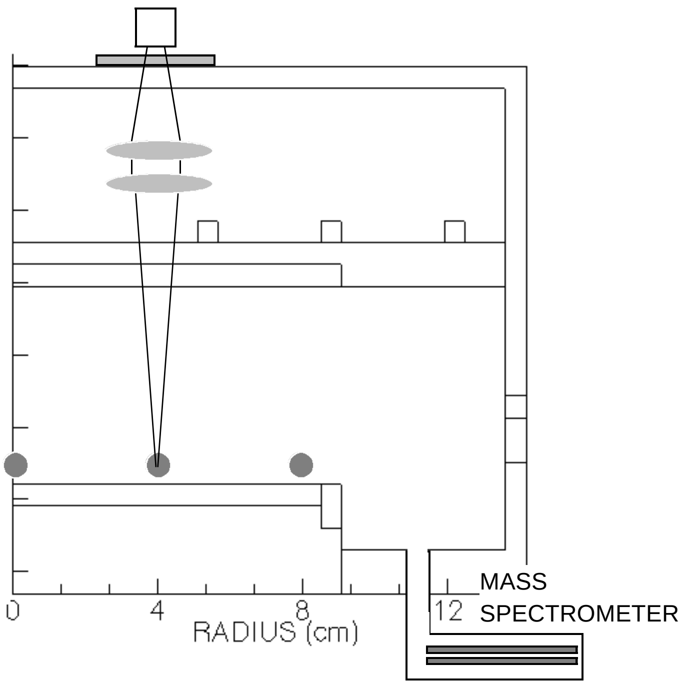
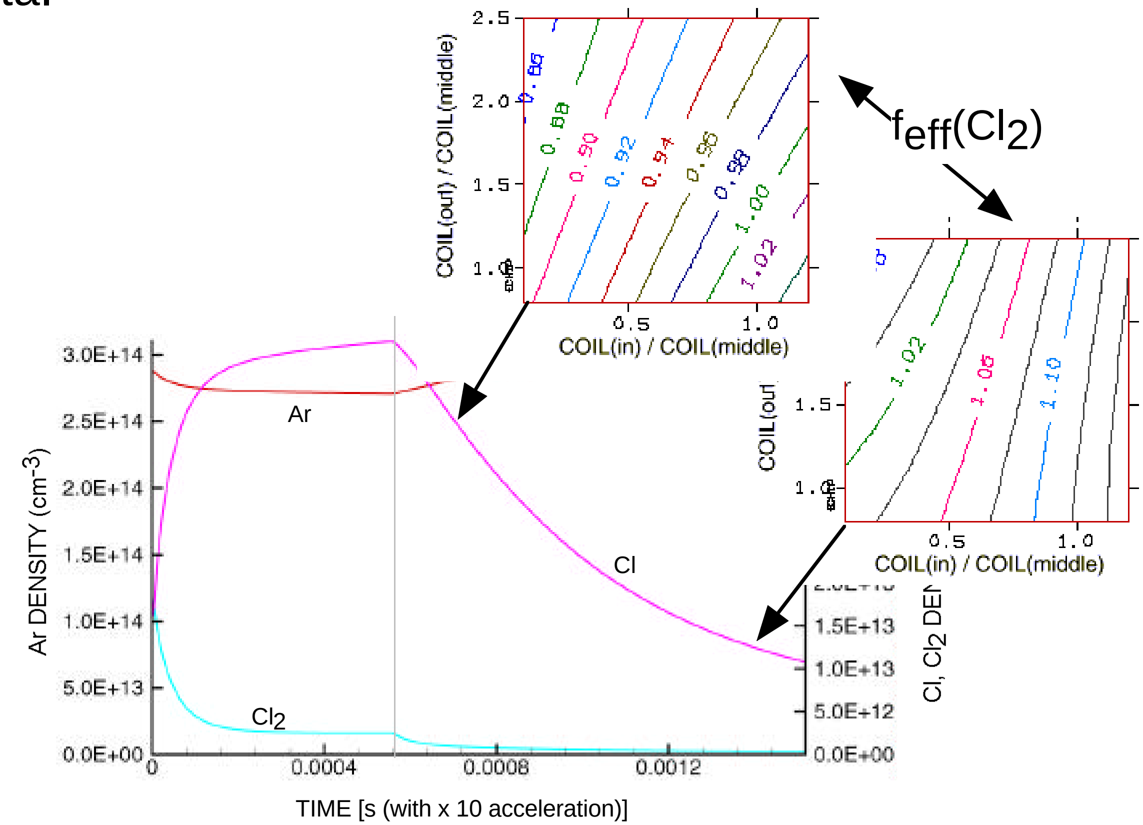
MULTI-PLANE RESPONSE SURFACES

- Although the additional sensor data from the mass spec cannot be used directly by the (2 x 2) controller, it can be used to select *coefficients* for the controller which better represent the current conditions.
- So interpolate *between* response surfaces developed for different Cl_2 flow rates based on mass spectrometer data.

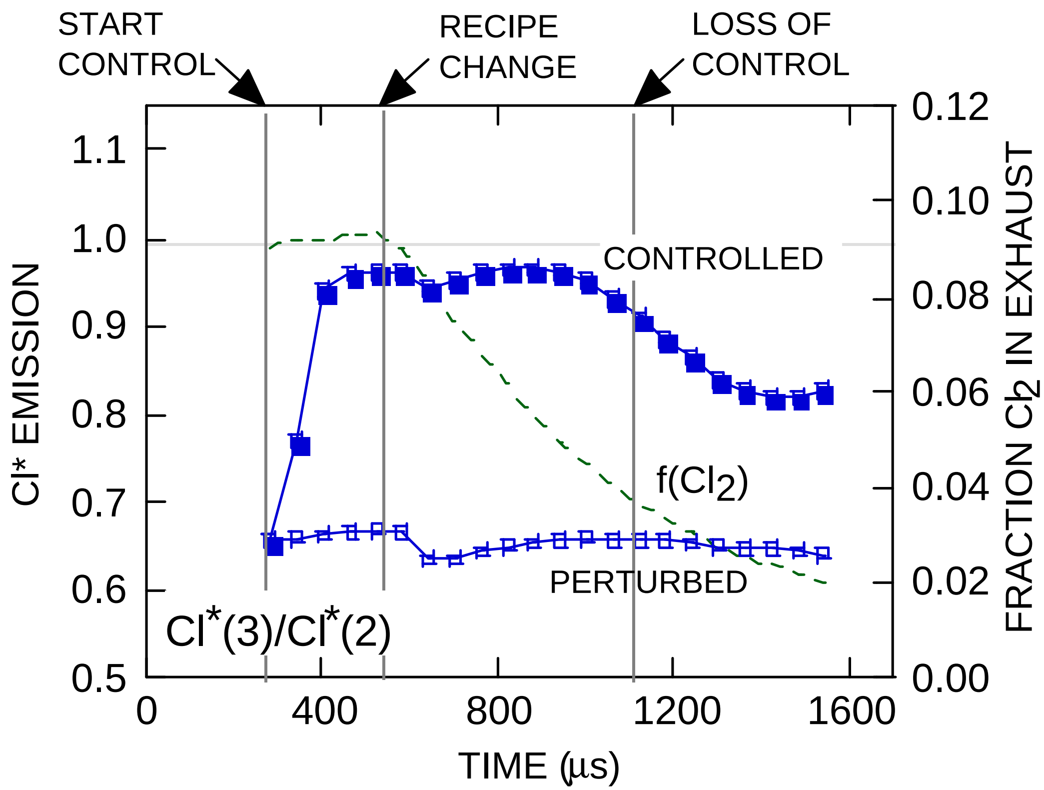




$$f_{eff}(Cl_2) = 0.5\, f(Cl) + f(Cl_2)$$

Ar/Cl_2 RECIPE CHANGE: SENSORS WITH 2 PLANE CONTROL

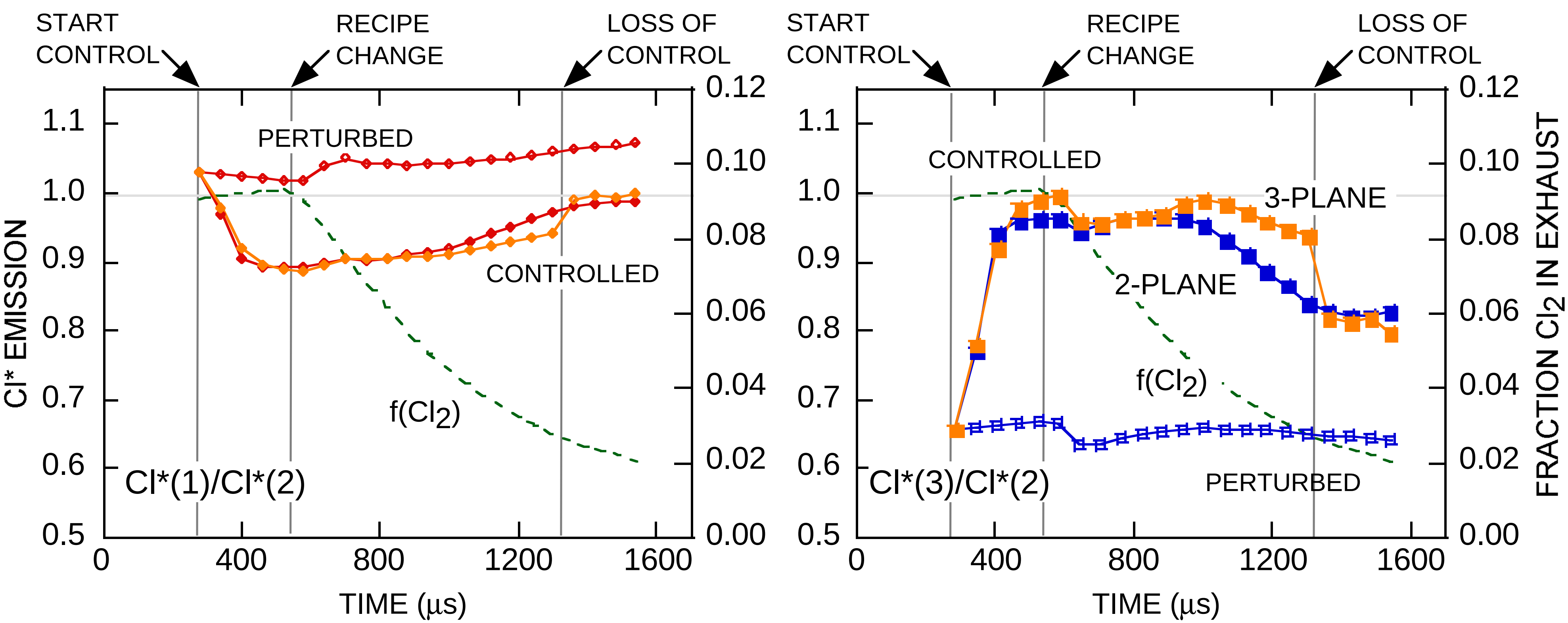
- In the absence of control, Cl* emission is peaked towards the center.
- With 2-plane control (Ar/Cl_2 = 90/10, 99/1), uniformity at large radii is significantly improved, leading to an overall improvement in uniformity.
- Control is lost half way through the transient when the control surfaces do not represent instantaneous reactor conditions well.



- Ar/Cl_2, 10 mTorr, 250 sccm, 200 W

Ar/Cl_2 RECIPE CHANGE: SENSORS WITH 3 PLANE CONTROL

- By adding an additional plane of response surfaces (Ar/Cl_2 = 90/10, 95/5, 99/1), the time of control is extended.
- Control is most difficult to maintain at low mole fractions of Cl_2 where the spatial distribution of the plasma is changing most rapidly.



- Ar/Cl_2, 10 mTorr, 250 sccm, 200 W

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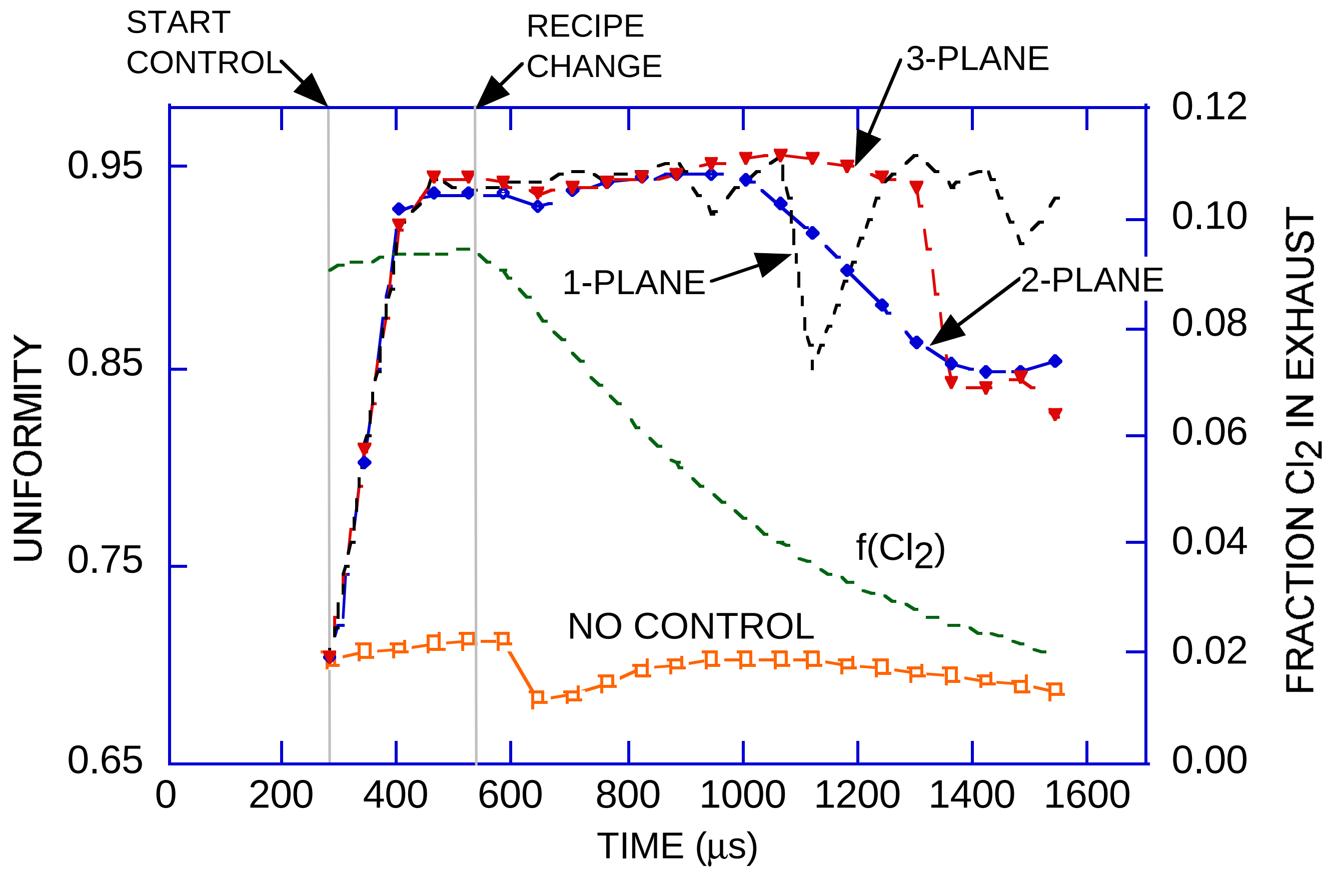
Ar/Cl_2 RECIPE CHANGE: UNIFORMITY vs PLANES

- The sensor readings can be quantified by weighting the local sensor signals by the relative underlying area of the wafer

$$\text{Uniformity} = ((S(in)/S(mid)-1)^2 A_{in}/A+(S(out)/S(mid)-1)^2 A_{out}/A))^{1/2}$$

- Increasing the number of “planes” of response surfaces enables the controller to maintain high uniformity for a longer period.



- Ar/Cl_2, 10 mTorr, 250 sccm, 200 W

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CONCLUDING REMARKS

- A modeling hierarchy has been developed to evaluate control strategies in plasma tools.
- The applicability of actinometry and PID control have been discussed in the context of transients.
- Under conditions where mole fractions are changing, as during recipe changes or changes in wall conditions, the use of actinometry should evaluated carefully.
- Examples of control strategies through transients were discussed.
- During "known" transients, such as recipe changes, gain scheduling is a viable control strategy.

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