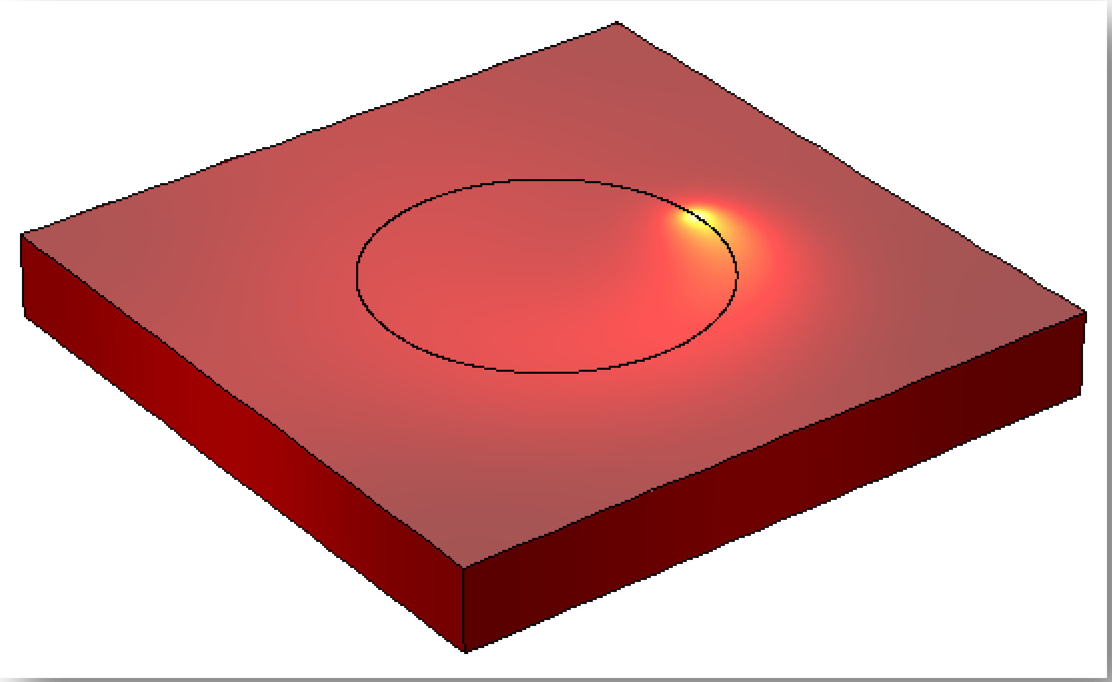
Laser Heating – A Self Guided Tutorial



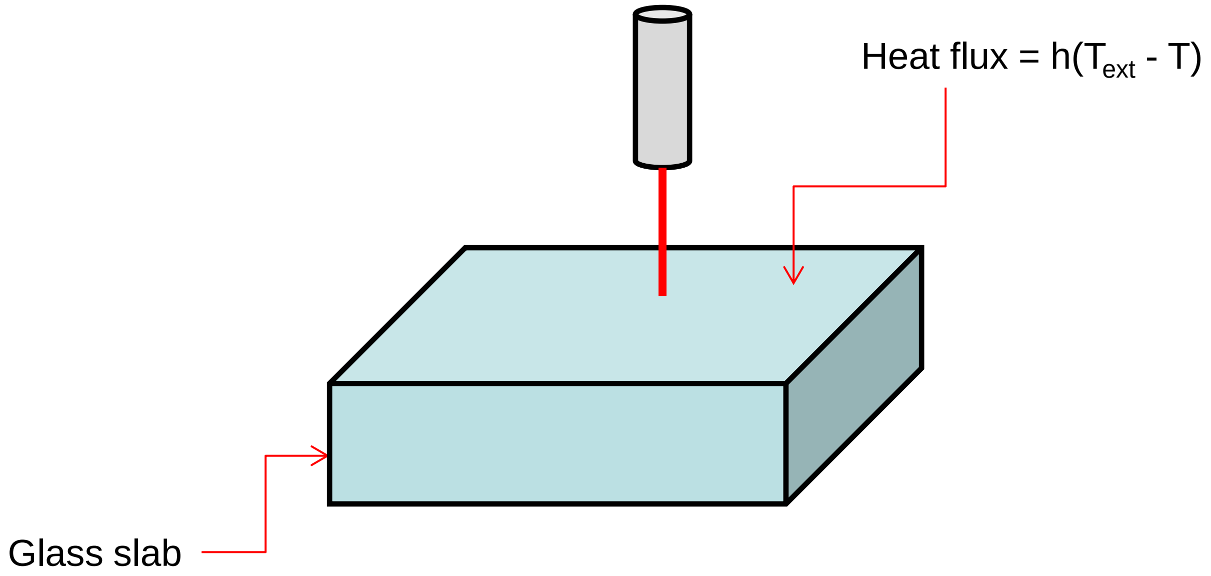
Introduction

- 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.

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

Total power input

Reflection coefficient

2D Gaussian distribution in *xy*-plane

Exponential decay due to absorption

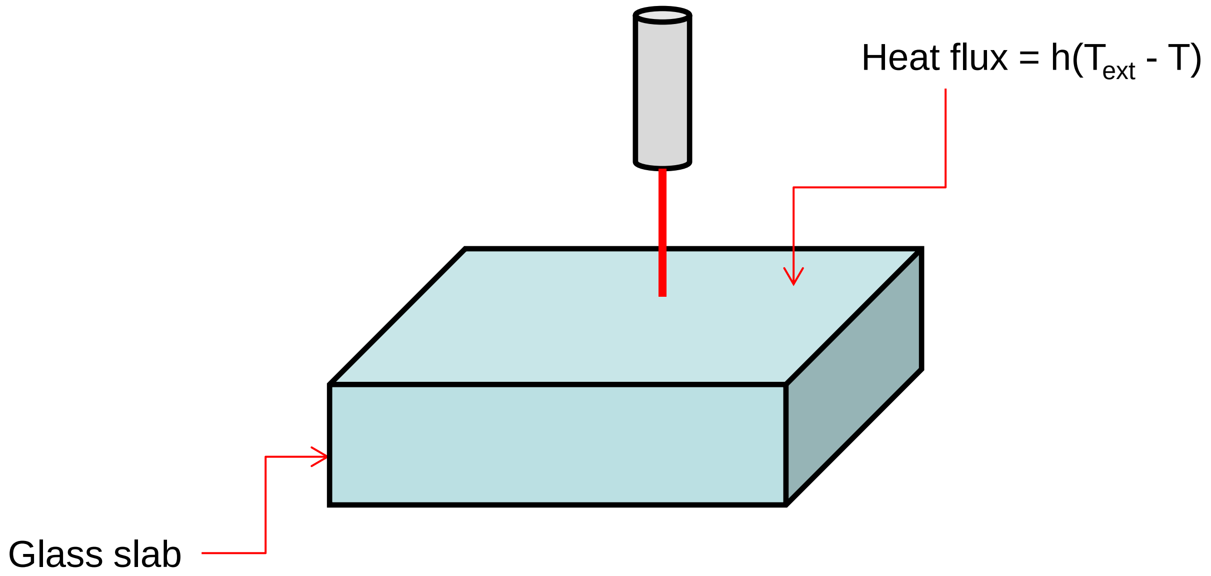
Reference: "Comparing the use of mid-infrared versus far-infrared lasers for mitigating damage growth on fused silica," Steven T. Yang, Manyalibo J. Matthews, Selim Elhadj, Diane Cooke, Gabriel M. Guss, Vaughn G. Draggoo, and Paul J. Wegner. *Applied Optics*, Vol. **49**, No. 14, 10 May 2010.

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*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; σ_x and σ_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.

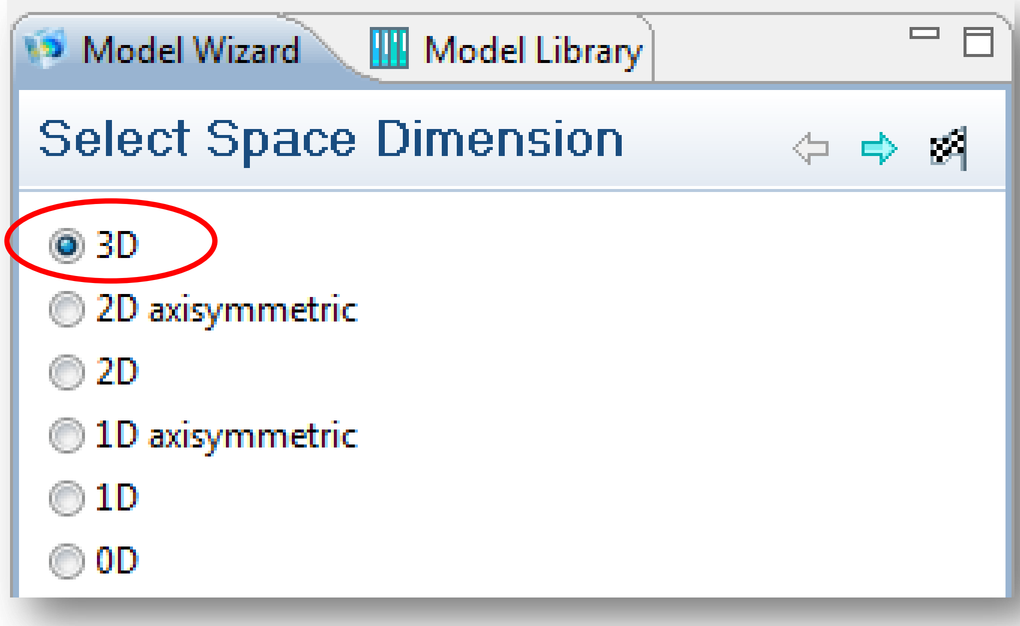


Modeling Instructions

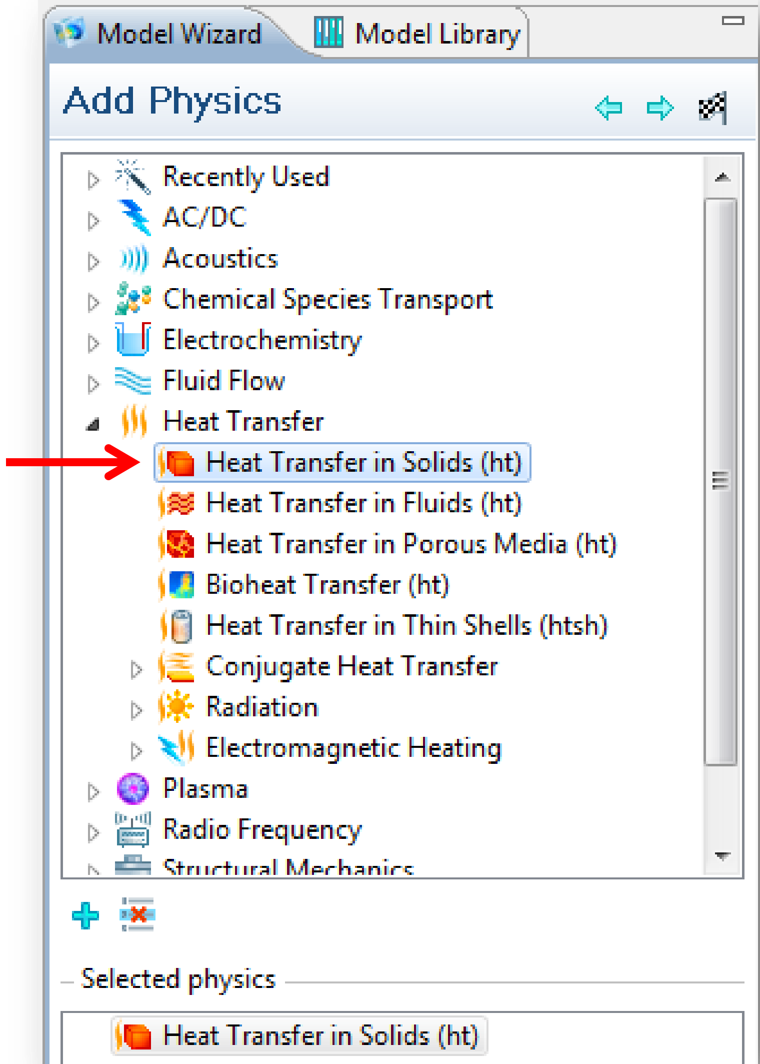
- The next few slides show the modeling steps and snapshots of the solution.

- For details refer to the model file: *laser_heat_transient_CW.mph*

Select Space Dimension

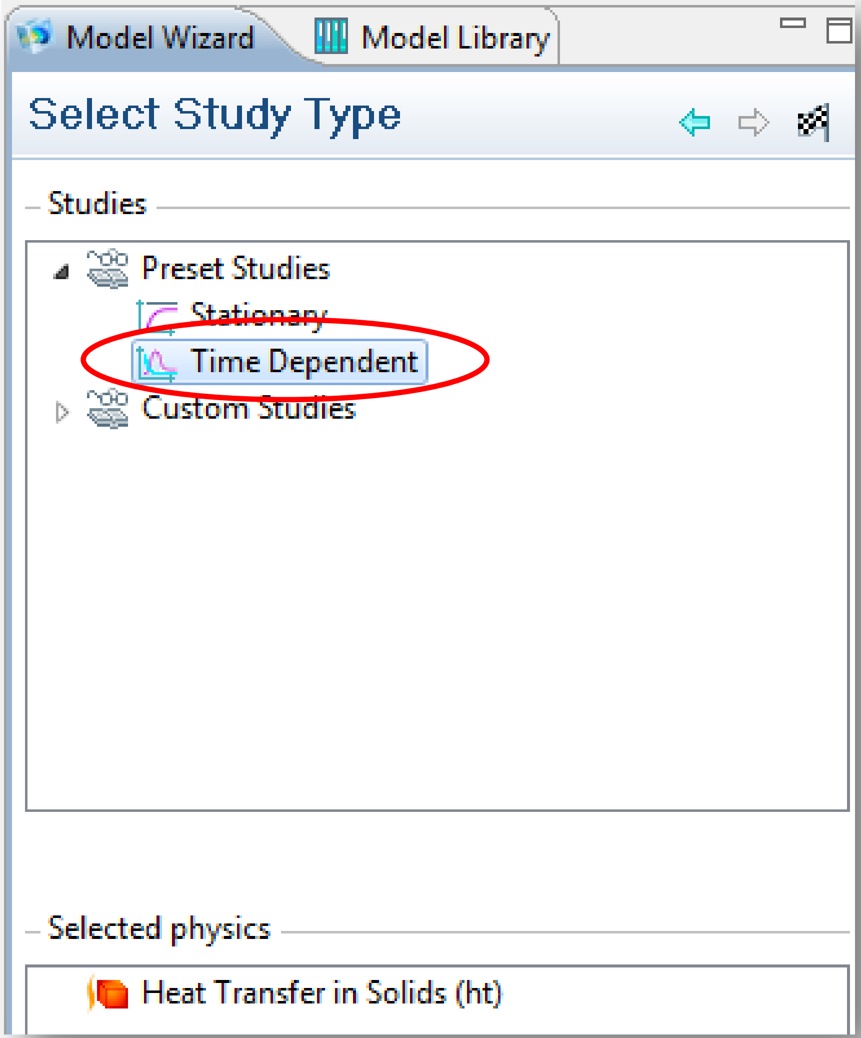


Add Physics



- **Heat Transfer > Heat Transfer in Solids (ht)**

Select Study Type



Parameters

- laser_heat_transient_CW.mph
  - Global Definitions
    - Parameters

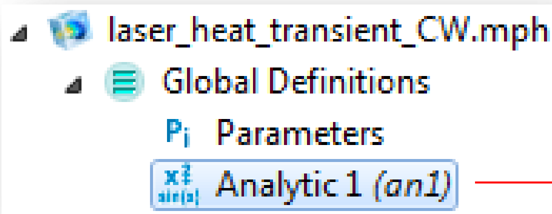
These numerical values are arbitrary and only for illustration purposes

Parameters

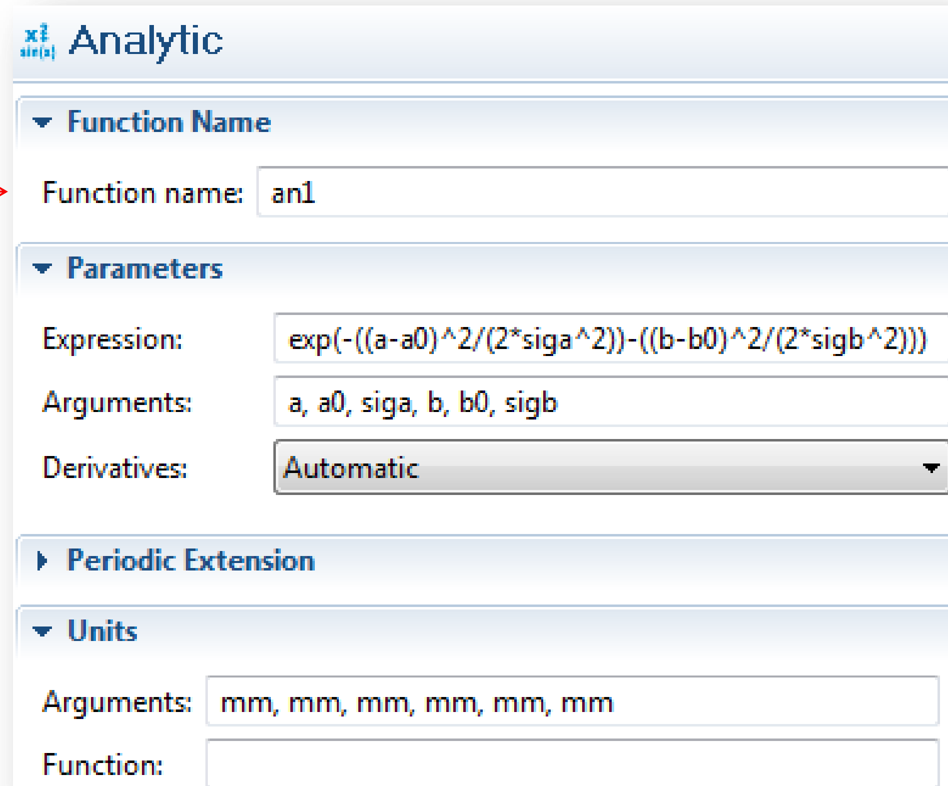
Parameters

Name	Expression	Value	Description
x0	0.5[mm]	5.0000E-4 m	Pulse center x-coordinate
y0	0[mm]	0 m	Pulse center y-ccordinate
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

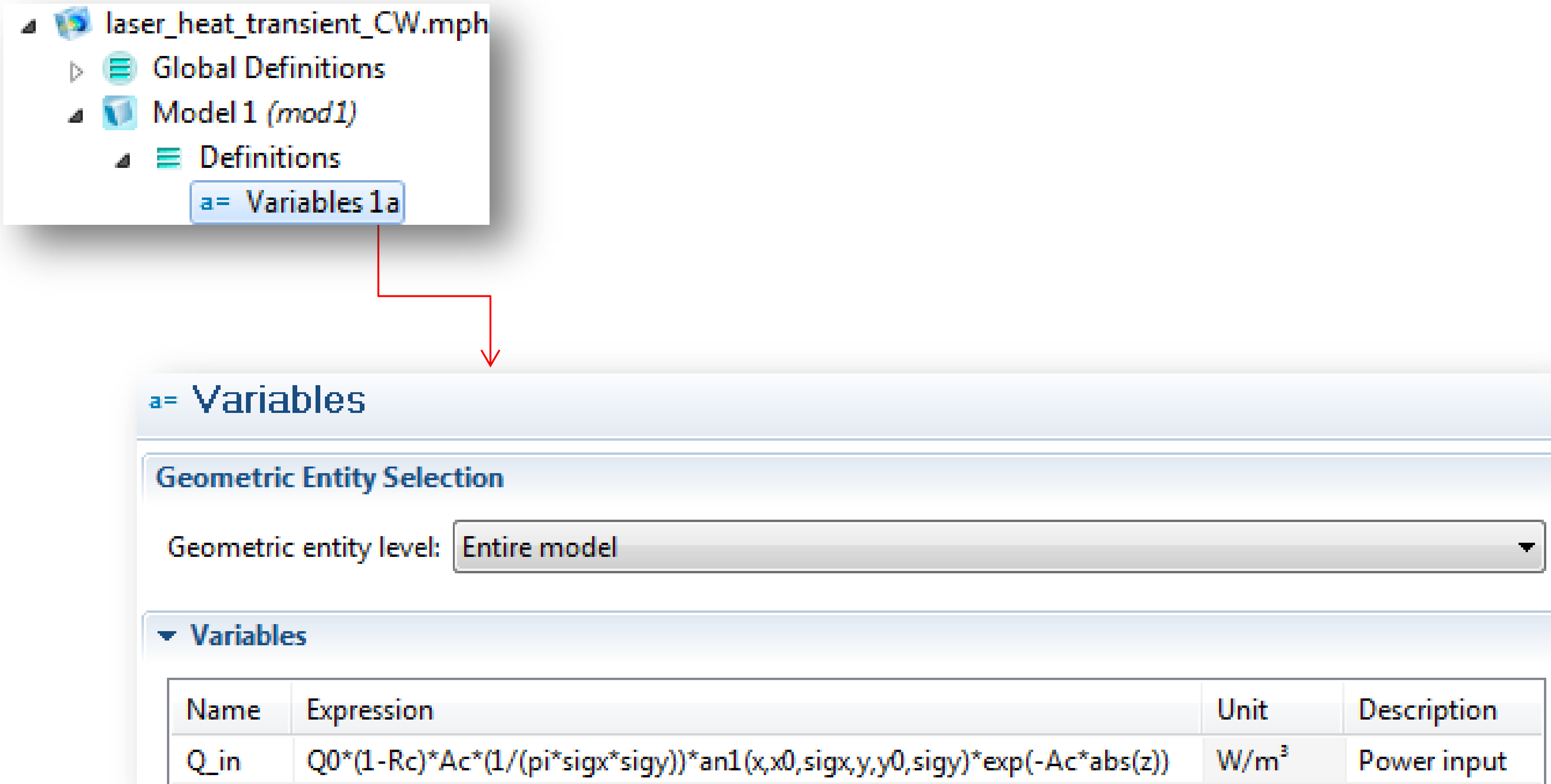
Global Definitions > Functions > Analytic



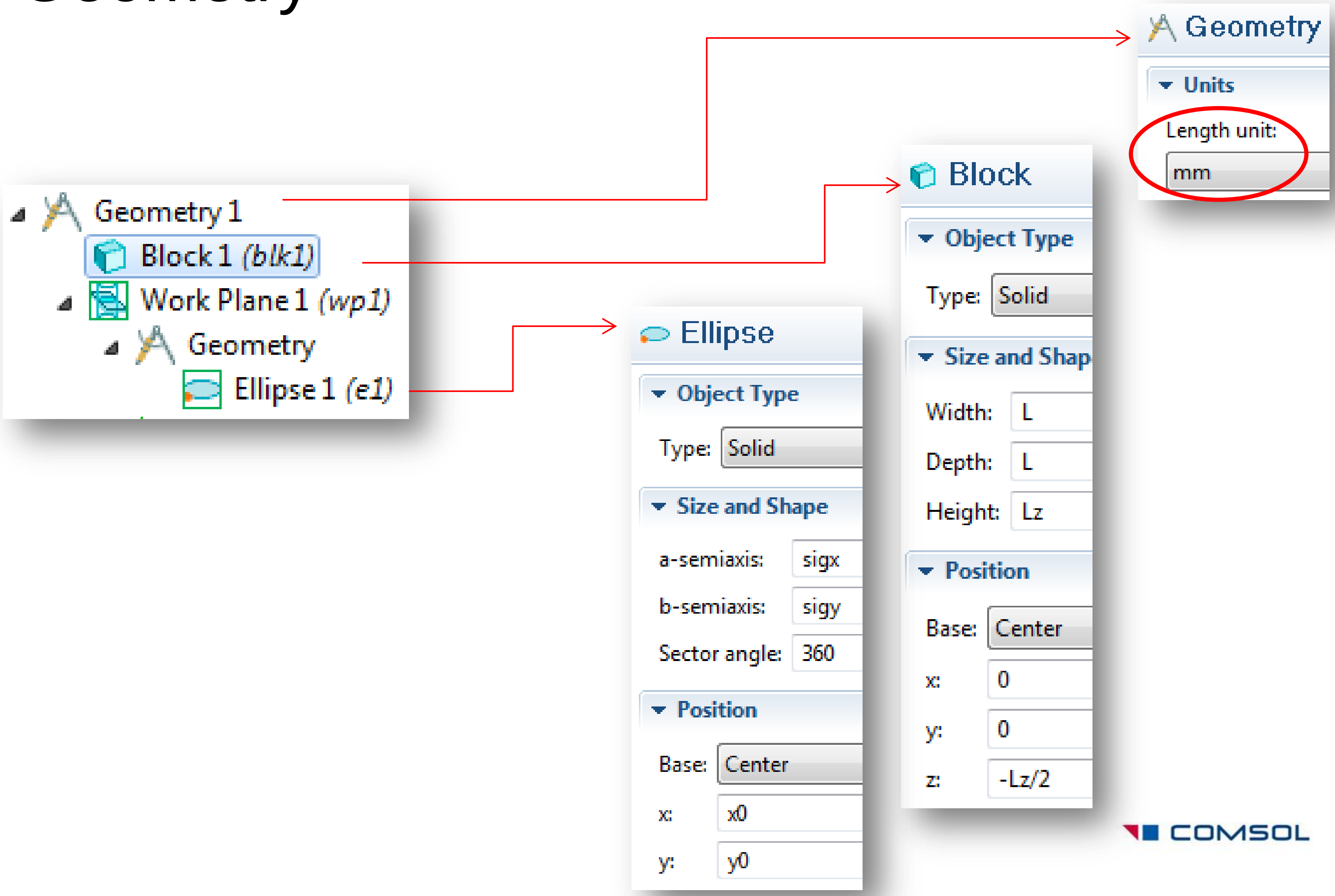
This analytic function represents a 2D Gaussian pulse



Variables


laser_heat_transient_CW.mph
Global Definitions
Model 1 (mod1)
Definitions
a= Variables 1a
a= Variables
Geometric Entity Selection
Geometric entity level:
Entire model
Variables
Name
Expression
Unit
Description
Q_in
Q0*(1-Rc)*Ac*(1/(pi*sigx*sigy))*an1(x,x0,sigx,y,y0,sigy)*exp(-Ac*abs(z))
W/m³
Power input

Geometry



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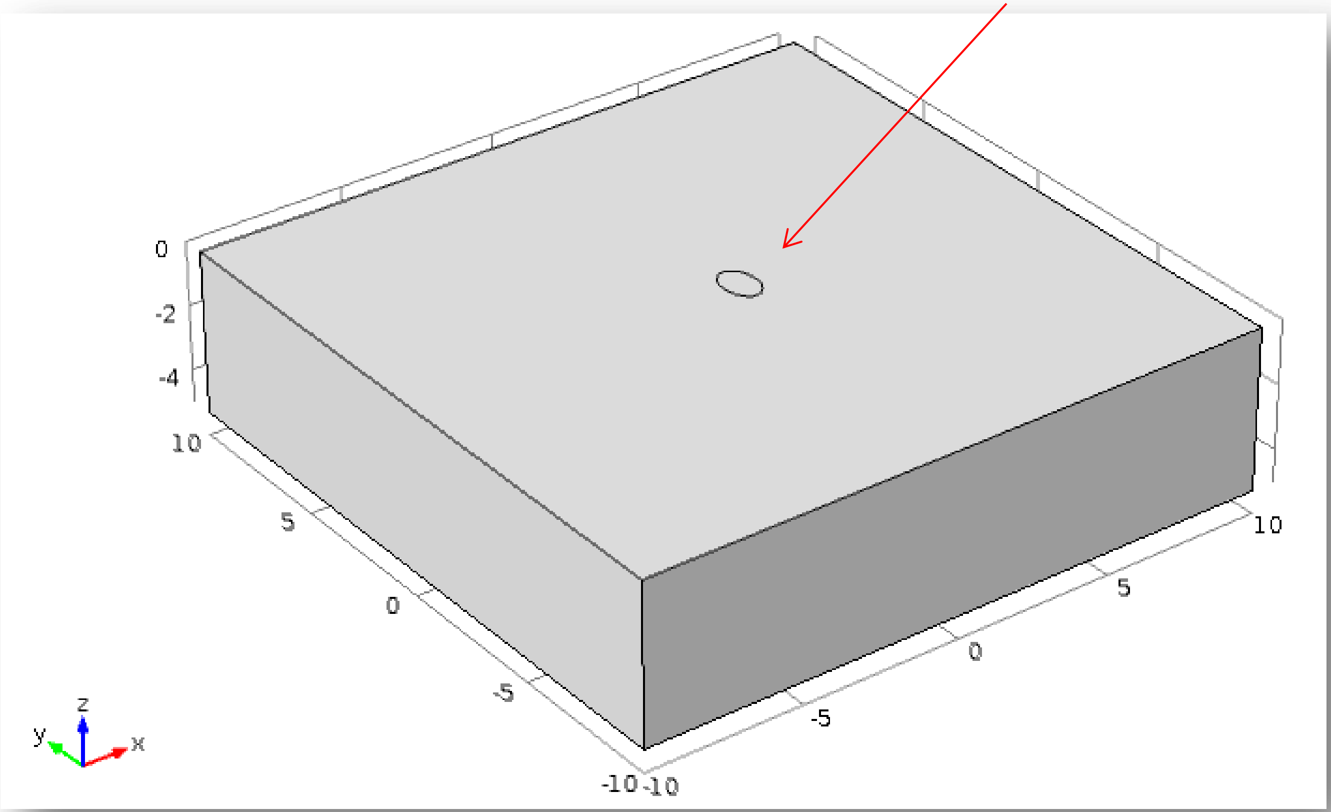
The actual geometry

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



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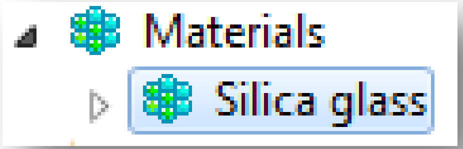
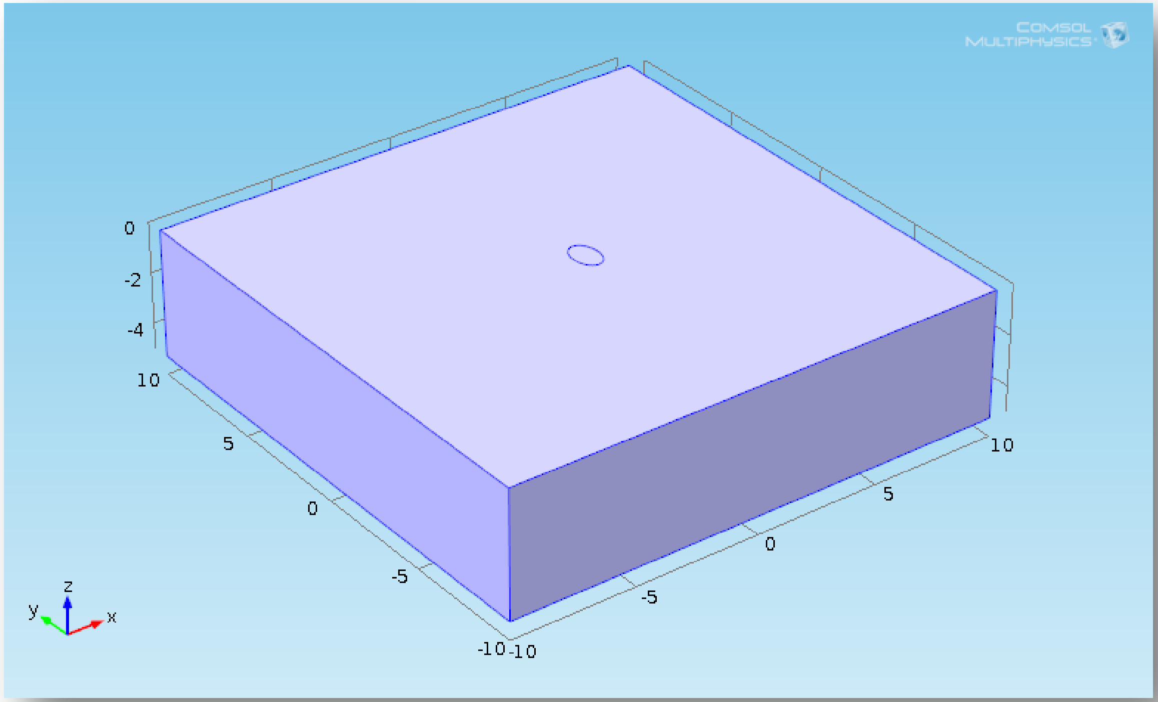
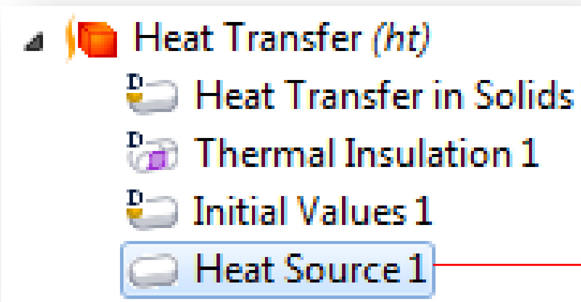
Material properties

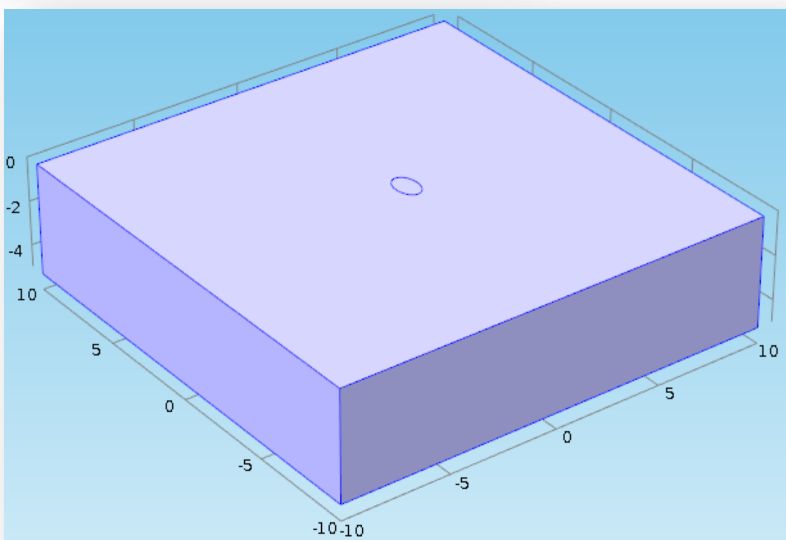


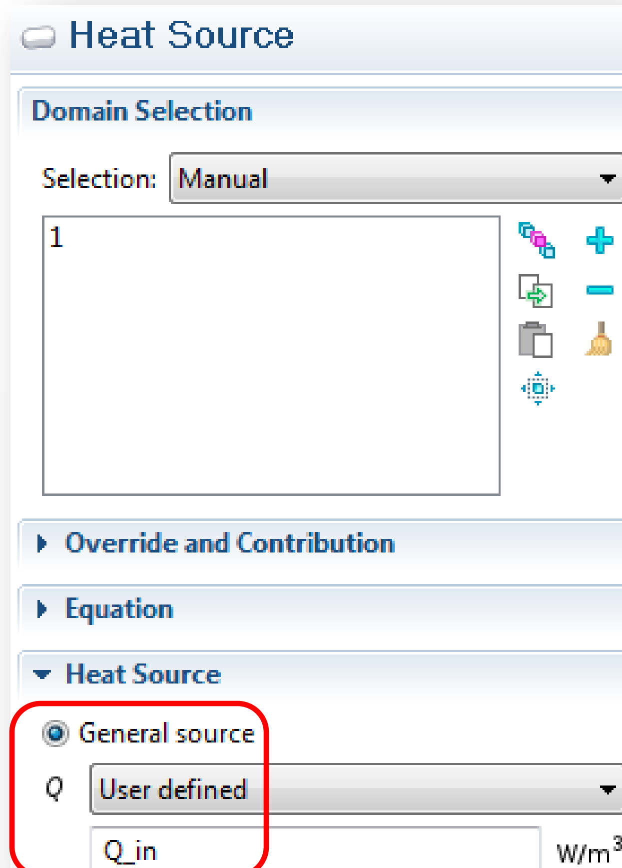
Material Browser > Built-In > Silica glass



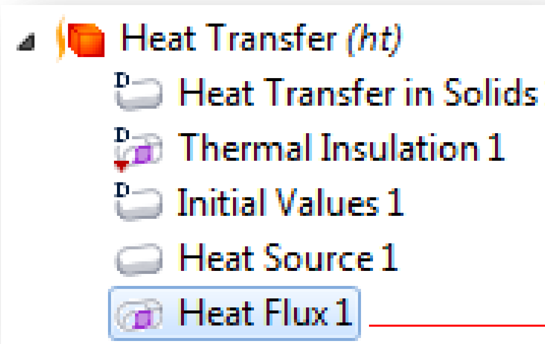
Heat Transfer > Heat Source

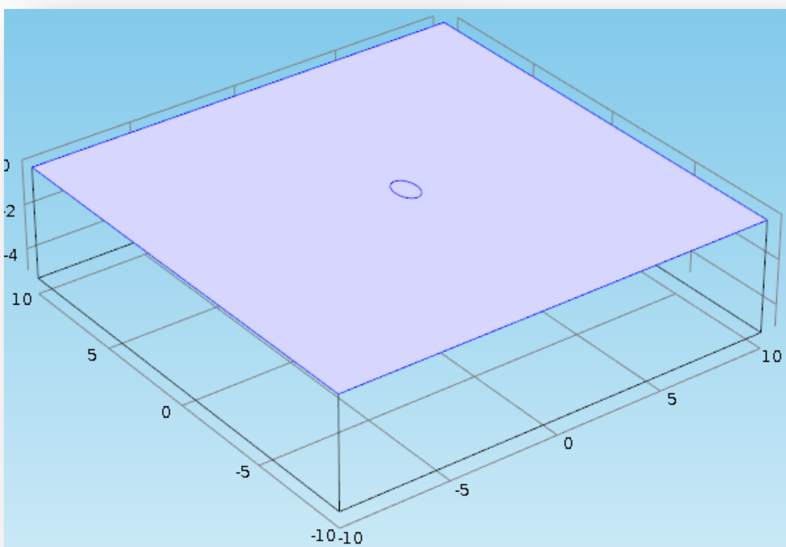


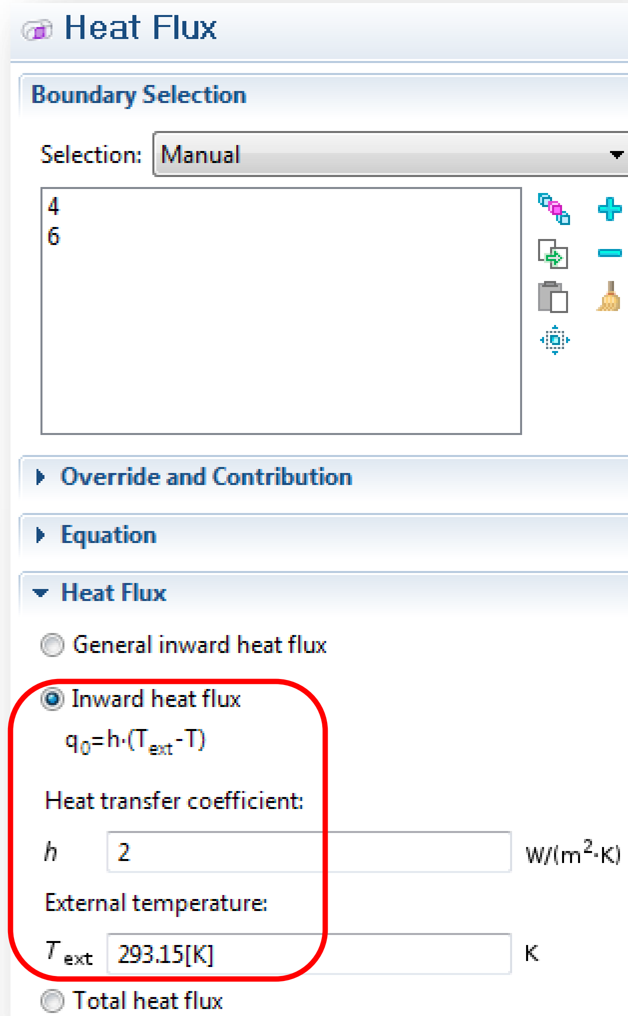




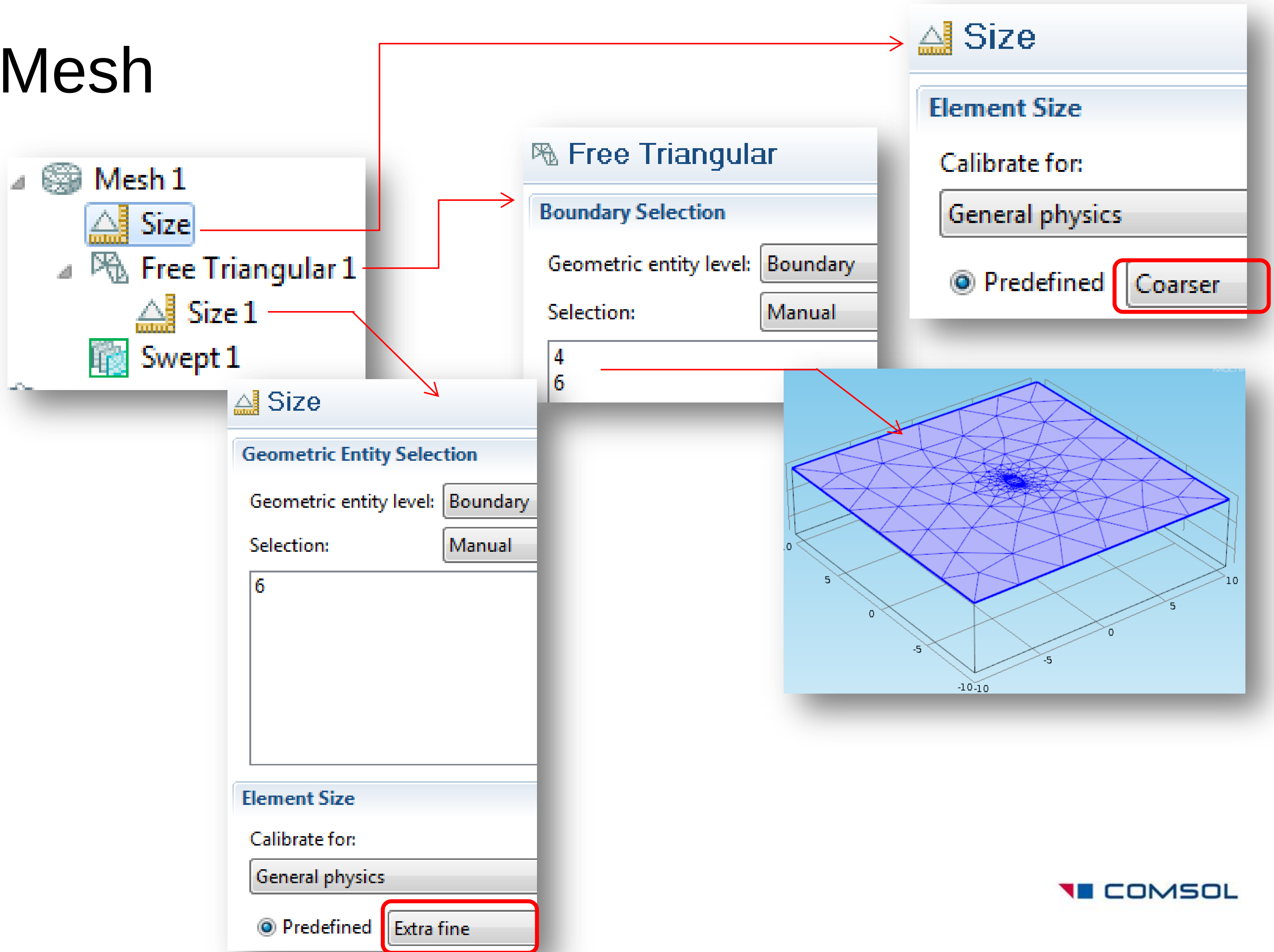
Heat Transfer > Heat Flux





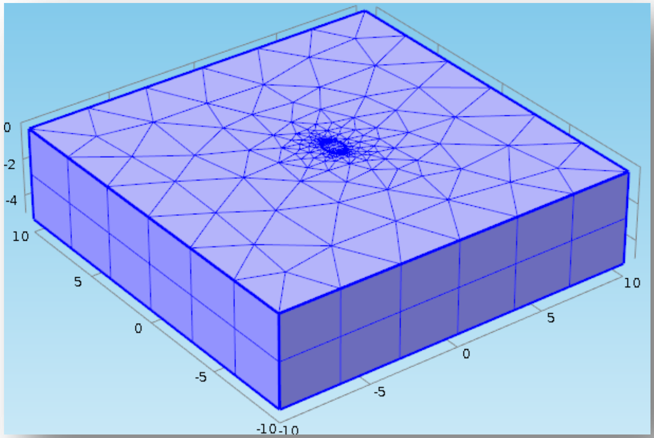


Mesh

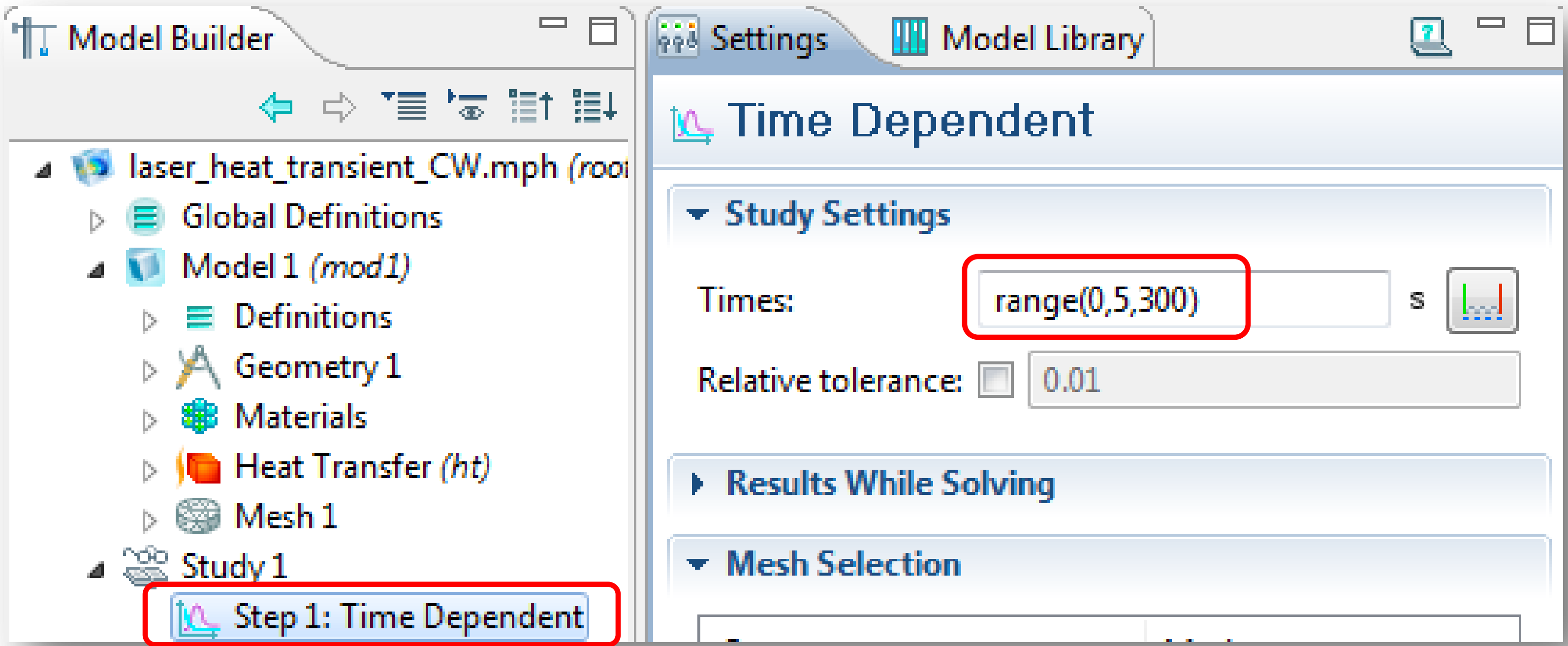

Mesh 1
Size
Free Triangular 1
Size 1
Swept 1
Size
Element Size
Calibrate for:
General physics
Predefined
Coarser
Free Triangular
Boundary Selection
Geometric entity level:
Boundary
Selection:
Manual
4
6
Size
Geometric Entity Selection
Geometric entity level:
Boundary
Selection:
Manual
6
Element Size
Calibrate for:
General physics
Predefined
Extra fine

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



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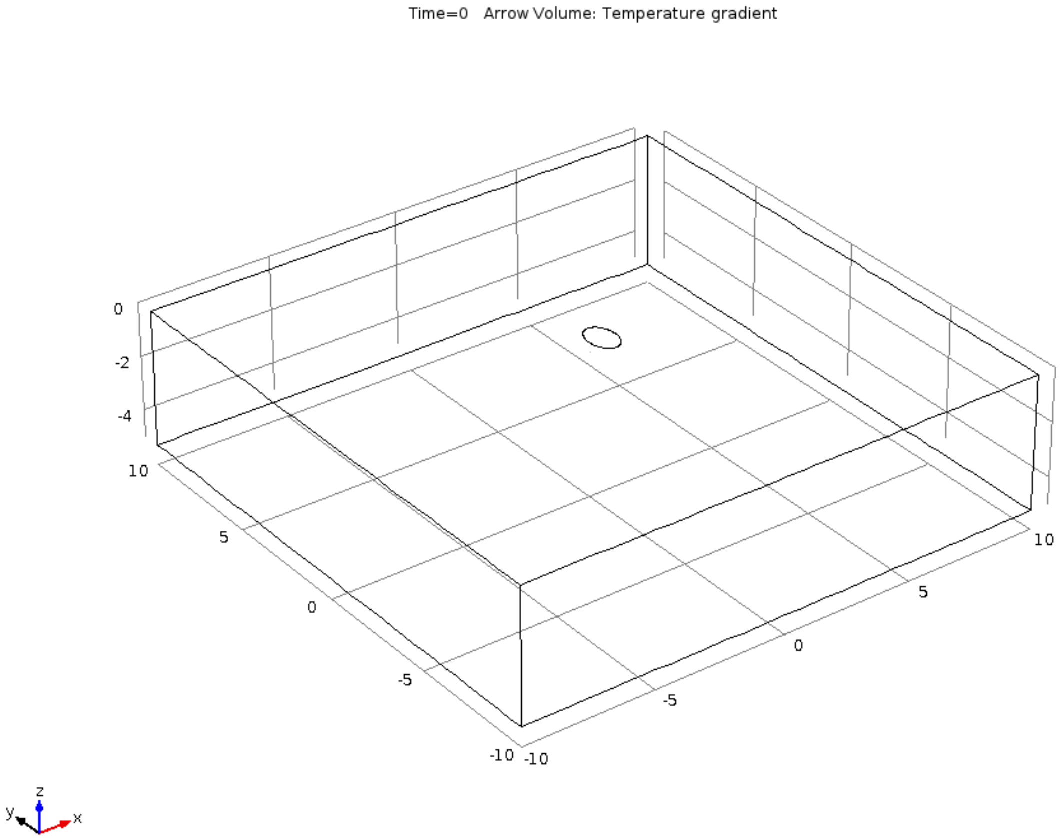
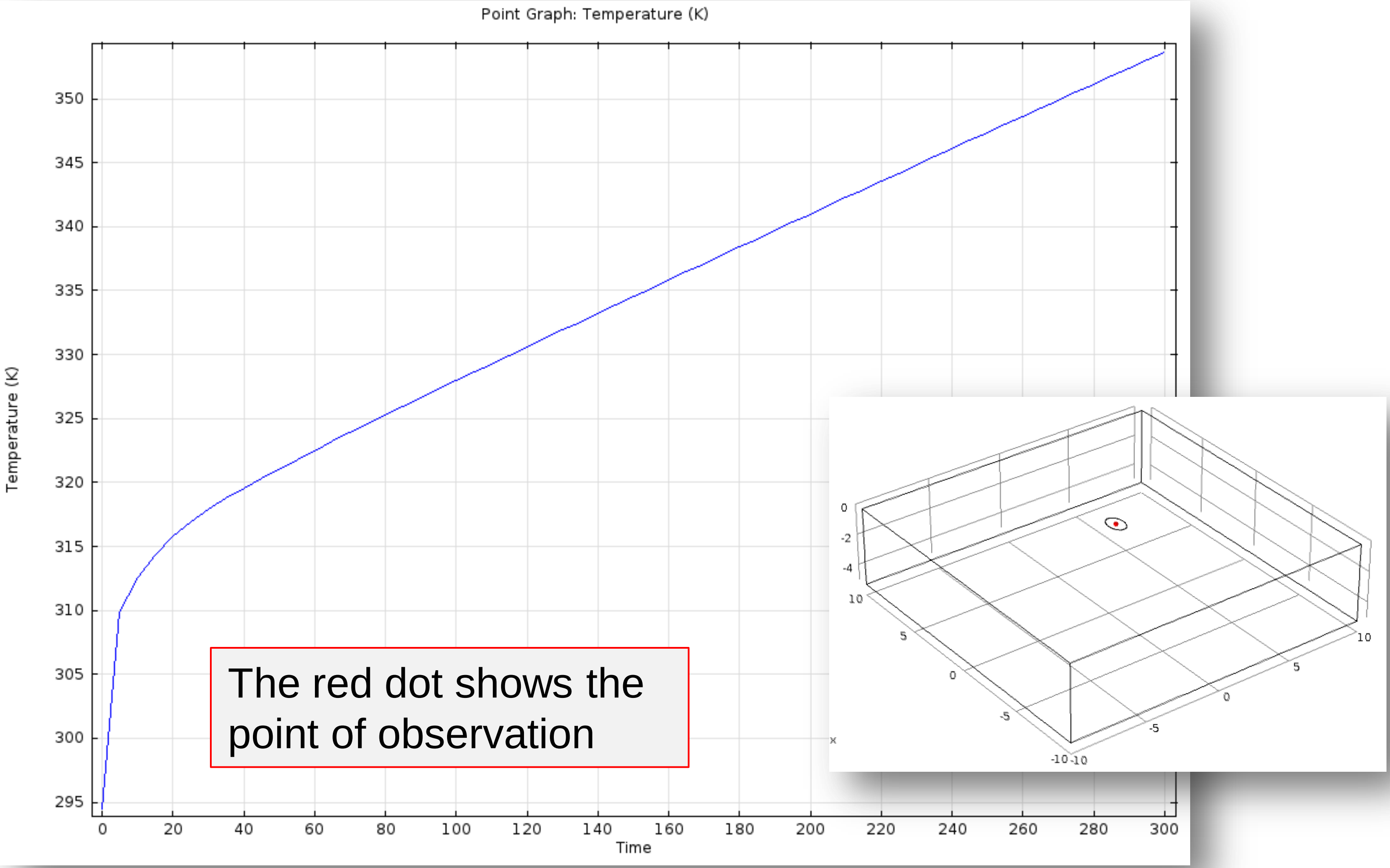
Results – Isosurface Temperature



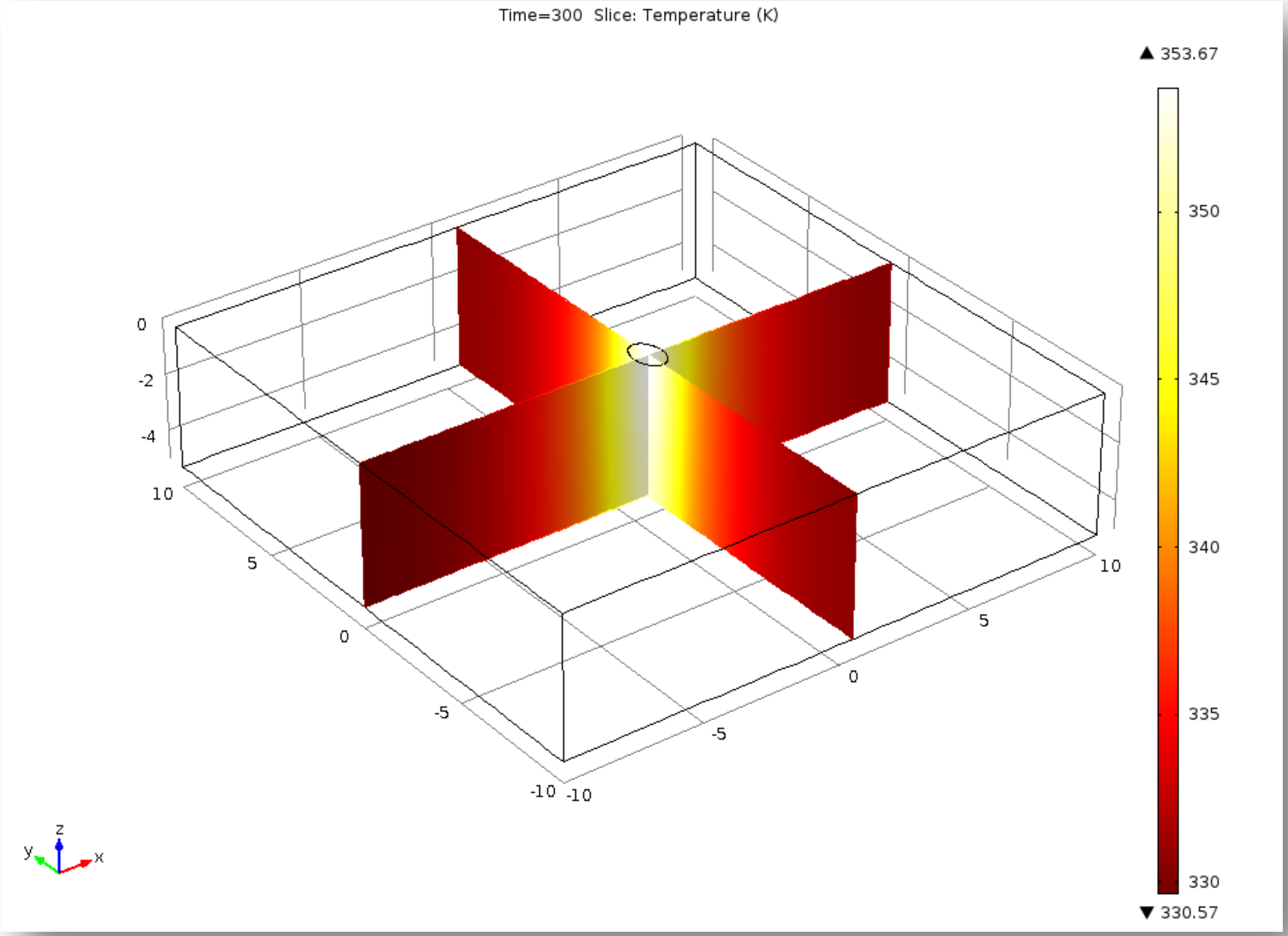
Enable slide show to see the movie

Temperature vs. Time



The red dot shows the point of observation

Slice plots of temperature



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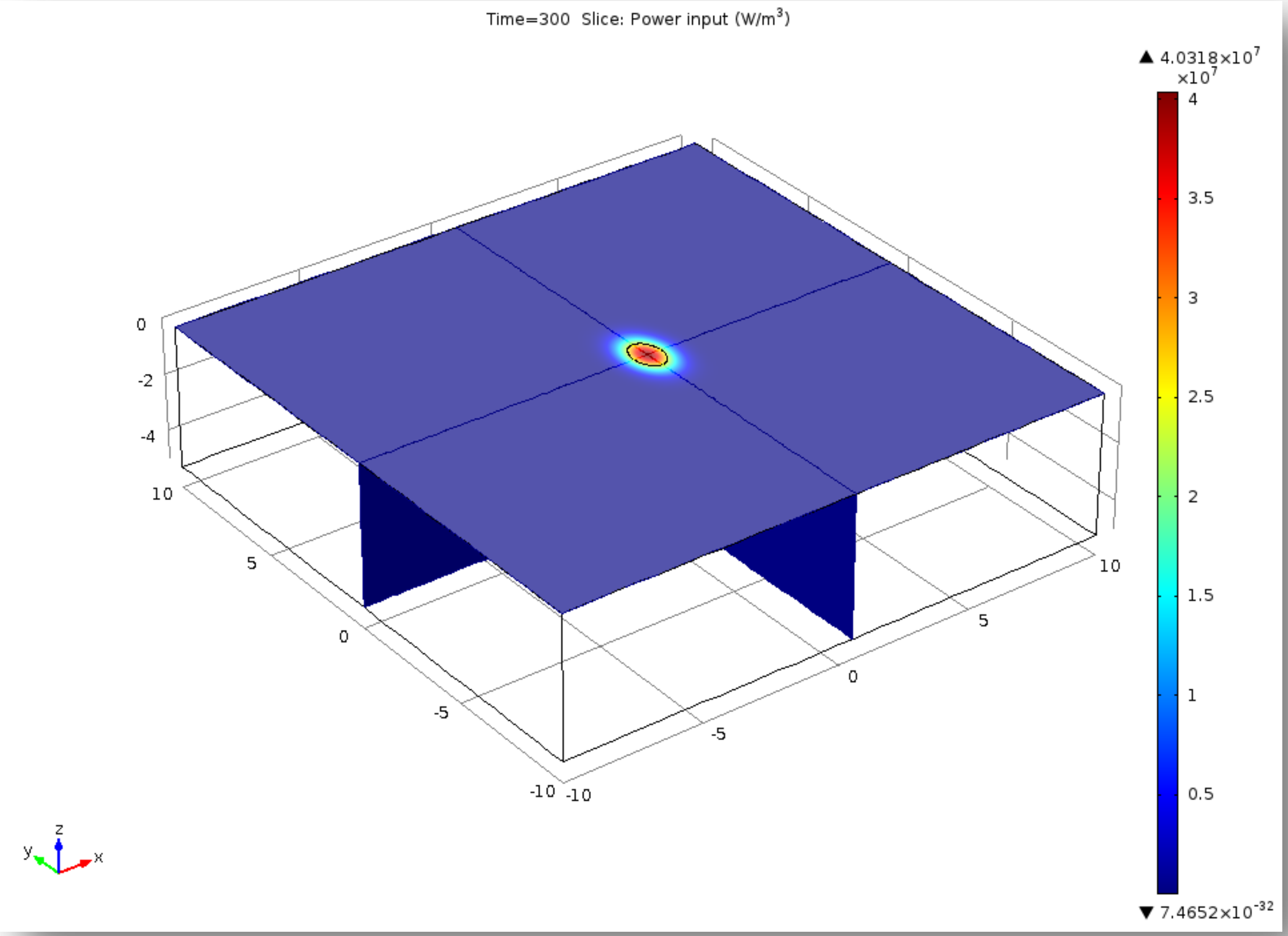
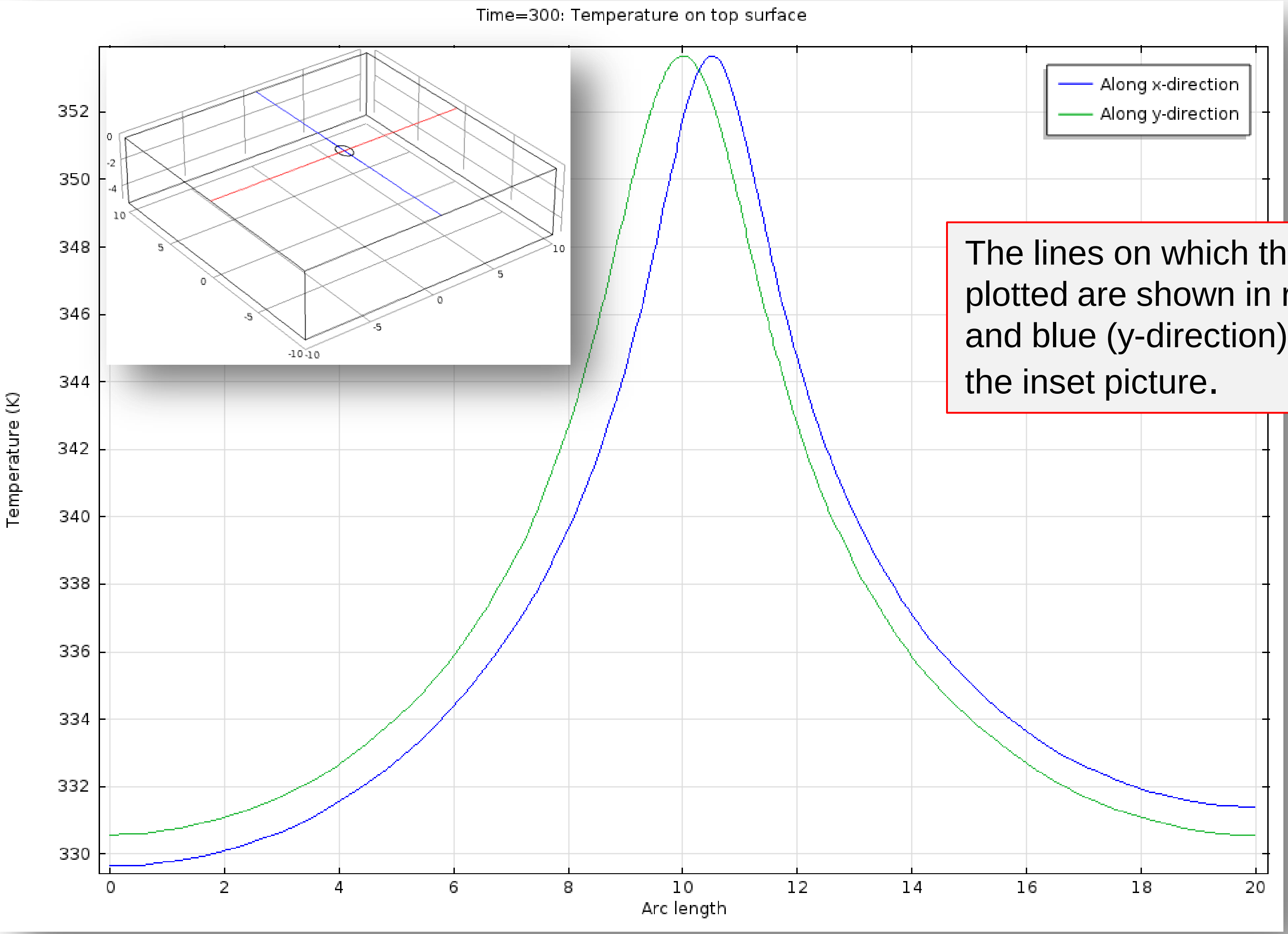
Slice plots of heat input

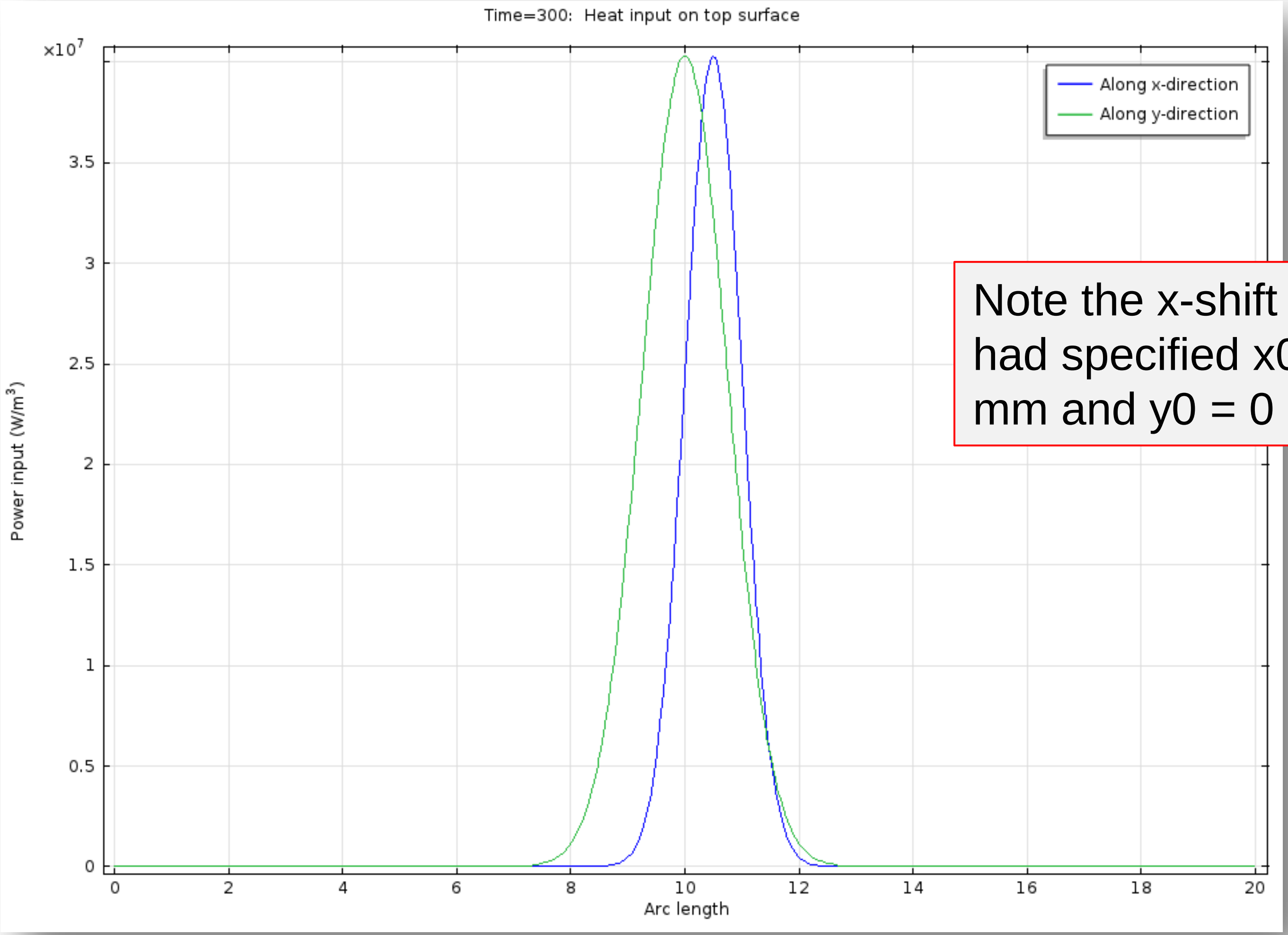


Temperature along top surface



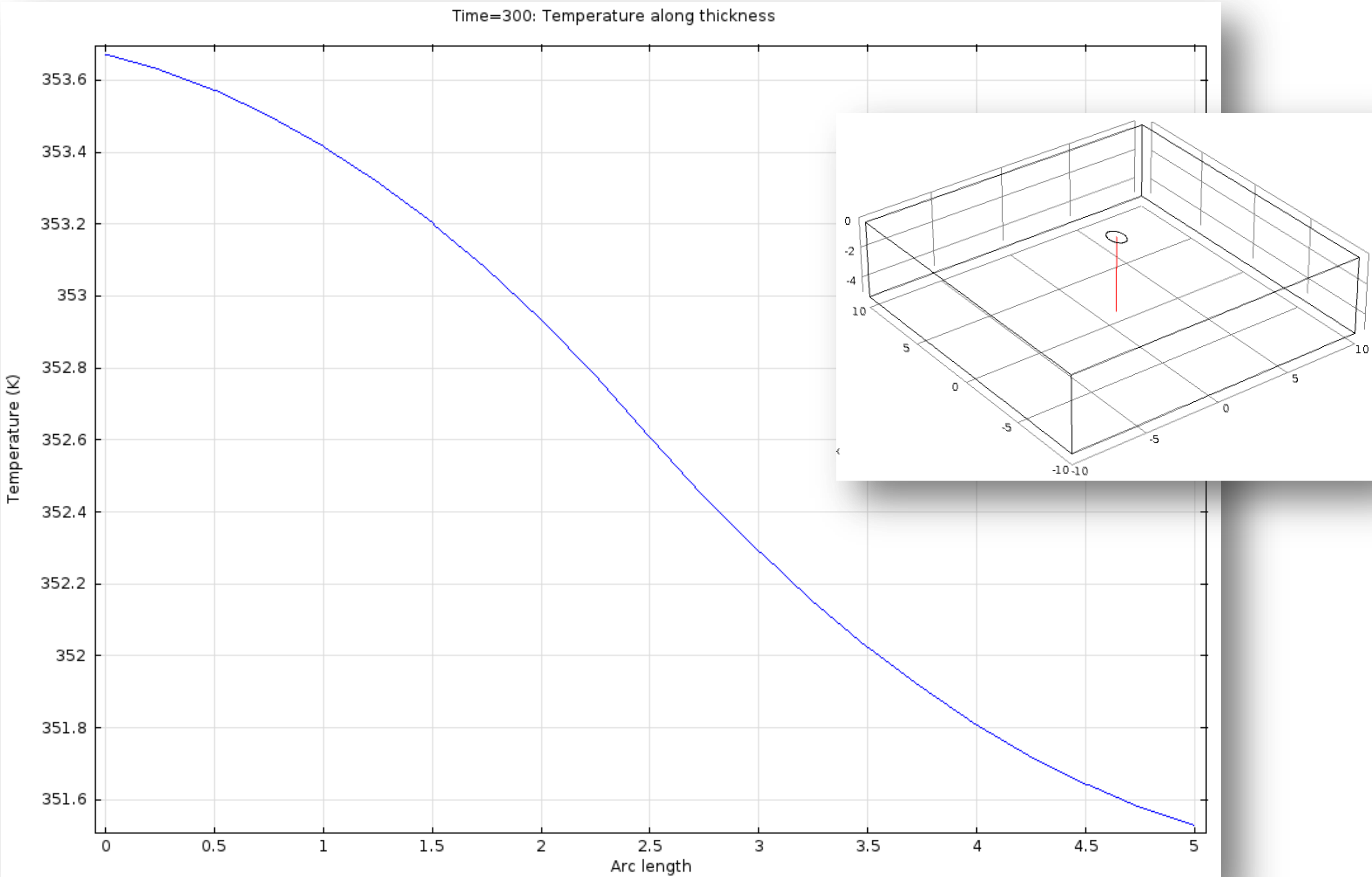
The lines on which the solution were plotted are shown in red (x-direction) and blue (y-direction) respectively in the inset picture.

Heat input along top surface

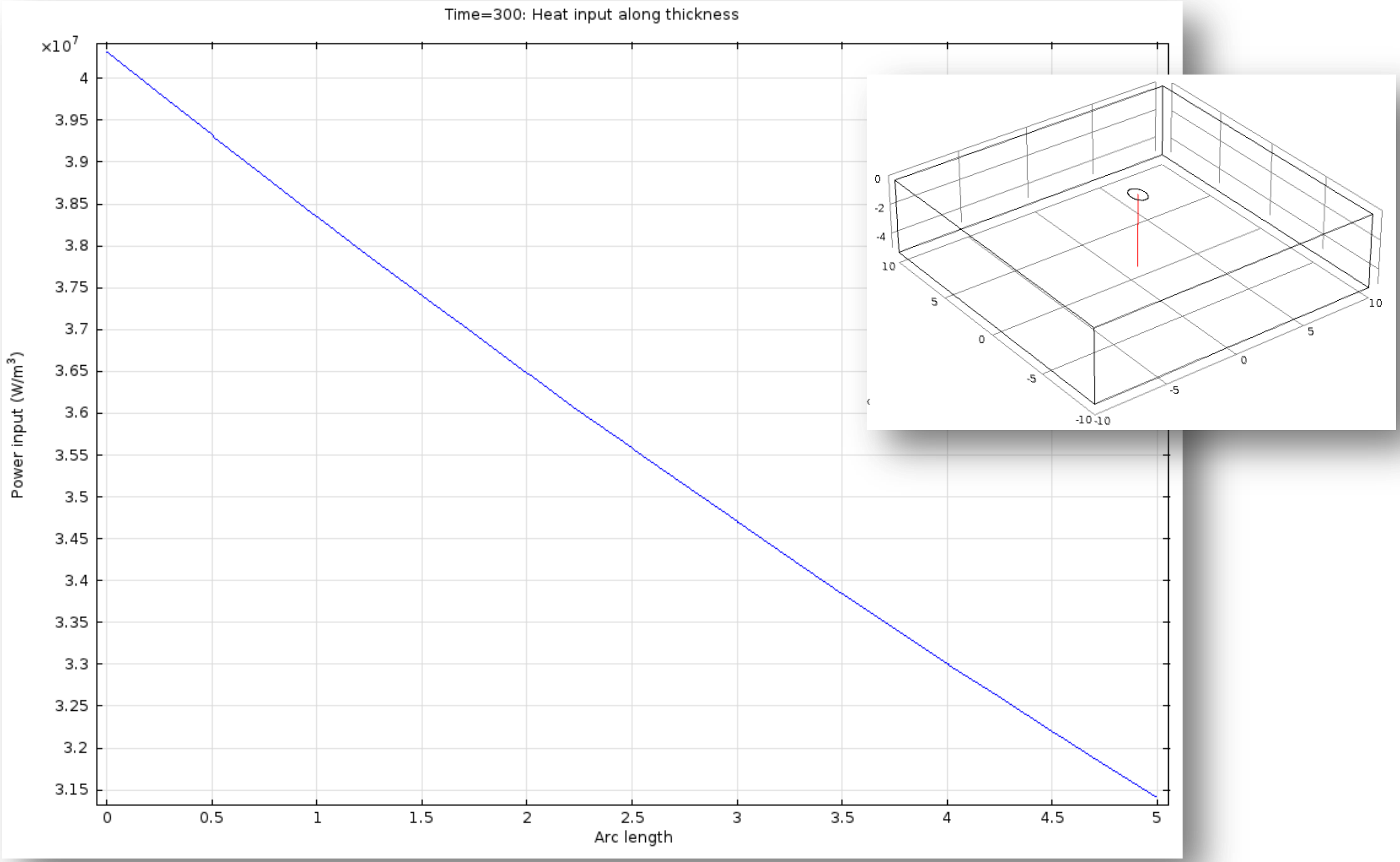


Note the x-shift since we had specified x0 = 0.5 mm and y0 = 0 mm

Temperature along thickness



Heat input along thickness

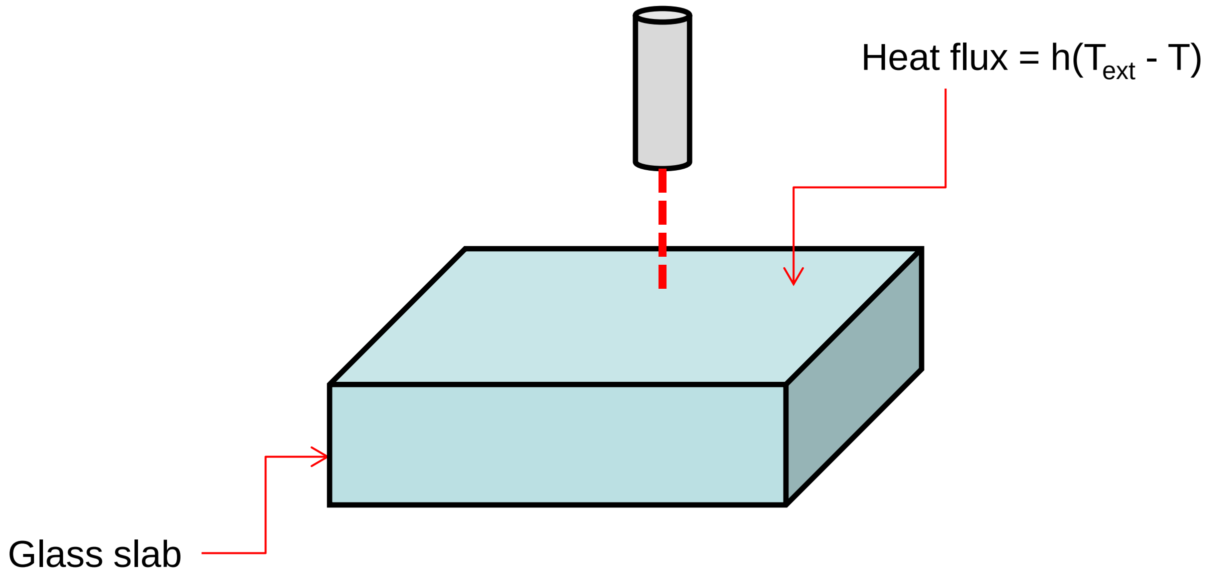


Things to try

- 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 sigx and sigy. 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

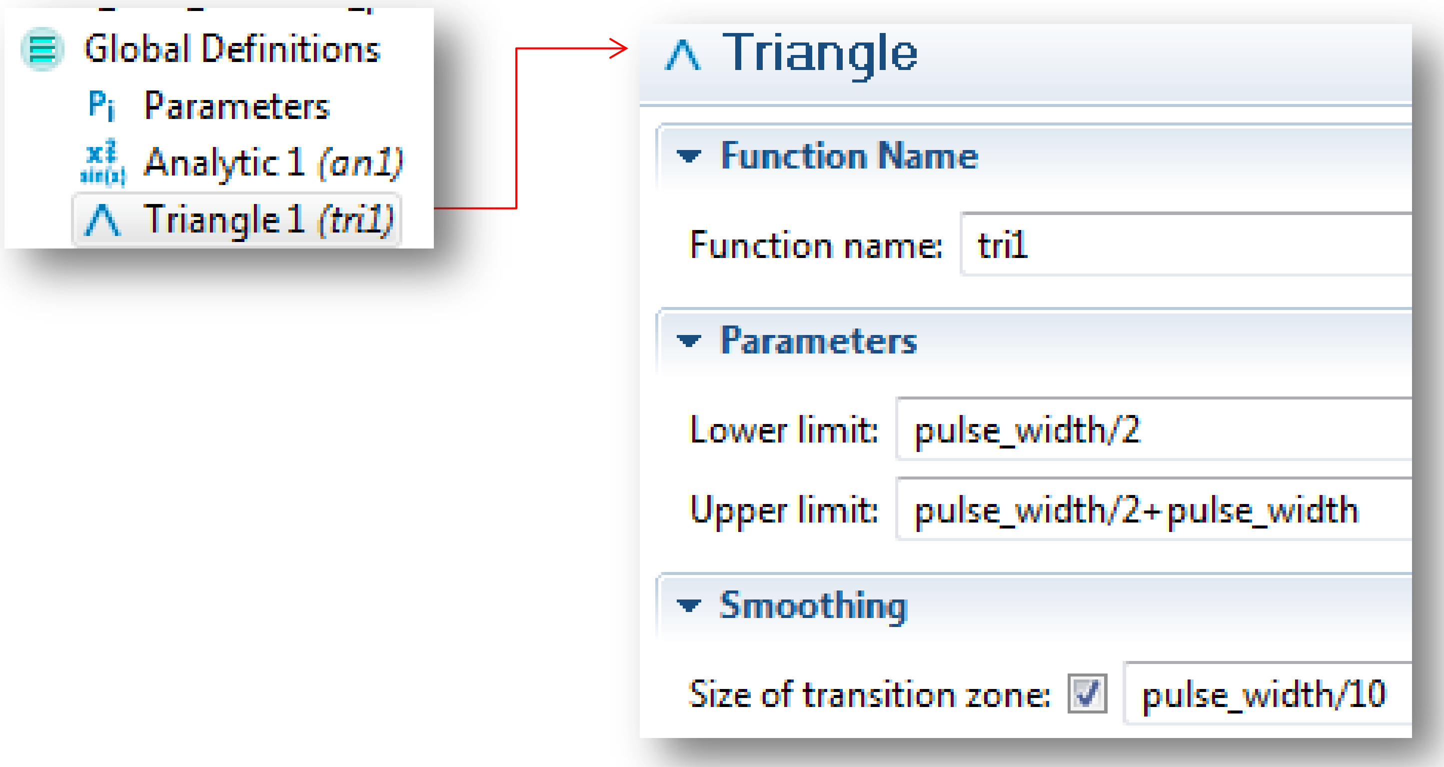
Note that the value of **Q0** is an arbitrary high number that is chosen for illustration purposes only.

Parameters

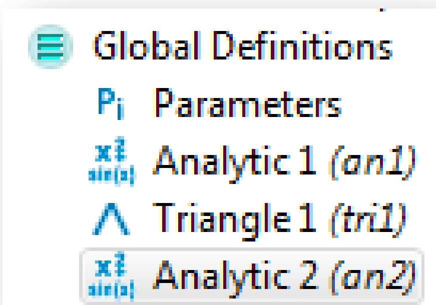
Parameters

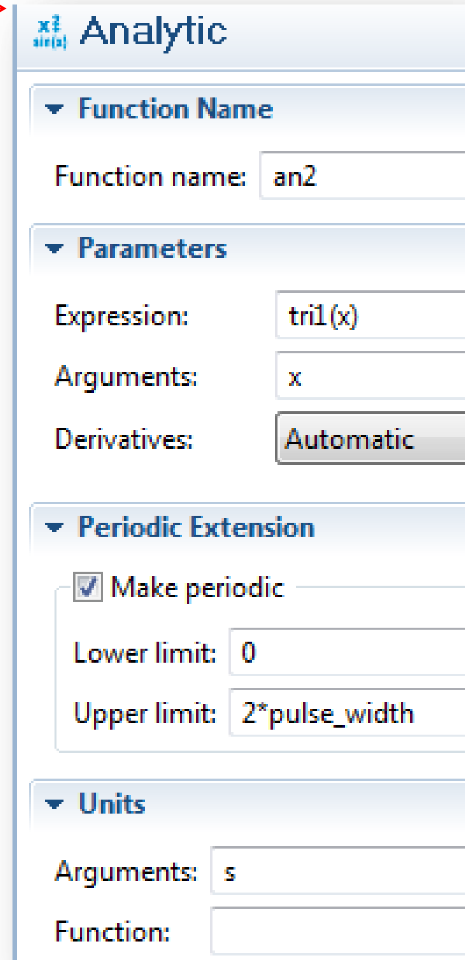
Name	Expression	Value	Description
x0	0.5[mm]	5.0000E-4 m	Pulse center x-coordinate
y0	0[mm]	0 m	Pulse center y-ccordinate
sigx	0.5[mm]	5.0000E-4 m	Pulse x standard deviation
sigy	0.75[mm]	7.5000E-4 m	Pulse y standard deviation
Q0	1[MW]	1.0000E6 W	Total laser power
Rc	0.05	0.050000	Reflection coefficient
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



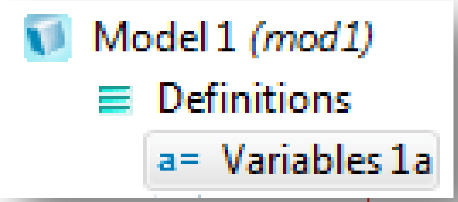
Global Definitions > Functions > Analytic



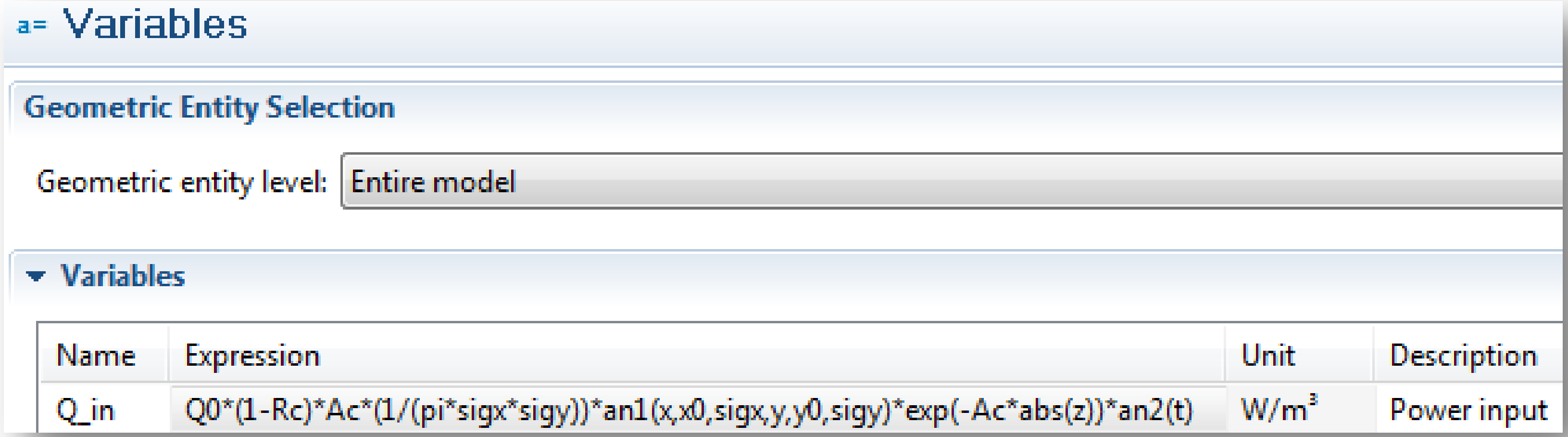


This approach can be used to create a series of periodic triangular pulses with variable duty cycle

Variables

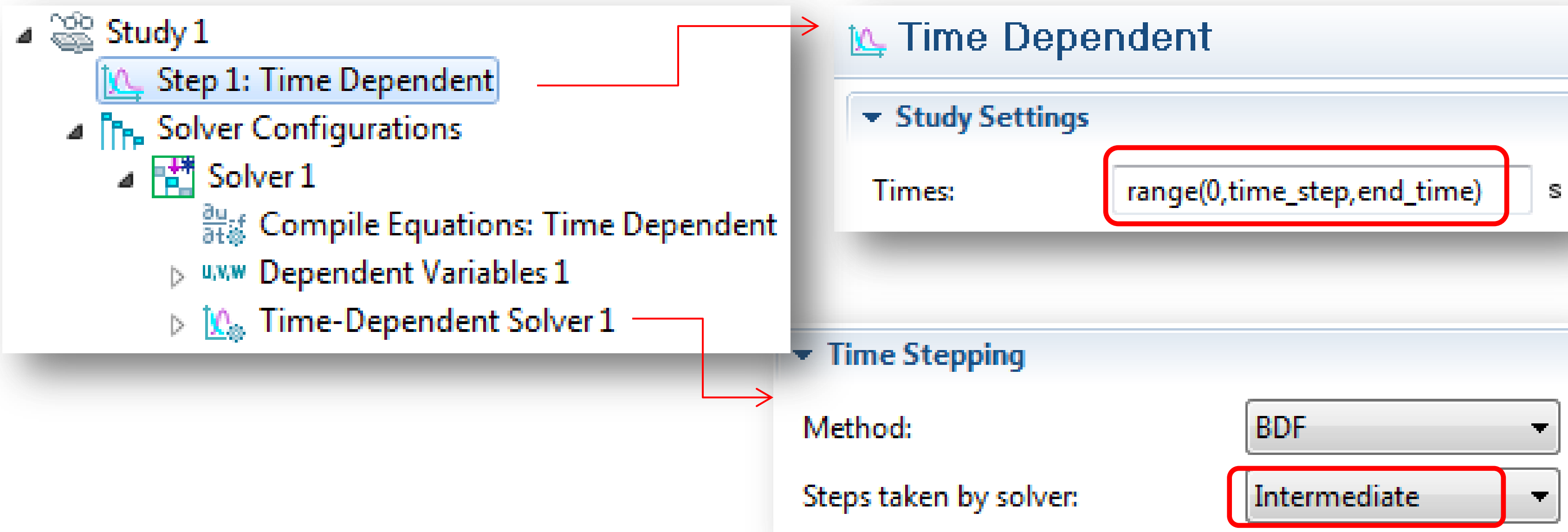


This is how the effect of pulsed heat input is simulated



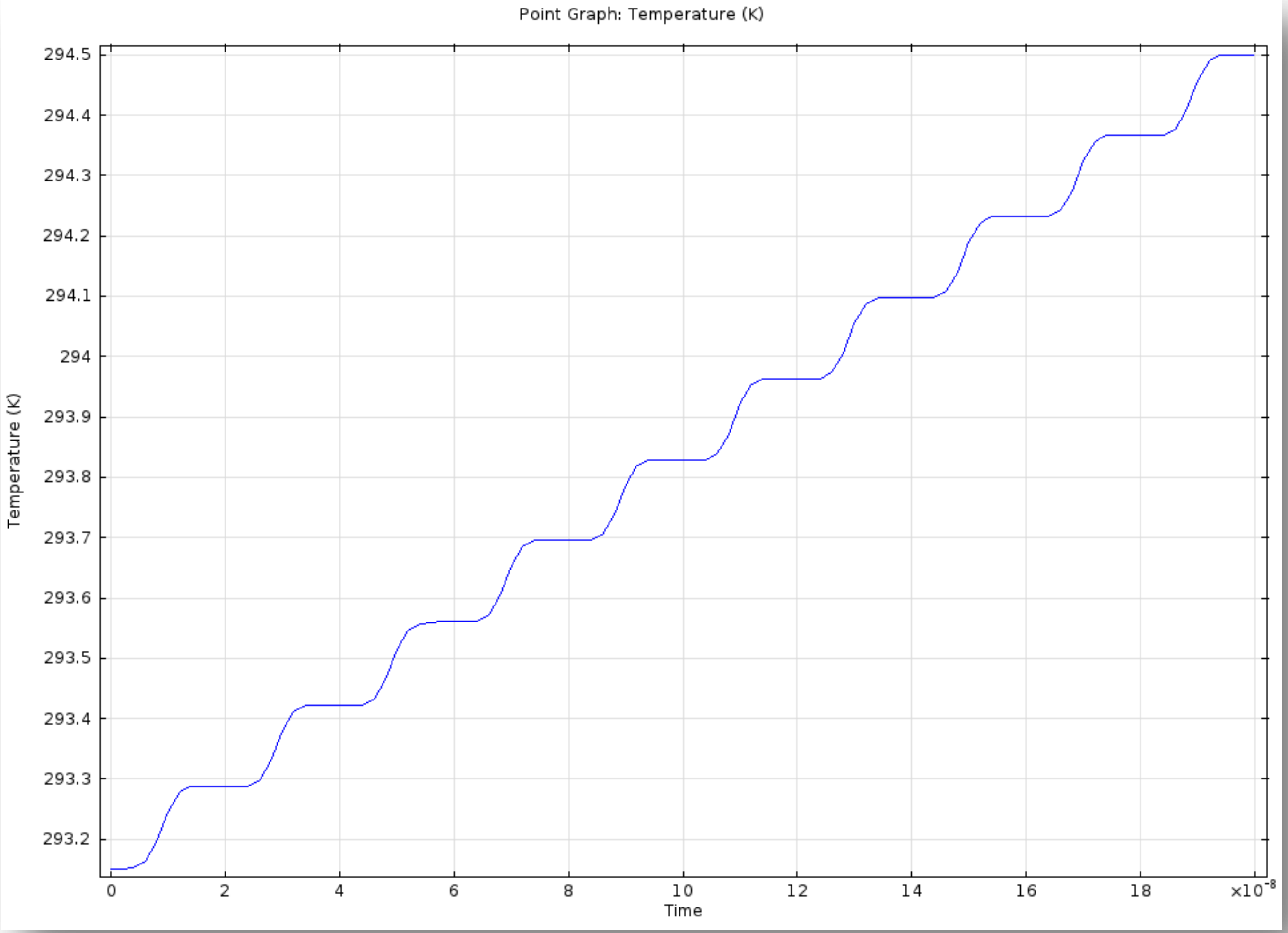
Multiply the original function with a function of time

Time-Dependent Study

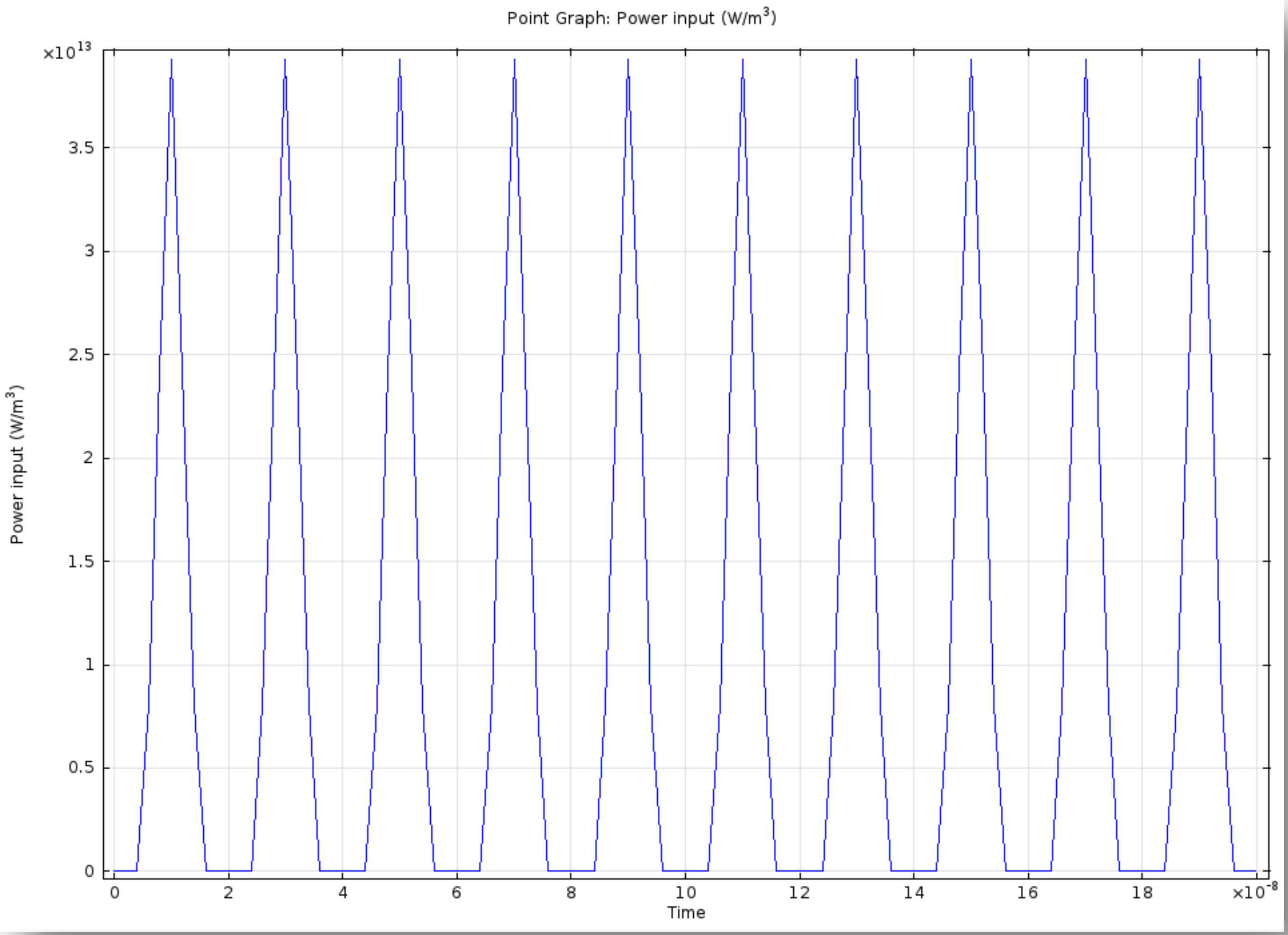


- For illustration purposes we have chosen the *end_time* such that this model will simulate only ten pulses.
- Note that solving for a longer time scale will involve more computational time and memory.

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



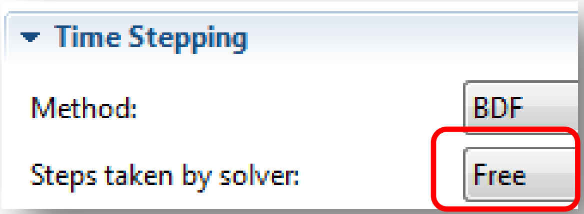
Results – Heat input at the center of beam spot as a function of time

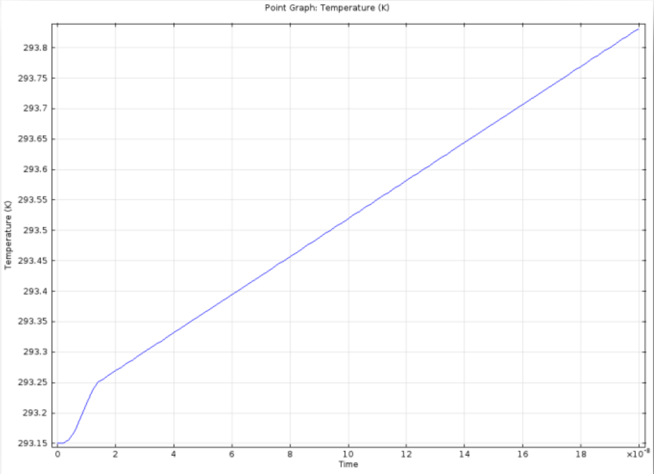


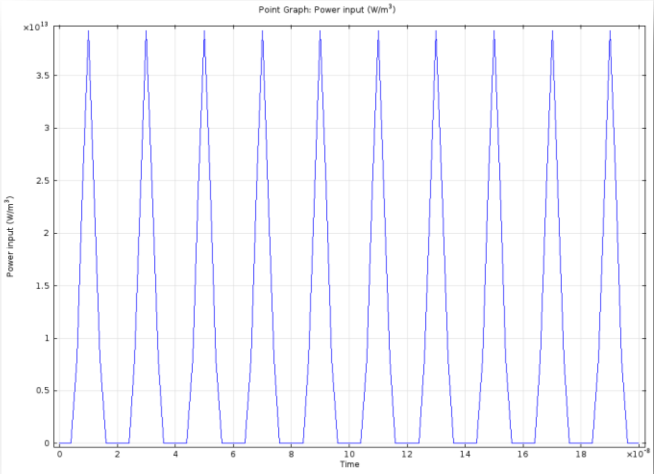
Suggestions on time stepping

- 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





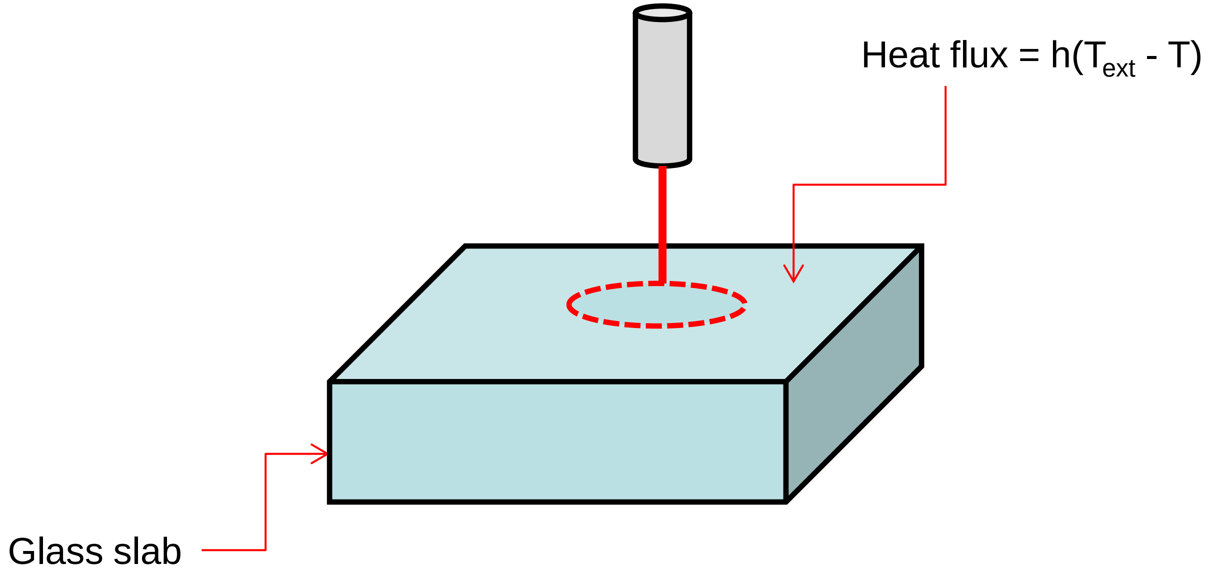


- Temperature vs. time behavior does not look correct!
- Maximum temperature is underpredicted.

- 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*

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Parameters

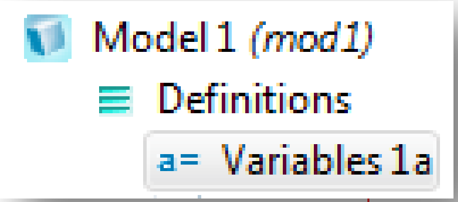
These numerical values are arbitrary and only for illustration purposes

Parameters

Parameters

Name	Expression	Value	Description
x0	0[mm]	0 m	Path center x-coordinate
y0	0[mm]	0 m	Path center y-ccordinate
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



- 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

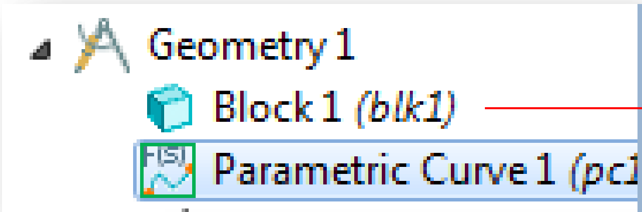
Geometric Entity Selection

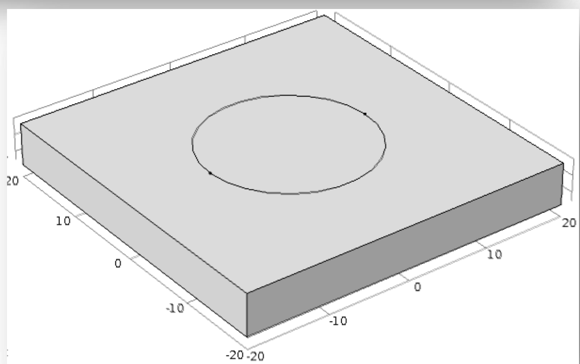
Geometric entity level: Entire model

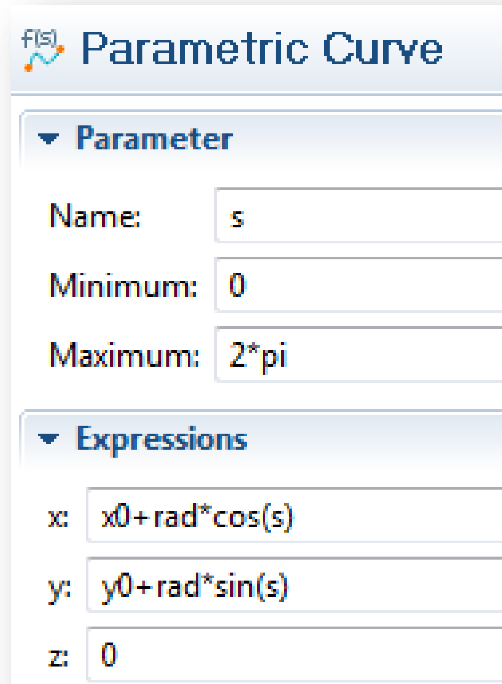
Variables

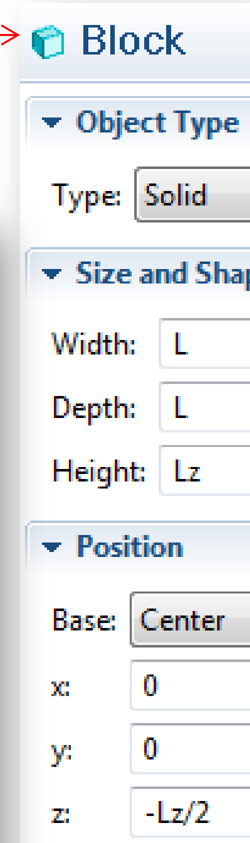
Name	Expression	Unit	Description
x00	x0+rad*cos(omega*t)	m	Pulse center x-coordinate
y00	y0+rad*sin(omega*t)	m	Pulse center y-coordinate
Q_in	Q0*(1-Rc)*Ac*(1/(pi*sigx*sigy))*an1(x,x00,sigx,y,y00,sigy)*exp(-Ac*abs(z))	W/m³	Power input

Geometry



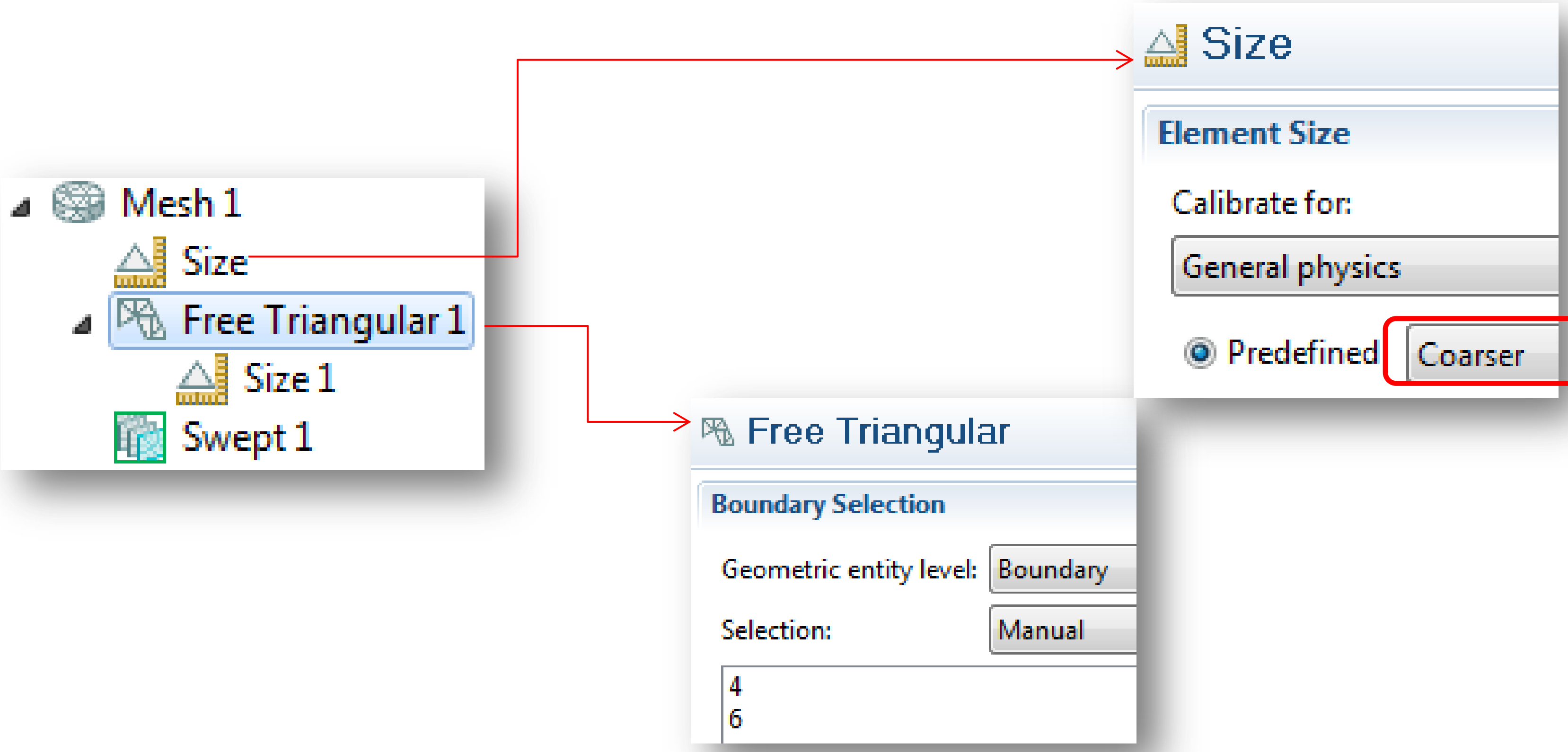






- We create extra geometric edges on the top surface which outline the path of laser motion.
- These edges are used to guide a finer mesh only along the path of laser motion.
- Although we use a circular path in this tutorial, in general you could create any arbitrary path using the Parametric Curve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

Mesh


Mesh 1
Size
Free Triangular 1
Size 1
Swept 1
Size
Element Size
Calibrate for:
General physics
Predefined
Coarser
Free Triangular
Boundary Selection
Geometric entity level:
Boundary
Selection:
Manual
4
6

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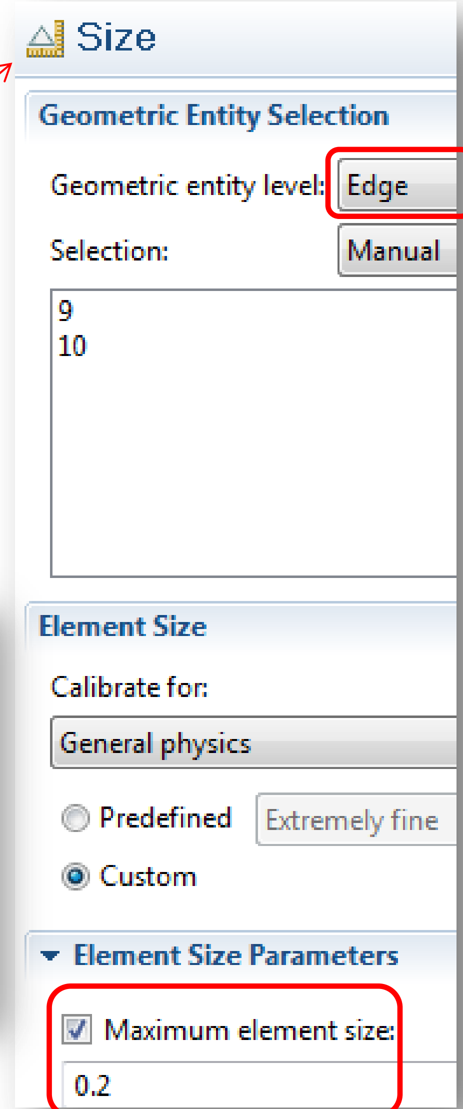
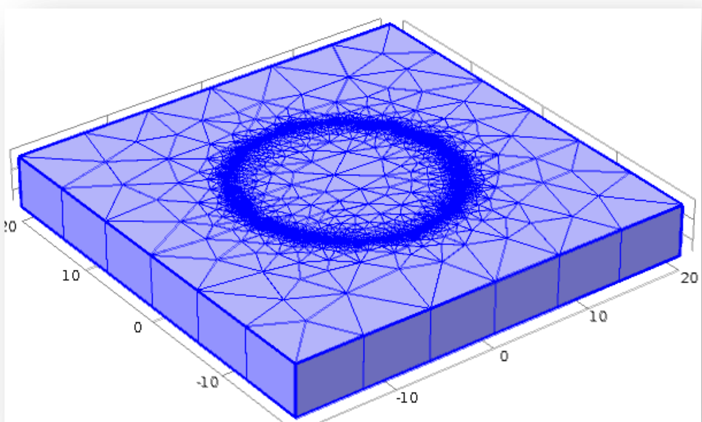
Mesh

Mesh 1
Size
Free Triangular 1
Size 1
Swept 1

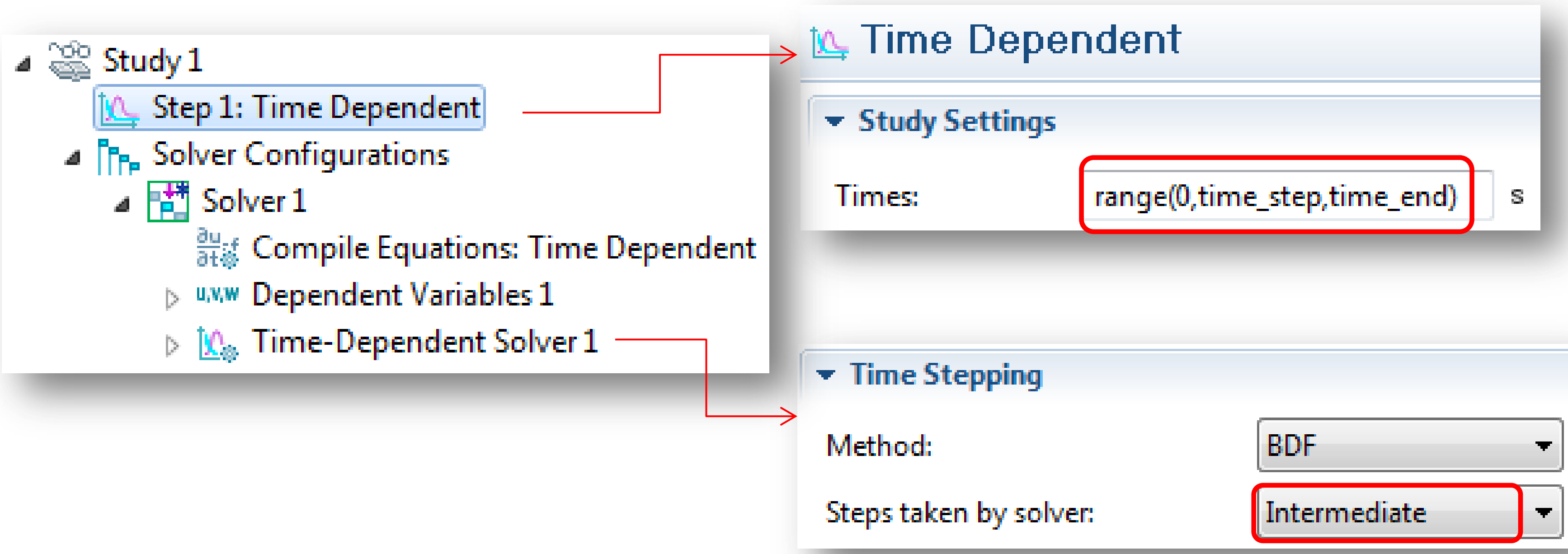


Size
Geometric Entity Selection
Geometric entity level:
Edge
Selection:
Manual
9
10
Element Size
Calibrate for:
General physics
Predefined
Extremely fine
Custom
Element Size Parameters
Maximum element size:
0.2



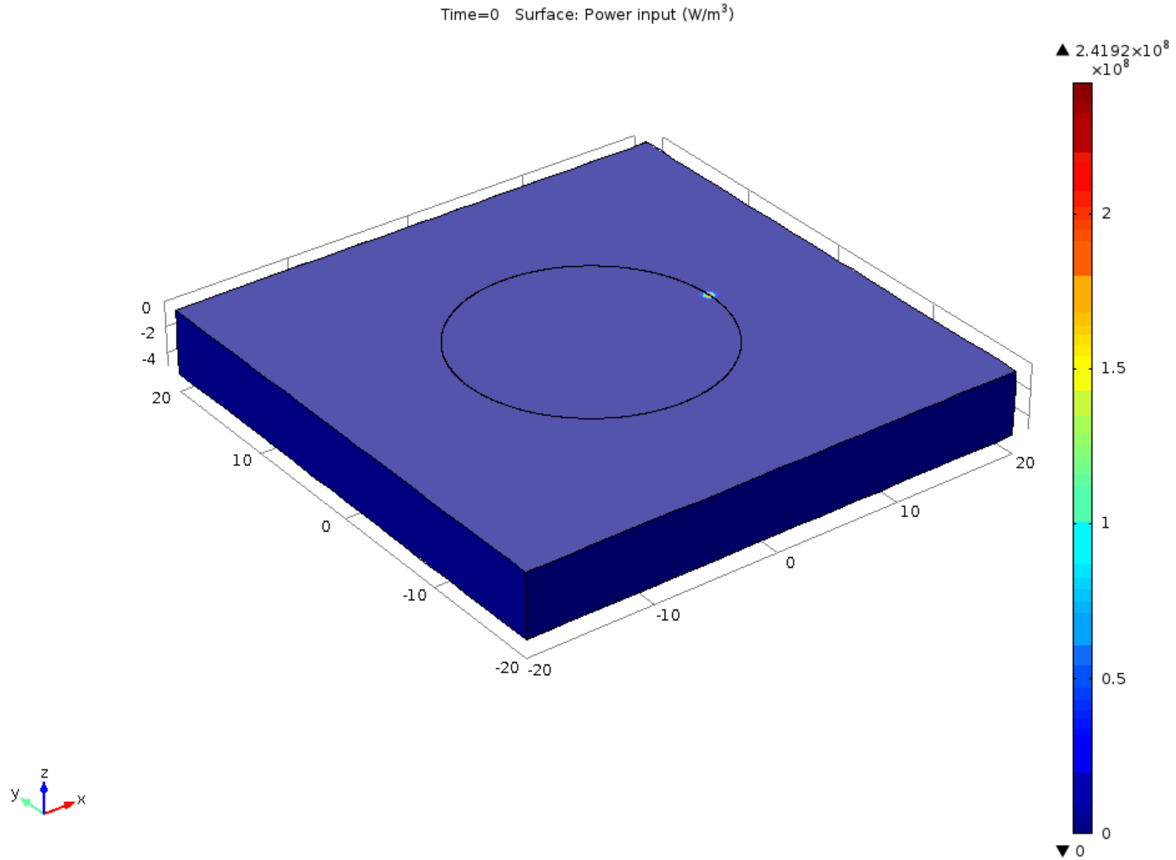
10
0
-10
20
10
0
-10

Time-Dependent Study



- 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

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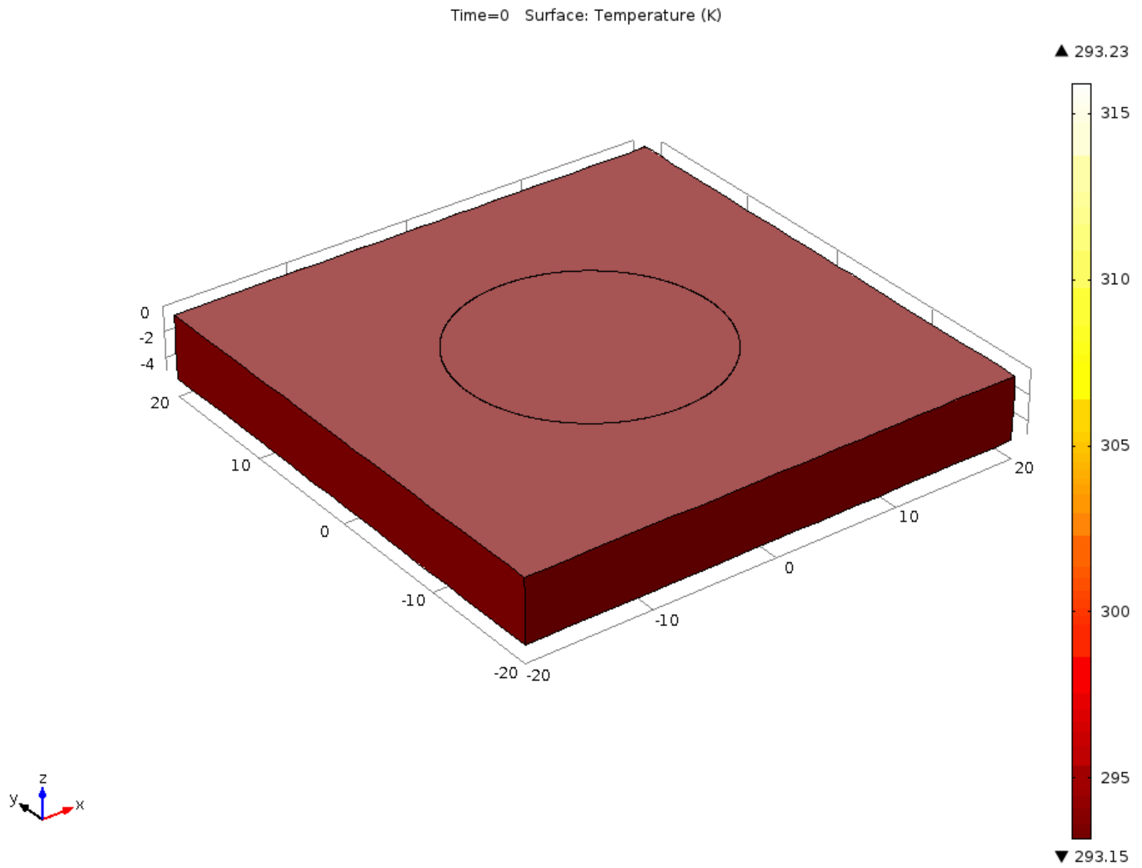
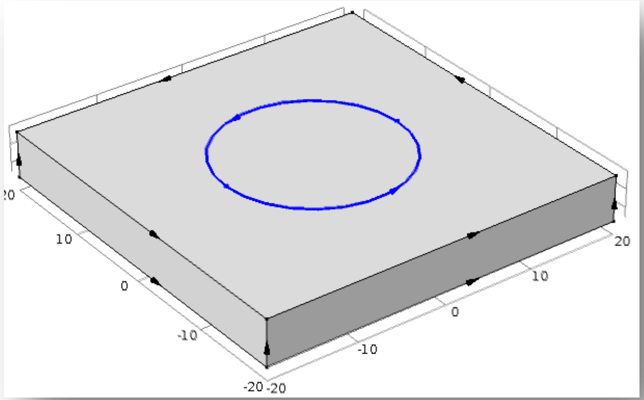
Results – Temperature profile

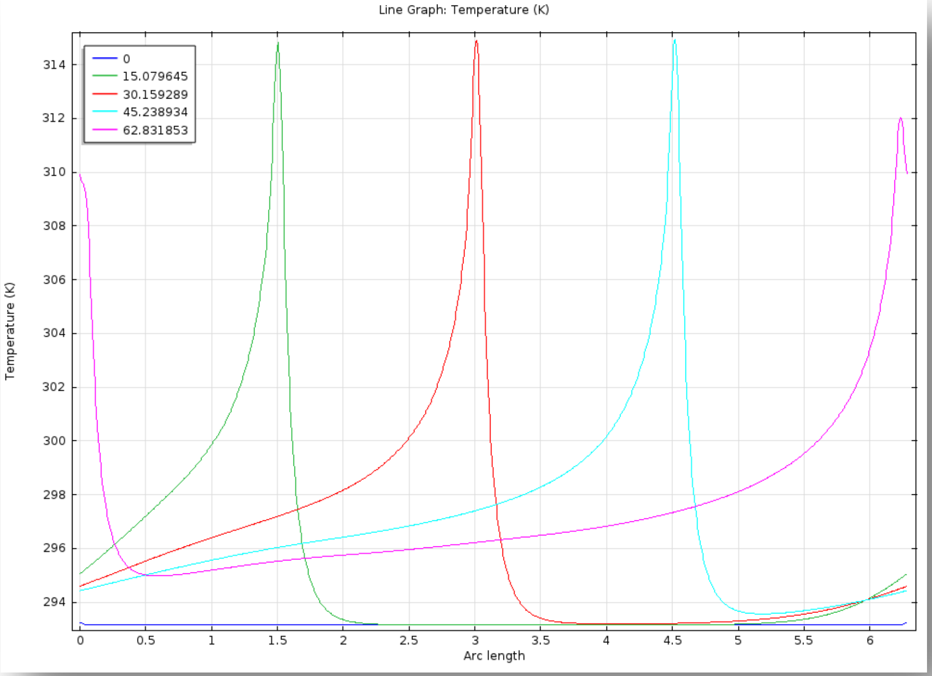


Enable slide show to see the movie

Results – Temperature profile

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





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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.