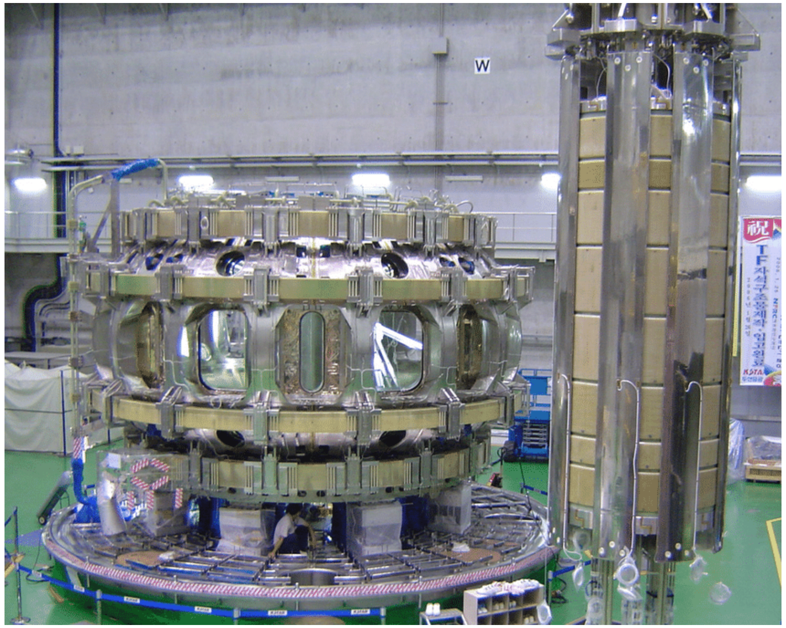
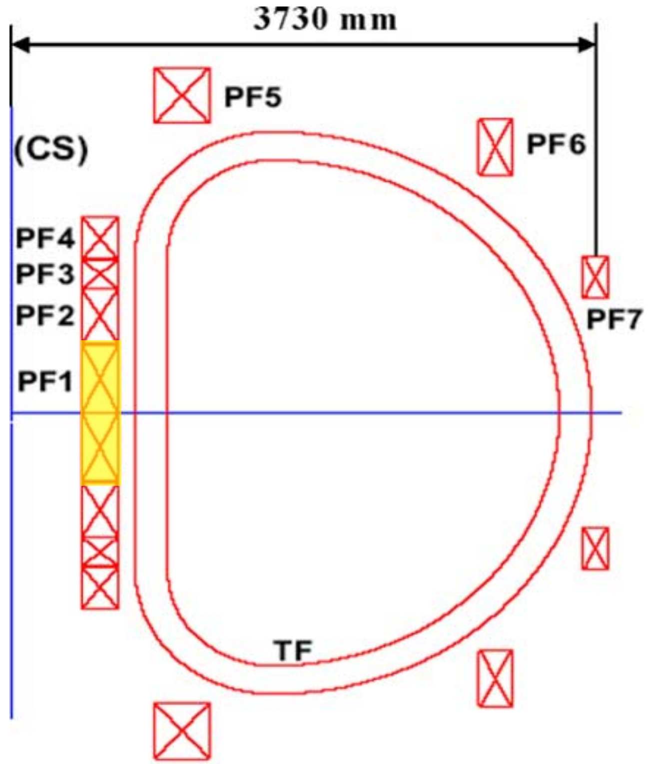
Numerical Investigation of Quench Event in the Innermost Pair of the KSTAR Central Solenoids





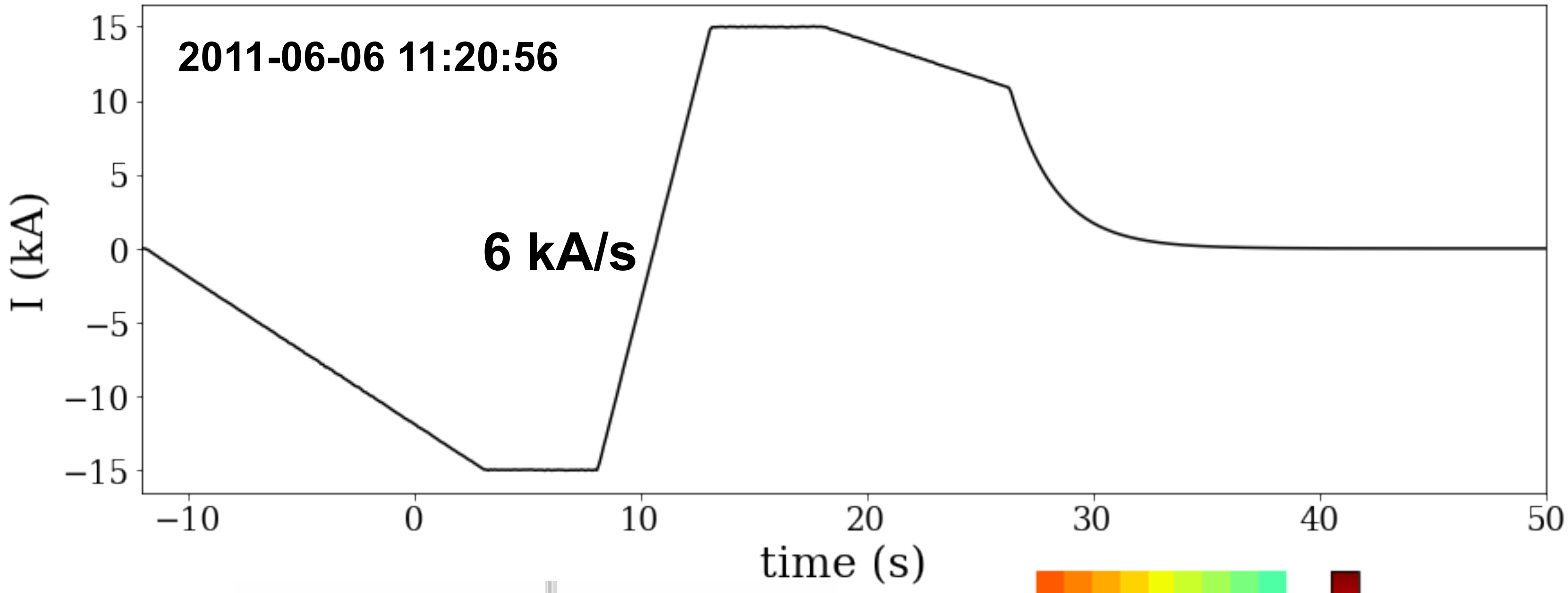
Dong Keun Oh, Sangjun Oh and Yong Chu

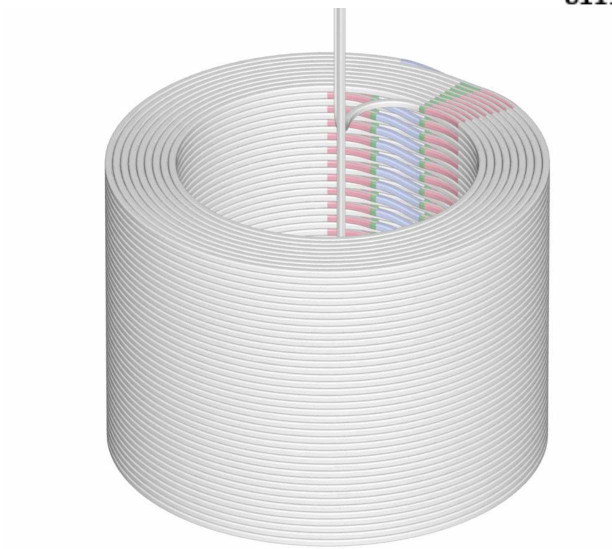
National Fusion Research Institute, Republic of Korea

National Fusion Research Institute

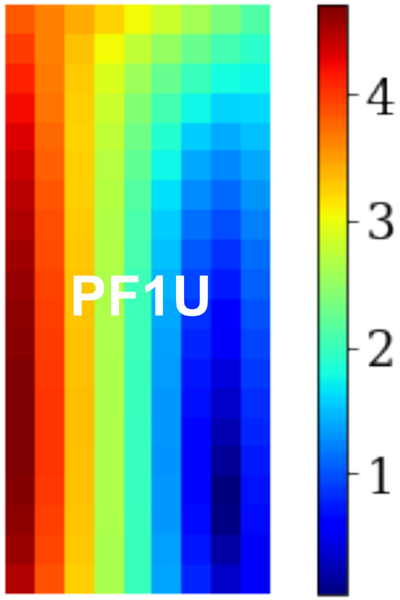
Shot 4856

✓ Magnet test during the 2011 KSTAR campaign :





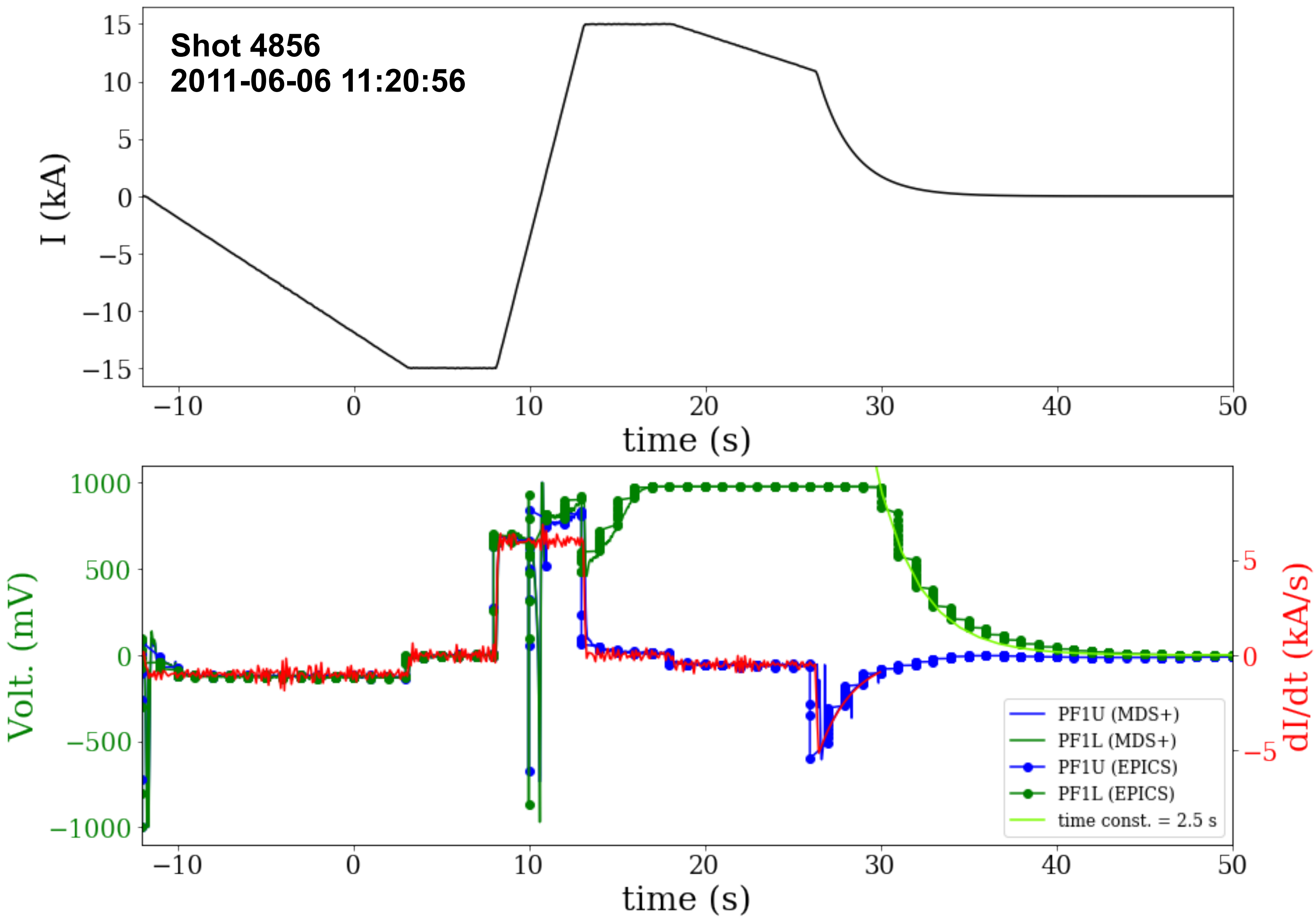
A single module of the innermost pair (PF1U)



I_{PF1} = 15 kA
B_{max} = 4.7 T
(T_{sc} ~12 K)
: at the flattop

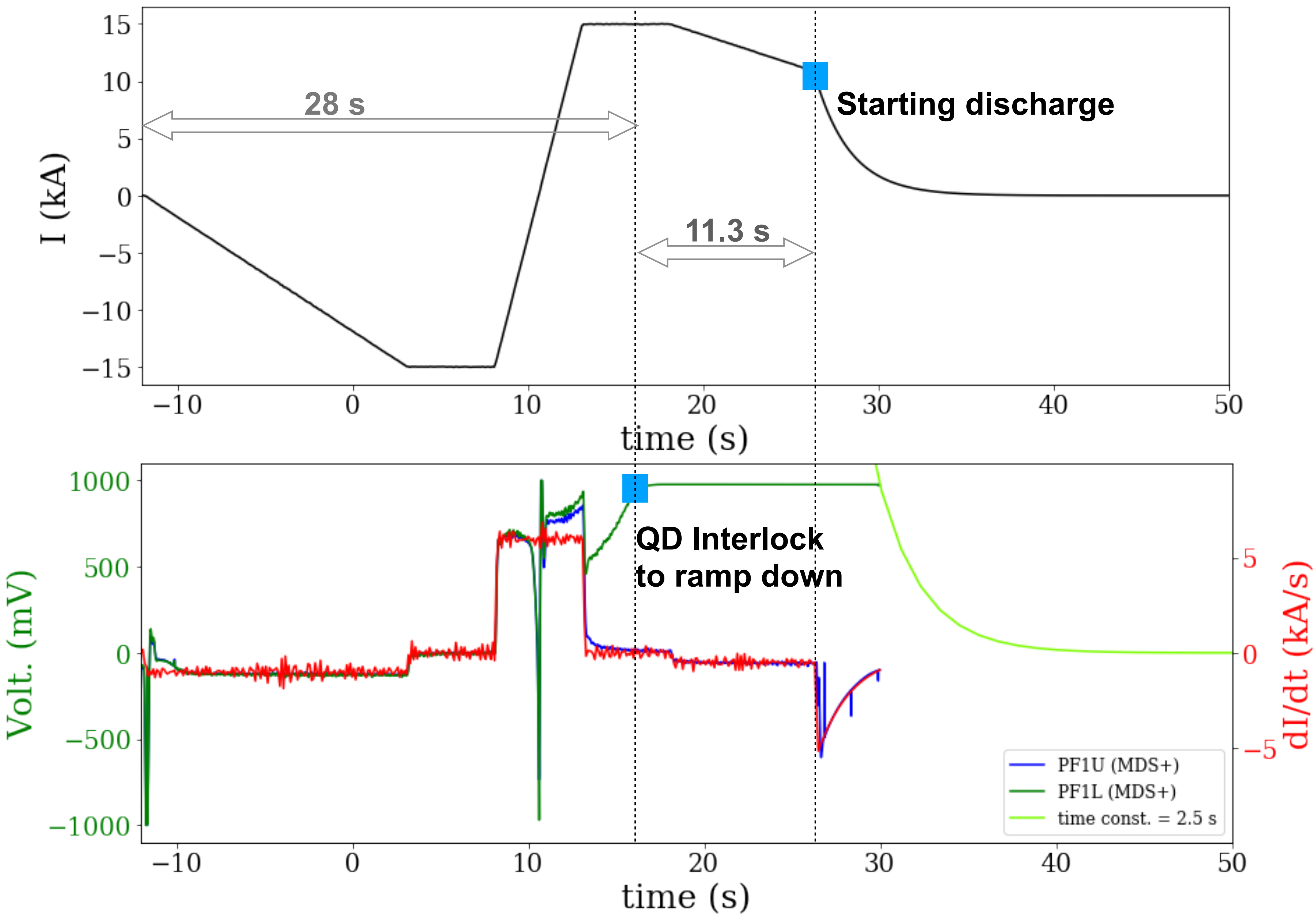
The Quench Event in 2011

✓ **As recorded in the archive, co-wound v-tap signals are..**



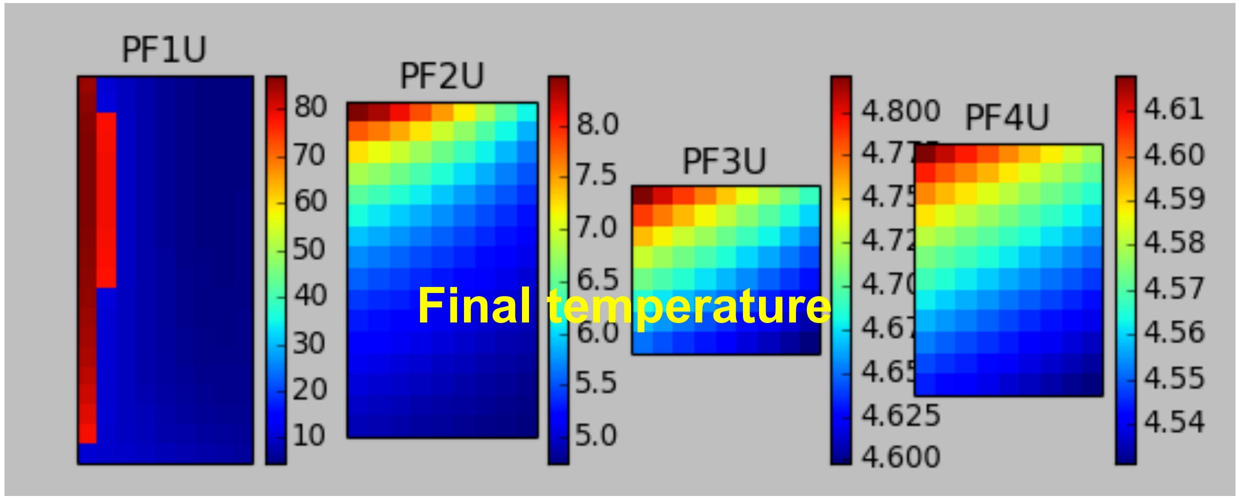
The Quench Event in 2011

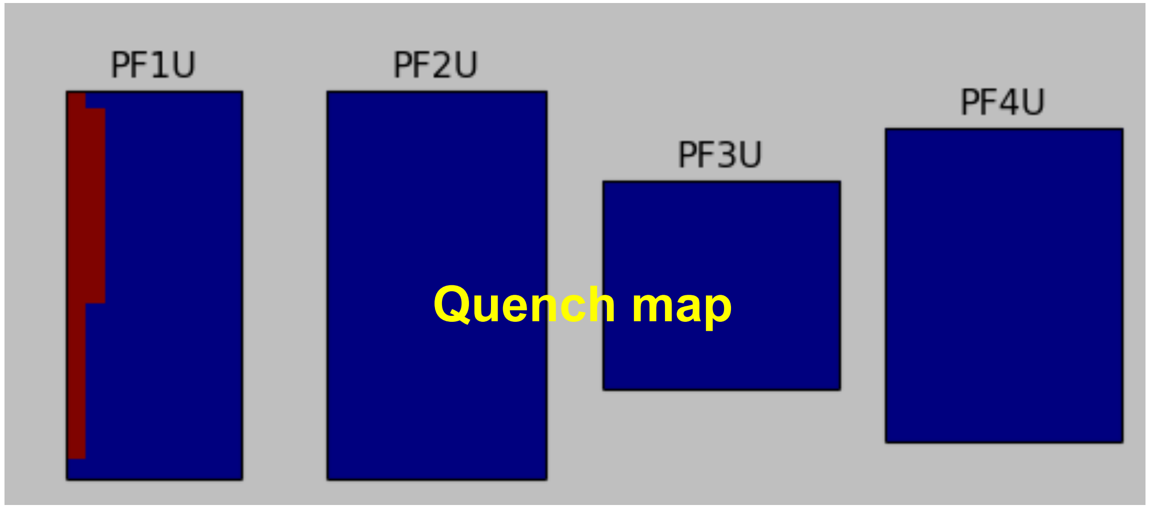
✓ **How was that?**



The Quench Event in 2011

Post-event analysis talks - No. Never. You should't!



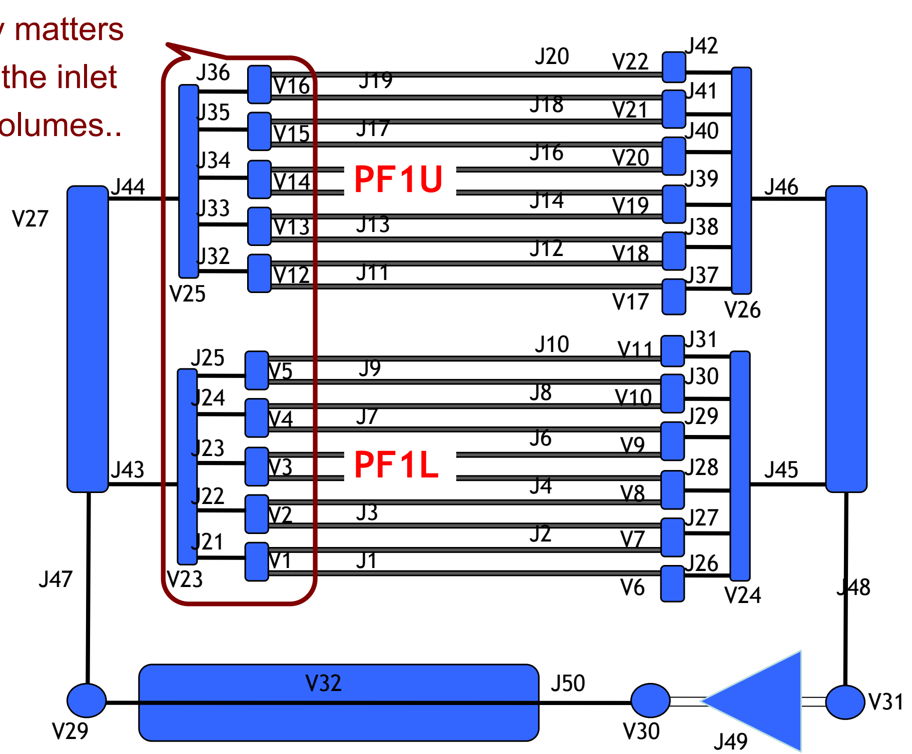


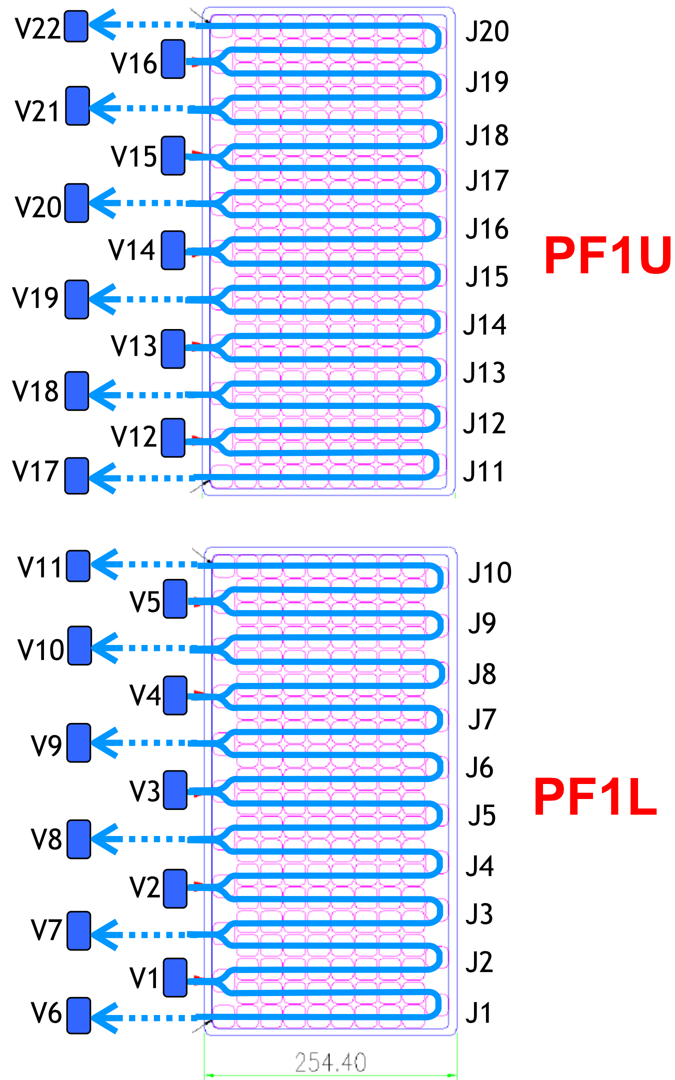
0-D modeling

: Coupling loss is specified according to the measurement as nτ = 200 ms.

: Any proper TH-modeling work is to be followed after such a ball-park analysis..

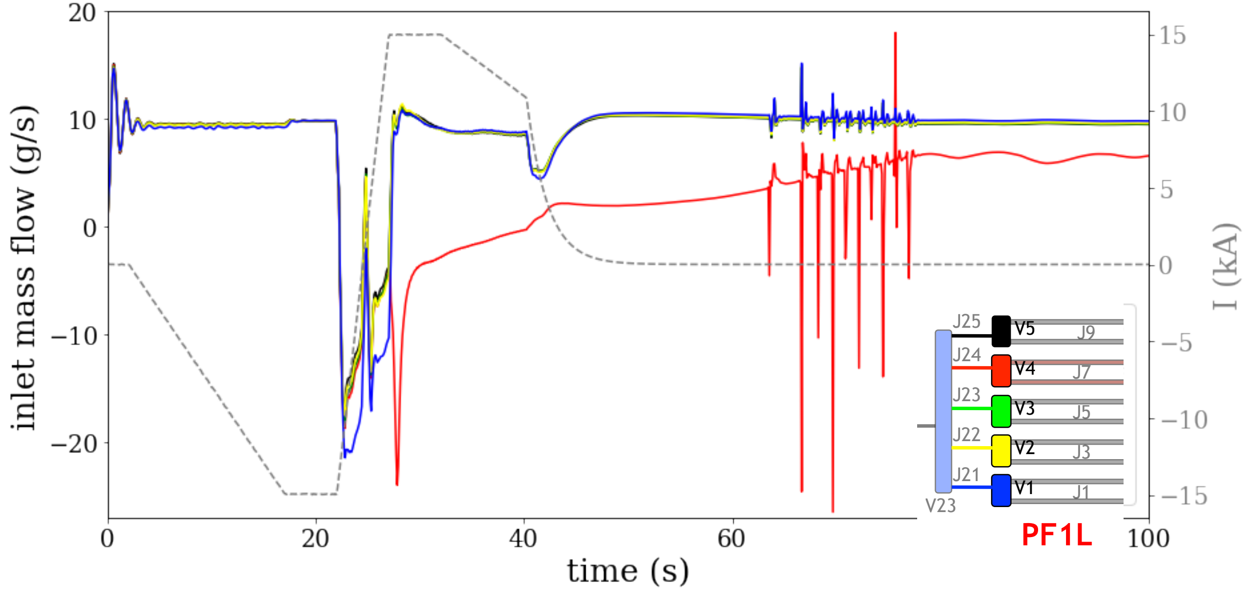
SuperMagnet model of the PF1UL pair





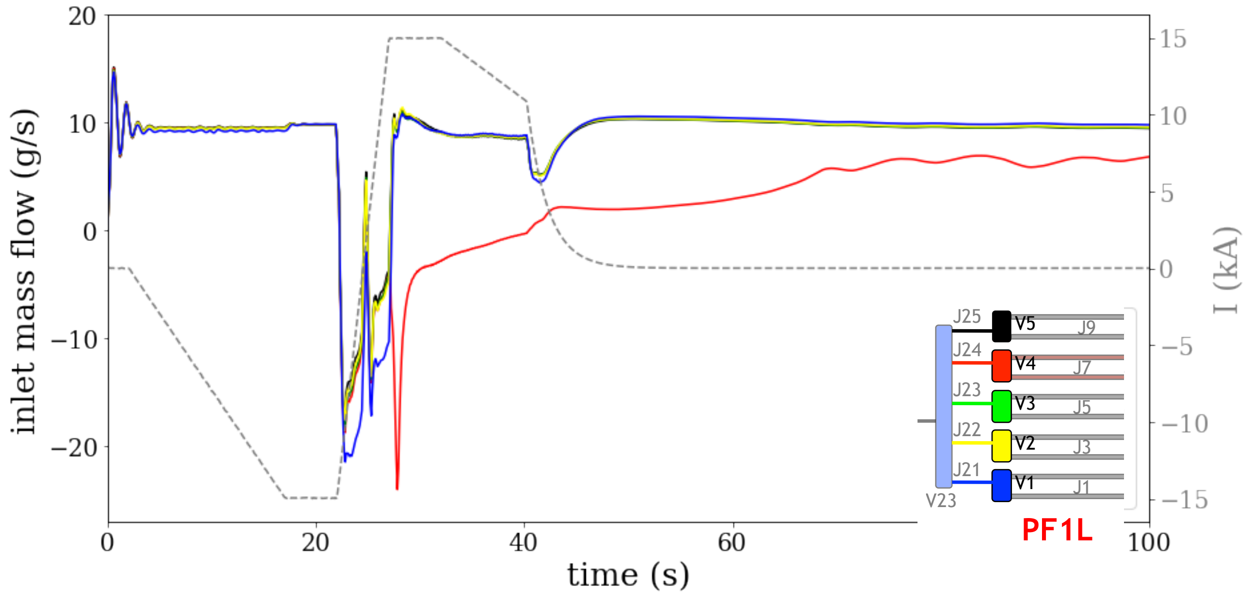
- A sub-network of the **PF magnet** loop
  : **PF1U + PF1L** with simplified circulation pump and HX
- 20 CICCs are included in the model
  : one THEA process per each hydraulic channel (cable annulus) and cable
  (20 THEA processes)
- Each boundary of 1-D conductor model was coupled to the volume nod in the hydraulic network model of helium circulation (one FLOWER model)
- **20 THEA** models + **1 FLOWER** model is managed by **SUPERMAGNET** code

Numerical Issue : Stability



- time step : **1 ms** (Flower) 10 μs ~ **0.5 ms** (THEA)

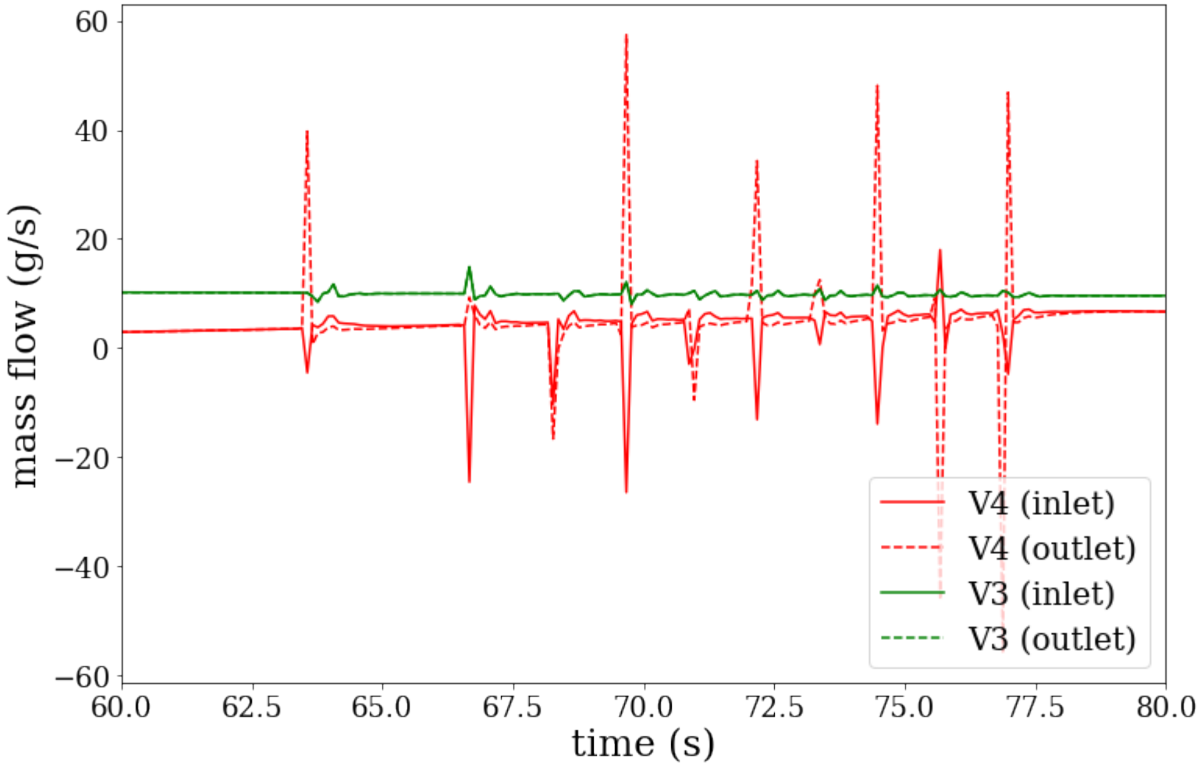
→ 19 hours of total CPU time
→ still unstable

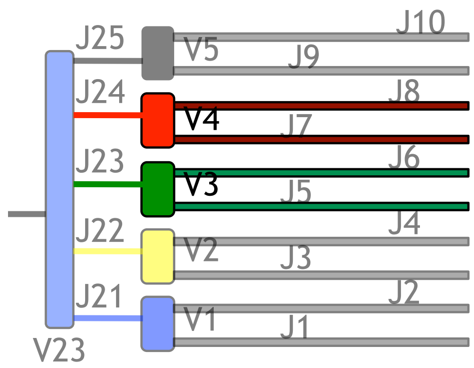


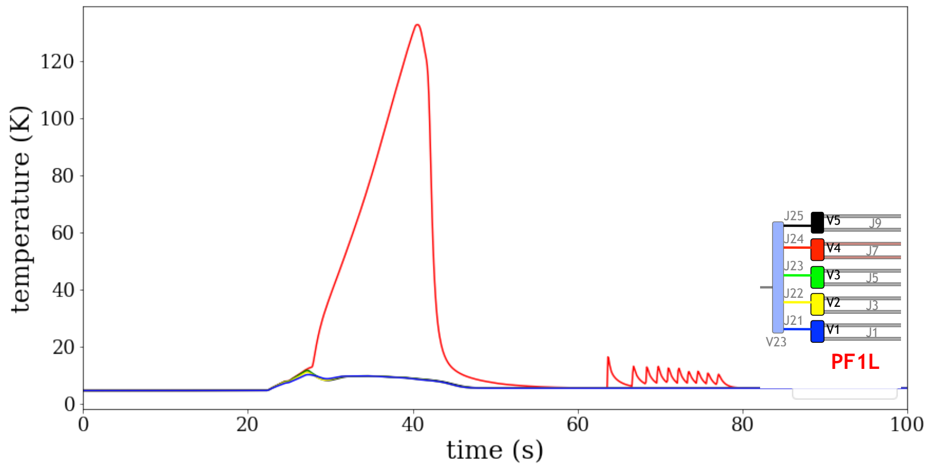
- time step : **0.5 ms** (Flower) 10 μs ~ **0.25 ms** (THEA)

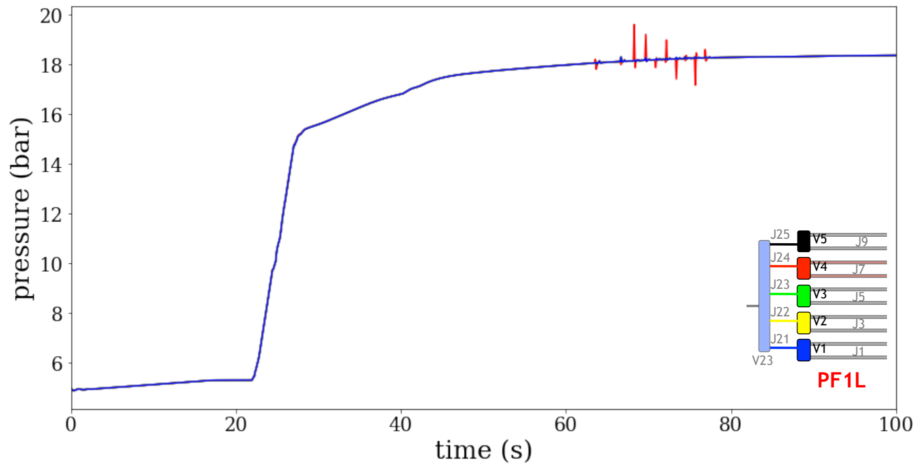
→ 36 hours!

So, what makes the conflict?

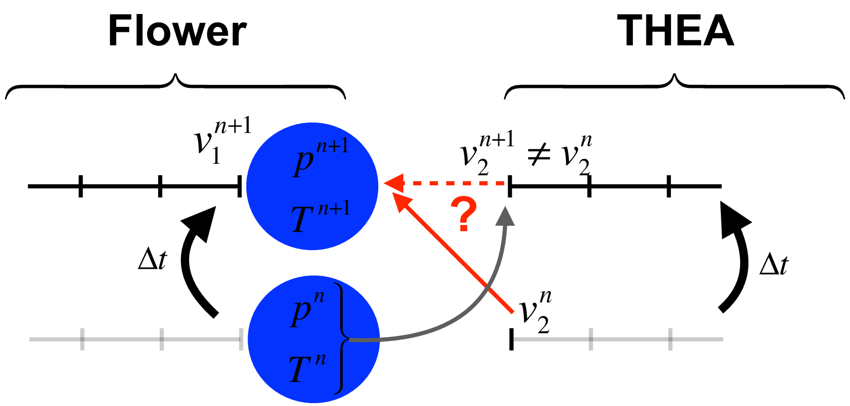






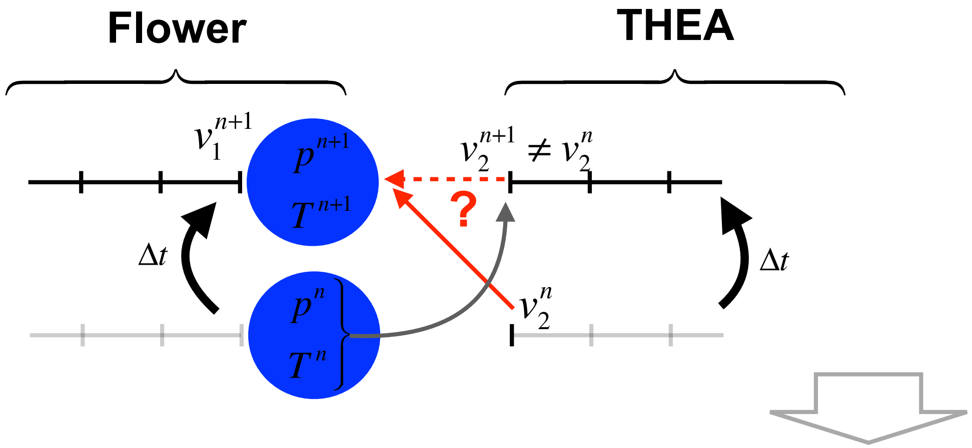


Issue #1 : loss of implicit coupling

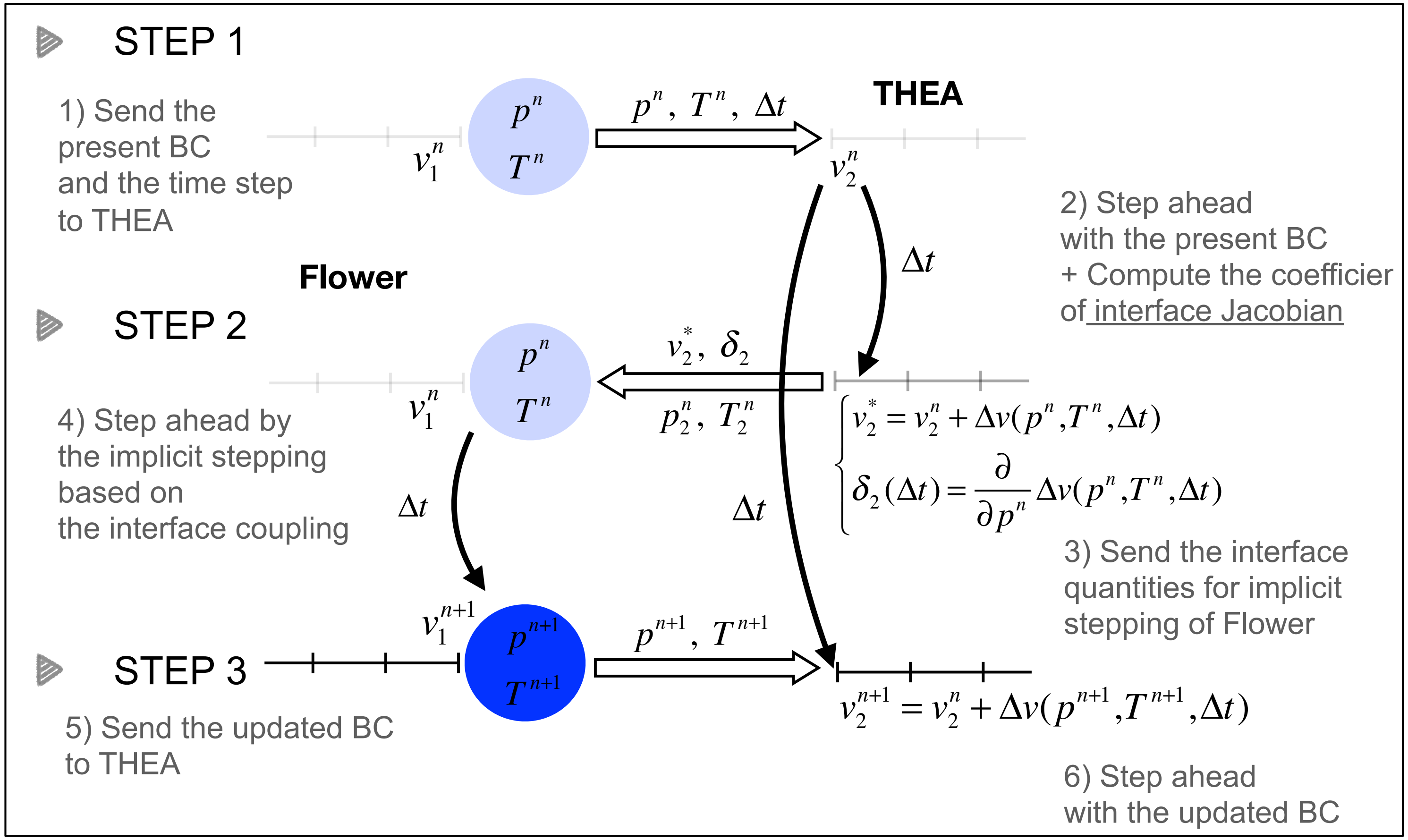


D. K. Oh,“[5LOrA6-08] Coupled Simulation Model of CICC Components Integrated into the Cooling Circuit” presented in ASC2019 Nov. 2 Seattle USA

Issue #1 : loss of implicit coupling

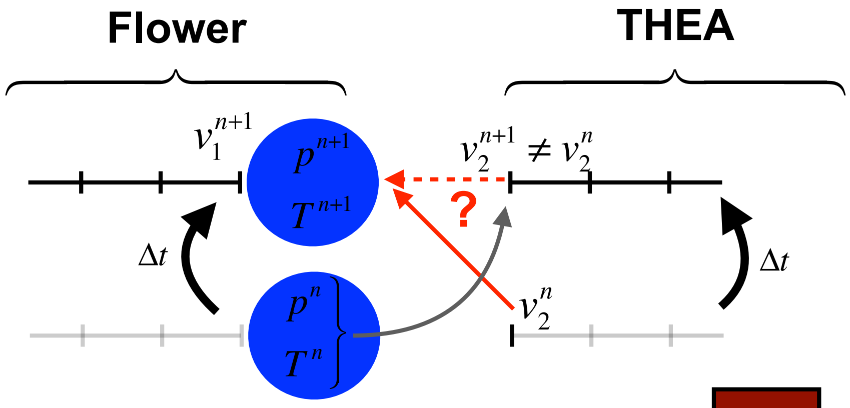


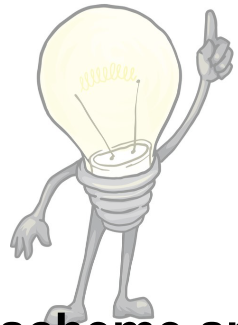
- To recover the implicit coupling, …



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

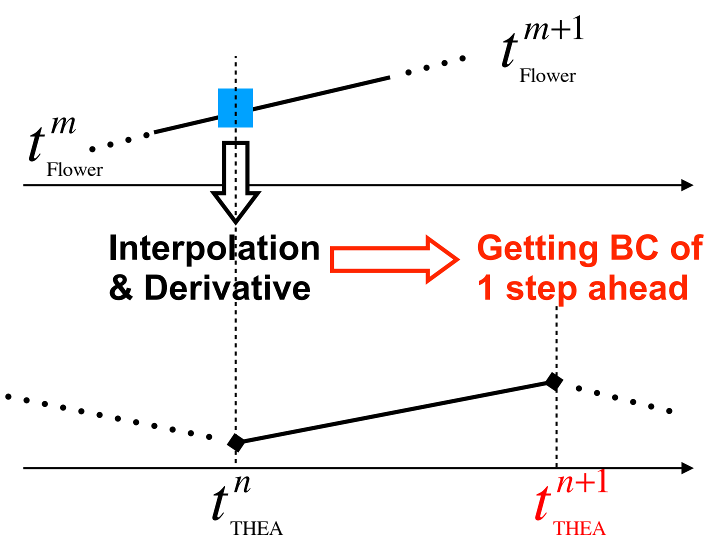
Issue #1 : loss of implicit coupling



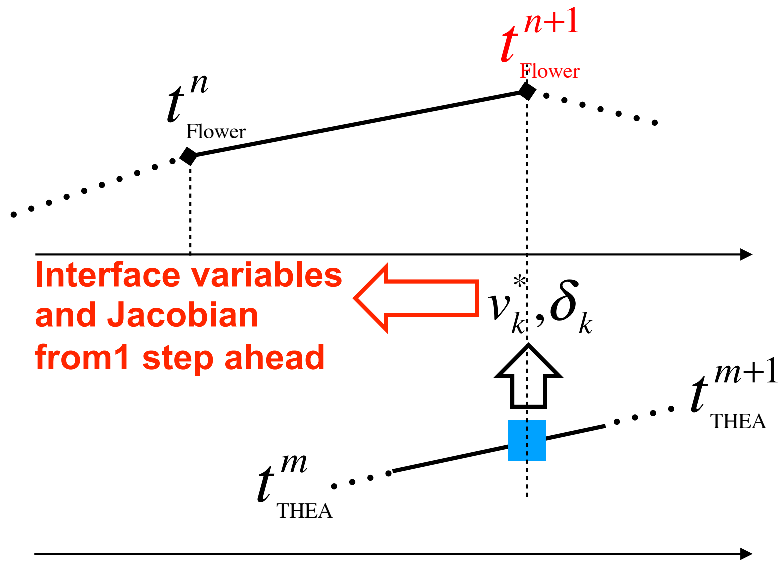


Here, it is the actual scheme applied to improve the THEA-Flower coupling

✱ THEA step

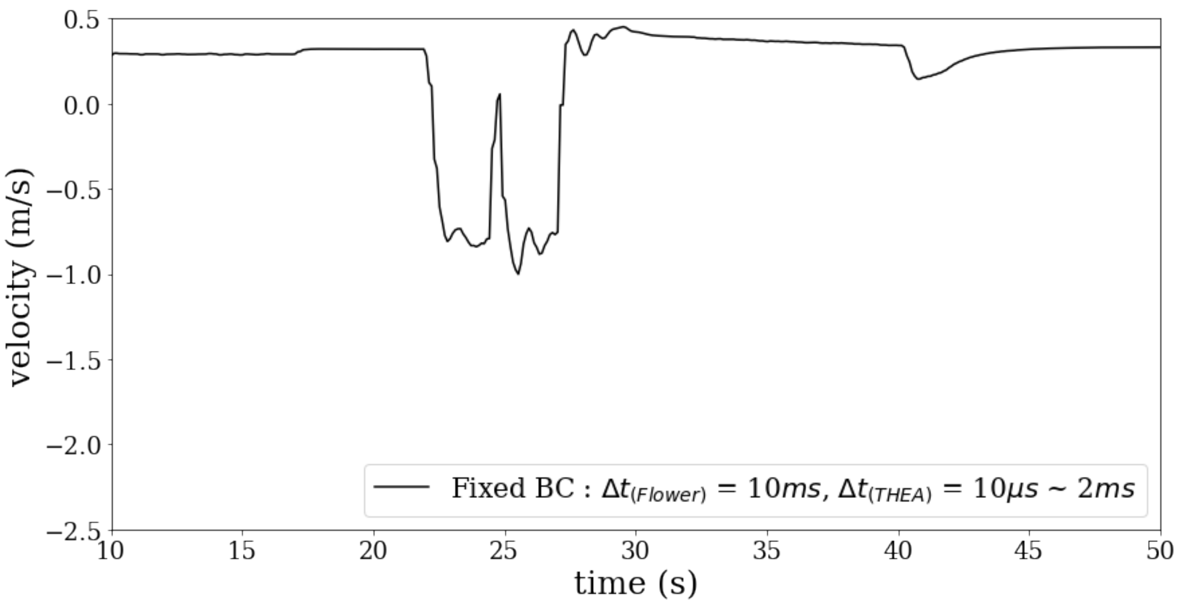


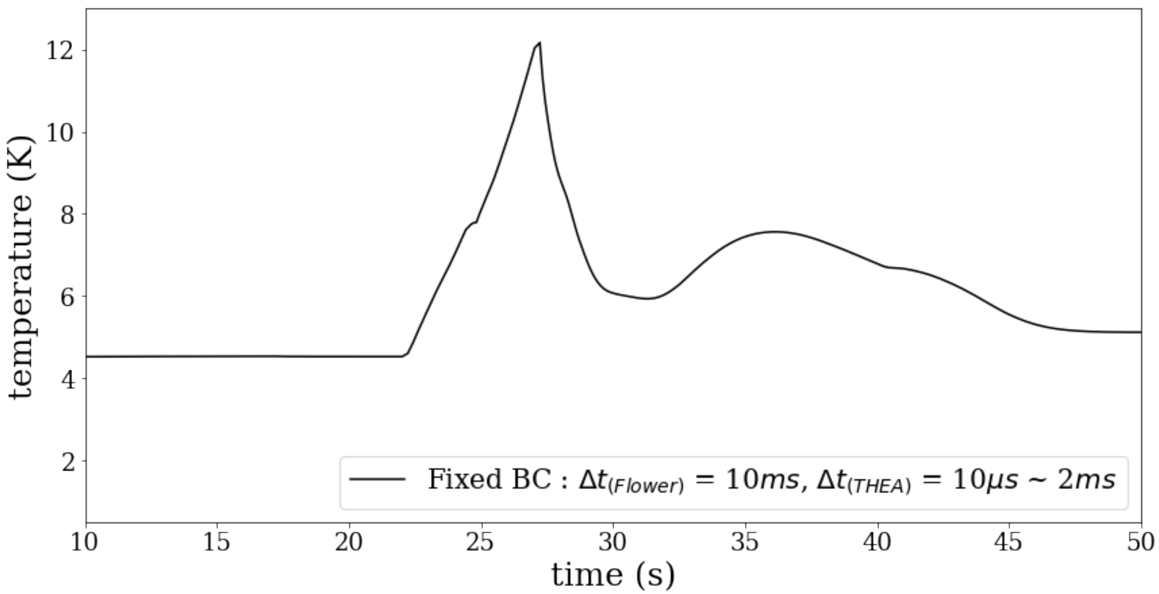
✱ Flower step



D. K. Oh, “Coupled Simulation Model of CICC Components Integrated into the Cooling Circuit”
IEEE Trans. Appl. Superconductivity 49 (2019) 4901505

Issue #2 : hard boundary constraints

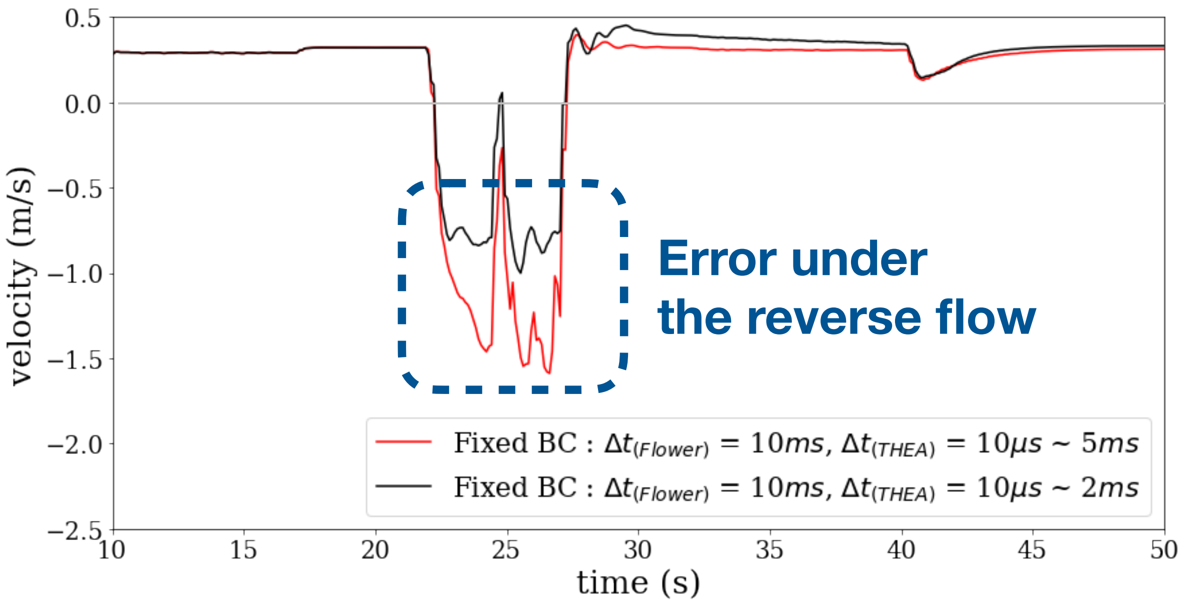




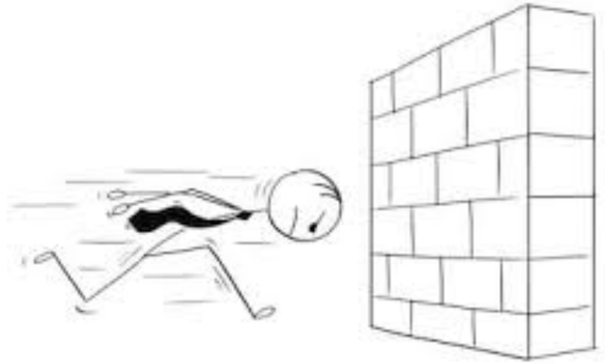
Good enough??

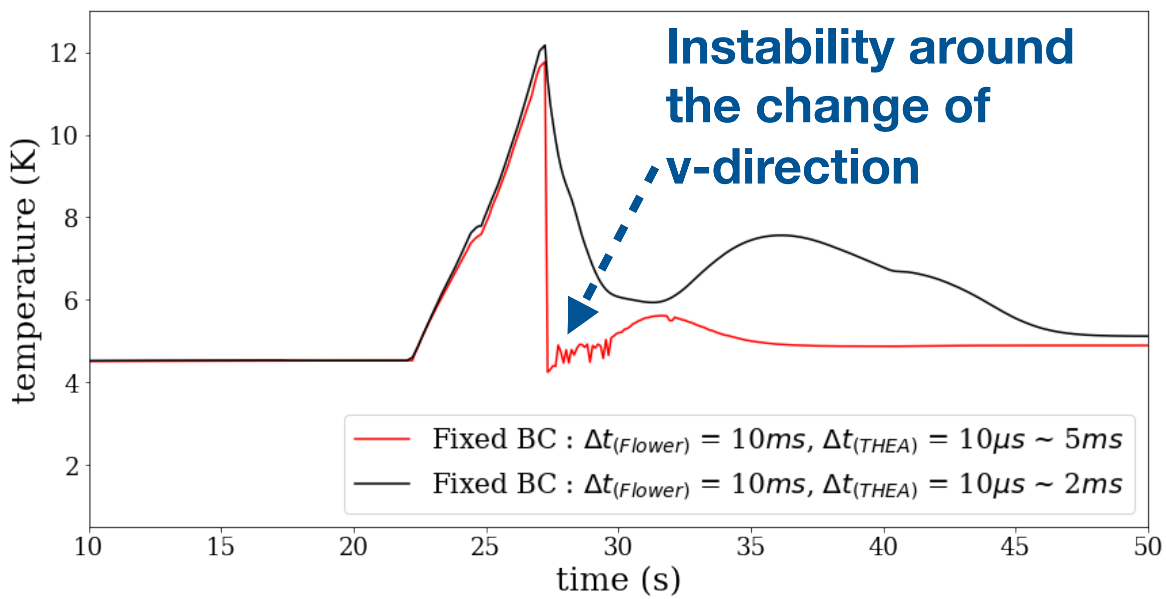
Issue #2 : hard boundary constraints

Not actually…



Fixed boundary (p, T)





For better performance, is there any nice way to transfer the constraints in the natural speed of the hydrodynamic system?

Issue #2 : hard boundary constraints

We already developed a usable boundary scheme..

* We applied them to the CICC (THEA) models..

Inlet :

$$\begin{cases} [\mathbf{AU}]_{v,\, i=1} = \bar{v}\left(\dfrac{v_2 - v_1}{2}\right) + \dfrac{1}{\bar{\rho}}\left(\dfrac{p_2 - p_0^{(\mathrm{in})}}{2}\right) + \dfrac{\bar{v}}{\overline{\rho c}}\left(\dfrac{p_1 - p_0^{(\mathrm{in})}}{2}\right) \\ [\mathbf{AU}]_{p,\, i=1} = \overline{\rho c}^2\left(\dfrac{v_2 - v_1}{2}\right) + \bar{v}\left(\dfrac{p_2 - p_0^{(\mathrm{in})}}{2}\right) + \bar{c}\left(\dfrac{p_1 - p_0^{(\mathrm{in})}}{2}\right) \\ [\mathbf{AU}]_{T,\, i=1} = \overline{\rho\phi C_{\mathrm{v}} T}\left(\dfrac{v_2 - v_1}{2}\right) + \overline{\rho C_{\mathrm{v}} v}\left(\dfrac{T_2 + T_1}{2} - T_0^{(\mathrm{in})*}\right) + \dfrac{\overline{\phi C_{\mathrm{v}} T}(\bar{c} - \bar{v})}{\bar{c}^2}\left(\dfrac{p_1 - p_0^{(\mathrm{in})}}{2}\right) \end{cases}$$

Negligible

The boundary pressure follows the constraint in the speed of sound.

The boundary temperature follows the upwind constraint in the flow velocity.

Outlet :

$$\begin{cases} [\mathbf{AU}]_{v,\, i=\mathrm{n}} = \bar{v}\left(\dfrac{v_{\mathrm{n}} - v_{\mathrm{n\text{-}1}}}{2}\right) + \dfrac{1}{\bar{\rho}}\left(\dfrac{p_0^{(\mathrm{out})} - p_{\mathrm{n\text{-}1}}}{2}\right) + \dfrac{\bar{v}}{\overline{\rho c}}\left(\dfrac{p_{\mathrm{n}} - p_0^{(\mathrm{out})}}{2}\right) \\ [\mathbf{AU}]_{p,\, i=\mathrm{n}} = \overline{\rho c}^2\left(\dfrac{v_{\mathrm{n}} - v_{\mathrm{n\text{-}1}}}{2}\right) + \bar{v}\left(\dfrac{p_0^{(\mathrm{out})} - p_{\mathrm{n\text{-}1}}}{2}\right) + \bar{c}\left(\dfrac{p_{\mathrm{n}} - p_0^{(\mathrm{out})}}{2}\right) \\ [\mathbf{AU}]_{T,\, i=\mathrm{n}} = \overline{\rho\phi C_{\mathrm{v}} T}\left(\dfrac{v_{\mathrm{n}} - v_{\mathrm{n\text{-}1}}}{2}\right) + \overline{\rho C_{\mathrm{v}} v}\left(T_0^{(\mathrm{out})*} - \dfrac{T_{\mathrm{n\text{-}1}} + T_{\mathrm{n}}}{2}\right) + \dfrac{\overline{\phi C_{\mathrm{v}} T}(\bar{c} - \bar{v})}{\bar{c}^2}\left(\dfrac{p_{\mathrm{n}} - p_0^{(\mathrm{out})}}{2}\right) \end{cases}$$

An application of the decomposed flux boundary (Eq 4 and Eq 5) in the reference, *i.e.*,
D. K. Oh and S. Oh, “Improved 1-d hydraulic network model for cryogenic circuits coupled to CICC models of fusion magnet systems” *Cryogenics 97 (2019) 133-143*

Issue #2 : hard boundary constraints

We already developed a usable boundary scheme..

* Those are the advective component in the FEM scheme **assuming linear shape function** just for demonstration.

$$v\frac{\partial v}{\partial x}+\frac{1}{\rho}\frac{\partial p}{\partial x}$$

$$\rho c^2\frac{\partial v}{\partial x}+v\frac{\partial p}{\partial x}$$

$$\rho C_v\phi T\frac{\partial v}{\partial x}+\rho C_v v\frac{\partial T}{\partial x}$$

Inlet :

$$\begin{cases}[\mathbf{AU}]_{v,\,i=1}=\bar{v}\left(\frac{v_2-v_1}{2}\right)+\frac{1}{\bar{\rho}}\left(\frac{p_2-p_0^{(\mathrm{in})}}{2}\right)+\frac{\bar{v}}{\overline{\rho c}}\left(\frac{p_1-p_0^{(\mathrm{in})}}{2}\right)\\ [\mathbf{AU}]_{p,\,i=1}=\overline{\rho c}^2\left(\frac{v_2-v_1}{2}\right)+\bar{v}\left(\frac{p_2-p_0^{(\mathrm{in})}}{2}\right)+\bar{c}\left(\frac{p_1-p_0^{(\mathrm{in})}}{2}\right)\\ [\mathbf{AU}]_{T,\,i=1}=\overline{\rho\phi C_v T}\left(\frac{v_2-v_1}{2}\right)+\overline{\rho C_v v}\left(\frac{T_2+T_1}{2}-T_0^{(\mathrm{in})*}\right)+\frac{\overline{\phi C_v T(\bar{c}-\bar{v})}}{\bar{c}^2}\left(\frac{p_1-p_0^{(\mathrm{in})}}{2}\right)\end{cases}$$

Outlet :

$$\begin{cases}[\mathbf{AU}]_{v,\,i=\mathrm{n}}=\bar{v}\left(\frac{v_\mathrm{n}-v_\mathrm{n\text{-}1}}{2}\right)+\frac{1}{\bar{\rho}}\left(\frac{p_0^{(\mathrm{out})}-p_\mathrm{n\text{-}1}}{2}\right)+\frac{\bar{v}}{\overline{\rho c}}\left(\frac{p_\mathrm{n}-p_0^{(\mathrm{out})}}{2}\right)\\ [\mathbf{AU}]_{p,\,i=\mathrm{n}}=\overline{\rho c}^2\left(\frac{v_\mathrm{n}-v_\mathrm{n\text{-}1}}{2}\right)+\bar{v}\left(\frac{p_0^{(\mathrm{out})}-p_\mathrm{n\text{-}1}}{2}\right)+\bar{c}\left(\frac{p_\mathrm{n}-p_0^{(\mathrm{out})}}{2}\right)\\ [\mathbf{AU}]_{T,\,i=\mathrm{n}}=\overline{\rho\phi C_v T}\left(\frac{v_\mathrm{n}-v_\mathrm{n\text{-}1}}{2}\right)+\overline{\rho C_v v}\left(T_0^{(\mathrm{out})*}-\frac{T_\mathrm{n\text{-}1}+T_\mathrm{n}}{2}\right)+\frac{\overline{\phi C_v T(\bar{c}-\bar{v})}}{\bar{c}^2}\left(\frac{p_\mathrm{n}-p_0^{(\mathrm{out})}}{2}\right)\end{cases}$$

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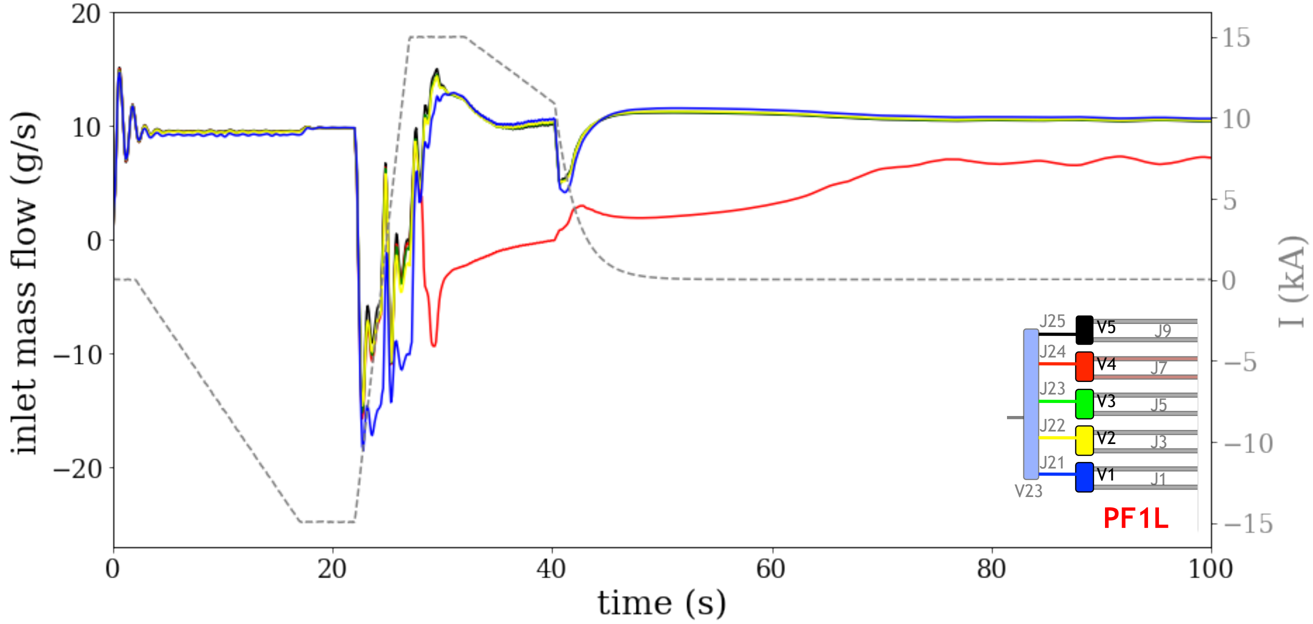
Now, it works!



☑ time step : 10 ms (Flower)
10 μs ~ 5 ms (THEA)

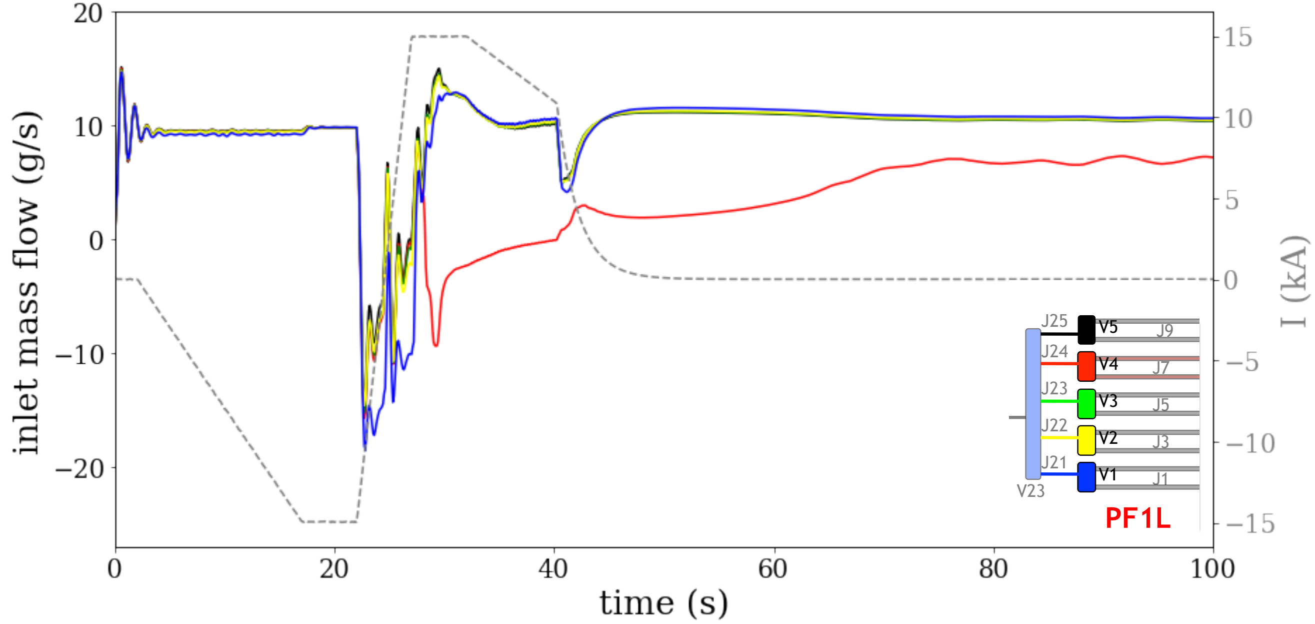
→ 20 times bigger time step!
→ It takes less than 2 hours!

Jacobian-based Coupling Scheme Adopted to the Asynchronous Steps

+

Natural Boundary Constraining by Characteristic Decomposition

Now, it works!



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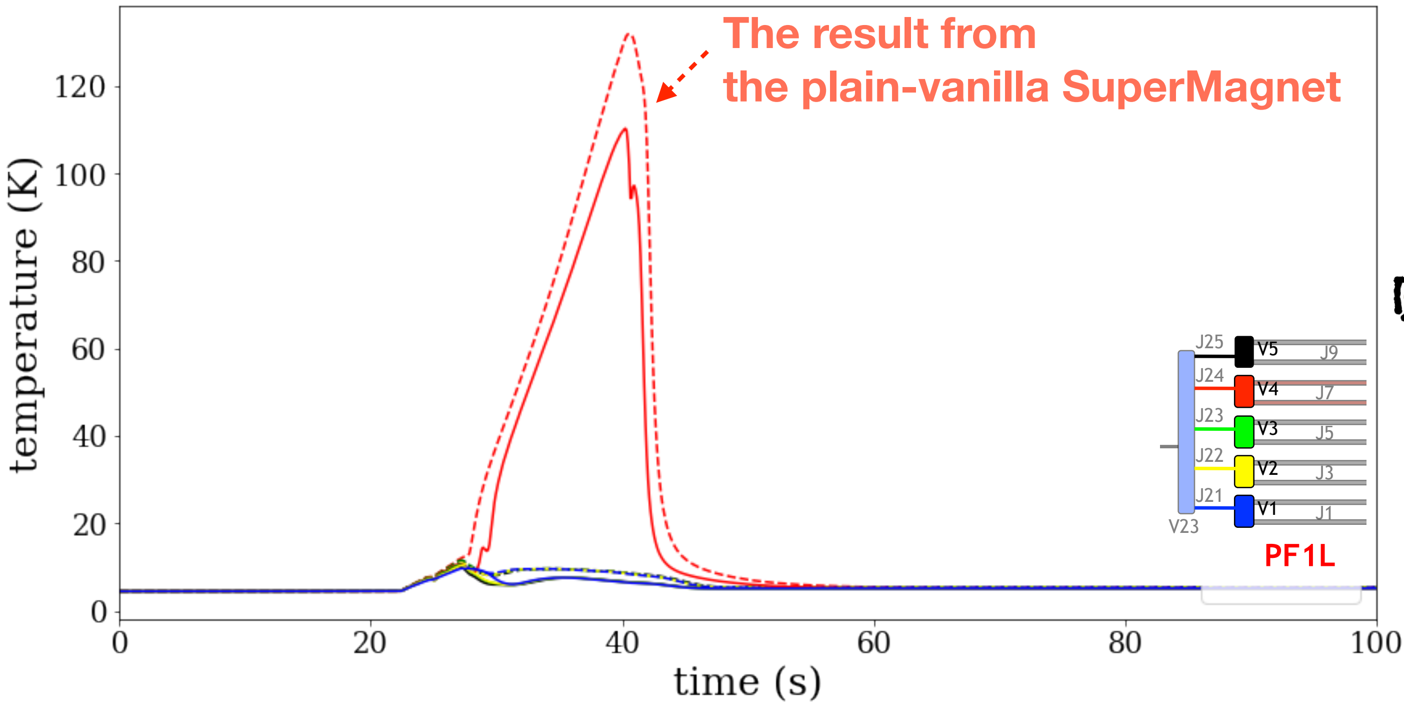
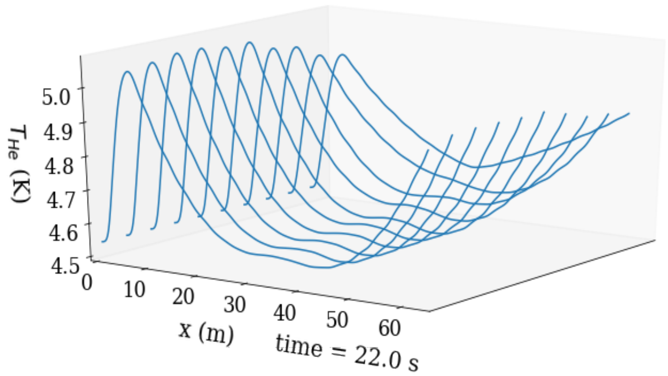


- ☑ Eventually, accuracy issue is resolved during this study.

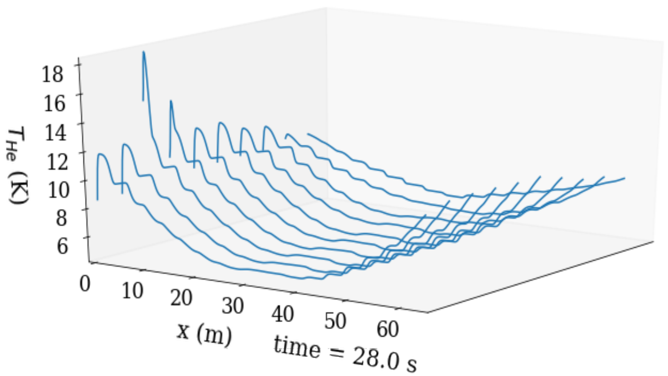
Let apply the properties of the KSTAR Nb_3Sn conductors..

Onset
(I_{PF1} = -15 kA)



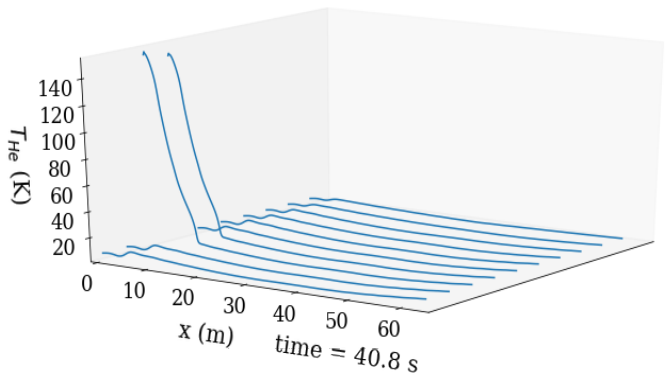
6 s

Flattop
(I_{PF1} = +15 kA)

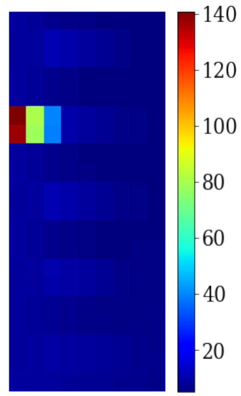


12.8 s

Hotspot



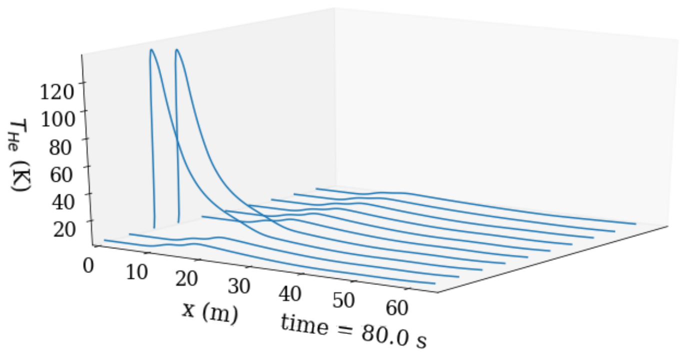
- ☞ J_c = **780** A/mm² : 12 T, 4.2 K
- ☞ T_{c0} = 16.94 K, B_{c20} = 31.3 T
  $\alpha_{\varepsilon>0}$ = 1250, $\alpha_{\varepsilon<0}$ = 900
  : Summer's scaling law
  (Υ=2, v=2.5, p=0.5, q=2, w=3,n=1)
- ☞ ε_{eff} = **-0.35** %
  : Incoloy 908 jacket
- ☞ conductor n-value = **10**

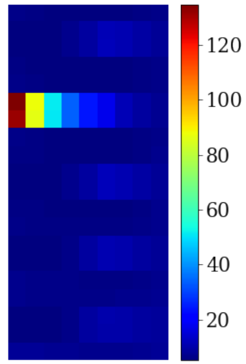


NFRI
National Fusion Research Institute

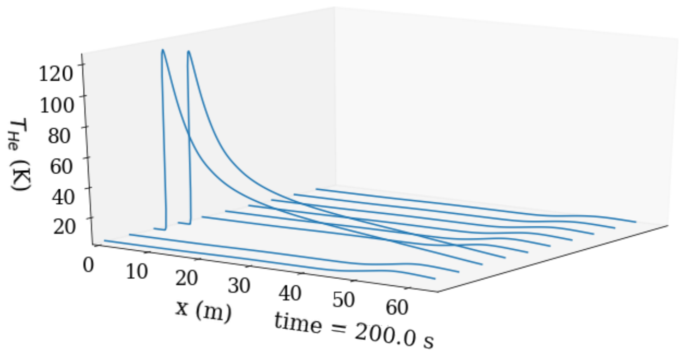
Then, can we match the result to the real quench?

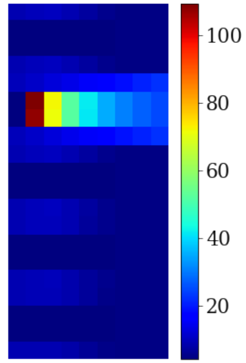
Quench is developing, and the joule heat goes out .

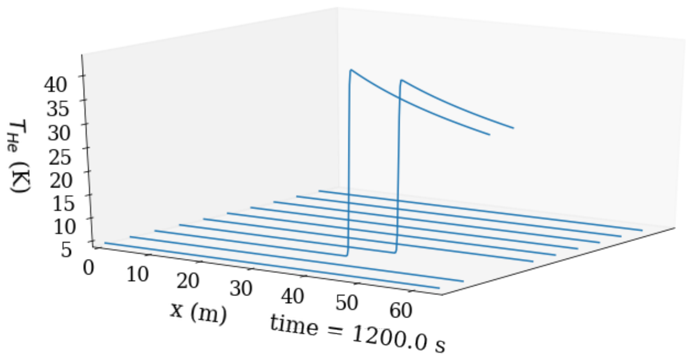


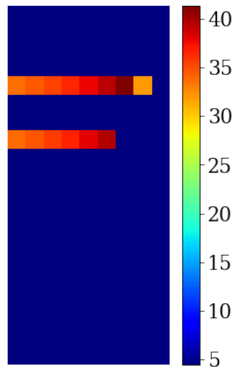


Well.. not exactly in reality..









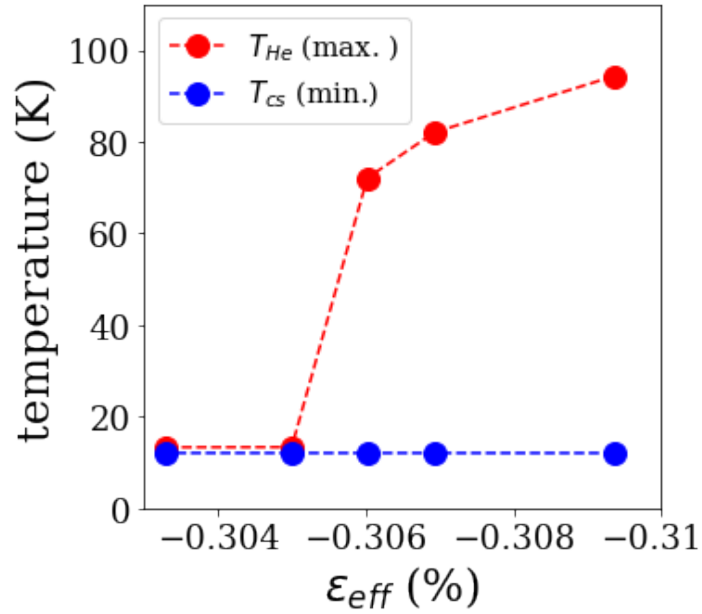
☞ Assuming the AC loss is accurate, in this simulation…

, quench appears in the **both of PF1** coils.

➡ It's different from the real situation..

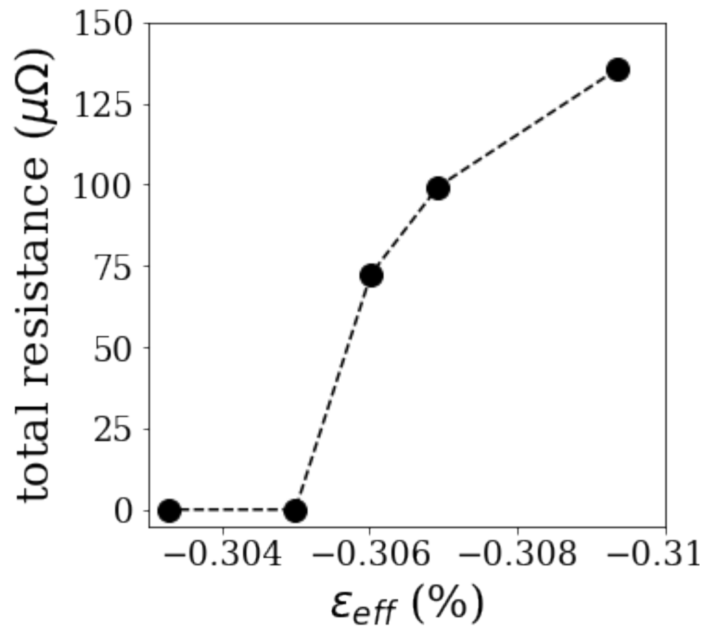
Conductor Performance

- For safe operation on the given scenario, the lower limit of ε_{eff} is **-0.305** % which is reasonable to secure the original design.



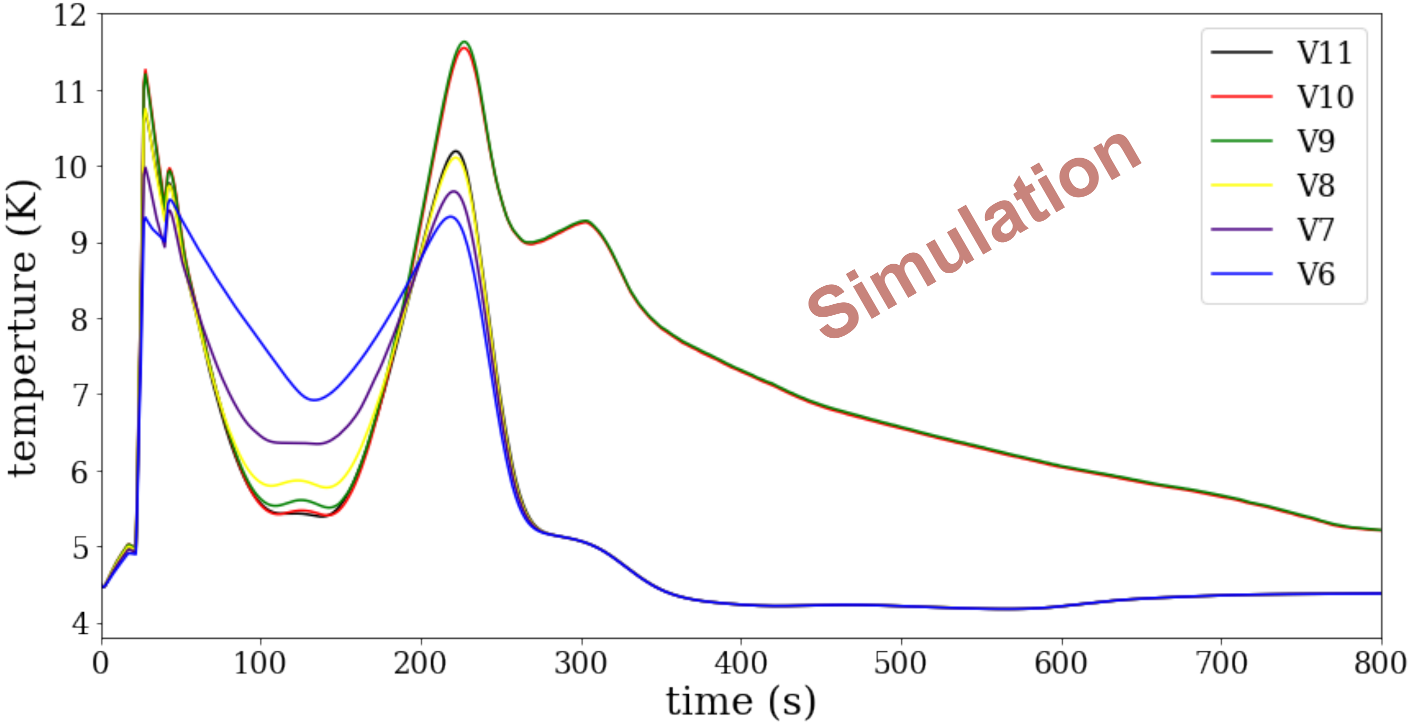
- The hotspot temperature is **at least more than ~70 K**, and the quench is very sensitive to the parameters.

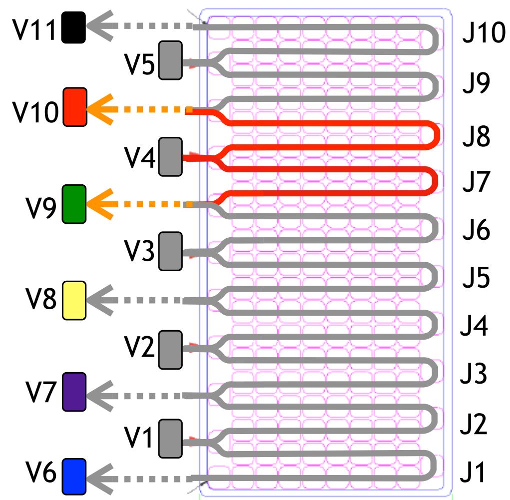
- Defective state of the top DP has to be assumed; **degradation? cooling? heat load?**



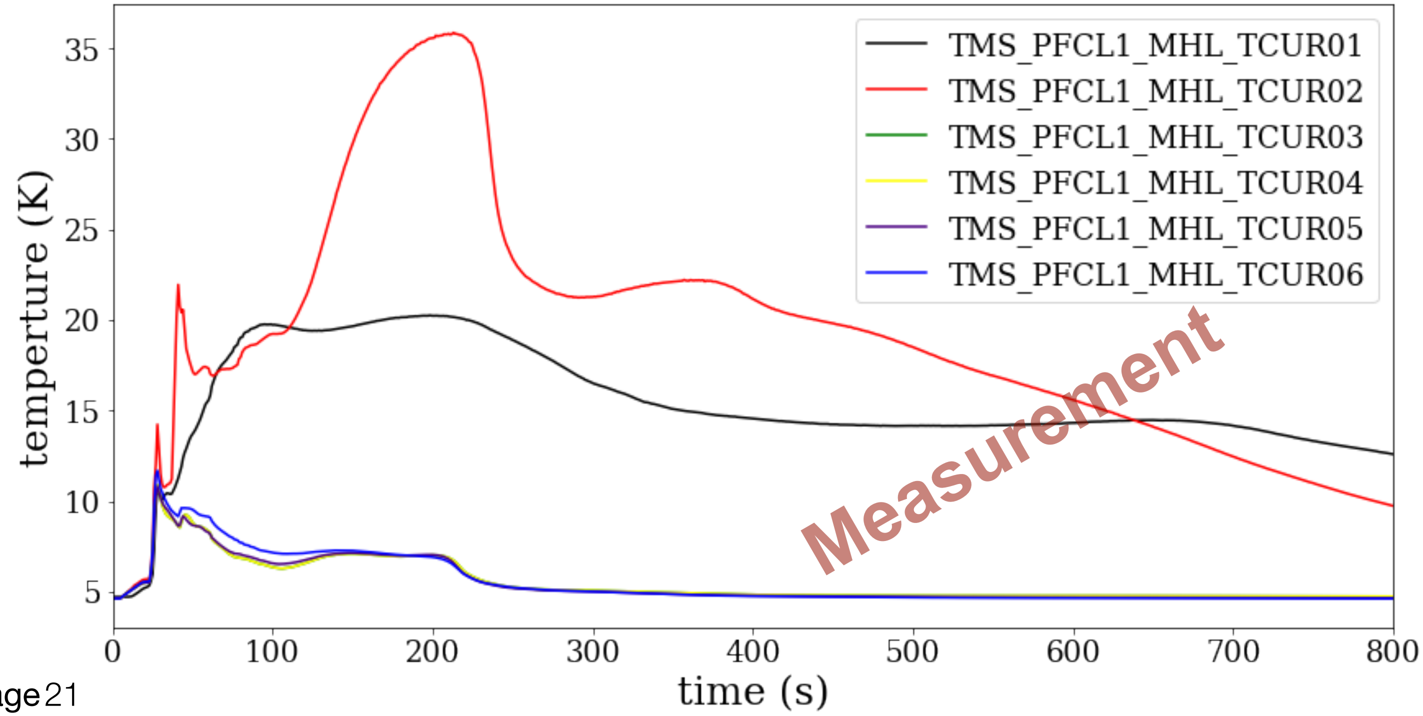
☞ *In spite of the overall conductors are robust enough, the quench happened **at the top DP (PF1L)** which has to be less vulnerable than the 2nd one.*

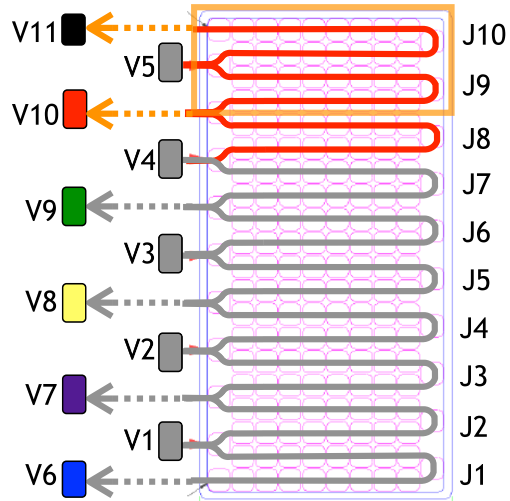
The CICC outlets - comparison to the measurement





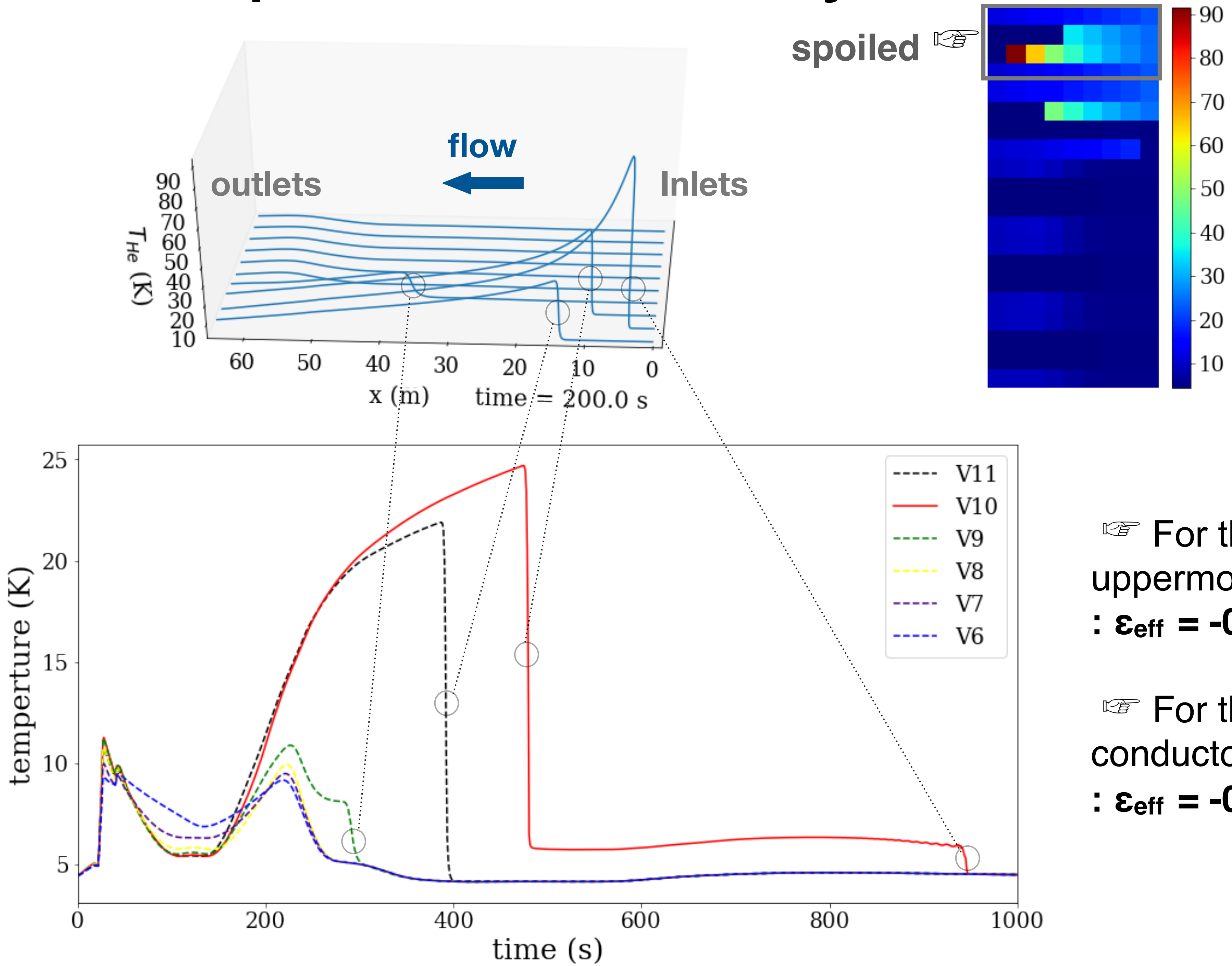
Analysis with the model





Deduction from the data

An Attempt of Parametric Study



☞ For the two uppermost DPs
: ε_{eff} = -0.576 %

☞ For the other conductors
: ε_{eff} = -0.305 %

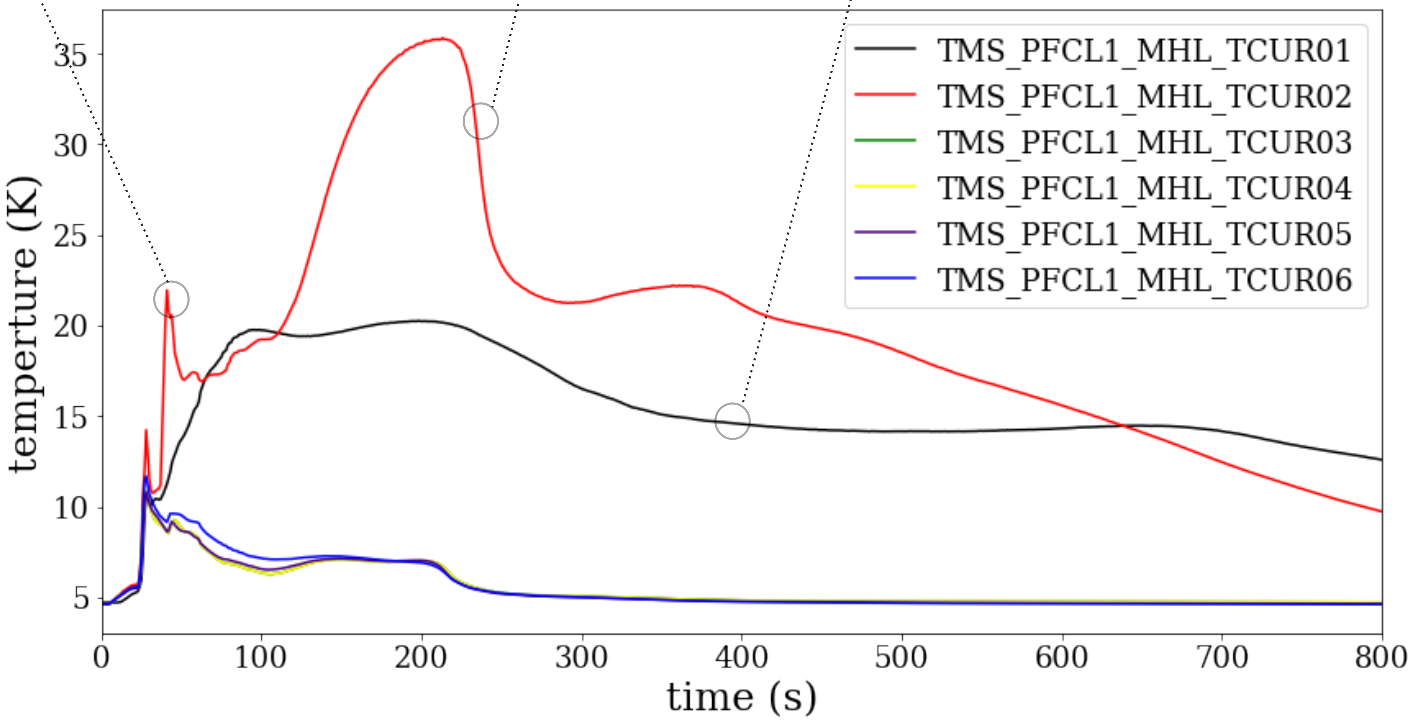
Conclusion

By means of improved numerical model, the quench event is clearly understood. As the next step, we will resolve the things still unknown ..

☞ The edge of residual Joule-heat looks too fast.

☞ Current sharing at the outlet-part?

☞ Additional heat exchange to the bus-line through the joint must be taken into account.



☞ The actual quench was triggered earlier than the estimation, and the magnet is stabilized easier than the model.