COUPLED NEUTRONICS AND THERMAL-HYDRAULICS NUMERICAL SIMULATIONS OF A MOLTEN SALT FAST REACTOR (MSFR)

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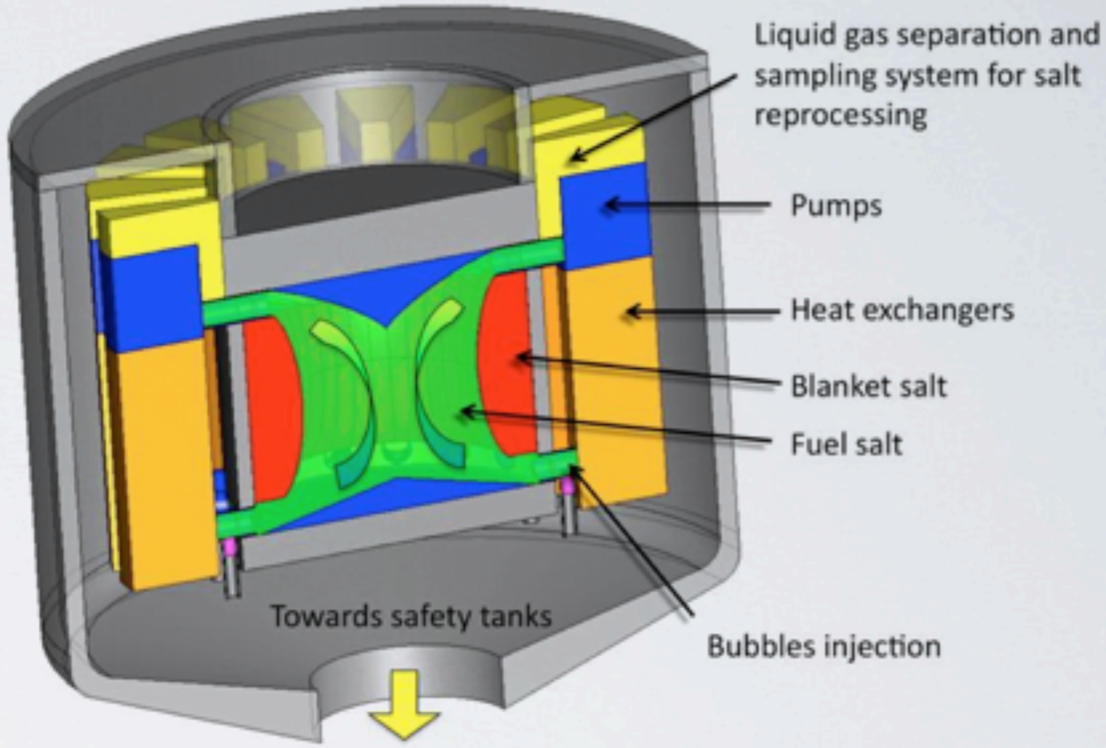
MSFR - PRESENTATION

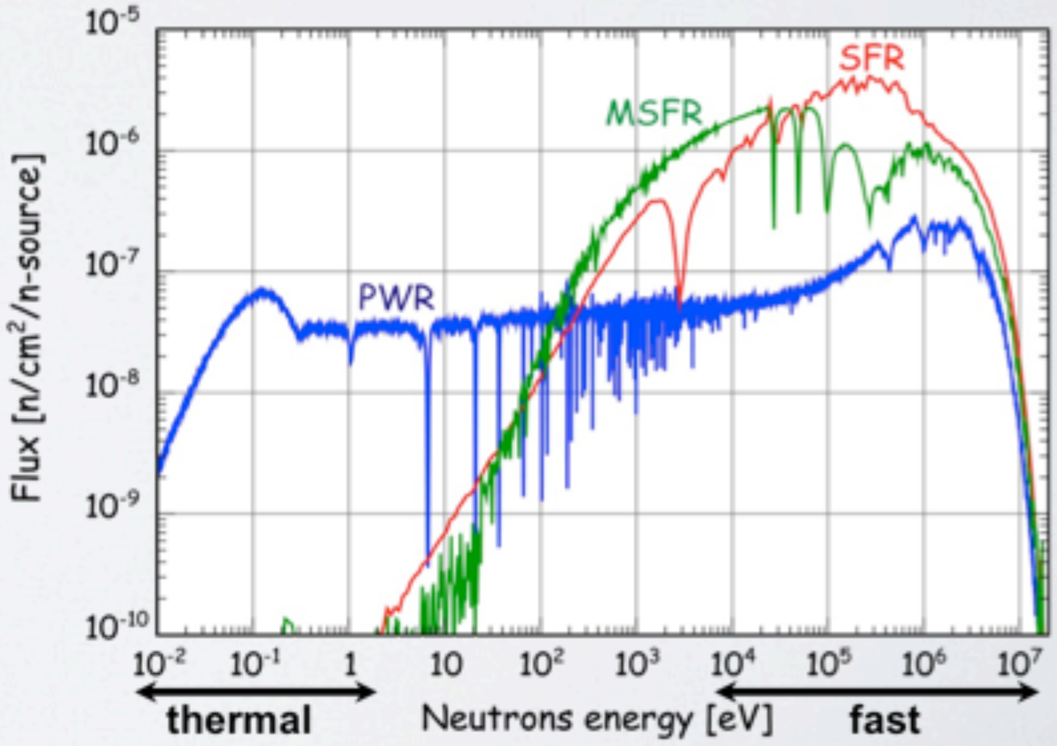
Molten Salt Fast Reactor

- Molten Salt
  - fuel = coolant
  - LiF_4 matrix
- Thorium fuel cycle
  - $^{232}Th/^{233}U$
- Fast spectrum
  - no solid moderator in the core

Objective → estimate key reactor parameters at steady state:

- temperature hot spot
- effective fraction of delayed neutrons (precursors circulation)





MSFR - OUTLINE

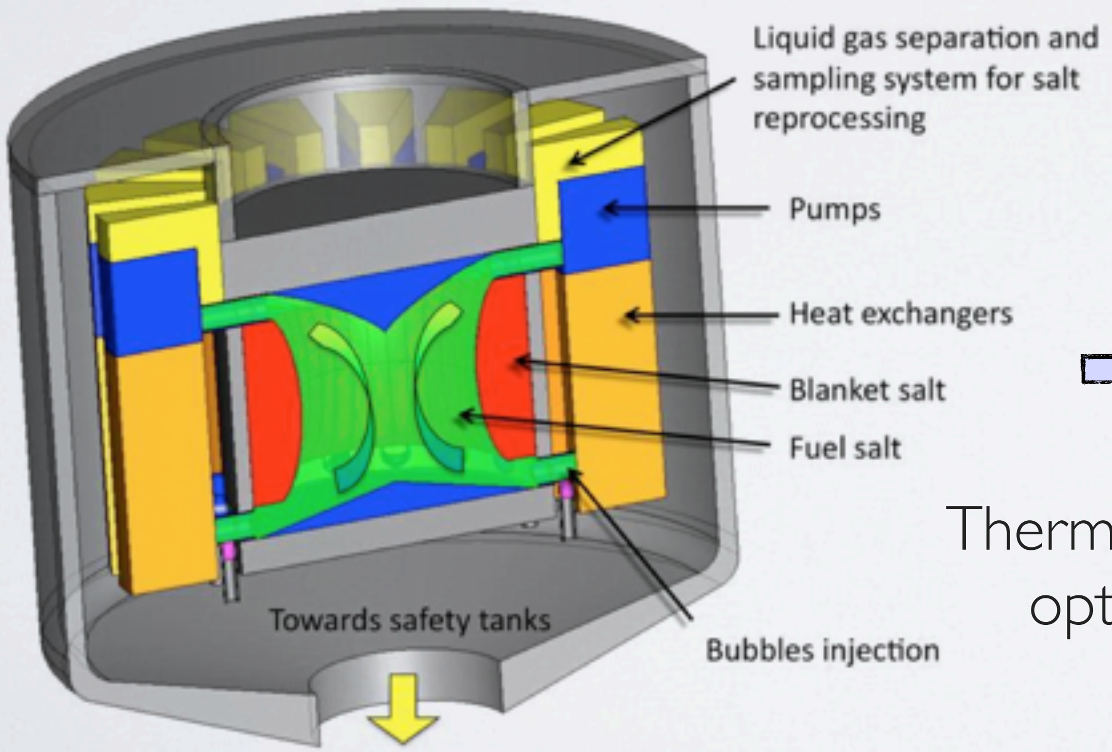
Problematic :

- Complex flow patterns
- Interest in local values

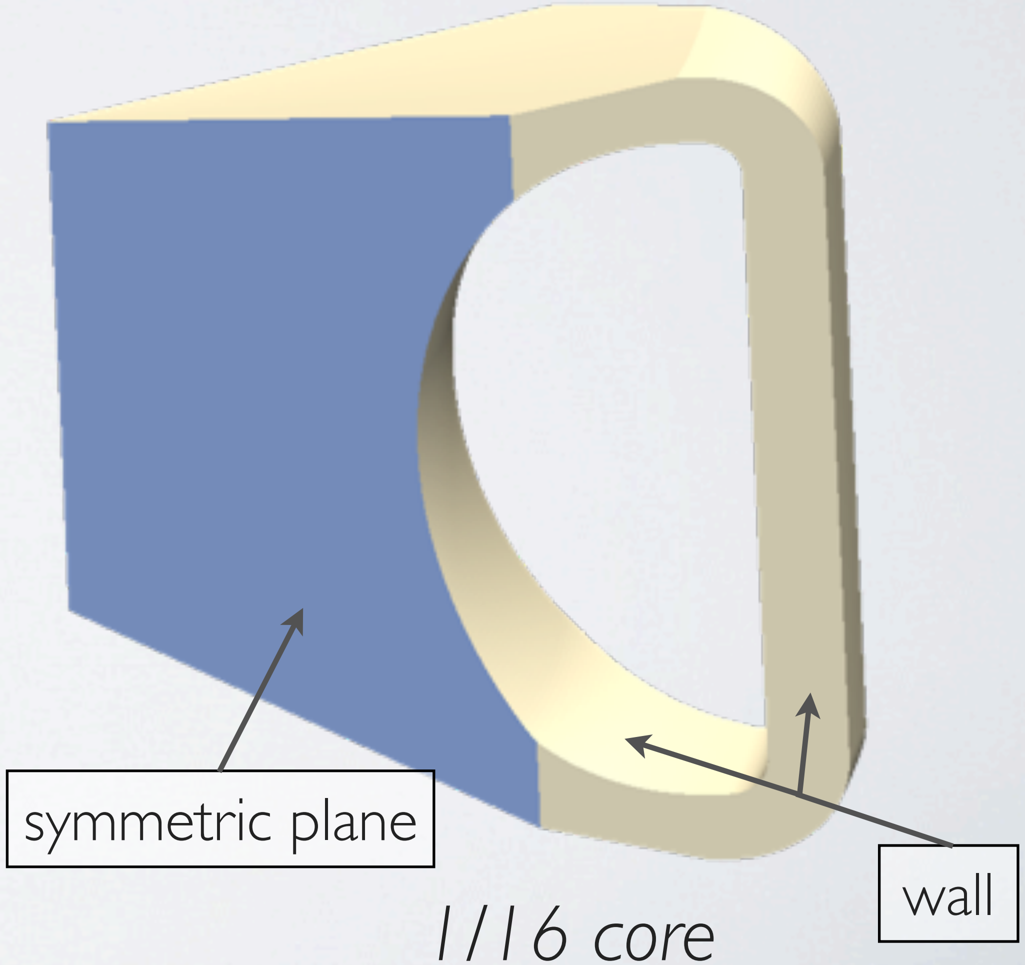
⇒ CFD calculation

- Conceptual design stage
- No experimental data

⇒ Monte Carlo neutronics calculation



Thermal-hydraulics optimization



1/16 core

MSFR - OUTLINE

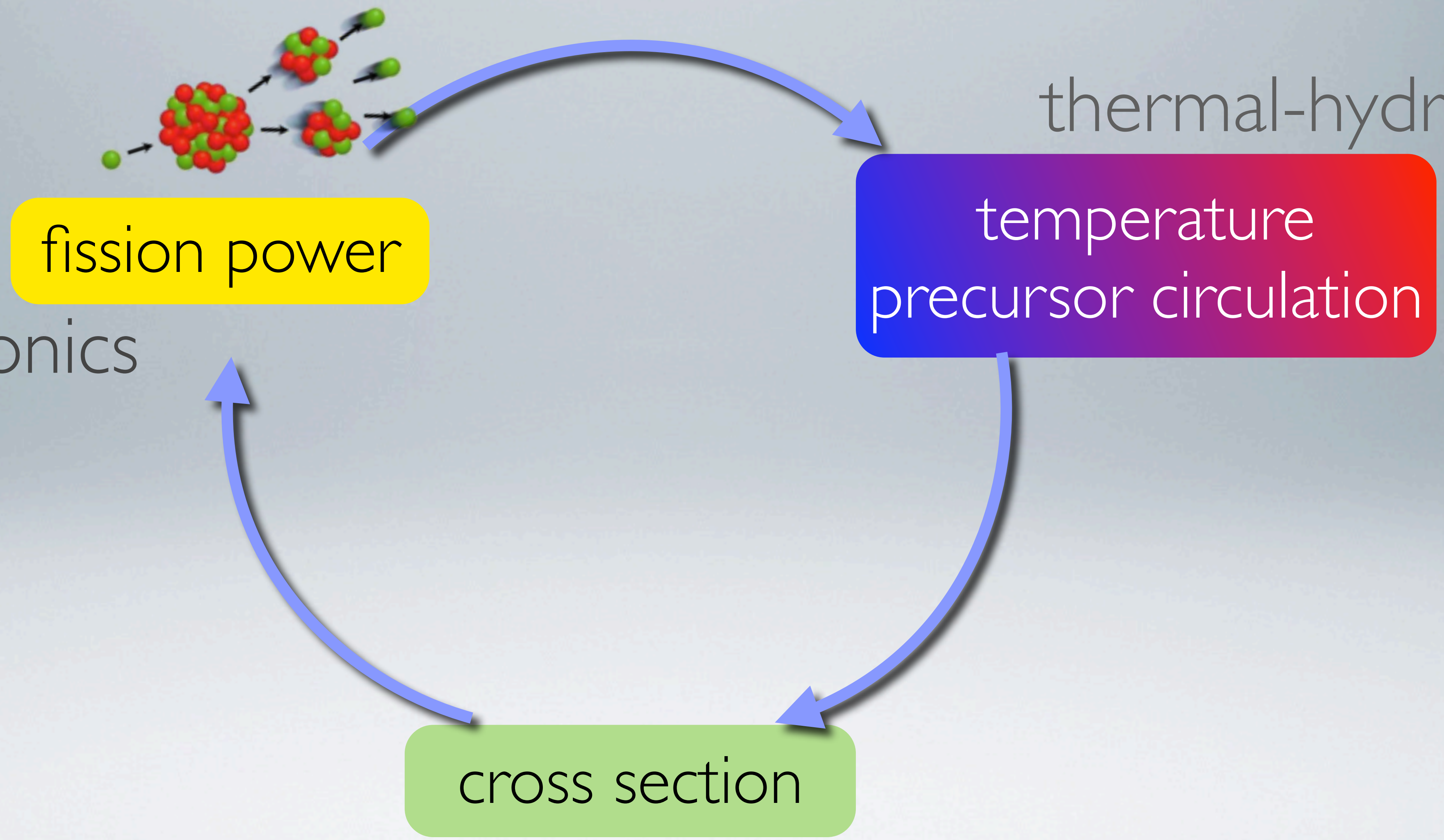
Coupling strategy

CFD - OpenFOAM
Neutronics - MCNP

Results

Neutronic parameters
Temperature and velocity distribution

MSFR - Coupling Strategy



thermal-hydraulics

temperature
precursor circulation

fission power

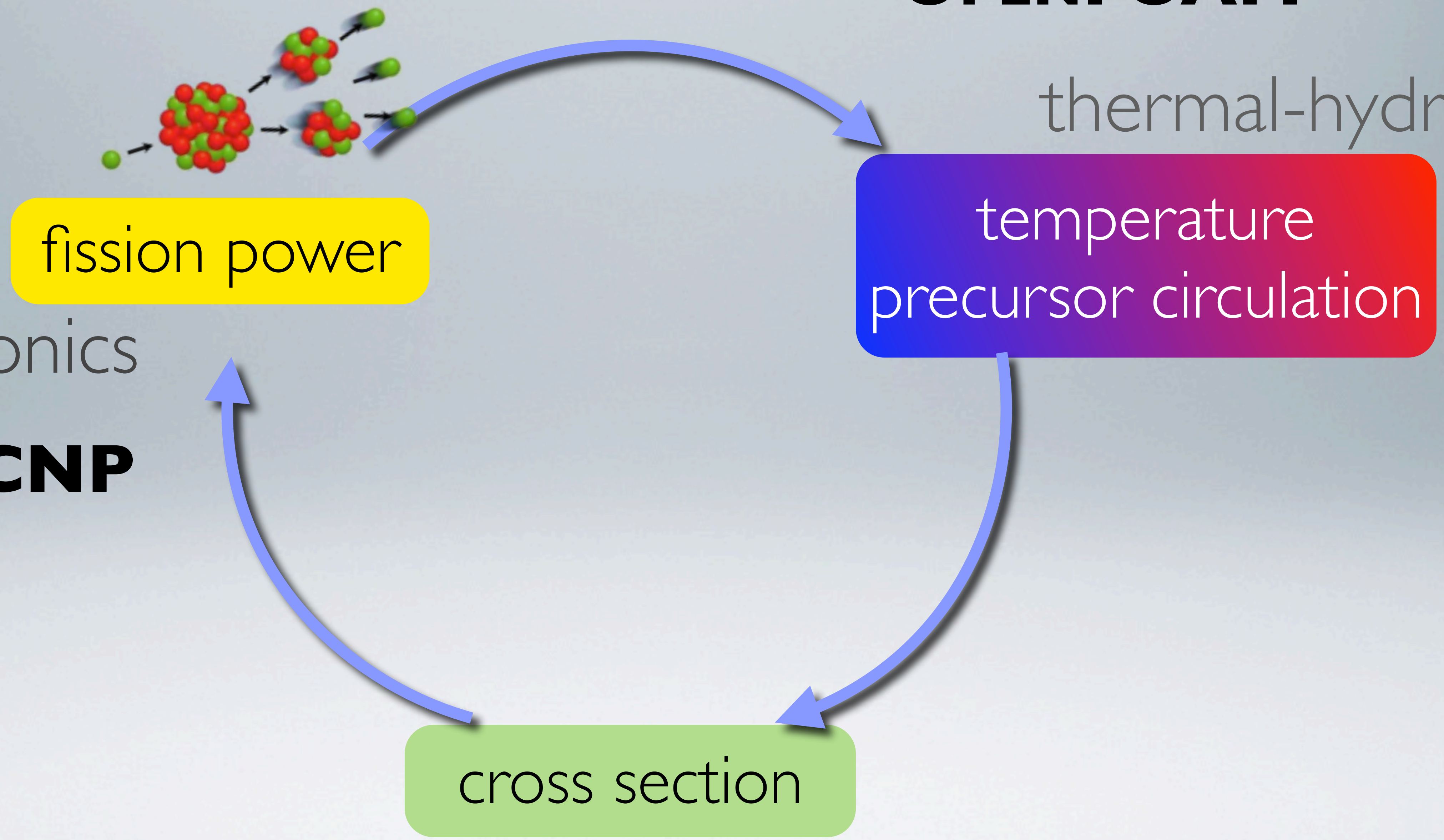
neutronics

cross section

nuclear database

ENDF-B7

MSFR - COUPLING STRATEGY



OpenFOAM

thermal-hydraulics

temperature
precursor circulation

fission power

neutronics

MCNP

cross section

nuclear database

MAKXSF

ENDF-B7

MSFR - CFD - OPENFOAM

Momentum Conservation Equation

expansion coefficient

$$\frac{\partial \overline{u_i}}{\partial t}+\frac{\partial}{\partial x_j}\left(\overline{u_j}\,\overline{u_i}\right)-\frac{\partial}{\partial x_j}\left\{(\nu+\nu_t)\left[\left(\frac{\partial \overline{u_i}}{\partial x_j}+\frac{\partial \overline{u_j}}{\partial x_i}\right)-\frac{2}{3}\left(\frac{\partial \overline{u_k}}{\partial x_k}\right)\delta_{ij}\right]\right\}=-\frac{\partial}{\partial x_i}\left(\frac{\overline{p}}{\rho_o}+\frac{2}{3}k\right)+g_i\left[1-\beta(\overline{T}-T_0)\right]$$

Continuity Equation

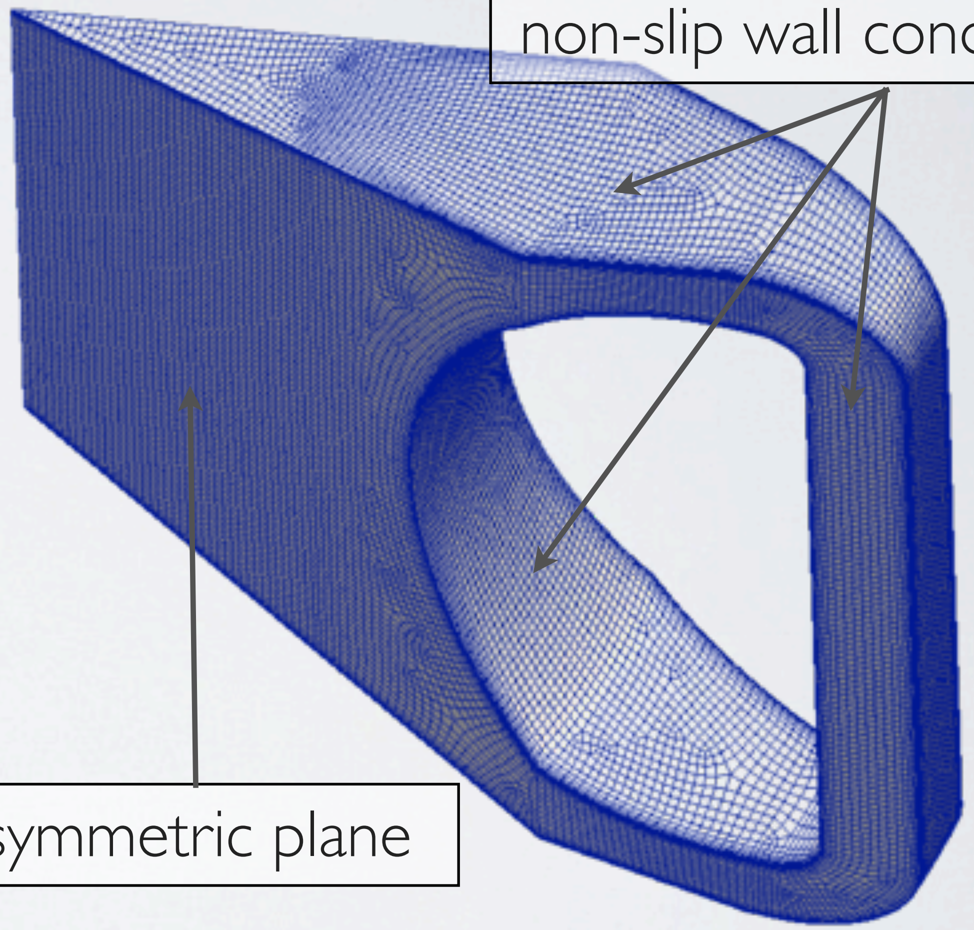
$$\frac{\partial \overline{u_j}}{\partial x_j}=0$$

Energy Conservation Equation

$$\frac{\partial \overline{T}}{\partial t}+\frac{\partial}{\partial x_j}\left(\overline{T}\,\overline{u_j}\right)=k_{eff}\frac{\partial}{\partial x_k}\left(\frac{\partial \overline{T}}{\partial x_k}\right)+S_{energy\ deposition}$$

Reynolds : ~500 000
RANS model : Realizable k-epsilon
Steady state calculations
Incompressible

Precursors circulation treated as a chemical specie

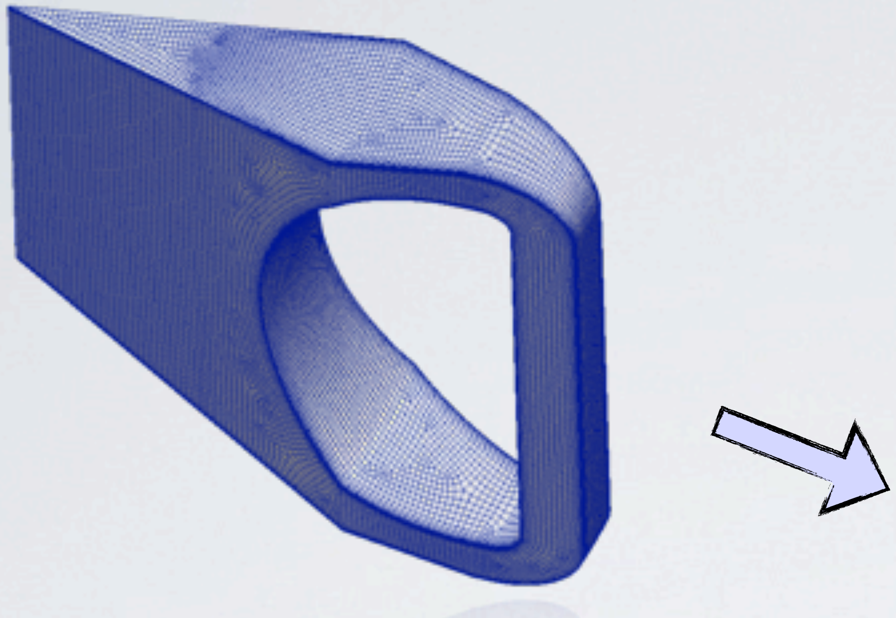


adiabatic,
non-slip wall condition

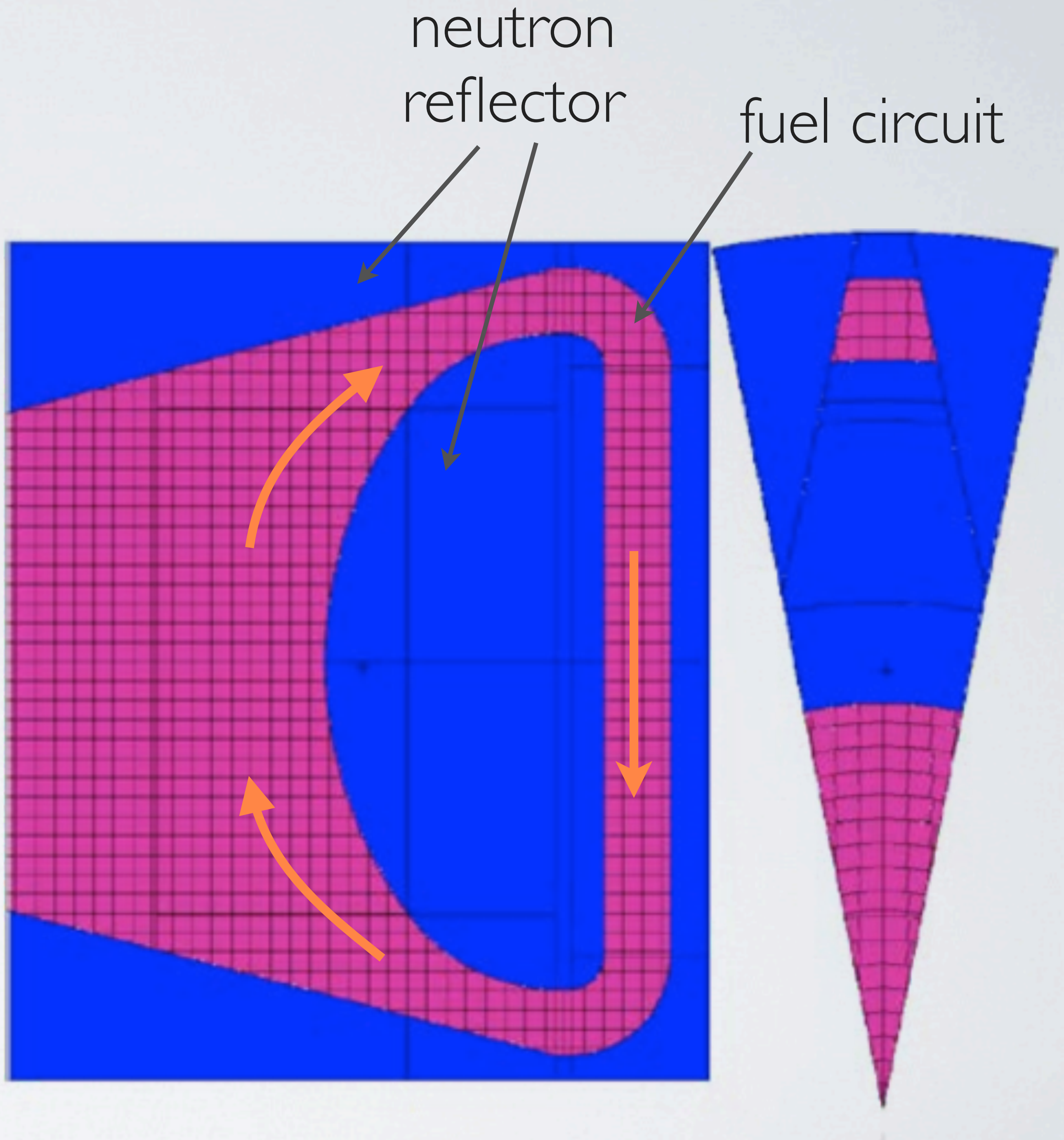
symmetric plane

CFD mesh - 1/16 core 300 k cells

MSFR - NEUTRONICS - MCNP



- Correspondence between neutronics and thermal-hydraulics geometry
- Elementary cell: brick with curved surfaces
- 5 000 volumes
- Precursors position considered as a neutron source term for MCNP
- Density/cross section recalculated from CFD results



MCNP geometry

MSFR - NEUTRONICS - FLUX ESTIMATION

The reactor can be considered as a prompt subcritical system with an exterior source of neutrons: decaying precursors

We focus on the neutronic “prompt ” flux resulting from a precursor decay, integrated over generations:

first generation of neutrons produced by the decaying precursors normalized per source

$$\Phi = \Phi_1 + k_1^p \Phi_2 + k_1^p k_2^p \Phi_3 + \ldots + \left(\prod_{m=1}^{m_0-1} k_m^p \right) \Phi_{m_0} + \left(\frac{\left(\prod_{m=1}^{m_0} k_m^p \right)}{1 - k_{eq}^p} \right) \Phi_{eq}$$

terms calculated using one simulation without discarded generation, up to the converged flux shape Φ_{m_0}

Equilibrium flux value, calculated discarding firsts generations

MSFR - NEUTRONICS - $\tilde{\beta} = 1 - k_p$ ESTIMATION

Objective = estimation of the margin to the prompt criticality: $1 - k_p = \tilde{\beta}$

Φ : flux associated to the neutron shower induced by the decaying precursors (reactor neutron source)

$\beta \nu \Sigma_f \Phi$: represents the precursor production

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Equilibrium condition, 1 decaying precursor creates 1 precursor:

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$$\left.\begin{aligned}
&\beta\nu\Sigma_f\Phi = \left\langle \beta\nu\Sigma_f\Phi \right\rangle_1 + k_1^p \left\langle \beta\nu\Sigma_f\Phi \right\rangle_2 + k_1^p k_2^p \left\langle \beta\nu\Sigma_f\Phi \right\rangle_3 + \ldots \\
&+ \left(\prod_{m=1}^{m_0-1} k_m^p \right) \left\langle \beta\nu\Sigma_f\Phi \right\rangle_{m_0} + \left(\frac{\left(\prod_{m=1}^{m_0} k_m^p \right)}{1 - k_{eq}^p} \right) \left\langle \beta\nu\Sigma_f\Phi \right\rangle_{eq}
\end{aligned}\right] = 1$$

MSFR - NEUTRONICS - $\tilde{\beta} = 1 - k_p$ ESTIMATION

The fuel enrichment is adjusted to obtain $\beta \nu \Sigma_f \Phi = 1$

- This enrichment corresponds to the steady state critical system
- The precursor circulation / spectrum effect are taken into account

The safety parameter can directly be deduced from:

$$1 - k_p = \tilde{\beta}$$

MSFR - OUTLINE

Coupling strategy

CFD - OpenFOAM
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Neutronic parameters
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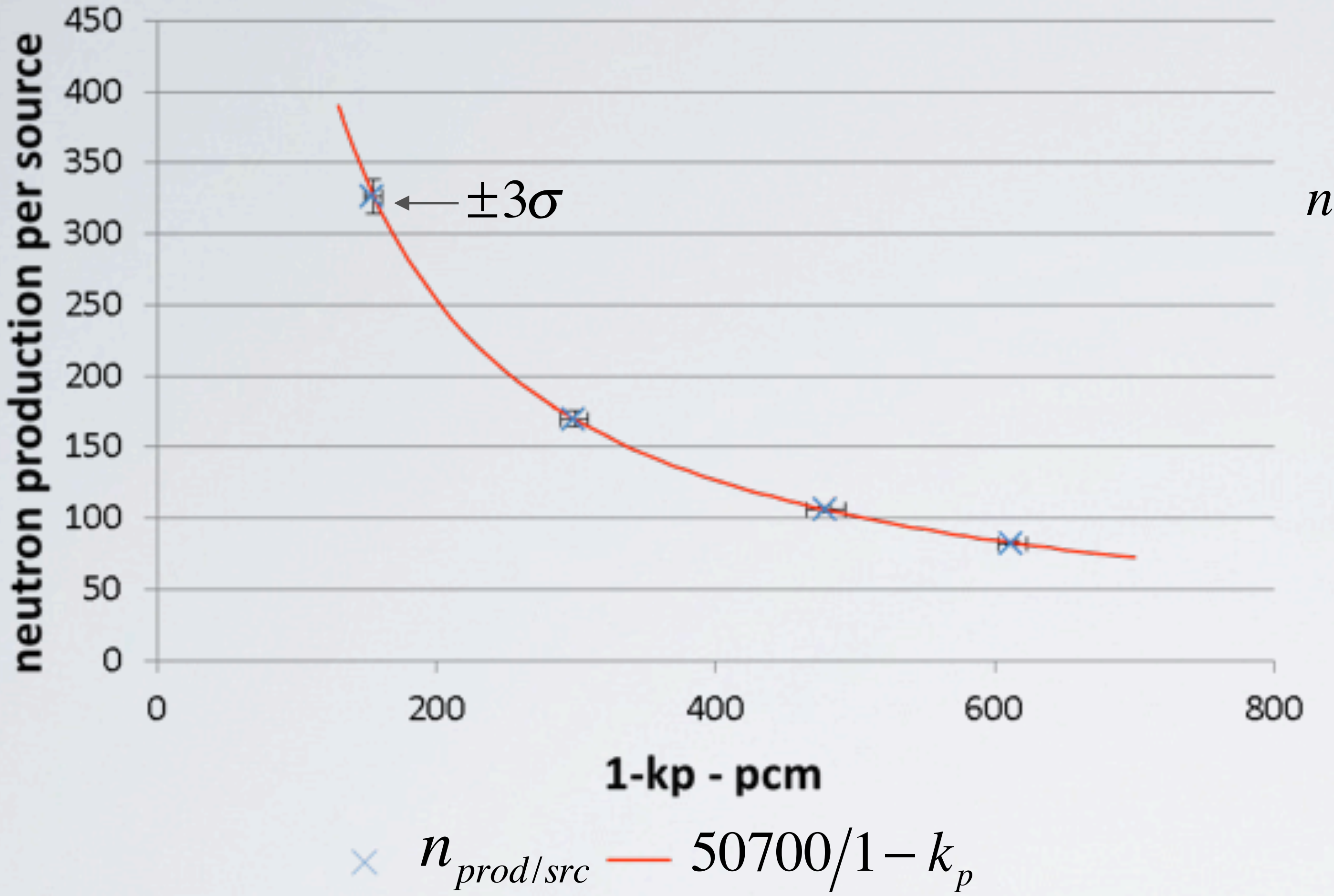
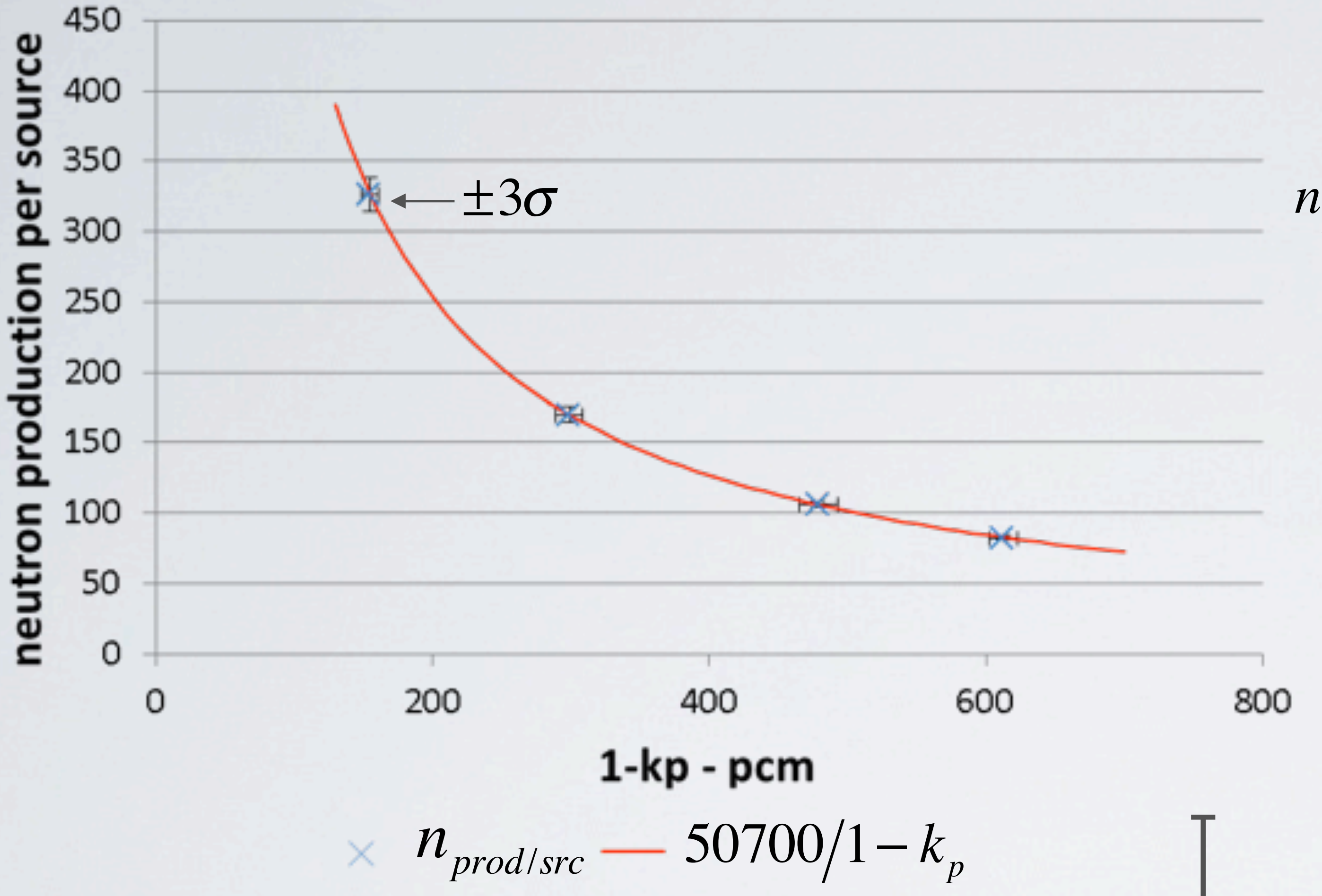
MSFR - COUPLING RESULTS - $\tilde{\beta} = 1 - k_p$ ESTIMATION



$$n_{prod/src} = \nu\Sigma_f\Phi = \langle \nu\Sigma_f\Phi \rangle_1 + k_1^p \langle \nu\Sigma_f\Phi \rangle_2 + k_1^p k_2^p \langle \nu\Sigma_f\Phi \rangle_3$$
$$+ \dots + \left(\prod_{m=1}^{m_0-1} k_m^p \right) \langle \nu\Sigma_f\Phi \rangle_{m_0} + \left(\frac{\left(\prod_{m=1}^{m_0} k_m^p \right)}{1 - k_{eq}^p} \right) \langle \nu\Sigma_f\Phi \rangle_{eq}$$

- Equilibrium condition: $n_{prod/src} . \beta = 1$

MSFR - COUPLING RESULTS - $\tilde{\beta} = 1 - k_p$ ESTIMATION



$$n_{prod/src} = \nu\Sigma_f\Phi = \left\langle \nu\Sigma_f\Phi \right\rangle_1 + k_1^p \left\langle \nu\Sigma_f\Phi \right\rangle_2 + k_1^p k_2^p \left\langle \nu\Sigma_f\Phi \right\rangle_3 + \ldots + \left(\prod_{m=1}^{m_0-1} k_m^p \right) \left\langle \nu\Sigma_f\Phi \right\rangle_{m_0} + \left(\frac{\left(\prod_{m=1}^{m_0} k_m^p \right)}{1 - k_{eq}^p} \right) \left\langle \nu\Sigma_f\Phi \right\rangle_{eq}$$

- Equilibrium condition: $n_{prod/src}.\beta = 1$

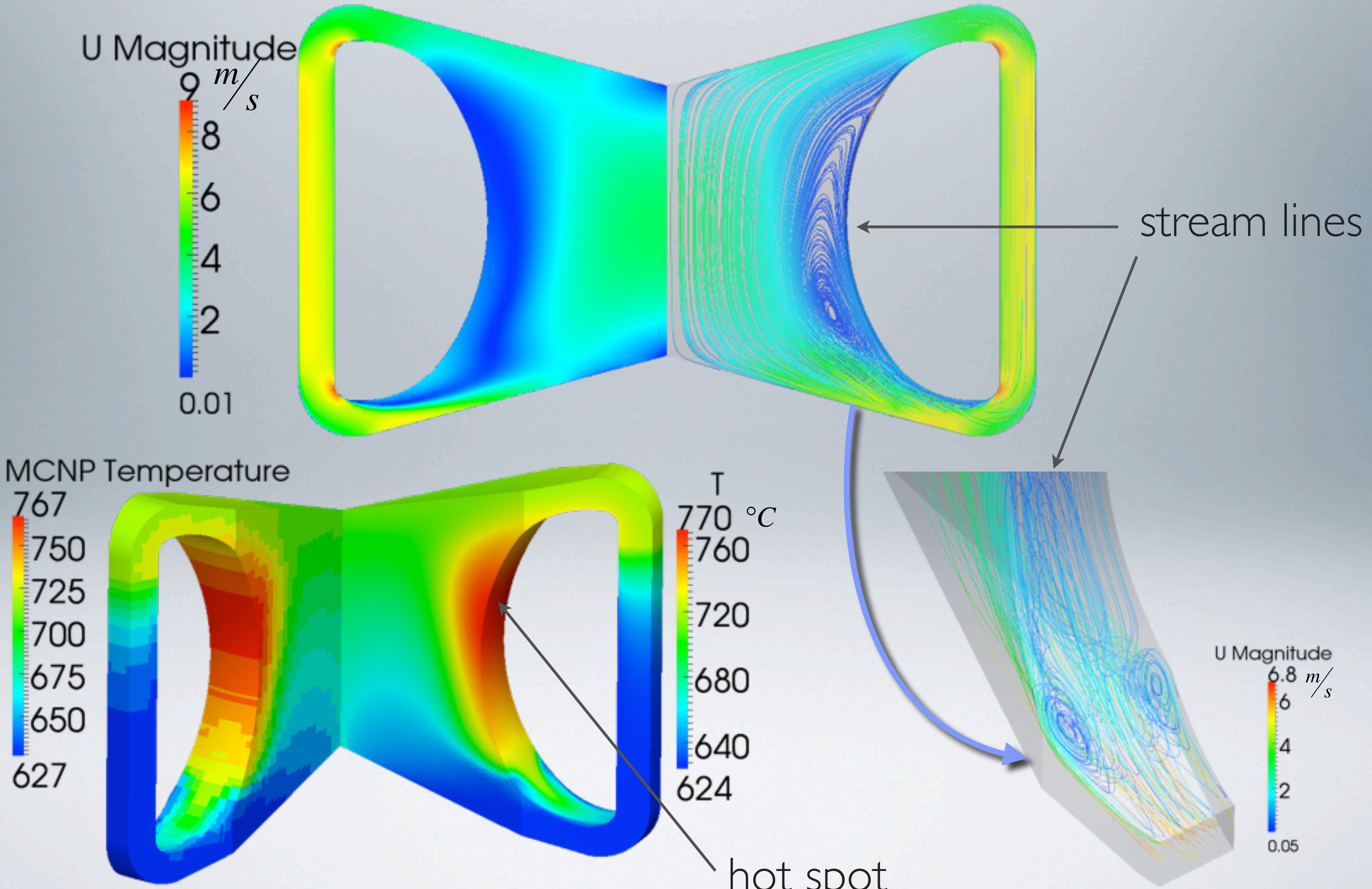
$\pm 0.5\%$

$$1 - k_p \simeq 50700.\beta$$

$322 \pm 6\, pcm$

$$\boxed{\tilde{\beta} = 1 - k_p = 163 \pm 5\, pcm}$$

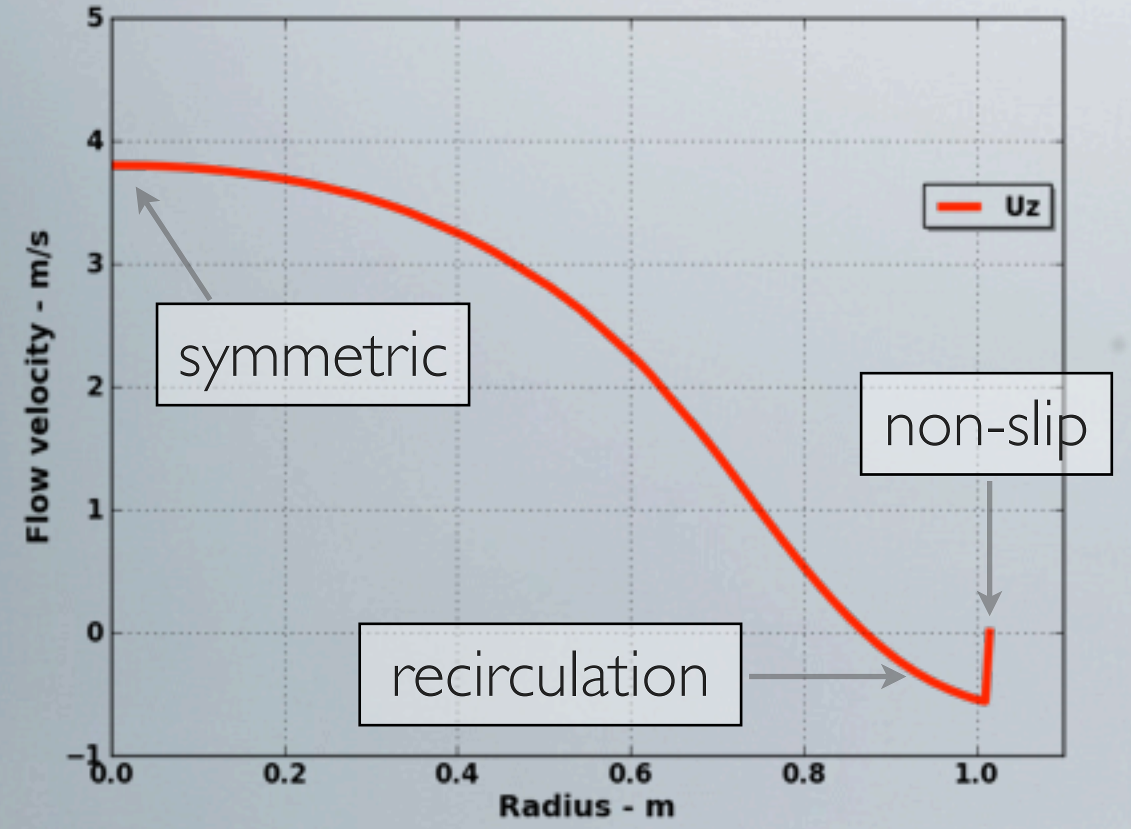
MSFR - COUPLING RESULTS



stream lines

hot spot

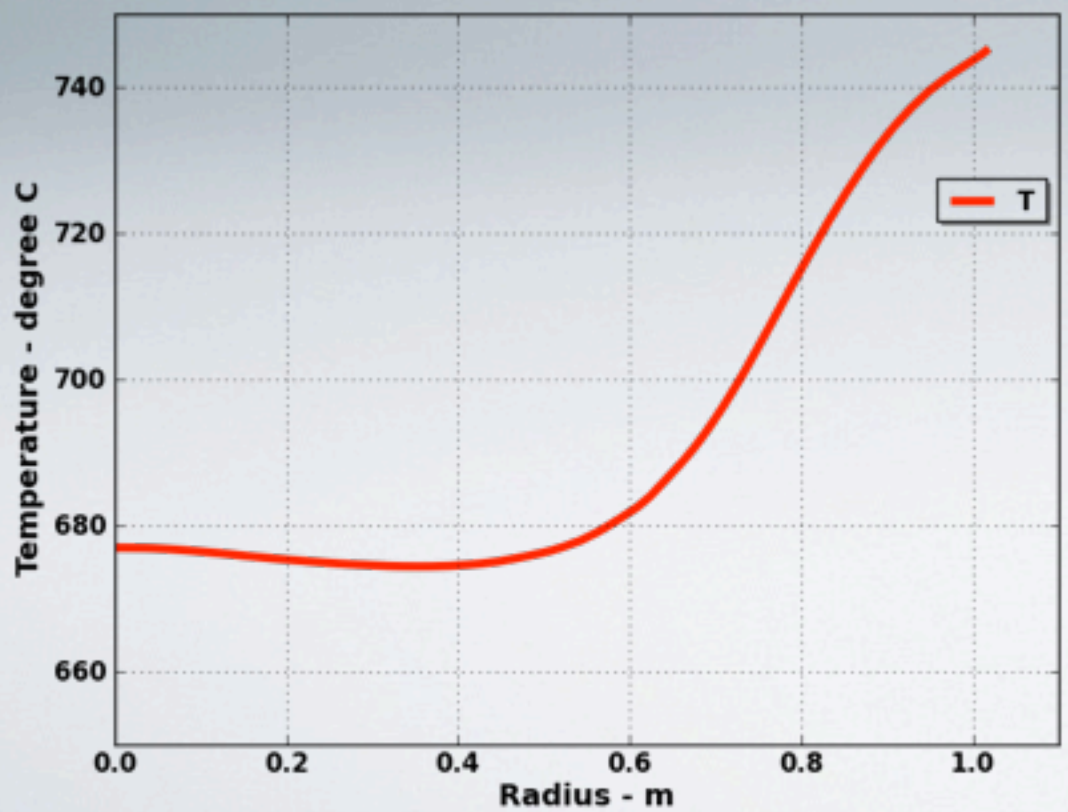
MSFR - COUPLING RESULTS

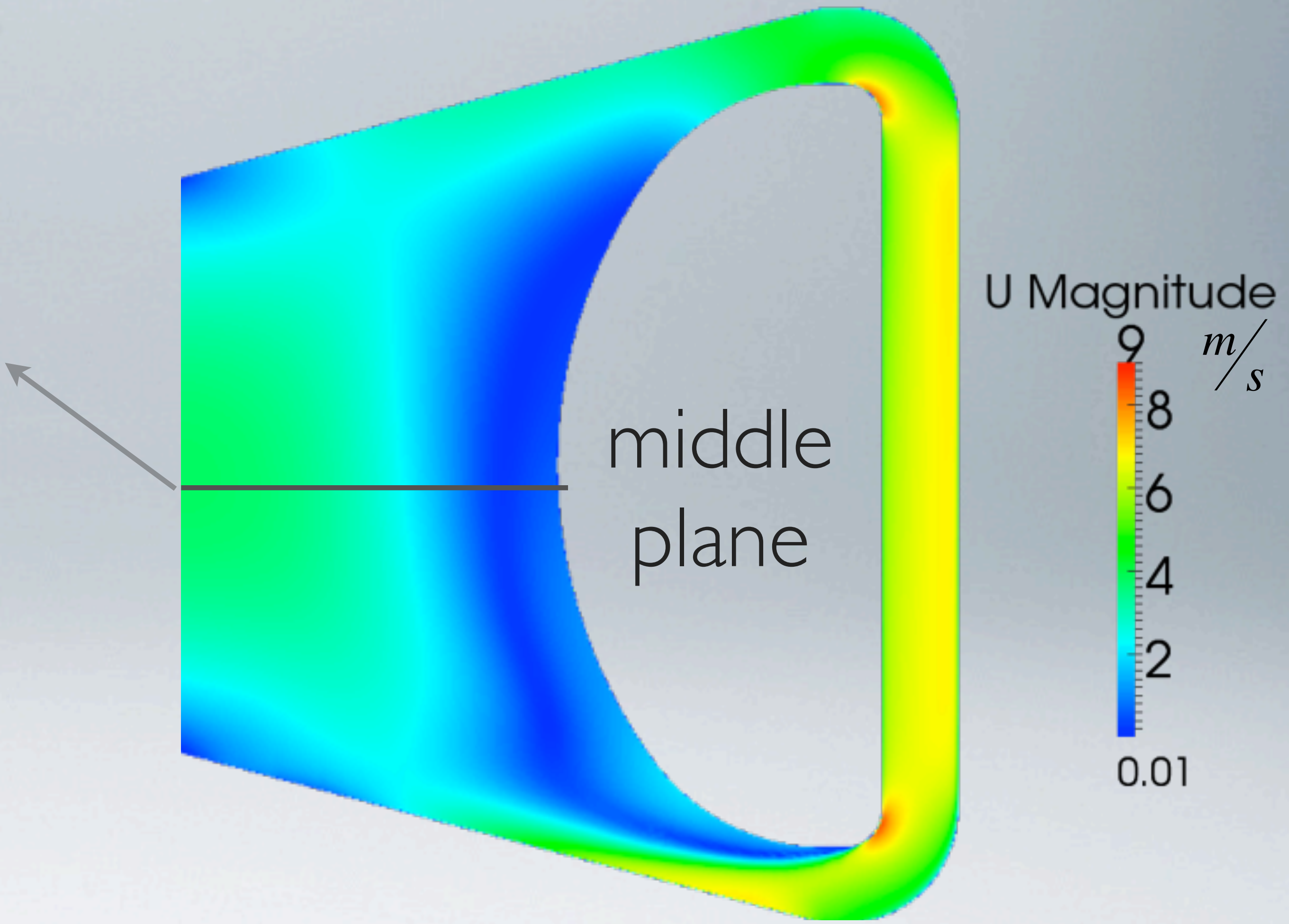


symmetric

non-slip

recirculation





middle plane

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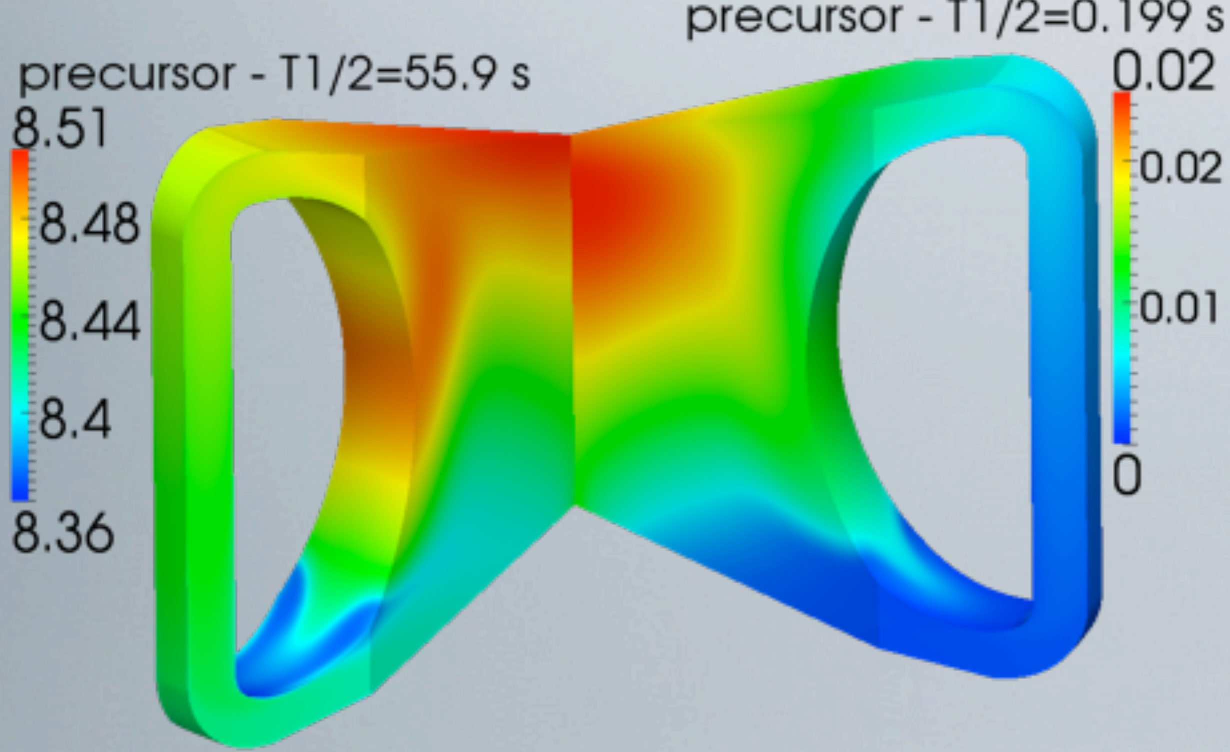
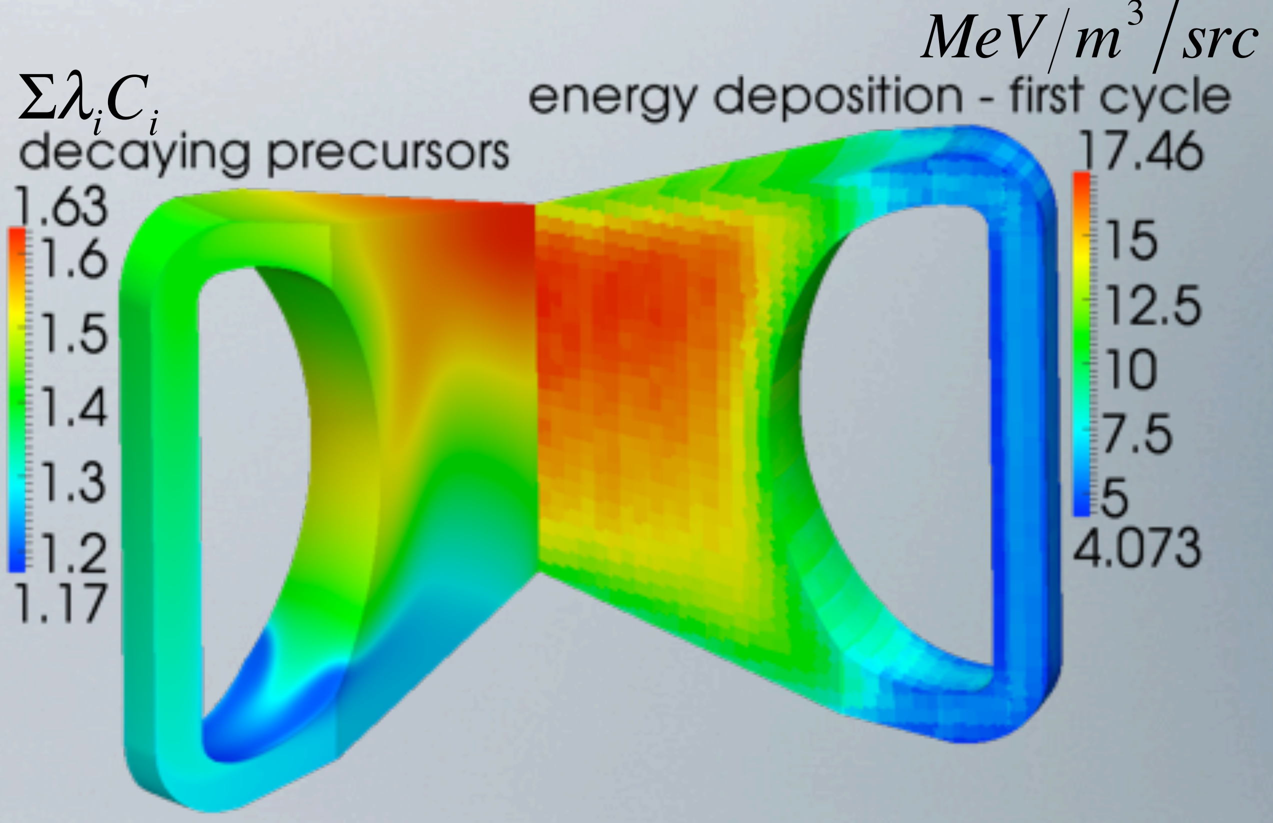
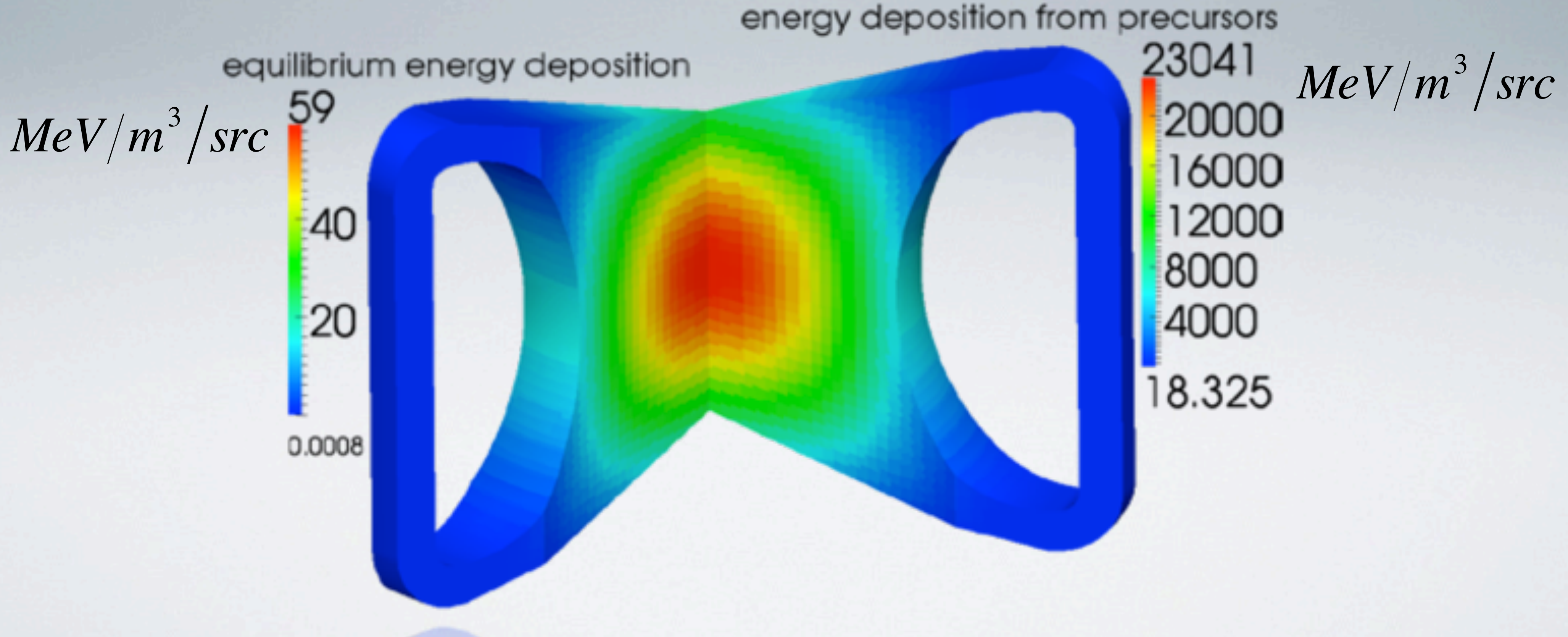
MSFR - COUPLING RESULTS







MSFR - CONCLUSION

CONCLUSION

- Steady state coupling dedicated to liquid fuel reactor
- Hight influence of recirculations on the temperature field in the core
- Significant influence of the precursors circulation on the effective fraction of delayed neutrons

PERSPECTIVES

- Modeling the heat exchangers with a porous media
- Unsteady calculations

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THANK YOU FOR YOUR ATTENTION
ANY QUESTIONS?

MSFR - APPENDIX

APPENDIX

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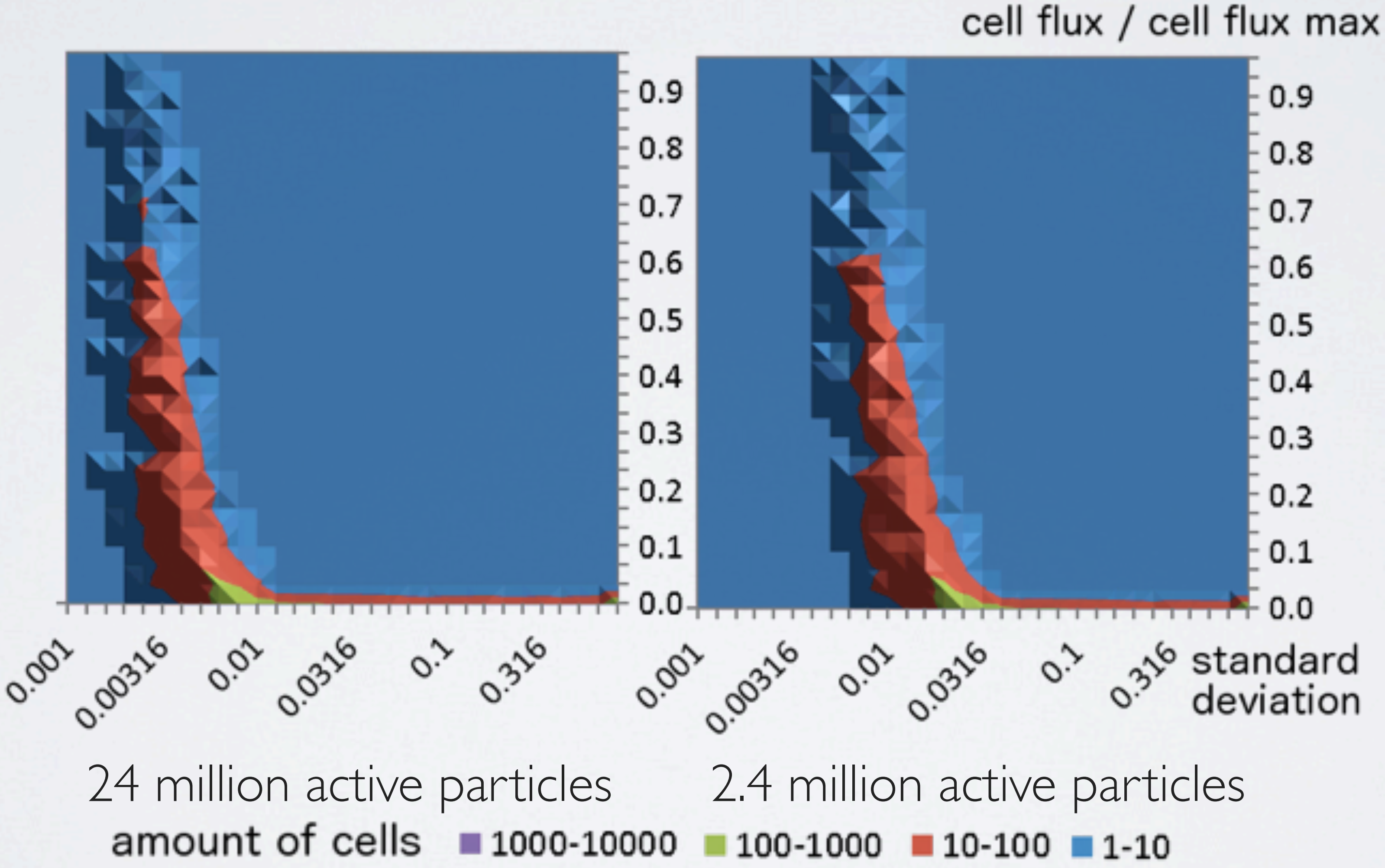
$$\sigma_{cell} = \frac{1}{\overline{tally}_{cell}} \sqrt{\frac{1}{nb_{simulation}} \sum_{j=1}^{nb_{simulation}} \left(tally_{cell_j} - \overline{tally}_{cell}\right)^2}$$

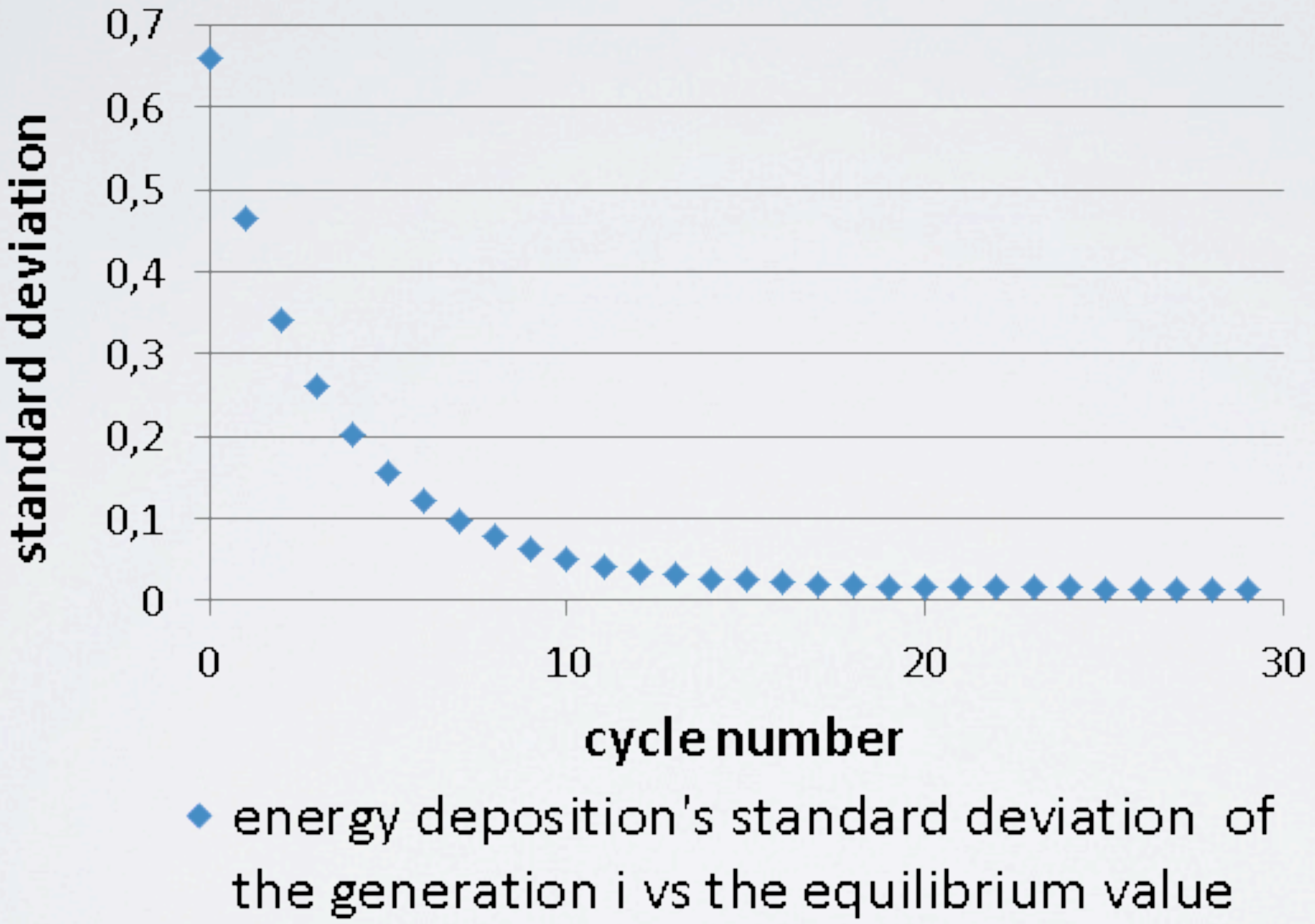


24 million active particles

2.4 million active particles

MSFR - APPENDIX

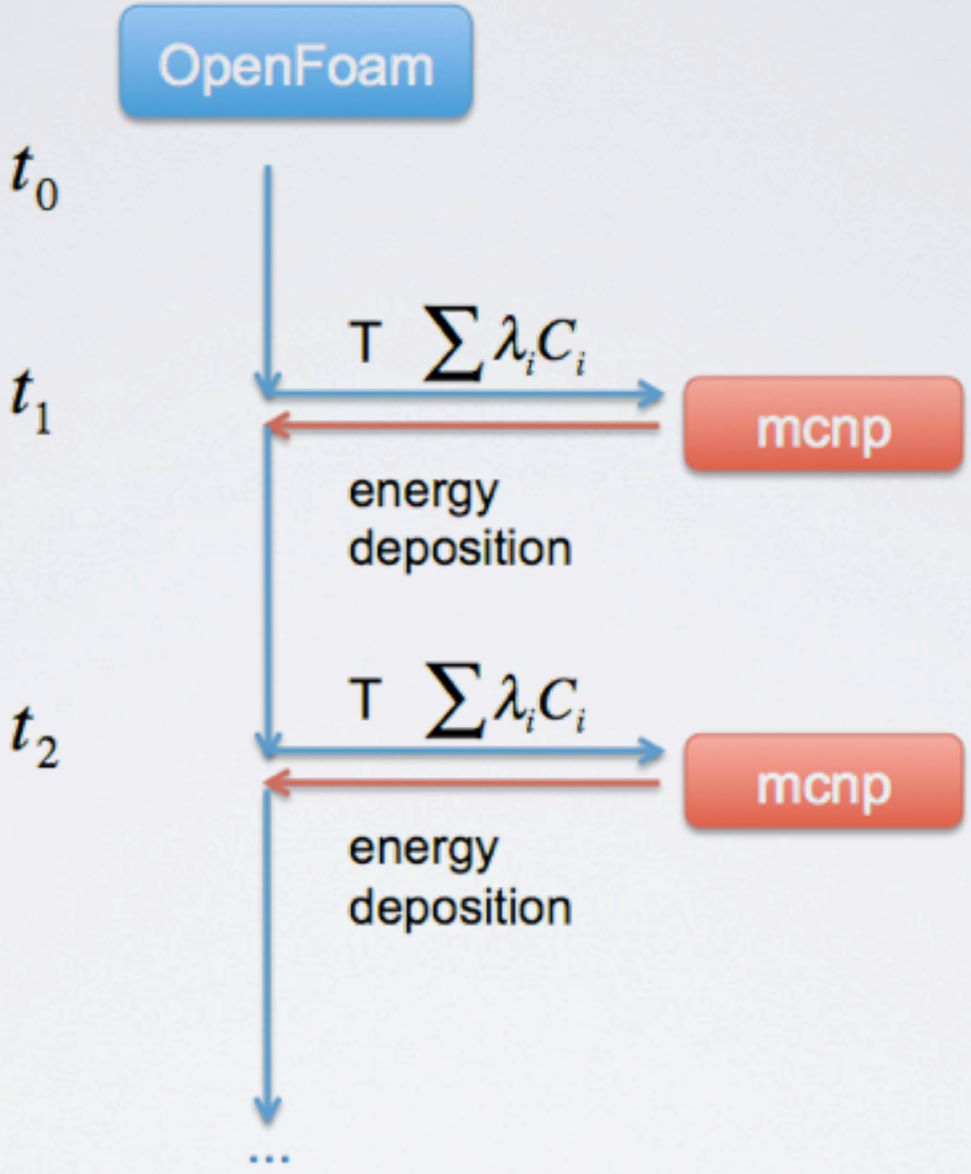
$$\langle \sigma_{cell} \rangle = \frac{1}{\sum_{cell} tally_{cell}} \sum_{cell} \left(\sigma_{cell} tally_{cell} \right)$$



24 million actives particles 2.4 million actives particles

amount of cells 🟪 1000-10000 🟩 100-1000 🟥 10-100 🟦 1-10

MSFR - APPENDIX



coupling schemes