



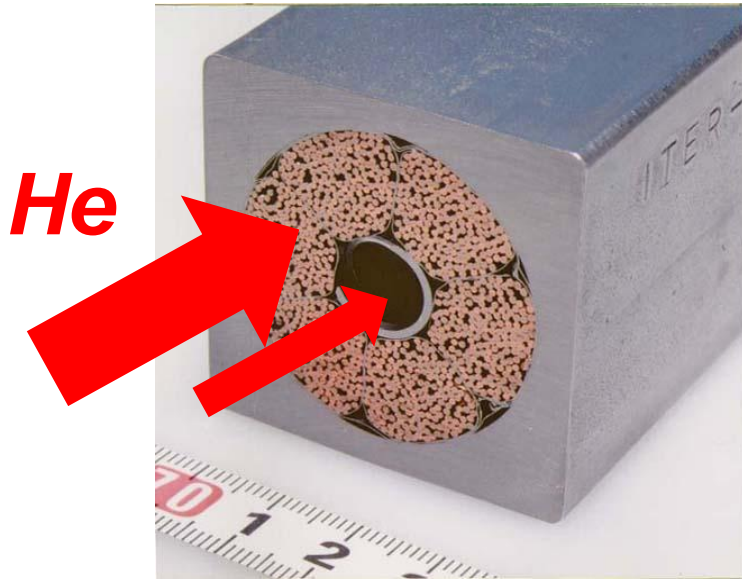
Progress in multi-physics modeling of innovative lead-cooled fast reactors

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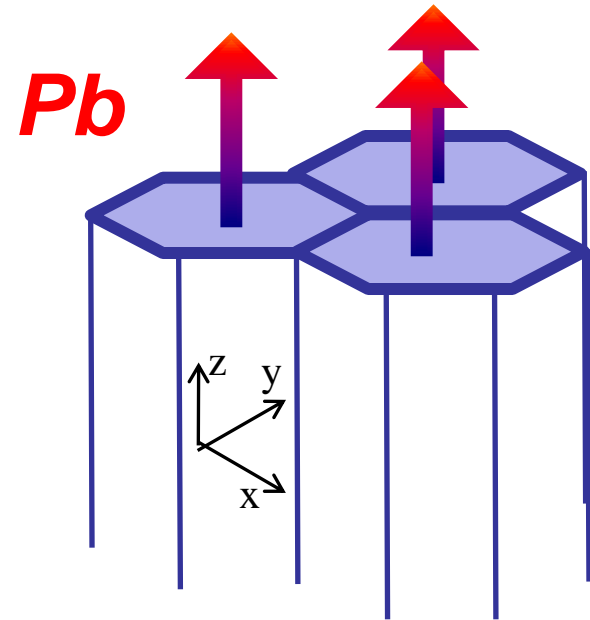
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FROM



TO





Outline



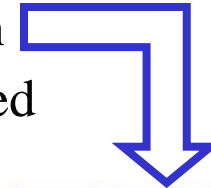
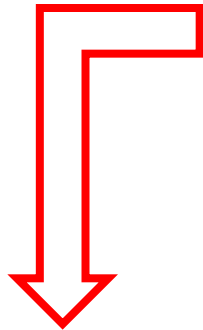
- Introduction
- Purpose of the work
- Model description
- Test case
- Conclusions and perspective



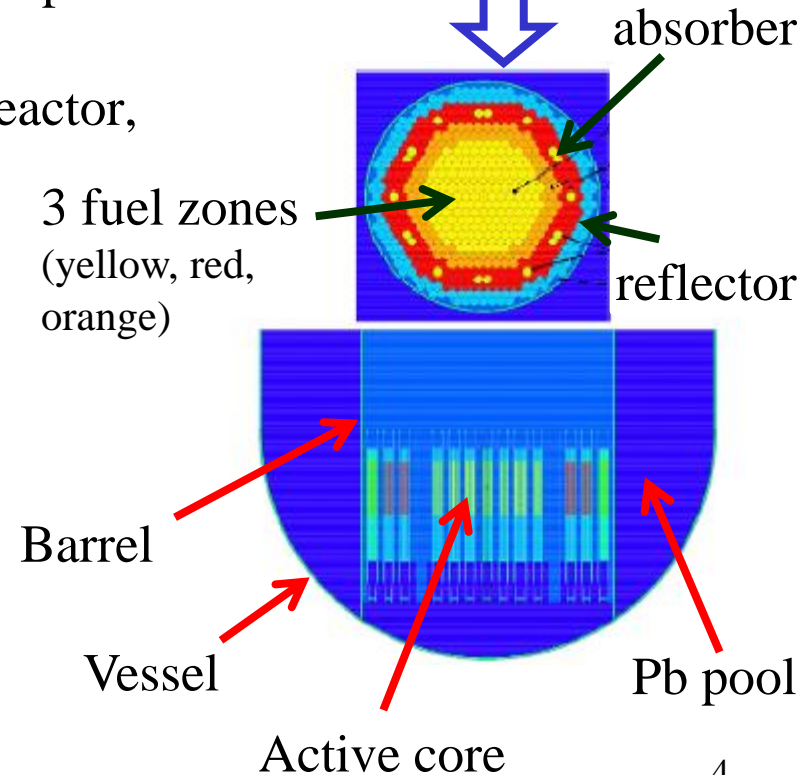
Introduction



- Generation IV reactors
 - Lead-cooled Fast Reactors (LFR)
 - European proposal in 6th and 7th Framework Program
 - **ELSY**: preliminary full-scale reactor design
 - **LEADER**: Lead-cooled European Advanced DEMonstration Reactor
 - » ALFRED - Prototype reactor, downscaled power



- *Core design*
- *Safety analysis*
 - *Multiphysics approach*
 - *Stability and sensitivity studies*
- *Transmutation evaluations*
- *Thermal-hydraulics*
- *Plant design*



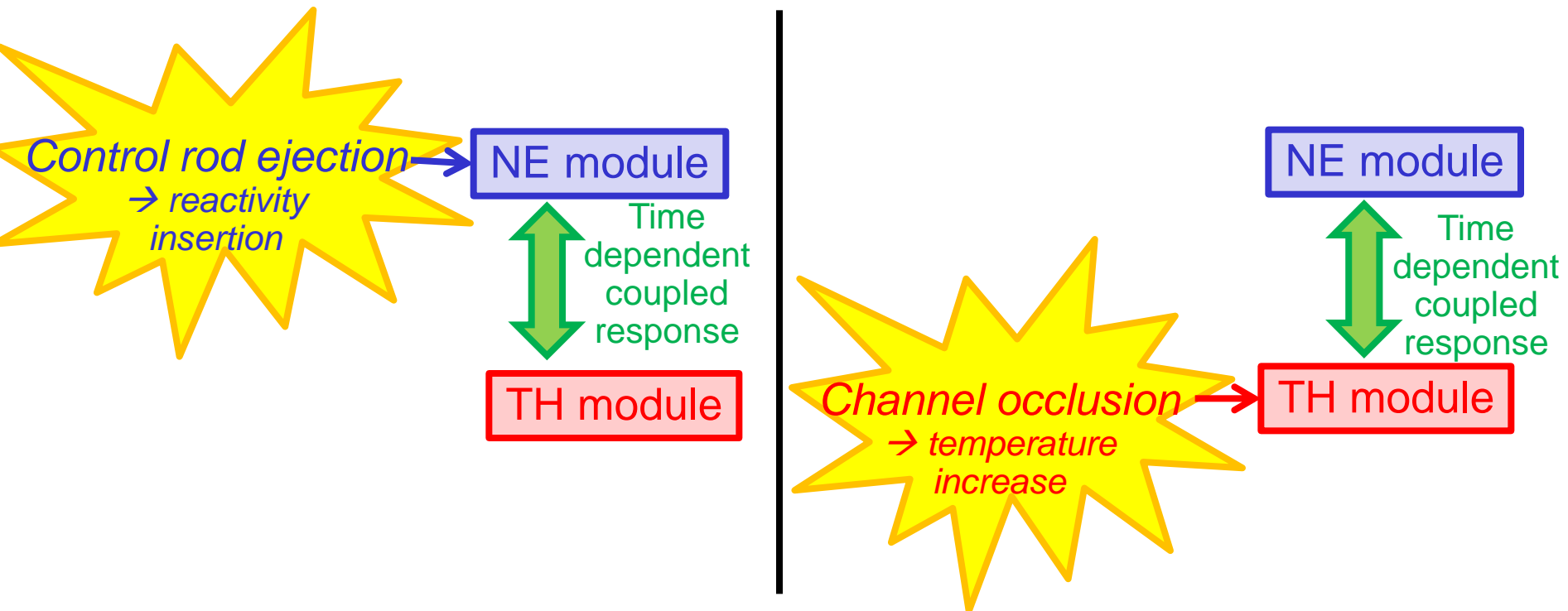


Purpose of the work



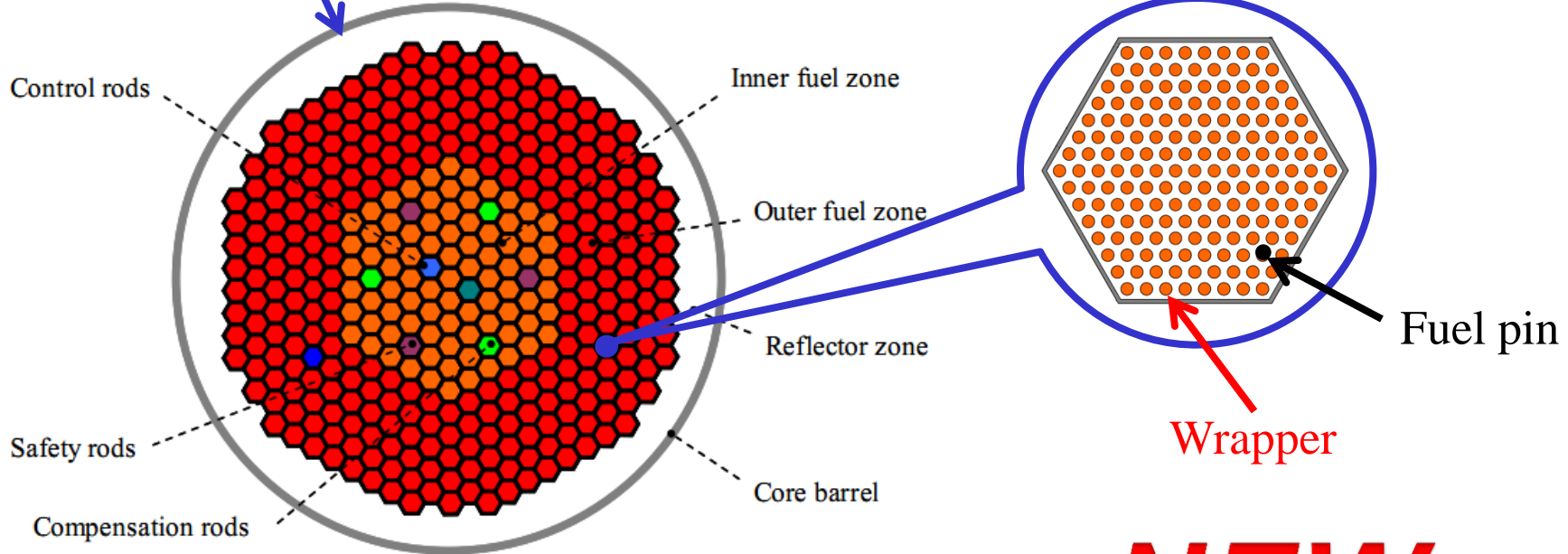
- Develop a **flexible and modular full-core coupled thermal-hydraulic (TH) and neutronic (NE) analysis** for simulation of control- and safety-relevant transients

Examples of possible initiating events:



Target model features

Full-core geometry with homogenized **hexagonal fuel assembly**



NEW

- Fast neutron dynamics → **3D NE analysis**
 - Molten Pb (coolant) → **Full core TH analysis**
- COUPLED!**



Relevant time-scales



- NE timescales:

- Prompt neutron lifetime $\sim 10^{-6}$ s

Shape scale (intermediate, depends on transient)

- Delayed neutron precursor lifetime $\sim 1-100$ s

NE-TH coupling time-scale

- TH timescales:

- $\tau_{\text{Pb-pin}} \sim 0.1$ s (coolant-pin surface coupling time)
- $\tau_z \sim 1$ s (transit time along channel)
- $\tau_{\text{hom}} \sim 1$ s (T_{pb} homogenization time inside a hexagon, assuming uniform T_{fuel} , ... *inside* pin needs ~ 10 s)
- $\tau_{\text{xy}} \sim 10$ s (heat diffusion through wrapper)



Neutronic model



AIM : Multigroup diffusion approximation of the transport equation

$$\left\{ \begin{array}{l} \frac{1}{v_g} \frac{\partial \phi_g}{\partial t} = \nabla D_g \nabla \phi_g - \Sigma_g \phi_g + \sum_{g'=1, g' \neq g}^G \Sigma_{s, g' \rightarrow g} \phi_{g'} + (1 - \beta) \chi_g \sum_{g'=1}^G v \Sigma_{f, g'} \phi_{g'} + \sum_{i=1}^R \chi_{i, g} \lambda_i C_i, \quad g = 1, \dots, G \\ \frac{\partial C_i}{\partial t} = -\lambda_i C_i + \beta_i \sum_{g'=1}^G v \Sigma_{f, g'} \phi_{g'} \end{array} \right. \quad i = 1, \dots, R$$

Temperature dependent

Coarse mesh approach (3D nodal scheme) for full-core evaluation in hexagonal geometry + **quasistatic method** for the time integration

$$\phi_g = \psi_g(x, y, z; t) \cdot A(t)$$

Shape function: slow time-scales

Amplitude function: fast time-scales

PRESENTLY: Point kinetic model

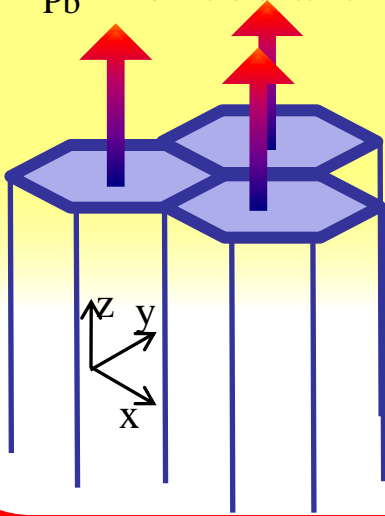


Thermal-hydraulic model



At given z :

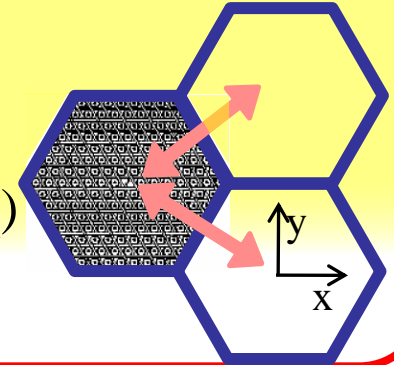
- $\langle T_{\text{fuel}} \rangle$ for fuel assembly
- $\langle T_{\text{Pb}} \rangle$ for coolant



3D thermal analysis approximated as:

1D (z) axial single channel analysis +
2D (xy) inter-channel coupling

Weak coupling to neighbouring
hexagonal assemblies ($\tau_{xy} \gg \tau_{\text{hom}}$)



- Molten Pb \rightarrow 1D mass/momentum/energy balance for (v , p , T_{Pb})
- Heat source terms \leftarrow neutronics
- Fuel assembly \rightarrow 1D transient heat conduction equation for (T_{fuel})

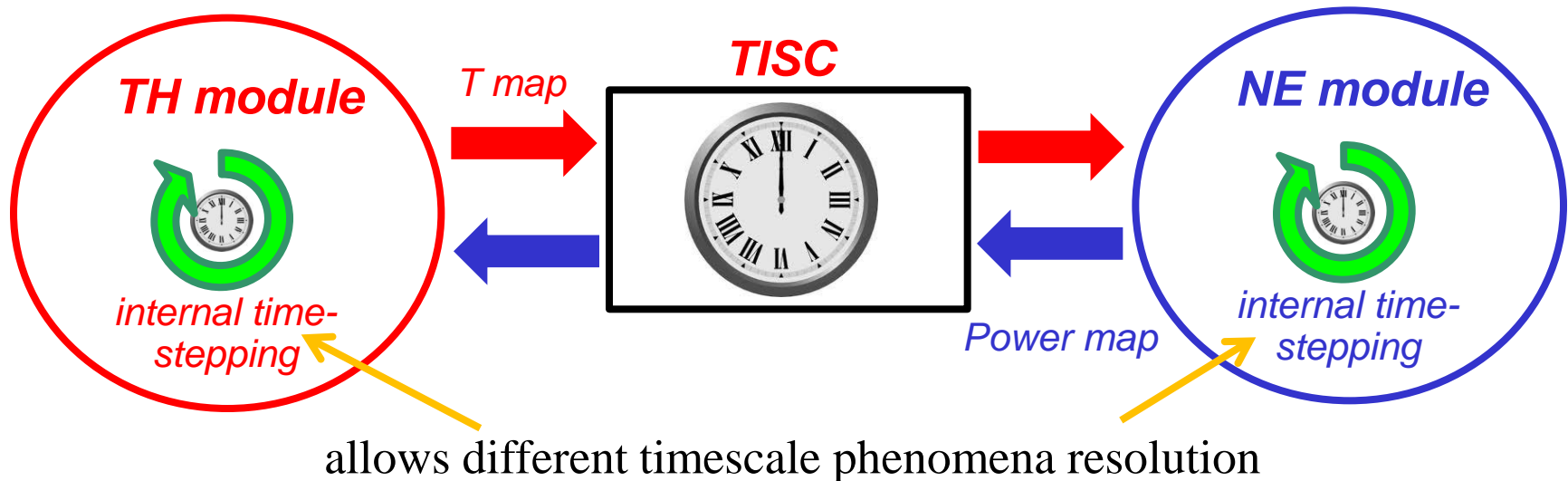


Coupling strategy



Neutron timescales \ll thermal-hydraulic timescales

Develop separately NE and TH modules,
and couple them explicitly on the shortest TH
timescales





Milestones of code development



- Development and coupling of TH and NE modules for 1 single hexagonal assembly (*z direction*): **ASSEMBLY LEVEL**
 - TH: 1 adiabatic assembly
 - NE: point kinetic method with a linear feedback model
- Development of the coupling between different hexagonal assemblies in both NE and TH modules + coupling of the two modules (*x&y directions*): **FULL-CORE LEVEL**

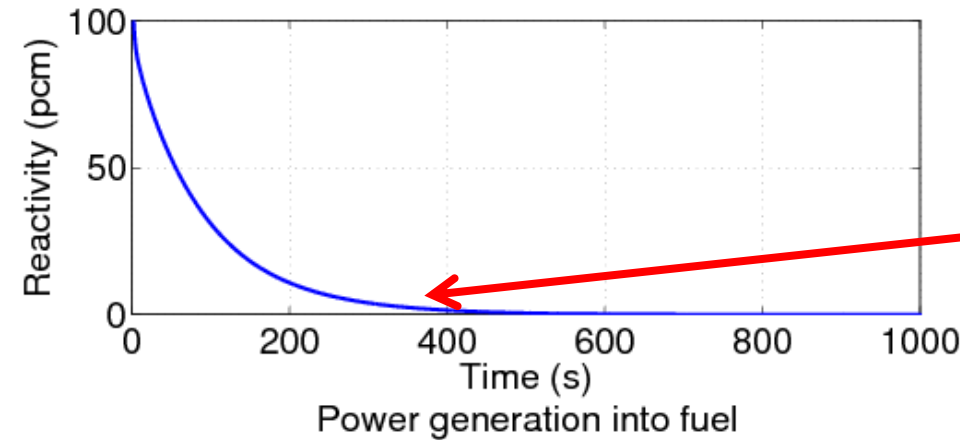


Test case definition



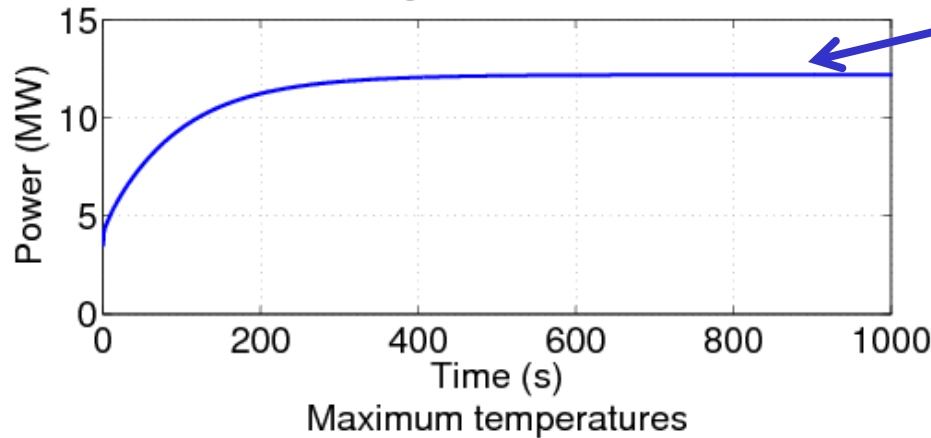
- **DRIVER : Reactivity introduction $\rho (t=0) = 100 \text{ pcm}$**
- Data from reference ELSY design:
 - Temperature feedback coefficients (MOX)
 - $\alpha_{\text{fuel}} = - 0.8 \text{ pcm/K}$
 - $\alpha_{\text{pb}} = + 0.35 \text{ pcm/K}$
 - Inlet $T_{\text{pb}} = 673 \text{ K}$; $\Delta p = 1.35 \text{ bar} \rightarrow v_{\text{pb}} \sim 1 \text{ m/s}$
 - Assembly geometry
 - Fuel thermophysical properties (presently UO_2)
 - Steady-state axial power shape (deposited in fuel only): sinusoidal, such that $\int P(z)dz = P_{\text{core}}(1500 \text{ MWth}) / N_{\text{assemblies}} (433)$

Results (I)

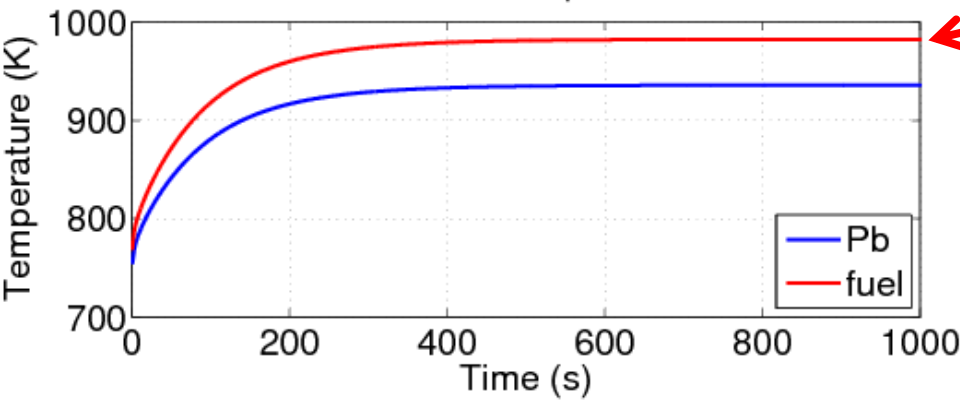


- ρ going back to 0 \leftarrow negative temperature feedback \leftarrow

- Neutronic flux $\uparrow \rightarrow$ Power steady state value $\uparrow \rightarrow$ temperature \uparrow



- Check T_{\max} stays well below $T_{\text{melt}}^{\text{UO}_2}$ (3120 K), $T_{\text{boil}}^{\text{Pb}}$ (2016 K)



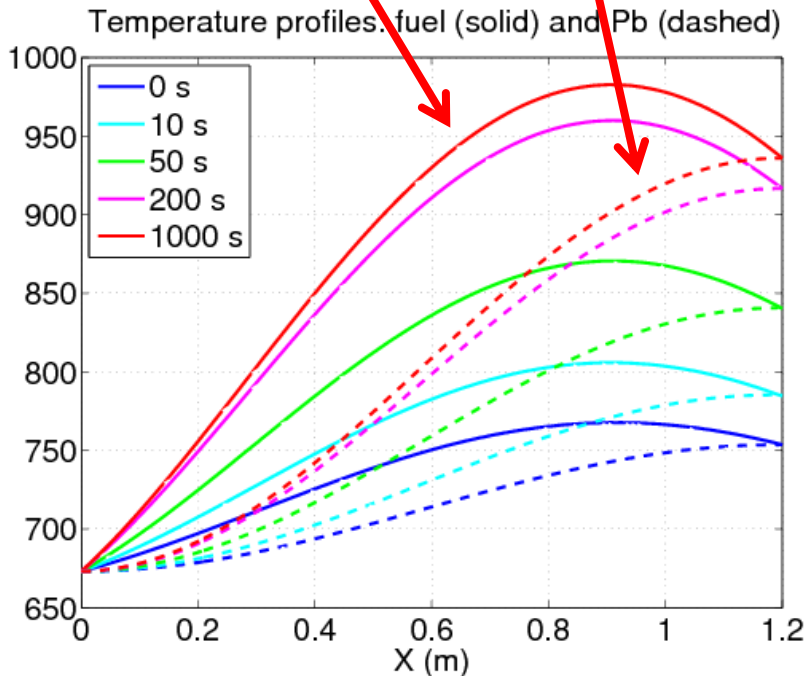


Results (II)

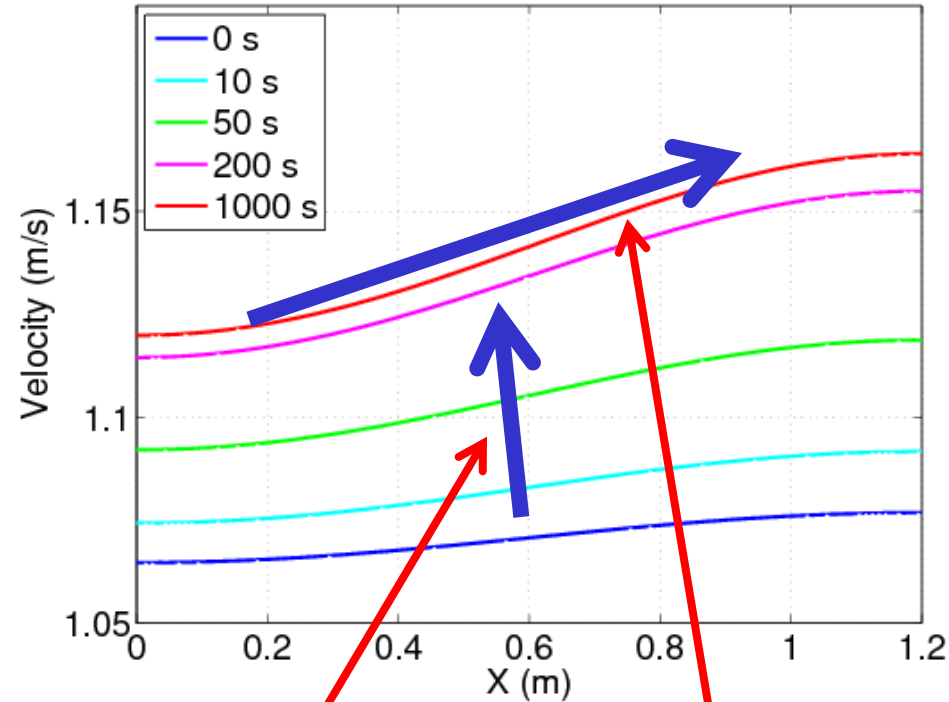


- Sinusoidal power axial distribution \rightarrow peaked T_{fuel} profiles

- T_{Pb} peak shifted downstream wrt T_{fuel} (advection effect)



Pb velocity profiles



- Higher power \rightarrow higher $T \rightarrow$ lower density \rightarrow lower pressure head \rightarrow higher $\langle v_{\text{Pb}} \rangle$

- Heating + BC (p_{in} and p_{out} imposed) \rightarrow acceleration along the channel



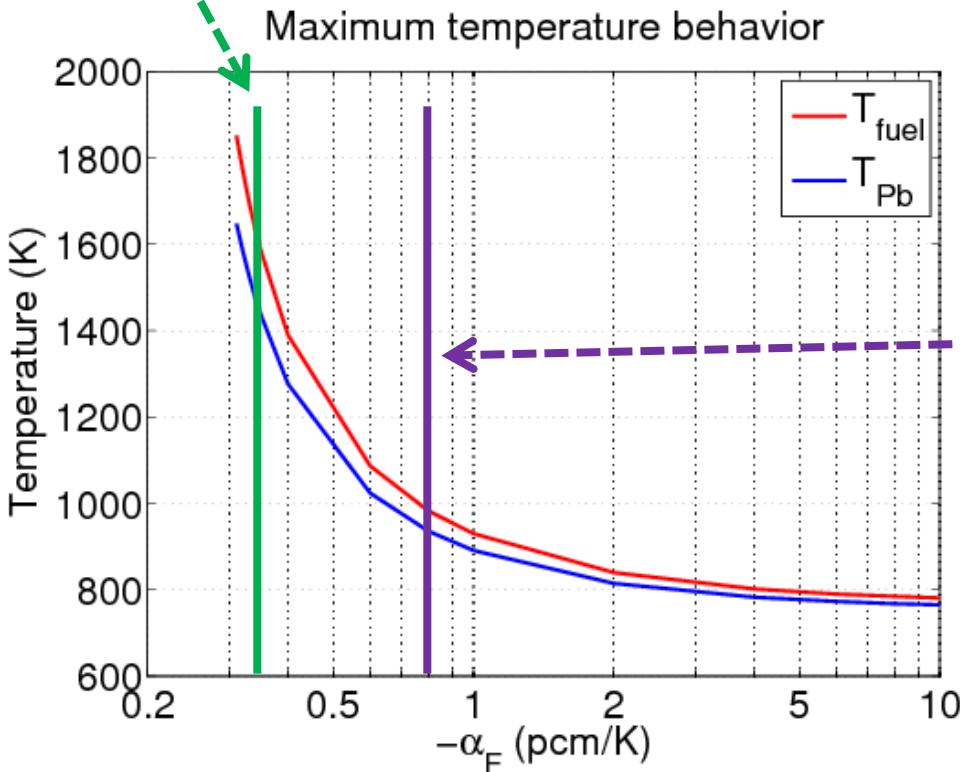
Parametric study of α_{fuel} effects



Behavior			
increasing ρ , unstable			
decreasing ρ , Pb boiling			
stable			
		-0.3	-0.2

Increasing Pu content

- Value of α_{Pb}



- Reference value

Heat deposition into fuel only $\rightarrow \Delta T_{\text{fuel}} > \Delta T_{\text{Pb}} \rightarrow$
stability limit: $\alpha_{\text{fuel}} < -|\alpha_{\text{Pb}}| + \delta$



Conclusions and perspective



- Coupled TH and NE modules for 1 single hexagonal assembly (*z-direction*) have been developed
 - TH: 1 adiabatic assembly
 - NE: point kinetics method with a linear feedback model
- The model has been applied to the study of a simple reactivity insertion transient and the parametric effect of the fuel temperature coefficient has been presented
- The model should now be extended from the single-assembly to the full-core level, implementing the coupling through different hexagonal assemblies in both NE and TH modules (*x&y directions*) and applied to the study of safety transients and stability analysis