Monte Carlo Ray Tracing methods for the determination of the radiative properties of materials

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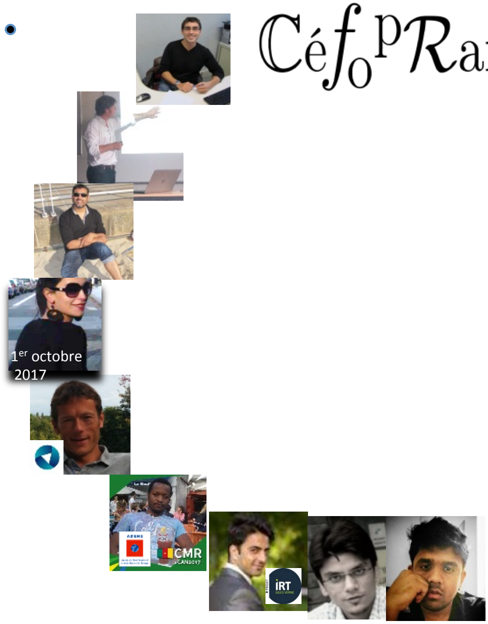
DU : Cathy Castelain

8 (+1) C CNRS, 17 EC UN, 4 EC ICAM, 5 IT CNRS- 4 BIATSS UN, 2 IE Cellule CAPACITES LTeN
23 doctorants – 2 ATER/post-doctorants

Transferts thermiques dans les matériaux et aux interfaces (S. Le Corre)

- Transferts aux interfaces et dans les micro-systèmes
- Transferts thermiques dans la mise en forme des polymères et composites
-

CéfoPRam



Metti ACCORT FédEsol

Transferts dans les fluides et systèmes énergétiques (L. Luo)

- Transferts chaleur & masse dans les écoulements complexes
- Transferts chaleur & masse dans les fluides complexes
- Conception et optimisation des systèmes et procédés énergétiques

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Professeurs invités

Fév. 2018

Mai 2018

Contrôle multi-échelle du transport de l'énergie

Caractérisation de la dépendance thermo-spectro-directionnelle des propriétés radiatives :
spectroscopie IR/Vis
(réflexion, transmission, émission→ 900 K)

D. Hakoume, AO, 2014, J. Mollicone, TSF, 2015
V. Le Louet, IJHMT, 2017

Modélisation multi-échelle
des propriétés radiatives :
DFT, DM classique, Lorentz-Drude,
Monte Carlo, Imagerie 3D
nm → m

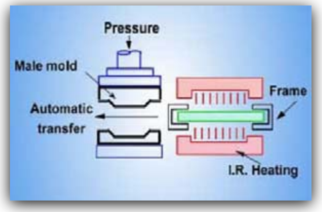
B. Rousseau, AIP, 2016, B. Rousseau, AS, 2016
S. Guévelou, IJHMT, 2016, S. Guévelou, JQSRT, 2017

Résolution numérique 3D de
l'Equation du Transfert Radiatif :
estimation de propriétés (TO),
optimisation énergétique

D. Le Hardy, JQSRT, 2016, D. Le Hardy, JCP, 2017
D. Le Hardy, JQSRT, 2017

Some thermal radiative issues…



How to determine the temperature fields in a part or a component exposed to thermal radiation?

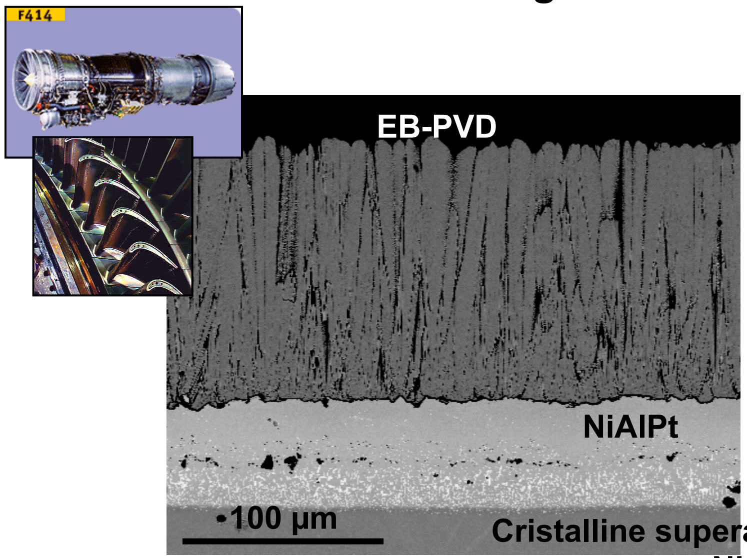
Need to achieve an energy balance between the energy provided by (the) source (s) heating (s) and the illuminated system

Resolving most often the Radiative Transfer Equation **(RTE)** in (fluids and solids) semi-transparent media

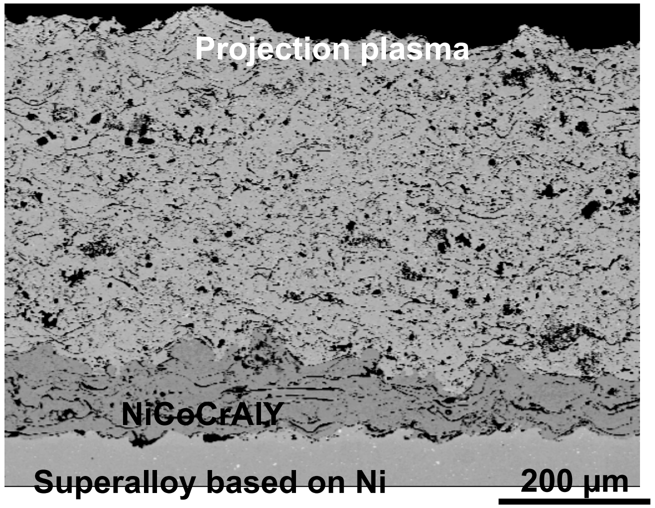
Material characteristics

Commercial glasses

Sapphire



ZrO_2 +
8% (weight) Y_2O_3



Turbine blade

Combustion chamber

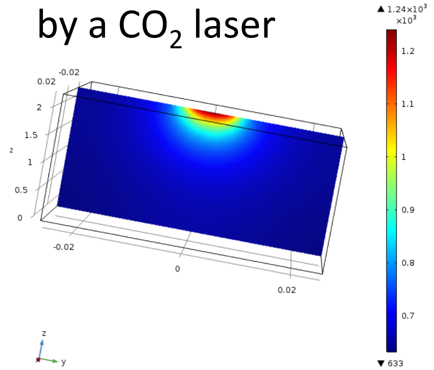
How can we solve a thermal issue ?

$$\rho c_p \frac{\partial T}{\partial t}(s) = \nabla.\left(k_{cond}\nabla T(s) - \dot{q}''(s)\right)$$

conductive flux

radiative flux

SiC foam heated by a CO_2 laser



Tseng et al., High Temp.-High Pres., 2013, 42, pp. 387-403

$$\nabla.\dot{q}''(s) = \int_0^\infty \kappa_{a\nu} 4\pi I_{b\nu}(T) d\nu - \int_0^\infty \int_{4\pi} \kappa_{a\nu} I_\nu(s,\hat{\Omega}) d\Omega d\nu$$

$$\frac{dI_\nu(s,\hat{\Omega})}{ds} = -(\kappa_{a\nu} + \kappa_{d\nu}) I_\nu(s,\hat{\Omega}) + \kappa_{a\nu} I_{b\nu}(T) + \frac{1}{4\pi}\int_{\Omega'=4\pi} \kappa_{d\nu} P_\nu(\hat{\Omega}' \to \hat{\Omega}) I_\nu(s,\hat{\Omega}') d\Omega'$$

Boundary conditions for RTE solving

$$I_\nu(s_p,\Omega) = e_\nu I_{b\nu}(T(s_p)) + \int_{\Omega'.n<0} \rho''_\nu(s_p,\Omega',\Omega)\, I_\nu(s_p,\Omega')\, |\Omega'.n|\, d\Omega'$$

$$e_\nu \equiv e_\nu(\Omega, T(s_p)) = I_\nu(\Omega, T(s_p)) / I_{b\nu}(T(s_p))$$

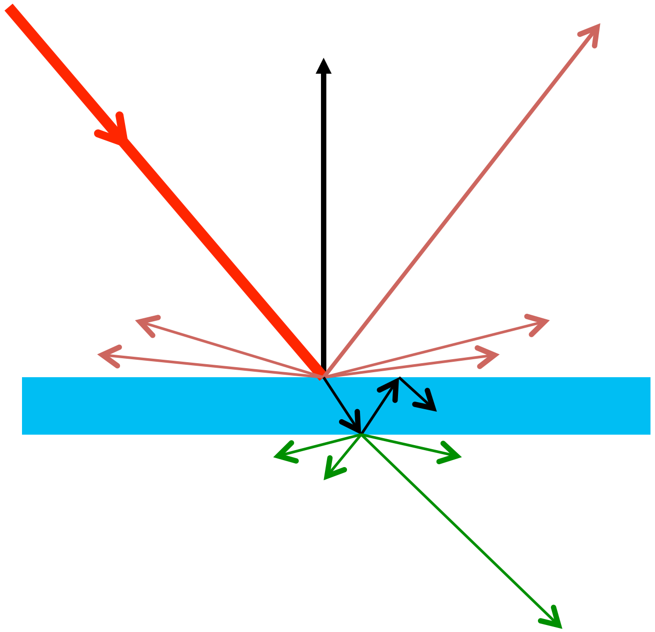
$$\rho''_\nu(s_p,\Omega',\Omega) = I^R_\nu(s_p,\Omega) / I_\nu(s_p,\Omega)\, \Omega'.n\ d\Omega'$$

→ $\rho^S_\nu(s_p,\Omega)$

→ $\rho^D_\nu(s_p,\Omega')$

$$\rho^D_\nu(s_p,\Omega') = \int_{2\pi} \rho''_\nu(s_p,\Omega',\Omega)\, \Omega.n\, d\Omega .$$

Kirchhoff law and thermal balance on 1D slab

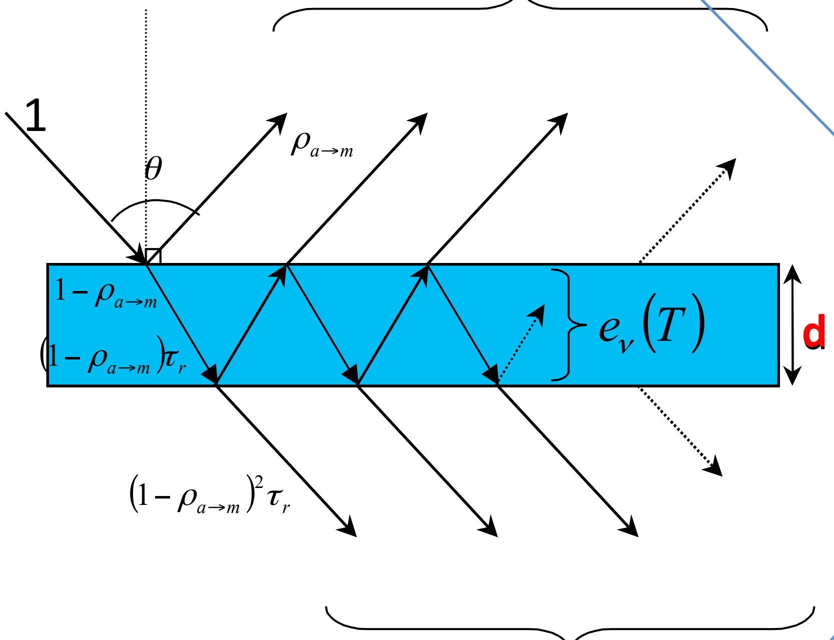


Heterogeneous material $e_{\nu}(\Omega, T(s_p)) = 1 - \rho_{\nu}^{D}(\Omega, T(s_p)) - t_{\nu}^{D}(\Omega, T(s_p))$

Homogeneous material $e_{\nu}(\Omega, T(s_p)) = 1 - \rho_{\nu}^{S}(\Omega, T(s_p)) - t_{\nu}^{S}(\Omega, T(s_p))$

Homogeneous 1D slab, optically polished with parallel faces

$$\rho^S_{N\nu}(T) = \rho_{a\to m,\nu}(T) + \rho_{a\to m,\nu}(T)\left(1-\rho_{a\to m,\nu}(T)\right)^2 \tau^2_{r,\nu}(T)\left[1 + \rho^2_{a\to m,\nu}(T)\tau^2_{r,\nu}(T) + \left(\rho^2_{a\to m,\nu}(T)\tau^2_{r,\nu}(T)\right)^2 + \ldots\right]$$



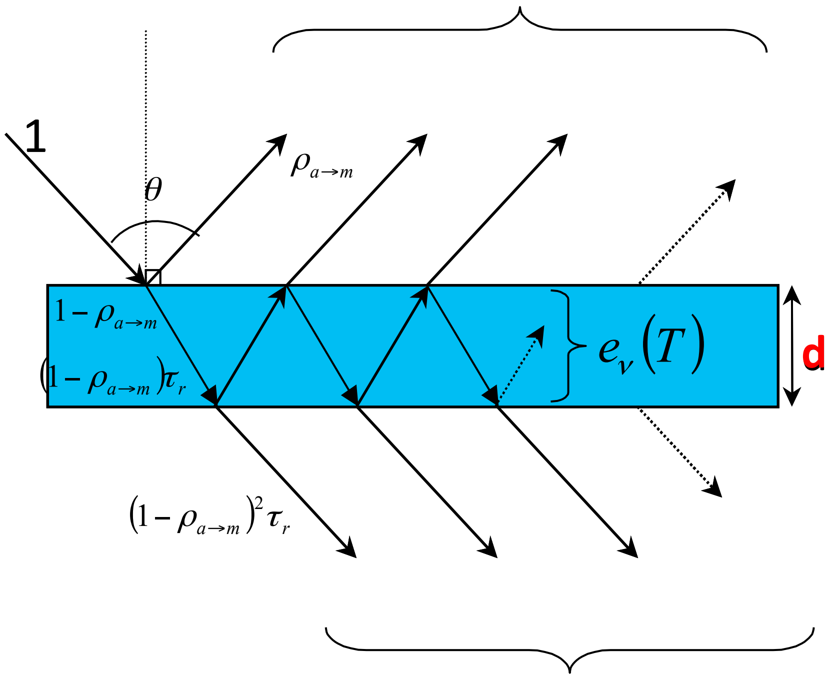
$$\rho_{a\to m,\nu}(T) = \frac{\left(n_\nu(T)-1\right)^2 + k_\nu(T)^2}{\left(n_\nu(T)+1\right)^2 + k_\nu(T)^2}$$

$$\tau_r(T) = e^{-K_\nu(T)d}$$

$$t^S_{N\nu}(T) = \left(1-\rho_{a\to m,\nu}(T)\right)^2 \tau^2_{r,\nu}(T)\left[1 + \rho^2_{a\to m,\nu}(T)\tau^2_{r,\nu}(T) + \left(\rho^2_{a\to m,\nu}(T)\tau^2_{r,\nu}(T)\right)^2 + \ldots\right]$$

Kirchhoff law and thermal balance on 1D slab

$$\rho^S_{N,\nu}(T) = \rho_{a\to m,\nu}(T)\left[1 + t^S_{N\nu}(T)\tau_{r,\nu}(T)\right]$$



Optical thickness $K_\nu(T)d$

$K_\nu(T)d > 1$ Optically thick media ***opacity***

$K_\nu(T)d < 1$ Optically thin media ***transparency***

$$t^S_{N,\nu}(T) = \frac{\left[1-\rho_{a\to m,\nu}(T)\right]^2}{1-\left(\rho_{a\to m,\nu}(T)\right)^2\left(\tau_{r,\nu}(T)\right)^2}\tau_{r,\nu}(T)$$

Homogeneous 1D slab, optically polished with parallel faces

$$e_{N,\nu}(T) = \frac{\left[1-\rho_{a\to m,\nu}(T)\right]\left[1-\tau_{r,\nu}(T)\right]}{1-\rho_{a\to m,\nu}(T)\tau_{r,\nu}(T)}$$

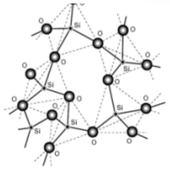
$$\rho_{a\to m,\nu}(T) = \frac{\left(n_\nu(T)-1\right)^2 + k_\nu(T)^2}{\left(n_\nu(T)+1\right)^2 + k_\nu(T)^2}$$

$$\tau_{r,\nu}(T) = e^{-K_\nu(T)d} = e^{-2k_\nu(T)\nu d/c}$$

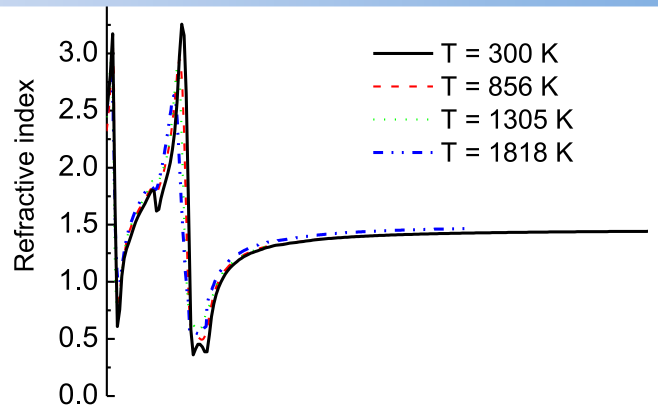
$$\tilde{n}_\nu(T) = n_\nu(T) + ik_\nu(T)$$

$$\sqrt{\tilde{\varepsilon}_\nu(T)} = \tilde{n}_\nu(T)$$

Homogeneous 1D slab, optically polished with parallel faces



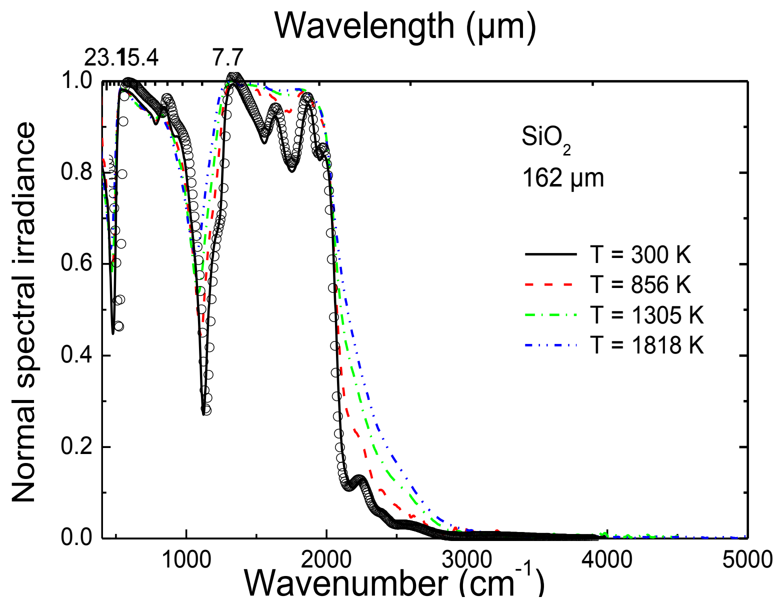
$$\begin{cases} \tilde{n} = \sqrt{\tilde{\varepsilon}} \\ \tilde{n}(\nu,T) = n(\nu,T) + ik(\nu,T) \\ K(\nu,T) = 4\pi\nu\, k(\nu,T) \end{cases}$$

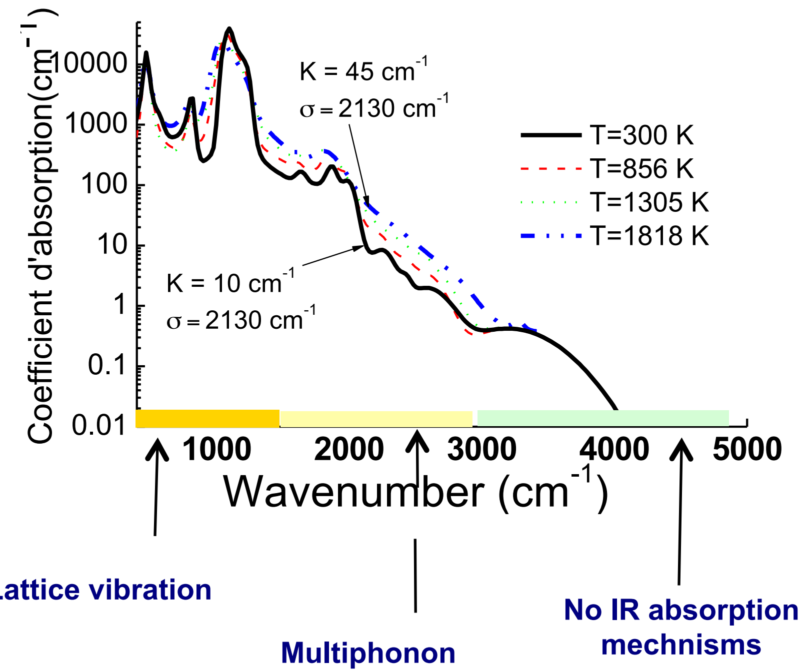


$$\tilde{\varepsilon}(\nu,T) = \varepsilon_\infty + \sum_j C_{V_j}\left(\nu;\nu_{0j},\gamma_{Gj},\gamma_{Lj}\right)$$

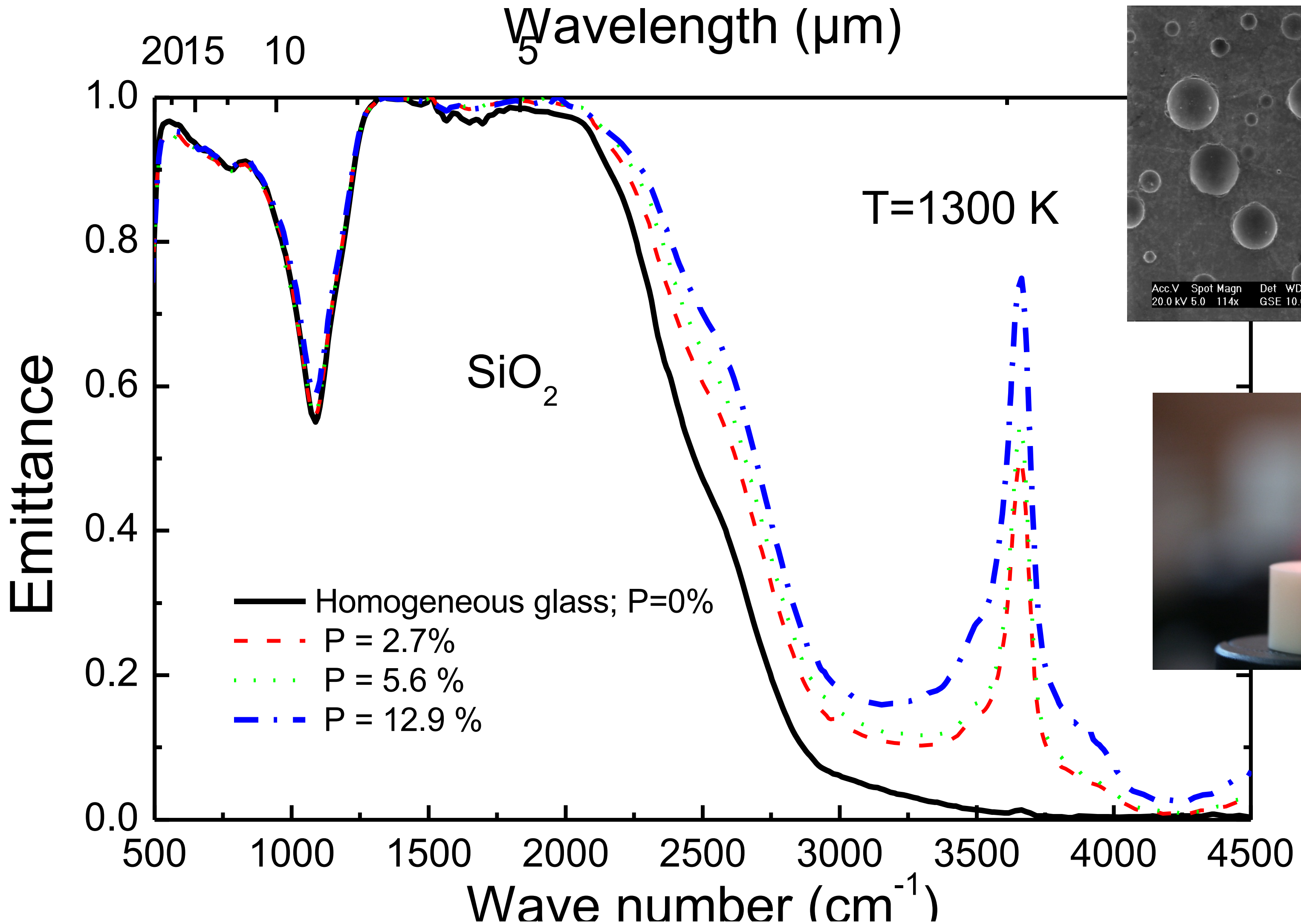
De Sousa Meneses et *al.*, *JNCS*, 351, (2005)

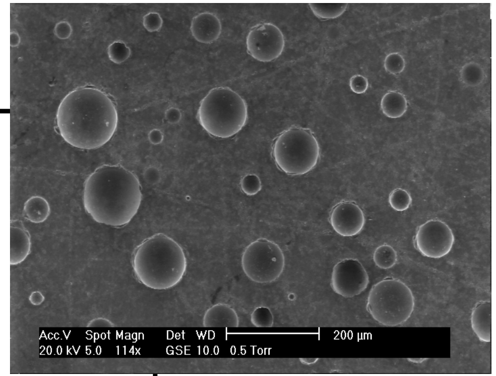
$$e(\nu,T) = \frac{\left(1-\rho_{a\to m}(\nu,T)\right)\left(1-e^{-K(\nu,T)d}\right)}{1-\rho_{a\to m}(\nu,T)e^{-K(\nu,T)d}}$$

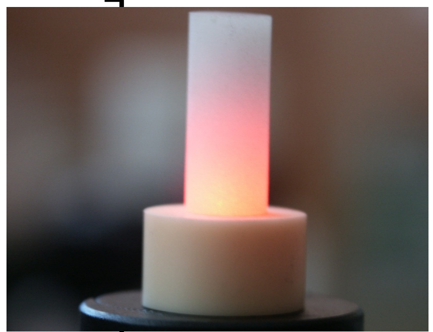




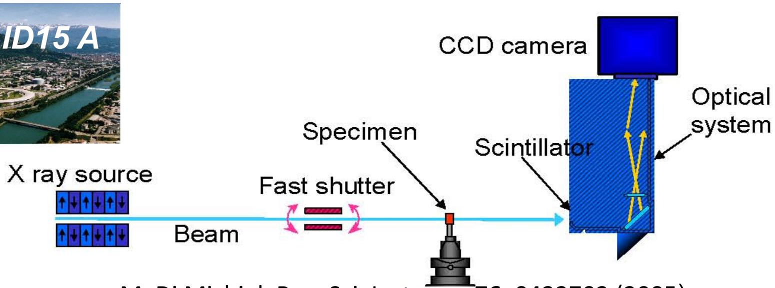
Homogeneous 1D slab, optically polished with parallel faces







A model case : silica glass with closed porosity

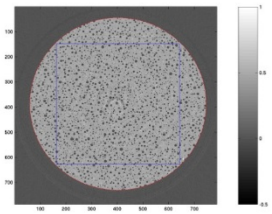


M. Di Michiel, Rev. Sci. Instrum. **76,** 0432702 (2005)

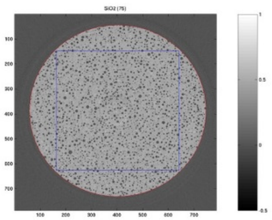
$$I/I_0 = \exp[-(\mu/\rho)x]$$

$$\mu/\rho \approx (\sigma_{pe} + \sigma_{coh} + \sigma_{incoh} + \sigma_{pair} + \sigma_{trip} + \sigma_{ph.n})/uZ$$

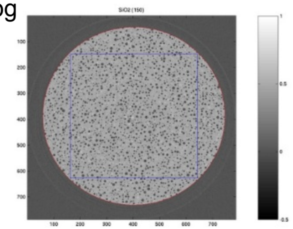
SiO2_plane_01.jpg

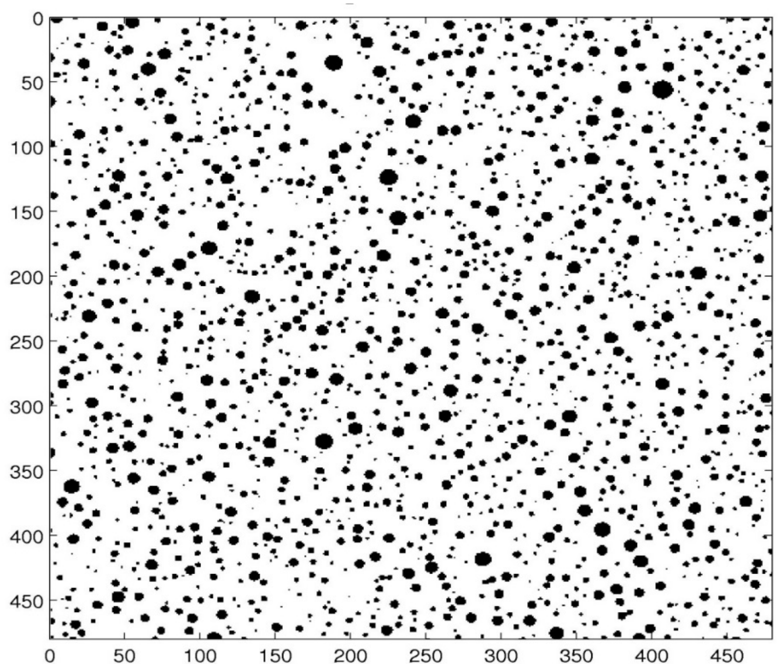


SiO2_plane_075.jpg

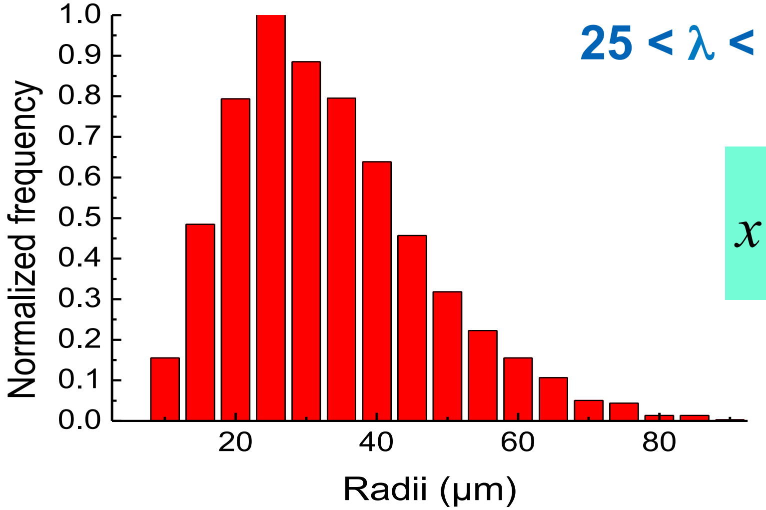


SiO2_plane_150.jpg





Geometrical Optics Approximation

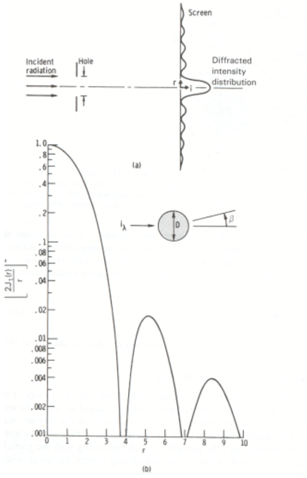


25 < λ < 2 µm (400 < σ < 5000 cm^{-1})

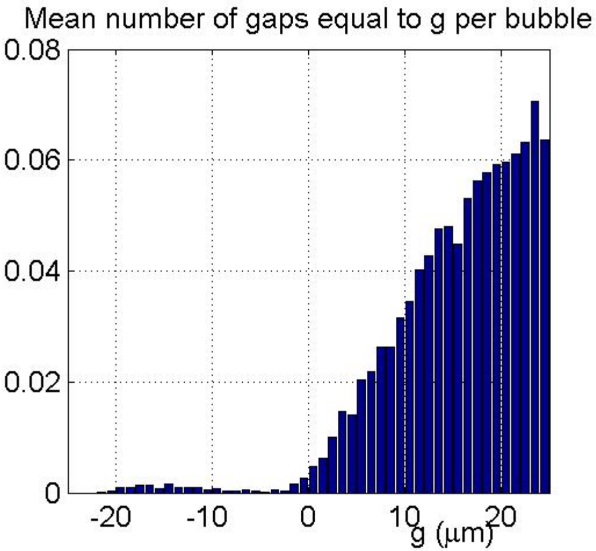
$$x = \frac{2\pi\langle r\rangle}{\lambda} > 1$$

❖Geometrical optics

❖No diffraction



Siegel & Howell, 1992



$$g/\lambda > 1/2$$

❖No interferences

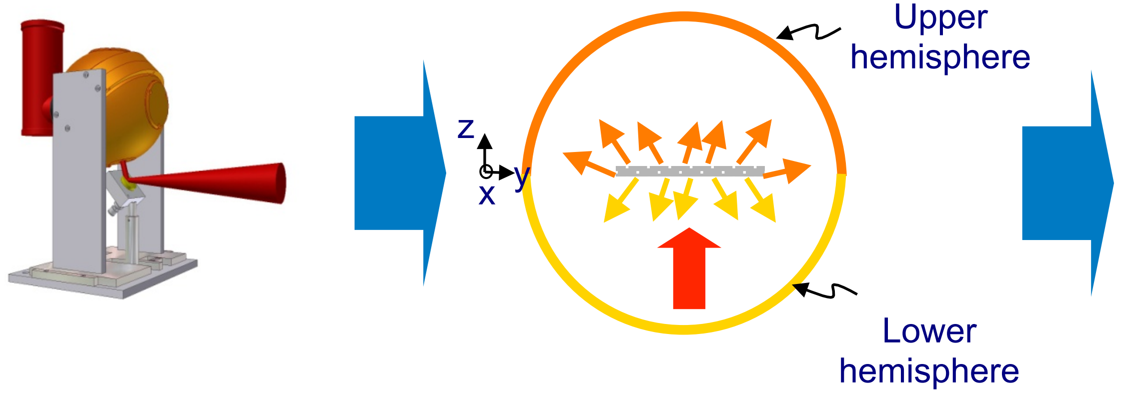
$$\langle r\rangle \approx g$$

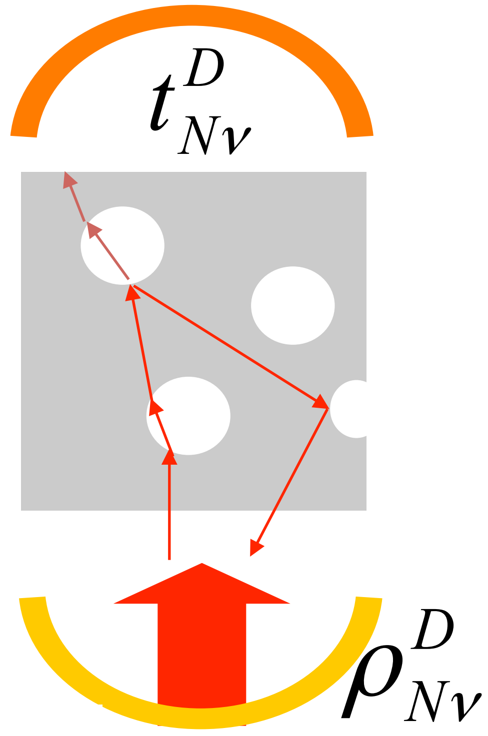
❖Multiple scattering

❖Multiple reflection

Radiative properties computation : MCRT

$$e_{N\nu}(\Omega, T(s_p)) = 1 - \rho_{N\nu}^{D}(\Omega, T(s_p)) - t_{N\nu}^{D}(\Omega, T(s_p))$$



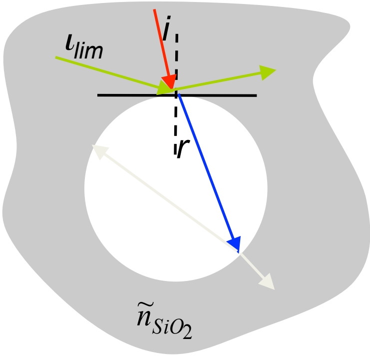


Monte Carlo Ray Tracing code C++

- Computing time: 10^5 rayons→ ~40 s/ wavelength (standard deviation, 0.01)
- Mean free path scattering/absorption
- Scattering phase function
- Scattering geometry

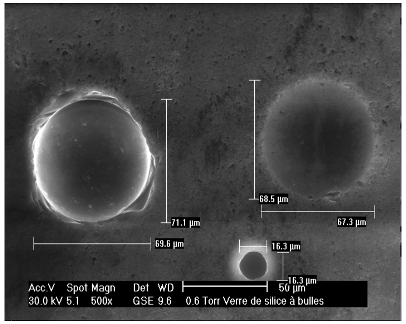
Absorption/scattering behavior

❖Refraction index gradient: **scattering**



MCRT process(0< ξ <1)

ξ<ρ : reflexion
ξ>ρ : refraction



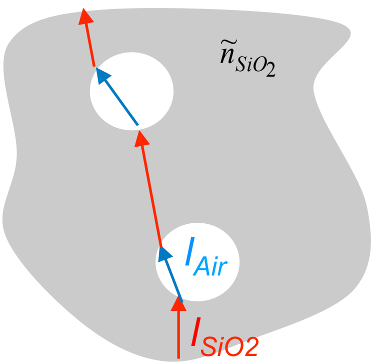
Fresnel law

$$\rho(\nu,T)=\frac{1}{2}\left[\left|\frac{\frac{\cos i}{\cos\tilde{r}(\nu,T)}-\frac{\tilde{n}_1(\nu,T)}{\tilde{n}_2(\nu,T)}}{\frac{\cos i}{\cos\tilde{r}(\nu,T)}+\frac{\tilde{n}_1(\nu,T)}{\tilde{n}_2(\nu,T)}}\right|^2+\left|\frac{\frac{\cos\tilde{r}(\nu,T)}{\cos i}-\frac{\tilde{n}_1(\nu,T)}{\tilde{n}_2(\nu,T)}}{\frac{\cos\tilde{r}(\nu,T)}{\cos i}+\frac{\tilde{n}_1(\nu,T)}{\tilde{n}_2(\nu,T)}}\right|^2\right]$$

Snell-Descartes law

$$\tilde{n}_{SiO_2}\sin i=\sin\tilde{r}$$

❖Optical path : **absorption**



MCRT process

$$\sum_i I_i < 0.01$$

Beer-Lambert law

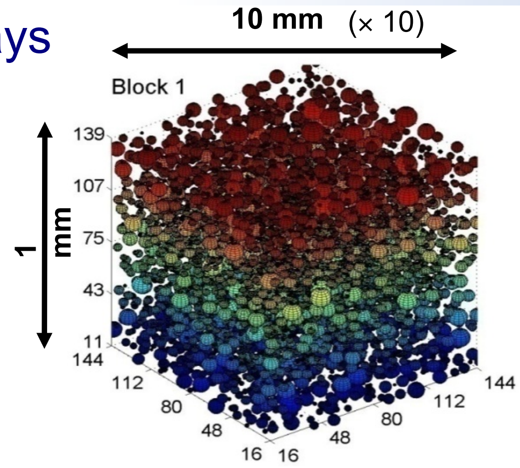
$$I_i = I_0 e^{-l_i K_i}$$

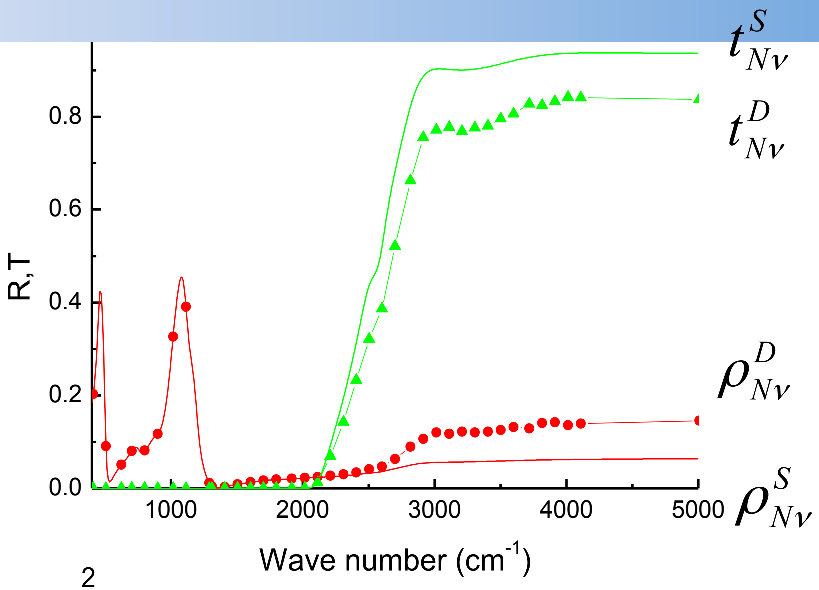
Key roles:

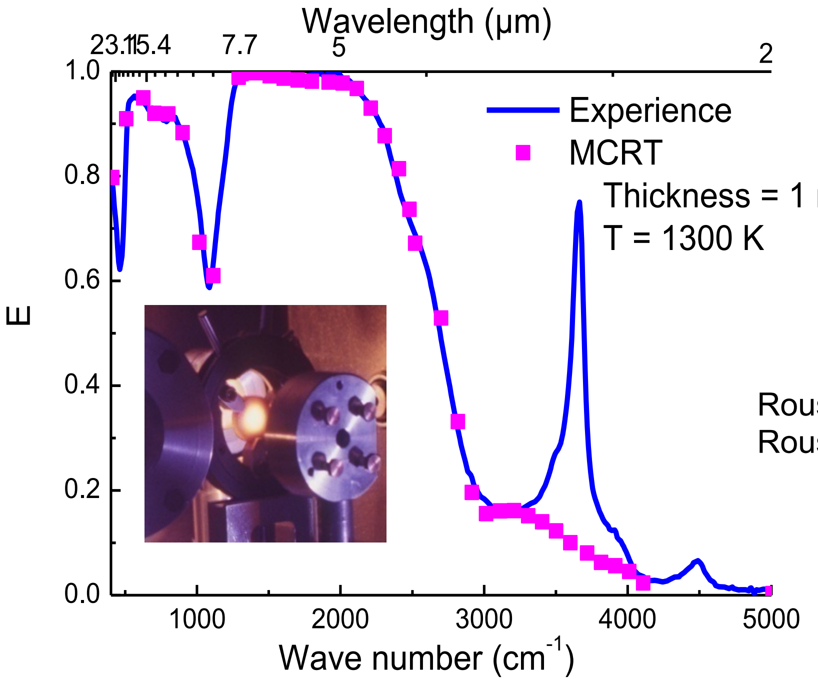
Optical function (n, k)

Validation : emittance computation

10^5 rays

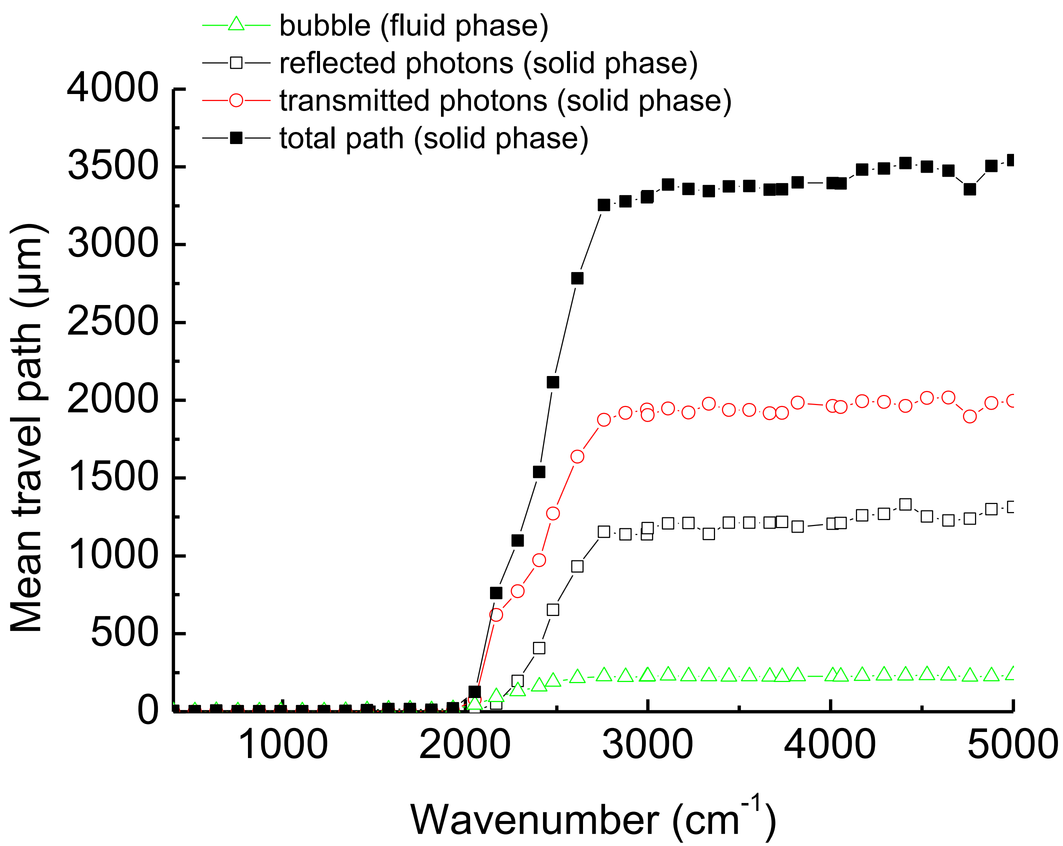






Rousseau et al., AO,(2007)
Rousseau et al., JQSRT (2006)

Agreement between Mie Scattering Theory and MCRT?



MCRT

$$\sum_i l_i = 3\,500\ \mu m$$

$$n_{\text{interfaces}} = 8$$

$$l_{MCRT} = 0.44\ mm$$

$$S_v = 3p \frac{\int_0^\infty f(r) r^2 dr}{\int_0^\infty f(r) r^3 dr} = 8.9\ mm^{-1}$$

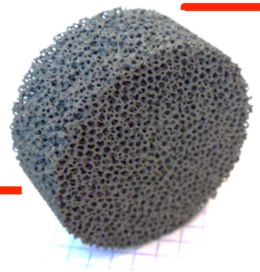
$$\kappa_{dv} \approx \frac{4}{S_V}$$

Independent Scattering Theory + Mie Theory

$$\kappa_{dv} = \pi Q_{dv} \int_0^\infty f(r) r^2 dr$$

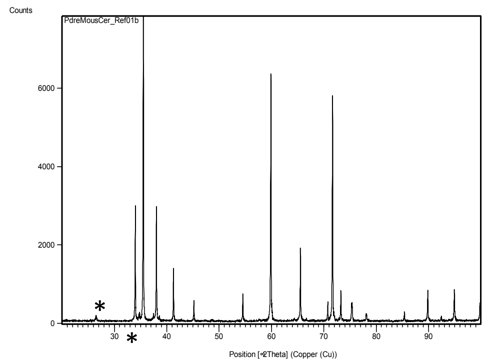
$$1/\kappa_d = 0.45\ mm$$

Silicon carbide open-cell foams : how can we connect their TRP to their textural features ?

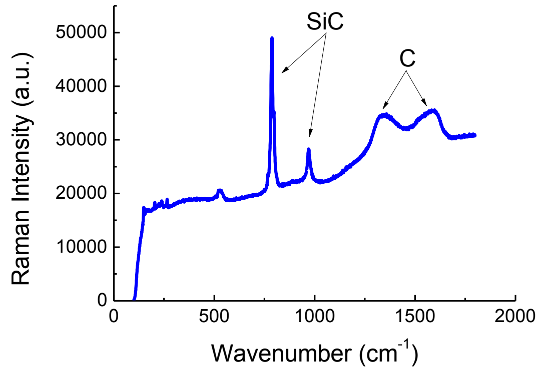


Thermal energy transport

➢Chemical composition→α-SiC

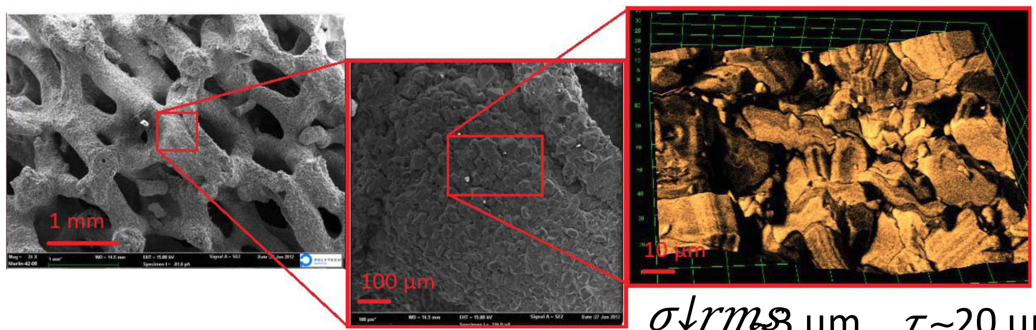


XRD (PROMES Odeillo, Eric Bèche)



Raman (IMN Nantes, France, J.-Y. Mevellec)

➢2D textural feature

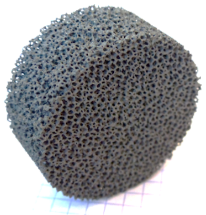


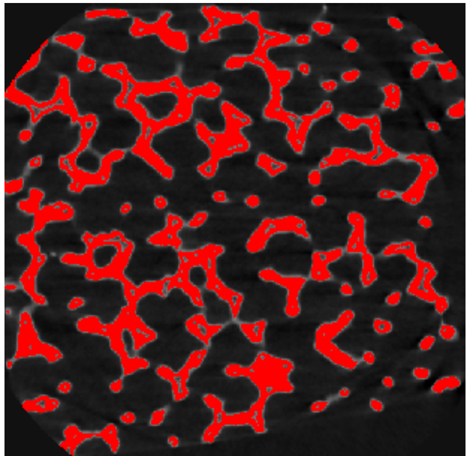
σ_{rms}~3 µm τ~20 µm

Textural characterization

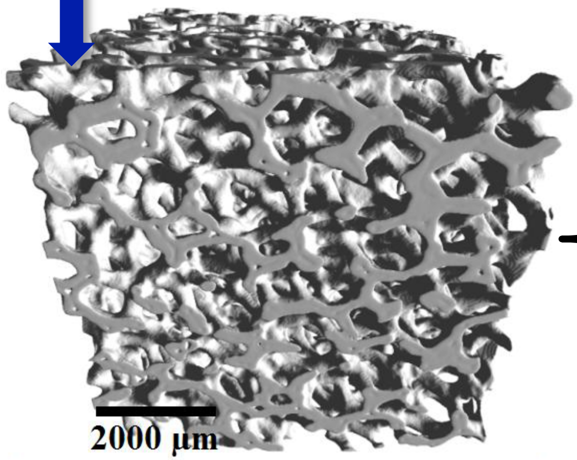
(iMorph software : http://www.imorph.fr/)

iusti
UMR 7343



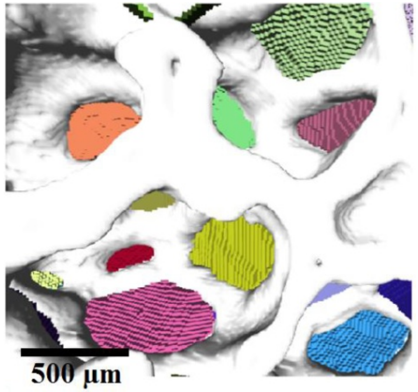


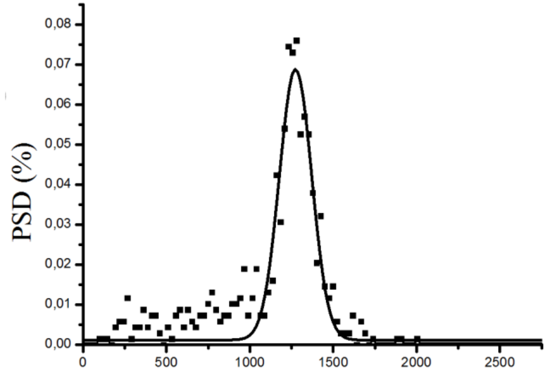
X-Ray µ-tomography



3D reconstruction .
Spatial resolution : 24µm/voxel

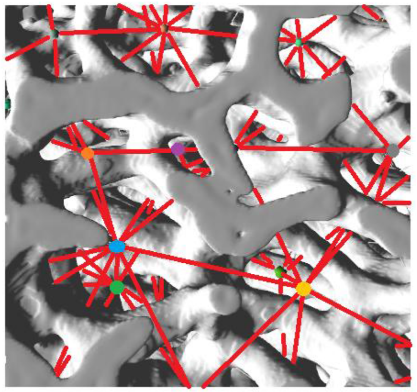
- Porosity= 70%
- Volumetric surface = 2800 m^2/m^3
- Pore size distribution

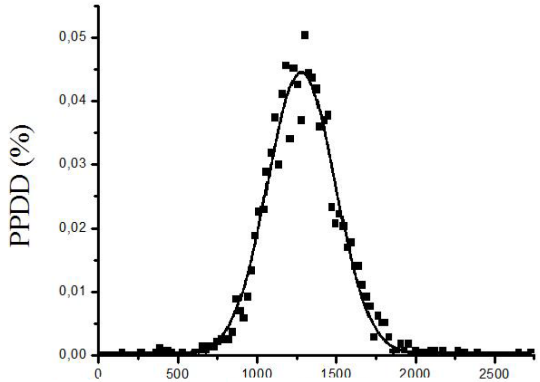




$2r\ (\mu m)$

- Pore-pore distance distribution





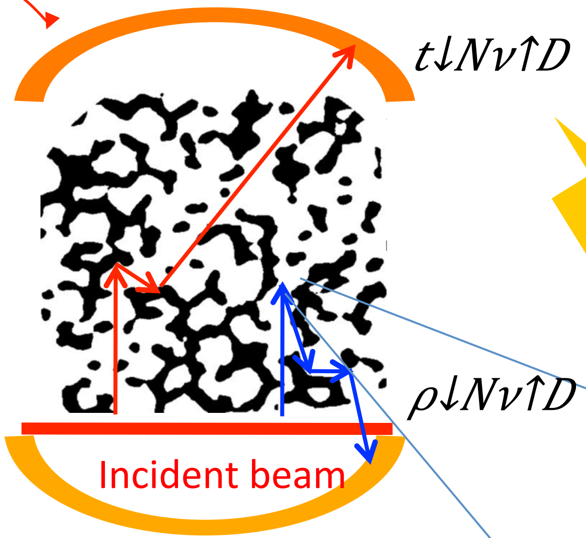
$g\ (\mu m)$

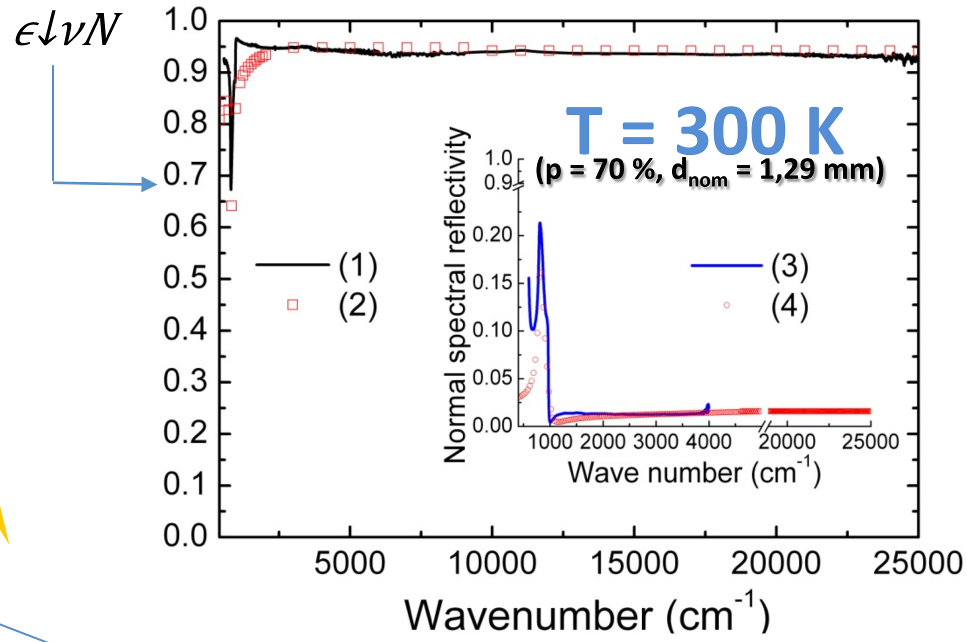
- Mean connectivity of 9,7

LTN UMR 6607

genMat : a predictive tool for computing emittances from 3D images

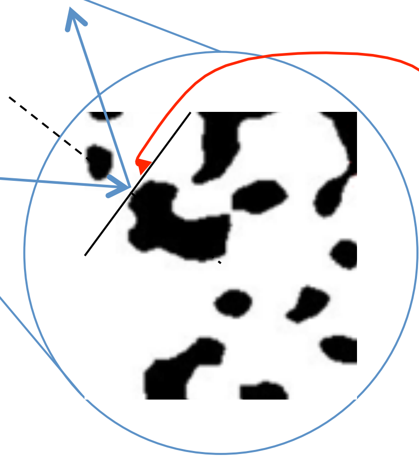
Monte Carlo Ray-Tracing code : **iMorphRad (C++)**





Macroscopic scale : ~10000 µm

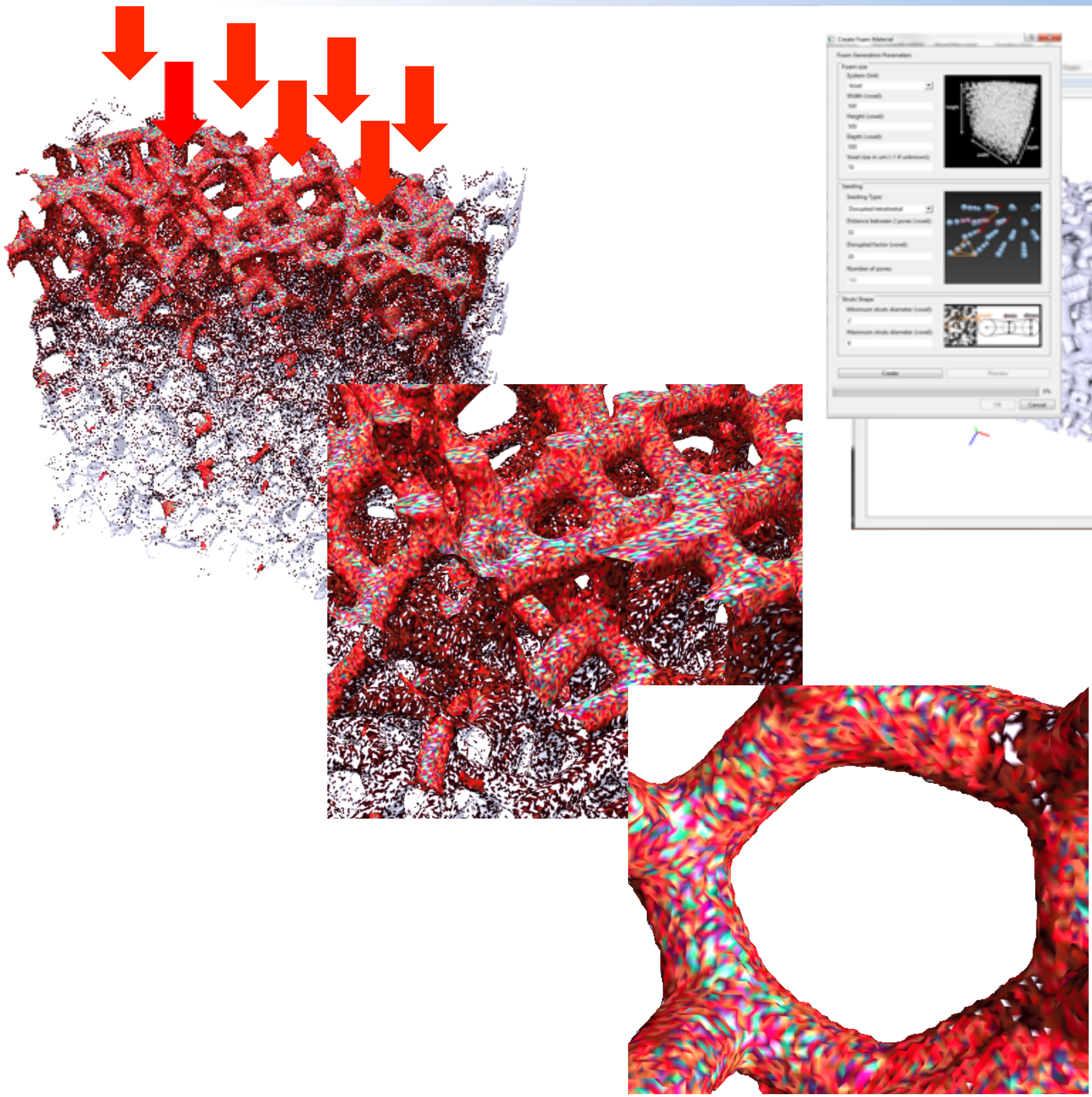
Rousseau et al., JCPS, 2012
Guevelou et al., IJHMT 2016

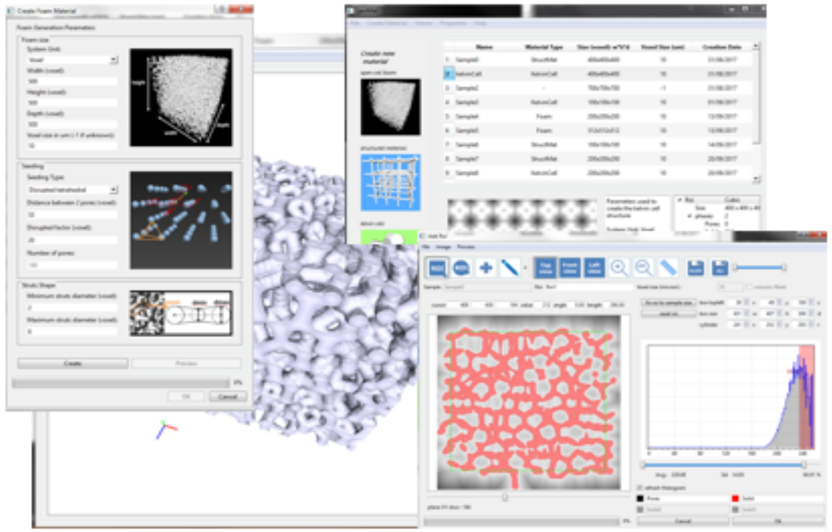


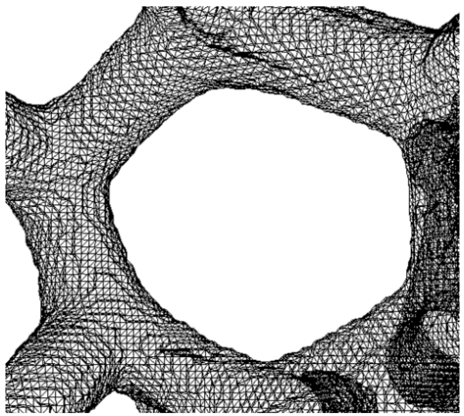
$$\rho_{n,\nu} = \left| \frac{\sqrt{\tilde{\varepsilon}_{\nu eff}} - 1}{\sqrt{\tilde{\varepsilon}_{\nu eff}} + 1} \right|^2$$

Local scale : ~100 µm

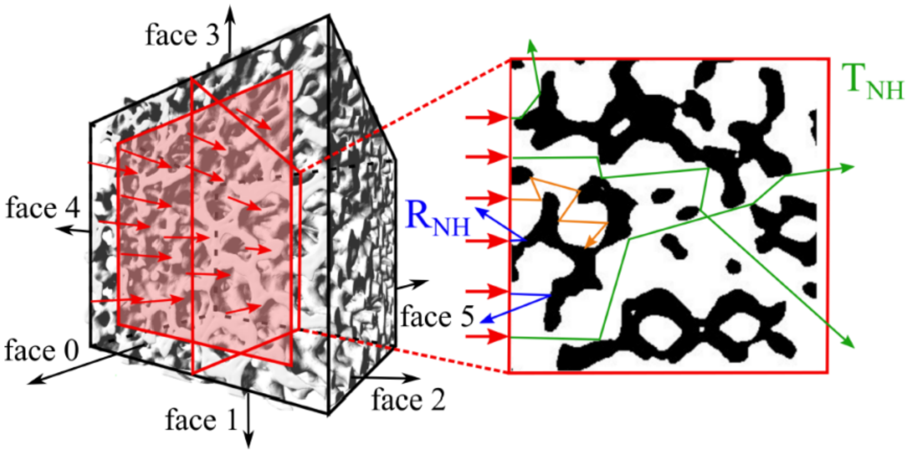
genMat : a predictive tool for computing emittances from 3D images







Integral formulation for MCRT?



$$q_{0,\lambda} = \int_{S_0} dS_0 \int_{2\pi} d\Omega(\vec{\omega})\, I_{0,\lambda}\, \vec{n}_0 \cdot \vec{\omega}\, \delta(\vec{\omega} - \vec{\omega}_0) = I_{0,\lambda}$$

$$q_{i,\lambda} = \int_{S_0} p_{S_0}\, dS_0 \left[H(\vec{r}_1 \in S_f)R_1 + H(\vec{r}_1 \in S_i)W_0\right]$$

$$R_j = \int_{2\pi} p_\Omega d\Omega(\vec{\omega}_j)\left[H(\vec{r}_j \in S_f)R_{j+1} + H(\vec{r}_j \in S_i)W_j\right]$$

$$p_{S_o} = \frac{1}{S_o} \qquad p_{\Omega_j} = \frac{\delta(\vec{\omega}_j - \vec{\omega}_{j-1})}{\vec{n}_j \cdot \vec{\omega}_j} \qquad W_j = I_{0,\lambda}\, S_o \prod_{k=1}^{j} \rho_F(\vec{r}_j, \vec{\omega}_j)$$

$$R_{NH} = q_{r,\lambda}/q_{0,\lambda} \qquad T_{NH} = (q_{l,\lambda} + q_{t,\lambda})/q_{0,\lambda}$$

International Journal of Heat and Mass Transfer 93 (2016) 118–129

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journal homepage: www.elsevier.com/locate/ijhmt

ELSEVIER

Representative elementary volumes required to characterize the normal spectral emittance of silicon carbide foams used as volumetric solar absorbers

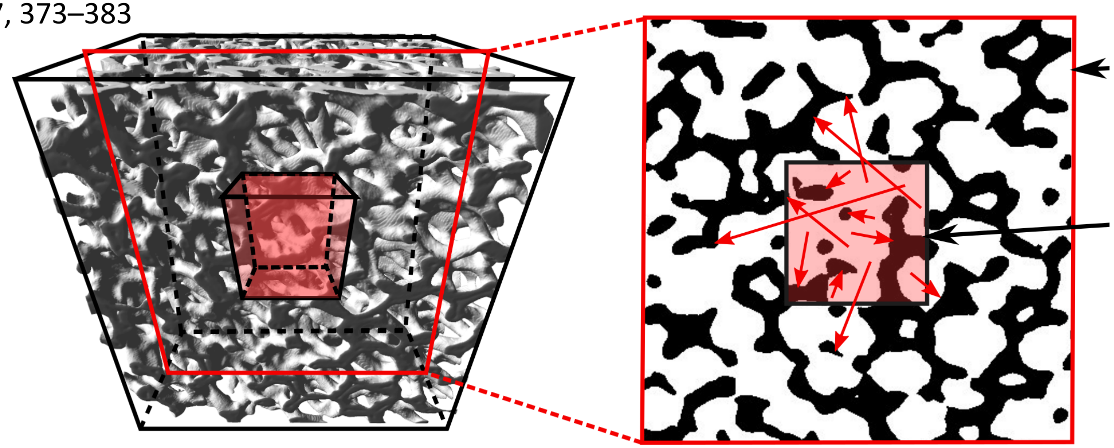
CrossMark

Simon Guévelou [a], Benoit Rousseau [a,*], Gilberto Domingues [a], Jérôme Vicente [b], Cyril Caliot [c]

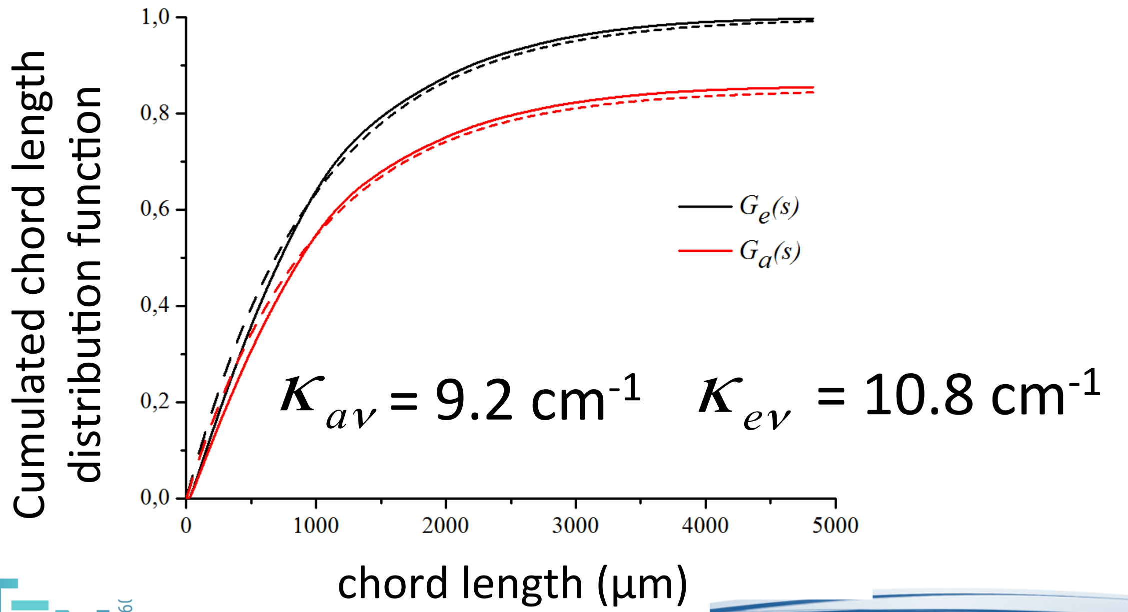
[a] CNRS, LTN, UMR 6607, Université de Nantes, Rue Christian Pauc, 44306 Nantes Cedex 3, France
[b] Aix-Marseille Université, CNRS, IUSTI UMR 7343, 13453 Marseille Cedex 13, France
[c] Processes, Materials and Solar Energy Laboratory, PROMES, UPR CNRS 8521, 66120 Font-Romeu-Odeillo-Via, France

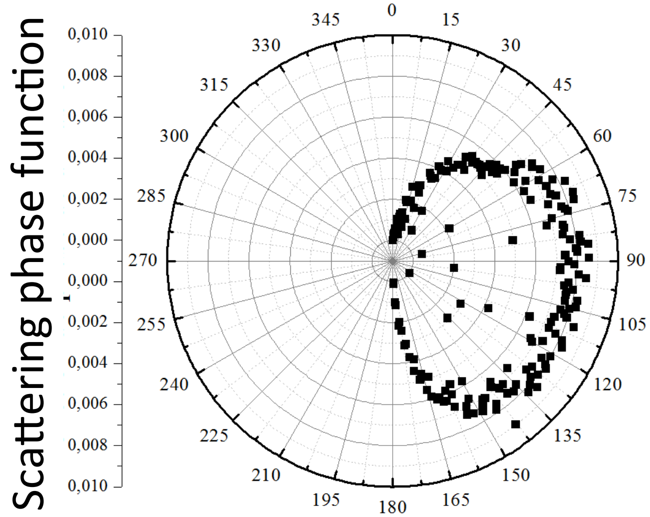
RDFI method

Tancrez et al., IJHMT, 2004, 47, 373–383



Guévelou et al., JPM, 2015, 18, 1031-1045





How can we go one step further now ?

TRP up to T = 1300 K and not only at T = 300 K !

Numerical foam generator : emissivity→ texture (300 K) ≅ texture (1300 K)

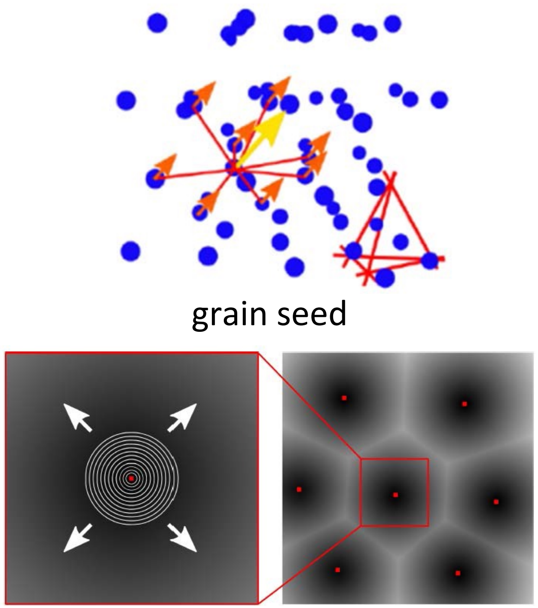
iusti UMR 7343

Infrared emission spectroscopy (SiC single crystals up to 1300 K)

Cemhti

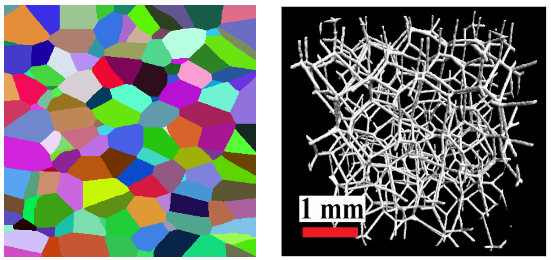
Numerical foam generator (genMat, C++) → p, d_{nom},…

Specific algorithm



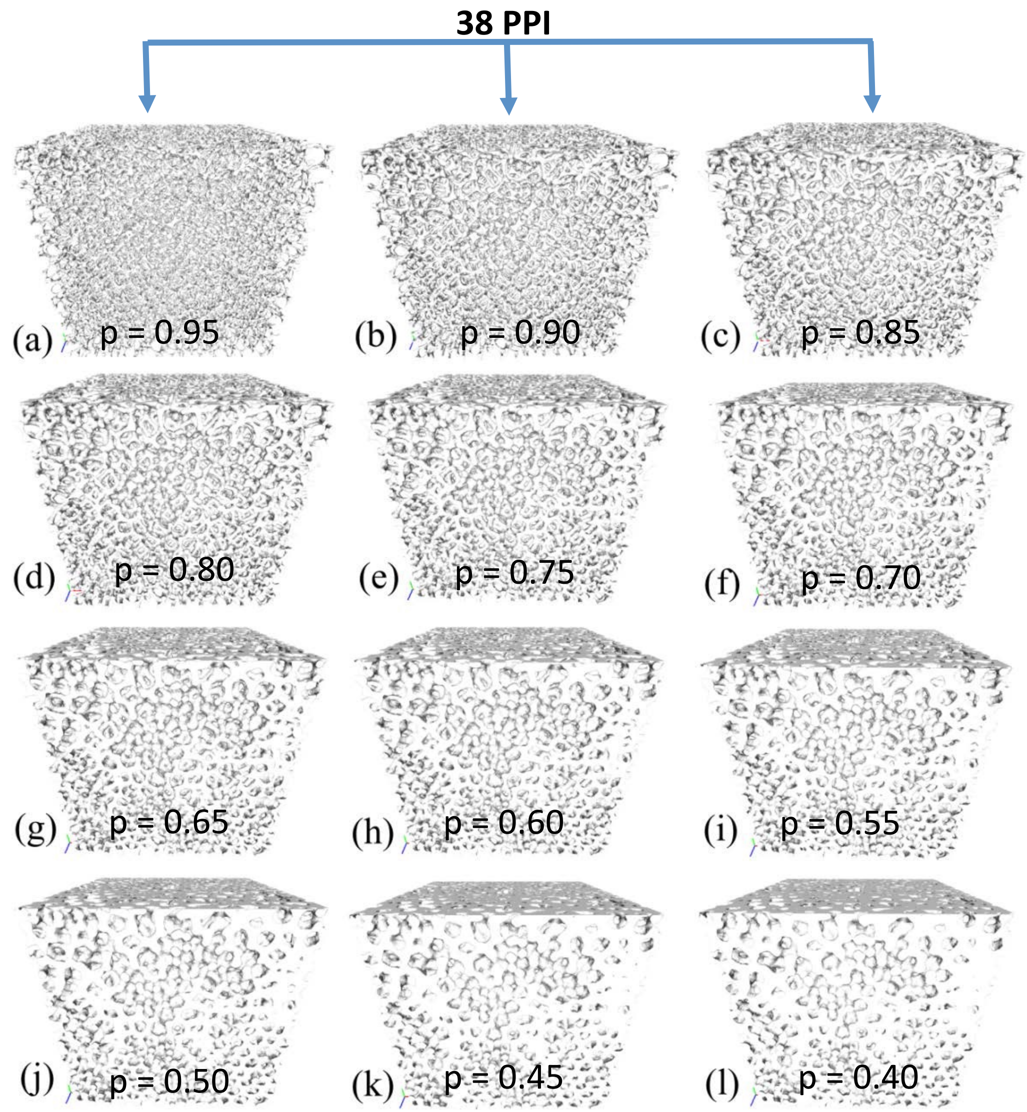
grain seed

fast-marching algorithm

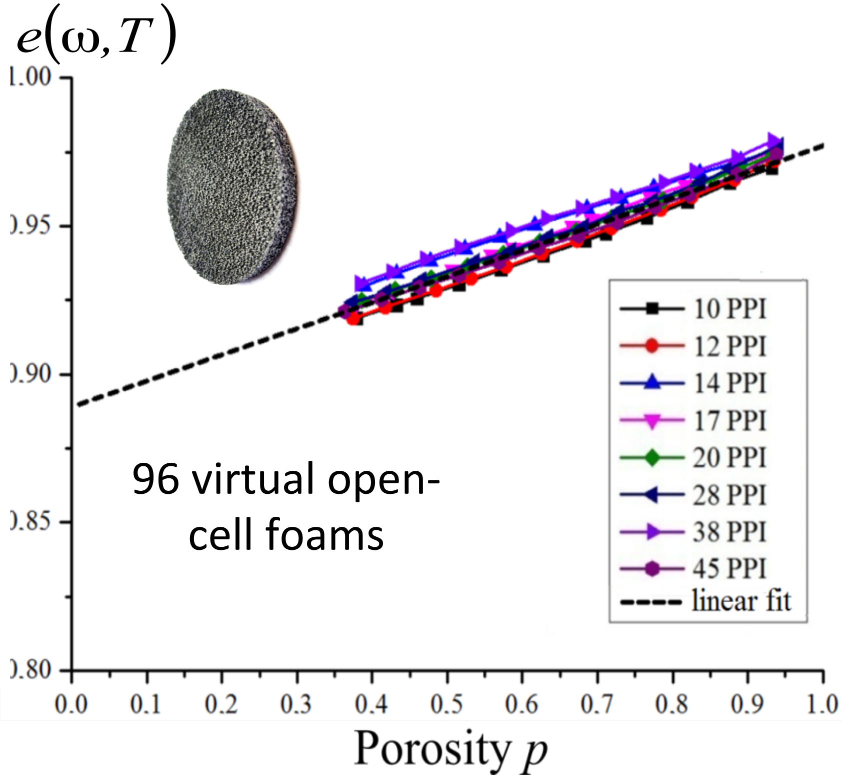


segmentation squelettisation

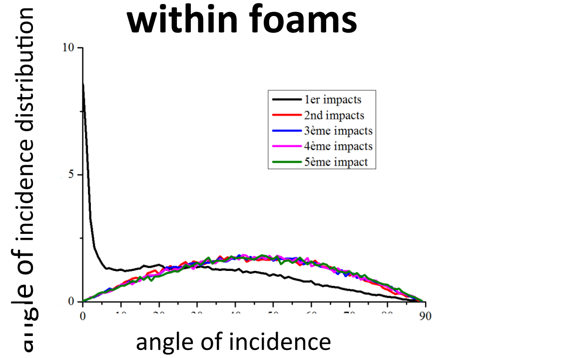
Guévelou et al. , JPM 2015 ; Guévelou et al., IHTC, Kyoto 2015

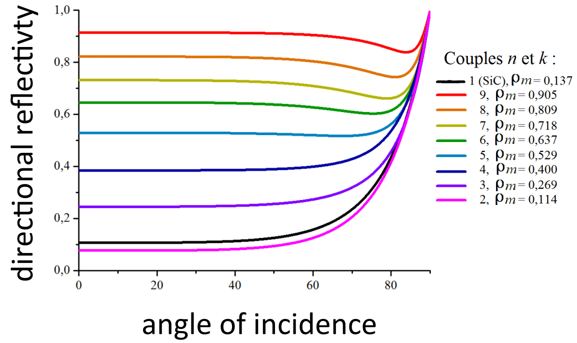


Thorough statistical study of ray paths with iMorphRad for 600 virtual open cell foams



Statistical study of ray transportation within foams





V_{foam} >$REV_{emissivity}$
Optically thick struts
optically smooth struts

$$e_{foam,\nu}(T) = 1 - \rho_{strut,\nu}(T)(1 - 0.8p)$$

$$\rho_{strut,\nu}(T) = \left| \frac{\sqrt{\tilde{\varepsilon}_\nu(T)} - 1}{\sqrt{\tilde{\varepsilon}_\nu(T)} + 1} \right|^2$$

Guévelou et al., JQSRT, 2017, 189, p. 329-338

Extraction of the dielectric function with an improved Lorentz-Drude model for an heavily doped SiC

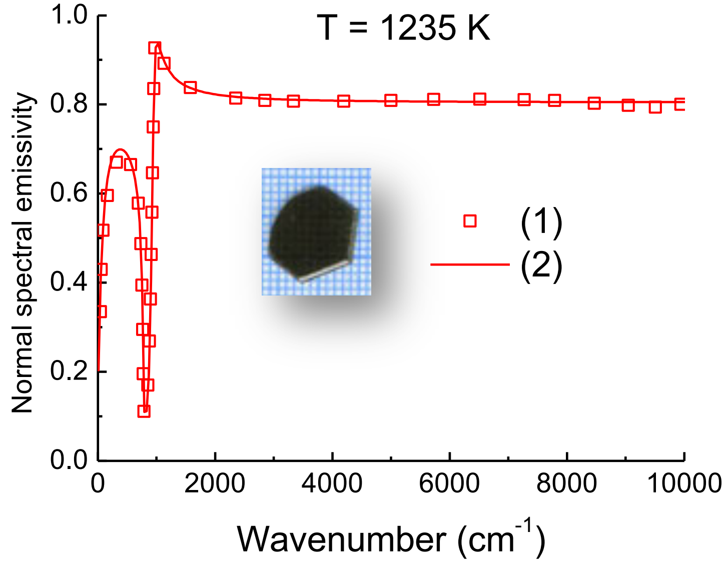
MICROSCALE

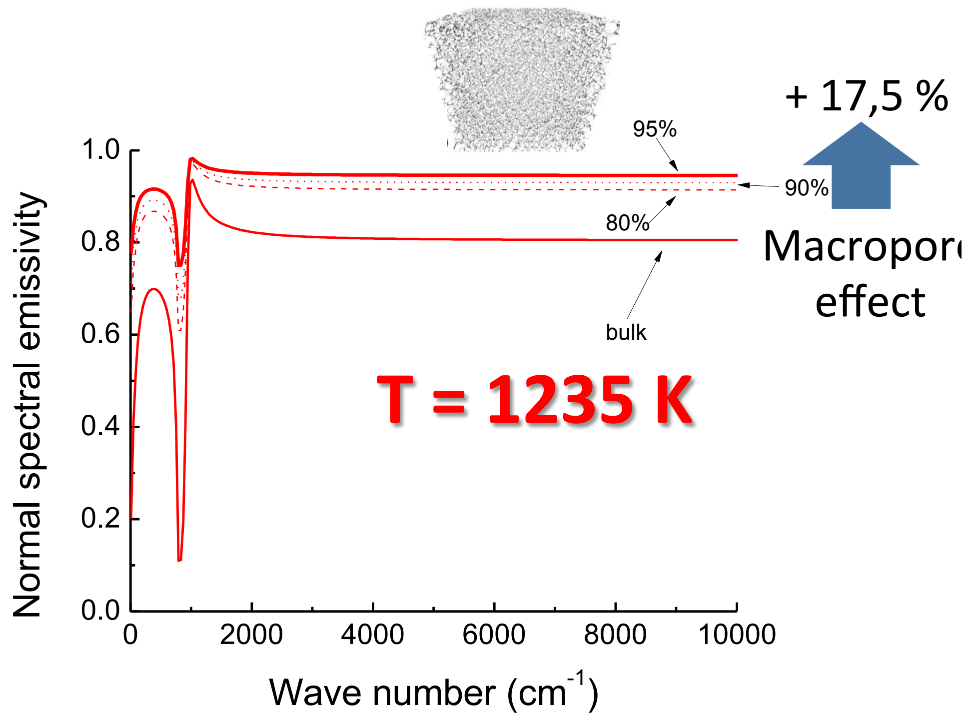
MACROSCALE

$$\tilde{\varepsilon}_{crystal,\nu}(T) \xleftrightarrow[\text{method : LM}]{\text{minimization}} e_{crystal,\nu}(T)$$

$$e_{foam,\nu}(T) = 1 - \left(1 - e_{crystal,\nu}(T)\right)\left(1 - 0.8p\right)$$

$$\tilde{\varepsilon}_{crystal}(\nu,T) = \varepsilon_\infty\left(1 - \frac{\Omega_p^2(T)}{\nu^2 - i\gamma_p(T)\nu}\right) + \frac{\Delta\varepsilon\,\nu^2(0,T)}{\nu^2(0,T) - \nu^2 - 2\nu(0,T)P(0,T;\nu)}$$

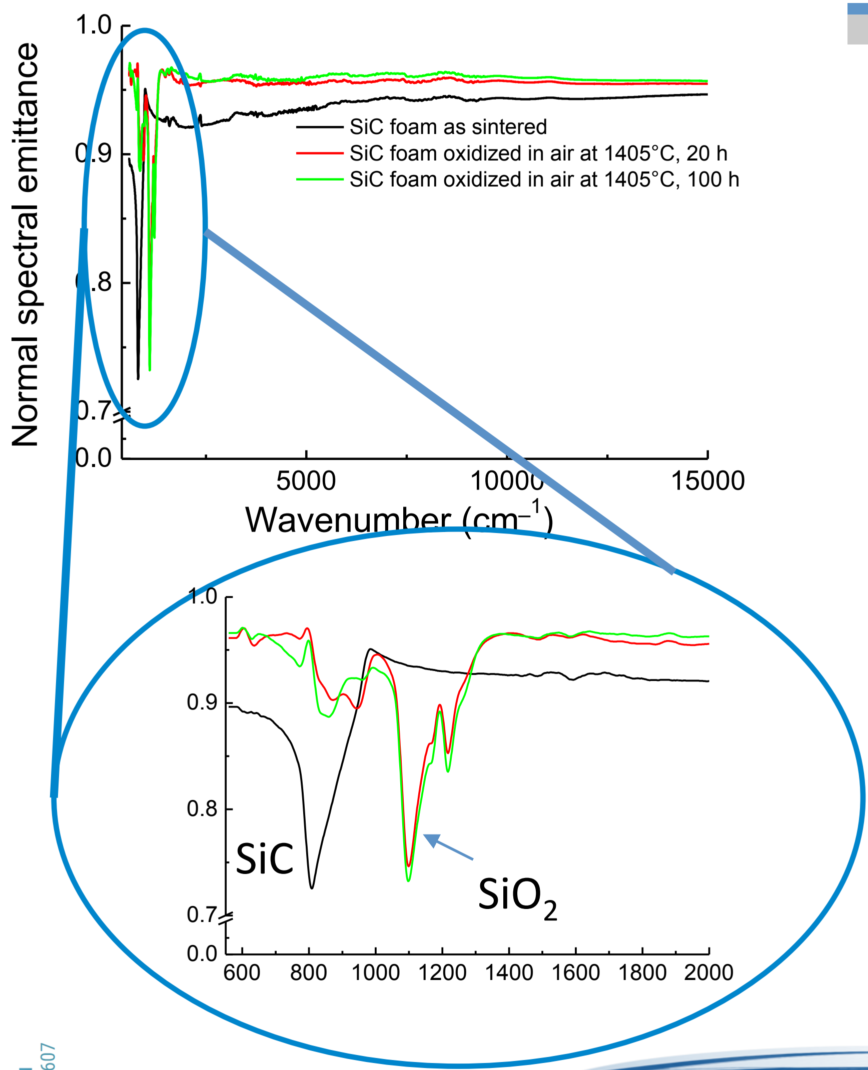


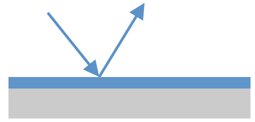


B. Rousseau et al. , AIP Advances 2016 6 065226

First oxidation at T = 1700 K, SIC foam p= 70 %

Fraunhofer IKTS

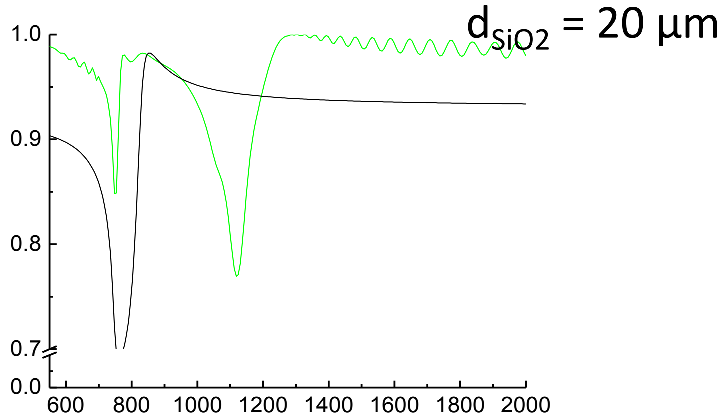




$$\rho_{film/strut}(\omega) = \left| \frac{r_{af}(\omega) + r_{fs}(\omega) e^{\left(-i 2\omega \tilde{\varepsilon}_{SiO_2}(\omega) d / c\right)}}{1 + r_{af}(\omega) r_{fs}(\omega) e^{\left(-i 2\omega \tilde{\varepsilon}_{SiO_2}(\omega) d / c\right)}} \right|^2$$

$$r_{af}(\omega) = \frac{1 - \sqrt{\tilde{\varepsilon}_{SiO_2}(\omega)}}{1 + \sqrt{\tilde{\varepsilon}_{SiO_2}(\omega)}} \qquad r_{fs}(\omega) = \frac{\sqrt{\tilde{\varepsilon}_{SiO_2}(\omega)} - \sqrt{\tilde{\varepsilon}_{SiC}(\omega)}}{\sqrt{\tilde{\varepsilon}_{SiO_2}(\omega)} + \sqrt{\tilde{\varepsilon}_{SiC}(\omega)}}$$

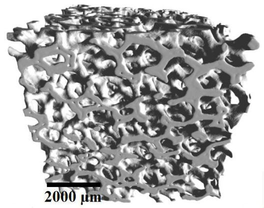
$$e_{film/foam}(\omega, T) = 1 - \rho_{film/strut}(\omega, T)(1 - 0.8p)$$



LTEN UMR 6607

Multi-length scale methods for computing the radiative properties of heterogeneous materials

Material design : genMat



Energy efficiency

complex refrative indices

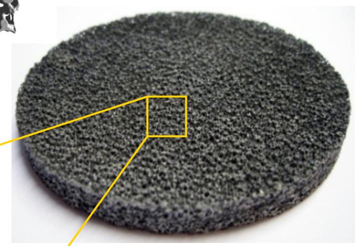
$$\tilde{r}_{perp} = \frac{E_{perp,r}}{E_{perp,i}} = \frac{\cos\Theta_i - \tilde{m}\cos\Theta_t}{\cos\Theta_i + \tilde{m}\cos\Theta_t}$$

$$\tilde{r}_{para} = \frac{E_{para,r}}{E_{para,i}} = \frac{\cos\Theta_t - \tilde{m}\cos\Theta_i}{\cos\Theta_t + \tilde{m}\cos\Theta_i}$$

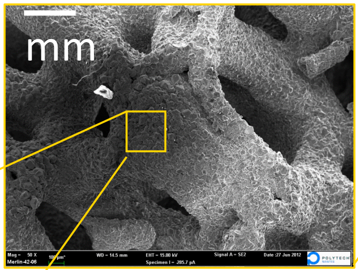
$$\rho_{2\to1} = \frac{1}{2}\left[\left|\tilde{r}_{perp}\right|^2 + \left|\tilde{r}_{para}\right|^2\right]$$

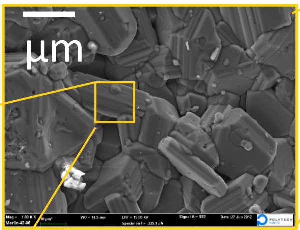
$$\tilde{m} = \frac{\tilde{n}_1}{\tilde{n}_2}$$

$$n + ik = \sqrt{\varepsilon' + i\varepsilon''}$$

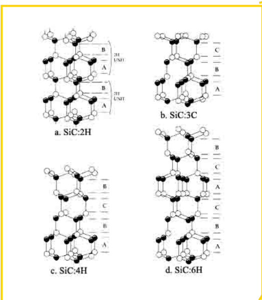


α-SiC foam





nm



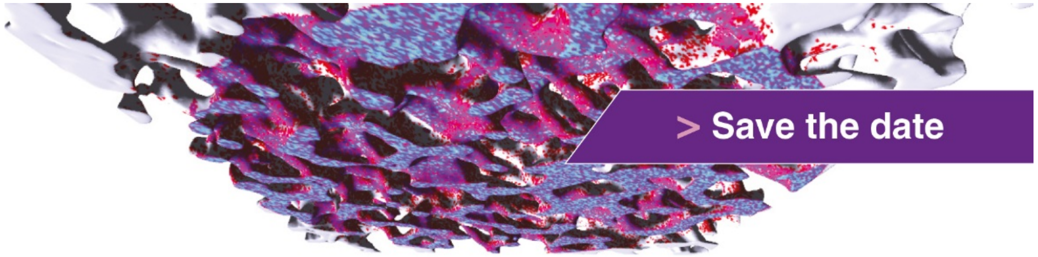
System

$$\beta = 2.45\frac{(1-0.7p)}{d_{nom}}$$

Numerical approach : iMorphRad

Textural features

$$e_{foam}(\omega,T) = 1 - \rho_{strut}(\omega,T)(1-0.8p)$$



French Interpore Conference on Porous Media

8 -10 October 2018 - La Cité Nantes Event Center Nantes (France)

Biennial conference
Understanding of the complex behavior of porous media

- > Registration opening and abstract submission : 15th January 2018
- > Deadline for abstract submission : 30th March 2018
- > Notification of acceptance : 13th April 2018
- > Standard registration deadline : 15th June 2018

Ideal place for scientific exchanges where fundamental and applied topics, often interdisciplinary, are discussed :

- > Energy storage
- > Pollution
- > Renewable energy
- > Petroleum engineering
- > Natural environment
- > Food and health

> Scientific topics

Mechanical and thermal behavior of porous media - Multi-physics coupling and numerical modelling - Fluid mechanics in Engineering processes - Porous media for energy production and storage - Imaging, numerical generation of porous media - Geotechnical and petroleum engineering - Reactive and dispersive transport - Multiscale fibrous media - Wave propagation

INTERPORE FIC French InterPore Chapter

https://jemp2018.sciencesconf.org/

twitter.com/JEMP2018

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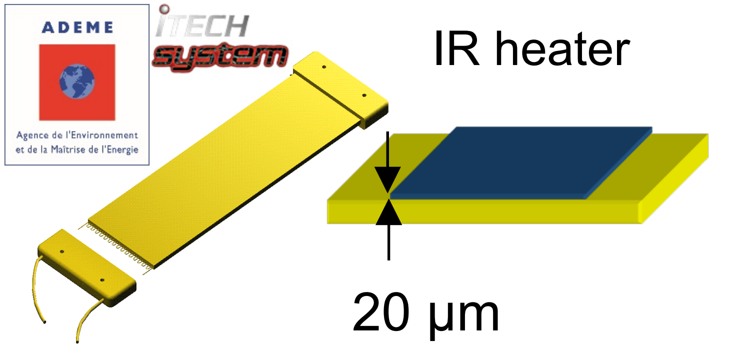
J.-Y. Rolland, V. Le Nader, J. Dausseins, A. Biallais

Thank you for your attention !
Some questions?

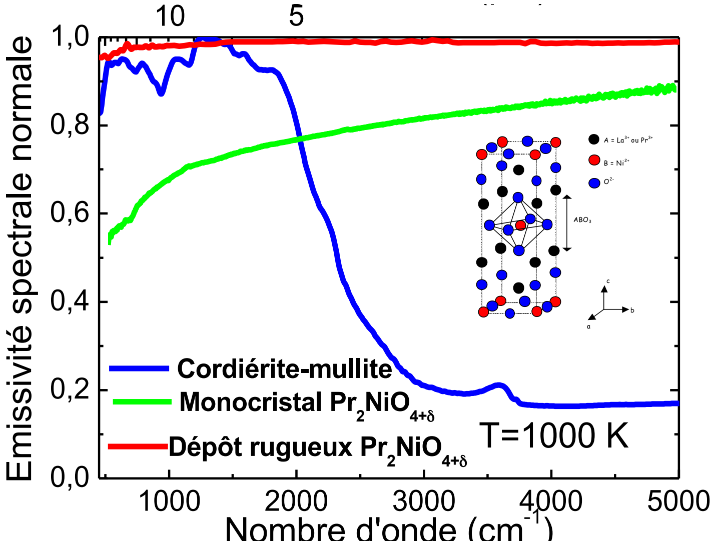
“Royal de Luxe” Theatre Company : an incredible show at Nantes!

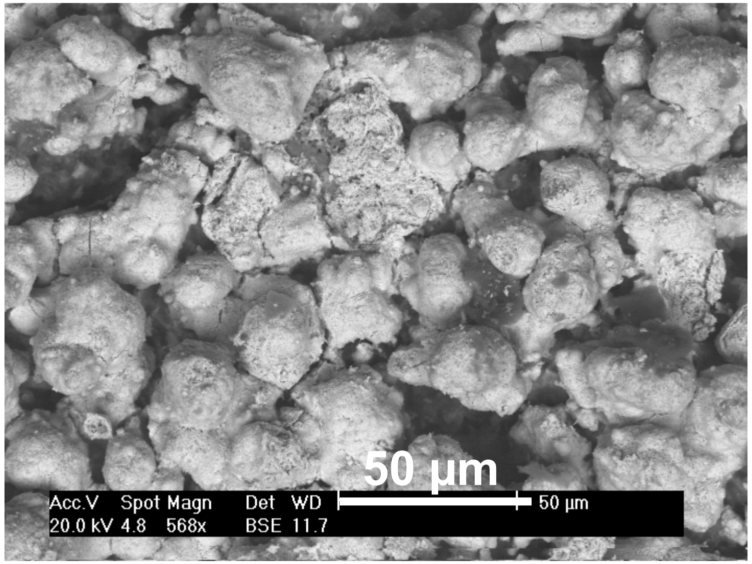
UMR 6607

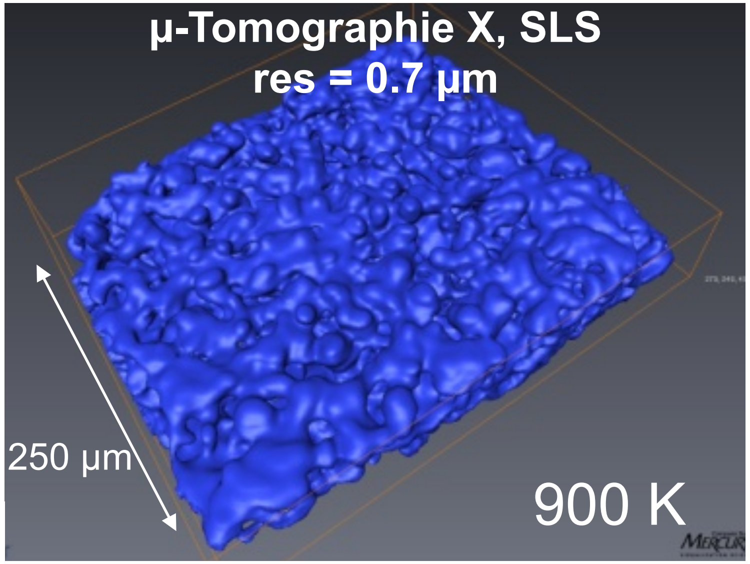
“Plate” black body



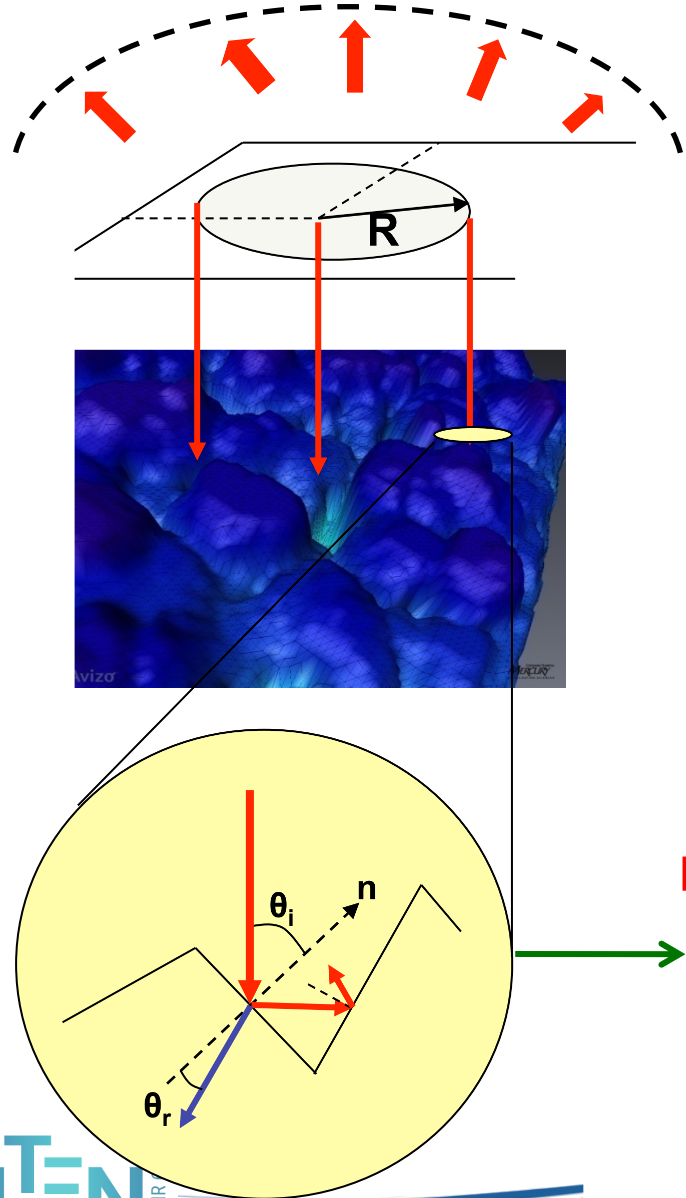
B. Rousseau et al., APL., 79 (2001)
European Patent, 99401558.4-2214 (1999)

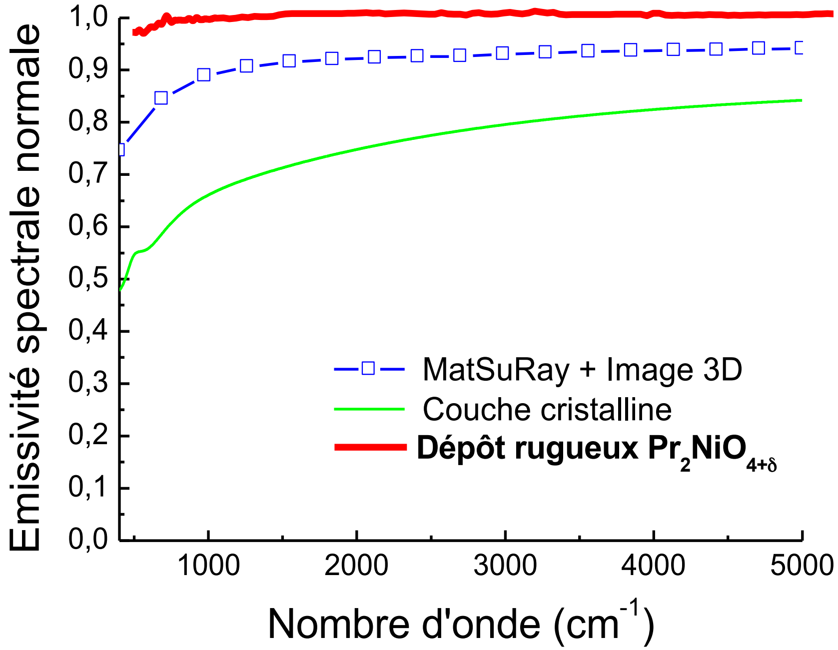






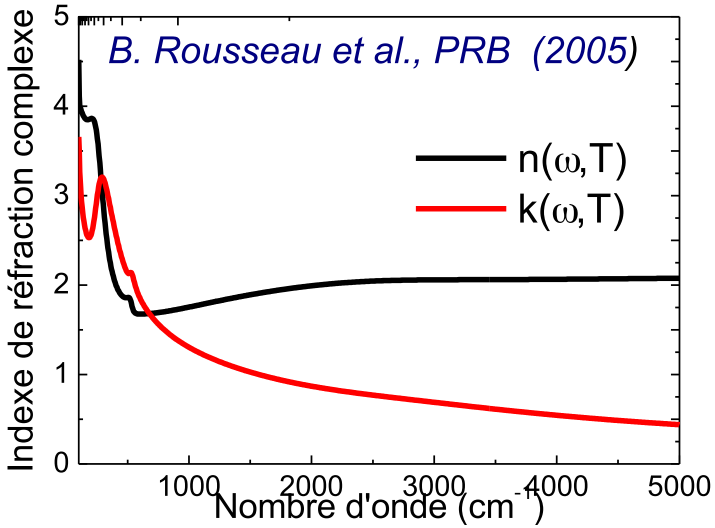
Role of the “macro” roughness : GOA



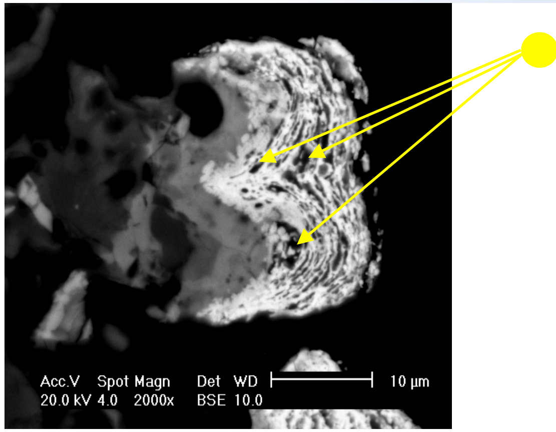


Local scale

ρ↓νN↑S



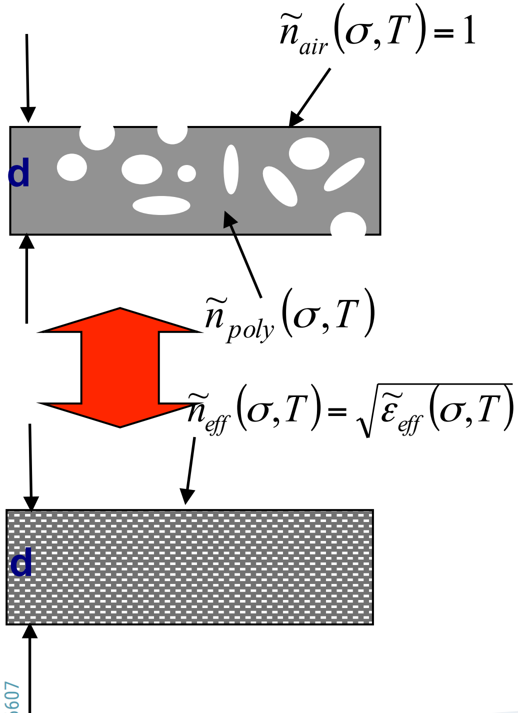
Role of the "micro" porosity : EMA

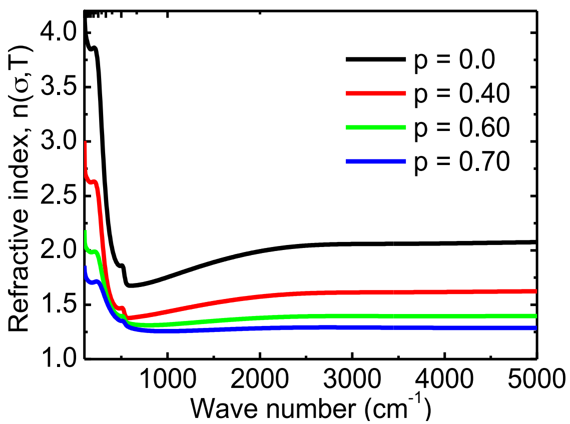


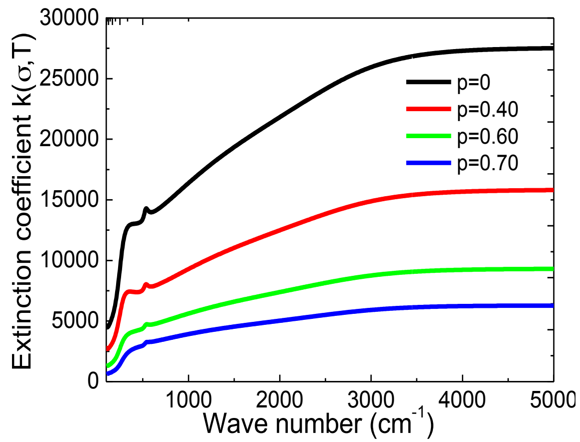
pore : 50 -200 nm $d_{pore} << \lambda_{IR}$ (2-20 **µm**)

$$(1-p)\frac{\tilde{\varepsilon}_{poly}(\sigma,T)-\tilde{\varepsilon}_{eff}(\sigma,T)}{\tilde{\varepsilon}_{eff}(\sigma,T)+y_{poly}\left(\tilde{\varepsilon}_{poly}(\sigma,T)-\tilde{\varepsilon}_{eff}(\sigma,T)\right)}+p\frac{\tilde{\varepsilon}_{pore}(\sigma,T)-\tilde{\varepsilon}_{eff}(\sigma,T)}{\tilde{\varepsilon}_{eff}(\sigma,T)+y_{pore}\left(\tilde{\varepsilon}_{pore}(\sigma,T)-\tilde{\varepsilon}_{eff}(\sigma,T)\right)}=0$$

D.E. Apnes, optical properties of thin films, Thin Solid Films 89 (1982) 249

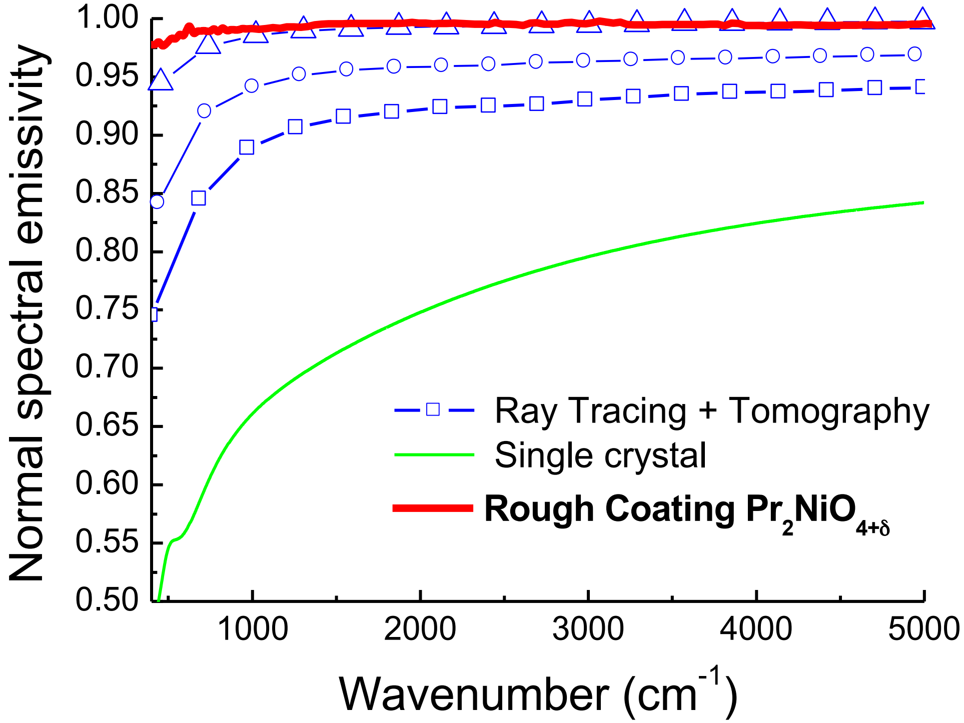


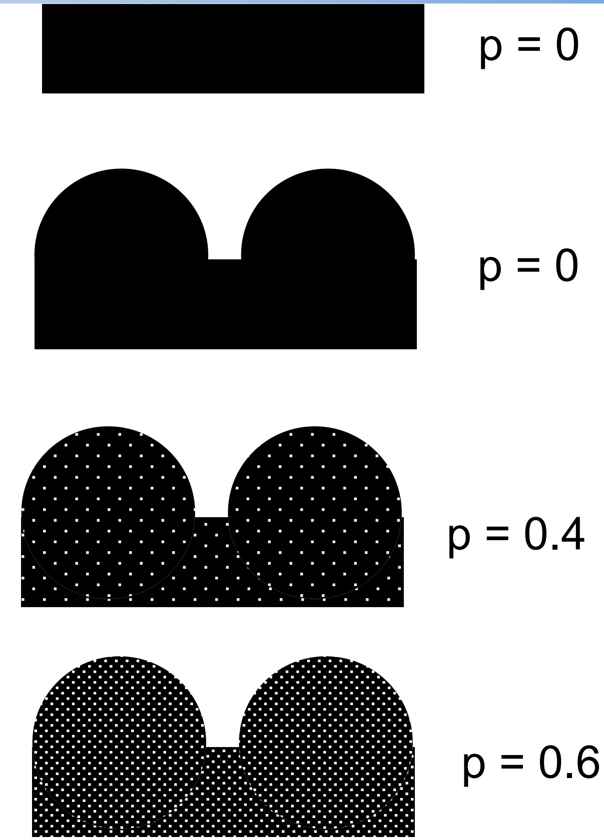


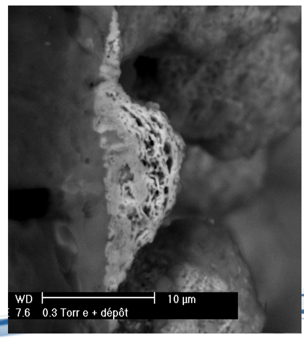


p =70% d> 11 µm (opaque)

Hybrid methodology : GOA+EMA

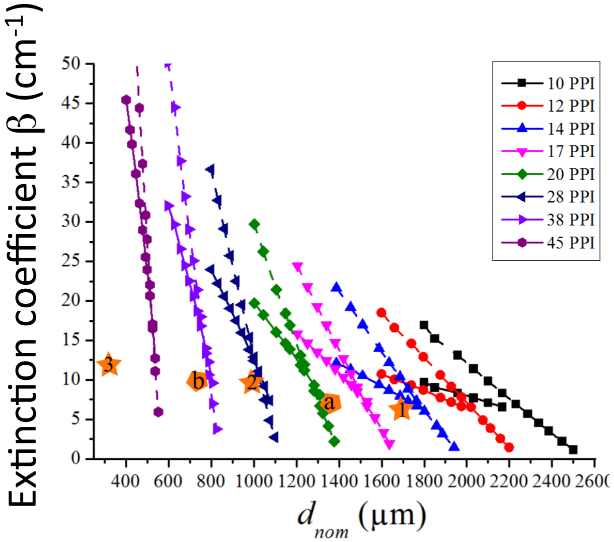






USAXS? SANS? Nanotomo X? FIB-SEM?

RDFI METHOD → extinction coefficient, albedo, scattering phase function

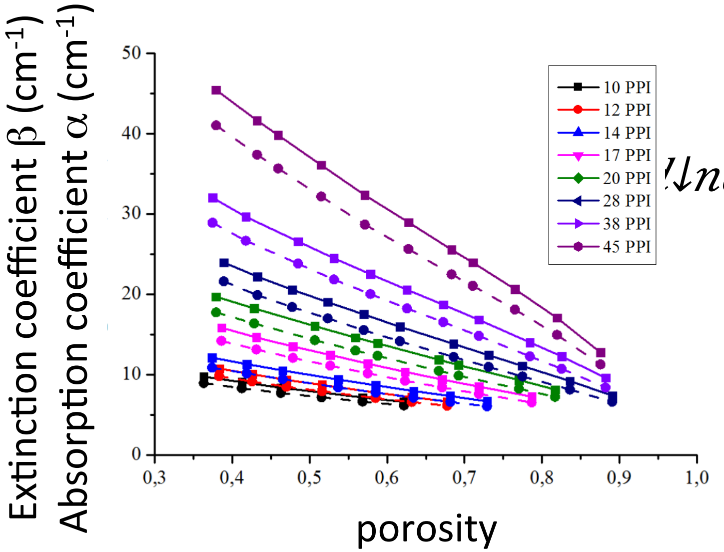


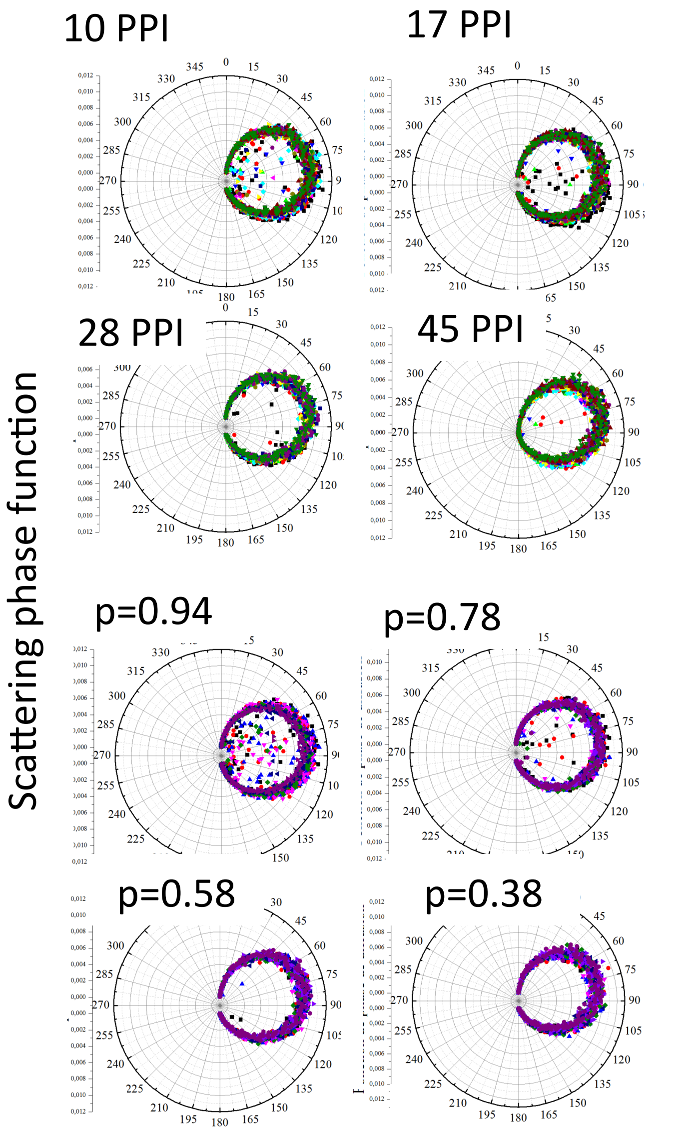
$$\kappa_{ev} = 2.45\frac{(1-0.7p)}{d_{nom}}$$

$$\kappa_{ev} = 4.8\frac{(1-p)}{d_{nom}}$$

Hendricks & Howell, Journal of Heat Transfer, 118(1):79–87 (1996)

$$d_{nom} = a_{PPI}\,p + b_{PPI}$$





Radiative conductivity : optically thick media
Rosseland approximation

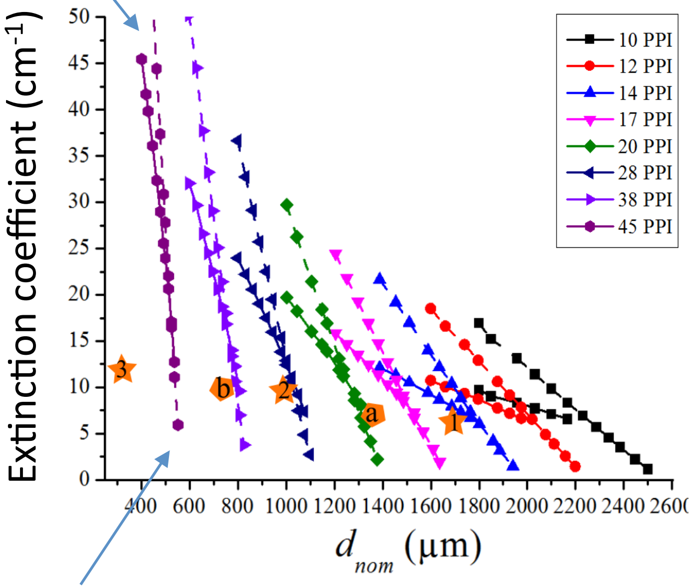
asymmetry factor

$$\Gamma_\nu = 3\kappa_{e\nu} - g_\nu \kappa_{d\nu}$$

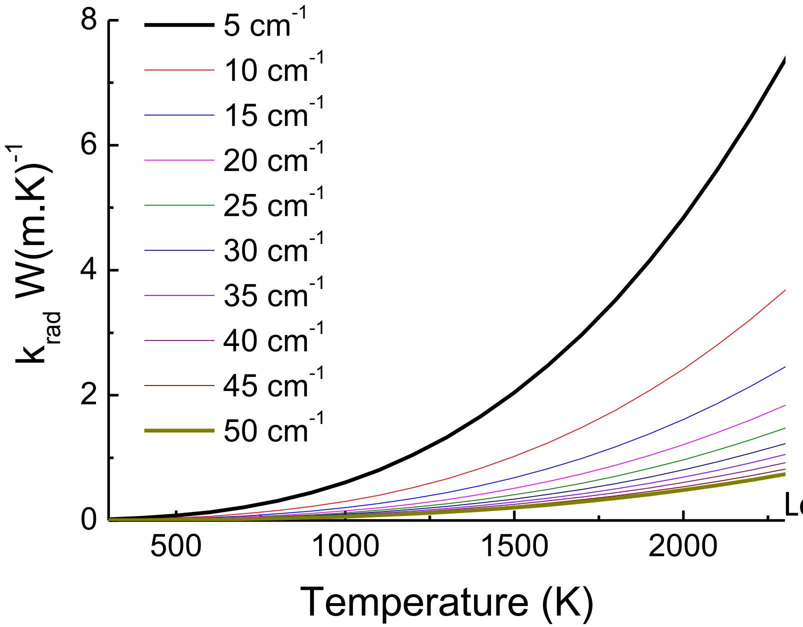
$$\Gamma_R = \frac{\int_0^\infty \frac{dI_\nu^0(T)}{dT} d\nu}{\int_0^\infty \frac{1}{\Gamma_\nu} \frac{dI_\nu^0(T)}{dT} d\nu}$$

$$k_{rad} = \frac{16 n^2 \sigma_B T^3}{\Gamma_R}$$

p=0.4



p=0.9



High porosity
low PPI

Low porosity
high PPI

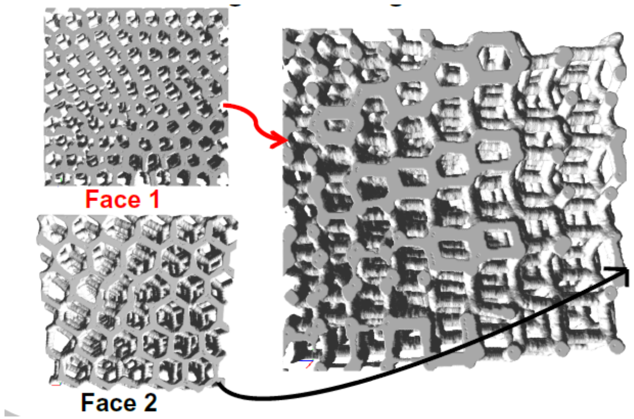
Future works…

➢To characterize the thermal behavior (conduction/radiation) of SiC open-cell foams above T = 1300 K in relation with degradation mechanisms (corrosion, mechanical failures,…)

➢To play, by numerical modelling, on the surface properties of the struts (roughness, selective/protective coatings) at high temperature

➢To compute thermal conductivities with FEM (Freefem++)

➢To design foam with pore size gradient : effect on the REV ? → 3D printing?



➢Applications with thermal insulators, heat exchangers, radiant gas burners,…

Materials and Design 44 (2013) 99–106

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A simple simulation method for designing fibrous insulation materials

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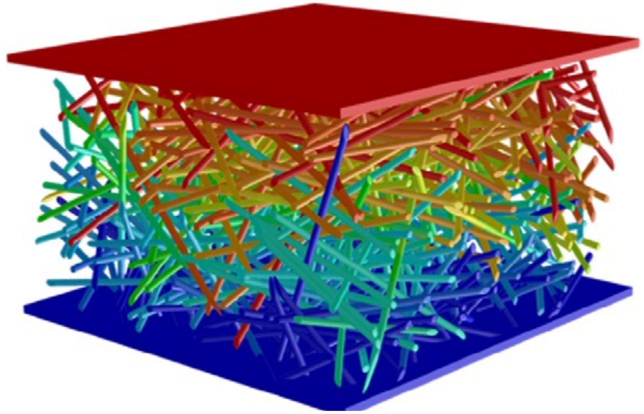
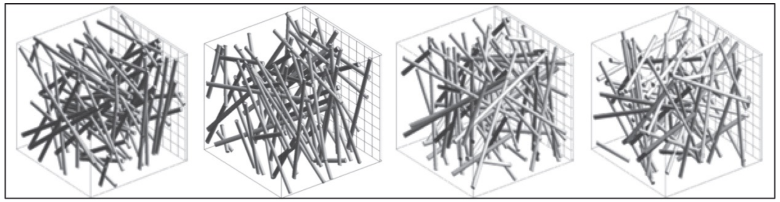
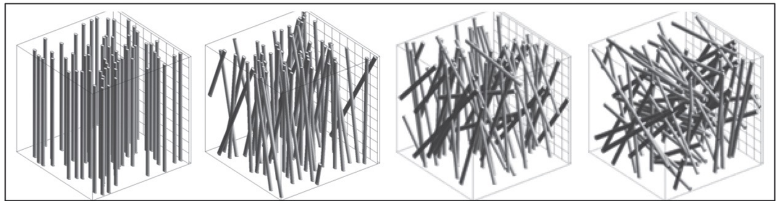
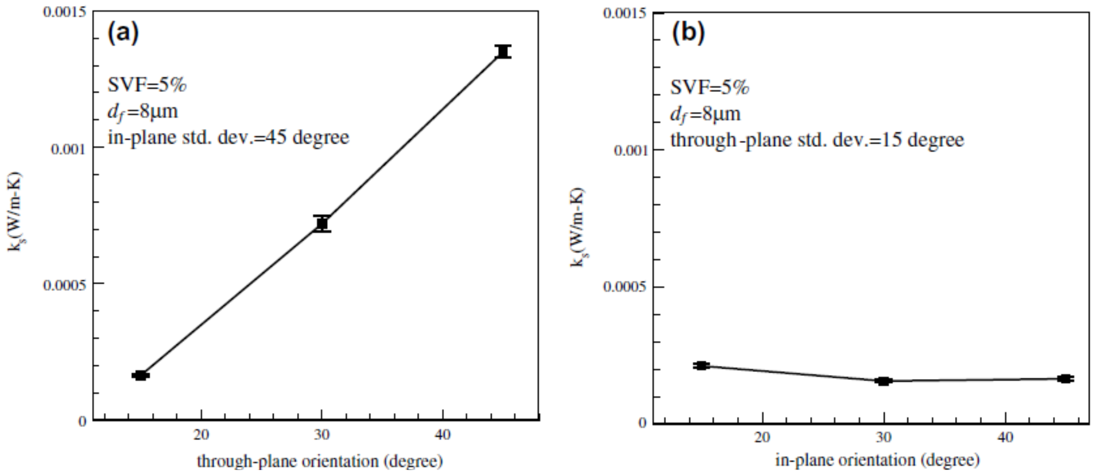








Five selected papers

2007 : B. Rousseau, D. de Sousa Meneses, P. Echegut, M. Di Michiel, and J.-F. Thovert, "Prediction of the thermal radiative properties of an x-ray µ-tomographied porous silica glass," *Applied Optics,* 46[20] 4266-76 (2007).

2010 : B. Rousseau, H. Gomart, D. Zanghi, D. Bernard, and S. M., "Synchrotron x-ray µ-tomography to model the thermal radiative properties of an opaque ceramic coating at T = 1000 K," *Journal of Materials Research,* 25 1890-97 (2010).

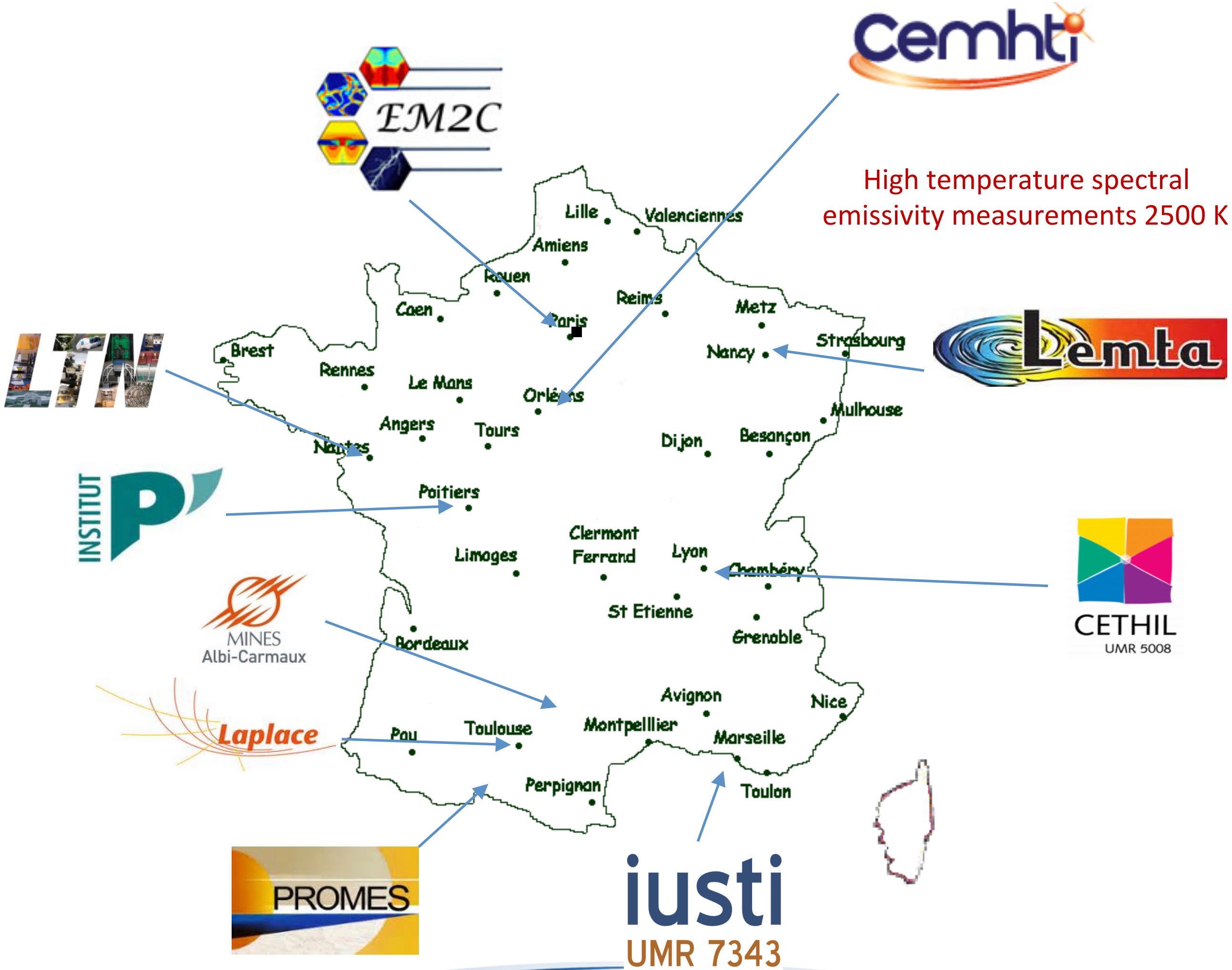
2011 : B. Rousseau, D. De Sousa Meneses, P. Echegut, and J.-F. Thovert, "Textural parameters influencing the radiative properties of a semitransparent porous media," *International Journal of Thermal Sciences,* 50[2] 178-86 (2011).

2015 : S. Guevelou, B. Rousseau, G. Domingues, J. Vicente, G. Flamant, and C. Caliot, "Evolution of the homogeneized volumetric radiative properties of a familliy of α-SiC foams with growing nominal pore diameter " *Journal of Porous Media,* 18[10] (2015).

2017 : S. Guévelou, B. Rousseau, G. Domingues, and J. Vicente, "A simple expression for the normal spectral emittance of open-cell foams composed of optically thick and smooth struts," *Journal of Quantitative Spectroscopy and Radiative Transfer,* 189 329-38 (2017)

GDR ACCORT : French research network from CNRS
Radiative heat transfer in semi-transparent materials

http://www.gdr-accort.cnrs.fr/

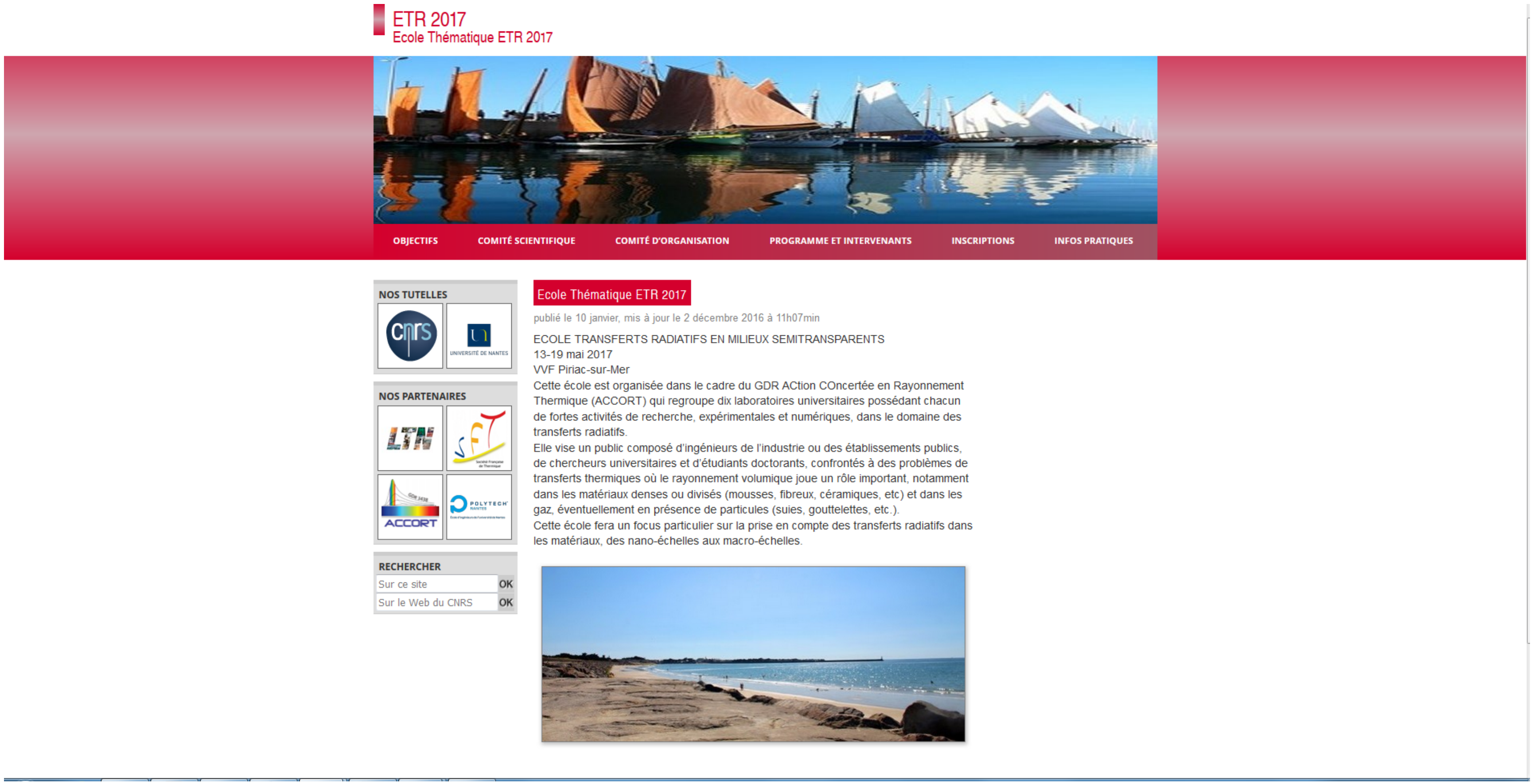


ETR 2017 “Ecole thématique transferts radiatifs en milieux semi-transparents”

Piriac-sur-Mer, France, May 13-19 2017

http://www.etr2017.cnrs.fr/

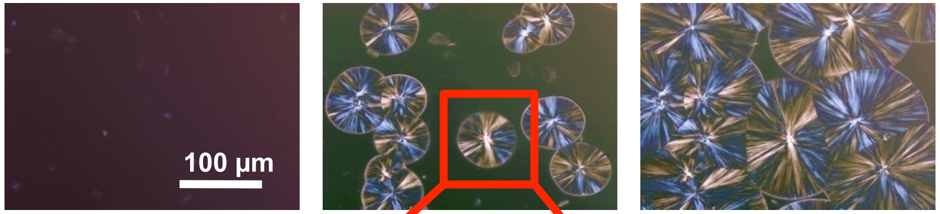
Responsible : Benoit Rousseau



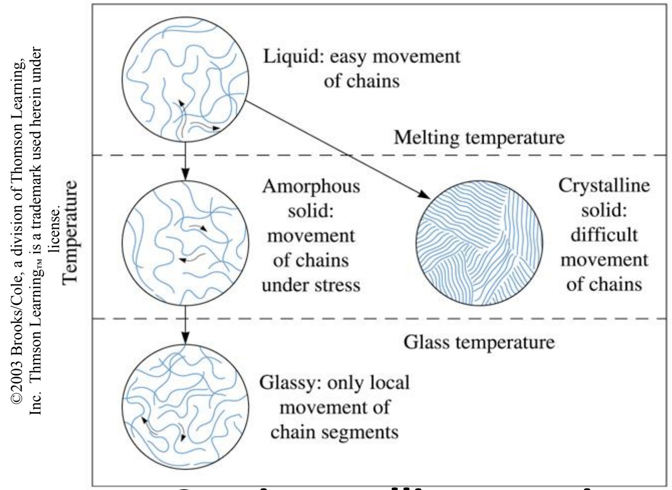
Isotactic PolyPropylene (iPP)* : a multi scale medium for scattering and absorbing thermal radiations

iPP pellets —T,P,s→ iPP slab

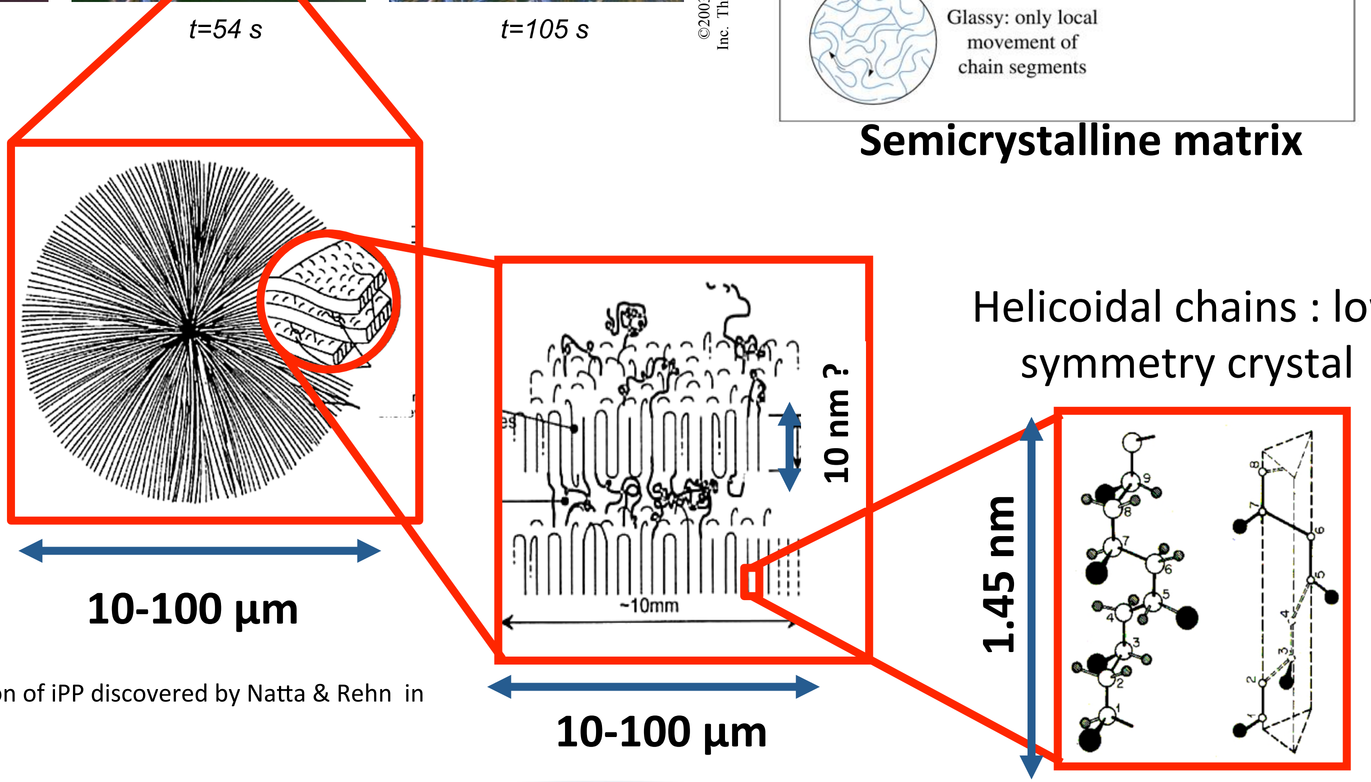
Thermal history↔elaboration process



t=0 s *t=54 s* *t=105 s*



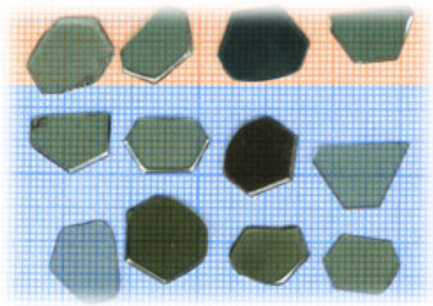
Semicrystalline matrix

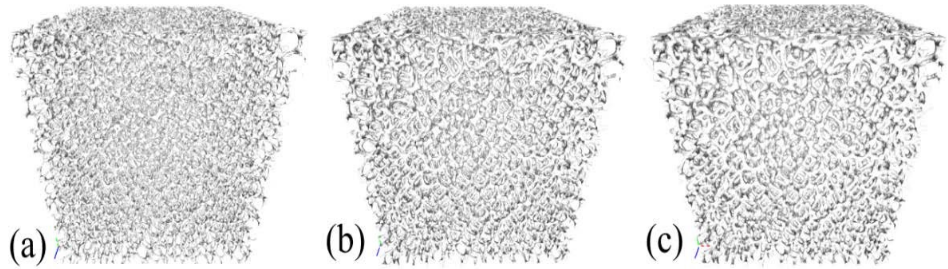


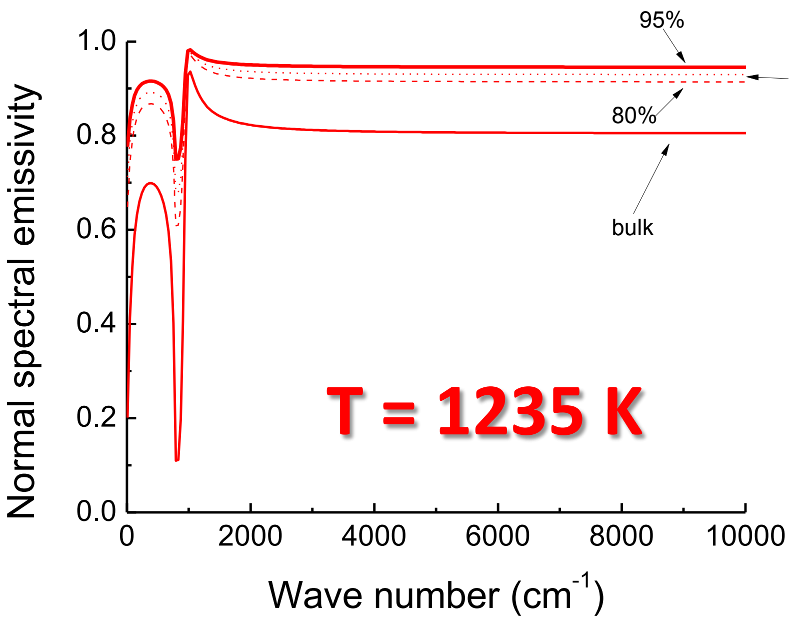
Helicoidal chains : low symmetry crystal

*Polymerization of iPP discovered by Natta & Rehn in 1954

Is there an additional phenomenon than that associated with texture?

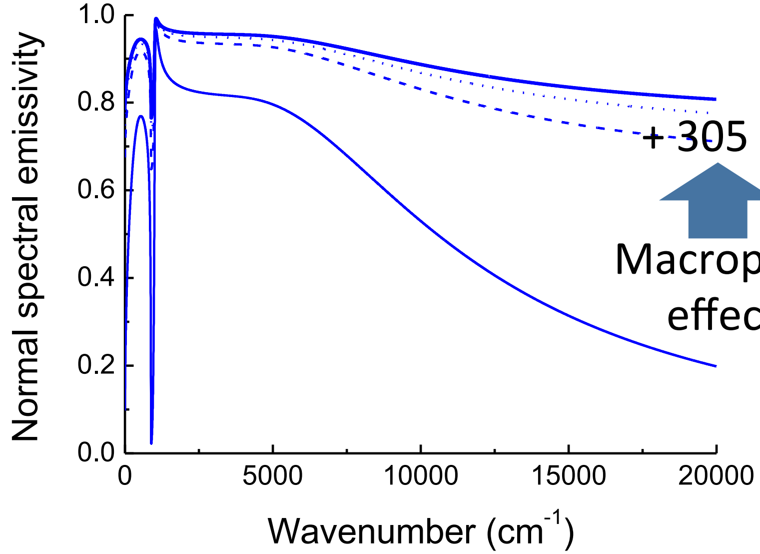






+ 17,5 %

Macropore effect

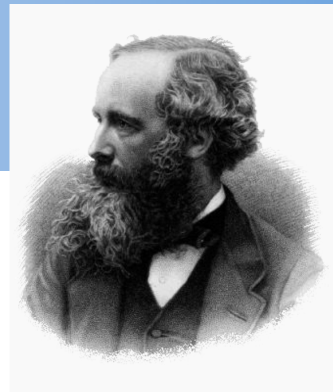


+ 305 %

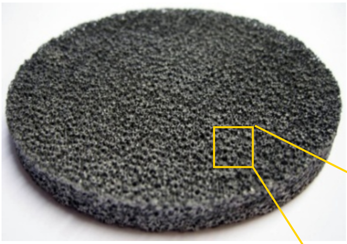
Macropore effect

B. Rousseau et al. , AIP Advances 2016 6 065226

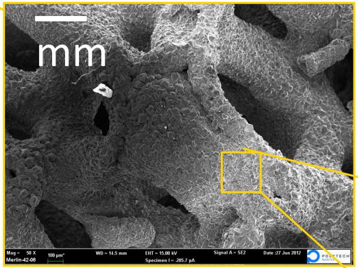
Need to develop a multi-length scale approach for modelling TRPs



complex refrative indexes



α-SiC foam

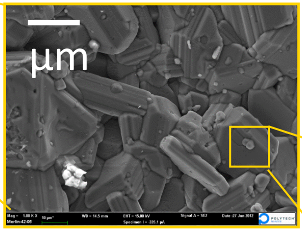


$$\rho_{2\to 1} = \frac{1}{2}\left[\left|\tilde{r}_{perp}\right|^2 + \left|\tilde{r}_{para}\right|^2\right]$$

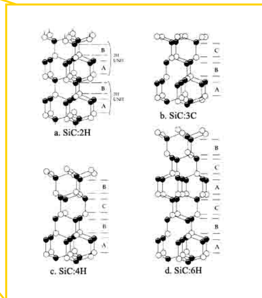
$$\tilde{r}_{perp} = \frac{E_{perp,r}}{E_{perp,i}} = \frac{\cos\Theta_i - \tilde{m}\cos\Theta_t}{\cos\Theta_i + \tilde{m}\cos\Theta_t}$$

$$\tilde{r}_{para} = \frac{E_{para,r}}{E_{para,i}} = \frac{\cos\Theta_t - \tilde{m}\cos\Theta_i}{\cos\Theta_t + \tilde{m}\cos\Theta_i}$$

$$\tilde{m} = \frac{\tilde{n}_1}{\tilde{n}_2}$$



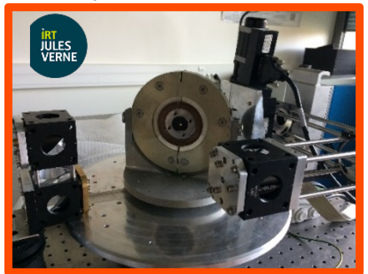
$$n + ik = \sqrt{\varepsilon' + i\varepsilon''}$$



nm

Spectroscopie de réflexion/transmission/émission → 900 K

BRDF/BTDF→ 700 K

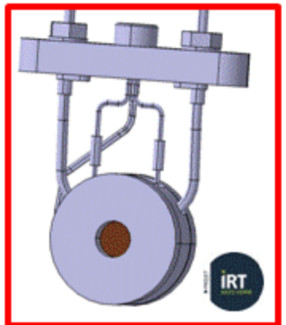


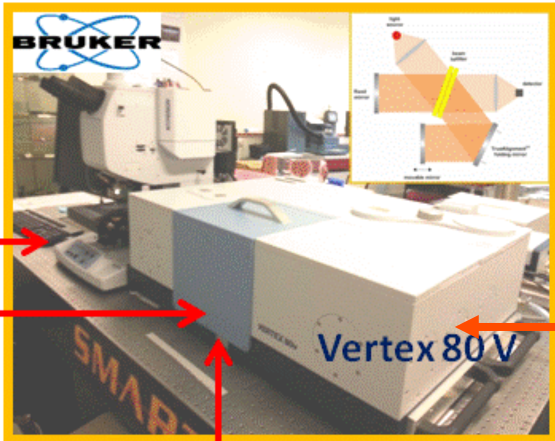
Financement : CPER 2007-2013 Région PAYS DE LA LOIRE

IR lointain→Visible (0.4< λ<200 µm)

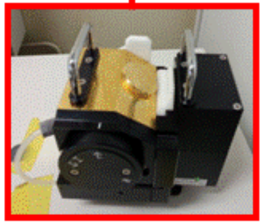
Microscope IR réflexion/transmission
(2<λ<25µm)

Cellule HT→900 K

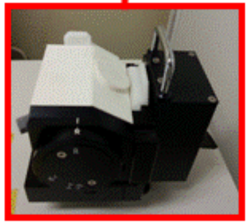




Platine réflexion/transmission
(1.4µm<λ<200µm)



Sphère intégrante dorée
Φ =75 mm
(1.4µm<λ<25µm)



Sphère intégrante téflon
Φ =75 mm
(0.4µm<λ<1.4µm)