Fluid and Thermal Simulations for Substrate Holder Design

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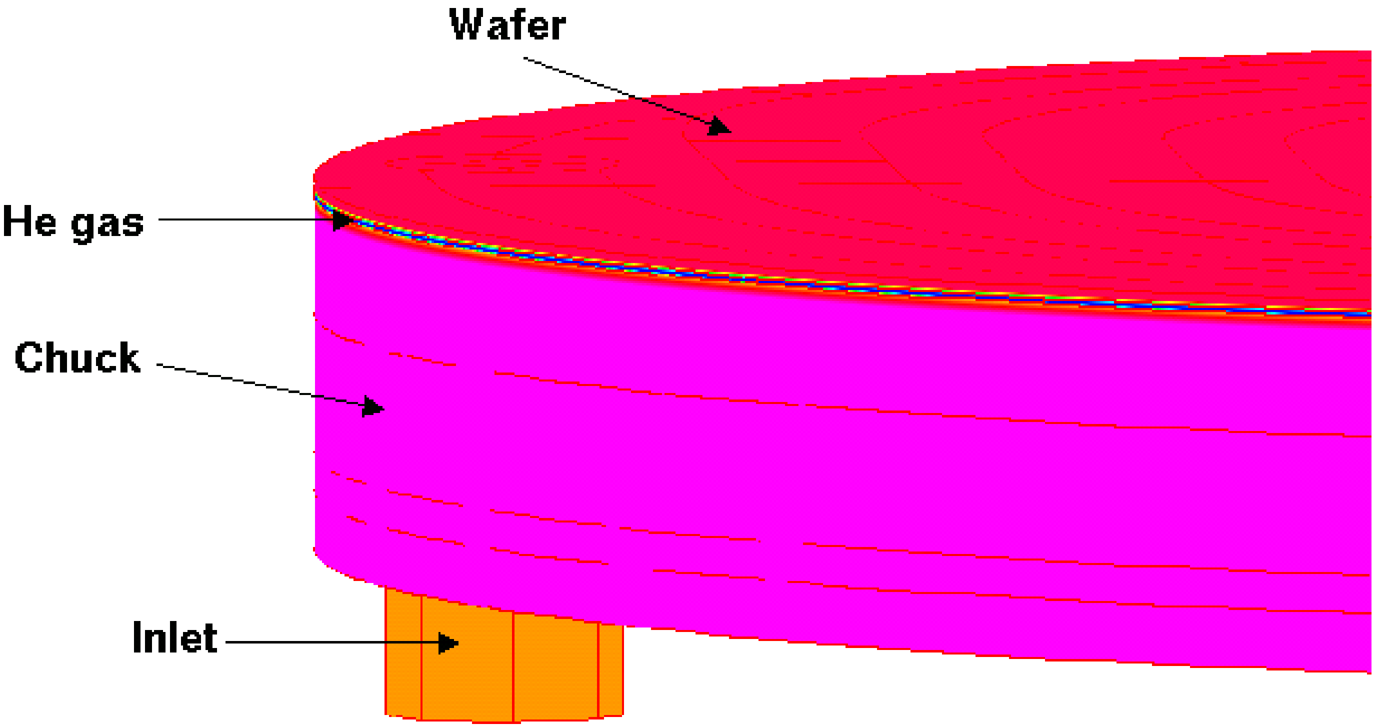
- Capabilities for temperature change and control of a substrate holder (chuck) are essential characteristics of a semiconductor processing system.
- Numerical simulations discussed in this report consist of a combination of 2D and 3D CFD and thermal models.
- The initial fluid-thermal 3D model provided the boundary layer parameters and justification for using simplified thermal models.
- Then, a few simplified approaches, requiring only short simulation time, were used to explore different configurations and to find optimal regimes
  - 3D fluid analysis of the cooling channel (but not the whole chuck)
  - 2D and 3D thermal (but not fluid) analyses of the substrate holder.
- Finally, the full 3D fluid-thermal model was used for fine improvement and for confirmation of superior characteristics of the design.
- While the actual substrate holder designs and motivations cannot be disclosed, simulation techniques for a simplified sample design are presented and discussed.

Simplified Geometry



Setup

- **Setup:**
  - The actual substrate holder designs cannot be disclosed, so although the setup for presented simulations is chosen to reflect real problems, the geometry and the design are different and significantly simplified.
  - A substrate holder (chuck) is a metal cylindrical block (in simulations presented, it is made of Al and is 32 cm in diameter and 3 cm thick).
  - A substrate or wafer (in simulations, it is made of Si and is 1 mm thick) is located above the chuck and is effectively separated from it on average by some distance (in simulations presented, it is 1.5 μm).
  - There is a small direct heat transfer between a wafer and the chuck because of non-uniformities of the surfaces, but the main heat transfer between the wafer and the chuck is caused by the gas backside pressure (in simulations presented, it is He at 40 Torr).
  - The coolant (in simulations presented, it is Fluorinert FC40) flows through the coolant channel in the chuck (in simulations, it is a single spiral path with the square cross-section of 1.5 x 1.5 cm, with one inlet for the coolant and one outlet).
  - The heat load (typically from the plasma) comes on the upper surface of the wafer (in simulations presented, it is 1kW of power).

Chosen Approach

- The coolant flow was strongly turbulent as the Reynold's number is high

$$\mathrm{Re} = \frac{\rho V d}{\mu} \approx 3 \cdot 10^4 > 2 \cdot 10^3$$

- In simulations presented, we have chosen the standard K-Epsilon turbulent model with the Prandtl number of 0.9 .
- The heat conduction through the micron-size gap has to take into account the Smoluchowski effect,

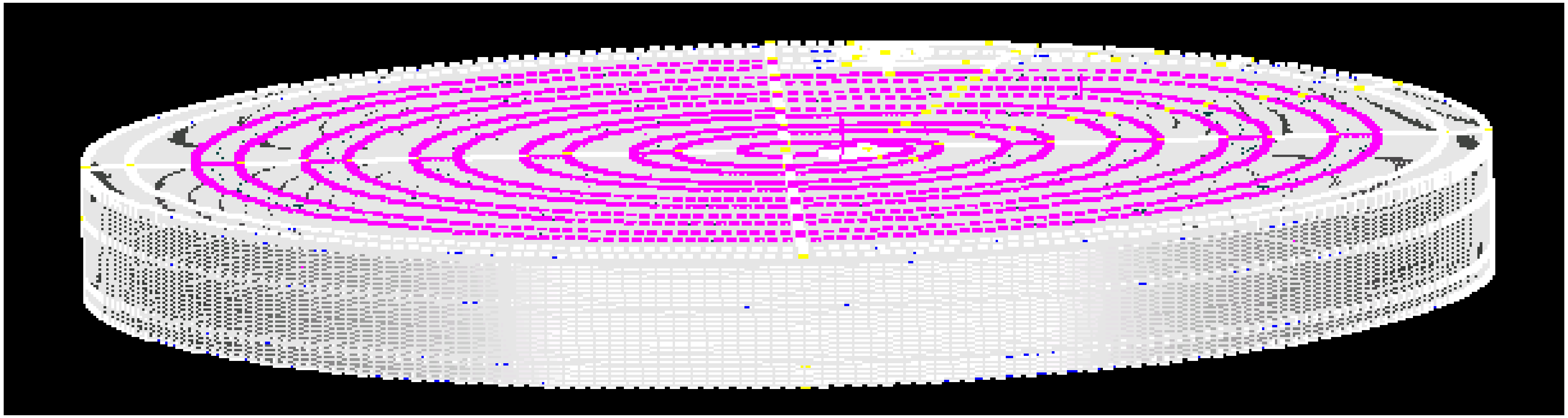
$$k = k_c / (1 + c \cdot Kn)$$

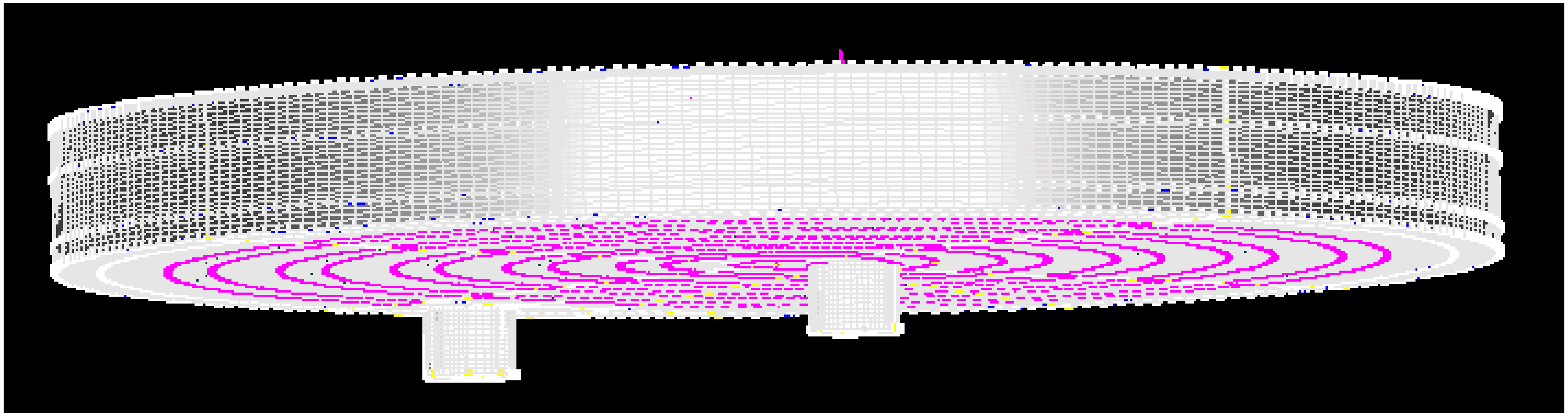
where the Knudson number is

$$Kn = \lambda / L \approx 12$$

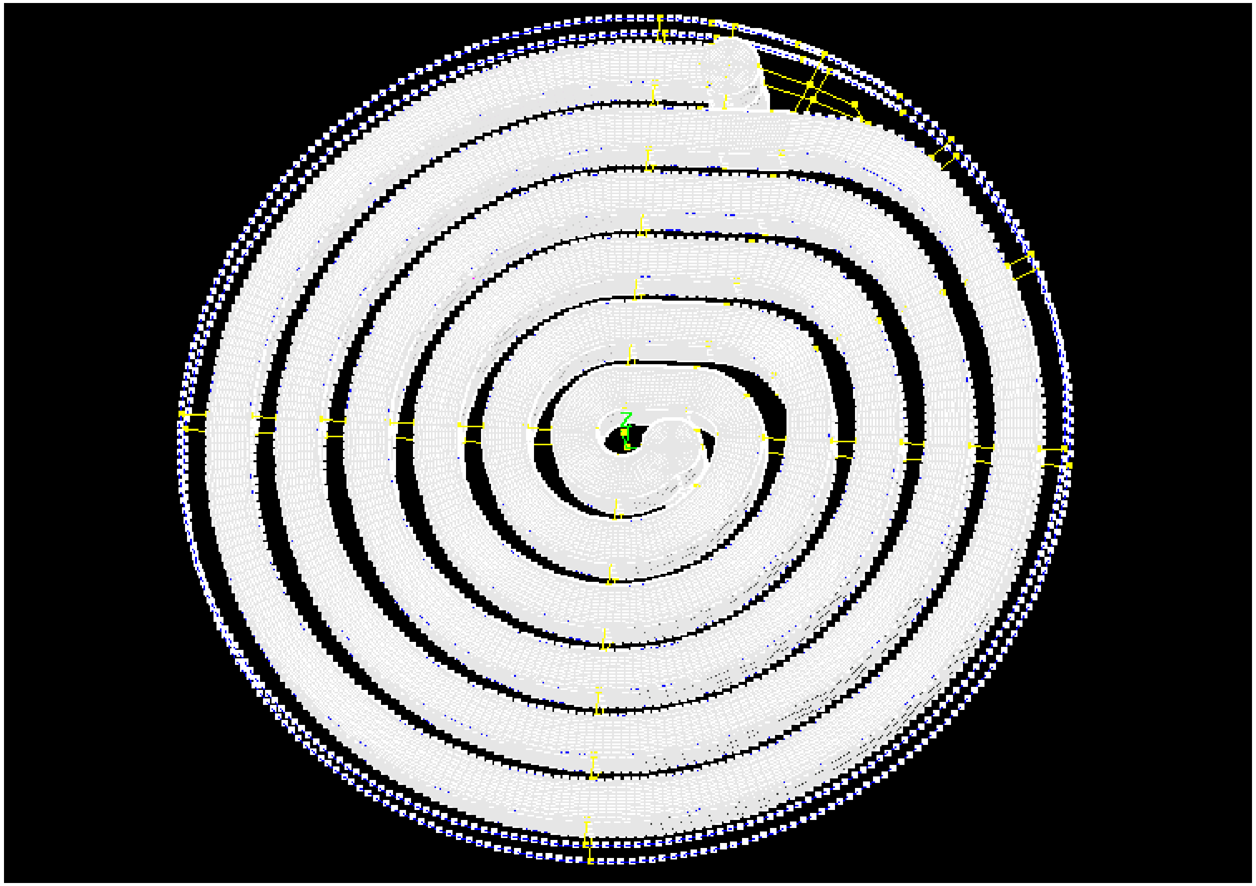
- The micron-size gap was simulated as a 0.5 mm gap with the same heat conductance k/L.

3D Geometric Model of the Chuck

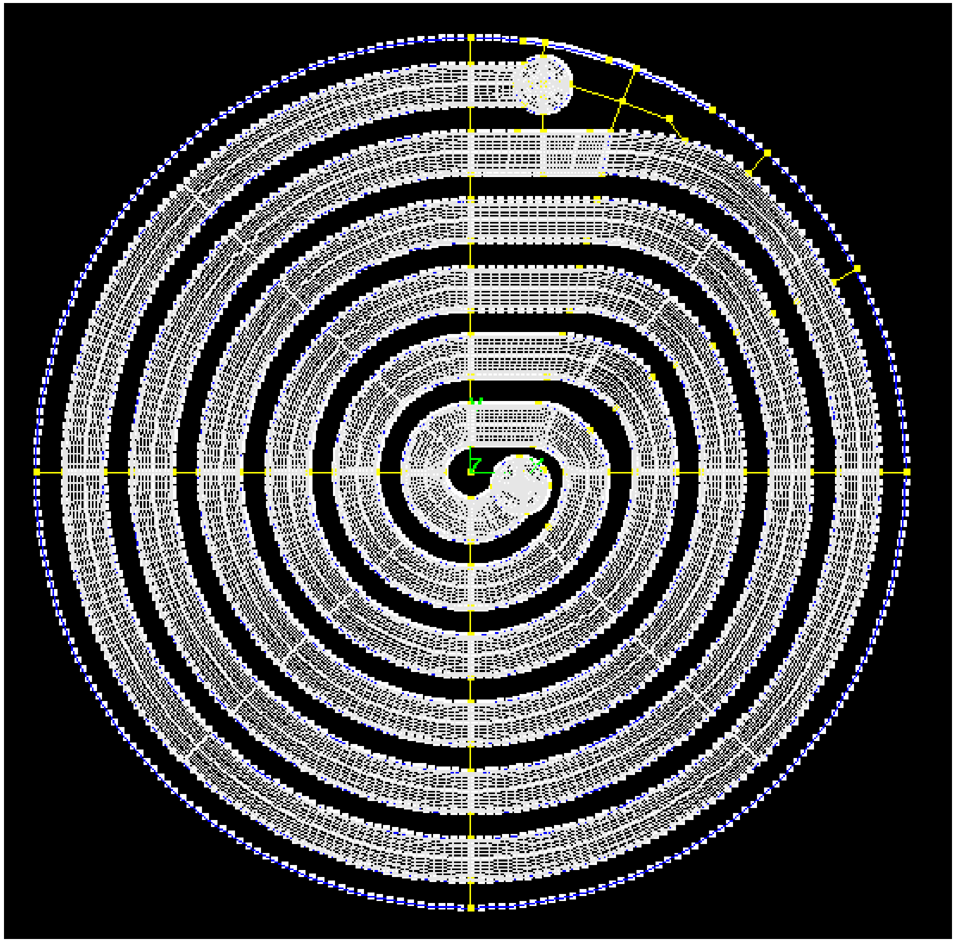




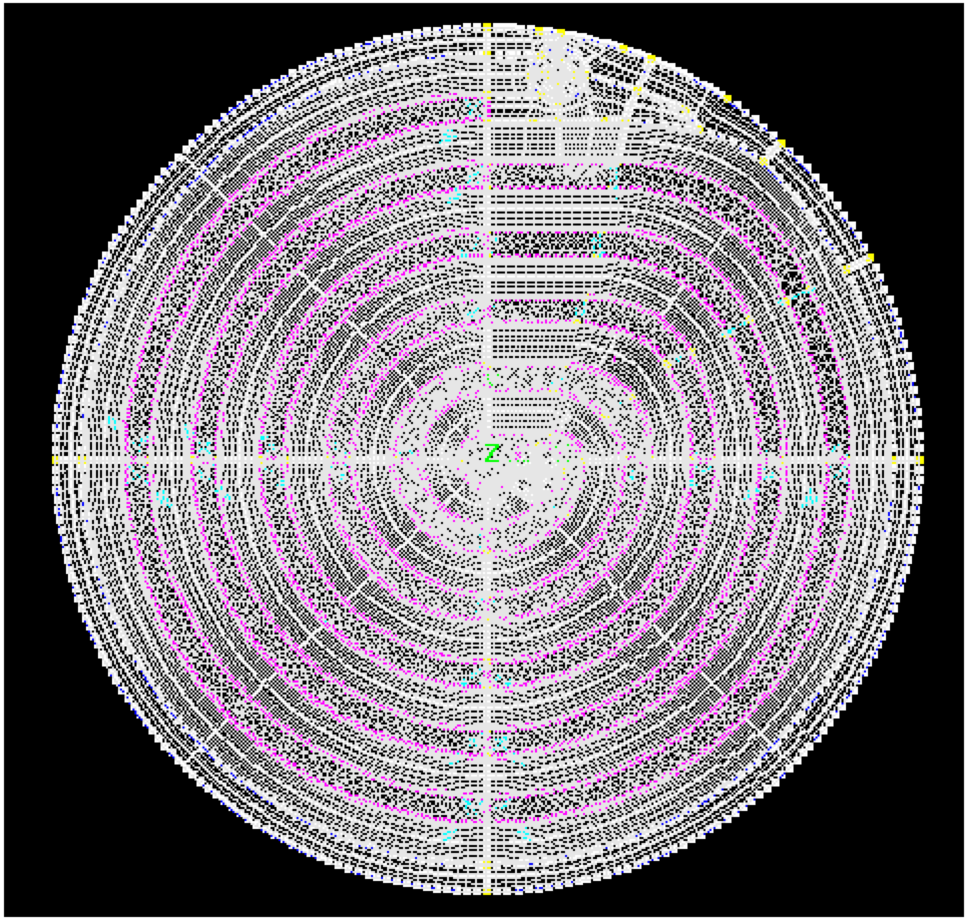
3D Model of a Spiral Cooling Channel



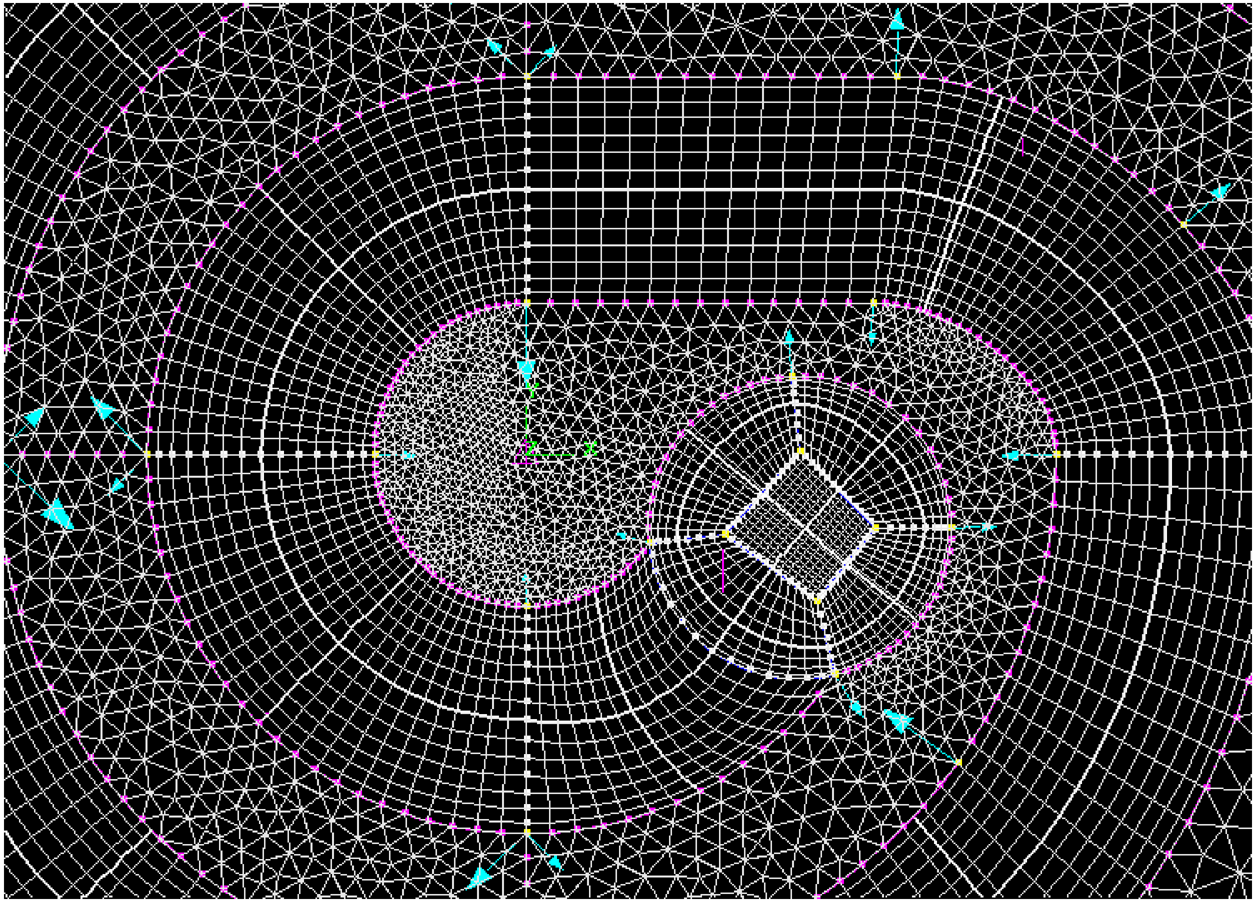
Structured Mesh of the Cooling Channel



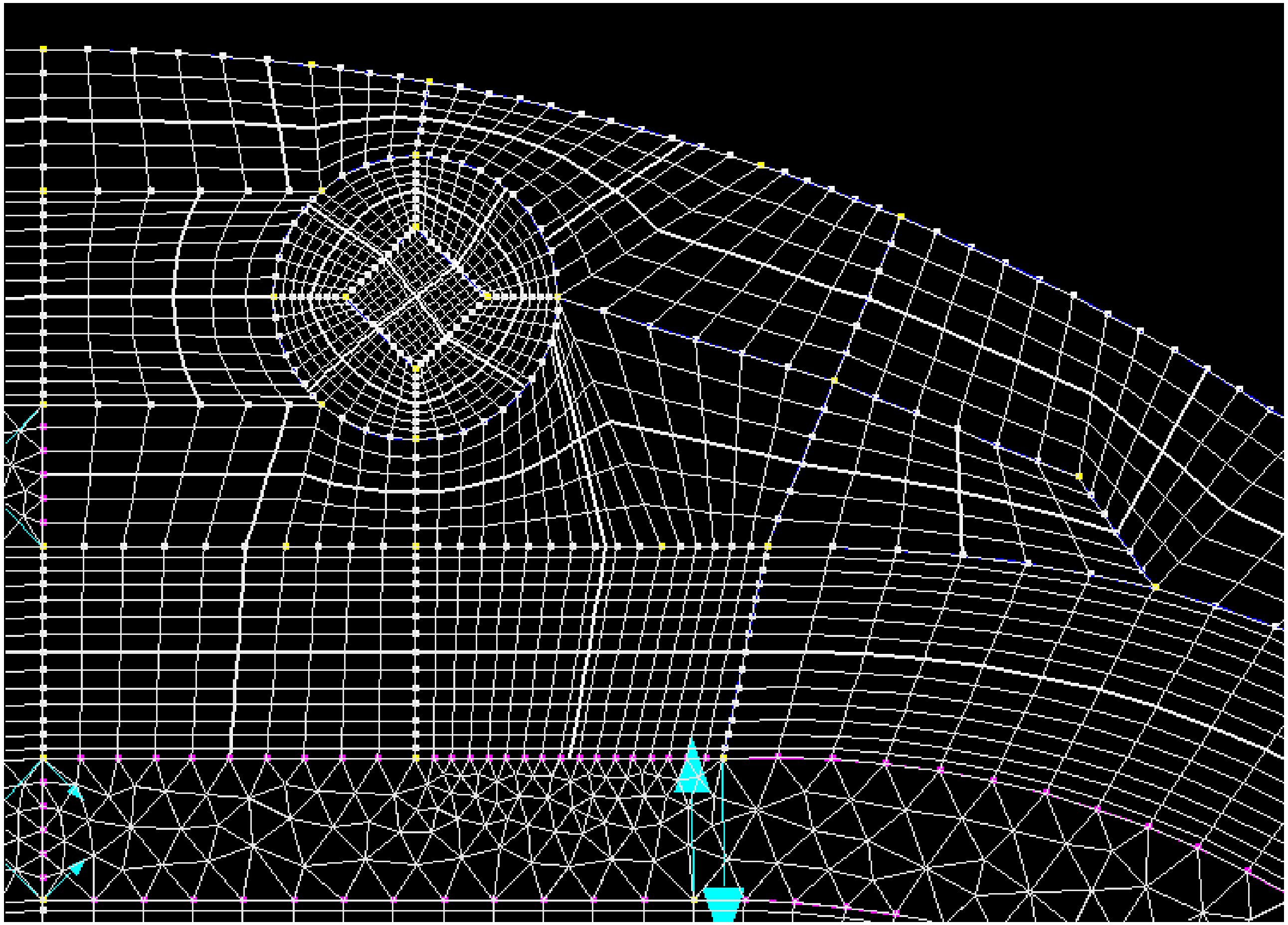
Cross-section of the Chuck Structured and Unstructured Mesh



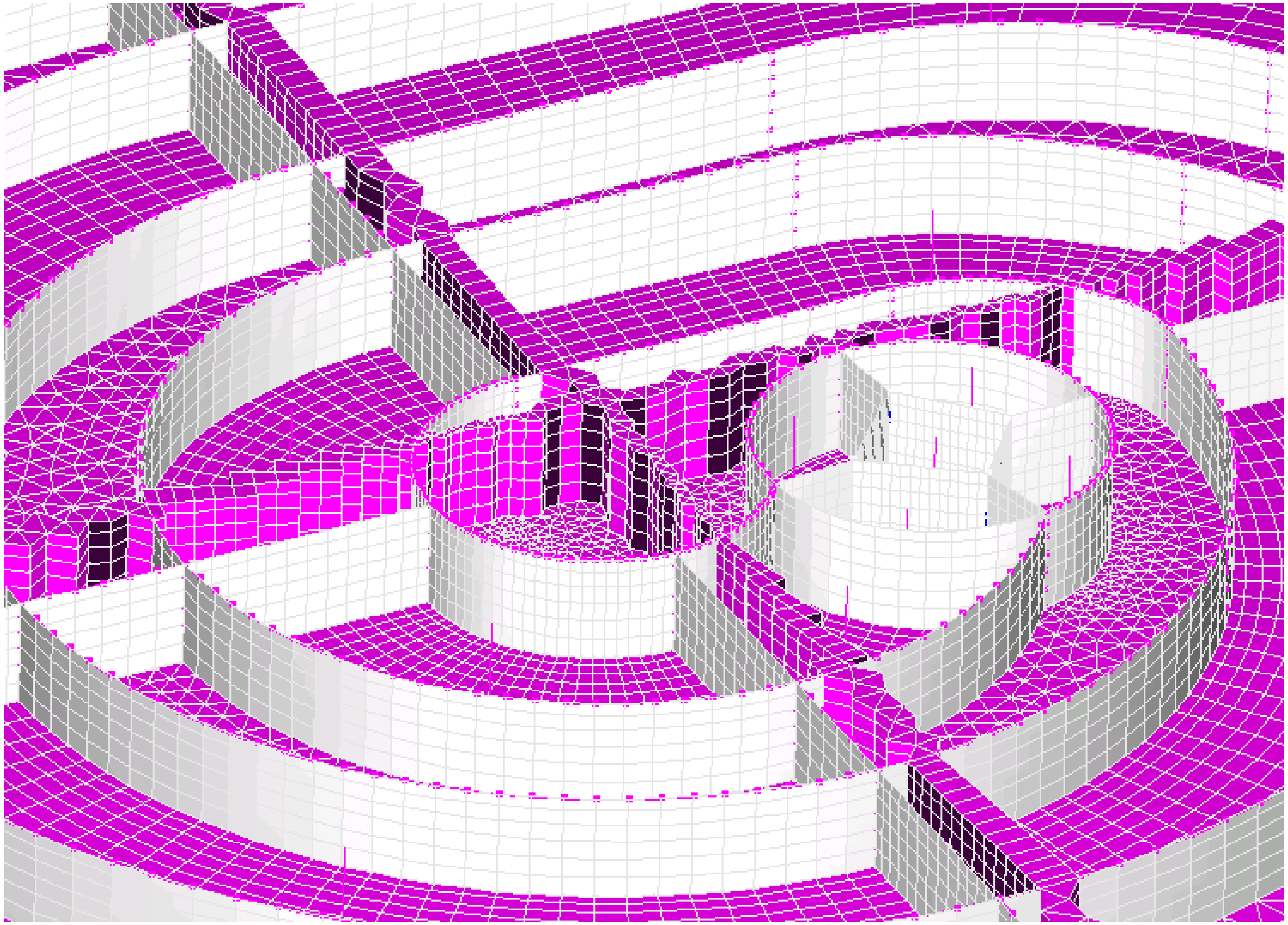
Mesh Detail Near the Outlet
Sample of Using Unstructured Mesh



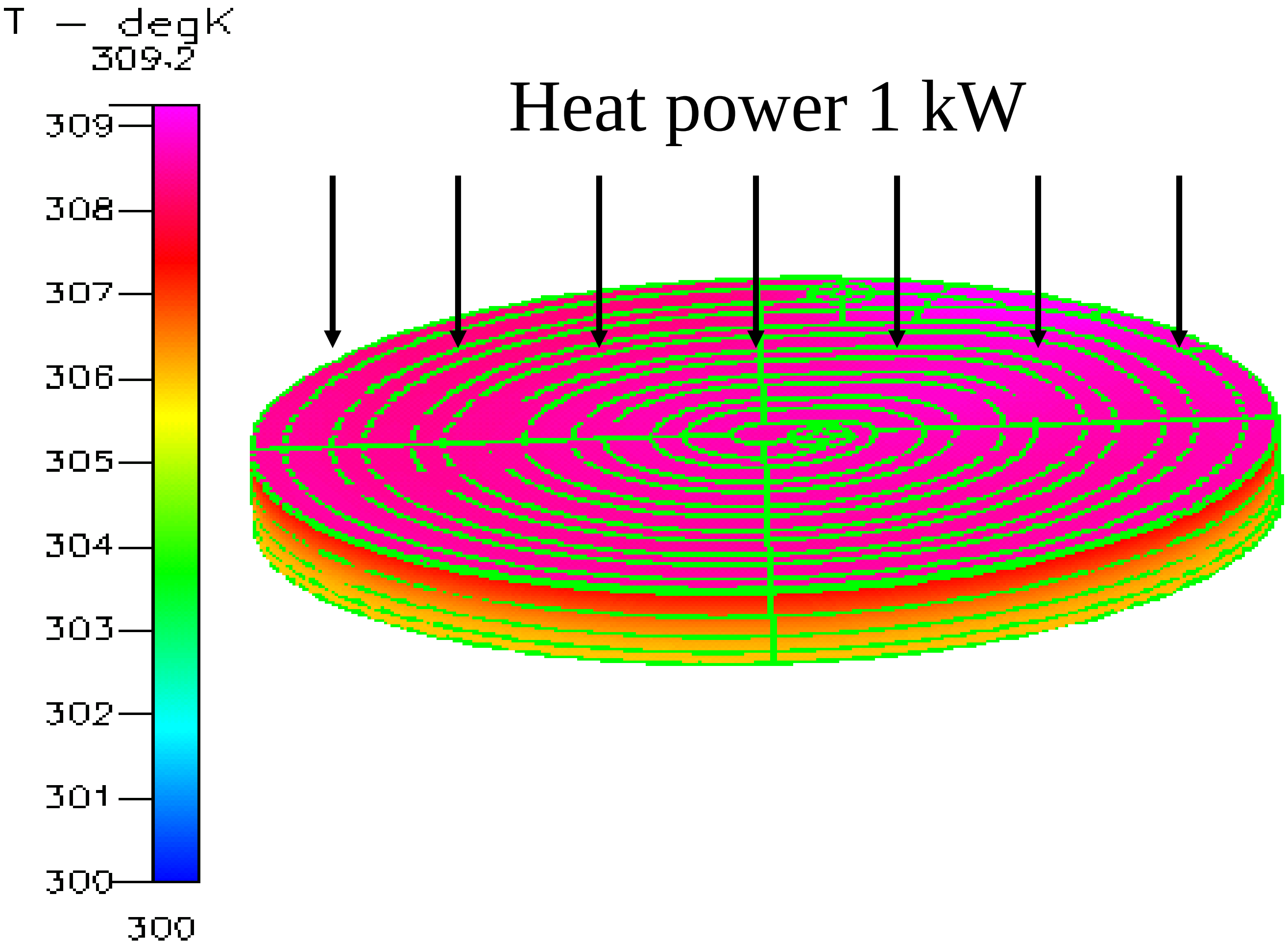
Mesh Detail Near the Inlet
Sample of Using Structured Mesh



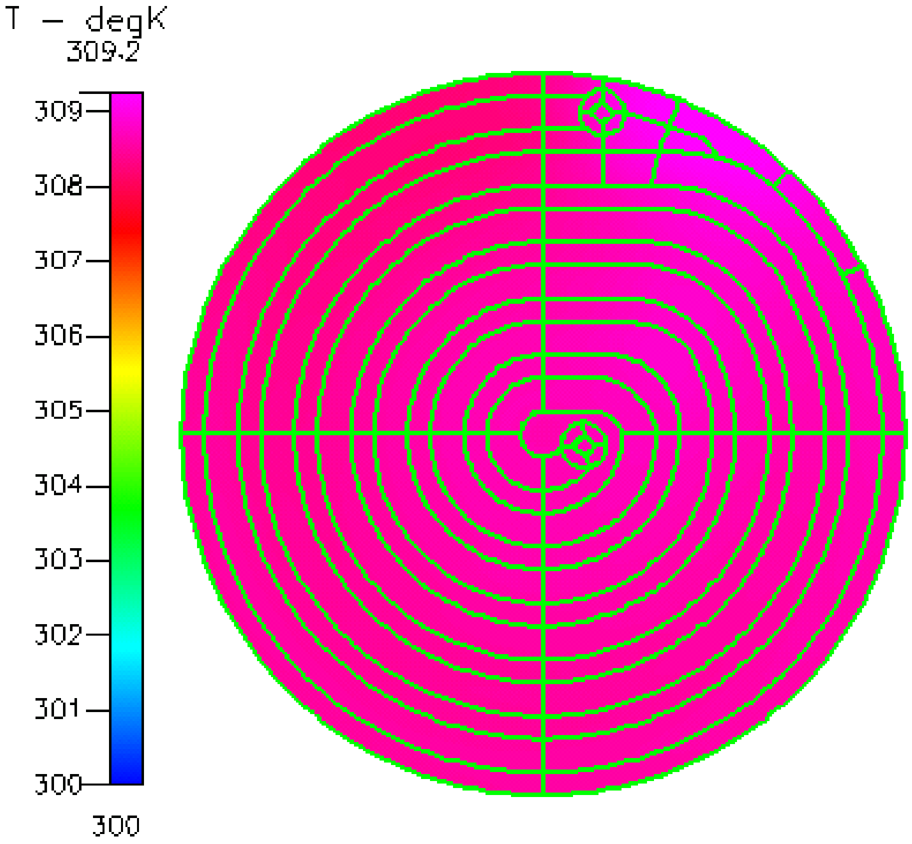
Mesh Viewer

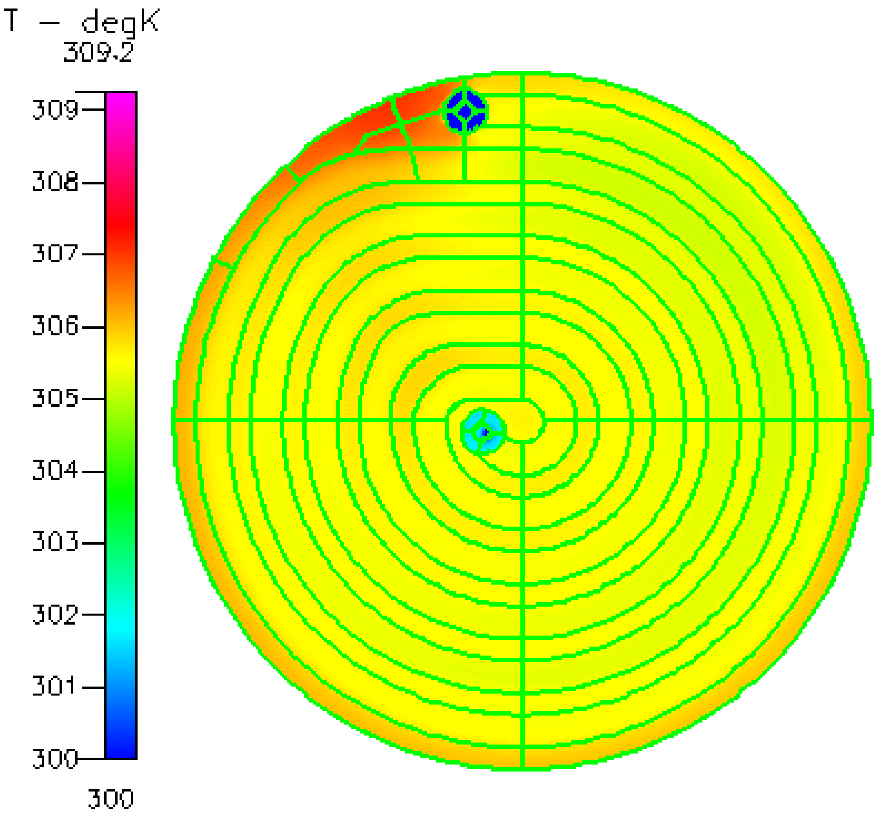


Sample Result of a 3D Fluid-Thermal Simulation of the Chuck

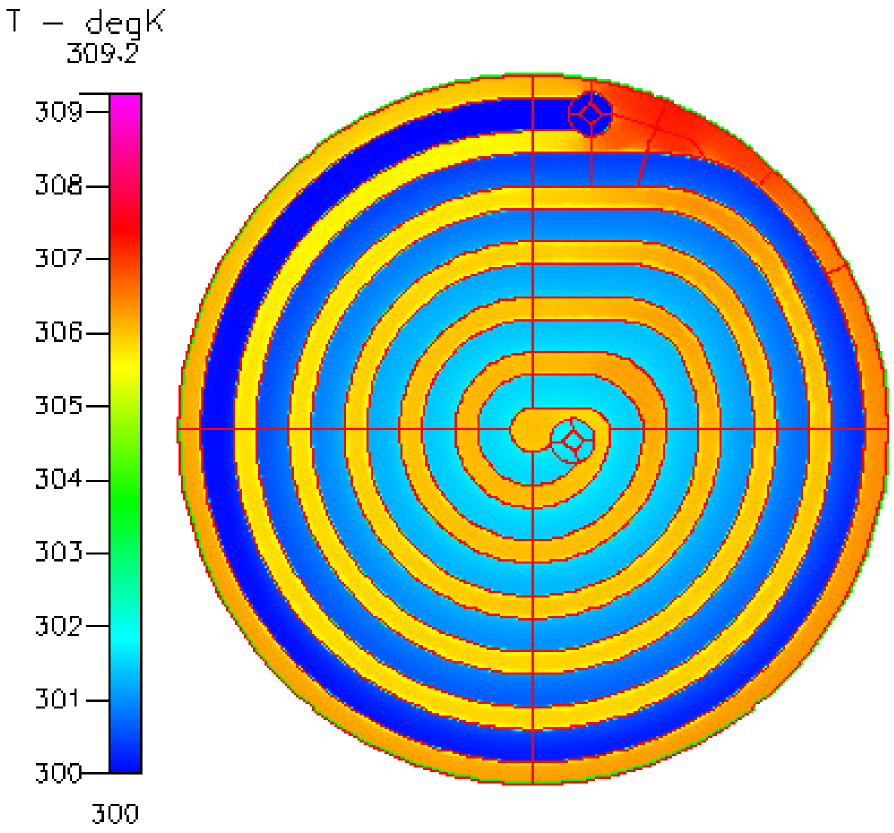


Top and Bottom View of the Chuck

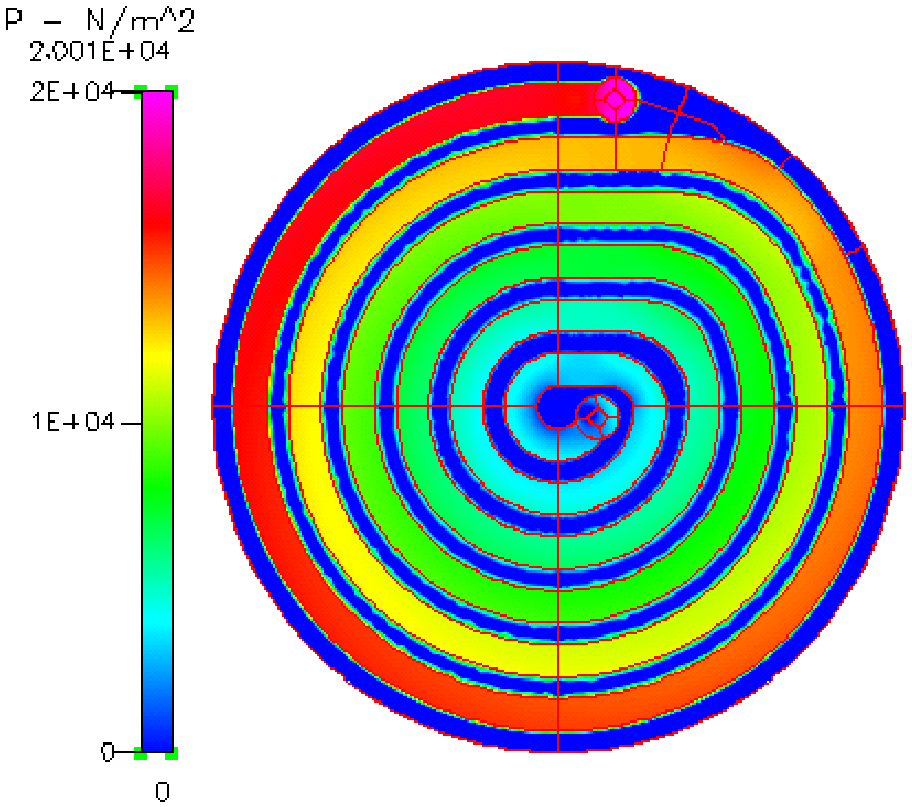




Cross-section at the Channel Level

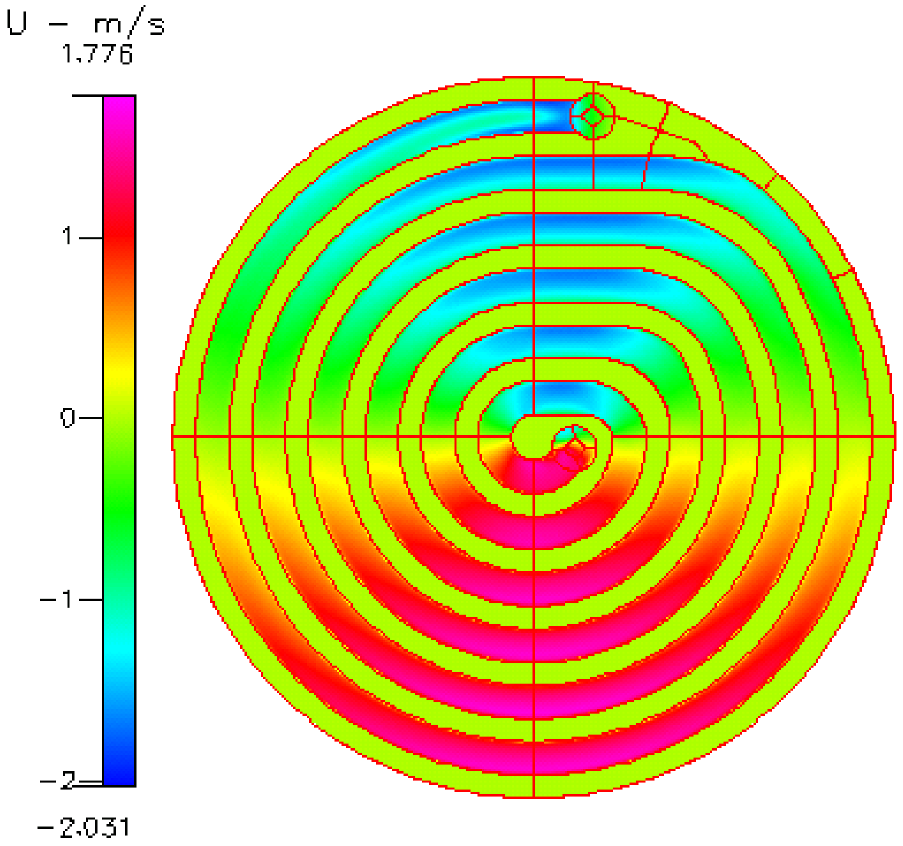


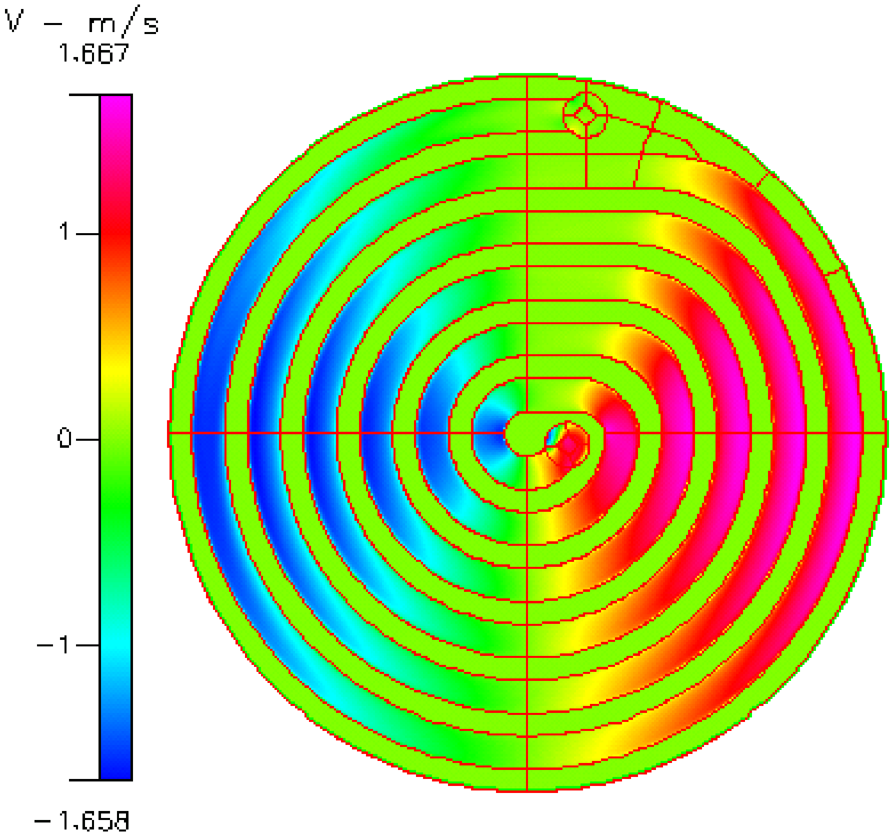
Temperature



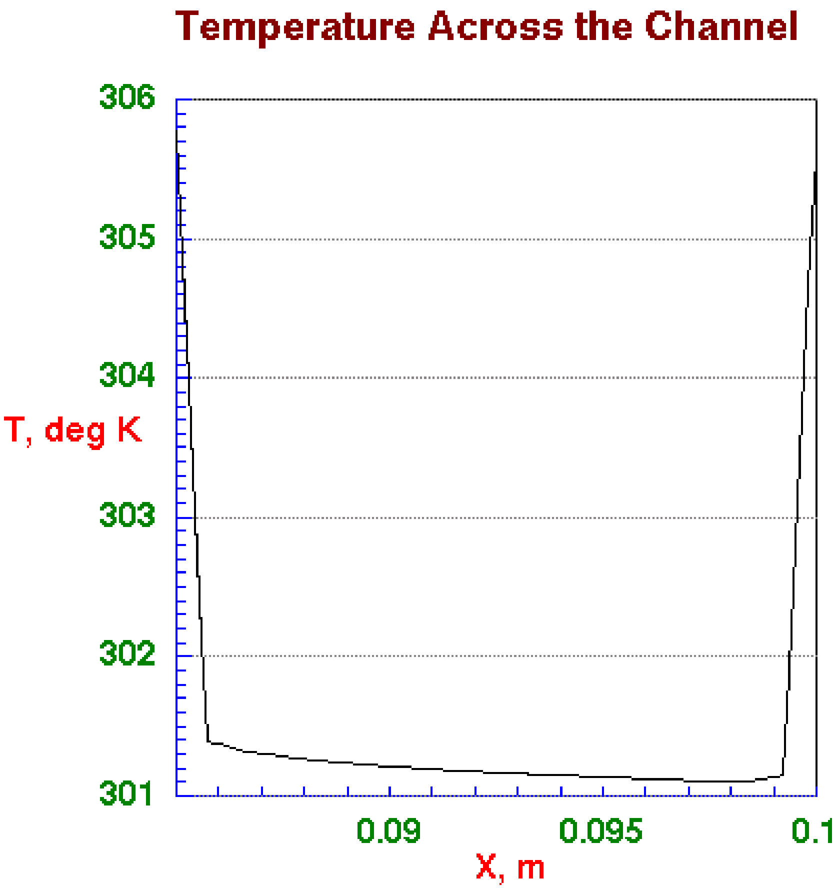
Extra pressure in the channel

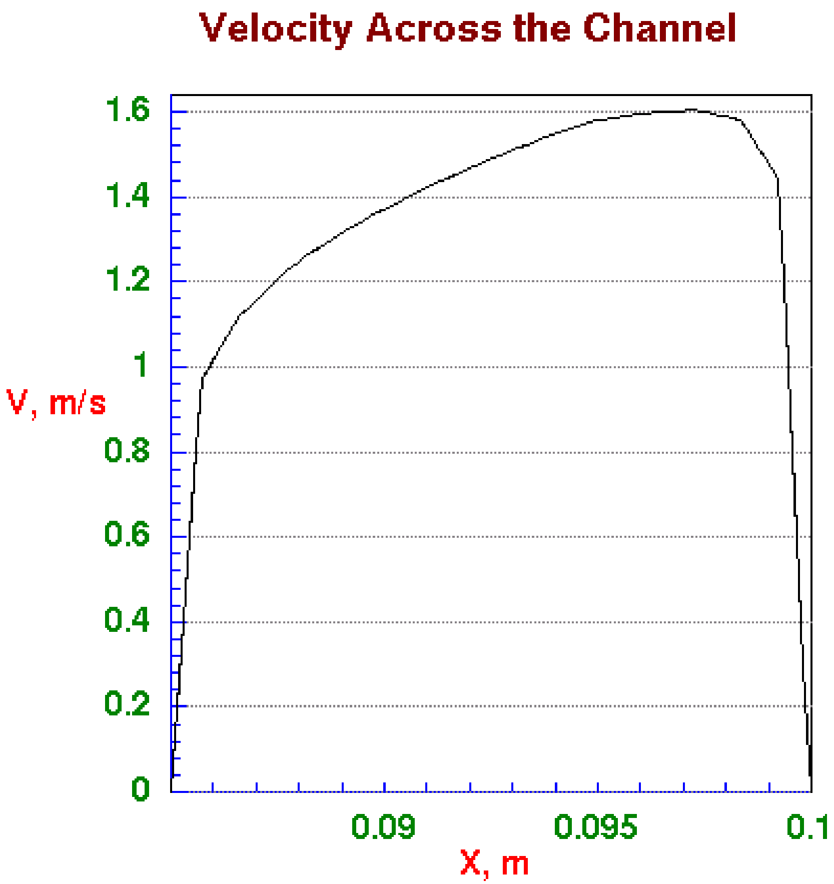
U and V components of Fluid Velocity



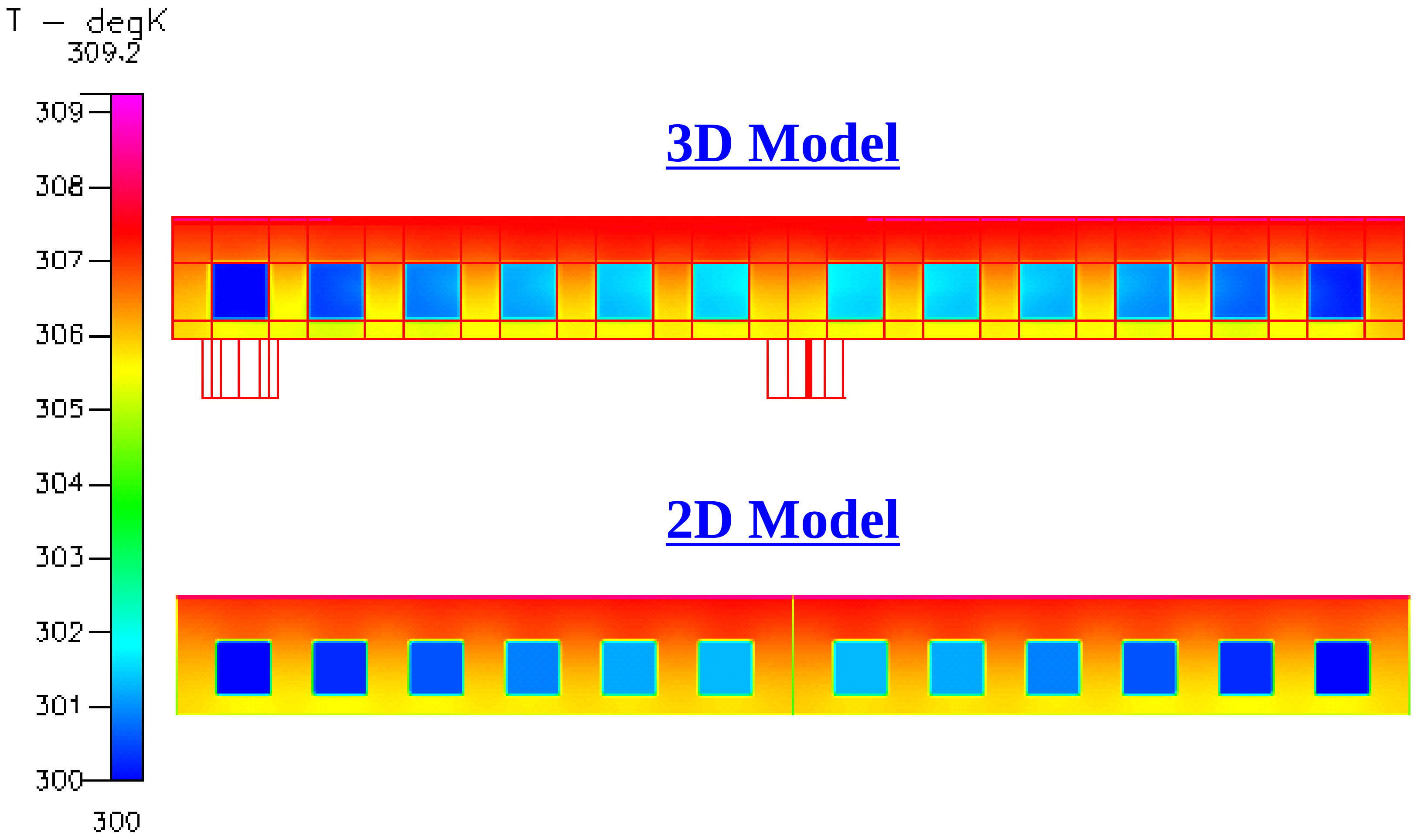


Fluid Temperature and Velocity Boundary Layer in the Channel

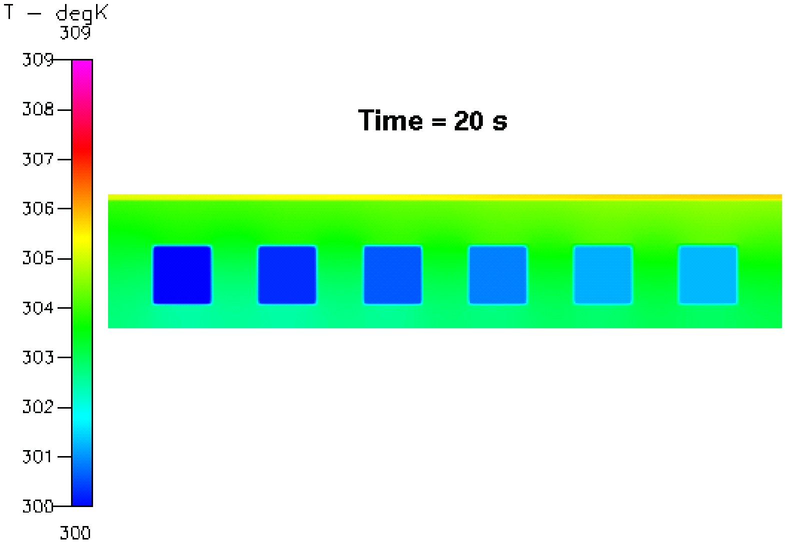

Temperature Across the Channel

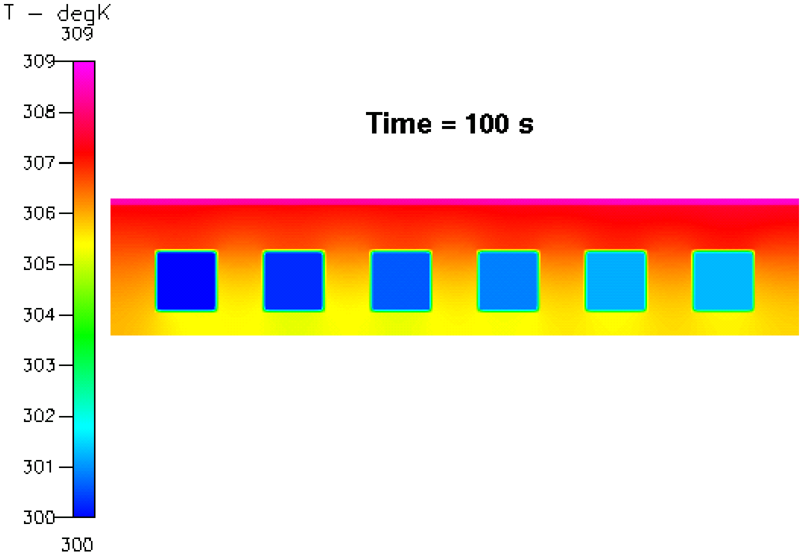

Velocity Across the Channel

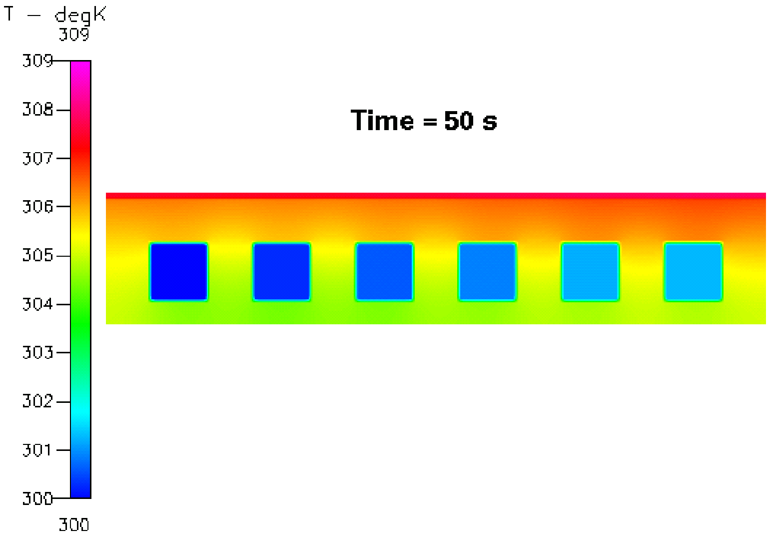
Correspondence of 2D and 3D Models

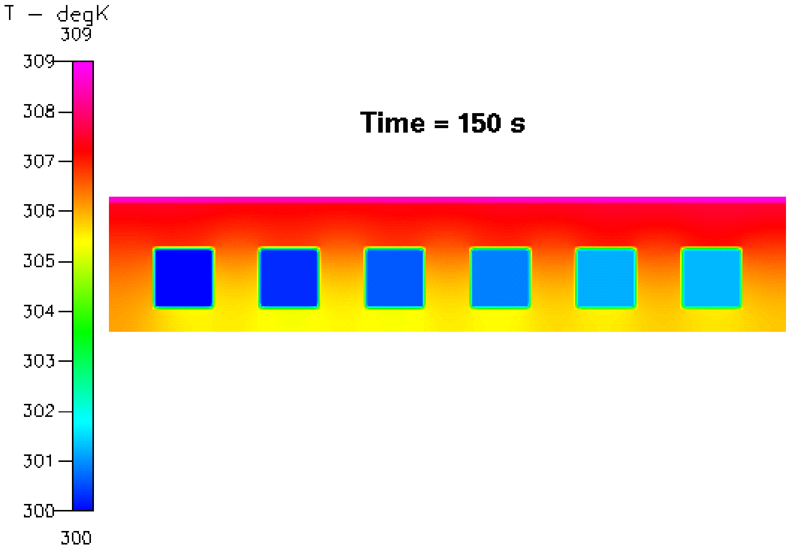


Transient Solution

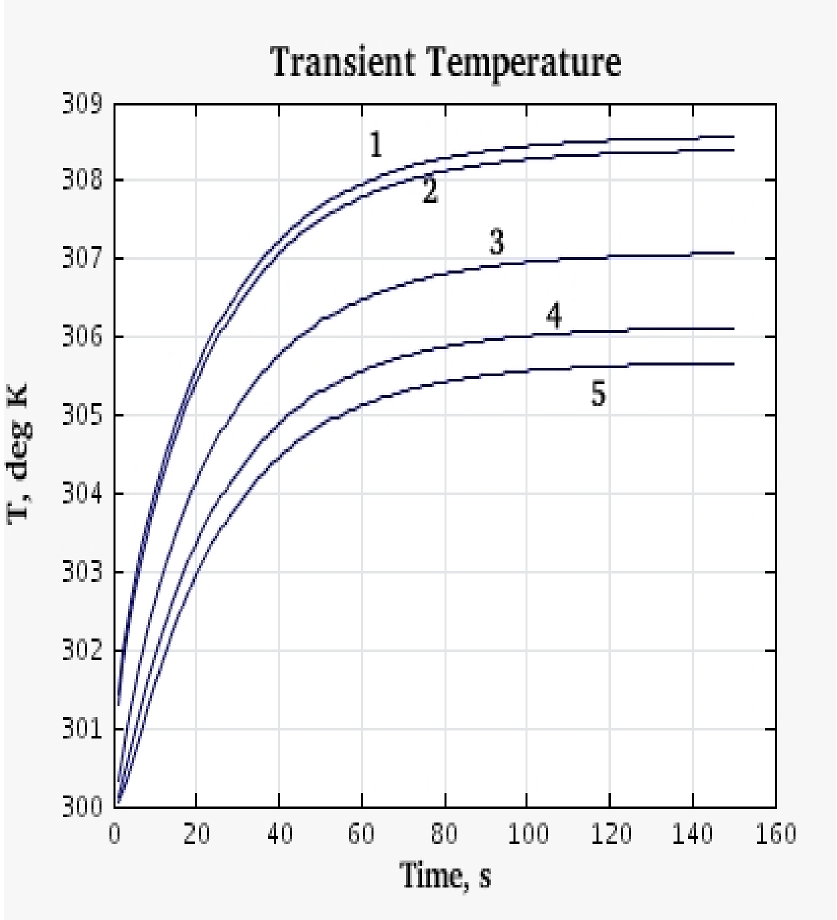

Time = 20 s

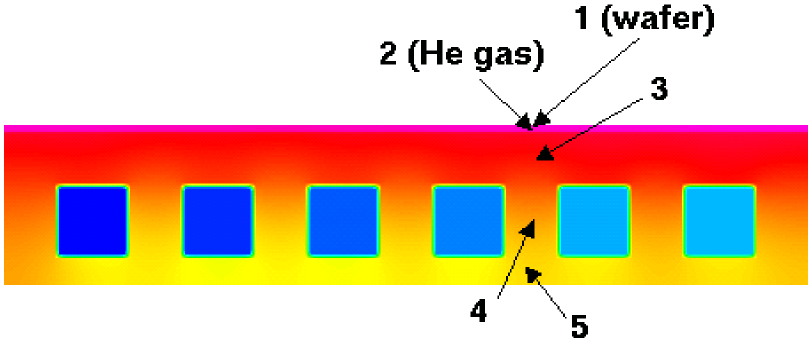

Time = 100 s


Time = 50 s


Time = 150 s

Transient Temperature





Sensor locations:

1 – at wafer
2 – at He gas layer
3 – above cooling channels
4 – between cooling channels
5 – below cooling channels

Discussion and Conclusions

- **Full transient 3D fluid-thermal simulations might be very time consuming (a few hours to a few months on a single-processor or dual-processor computer) which makes design and optimization difficult.**
- **Simplified only-fluid or only-thermal models, especially the 2D ones, could bring the run time to a few minutes, or even to a few seconds.**
- **Presented and discussed are a full 3D fluid-thermal model, a 3D only-fluid model for the cooling channel, and a 2D only-thermal model for the chuck. The key point is how to choose simplified models that still can provide reasonable results.**
- **Results of simulations could be used for finding improved design and attractive operational regimes, and to determine**
  - Acceptable heat loads
  - Rate of cooling and heating
  - Temperature non-uniformity on the wafer
  - Acceptable coolant pressure at inlet
  - Other characteristics.