Optimization of Heater Zone Layout for a Rotating Susceptor in a Cold-wall MOCVD Reactor

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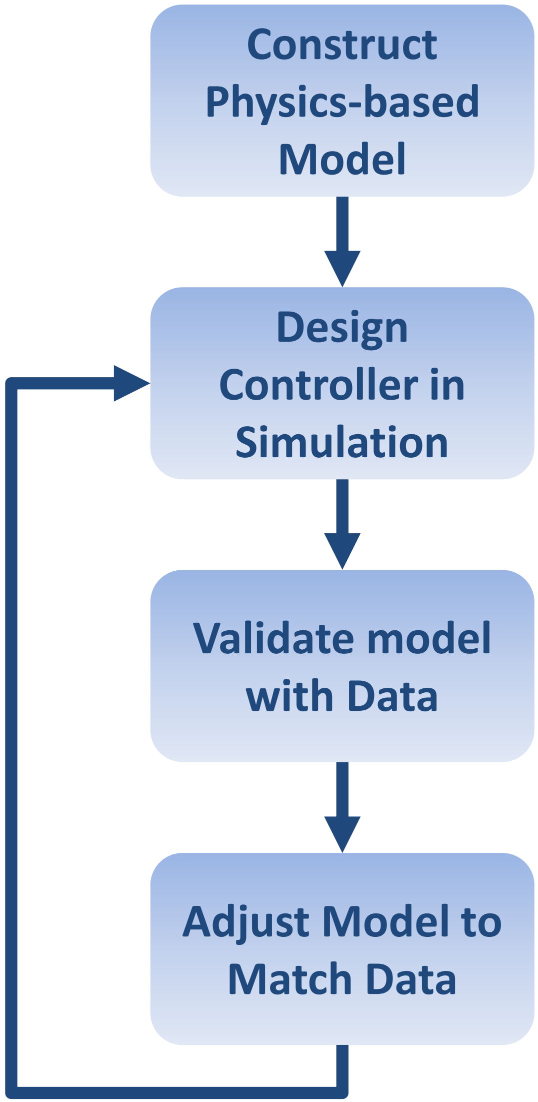
Overview

- **Metal-organic Chemical Vapor Deposition (MOCVD)**
  - CVD with metal-organic precursors (e.g., tri-methyl gallium)
  - Used to manufacture Light Emitting Diodes (LEDs)
- **A Case Study of Temperature Control of a Rotating Susceptor CVD Reactor**
  - Describes our Model-Based Control (MBC) approach using modeling, optimization and, control tools.
  - Evaluate design limits for a range of operating conditions.
- **Summary**

Physical Model-Based Control

Design Process



Advantages

Modeling for Control Design

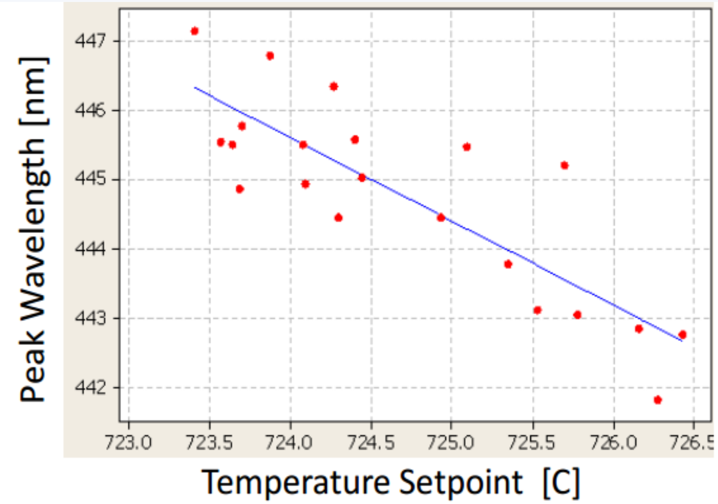
- **Controller is tested in simulation for wide range of conditions.**
- **Much of the control design can be done without access to equipment.**
- **Ability to do controller development in parallel with chamber development.**

Modeling for Equipment Design

- **A model of the system that can be modified for "what-if" studies.**
- **Provides a tool for troubleshooting.**
- **Path for continued improvement.**

MOCVD for LEDs

- **MOCVD is used to produce Light Emitting Diodes (LEDs) by reacting metal-organic precursors (e.g.,tri-methyl gallium, tri-methyl indium, etc.).**
- **Increasingly important for many applications (LED TV's, Lighting, etc.) due to potential for high efficiency.**
- **InGaN/GaN multiple quantum well (MQW) structures are grown on sapphire substrates for green, blue, and white LEDs.**



W. E. Quinn, *Driving Down HB-LED Costs: Implementation of Process Simulation Tools and Temperature Control Methods for High Yield MOCVD Growth*, Final Technical Report DoE Grant DE-EE0003252, p. 2012

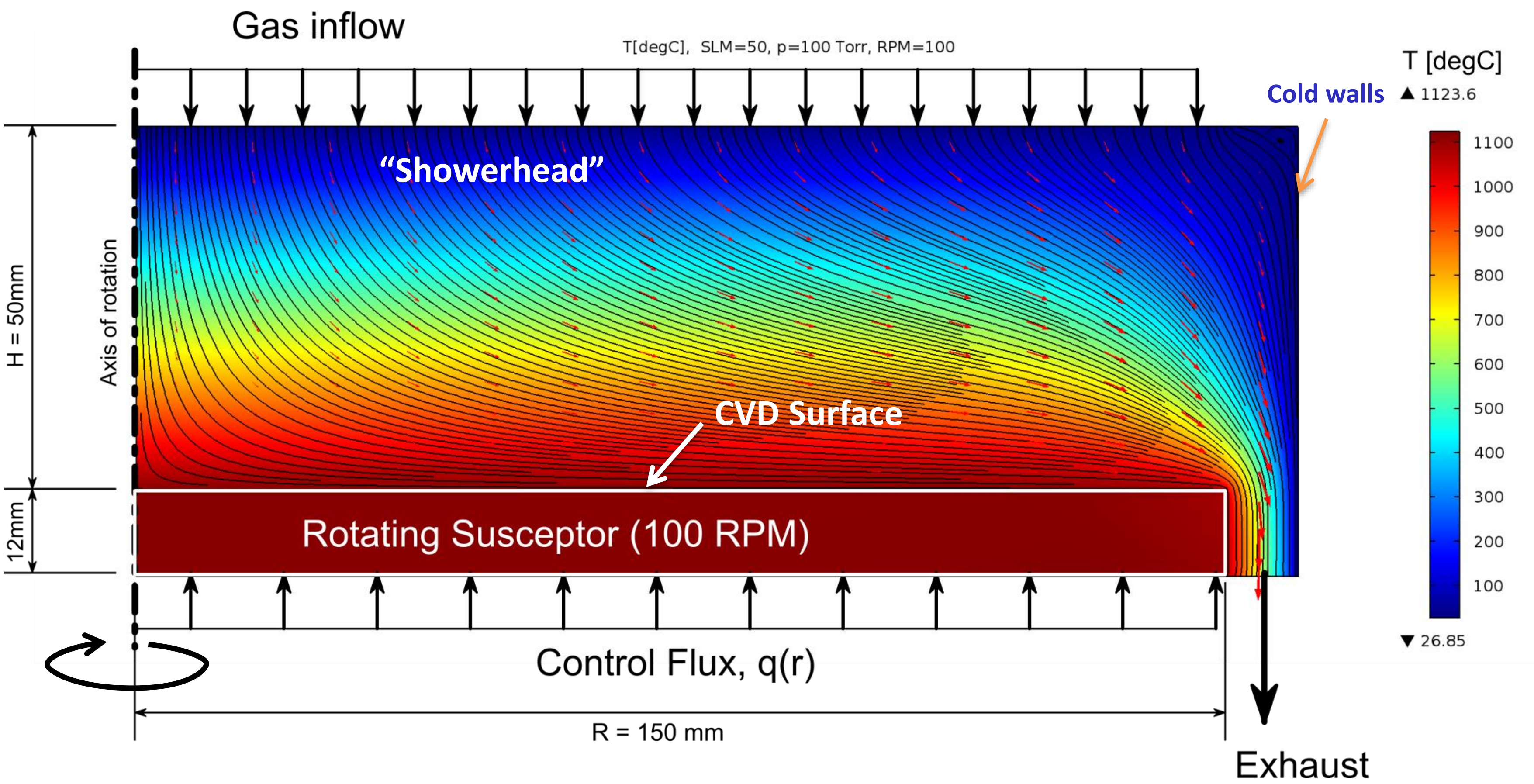
- **Studies* have shown that LED properties such as photoluminescence and electroluminescence can vary by a *factor of two* if the substrate temperature is changed from 1000°C to 1030°C.**
- **Involves many process steps over a wide temperature range (500-1100°C).**
- **As a result, *real-time control* of substrate temperature to within 1°C or less is essential for repeatable manufacturing of LEDs with *desired color*.**

* For example, see J. W. Ju, *et al.,* "Effects of p-GaN Growth Temperature on a Green InGaN/GaN Multiple Quantum Well," Journal of the Korean Physical Society, Vol. 50, No. 3, March 2007, pp. 810-813.

Finite Element (FEM) Model

A vertical reactor with top-side showerhead and rotating susceptor.

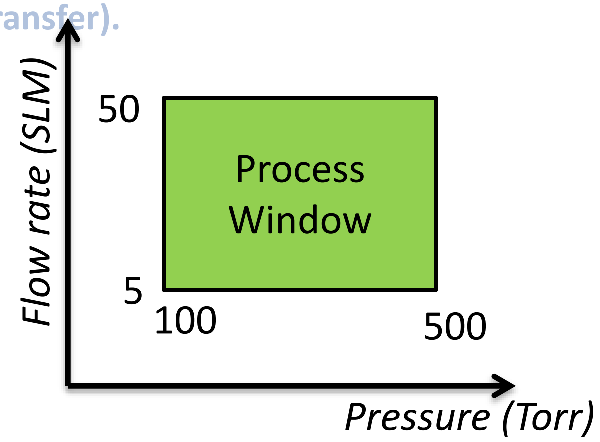
2D Axisymmetric FEM model – Non-isothermal flow, with swirl and buoyancy.



The temperature on the CVD Surface is critically important

Example Operating Conditions

- Hydrogen is the main carrier gas (no reactions, only heat transfer).



- Nominal operating temperature is 1100°C.
- Susceptor rotation rate = 100 RPM
- Operating pressure range is 100 Torr ≤ p ≤ 500 Torr (1 Atm = 760 Torr)
- Operating flow rate range is 5 slm ≤ Q ≤ 50 slm (slm = standard liters per minute)
- Required temperature uniformity of ± 0.5°C (over widest possible area of susceptor)

The goal is to adjust the control flux, q(r), to get good temperature uniformity on the CVD Surface.

❑ Gas Convection and Conduction

- The cold gas (27°C) is injected at the showerhead.
- Convective cooling flux of the susceptor is of order 10^4 W/m^2.
- $q_c = h(T_{sus}-T_{wall})$,   h is of order 10-100 W/m^2°C.

❑ Radiation

- $q_r = \varepsilon\sigma\,(T_{sus}^{\,4} - T_{wall}^{\,4})$, ε = effective emissivity, σ = Stefan-Boltzmann constant.
- Radiation losses are of order 10^5 W/m^2.
- Radiation does not vary with flow rate or pressure.

❑ Conduction

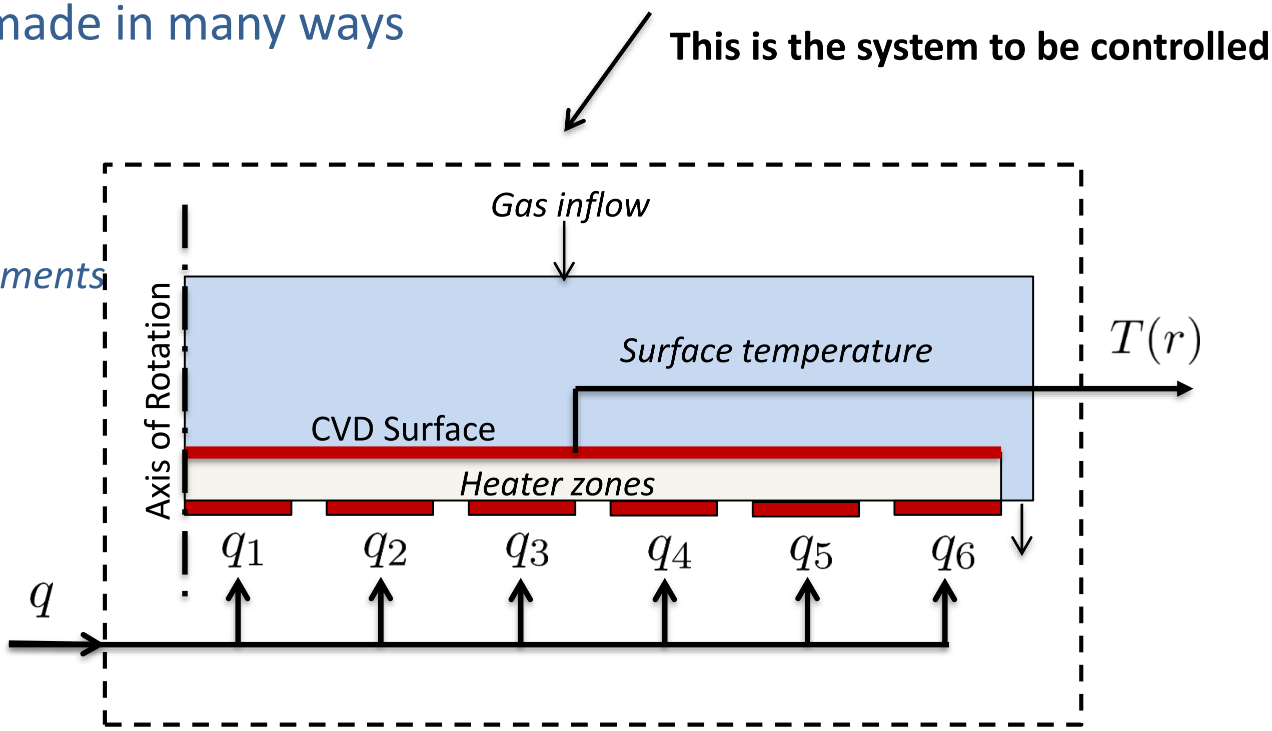
- Gas conduction is fairly high for Hydrogen (compared to other gases).
- Solid conduction in susceptor is important since we heat from backside.

❑ The distribution of heat transfer at the CVD surface varies with flow rate and pressure due to changes in convection heat transfer.

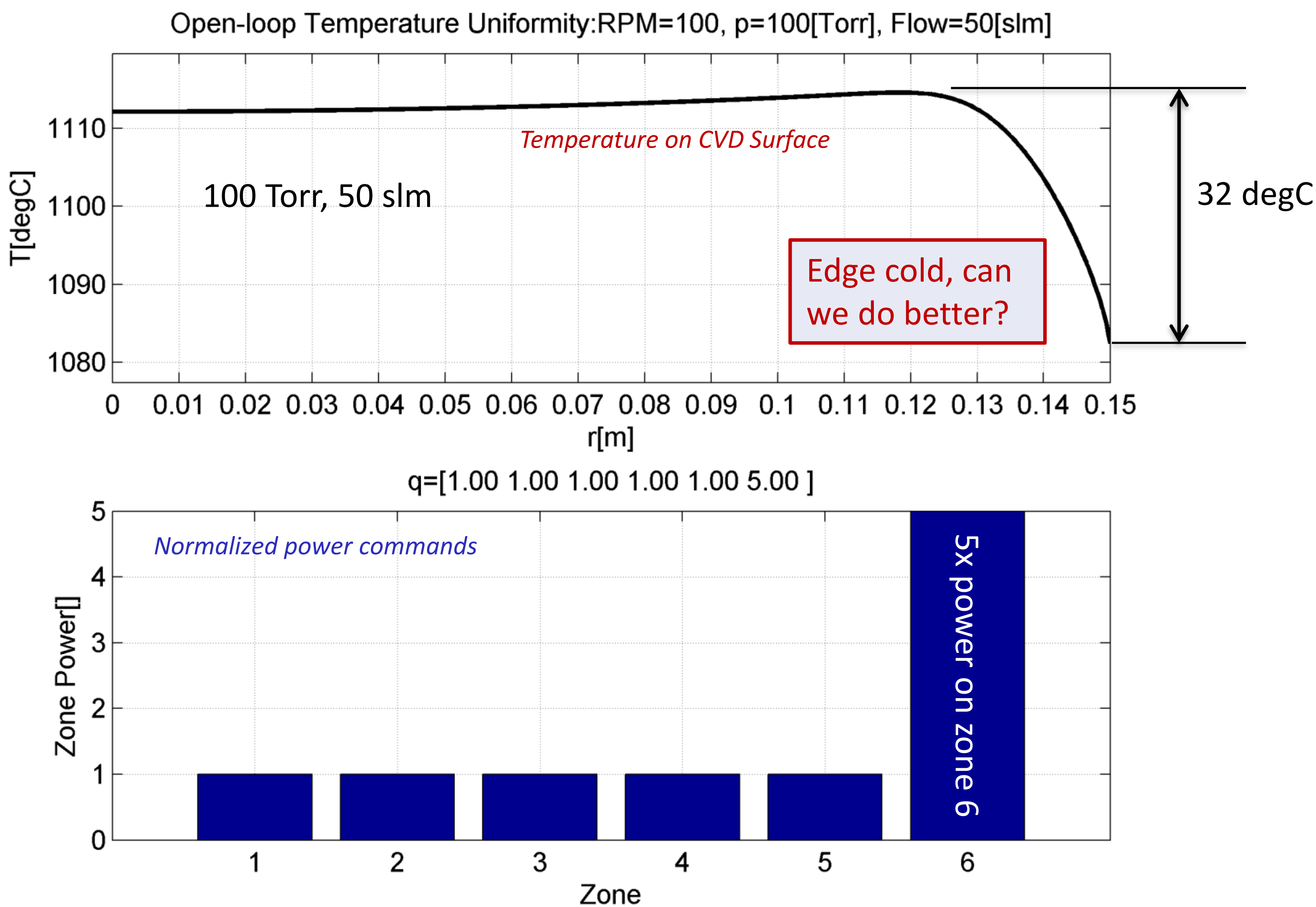
Heater Zone Definition

- It is common to divide the control flux into a number of independently controlled "zones".

- Here we divide the control flux into six independent zones.
  - Uniformly divided along the radius
  - Heaters can be made in many ways
    - *Resistive films*
    - *Lamp arrays*
    - *Hot filaments*
    - *RF Inductive elements*



Baseline System Performance



Optimal Control

In words:

- Find the input control flux, q, for each heater that produces the best temperature uniformity.
- subject to the constraint that q ≥ 0.
- the uniformity is optimized over limited radius (r < Rmax).

Mathematically:

$$q_{\text{opt}} = \arg\min_{q} ||T_{\text{ref}} - T(r,q)||$$

$$s.t. \quad q \geq 0$$

$$0 \leq r \leq R_{\text{max}}$$

How Many Independent Heaters do we Need?

- **In practice, for each independent heater we need additional power supply and additional temperature sensor which is expensive. We want as few as possible.**

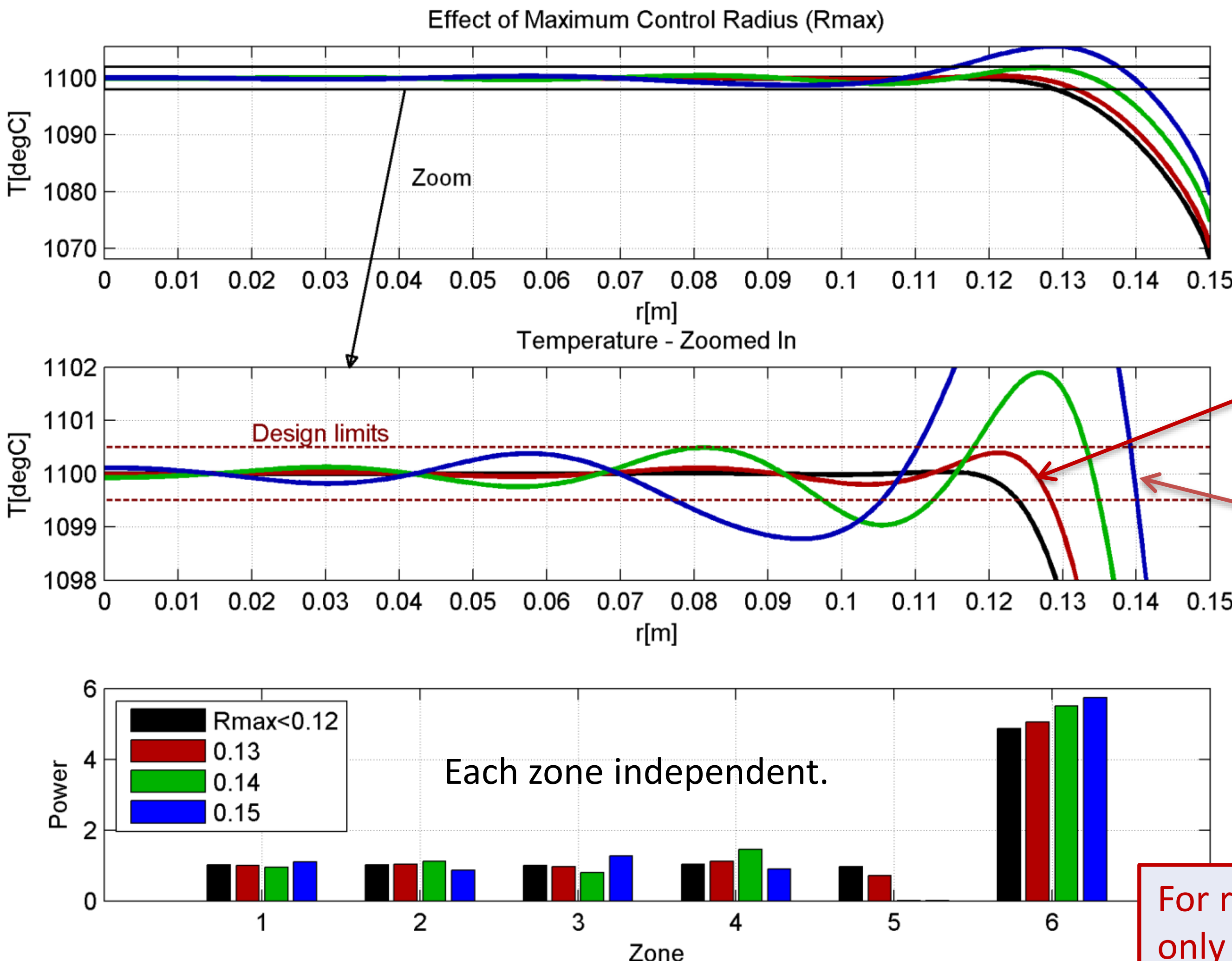
- **We also want uniformity over the largest possible radius (Rmax).**

- **Can we make ONE heater work for the entire operating range of pressure and flow rate?**

- **Strategy: *fix the ratio of each heater power* from baseline optimal result (100 Torr, 50 slm) and scale this power distribution up and down with one input scaling.**
  - This ratio can be done in hardware (e.g., filament density distribution, or resistance variation, etc.)
  - One zone control requires only one temperature sensor.

Optimizing Rmax (6-zone control)

100 Torr, 50 slm



It is only possible to get the inner 0.13 m radius within the design limits.

Rmax = 0.13 m

Rmax = 0.15 m

Optimizing T over the full radial span (0 < r < 0.15 m) results in a large region of the susceptor falling outside the design limits.

For remaining analysis we will only control the temperature for radius r < 0.13 m.

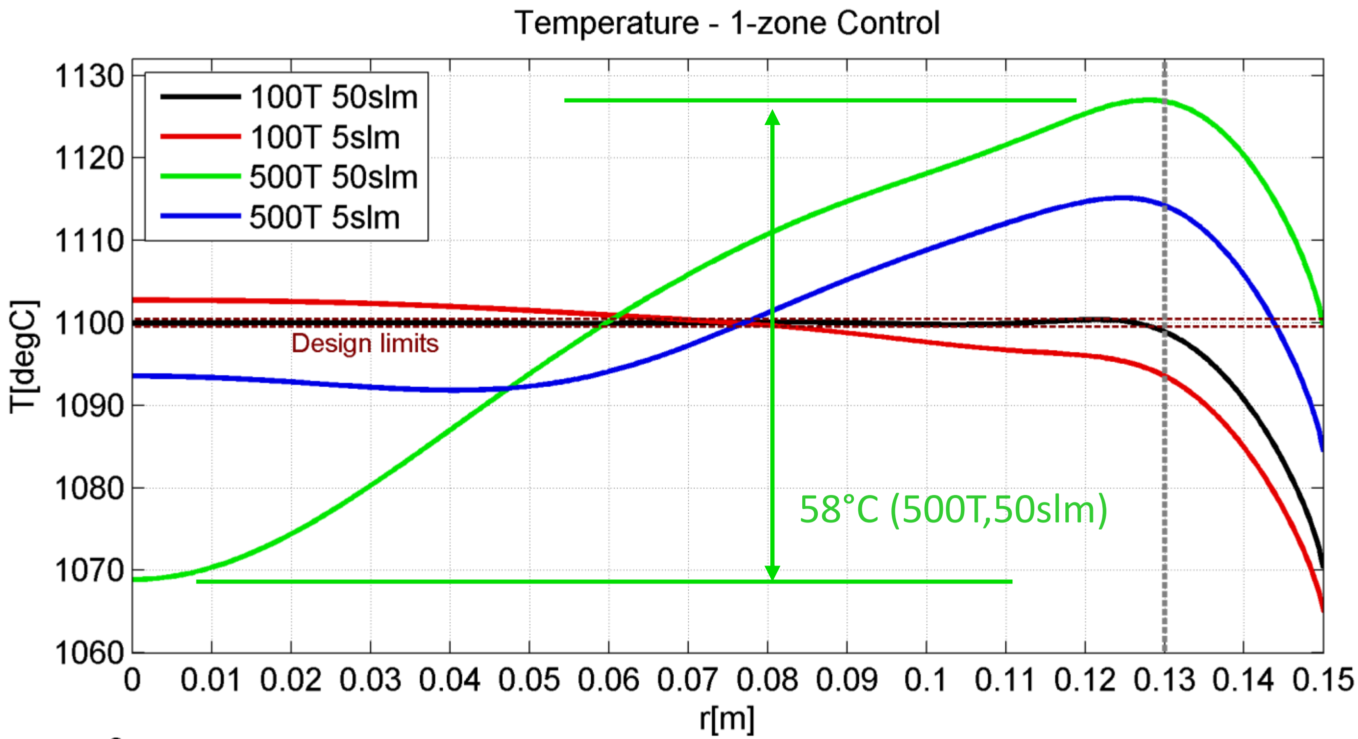
One-zone Control

- We found the "optimal" Rmax to produce the largest area of temperature within design limits.

- Next we want to optimize the input flux distribution for different operating conditions.

- First we look at 1-zone control, then look at the improvement of increasing the number of independent control zones.

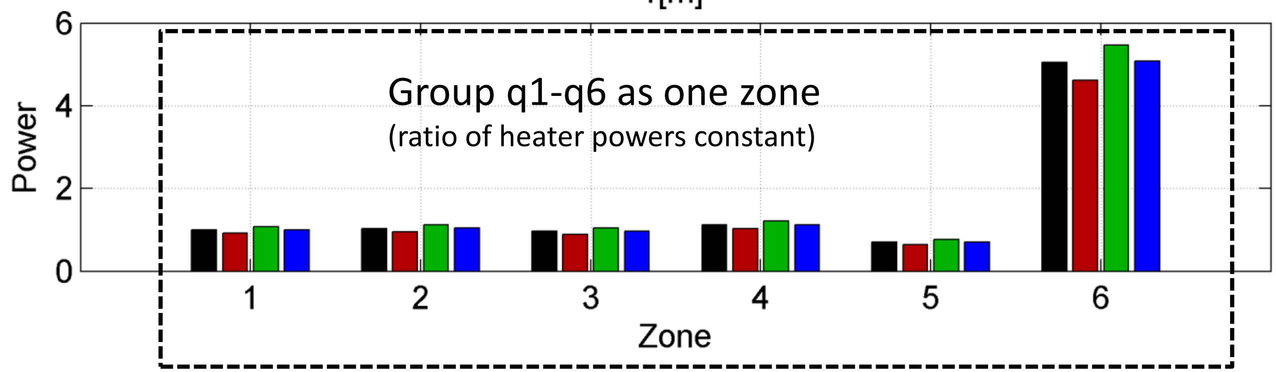
One Zone Control

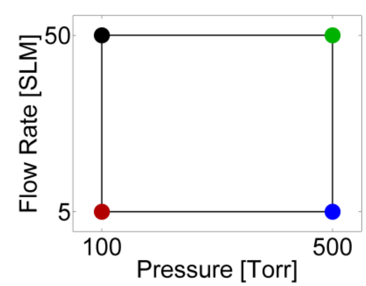


In all cases the mean temperature optimized for r<0.13m and Tref= 1100°C

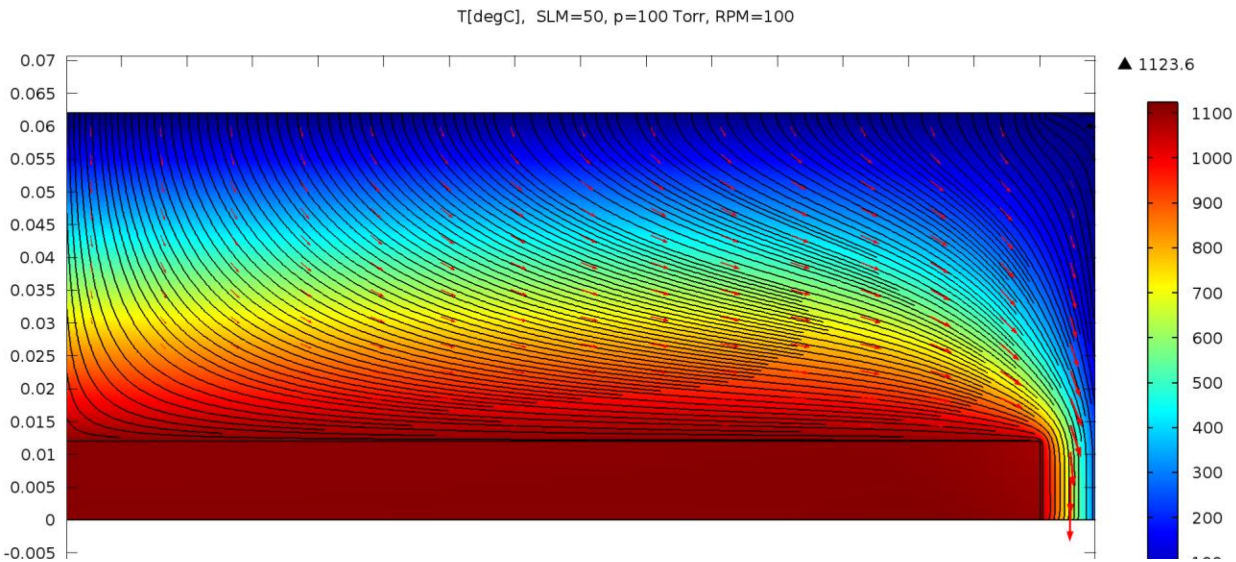
Except for the baseline case (100T, 50slm), the uniformity is poor.

High pressure is a problem. Look at the flows to see why.



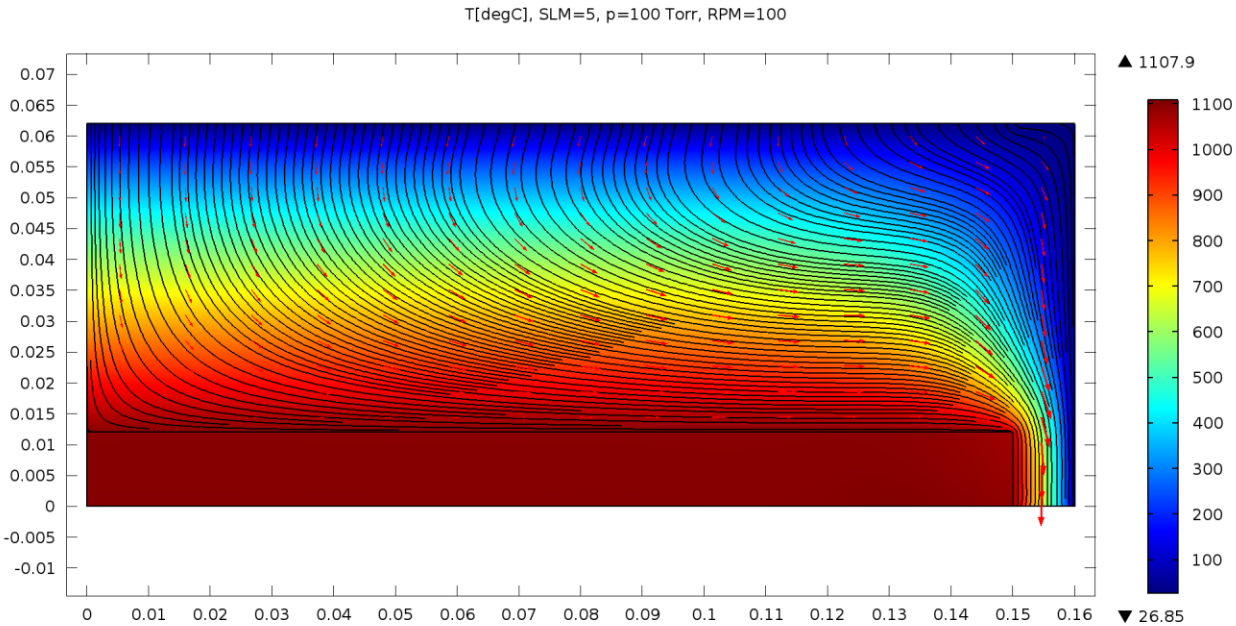


Lower Pressure Flow fields (100 Torr)



100 Torr, 50 slm

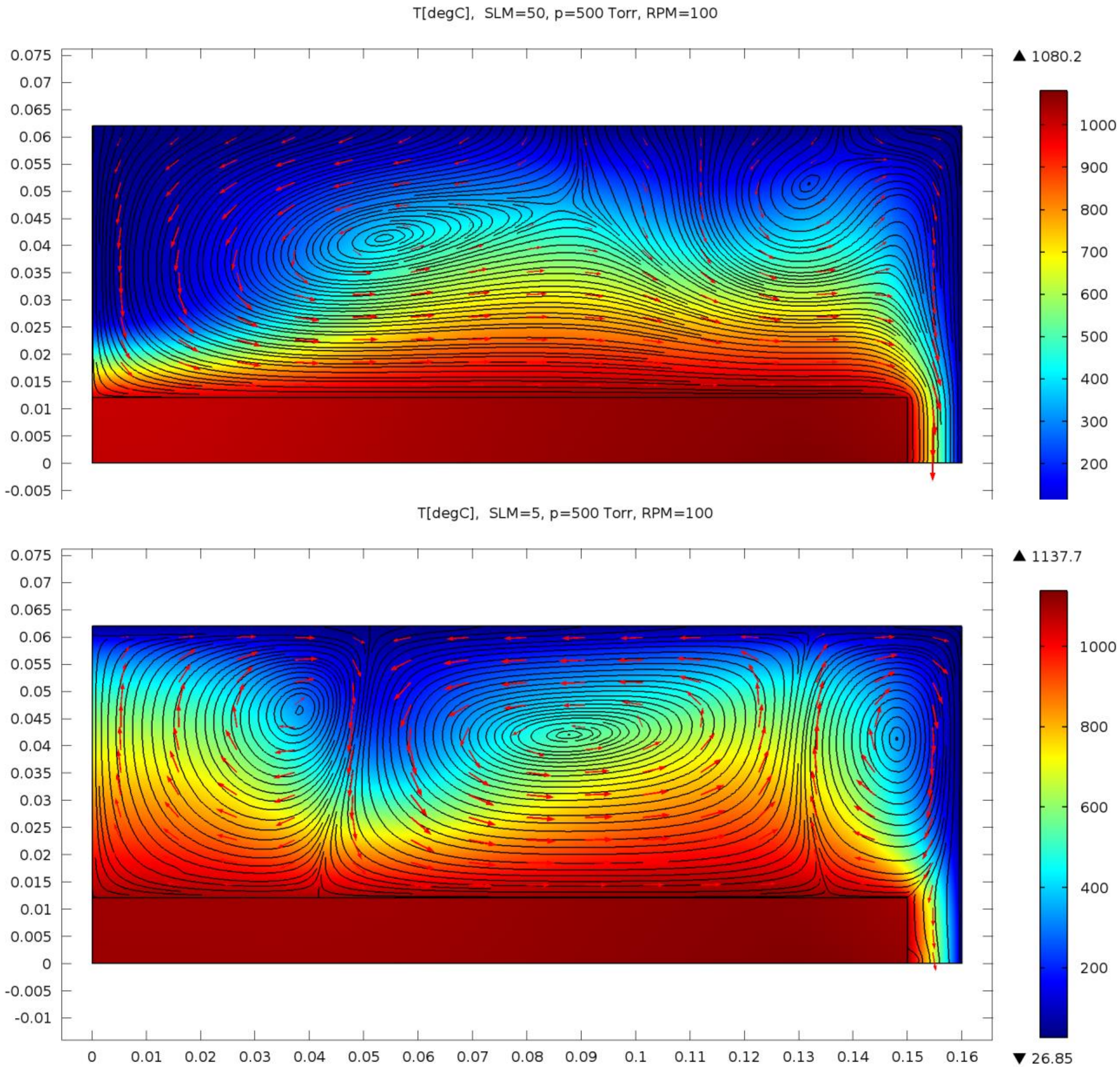
Baseline case.



100 Torr, 5 slm

For slower flow we start to see some “lift” of the streamlines at larger radius.

Higher Pressure Flow fields (500 Torr)



500 Torr, 50slm

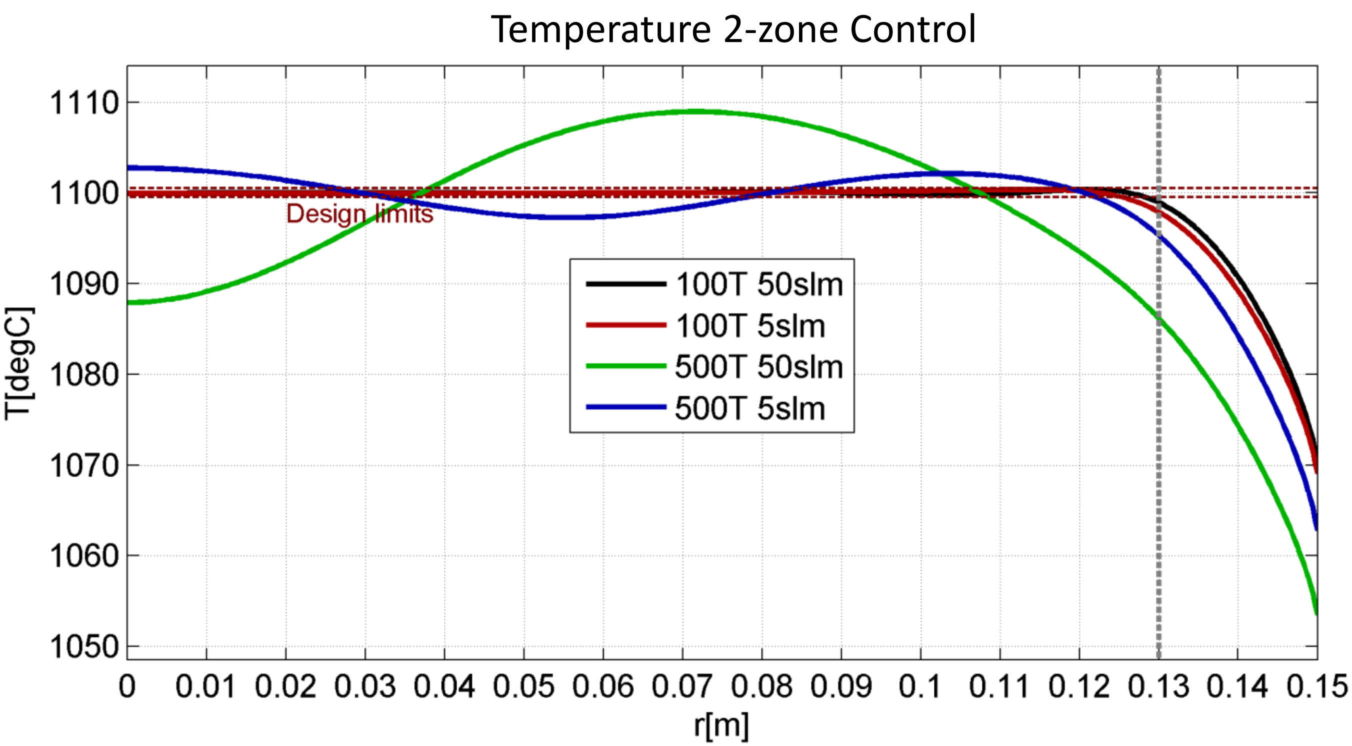
Buoyancy driven recirculation is causing a significant redistribution of the convective losses.

500 Torr, 5slm

Buoyancy driven recirculation even more complex here.

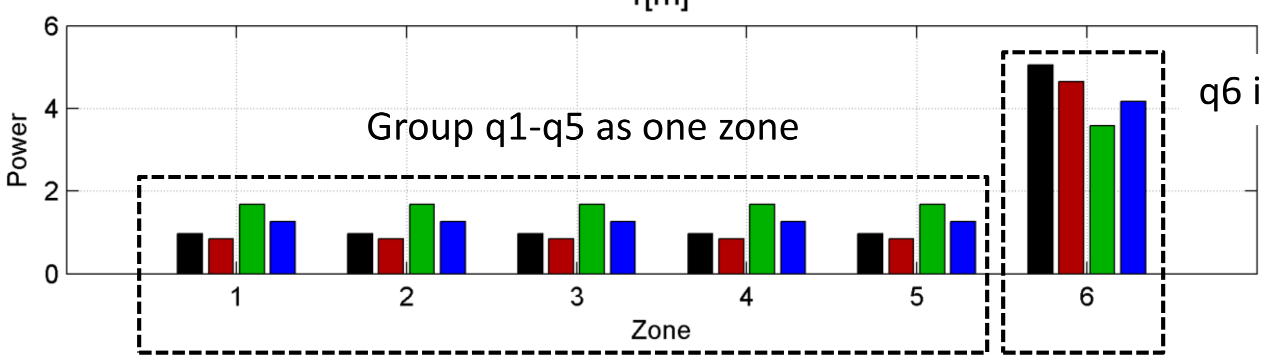
1-zone control cannot work for this range of operating conditions.

Two-zone Control

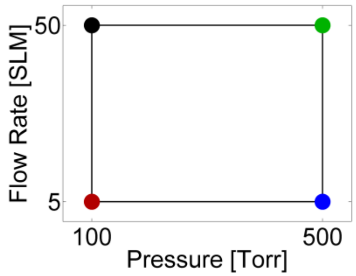


Much better, but still not within design limits.

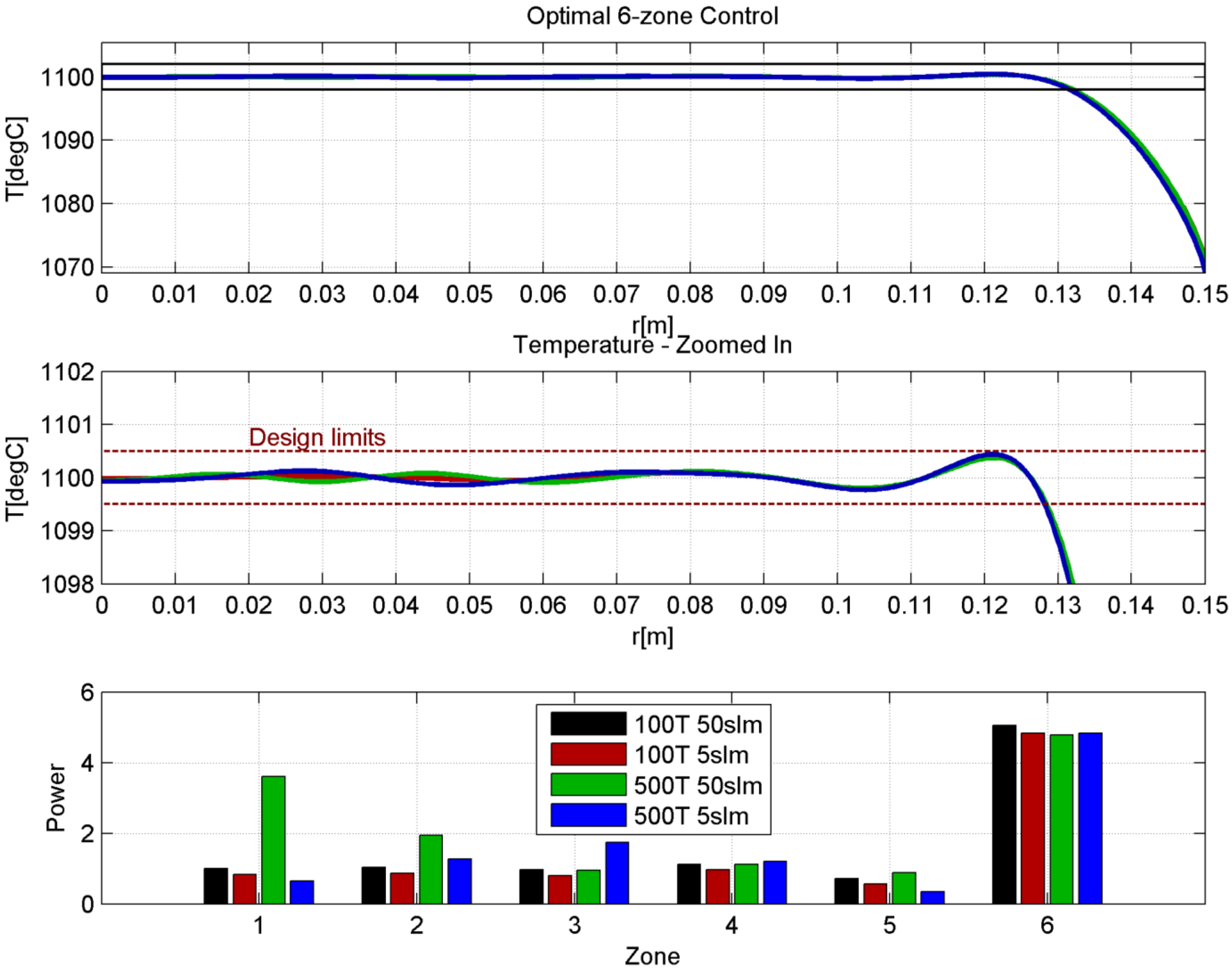
Both 100 Torr processes are close to being within the design limits.



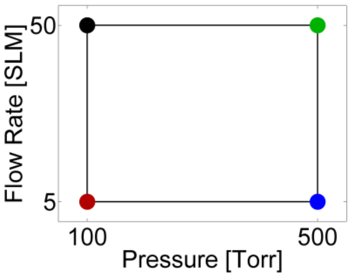
q6 is second zone



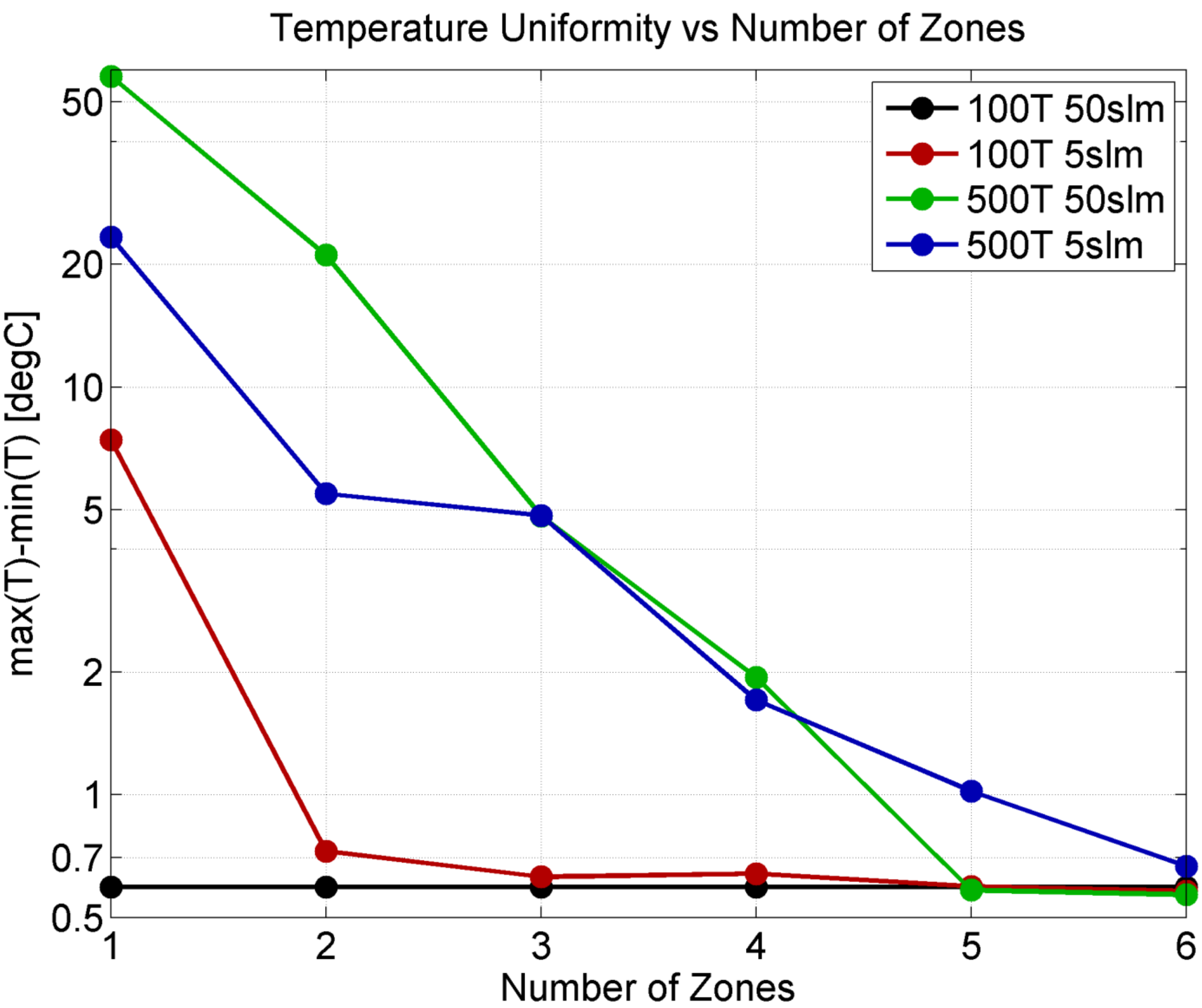
Six-zone Control

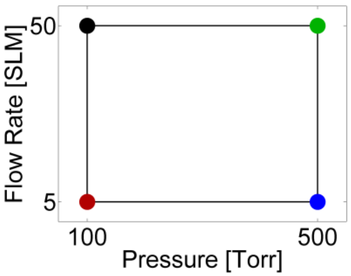


With Six Zones, the design specifications are met.



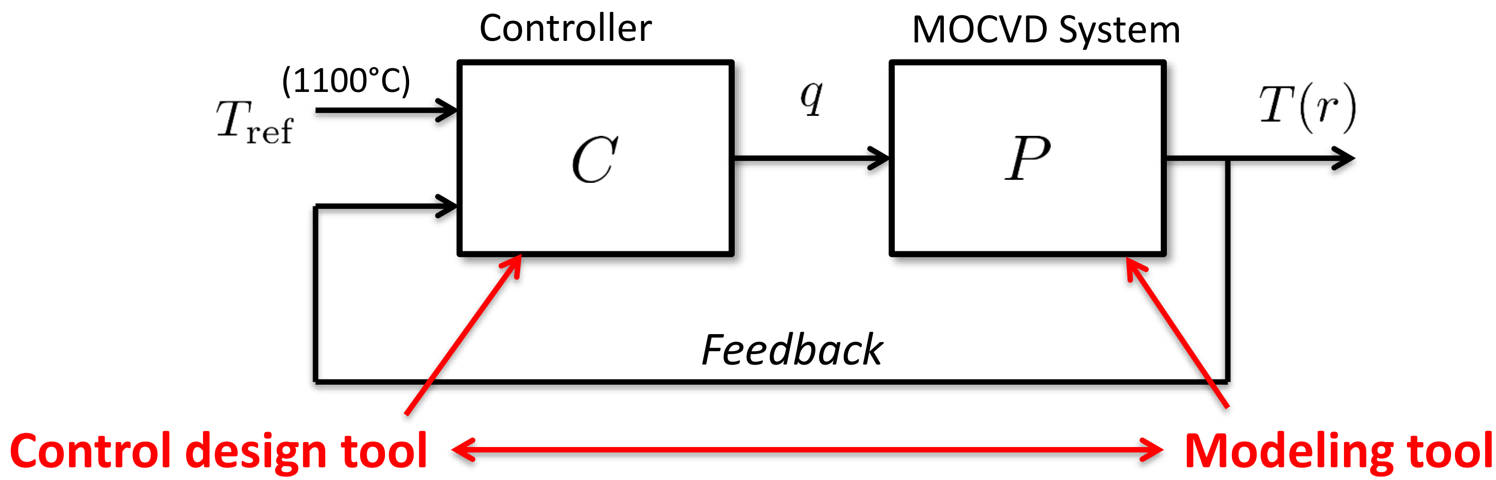
Temperature Uniformity vs Number of Control Zones





Implementation using Model-Based Control (MBC)

- **The controller, C, adjusts the flux, q, to make the temperature T on the CVD surface uniform at the reference temperature, T_{ref}.**



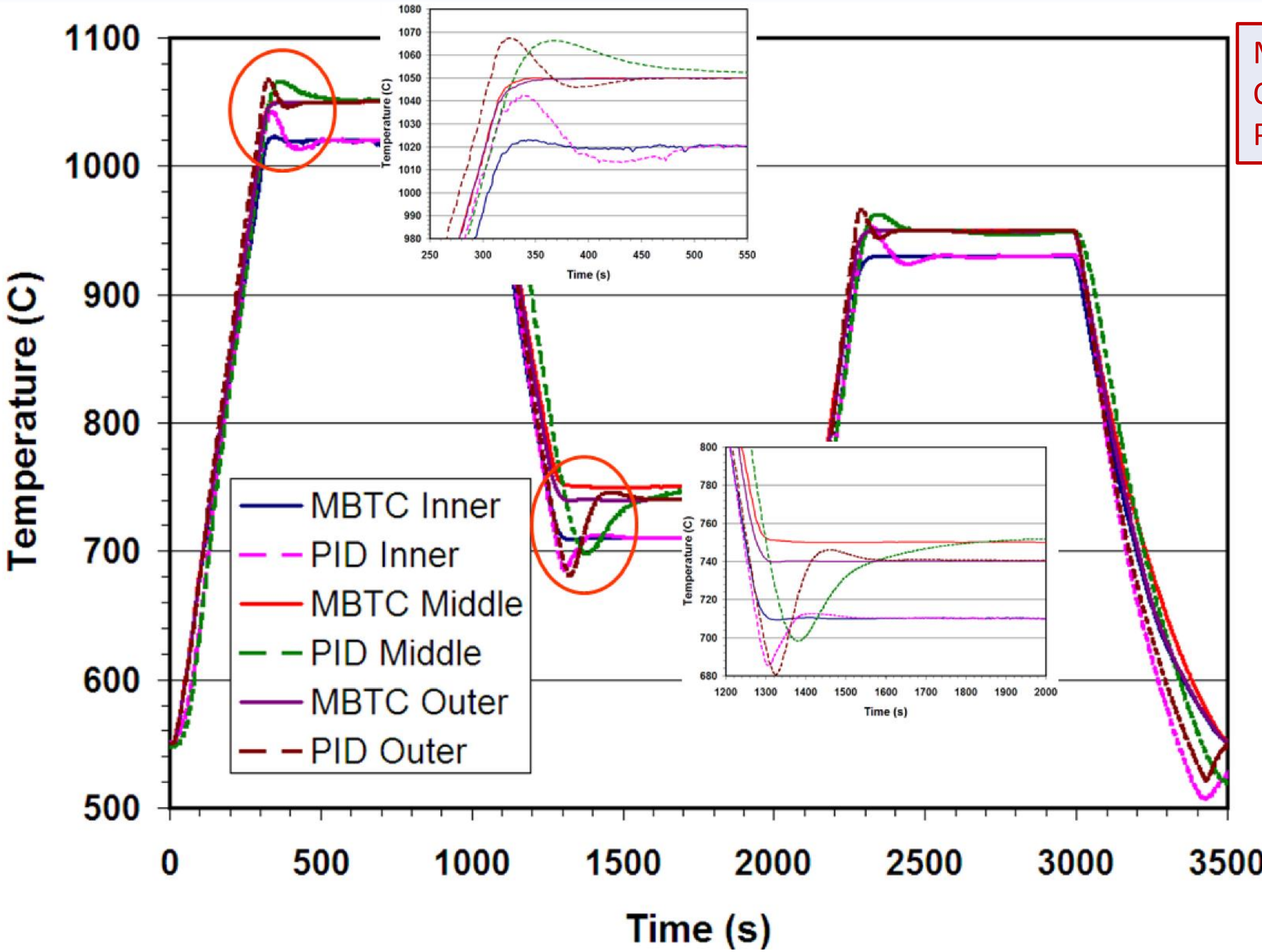
- **This is a form of the "inverse problem".**

  (What inputs do I need to produce a given output?)

- **Real-time feedback is a common method of dynamically solving this problem.**

Here we focus on steady-state, but the same methods are used to solve the time-varying dynamic control problem (e.g., uniformity during temperature ramp, stabilization, etc.).

Dynamic Control Performance using Model-Based Control



MBC Outperforms PID

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Summary

- This study illustrates how modeling tools can be used together with control design tools to evaluate optimal closed-loop control performance of a system using Model-Based Control (MBC).
- In this particular study with a MOCVD system, after testing various multizone heater configurations, a six-zone control scheme was adopted with each heater being controlled independently.
- Temperature uniformity is much better than the specification over most of the area (0.7°C compared to 1°C specification).
- Fewer independent heater zones are needed if uniformity requirement is relaxed slightly (4 zones sufficient for ± 1°C).
- Additionally, the results point to a need to eliminate "roll cells" in the flow, either by changing the geometry, increasing the flow rate, or increasing the rotation rate.

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