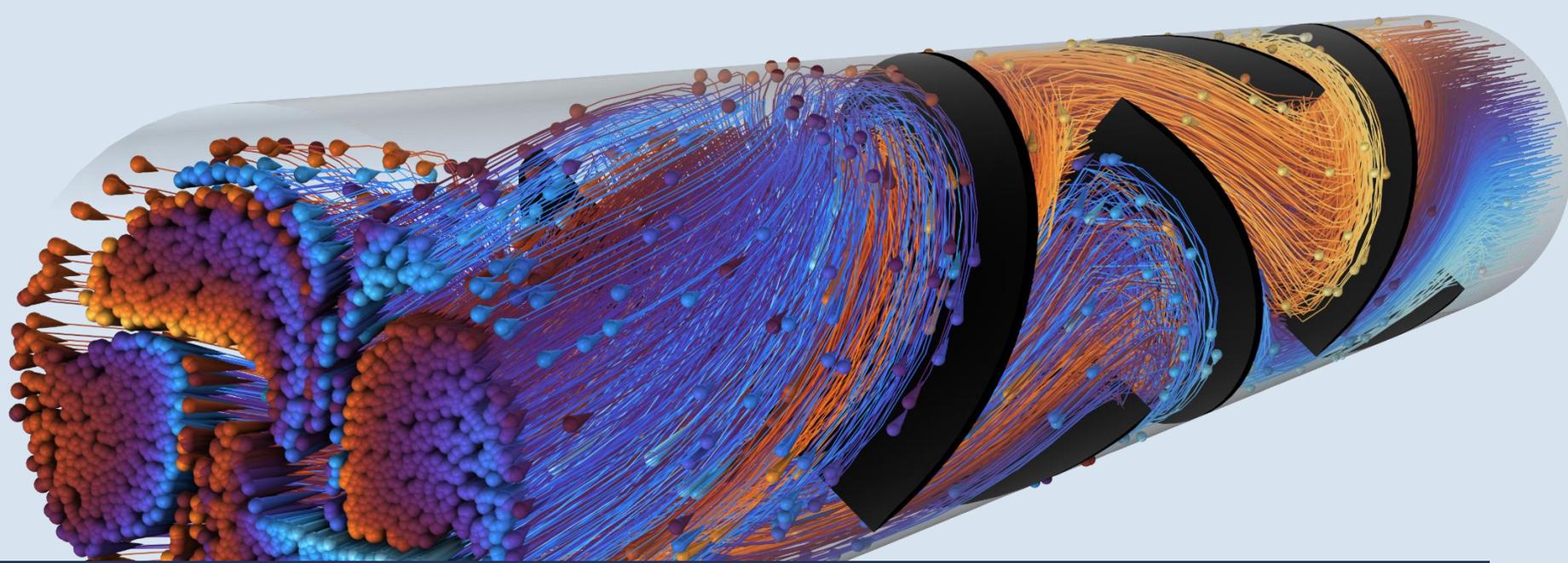


Particle Tracing Module

Tomáš Vrbata
HUMUSOFT s.r.o.



Particle Tracing Module

Particle Tracing

- Positions and velocities of particles over time
- Wide variety of particle releases, boundary conditions, forces, ...
- Alternative to field-based methods

Physics Interfaces

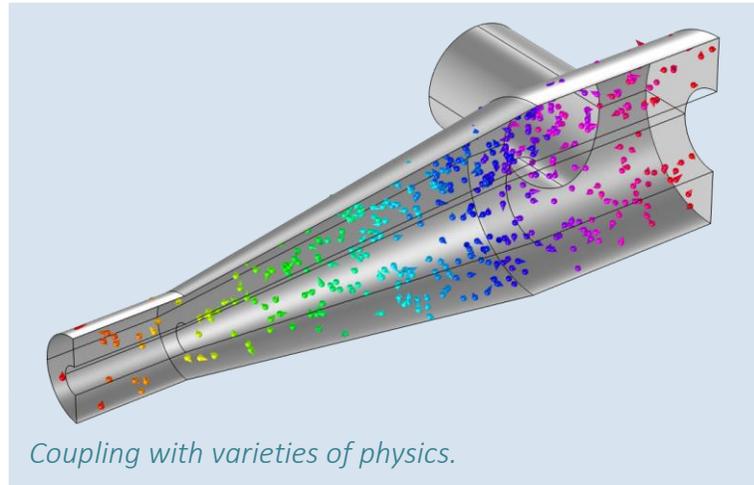
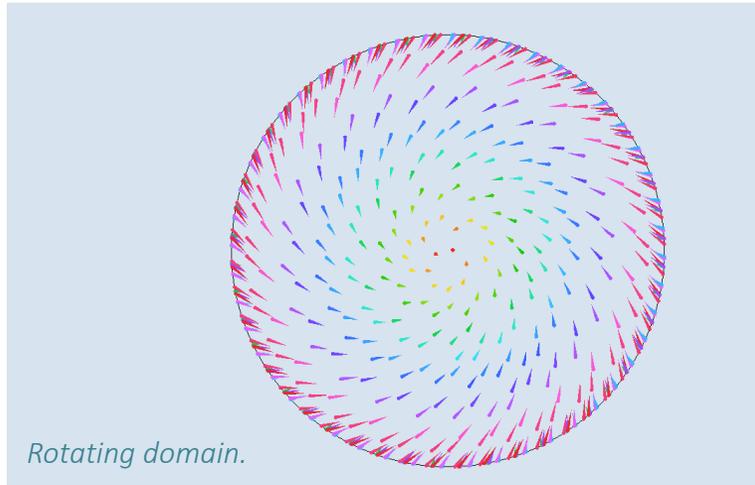
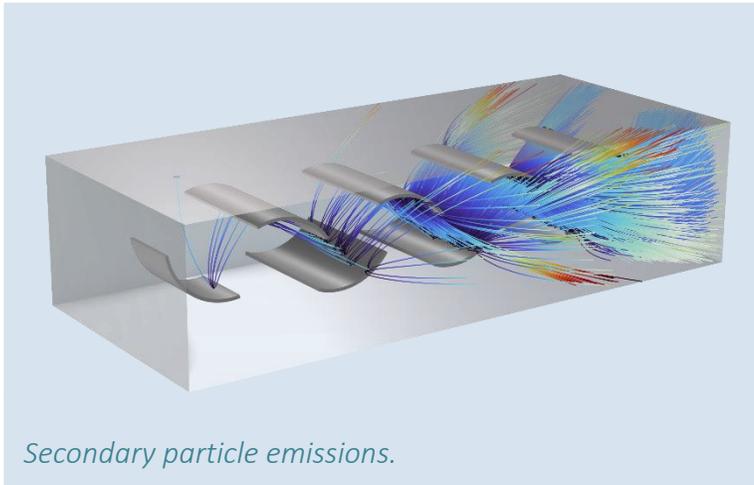
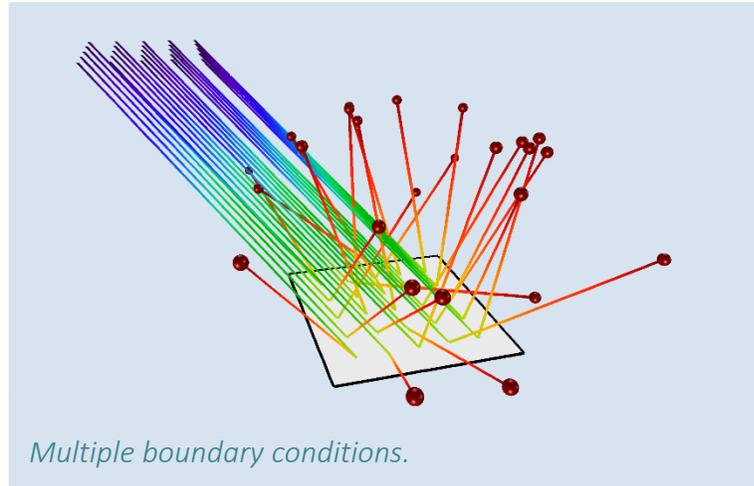
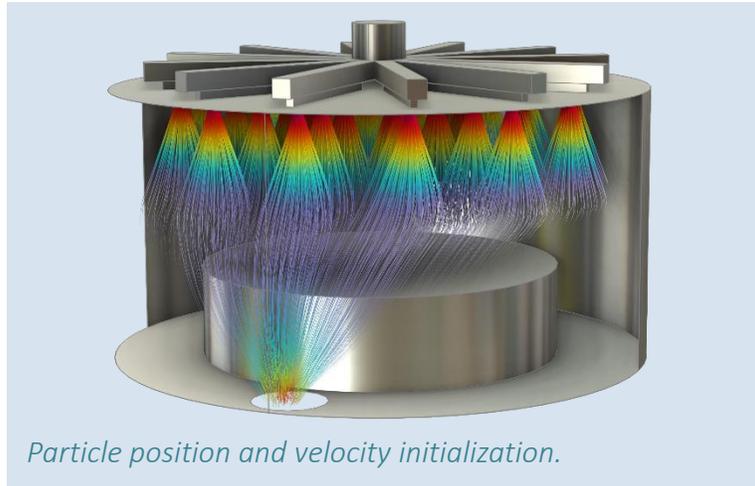
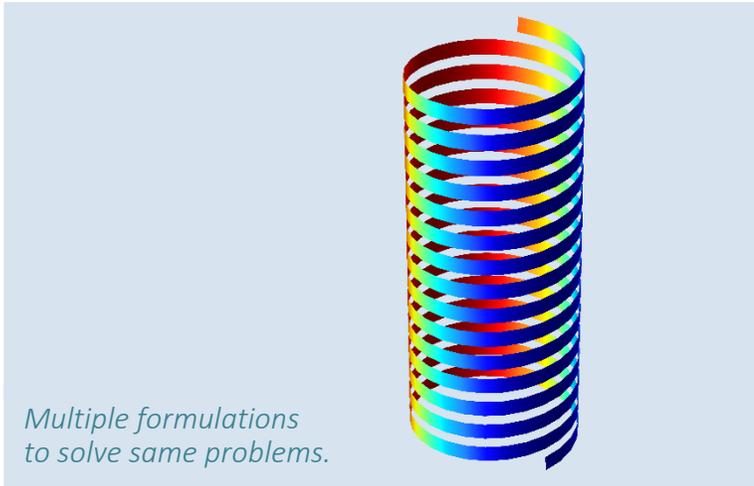
- Mathematical Particle Tracing
- Charged Particle Tracing
- Particle Tracing for Fluid Flow

Application Areas

- Mass spectrometry
- Separation and filtration
- Droplets and sprays
- Erosion
- Plasmas

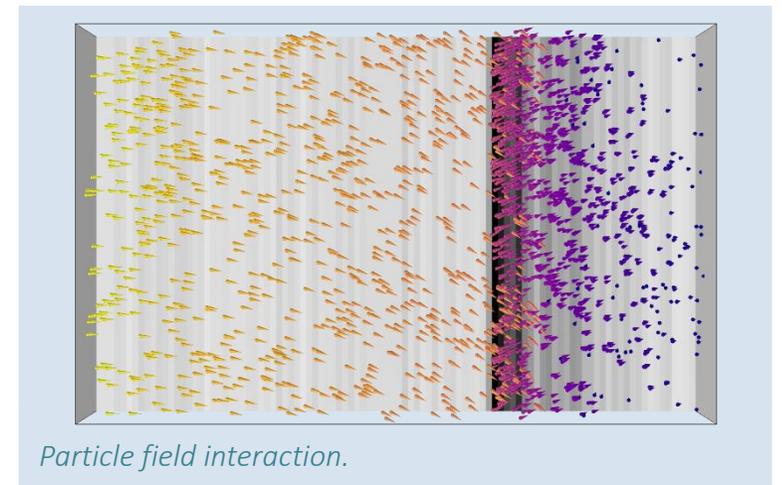
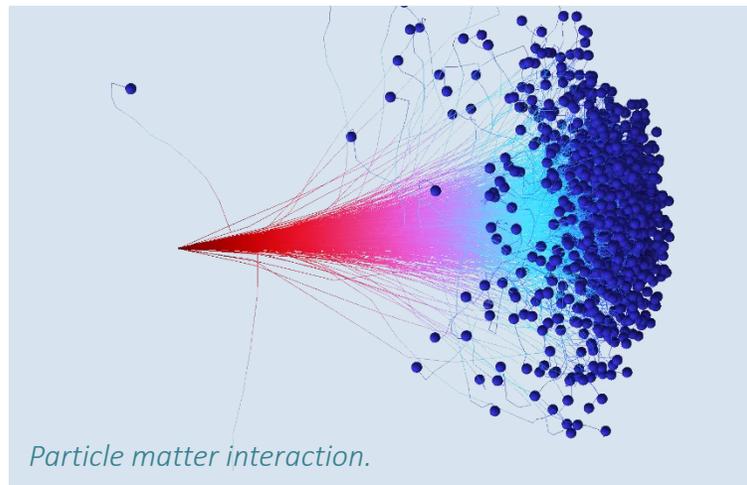
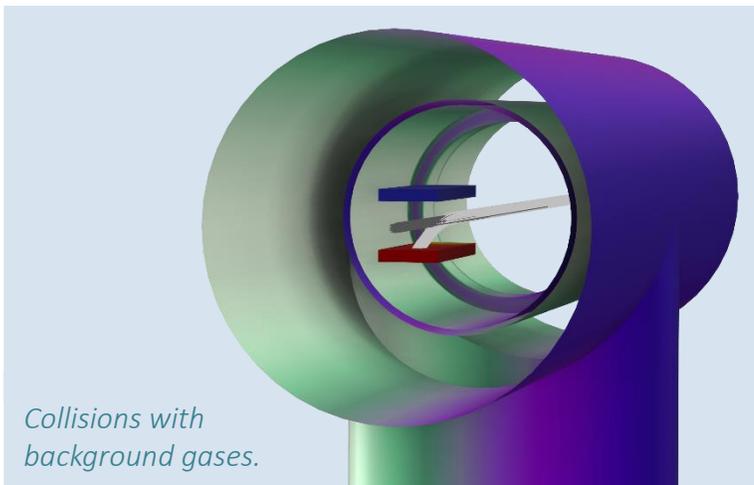
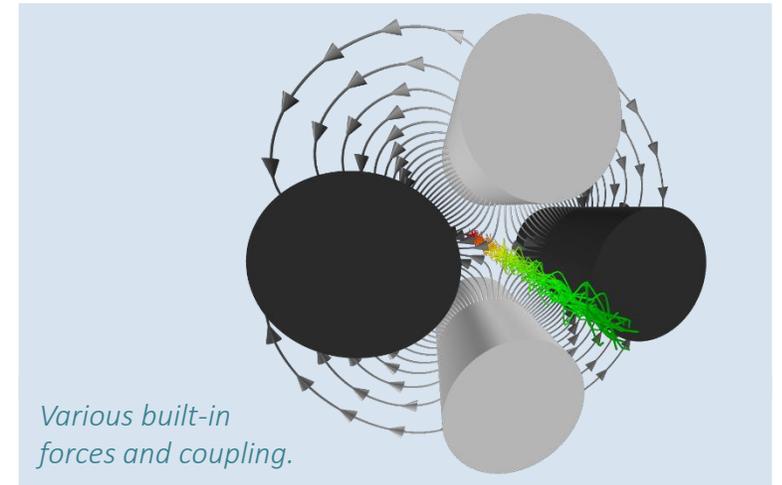
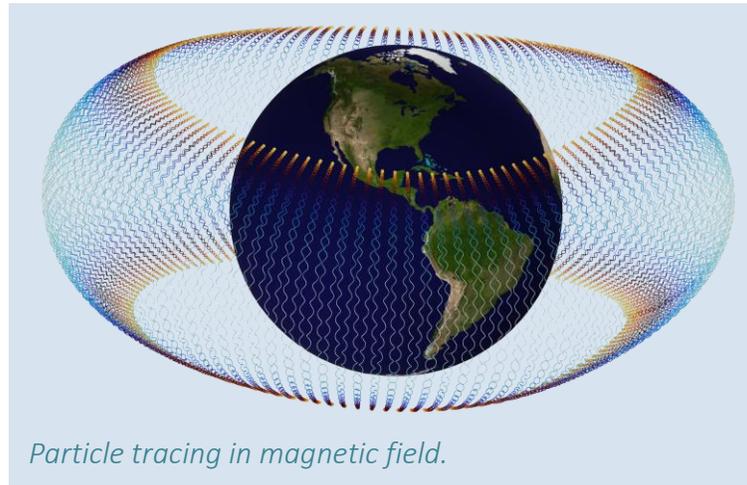
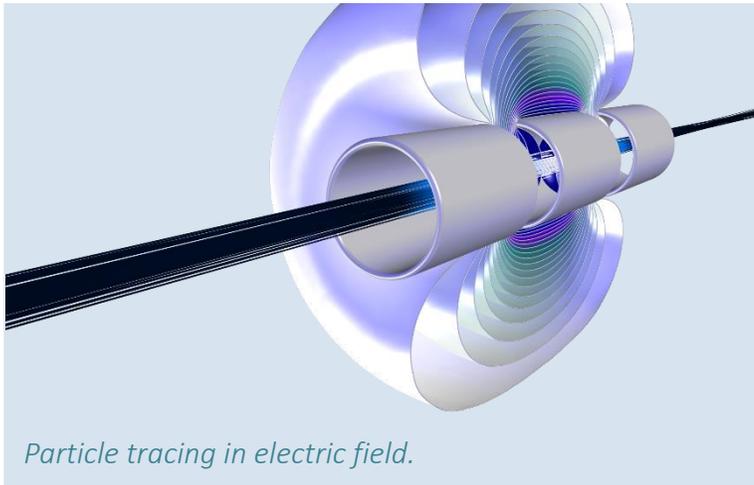
MODELING CAPABILITIES

Particle Tracing Functionalities



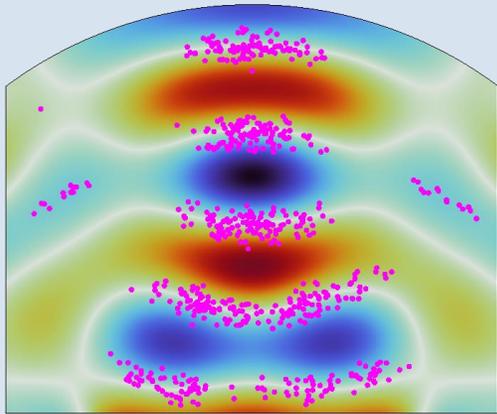
MODELING CAPABILITIES

Charged Particle Tracing

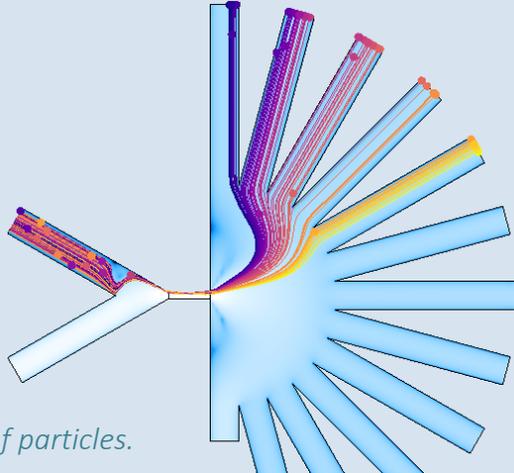


MODELING CAPABILITIES

Particle Tracing for Fluid Flow



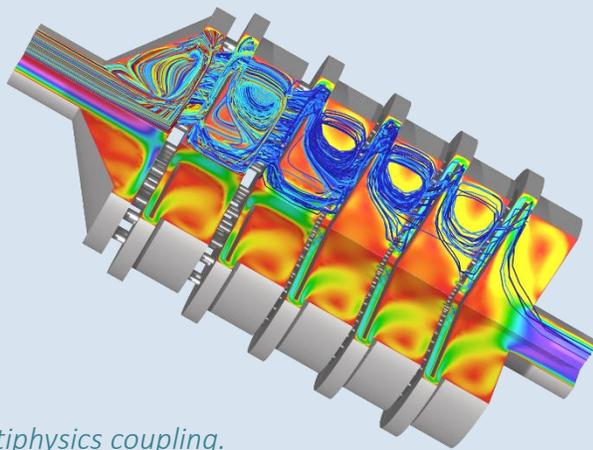
Multiple built-in forces.



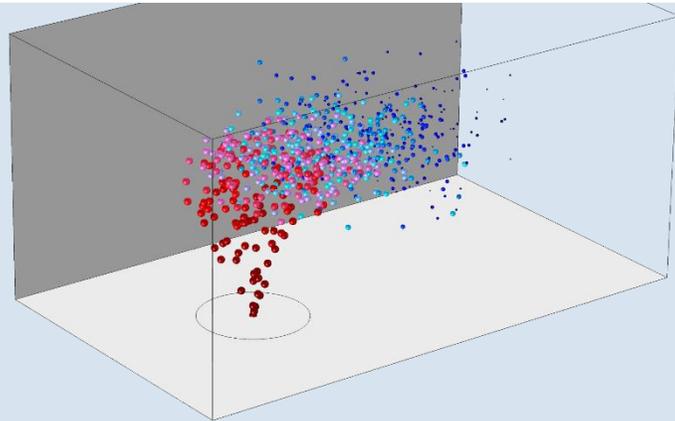
Multi species of particles.



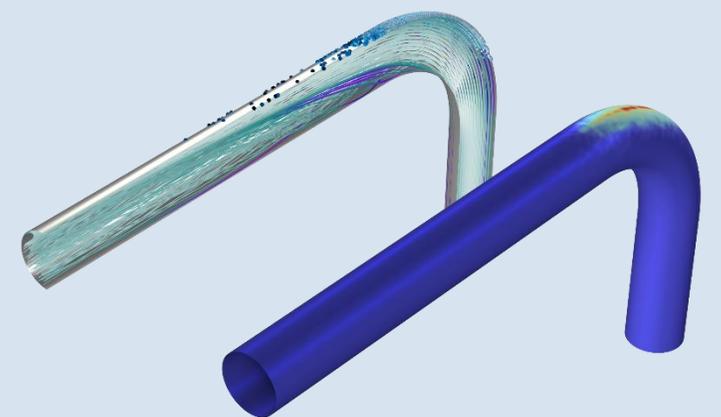
Particle tracing in turbulent fluid flow.



Multiphysics coupling.



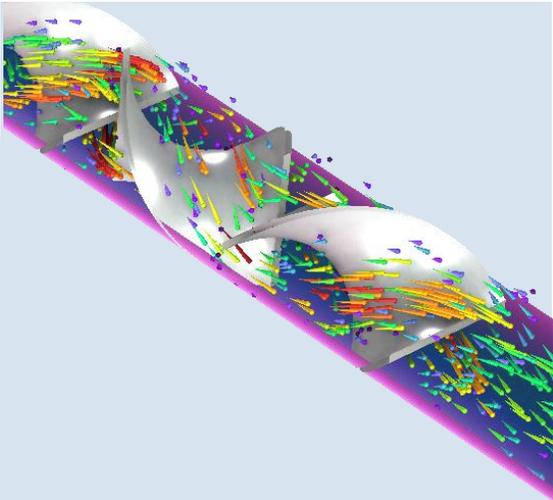
Droplet spraying and evaporation.



Erosion modeling.

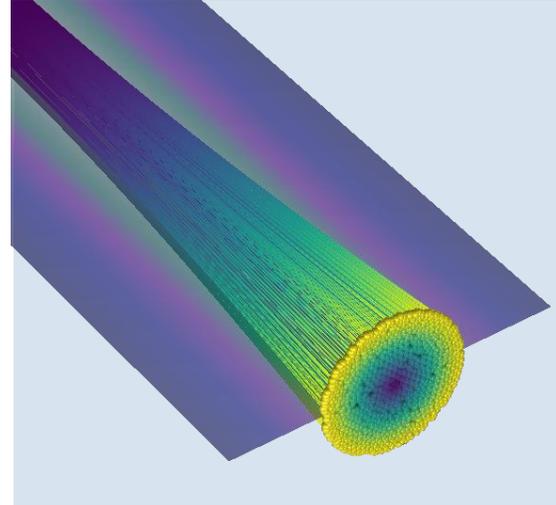
MODELING CAPABILITIES

Multiphysics Couplings with Particle Tracing



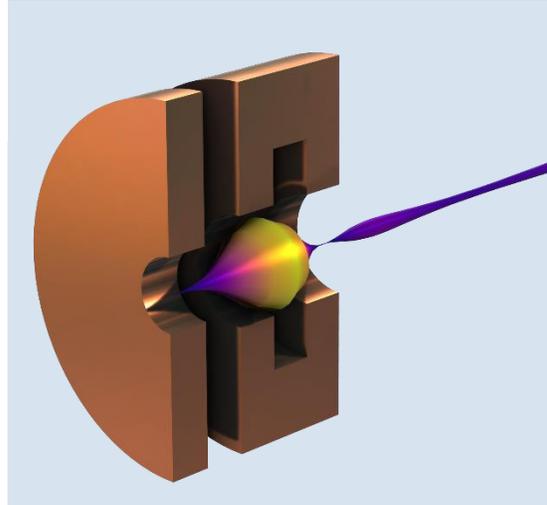
Fluid-Particle Interaction

This capability computes drag force exerted on particles in each mesh element in selected domains.



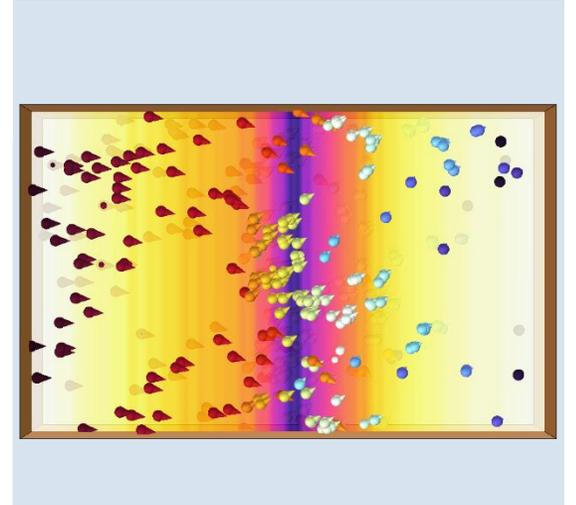
Electric Particle Field Interaction

You can compute space charge density due to particles and also apply it as a source when computing the electric potential



Magnetic Particle Field Interaction

You can compute accumulated current density due to motion of charged particles and use it as a source for the computation of the magnetic vector potential.



Space Charge limited Emission

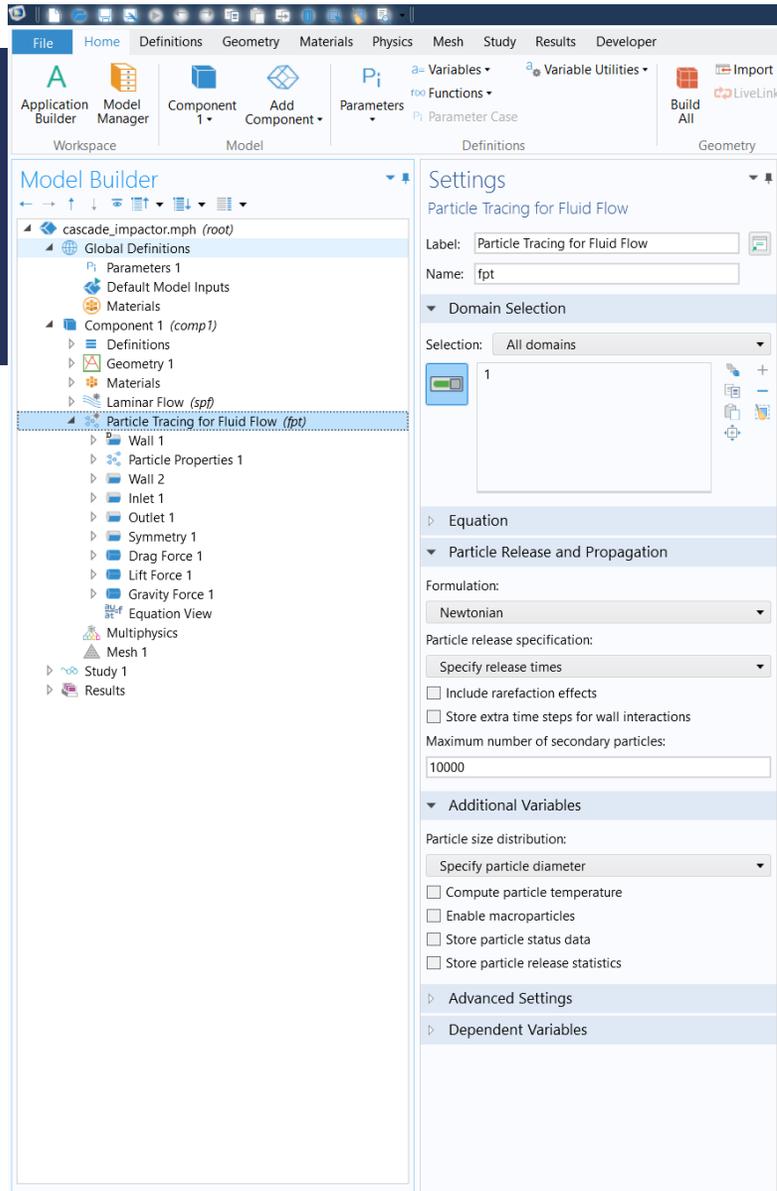
This Multiphysics coupling models the space charge limited emission of electrons from a surface.

*Requires the CFD Module and Acoustics Module.

- A) What?
- B) From?
- C) What happens on walls?
- D) Which forces?

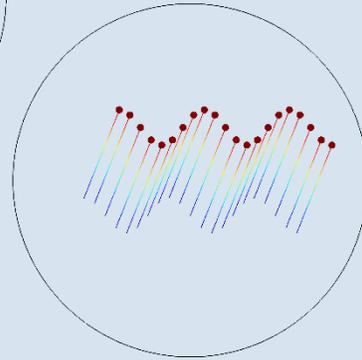
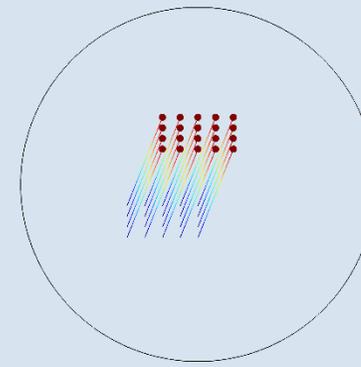
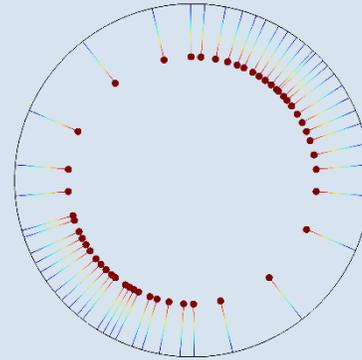
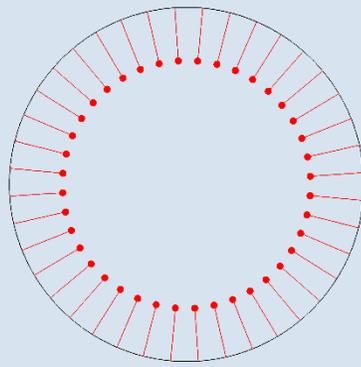
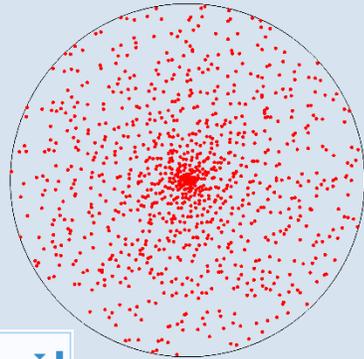
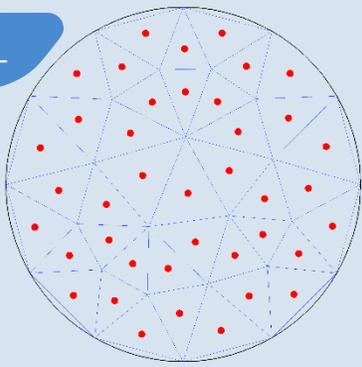


Essential Features in a PT Modul



Essential Features in a PT Model

- At least one Particle Properties node (particle size, etc.)
- At least one release feature (Release, Inlet, etc.)
- At least one boundary condition (a default Wall node)
- Applied Forces
- (Optional) – Domain interactions
 - Secondary particle emissions



Settings

Release from Grid

Label: Release from Grid 1

Equation

Show equation assuming:

Study 1, Time Dependent

$$\mathbf{q} = \mathbf{q}_0$$

$$v = v_0$$

$$f(\theta, \varphi) = \frac{1}{4\pi} \sin \theta$$

$$\theta \in [0, \pi]$$

$$\varphi \in [0, 2\pi]$$

Release Times

Initial Coordinates

Grid type:

All combinations

$q_{x,0}$ dx m

$q_{y,0}$ dy m

$q_{z,0}$ dz m

Initial Velocity

Initial velocity:

Constant speed, spherical

Sampling from distribution:

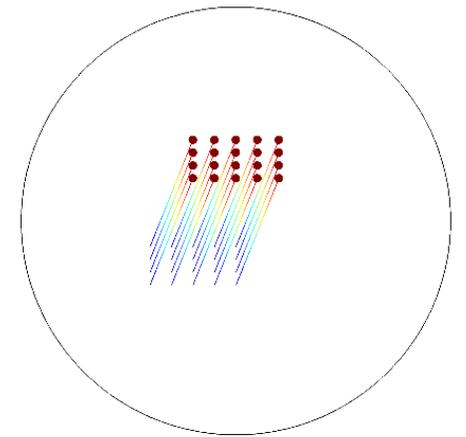
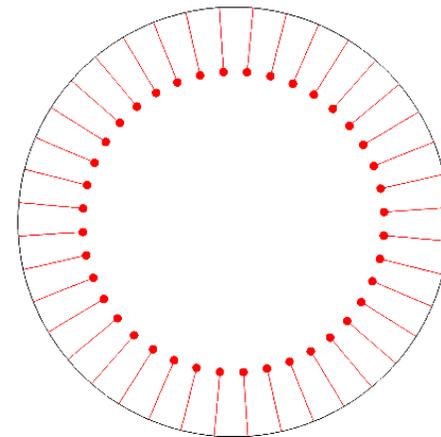
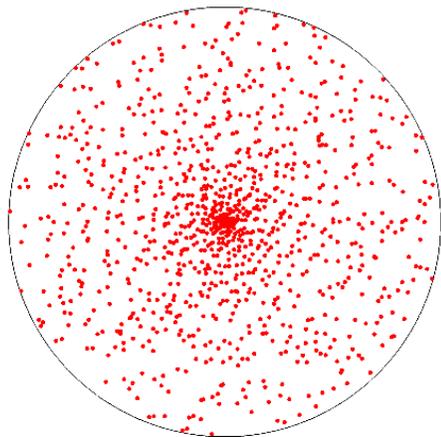
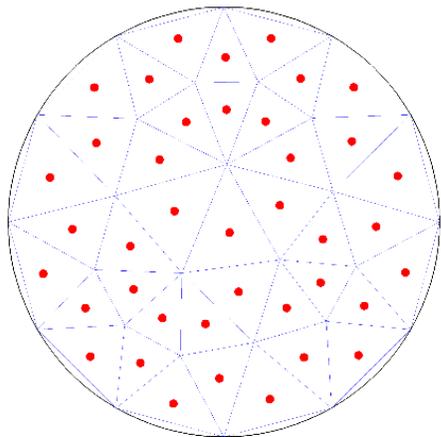
Random

Releasing Particles

- Release from grid or data file
- Release from data file
- Release from domain, boundary, edges, and points based on user-defined density functions, uniform, or random

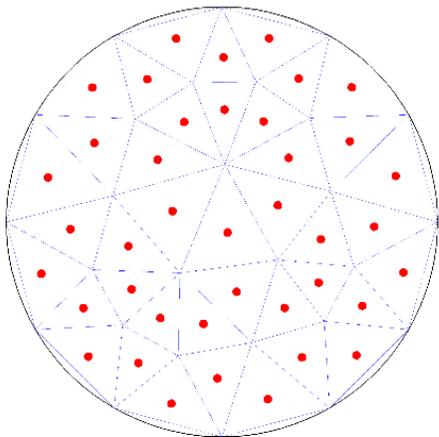
Guess the Method of Release

- A) Rectangular grid
- B) Density proportional to an expression
- C) Mesh-based
- D) Arbitrary grid
- E) Uniform release from boundary

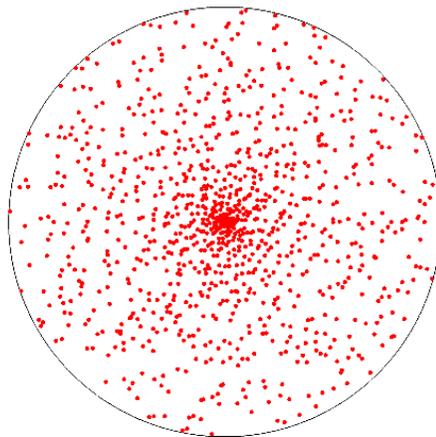


Guess the Method of Release

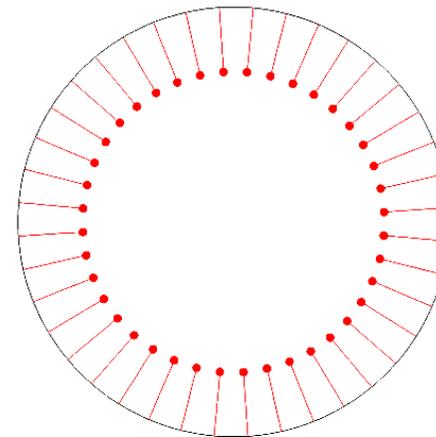
- A) Rectangular grid
- B) Density proportional to an expression
- C) Mesh-based
- D) Arbitrary grid
- E) Uniform release from boundary



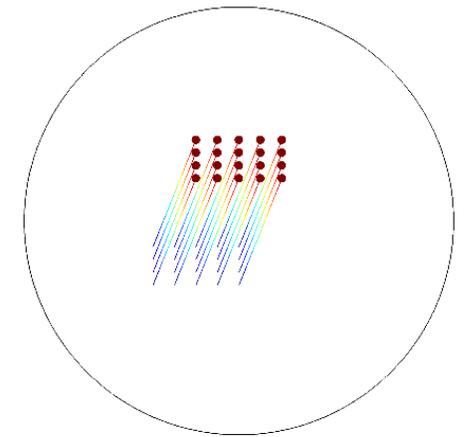
Mesh-based



Density proportional



Uniform release from boundary

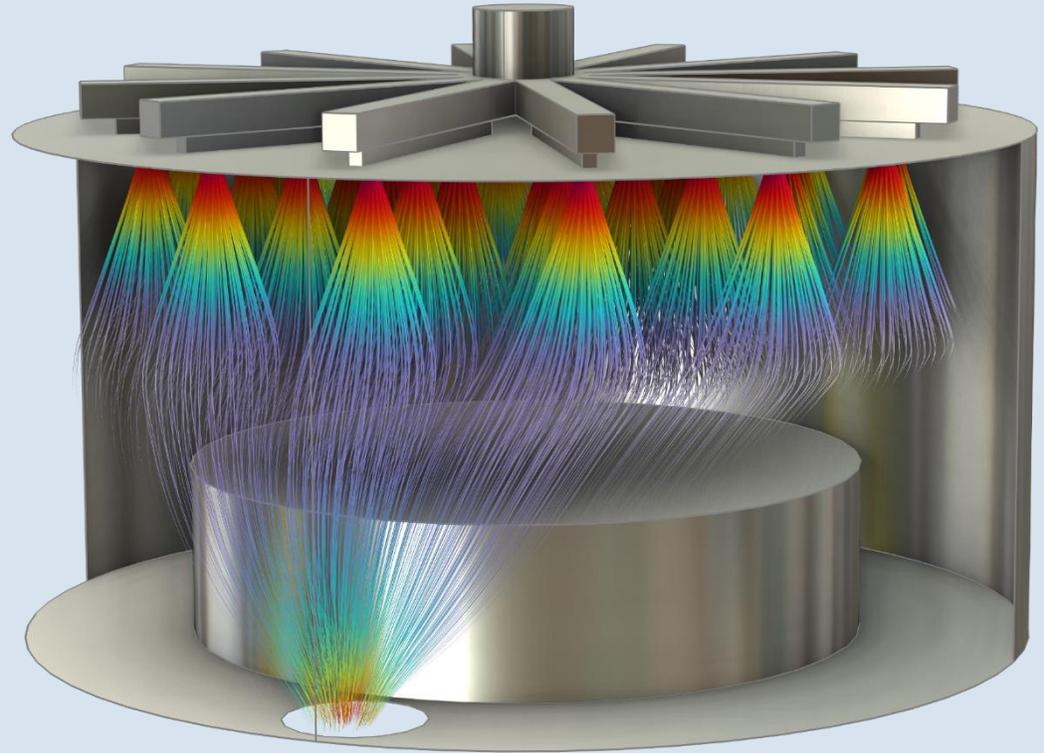


Rectangular grid

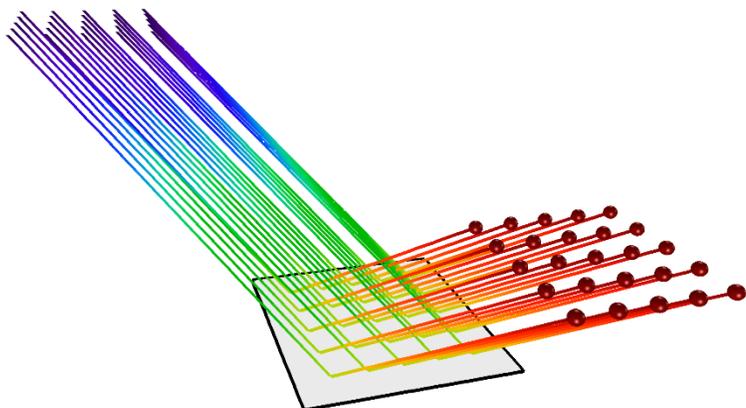
Initializing Particle Velocity

Initialize velocity by:

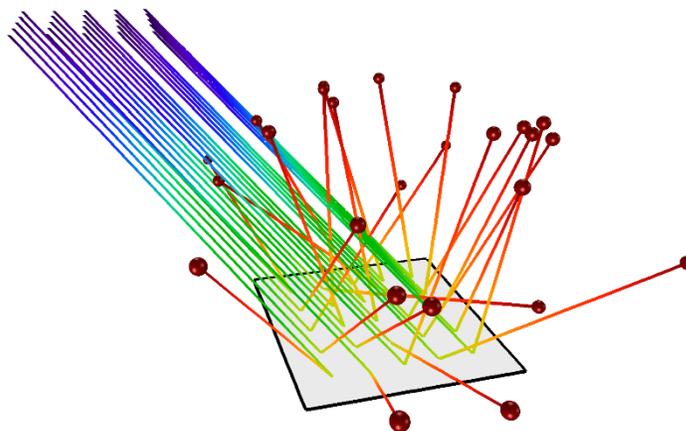
- Specifying components directly
- Using kinetic energy and direction
- Uniform distributions:
 - Sphere
 - Hemisphere
 - Cone
 - Lambertian



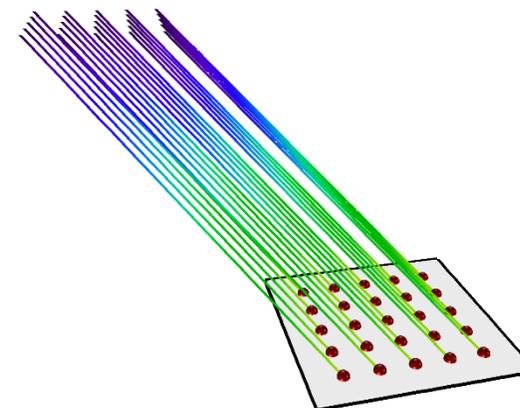
Cone-based release of particles can be used to model sprays in devices such as CVD chambers.



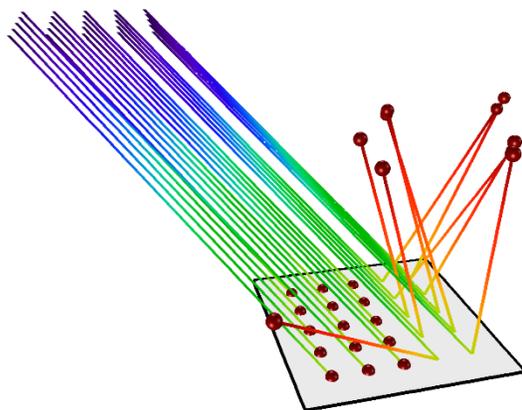
Specular reflection.



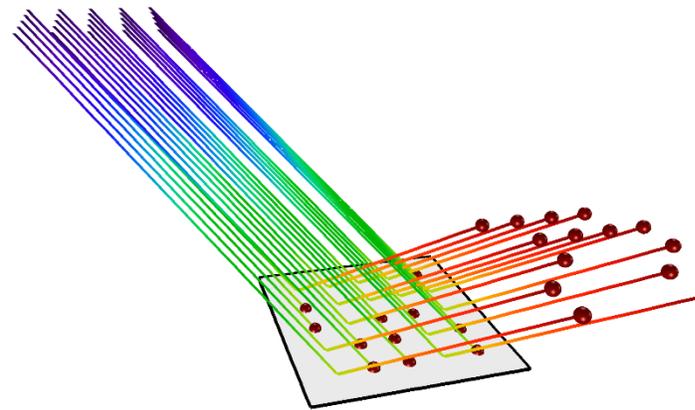
Diffuse or isotropic scattering.



Absorption: stop or remove particles.



*Conditional interactions,
based on a custom expression.*



*Conditional interactions,
based on probability.*

Forces

- User-defined expressions
- Can query any field variable defined in the modeling domain
- Particle-particle interactions
- Many forces can be combined in a single model
- Forces can apply to all particles or just to a certain species

three_body_problem.mph - COMSOL Multiphysics

File Home Definitions Geometry Sketch Materials Physics Mesh Study Results Developer

Application Builder Model Manager Component 1 Add Component Parameters Functions Import Build All Add Material Mathematical Particle Tracing Add Physics Build Mesh Mesh Compute Study 2: Lagrange Configuration Add Study Lagrange Configuration

Model Builder

- three_body_problem.mph
 - Global Definitions
 - Component 1
 - Definitions
 - Geometry 1
 - Materials
 - Mathematical Particle Tracing
 - Wall 1
 - Particle Properties 1
 - Particle-Particle Interaction 1
 - Release from Grid 1
 - Release from Grid 2
 - Release from Grid 3
 - Release from Grid 4
 - Release from Grid 5
 - Release from Grid 6
 - Mesh 1
 - Study 1: Figure-Eight Configuration
 - Study 2: Lagrange Configuration
 - Results
 - Datasets
 - Derived Values
 - Tables
 - Color Tables
 - Figure-Eight Configuration
 - Check Energy Conservation
 - Lagrange Configuration
 - Export
 - Reports

Settings

Particle-Particle Interaction

Label: Particle-Particle Interaction 1

Domain Selection

Override and Contribution

Equation

Show equation assuming:

Study 1: Figure-Eight Configuration, Time Dependent

$\mathbf{F} = \mathbf{F}_u$

Force

Interaction force:

User defined

Force:

F_u	$\text{gravity} \cdot \text{pt.mp} \cdot \text{dest}(\text{pt.mp}) \cdot (\text{qx} - \text{dest}(\text{qx})) / \text{pt.r}^3$	x	N
	$\text{gravity} \cdot \text{pt.mp} \cdot \text{dest}(\text{pt.mp}) \cdot (\text{qy} - \text{dest}(\text{qy})) / \text{pt.r}^3$	y	

Advanced Settings

Exclude Jacobian contribution for particle-particle interaction

Apply cutoff length

Graphics Plot 1 X

Time=5.2201E10 s

Particle traj

Messages Progress Log

Fictitious Forces in Rotating Frames

- Centrifugal force
- Coriolis force
- Euler force

rotating_frame.mph - COMSOL Multiphysics

File Home Definitions Geometry Sketch Materials Physics Mesh Study Results Developer

Application Builder Model Manager Component 1 Add Component Parameters Variables Functions Parameter Case Variable Utilities Build All Import LiveLink Add Material Mathematical Particle Tracing Add Physics Build Mesh Mesh 1 Compute Study 1 Add Study

Workspace Model Definitions Geometry Mesh Study

Model Builder

- rotating_frame.mph
 - Global Definitions
 - Parameters 1
 - Materials
 - Component 1
 - Definitions
 - Geometry 1
 - Circle 1
 - Form Union
 - Materials
 - Mathematical Particle Tracing
 - Wall 1
 - Particle Properties 1
 - Release 1
 - Rotating Frame 1**
 - Equation View
 - Mesh 1
 - Study 1
 - Step 1: Time Dependent
 - Solver Configurations
 - Job Configurations
 - Results
 - Datasets
 - Views
 - Derived Values
 - Tables
 - Color Tables
 - Particle Trajectories (pt)
 - Frame Velocity (pt)
 - Export
 - Reports

Settings
Rotating Frame

Label: Rotating Frame 1

Domain Selection

Selection: All domains

1

Override and Contribution

Equation

Show equation assuming: Study 1, Time Dependent

$$\frac{d(m_p \mathbf{v})}{dt} = m_p \boldsymbol{\Omega} \times (\mathbf{r}_{cr} \times \boldsymbol{\Omega}) + 2m_p \mathbf{v} \times \boldsymbol{\Omega} + m_p \mathbf{r}_{cr} \times \dot{\boldsymbol{\Omega}}$$

$\mathbf{r}_{cr} = \mathbf{q} - \mathbf{r}_{bp}$, \mathbf{r}_{bp} is the rotation axis base point

Rotating Frame

Rotation axis base point:

\mathbf{r}_{bp}	0	x	m
	0	y	

Rotational direction: Counterclockwise

Rotational frequency: Angular velocity

Angular velocity, magnitude: Ω 10 [rad/s] rad/s

Centrifugal force

Coriolis force

Euler force

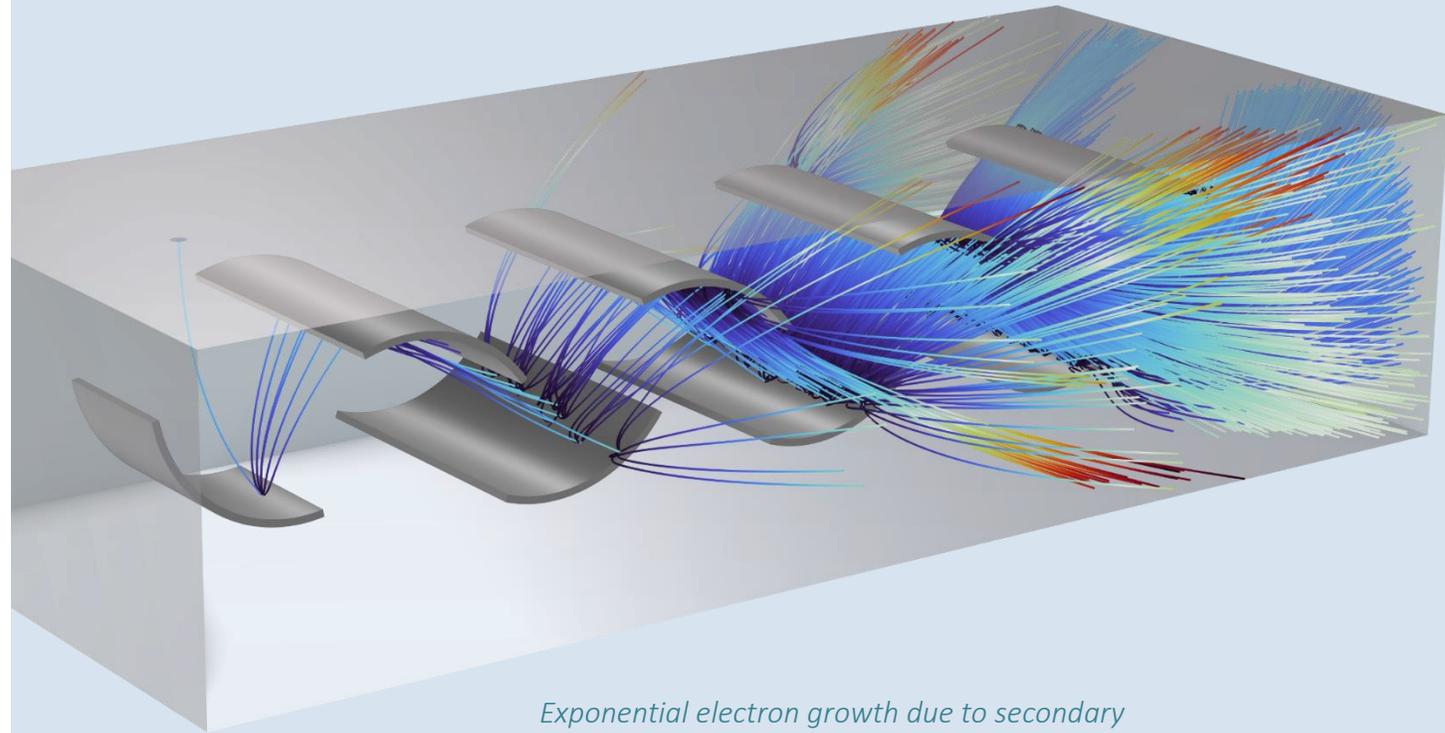
Affected Particles

Plot 1

Time=0.0987 s Particle trajectories

Secondary Particle Emission

- Particles in a model can release secondary particles in domains or while hitting boundaries
- Secondary emission can be based on a probability or a logical expression



Exponential electron growth due to secondary emission in a photomultiplier.

Charged Particle Tracing Interface

- For computing ion and electron trajectories
- Built-in electric and magnetic forces
- Easy coupling to electric or magnetic fields solved for by one of the AC/DC interfaces
- Monte Carlo collision model for rarefied gases

einzel_lens.mph - COMSOL Multiphysics

File Home Definitions Geometry Materials Physics Mesh Study Results Developer

Application Builder Model Manager Component 1 Add Component Parameters Variables Functions Parameter Case Build All Import LiveLink Add Material Charged Particle Tracing Add Physics Build Mesh Mesh 1 Compute Study 2 Add Study Equipotential Surfaces Add Plot Group Results

Model Builder

- einzel_lens.mph
 - Global Definitions
 - Component 1
 - Definitions
 - Geometry 1
 - Materials
 - Electrostatics
 - Charged Particle Tracing
 - Wall 1
 - Particle Properties 1
 - Electric Force 1
 - Particle Beam 1
 - Multiphysics
 - Mesh 1
 - Study 1
 - Study 2
 - Results
 - Datasets
 - Views
 - Derived Values
 - Tables
 - Color Tables
 - Equipotential Surfaces
 - Fringe Field
 - Particle Trajectories (cpt)
 - Average Beam Position (cpt)
 - Export
 - Reports

Settings

Charged Particle Tracing

Label: Charged Particle Tracing

Name: cpt

Domain Selection

Equation

Equation form: Study controlled

Show equation assuming: Study 1, Stationary

$$\frac{d(m_p \mathbf{v})}{dt} = \mathbf{F}_t, m_p = \frac{m_r}{\sqrt{1 - \mathbf{v} \cdot \mathbf{v}/c^2}}$$

Particle Release and Propagation

Formulation: Newtonian

Particle release specification: Specify release times

Relativistic correction

Store extra time steps for wall interactions

Maximum number of secondary particles: 10000

Additional Variables

Store particle status data

Store particle release statistics

Dependent Variables

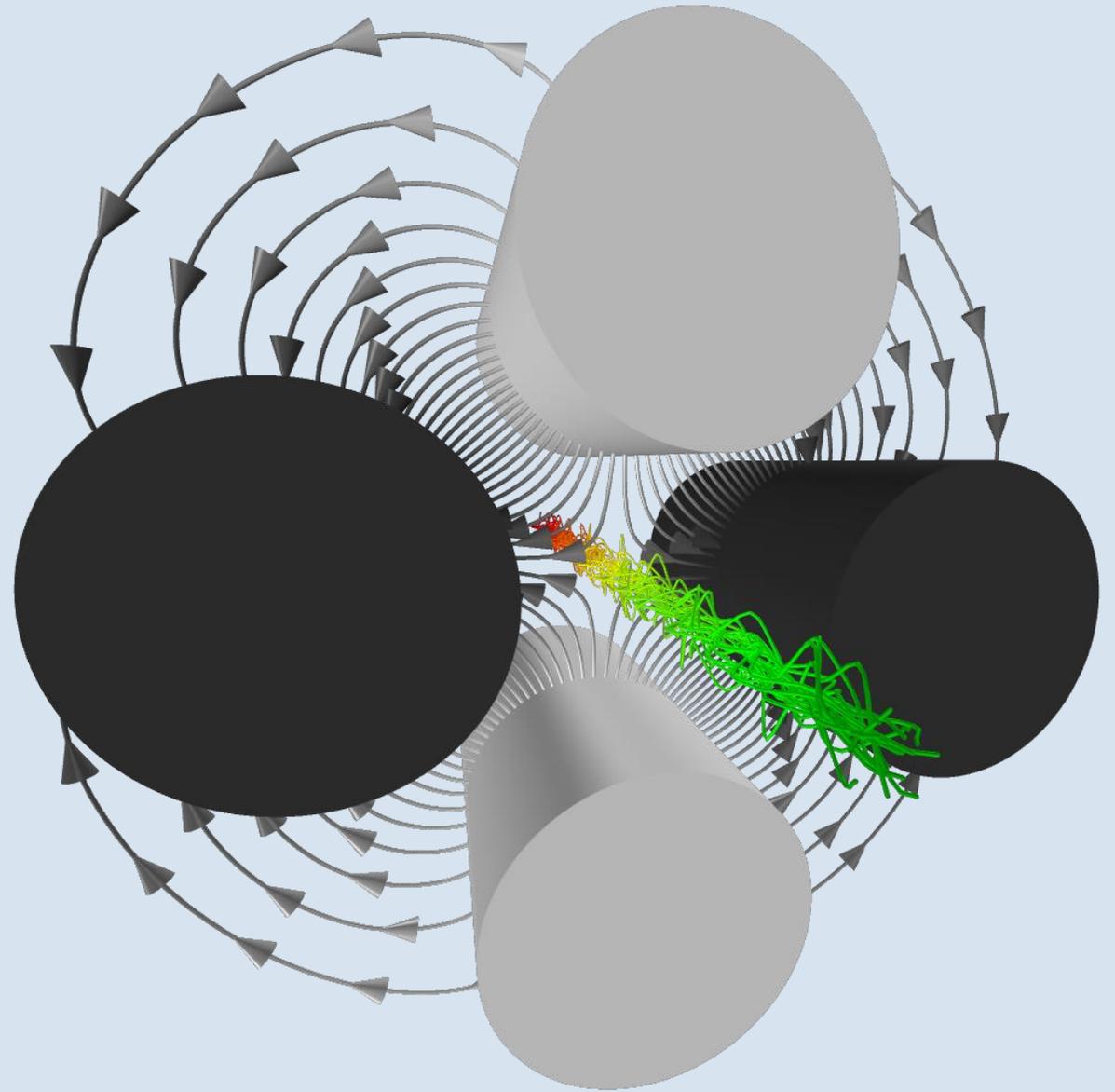
Graphics Plot 1 X

Isosurface: Electric p

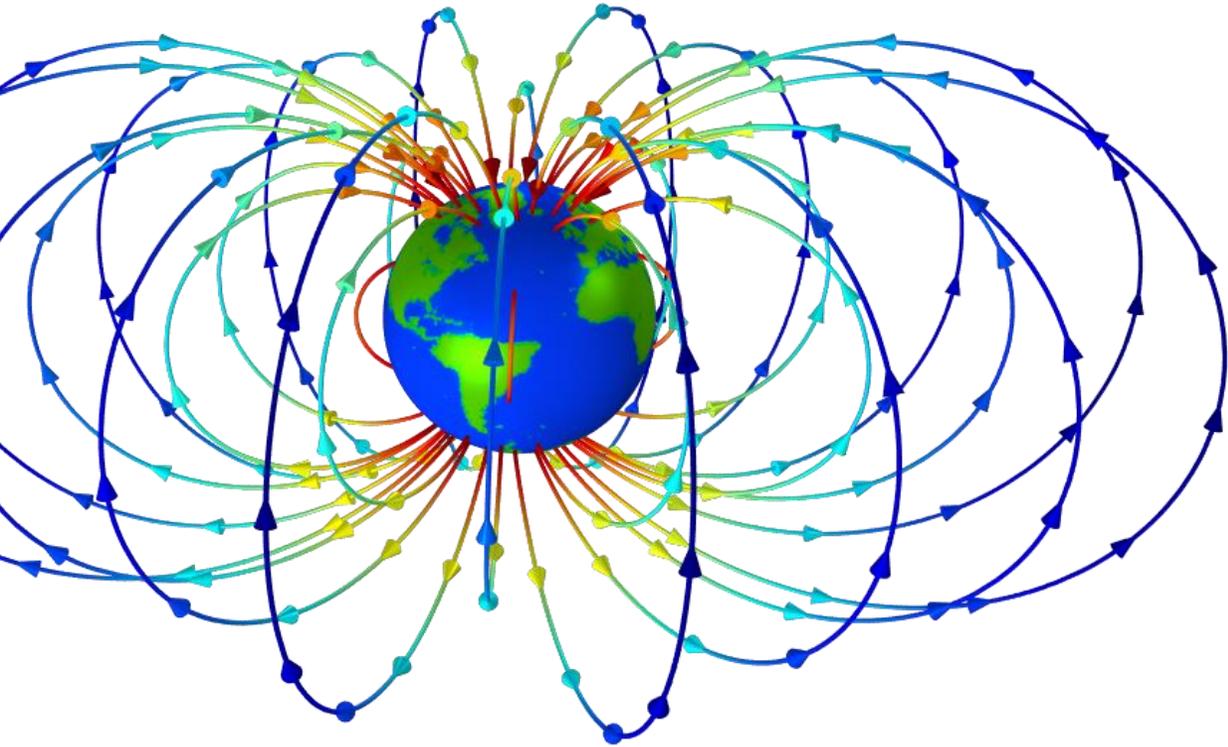
Messages Progress Log

Electric and Magnetic Forces

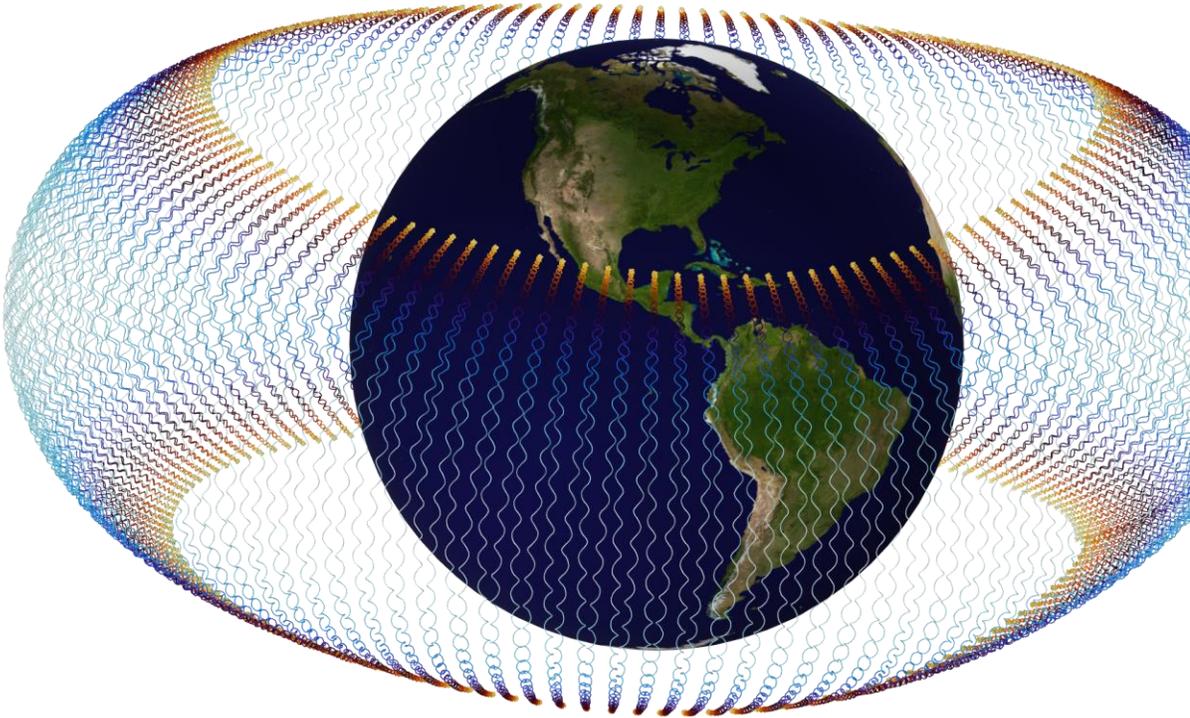
- Automatically couple electric and magnetic forces to previously computed potentials or fields
- Combinations of stationary, transient, time-harmonic, and other time-periodic fields



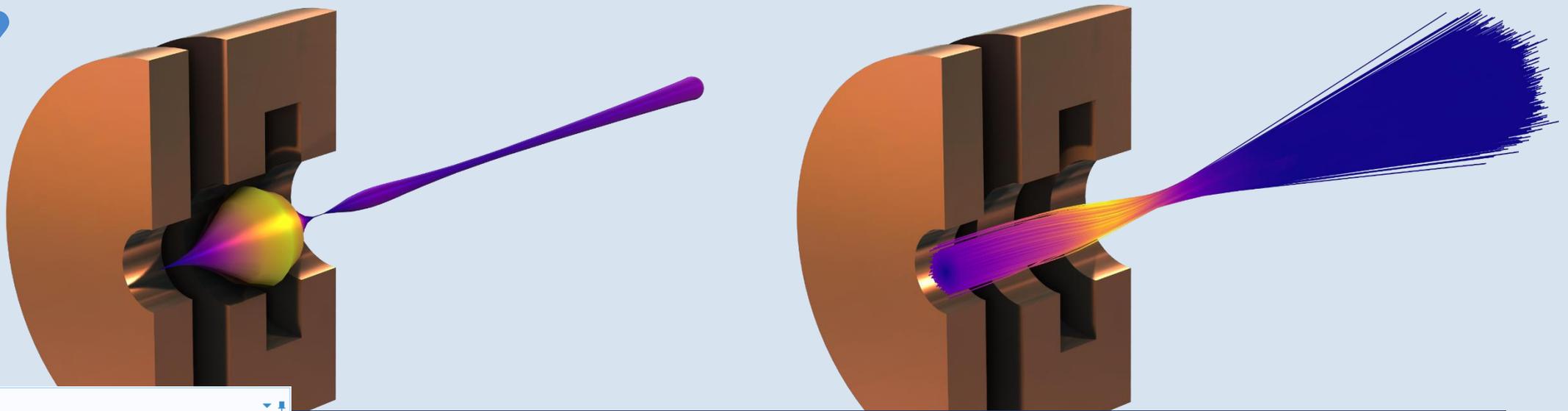
Quadrupole mass spectrometer: ions are trapped by the combined AC and DC fields of two oppositely biased pairs of electrodes.



Field lines of Earth's magnetic field, from the International Geomagnetic Reference Field (IGRF).



Proton trajectory.



Settings

Particle Beam

Label: Particle Beam 1

▷ Boundary Selection

▷ Override and Contribution

▼ Equation

Show equation assuming:

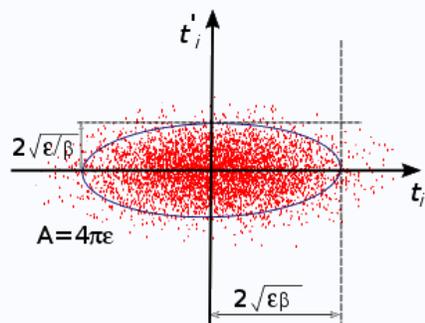
Study 1, Stationary

$$\gamma_i t_i^2 + \beta_i t_i'^2 = 4\epsilon_{rms,i} \quad i \in \{1, 2\}$$

$$\gamma_i \beta_i = 1$$

$$\beta_1 = \beta_2, \quad \epsilon_{rms,1} = \epsilon_{rms,2}$$

$$t_i = (\mathbf{r} - \mathbf{r}_c) \cdot \hat{\mathbf{t}}_i, \quad t_i' = \frac{\mathbf{v} \cdot \hat{\mathbf{t}}_i}{\mathbf{v} \cdot \hat{\mathbf{n}}}$$



▼ Release Times

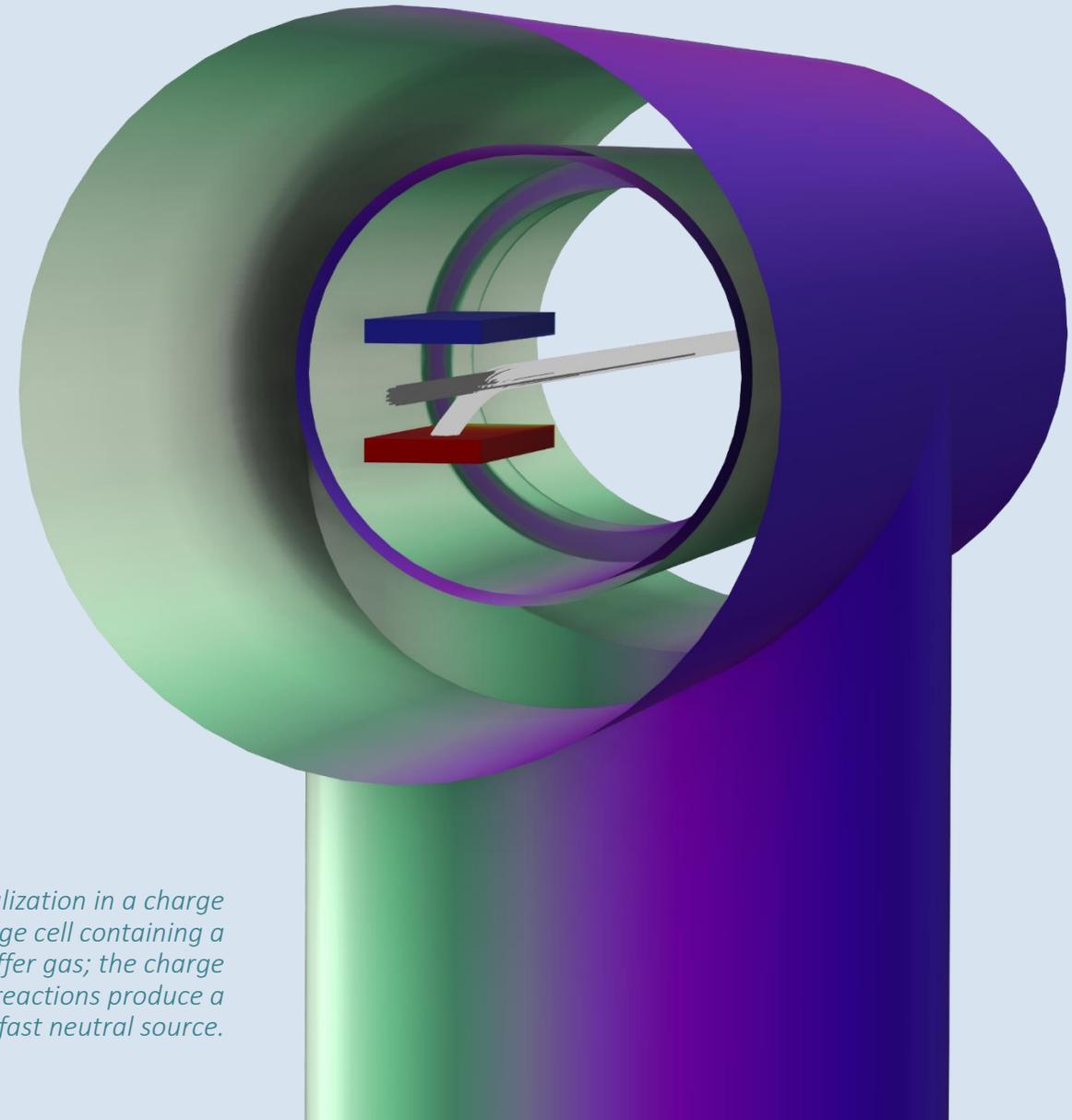
Beam Simulations

- Release nonlaminar beams of charged particles with ellipses or Gaussian distributions in transverse phase space
- Symmetric or asymmetric beams in 3D
- Specify either beam dimensions or initial Twiss parameters
- Built-in variables for computing Twiss parameters and beam emittance

Monte Carlo Collision Modeling

Built-in options are available for modeling collisions between particles and a background gas:

- Elastic
- Inelastic
- Attachment
- Ionization
- Resonant and nonresonant charge exchange
- User-defined expressions



Beam neutralization in a charge exchange cell containing a rarefied buffer gas; the charge exchange reactions produce a fast neutral source.

Ion Interactions with Solid Matter

Built-in features for modeling interaction of energetic ions with solids:

- Ionization Loss: continuous deceleration from interaction with target electrons
- Nuclear Stopping: discrete scattering by target nuclei

ion_range_benchmark.mph - COMSOL M

File Home Definitions Geometry Materials Physics Mesh Study Results Developer

Application Builder Model Manager Component 1 Add Component Parameters Pi a= Variables f Functions Build All Import LiveLink Add Material Charged Particle Tracing Add Physics Build Mesh Mesh 1 Compute Study 1 Add Study Particle Trajectories (cpt)

Workspace Model Definitions Geometry Materials Physics Mesh Study

Model Builder

- ion_range_benchmark.mph
 - Global Definitions
 - Component 1
 - Definitions
 - Geometry 1
 - Materials
 - Charged Particle Tracing
 - Wall 1
 - Proton
 - Particle-Matter Interactions 1
 - Ionization Loss 1
 - Nuclear Stopping 1
 - Release from Grid 1
 - Auxiliary Dependent Variable 1
 - Mesh 1
 - Study 1
 - Results
 - Datasets
 - Derived Values
 - Tables
 - Color Tables
 - Particle Trajectories (cpt)
 - Stopping Distance
 - Export
 - Reports

Settings

Nuclear Stopping

Label: Nuclear Stopping 1

Domain Selection

Override and Contribution

Equation

Show equation assuming: Study 1, Time Dependent

If $\chi \geq \chi_c$

$$|\mathbf{v}'| = \frac{\sqrt{m_p^2 + m_m^2 + 2m_p m_m \cos \chi}}{m_p + m_m} |\mathbf{v}|$$

$$\mathbf{v}' = \mathbf{v}_{\parallel} \cos \chi + \mathbf{v}_{\perp} \sin \chi$$

$$\mathbf{v}_{\parallel} = \frac{|\mathbf{v}'|}{|\mathbf{v}|} \mathbf{v}, \quad \mathbf{v}_{\perp} = |\mathbf{v}'| (\cos \phi \cdot \hat{\mathbf{e}}_1 + \sin \phi \cdot \hat{\mathbf{e}}_2), \quad \hat{\mathbf{e}}_1 \cdot \mathbf{g} = \hat{\mathbf{e}}_2 \cdot \mathbf{g} = 0$$

$$\chi = \pi - 2 \int_{\xi_{\min}}^{\infty} \frac{bd\xi}{\xi^2 \left(1 - \frac{\Phi(\xi)}{\xi \epsilon} - \frac{b^2}{\epsilon^2}\right)^{1/2}}, \quad \phi \in [0, 2\pi], \quad -\xi_{\min}^2 + \frac{\Phi(\xi_{\min})}{\epsilon} \xi_{\min} + b^2 = 0$$

$$\Phi(\xi) = 1$$

$$b = \frac{1}{a_1} \sqrt{\frac{-\log U}{\pi L N}}, \quad U \in [0, 1], \quad N = \frac{\rho}{m_m}, \quad L = |\mathbf{v}| \Delta t$$

$$\epsilon = \frac{4\pi \epsilon_0}{Z_p Z_m e^2} a_1 E_{cm}, \quad E_{cm} = \frac{1}{2} \frac{m_p m_m}{m_p + m_m} |\mathbf{v}|^2$$

$$a_1 = \frac{0.8853 a_0}{Z_p^{0.23} + Z_m^{0.23}}, \quad a_0 = 0.523 \text{ \AA}$$

Loss Mechanism

Screening function: None

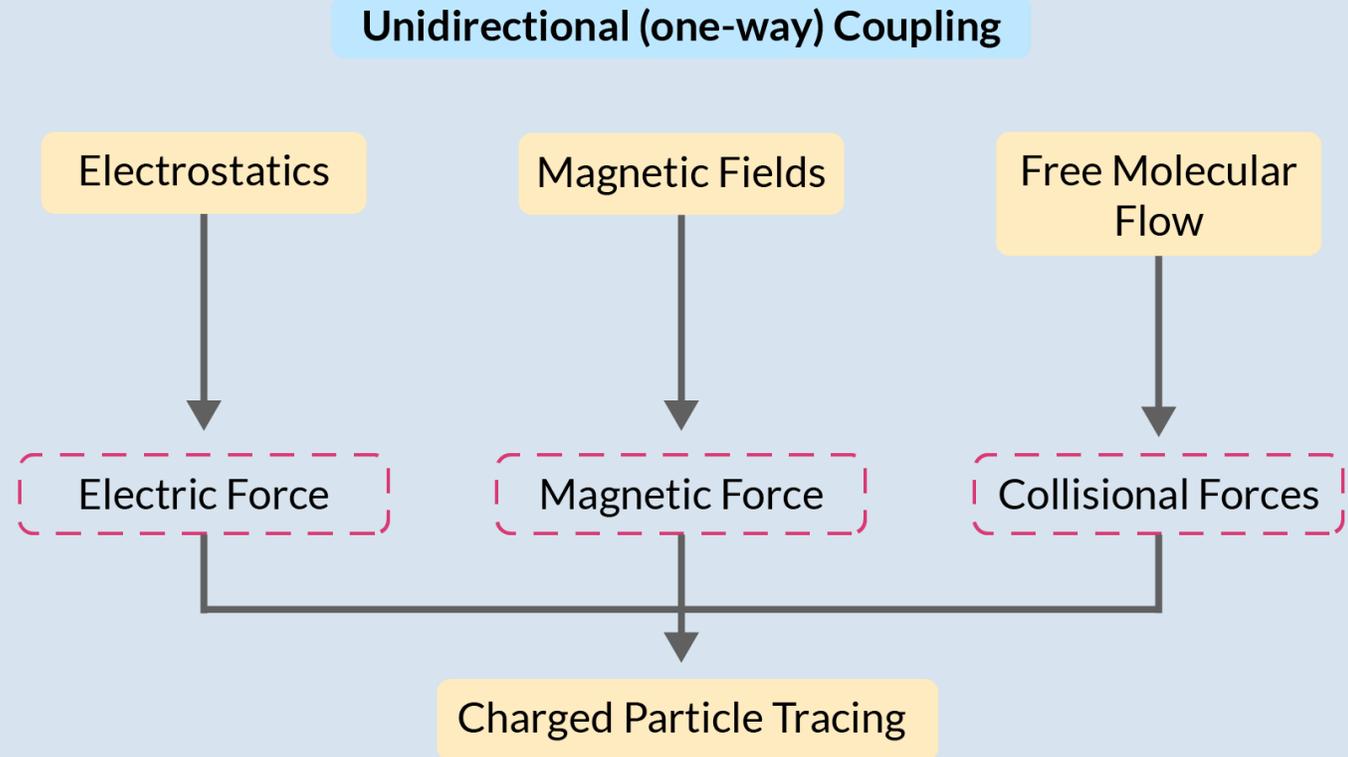
Cutoff scattering angle: χ_c 0.1[deg] rad

Graphics Plot 1 X

E0(3)=0.1 MeV Time=4.5737E-13 s

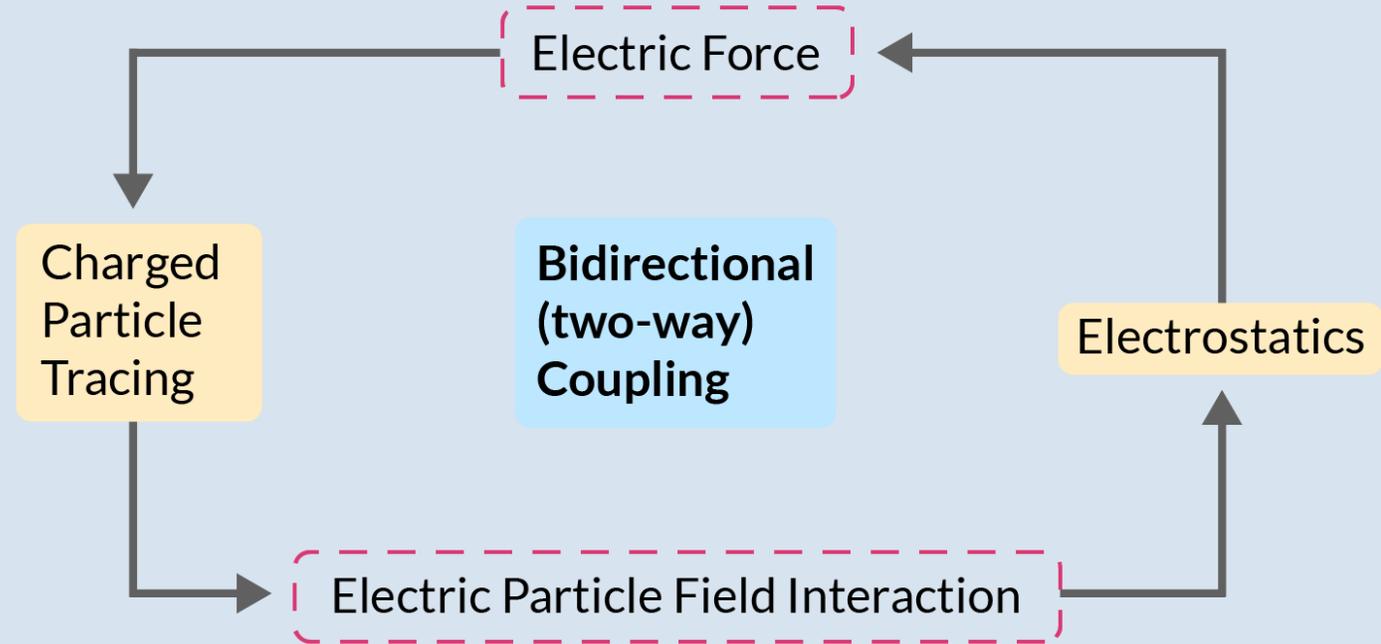
Coupling Particles and Fields

- Unidirectional couplings – simplest and fastest to solve
- Fields are solved for first
- Fields exert forces on particles
- Particle trajectories are computed last
- Particles don't have a large effect on the fields



Two-way Particle Field Interactions

- Solve for electric potential and particle trajectories together
- Particles are affected by electric forces
- Fields are affected by the space charge density of particles
- More complicated and computationally demanding than the unidirectional coupling

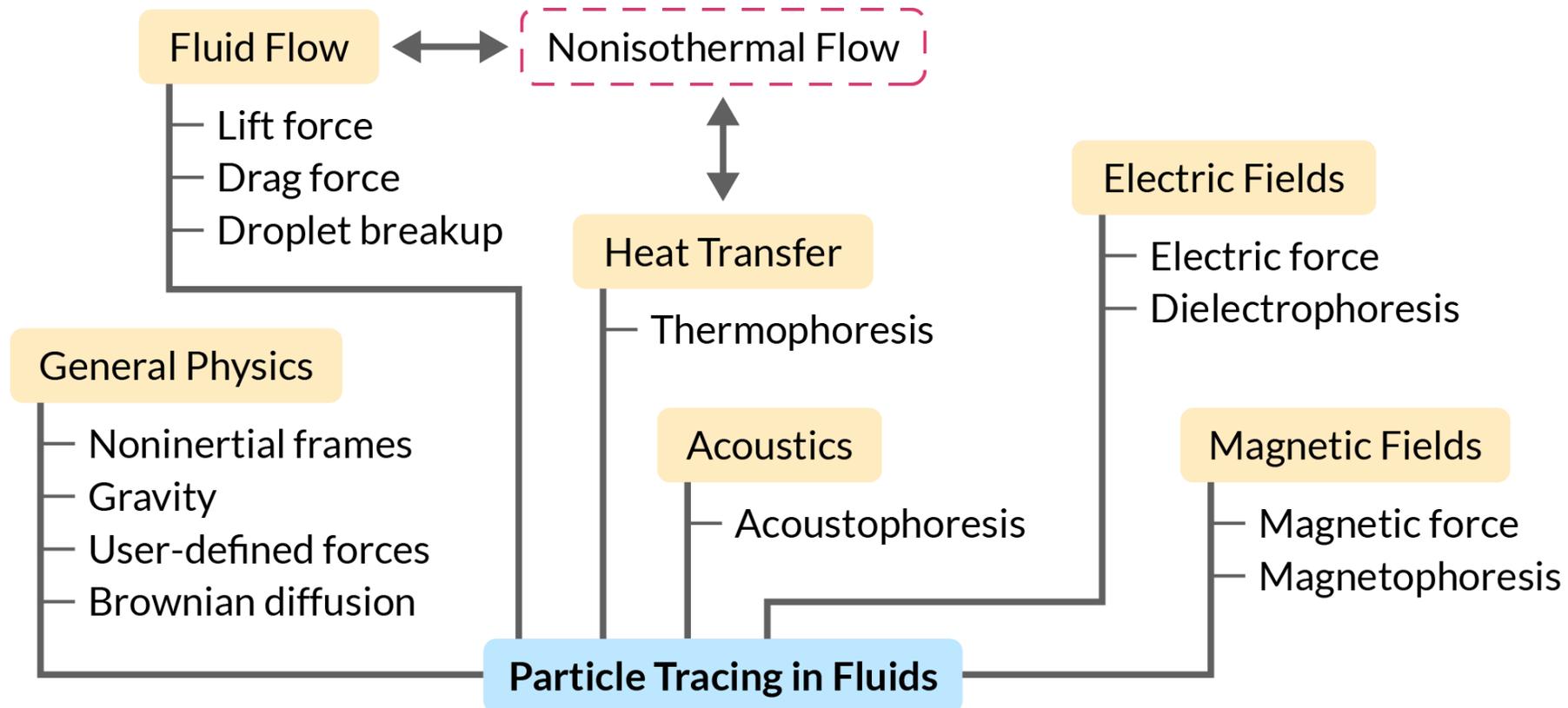


Particle Tracing for Fluid Flow Interface

- Compute trajectories of particles in a fluid
- Separate formulations for inertial particle tracing (for larger particles) and for smaller particles with negligible inertia
- Wide variety of predefined forces

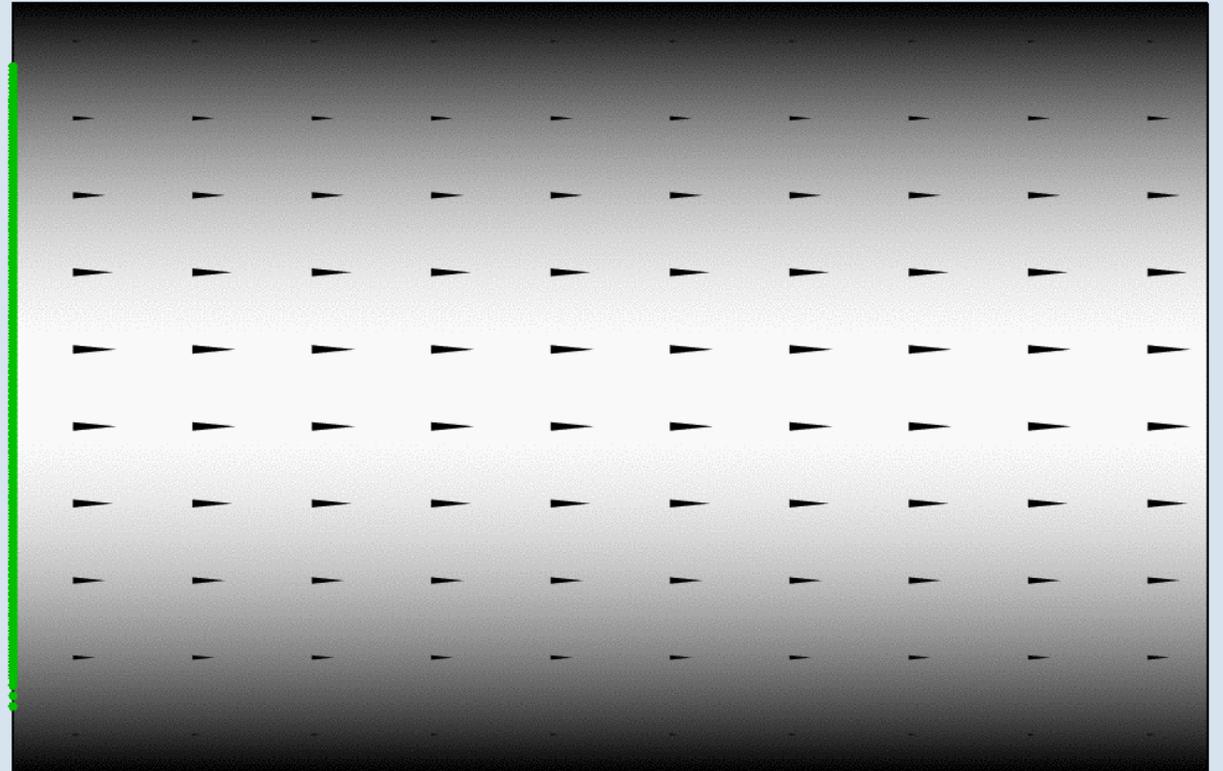
The screenshot displays the COMSOL Multiphysics interface for a simulation titled "cascade_impactor.mph". The interface is divided into several panes:

- Model Builder:** Shows the hierarchical structure of the model, including Global Definitions, Component 1, and various physics interfaces like Laminar Flow, Particle Tracing for Fluid Flow, and Mesh 1.
- Settings:** Configures the "Particle Tracing for Fluid Flow" interface. Key settings include:
 - Label: Particle Tracing for Fluid Flow
 - Name: fpt
 - Equation form: Study controlled
 - Show equation assuming: Study 1, Stationary
 - Equations: $m_p \frac{dv}{dt} = F_t$ and $\frac{dd_p}{dt} = \frac{2R}{\pi \rho_p d_p^2}$
 - Formulation: Newtonian
 - Particle release specification: Specify release times
 - Maximum number of secondary particles: 10000
 - Particle size distribution: Specify particle diameter
- Plot 1:** Displays a 3D visualization of particle trajectories within a complex, multi-part geometry. The trajectories are color-coded, and the plot shows the velocity magnitude (m/s) on the surface. The time is set to 2.4 s.



Lift and Drag Forces

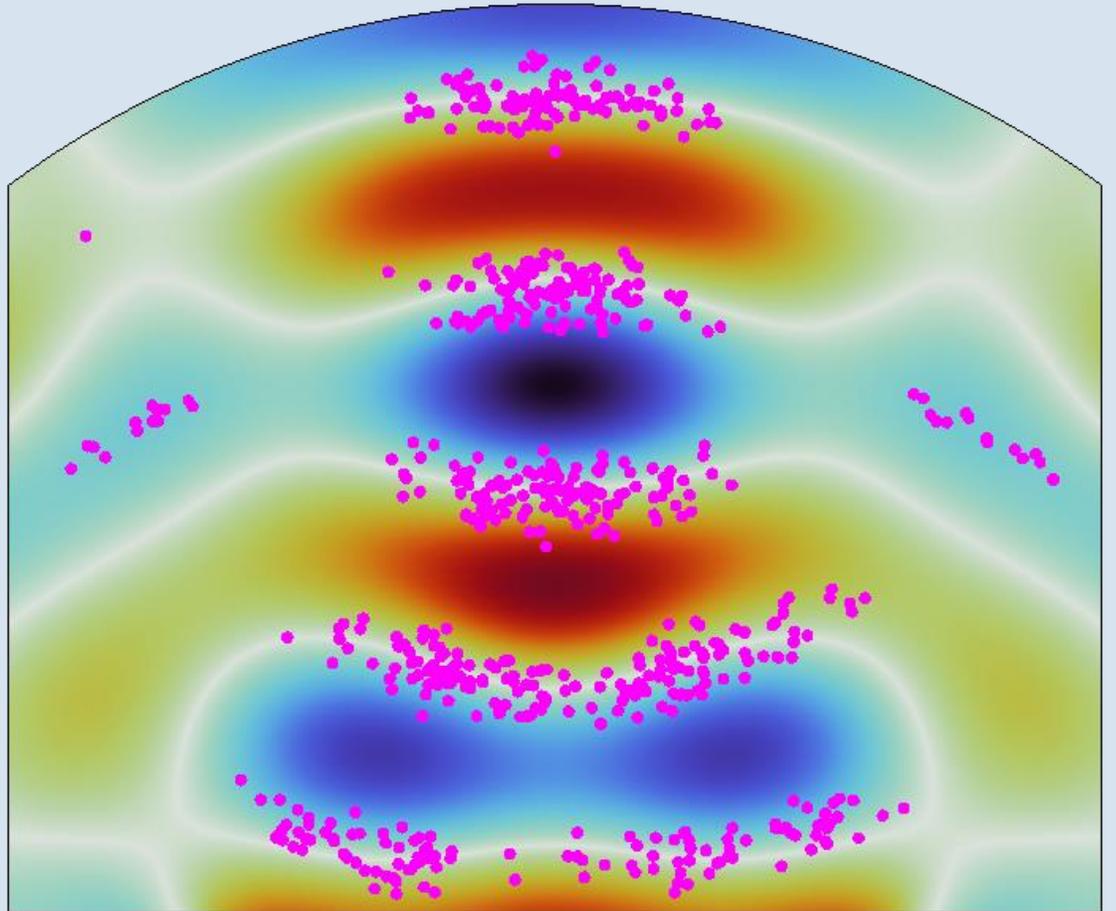
- Drag forces:
 - Different drag models for high and low relative Reynolds numbers
- Lift forces



Inertial focusing: Neutrally buoyant particles in a channel with a parabolic velocity profile approach equilibrium positions relative to the channel walls due to lift and drag forces.

Other Built-in Forces

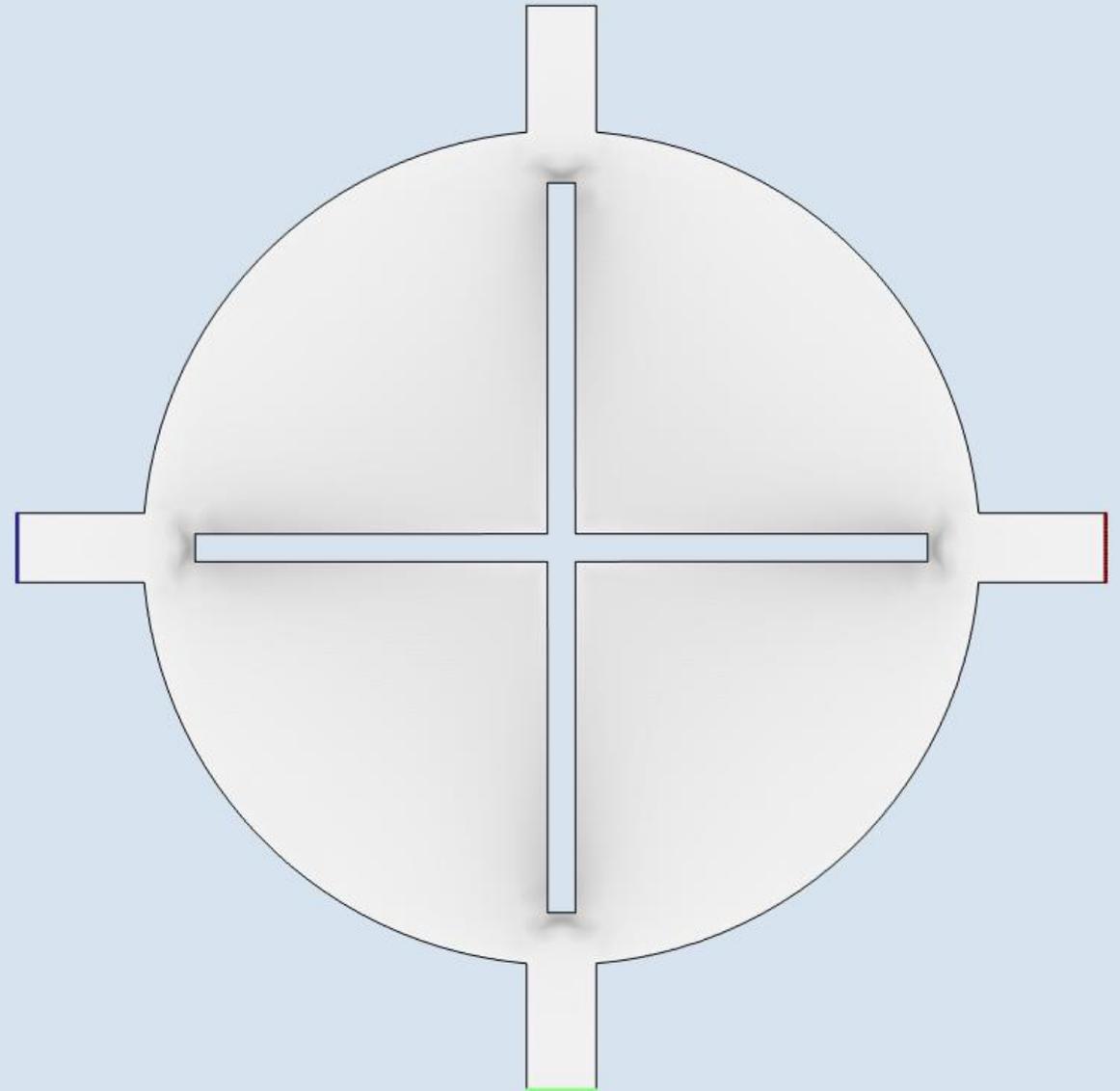
- Electric, magnetic, dielectrophoretic, and magnetophoretic:
 - Coupling to electric and magnetic fields
- Thermophoretic:
 - Coupling to temperature field
- Acoustophoretic radiation force:
 - Coupling to sound pressure field
- Gravity



Acoustic levitator: particles are suspended by the balance of gravitational and acoustophoretic radiation forces. The grayscale background shows the sound pressure level in dB.

Mixer Modeling

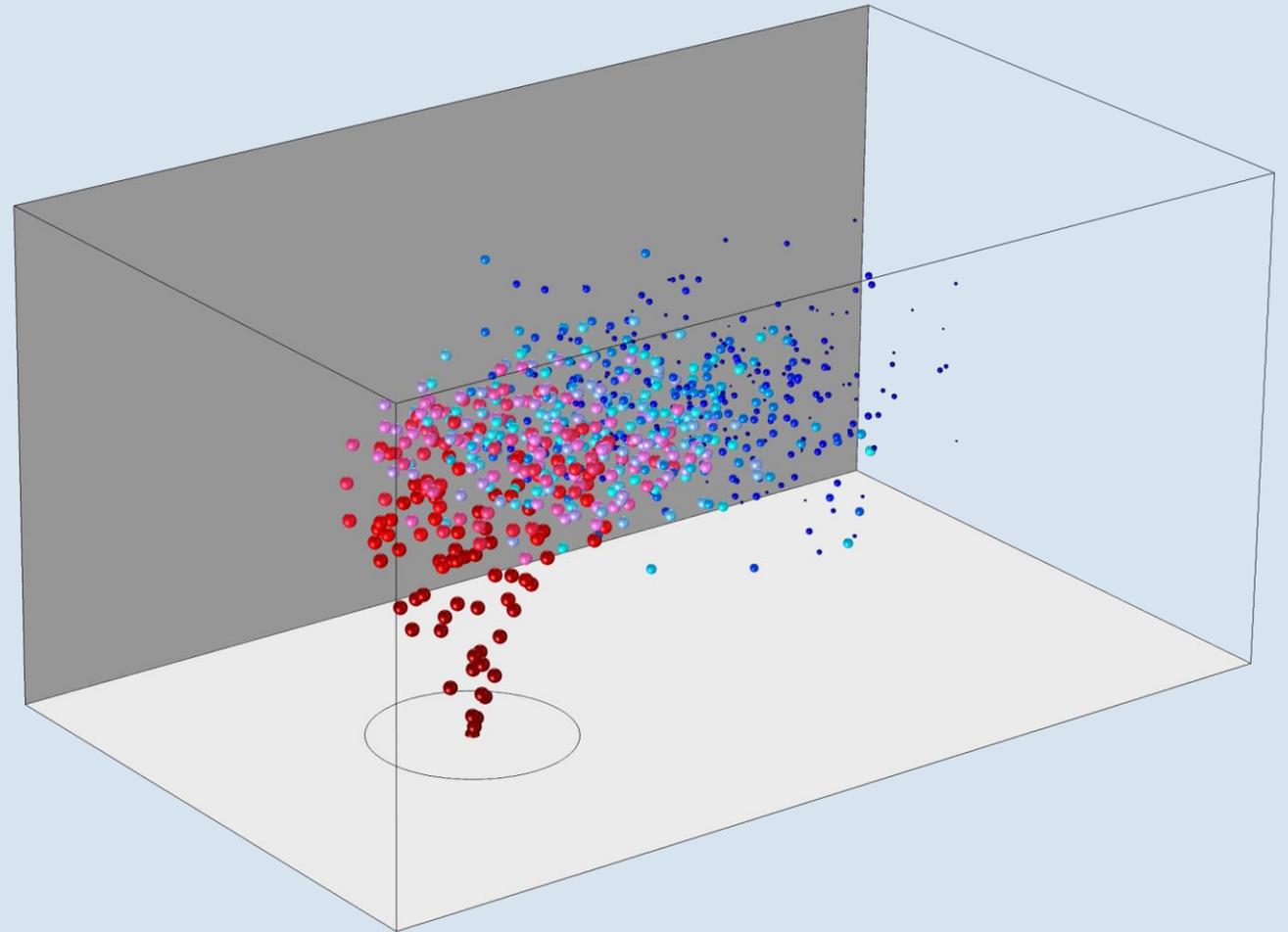
- Fully compatible with Deformed Geometry / Moving Mesh (ALE)
- Combines with fluid flow physics in rotating domains
- Moving boundaries can strike or capture particles
- Particles can stick to, and then follow, a moving boundary



Three species of particles mixed by micromixer.

Spray Modeling

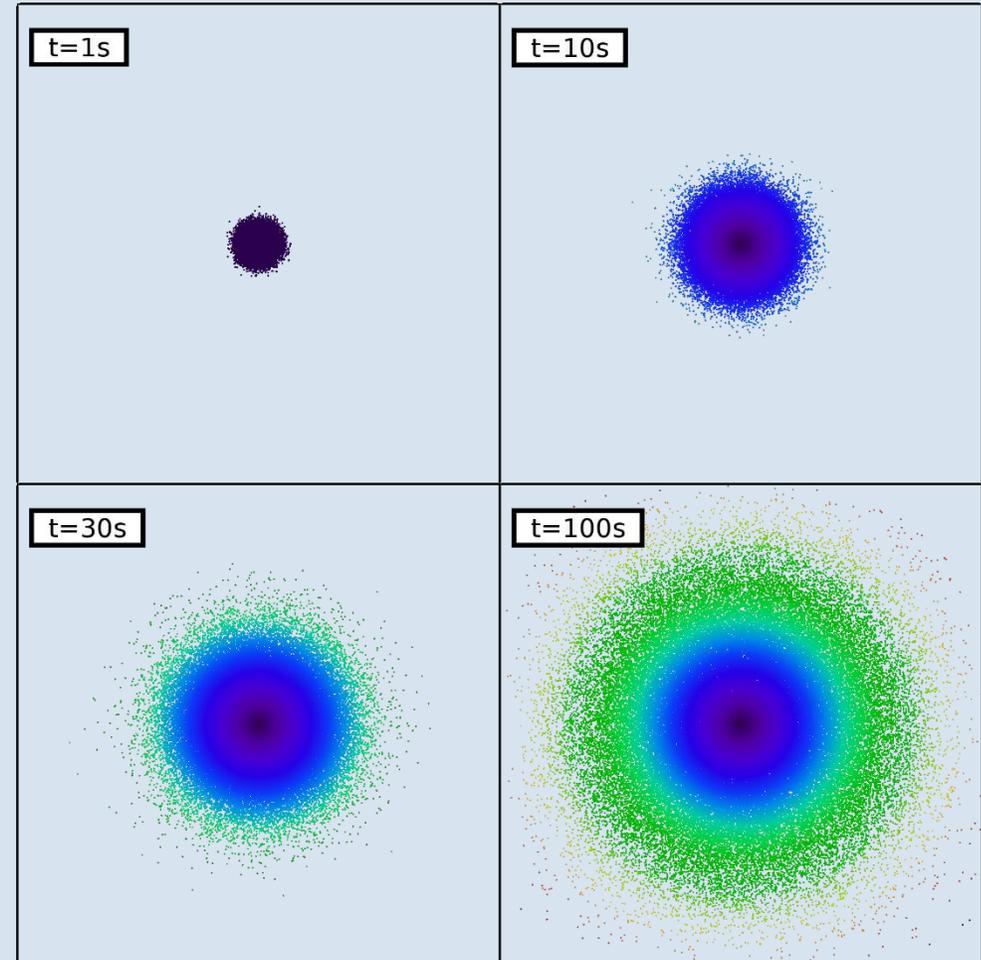
- Model solid particles, liquid droplets, or gas bubbles
- Built-in features for modeling breakup of liquid droplets
- Built-in feature to model the release of a spray from a nozzle
- Built-in droplet evaporation models
 - Maxwell
 - Stefan-Fuchs
 - User defined



Liquid droplets are sprayed into a channel. As they accelerate due to the drag force, they also break up into smaller droplets. The child droplets spread out due to turbulent dispersion in the channel.

Brownian Motion

- Built-in Brownian force for Monte Carlo diffusion models
- Random contributions to particle motion at each time step taken by the solver
- The computed transmission probability agrees with the value computed by solving the diffusion equation



Diffusion of particles in a background fluid due to the Brownian force.

Simulate with Multiple Species

- Define several sets of particle properties
- Choose which species to release
- Apply forces to specific particle types

dielectrophoretic_separation.mph - COMSOL Multiphysics

File Home Definitions Geometry Sketch Materials Physics Mesh Study Results Developer

Application Builder Model Manager Component 1 Add Component Parameters Variables Functions Parameter Case Import Build All LiveLink Add Material Particle Tracing for Fluid Flow Add Physics Build Mesh Mesh 1 Compute Study 3, Dielectrophoretic Force Add Study Particle Trajectories

Workspace Model Definitions Geometry Materials Physics Mesh Study Results Developer

Model Builder

- dielectrophoretic_separation.mph
 - Global Definitions
 - Component 1
 - Definitions
 - Geometry 1
 - Materials
 - Electric Currents
 - Creeping Flow
 - Particle Tracing for Fluid Flow
 - Wall 1
 - Platelets
 - Red Blood Cells
 - Inlet, Platelets
 - Inlet, Red Blood Cells
 - Outlet 1
 - Drag Force 1
 - Dielectrophoretic Force, Platelets
 - Dielectrophoretic Force, Red Blood Cells
 - Multiphysics
 - Mesh 1
 - Study 1
 - Study 2, no Dielectrophoretic Force
 - Study 3, Dielectrophoretic Force
 - Results
 - Datasets
 - Derived Values
 - Tables
 - Color Tables
 - Electric Potential (ec)
 - Electric Field Norm (ec)
 - Velocity (spf)
 - Pressure (spf)
 - Particle Trajectories (fpt)
 - Particle Trajectories (fpt) 1
 - Export
 - Reports

Settings

Particle Properties

Label: Red Blood Cells

Equation

Show equation assuming: Study 1, Stationary

$$\frac{d\mathbf{q}}{dt} = \mathbf{u} + \frac{\tau_p}{m_p} \mathbf{F}_{\text{ext}}$$

Particle Properties

Particle material properties: None

Particle property specification: Specify particle density and diameter

Particle density: ρ_p User defined rho_p kg/m³

Particle diameter: d_p dp2 m

Particle type: Solid particles

Charge Number

Charge specification: User defined

Charge number: Z 0 1

Additional Material Properties

Particle relative permittivity: $\epsilon_{r,p}$ User defined epsilon_p2 1

Particle electrical conductivity: σ_p User defined sigma_p2 S/m

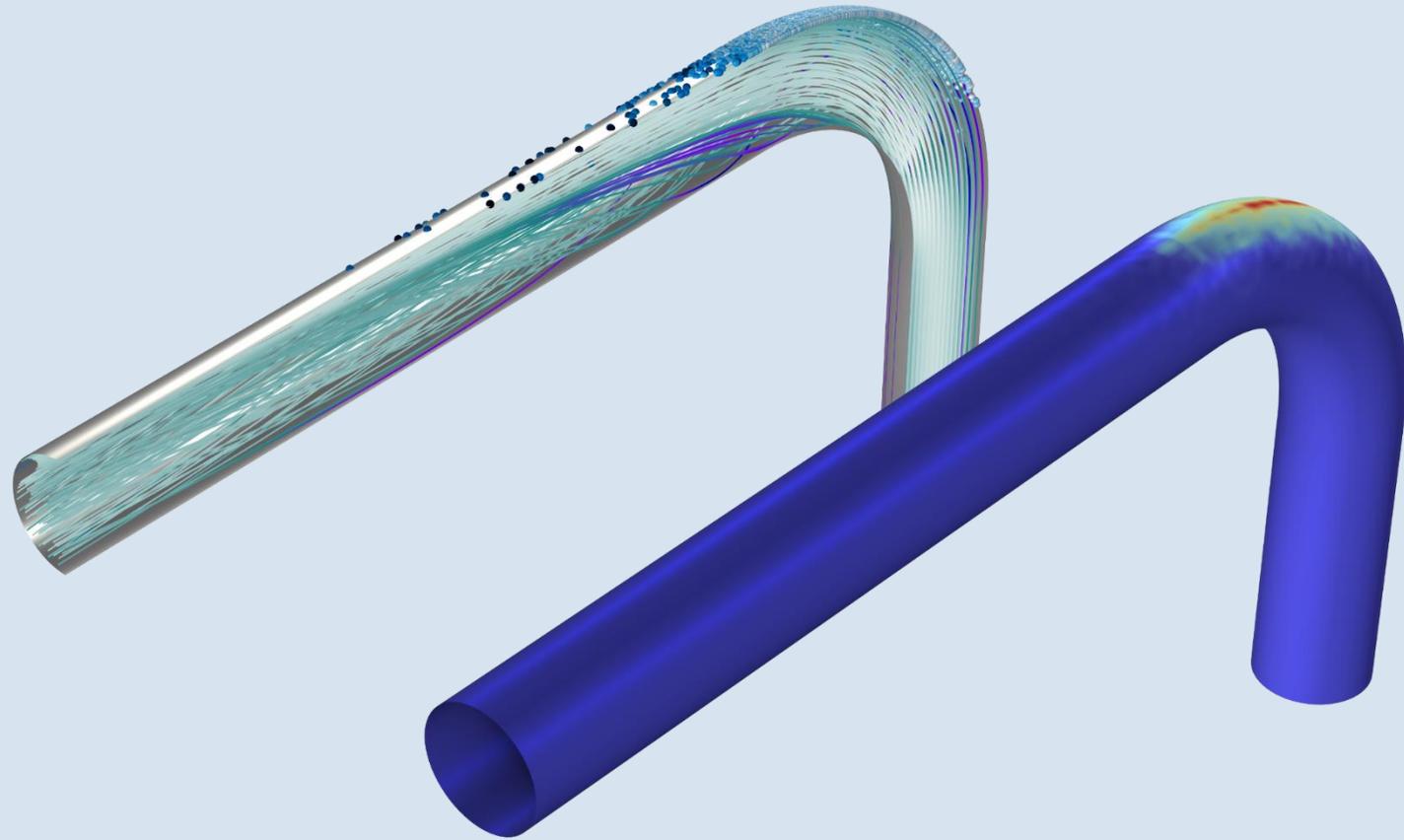
Graphics Plot 1

Time=3 s Streamline: Electric field Part

Messages Progress Log

Erosion Modeling

- Built-in variables for rate of erosive wear at boundaries
- Variety of built-in erosion models



Particle trajectories in a pipe elbow (left) and rate of erosive wear on the surface (right).

Mathematical Particle Tracing Interface

- Complete freedom over the equations solved for each particle
- Different formulations to solve the same problem
 - Lagrangian
 - Hamiltonian
 - Newtonian
 - Massless

The screenshot displays the COMSOL Multiphysics software interface for the 'ideal_cloak.mph' project. The top menu bar includes File, Home, Definitions, Geometry, Materials, Physics, Mesh, Study, Results, and Developer. The main workspace is divided into three panels: Model Builder, Settings, and Plot 1.

Model Builder: Shows a hierarchical tree of the model structure. The 'Mathematical Particle Tracing' node is selected, showing its sub-nodes: Wall 1, Particle Properties 1, Release from Grid 1, Mesh 1, Study 1, Step 1: Time Dependent, Solver Configurations, and Results (including Datasets, Views, Derived Values, Tables, Particle Trajectories (pt), Ray Position Relative to Initial Position, Change in Lateral Position, Export, and Reports).

Settings: Configures the 'Mathematical Particle Tracing' node. The 'Label' is 'Mathematical Particle Tracing' and the 'Name' is 'pt'. The 'Equation form' is set to 'Study controlled'. The 'Show equation assuming' is set to 'Study 1, Time Dependent'. The equations are defined as:

$$\frac{dq}{dt} = v_H$$

$$\frac{dp}{dt} = F_H$$
 The 'Formulation' is set to 'Hamiltonian'. The 'Maximum number of secondary particles' is set to 10000. The 'Particle position' is set to 'q', and the 'Particle velocity' is set to 'v'. The 'Particle momentum' is set to 'p'. The 'Particle position components' are 'qx', 'qy', and 'qz'. The 'Particle velocity components' are 'vx', 'vy', and 'vz'. The 'Particle momentum components' are 'px', 'py', and 'pz'.

Plot 1: Displays a 3D visualization of a particle's trajectory. The particle is shown as a small sphere moving through a complex, multi-layered structure. The trajectory is represented by a series of colored lines (yellow, green, blue) that curve around the structure, illustrating the particle's path through the cloak.

Mathematical Particle Tracing

Formulation	Equation of motion	Charged Particle in a Magnetic field
Lagrangian	$\frac{d}{dt} \frac{\partial L}{\partial \mathbf{v}} = \frac{\partial L}{\partial \mathbf{q}}$	$L = \frac{m_p(\mathbf{v} \cdot \mathbf{v})}{2} + eZ(\mathbf{v} \cdot \mathbf{A})$
Hamiltonian	$\frac{d\mathbf{q}}{dt} = \frac{\partial H}{\partial \mathbf{p}'}$ $\frac{d\mathbf{p}}{dt} = -\frac{\partial H}{\partial \mathbf{q}}$	$H = \frac{(\mathbf{p} - eZ\mathbf{A})^2}{2m_p}$
Newtonian	$\frac{d}{dt}(m_p \mathbf{v}) = \mathbf{F}$	$\frac{d}{dt}(m_p \mathbf{v}) = eZ(\mathbf{v} \times \mathbf{B})$
Massless	$\frac{d\mathbf{q}}{dt} = \mathbf{v}$	N/A



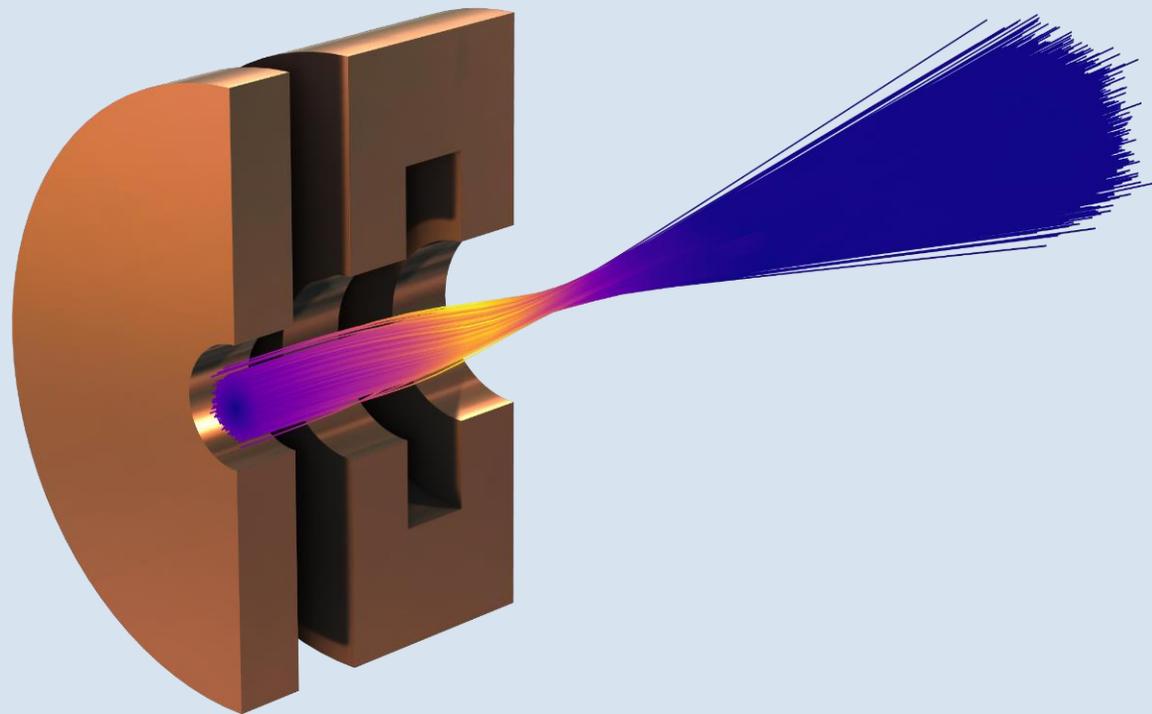
Motion of a charged particle in a uniform magnetic field.

Demonstration of the Module on User Cases

USER CASE

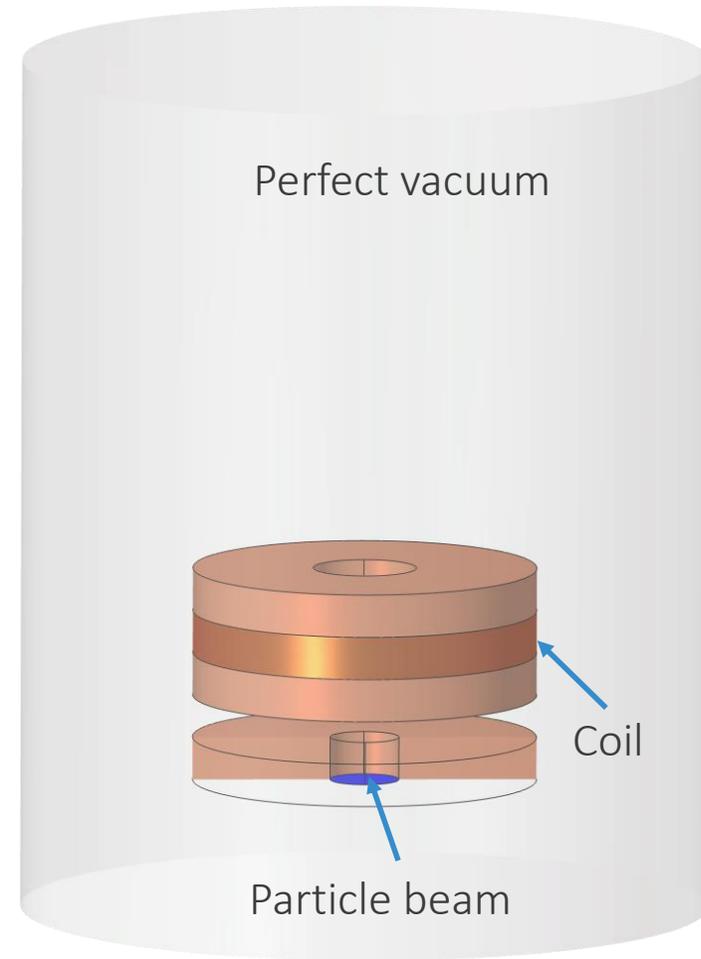
Charged Particle Tracing

Magnetic Lens



Model Setup

- Magnetic Field
- Coil
- Perfect vacuum
- Electrons
- Particle beam



New



Model Wizard



Blank Model

Application Builder Model Component 1 Add Component Parameters Variables Variable Utilities Import Build All Add Material Charged Particle Tracing Add Physics Build Mesh Mesh 1 Compute Select Study Add Study Select Plot Group Add Plot Group Add Predefined Plot Windows Reset Desktop

Model Builder

- Untitled.mph (root)
 - Global Definitions
 - Parameters 1
 - Default Model Inputs
 - Materials
 - Component 1 (comp1)
 - Definitions
 - Geometry 1
 - Cylinder 1 (cyl1)
 - Cylinder 2 (cyl2)
 - Cylinder 3 (cyl3)
 - Cylinder 4 (cyl4)
 - Cylinder 5 (cyl5)
 - Cylinder 6 (cyl6)
 - Cylinder 7 (cyl7)
 - Cylinder 8 (cyl8)
 - Cylinder 9 (cyl9)
 - Difference 1 (dif1)
 - Work Plane 1 (wp1)
 - Work Plane 2 (wp2)
 - Form Union (fn)
 - Materials
 - Copper (mat1)
 - Perfect vacuum (mat2)
 - Magnetic Fields (mf)
 - Ampère's Law 1
 - Magnetic Insulation 1
 - Initial Values 1
 - Coil 1
 - Coil Geometry 1
 - Equation View
 - Equation View
 - Charged Particle Tracing (cpt)
 - Wall 1
 - Electron
 - Magnetic Force 1
 - Particle Beam 1
 - Equation View
 - Multiphysics
 - Mesh 1
 - Results

Settings

Mesh

Build All

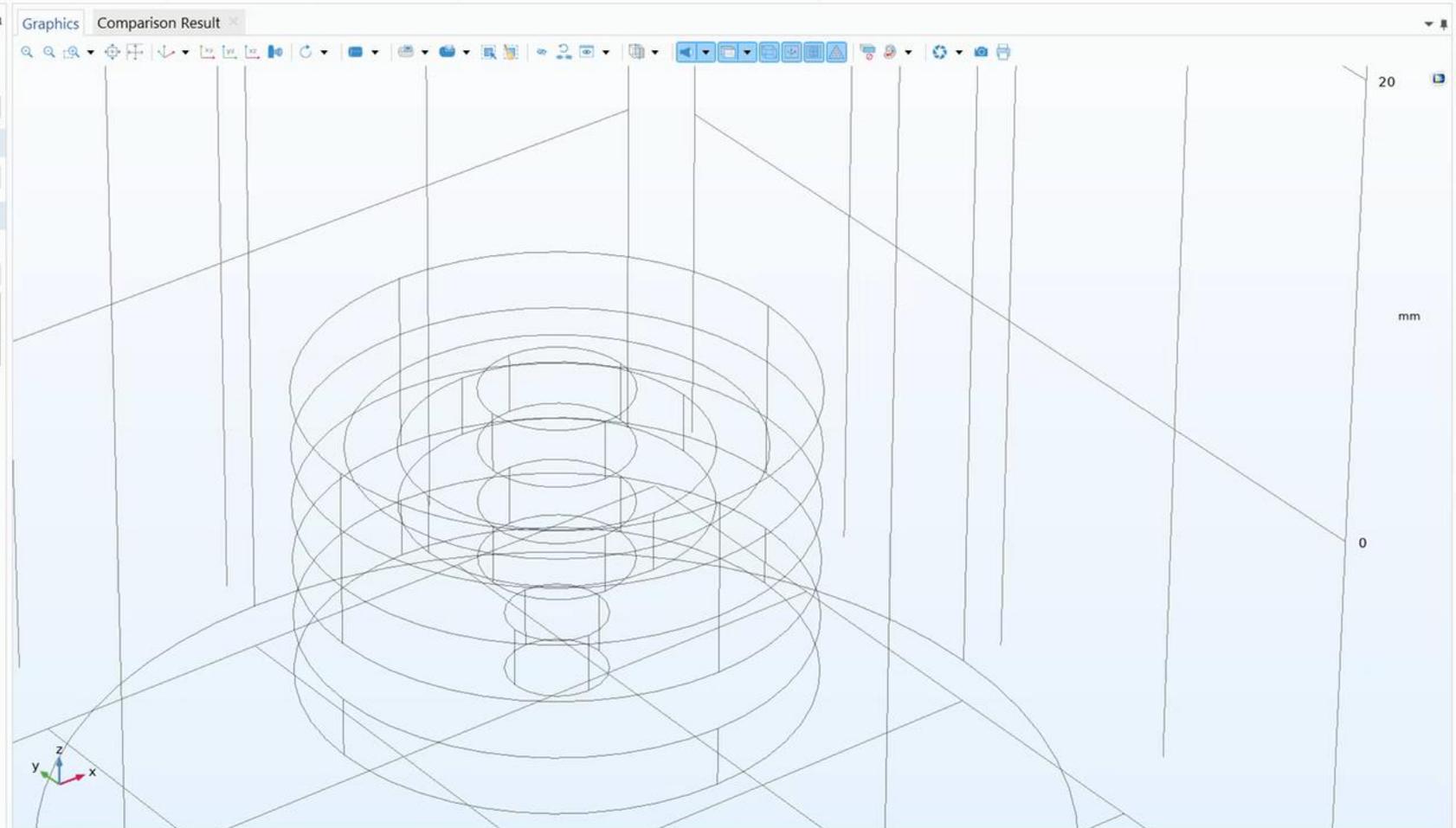
Label: Mesh 1

Sequence Type: Physics-controlled mesh

Physics-Controlled Mesh

Element size: Normal

Contributor	Use
Magnetic Fields (mf)	<input checked="" type="checkbox"/>
Charged Particle Tracing (cpt)	<input checked="" type="checkbox"/>



Messages x Progress Log Table

File Home Definitions Geometry Materials Physics Mesh Study Results Developer Particle Trajectories (cpt)

Plot Plot In Plot Add Plot

Volume Slice Line Arrow Line Image Color Expression Material Appearance Evaluate Along Normal Cut Line Direction Second Point for Cut Plane Normal
 Arrow Volume Isosurface Contour Mesh Deformation Selection First Point for Cut Line Cut Line Surface Normal Cut Plane Normal
 Surface Arrow Surface Streamline Annotation More Plots Filter Transparency More Attributes First Point for Cut Plane Normal Cut Plane Normal from Surface
 Attributes Select Export

Model Builder

- Cylinder 5 (cyl5)
- Cylinder 6 (cyl6)
- Cylinder 7 (cyl7)
- Cylinder 8 (cyl8)
- Cylinder 9 (cyl9)
- Difference 1 (dif1)
- Work Plane 1 (wp1)
- Work Plane 2 (wp2)
- Form Union (fn)
- Materials
 - Copper (mat1)
 - Perfect vacuum (mat2)
- Magnetic Fields (mf)
 - Ampère's Law 1
 - Magnetic Insulation 1
 - Initial Values 1
 - Coil 1
 - Coil Geometry 1
 - Equation View
- Charged Particle Tracing (cpt)
 - Wall 1
 - Electron
 - Magnetic Force 1
 - Particle Beam 1
 - Equation View
- Multiphysics
 - Mesh 1
 - Size
 - Scale 1
 - Free Triangular 1
 - Size 1
 - Free Tetrahedral 1
- Study 1
 - Step 1: Stationary
 - Solver Configurations
 - Job Configurations
- Study 2
 - Step 1: Time Dependent
 - Solver Configurations
 - Job Configurations
- Results
 - Datasets
 - Views
 - Derived Values
 - Tables
 - Color Tables
 - Magnetic Flux Density Norm (mf)
 - Particle Trajectories (cpt)
 - Particle Trajectories 1

Settings

Particle Trajectories

Plot Plot In Plot Add Plot

Label: Particle Trajectories 1

Dataset: From parent

Title

Coloring and Style

Line style

Type: Line

Interpolation: None

Point style

Type: None

Plot along lines when animating

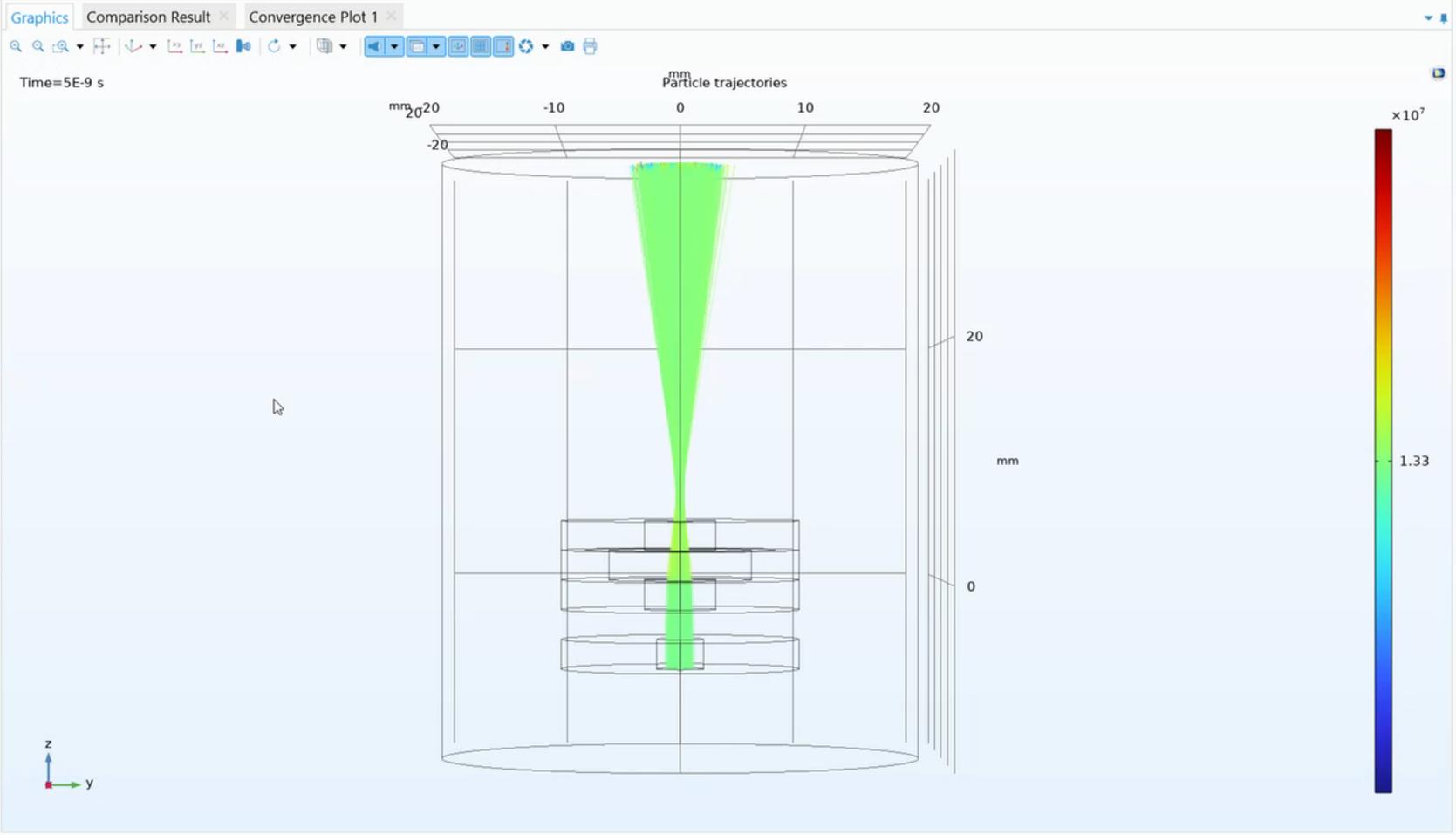
Extra Time Steps

Maximum number of extra time steps rendered: All

Inherit Style

Information

Name	Value
Plotting time	0.2 s
Number of points	330000
Number of segments	320000



Messages

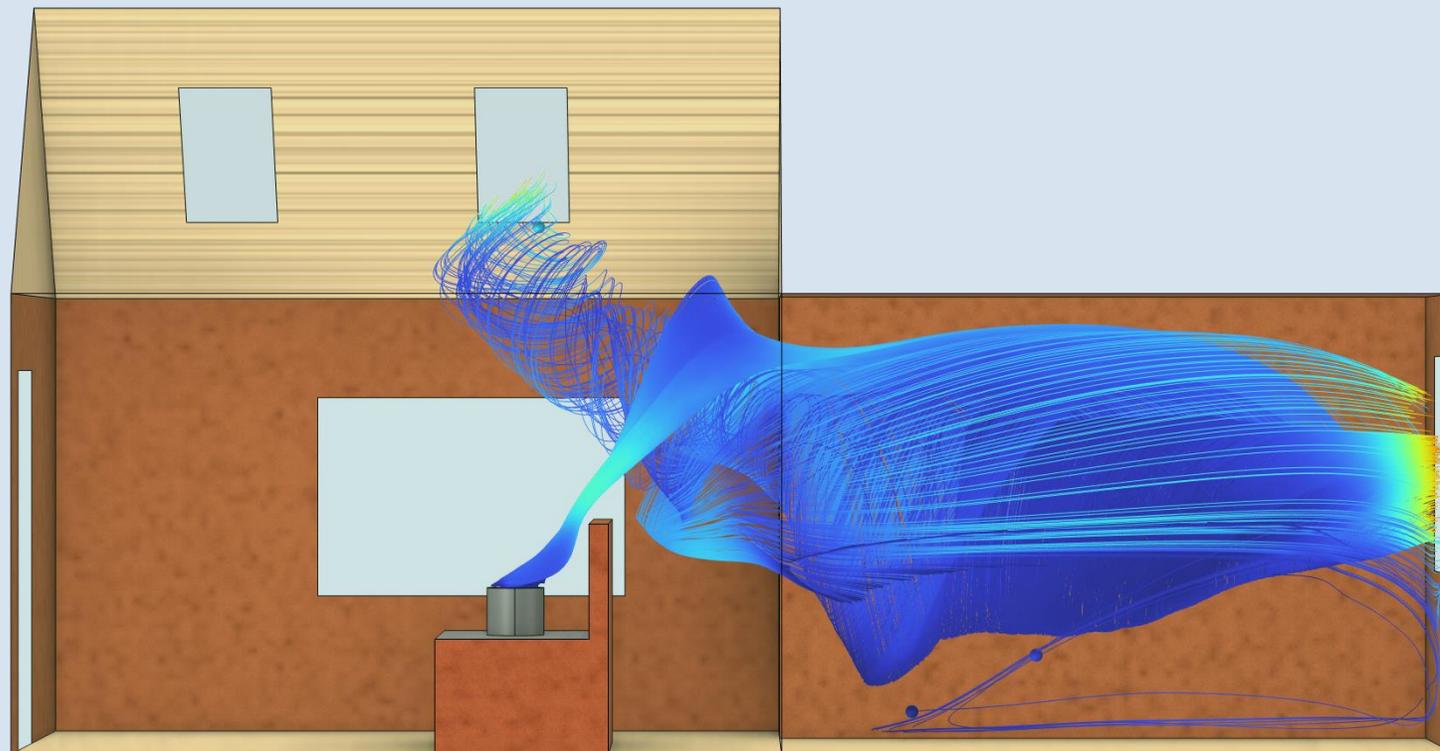
Progress Log Table

[May 12, 2023, 2:41 PM] Complete mesh consists of 49724 domain elements, 5562 boundary elements, and 592 edge elements.
 [May 12, 2023, 2:42 PM] Number of degrees of freedom solved for: 317552.
 [May 12, 2023, 2:42 PM] Solution time (Study 1): 6 s.
 [May 12, 2023, 2:42 PM] Number of degrees of freedom solved for: 30000.
 [May 12, 2023, 2:43 PM] Solution time (Study 2): 9 s.
 [May 12, 2023, 2:44 PM] Saved file: \\hay\ARCHIVE\USERS\rbata\PROFILE\Desktop\Magnetic_Lens.mph (59 MB)
 [May 12, 2023, 3:48 PM] Opened file: \\hay\ARCHIVE\USERS\rbata\PROFILE\Desktop\Magnetic_Lens.mph

USER CASE

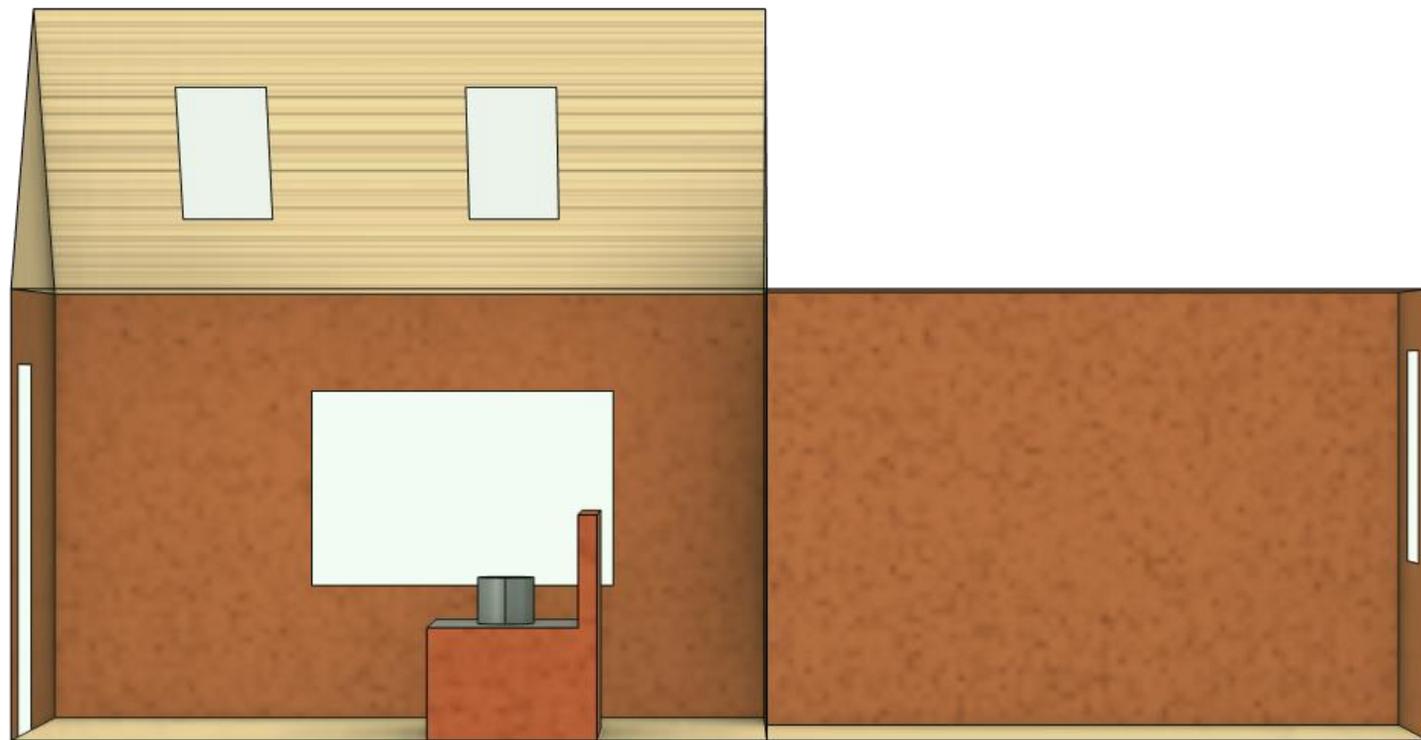
Particle Tracing For Fluid Flow

Ventilation Of The House



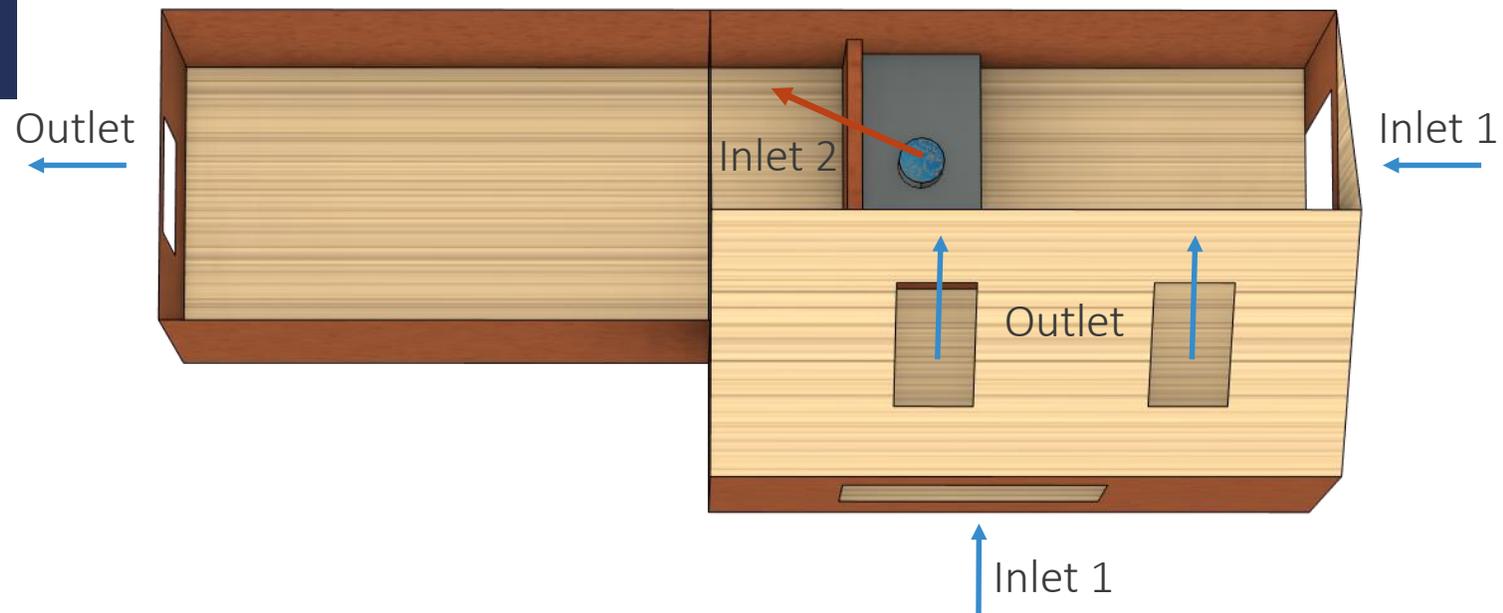
Model Description

- Family house
- Stinking pot
- Open windows and doors
- Air



Model Setup

- Turbulent flow
- Inlet 1 (fresh air): 0.1 m/s
- Inlet 2 (pot): 0.01 m/s
- Pressure outlet
- Massless particles



New



Model Wizard

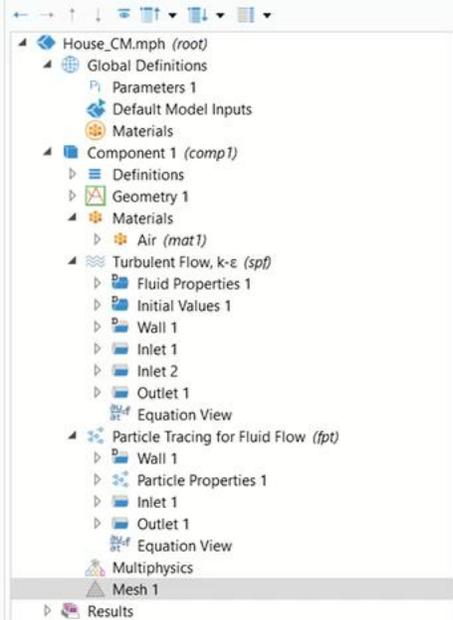


Blank Model

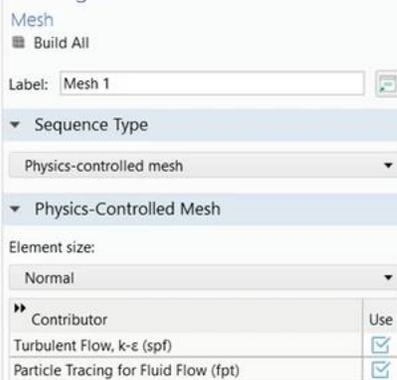




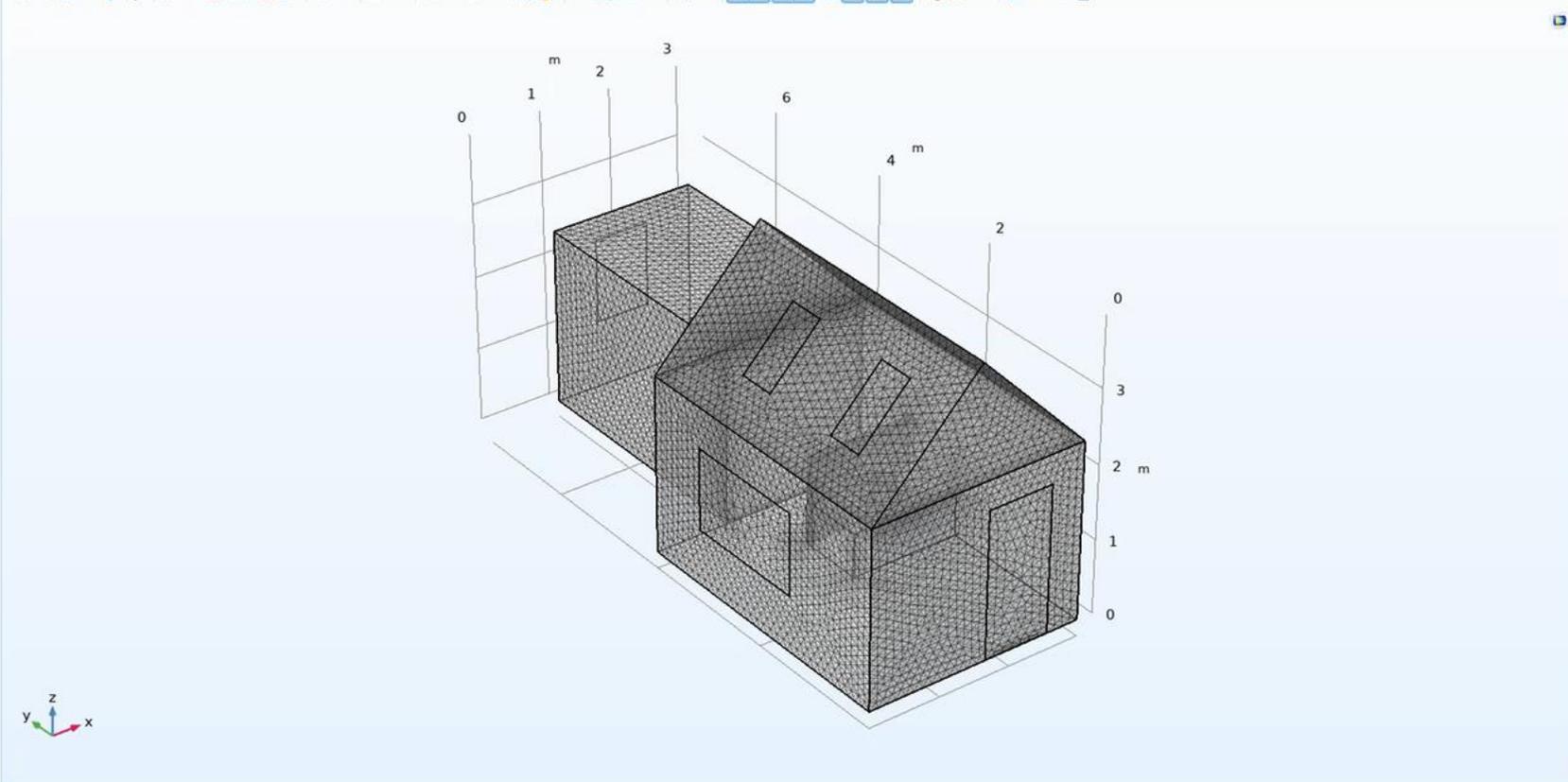
Model Builder



Settings

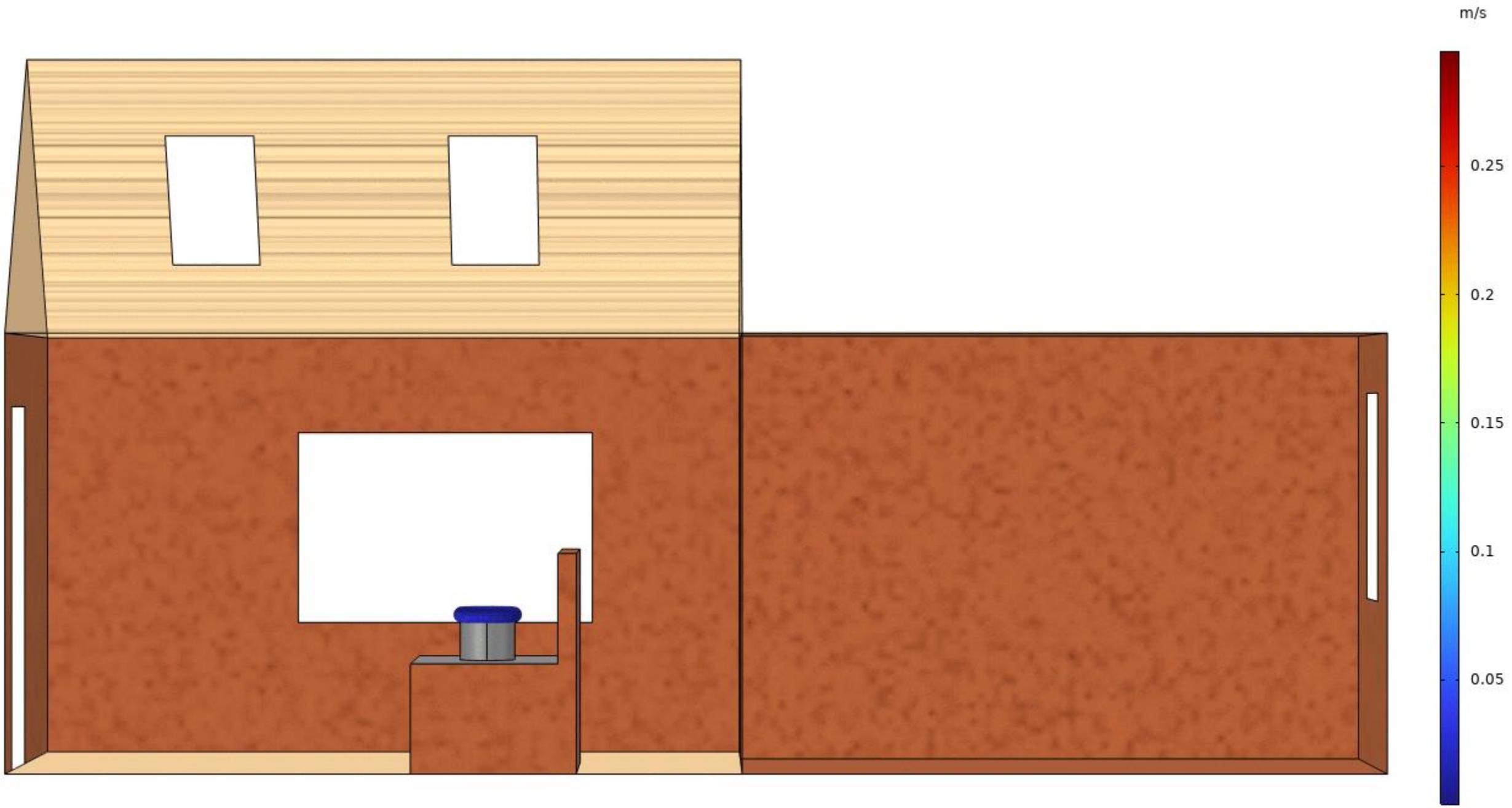


Graphics



Messages

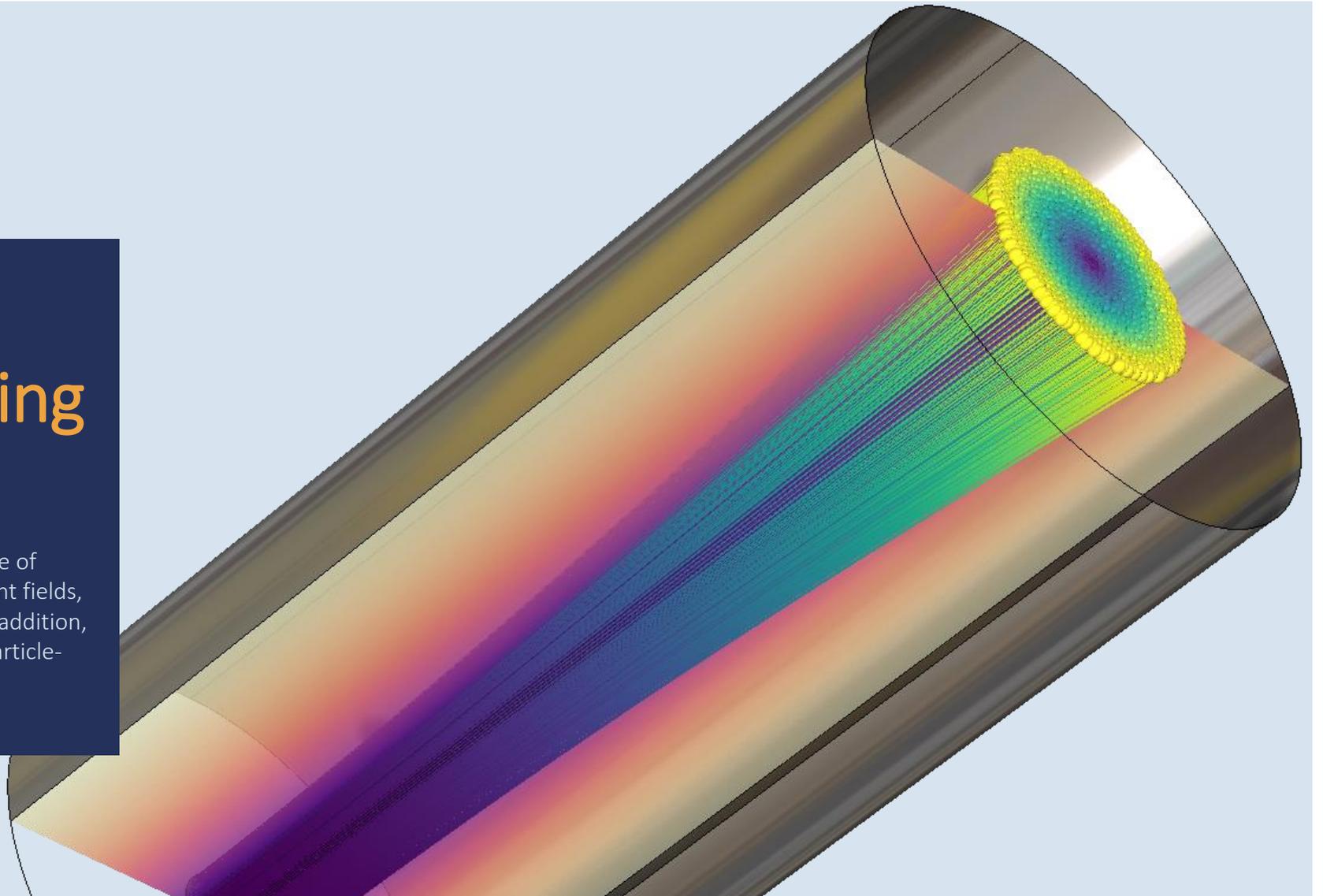




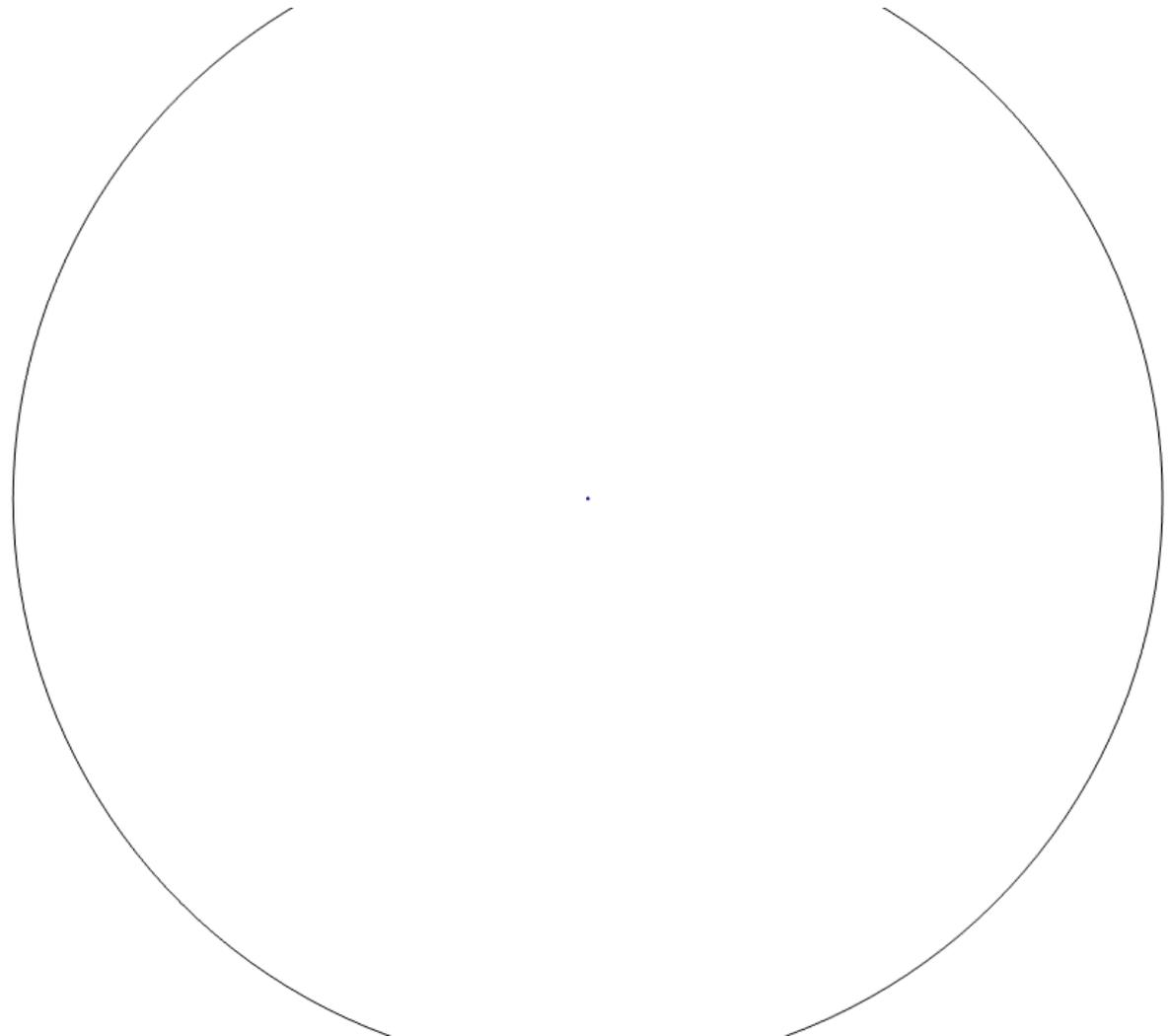
CONCLUDING REMARKS

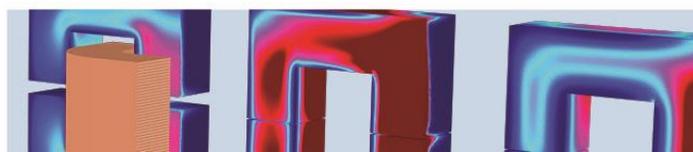
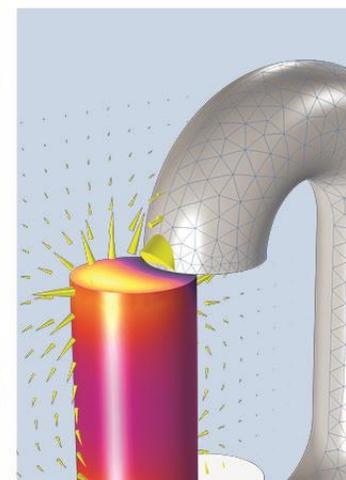
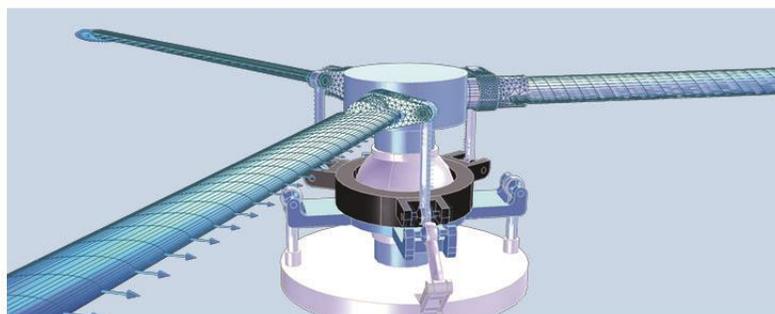
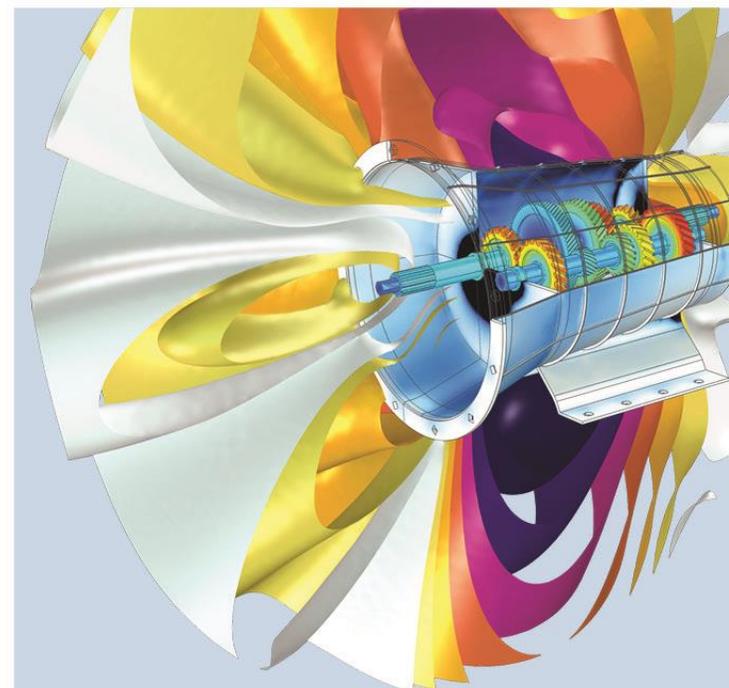
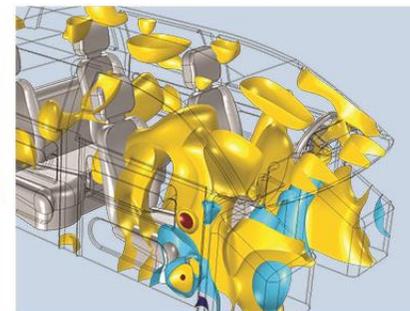
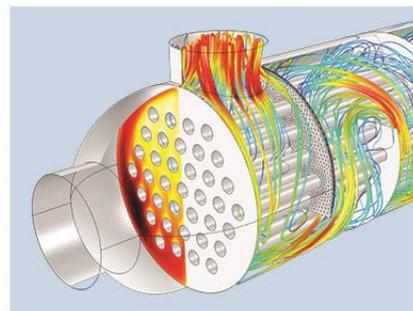
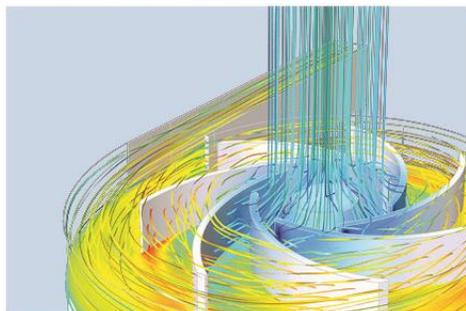
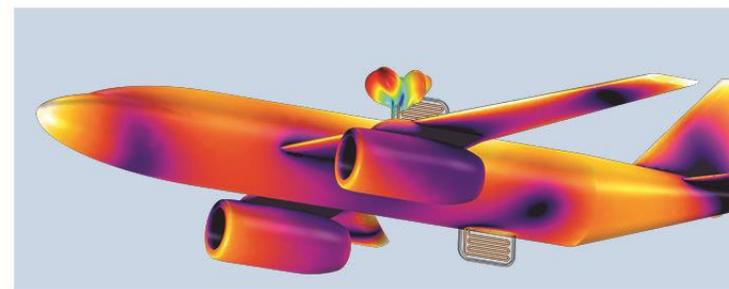
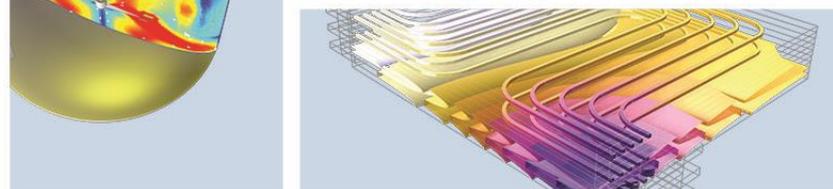
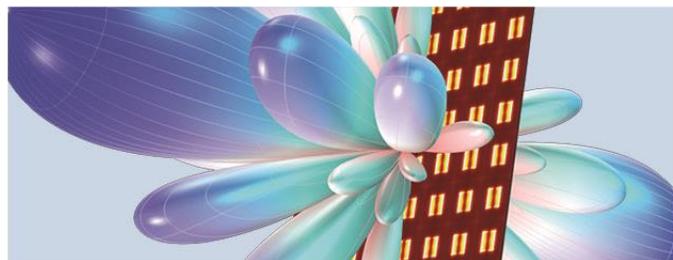
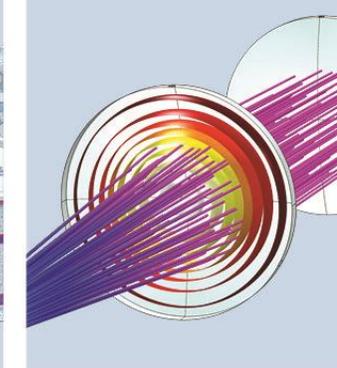
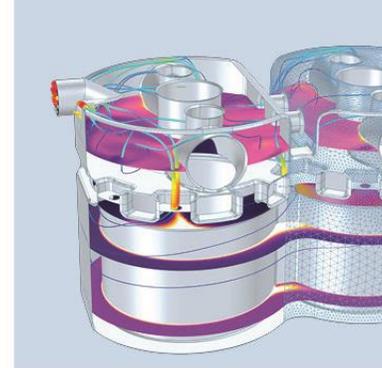
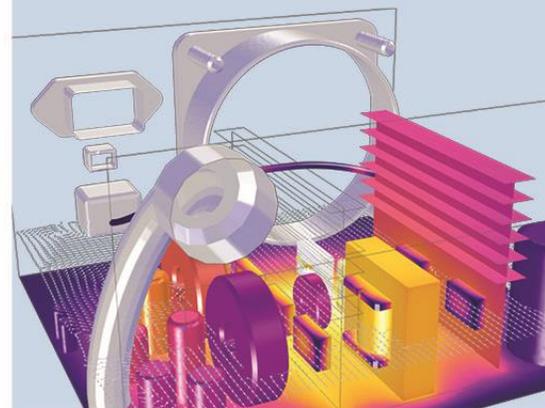
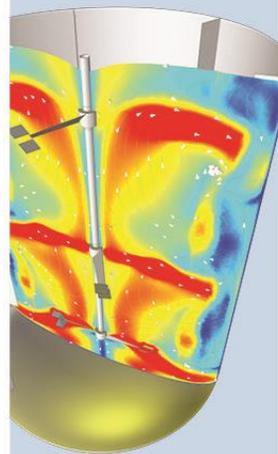
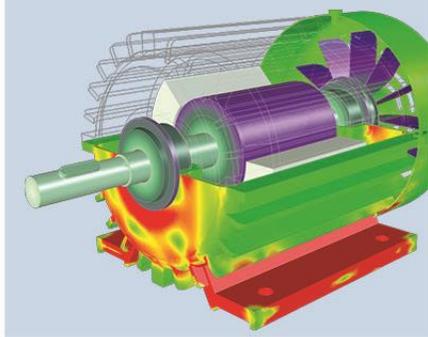
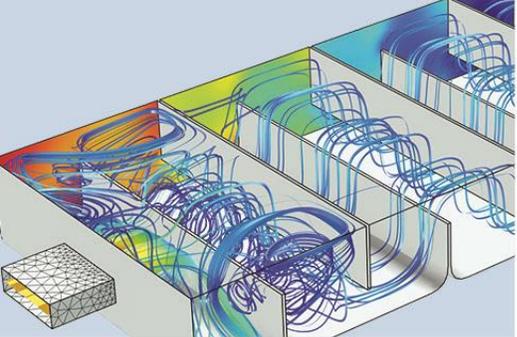
The Particle Tracing Module

The Particle Tracing Module features a wide range of functionality for computing the impact of different fields, such as electric fields, on particle trajectories. In addition, it has the unique ability to model bidirectional particle-field interactions.



Thank you for your attention





Contact Us

support@humusoft.cz