Performance of the Thermal-Hydraulic Model for the ITER TF Magnets

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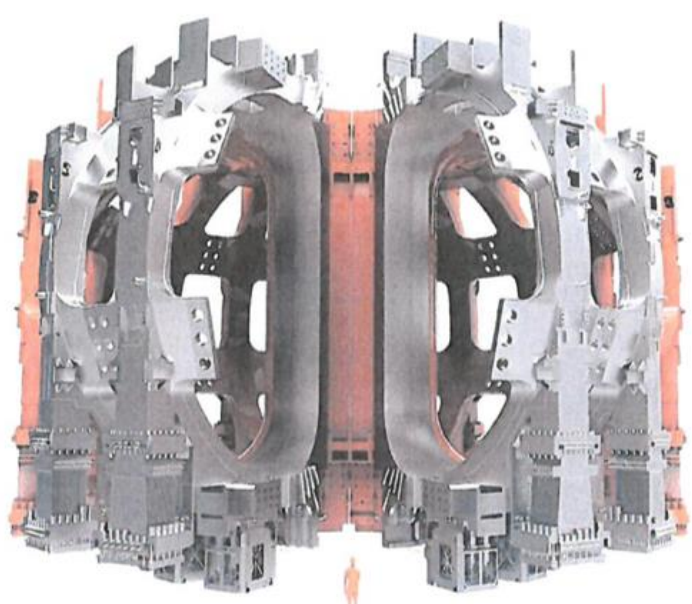
Introduction

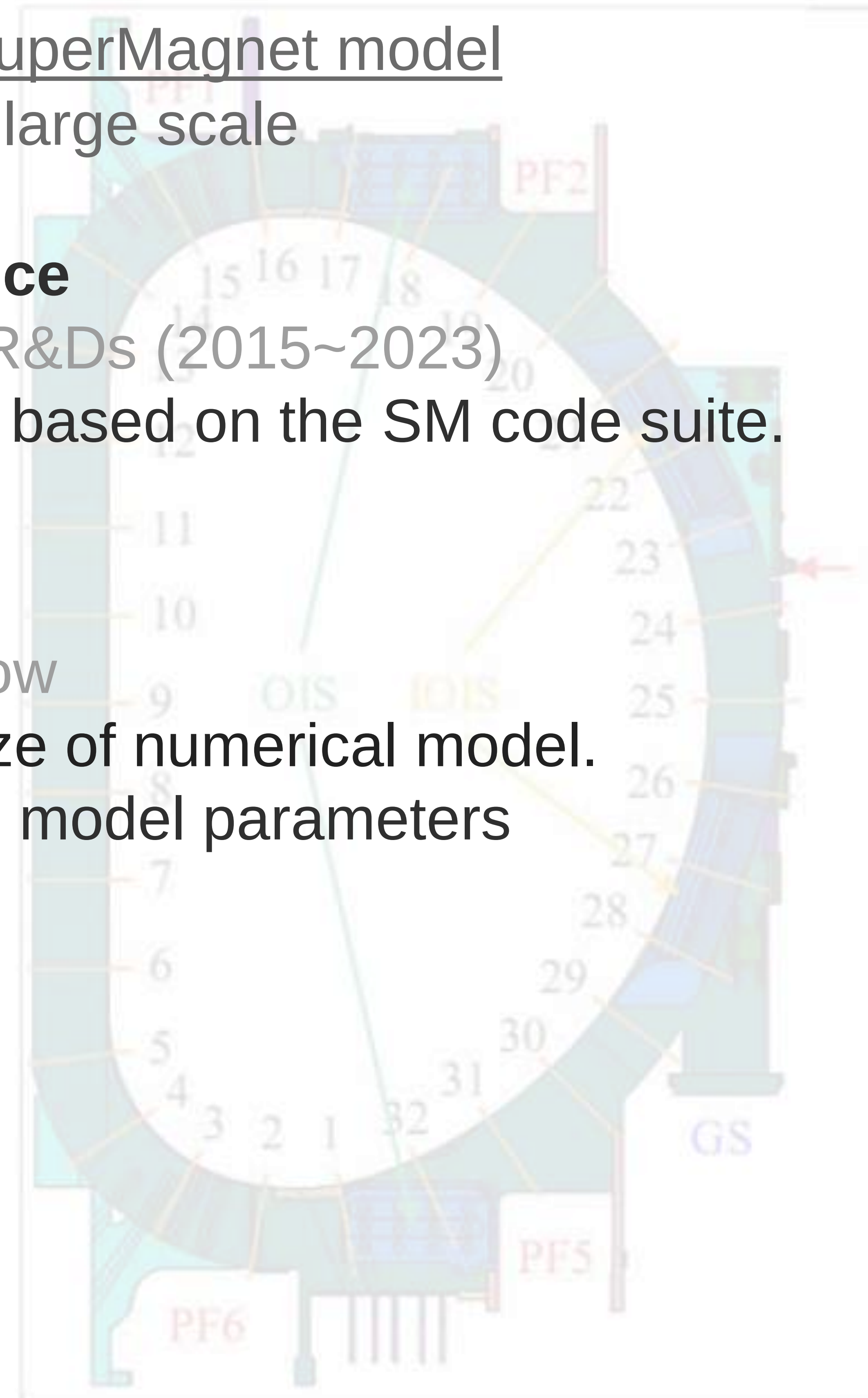
ITER TF model = a representative case of SuperMagnet model (thermal-hydraulic model) in large scale

- **Testing New Ideas of Enhanced Performance**
  : it is the best targets to validate the previous R&Ds (2015~2023)
  → an augmented edition has been proposed based on the SM code suite.

- **Live Issues in Computation**
  : they have been revealed in the onsite workflow
  → It was rather slow, even considering the size of numerical model.
  → Instability was observed as sensitive to the model parameters



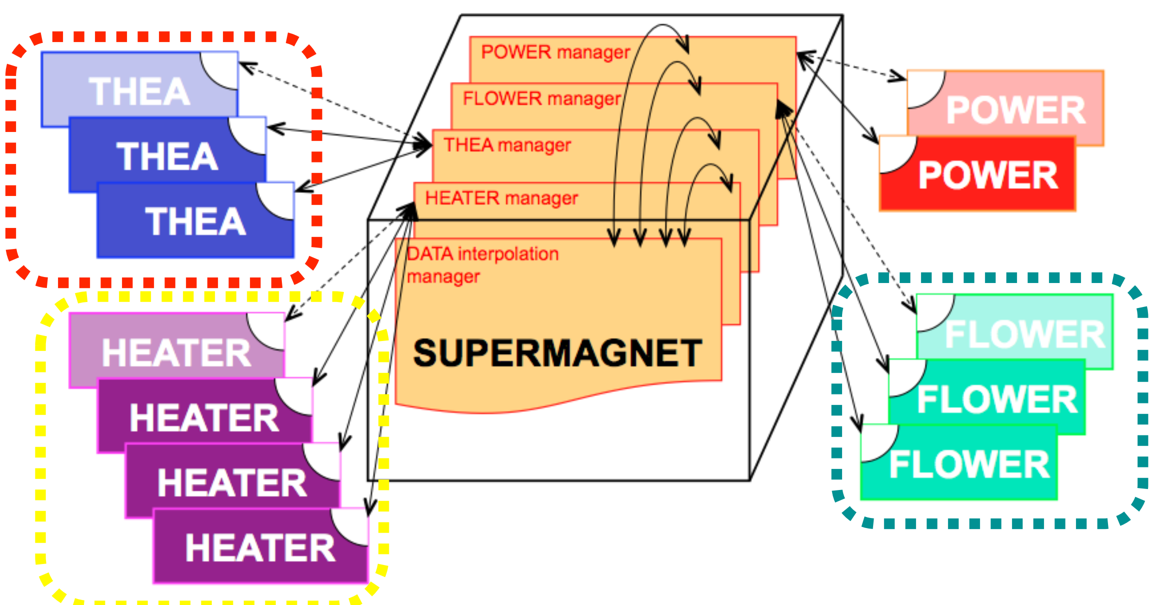
ITER TF coils [1]

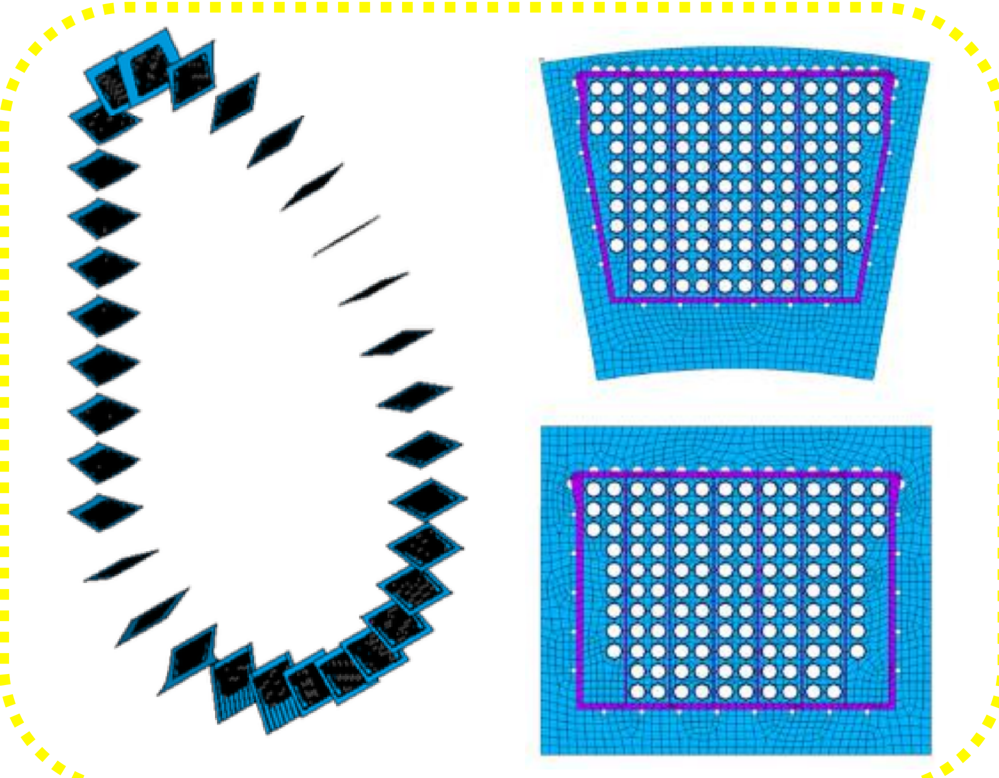


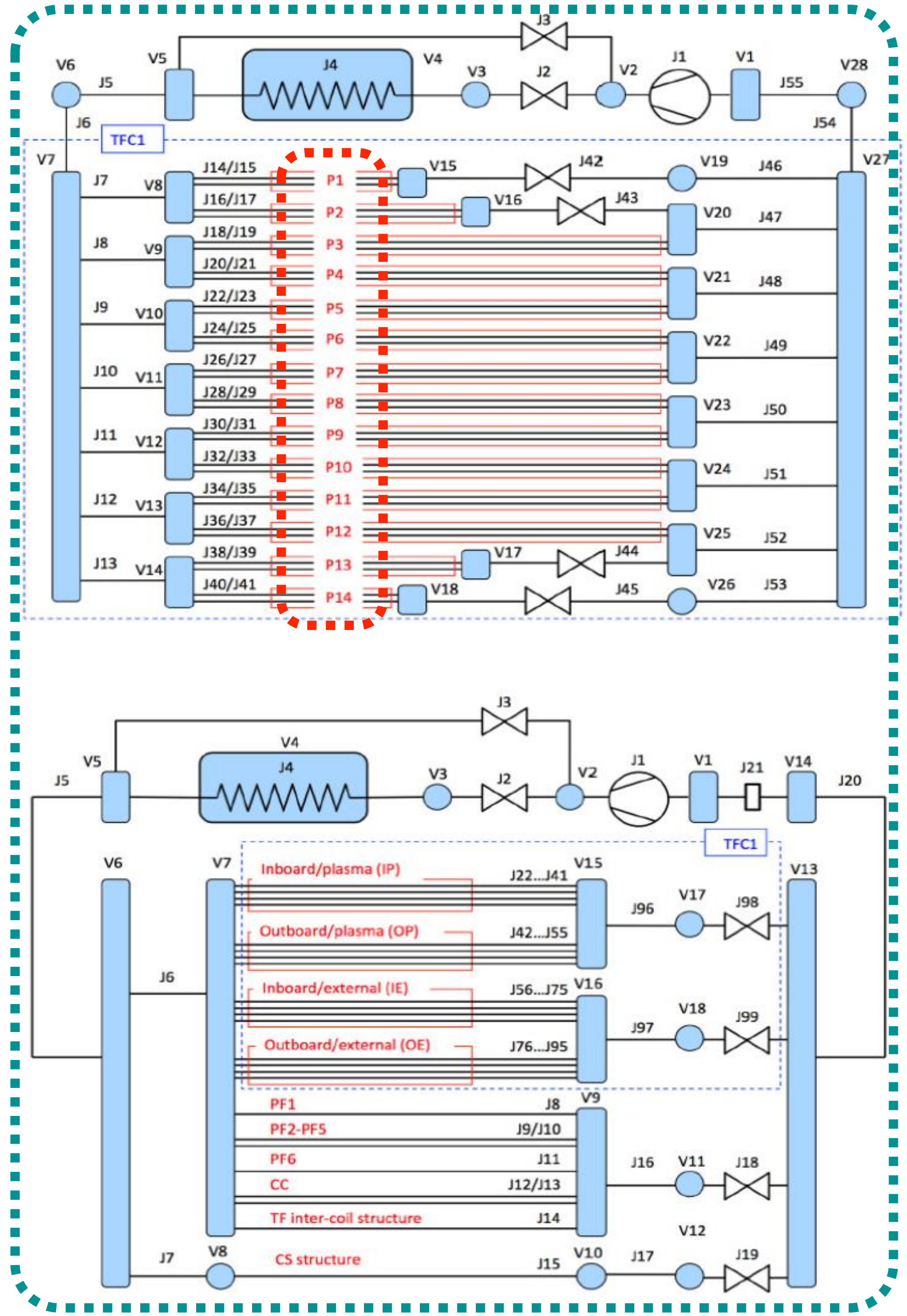
Note) TF model (TF WP + STR)

SuperMagnet : CryoSoft

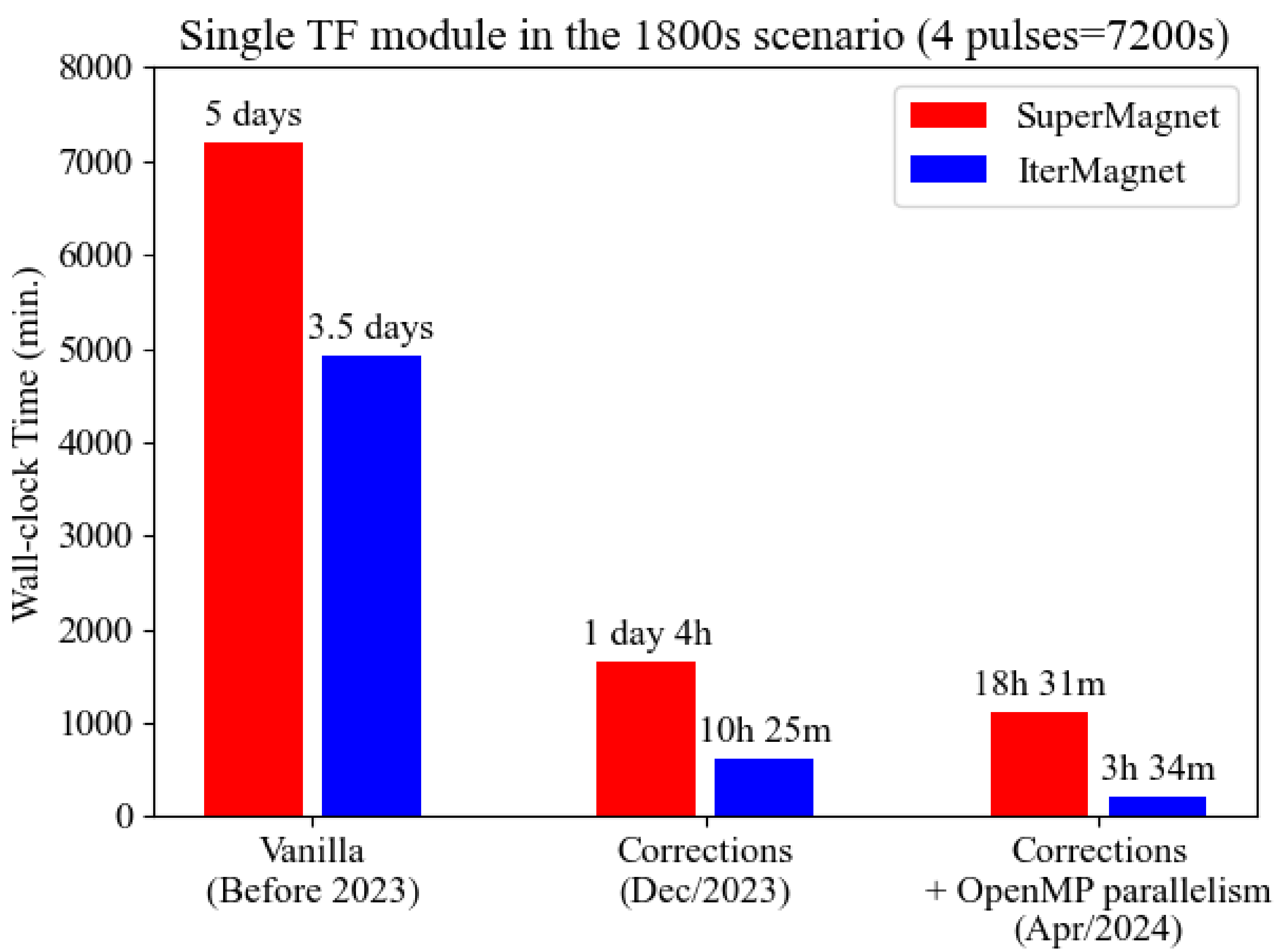
P1~P14
Conductors
(CICCs)







Performance of the ITER TF model (solved issue)

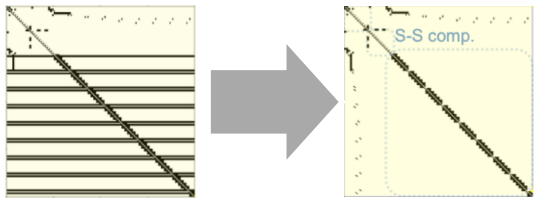


- **IterMagnet**

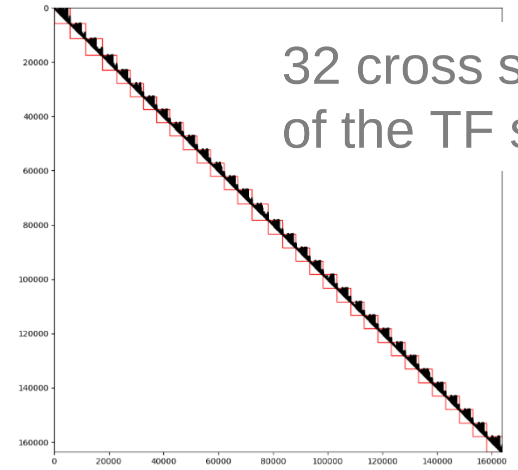
: a replica of the SM code with improved inter-communication scheme

- **Some corrections**

ex) matrix entries of Flower



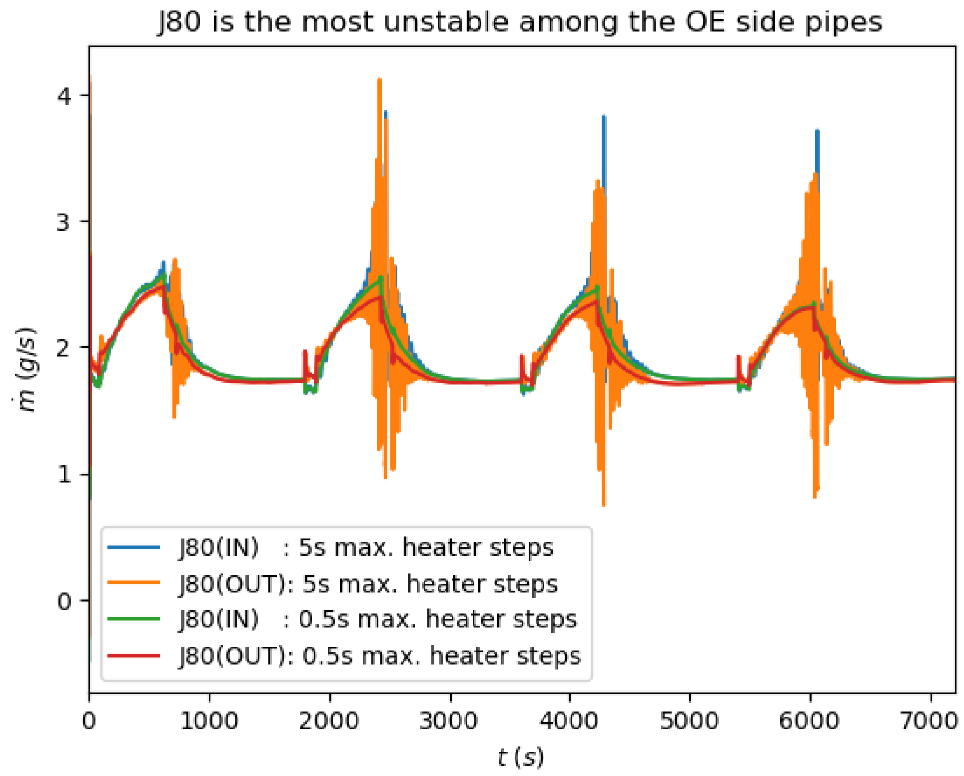
- **Parallelism with separable sub-domains**

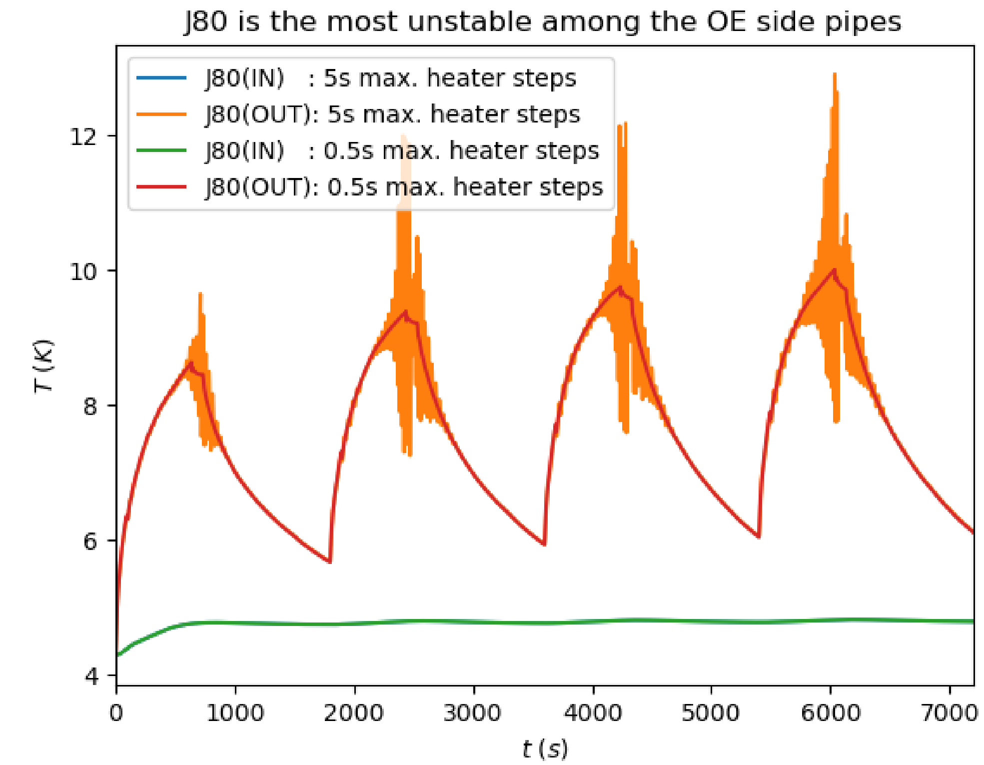


32 cross sections of the TF structure

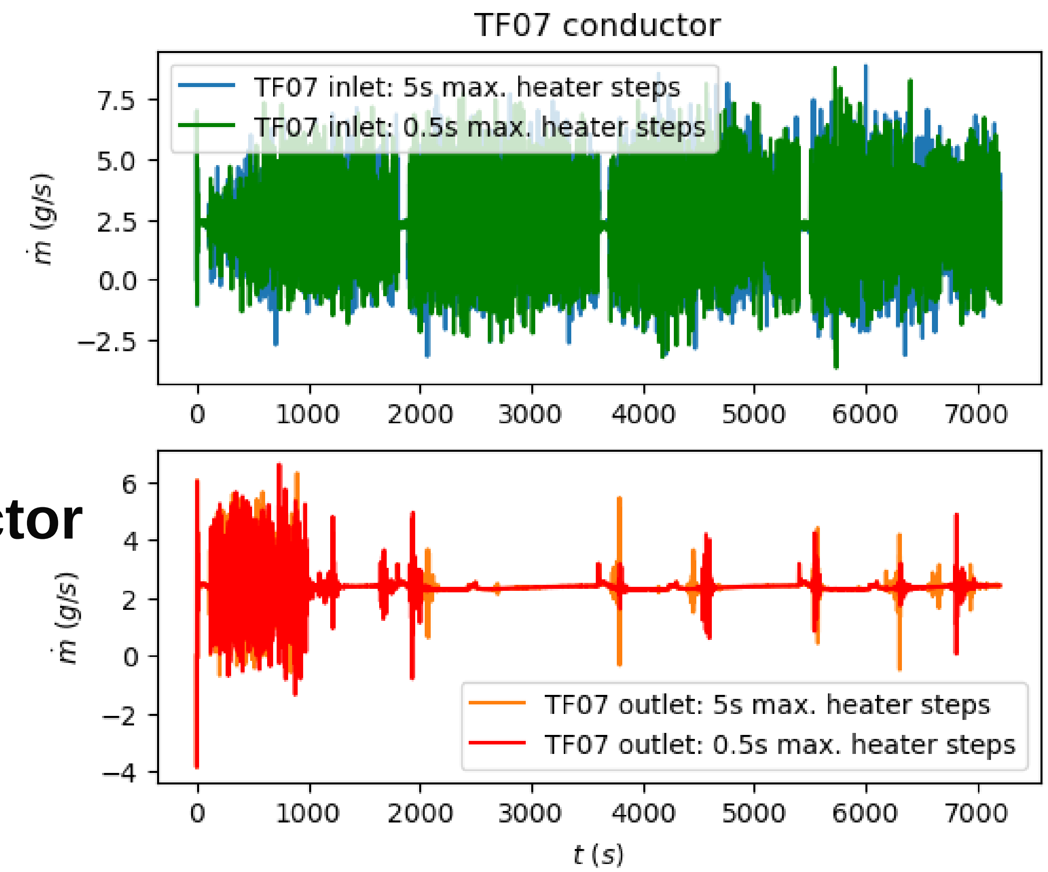
Numerical Instability (solved issue)

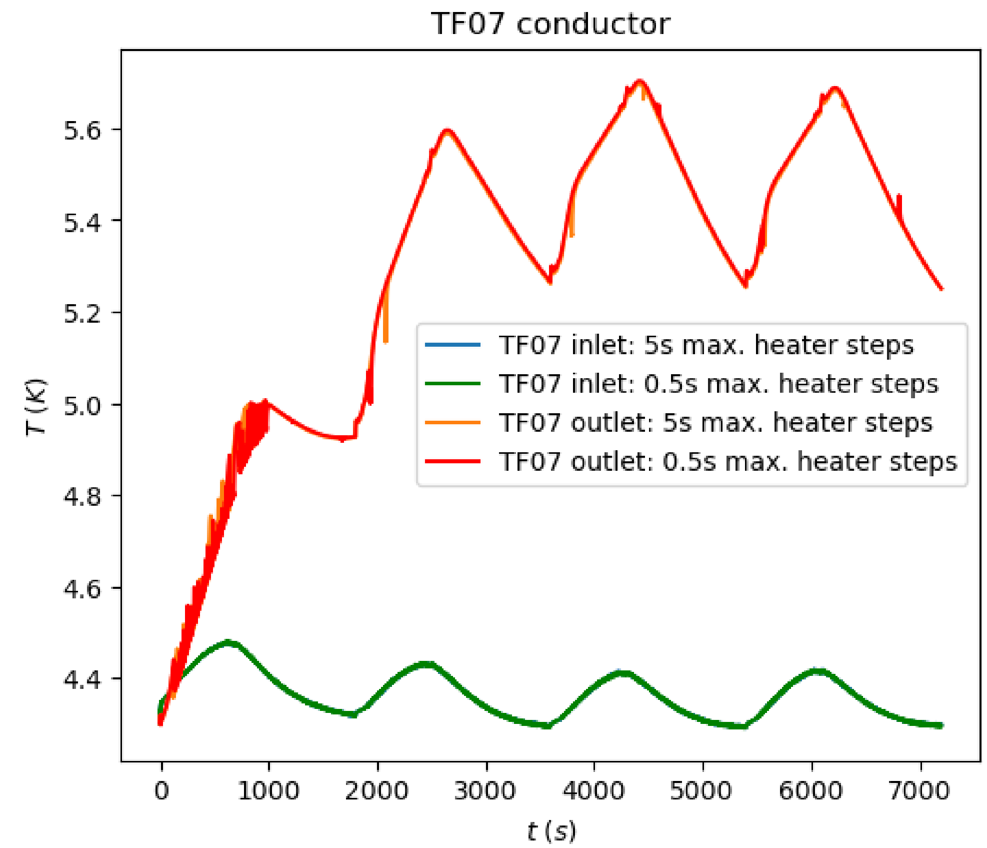
TF structure



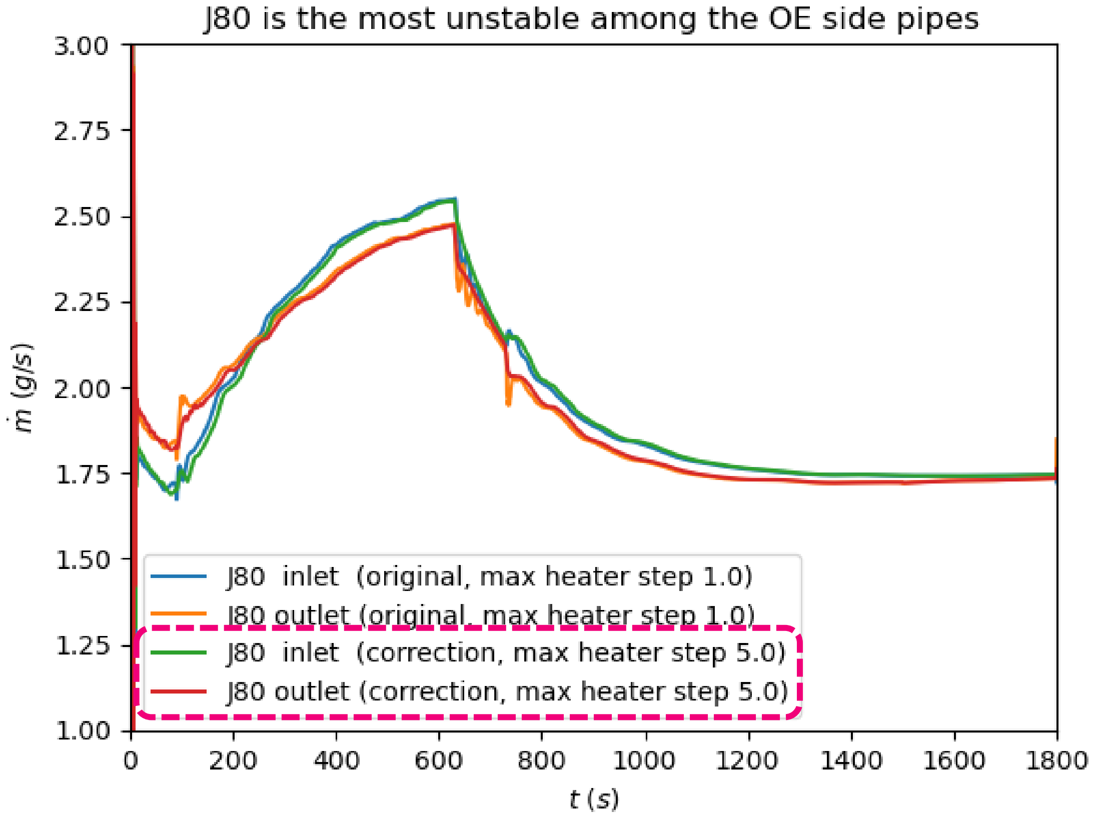


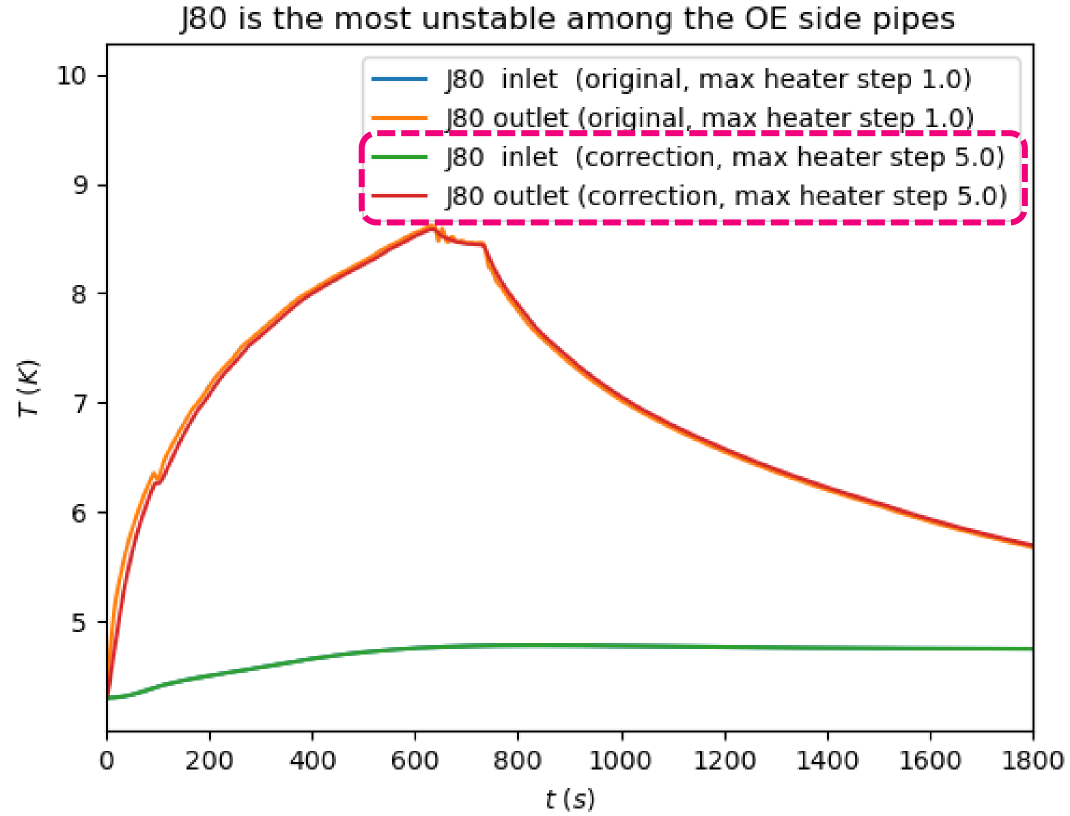
TF conductor

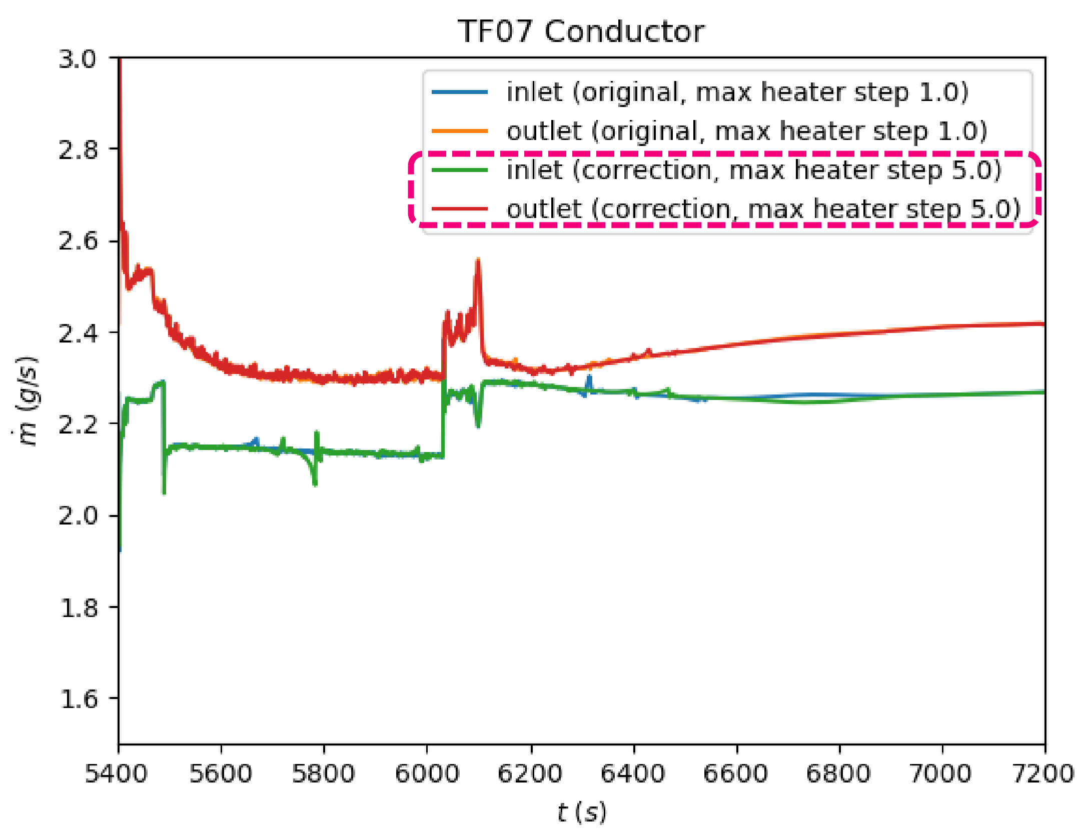


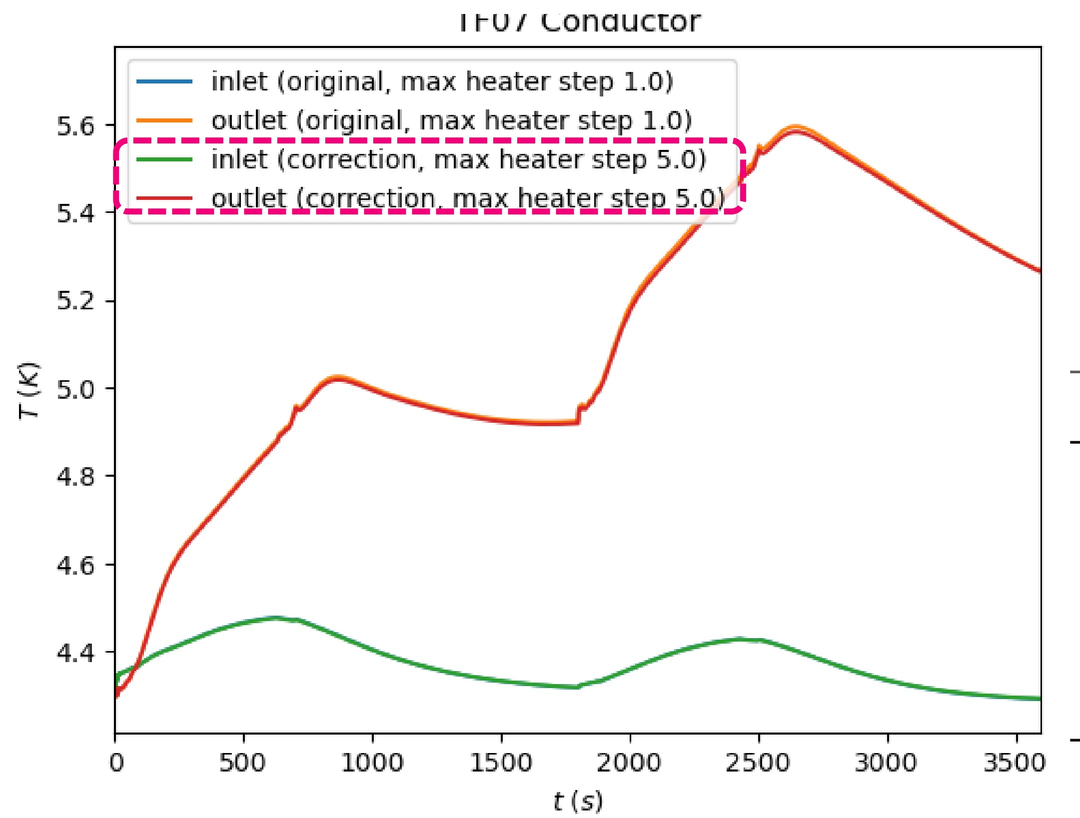


Finally improved.





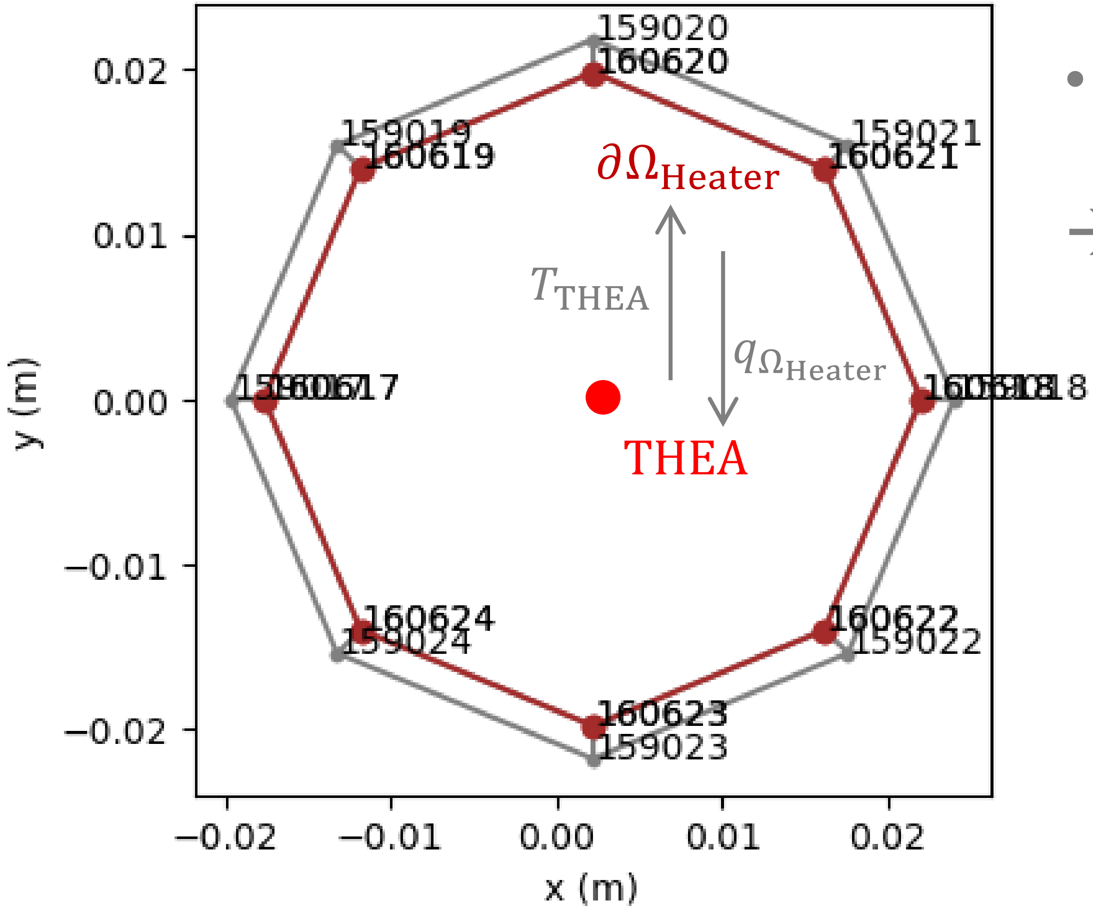




	THEA	Flower
steps	**10^{-3} s ~ .25 s**	**10^{-3} s ~ 0.5s**
tol.	**10^{-3}**	**10^{-3}**
control	**ON**	**ON**

5s is OK for the maximum heater time step, and it's rather stable!

Interfacial Problem



- In theory, the heat flow is defined as a line-integral along the mesh.

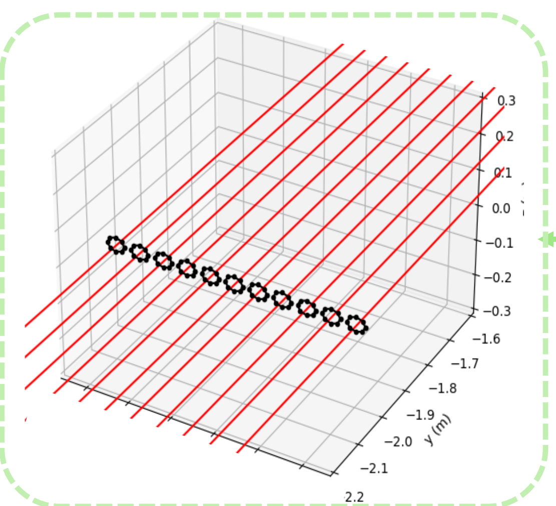
→ however, it has been substituted with the nodal output (= residual) being additive amount to the heat load to the THEA model

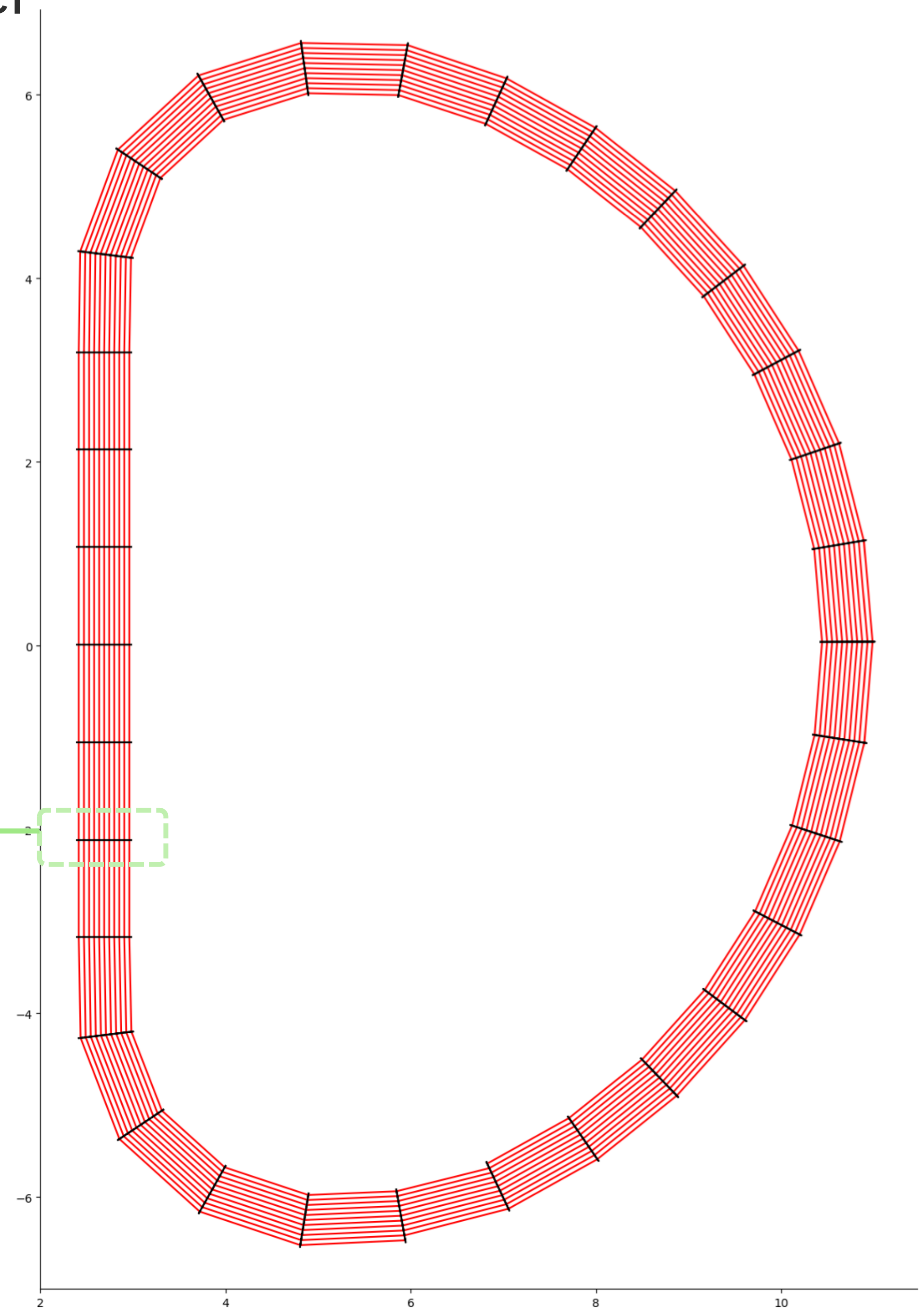
✓ **Boundary Temperature:**

$$T_{\text{THEA}} \longrightarrow T_{\Omega_{\text{Heater}}}$$

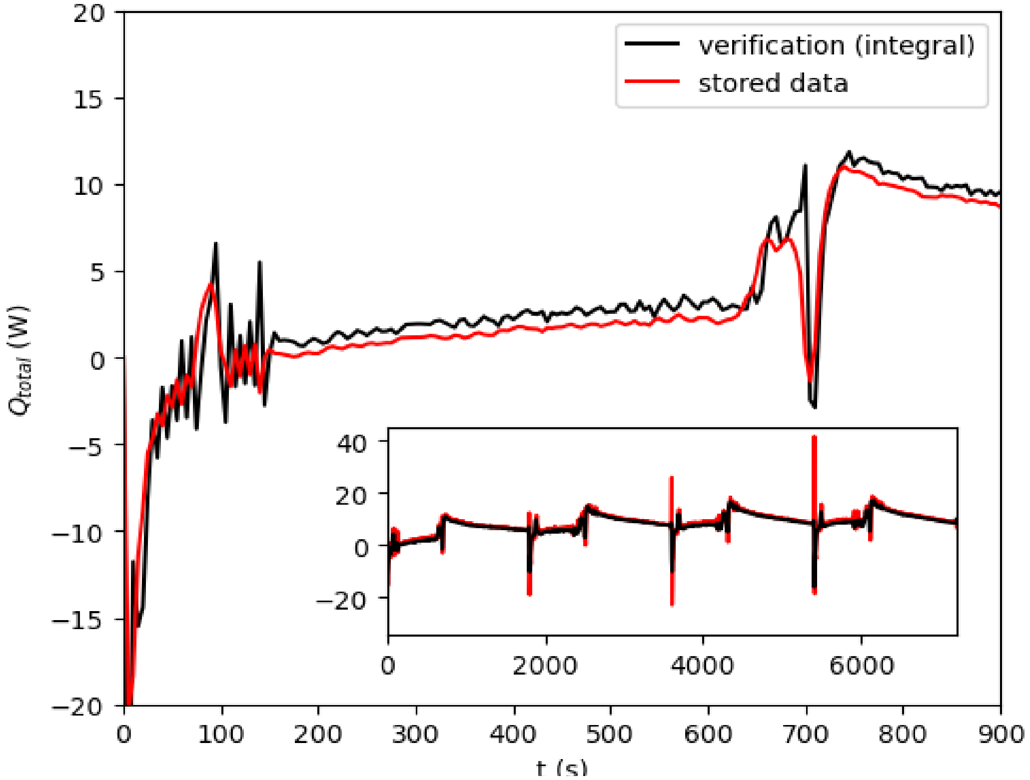
✓ **Boundary Heat Flux:**

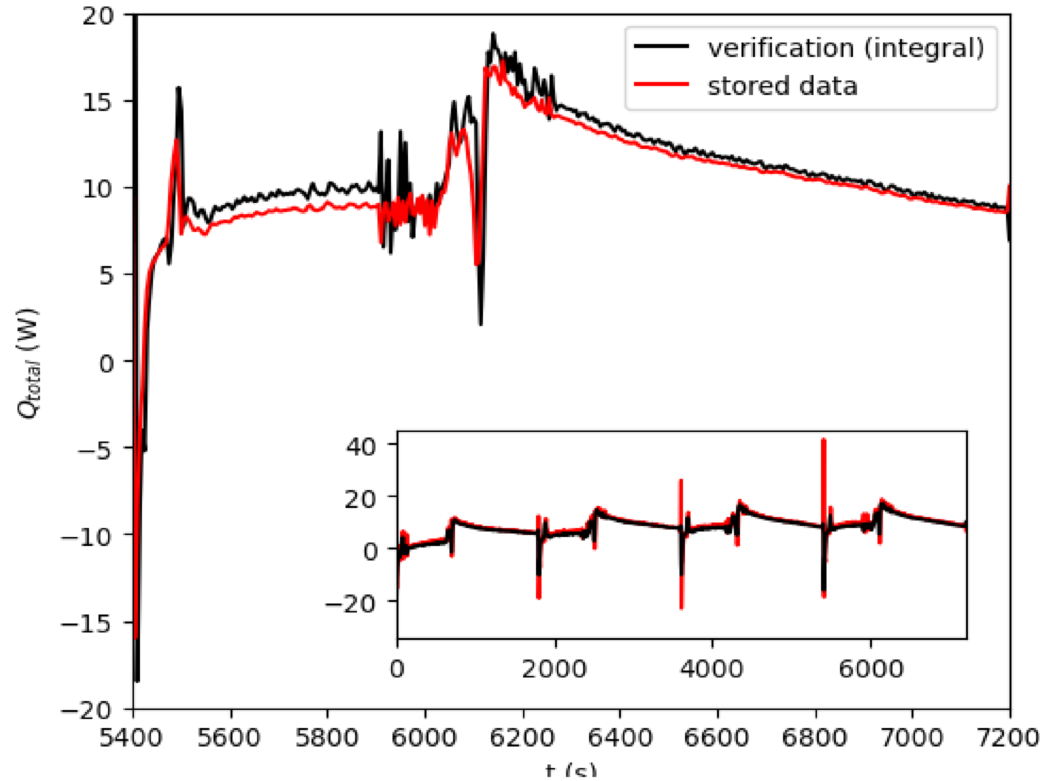
$$-\oint_{\Omega_{\text{Heater}}} k \frac{\partial T}{\partial n} dl \longrightarrow q_{\Omega_{\text{Heater}}}$$



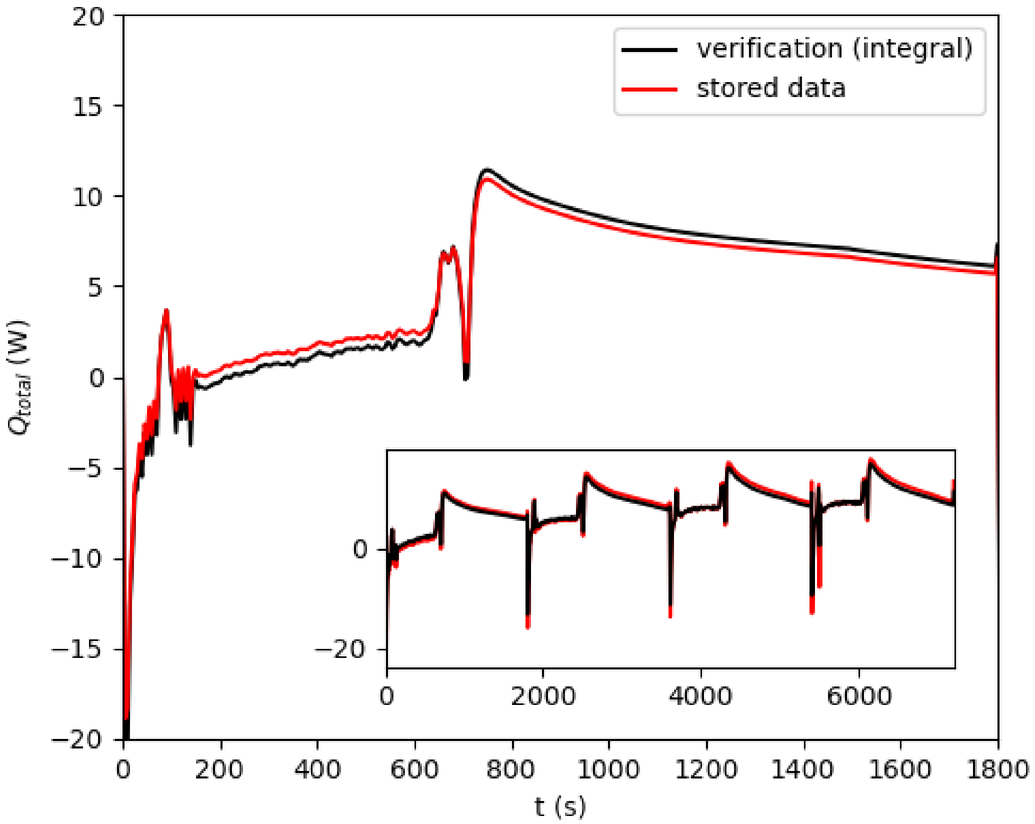


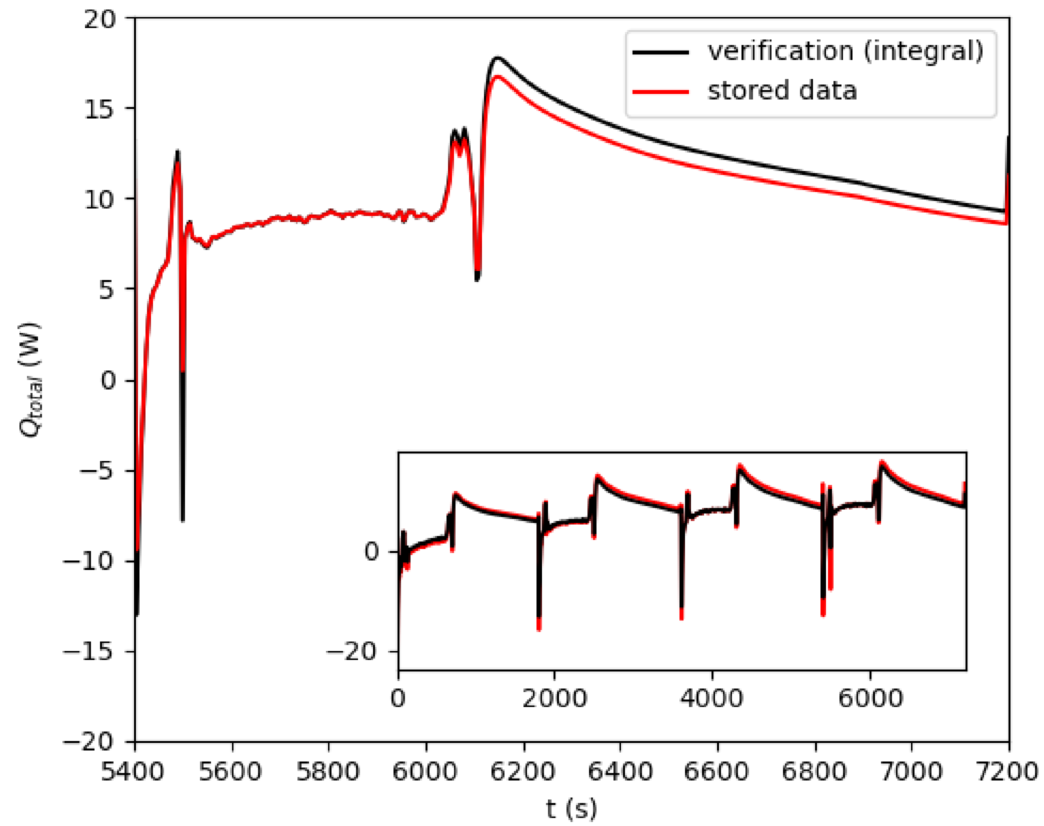
Correction & Test





Before correction
: max. Δt_{heater}
is 5 s





After correction
: max. Δt_{heater}
is 5 s

Residual vs. Line Integral

→ Yes, it's FEM.

$$\rho C_v \frac{\partial T}{\partial t} - k\nabla^2 T = q, \text{ where } T(x,y;t) \cong \sum T_i(t) w_i(x,y)$$

$$\int_t^{t+\Delta t} dt \left[\int_\Omega \overline{\rho C_v} w_i w_j dS\right] \cdot \frac{d\vec{T}}{dt} + \int_t^{t+\Delta t} dt \left[\int_\Omega \bar{k}\, \nabla w_i \cdot \nabla w_j \, dS\right] \cdot \vec{T} - \int_t^{t+\Delta t} dt \left[\oint_{\partial\Omega} w_i \, \bar{k} \cdot \frac{\partial w_j}{\partial n} dl\right] \cdot \vec{T} \cong \int_t^{t+\Delta t} \vec{Q} dt$$

$$\begin{bmatrix} \; & \; \\ \tilde{\mathbf{K}}_{bf} & \tilde{\mathbf{K}}_{bb} \end{bmatrix}$$

$$\frac{1}{\Delta t}\begin{bmatrix} \mathbf{M}_{ff} & \mathbf{M}_{fb} \\ \mathbf{M}_{bf} & \mathbf{M}_{bb} \end{bmatrix} \cdot \begin{bmatrix} \Delta\vec{T}_f \\ \Delta\vec{T}_b \end{bmatrix} + \begin{bmatrix} \mathbf{K}_{ff} & \mathbf{K}_{fb} \\ \mathbf{K}_{bf} & \mathbf{K}_{bb} \end{bmatrix} \cdot \begin{bmatrix} \theta\Delta\vec{T}_f + \vec{T}_f^n \\ \theta\Delta\vec{T}_b + \vec{T}_b^n \end{bmatrix} - \begin{bmatrix} 0 \\ \vec{Q}_b^{res} \end{bmatrix} \cong \begin{bmatrix} \vec{Q}_f \\ \vec{Q}_b \end{bmatrix}$$

$$\left[\frac{\mathbf{M}_{ff}}{\Delta t} + \theta \mathbf{K}_{ff}\right] \cdot \Delta\vec{T}_f = \vec{Q}_f - \left[\frac{\mathbf{M}_{fb}}{\Delta t} + \theta \mathbf{K}_{fb}\right] \cdot \Delta\vec{T}_b - \left[\mathbf{K}_{ff} \cdot \vec{T}_f^n + \mathbf{K}_{fb} \cdot \vec{T}_b^n\right]$$

$$\vec{Q}_b^{res} = \vec{Q}_b - \frac{1}{\Delta t}\begin{bmatrix} \; & \; \\ \mathbf{M}_{bf} & \mathbf{M}_{bb} \end{bmatrix} \cdot \begin{bmatrix} \Delta\vec{T}_f \\ \Delta\vec{T}_b \end{bmatrix} + \begin{bmatrix} \; & \; \\ \mathbf{K}_{bf} & \mathbf{K}_{bb} \end{bmatrix} \cdot \begin{bmatrix} \theta\Delta\vec{T}_f + \vec{T}_f^n \\ \theta\Delta\vec{T}_b + \vec{T}_b^n \end{bmatrix}$$

→ Residual means energetic balance which is rather consequential in average up to the approximate we used.

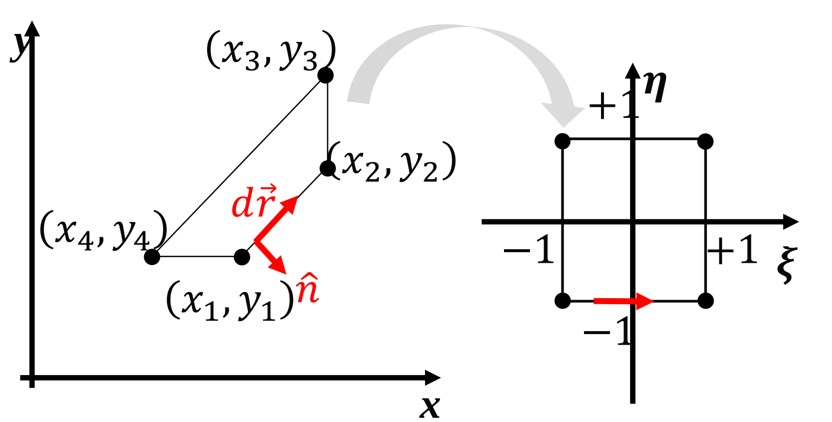
$$-\oint_{\partial\Omega} k(T)\frac{\partial T}{\partial n} dl = \sum_{i=1}^{N} \int_{-1}^{1} k(\xi) \begin{bmatrix} -\frac{\partial y}{\partial \xi} & \frac{\partial y}{\partial \xi} \end{bmatrix} \begin{bmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial y}{\partial \xi} \\ \frac{\partial x}{\partial \eta} & \frac{\partial y}{\partial \eta} \end{bmatrix}^{-1} \begin{bmatrix} \frac{\partial T}{\partial \xi} \\ \frac{\partial T}{\partial \eta} \end{bmatrix} d\xi$$

→ This integral draws heat flux of the present temperature profile in approximation.

at $\eta = -1$,

where $x = \sum_{k=1}^4 x_k W_k(\xi,\eta)$, $y = \sum_{k=1}^4 y_k W_k(\xi,\eta)$, $T = \sum_{k=1}^4 T_k W_k(\xi,\eta)$ and

$$\begin{cases} W_1(\xi,\eta) = \frac{1}{4}(1-\xi)(1-\eta) \\ W_2(\xi,\eta) = \frac{1}{4}(1+\xi)(1-\eta) \\ W_3(\xi,\eta) = \frac{1}{4}(1+\xi)(1+\eta) \\ W_4(\xi,\eta) = \frac{1}{4}(1-\xi)(1+\eta) \end{cases}$$



Verification?

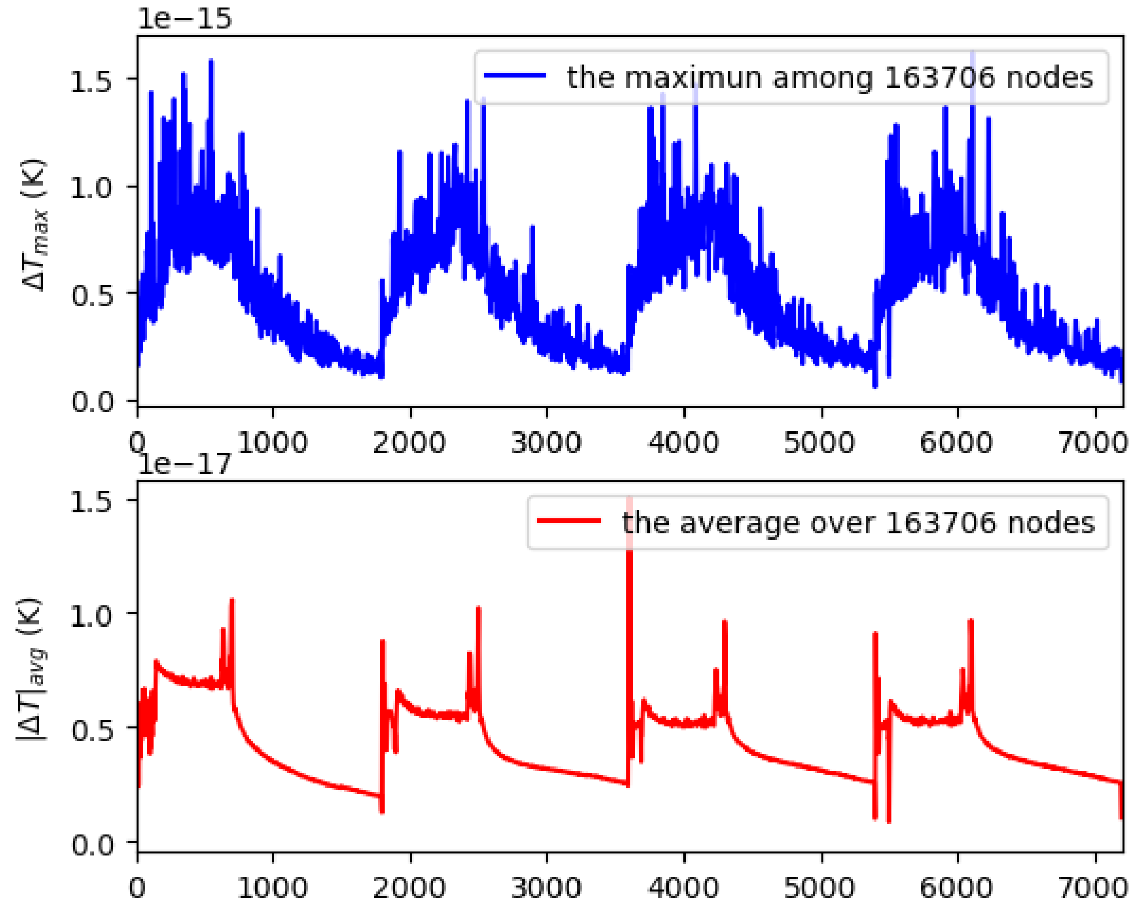
- **We observe systematic deviation which may matter; I hope not!**

  → Let's solve the full matrix again using the new constraint $\vec{Q}_{\mathrm{b}}^{\mathrm{res}}$ (a.k.a. Neumann), and override all the solution including the boundary.

$$\frac{1}{\Delta t}\begin{bmatrix} \mathbf{M}_{\mathrm{ff}} & \mathbf{M}_{\mathrm{fb}} \\ \mathbf{M}_{\mathrm{bf}} & \mathbf{M}_{\mathrm{bb}} \end{bmatrix} \cdot \begin{bmatrix} \Delta\vec{T}_{\mathrm{f}}' \\ \Delta\vec{T}_{\mathrm{b}}' \end{bmatrix} + \begin{bmatrix} \mathbf{K}_{\mathrm{ff}} & \mathbf{K}_{\mathrm{fb}} \\ \mathbf{K}_{\mathrm{bf}} & \mathbf{K}_{\mathrm{bb}} \end{bmatrix} \cdot \begin{bmatrix} \theta\Delta\vec{T}_{\mathrm{f}}' + \vec{T}_{\mathrm{f}}^{n} \\ \theta\Delta\vec{T}_{\mathrm{b}}' + \vec{T}_{\mathrm{b}}^{n} \end{bmatrix} \cong \begin{bmatrix} \vec{Q}_{\mathrm{f}} \\ \vec{Q}_{\mathrm{b}} + \vec{Q}_{\mathrm{b}}^{\mathrm{res}} \end{bmatrix}$$

Then, $\begin{cases} \Delta\vec{T}_{\mathrm{b}} = \Delta\vec{T}_{\mathrm{b}}' \\ \Delta\vec{T}_{\mathrm{f}} = \Delta\vec{T}_{\mathrm{f}}' \end{cases}$??

→ Neither actual discrepancy nor evidence of error propagation!



Lessons Learned

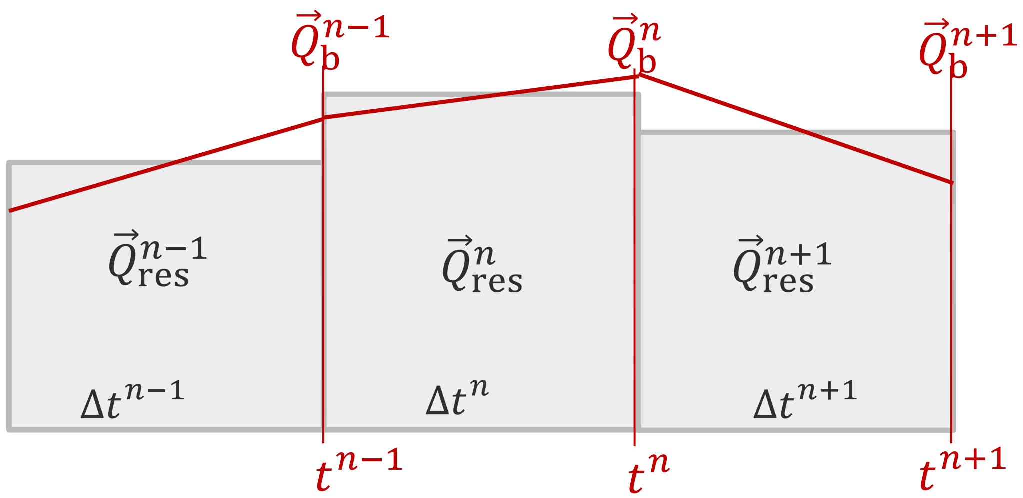
- The solution scheme is good enough for a complete interfacial balance, for which the residuals just close the discretized form i.e. the equations in approximation.
  → So, the systematic deviation is better to be understood as a limit which may be subject to the (geometric) fineness of modelling.

- Basically, it is average over the time step (i.e. the residual runs half-step behind), when the solver gives the present temperature.
  → It sounds serious, because it is a key to the better stability to estimate the interfacial values even "one step ahead".

✓ *In short, "Residual" is a legitimate idea, but it is necessary to get a measure of upcoming value..*

An idea? (not working)

- How about evaluating the present value of heat flux from the residual (i.e. an average)?



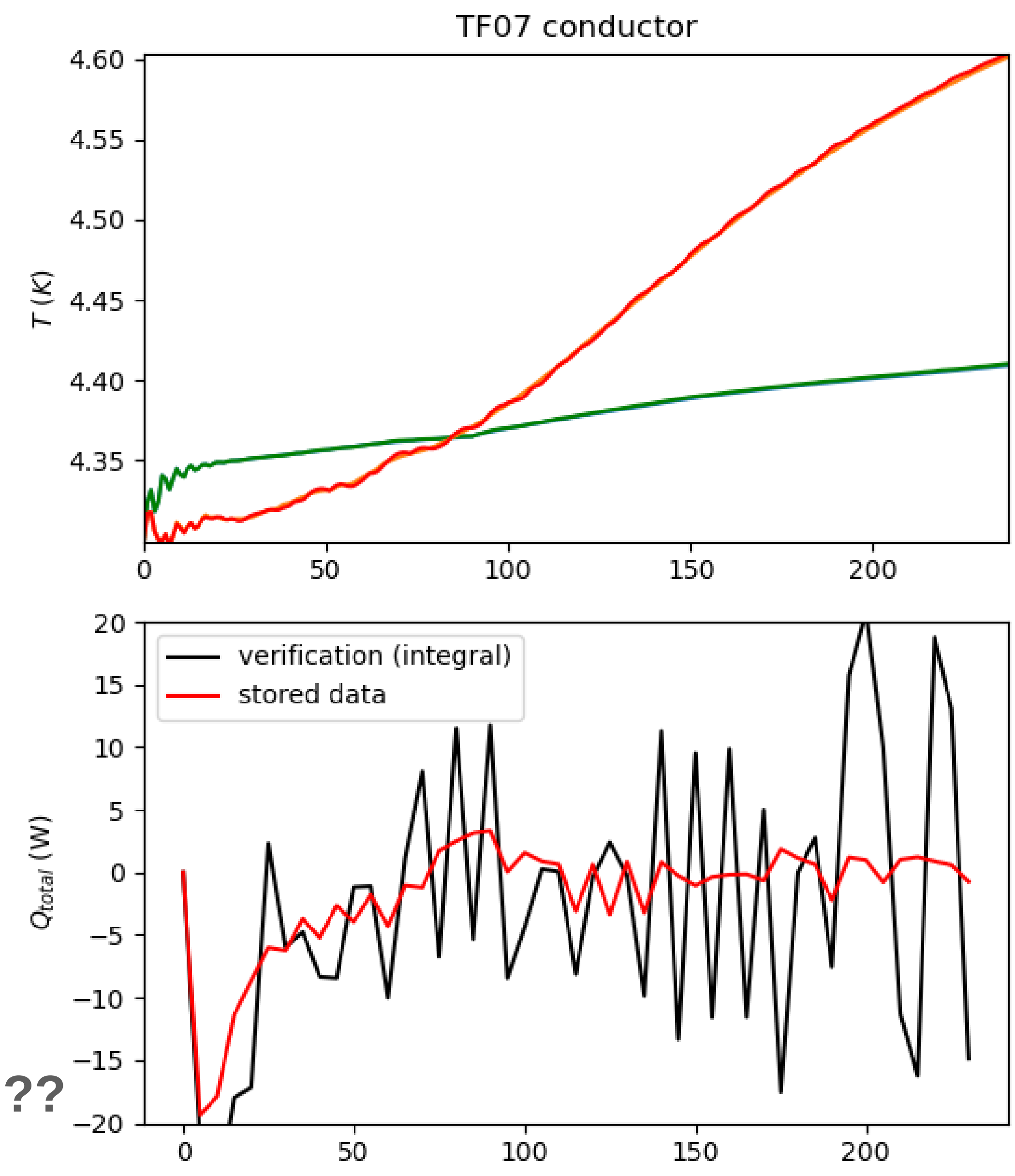
$$\vec{Q}_{\mathrm{b}}^{n} = 2 \times \vec{Q}_{res}^{n} - \vec{Q}_{\mathrm{b}}^{n-1}$$

Well,
It looked vulnerable.

→ Unstable!
Indeed..

$$\begin{aligned}
\vec{Q}_{\mathrm{b}}^{n} &= 2\vec{Q}_{\mathrm{res}}^{n} - 2\vec{Q}_{\mathrm{res}}^{n-1} + 2\vec{Q}_{\mathrm{res}}^{n-2} - \cdots \pm 2\vec{Q}_{\mathrm{res}}^{1} \mp \vec{Q}_{\mathrm{b}}^{0} \\
\vec{Q}_{\mathrm{b}}^{n-1} &= + 2\vec{Q}_{\mathrm{res}}^{n-1} - 2\vec{Q}_{\mathrm{res}}^{n-2} + \cdots \mp 2\vec{Q}_{\mathrm{res}}^{1} \pm \vec{Q}_{\mathrm{b}}^{0} \\
&\vdots \\
\vec{Q}_{\mathrm{b}}^{2} &= 2\vec{Q}_{\mathrm{res}}^{2} - 2\vec{Q}_{\mathrm{res}}^{1} + \vec{Q}_{\mathrm{b}}^{0} \\
\vec{Q}_{\mathrm{b}}^{1} &= + 2\vec{Q}_{\mathrm{res}}^{1} - \vec{Q}_{\mathrm{b}}^{0}
\end{aligned}$$

Isn't the memory too long??



Any clue then?? (not a solution yet)

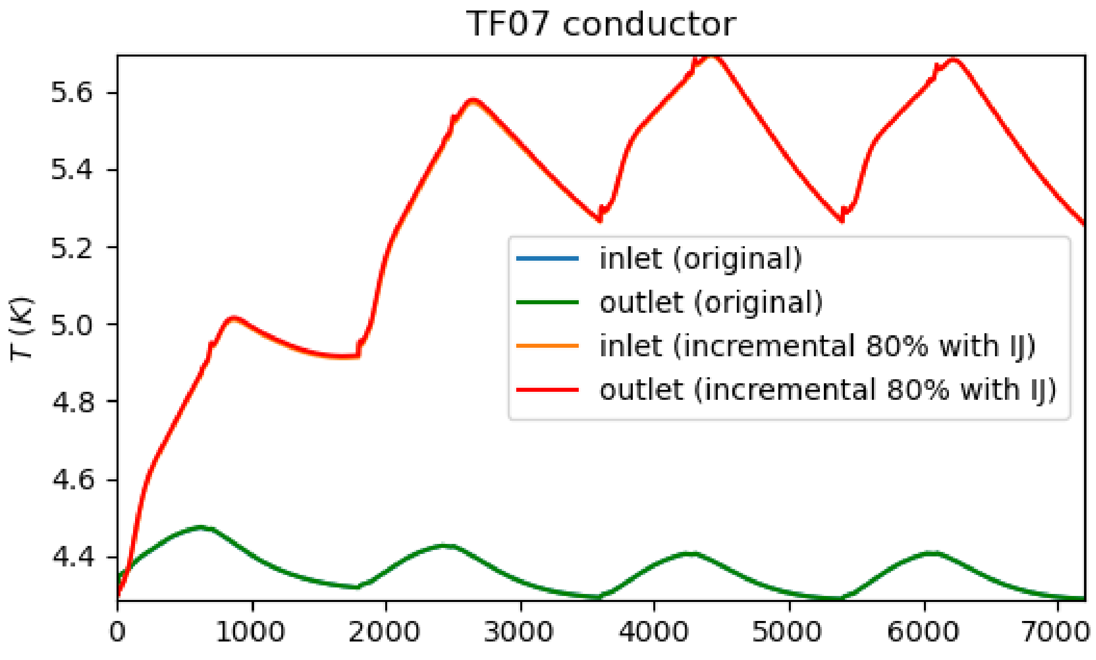
→ Let the past memory diminished by introducing retardation (20%).

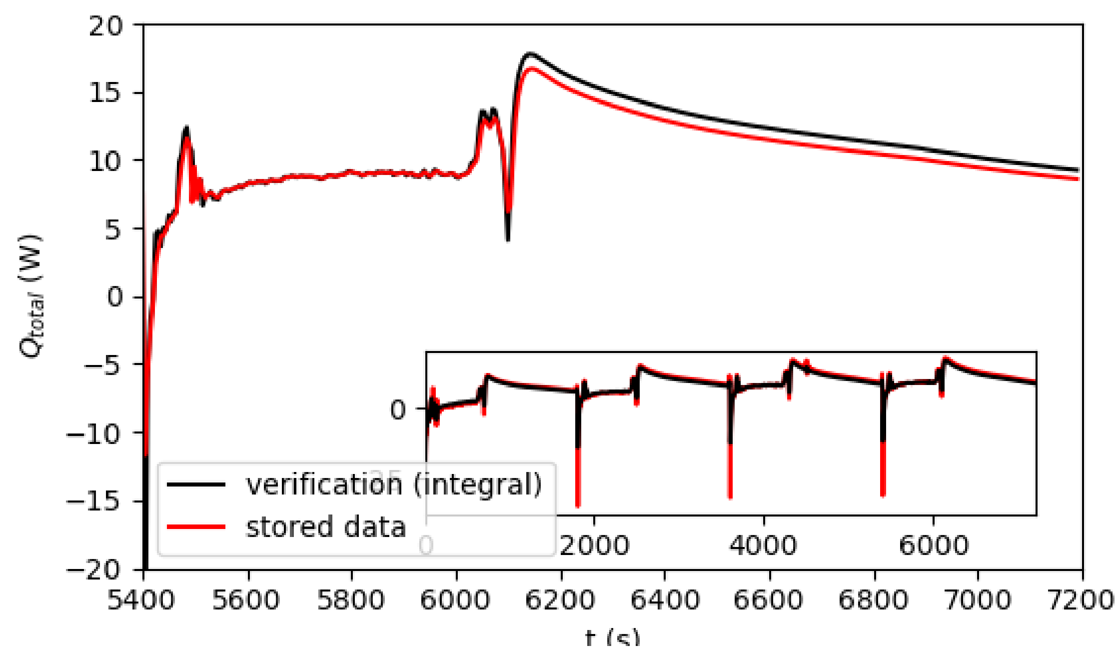
$$\vec{Q}_{\mathrm{b}}^{n} = 1.8 \times \vec{Q}_{\mathrm{res}}^{n} - 0.8 \times \vec{Q}_{\mathrm{b}}^{n-1}$$

→ The upcoming heat flux is estimated based on this approximation (20% retardation) taking into account the additional information i.e. the interface Jacobian.

$$\frac{\Delta\vec{Q}_{\mathrm{b}}^{n}}{\Delta\vec{T}_{\mathrm{b}}} = 1.8 \times \frac{\Delta\vec{Q}_{\mathrm{res}}^{n}}{\Delta\vec{T}_{\mathrm{b}}}, \quad \text{where} \begin{bmatrix} 0 \\ \frac{\Delta\vec{Q}_{\mathrm{res}}^{n}}{\Delta\vec{T}_{\mathrm{b}}} \end{bmatrix} \cong \frac{1}{\Delta t} \begin{bmatrix} \mathbf{M}_{\mathrm{ff}} & \mathbf{M}_{\mathrm{fb}} \\ \mathbf{M}_{\mathrm{bf}} & \mathbf{M}_{\mathrm{bb}} \end{bmatrix} \cdot \begin{bmatrix} \vec{\varepsilon} \\ -1 \end{bmatrix} + \begin{bmatrix} \mathbf{K}_{\mathrm{ff}} & \mathbf{K}_{\mathrm{fb}} \\ \mathbf{K}_{\mathrm{bf}} & \mathbf{K}_{\mathrm{bb}} \end{bmatrix} \cdot \begin{bmatrix} \theta\vec{\varepsilon} \\ -\theta \end{bmatrix}$$

→ Make the THEA and Flower models one step ahead: Heater will get the upcoming BC.





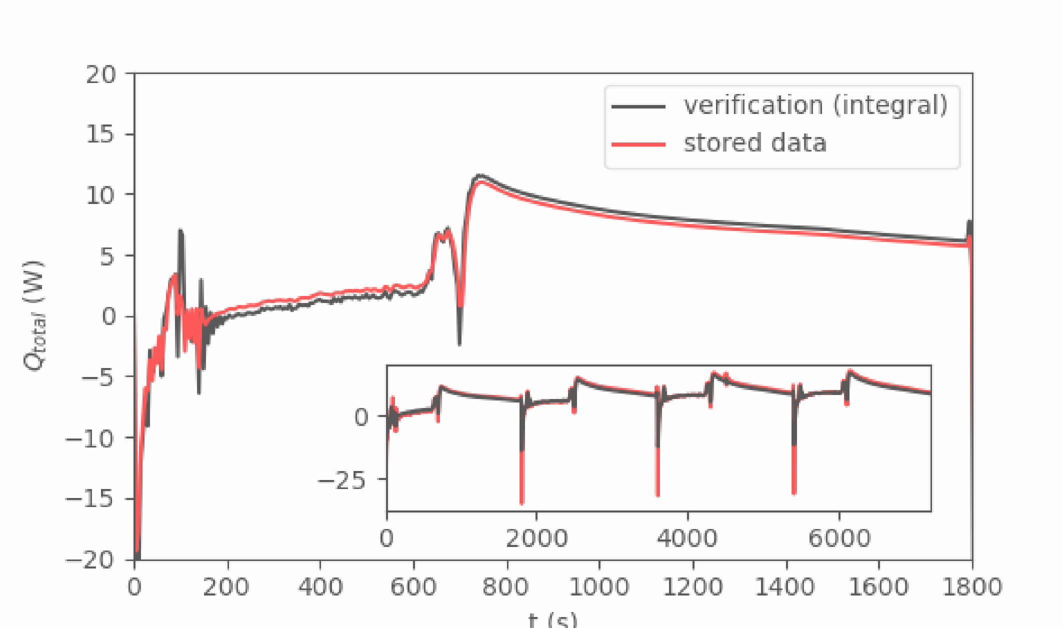
Conclusion

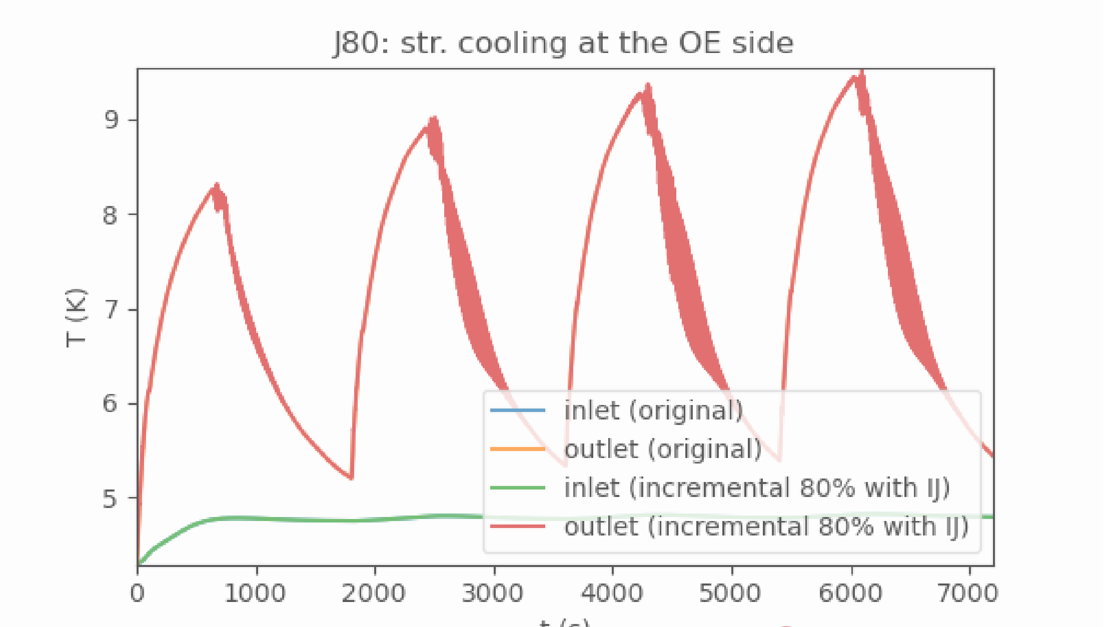
- Now, <u>the interfacial problem is clarified enough</u> for further development, i.e., an augmented edition of the SuperMagnet suite.

  → The biggest gain in practice is enhanced performance of the TF model, which enables an agile workflow with more accurate analyses.

  → Nonetheless, the interface Jacobian didn't show any great impact, because the TF model is already stable enough after correction for the linear solver.

  → It deserves to work out for any other <u>boundary scheme in time stepping</u>, taking into account the basic limitation of residual, i.e. evaluating "half-step behind", with the interface Jacobian.





So, we will see..

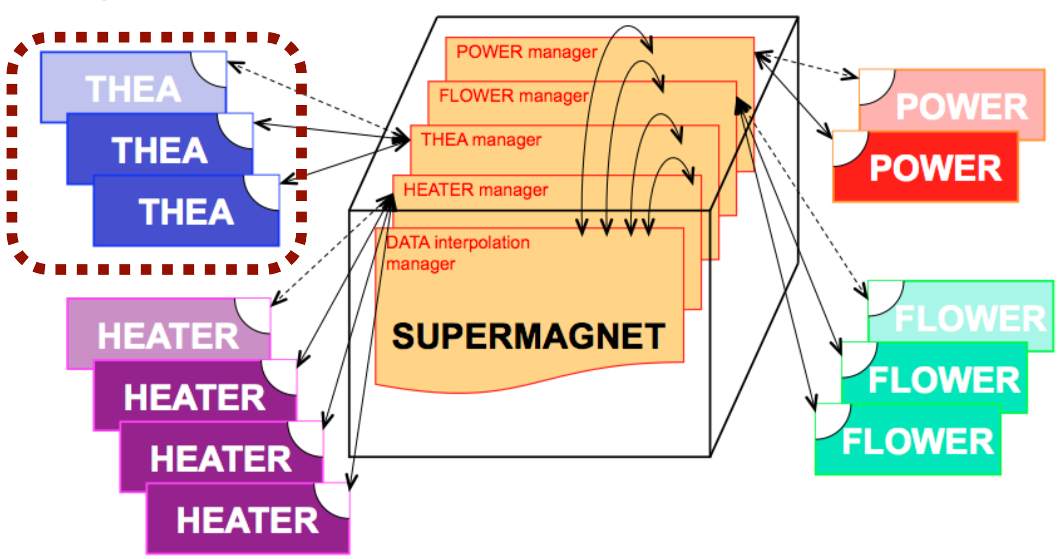
Discussion

Co-simulation (the basic idea)

Model integration* (i.e. co-simulation) is a common idea to implement such a TH-simulator in large scale.

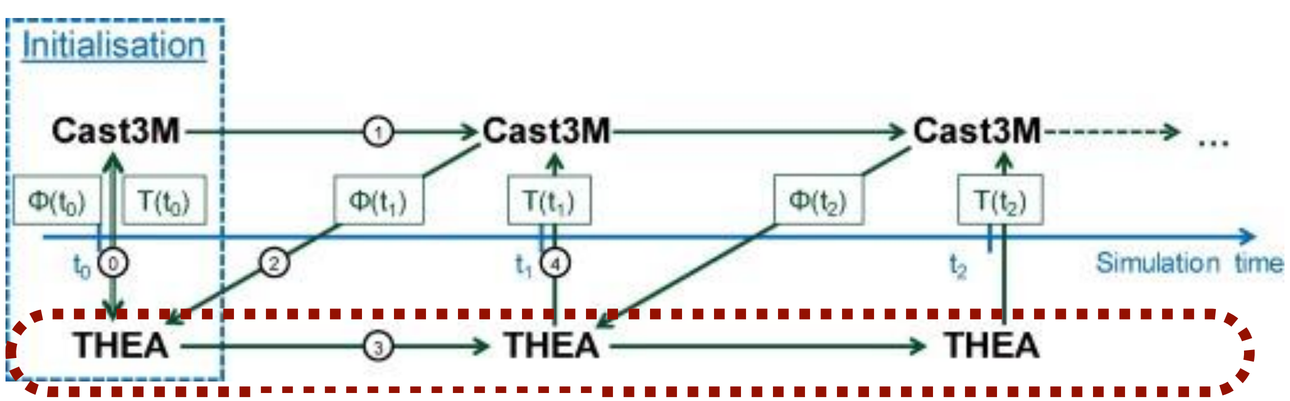
SuperMagnet : CryoSoft

THEA code



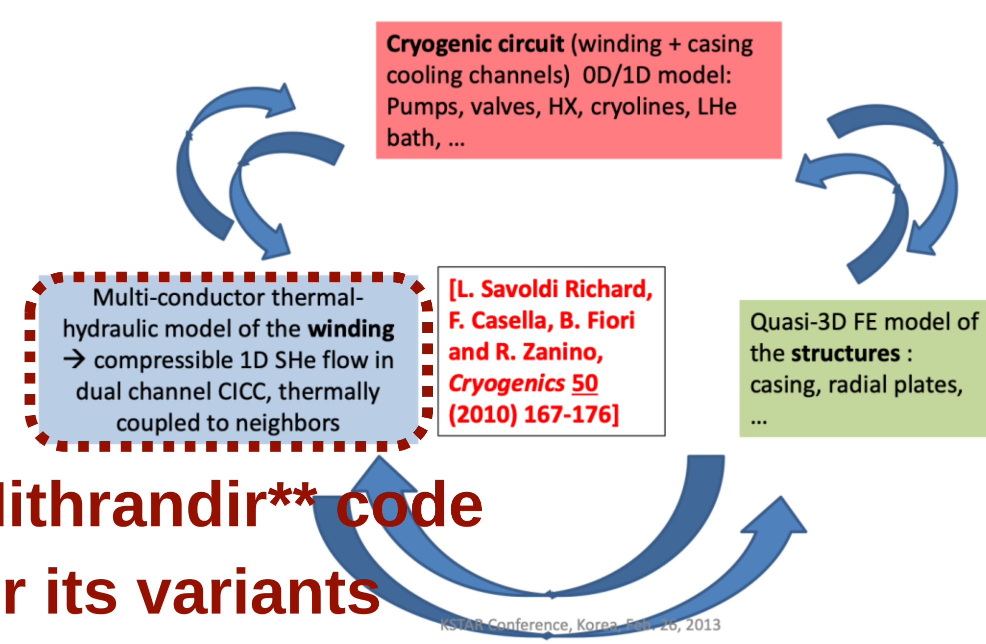
Indeed, the **conductor code** (THEA, Mitrandir, Gandalf etc) is the core part in such an approach.

TACTICS (*THEA*-*Cast*3M-*Sim*Cryogenics) model : CEA



THEA code

The 4C code (TISC platform): PoliTo



Mithrandir** code or its variants

* Vincenta and REIMS are monolithic models

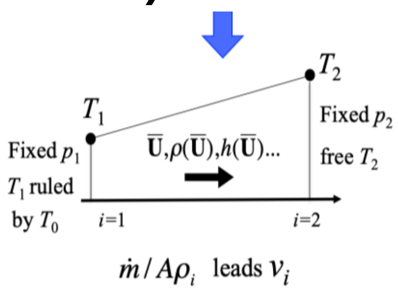
** A derivative of the Gandalf code

Developing an Augmented Edition

2015

✳ **New decomposed BC**

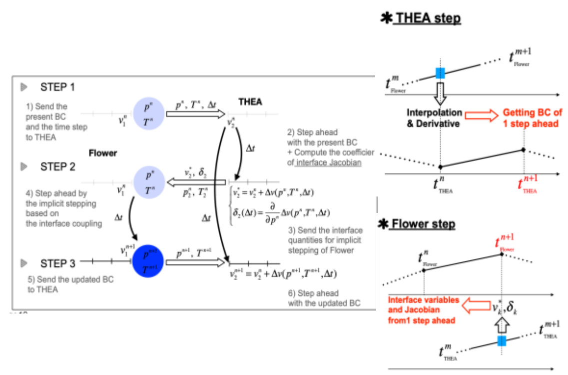
✳ **New steady state (quasi-1d) model**



A single element of FEM

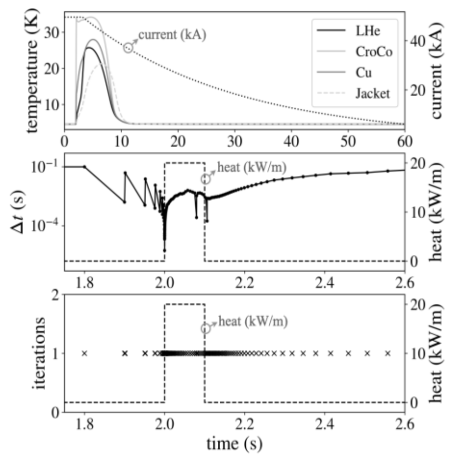
2017

✳ **Improved stability of the SuperMagnet model**



2019

✳ **Issue solved in adaptive time stepping**

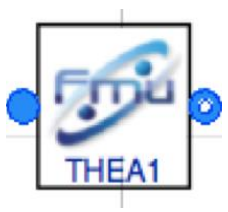


- **The intrinsic matters of the CICC code, in numerical point of view, particularly, in the co-simulation framework**

➡ They have been solved by many recent efforts, and the outcome is now being migrated to the workflow of ITER magnet analysis.

+

✳ **Component-wise Modulation**



✳ **Connection Scheme for Better Performance**

MPI or ZeroMQ?

✳ **Usability**

GUI or other utilities

- **They are subject to the coding style of the present codeworks for the SuperMagnet suite**

➡ The IterMagnet code just proved such a way of “refactoring” to modernize the legacy style codes.

➡ The object of the latest contract (for the new version 9.x) with CryoSoft has been made also in this context, namely, to remove the bottleneck of the master code by developing a versatile data format as called as the UDX (Universal Data eXchange) format.

On-going Activity

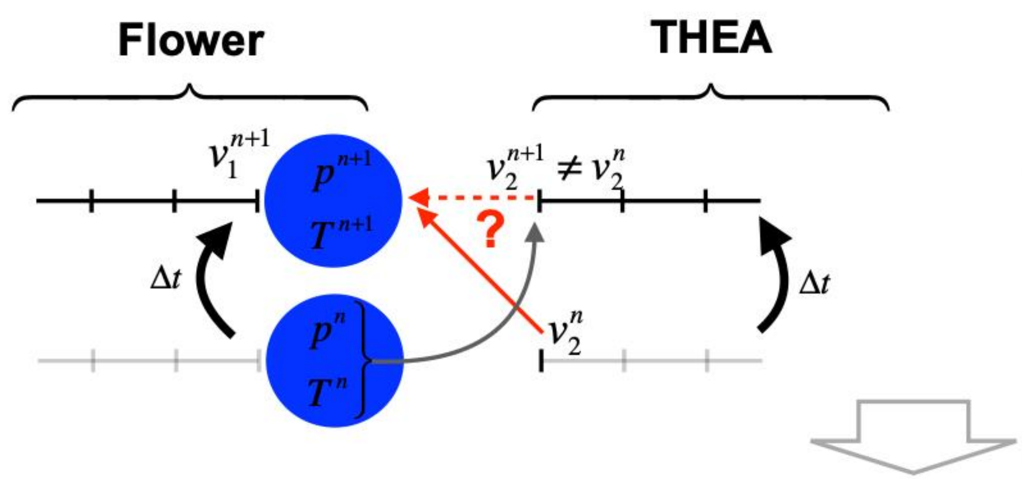
Activity	Subject	Design in Theory	Code Work	Test & Benchmark	Documents & Application
Solutions to the Group's Workflow	Numerical stability issue of the TF model				
	True windows version of the SM suite				
	Auto-generated Python class for post-processing				
Augmented Edition of the SM suite	Accuracy issue on the interfacial heat flux: Heater models				
	Natural BC around the nodal volumes (Flower)**				
	Interface Jacobian for the structural boundaries (Heater-THEA)*				
	Interface Jacobian for the nodal volumes (THEA-Flower)				
	More accurate adaptive time stepping scheme (THEA and Flower)				
	New steady-state components to fix massflow conflicts (Flower)				
Modeling for Operation	Modeling with interfaces to the cryo-plant: optimal operation				
Advanced Topics	Parallelization in shared memory architecture: OpenMP for Heater				
	Refactoring the UDX library (the SM suite v9.0) based on HDF				
Items for the Future	Contributing to R&D activities for the new SM suite v9.0				
	Physics-inform neural model for magnet operation analysis				

Subjects in urgent issues
Practicals topic for machine operation

* Heater-Flower too
** This can be extended to Riemann solution based scheme for hyperbolic-type PDEs (i.e. for the Euler equations) -> new THEA

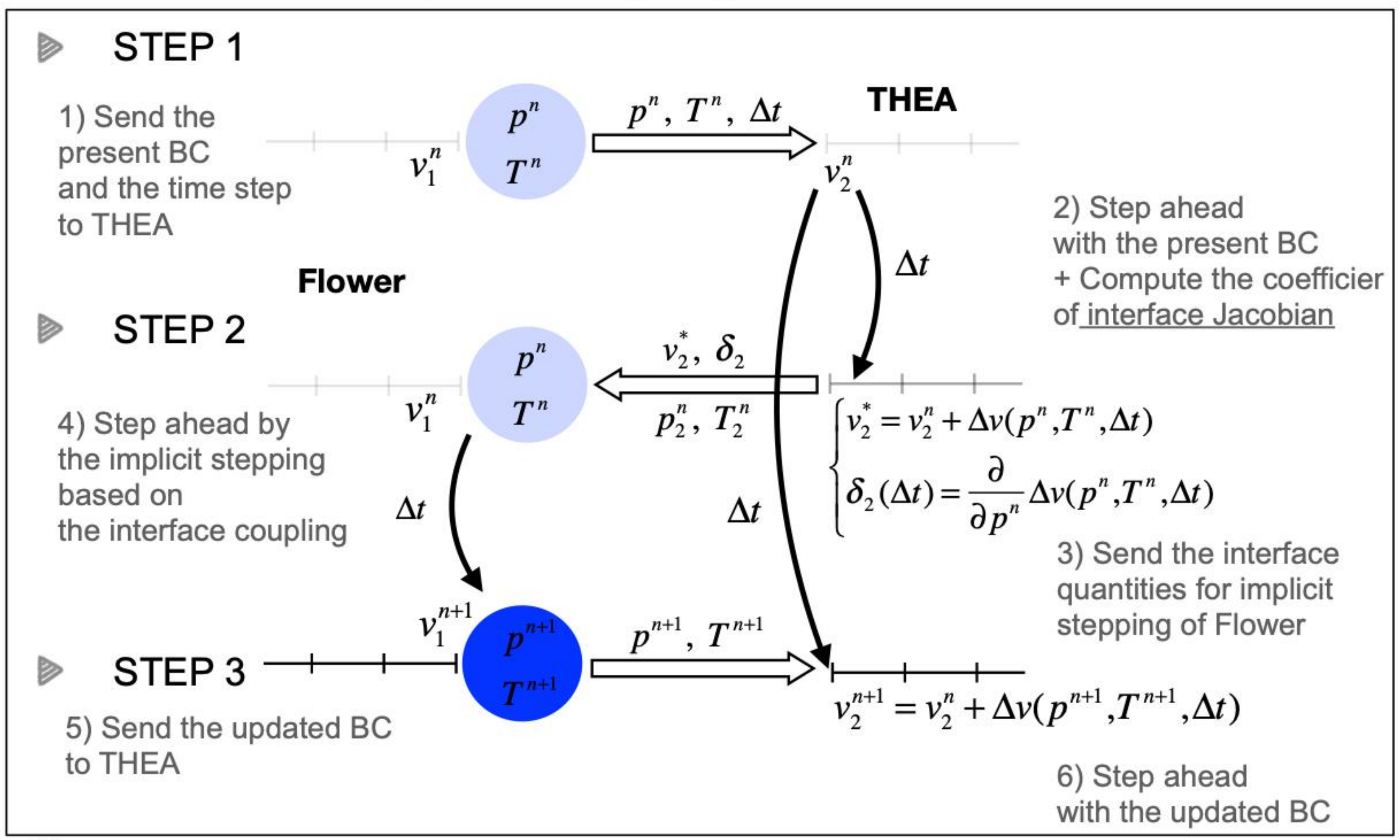
Note) Interface matters!

Issue #1 : loss of implicit coupling



✓ Interfacial problem is rather essential!

- **To recover the implicit coupling, …**



The idea is derived relying on the concept of interface Jacobian!

D. K. Oh, "[5LOrA6-08] Coupled Simulation Model of CICC Components Integrated into the Cooling Circuit" presented in ASC2019 Nov. 2 Seattle USA

Note) Introducing the interface Jacobian

Let's revise the THEA code..

$$\left\{ \frac{[\mathbf{M}]}{\Delta t} + \left([\mathbf{A}] + [\mathbf{G}] - [\mathbf{S}] \right) \right\} \cdot \mathbf{\Delta U} = \mathbf{Q} - \left([\mathbf{A}] + [\mathbf{G}] - [\mathbf{S}] \right) \cdot \mathbf{U}^n$$

$$\mathbf{Q} = \mathbf{Q}^n + [\mathbf{C}] \cdot \Delta \mathbf{T}_{\mathrm{bc}} \longleftarrow \quad [\mathbf{C}] = \left[\int_L w_i^{\mathrm{T}} \left(\frac{\Delta q_i}{\Delta T_j} \right)_{\text{per BC DoF}} w_j \, dx \right]$$

☞ Actually, $\left(\frac{\Delta q_i}{\Delta T_j} \right)$ is diagonal.

$$\left\{ \frac{[\mathbf{M}]}{\Delta t} + \left([\mathbf{A}] + [\mathbf{G}] - [\mathbf{S}] - [\mathbf{C}] \right) \right\} \cdot \mathbf{\Delta U} = \mathbf{Q}^n - \left([\mathbf{A}] + [\mathbf{G}] - [\mathbf{S}] \right) \cdot \mathbf{U}^n$$

That's it!

: The THEA code is now revised in consistent with our idea to include the IJ terms.