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Towards a Finite Element Calculation of Acoustical Amplitudes in HID Lamps

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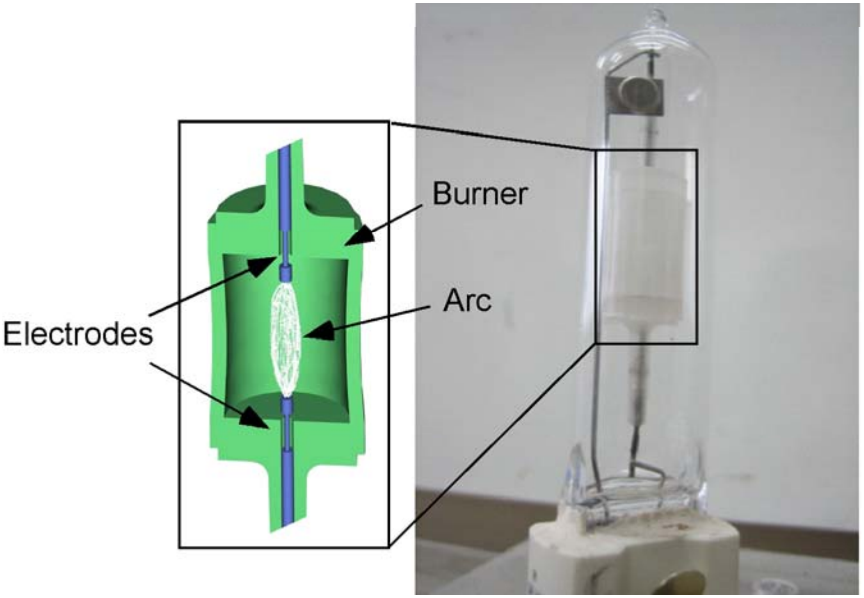
Energy Consumption

- Industrial production
- Transportation
- Heating and cooling
- Lighting
- …

High Intensity Discharge (HID) Lamp

- Arc tube / burner
  - Wall: Quartz or ceramics
  - Filling: Mercury
  - Additives: Metal halides etc
- Electrodes
  - Tungsten
- Discharge arc
  - Light source
  - Temperature 5000 – 6000 K



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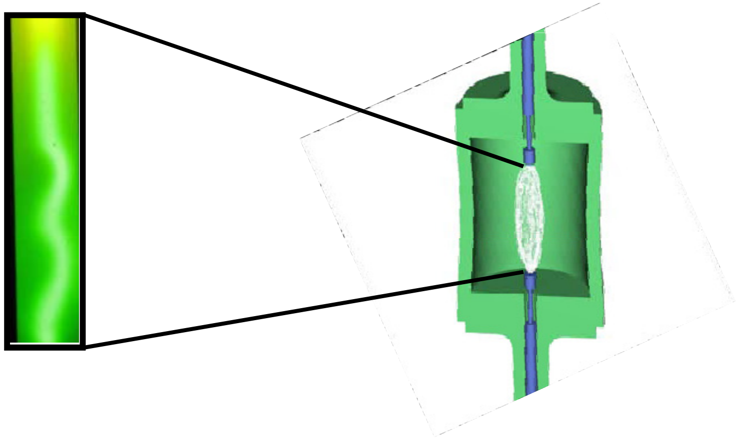
AC Operation

- Advantages:
  - Avoids demixing
  - Avoids electrode errosion
- Acoustic resonance problem:
  - Flickering
  - Reduction of lamp's lifetime
  - Lamp destruction
- Counteraction:
  - Electronical measures
  - Lamp design



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Objective and Scope

- Numerical calculation of acoustic amplitudes in HID lamps
- Enhancement of unterstanding of acoustical resonance problem
- Simplifications:
  - No inclusion of plasma dynamics
  - Simplified geometry
  - 2 dimensional axisymmetric FE model

Temperature Profile

$$T(r_\perp) = T_a - (T_a - T_w)\left(\frac{r_\perp}{R}\right)^2$$

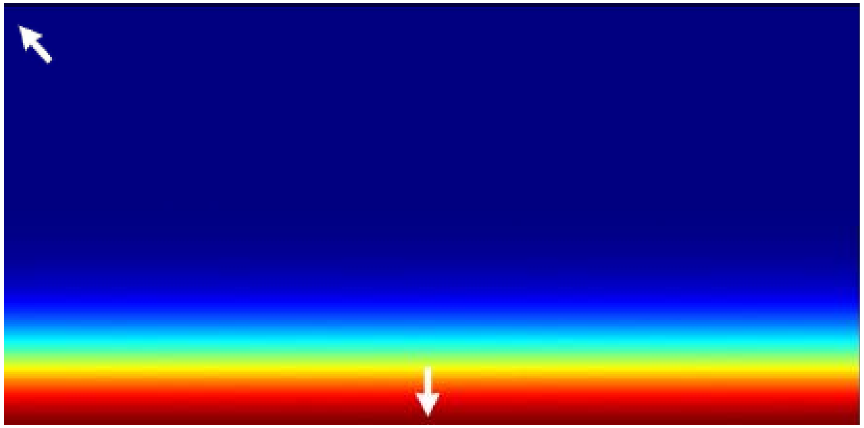
$$\eta = \eta_0 \left(\frac{T}{T_0}\right)^{3/2} \frac{T_0 + T_S}{T + T_S}$$

(Sutherland’s law)

$$\kappa = \kappa_0 \exp\left(\frac{T}{T_1} + \arctan\left(\frac{T - T_2}{T_3}\right) - 1.3\right)$$

Gaussian Power Density

$$\mathcal{H}(\vec{r}) = \mathcal{H}_0 \exp\left(-2\left(\frac{r_\perp}{w}\right)^2\right)$$



Cylinder axis

Inhomogenous Helmholtz Equation

$$\vec{\nabla}\left(\frac{1}{\rho}\vec{\nabla}p\right)+\frac{\omega^2}{\rho c^2}p = \mathrm{i}\omega\frac{\gamma-1}{\rho c^2}\mathcal{H}$$

Ideal gas law

$$c = \sqrt{\gamma R_{\mathrm{m}} T/M}$$

Solution

$$p(\vec{r},\omega) = \sum_j A_j(\omega) p_j(\vec{r})$$

Eigenmodes

Boundary conditions: Burner walls sound hard

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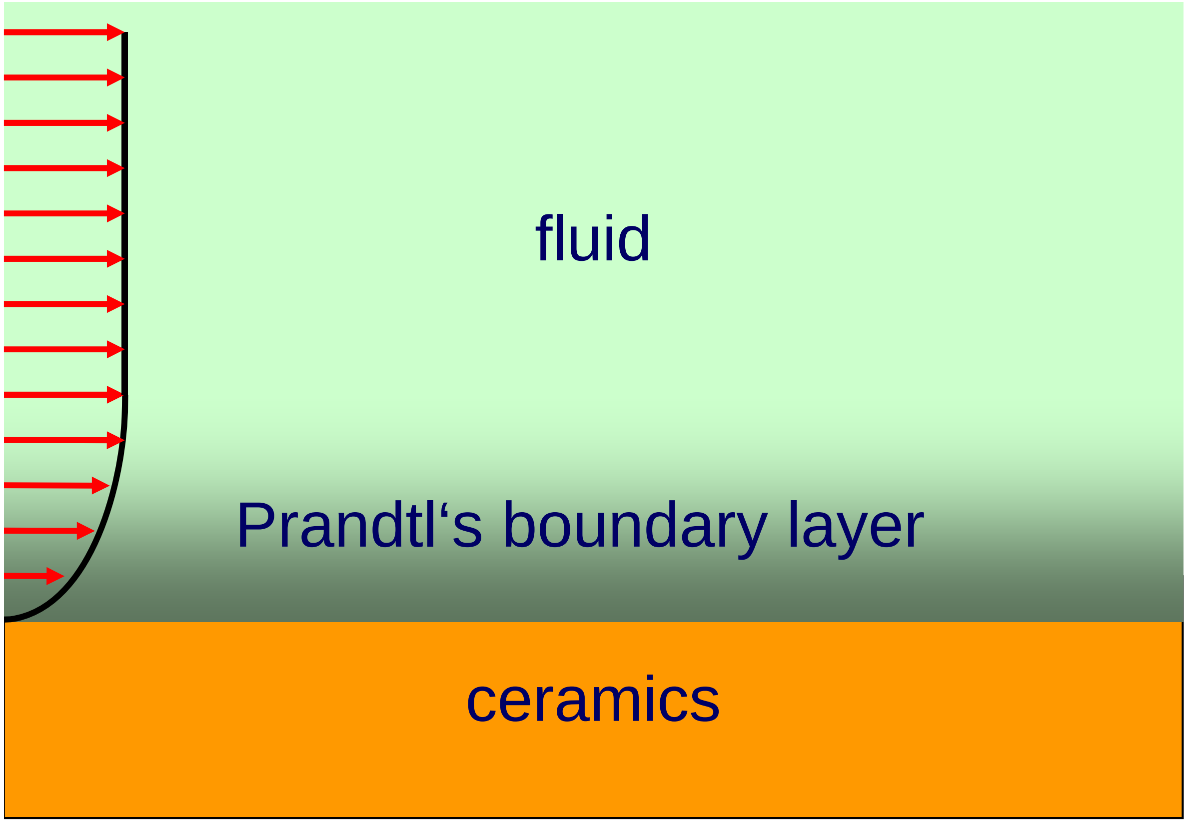
Amplitudes

Excitation amplitude: $$\mathcal{A}_j = \frac{(\gamma - 1)}{V_\mathrm{C}} \int_{V_\mathrm{C}} p_j^* \mathcal{H} \, \mathrm{d}V$$

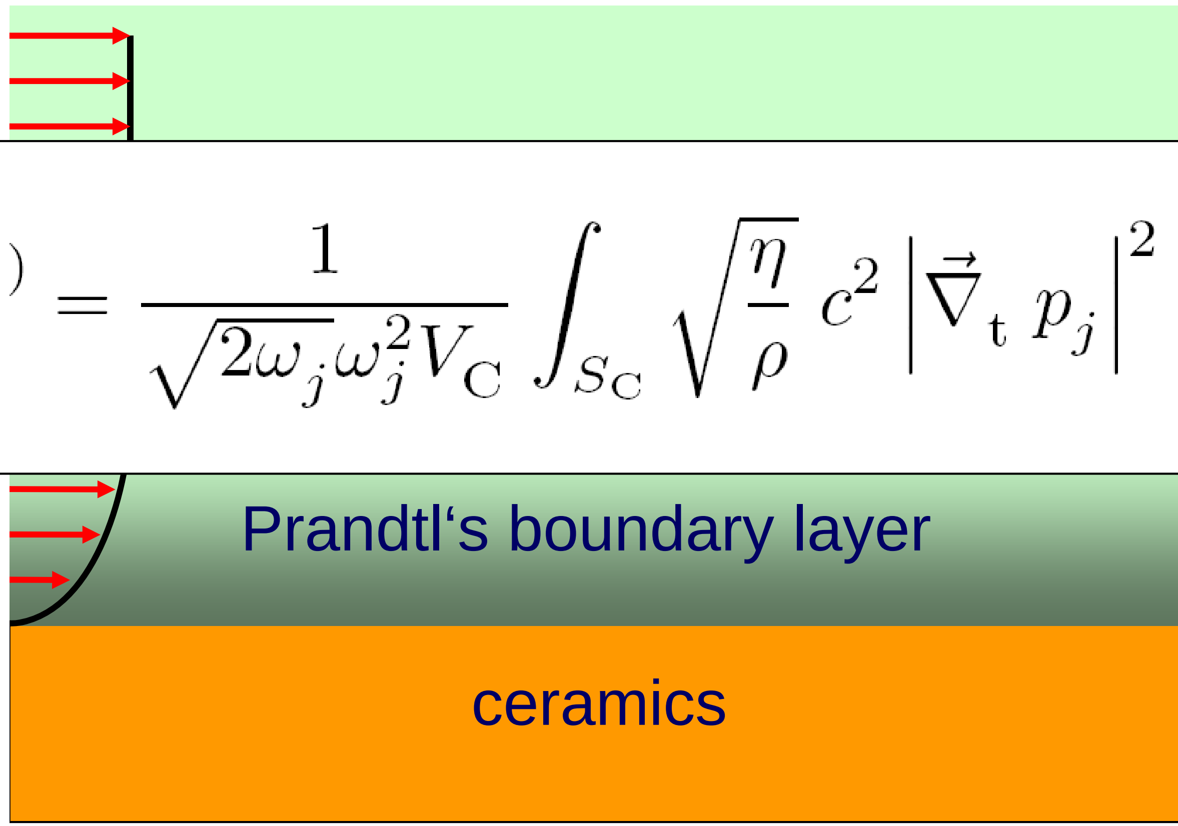
Loss factor

$$A_j(\omega) = \mathrm{i} \frac{\mathcal{A}_j \omega}{\omega^2 - \omega_j^2 + \mathrm{i}\omega\omega_j L_j}$$

Surface Loss: Shear Stress

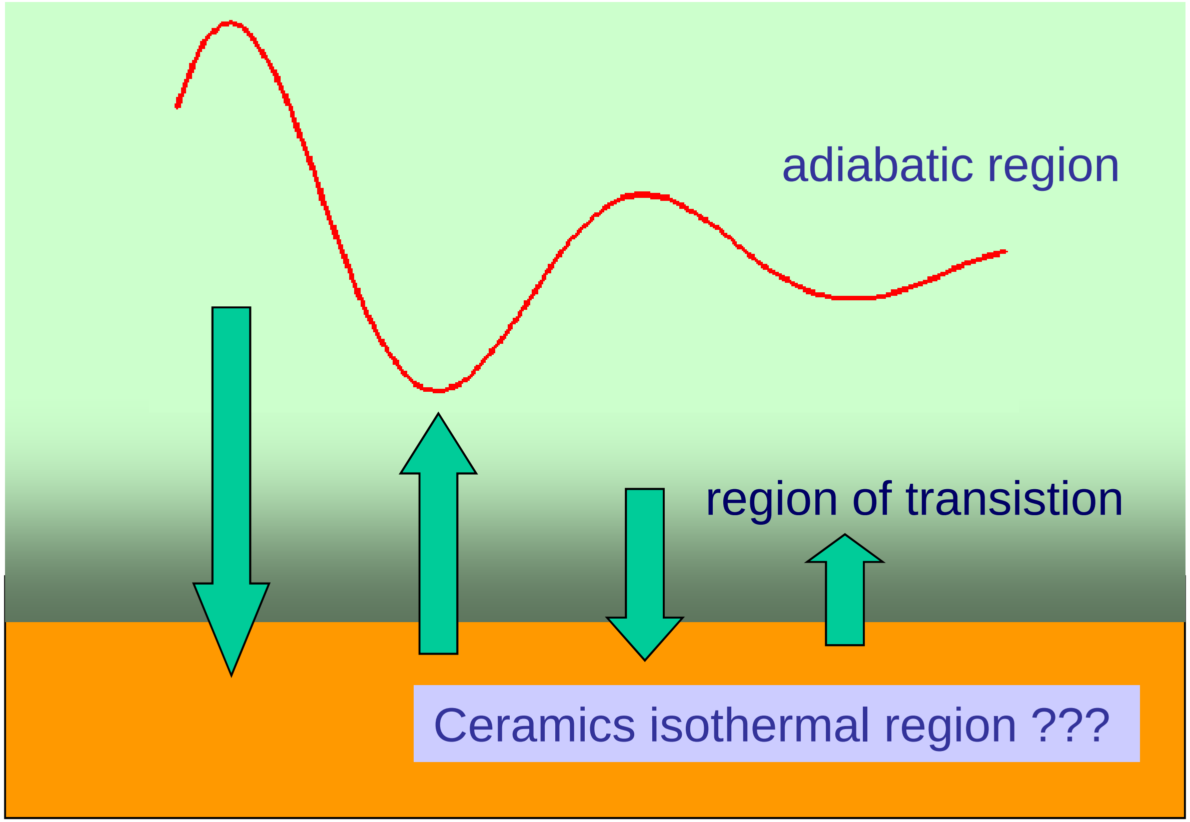


Surface Loss: Shear Stress



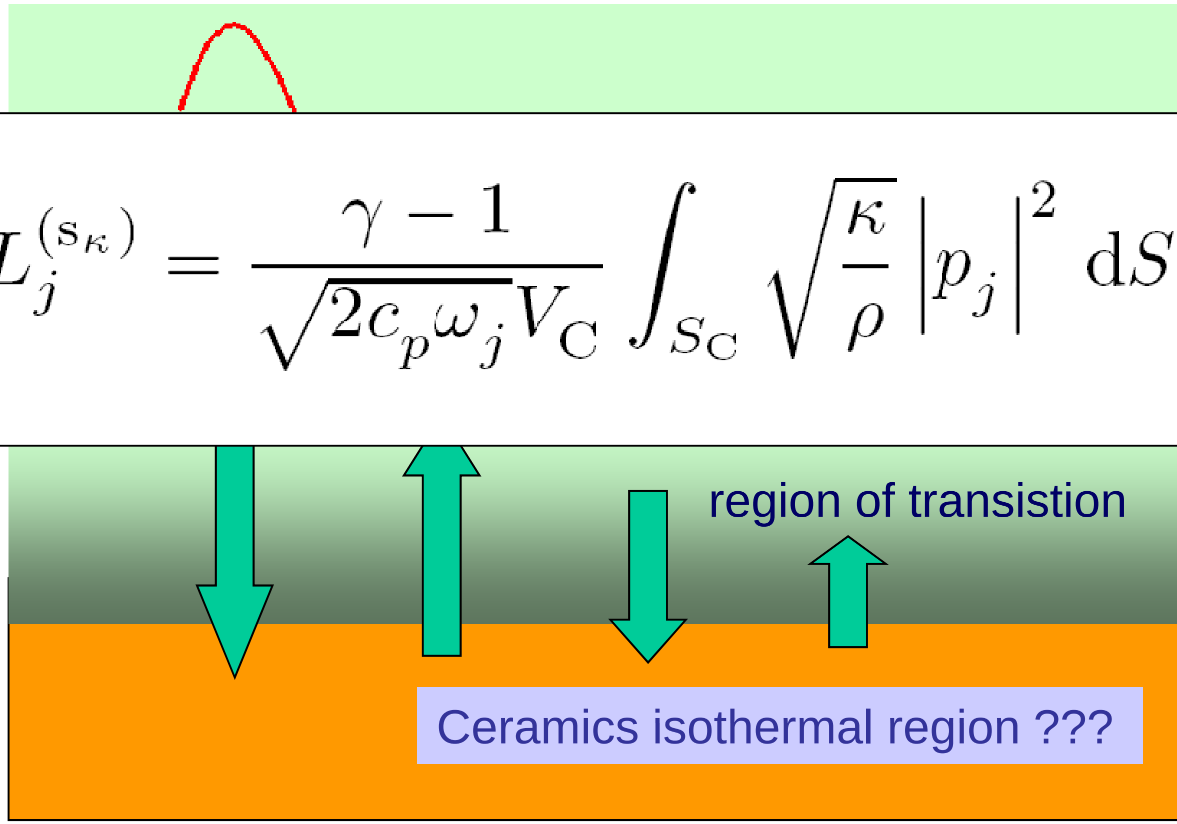
$$L_j^{(\mathrm{s}_\eta)} = \frac{1}{\sqrt{2\omega_j}\,\omega_j^2 V_\mathrm{C}} \int_{S_\mathrm{C}} \sqrt{\frac{\eta}{\rho}}\; c^2 \left| \vec{\nabla}_\mathrm{t}\, p_j \right|^2 \mathrm{d}S$$

Surface Loss: Thermal Conduction



Surface Loss: Thermal Conduction

$$L_j^{(\mathrm{s}_\kappa)} = \frac{\gamma - 1}{\sqrt{2c_p\omega_j}\,V_\mathrm{C}} \int_{S_\mathrm{C}} \sqrt{\frac{\kappa}{\rho}} \left|p_j\right|^2 \mathrm{d}S$$



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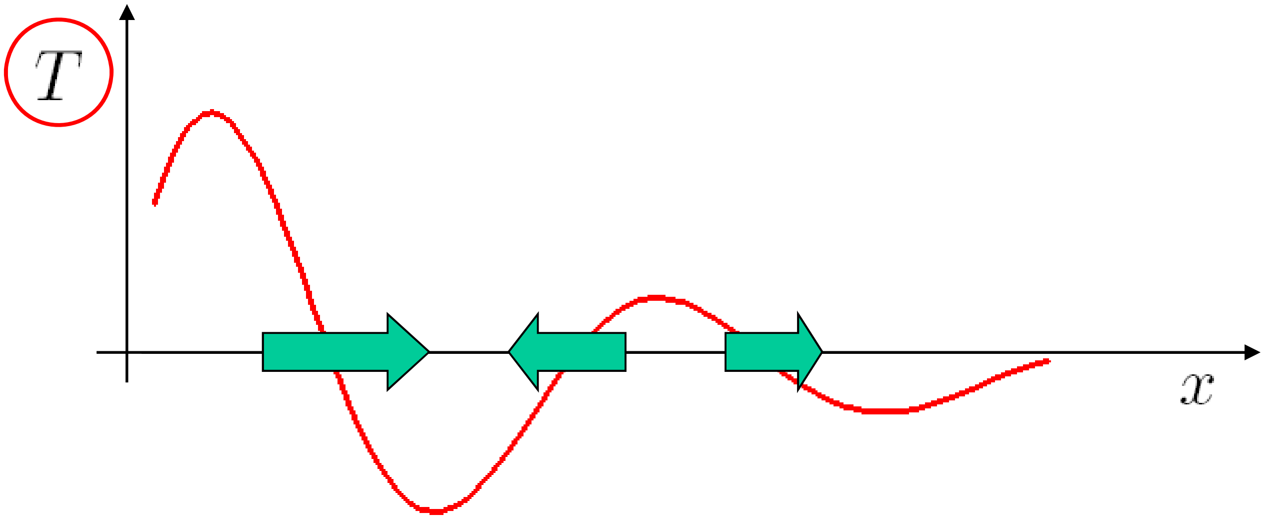
Surface Loss: Thermal Conduction

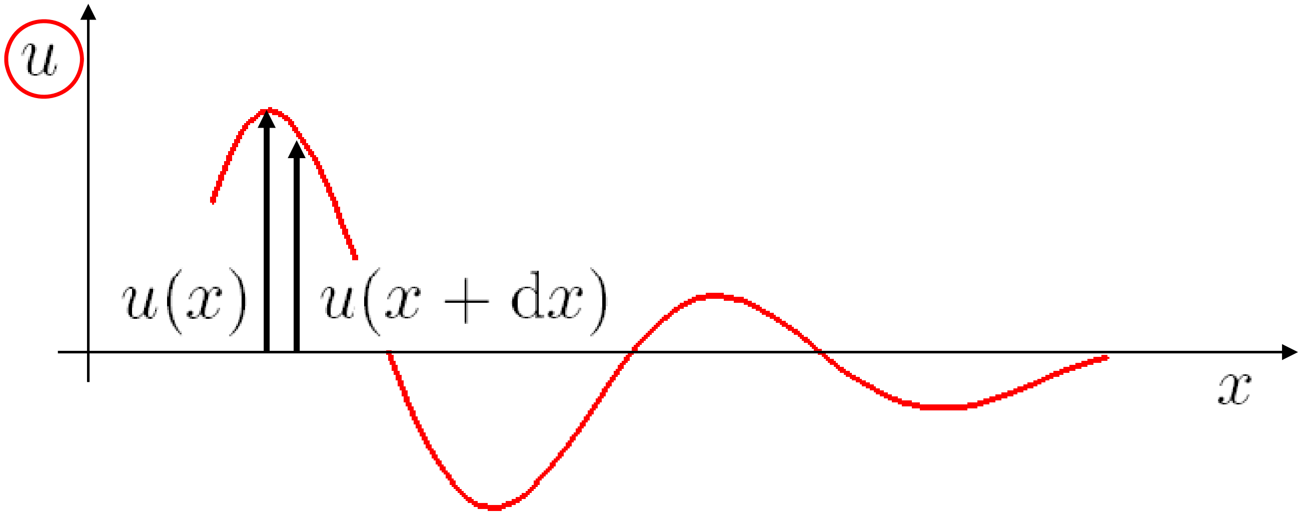
Metallic wall: $$\frac{\kappa_{\text{wall}}}{\kappa_{\text{gas}}} = \mathcal{O}(10^4) \approx \infty$$

Ceramic wall: $$\frac{\kappa_{\text{wall}}}{\kappa_{\text{plasma}}} = \mathcal{O}(50)$$

Volume Loss: Thermal Conduction



Volume Loss: Shear Stress



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Volume Loss: Shear Stress

$$L_j^{(\mathrm{v}\eta)} = \frac{4}{3\rho c^2} \sum_i \omega_i \left(\frac{A_i}{A_j} \right)^* \frac{1}{V_\mathrm{C}} \int_{V_\mathrm{C}} \eta \, p_i^* p_j \,\mathrm{d}V$$

$$\int_{V_\mathrm{C}} p_i^* \cdot p_j \,\mathrm{dV} = V_\mathrm{C} \delta_{ij}$$

Volume Loss

$$\eta(\vec{r}) := \bar{\eta} + \hat{\eta}(\vec{r})$$

$$\Rightarrow \quad L_j^{(\mathrm{v}_\eta)} = \frac{4}{3}\,\frac{\bar{\eta}}{\rho c^2}\,\omega_j + \text{corrections}$$

$$\kappa(\vec{r}) := \bar{\kappa} + \hat{\kappa}(\vec{r})$$

$$\Rightarrow \quad L_j^{(\mathrm{v}_\kappa)} = \frac{(\gamma - 1)\bar{\kappa}}{c_p \rho c^2}\,\omega_j + \text{corrections}$$

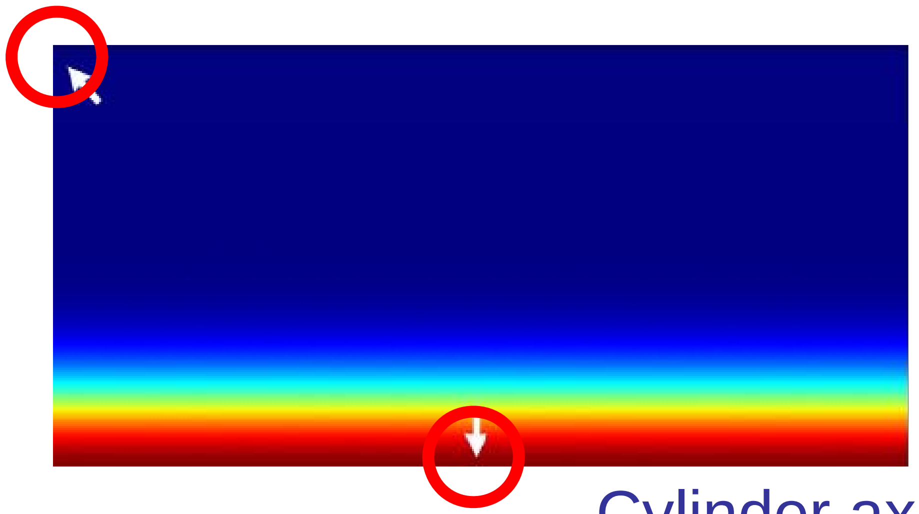
Volume Loss

$$L_j^{(\mathrm{v})} = L_j^{(\mathrm{v}_\kappa)} + L_j^{(\mathrm{v}_\kappa)} \sim \omega_j$$

Critical damping:

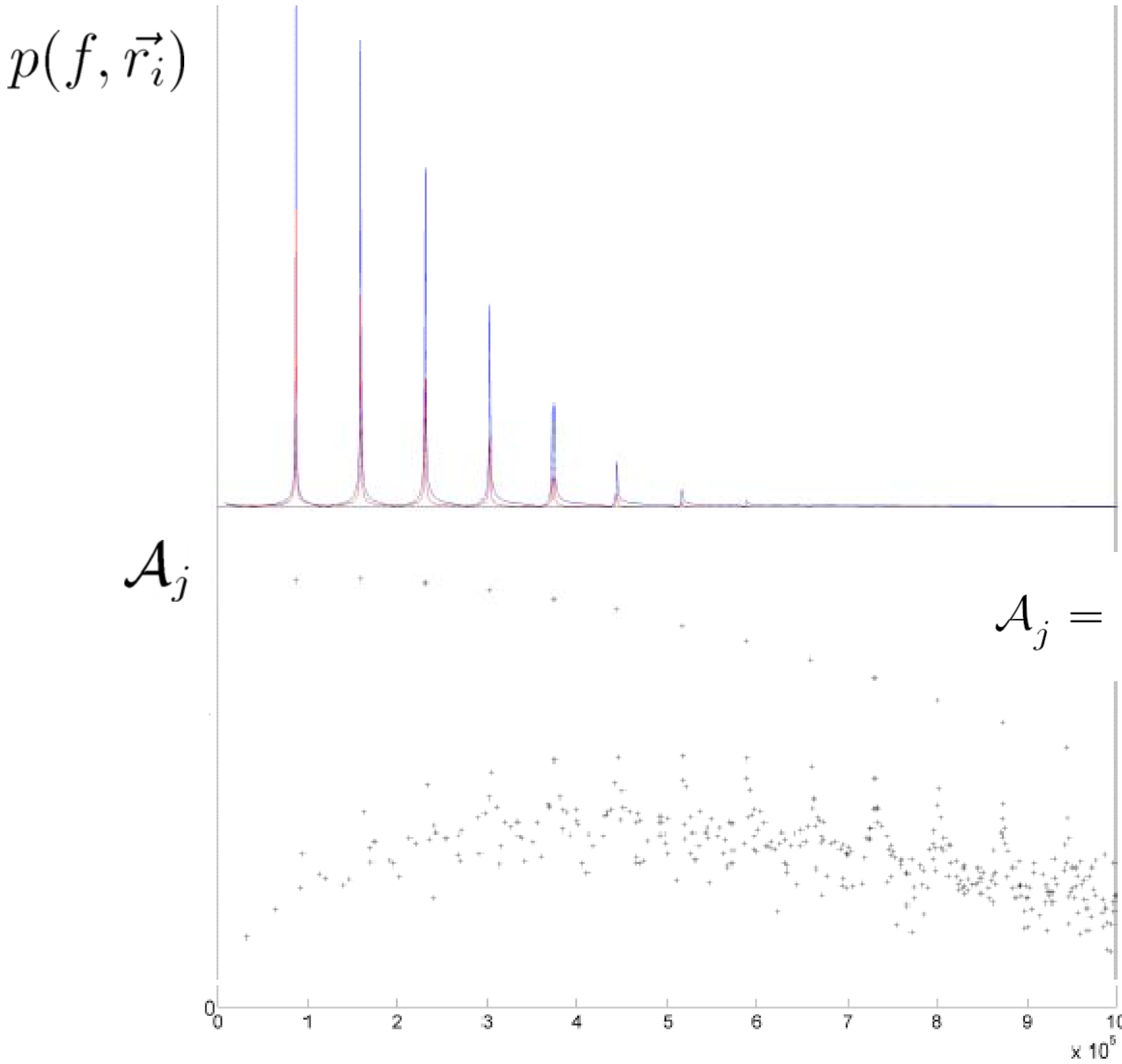
$$L_j^{(\mathrm{v})} = 2 \qquad \Rightarrow \qquad f_{\mathrm{crit}} \approx 1\ \mathrm{GHz}$$

Measuring Points



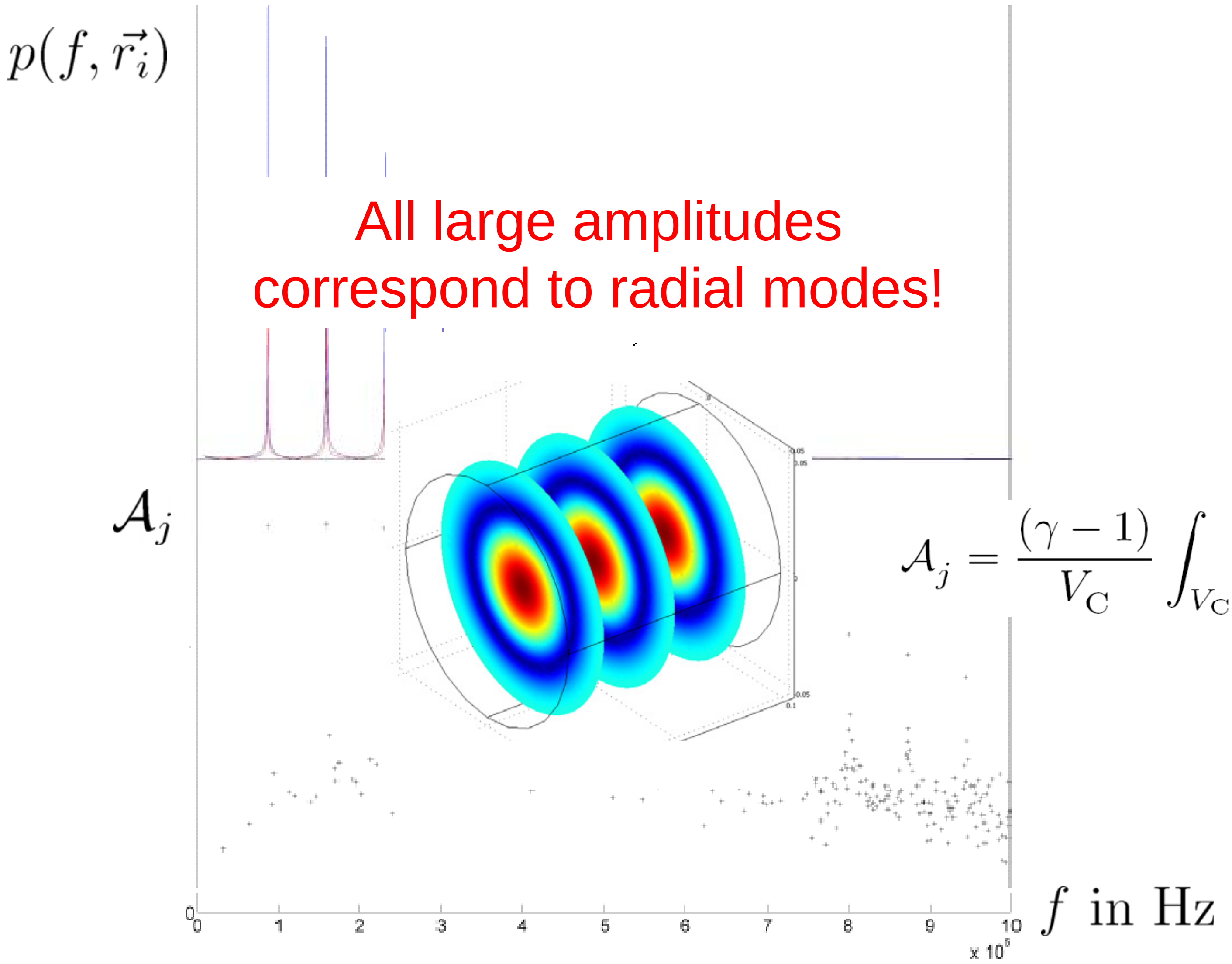
Cylinder axis

Response Function and Excitation Amplitude



$$\mathcal{A}_j = \frac{(\gamma - 1)}{V_\mathrm{C}} \int_{V_\mathrm{C}} p_j^* \mathcal{H} \, \mathrm{d}V$$

Response Function and Excitation Amplitude

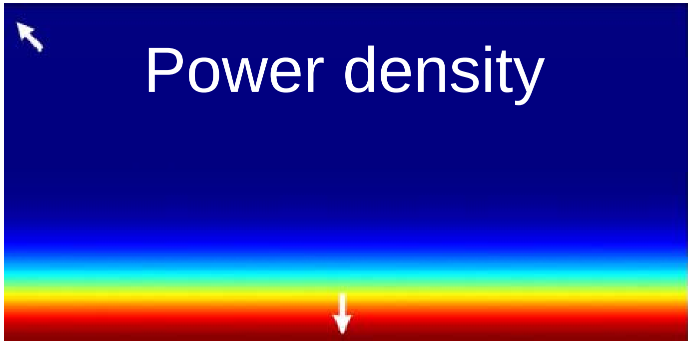


All large amplitudes correspond to radial modes!

$$\mathcal{A}_j = \frac{(\gamma - 1)}{V_\mathrm{C}} \int_{V_\mathrm{C}} p_j^* \mathcal{H} \,\mathrm{d}V$$

Radial Modes

$$\mathcal{A}_j = \frac{(\gamma - 1)}{V_\mathrm{C}} \int_{V_\mathrm{C}} p_j^* \mathcal{H} \, \mathrm{d}V$$



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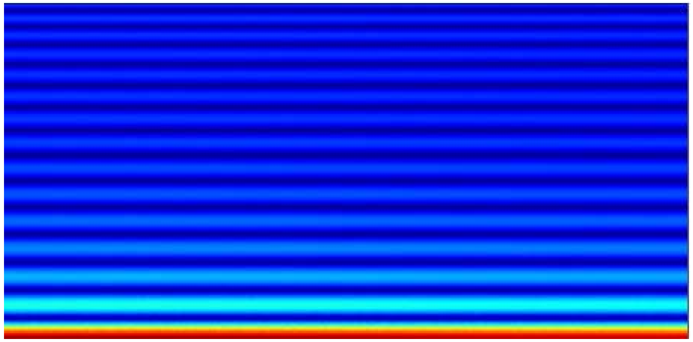
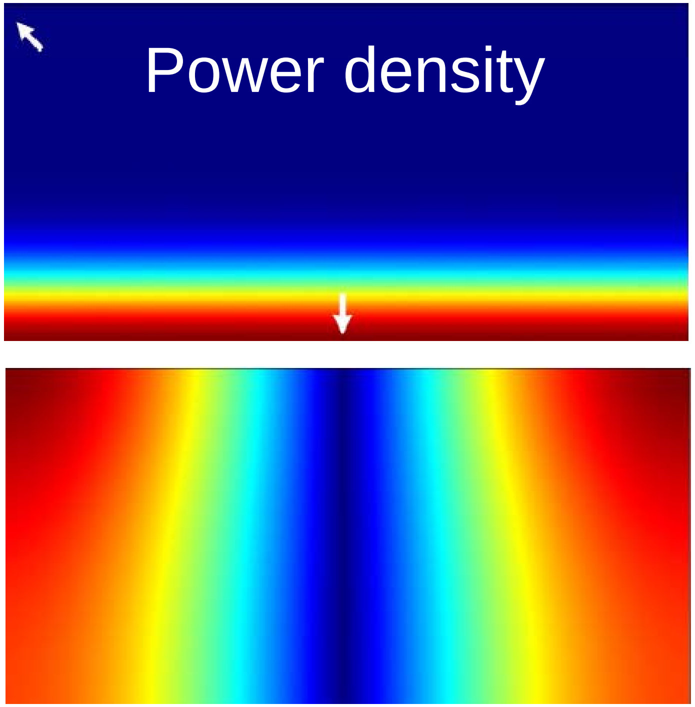


Nonradial Modes

$$\mathcal{A}_j = \frac{(\gamma - 1)}{V_\mathrm{C}} \int_{V_\mathrm{C}} p_j^* \mathcal{H} \, \mathrm{d}V$$



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Nonradial Modes

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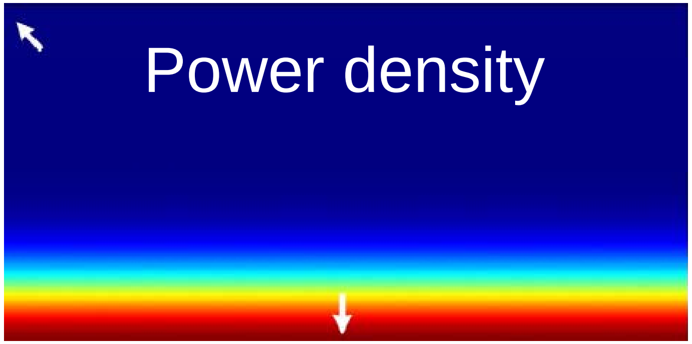

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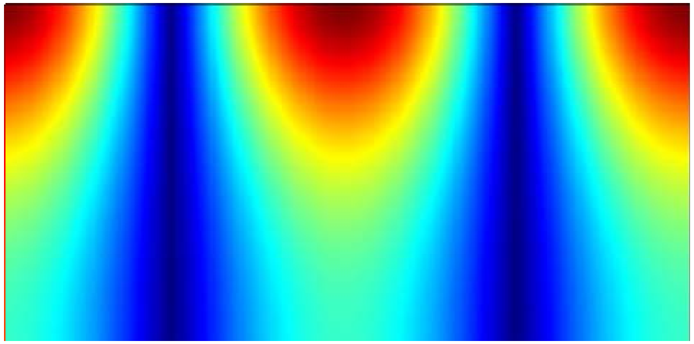
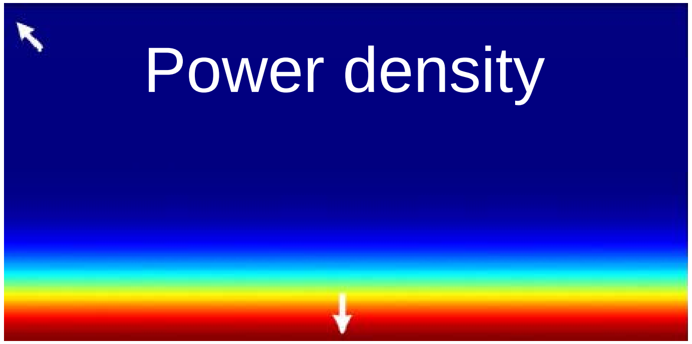


Nonradial Modes

$$\mathcal{A}_j = \frac{(\gamma - 1)}{V_\mathrm{C}} \int_{V_\mathrm{C}} p_j^* \mathcal{H} \, \mathrm{d}V$$



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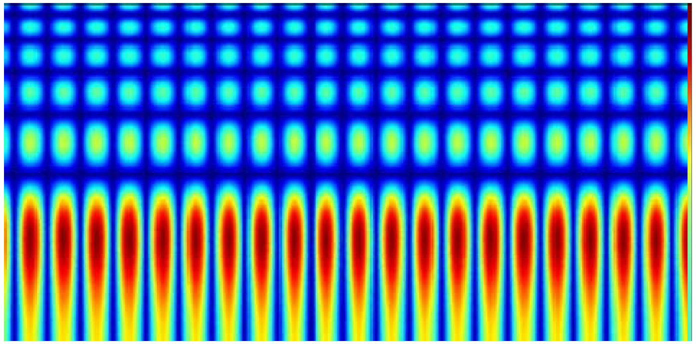

Summary, Conclusions and Prospect

- Simplified model for calculation of acoustical resonances in HID lamps
- Finding: Excitation amplitudes are the key for controlling acoustical resonances
- Next steps
  - Inclusion of plasma dynamics
  - Extension to 3d model
  - Optimization of burner geometry

Molto grazie!