# Coupled Neutronics and Thermal-Hydraulics Transient Calculations Based on a Fission Matrix Approach: Application to the Molten Salt Fast Reactor

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ANS MC2015

# SUMMARY

INTRODUCTION: OBJECTIVE OF THE CURRENT DEVELOPMENTS

I. TRANSIENT FISSION MATRIX
   - PRESENTATION
   - TFM KINETICS EQUATIONS
   - KINETICS PARAMETERS CALCULATION
   - TFM SIMPLIFIED KINETICS EQUATIONS

II. GENERAL COUPLING STRATEGY

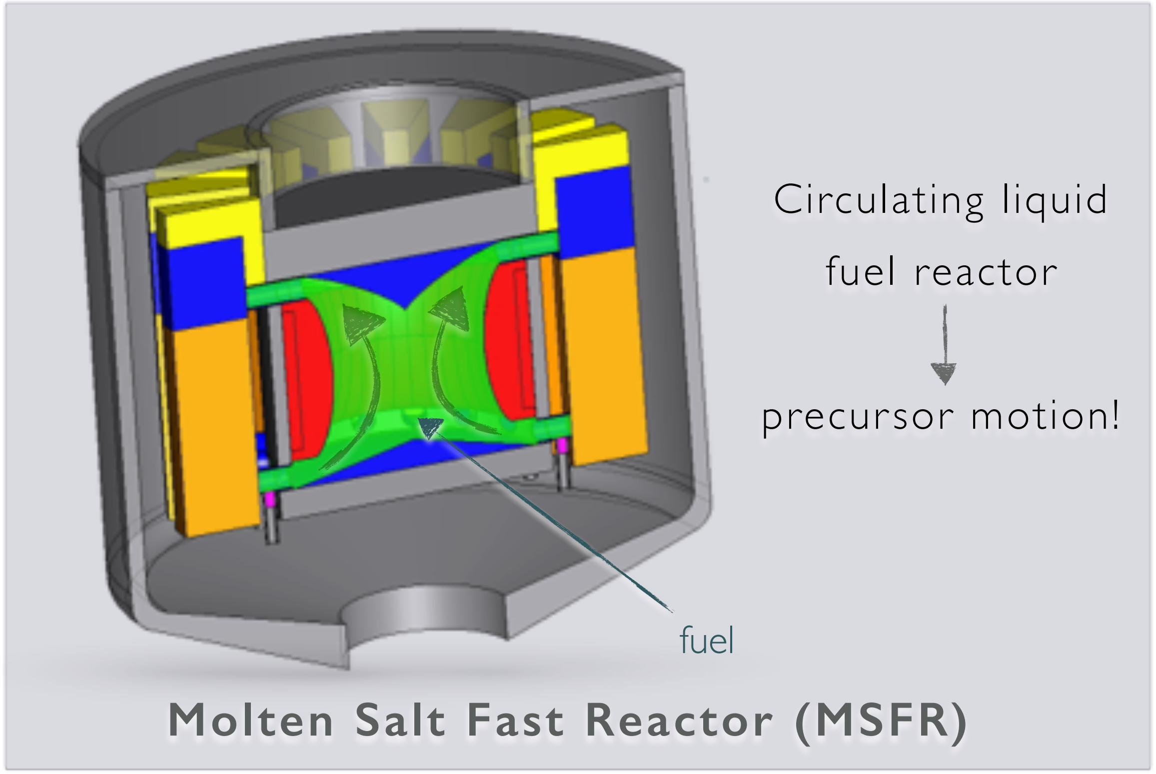
III. APPLICATION CASES
   - MSFR PRESENTATION
   - OVER COOLING TRANSIENT CALCULATION
   - REACTIVITY INSERTION

# INTRODUCTION: OBJECTIVE OF THE CURRENT DEVELOPMENTS

**Context:**

- Need to perform transient calculations for the MSFR

  ⟶ neutronics / thermal-hydraulics coupling



**Molten Salt Fast Reactor (MSFR)**

**Objectives:**

- with a high precision of the T&H modeling (flow distribution, precursor transport, …)

  ⟶ CFD code (OpenFOAM)

- with a high precision of the neutronics modeling

  ⟶ Monte Carlo code (MCNP and SERPENT) …

- … with a low computational cost (need to perform many cases)

  ⟶ Diffusion? Improved point kinetics? … something else?

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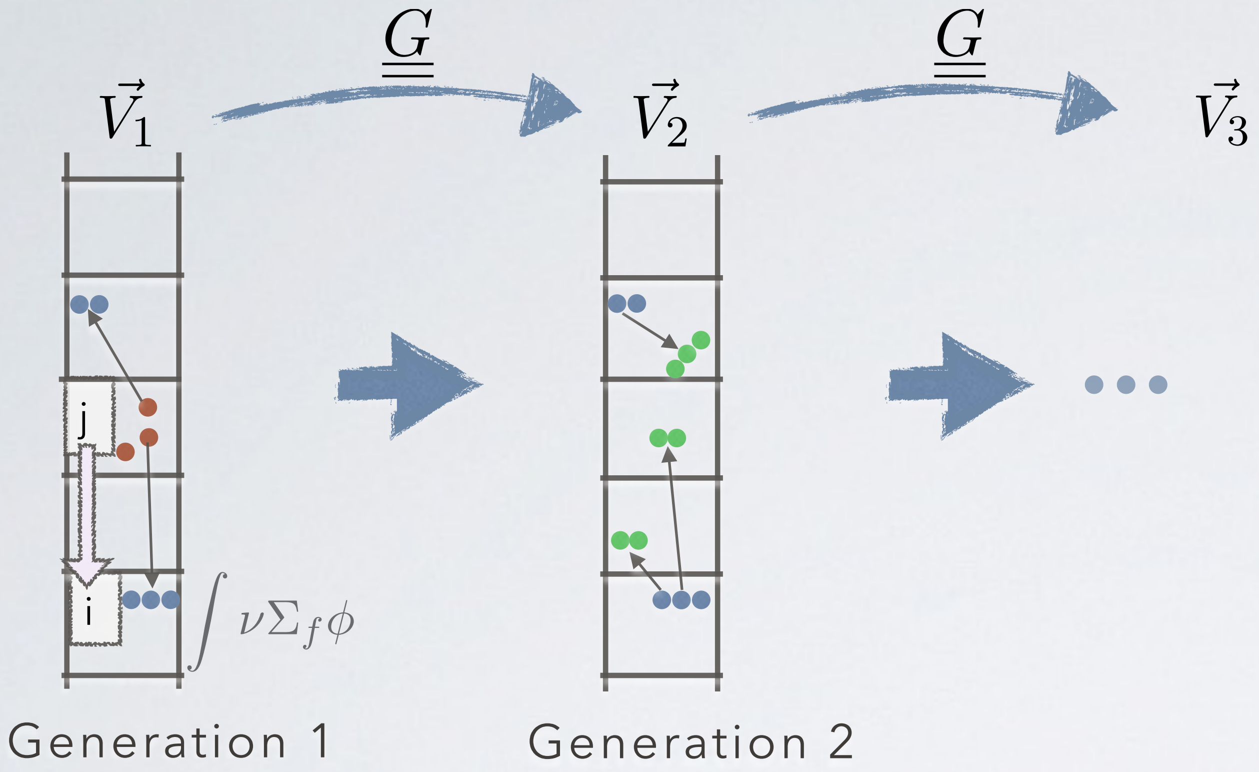
# I. TRANSIENT FISSION MATRIX: PRESENTATION



OVERALL PRINCIPE:

CHARACTERIZE THE SYSTEM RESPONSE
ON ONE GENERATION (GREEN FUNCTION)

step 1: Matrix element *ij*: volume *i* neutron production probability induced by an incoming source neutron injected in *j*

↓ TFM

step 2: Discretization of this matrix through time to get the temporal response

↓

step 3: Interpolation (Doppler & density feedback effects)

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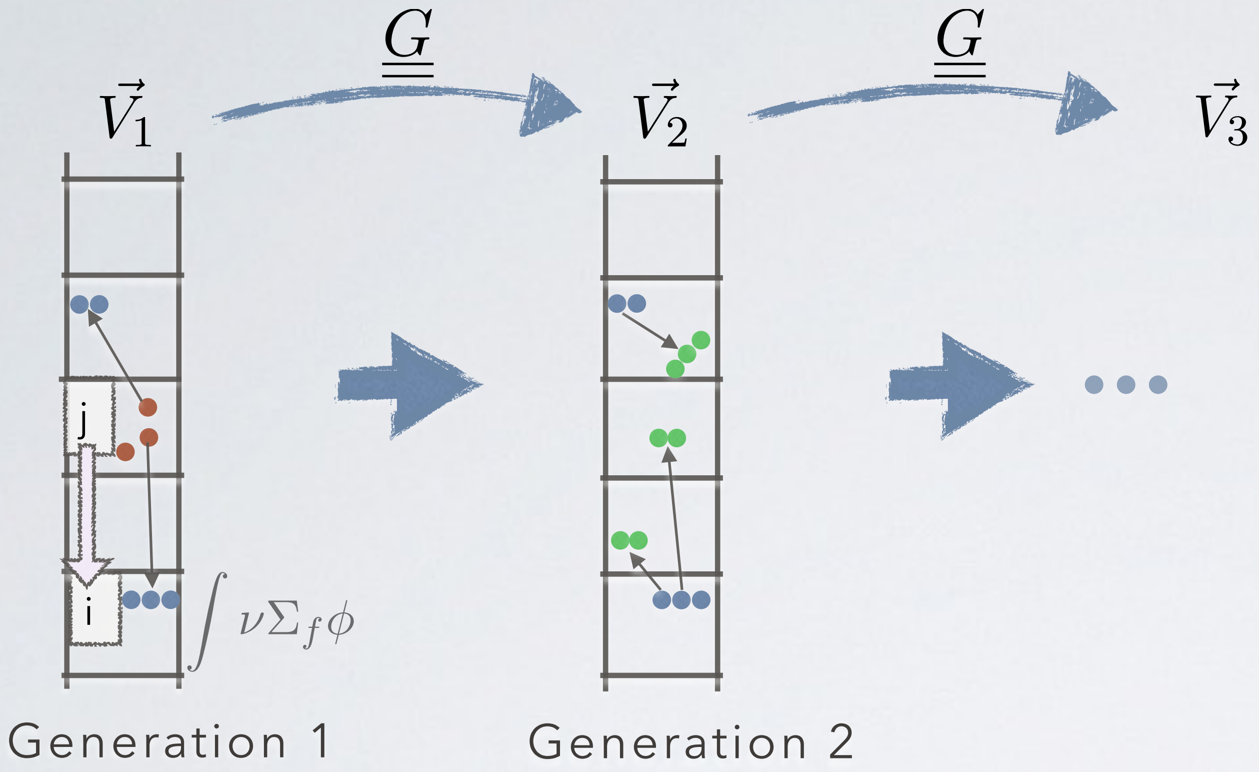

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With $S(\boldsymbol{r}, t)$ the prompt source neutron distribution rate at time $t$ in $\boldsymbol{r}$

With $G_{\chi_p \nu_p}(t' - t, \boldsymbol{r'}, \boldsymbol{r})$ the continuous operator associated to the transient fission matrix: the probability that a neutron created in $\boldsymbol{r'}, t'$ induces a new neutron in $\boldsymbol{r}, t$

prompt emission spectrum

prompt production

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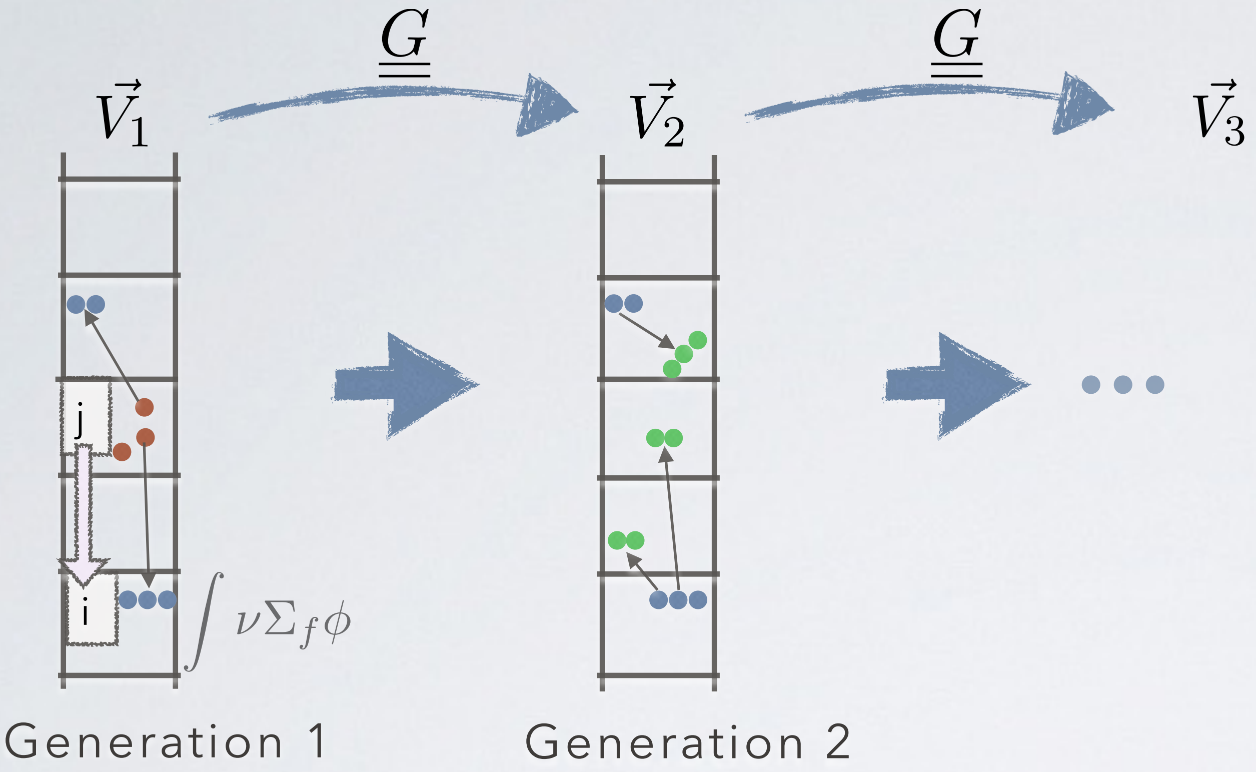

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prompt emission spectrum

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The kinetics of a prompt neutron population is given by:

$$S(\boldsymbol{r}, t) = \Big| G_{\chi_p \nu_p}(t' - t, \boldsymbol{r'}, \boldsymbol{r}) \Big| S(\boldsymbol{r'}, t') \Big\rangle = \iint_{t' < t, \boldsymbol{r'} \in \mathcal{R}} G_{\chi_p \nu_p}(t' - t, \boldsymbol{r'}, \boldsymbol{r}) \cdot S(\boldsymbol{r'}, t') \, \mathrm{d}\boldsymbol{r'} \, \mathrm{d}t'$$

# I. TRANSIENT FISSION MATRIX: KINETICS EQUATIONS

## AND WITH THE DELAYED NEUTRON PRECURSORS:

- Prompt source neutron distribution rate

prompt ← prompt ←

$$S(t,\boldsymbol{r}) \quad = \quad \Big|G_{\chi_p\nu_p}(t-t',\boldsymbol{r'},\boldsymbol{r})\Big|S(t',\boldsymbol{r'})\Big\rangle + \Big|G_{\chi_d\nu_p}(t-t',\boldsymbol{r'},\boldsymbol{r})\Big|\sum_f \lambda_f P_f(t',\boldsymbol{r'})\Big\rangle$$

- Precursor family $f$

delayed ← delayed ←

$$\frac{dP_f}{dt}(t,\boldsymbol{r}) \quad = \quad \frac{\beta_f}{\beta_0}\left[\Big|G_{\chi_p\nu_d}(t-t',\boldsymbol{r'},\boldsymbol{r})\Big|S(t',\boldsymbol{r'})\Big\rangle + \Big|G_{\chi_d\nu_d}(t-t',\boldsymbol{r'},\boldsymbol{r})\Big|\sum_f \lambda_f P_f(t',\boldsymbol{r'})\Big\rangle\right] - \lambda_f P_f$$

↑ family ratio ↑ decay constant

The time integration requires one matrix-vector product by time discretization of the Green operators…

→ Too long for our objective

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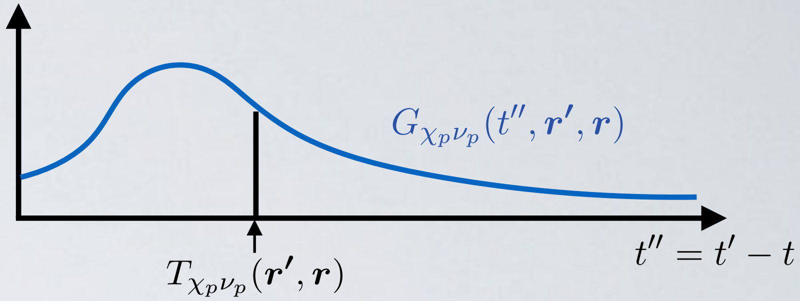

EFFECTIVE LIFE TIME $l_{eff}$ CALCULATION:

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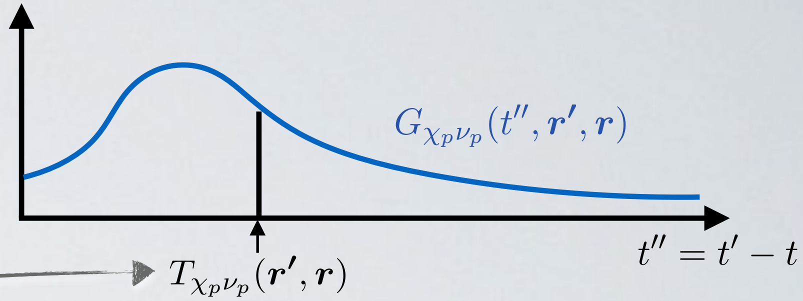

We need the average time response:
directly computed in the SERPENT code

$$T_{\chi_p\nu_p}(\boldsymbol{r'}, \boldsymbol{r}) = \frac{\displaystyle\int_{t''>0} G_{\chi_p\nu_p}(t'', \boldsymbol{r'}, \boldsymbol{r}) \cdot t''\, \mathrm{d}t''}{\displaystyle\int_{t''>0} G_{\chi_p\nu_p}(t'', \boldsymbol{r'}, \boldsymbol{r})\, \mathrm{d}t''}$$

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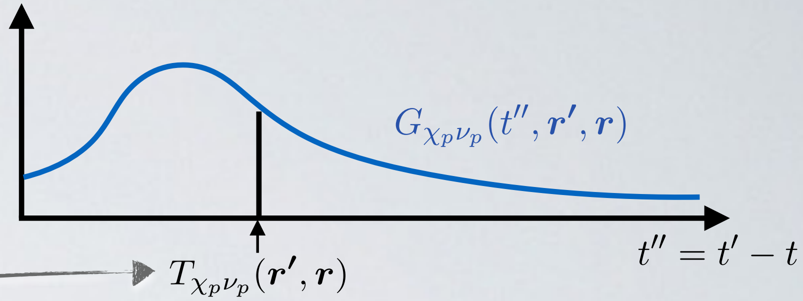

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With the total response through time:
the classic FM operator

$$\widetilde{G}_{\chi_p\nu_p}(\boldsymbol{r'}, \boldsymbol{r}) = \int_{-\infty}^{t} G_{\chi_p\nu_p}(t - t', \boldsymbol{r'}, \boldsymbol{r}) dt'$$

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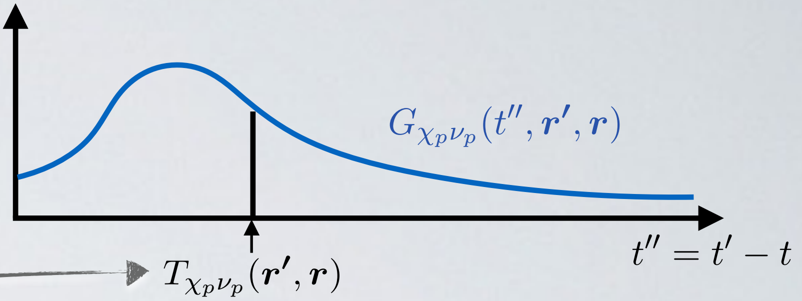

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The adjoint operator and its Eigenvector
the neutron goes backward in generation = importance!

$$\widetilde{G}^{adj}_{\chi_p\nu_p} \longrightarrow N_p^*(\boldsymbol{r})$$

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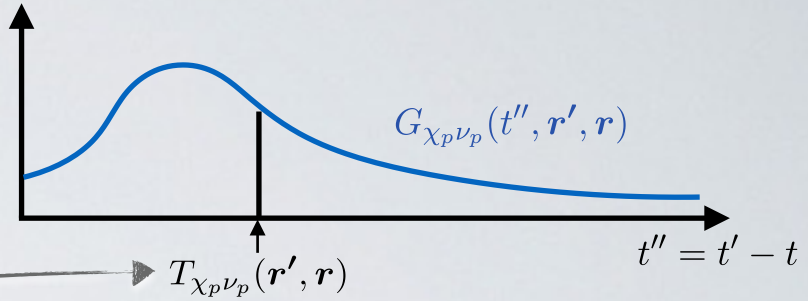

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Finally:

$$l_{eff} = \frac{\displaystyle\iint_{\boldsymbol{r}'\in\mathcal{R},\boldsymbol{r}\in\mathcal{R}} N_p^*(\boldsymbol{r})\left[T_{\chi_p\nu_p}(\boldsymbol{r}',\boldsymbol{r}).\tilde{G}_{\chi_p\nu_p}(\boldsymbol{r}',\boldsymbol{r})\right] N_p(\boldsymbol{r}')\,\mathrm{d}\boldsymbol{r}'\,\mathrm{d}\boldsymbol{r}}{\displaystyle\iint_{\boldsymbol{r}'\in\mathcal{R},\boldsymbol{r}\in\mathcal{R}} N_p^*(\boldsymbol{r})\tilde{G}_{\chi_p\nu_p}(\boldsymbol{r}',\boldsymbol{r})N_p(\boldsymbol{r}')\,\mathrm{d}\boldsymbol{r}'\,\mathrm{d}\boldsymbol{r}}$$

And its discretized version:

$$l_{eff} = \frac{\displaystyle\sum_{\mathcal{R}} \boldsymbol{N_p^*}\left(\underline{\underline{T_{\chi_p\nu_p}}}\cdot\underline{\underline{\tilde{G}_{\chi_p\nu_p}}}\right)\boldsymbol{N}_p}{\displaystyle\sum_{\mathcal{R}} \boldsymbol{N_p^*}\,\underline{\underline{\tilde{G}_{\chi_p\nu_p}}}\boldsymbol{N}_p}$$

aimed average time × neutron production per incoming neutron × neutron population

importance weighting

produced neutron

# I. TRANSIENT FISSION MATRIX: TFM SIMPLIFIED KINETIC EQUATIONS

## OVERALL PRINCIPLE:

Replace the neutron production rate $S(\boldsymbol{r},t)$ by a neutron population $N(t,\boldsymbol{r})$ associated to a time constant $l_{eff}$:
note: can not model phenomena with a shorter time constant

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$$\begin{tikzcd}
 & & \Big|\widetilde{G}_{\chi_p\nu_p}(\boldsymbol{r}',\boldsymbol{r})\Big|N(t,\boldsymbol{r}')\frac{\mathrm{d}t}{l_{eff}}\Big\rangle & \text{new prompt neutrons} \\
\text{prompt neutron disappearance during dt} & N(t,\boldsymbol{r})\frac{\mathrm{d}t}{l_{eff}} \arrow[ur] \arrow[dr] & & \\
 & & \Big|\widetilde{G}_{\chi_p\nu_d}(\boldsymbol{r}',\boldsymbol{r})\Big|N(t,\boldsymbol{r}')\frac{\mathrm{d}t}{l_{eff}}\Big\rangle & \text{new precursors}
\end{tikzcd}$$

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 & & \Big|\widetilde{G}_{\chi_d\nu_p}(\boldsymbol{r}',\boldsymbol{r})\Big|\sum_f \lambda_f P_f(t,\boldsymbol{r}')\,\mathrm{d}t\Big\rangle & \text{new prompt neutrons} \\
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## NEW SET OF EQUATIONS:

$$\begin{aligned} \frac{dP_f}{dt}(t,\boldsymbol{r}) &= \frac{\beta_f}{\beta_0}\left[\frac{1}{l_{eff}}\left|\widetilde{G}_{\chi_p\nu_d}(\boldsymbol{r}',\boldsymbol{r})\middle|N(t,\boldsymbol{r}')\right\rangle + \left|\widetilde{G}_{\chi_d\nu_d}(\boldsymbol{r}',\boldsymbol{r})\middle|\sum_f \lambda_f P_f(t,\boldsymbol{r}')\right\rangle\right] - \lambda_f P_f(t,\boldsymbol{r}) \\ \frac{dN}{dt}(t,\boldsymbol{r}) &= \frac{1}{l_{eff}}\left|\widetilde{G}_{\chi_p\nu_p}(\boldsymbol{r}',\boldsymbol{r})\middle|N(t,\boldsymbol{r}')\right\rangle + \left|\widetilde{G}_{\chi_d\nu_p}(\boldsymbol{r}',\boldsymbol{r})\middle|\sum_f \lambda_f P_f(t,\boldsymbol{r}')\right\rangle - \frac{1}{l_{eff}}N(t,\boldsymbol{r}) \end{aligned}$$

this simplified formulation only requires simple matrix-vector products (instead of series of matrix vector previously)

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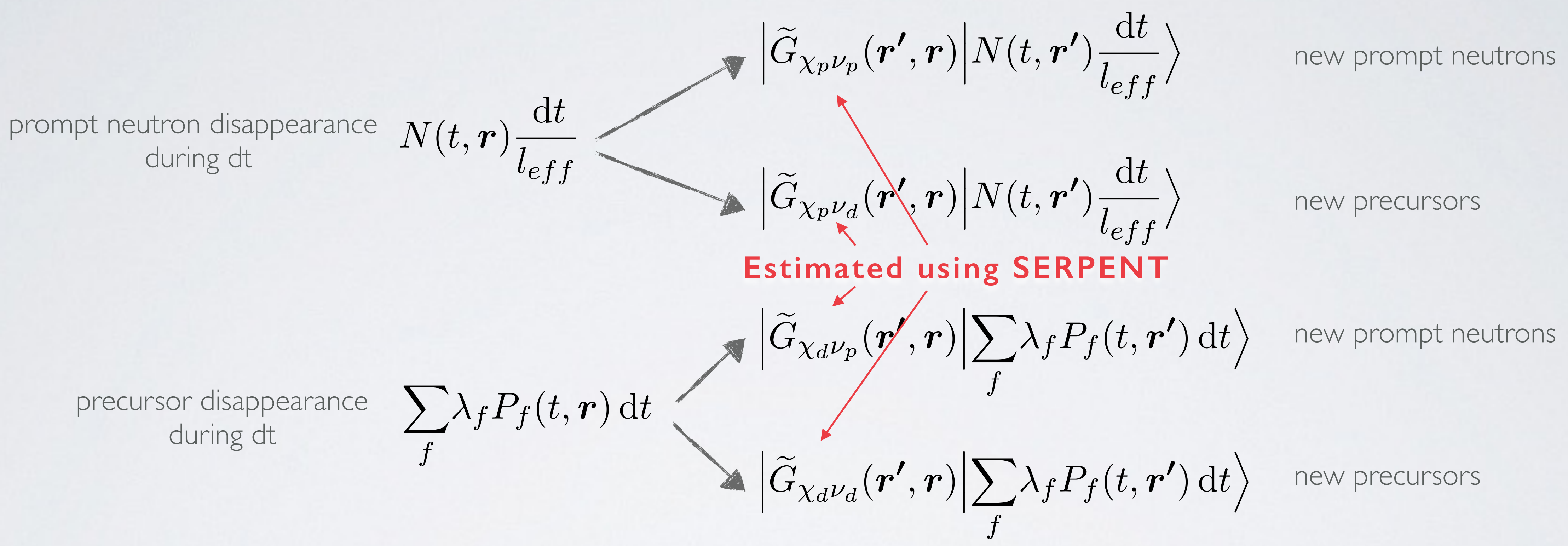

prompt neutron disappearance during dt

$$N(t,\boldsymbol{r})\frac{\mathrm{d}t}{l_{eff}}$$

$$\Big|\widetilde{G}_{\chi_p\nu_p}(\boldsymbol{r}',\boldsymbol{r})\Big|N(t,\boldsymbol{r}')\frac{\mathrm{d}t}{l_{eff}}\Big\rangle$$

new prompt neutrons

$$\Big|\widetilde{G}_{\chi_p\nu_d}(\boldsymbol{r}',\boldsymbol{r})\Big|N(t,\boldsymbol{r}')\frac{\mathrm{d}t}{l_{eff}}\Big\rangle$$

new precursors

**Estimated using SERPENT**

precursor disappearance during dt

$$\sum_f \lambda_f P_f(t,\boldsymbol{r})\,\mathrm{d}t$$

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## NEW SET OF EQUATIONS:

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$$\frac{dN}{dt}(t,\boldsymbol{r}) = \frac{1}{l_{eff}}\Big|\widetilde{G}_{\chi_p\nu_p}(\boldsymbol{r}',\boldsymbol{r})\Big|N(t,\boldsymbol{r}')\Big\rangle + \Big|\widetilde{G}_{\chi_d\nu_p}(\boldsymbol{r}',\boldsymbol{r})\Big|\sum_f \lambda_f P_f(t,\boldsymbol{r}')\Big\rangle - \frac{1}{l_{eff}}N(t,\boldsymbol{r})$$

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# I. Transient Fission Matrix: Fission matrix interpolation

## And for transient calculations?

Matrix interpolation!

$$\widetilde{G}(\boldsymbol{r'},\boldsymbol{r}) = \widetilde{G}_{ref}(\boldsymbol{r'},\boldsymbol{r}) + \underbrace{(T(\boldsymbol{r'}) - T_{ref})}_{\text{linear dependency}} \cdot \Delta_\rho \widetilde{G}(\boldsymbol{r'},\boldsymbol{r}) + \underbrace{\log \frac{T(\boldsymbol{r'})}{T_{ref}}}_{\text{logarithmic dependency}} \cdot \Delta_{Doppler} \widetilde{G}(\boldsymbol{r'},\boldsymbol{r})$$

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## AND FOR TRANSIENT CALCULATIONS?

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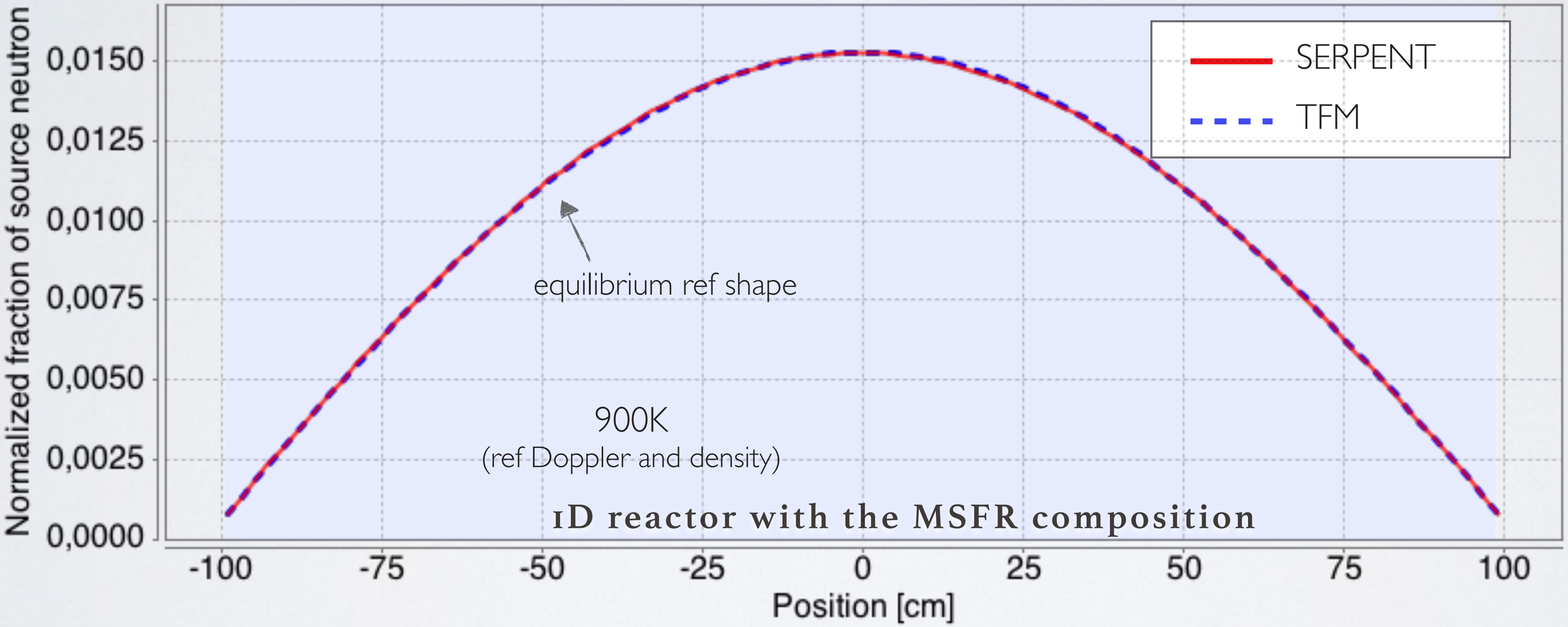
linear dependency

logarithmic dependency



- good modeling of the neutron shift
- good prediction of the multiplication factor variation (~1-2% error on 1000pcm)

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## AND FOR TRANSIENT CALCULATIONS?

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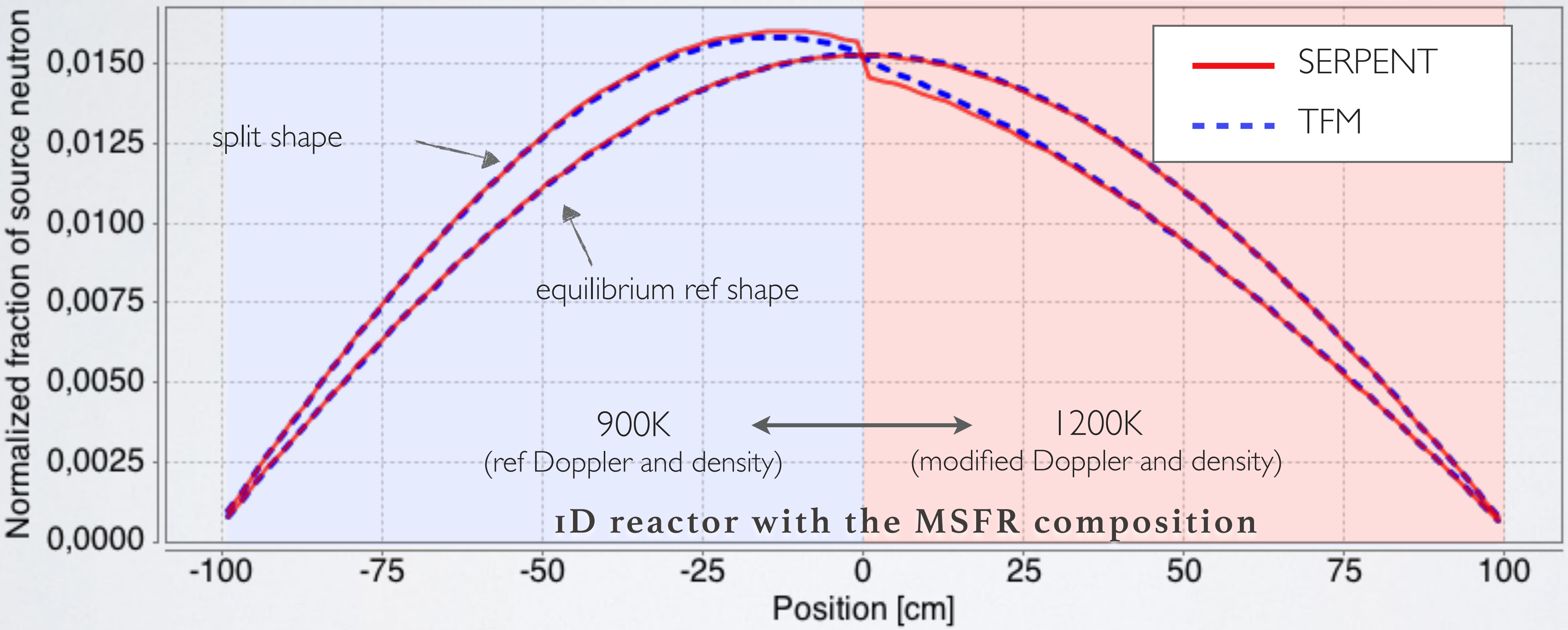

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II.

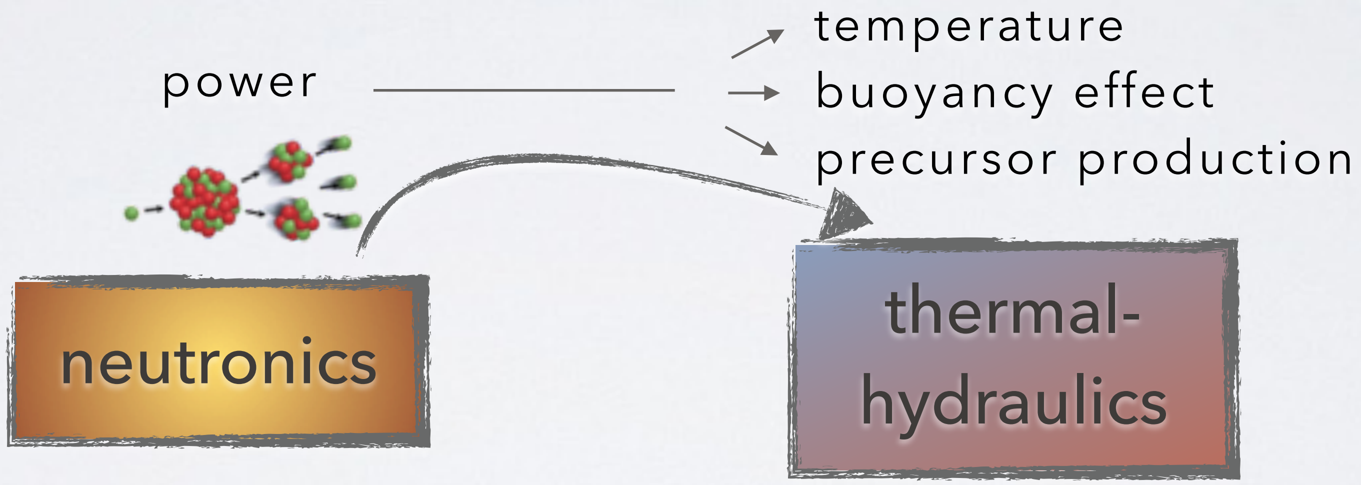
# GENERAL COUPLING STRATEGY

neutronics

thermal-hydraulics

II.

# GENERAL COUPLING STRATEGY



power

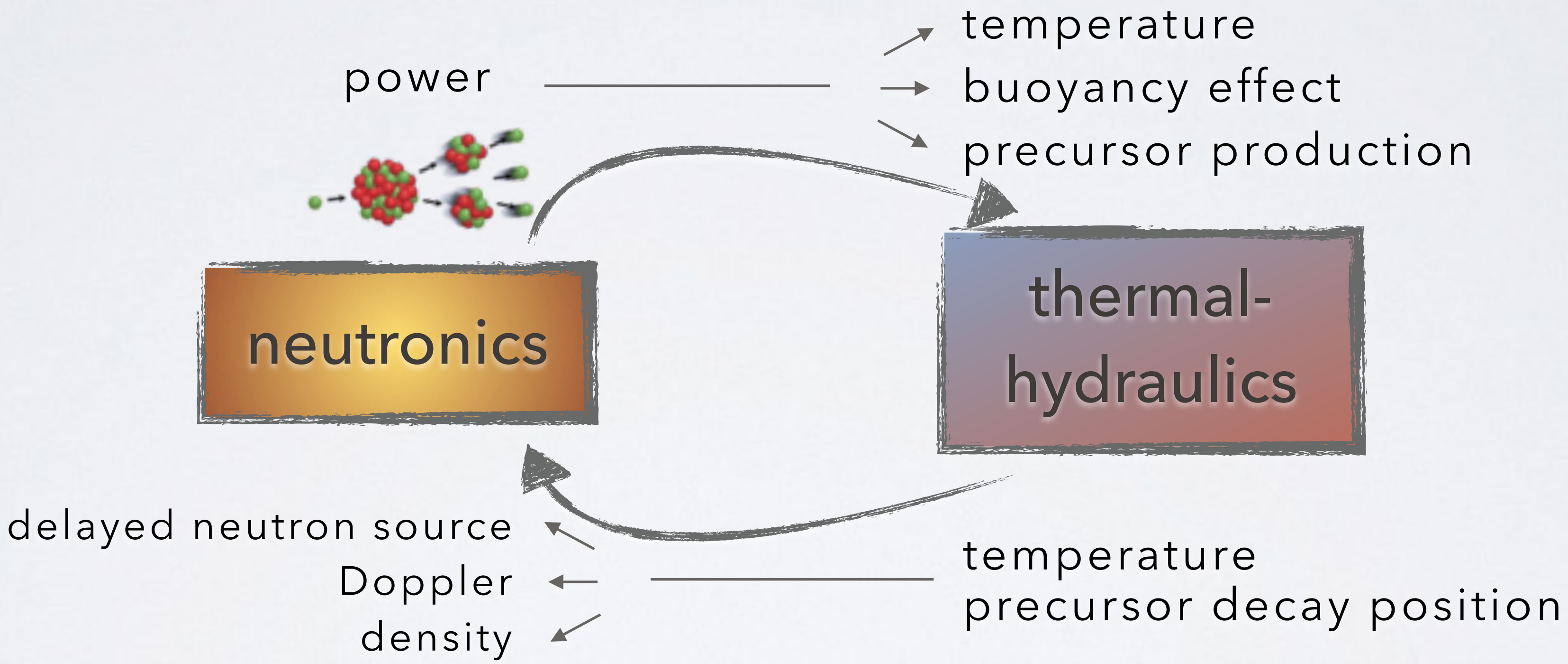
- temperature
- buoyancy effect
- precursor production

**neutronics**

**thermal-hydraulics**

II.

# GENERAL COUPLING STRATEGY



power

temperature

buoyancy effect

precursor production

neutronics

thermal-hydraulics

delayed neutron source

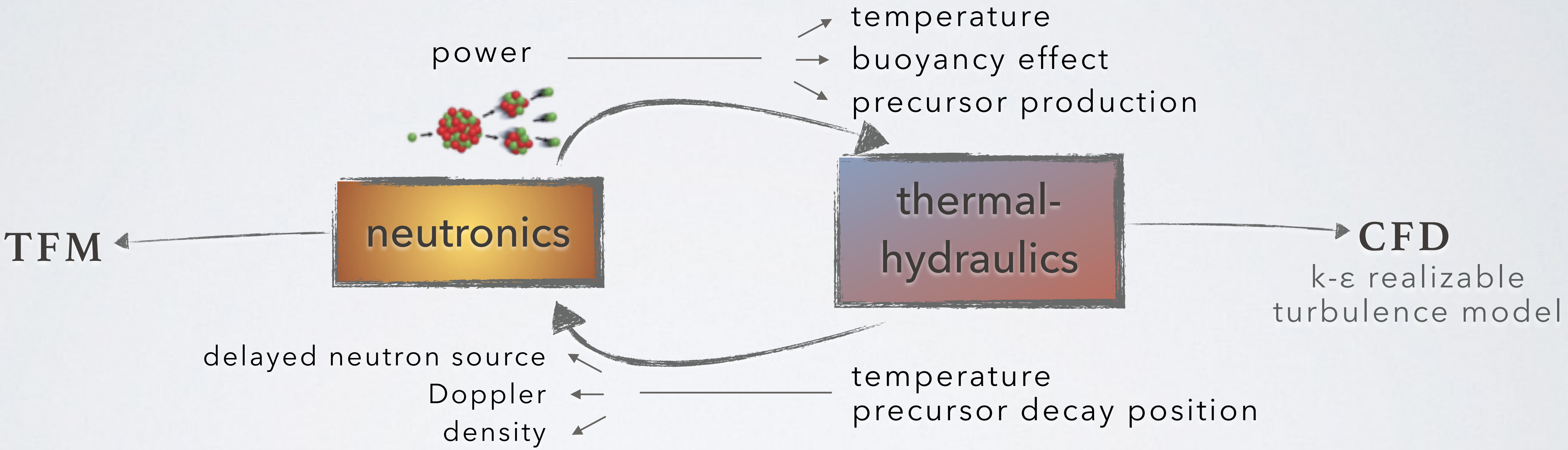
Doppler

density

temperature

precursor decay position

# GENERAL COUPLING STRATEGY



power

temperature
buoyancy effect
precursor production

**TFM**

neutronics

thermal-hydraulics

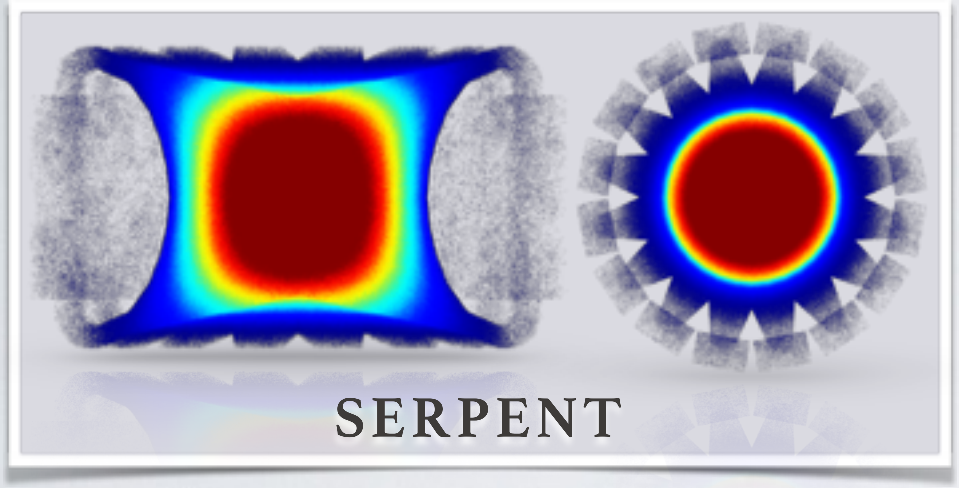
**CFD**

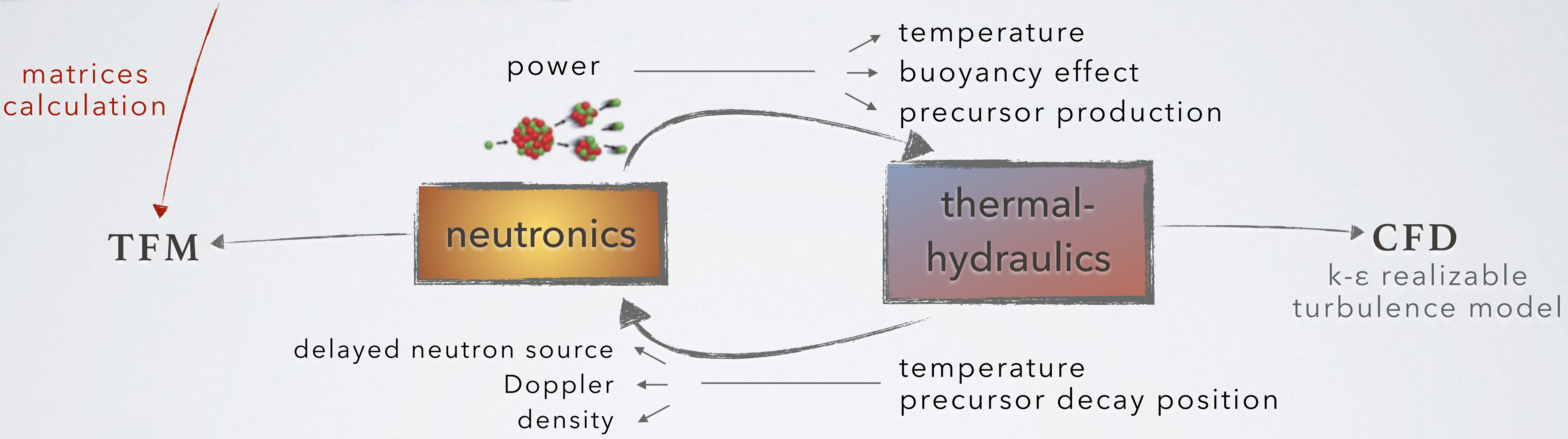
k-ε realizable turbulence model

delayed neutron source
Doppler
density

temperature
precursor decay position

# GENERAL COUPLING STRATEGY





matrices
calculation

**TFM**

**neutronics**

power

temperature
buoyancy effect
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**thermal-hydraulics**

**CFD**

k-ε realizable
turbulence model

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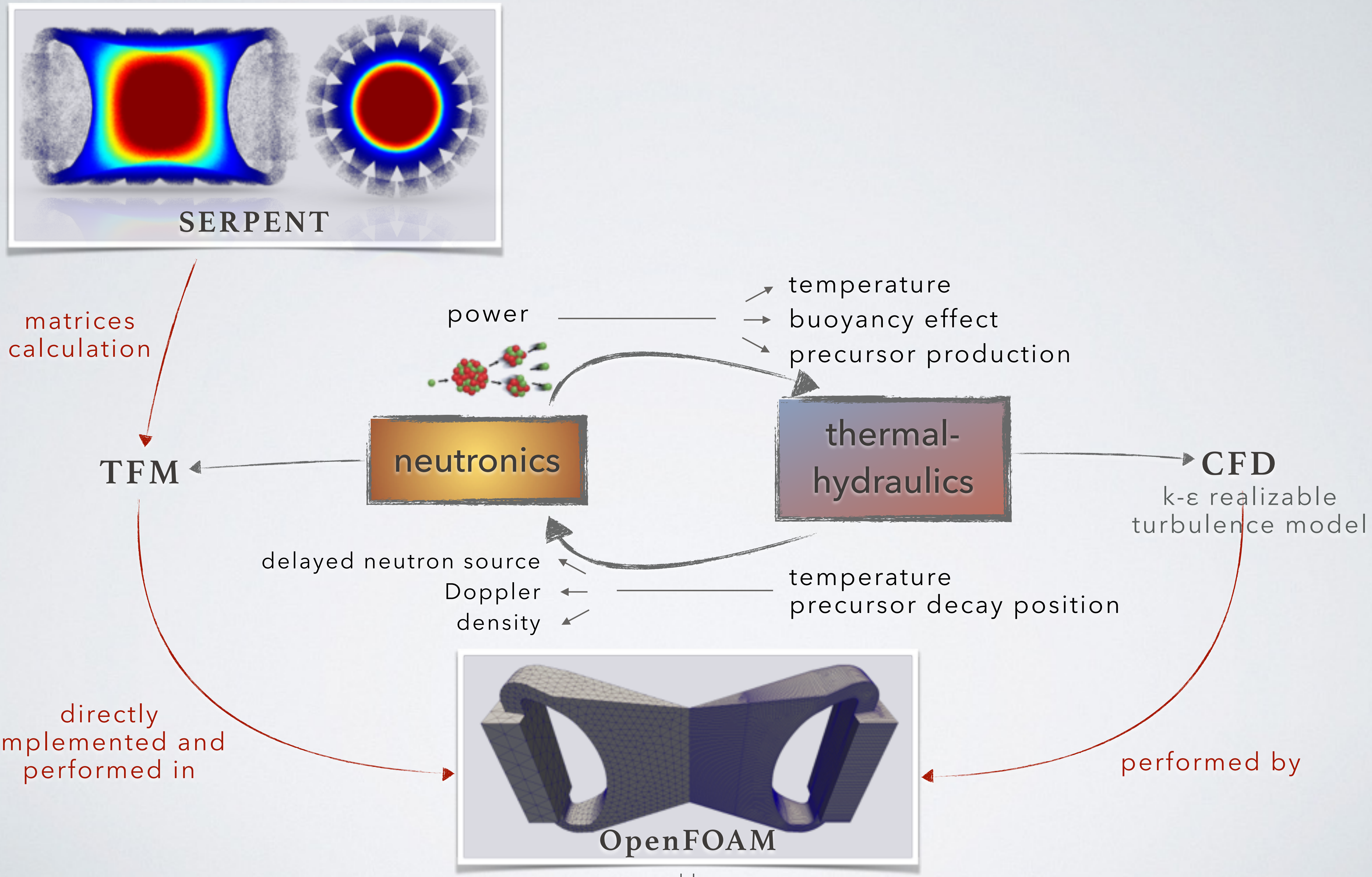
# II. GENERAL COUPLING STRATEGY



SERPENT

matrices calculation

TFM

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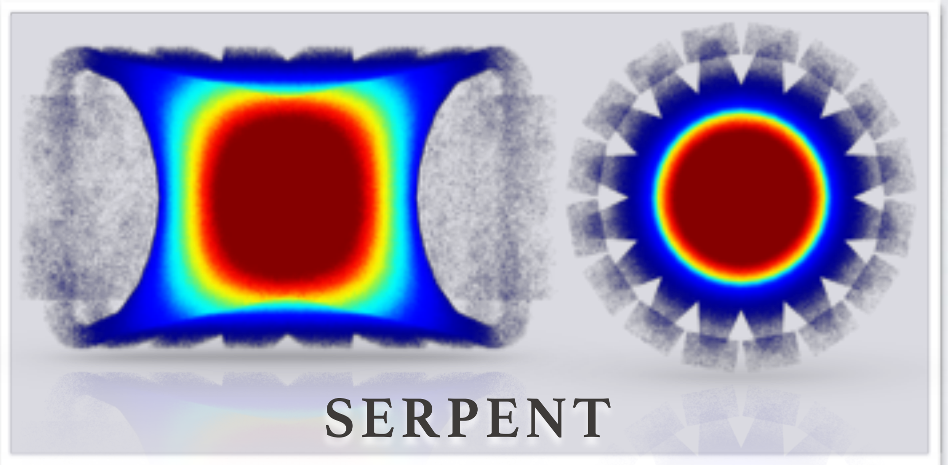
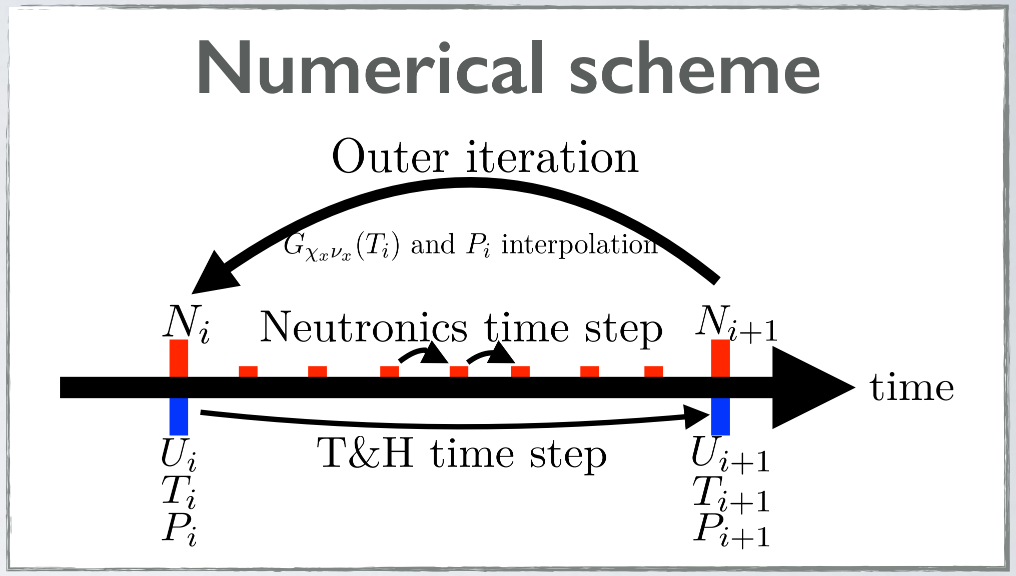
directly implemented and performed in

performed by

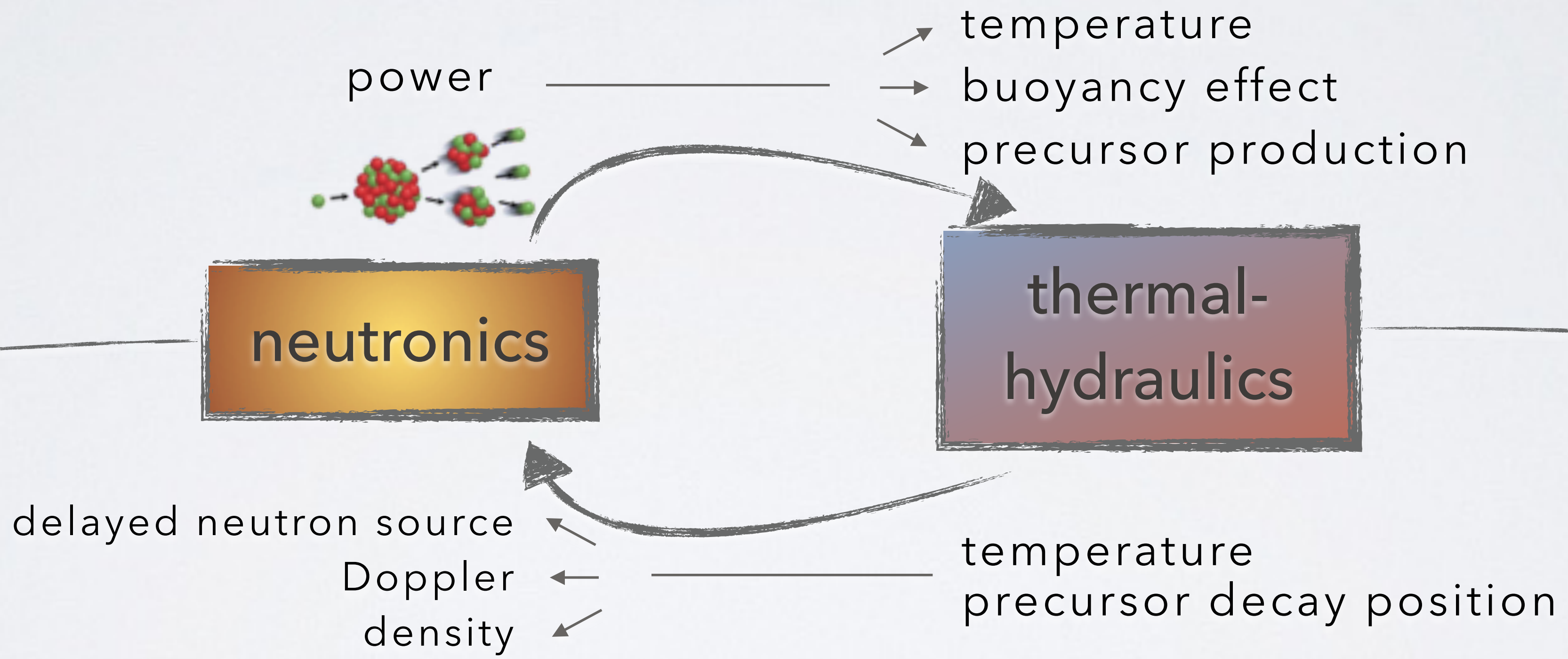
OpenFOAM

# II. GENERAL COUPLING STRATEGY




Numerical scheme

matrices calculation



**TFM**

power

temperature
buoyancy effect
precursor production

neutronics

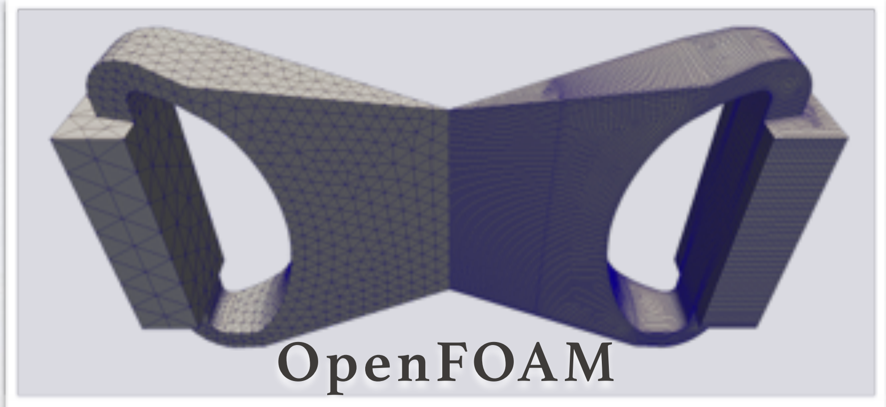
thermal-hydraulics

**CFD**
k-ε realizable
turbulence model

delayed neutron source
Doppler
density

temperature
precursor decay position

directly implemented and performed in



performed by

# SUMMARY

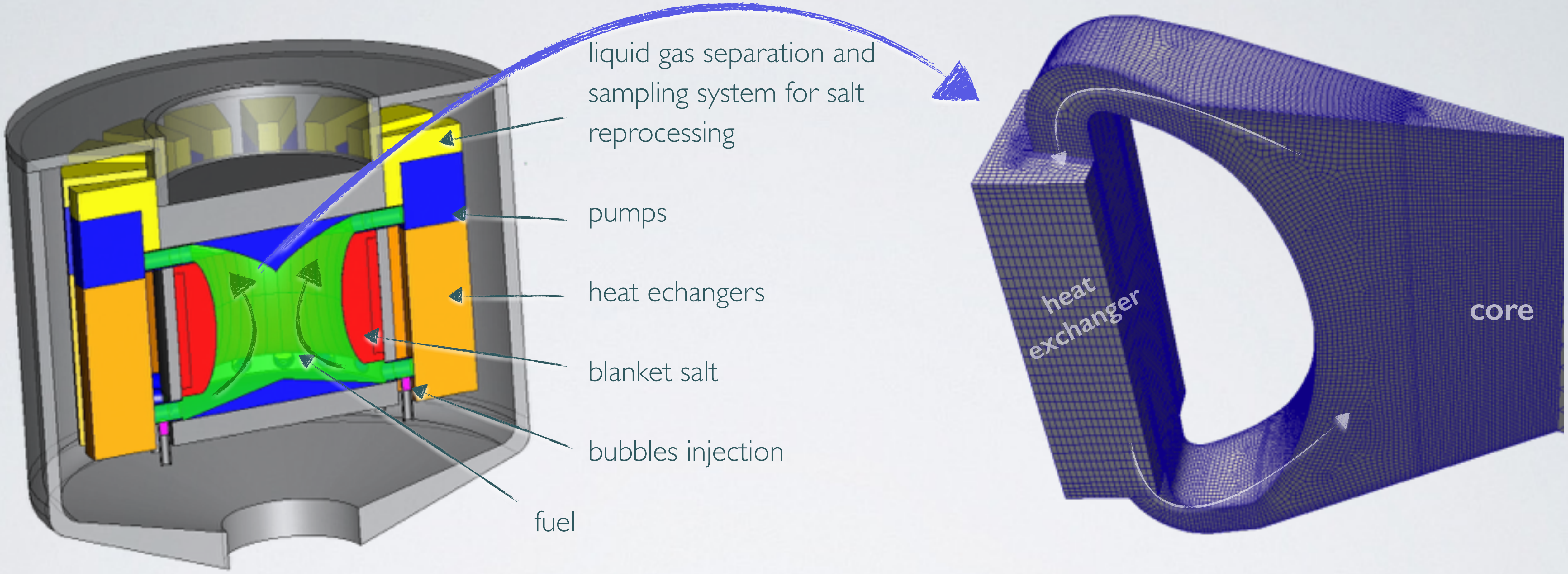
INTRODUCTION: OBJECTIVE OF THE CURRENT DEVELOPMENTS

I. TRANSIENT FISSION MATRIX
  - PRESENTATION
  - TFM KINETICS EQUATIONS
  - KINETICS PARAMETERS CALCULATION
  - TFM SIMPLIFIED KINETICS EQUATIONS

II. GENERAL COUPLING STRATEGY

III. APPLICATION CASES
  - MSFR PRESENTATION
  - OVER COOLING TRANSIENT CALCULATION
  - REACTIVITY INSERTION

# II. APPLICATION CASE: MOLTEN SALT FAST REACTOR (MSFR) PRESENTATION



1/16 of the reactor modeled

liquid gas separation and sampling system for salt reprocessing

pumps

heat echangers

blanket salt

bubbles injection

fuel

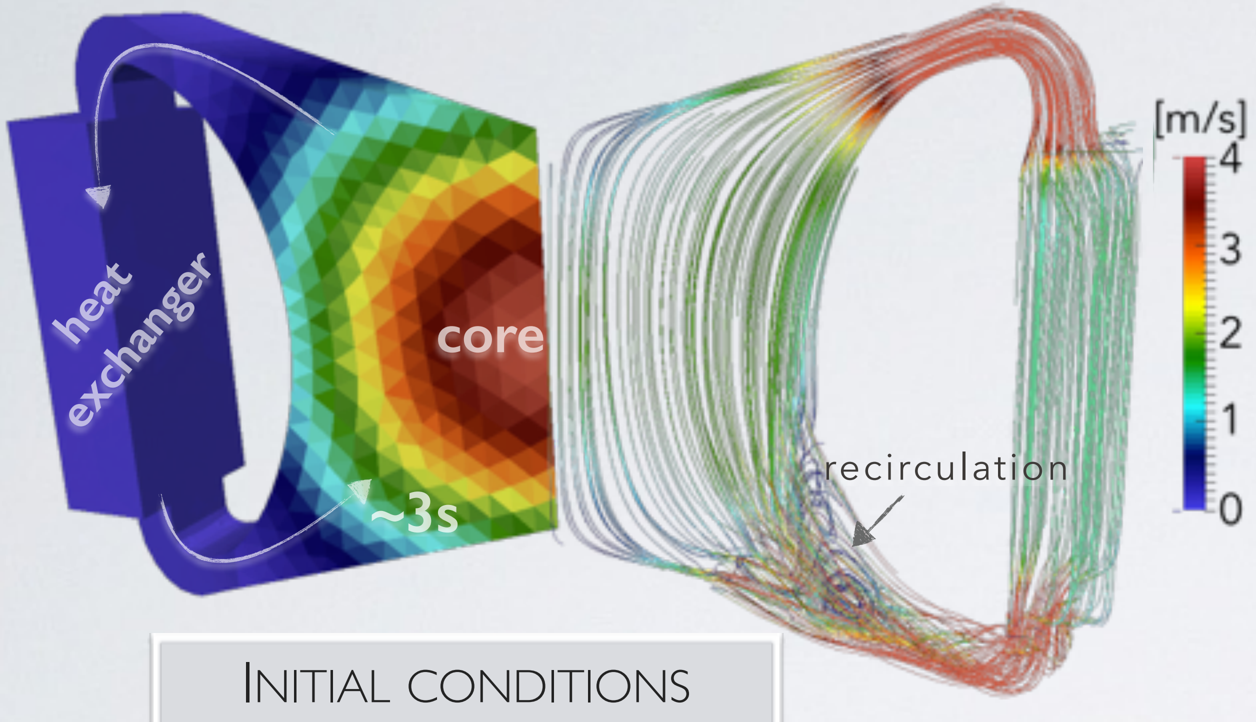
**Molten Salt Fast Reactor (MSFR)**

- Liquid fuel (precursor motion)
- Fuel = coolant
- Fast neutron spectrum
- Circulation time ~ 3 s
- Reynolds in core: ~ 500000

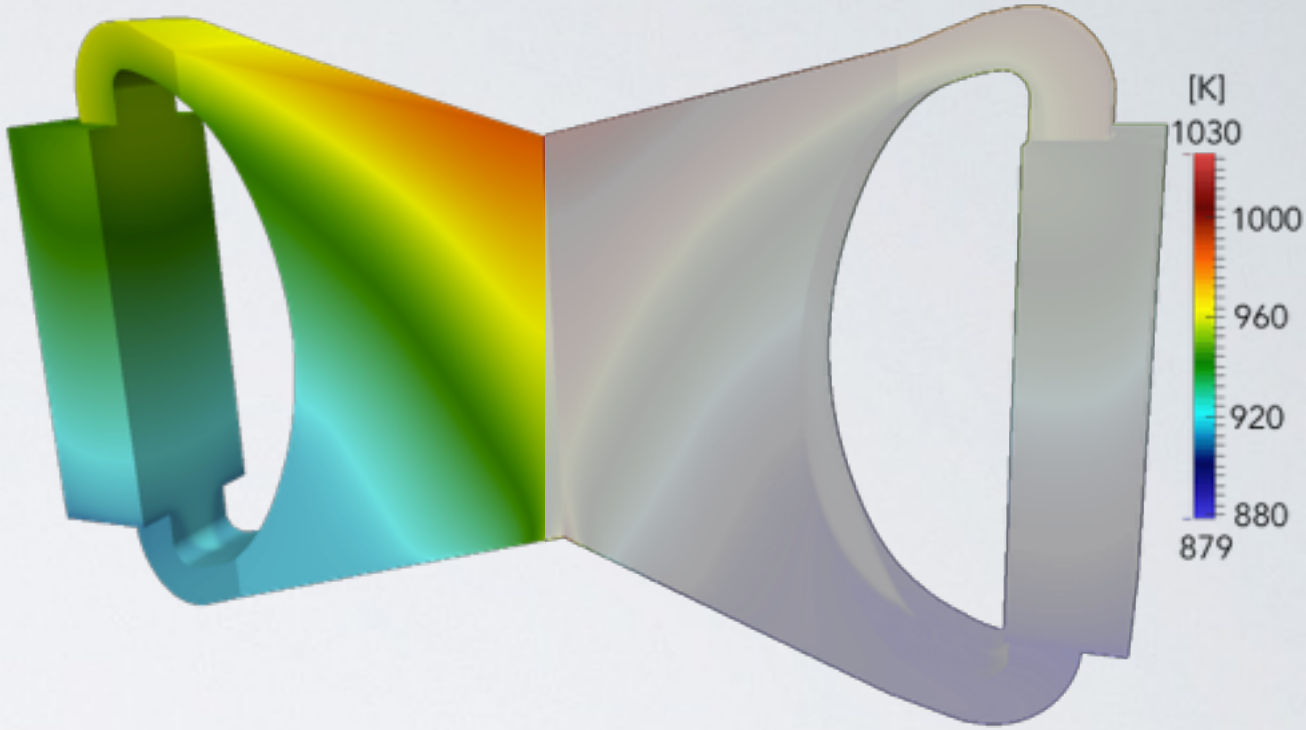
- Power: 3GWth
- Molten Salt : LiF - (Th/$^{233}$U)F$_4$
  density: 4 x water
  viscosity: 2 x water (oil ~ 1000x water)
  low pressure
  mean fuel temperature ~ 900 K

# II. APPLICATION CASES: INSTANTANEOUS OVER COOLING TRANSIENT

## Intermediate fluid temperature variation in the heat exchanger



INITIAL CONDITIONS
(STEADY STATE)



INITIAL / FINAL TEMPERATURE DISTRIBUTION

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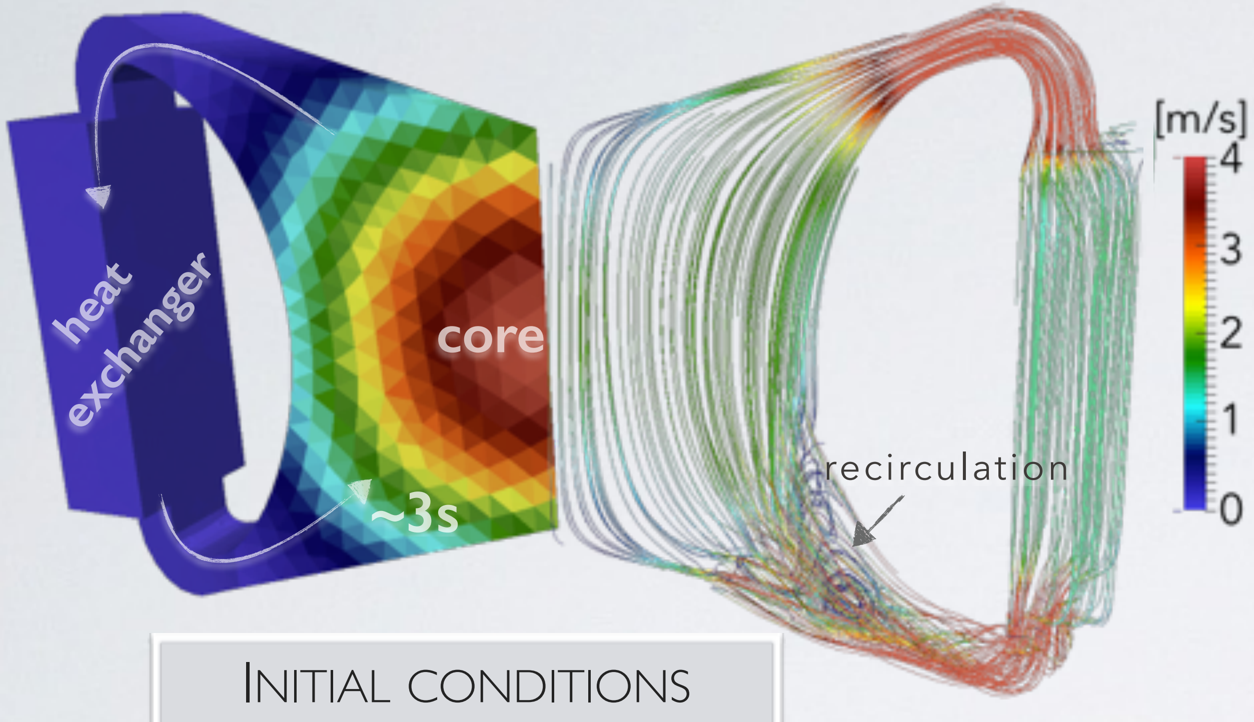

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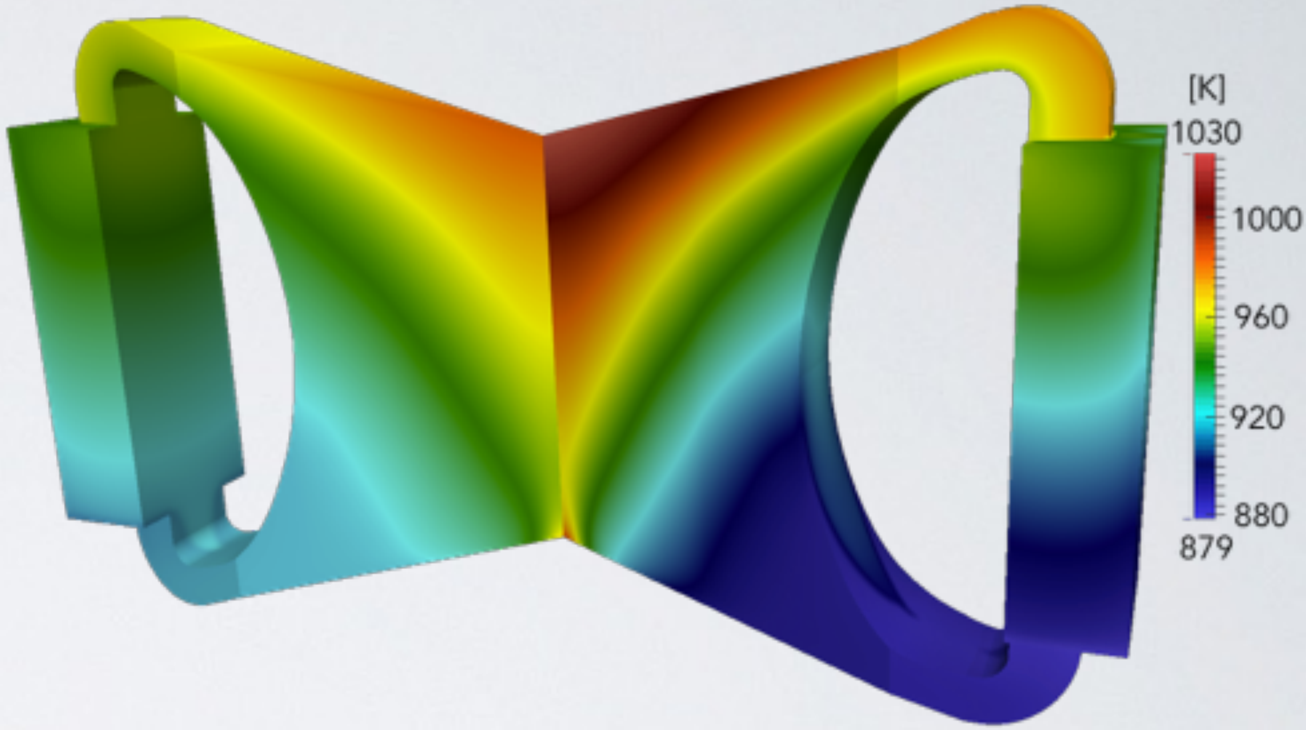

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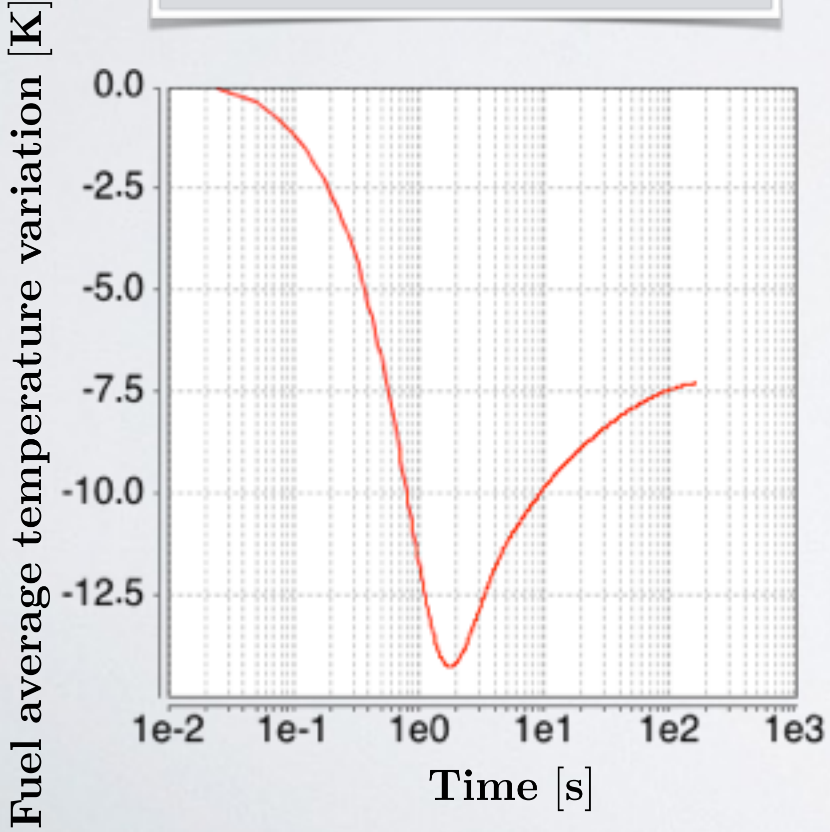

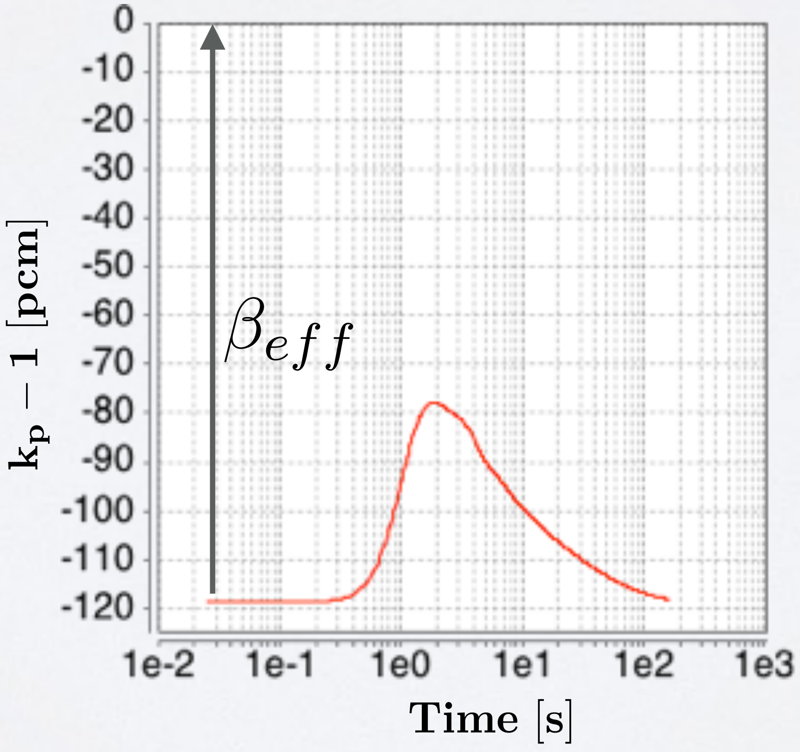

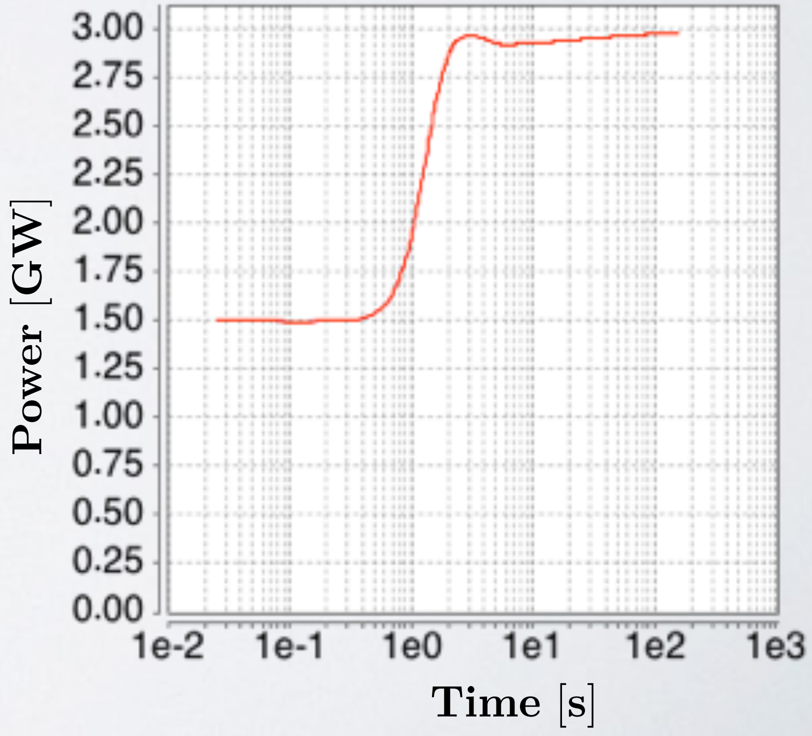

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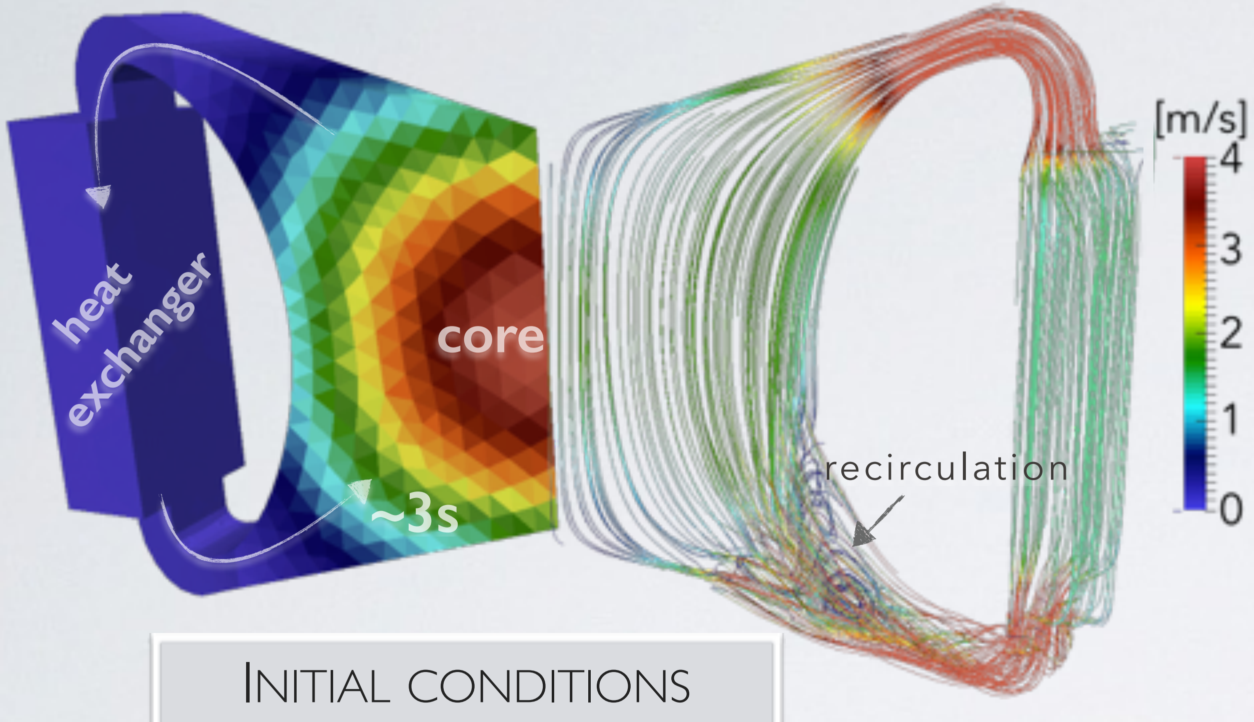

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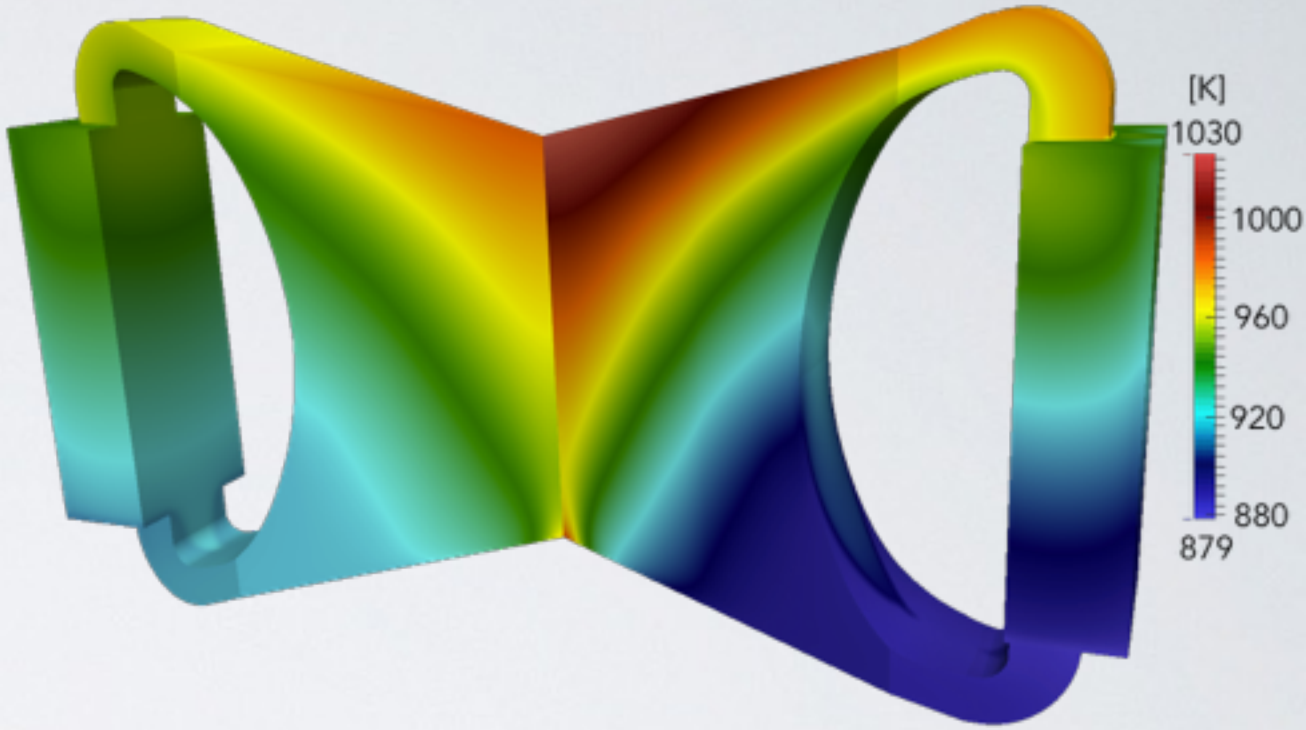

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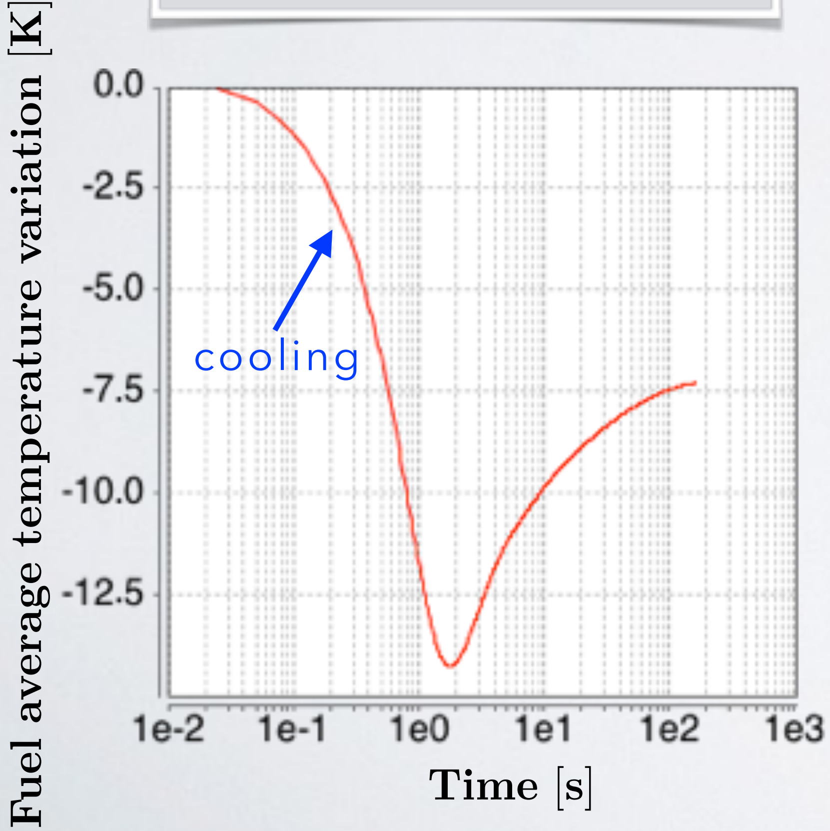

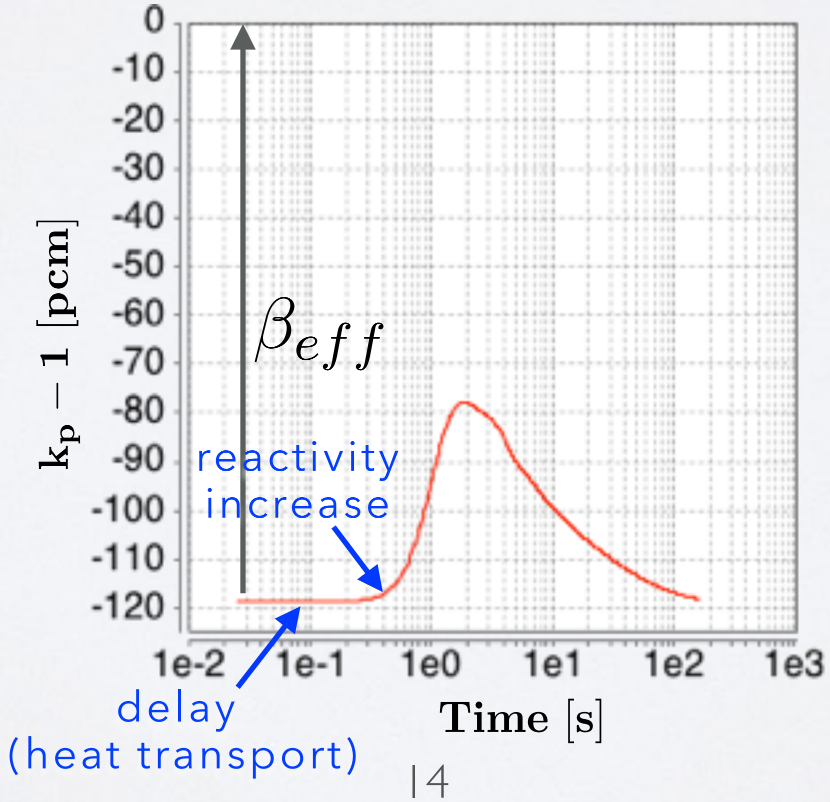

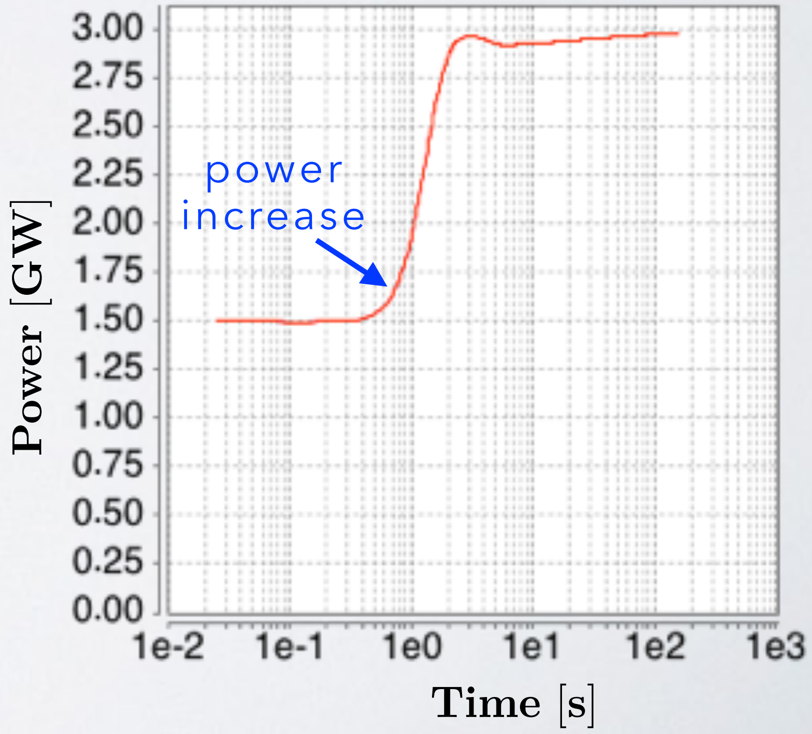

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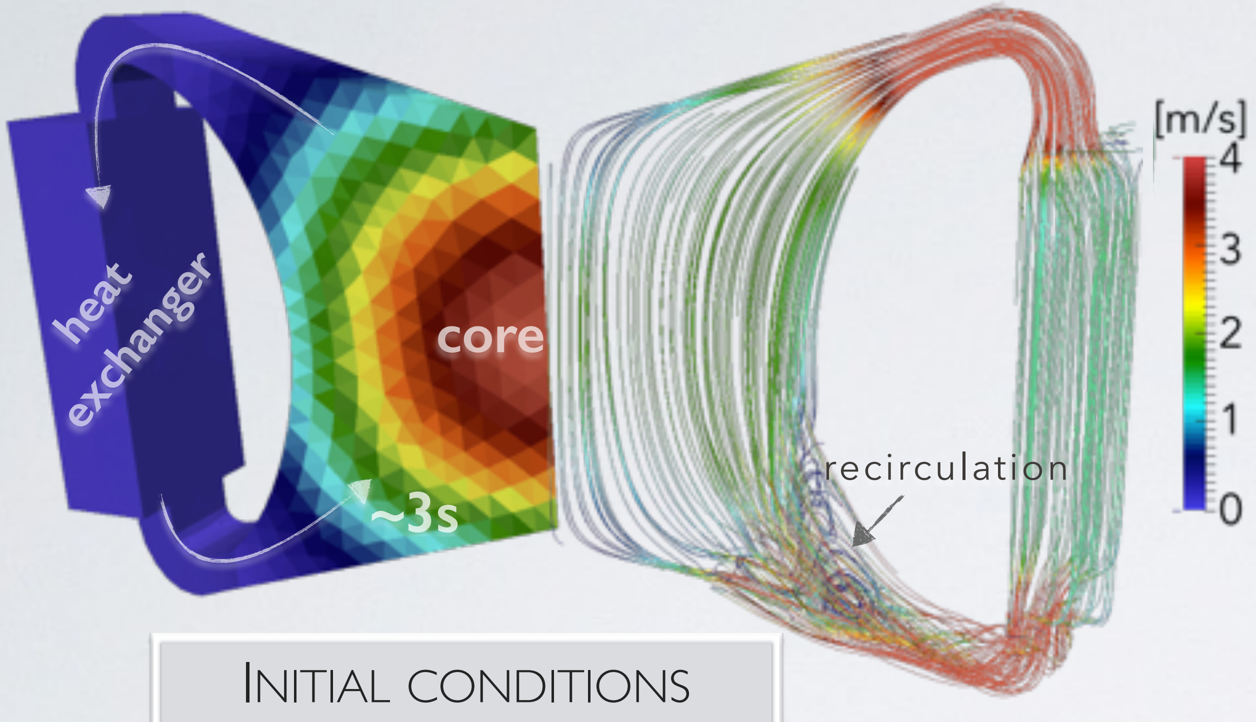

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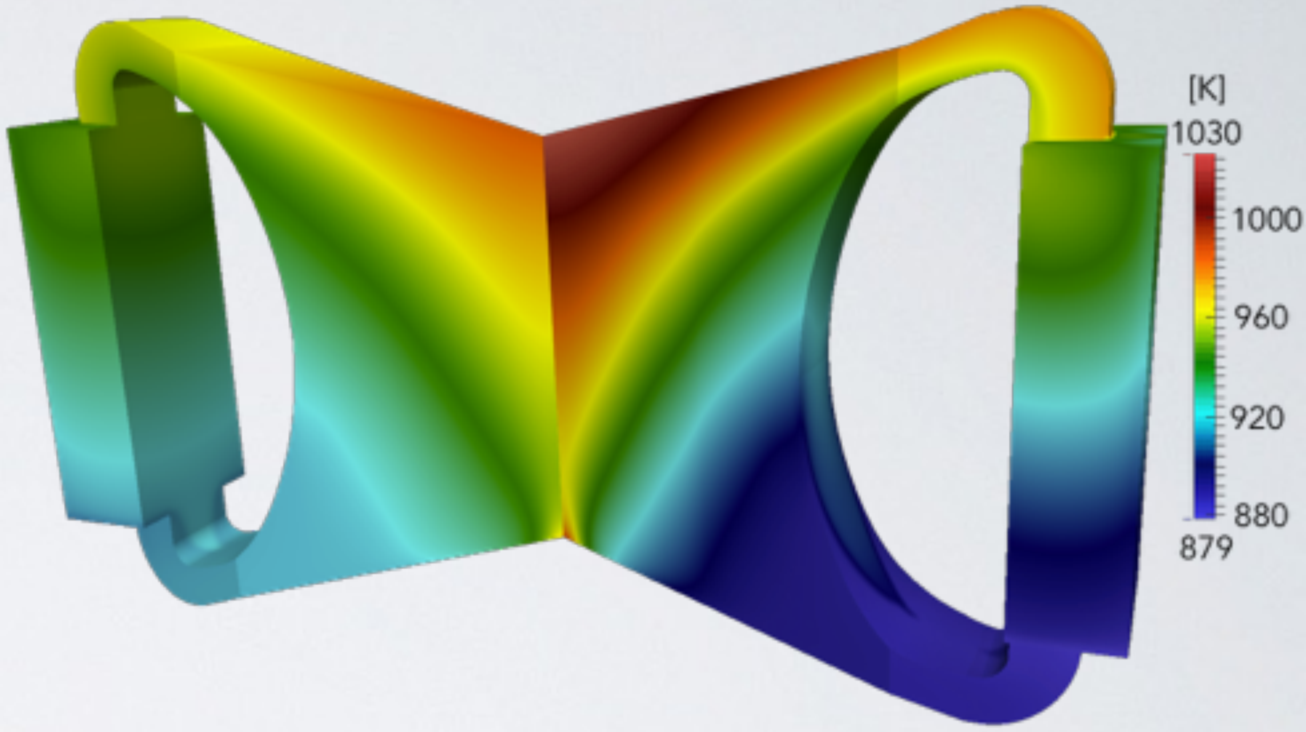

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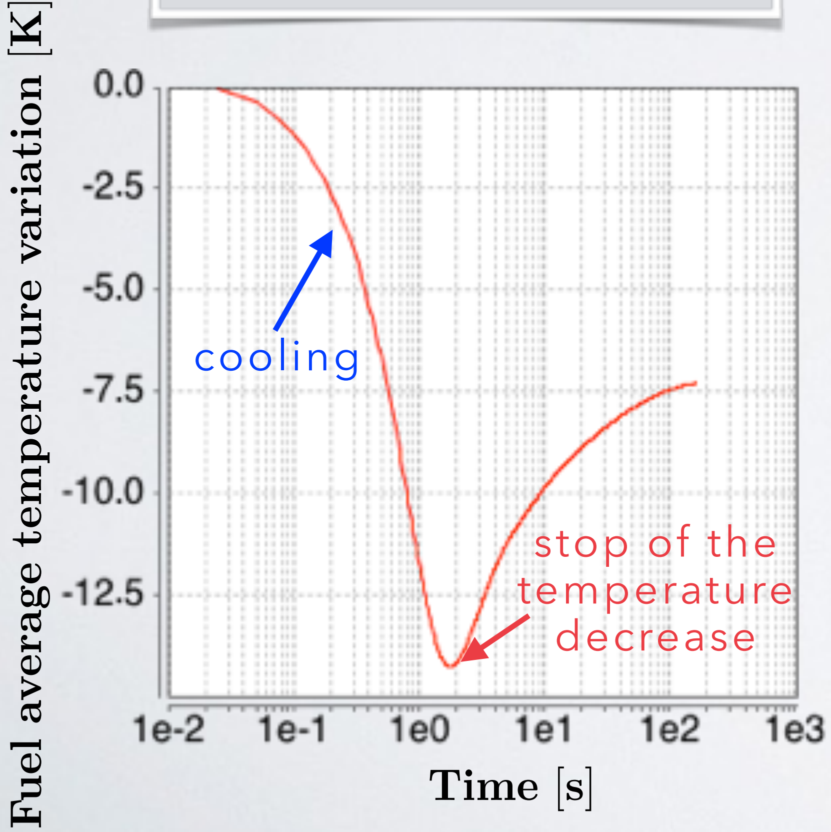

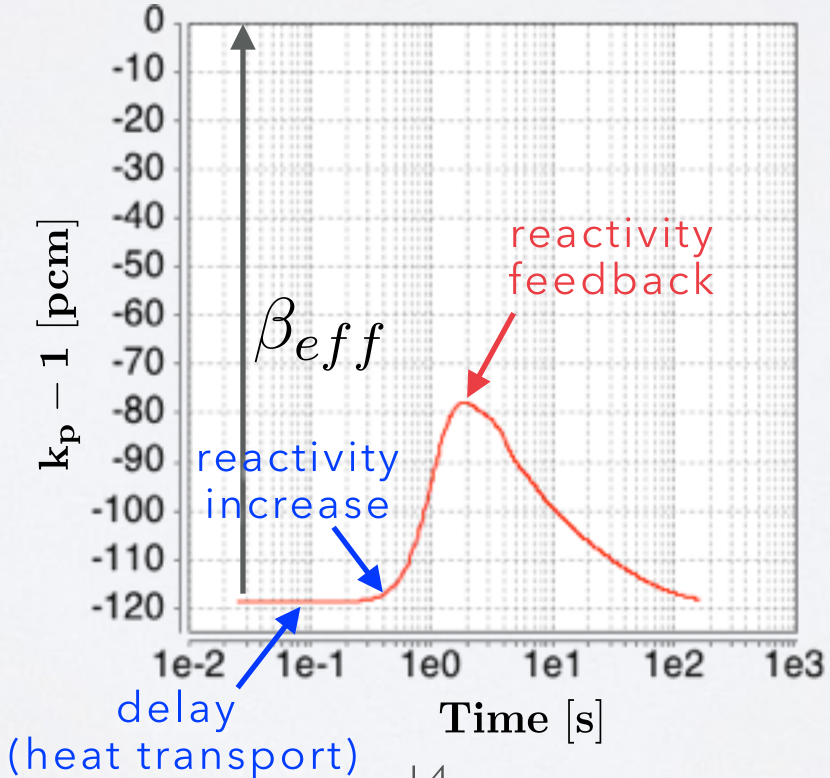

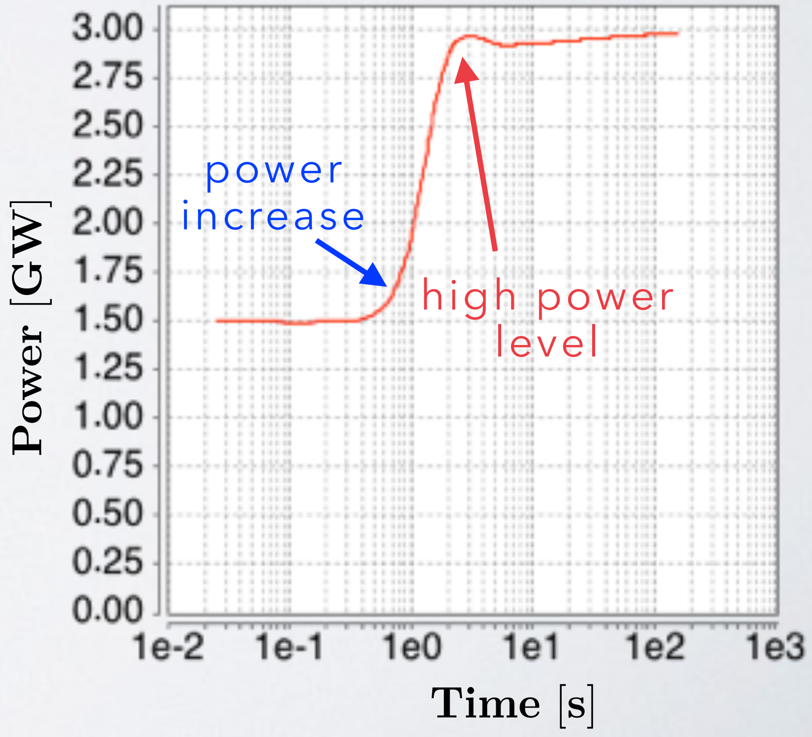

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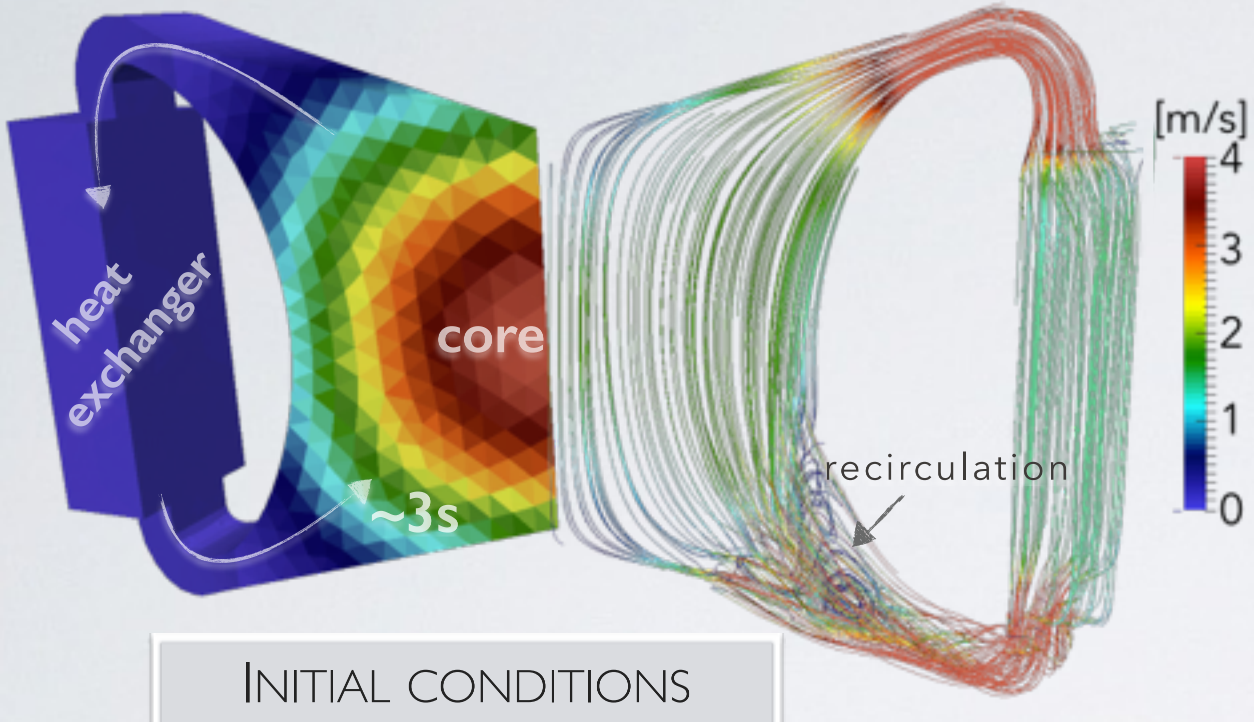

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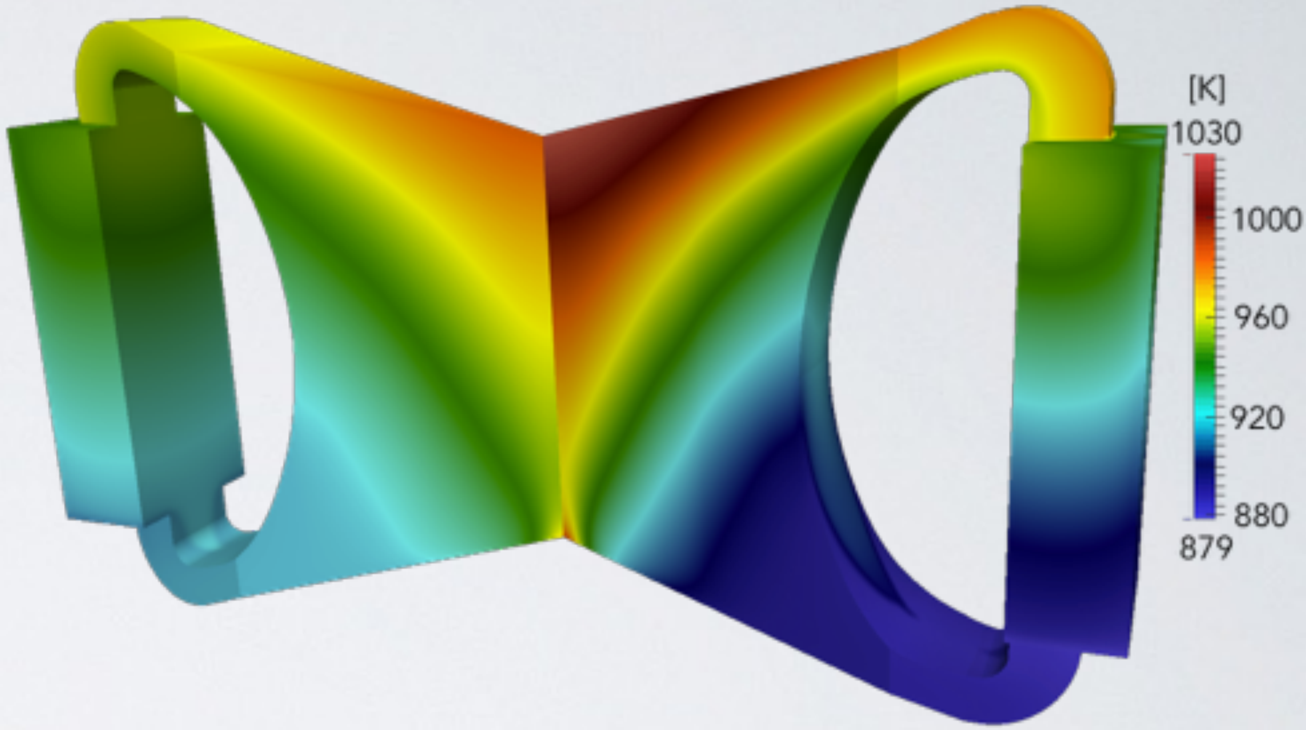

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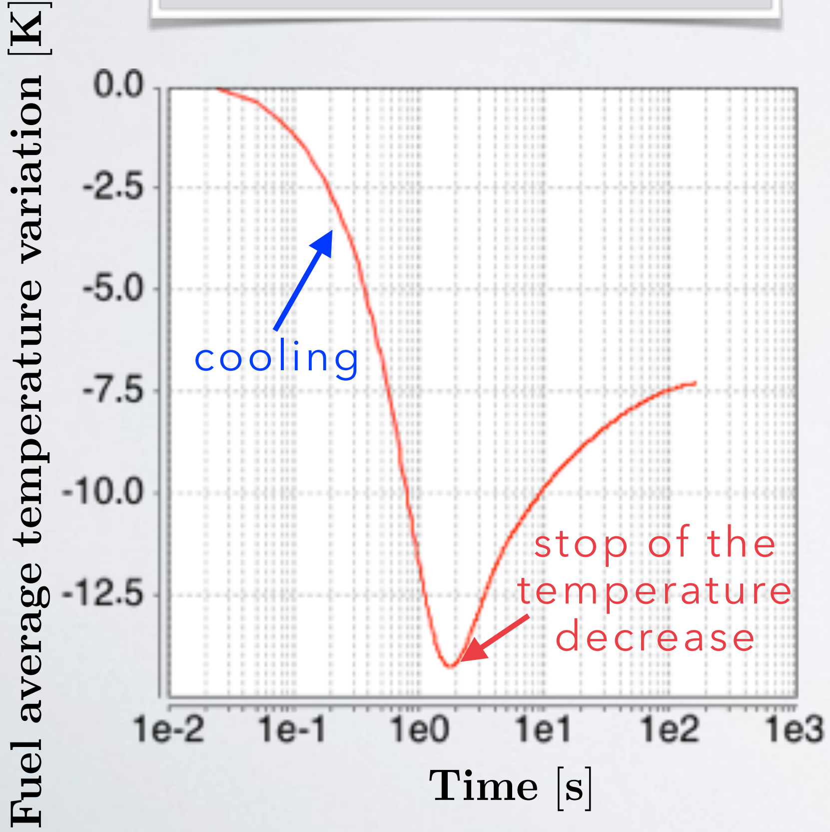
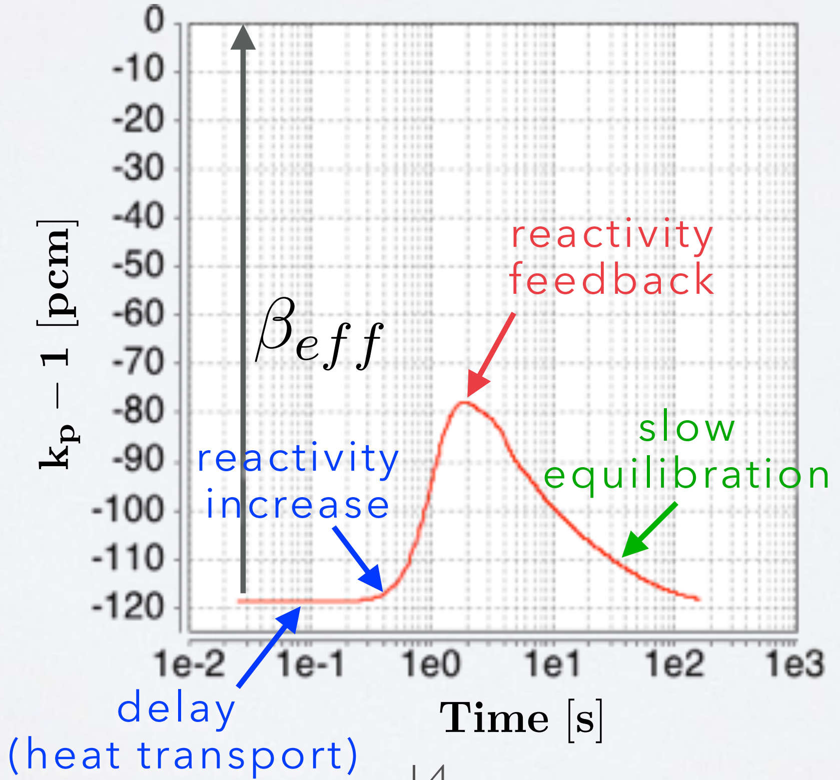


cooling

stop of the temperature decrease

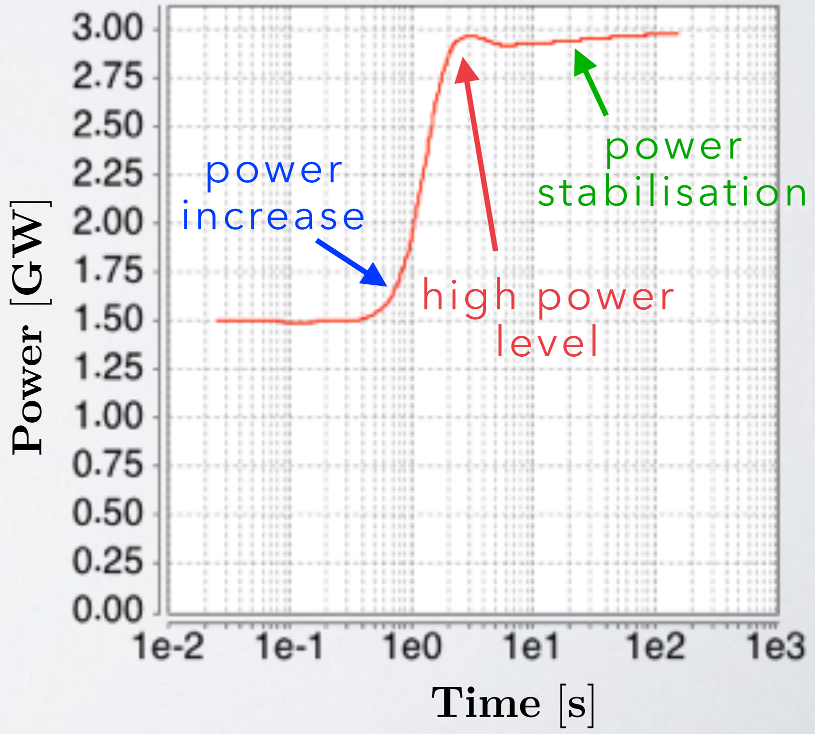


reactivity feedback

reactivity increase

slow equilibration

delay (heat transport)



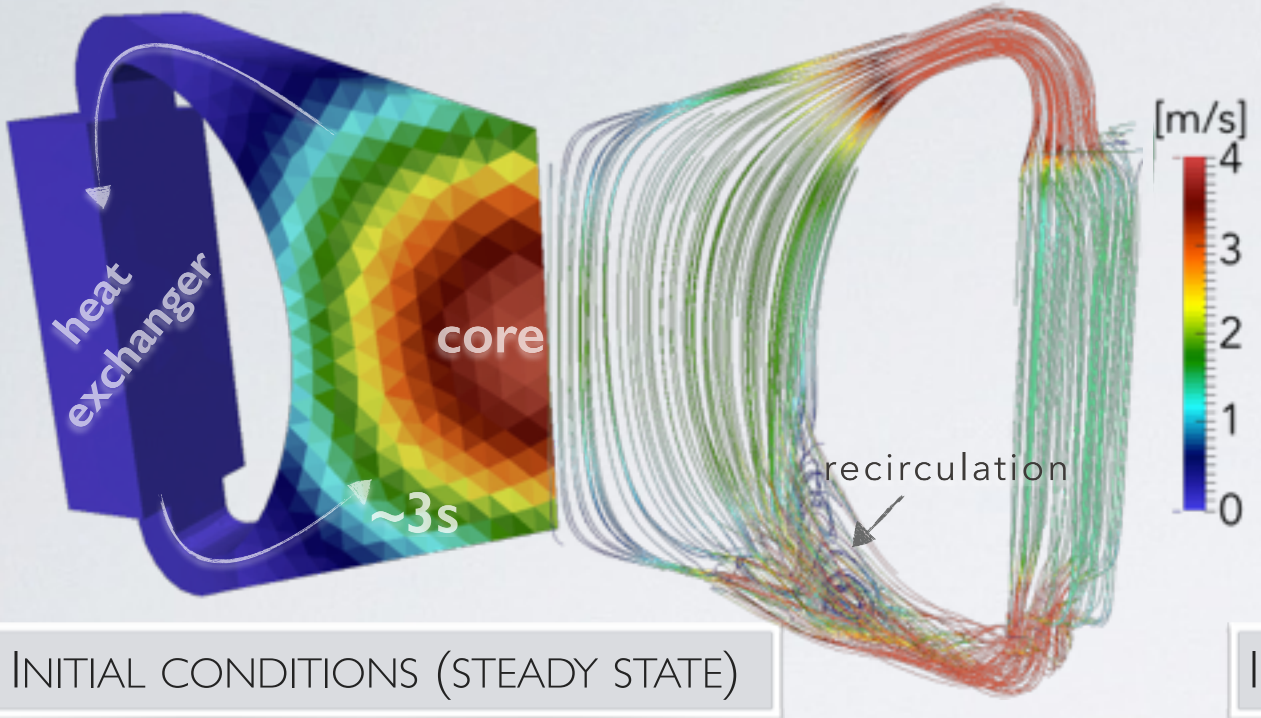
power increase

high power level

power stabilisation

# II. APPLICATION CASES: INSTANTANEOUS OVER COOLING TRANSIENT

## Intermediate fluid temperature variation in the heat exchanger



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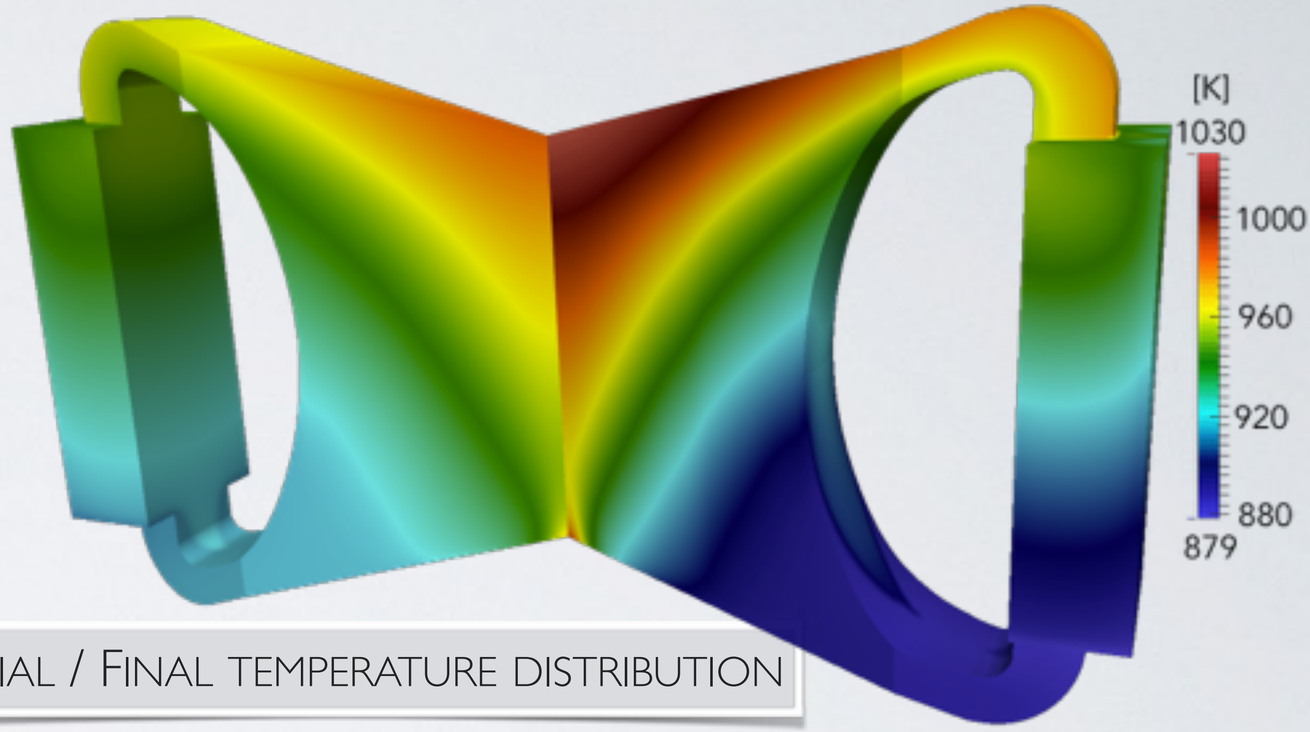

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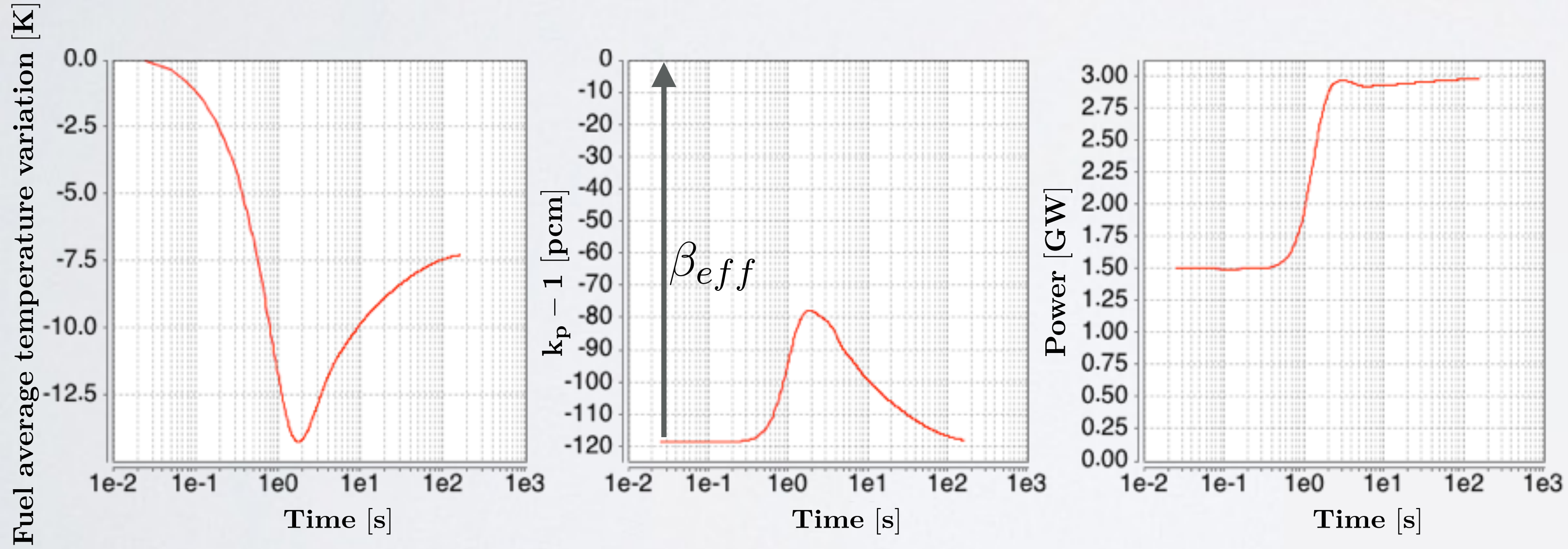

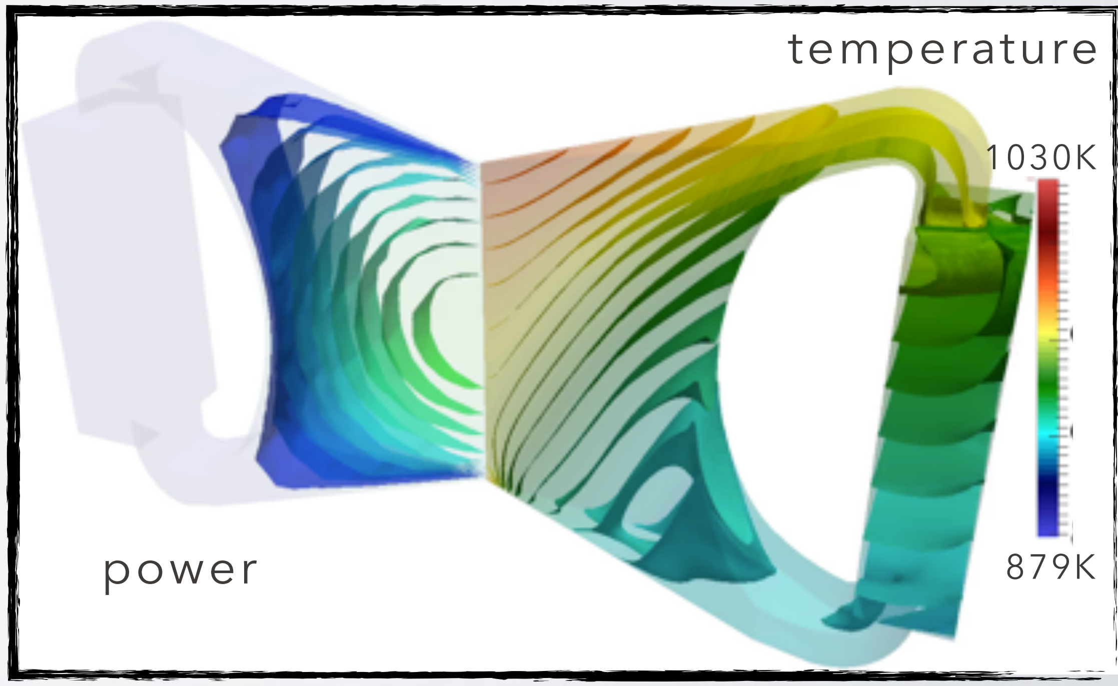

- Good behavior of the neutronics - T&H response of the MSFR
- TFM-OpenFOAM coupling operational
- High precision & low computational cost

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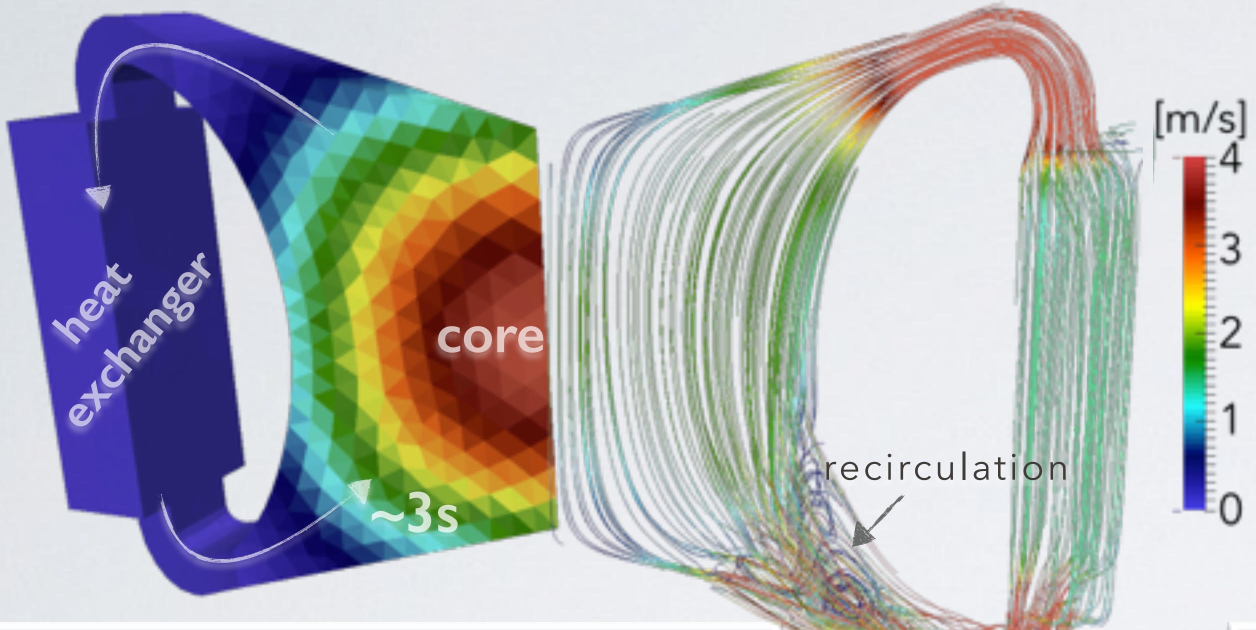

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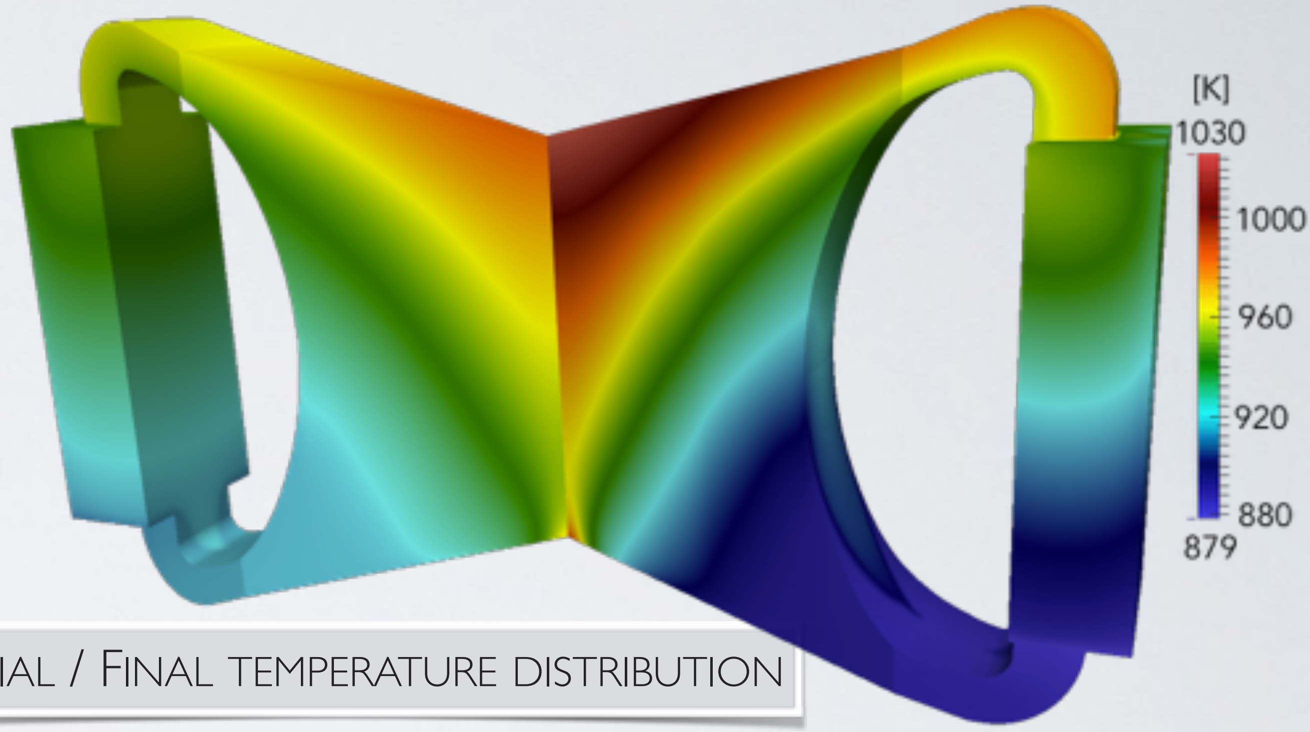

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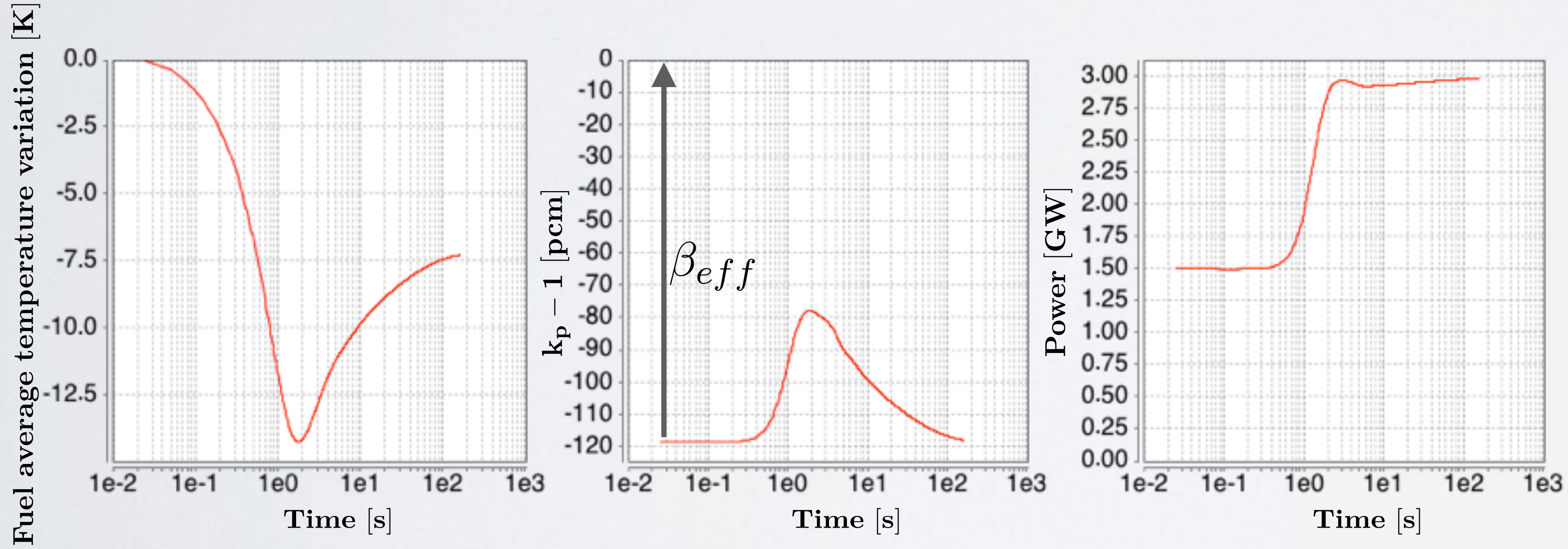

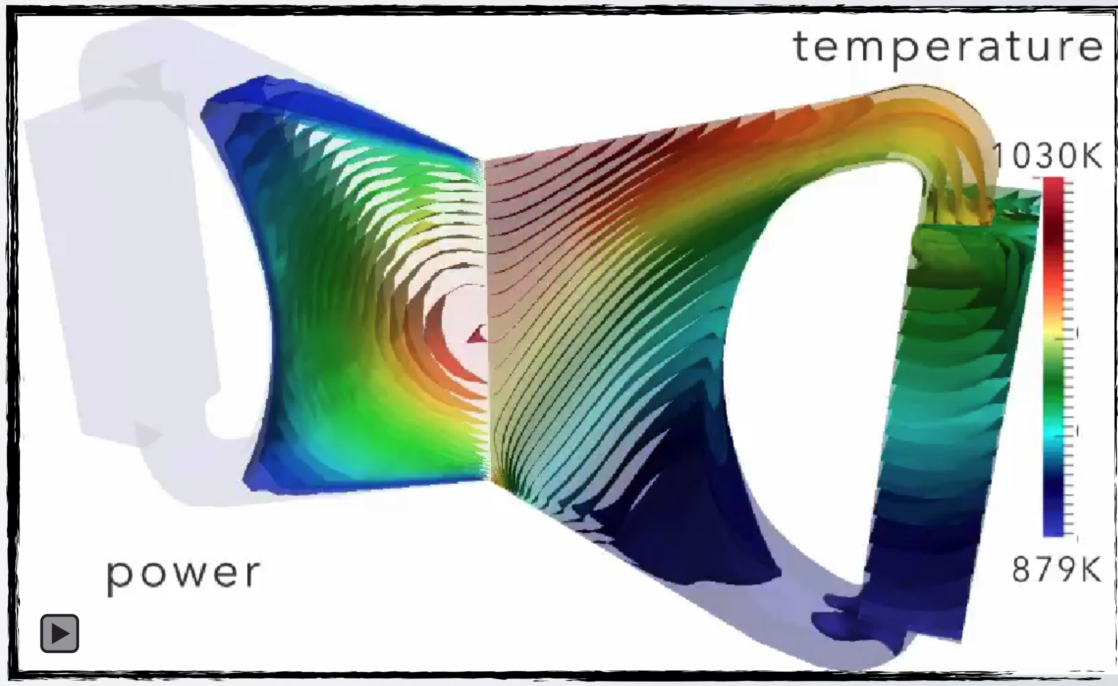

- Good behavior of the neutronics - T&H response of the MSFR
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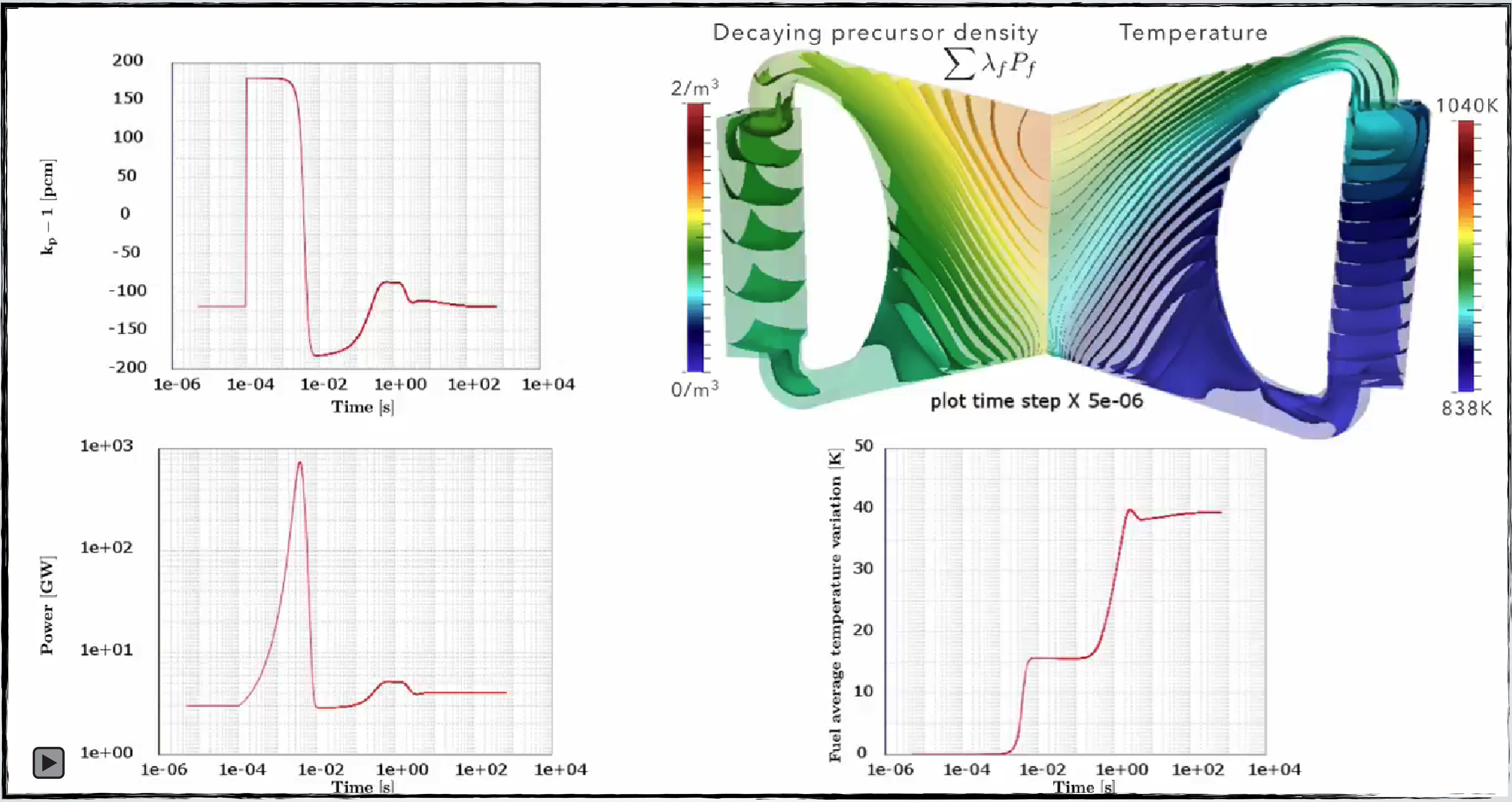
# II. APPLICATION CASES: INSTANTANEOUS REACTIVITY INSERTION OF 300 PCM

## Instantaneous &unrealistic reactivity insertion



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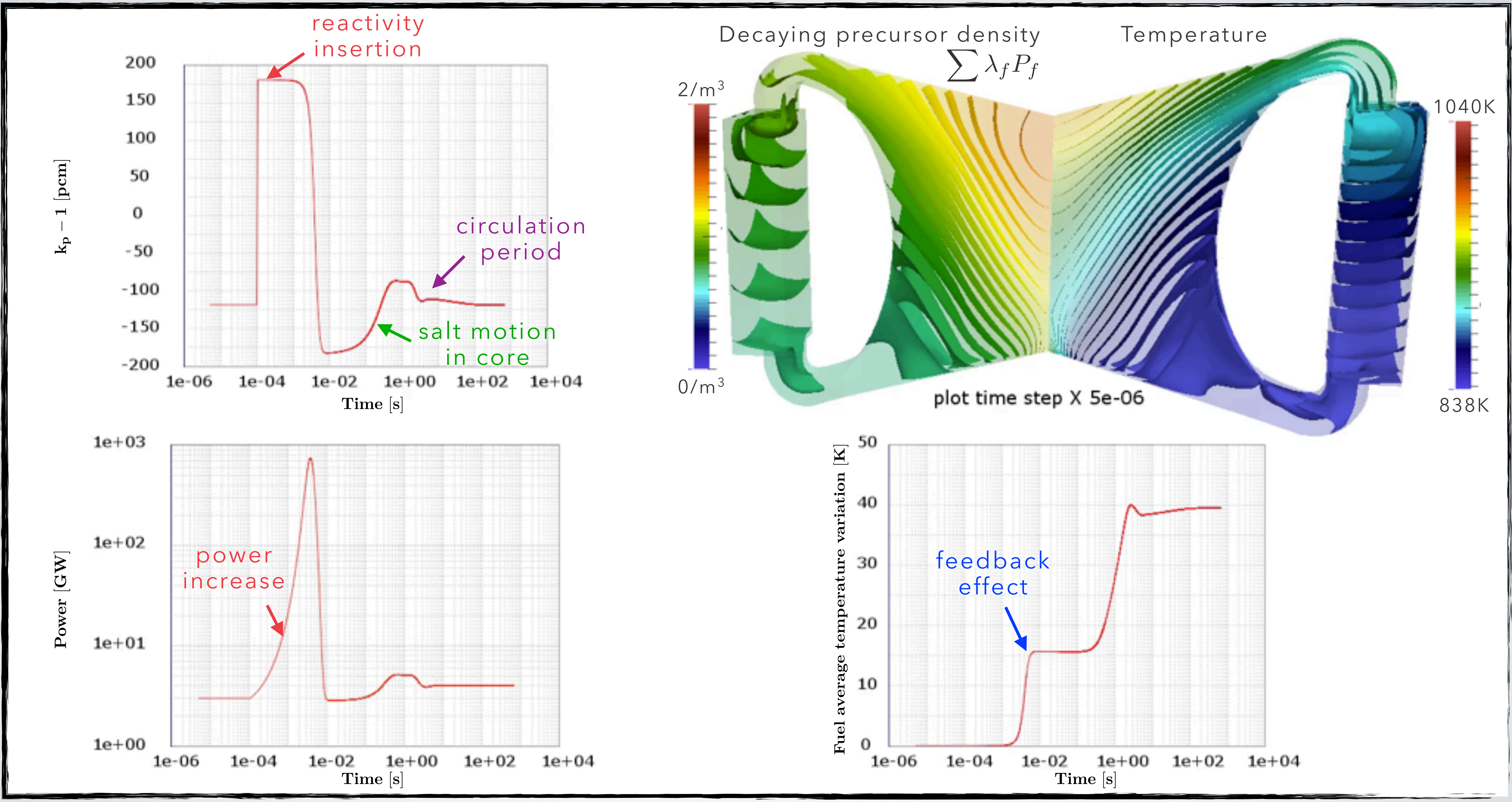


reactivity insertion

circulation period

salt motion in core

Decaying precursor density $\sum \lambda_f P_f$

Temperature

plot time step X 5e-06

power increase

feedback effect

# III. CONCLUSION

**Conclusions**

- TFM-OpenFOAM coupling operational: high precision & low computational cost
- Implementation of the transient fission matrices calculation in the SERPENT code
- Good results for kinetics parameters and transient calculations

**Future work**

- Compare the model to a dedicated numerical benchmark
- Include the sensibility to the crossed cells in the fission matrices
- Application of the TFM approach on different nuclear systems

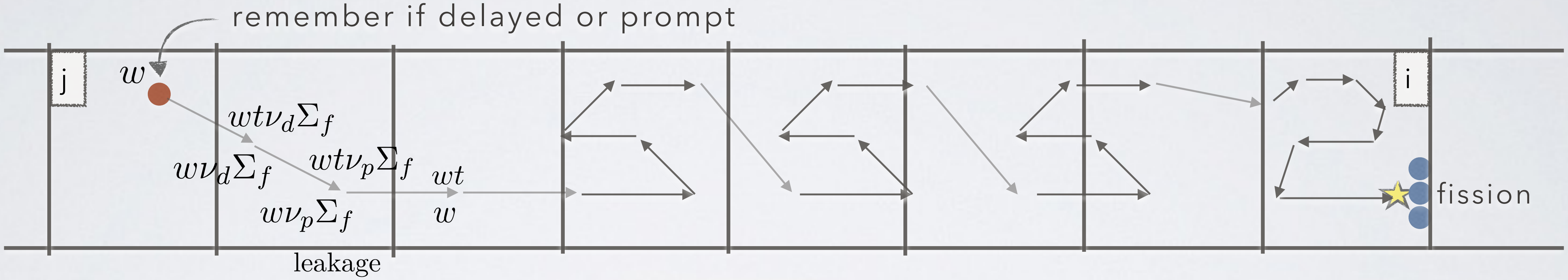
Thanks for your attention!

# BACKUP SLIDES

# BACKUP SLIDES

## SERPENT ESTIMATION OF THE MATRICES:

During a classical critical calculation:



Simple explicite implementation: summing the neutron production of the fission events normalized by the neutron creation amount (prompt and delayed).
*Trouble: extremely slow convergence*

Better implicite implementation (*this work*): integration of the fission neutron production and absorption at each interaction (« delta tracking on »)
*Advantage: much more events per neutron history, improved statistics*

Advantages of the matrices estimation in a critical calculation:

- Utilisation of the correct emission spectrum
- Utilisation of the correct source neutron distribution inside the elementary volume (j)

# BACKUP SLIDES

## EFFECTIVE FRACTION OF DELAYED NEUTRON $\beta_{eff}$ CALCULATION:

We create the prompt and delay matrix operator:
+ Eigenvalue & Eigenvector

$$\underline{\underline{\widetilde{G}_{all}}} = \begin{pmatrix} \underline{\underline{\widetilde{G}_{\chi_p\nu_p}}} & \underline{\underline{\widetilde{G}_{\chi_d\nu_p}}} \\ \underline{\underline{\widetilde{G}_{\chi_p\nu_d}}} & \underline{\underline{\widetilde{G}_{\chi_d\nu_d}}} \end{pmatrix} \longrightarrow k_{eff} \quad \& \quad \boldsymbol{N} = (\boldsymbol{N}_p \ \boldsymbol{N}_d)$$

Its importance:
transpose matrix and Eigenvector

$$\underline{\underline{\widetilde{G}^{adj}_{all}}} \longrightarrow \boldsymbol{N}^* = \left(\boldsymbol{N}^*_p \ \boldsymbol{N}^*_d\right)$$

Finally, we can calculate the physical and effective fractions of delayed neutrons:

$$\beta_0 = \cfrac{\overset{\text{delayed}}{\sum \boldsymbol{N}_d}}{\underset{\text{total}}{\sum \boldsymbol{N}}} = \frac{k_{eff}.\sum(\boldsymbol{N}_d)}{k_{eff}.\sum(\boldsymbol{N})} = \frac{\sum\left(\underline{\underline{G_{\chi_p\nu_d}}}\boldsymbol{N}_p + \underline{\underline{G_{\chi_d\nu_d}}}\boldsymbol{N}_d\right)}{\sum\left(\underline{\underline{G_{all}}}\boldsymbol{N}\right)}$$

$$\boxed{\beta_{eff} = \frac{\boldsymbol{N}^*_d\boldsymbol{N}_d}{\boldsymbol{N}^*\boldsymbol{N}}} = \frac{\boldsymbol{N}^*_d\left(\underline{\underline{G_{\chi_p\nu_d}}}\boldsymbol{N}_p + \underline{\underline{G_{\chi_d\nu_d}}}\boldsymbol{N}_d\right)}{\boldsymbol{N}^*\underline{\underline{G_{all}}}\boldsymbol{N}}$$

importance
weighting

$$\updownarrow$$

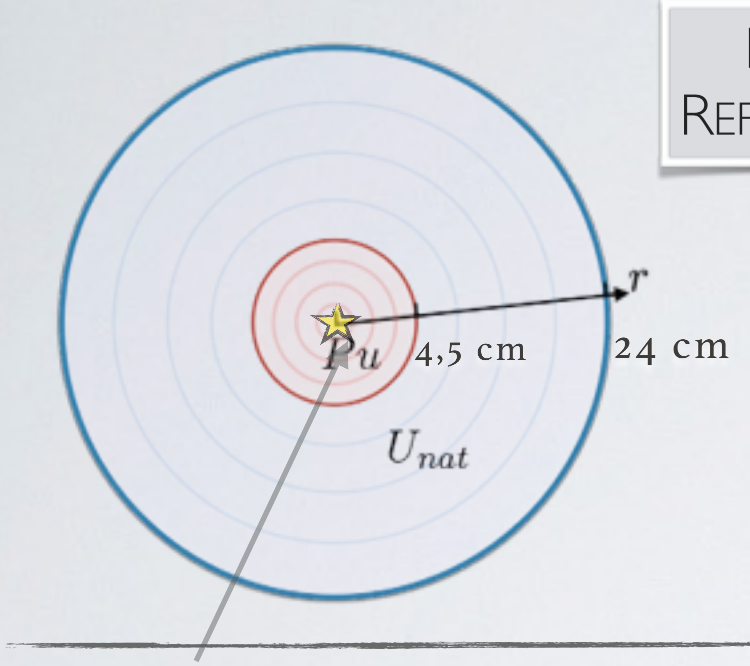
classic formulation:

$$\beta_{eff} = \frac{\int \psi^*\chi_d\nu_d\Sigma_f\psi \ \ \mathrm{d}E\,\mathrm{d}\Omega\,\mathrm{d}E'\,\mathrm{d}\Omega'\,\mathrm{d}\boldsymbol{r}}{\int \psi^*\chi\nu\Sigma_f\psi \ \ \mathrm{d}E\,\mathrm{d}\Omega\,\mathrm{d}E'\,\mathrm{d}\Omega'\,\mathrm{d}\boldsymbol{r}}$$

# BACKUP SLIDES

## BENCH CASE

FLATTOP EXPERIMENT
REFERENCE CODE: SERPENT

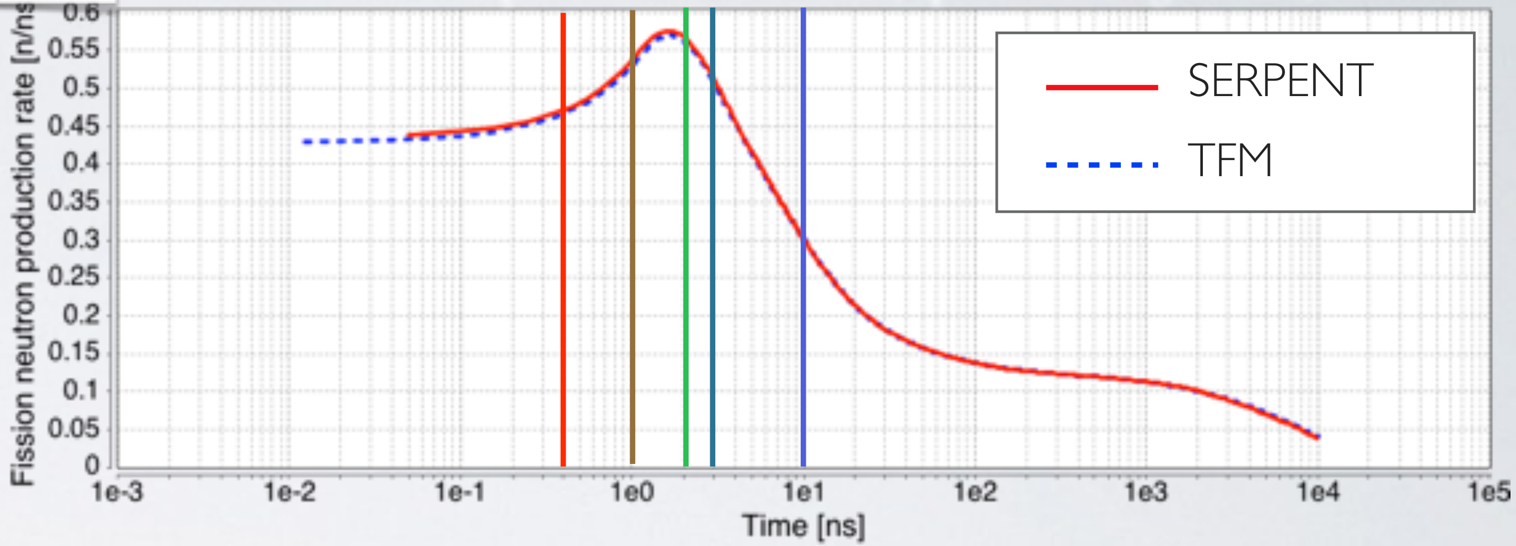


Flattop subjected to a neutron burst release

## TFM EQUATION & IMPLEMENTATION TO CHECK:

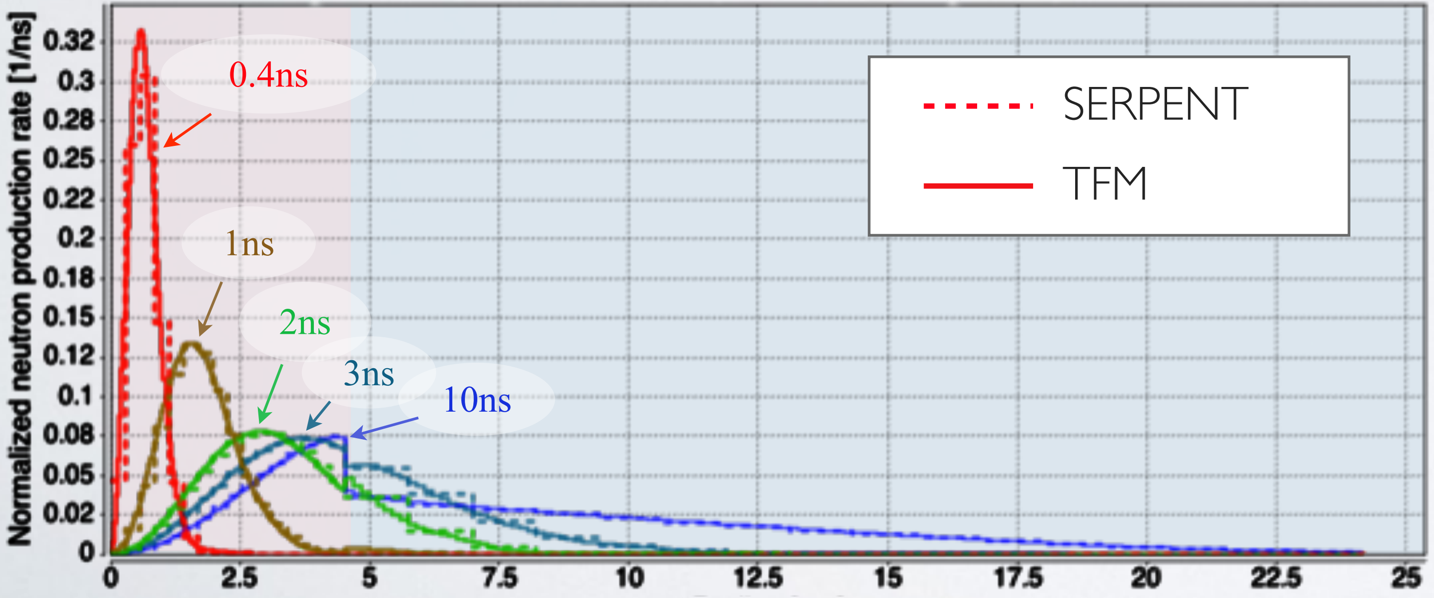
$$S(\boldsymbol{r},t) = \left|G_{\chi_p\nu_p}(t'-t,\boldsymbol{r'},\boldsymbol{r})\middle|S(\boldsymbol{r'},t')\right\rangle$$

**Temporal evolution (space integrated)**



- Same evolution behavior of the neutron population through time

**Spatial evolution (time sampled)**



- Good agreement of the spatial neutron propagation

🟥🟫 The neutron burst is limited to the Pu area: $k_p >> 1$

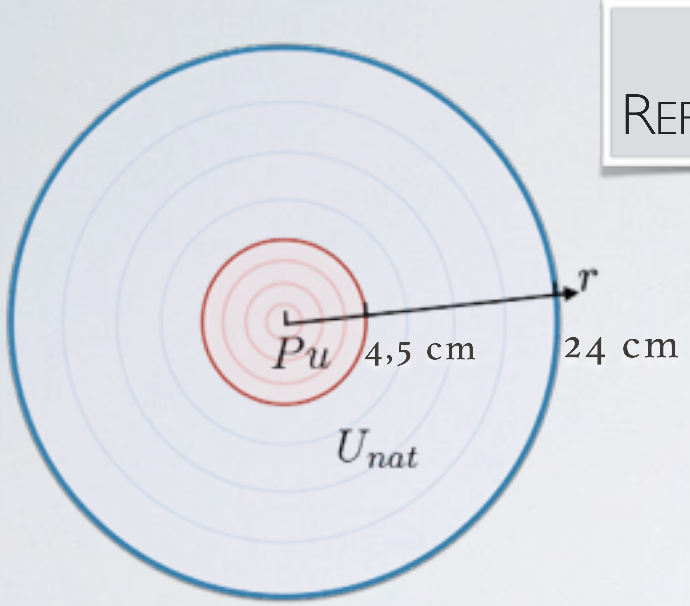
🟩🟦🟦 The neutron burst reaches the $U_{nat}$ area: $k_p << 1$

The neutron distribution tends to the equilibrium's one: $k_p \sim 0.997$

# BACKUP SLIDES

## BENCH CASE

FLATTOP EXPERIMENT
REFERENCE CODE : SERPENT



**Flattop kinetics calculated parameters:**

- effective fraction of delayed neutron:

$$\beta_{eff}$$

- effective generation time:

$$\Lambda_{eff} = \frac{l_{eff}}{k_p}$$

**Experimental observable:**

$$\alpha_{Rossi} = -\frac{\beta_{eff}}{\Lambda_{eff}}$$

| method | $\beta_{eff}$ | $\Lambda_{eff}$ | $\alpha_{Rossi}$ |
|---|---|---|---|
| TFM (this work) | $275 \pm 4\ pcm$ | $13.351 \pm 0.03$ ns | $0.206 \pm 0.004\ \mu s^{-1}$ |
| SERPENT IFP | $274 \pm 2\ pcm$ | $13.24 \pm 0.02$ ns | $0.207 \pm 0.002\ \mu s^{-1}$ |
| Experiment | - | - | $0.214 \pm 0.005\ \mu s^{-1}$ |

- good agreement between TFM and SERPENT…
- … and with the experimental measurements!

# BACKUP SLIDES

Reynolds Average Navier Stokes (RANS) equations:

Mass equation

velocity

$$\nabla.\left(\overline{\boldsymbol{u}}\right) = 0$$

Momentum equation

pressure

$$\frac{\partial(\overline{\boldsymbol{u}})}{\partial t} + \nabla.\left(\overline{\boldsymbol{u}} \otimes \overline{\boldsymbol{u}}\right) = -\frac{1}{\rho_0}\nabla\left(\overline{p} + \frac{2}{3}k\right) + \nabla.\left(\nu_{eff}\left(\frac{1}{2}\left(\nabla\left(\overline{\boldsymbol{u}}\right) + \nabla\left(\overline{\boldsymbol{u}}\right)^t\right) - \frac{2}{3}\nabla.\left(\overline{\boldsymbol{u}}\right)\underline{\underline{Id}}\right)\right)$$
$$+\boldsymbol{g}\left(1 + \beta_{boyancy}\left(\overline{T} - T_0\right)\right)$$

turbulent energy
(provided by the turbulence model)

Energy equation

$$\frac{\partial\overline{T}}{\partial t} + \nabla.\left(\overline{T}\overline{\boldsymbol{u}}\right) = \kappa_{eff}\Delta\left(\overline{T}\right) + S_{external}$$

temperature