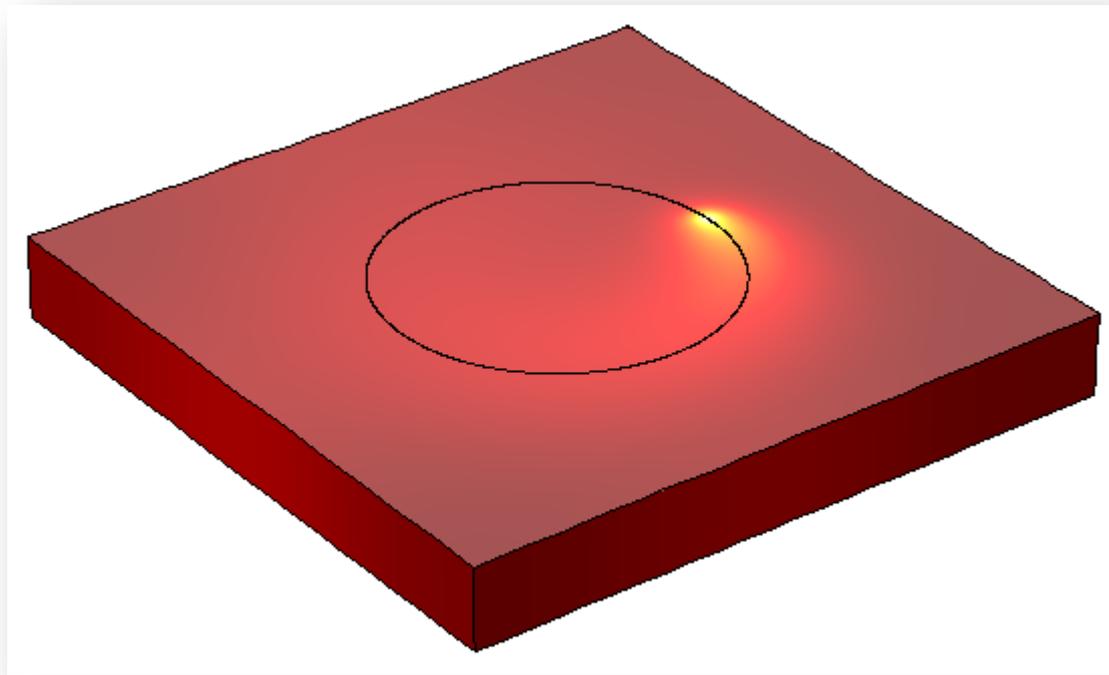


# Laser Heating – A Self Guided Tutorial



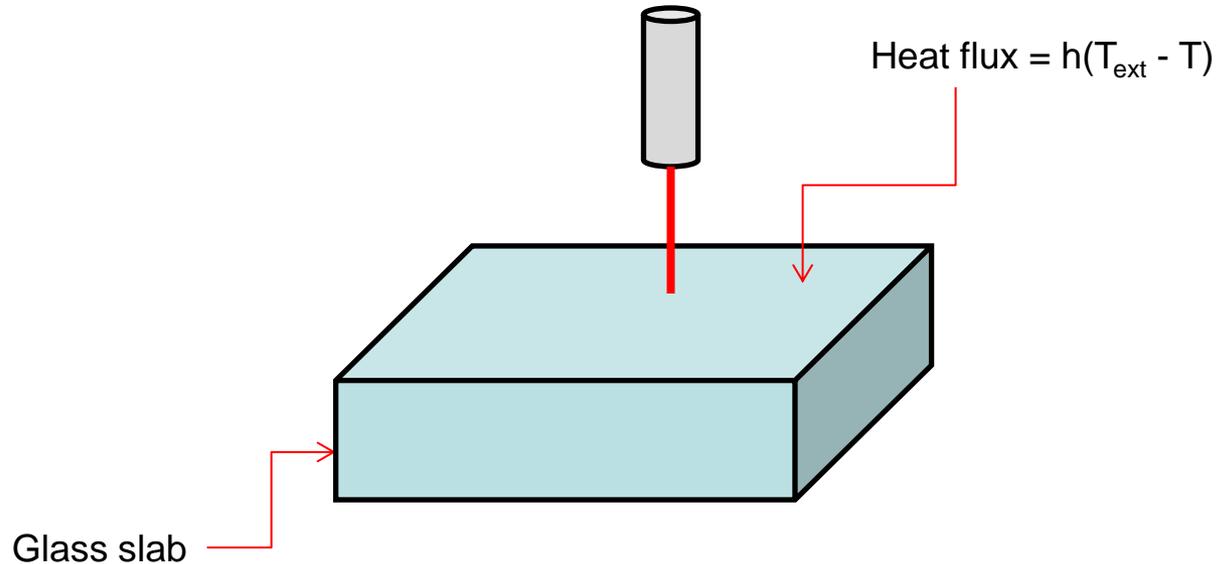
# Introduction

- This series of tutorials show how to simulate laser heating of glass.
- The heating due to laser is treated as a body heat source.
- The scenarios investigated are:
  - Stationary laser with constant power – CW mode
  - Stationary laser with pulsed power – Pulsed mode
  - Moving laser with constant power – CW mode

# Assumptions

- Material properties are assumed to be constant.
- The electromagnetics of the laser beam is not simulated.
- The effect of electromagnetic wavelength is not explicitly modeled.
- The effect of complex refractive index of glass is modeled using an absorption and reflection coefficient.
- The simulation does not involve modeling phase change.

# Model Definition



- The modeling geometry only includes the glass slab.
- Except the top surface, all other boundaries are assumed to be thermally insulated.
- The heat flux on the top surface simulates convective cooling.

# Calculating the heat input

- The body heat load within the glass slab is given by the following expression.

$$Q(x, y, z) = Q_0 (1 - R_c) \cdot \frac{A_c}{\pi \sigma_x \sigma_y} e^{-\left[ \frac{(x-x_0)^2}{2\sigma_x^2} + \frac{(y-y_0)^2}{2\sigma_y^2} \right]} \cdot e^{-A_c z}$$

Total power input

Reflection coefficient

2D Gaussian distribution in xy-plane

Exponential decay due to absorption

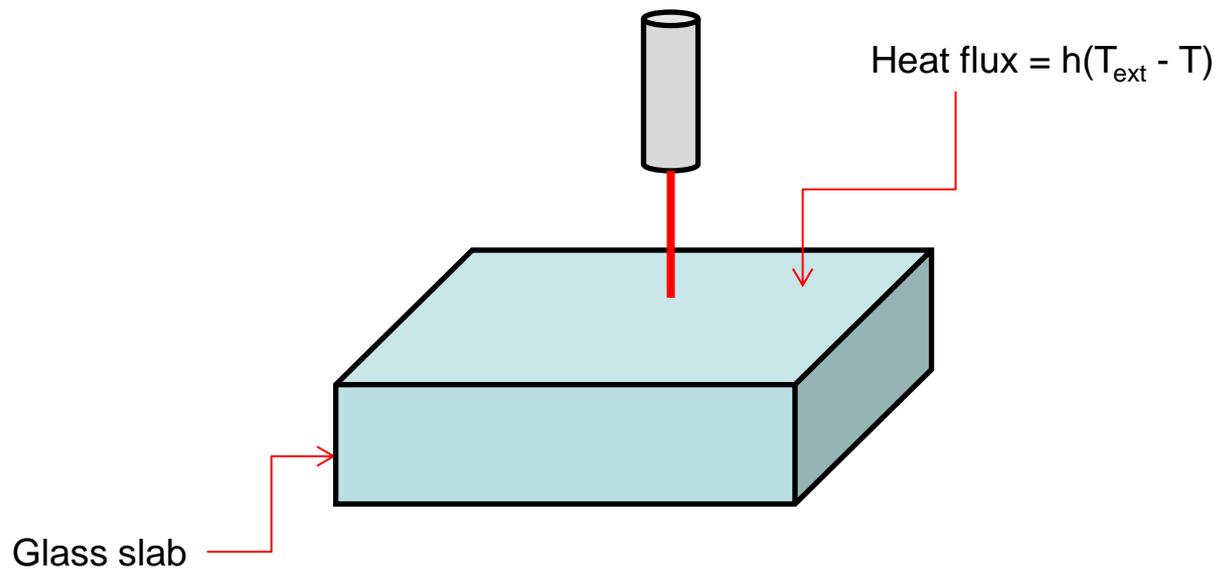
Reference: "Comparing the use of mid-infrared versus far-infrared lasers for mitigating damage growth on fused silica," Steven T. Yang, Manyalibo J. Matthews, Selim Elhadj, Diane Cooke, Gabriel M. Guss, Vaughn G. Draggoo, and Paul J. Wegner. *Applied Optics*, Vol. 49, No. 14, 10 May 2010.

# Information on model implementation

- The reflection and absorption coefficients are assumed to be constants.
- The planar surface of the glass slab incident to the laser beam is assumed to be aligned with the  $xy$ -plane of the global coordinate system.
- The top planar surface is aligned with  $z = 0$ . Hence the effect of absorption can be simulated by the term  $\exp(-Ac*\text{abs}(z))$ .
- The center of the beam can be easily shifted by changing  $x_0$  and  $y_0$ .
- The beam width and astigmatism can be easily controlled by the standard deviation parameters;  $\sigma_x$  and  $\sigma_y$ .

# Case 1: Stationary laser with constant power

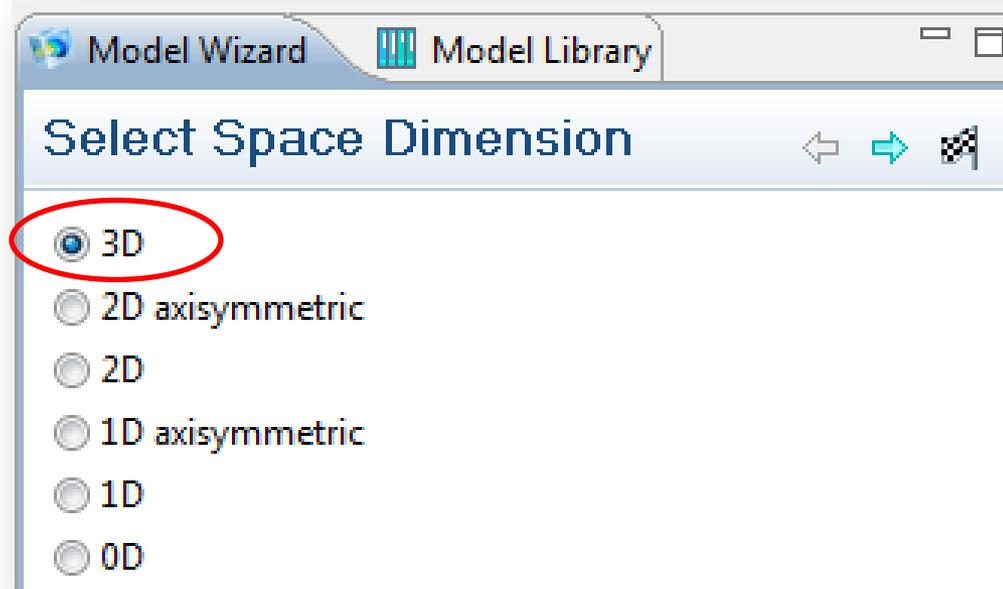
- This model investigates the transient heating of a glass slab when an incident laser beam in CW mode shines upon it for a given time.



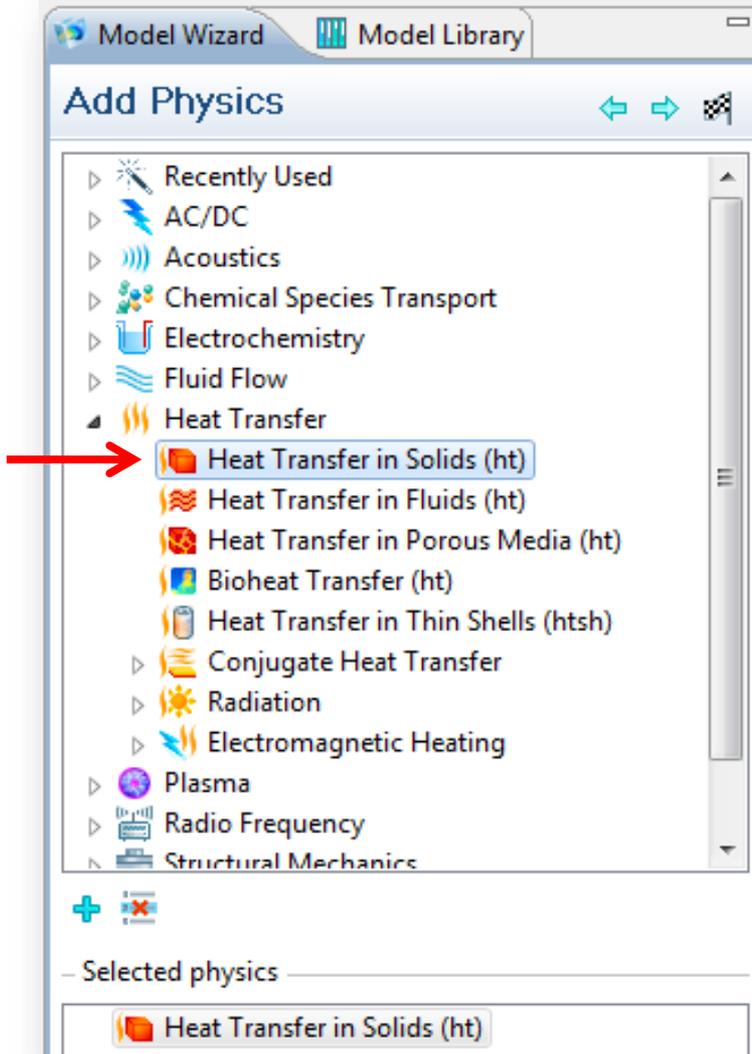
# Modeling Instructions

- The next few slides show the modeling steps and snapshots of the solution.
- For details refer to the model file: *laser\_heat\_transient\_CW.mph*

# Select Space Dimension

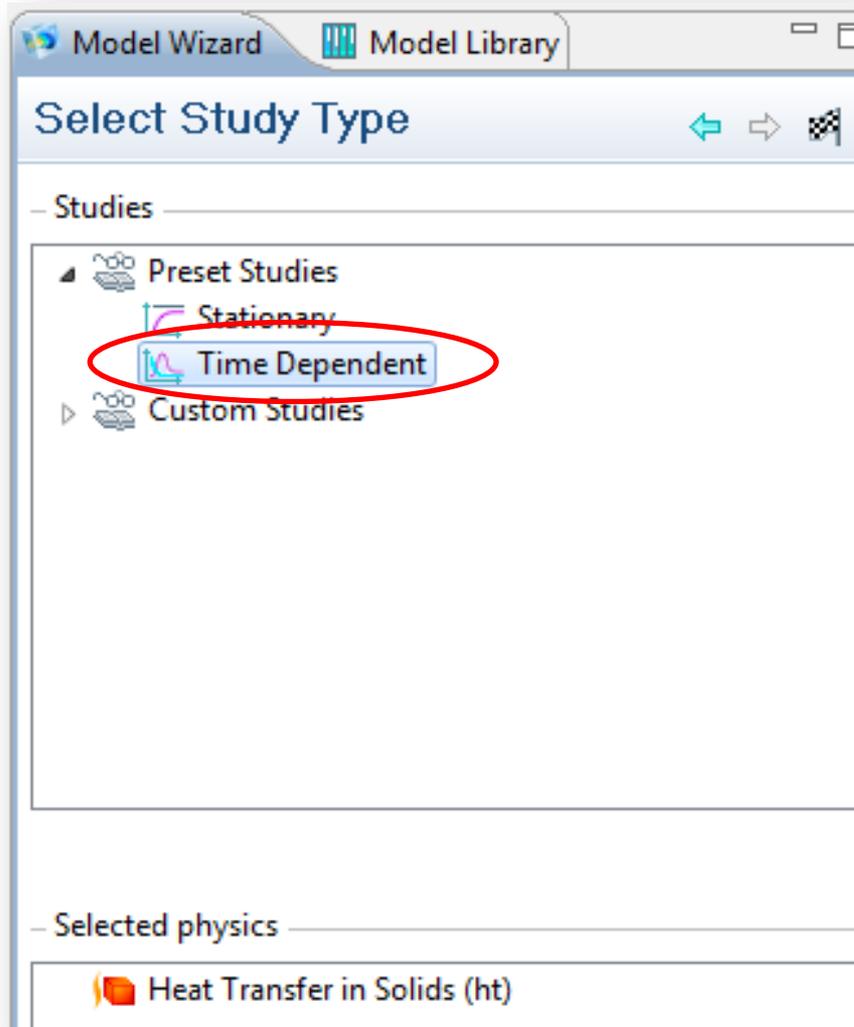


# Add Physics

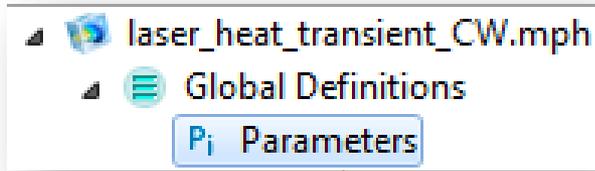


- Heat Transfer > Heat Transfer in Solids (ht)

# Select Study Type



# Parameters



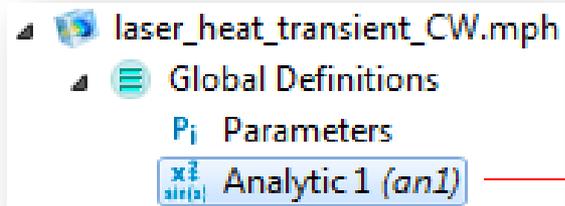
These numerical values are arbitrary and only for illustration purposes

Parameters

Parameters

Name	Expression	Value	Description
x0	0.5[mm]	5.0000E-4 m	Pulse center x-coordinate
y0	0[mm]	0 m	Pulse center y-coordinate
sigx	0.5[mm]	5.0000E-4 m	Pulse x standard deviation
sigy	0.75[mm]	7.5000E-4 m	Pulse y standard deviation
Q0	1[W]	1.0000 W	Total laser power
Rc	0.05	0.050000	Reflection coefficient
Ac	0.5[1/cm]	50.000 1/m	Absorption coefficient
L	20[mm]	0.020000 m	Slab size
Lz	5[mm]	0.0050000 m	Slab thickness

# Global Definitions > Functions > Analytic



This analytic function represents a 2D Gaussian pulse

**Analytic**

▼ Function Name

Function name:

▼ Parameters

Expression:

Arguments:

Derivatives:

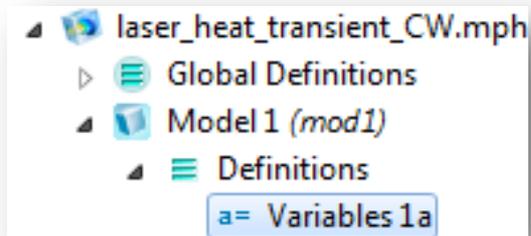
► Periodic Extension

▼ Units

Arguments:

Function:

# Variables



a= Variables

Geometric Entity Selection

Geometric entity level: Entire model

Variables

Name	Expression	Unit	Description
Q_in	$Q_0 \cdot (1 - R_c) \cdot A_c \cdot (1 / (\pi \cdot \sigma_x \cdot \sigma_y)) \cdot \text{an1}(x, x_0, \sigma_x, y, y_0, \sigma_y) \cdot \exp(-A_c \cdot \text{abs}(z))$	W/m <sup>3</sup>	Power input

# Geometry

The image displays the COMSOL software interface for defining geometry. On the left, the **Geometry 1** tree shows a hierarchy: **Block 1 (blk1)**, **Work Plane 1 (wp1)**, **Geometry**, and **Ellipse 1 (e1)**. Red arrows point from these items to their respective property panels:

- Block 1 (blk1)** points to the **Block** property panel.
- Ellipse 1 (e1)** points to the **Ellipse** property panel.
- The top-level **Geometry 1** points to the main **Geometry** property panel.

The **Block** property panel includes:

- Object Type:** Type: Solid
- Size and Shape:** Width: L, Depth: L, Height: Lz
- Position:** Base: Center, x: 0, y: 0, z: -Lz/2

The **Ellipse** property panel includes:

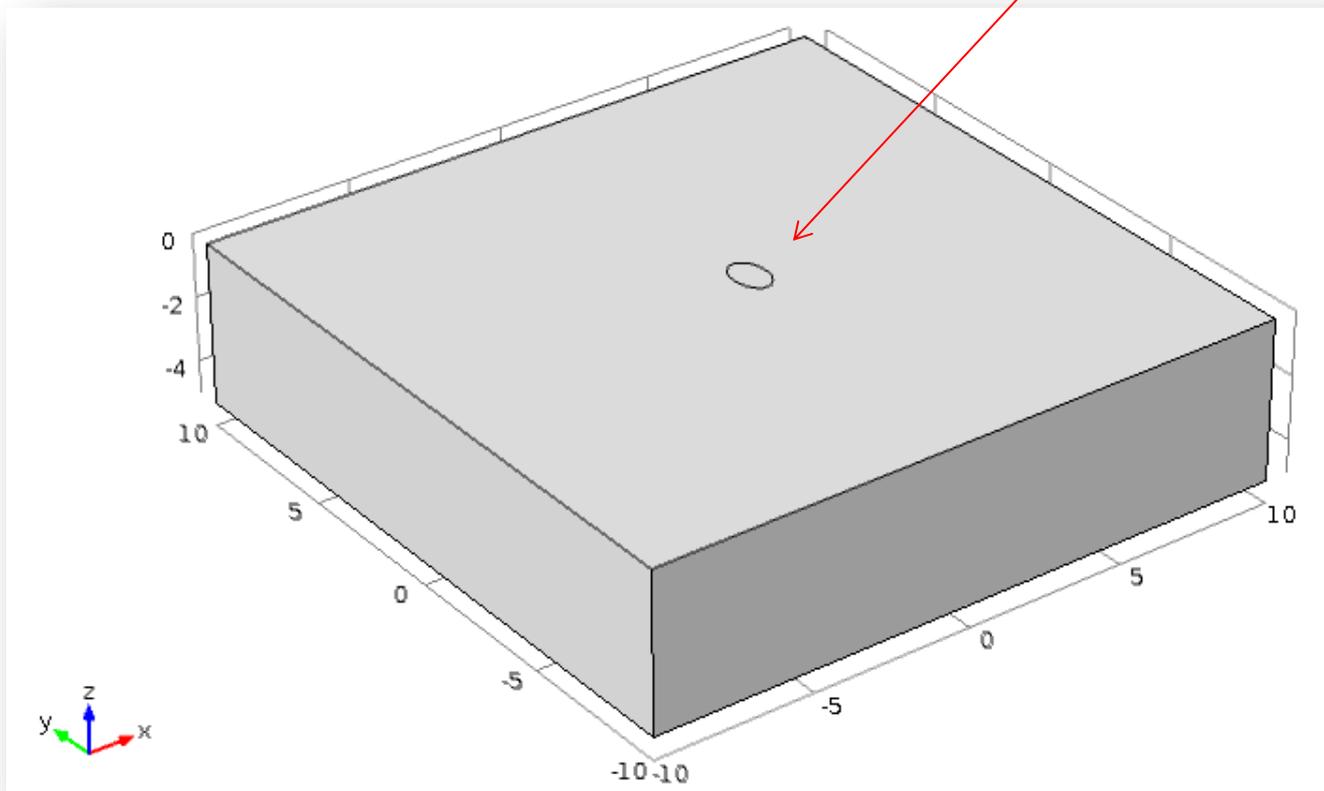
- Object Type:** Type: Solid
- Size and Shape:** a-semiaxis: sigx, b-semiaxis: sigy, Sector angle: 360
- Position:** Base: Center, x: x0, y: y0

The main **Geometry** property panel includes:

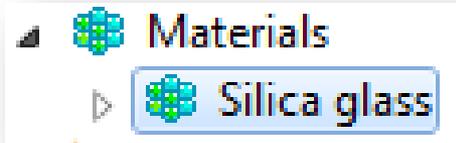
- Units:** Length unit: mm (circled in red)

# The actual geometry

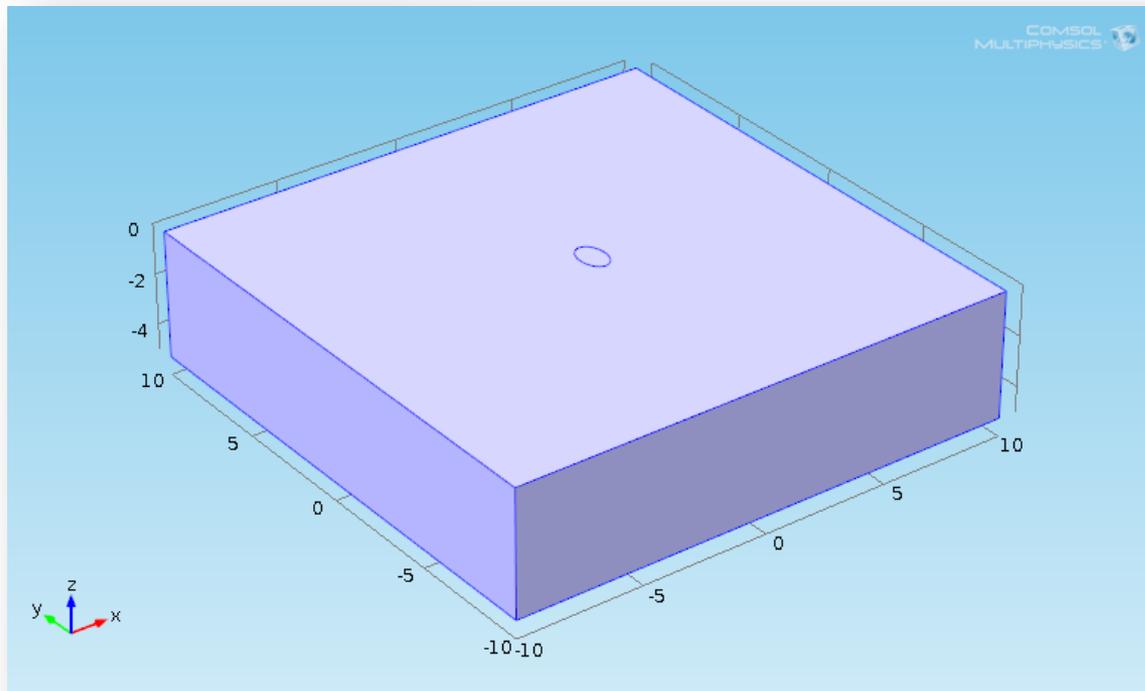
This elliptical surface created on the top surface is used to guide a finer mesh in the area where the laser beam is incident upon



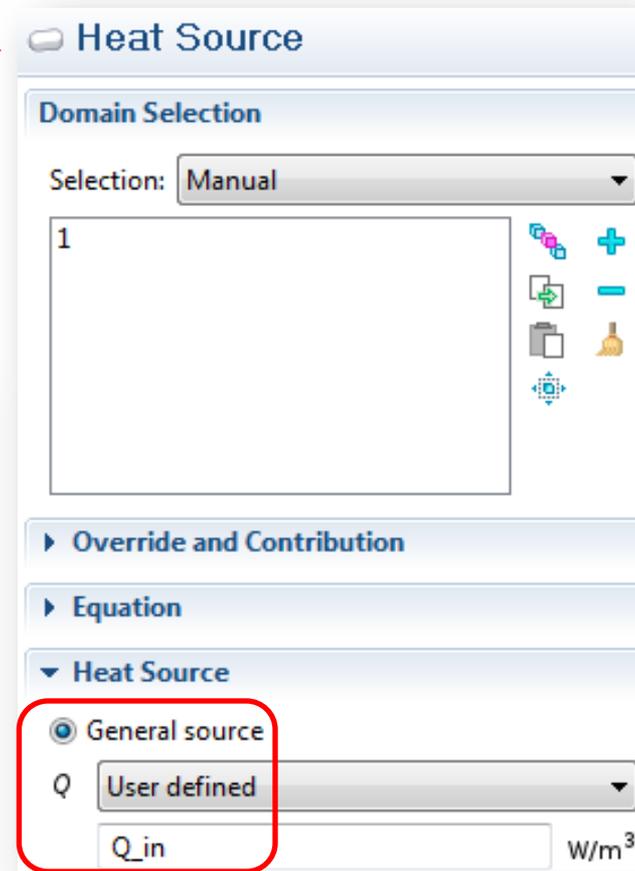
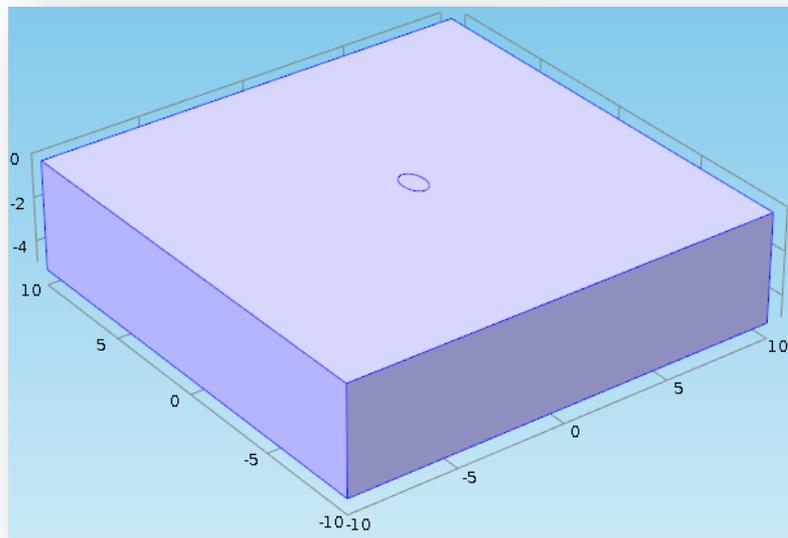
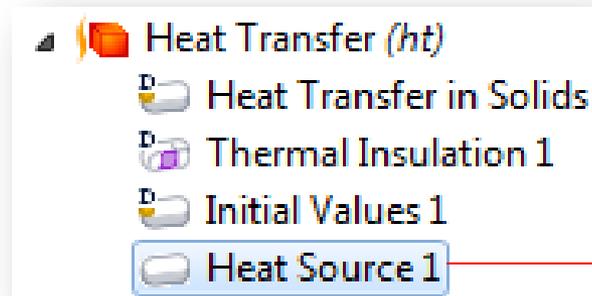
# Material properties



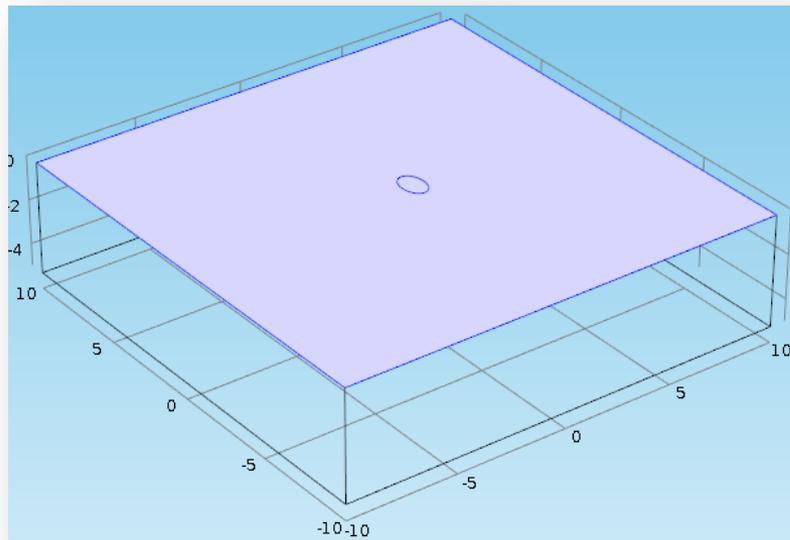
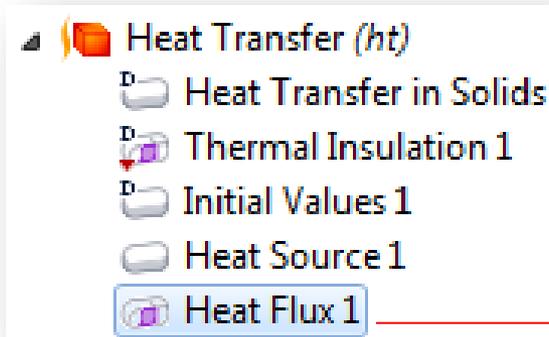
**Material Browser > Built-In > Silica glass**



# Heat Transfer > Heat Source



# Heat Transfer > Heat Flux



### Heat Flux

Boundary Selection

Selection: Manual

4  
6

Override and Contribution

Equation

Heat Flux

General inward heat flux

Inward heat flux

$q_0 = h \cdot (T_{\text{ext}} - T)$

Heat transfer coefficient:

$h$  2 W/(m<sup>2</sup>·K)

External temperature:

$T_{\text{ext}}$  293.15[K] K

Total heat flux

# Mesh

The image displays the COMSOL Mesh settings interface. On the left, a tree view shows 'Mesh 1' with sub-items: 'Size', 'Free Triangular 1', 'Size 1', and 'Swept 1'. Red arrows point from these items to their respective configuration panels. The 'Free Triangular' panel shows 'Geometric entity level: Boundary' and 'Selection: Manual' with a list containing '4' and '6'. The 'Size' panel (top right) shows 'Calibrate for: General physics' and 'Predefined' selected, with 'Coarser' highlighted in a red box. The 'Size' panel (bottom left) shows 'Geometric Entity Selection' with '6' in the list, 'Calibrate for: General physics', and 'Predefined' selected, with 'Extra fine' highlighted in a red box. A 3D plot on the right shows a square mesh with a central point, with a red arrow pointing from the '6' in the 'Free Triangular' panel to the mesh.

Mesh 1

- Size
- Free Triangular 1
- Size 1
- Swept 1

**Free Triangular**

Boundary Selection

Geometric entity level: Boundary

Selection: Manual

4  
6

**Size**

Element Size

Calibrate for: General physics

Predefined **Coarser**

**Size**

Geometric Entity Selection

Geometric entity level: Boundary

Selection: Manual

6

Element Size

Calibrate for: General physics

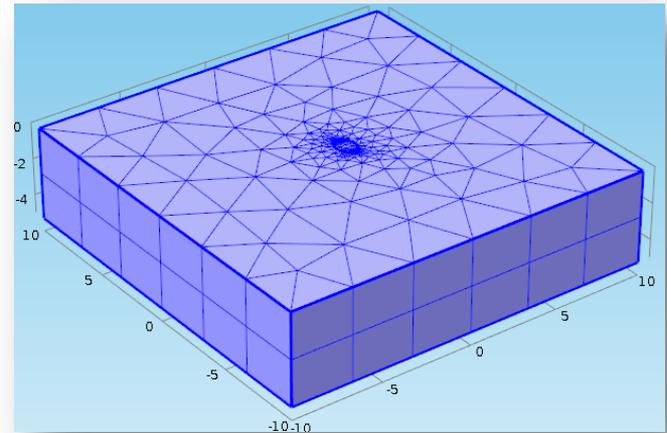
Predefined **Extra fine**

3D Mesh Plot

COMSOL

# Technical note on meshing

- We created an extra elliptical boundary on the top surface to represent the zone of heat input.
- The shape and position of this ellipse is parameterized.
- Use a fine enough mesh only on this ellipse to resolve the Gaussian pulse.
- Try to keep the overall mesh count low by using a swept mesh.
- \* If the absorption coefficient is very large then the heat source would be only effective near the top surface. This would require you to create a graded swept mesh with more layers.

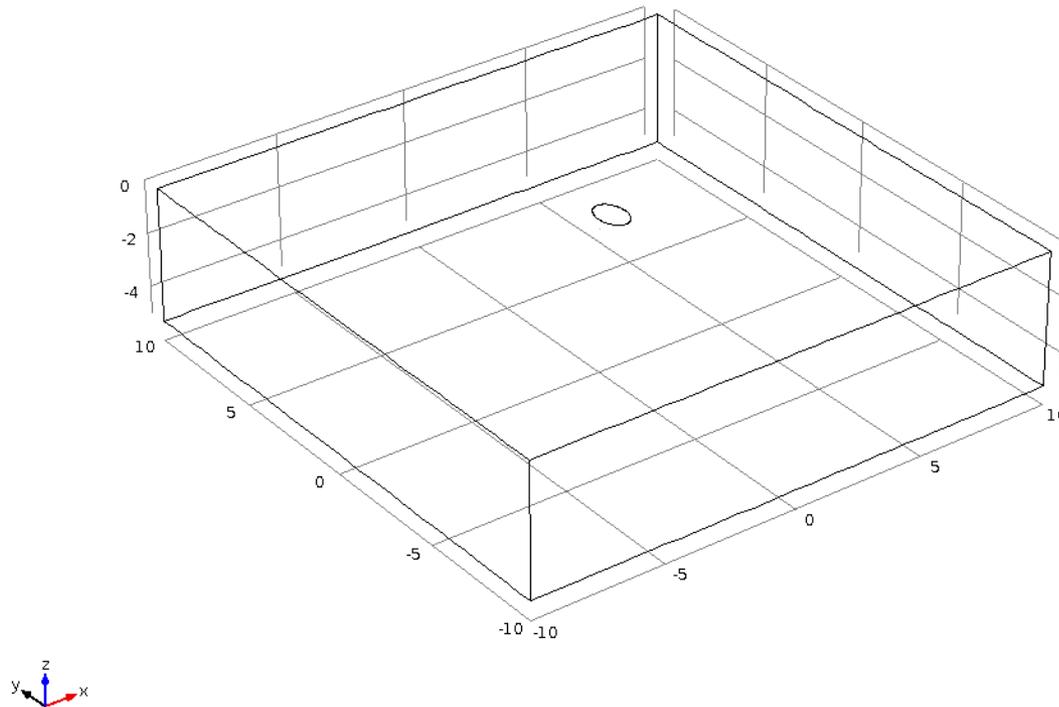


# Time-Dependent Study

The screenshot displays the COMSOL Multiphysics interface. On the left, the 'Model Builder' tree shows a project named 'laser\_heat\_transient\_CW.mph (root)'. Under 'Model 1 (mod1)', the 'Study 1' folder is expanded, and 'Step 1: Time Dependent' is highlighted with a red box. The right-hand side shows the 'Settings' window for the 'Time Dependent' study. The 'Study Settings' section is expanded, showing the 'Times' field set to 'range(0,5,300)' with a unit of 's', highlighted by a red box. Below this, the 'Relative tolerance' is set to '0.01'. Other sections like 'Results While Solving' and 'Mesh Selection' are partially visible.

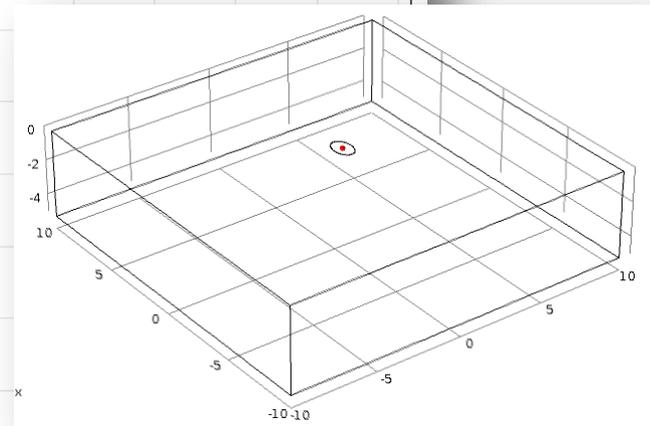
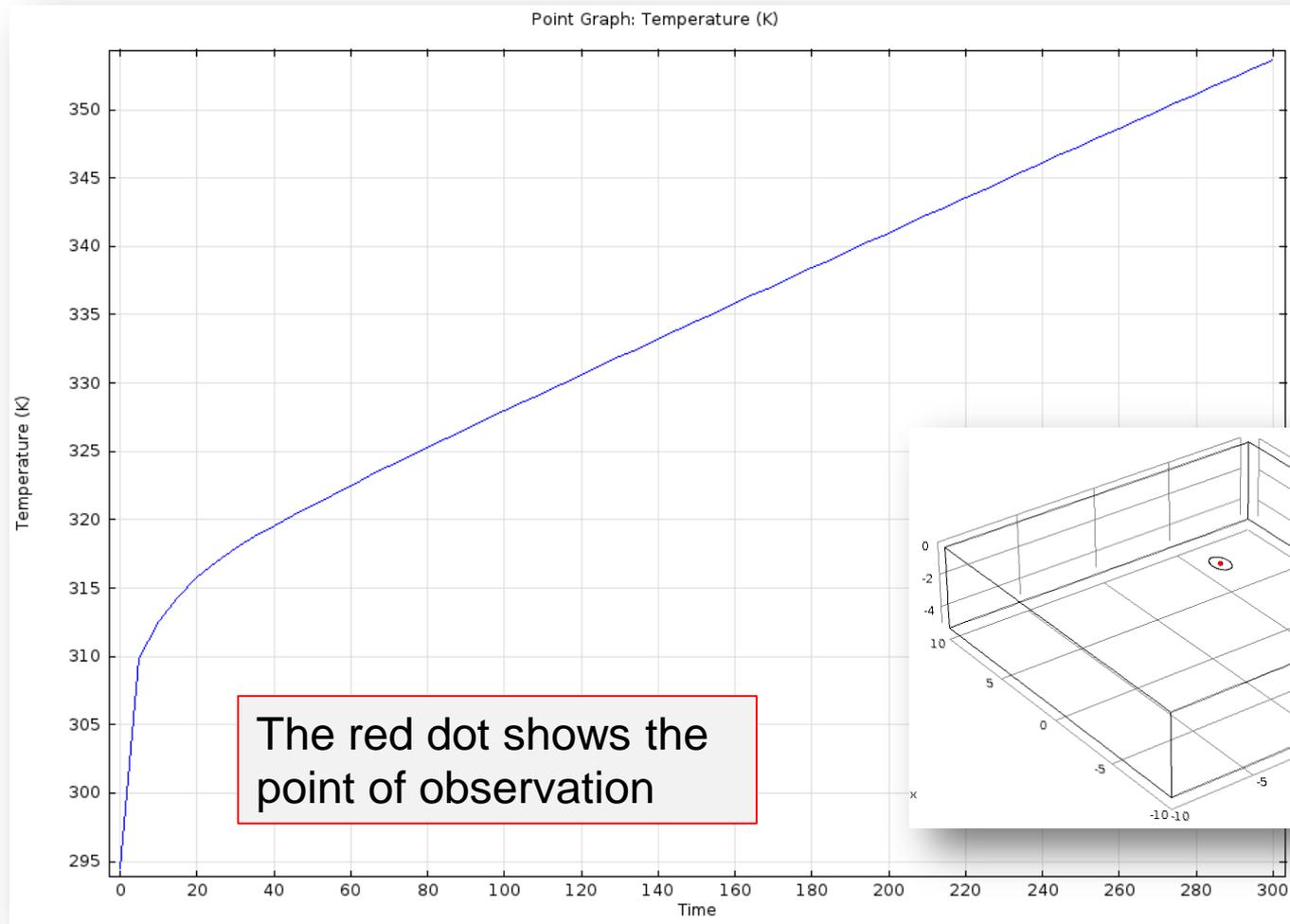
# Results – Isosurface Temperature

Time=0 Arrow Volume: Temperature gradient

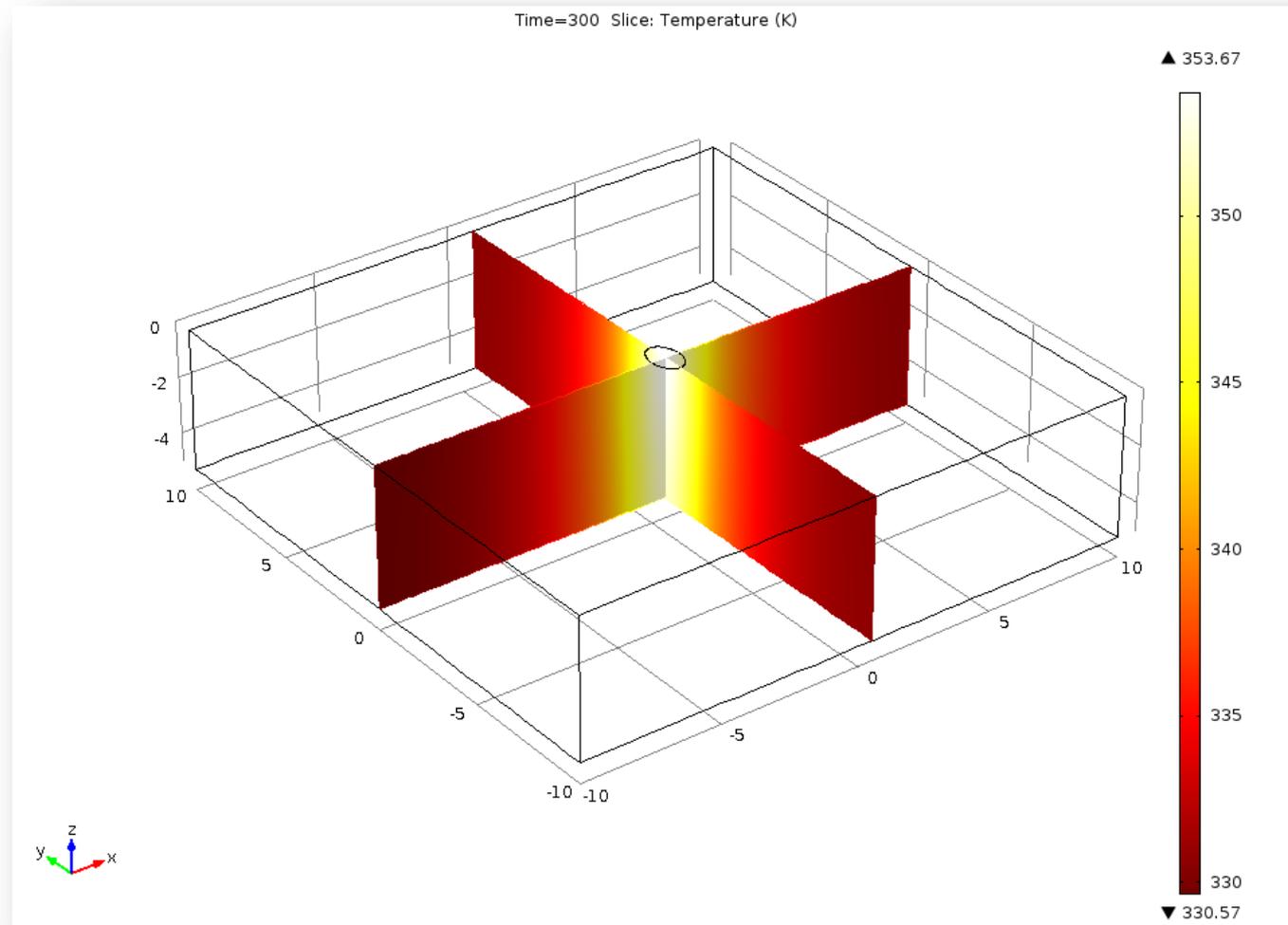


***Enable slide show to see the movie***

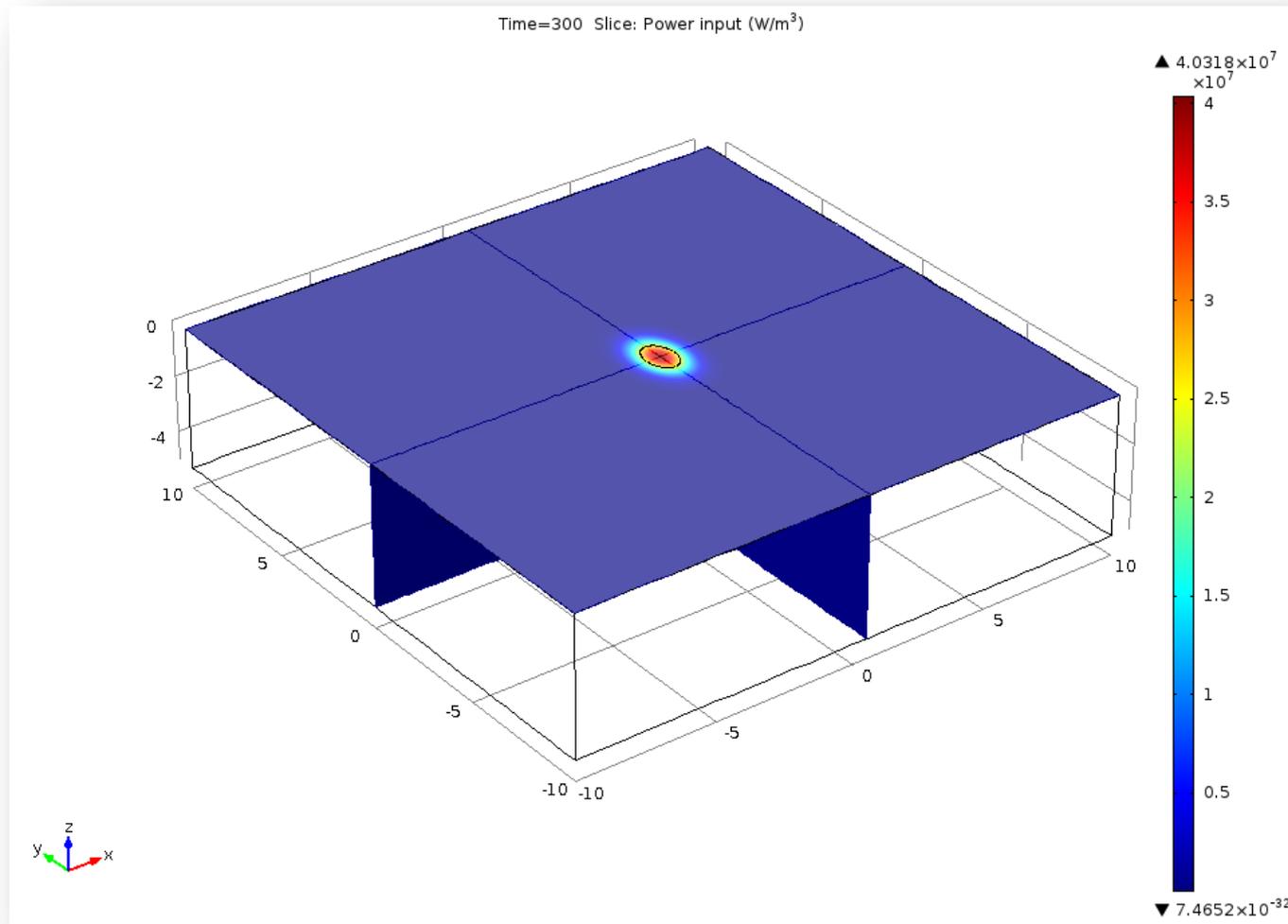
# Temperature vs. Time



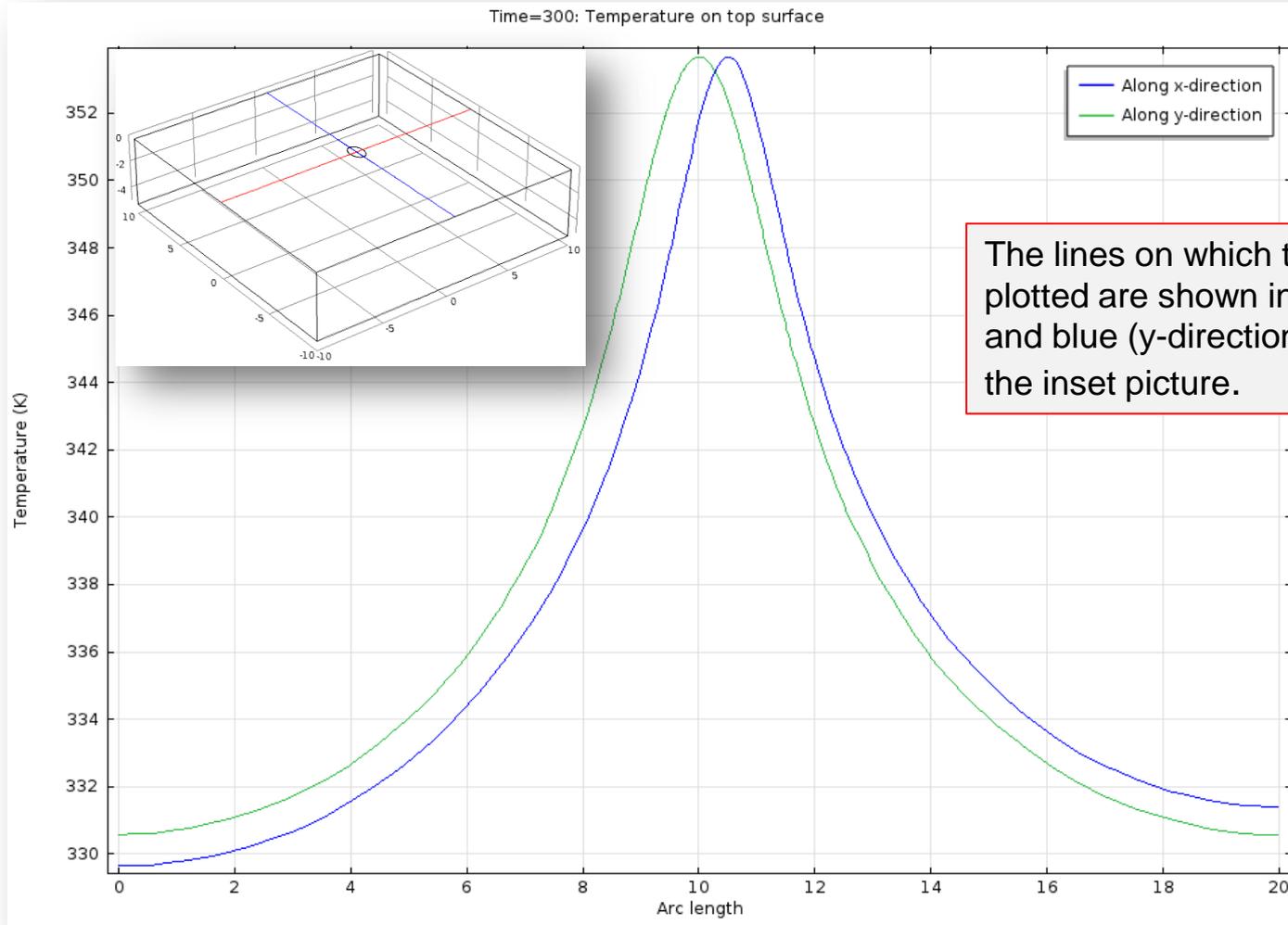
# Slice plots of temperature



# Slice plots of heat input

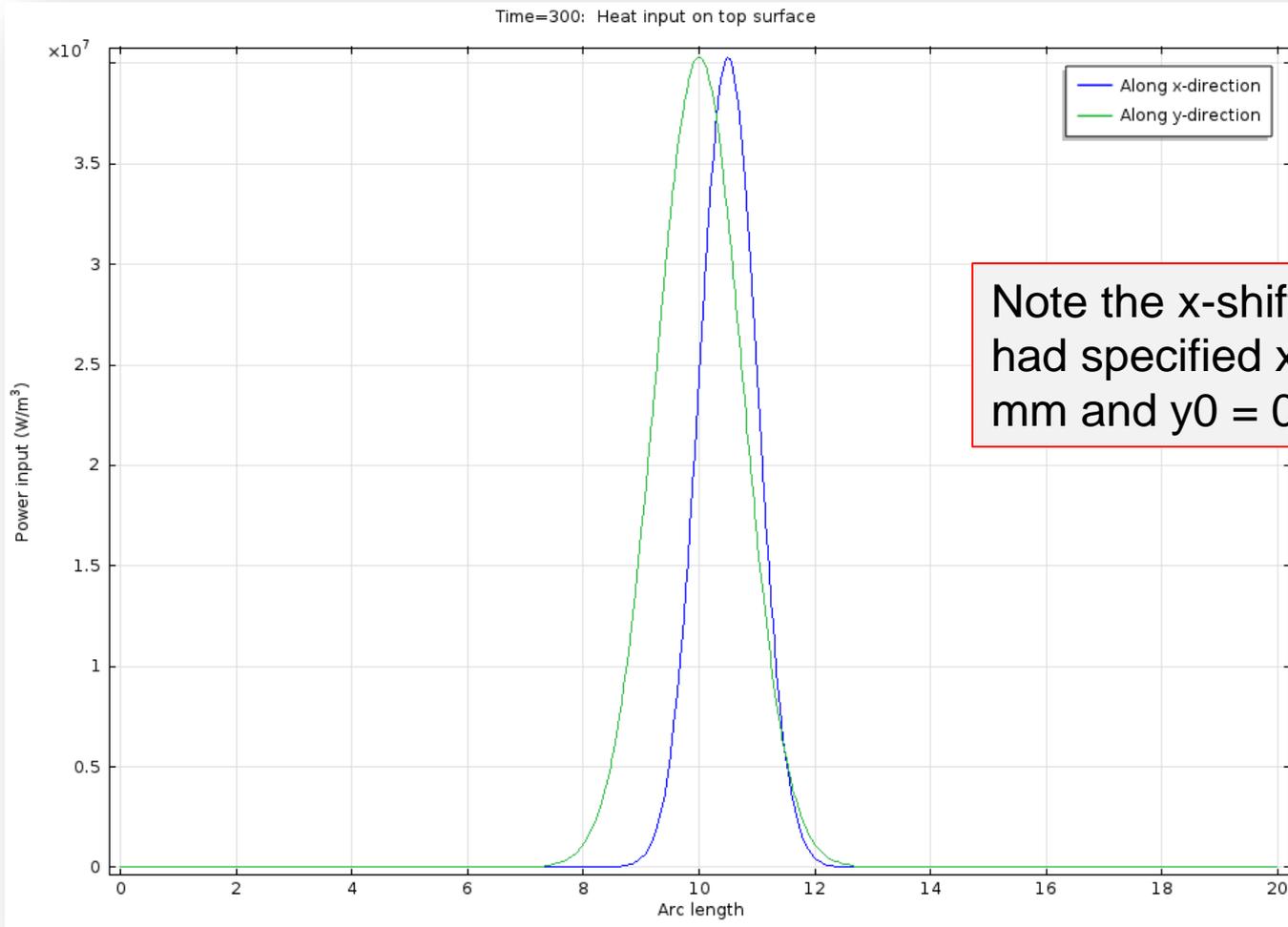


# Temperature along top surface



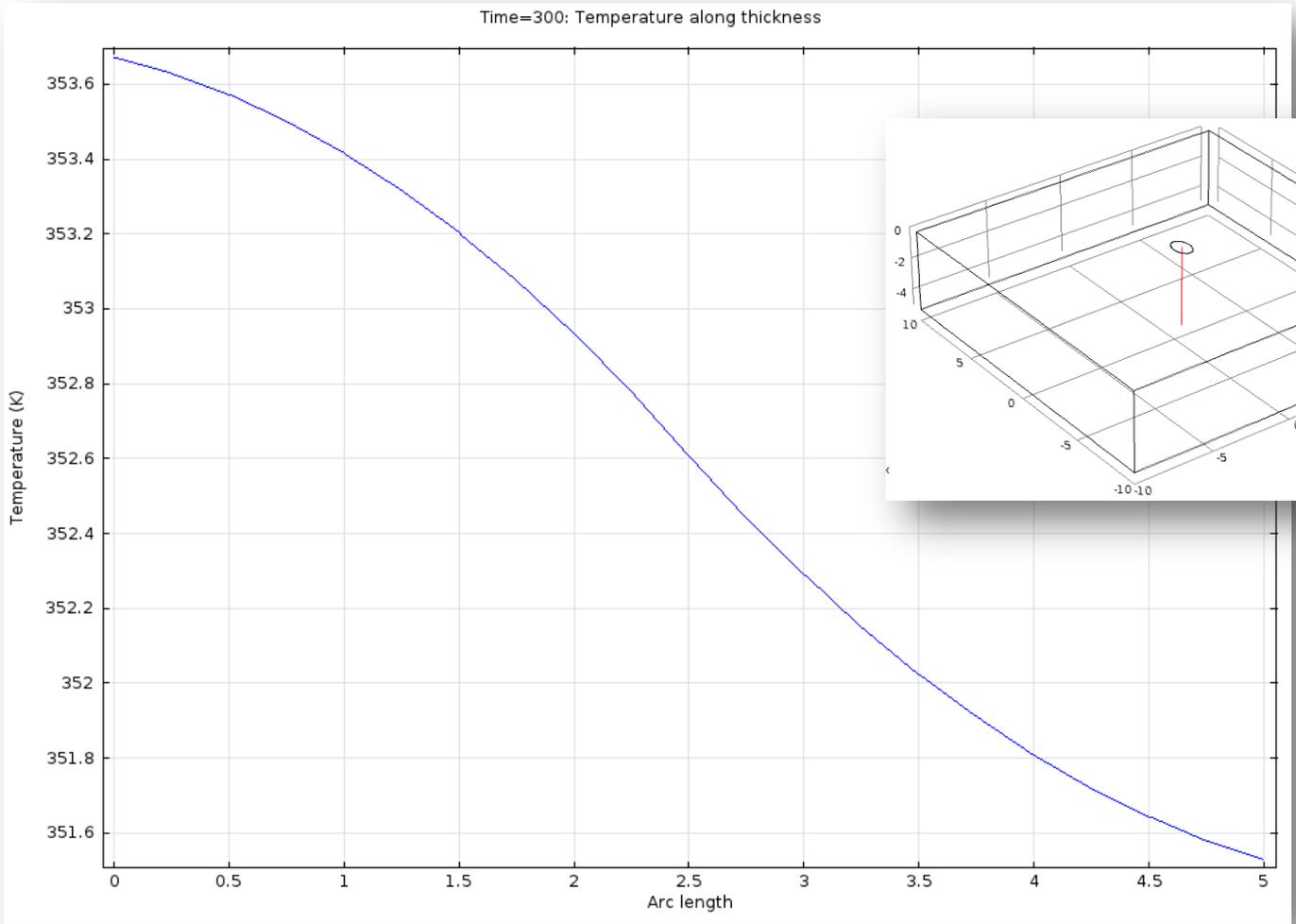
The lines on which the solution were plotted are shown in red (x-direction) and blue (y-direction) respectively in the inset picture.

# Heat input along top surface

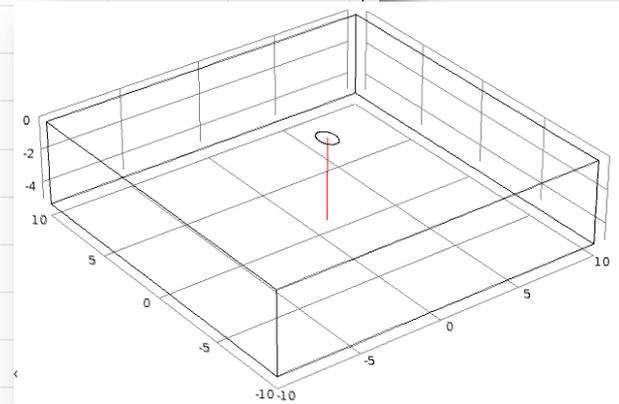
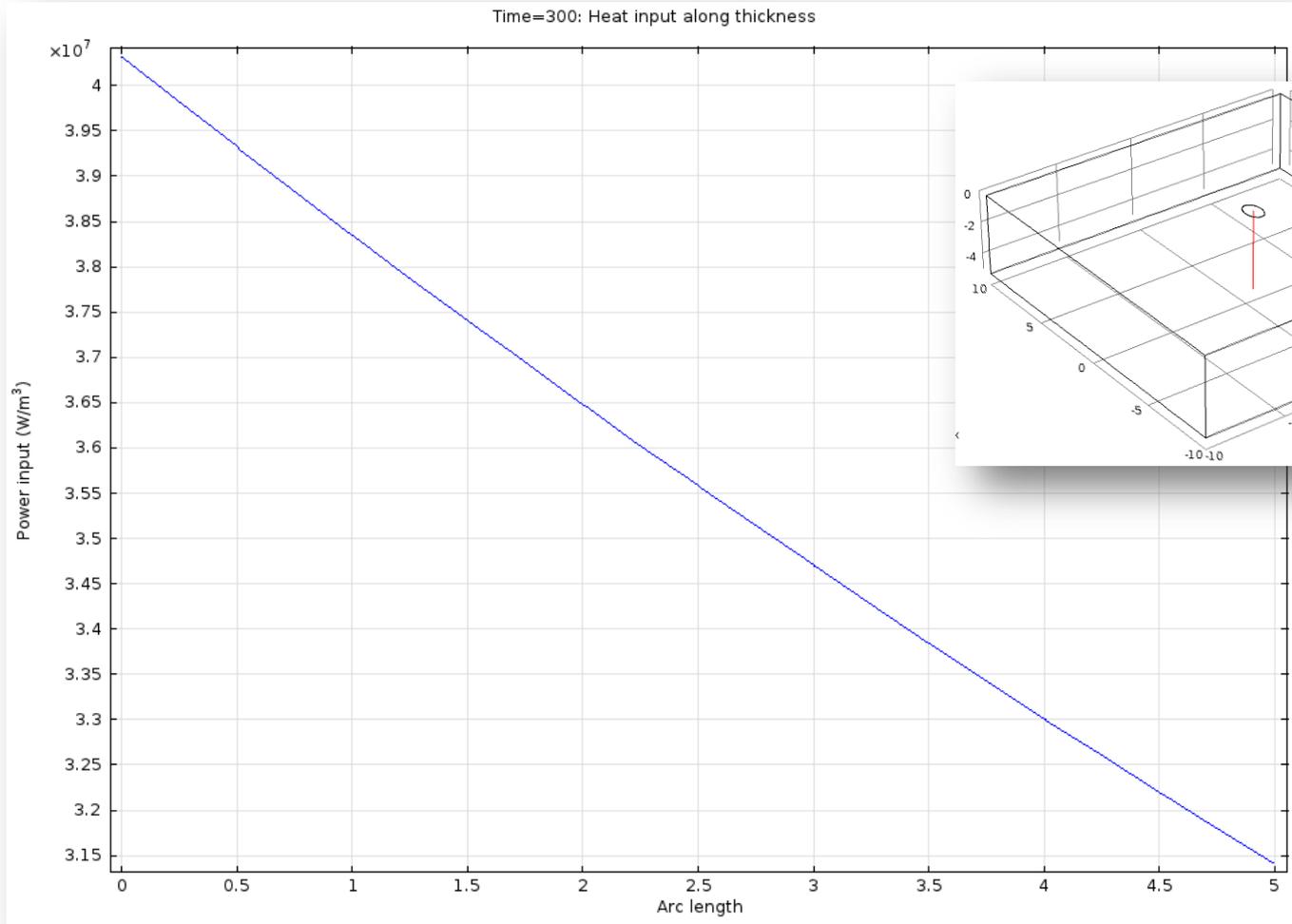


Note the x-shift since we had specified  $x_0 = 0.5$  mm and  $y_0 = 0$  mm

# Temperature along thickness



# Heat input along thickness

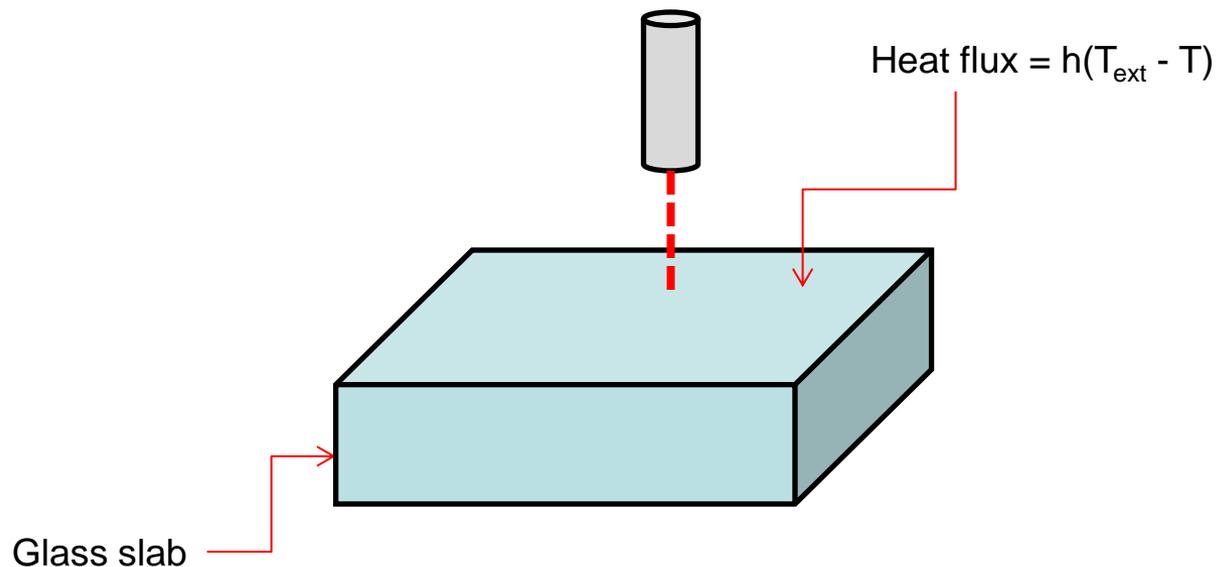


# Things to try

- Use an Extremely Coarse mesh and solve the model again. How does the solution look?
- Go to **Global Definitions > Parameters** and use a much smaller value of  $\text{sig}_x$  and  $\text{sig}_y$ . Is the same mesh good enough?

## Case 2: Stationary laser with pulsed power

- This model investigates the transient heating of a glass slab when an incident laser beam in pulsed mode shines upon it for a given time.



# Modeling Instructions

- The next few slides show the modeling steps and snapshots of the solution.
- You can start from the previous model and make changes or add new steps as shown in the following slides.
- For details refer to the model file: *laser\_heat\_transient\_pulsed.mph*

# Parameters

## P<sub>i</sub> Parameters

Note that the value of **Q0** is an arbitrary high number that is chosen for illustration purposes only.

### Parameters

Name	Expression	Value	Description
x0	0.5[mm]	5.0000E-4 m	Pulse center x-coordinate
y0	0[mm]	0 m	Pulse center y-coordinate
sigx	0.5[mm]	5.0000E-4 m	Pulse x standard deviation
sigy	0.75[mm]	7.5000E-4 m	Pulse y standard deviation
Q0	1[MW]	1.0000E6 W	Total laser power
Rc	0.05	0.050000	Reflection coefficient
Ac	0.5[1/cm]	50.000 1/m	Absorption coefficient
L	20[mm]	0.020000 m	Slab size
Lz	5[mm]	0.0050000 m	Slab thickness
pulse_wid...	10[ns]	1.0000E-8 s	Temporal pulse width
time_step	pulse_width/5	2.0000E-9 s	Time step to store solution
end time	0.2[us]	2.0000E-7 s	Last time step

# Global Definitions > Functions > Triangle

The image shows a software interface with two panels. The left panel, titled 'Global Definitions', contains a list of items: 'Parameters', 'Analytic 1 (an1)', and 'Triangle 1 (tri1)'. A red arrow points from the 'Triangle 1 (tri1)' item to the right panel. The right panel, titled '^ Triangle', displays configuration options for the function. It is organized into three sections: 'Function Name', 'Parameters', and 'Smoothing'. The 'Function Name' section has a text input field containing 'tri1'. The 'Parameters' section has two text input fields: 'Lower limit' with the value 'pulse\_width/2' and 'Upper limit' with the value 'pulse\_width/2+pulse\_width'. The 'Smoothing' section has a checked checkbox for 'Size of transition zone' and a text input field containing 'pulse\_width/10'.

Global Definitions

- Parameters
- Analytic 1 (*an1*)
- Triangle 1 (*tri1*)

^ Triangle

Function Name

Function name:

Parameters

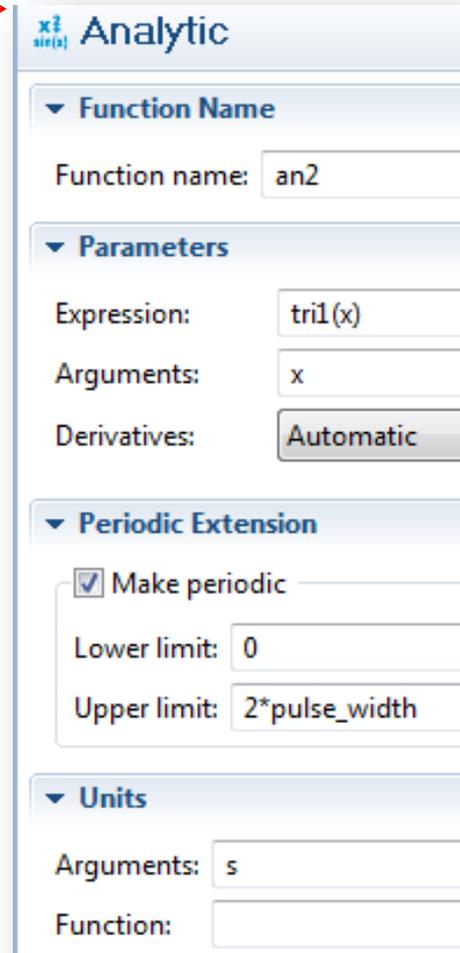
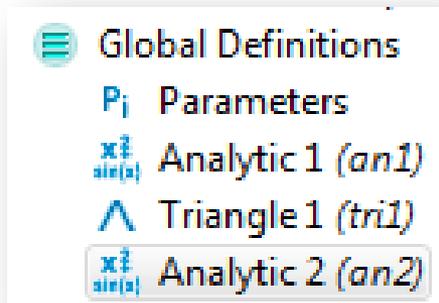
Lower limit:

Upper limit:

Smoothing

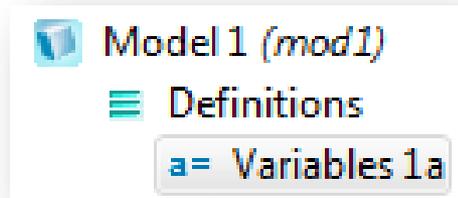
Size of transition zone:

# Global Definitions > Functions > Analytic



This approach can be used to create a series of periodic triangular pulses with variable duty cycle

# Variables



This is how the effect of pulsed heat input is simulated

a= Variables

Geometric Entity Selection

Geometric entity level: Entire model

Variables

Name	Expression	Unit	Description
Q_in	$Q_0 \cdot (1 - R_c) \cdot A_c \cdot \frac{1}{(\pi \cdot \text{sig}_x \cdot \text{sig}_y)} \cdot \text{an1}(x, x_0, \text{sig}_x, y, y_0, \text{sig}_y) \cdot \exp(-A_c \cdot \text{abs}(z)) \cdot \text{an2}(t)$	W/m <sup>3</sup>	Power input

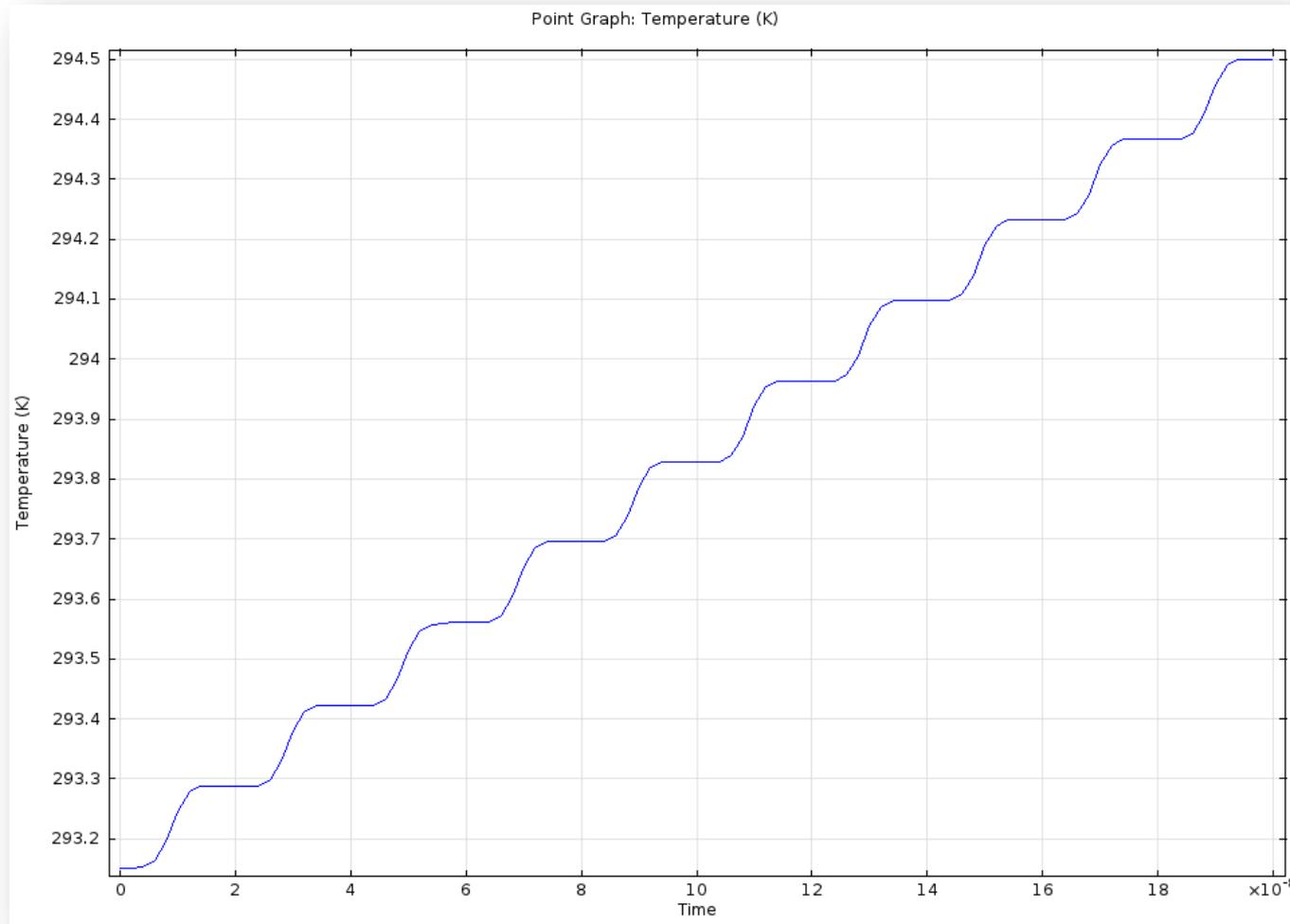
Multiply the original function with a function of time

# Time-Dependent Study

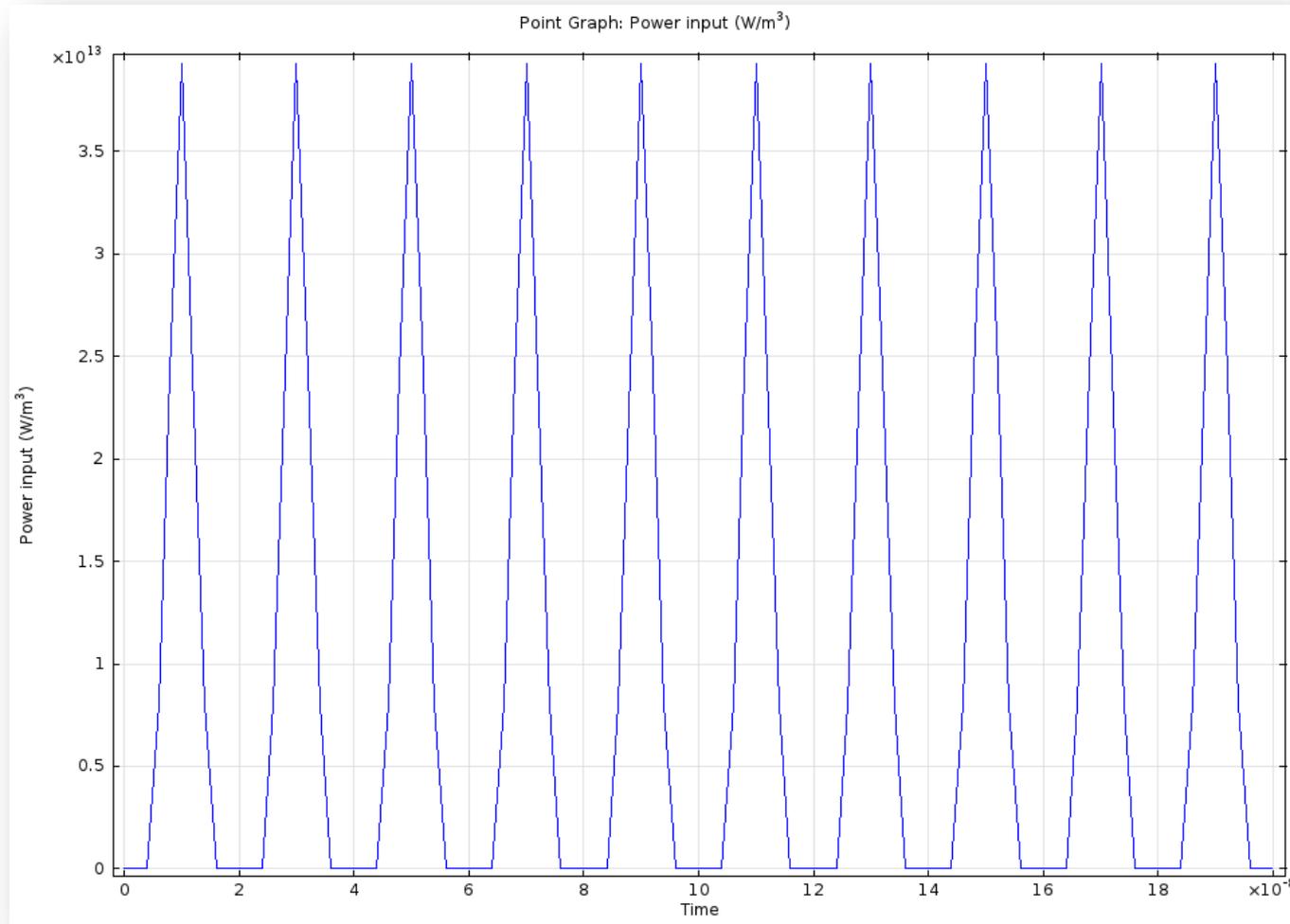
The screenshot displays the COMSOL software interface for setting up a Time-Dependent Study. On the left, the 'Study 1' tree view is expanded to show 'Time-Dependent Solver 1'. On the right, the 'Time Dependent' settings panel is visible, showing the 'Times' field set to 'range(0,time\_step,end\_time)' and the 'Steps taken by solver' dropdown set to 'Intermediate'.

- For illustration purposes we have chosen the *end\_time* such that this model will simulate only ten pulses.
- Note that solving for a longer time scale will involve more computational time and memory.

# Results – Temperature at the center of beam spot as a function of time



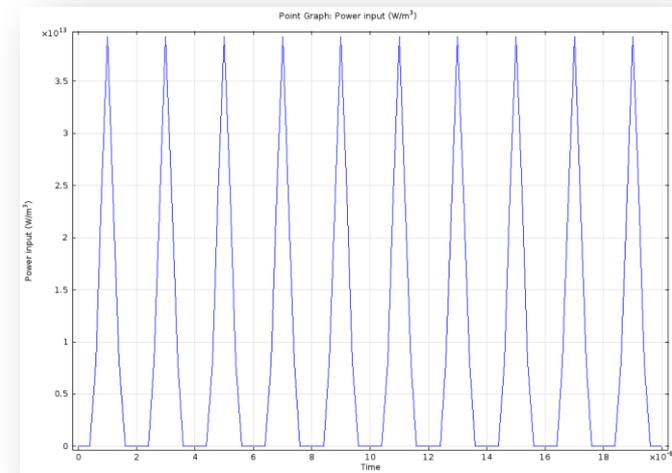
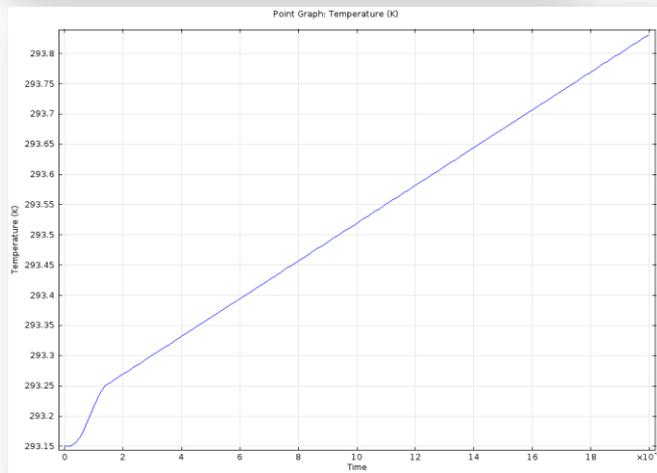
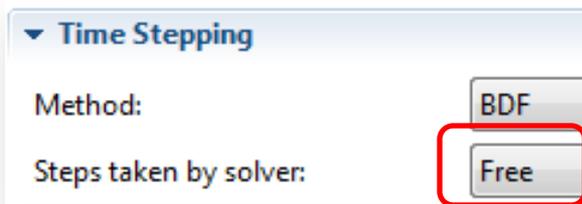
# Results – Heat input at the center of beam spot as a function of time



# Suggestions on time stepping

- The choice of *intermediate* steps provides better resolution of the solution over time without saving the solution at too many small time steps.
- This choice could be useful when the input to the model are short pulses.
- The default *free* time stepping may completely ignore these pulses.
- The *intermediate* option involves more computational time than the default *free* option.
- Hence we should always solve the model once with the default *free* time stepping and inspect the solution to see whether it is lacking any physical behavior.

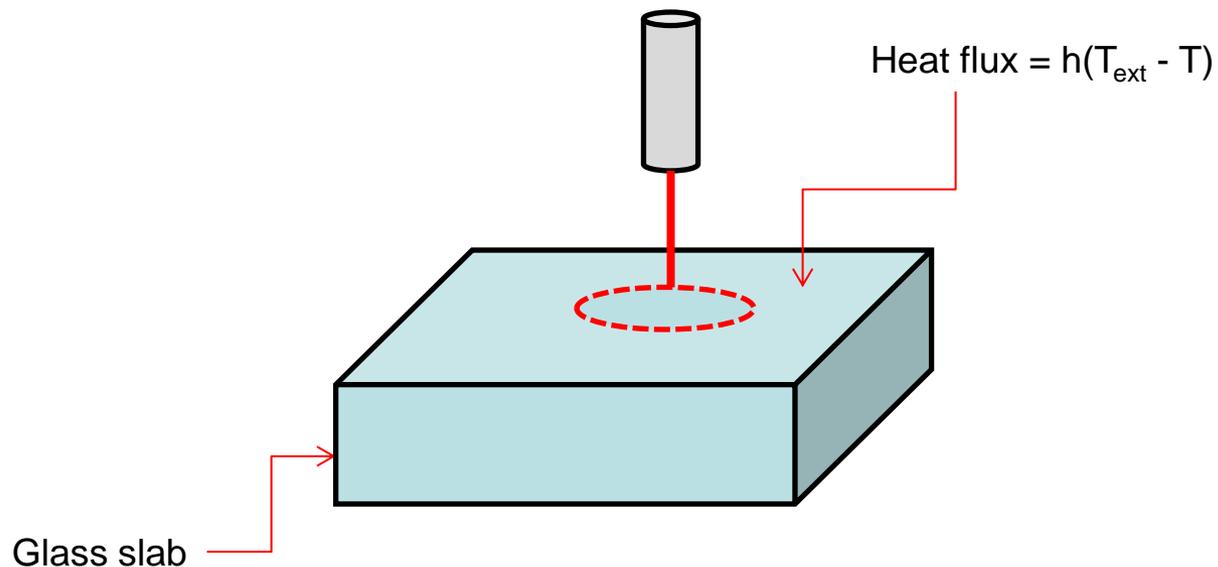
# Solving the same model with free time stepping algorithm



- Temperature vs. time behavior does not look correct!
- Maximum temperature is underpredicted.
- Heat input profile is accurately captured.

# Case 3: Moving laser with constant power

- This model investigates the transient heating of a glass slab when an incident laser beam in CW mode shines upon it for a given time.
- The laser beam also moves over the surface at a given speed along a prescribed path.



# Modeling Instructions

- The next few slides show the modeling steps and snapshots of the solution.
- You can start from the first model and make changes or add new steps as shown in the following slides.
- For details refer to the model file:  
*laser\_heat\_transient\_CW\_moving.mph*

# Parameters

## Parameters

These numerical values are arbitrary and only for illustration purposes

### Parameters

Name	Expression	Value	Description
x0	0[mm]	0 m	Path center x-coordinate
y0	0[mm]	0 m	Path center y-coordinate
sigx	0.25[mm]	2.5000E-4 m	Pulse x standard deviation
sigy	0.25[mm]	2.5000E-4 m	Pulse y standard deviation
Q0	1[W]	1.0000 W	Total laser power
Rc	0.05	0.050000	Reflection coefficient
Ac	0.5[1/cm]	50.000 1/m	Absorption coefficient
L	40[mm]	0.040000 m	Slab size
Lz	5[mm]	0.0050000 m	Slab thickness
rad	10[mm]	0.010000 m	Laser path radius
v	1[mm/s]	0.0010000 m/s	Laser velocity
omega	v/rad	0.10000 1/s	Angular velocity
time_end	2*pi/omega	62.832 s	Last time step
time_step	time_end/50	1.2566 s	Time step

# Variables

Model 1 (mod1)  
Definitions  
a= Variables 1a

- Note how the center spot of the beam is obtained from the parametric equation of the path of laser motion.
- This is how the time-dependency in the beam position is implemented.

a= Variables

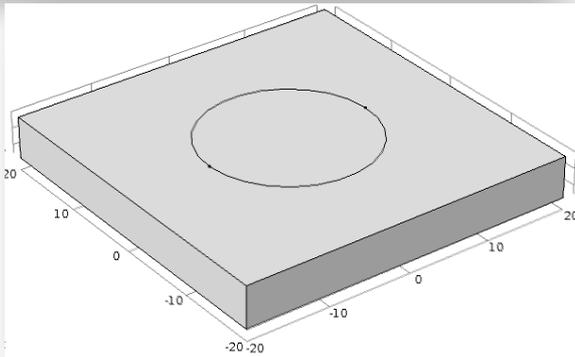
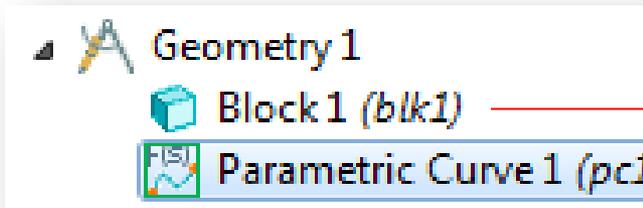
## Geometric Entity Selection

Geometric entity level: Entire model

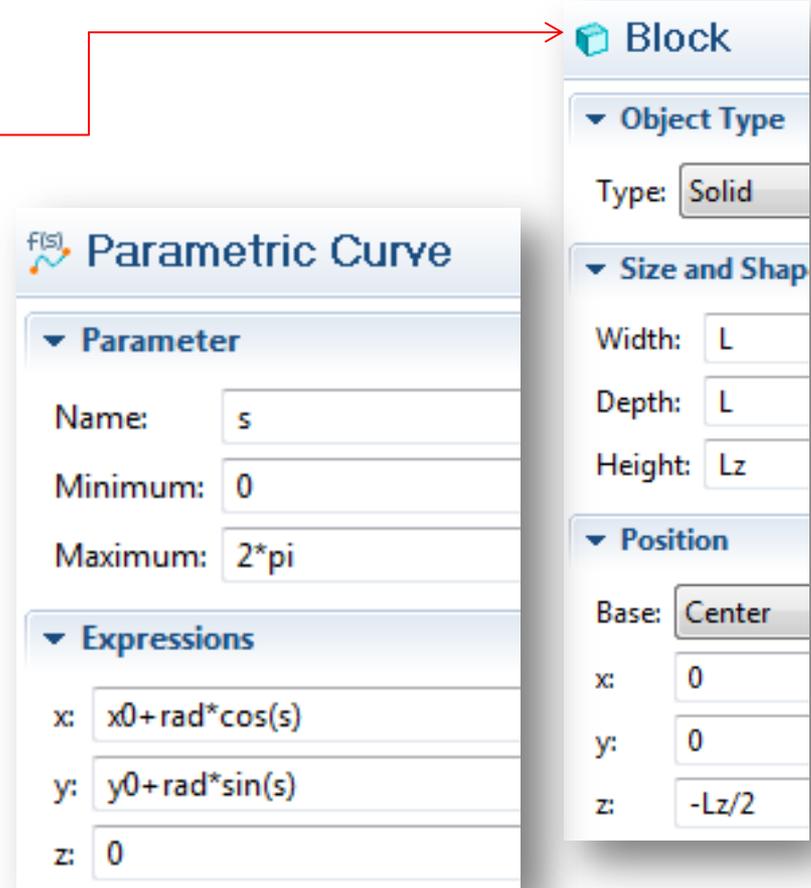
## Variables

Name	Expression	Unit	Description
x00	$x_0 + \text{rad} \cdot \cos(\omega \cdot t)$	m	Pulse center x-coordinate
y00	$y_0 + \text{rad} \cdot \sin(\omega \cdot t)$	m	Pulse center y-coordinate
Q_in	$Q_0 \cdot (1 - R_c) \cdot A_c \cdot (1 / (\pi \cdot \text{sig}_x \cdot \text{sig}_y)) \cdot \text{an1}(x, x_{00}, \text{sig}_x, y, y_{00}, \text{sig}_y) \cdot \exp(-A_c \cdot \text{abs}(z))$	W/m <sup>3</sup>	Power input

# Geometry



- We create extra geometric edges on the top surface which outline the path of laser motion.
- These edges are used to guide a finer mesh only along the path of laser motion.
- Although we use a circular path in this tutorial, in general you could create any arbitrary path using the Parametric Curve or Interpolation Curve geometry features.



**Block**

Object Type: Solid

Size and Shape: Width: L, Depth: L, Height: Lz

Position: Base: Center, x: 0, y: 0, z: -Lz/2

**Parametric Curve**

Parameter: Name: s, Minimum: 0, Maximum:  $2\pi$

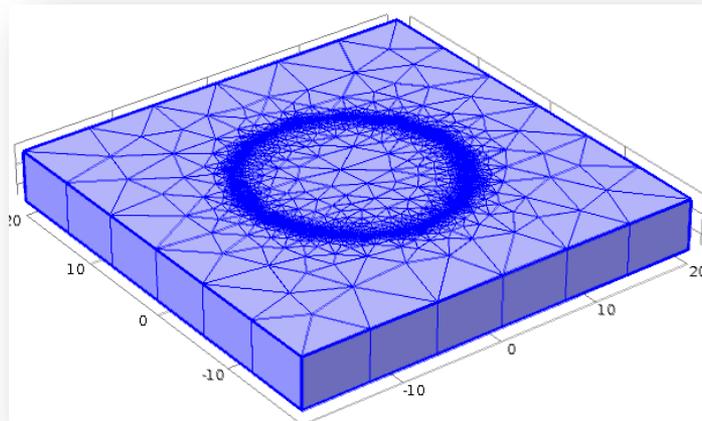
Expressions: x:  $x_0 + \text{rad} \cdot \cos(s)$ , y:  $y_0 + \text{rad} \cdot \sin(s)$ , z: 0

# Mesh

The image shows a screenshot of the COMSOL Mesh settings interface. On the left, a tree view shows the mesh hierarchy: Mesh 1, Size, Free Triangular 1, Size 1, and Swept 1. The 'Free Triangular 1' node is selected. Three red arrows point from this node to three different panels:

- The top-right panel is titled 'Size' and shows 'Element Size' settings. Under 'Calibrate for', 'General physics' is selected. Under 'Predefined', the 'Coarser' button is highlighted with a red box.
- The bottom-center panel is titled 'Free Triangular' and shows 'Boundary Selection' settings. 'Geometric entity level' is set to 'Boundary' and 'Selection' is set to 'Manual'. A list below shows '4' and '6'.
- The 'Free Triangular 1' node in the tree view is highlighted with a blue selection box.

# Mesh



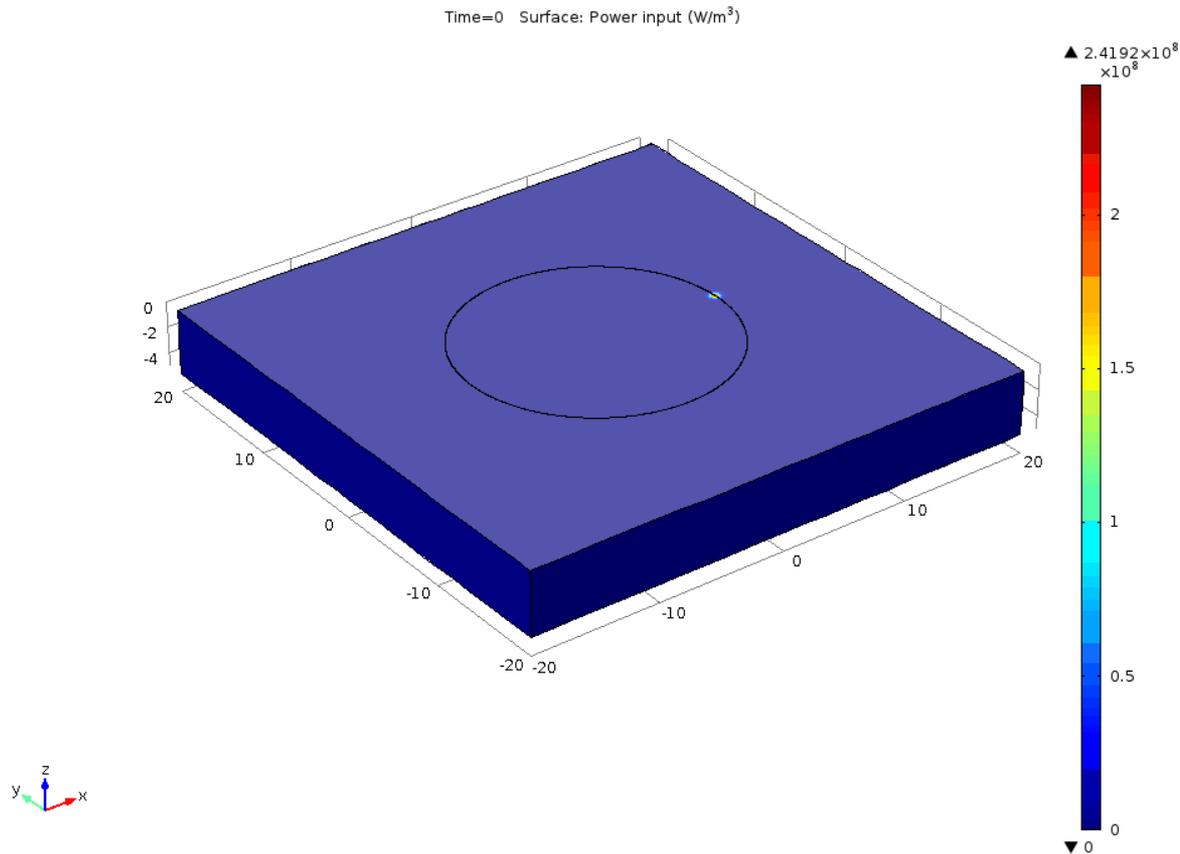
The 'Size' property panel is shown on the right. It has a title bar with a mesh icon and the word 'Size'. Below the title bar, there are two sections: 'Geometric Entity Selection' and 'Element Size'. In the 'Geometric Entity Selection' section, the 'Geometric entity level:' dropdown is set to 'Edge' and is highlighted with a red box. Below it, the 'Selection:' dropdown is set to 'Manual'. A list box contains the numbers '9' and '10'. In the 'Element Size' section, 'Calibrate for:' is set to 'General physics'. Under 'Predefined', 'Extremely fine' is selected. Under 'Custom', the 'Custom' radio button is selected. In the 'Element Size Parameters' section, the 'Maximum element size:' checkbox is checked and highlighted with a red box, and the value '0.2' is entered in the adjacent text box.

# Time-Dependent Study

The screenshot displays the COMSOL software interface for setting up a Time-Dependent Study. On the left, the 'Study 1' tree view is expanded to show 'Time-Dependent Solver 1'. On the right, the 'Time Dependent' settings panel is visible, showing the 'Study Settings' and 'Time Stepping' sections. The 'Times' field is set to 'range(0,time\_step,time\_end)' and the 'Steps taken by solver' dropdown is set to 'Intermediate'.

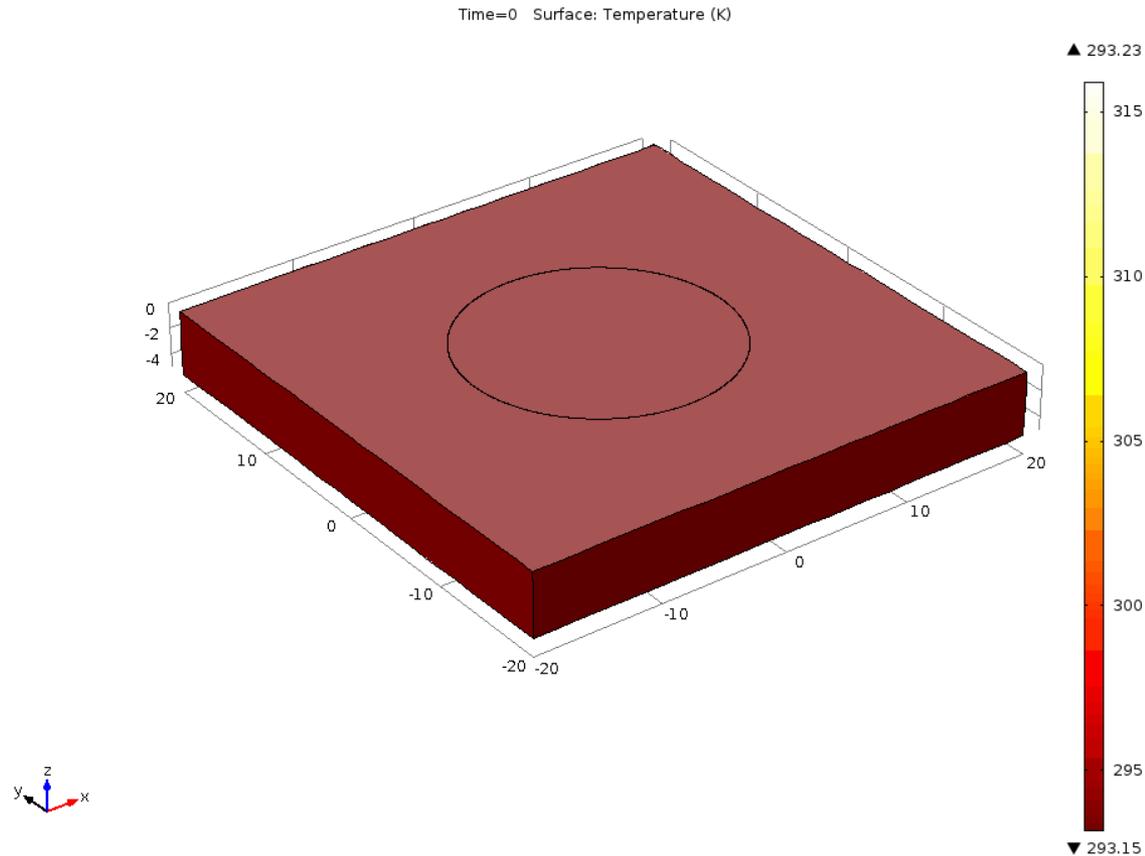
- For illustration purposes we have chosen the *time\_end* such that this model will simulate one revolution of the laser beam along the circular path.

# Results – Moving laser beam



***Enable slide show to see the movie***

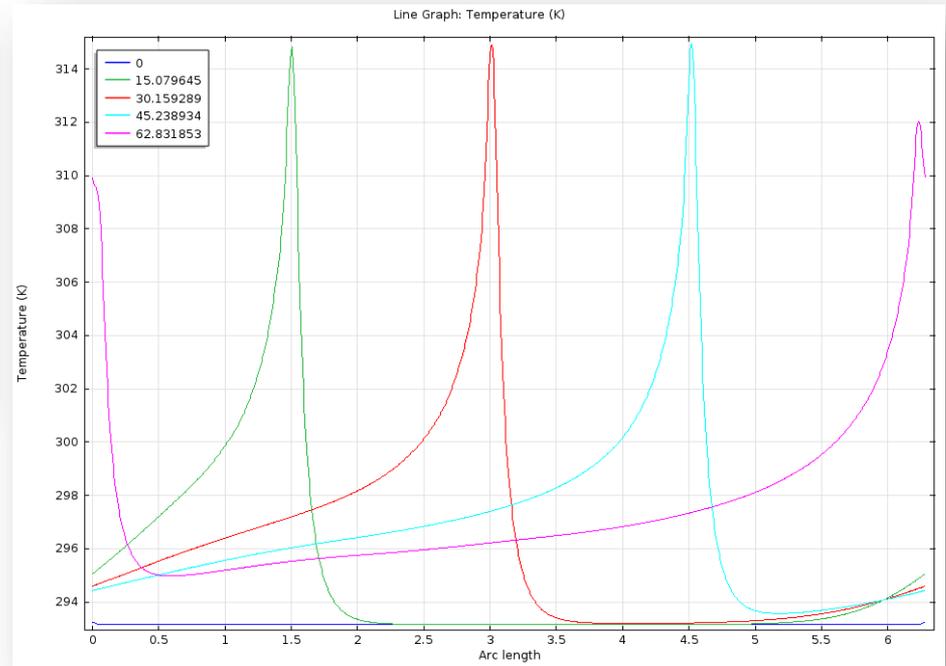
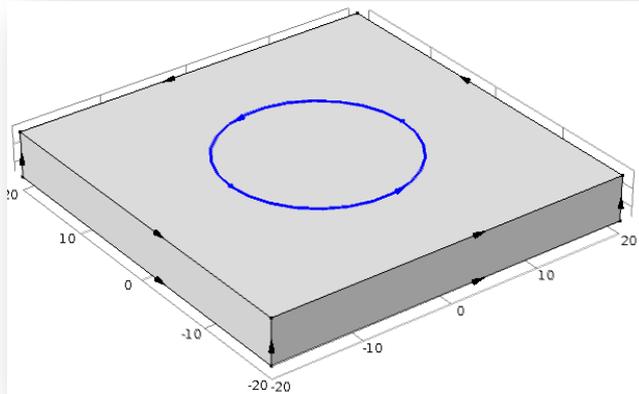
# Results – Temperature profile



***Enable slide show to see the movie***

# Results – Temperature profile

Temperature profile along the path of laser motion at different times.



# Summary

- This tutorial showed how to model transient heat conduction in a glass slab heated by a laser beam.
- Three different modes of operation were investigated.
  - Stationary laser emitting constant power
  - Stationary laser emitting power pulses
  - Moving laser emitting constant power
- The tutorial emphasizes on the use of functions to model the laser power as a body heat source.
- Several key design variables have been parameterized.
- Suggestions on meshing and solver settings were provided.