Computational Fluid Radiative Dynamics of the Galileo Jupiter Entry at 47.5 km/s

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Outline

I. Mission Context and High-Temperature Effects

II. Objectives

III. Flowfield Models and Database Definition

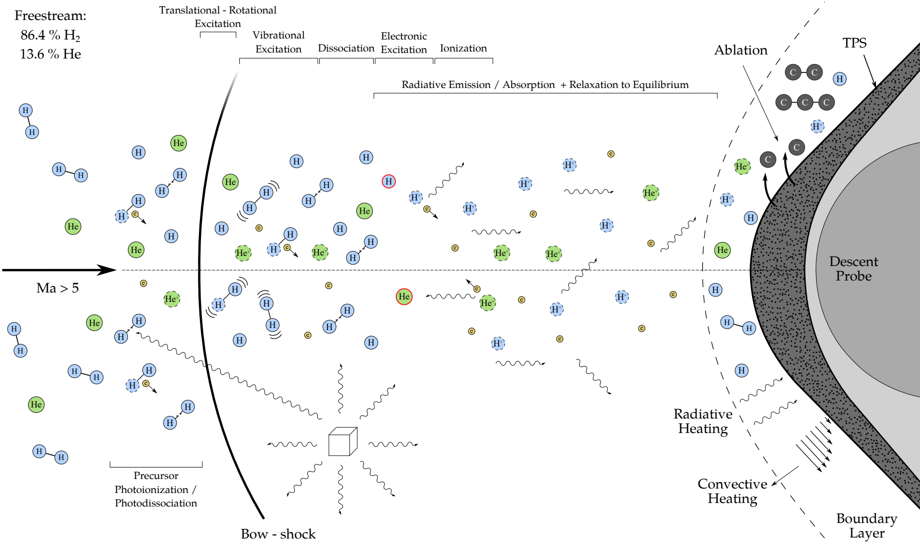
IV. Radiation Models and Database Definition

V. Flowfield Results

VI. Sensitivity Studies on Radiation

VII. Achievements and Future Work

High-Temperature Effects



High-temperature effects in hypersonic flow (H_2 – He mixture).

Galileo Mission

- Designed to study Jupiter's atmosphere, cloud structure and moons

Mission details:

- December 1995
- Entry velocity of 47 $\mathrm{km\,s^{-1}}$
- Heat fluxes $> 300\ \mathrm{MW\,m^{-2}}$

Jupiter's Atmosphere:

- 86.4% H_2, 13.6% He [1]

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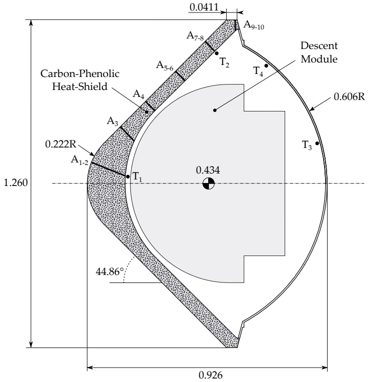

Galileo probe geometry.

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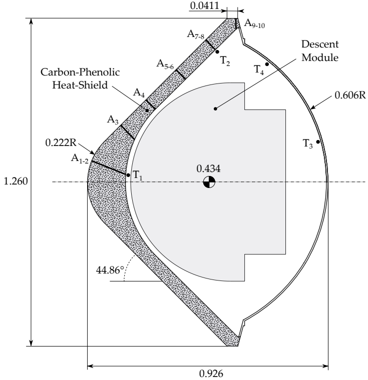
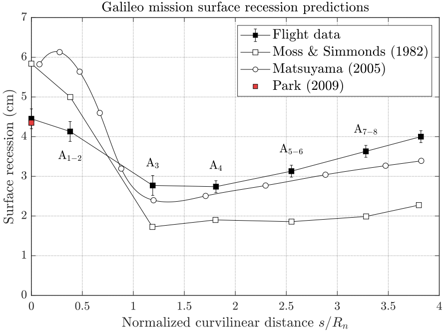
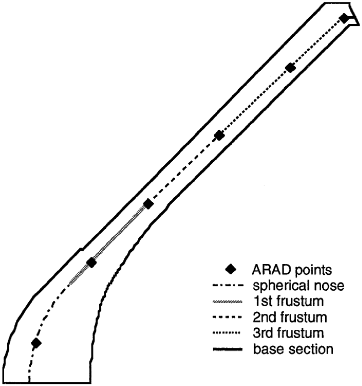


Galileo probe geometry.

Predictions vs Flight Data



Surface recession predictions.



Reconstructed geometry after flight.

- Recession **overpredicted** at stagnation region and **underpredicted** at shoulder

Past Works

1978 Tiwari *et al.* studied **thermo-chemical non-equilibrium** and **precursor heating**

1978-82 Moss *et al.* studied effects of **turbulence**, **ablation** and **spallation**

2002 Matsuyama *et al.* compared **tangent-slab** and **ray-tracing** approaches

2005 Matsuyama *et al.* coupled **turbulence** to **ablation products injection**

2009 Park studied **ablation products injection** at stagnation point

2018 Reynier *et al.* reviewed effects of **updated databases** on convective heating

Past Works (Thermo-Chemical Equilibrium)

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- Most works rely on **thermo-chemical equilibrium**
- **He and H_2** radiation is always neglected

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Objectives

Perform sensitivity studies to assess influence of:

- **Wilke/Blottner/Eucken** *vs* **Gupta/Yos** transport models
- **Tangent-slab** *vs* **ray-tracing** approaches for radiative transfer
- **Thermal non-equilibrium** assumption
- **He** and **H_2 radiation**
- **Precursor heating** effects
- **Ablation products** injection

SPARK CFD Code

Multi-physics CFD code suited for hypersonic flow applications

- Written in Modern Fortran 03/08
- Euler and Navier-Stokes formulations
- Multi-species chemically reacting flows
- Chemical and thermal non-equilibrium models
- State-to-state kinetics

SPARK

Software Package for Aerodynamics Radiation and Kinetics

Flowfield and radiation treated in **uncoupled** approach:

- Flowfield solved without radiative source term
- Radiative heat fluxes computed in post-processing

Non-equilibrium Models

Chemical Kinetics

- Chemical species: **H, He, H_2, H^+, He^+, $H_2{}^+$ and e^-**
- Leibowitz and Kuo's kinetic rates [2]

Thermal Non-equilibrium

- 2T model with T_{v,H_2}
- V–T energy exchanges use Millikan-White's correlation and DPLR's coefficients [3]
- Park's model applied to dissociation reactions of H_2

$$T = T_v^q T_{tr}^{1-q} \quad \text{with } q = 0.7$$

Reaction
$H + He \longleftrightarrow H^+ + e^- + He$
$H + H \longleftrightarrow H^+ + e^- + H$
$H + e^- \longleftrightarrow H^+ + e^- + e^-$
$He + e^- \longleftrightarrow He^+ + e^- + e^-$
$H_2 + H \longleftrightarrow H + H + H$
$H_2 + He \longleftrightarrow H + H + He$
$H_2 + H_2 \longleftrightarrow H + H + H_2$
$H_2 + H^+ \longleftrightarrow H + H + H^+$
$H_2 + e^- \longleftrightarrow H + H + e^-$
$H_2{}^+ + e^- \longleftrightarrow H + H$

Kinetic scheme employed.

Transport Models

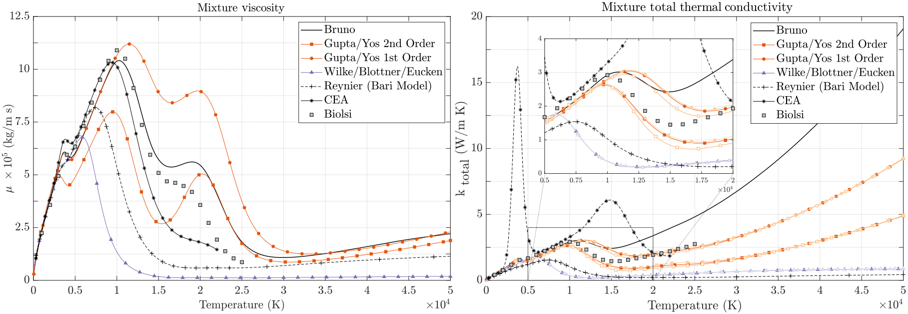
For thermal conductivity, viscosity and mass diffusion coefficients

1. **Wilke/Blottner/Eucken Model**
   - Wilke's mixing rules: $\mu = \sum_s \frac{x_s \mu_s}{\phi_s}$, and $k_k = \sum_s \frac{x_s k_{k_s}}{\phi_s}$
   - μ_s from Blottner's correlation, k_{k_s} from Eucken's relation, D_s from Lewis number
   - Most used model but lacks accuracy at high temperatures
2. **Gupta/Yos Model (1$^{\text{st}}$ and 2$^{\text{nd}}$ Order)**
   - Mixing rule for global parameters: $\left\{\mu, k_k, D_s\right\} = f(\Delta_{s,l}^{(1)}, \Delta_{s,l}^{(2)})$
   - $\Delta_{s,l}^{(1,2)}$ defined for each interaction (large CCS database)
   - Computationally more costly, but accurate at high temperature

> Transport module in SPARK rebuilt to be compatible with new CCS databases

> Now suitable for all Solar System atmospheres, previously hard-coded for air

Transport Properties Verification



Viscosity (left) and total thermal conductivity (right) comparison with literature results [4, 5, 6, 7].

- Wilke/Blottner/Eucken model underpredicts mass, momentum and energy diffusion above 5, 000 K
- Gupta/Yos model selected for Galileo entry studies

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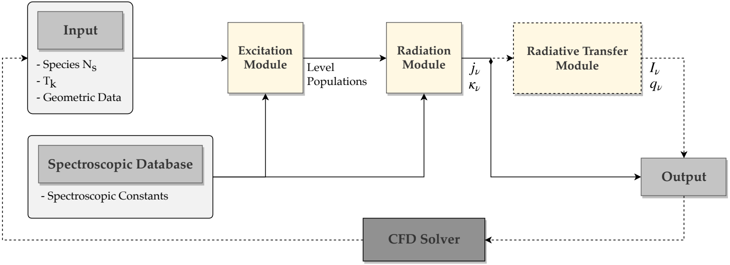
SPARK Line-by-Line Radiative Code

- Combines a detailed line-by-line spectroscopic database with a radiative transfer module for hypersonic flow applications



SPARK LbL code structure.

- Calculation of radiative heat fluxes at the wall of entry probes (TPS design)
- Radiative transfer optimization required: $\mathcal{O}(10^6\text{-}10^7)$ spectral coefficients per cell
- Tangent-slab and ray-tracing models re-written in Fortran (structured mesh)

Radiative Transfer Equation

Models the variation of radiative intensity across an emitting, absorbing and non-scattering medium

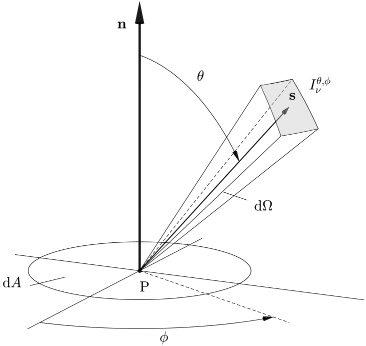
$$s \cdot \nabla I_\nu^{\theta,\phi} = \frac{\mathrm{d}I_\nu^{\theta,\phi}}{\mathrm{d}s} = j_\nu - \kappa_\nu I_\nu^{\theta,\phi}$$

The radiative heating is obtained from

$$q_{\mathrm{rad}} = \int_0^\infty \int_0^{2\pi} \int_0^{\frac{\pi}{2}} I_\nu^{\theta,\phi} \cos\theta \sin\theta \, \mathrm{d}\theta \, \mathrm{d}\phi \, \mathrm{d}\nu$$

Two models for radiative transfer:

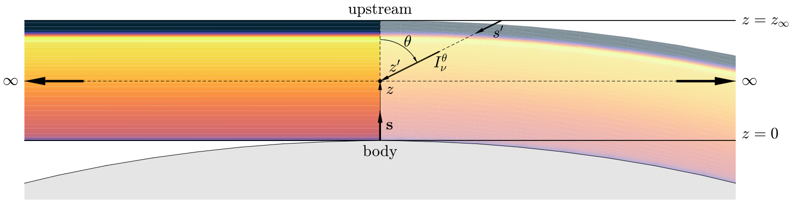
- Tangent-Slab Approximation
- 3D Ray-Tracing Model



Geometric model for radiation.

Tangent-Slab Approximation

Properties assumed to vary only in the direction normal to the wall



Tangent-slab approximation.

- Allows analytic simplification ⟶ $q_{\text{rad}} = 2\pi \int_0^\infty \int_0^{z_\infty} j_\nu \mathscr{E}_2 \left[\tau_\nu(0, s)\right] \mathrm{d}s \, \mathrm{d}\nu$
- Overpredicts radiative heating at stagnation point by 10–15%, and up to 70% on the shoulder and afterbody regions
- Between 1 and 2 orders of magnitude faster than ray-tracing calculation

Ray-Tracing Approach

- The radiative transfer equation is solved along a set of directions (**rays**).
- Directional and spectral integration then results in the radiative heating

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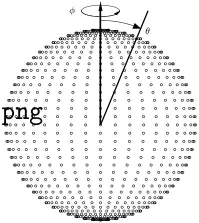
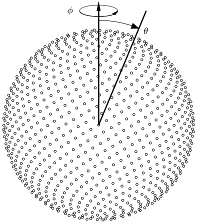


Constant ($\Delta\theta$, $\Delta\phi$).



Fibonacci Lattice.

- Requires uniform ray distribution ⟶ **Fibonacci Lattice algorithm**
- Convergence study on number of rays resulted in 500 rays per hemisphere

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Test Matrix and Computational Framework

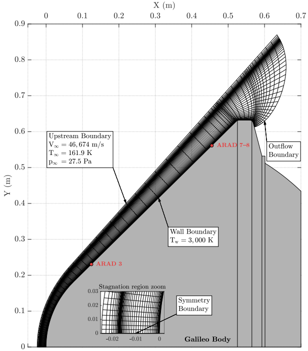
Test matrix used in the present work [1, 6].

Case	**Altitude** (km)	**Time** (s)	**Velocity** ($\mathrm{m\,s^{-1}}$)	**Temperature** (K)	**Pressure** (Pa)
Wilke 1T Wilke 2T Gupta/Yos 1T Gupta/Yos 2T	180	42.06	46, 674	161.9	27.5

- Strong **non-equilibrium**
- Mesh convergence study → 72×60 mesh

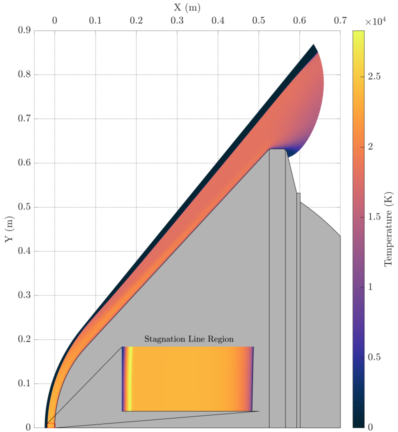
Numerical challenges

- Unstable shoulder expansion
- Time step $\mathcal{O}(10^{-12})$
- Upstream velocity incremented from $2\ \mathrm{km\,s^{-1}}$ to $46\ \mathrm{km\,s^{-1}}$

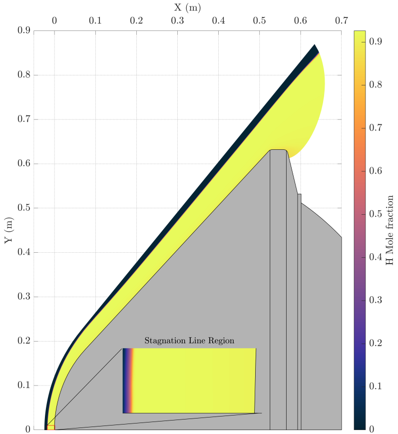


Mesh and boundary conditions.

Flowfield Features



Temperature field.

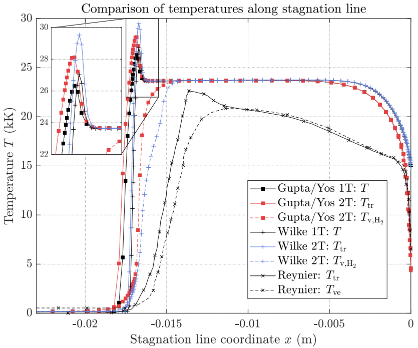


H mole fraction field.

- Maximum temperature above $28,000$ K in stagnation line
- H_2 dissociation leads to 90% H present throughout most of shock layer

Stagnation Line Temperatures

- Wilke model predicts **5% higher temperature peak** and **narrower shock** due to lower thermal conductivity
- Non-equilibrium cases (2T) predict **6% higher temperature peak** compared to equilibrium solution
- Poor mesh refinement near wall in Wilke case, even using a 72 × 90 mesh, resulting in excessively high temperatures in boundary layer
  - 20 nm first-cell height used by Reynier *et al.* [6] proved unfeasible



Stagnation line temperature profiles.

- ▶ Higher temperatures in Wilke model will have a big impact in radiative heating

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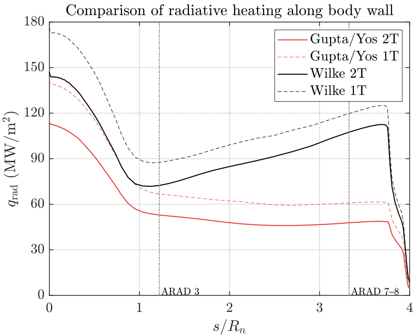
Influence of Transport and Thermal Non-equilibrium Models

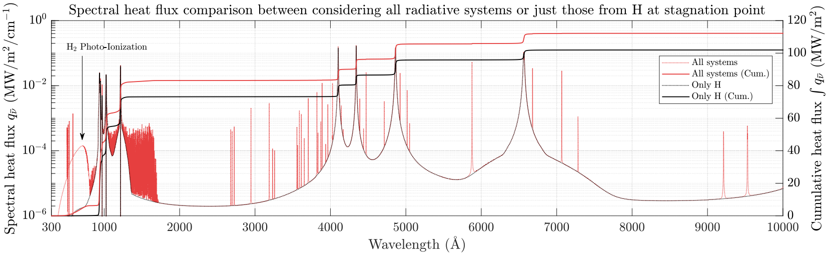
- **Non-equilibrium** predicts 20-30% **lower** radiative heating
- Wilke overpredicts radiative heating
  - Mesh refinement problem
  - High shock temperatures
- Wilke shoulder overprediction translates to better agreement with flight data



Radiative heat fluxes along wall.

- Difficult to conclude if higher radiative heating results from poor mesh refinement or Wilke's inability to capture high thermal conductivity

Influence of He and H_2 Radiation

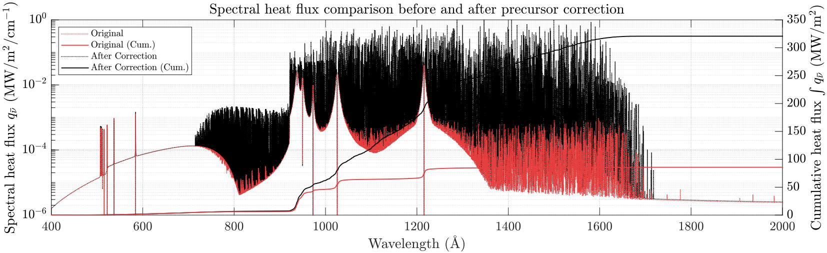


Spectral radiative heating at stagnation point.

- Overall, strong H lines are biggest contributor to radiative heat fluxes
- Considering all systems, radiative heating increases 9.5% (H_2 photo-ionization)
- Difference decreases to 1.7% at shoulder

Influence of Precursor Heating at Stagnation Point

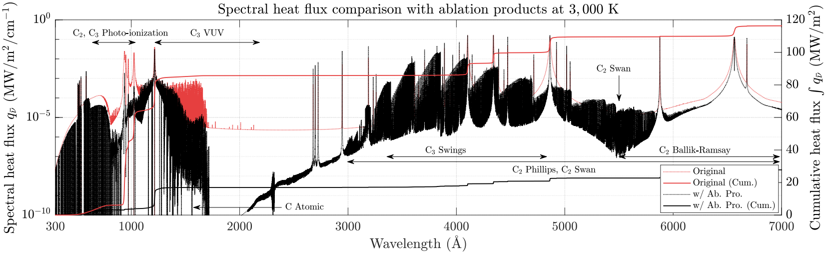
- Different story when precursor heating is taken into account...



Spectral radiative heating at stagnation point with precursor heating (using results from Tiwari *et al.* [8]).

- Radiation emitted upstream from shock layer is absorbed by freestream H_2
- 200% increase in radiative heating, now due to H_2 Lyman and Werner bands
  - > **H_2 radiation must be accounted for in entry to Jupiter!**

Influence of Ablation Products Injection at Stagnation Point



Spectral radiative heating at stagnation point with ablation products (using results from Park [9]).

- 74% reduction in radiative heating in 3,000 K case (C_2,C_3 photo-ionization and C_3 VUV absorption)
- 400% increase if flowfield temperatures are kept unchanged

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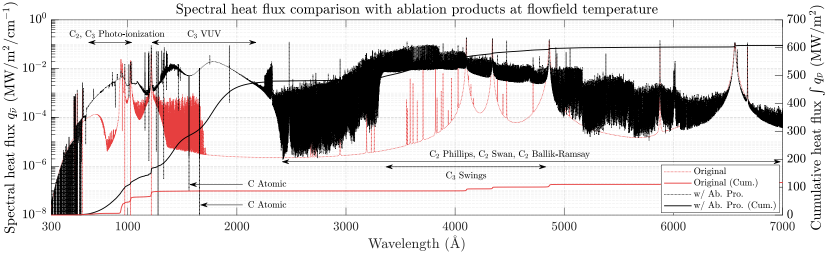

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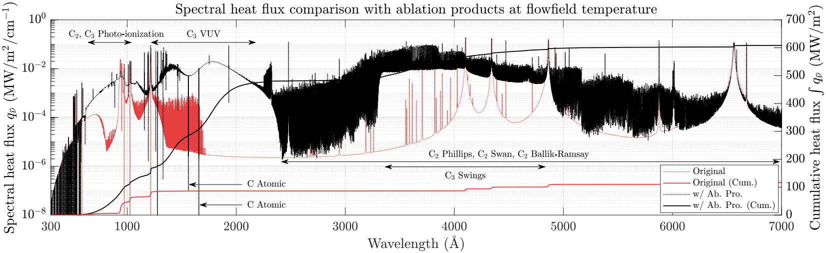

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- 400% increase if flowfield temperatures are kept unchanged
  - > **Suitable modeling of ablation layer temperature is crucial!**

Achievements

Code Development

1. Transport module in SPARK redesigned
2. Radiative transfer models implemented in SPARK LbL

Galileo entry mission

1. Wilke transport model unsuitable for entry in Jupiter
2. Non-equilibrium is important at 180 km, with 20-30% lower radiative heating
3. H_2 radiation must be accounted for due to precursor heating
4. Ablation products absorption may counterbalance precursor heating effects, but a material response code is required to model ablation-flowfield coupling
5. Maximum 10% difference between tangent-slab and ray-tracing models

Future Work and Acknowledgments

Future Work

- Model the effects of precursor heating while including H_2 in radiative analysis
- Couple the flowfield to a material-response code

Acknowledgments

- Prof. Mário Lino da Silva, for important suggestions, mentorship and RHTG opportunity
- J. Vargas and B. Lopez for support with SPARK

> Paper submission for **Physics of Fluids** Journal

“Numerical Simulations of Galileo Jupiter entry with Non-Equilibrium and Radiation”

Luís Santos Fernandes, Mário Lino da Silva, Bruno Lopez

Questions?

Thank you for your attention!

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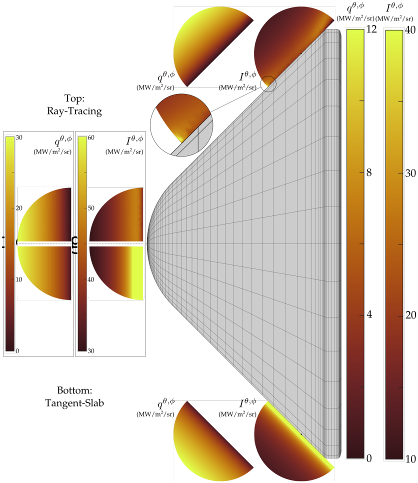

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