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FEEDBACK CONTROL OF POLYSILICON ETCHING: CONTROLLER DESIGN ISSUES*

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AGENDA

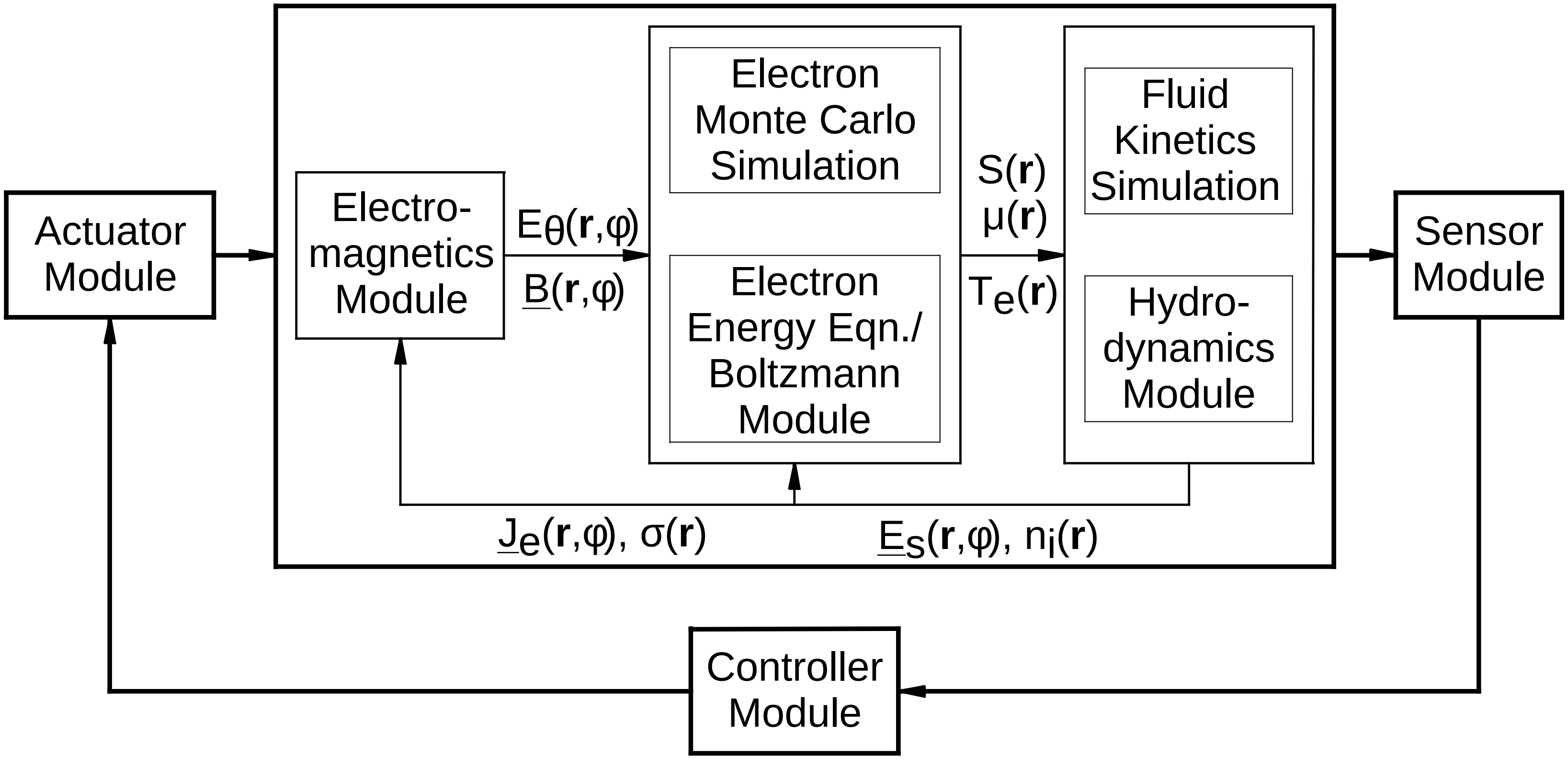
- Introduction
- Computational model
- Experimental validation
- Control of polysilicon etching in a Cl_2 plasma
- Conclusions

INTRODUCTION

- The reliability of plasma processing equipment can be considerably improved using feedback control.
- To aid in control strategy refinement and controller design, we have recently developed a computational tool called the Virtual Plasma Equipment Model (VPEM).
- It was demonstrated that controllers designed using response surface (RS) based techniques can stably control actuator drifts and external perturbations.
- The issues that are addressed in this talk are:
    - Validation of the VPEM results against experiments,
    - Use of the VPEM to investigate feedback control problems of practical interest,
    - Improvement of controller design.

THE VIRTUAL PLASMA EQUIPMENT MODEL

- An actuator model, the HPEM, a sensor module and a programmable controller are connected to form a feedback control loop.



The Hybrid Plasma Equipment Model (HPEM)

Actuator Module

Electro-magnetics Module

$E_\theta(\mathbf{r},\varphi)$

$\underline{B}(\mathbf{r},\varphi)$

Electron Monte Carlo Simulation

Electron Energy Eqn./ Boltzmann Module

$S(\mathbf{r})$

$\mu(\mathbf{r})$

$T_e(\mathbf{r})$

Fluid Kinetics Simulation

Hydro-dynamics Module

Sensor Module

$\underline{J}_e(\mathbf{r},\varphi)$, $\sigma(\mathbf{r})$

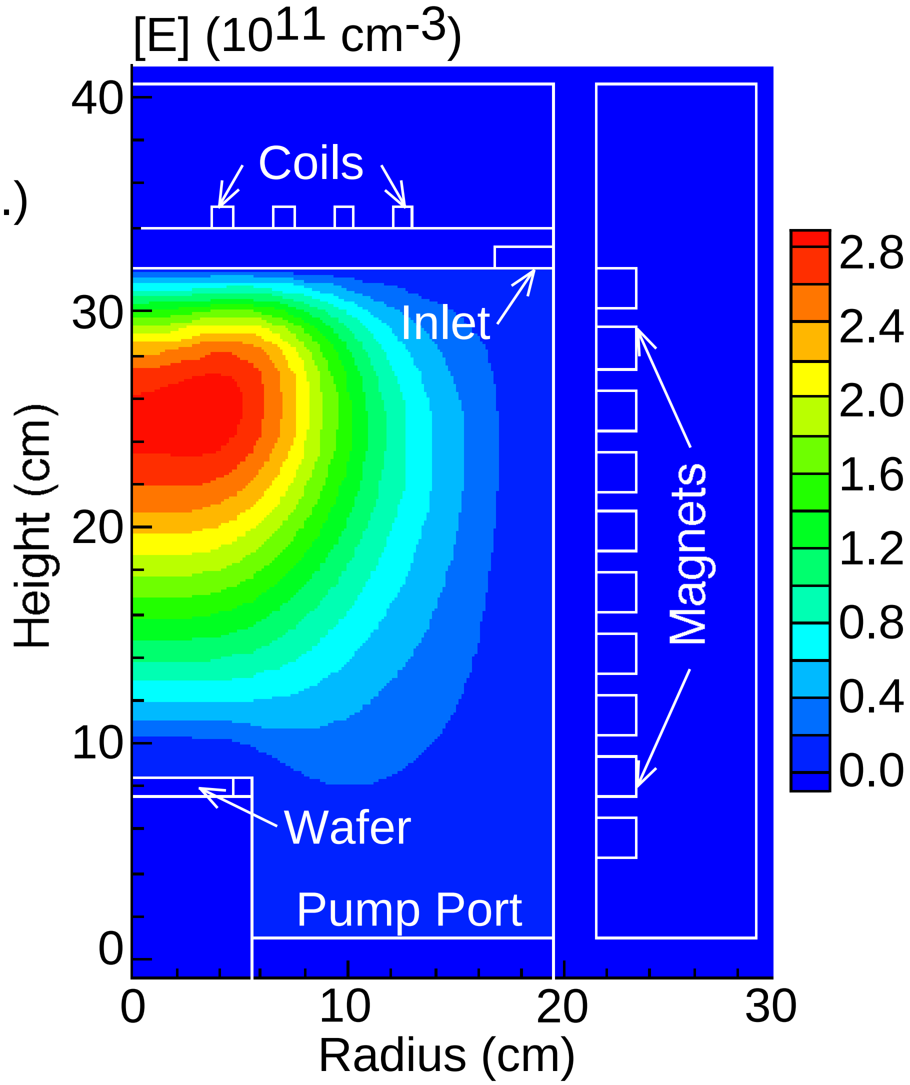
$\underline{E}_s(\mathbf{r},\varphi)$, $n_i(\mathbf{r})$

Controller Module

VPEM VALIDATION

- To validate the VPEM, we simulated the control experiments conducted at the Univ. of Wisconsin (M. Sarfaty *et al.*, ECS Proceedings, pg. 94, 1997.)
- These experiments have been done in the magnetized ICP reactor shown here.
- Etch rate was controller in the experiment using chuck power.
- The operating conditions are:

Gas Mixture:	$Cl_2/Ar = 96/4$
Pressure:	4 mTorr
Gas flow rate:	30 sccm
ICP power:	1000 W
Applied voltage:	50-180 V

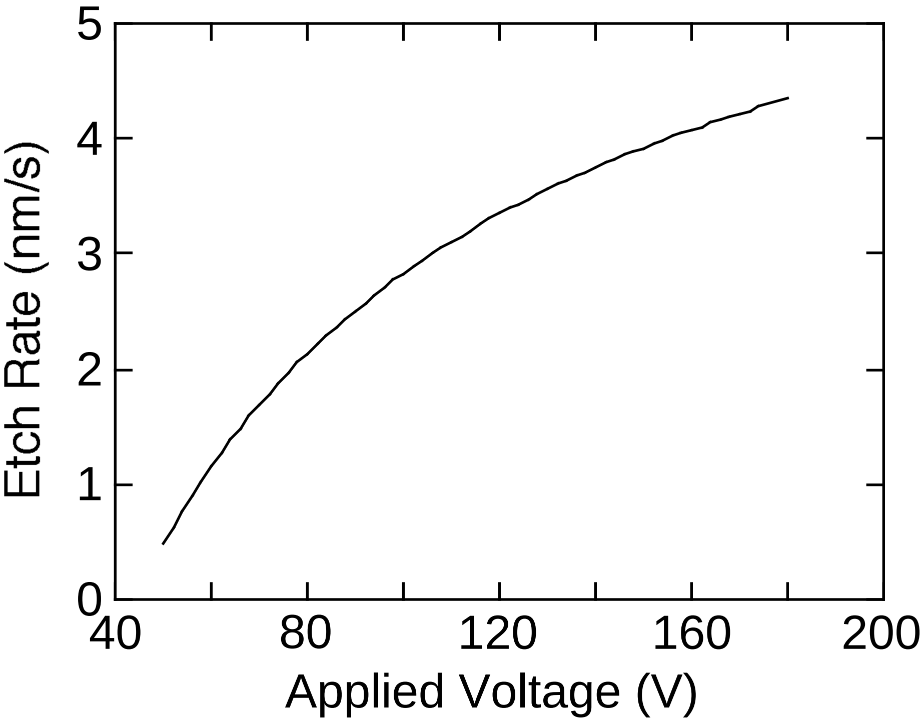


THE RESPONSE SURFACE

- As in the experiment, we designed a 1-input 1-output controller with etch rate (*ER*) as the sensor.

- The *ER* has been computed using Dane & Mantie's expression:

$$ER = \left(\frac{1}{2300\, P_{mTorr}^{0.5}} + \frac{1}{23(V.I_i - 85)} \right)^{-1}$$

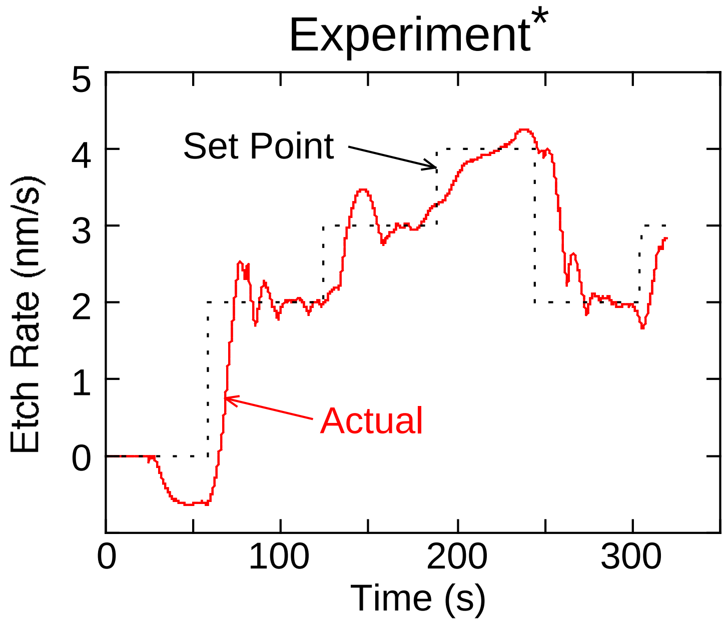


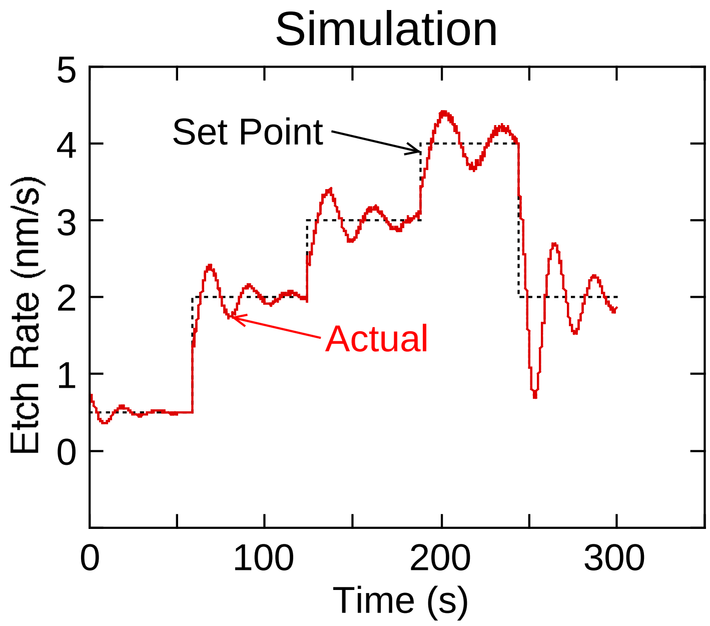
- Instead of chuck power, we have used applied voltage (which is proportional to chuck power) as the actuator.

- Cl_2/Ar=96/4, 4 mTorr, 1000 W.

CONTROL USING PID CONTROLLER

- With a Proportional Integro-Differential (PID) controller, the *ER* oscillates many times before settling down to the specified value.
- There is also a delay in response after the step change in input signal.





- Cl_2/Ar=96/4, 4 mTorr, 1000 W.

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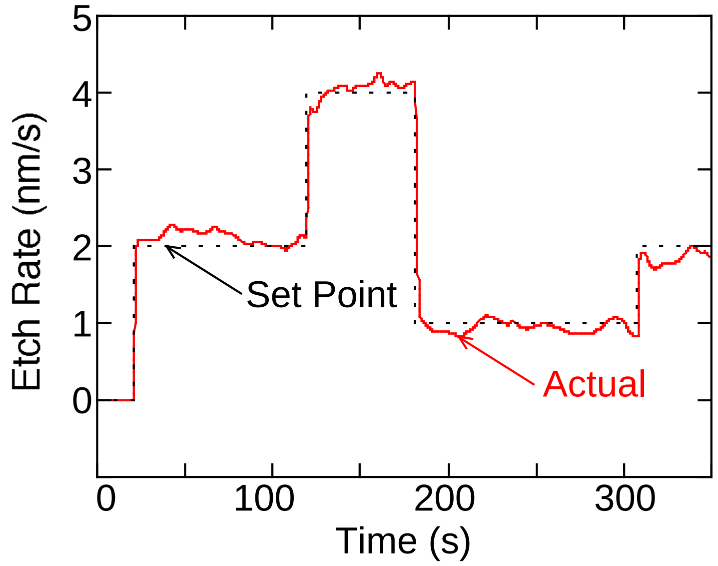
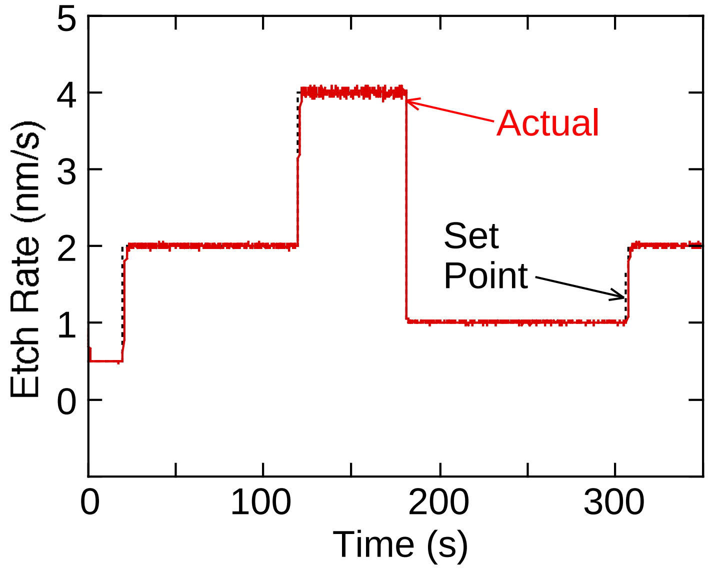
CONTROL USING PID-FF CONTROLLER

- When a feed forward contribution (computed using the response surface shown earlier) is added, the oscillations reduce considerably in the sensor signal.
- The response is also much faster.

Experiment*



Simulation



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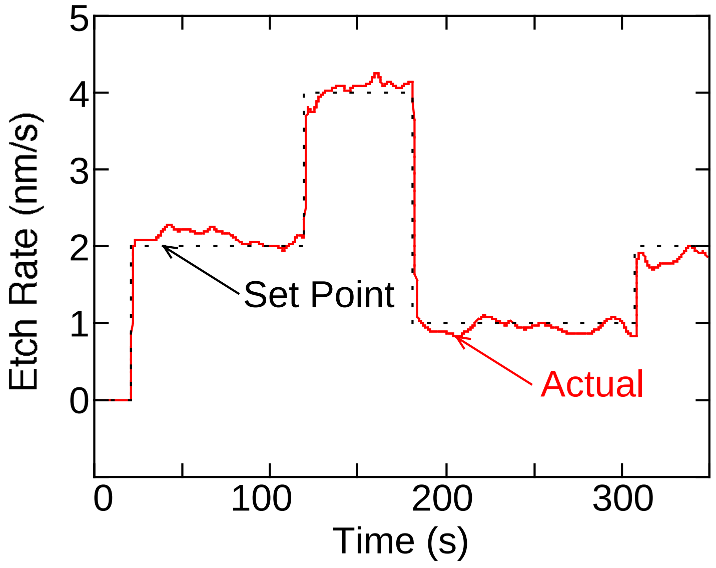
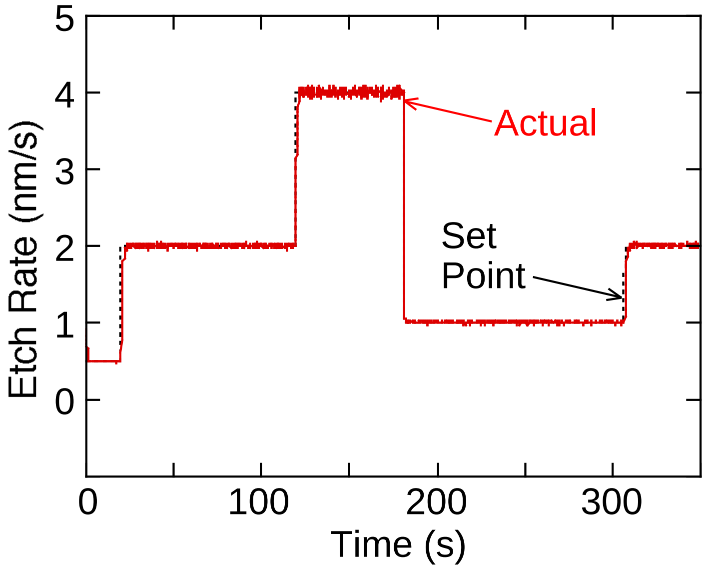


Experiment*



Simulation

- $Cl_2/Ar=96/4$, 4 mTorr, 1000 W.

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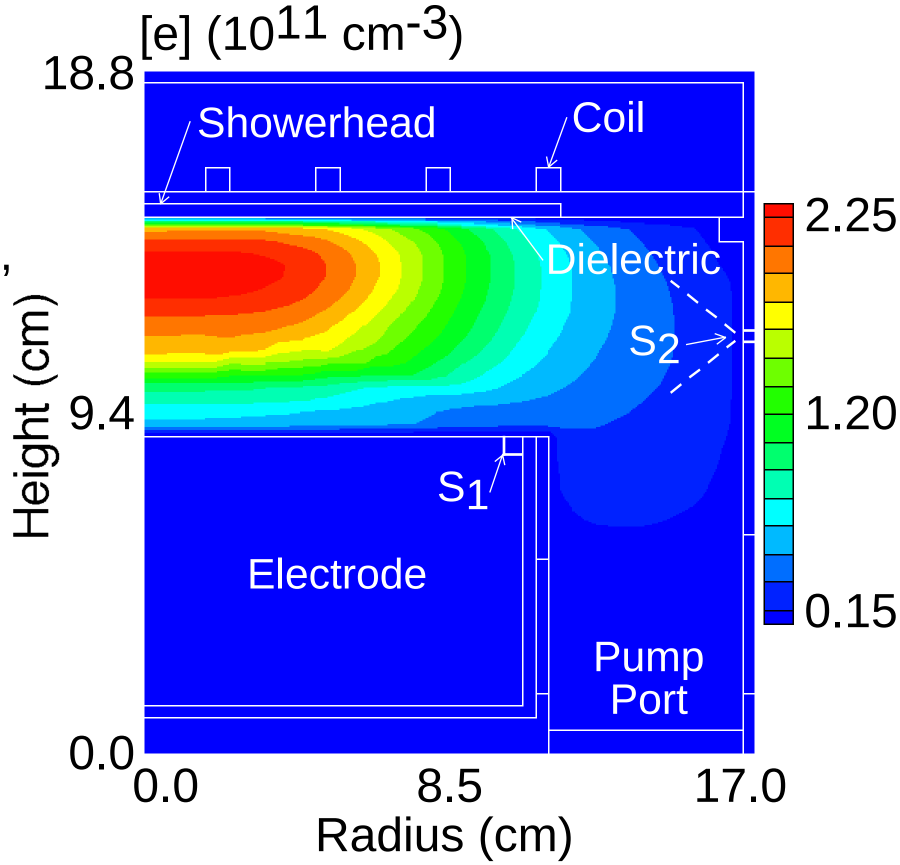
CONTROL OF FACTORS THAT EFFECT ETCH RATE

- 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.

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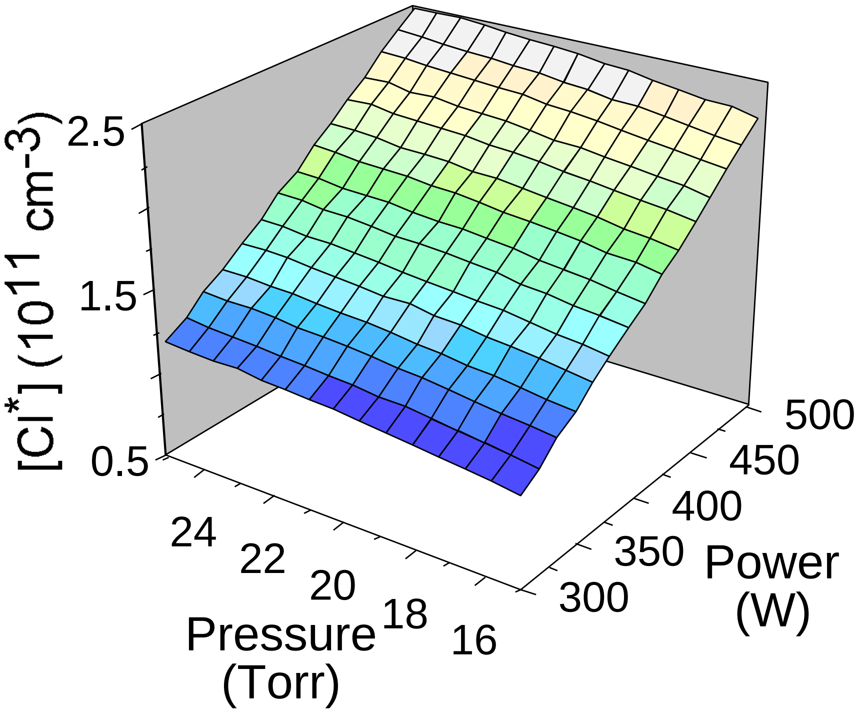
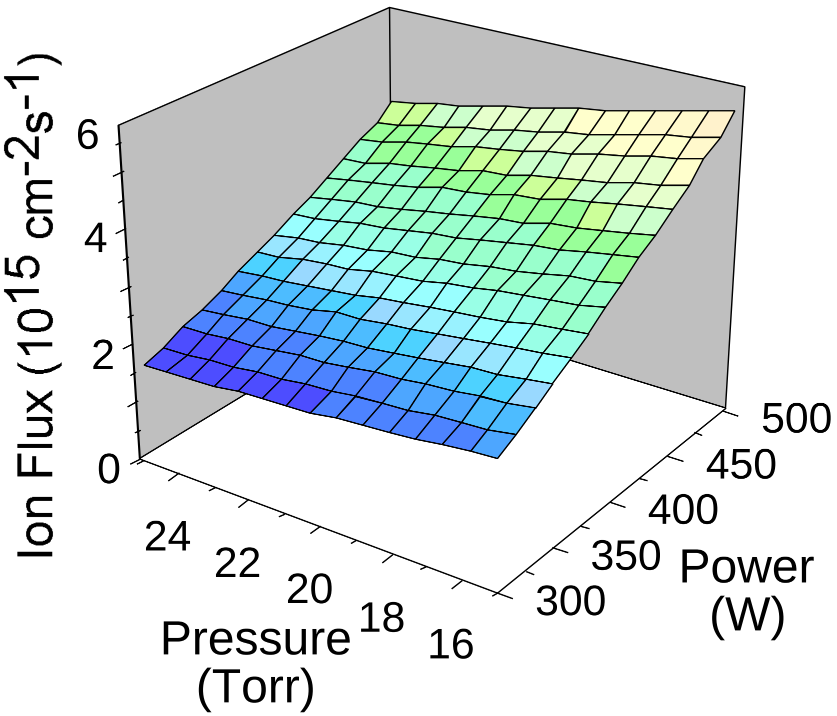
RESPONSE SURFACES

- 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.

DESIGN OF CONTROLLERS

- We assume that we have a 2-input 2-output system.
- The quadratic fit to the response surface is

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

where (x_1,x_2) are the inputs (actuators) and (y_1,y_2) are the outputs (sensors).

- To design the controller, we consider a small change (dx_1,dx_2) in the actuators.
- The effect on the sensors is

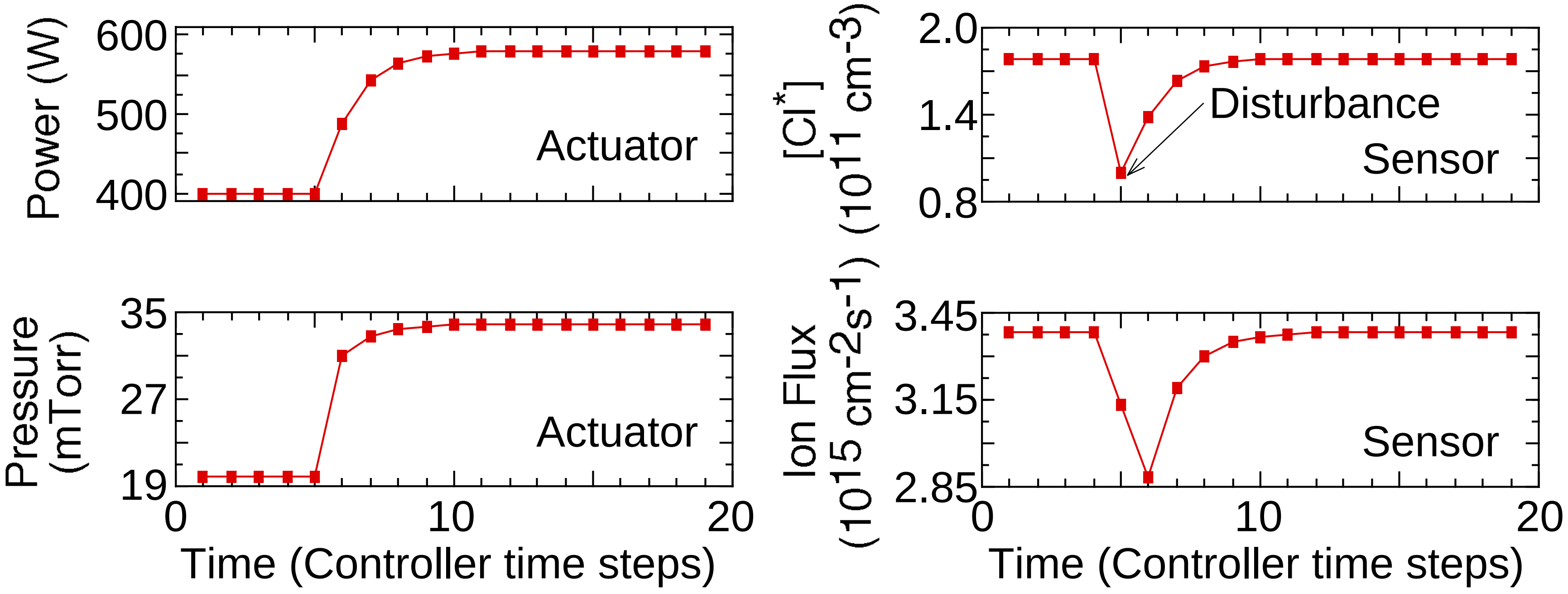
$$\begin{bmatrix} dy_1 \\ dy_2 \end{bmatrix} = \begin{bmatrix} b_{11} + 2c_{11}x_1 + d_1 x_2 & b_{12} + 2c_{12}x_2 + d_1 x_1 \\ b_{21} + 2c_{21}x_1 + d_2 x_2 & b_{22} + 2c_{22}x_2 + d_2 x_1 \end{bmatrix} \begin{bmatrix} dx_1 \\ dx_2 \end{bmatrix} = \underline{\underline{A}} \begin{bmatrix} dx_1 \\ dx_2 \end{bmatrix}. \qquad (2)$$

- Taking inverse of Eq. (2),

$$\begin{bmatrix} x_{1(new)} - x_{1(old)} \\ x_{2(new)} - x_{2(old)} \end{bmatrix} = \begin{bmatrix} dx_1 \\ dx_2 \end{bmatrix} = \underline{\underline{A}}^{-1} \begin{bmatrix} dy_1 \\ dy_2 \end{bmatrix} = \underline{\underline{A}}^{-1} \begin{bmatrix} T_1 - y_{1(old)} \\ T_2 - y_{2(old)} \end{bmatrix}. \qquad (3)$$

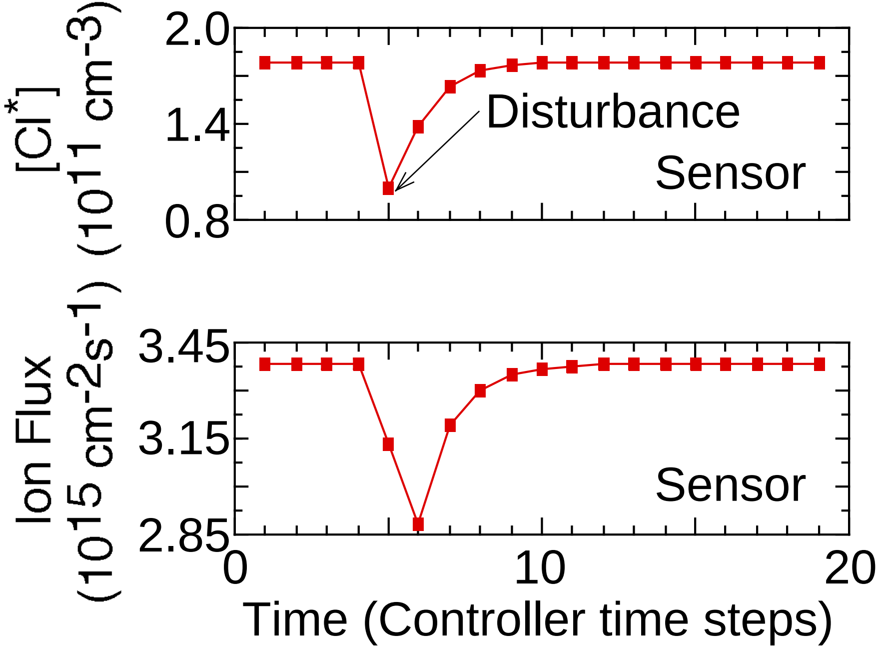
CONTROL OF CHANGE IN WALL CONDITIONS

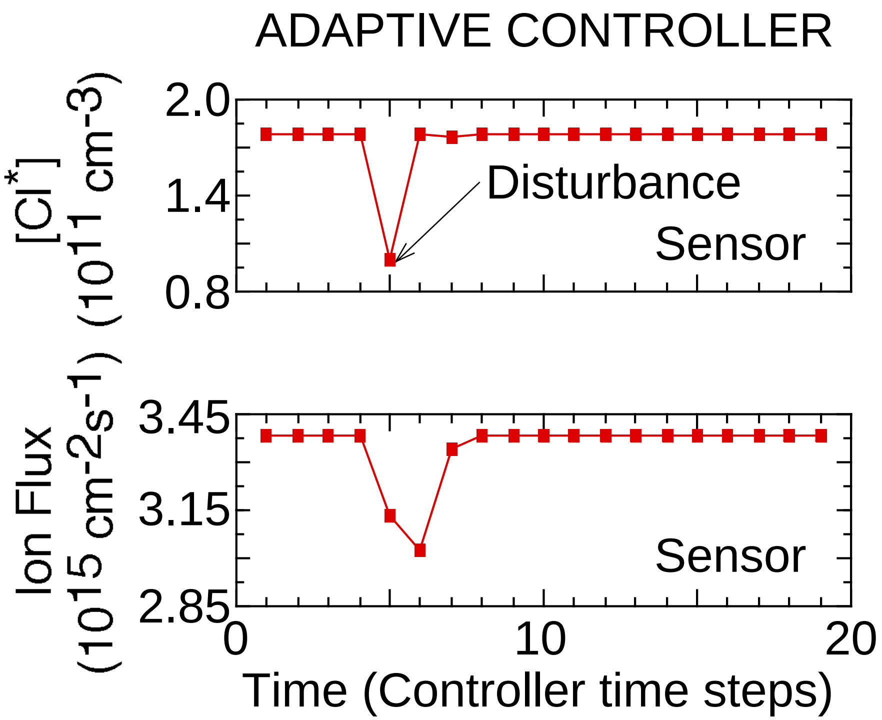
- At T=5, we artificially increase the Cl→Cl_2 sticking coefficient at the wall to simulate a change in wall conditions.
- This decreases the Cl^* density because of enhanced loss of Cl at the walls and decreases ion flux to substrate because the gas becomes more electro-negative.
- The RS based controller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



ADVANTAGE OF AN ADAPTIVE CONTROLLER

- To control change in wall conditions, we also used an adaptive controller.
- Using random measurements near the operating point, the adaptive algorithm adjusted the coefficients of the RS-based model to better represent the actual situation.
- As shown below, the adaptive controller is able to bring the sensors back to their original values much more quickly.


CONTROLLER WITH FIXED COEFFICIENTS


ADAPTIVE CONTROLLER

CONCLUSIONS

- A computational plasma equipment model (VPEM) has been used to evaluate feedback control strategies and controller designs.
- In agreement with experiments, it was found that a feed-forward contribution to a PID controller can reduce controller response time and eliminate unnecessary oscillations.
- The VPEM was also used to investigate the control of Cl^* density and total ion flux to the substrate in an ICP reactor using inductive power and gas pressure as actuators.
- It was demonstrated that controllers based on response surfaces (RS) can stably control external perturbations and long term changes in reactor conditions.
- The functionality of the RS-based controllers can be considerably improved by including an adaptive component that tunes the controller coefficients to better represent the operating conditions.