

Multiphysical couplings in polymer and composite manufacturing processes. Heat transfer, solidification, adhesion...

[Arthur Levy](#)

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Arthur Levy

Grew up in Paris

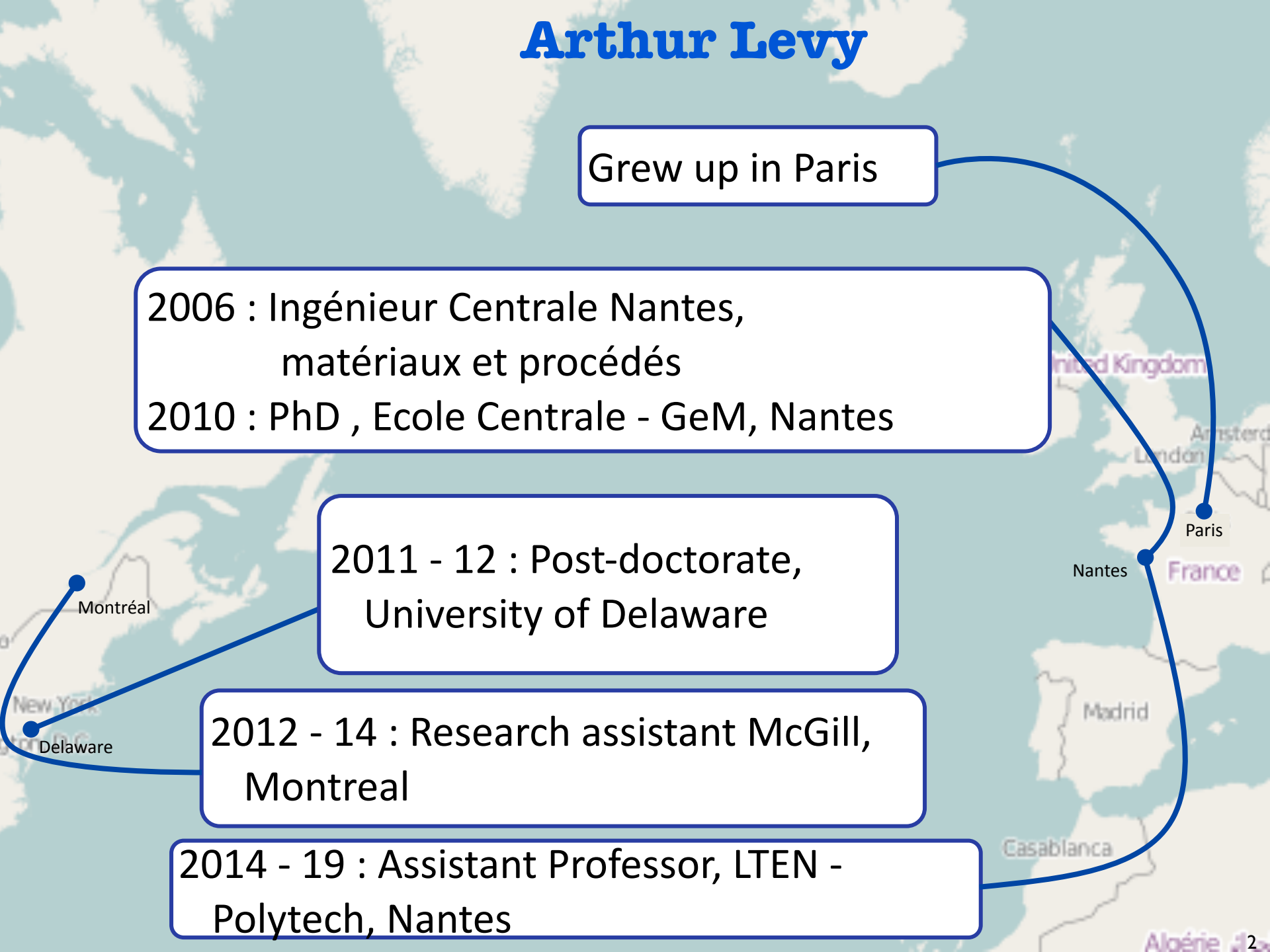
2006 : Ingénieur Centrale Nantes,
matériaux et procédés

2010 : PhD , Ecole Centrale - GeM, Nantes

2011 - 12 : Post-doctorate,
University of Delaware

2012 - 14 : Research assistant McGill,
Montreal

2014 - 19 : Assistant Professor, LTEN -
Polytech, Nantes



Agenda

- Nantes, France.
- Laboratoire de Thermique et Energie de Nantes
- Polymer and composite manufacturing team
- Simulating composite manufacturing processes

Nantes

Nantes (600 000 inhab.)

Région
PAYS DE LA LOIRE



main campus



UNIVERSITÉ DE NANTES

Centrale
Nantes

Chantrerie



UNIVERSITÉ DE NANTES



AIRBUS
GROUP

IRT
JULES
VERNE



University of Nantes

Second biggest university in France by number of students
The largest University and second most important centre
for research in the West of France.



UNIVERSITÉ DE NANTES

20 Faculties, Schools ou Institutes
300 undergraduate and postgraduate degrees
based on European model :
Degree-Master-Doctorats

more than **38,000** undergraduates and postgraduates

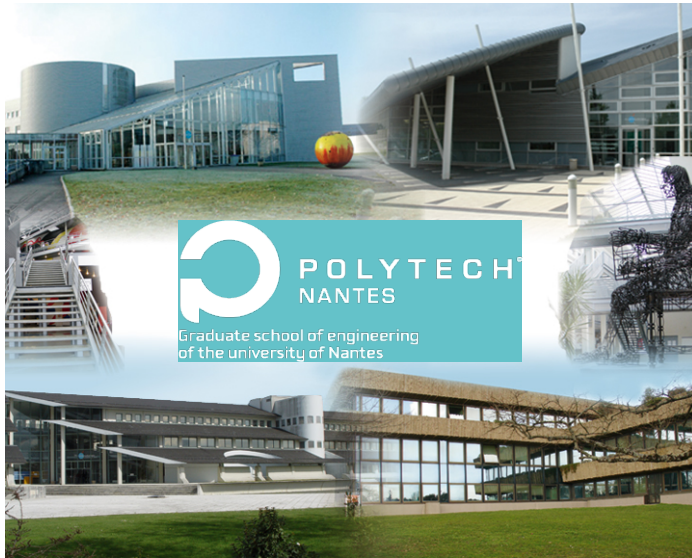
12,000 students in continuing education

1,760 permanent teaching staff

1,045 library, technical and administrative personnel

1,400 part-time teachers including experienced professionals

Polytech' Nantes



7 engineering specialities

ETN	Electronic and Digital Technologies
GC	Civil Engineering
GE	Electrical Engineering
GPB	Process and Bioprocess Engineering
INFO	Computer Science
MAT	Materials Sciences
TE	Thermal and Energy Sciences

400
Graduates every year

1500
Engineering
students

250
Master's and
PhD students

7100
Alumni

120
Professors and
assistants professors

Laboratoire de Thermique et Energie de Nantes (LTEN)

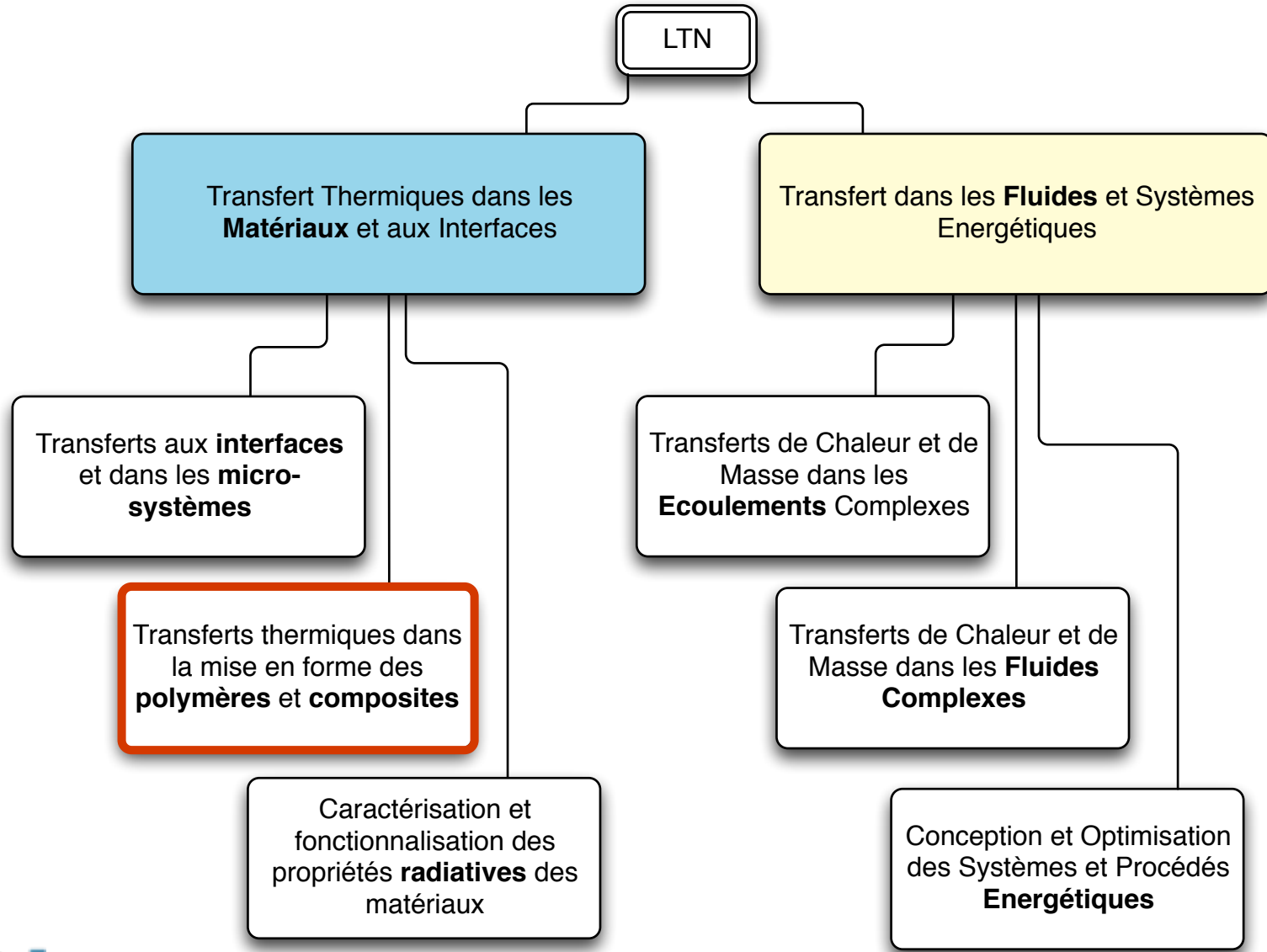


~70 people



UNIVERSITÉ DE NANTES





Composite team



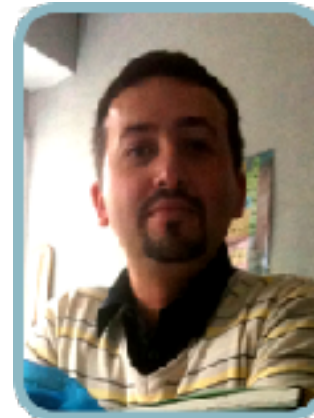
Didier Delaunay



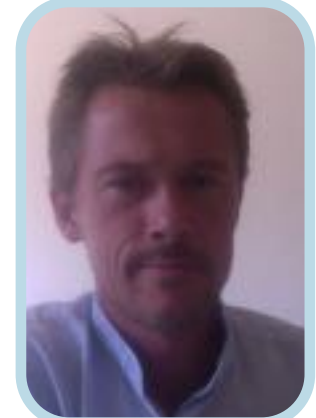
Jean-Luc Bailleul



Vincent Sobotka



Nicolas Boyard



Steven Le Corre

A Composite hub in France

Industries

AIRBUS
GROUP

ARKEMA
INDUSTRIALS

DAHER

OP
PLASTIC OMNIUM

SOLVAY

CORIBUS
COMPOSITES

PSA PEUGEOT CITROEN

Academics

UNIVERSITÉ DE NANTES

cnrs

MINES
Nantes

ECN
Centrale
Nantes


icam

Institutes

IRT
JULES
VERNE

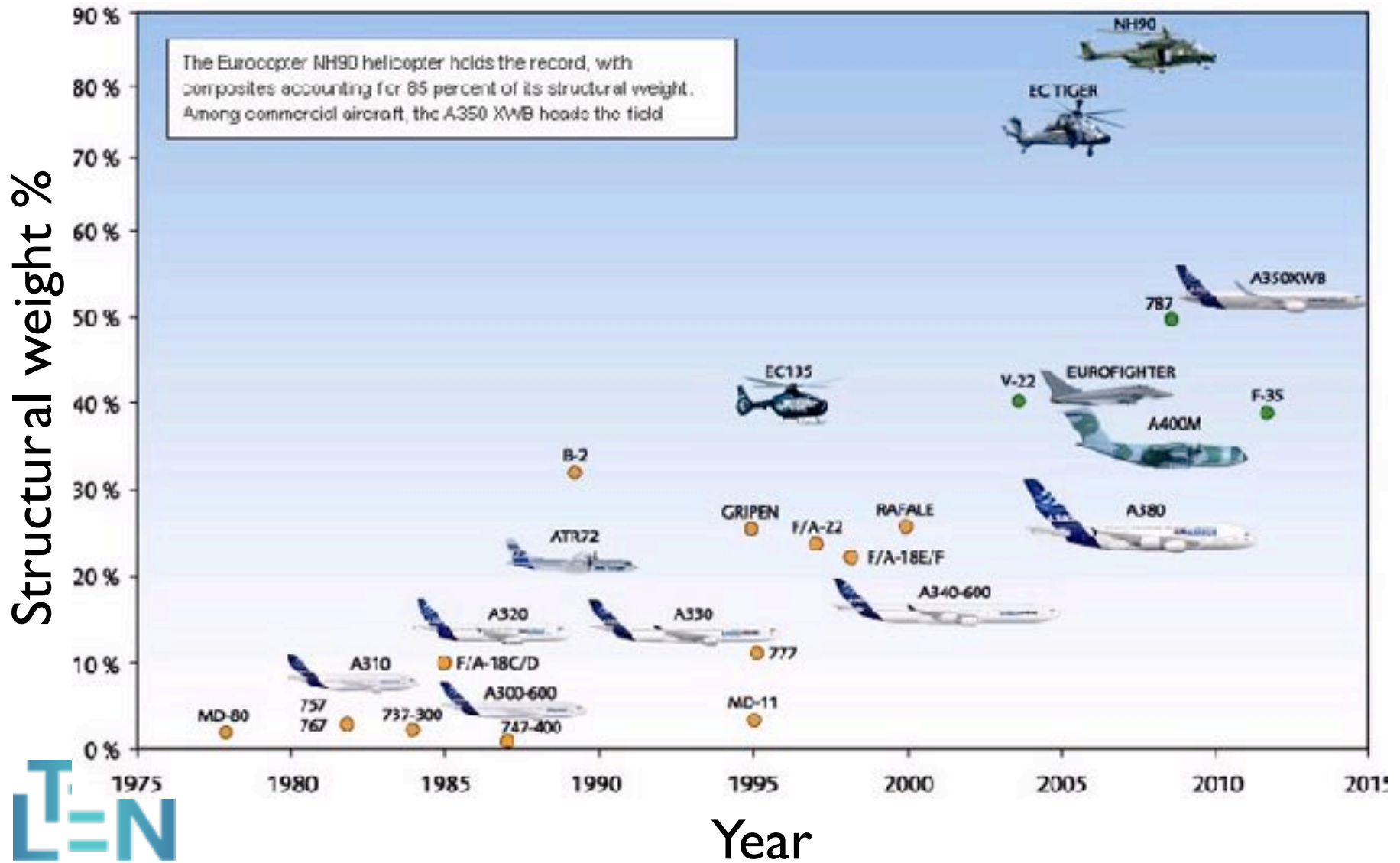
EMC2

Technocampus
Composites



Multiphysical modeling of composite manufacturing processes

Composite use in aeronautical industry



Today's challenges

Increase part complexity



Ultra-thick laminate Airbus



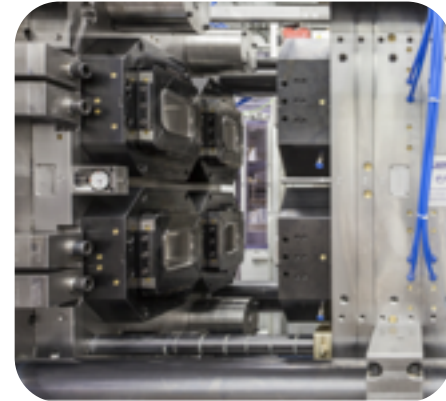
Boeing assembly line

- Intricate / thick parts
- Large parts

Reduce cost

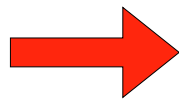


www.sabca.be



Plastic Omnium

- Fast and efficient cycles
- Out-of-autoclave



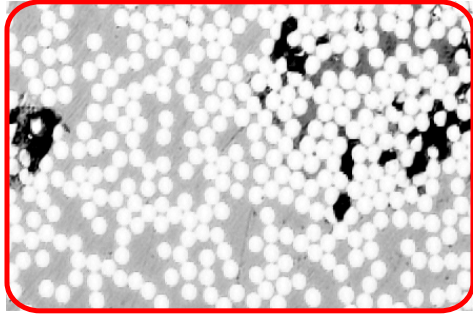
New forming processes

Motivation

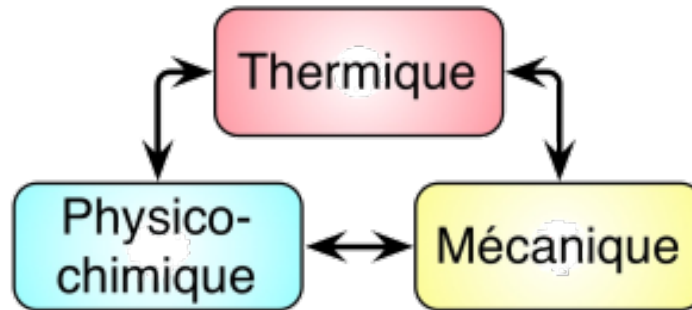
Industrial goal: control and optimize forming/ assembling processes.

Method: develop predictive tools (simulation)

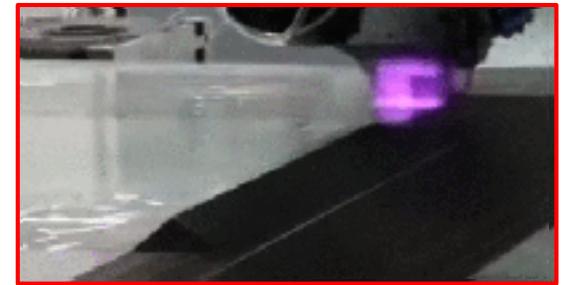
scientific challenges



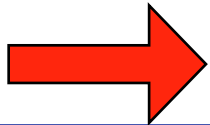
Complex morphology



Multi physical couplings

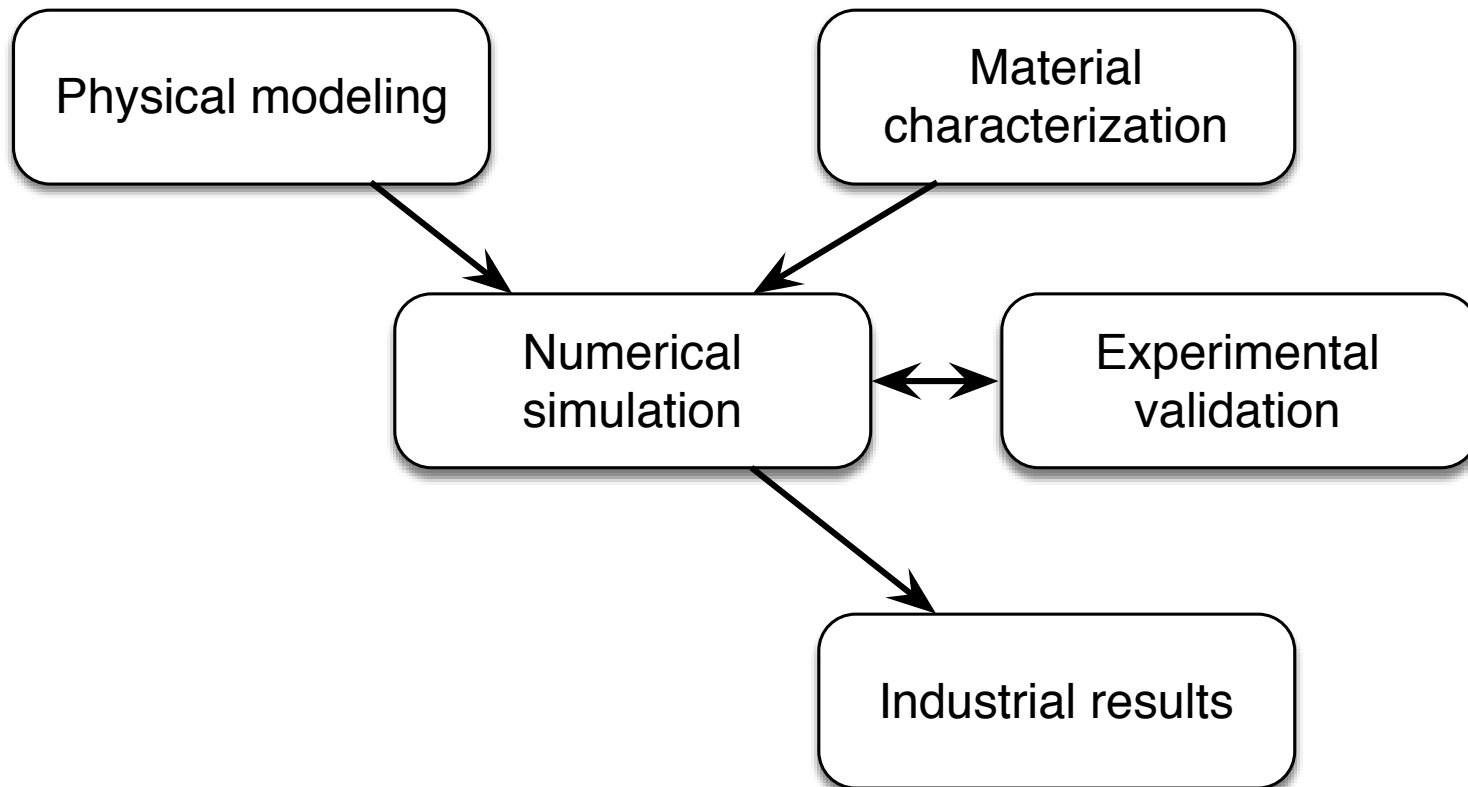


Severe loading

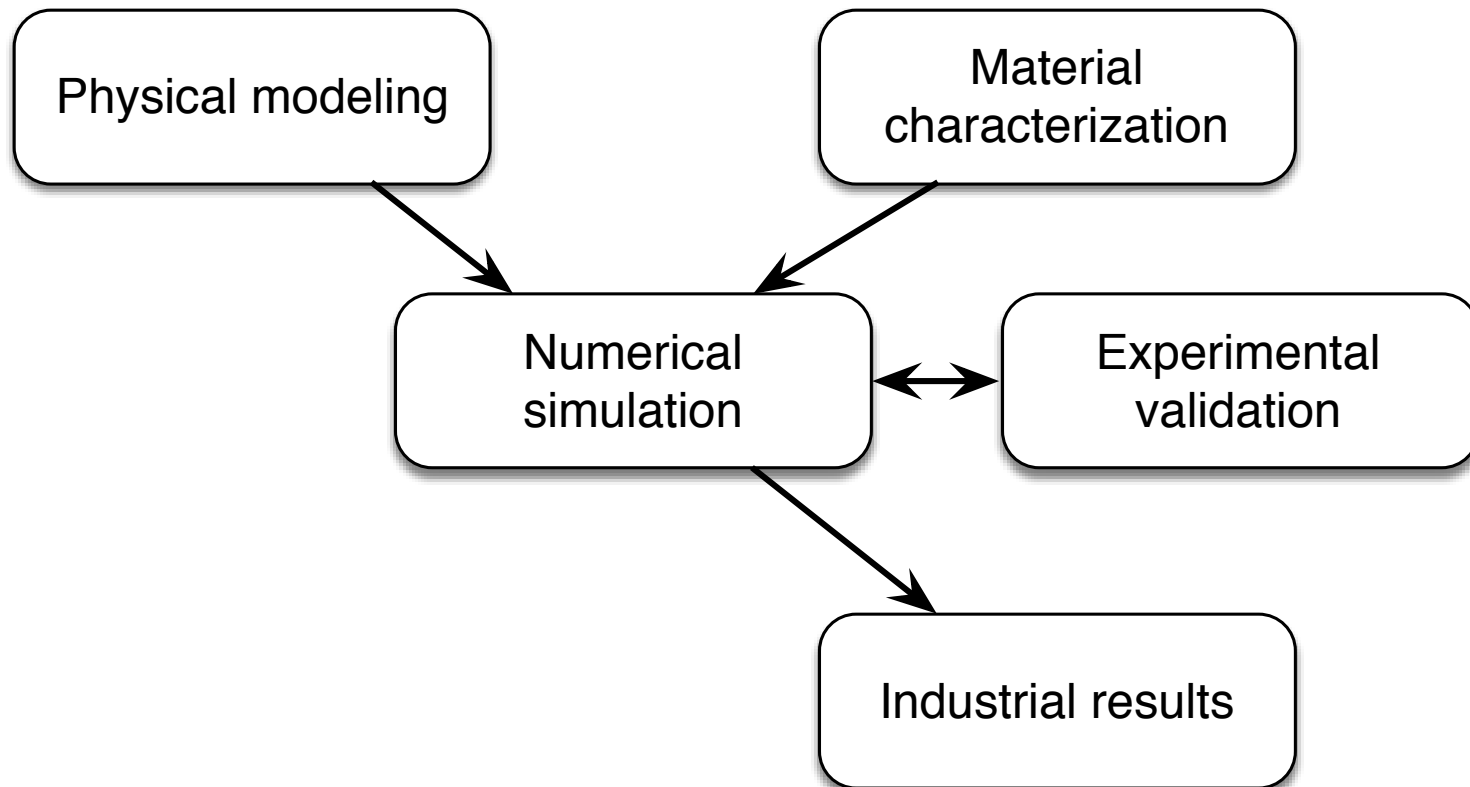


Theoretical and numerical methods

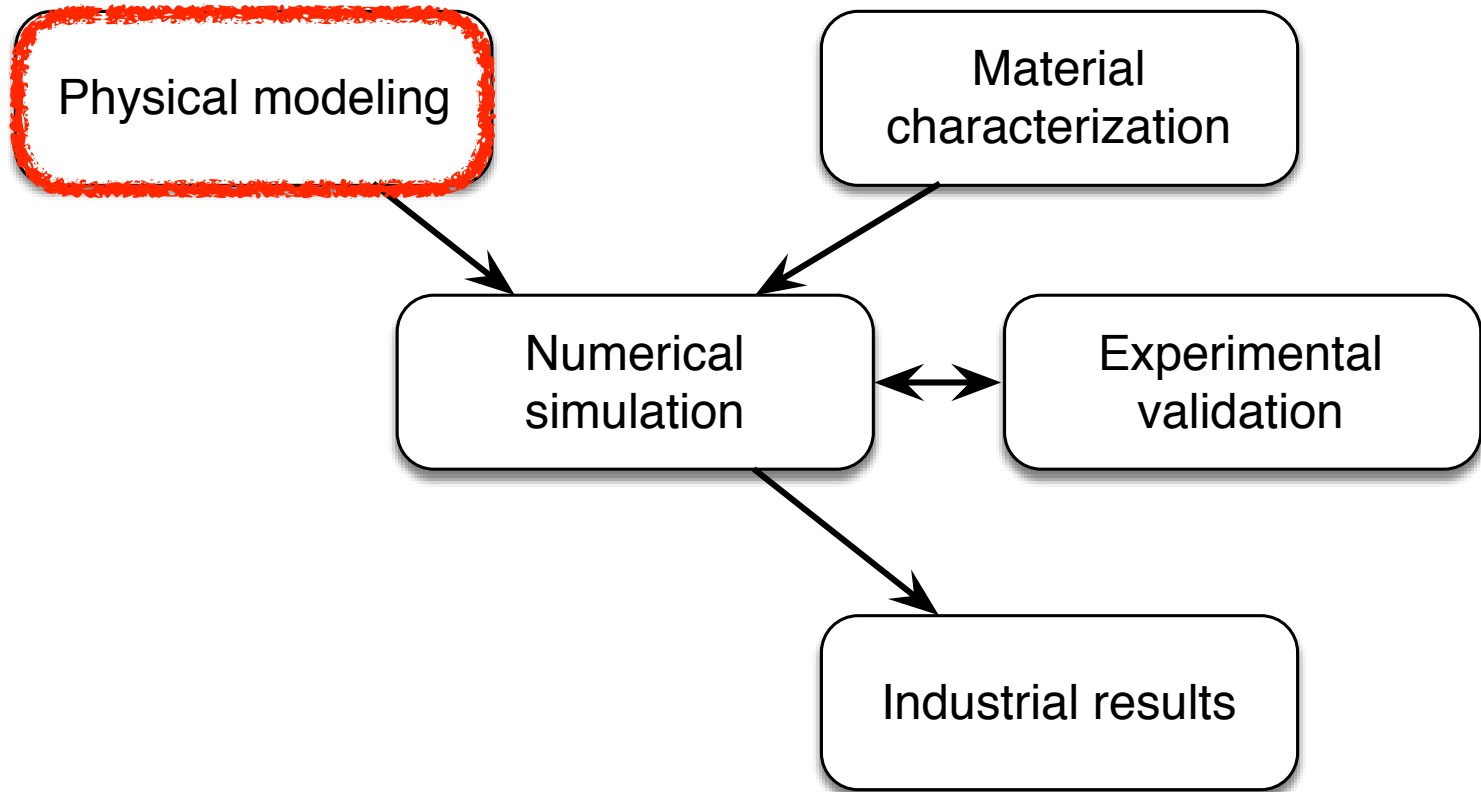
Scientific approach



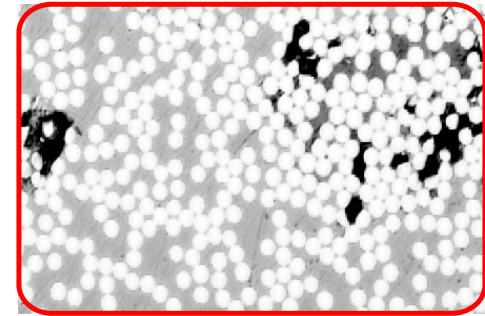
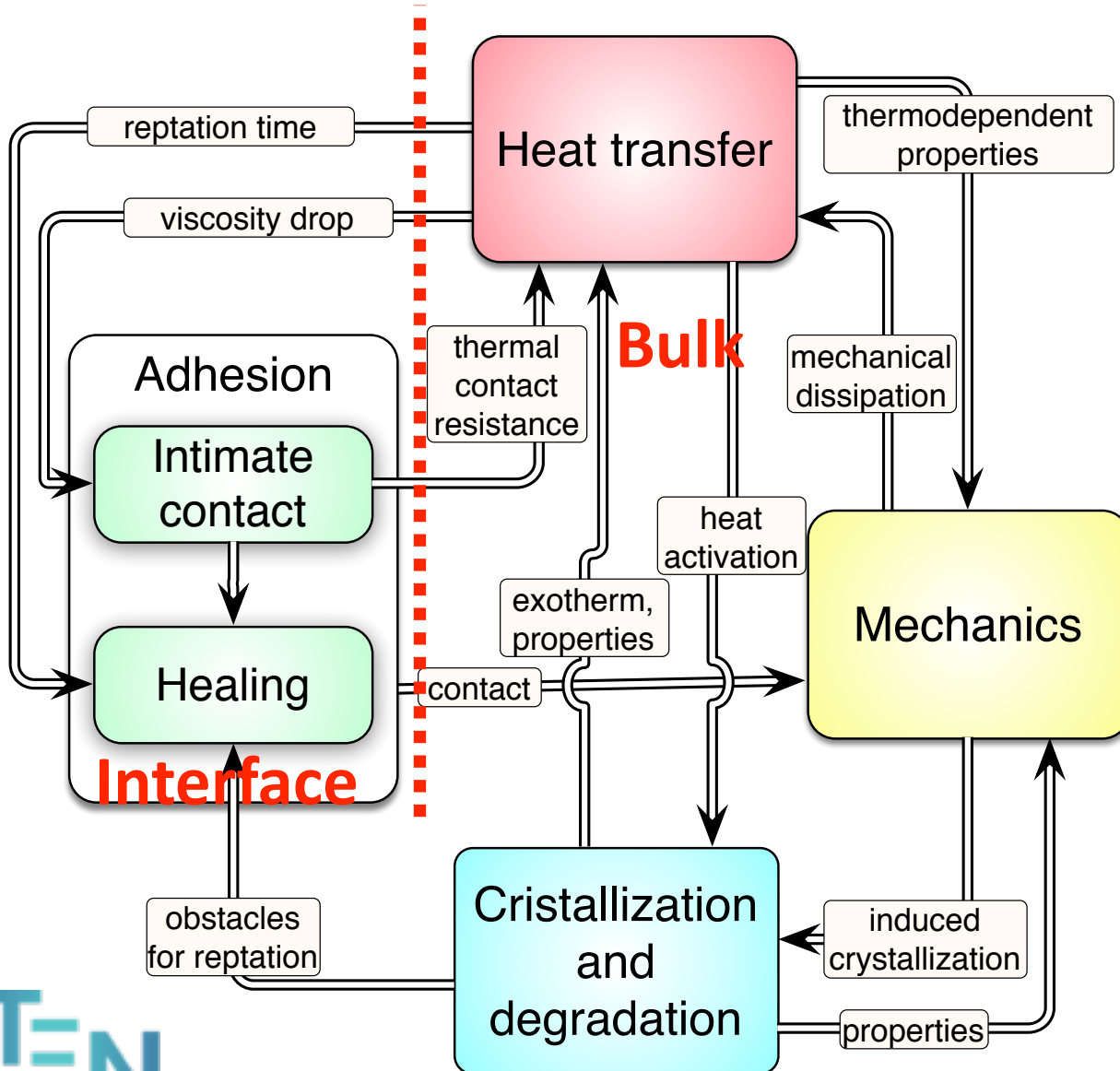
Outlines



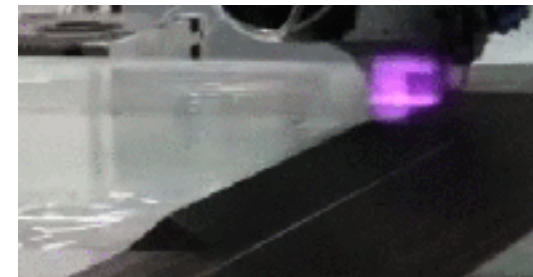
I - Introduction



Physical modeling



Complex morphology



Severe loading

Heat transfer and crystallization kinetics in thermoplastic composite processing. A coupled modelling framework.



Arthur Levy, Steven Le Corre, Vincent Sobotka, Maxime Villière

Thermoplastic compression moulding

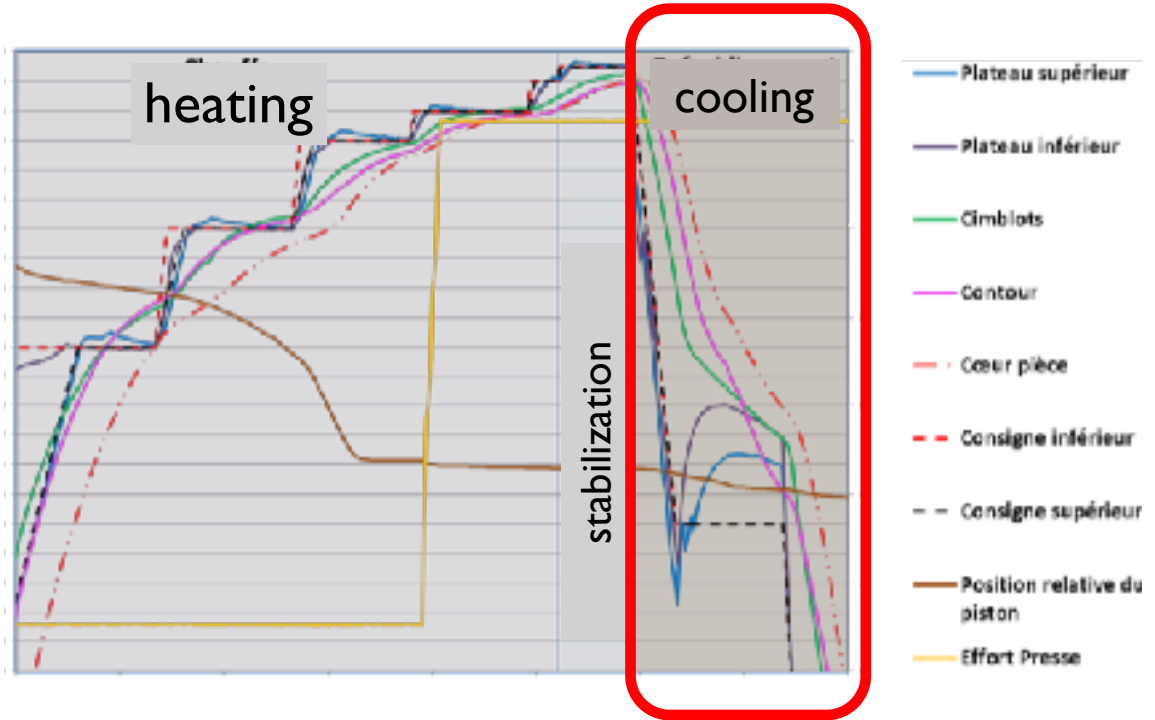
Procedure



Pinette Press

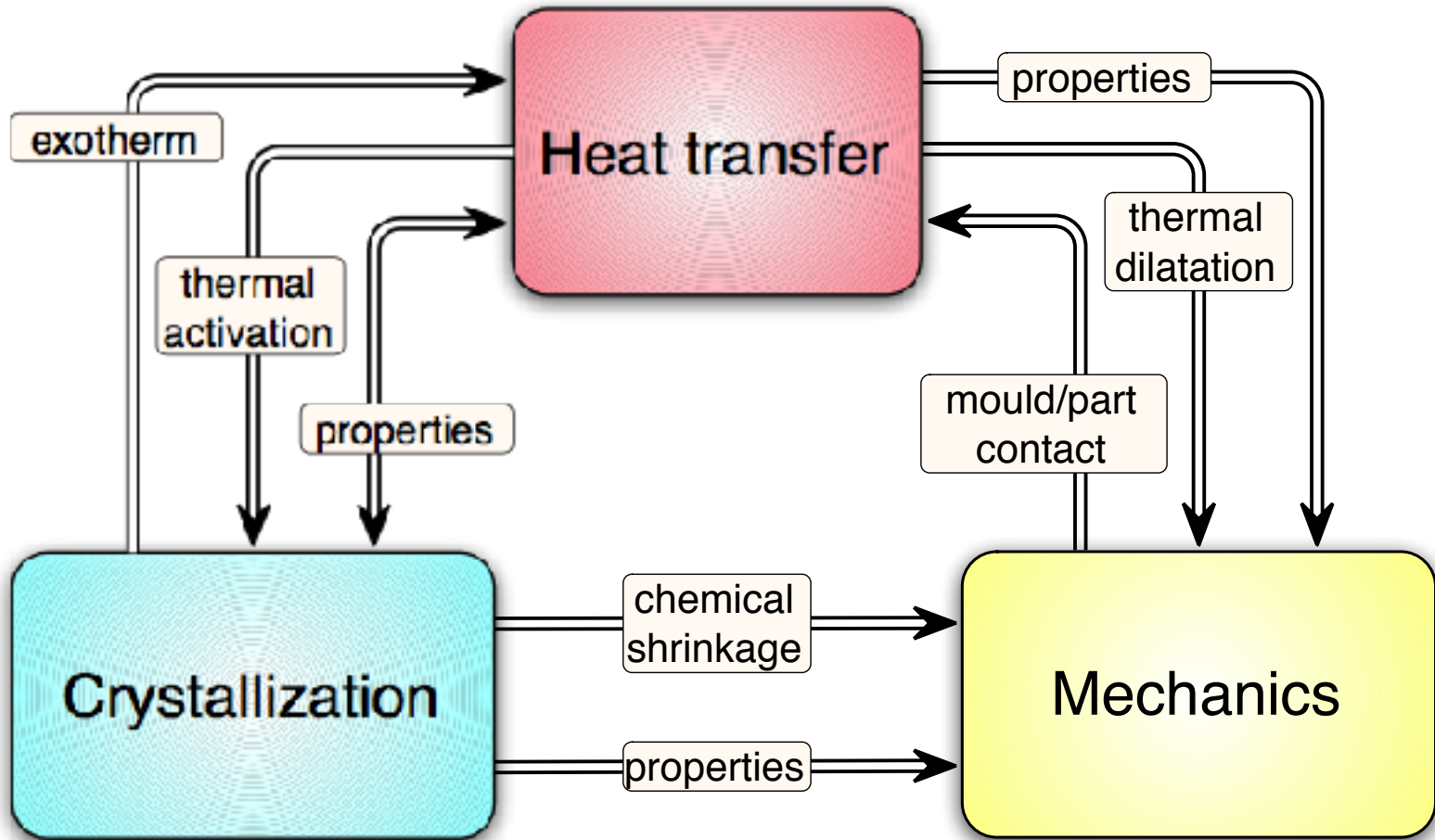
Thick part

Complex temperature cycle



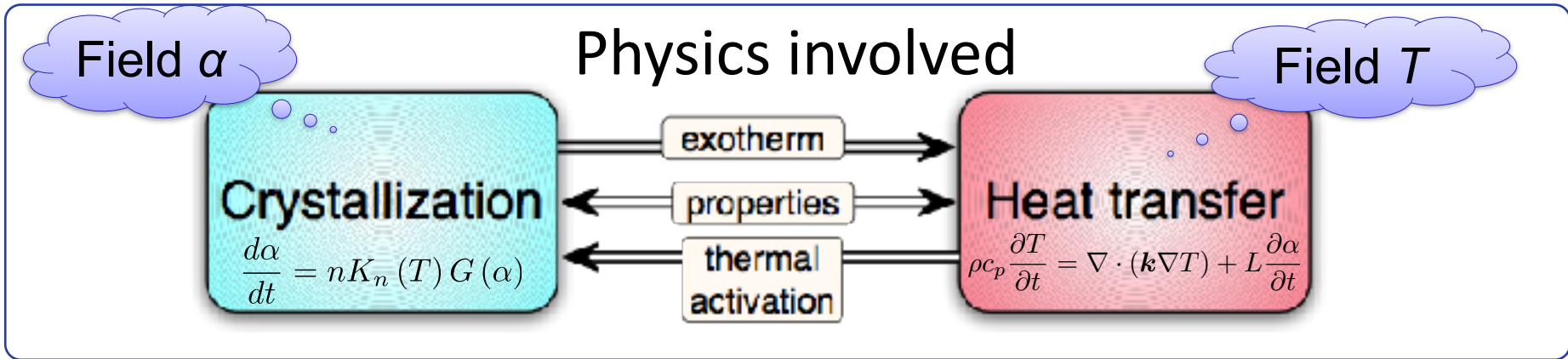
Study of the cooling phase

Motivation

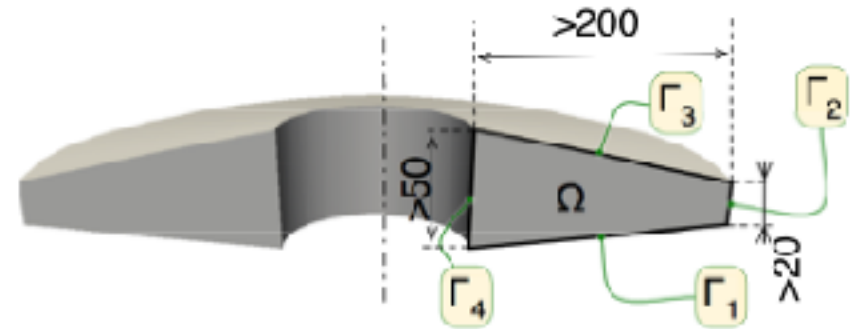
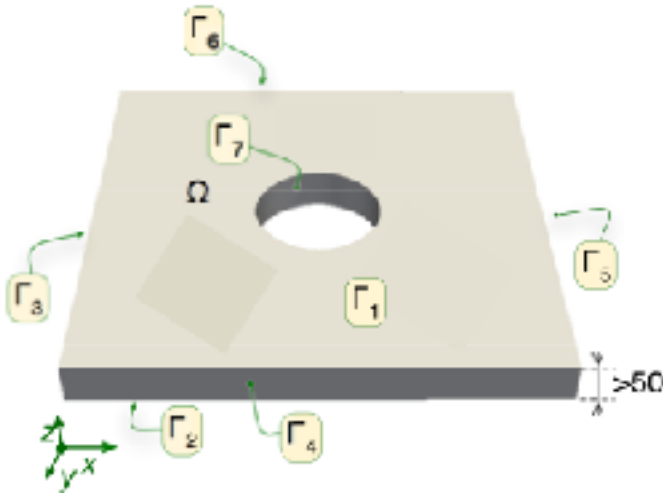


Prediction of heat transfer and crystallization.
Understanding / control / optimization of the process

Framework



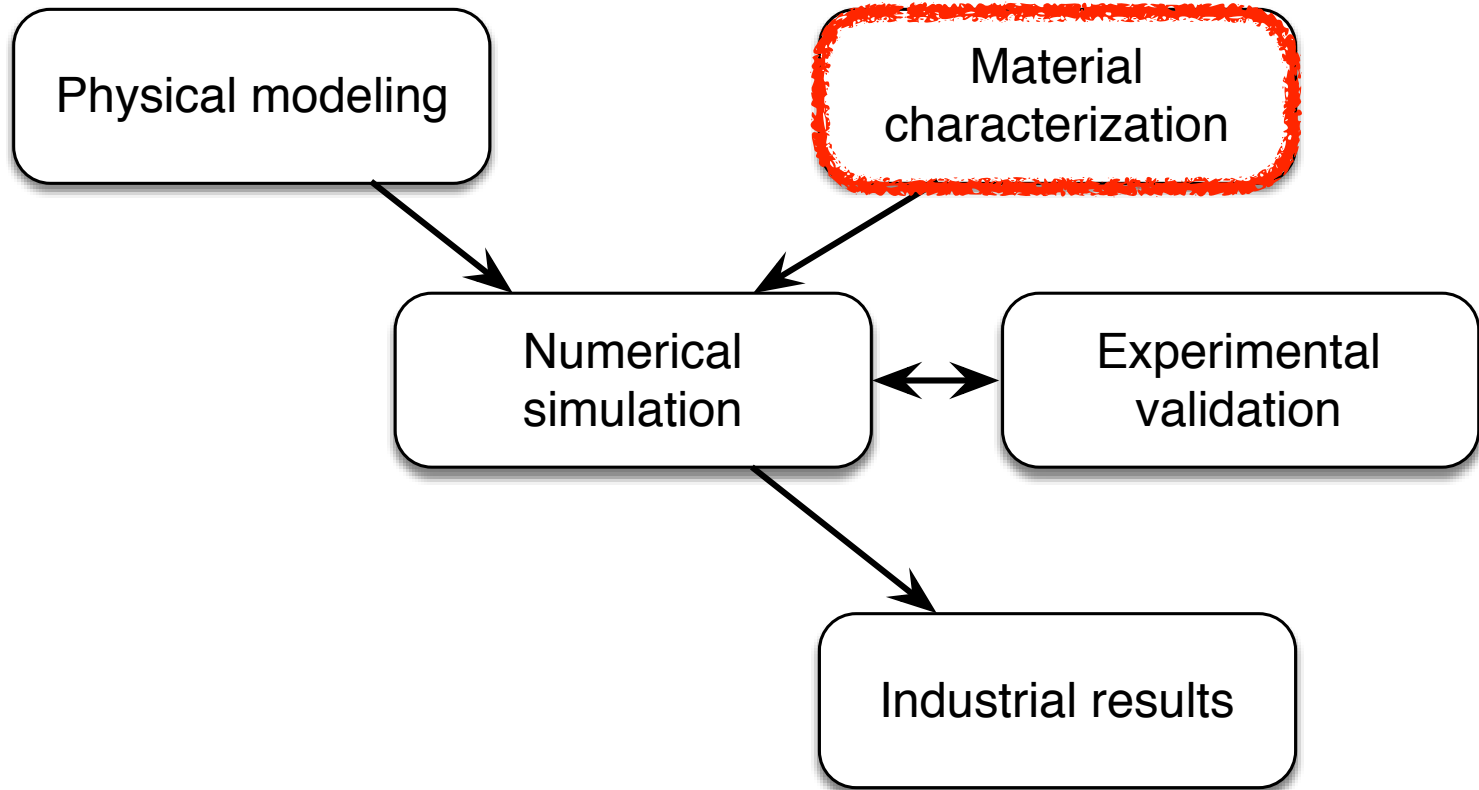
Thick geometries



Real 3D industrial intricate domain
(idealized here for confidentiality reasons)

Simplified 2D geometry

II - Characterization



$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\mathbf{k} \nabla T) + L \frac{\partial \alpha}{\partial t}$$

Anisotropic thermal conductivity characterization using the PIMS bench

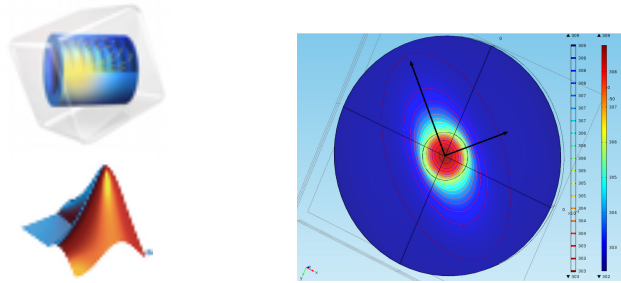


Vincent Sobotka, Maxime Villière

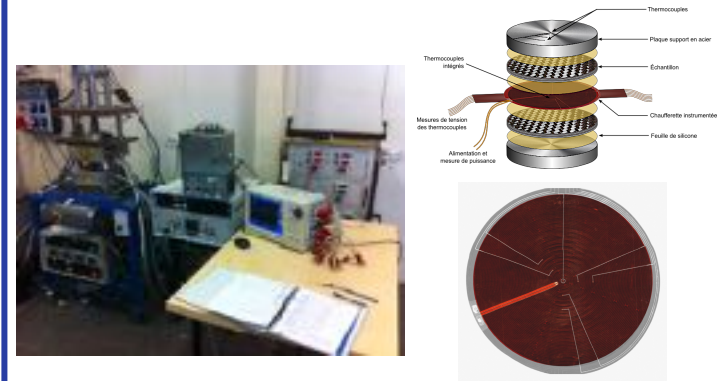
Characterization

Example of inverse method: the PIMS bench

Numerical simulation



Experimental setup



Parameter set

conductivities
heat capacities
TCR

Error estimation

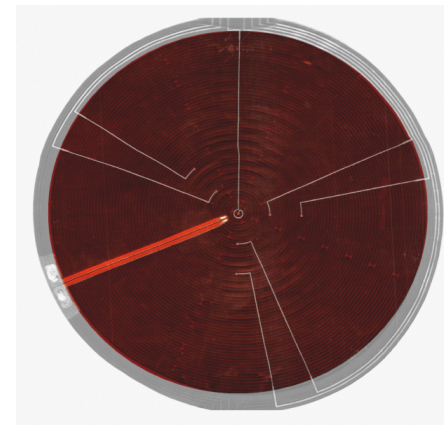
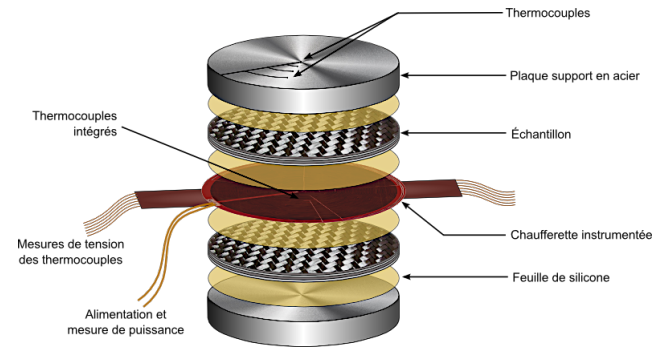
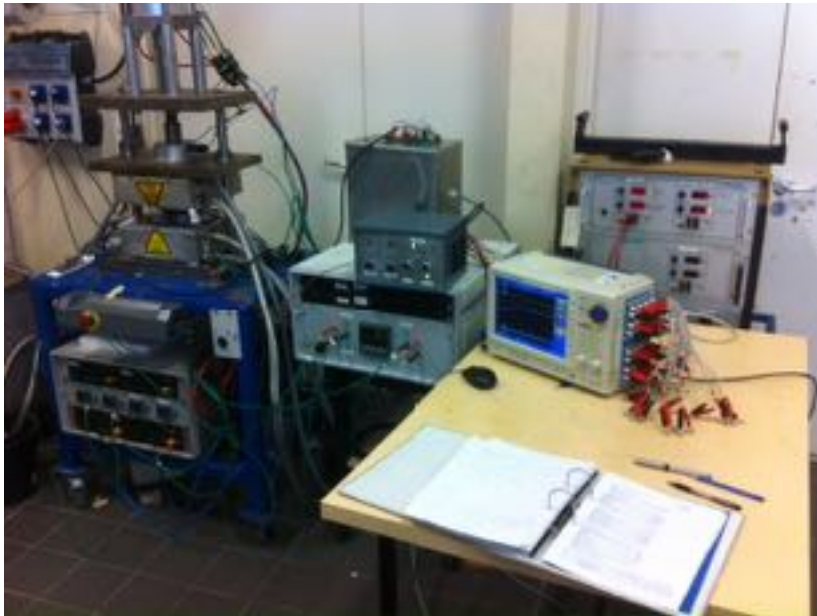
$$\sum_{TC \text{ times}} (T_{num} - T_{exp})^2$$

Minimization

Characterization

Example of inverse method: the PIMS bench

Experimental setup



Pa

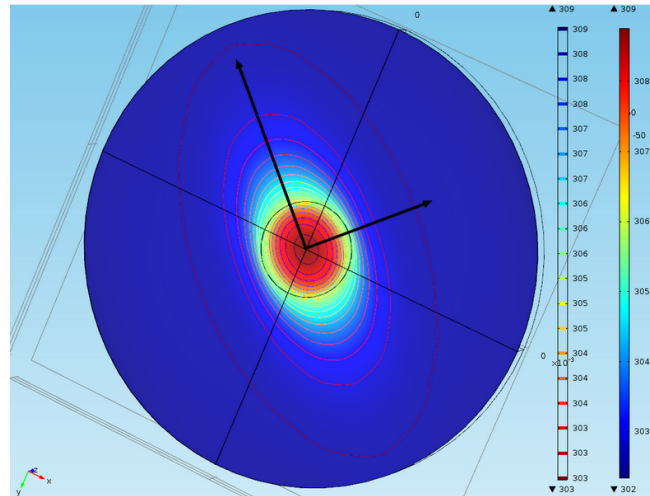
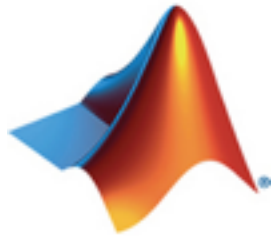
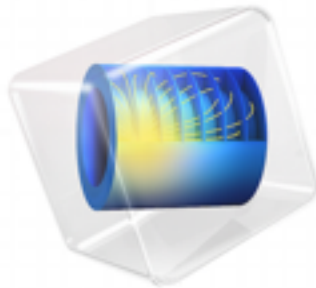
ch
T

Characterization

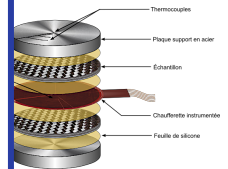
Example of inverse method: the PIMS bench

Numerical simulation

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T)$$



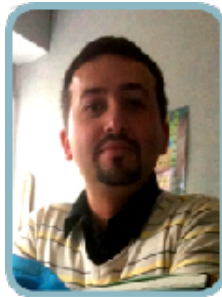
setup



Par

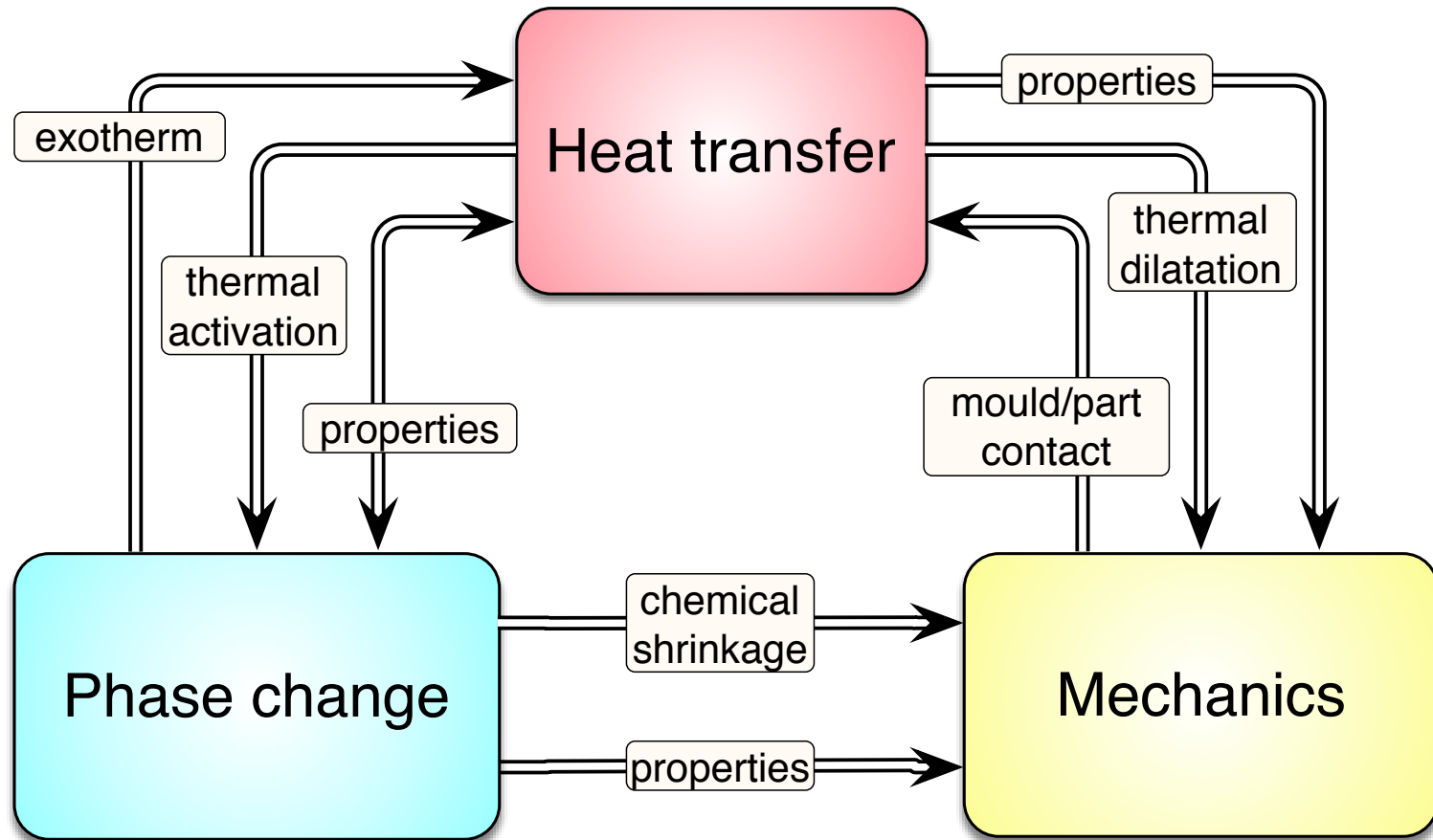
con
hed
TCH

Multiphysical characterization: PVT-Family



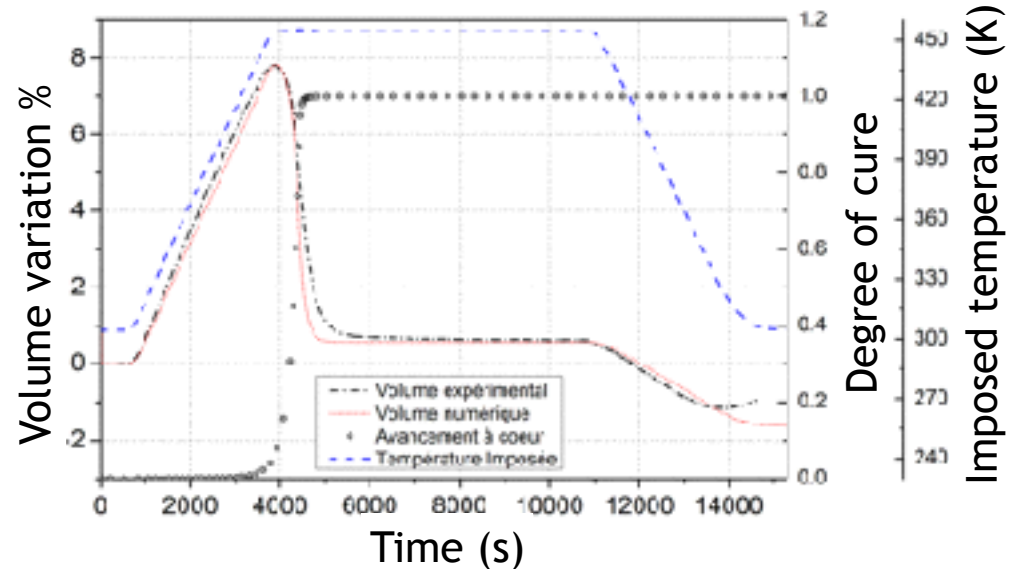
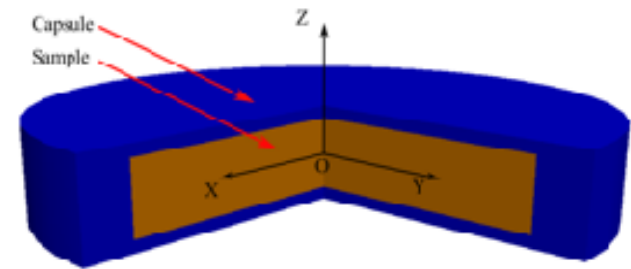
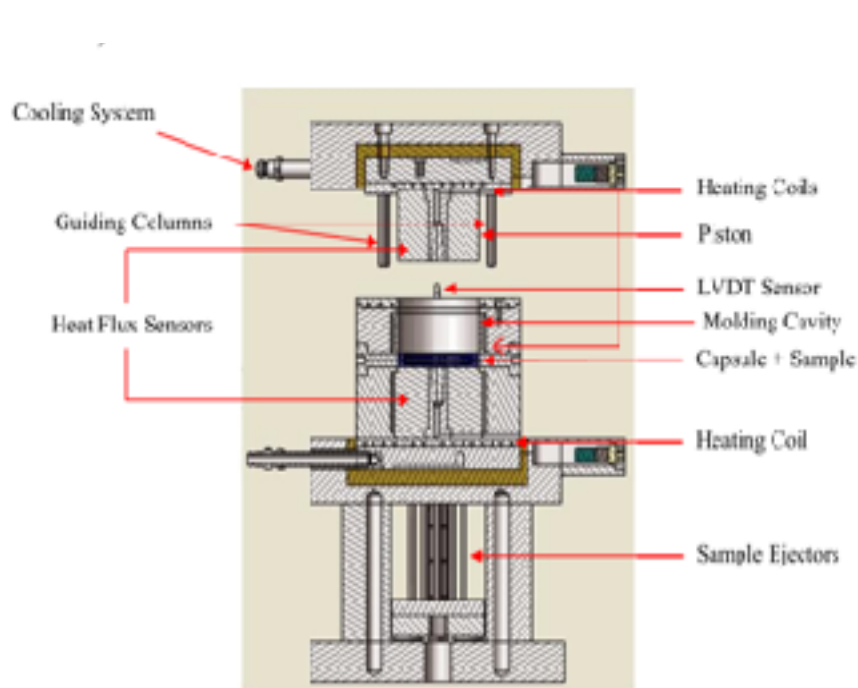
Mael Peron, Vincent Sobotka, Nicolas Boyard, Steven Le Corre, Xavier Tardif,
Didier Delaunay

Motivation



Existing PVT α

Multiphysical characterization of neat resin



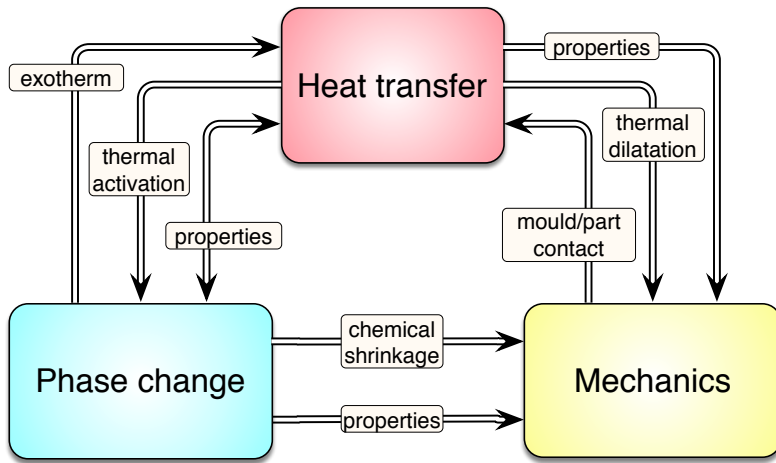
[Millischer & Delaunay 00, Yassir et al 13, Peron et al 16]

Analytical data extraction: strong assumptions
Incompressible, contact, hydrostatic

→ α, β, λ

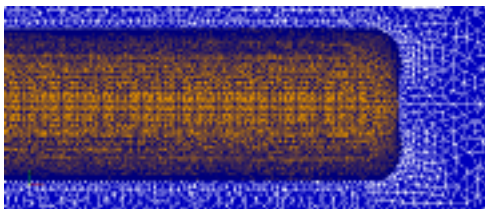
Improved analysis

Multiphysical numerical resolution



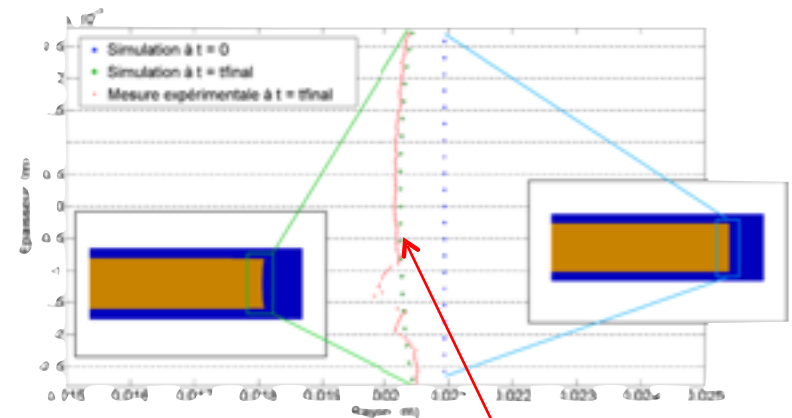
FreeFem++

Contact handling



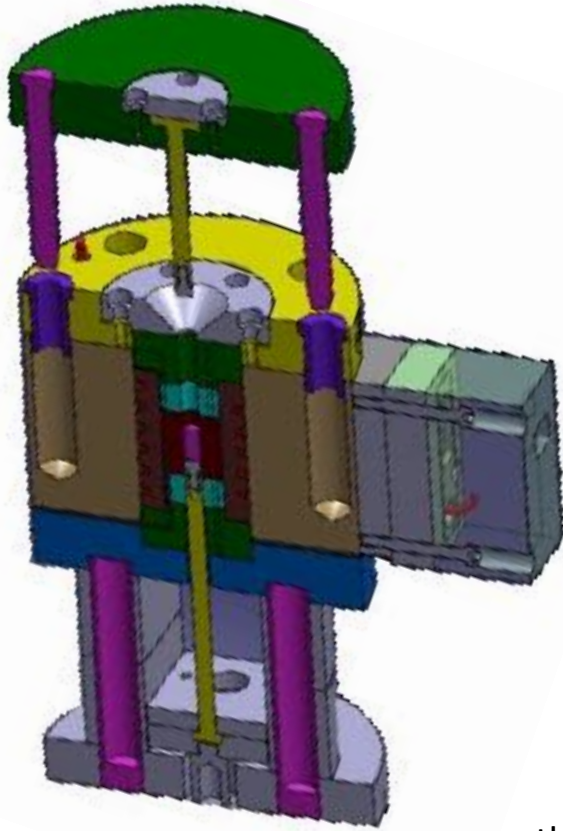
Results

- Compressible material
- Possible loss of contact
- Good correlation

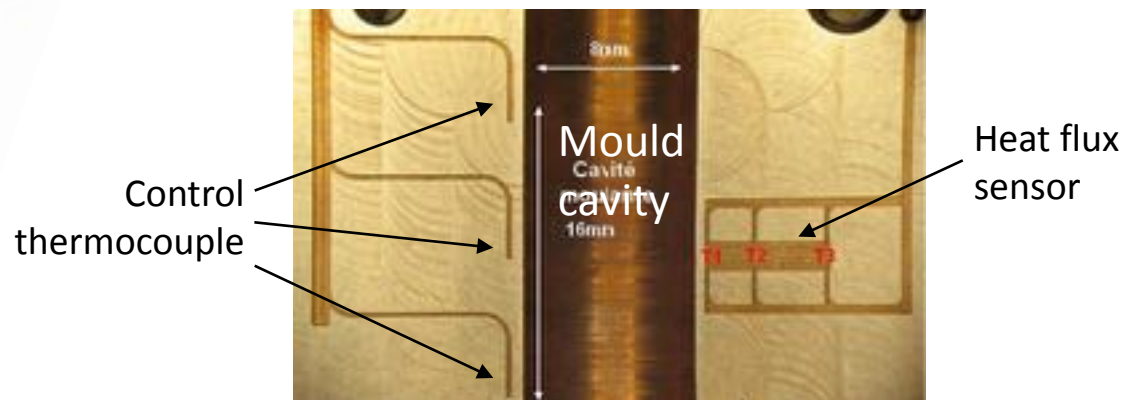


[Peron et al 16]

PVT - XT



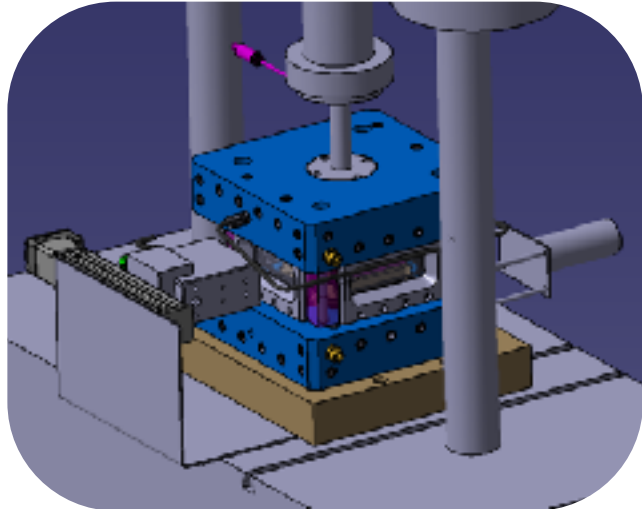
Sample



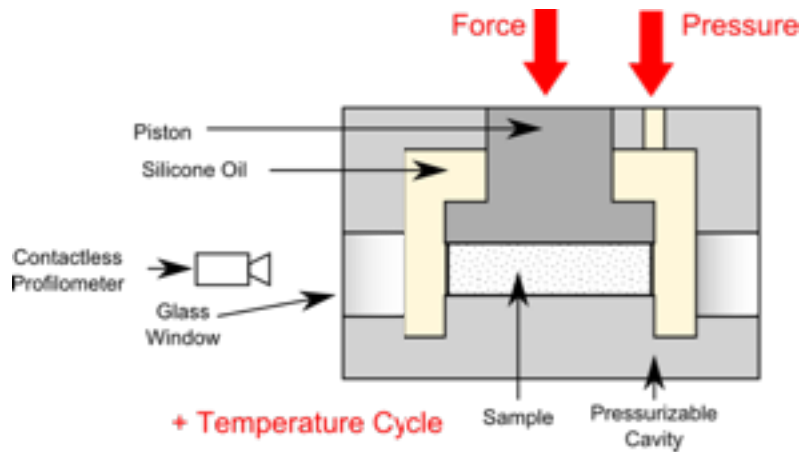
[Tardif et al 12]

PVT-HADDOC

Homogeneous Anisotropic Deformation and Degree of Cure



Procedure



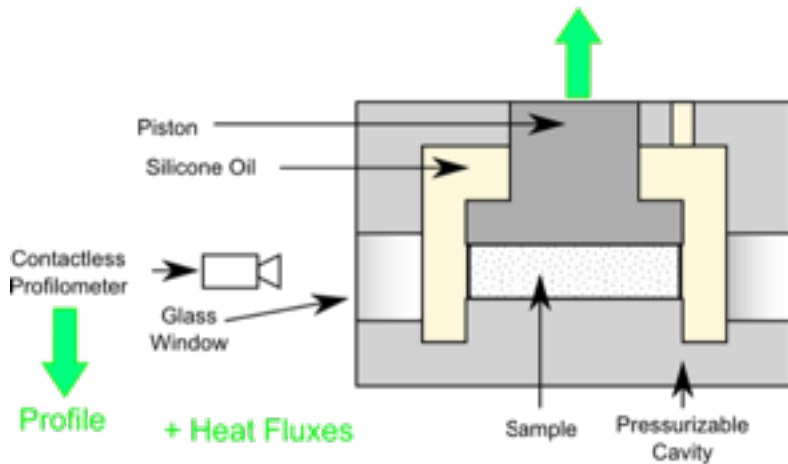
Loading range

$$T \in [20^\circ - 200^\circ], \quad \dot{T} < 5\text{K}\cdot\text{min}^{-1}$$

$$p < 10\text{bars}(\pm 0.1\text{bar})$$

$$F \leq 10(\text{kN}), \quad f \leq 100\text{Hz} \quad : \text{Instron Electropulse Press}$$

Displacement



Measured data

2D dimensional variation (thickness & in-plane)

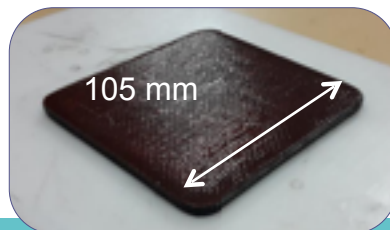
Extraction over the **whole curing cycle**

Heat flux sensor : évolution of **curing state**

Dimensions

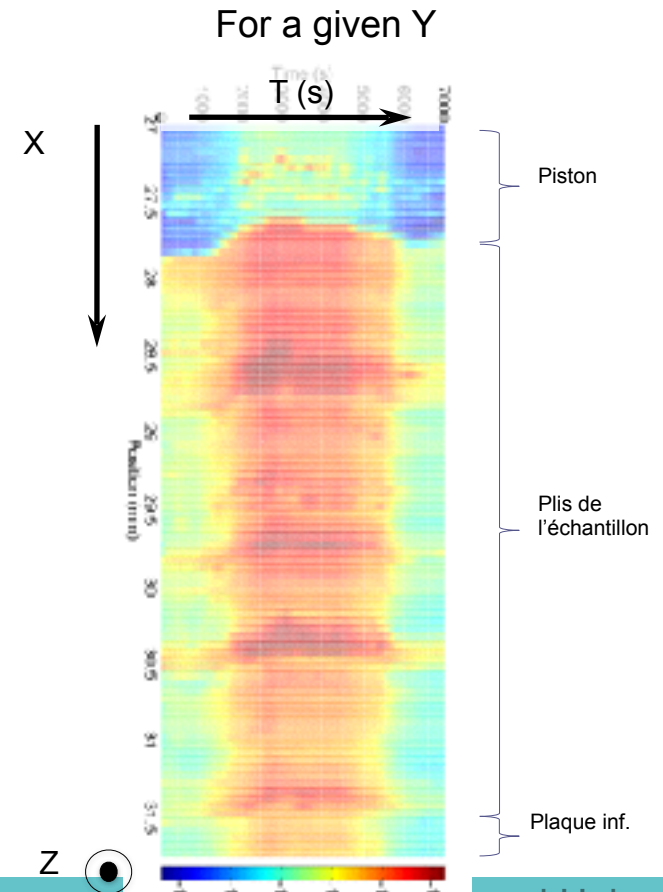
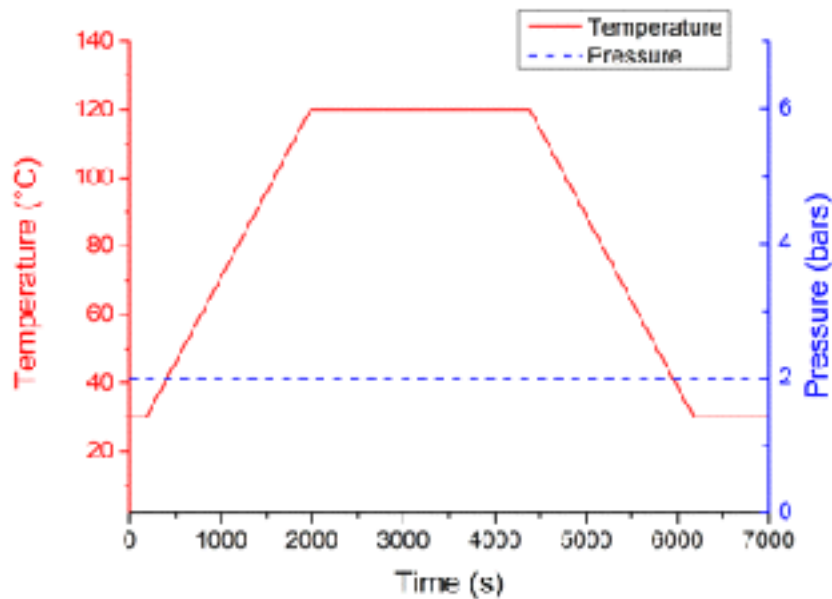
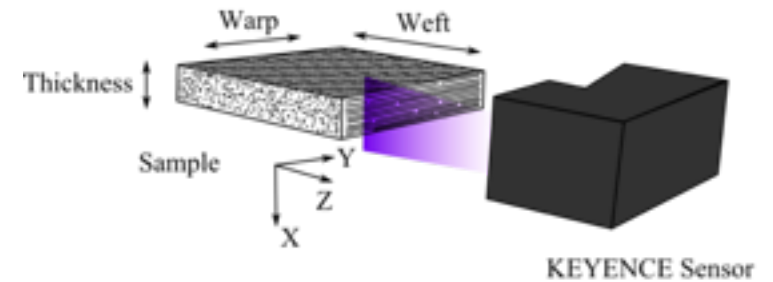
105 mm x 105 mm

thickness : up to 20mm

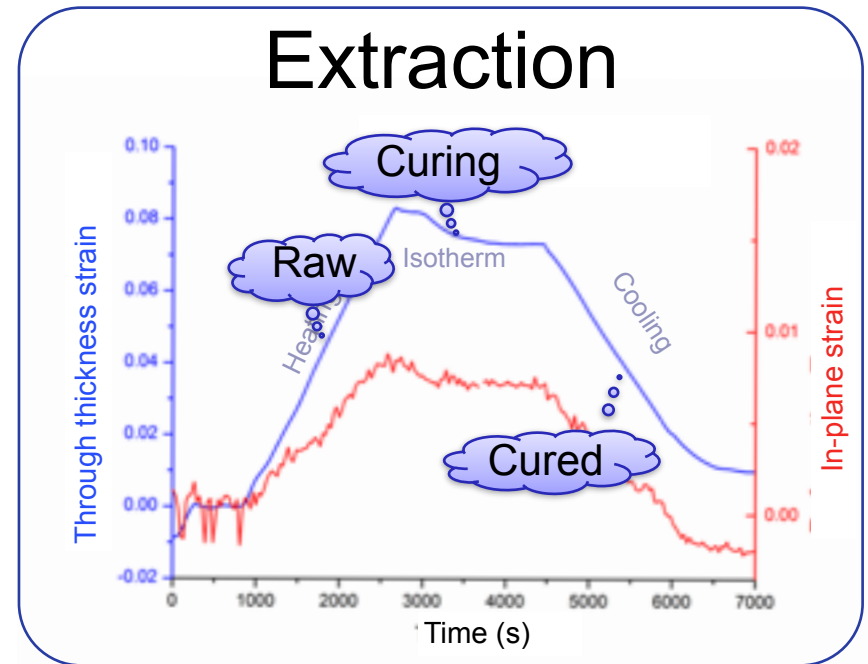
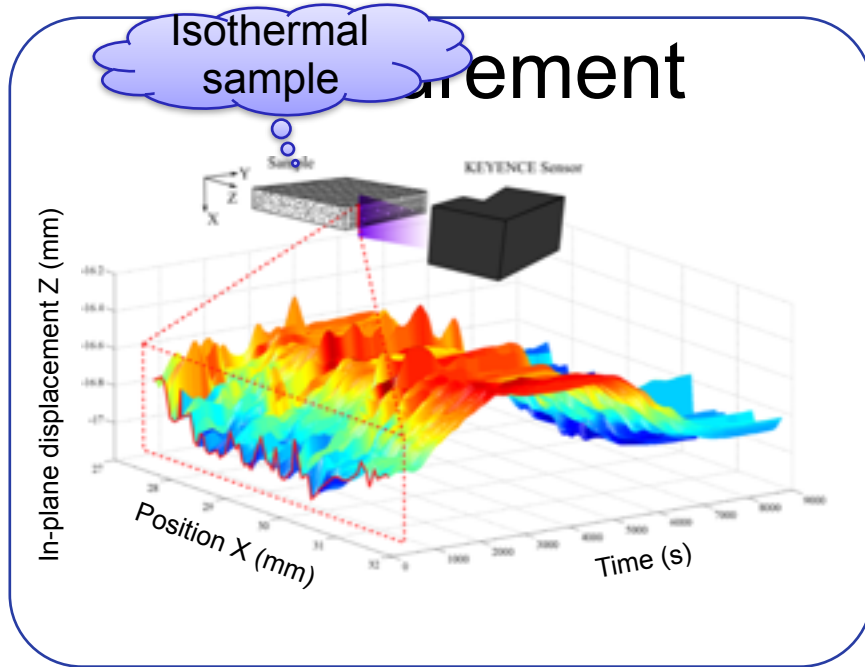


First test

- quasi UD glass-epoxy
- 16 plis prepreg
- Manual layup + precompaction
- hydrostatic 2 bars load



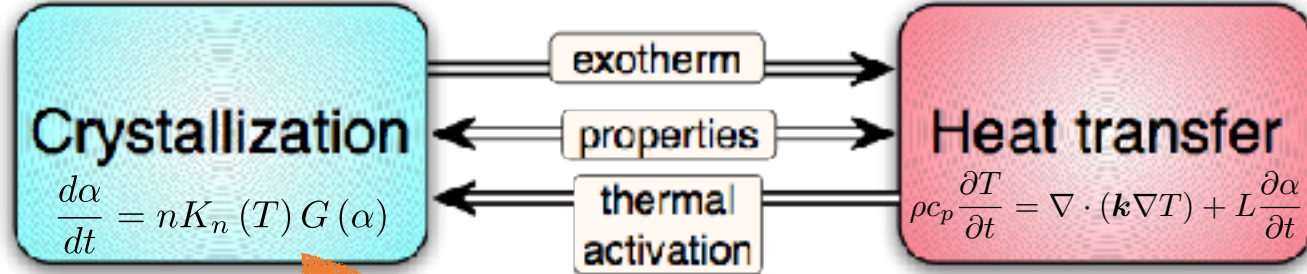
First results



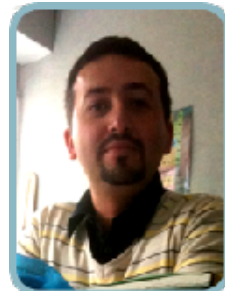
Results

		Through thickness	In-plane
CTE raw	[K ⁻¹]	317.0 10 ⁻⁶ (±2.0 10 ⁻⁶)	117.0 10 ⁻⁶ (±7.0 10 ⁻⁶)
CTE cured	[K ⁻¹]	47.4 10 ⁻⁶ (±3.0 10 ⁻⁶)	90.4 10 ⁻⁶ (±6.0 10 ⁻⁶)
CCS	[%]	0.77 (±0.02 10 ⁻⁴)	0.12 (±0.02 10 ⁻⁴)

[Peron et al 18]



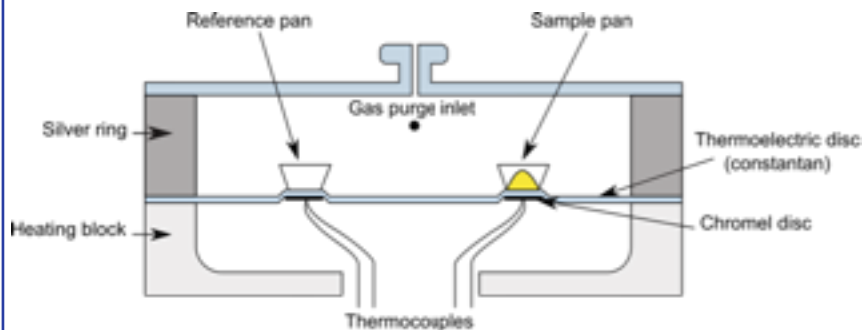
Flash DSC method for crystallization characterization



Baptiste Pignon, Nicolas Boyard, Vincent Sobotka, Didier Delaunay : LTN
 Xavier Tardif : IRT Jules Vernes

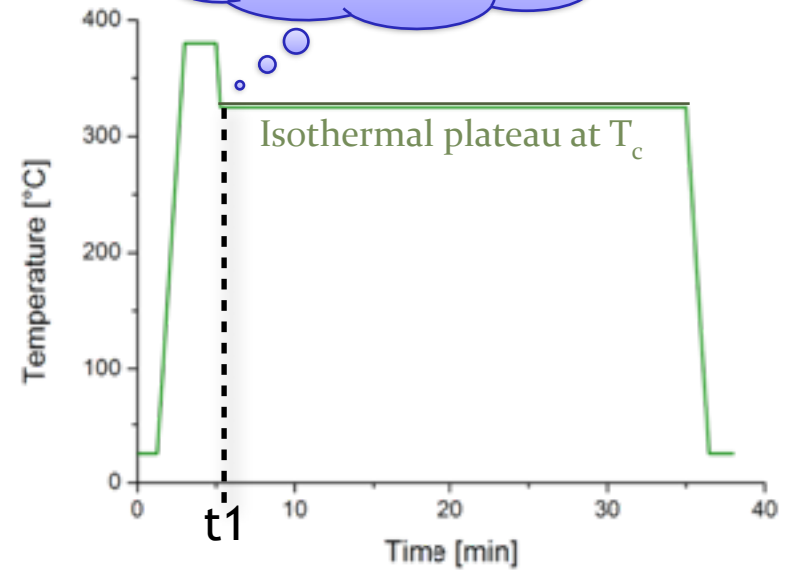
Classical DSC

Apparatus

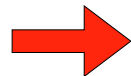


Method

Cooled as fast as possible

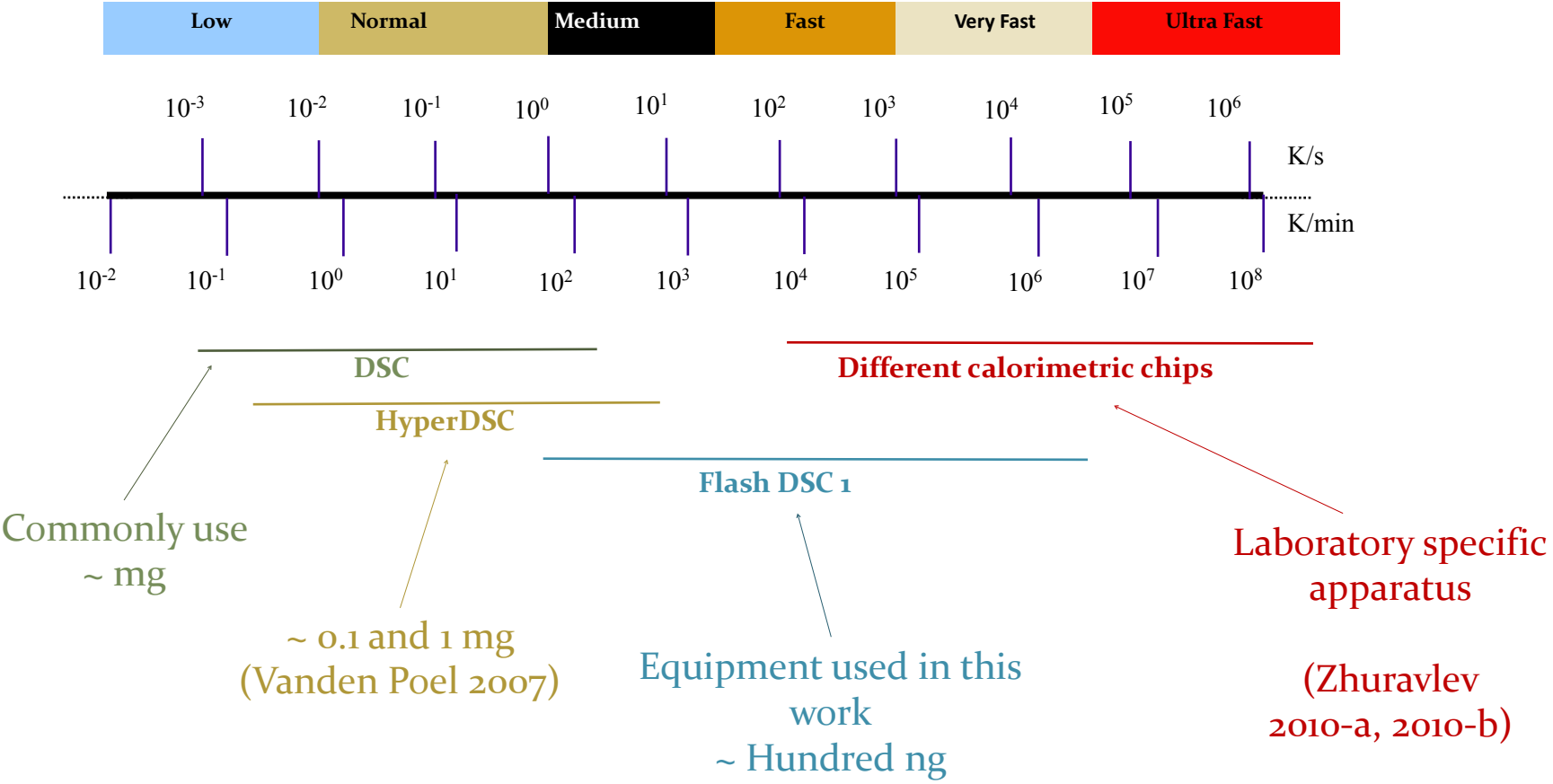


$$\alpha(t) = \frac{\int_{t_1}^t dh}{H}$$



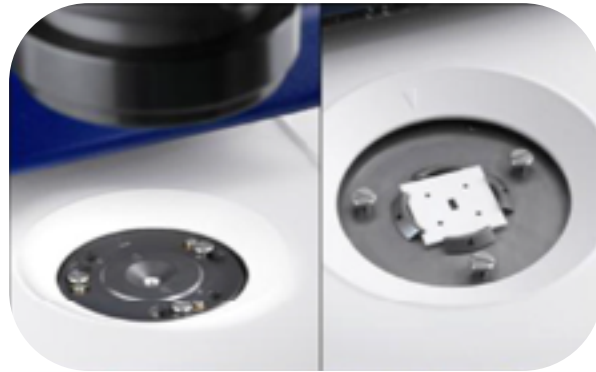
too slow to reach all T_c

Alternatives

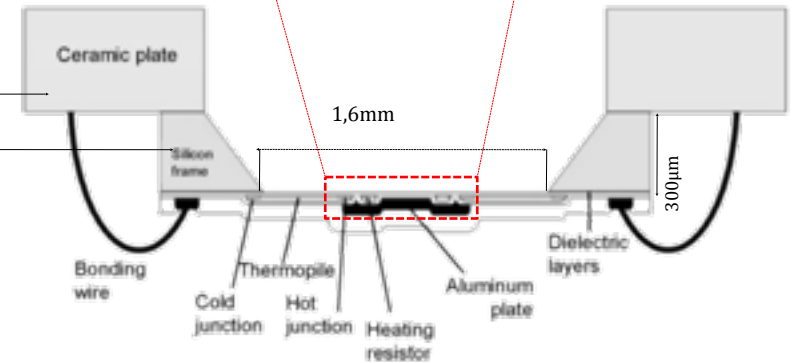
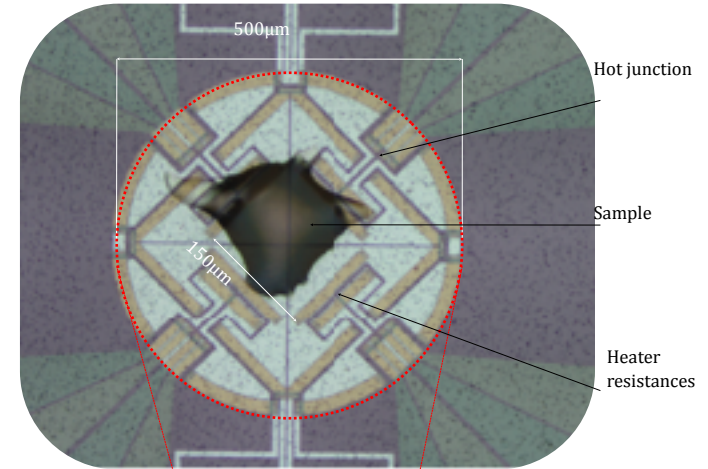
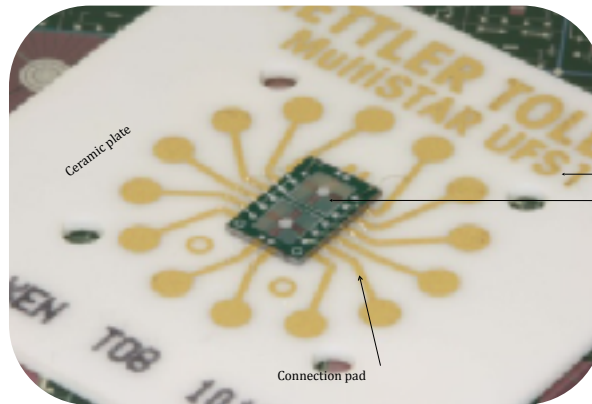


Flash DSC apparatus

Working zone
 $150 \times 150 \mu\text{m}^2$



Membrane
 $1.6\text{mm} \times 1.6\text{mm} \times 2\mu\text{m}$



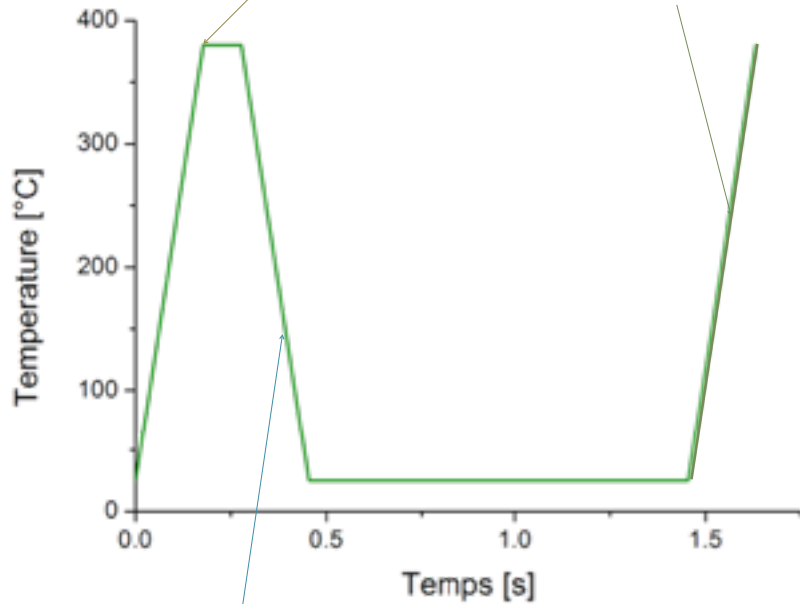
[V. Mathot 11, Pignon et al 15]

Difficulties

Mass measurement

Melt at 380°C
erase thermal history
avoid degradation

Heat flow measured
in heating
at 2 000 K/s

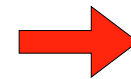


Quenched at
2 000 K/s:
fully amorphous
sample

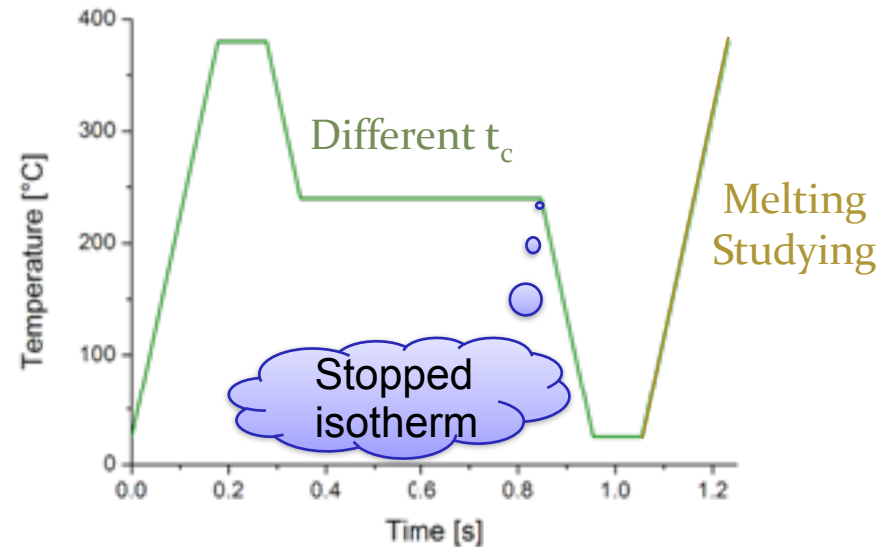
$$\Phi_{\text{exp}} = m c_p \frac{dT}{dt}$$

Sensitivity

reached when very slow
crystallization (ie. low heat flux)

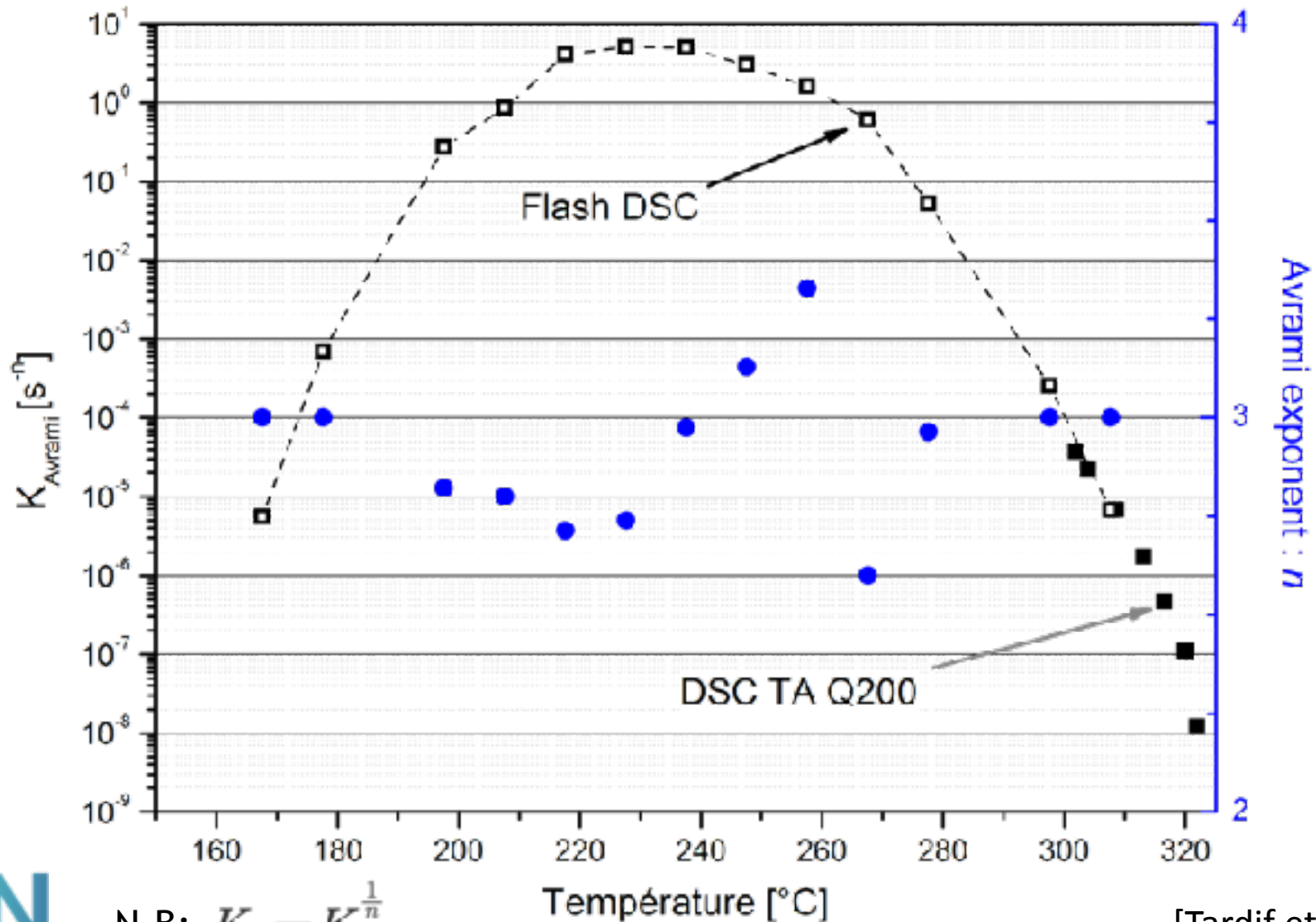


Discrete method



Results for PEEK

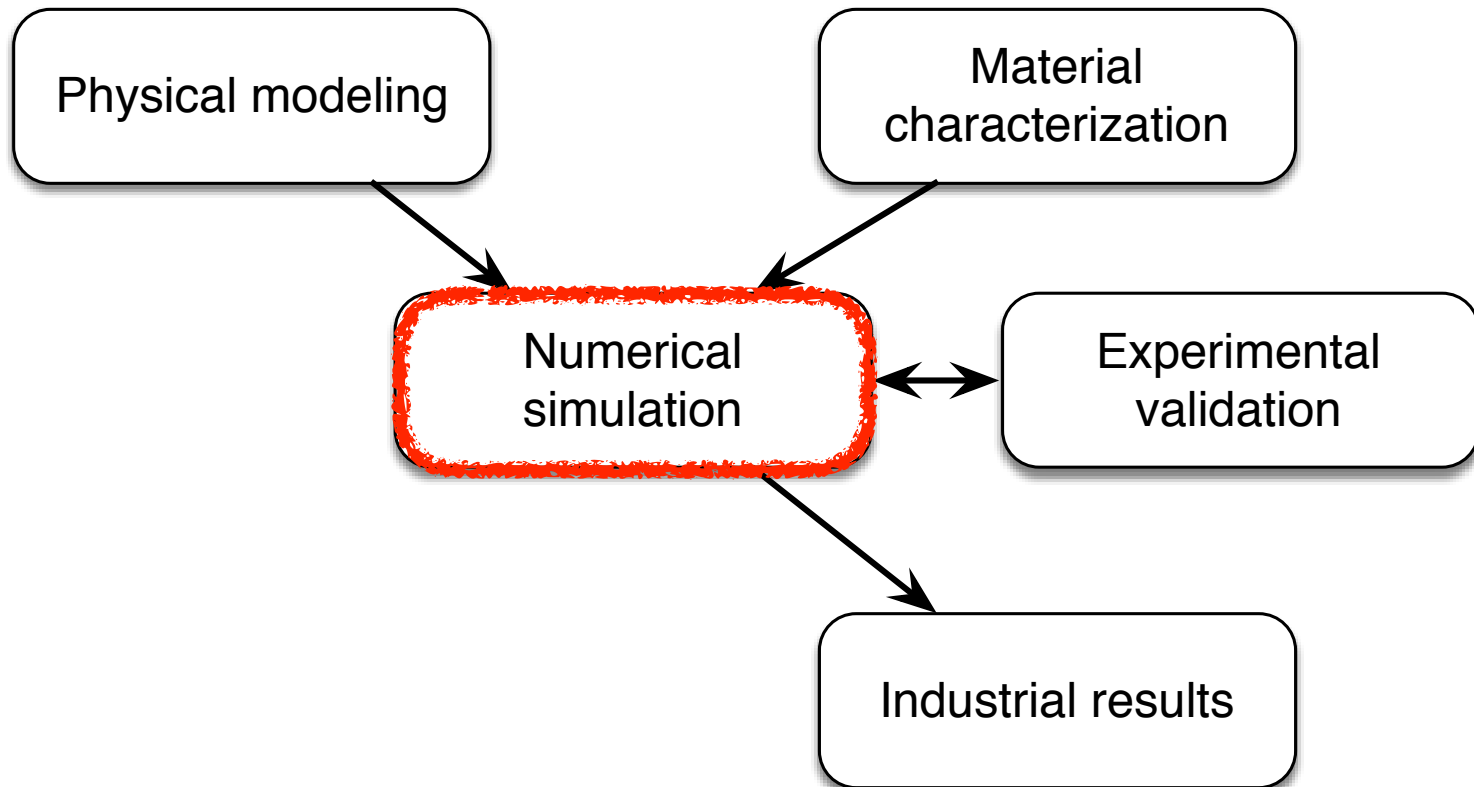
$$\frac{d\alpha}{dt} = nK_n(T)g(\alpha)$$



N.B: $K_n = K_{avrami}^{\frac{1}{n}}$

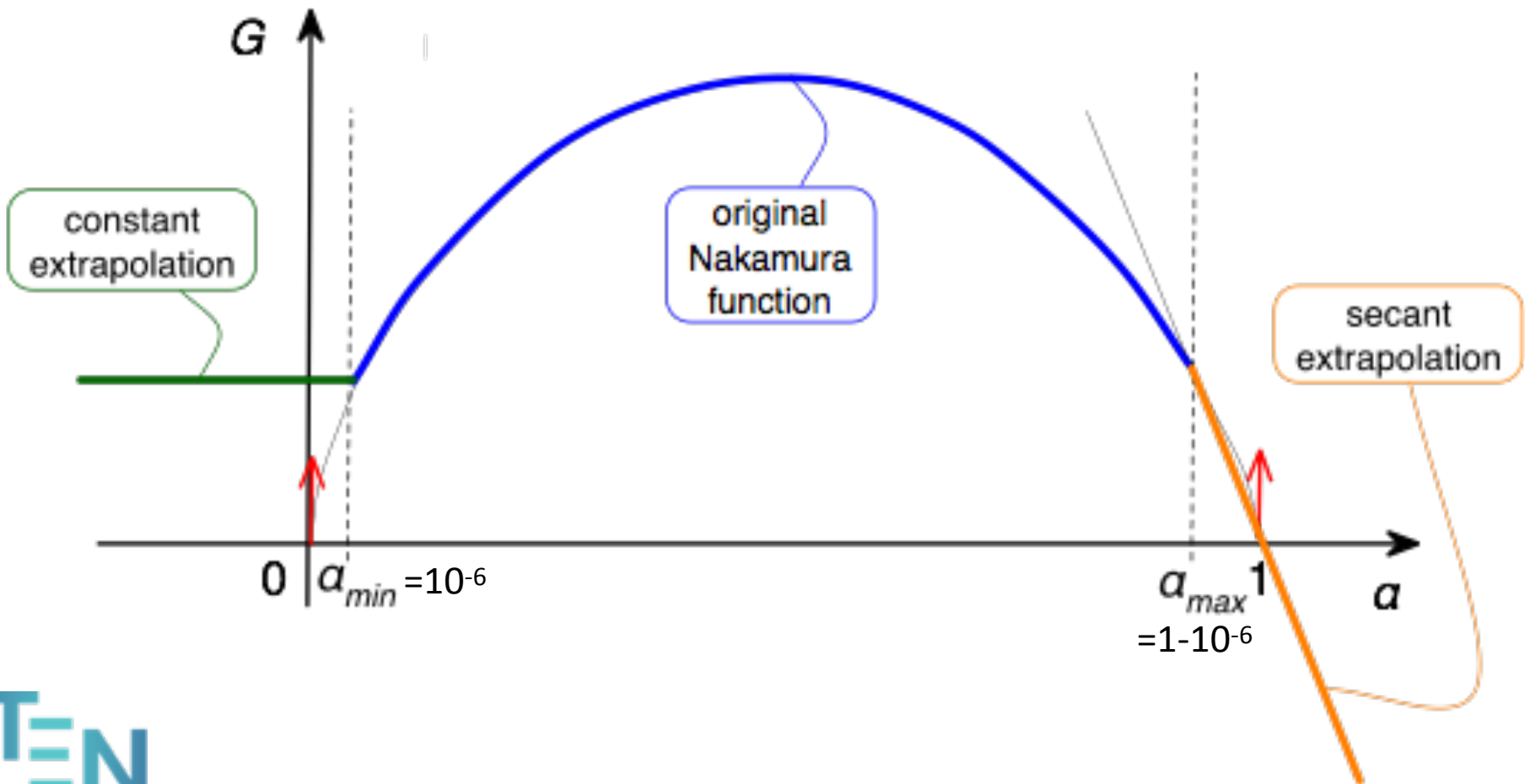
[Tardif et al 14]

III - Simulation



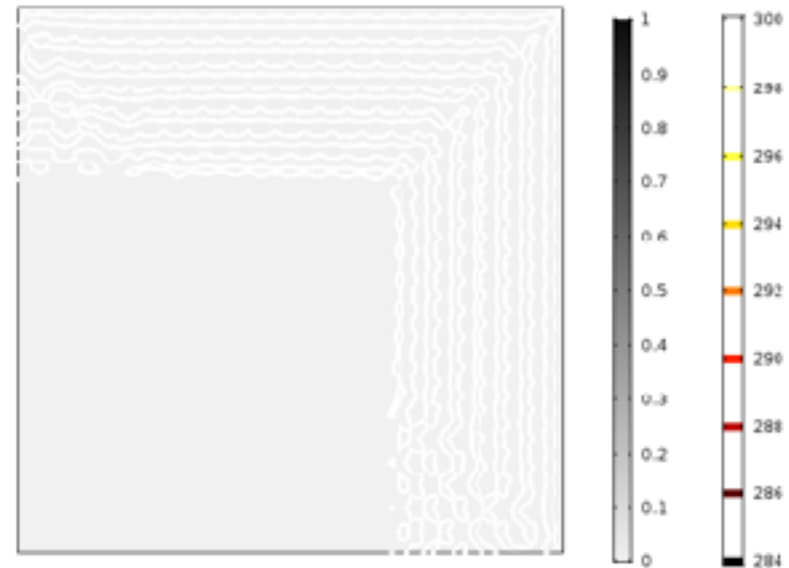
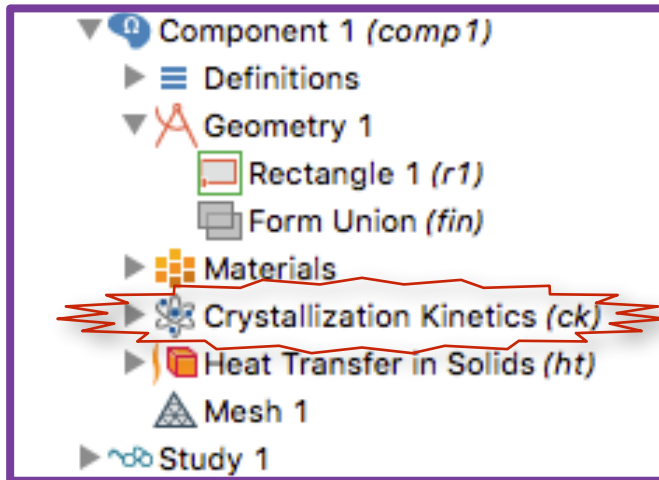
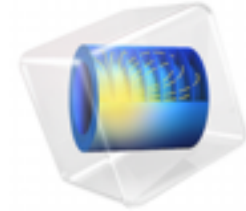
Nakamura Robustness

$$\frac{d\alpha}{dt} = nK_{\tau_1}(T) G(\alpha)$$



COMSOL Implementation

New COMSOL module (open source GPL)

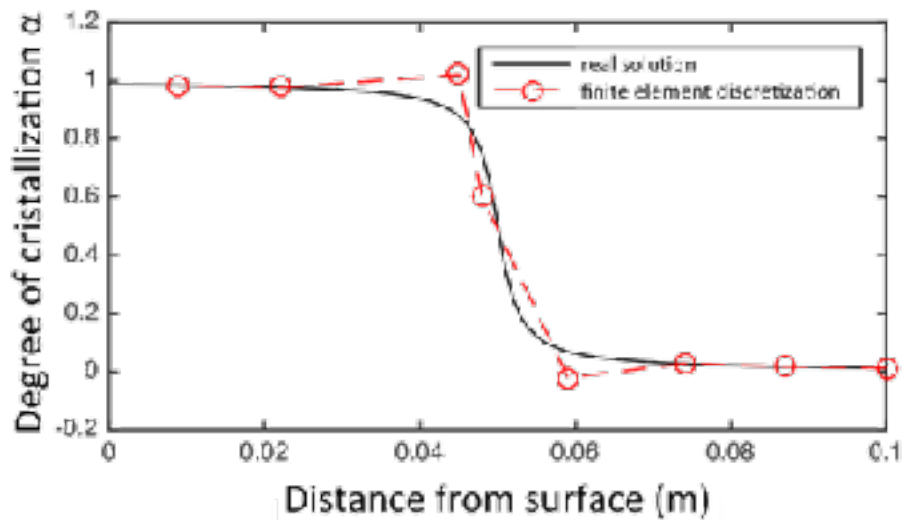


Difficulties

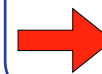
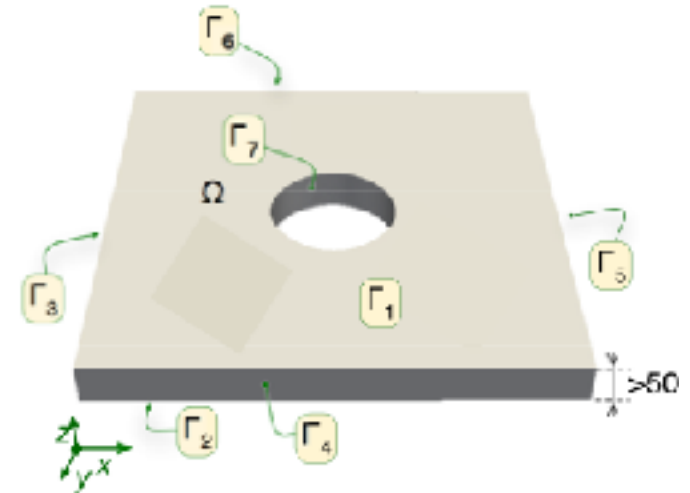
Crystallization front



[Mat & Zubeldia 14]



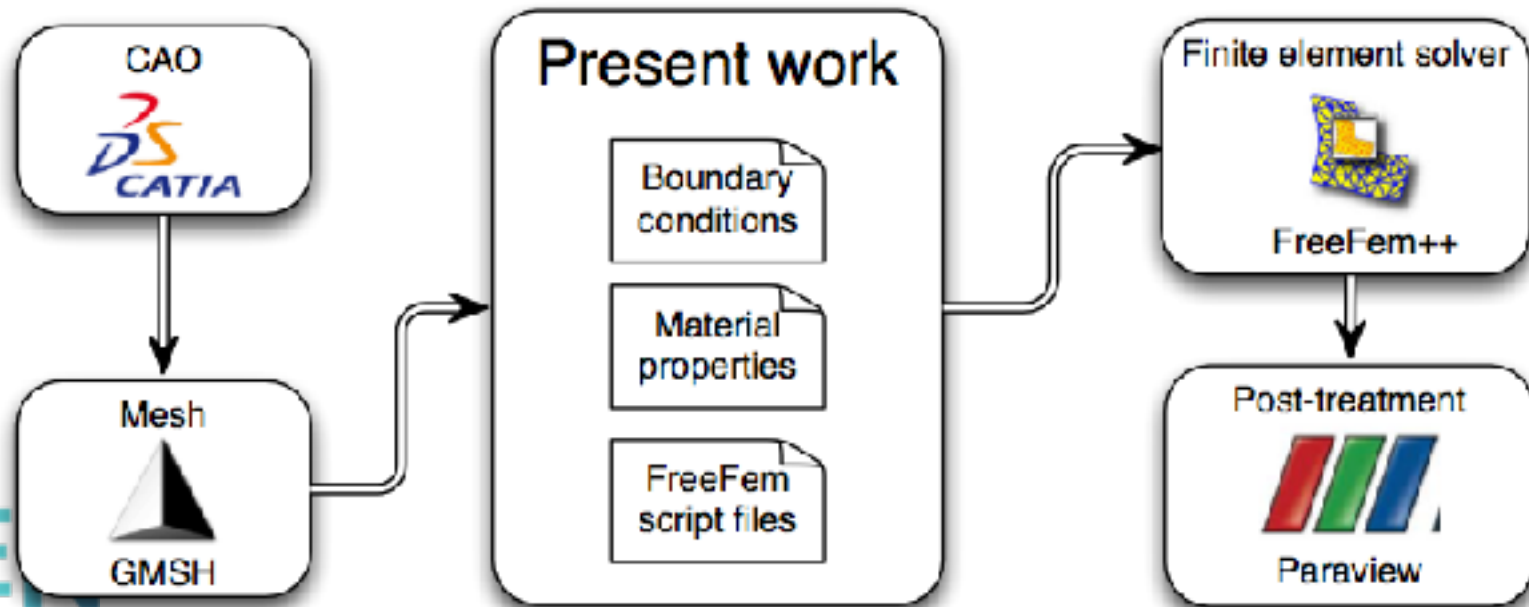
Computation time



millions of dofs

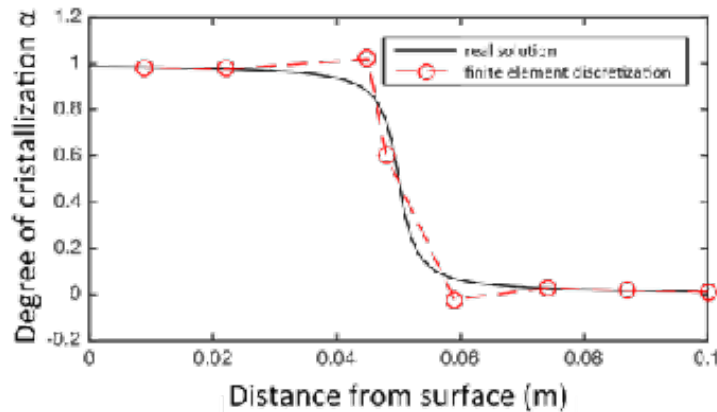
Implementation Framework

- Standard P1 finite elements
- Strong coupling using mixed field (T, α)
- Nonlinear solving
- Implicit time integration w/ adaptive time stepping



Numerical Methods

Crystallization front



Automatic remeshing

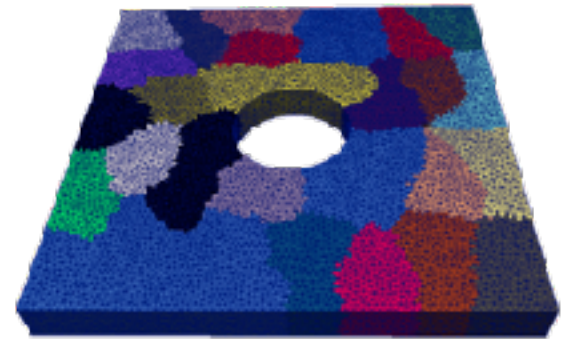
While α field is not physical

- Compute α Hessian
- Remesh using this metrics

MMG3D

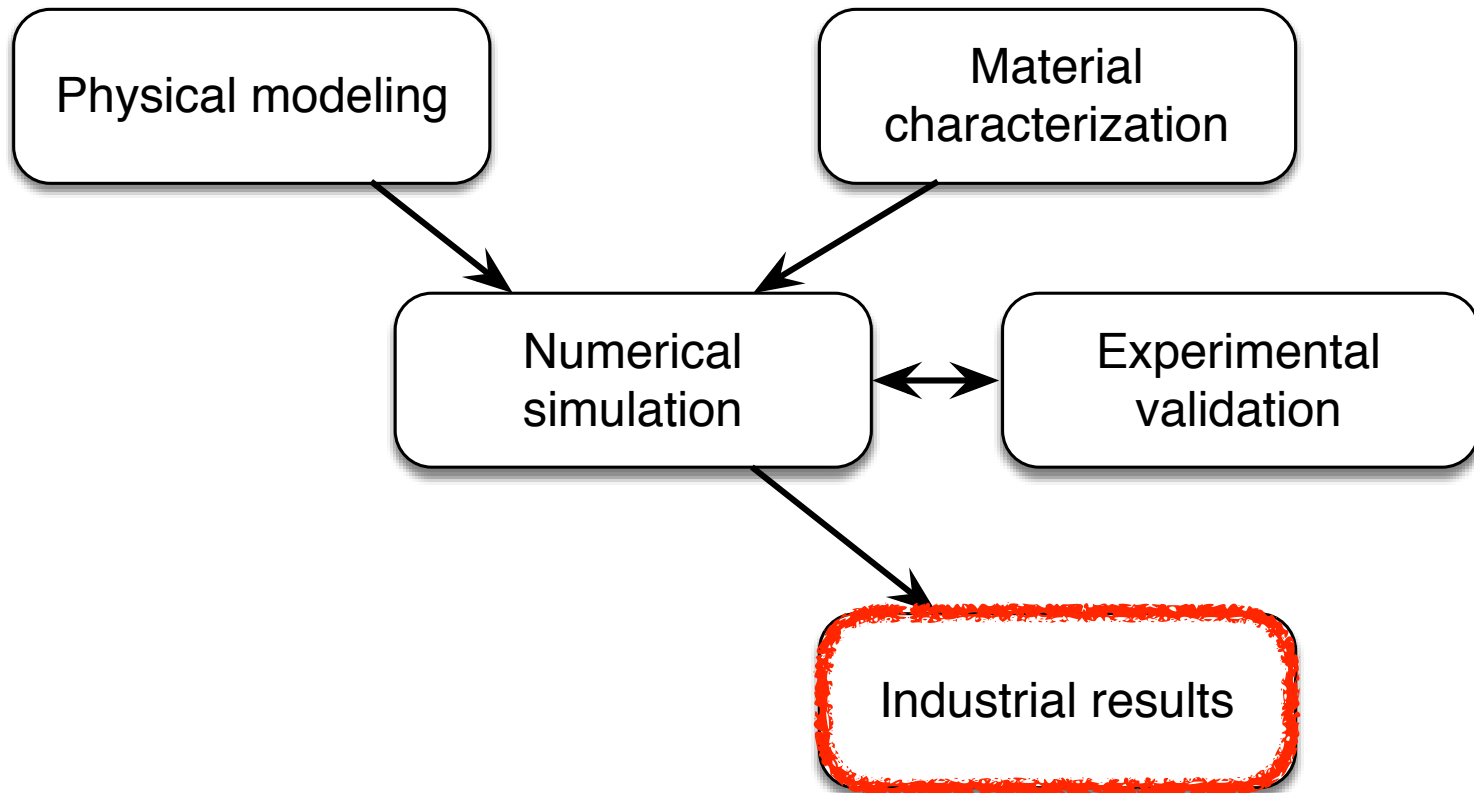
Parallel computation

- Partitioning (METIS)
- Parallel
 - assembly
 - solving (MUMPS)

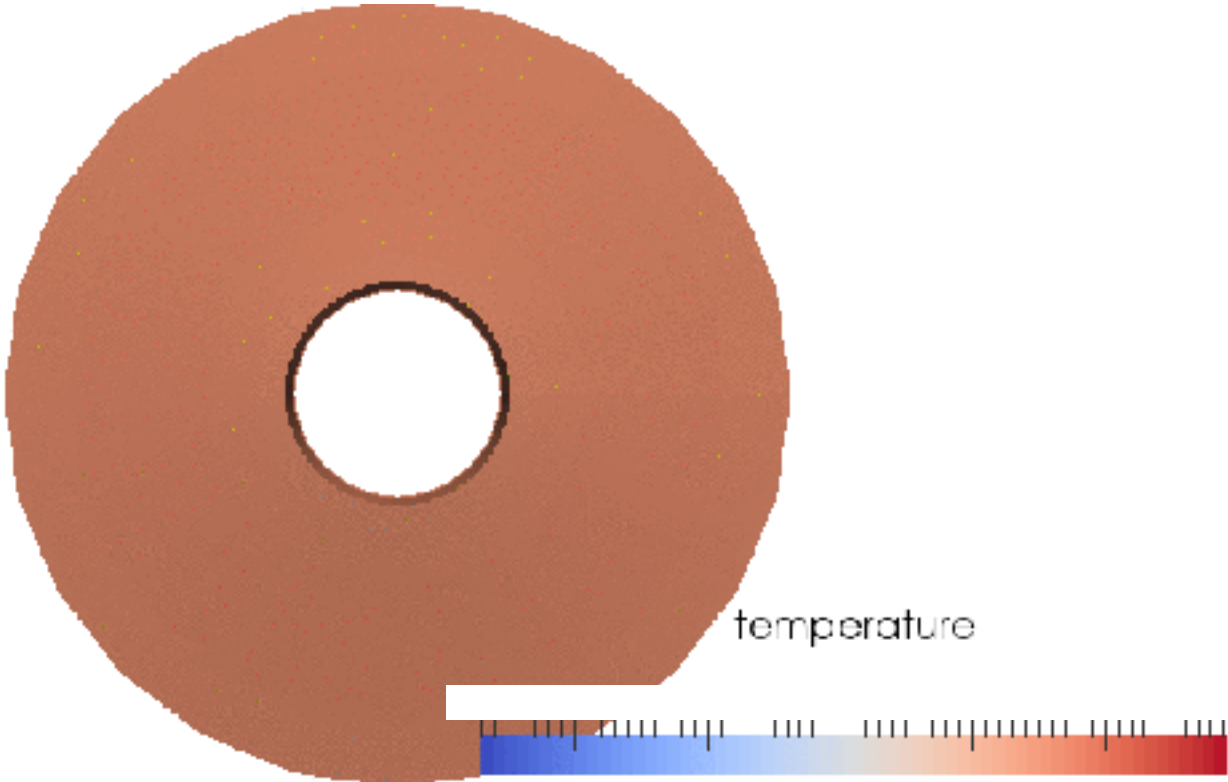


➔ Up to 4 million dofs

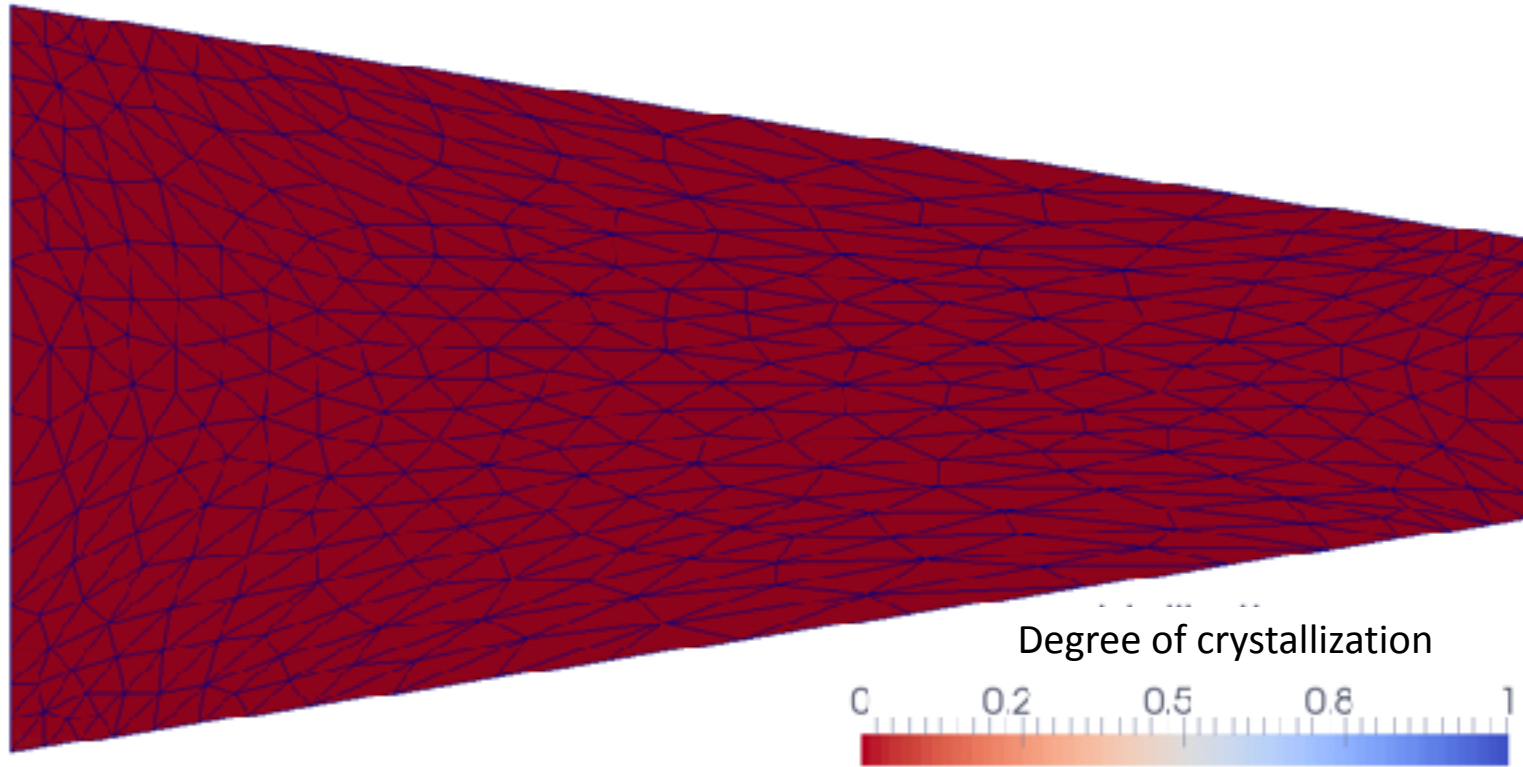
IV - RESULTS



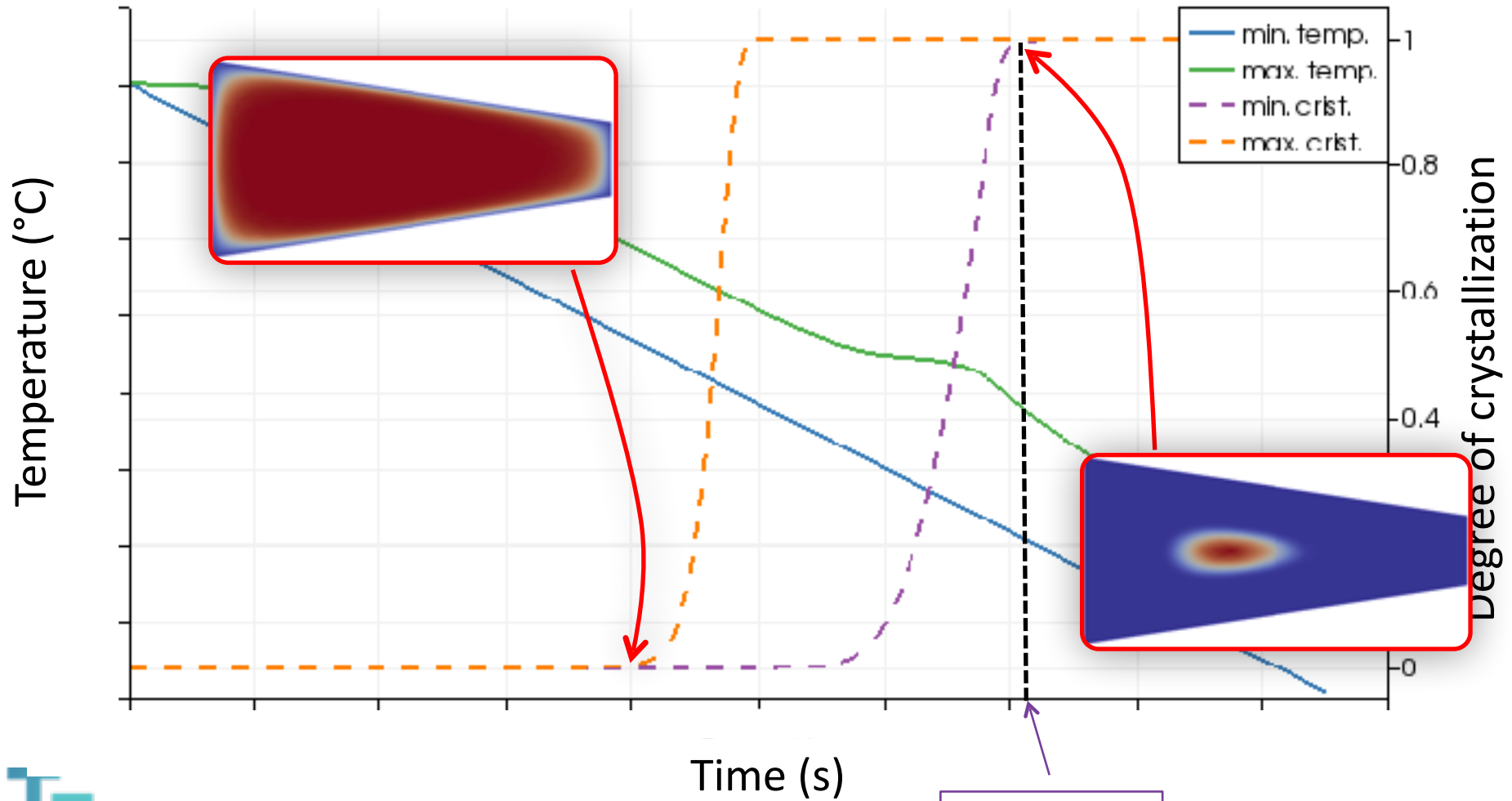
Temperature



Crystallization



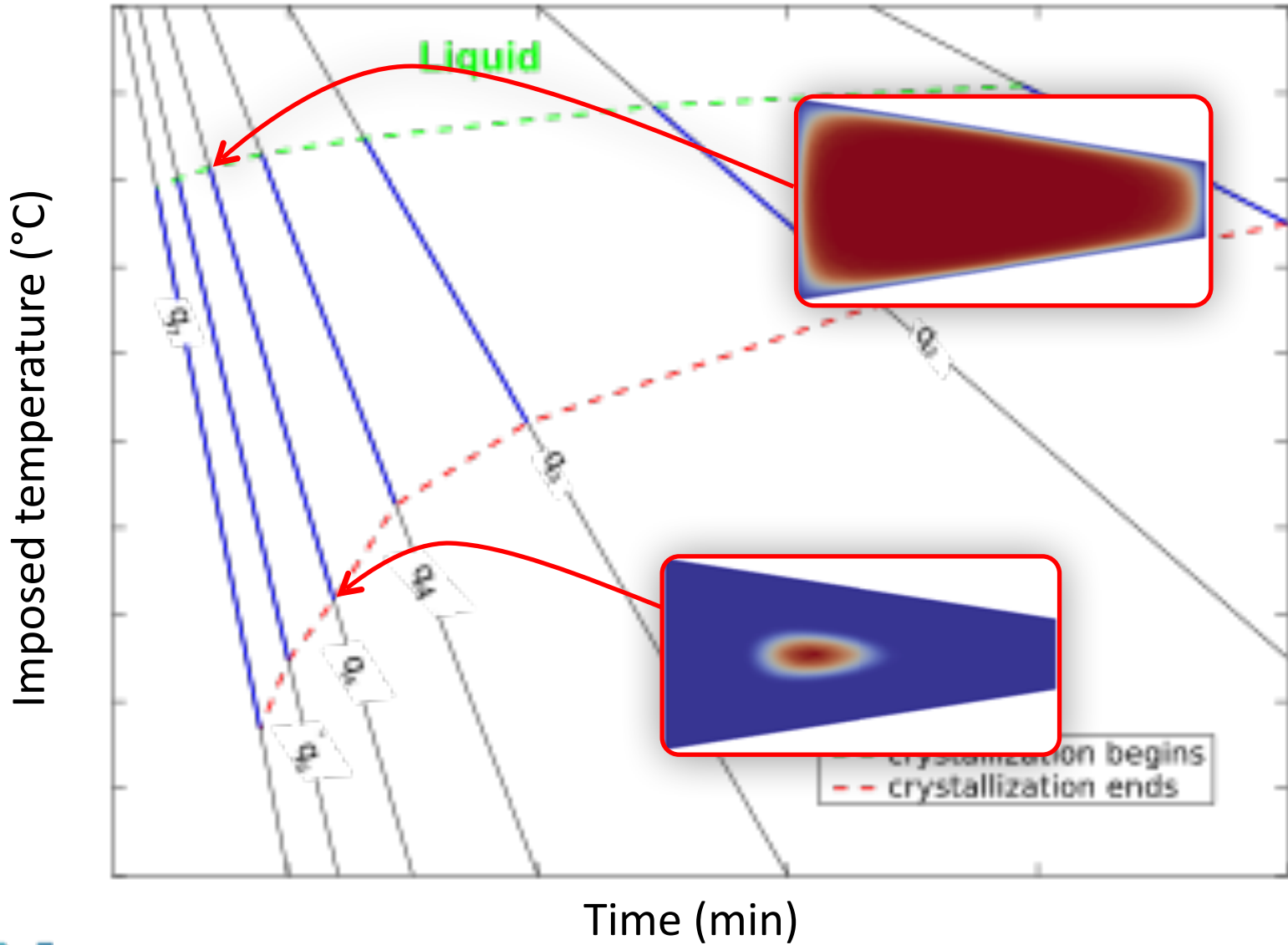
Extrema in the domain



Ejection time

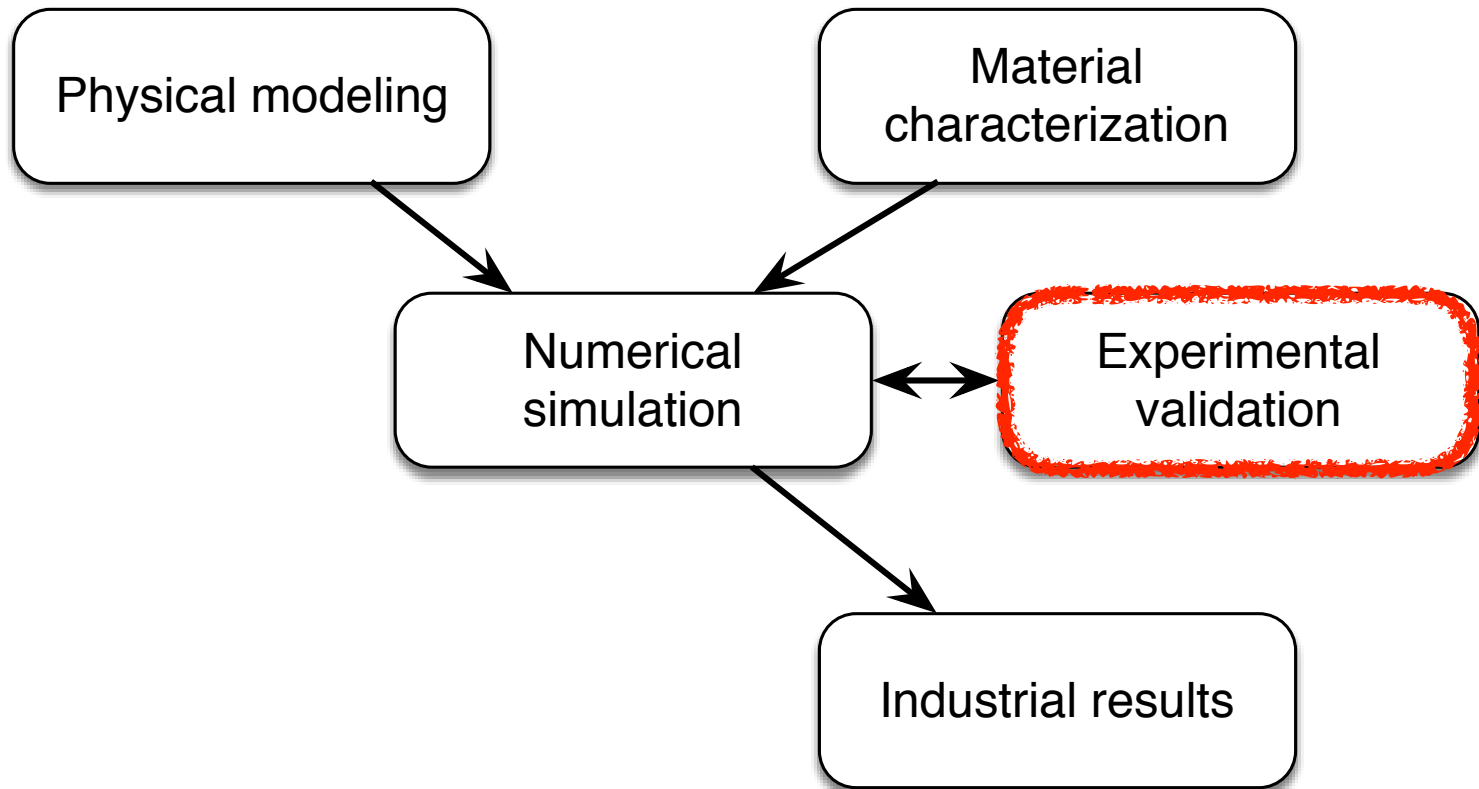
[Landry, Hubert 15]

Continuous cooling diagram

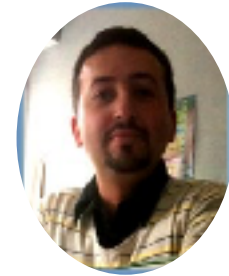


➔ Slow cooling = solidification at higher temperature.

V - EXPERIMENT

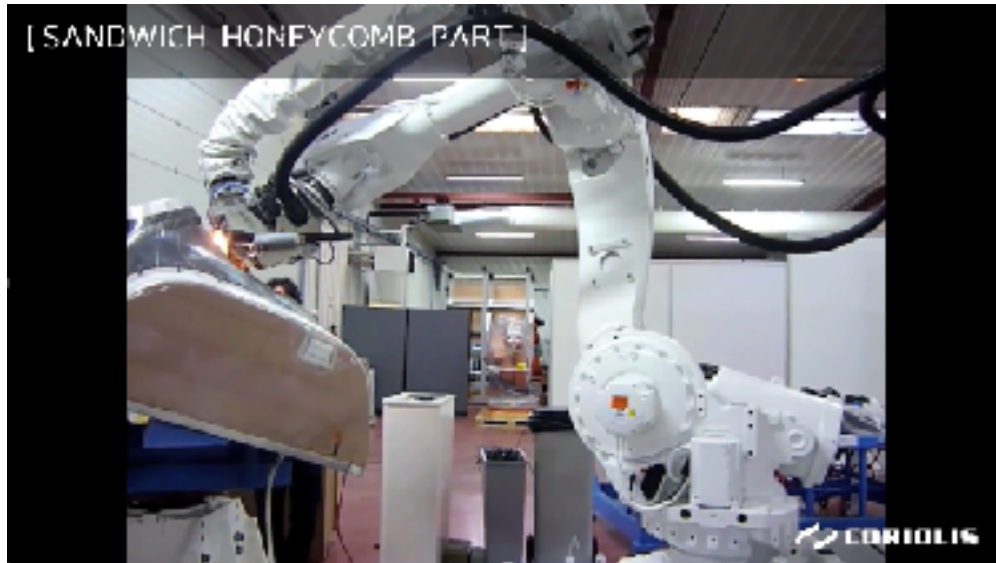


Laser assisted tape placement process



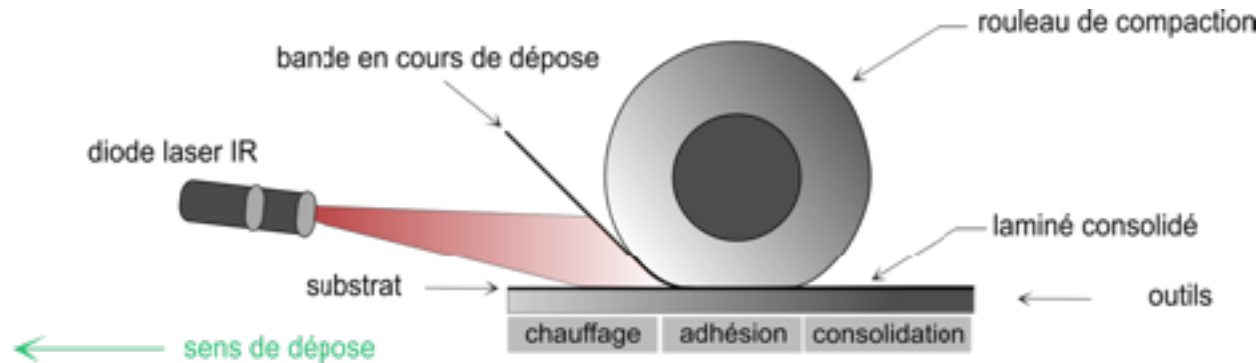
Violaine Le Louet, Steven Le Corre, Nicolas Boyard

Procédé AFP (Automated Fiber Placement)

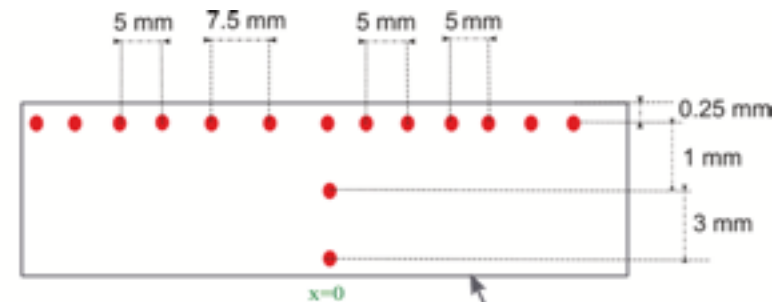
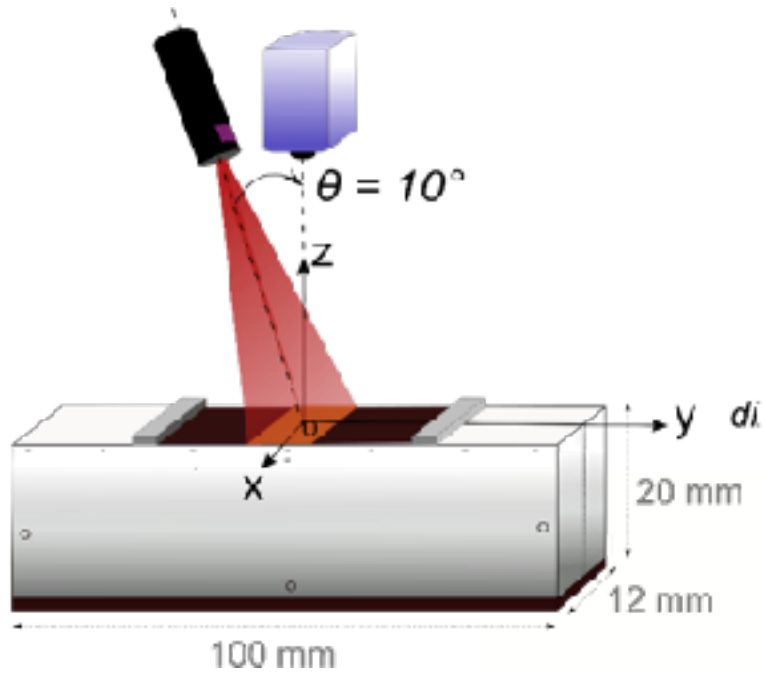


Challenge:

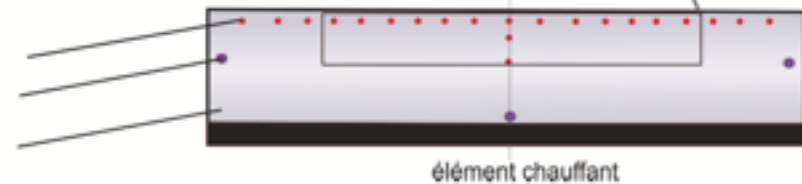
- Mimic the process at the lab scale
- Mesure surface température et heat flux
- *Short times / high power*



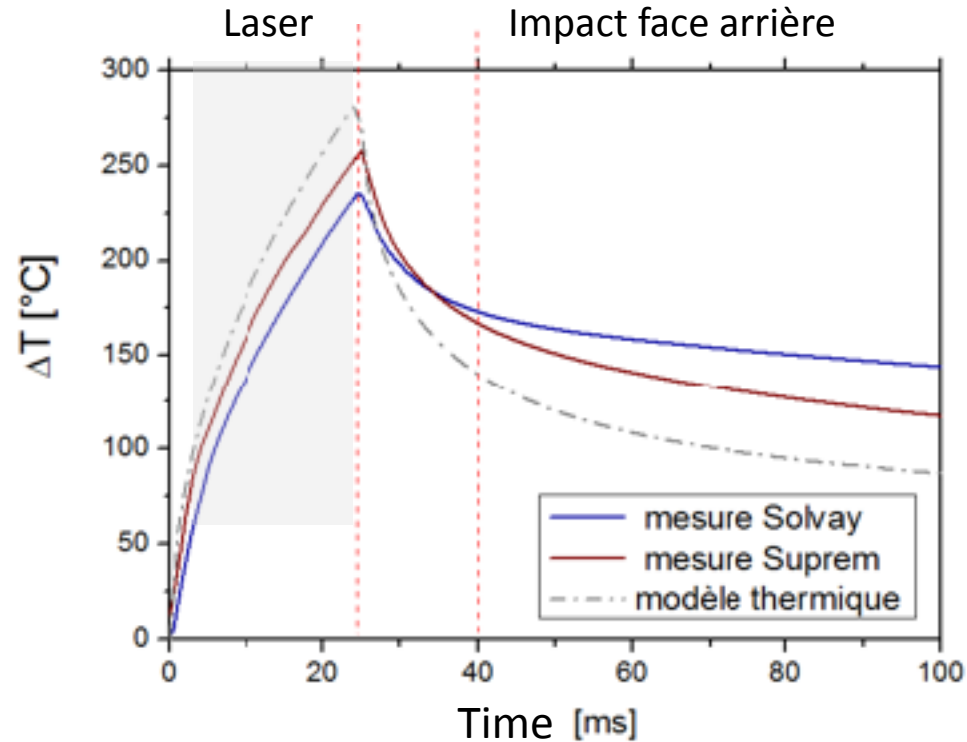
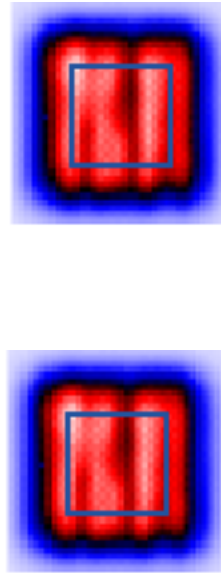
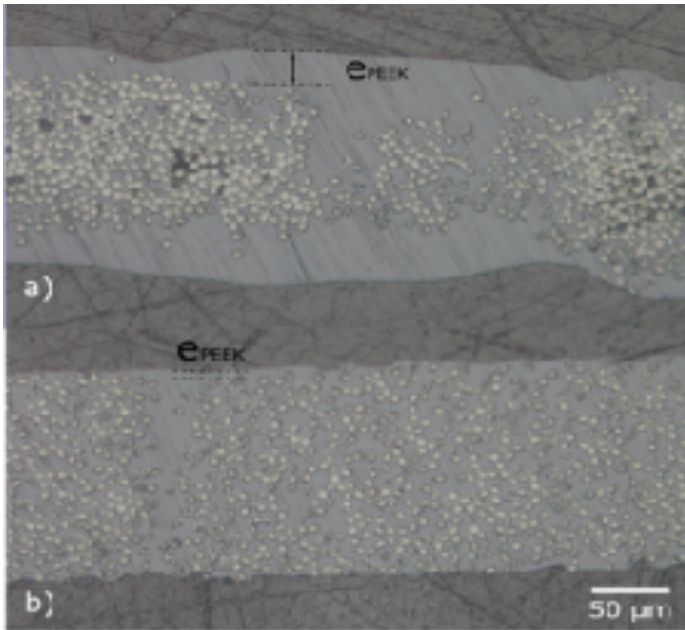
Instrumented bench



thermocouple de mesure
thermocouple de contrôle
bâti en acier inox



First results

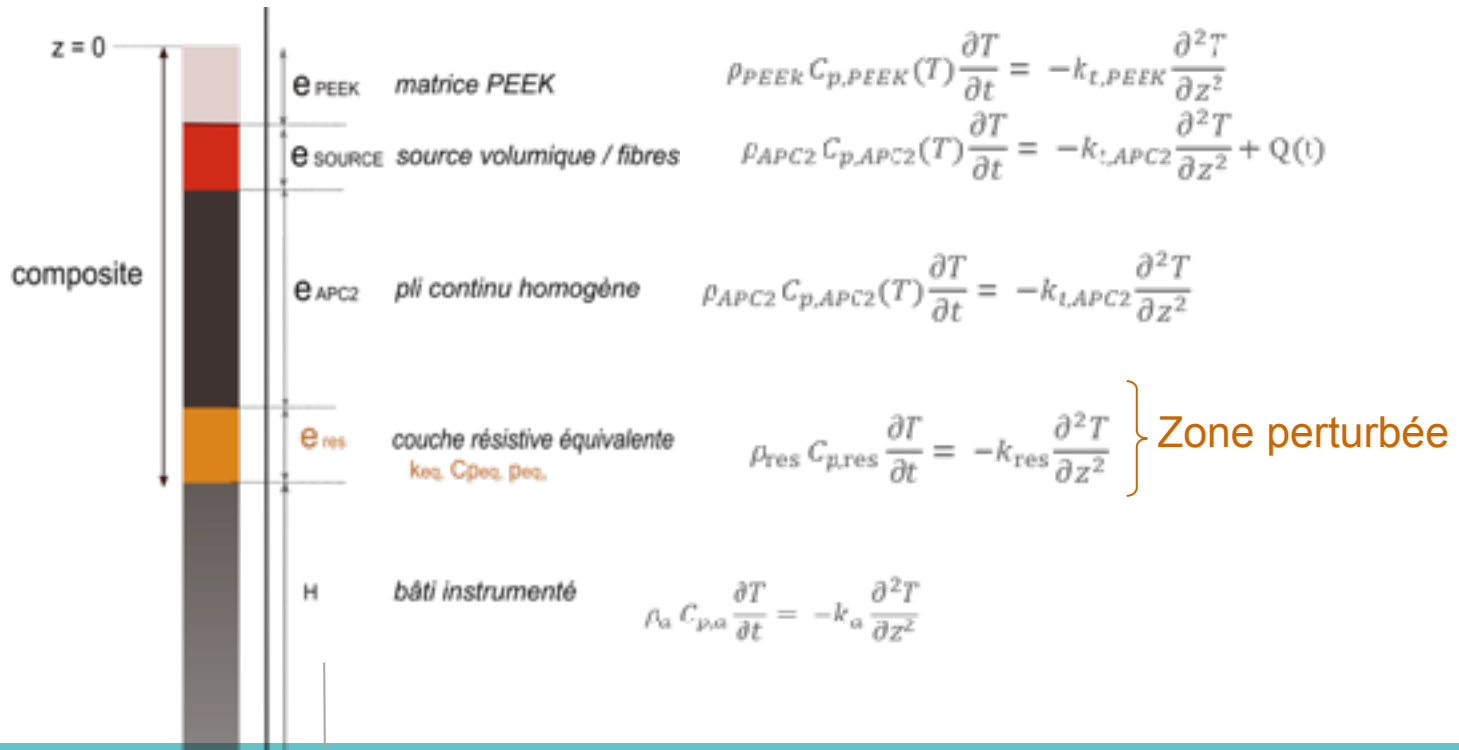


Heterogeneous medium
Bulk heating
Interfacial artifacts

Thermal modeling

Modified model :

- Equivalent homogeneous ply
- bulk heat source in a surface layer.
- thermal contact resistance



Conclusion



Multiphysical **modelling** of composite processing
Heat transfer + phase change + mechanics

Specific material **characterization** techniques

Simulation tool 2D+3D
Specific methods (contact, mesh refinement...)

Better understanding of the process
Parametric study

Acknowledgments

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