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Effects of the Microstructure of Fibrous Media on their Acoustic Properties

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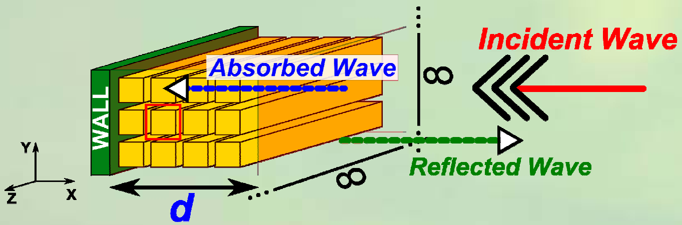

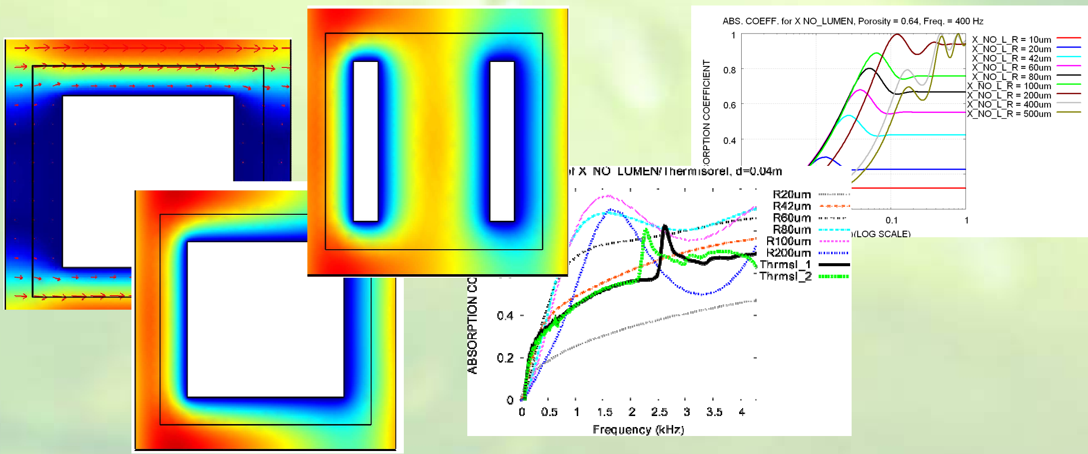

Outline

I-The ANR Silent Wall project

II-Acoustic modelling of periodic fibrous media

III-Influence of the boundary layer on absorption

IV-Influence of the radii of the fibres on absorption

V-Influence of the thickness of the sample

CONCLUSIONS

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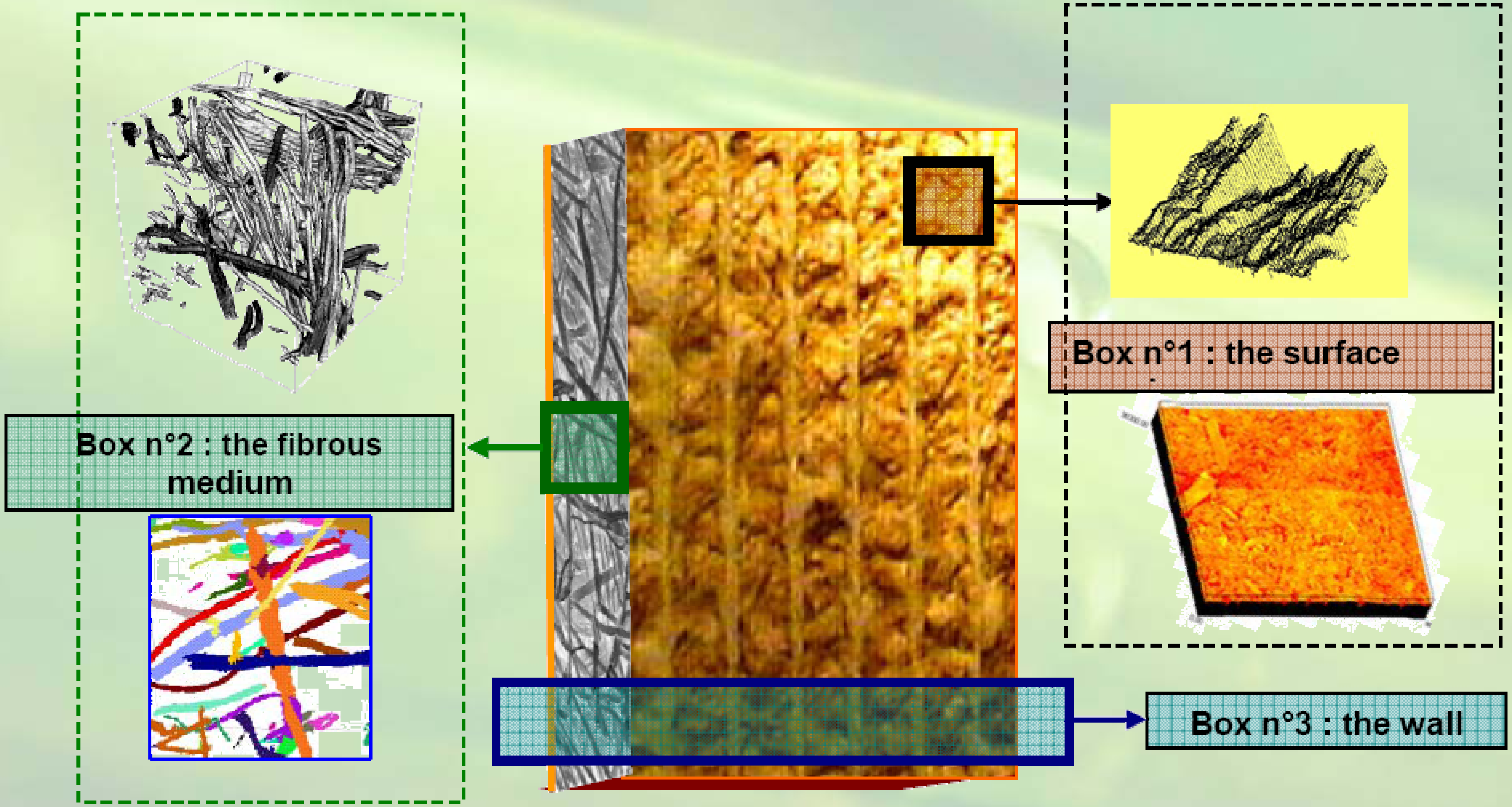
CONCLUSIONS

I-The ANR Silent Wall project

- **Acoustic-insulating system**



I-The ANR Silent Wall project

- **The Thermisorel** STEICO L'habitat sain, naturellement

  - Thermal and acoustic insulation
  - Wooden fibre board 100% natural, recycled without any chemical additive
  - Steam permeable board able to regulate the hygrometry of the house
  - Paper-like process
  - Homogeneous density profile in the thickness of the board
    - NO over-density on the faces

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II-Acoustic modelling of periodic fibrous media

Objectives

- Simulating the thermo-acoustic physical phenomena at the microstructural scale of periodic fibrous media (homogenization)

- Characterizing the effects of the radii of the fibres on their acoustic properties

- Characterizing the effects of the thickness of the samples on their acoustic absorption

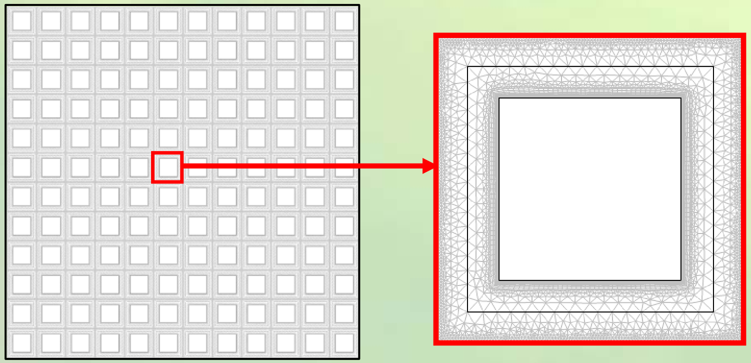
- Modelling periodic fibrous media with similar acoustic absorption than the Thermisorel

II-Acoustic modelling of periodic fibrous media

- Small Harmonic Oscillations

$$\begin{cases} \vec{U} = \vec{U}_0 + \vec{u}e^{i\omega t} \\ P = P_0 + pe^{i\omega t} \\ T = T_0 + \tau e^{i\omega t} \end{cases}$$

- Homogenization of Periodic Structures



- Thermo-acoustics Equations for Time Harmonic Fields $\vec{\mathbf{u}}$, **p**, and $\boldsymbol{\tau}$

- Linearized Compressible Flow Equations

$$\begin{cases} \rho\left[\frac{\partial \vec{U}}{\partial t} + \vec{U}\bullet\vec{\nabla}\vec{U}\right] = -\vec{\nabla}P + \left(\frac{\eta}{3}+\zeta\right)\vec{\nabla}\left(\vec{\nabla}\bullet\vec{U}\right) + \eta\Delta\vec{U} + \vec{F} \\ \frac{\partial\rho}{\partial t} + \vec{\nabla}\bullet\left(\rho\vec{U}\right) = 0 \\ \rho C_p\left(\frac{\partial T}{\partial t} + \vec{U}\bullet\vec{\nabla}T\right) = \kappa\Delta T + \frac{\partial P}{\partial t} + \vec{U}\bullet\vec{\nabla}P + \eta\Xi\left(\vec{U},\eta,\zeta\right) + Q \\ \rho(P,T)\big|_{P_0,T_0} = \rho_0\left(\frac{P}{P_0} - \frac{T}{T_0}\right) \end{cases}$$

$$\begin{cases} i\omega\rho_0\vec{u} = -\vec{\nabla}p + \left(\frac{\eta}{3}+\zeta\right)\vec{\nabla}\left(\vec{\nabla}\bullet\vec{u}\right) + \eta\Delta\vec{u} \\ i\omega\frac{\rho}{\rho_0} + \vec{\nabla}\bullet\vec{u} = 0 \\ i\omega\rho_0 C_p\tau = \kappa\Delta\tau + i\omega p \\ i\omega\left(\frac{p}{P_0} - \frac{\tau}{T_0}\right) = -\vec{\nabla}\bullet\vec{u} \end{cases}$$

II-Acoustic modelling of periodic fibrous media

Porous medium → **Equivalent fluid Rigid skeleton** → **Homogenization**

Viscous dissipation

$$\vec{u}^{(0)}(\vec{x},\vec{y}) = \frac{-\mathbf{K}(\vec{y},\omega)}{\eta} \bullet \vec{\nabla}_x p^{(0)}(\vec{x})$$

$$\boldsymbol{\rho}_{\mathbf{eff}} = \frac{\eta}{i\omega}\langle \mathbf{K} \rangle^{-1} = \boldsymbol{\alpha}(\omega)\rho_0$$

$$p^{(0)} = p e^{i(\omega t - \vec{Q} \bullet \vec{x})}$$

$$c_{eff} = \sqrt{\frac{\vec{\xi}^T \boldsymbol{\rho}_{\mathbf{eff}}^{\mathbf{-1}} \vec{\xi}}{\chi_{eff}}} = \frac{\omega}{Q}$$

Thermal dissipation

$$\tau^{(0)}(\vec{x},\vec{y}) = \frac{K'(\vec{y},\omega)}{\kappa} i\omega p^{(0)}(\vec{x})$$

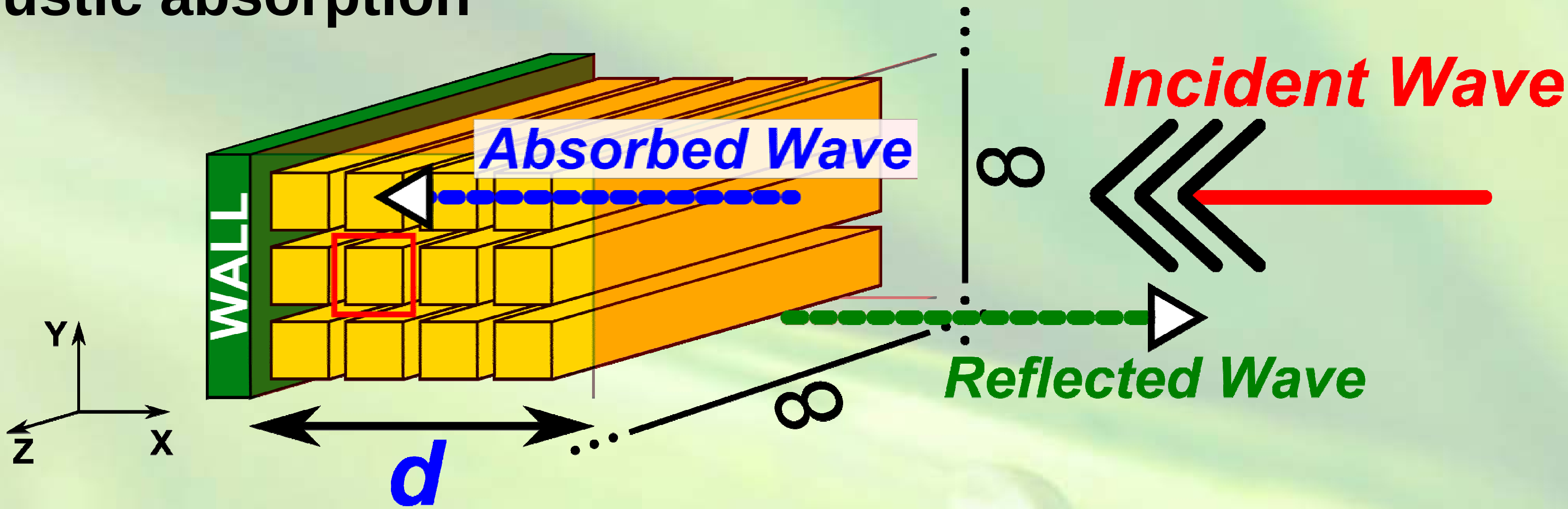
$$\chi_{eff} = \frac{1}{\gamma P_0}\left(\gamma - \left[(\gamma - 1)\frac{\rho_0 \Pr}{\eta} i\omega \langle K' \rangle\right]\right)$$

$$\Pr = \frac{\eta C p}{\kappa}$$

$$Zc_{eff} = \frac{1}{\phi}\sqrt{\frac{\vec{\xi}^T \boldsymbol{\rho}_{\mathbf{eff}} \vec{\xi}}{\chi_{eff}}}$$

II-Acoustic modelling of periodic fibrous media

Acoustic absorption



$$H = \left(\frac{1 + e^{\frac{-2i\omega d}{c_{eff}}}}{1 - e^{\frac{-2i\omega d}{c_{eff}}}} \right) = \mathrm{cotanh}(iQd)$$

$$Zc_{eff} = \frac{1}{\phi} \sqrt{\frac{\vec{\xi}^{T} \boldsymbol{\rho}_{\mathbf{eff}} \vec{\xi}}{\chi_{eff}}}$$

$$Z_0 = \rho_0 c_0$$

$$R(\omega) = \frac{p_{reflected}}{p_{incident}} = \frac{HZc_{eff} - Z_0}{HZc_{eff} + Z_0}$$

$$A(\omega) = 1 - |R(\omega)|^2$$

II-Acoustic modelling of periodic fibrous media

Modelling with the COMSOL Multiphysics™ *thermo-acoustics template*

Subdomain properties:

• **Thermo-acoustic** equations are solved into the meshed **air** (**purple** area)

Boundary conditions:

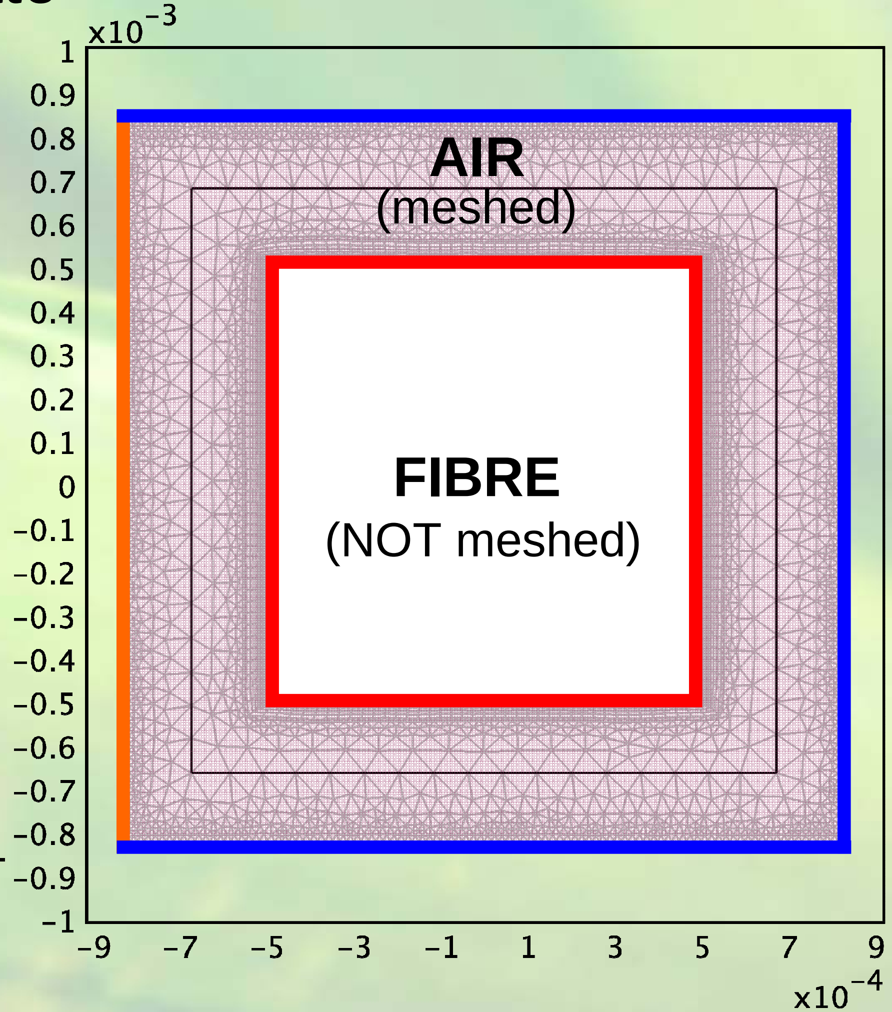
• **Transverse** oscillatory **pressure stimulation** of 1 Pa amplitude on the left boundary of the unit cell (**orange** boundary)

• **NO constraint** on the 3 other boundaries of the unit cell (**blue** boundaries)

• **Periodic** boundary conditions for $\vec{\mathbf{u}}$, **p** and $\boldsymbol{\tau}$ for the 4 boundaries of the unit cell (**orange** and **blue** boundaries)

• **Isothermal wall (rigid solid skeleton)** at the air-fibre interface Γ (**red** boundaries)

$$\begin{cases} \vec{u}_\Gamma = \vec{0} \\ \tau_\Gamma = 0 \end{cases}$$



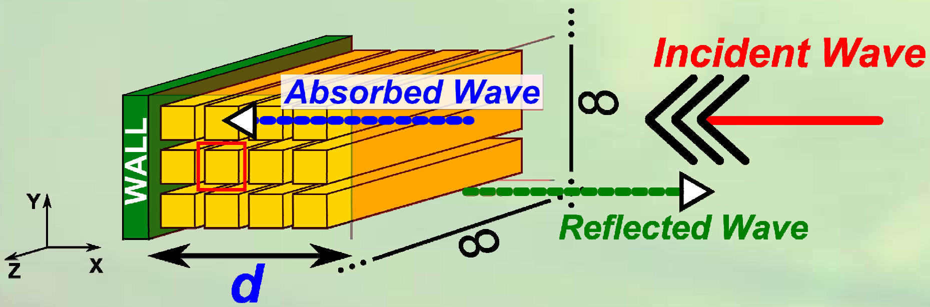
II-Acoustic modelling of periodic fibrous media

2D PASC
NO LUMEN

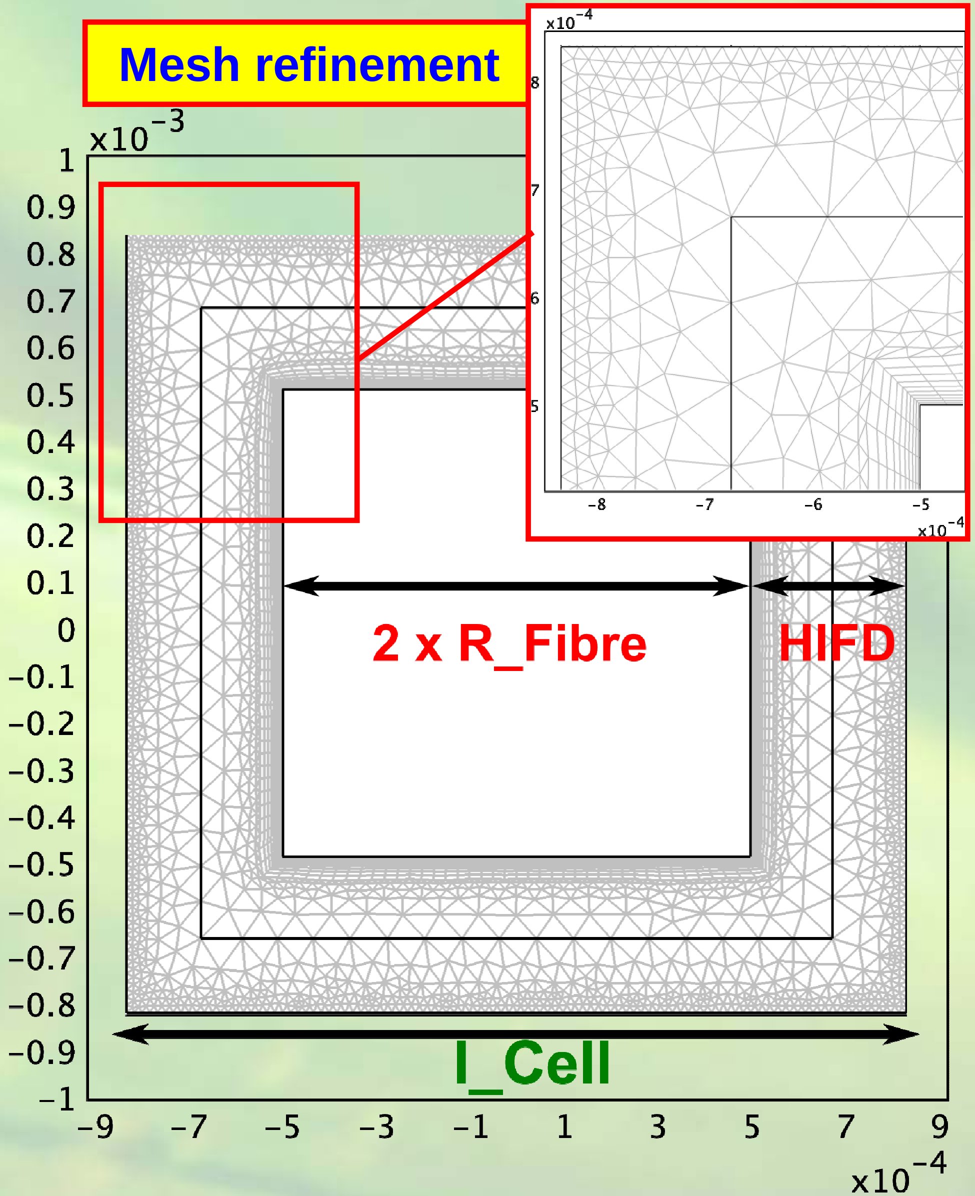
Constant Porosity: 64 %

PASC: Periodic Array of Square Cylinders according to

Venegas R., Umnova O. (2008).
On the influence of the micro-geometry on sound propagation through periodic array of cylinders.
In: Proceedings Acoustics 08 Paris



Mesh refinement

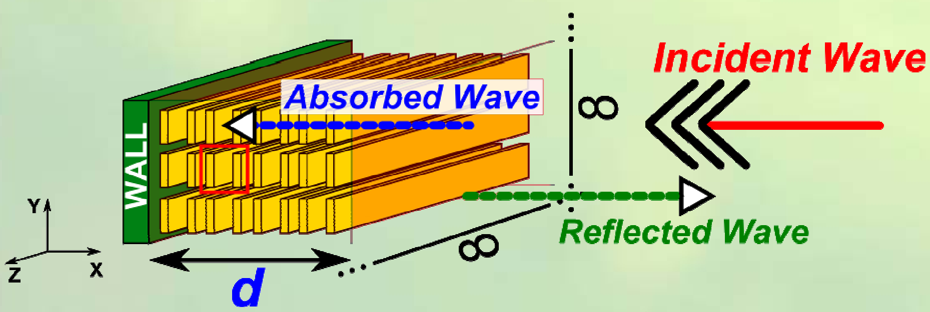


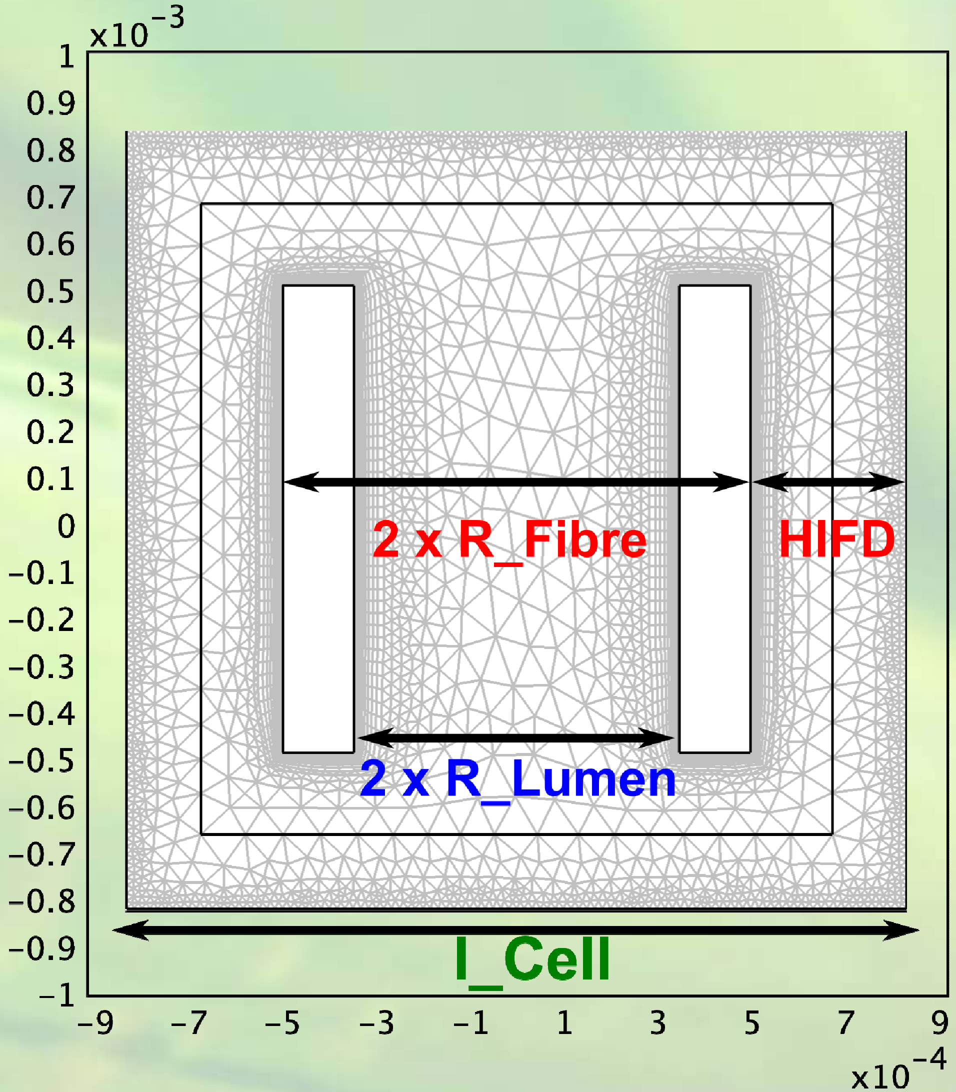
II-Acoustic modelling of periodic fibrous media

2D PASC LUMEN

Constant Porosity: 89 %

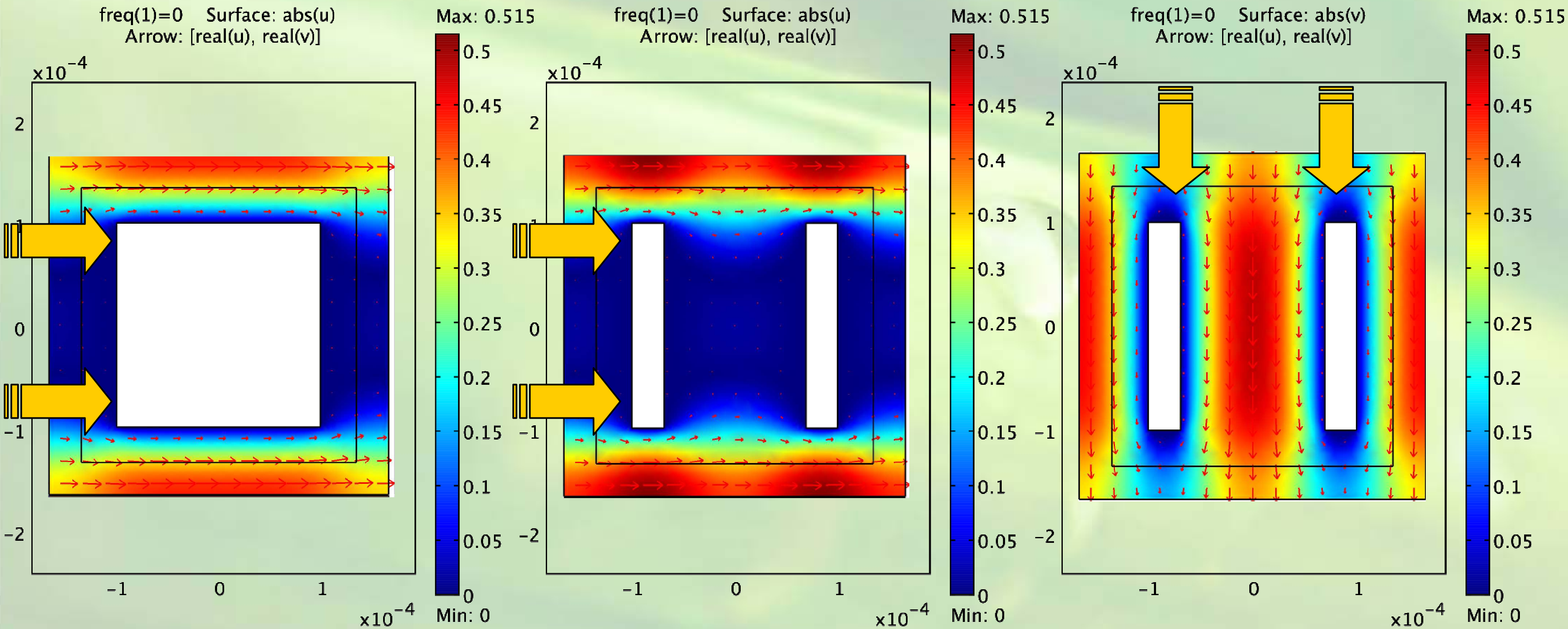
External Porosity: 64 %
Internal Porosity: 25 %





Static velocity of the air (m/s)

R_F = 100 µm
f = 0 Hz



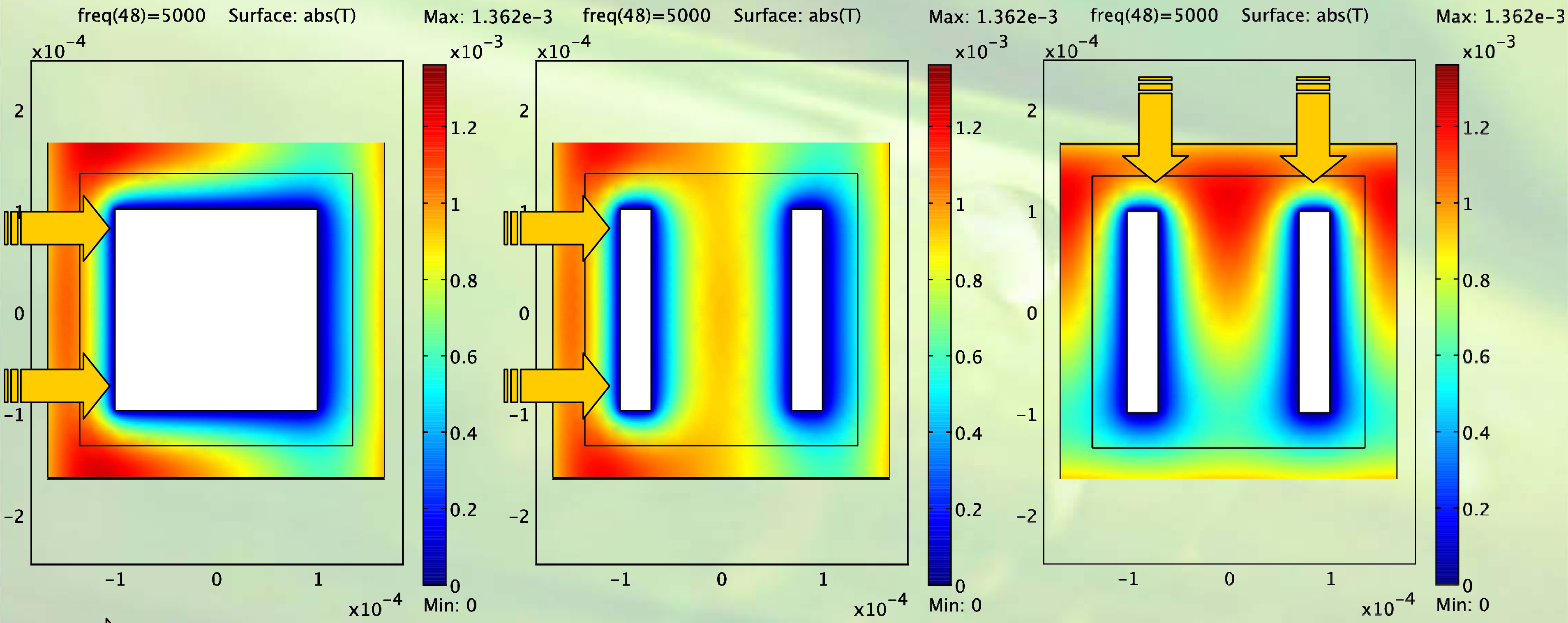
Direction of acoustic stimulation

II-Acoustic modelling of periodic fibrous media

Harmonic Acoustic Temperature (K)

$$\delta_{BL} = \sqrt{\frac{2.\eta}{\omega.\rho_0}}$$

R_F = 100 µm
f = 5000 Hz



Direction of acoustic stimulation

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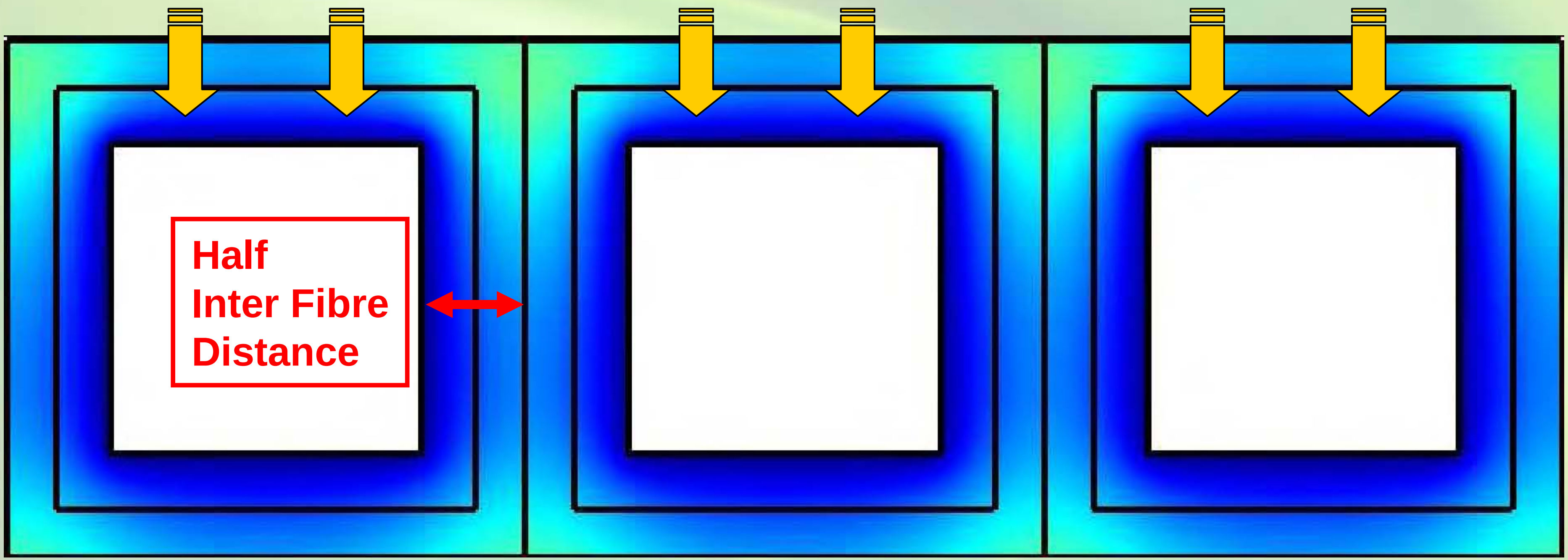
CONCLUSIONS

III-Influence of the boundary layer on absorption

Overlapping neighbor Boundary Layers
(f < MAF ; HIFD < δ_{BL})

$$\delta_{BL} = \sqrt{\frac{2.\eta}{\omega.\rho_0}}$$

(MAF = Minimum Absorbed Frequency)



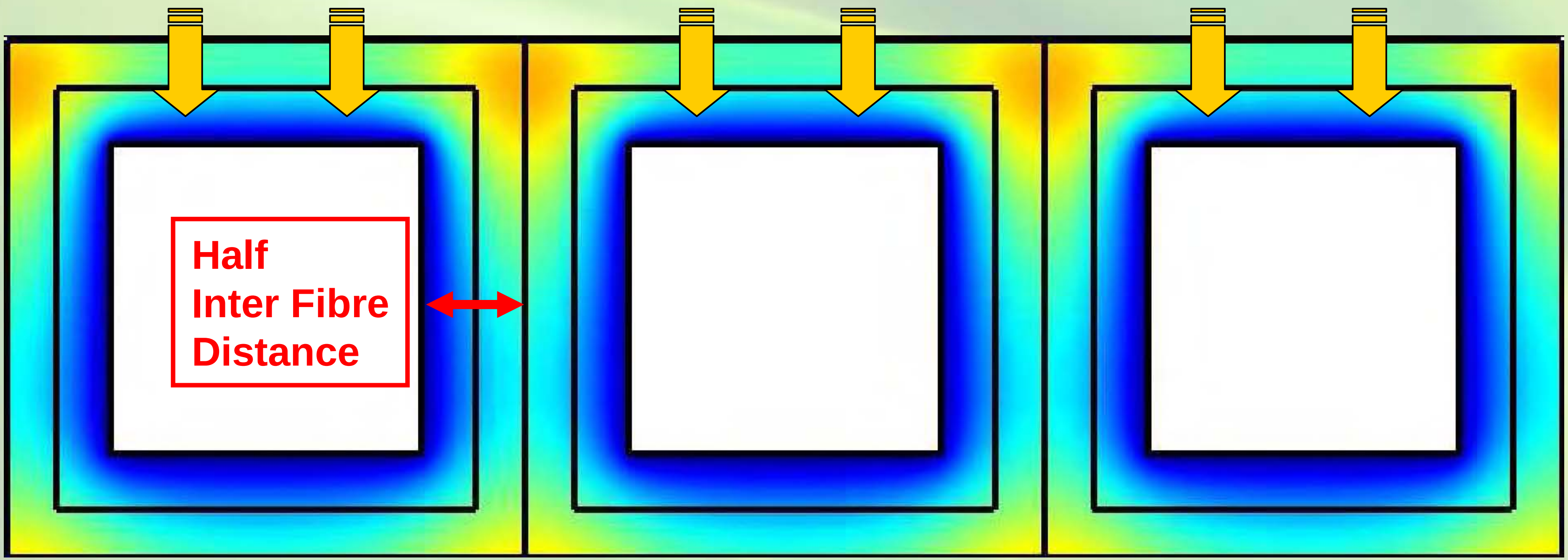
Direction of acoustic stimulation

III-Influence of the boundary layer on absorption

Tangent neighbor Boundary Layers
(f = MAF ; HIFD = δ_{BL})

(MAF = Minimum Absorbed Frequency)

$$\delta_{BL} = \sqrt{\frac{2.\eta}{\omega.\rho_0}}$$



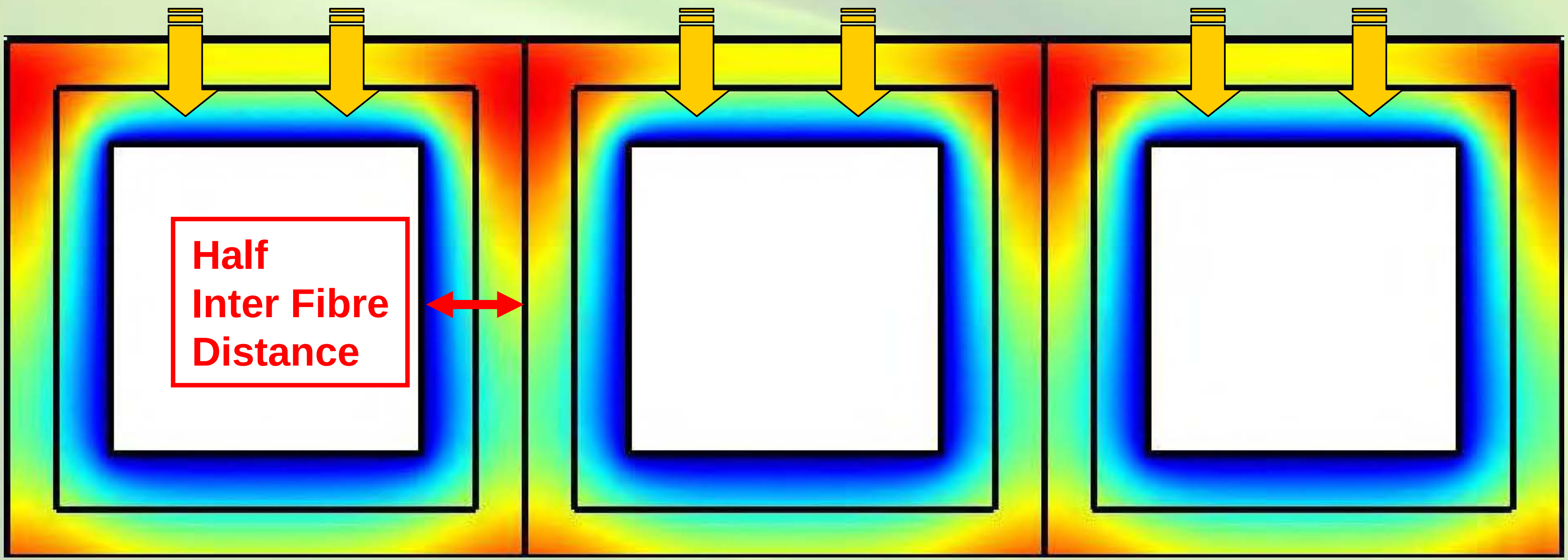
Direction of acoustic stimulation

III-Influence of the boundary layer on absorption

Separated neighbor Boundary Layers
(f > MAF ; HIFD > δ_{BL})

(MAF = Minimum Absorbed Frequency)

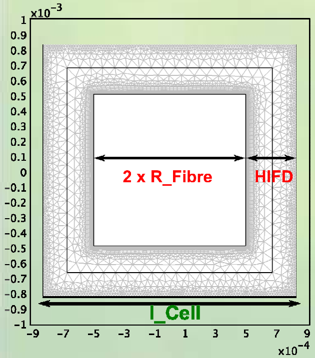
$$\delta_{BL} = \sqrt{\frac{2.\eta}{\omega.\rho_0}}$$

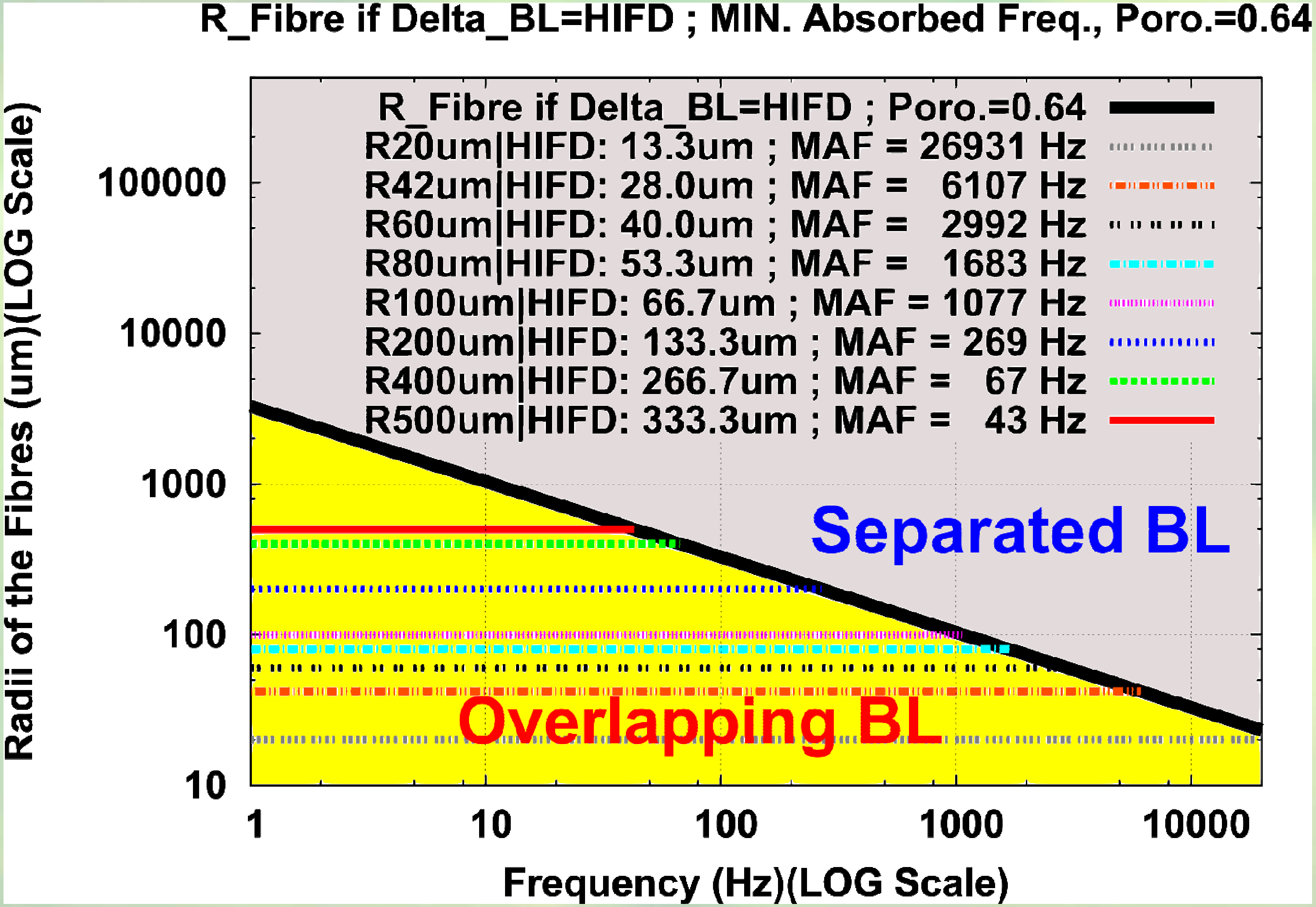


Direction of acoustic stimulation

III-Influence of the boundary layer on absorption

$$\delta_{BL} = \sqrt{\frac{2.\eta}{\omega.\rho_0}}$$





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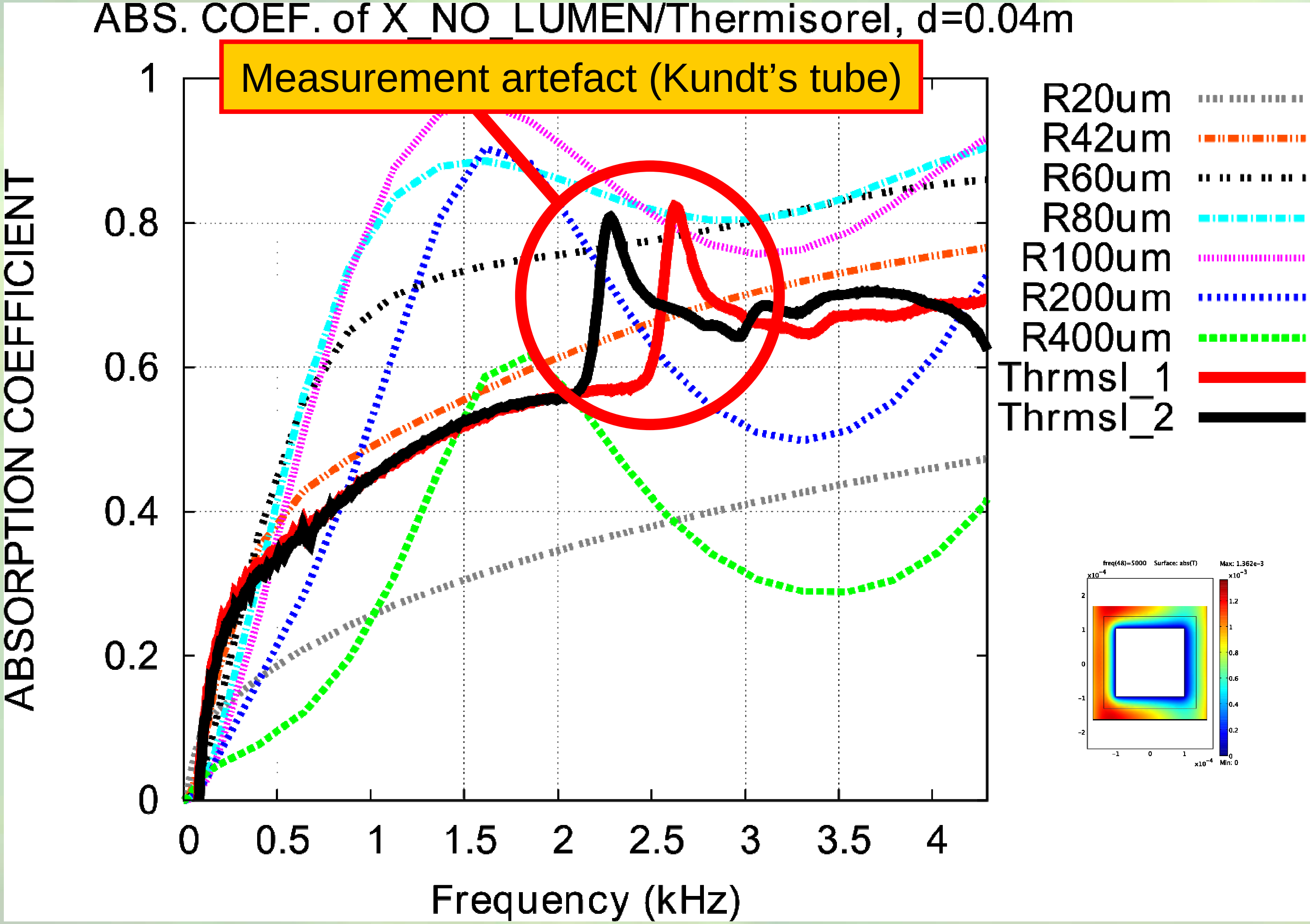
IV-Influence of the radii of the fibres on absorption

Comparison to the absorption of the Thermisorel

X_NO_LUMEN
Vs
Thermisorel
(LAUM)

Average R_{Fibres} of Thermisorel: 42 µm



IV-Influence of the radii of the fibres on absorption

Comparison to the absorption of the Thermisorel

X_LUMEN
Vs
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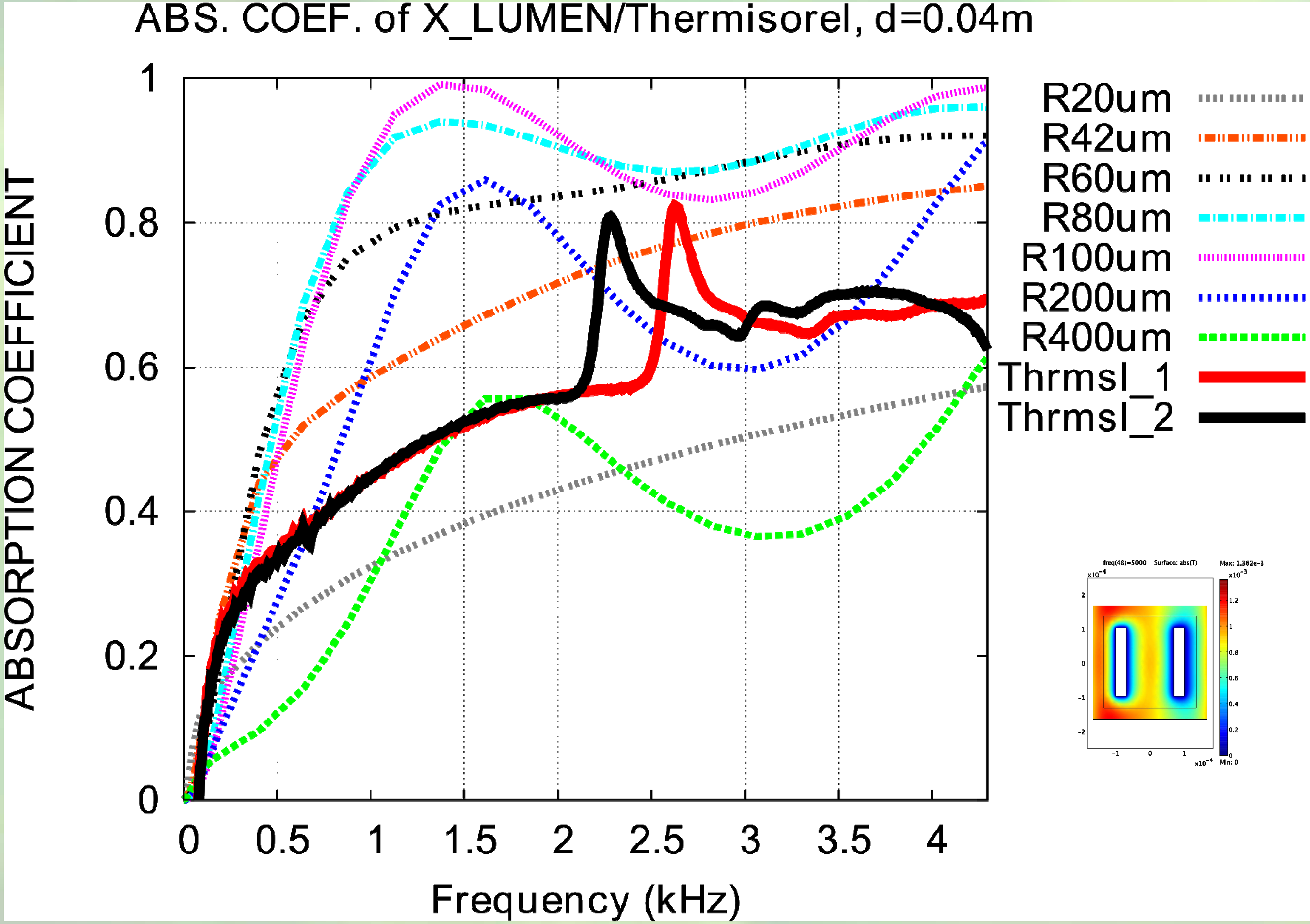
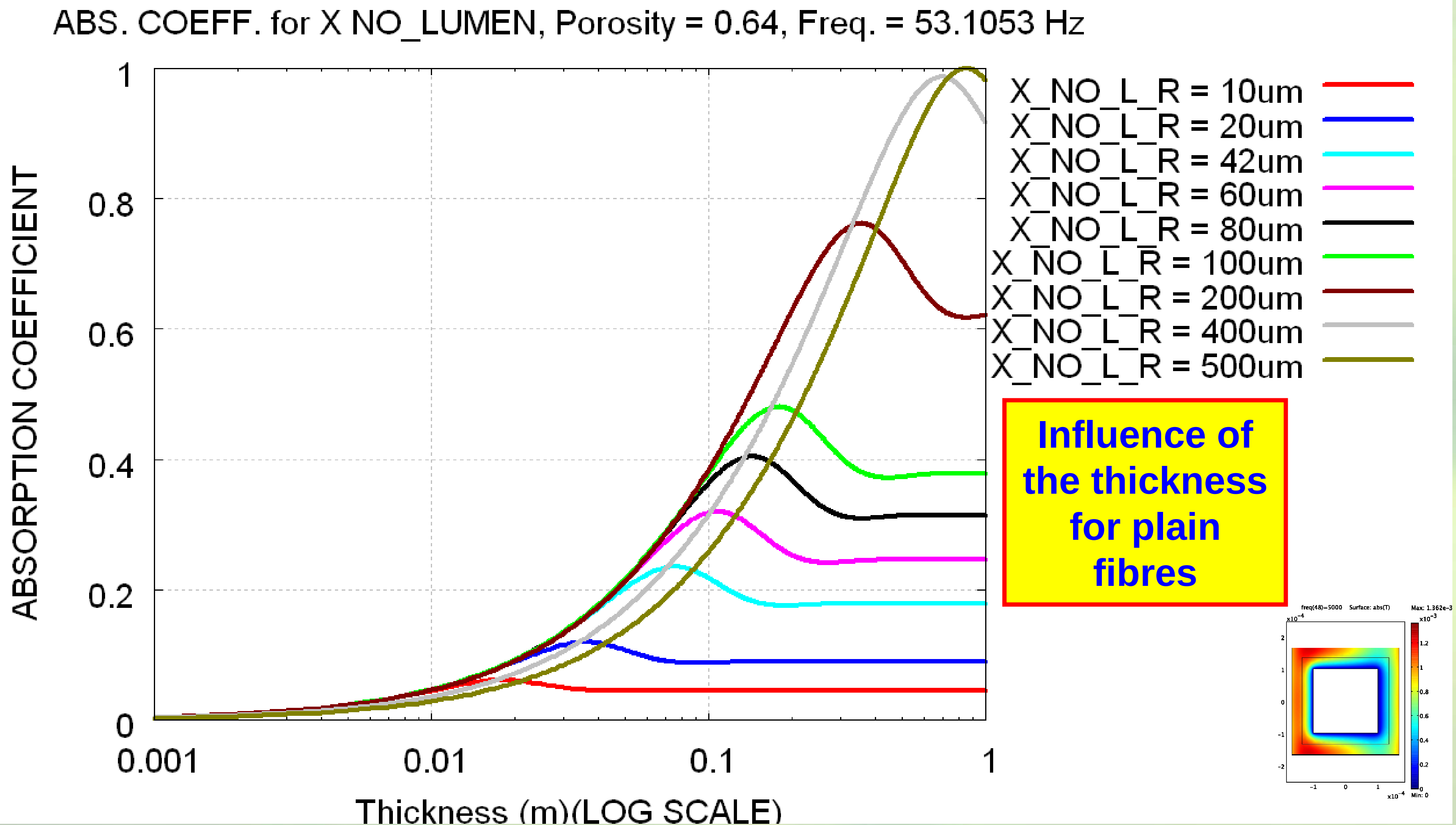
Average R_{Fibres} of Thermisorel:
42 µm



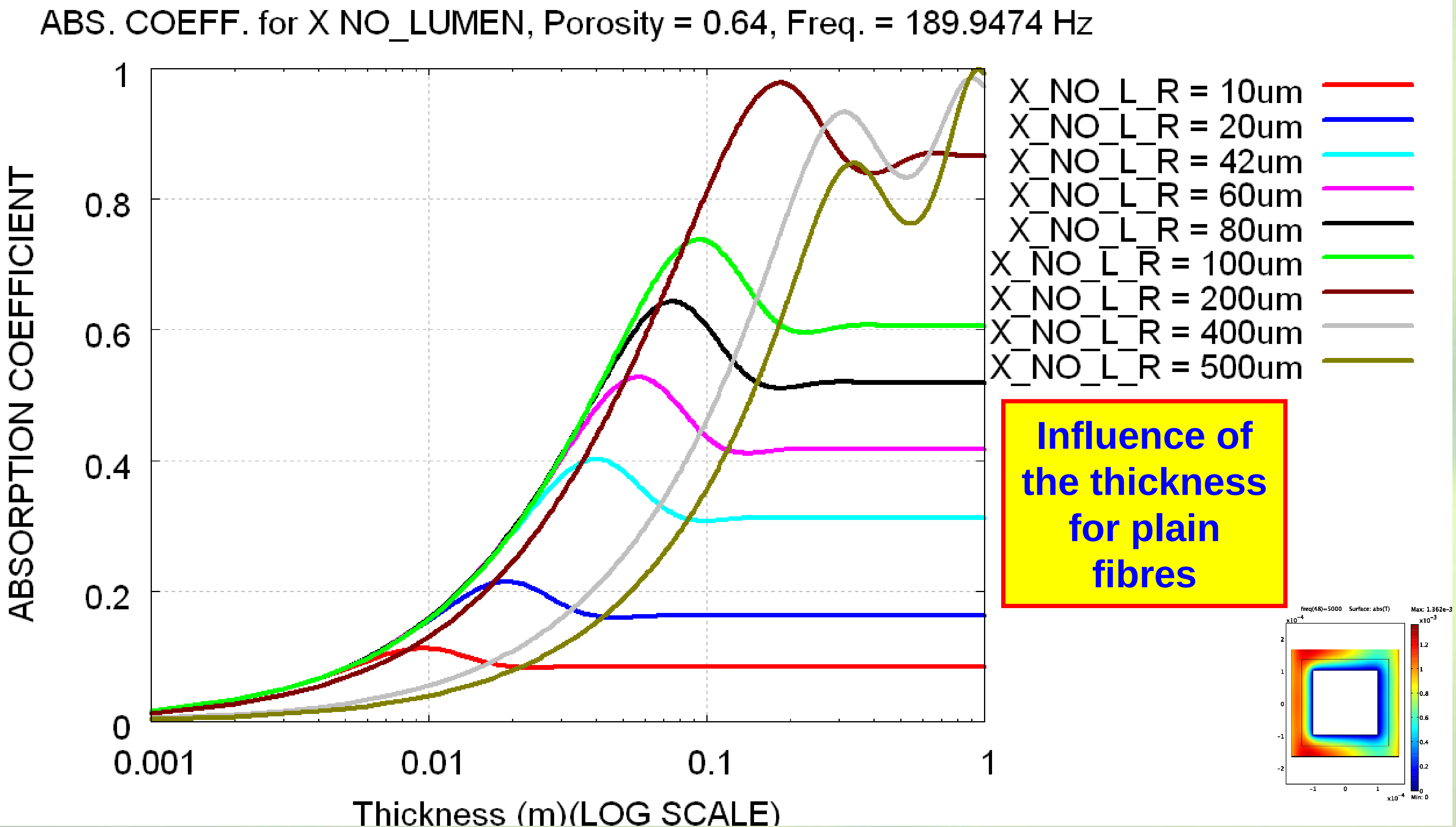
Outline

V-Influence of the thickness of the sample



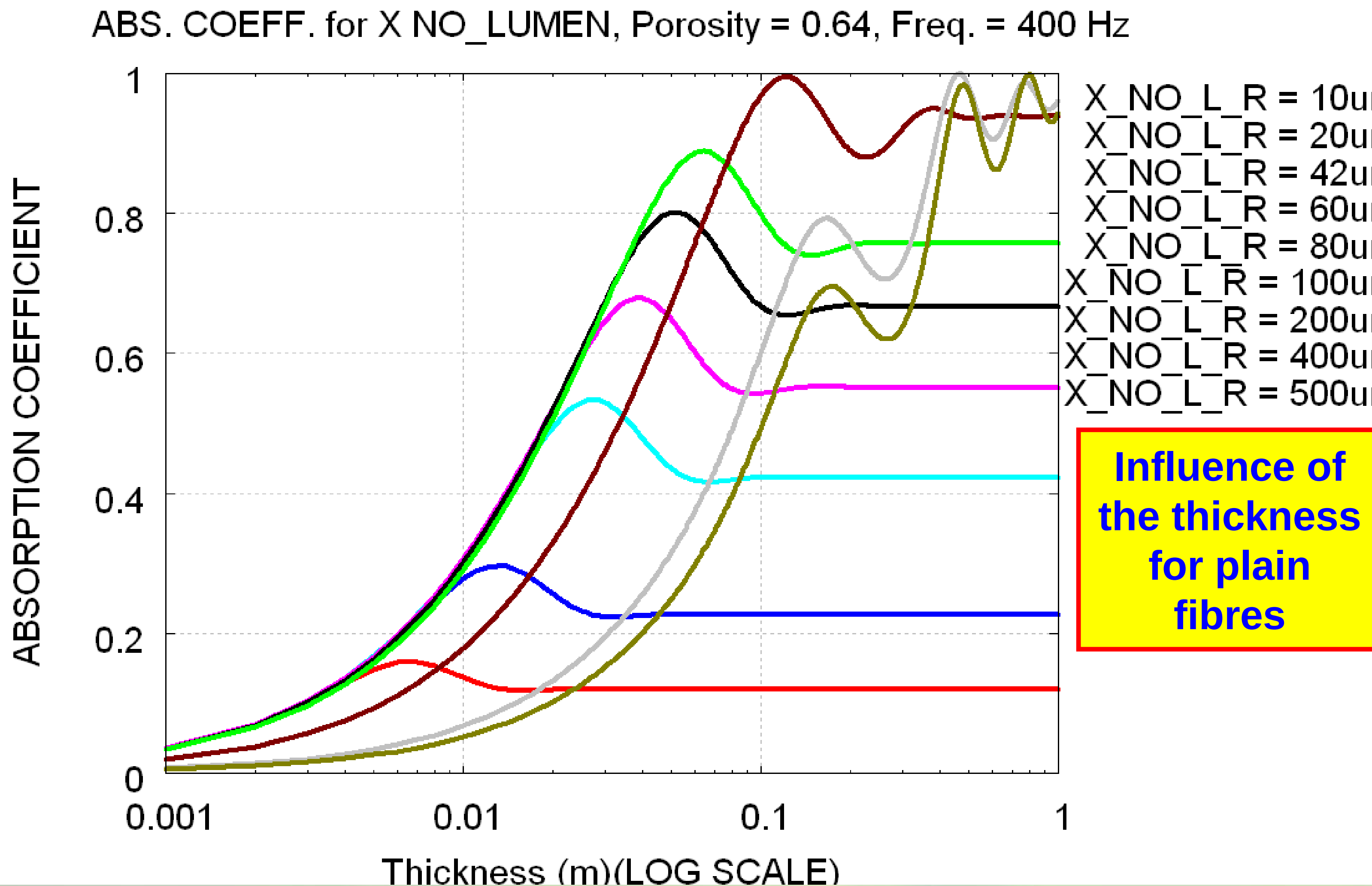
Influence of the thickness for plain fibres

V-Influence of the thickness of the sample

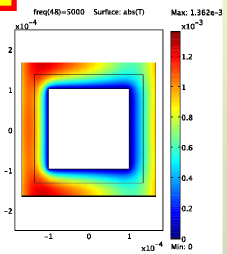


Influence of the thickness for plain fibres

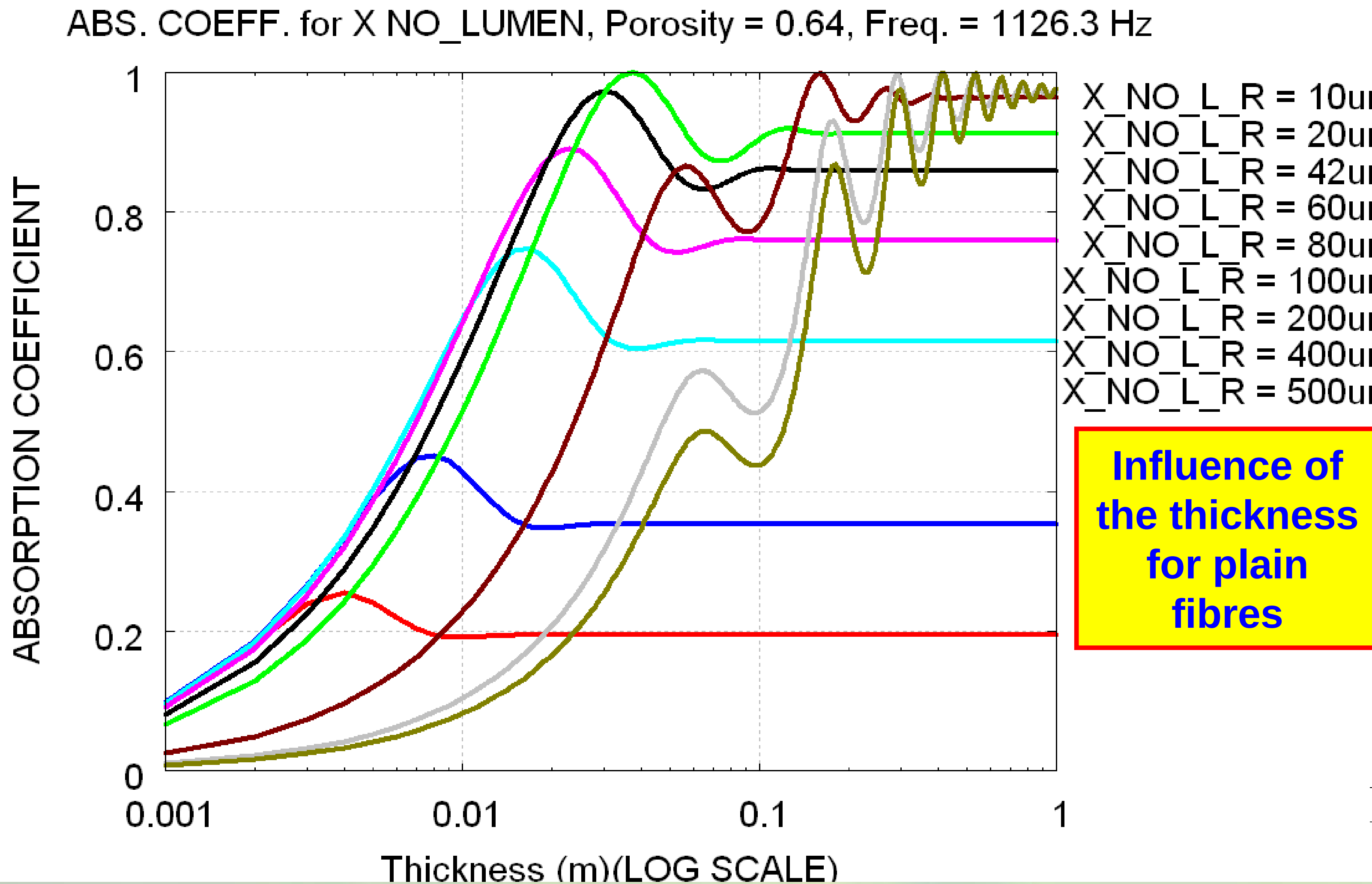
V-Influence of the thickness of the sample



Influence of the thickness for plain fibres



V-Influence of the thickness of the sample



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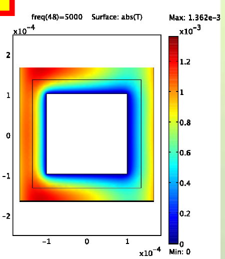

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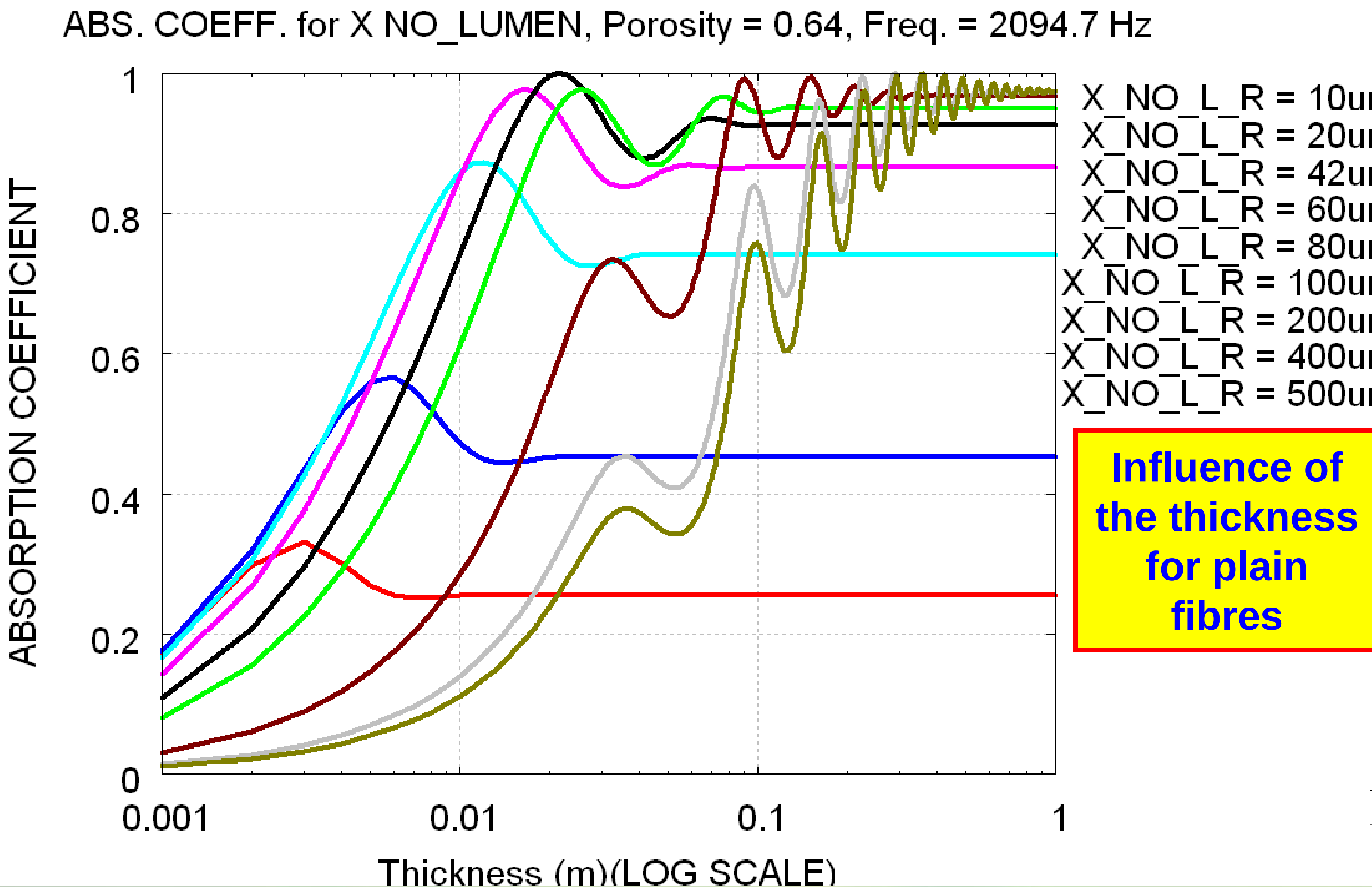

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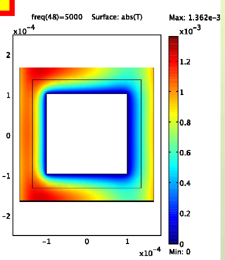

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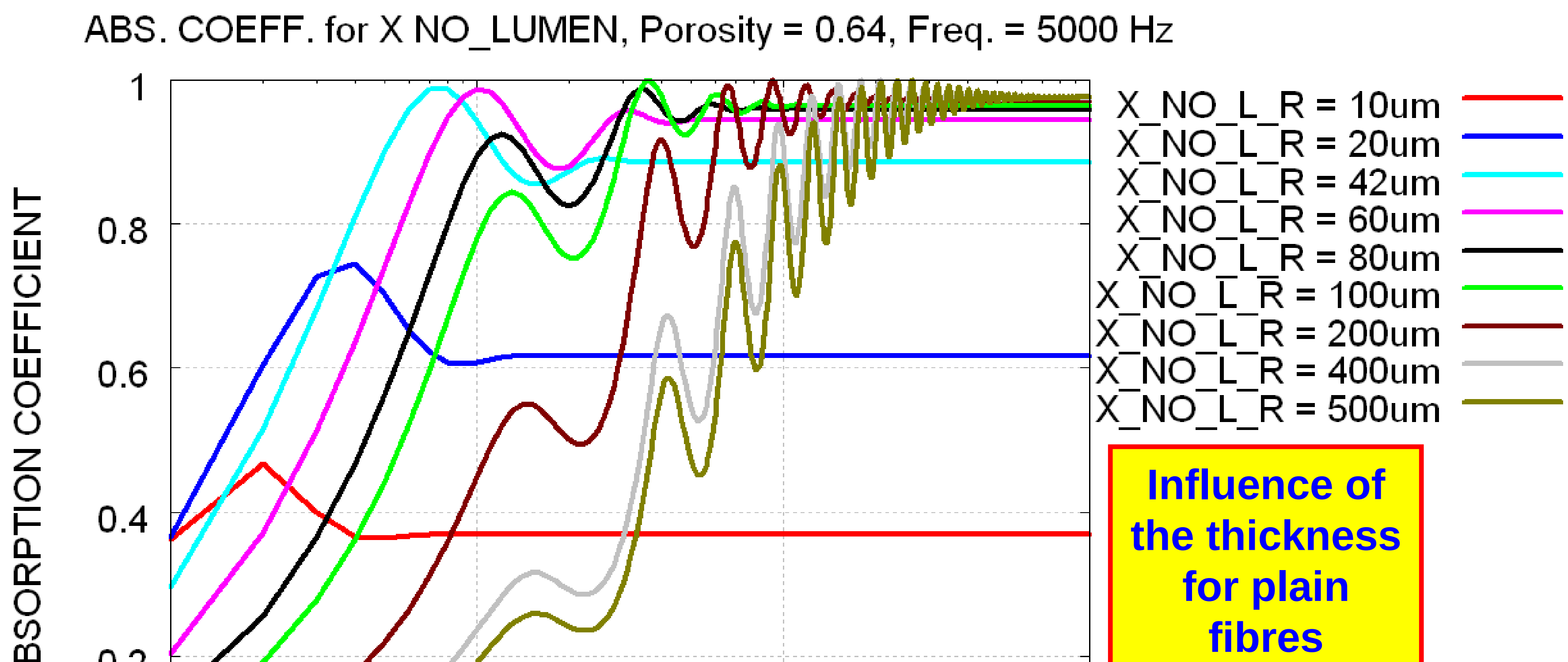
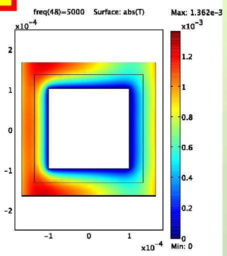


Influence of the thickness for plain fibres



CONCLUSIONS

– **Modelling the acoustic properties of periodic fibrous media:**
  - Thermo-acoustics
  - Numerical results limited to parallel fibres

– **Effects of the radii of the fibres on their acoustic properties:**
  - Overlap of BL strongly influences small fibres

– **Effects of the thickness of the samples on their acoustic properties:**
  - Existence of a critical thickness

– **Comparision to the Thermisorel:**
  - Good agreement for **R_F = 42 µm** between the simulated thermo-acoustic properties of PASC NO LUMEN **plain fibres** and the LAUM measurements on Thermisorel on the full range of frequency, WITHOUT any adjustable parameter

– ***Acknowledgements to Stephan Savarese (COMSOL France) and Nils MALM (COMSOL Sweden) for having provided us the "thermo-acoustics" COMSOL template***

Thank you for your attention