4C analysis of thermal-hydraulic transients in the KSTAR PF1 superconducting coil

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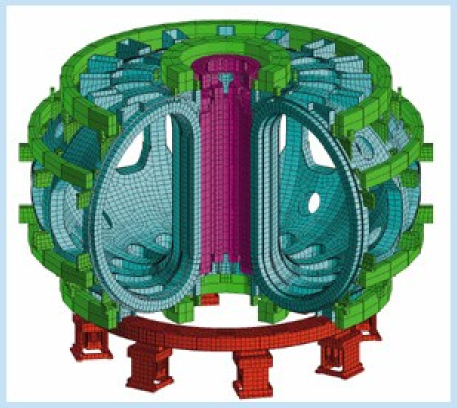
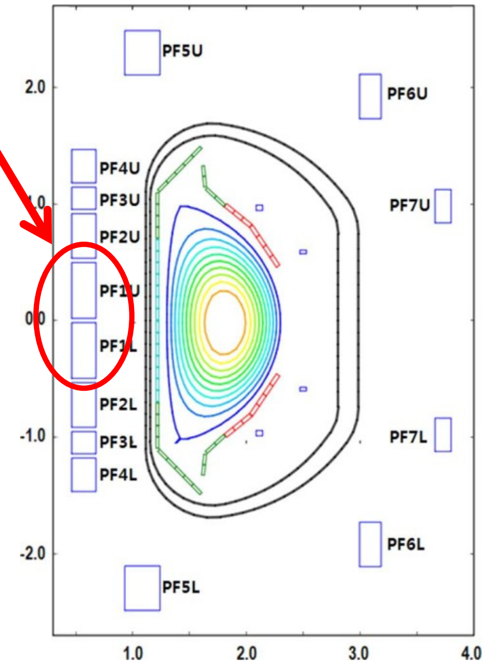
Outline

- Introduction
- The KSTAR PF1 coil
- Scenario
- Simulation strategy
- Simulation results and comparison with experiment
- Conclusions and perspective

Introduction

- The KSTAR tokamak is operating since 2008 at the National Fusion Research Institute in Korea.
- KSTAR is equipped with a full superconducting magnet system including the central solenoid (CS) made of four pairs of coils (PF1L/U-PF4L/U)
- The coils are pancake-wound using Nb_3Sn CICC, cooled with SHe in forced flow at ~4.5 K and ~5.5 bar inlet conditions.
- In the KSTAR campaigns, **a higher temperature rise than estimated was observed in the CS during current pulses** – dedicated tests were performed
- Here we analyze a thermal-hydraulic transient due to AC losses in the PF1L/U coils with the 4C code





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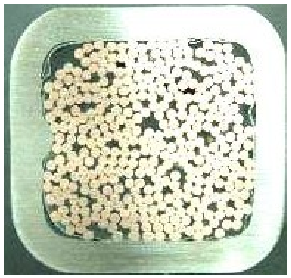
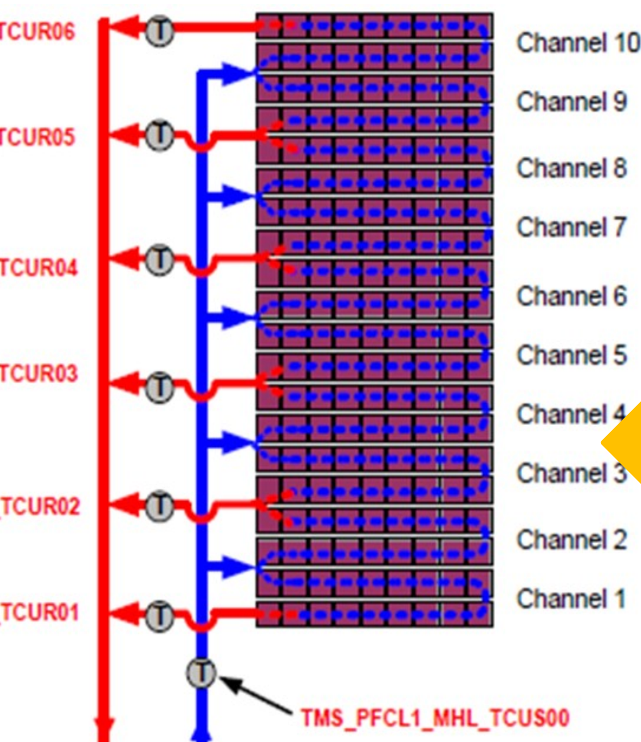
KSTAR PF1 conductors & coil

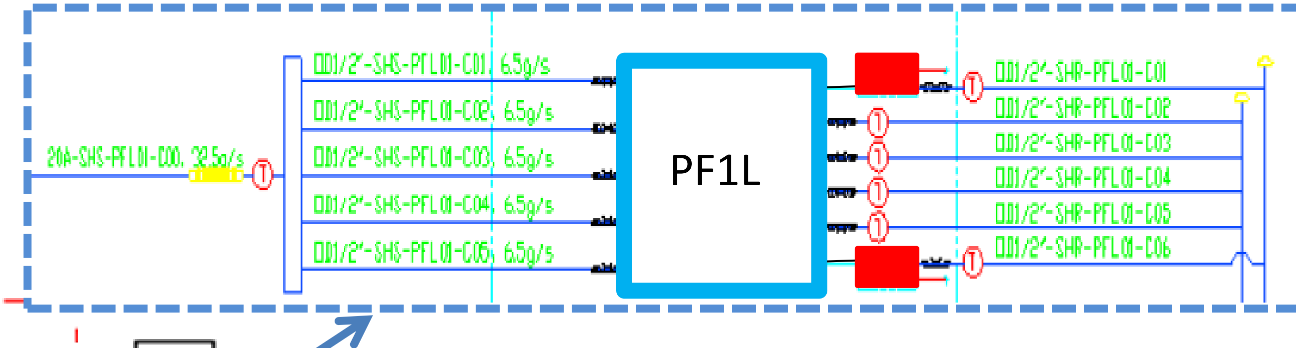


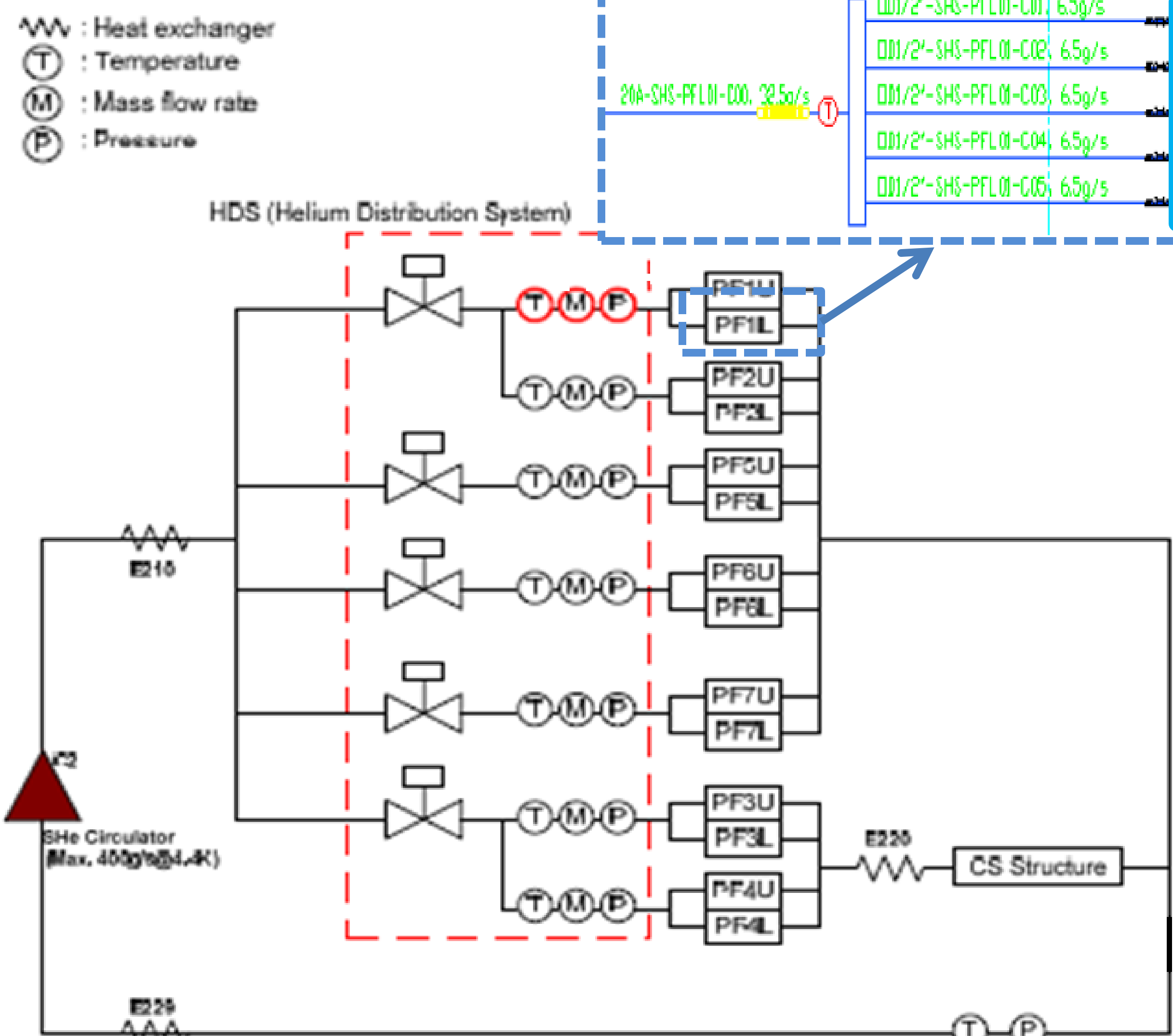
Superconductor	Nb_3Sn
Cable pattern	3 × 4 × 5 × 6
SC / Cu strands	240/120
Strand diameter (mm)	0.78
Conduit material	Incoloy 908
Void fraction (%)	32.7
Channel hydraulic length (m)	64.5



Coil made of 10 double-pancakes (channels)

Hydraulic circuit of KSTAR PF1 coils





- **Concentrate on PF1L (PF1U shows same/symmetric behavior ← both charged)**

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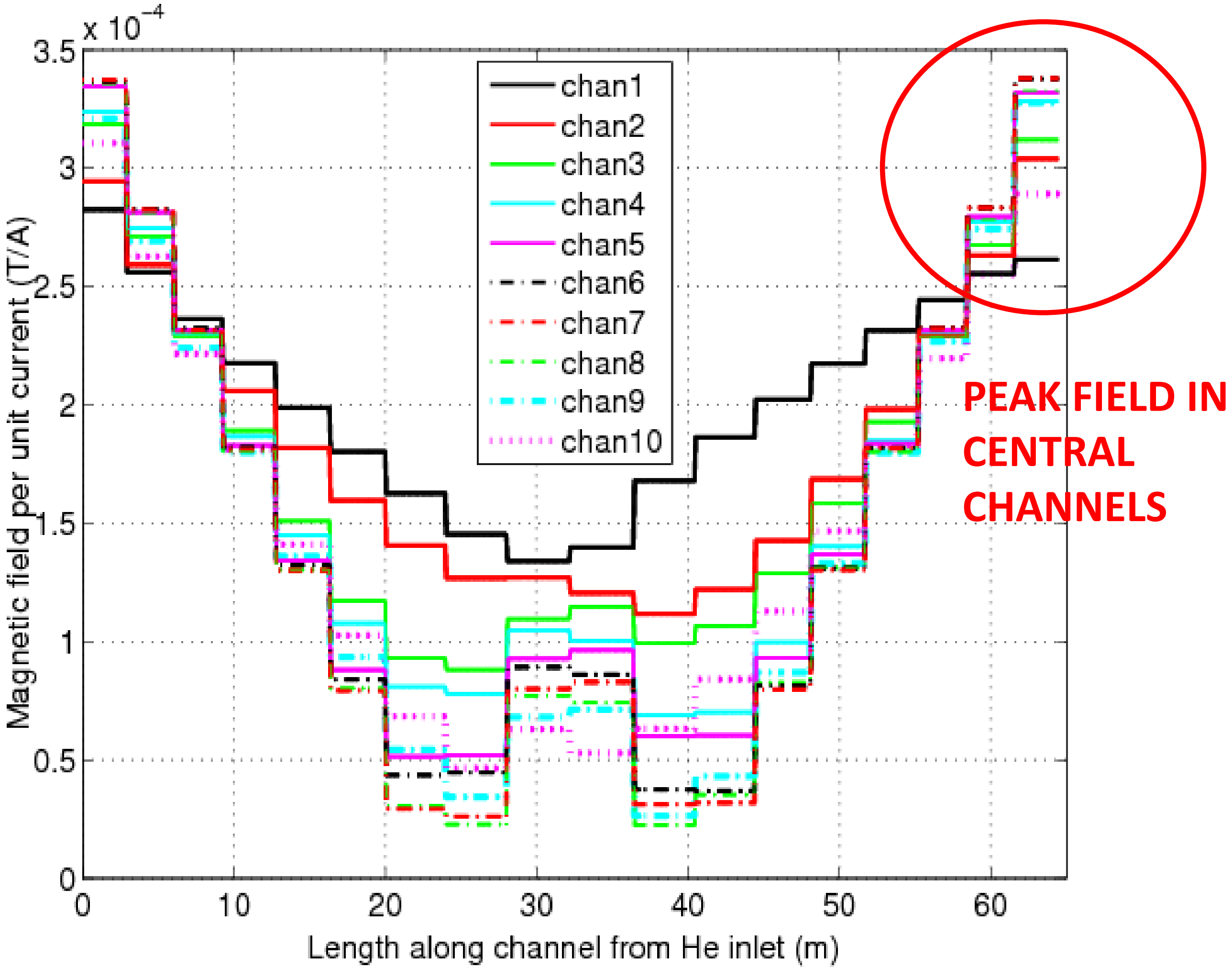
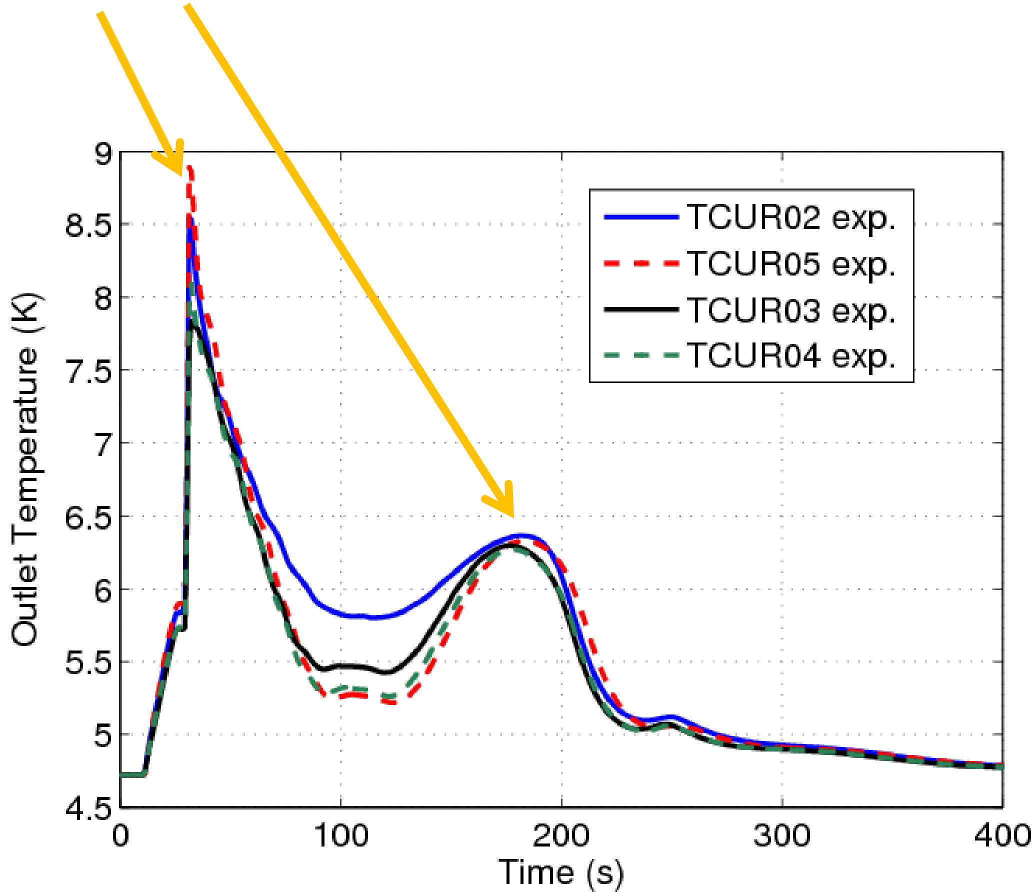
Scenario

- Runs analyzed here from 2011 campaign: 1 kA/s up to 15 kA; 5 s plateau; 0.5 - 1 - 2 - 4 - 6 kA/s down **in PF1L/U only**



Thermal-hydraulic effects of AC losses

- 2 main peaks in all outlet T signals



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The 4C model

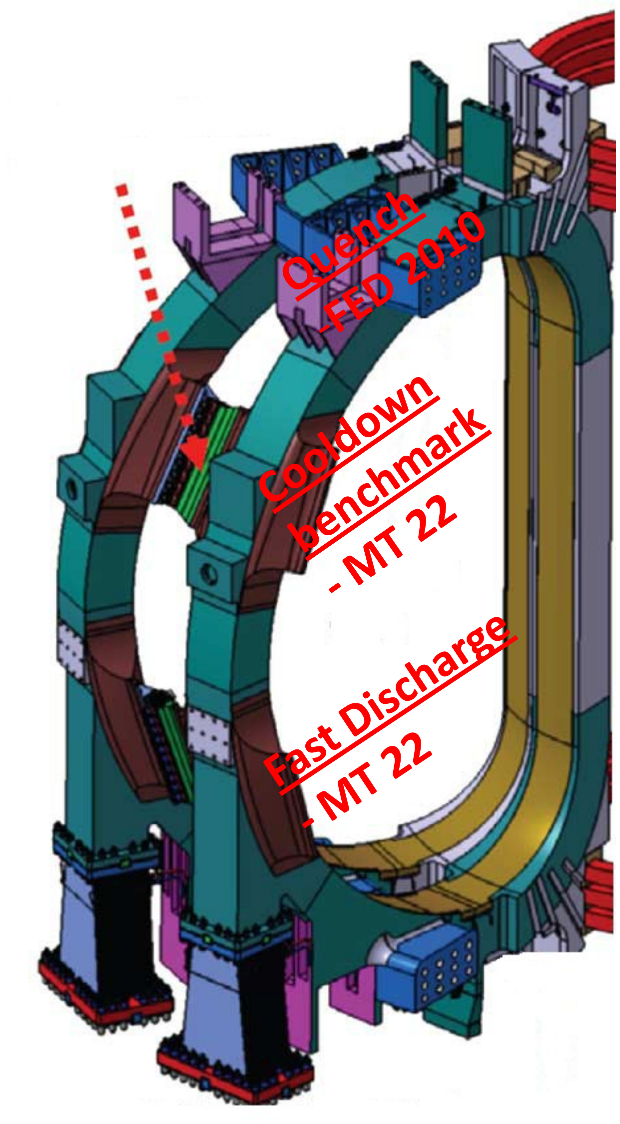
- Multi-conductor thermal-hydraulic model of the **winding** → compressible 1D SHe flow in dual channel CICC, thermally coupled to neighbors
- Model of He cooling paths

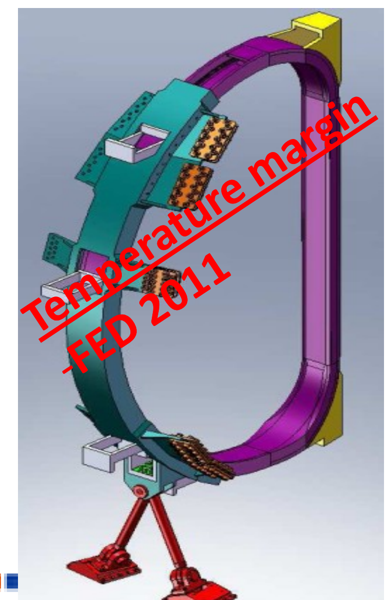
Quasi-3D FE model of the **structures** : casing, radial plates, …

[L. Savoldi Richard, F. Casella, B. Fiori and R. Zanino, *Cryogenics* **50** (2010) 167-176]

Cryogenic circuit (winding + casing cooling channels) 0D/1D model: Pumps, valves, HX, cryolines, LHe bath, …

4C validation and application (so far)





Model of AC losses in PF1

- Hysteresis losses in SC

$$Q_{hys} = \frac{2}{3\pi} J_c d_{eff} \left| \frac{dB}{dt} \right| A_{non\_cu} \quad \text{(W/m)}$$

- Coupling losses in SC strands

$$Q_{cp} = \frac{n\tau_{cp}}{\mu_0} \left(\frac{dB}{dt} \right)^2 \left\{ 1 - \frac{\tau_{cp}}{\tau_m} [1 - \exp(-\tau_m / \tau_{cp})] \right\} A_{st} \quad \text{(W/m)}$$

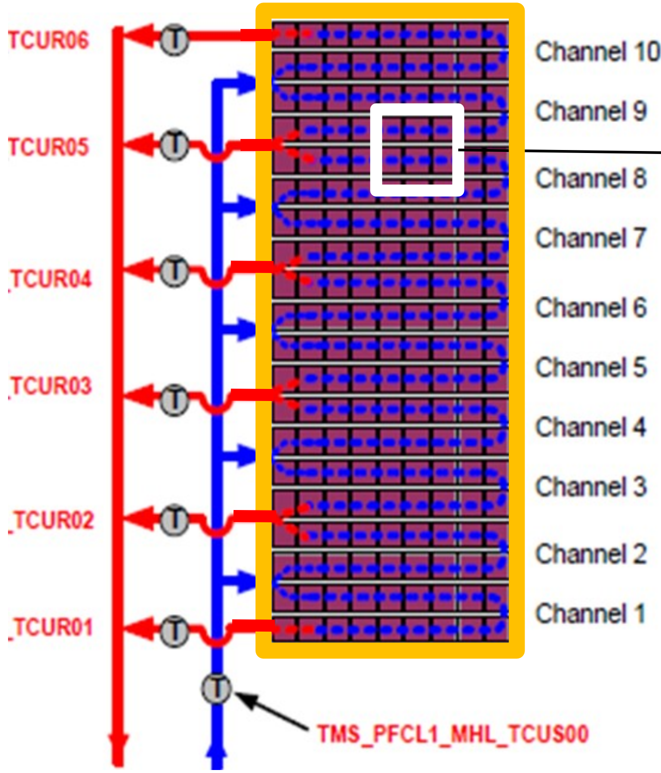
- *Eddy currents in jacket and Cu strands accounted for (but small)*
- *Hysteresis losses in jacket neglected*

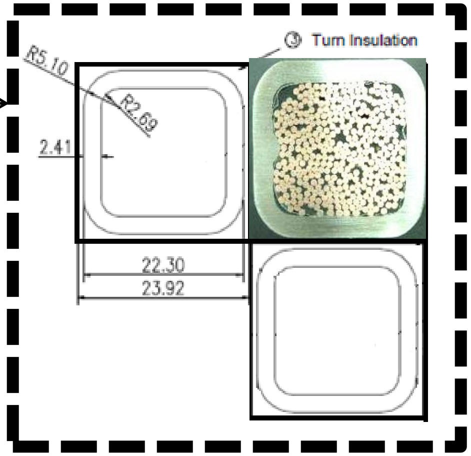
4C simulation strategy

1. Evaluate **hysteresis** losses from available experimental data
2. Introduce PF1 simplified **circuit** model → find suitable $n\tau$ to best fit experimental data (1st peak in T_{out}) **in PF1 1kA/s-1kA/s scenario**
3. Assess effect of inter-turn/inter-pancake (ITIP) thermal coupling on **2nd** peak in T_{out}^{max}
4. Freeze $n\tau$ and check the model in the other PF1 scenarios

4C simulation assumptions (I)

- All 10 channels and their thermal coupling simultaneously accounted for





•Ground insulation / outer shell (structures) neglected
•External (radiation /conduction) heat loads neglected

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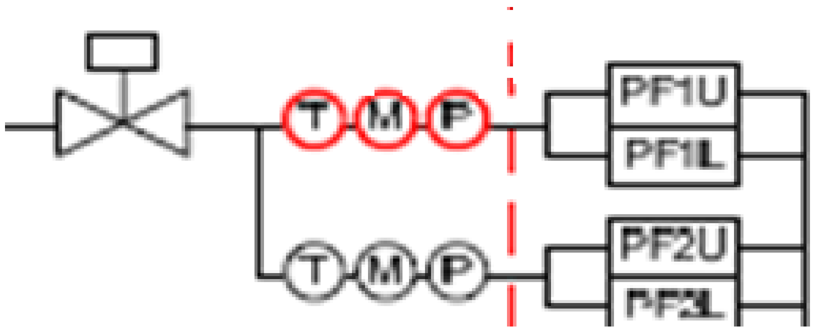
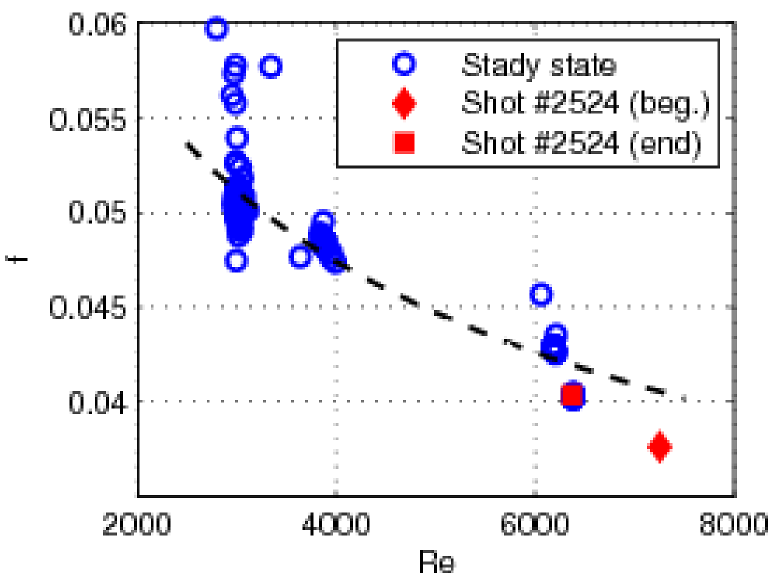
4C simulation assumptions (II)

- Assume mass flow rate equally split between channels

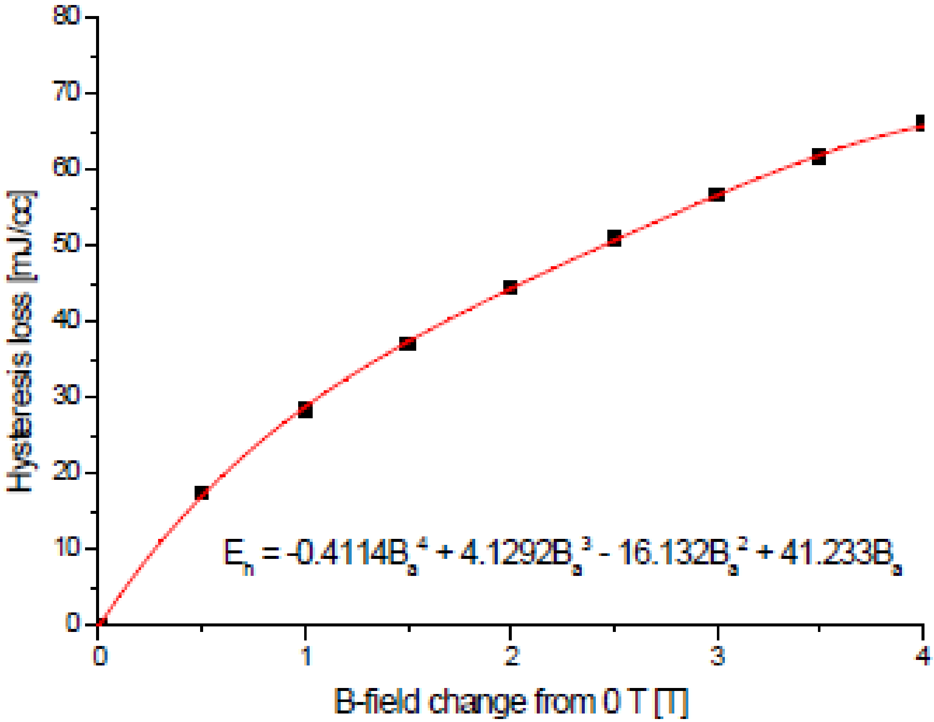




- Friction factor derived from end-of-cool-down data

Evaluation of hysteresis losses(I)

- Hysteresis losses measured on KSTAR Nb_3Sn **strand**
- Average hysteresis loss within 200- 250 mJ/cc @ +/- 3T
- On PF1 chan8 the fit gives ~ 300 J for the AC loss scenarios analyzed here
- Formula for Q_{hys} gives similar result



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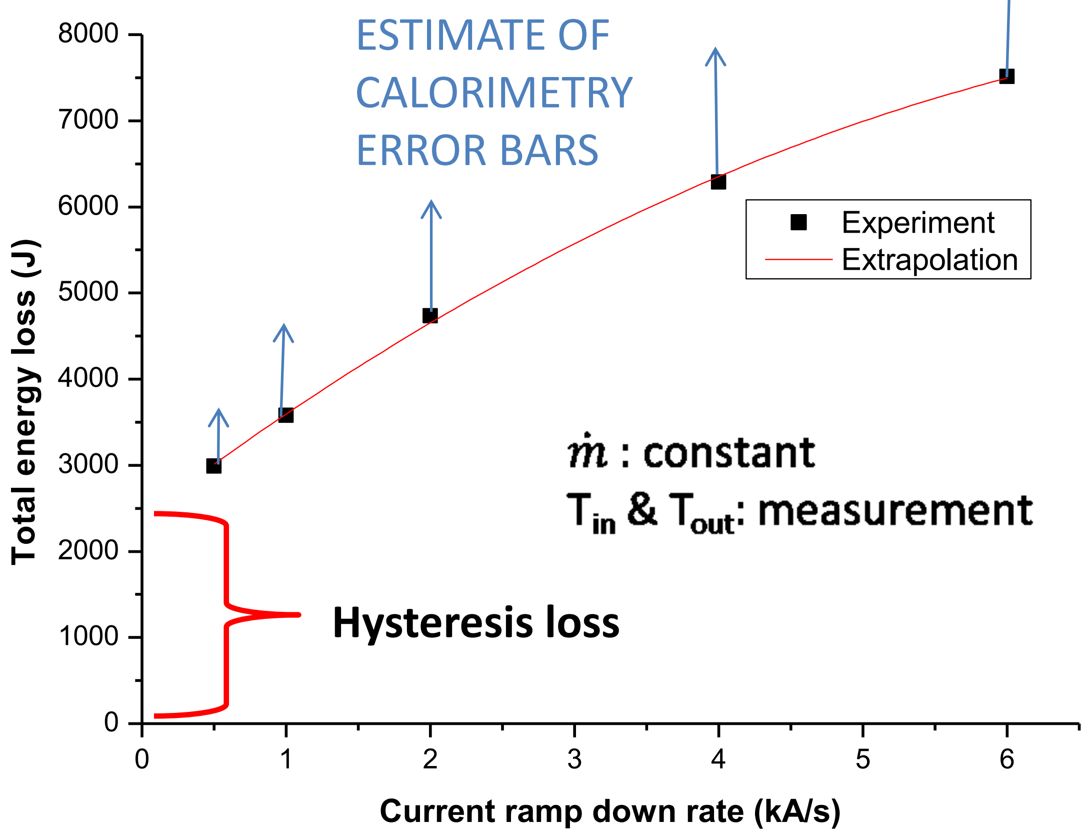
Evaluation of hysteresis losses(II)

- Hysteresis loss estimated from the extrapolation of experiment results (calorimetry) at zero current ramp rate
- Result on chan8 here is about 2.400 J (upper bound)



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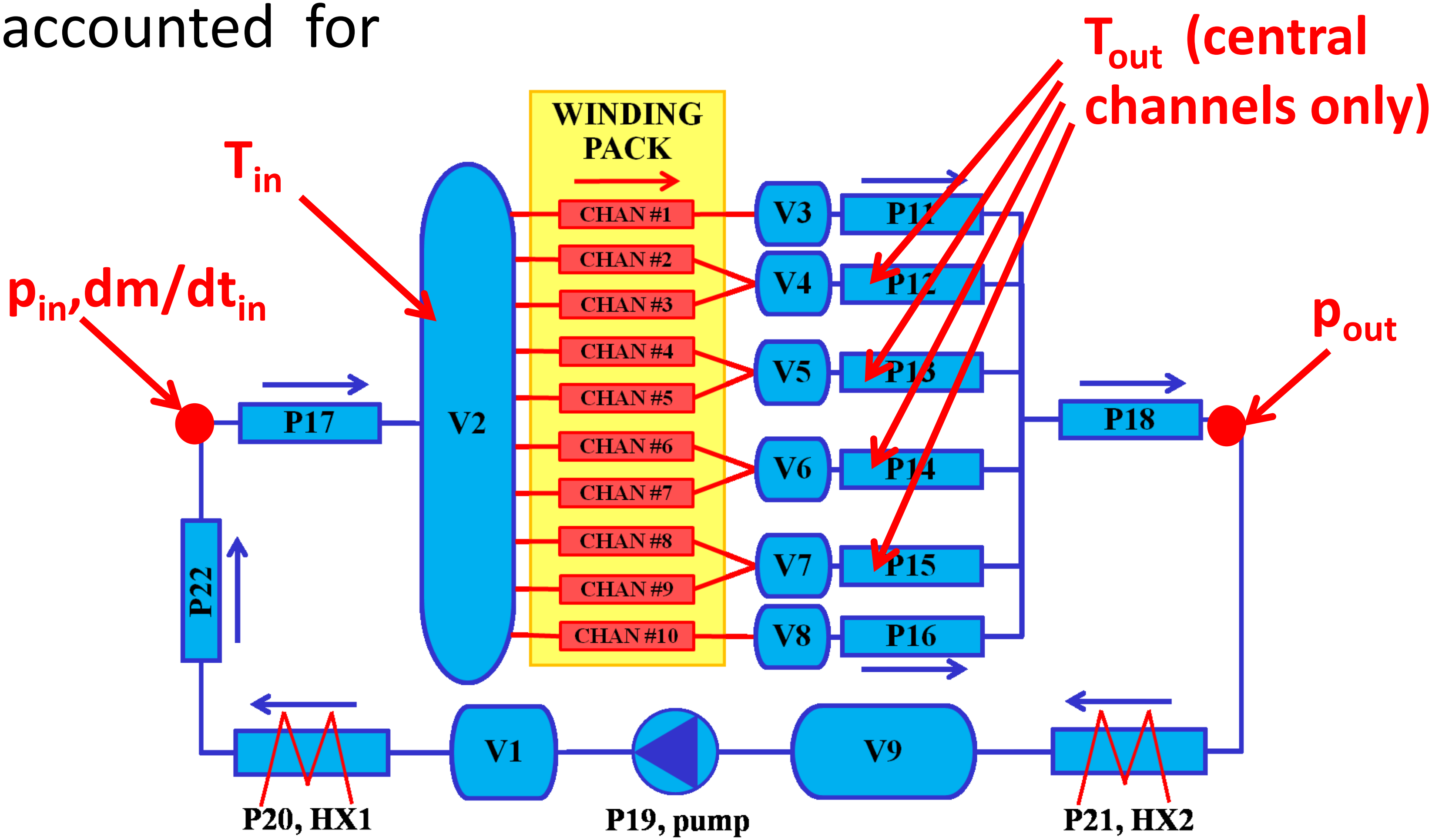
Circuit model

Very simplified circuit model introduced to account for pressure rise at boundaries – PF2-7 in parallel are NOT accounted for

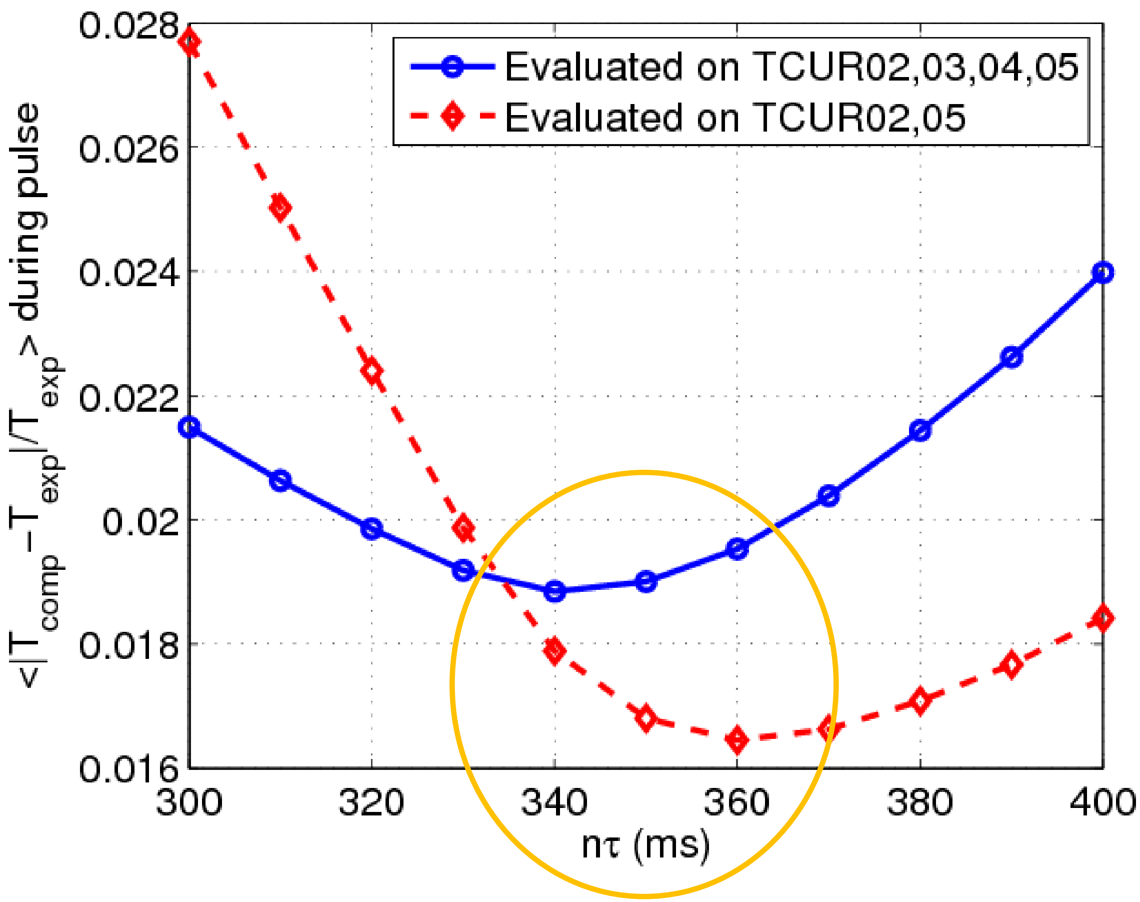


Calibration of nτ (I) (PF1 –1kA/s-1kA/s)

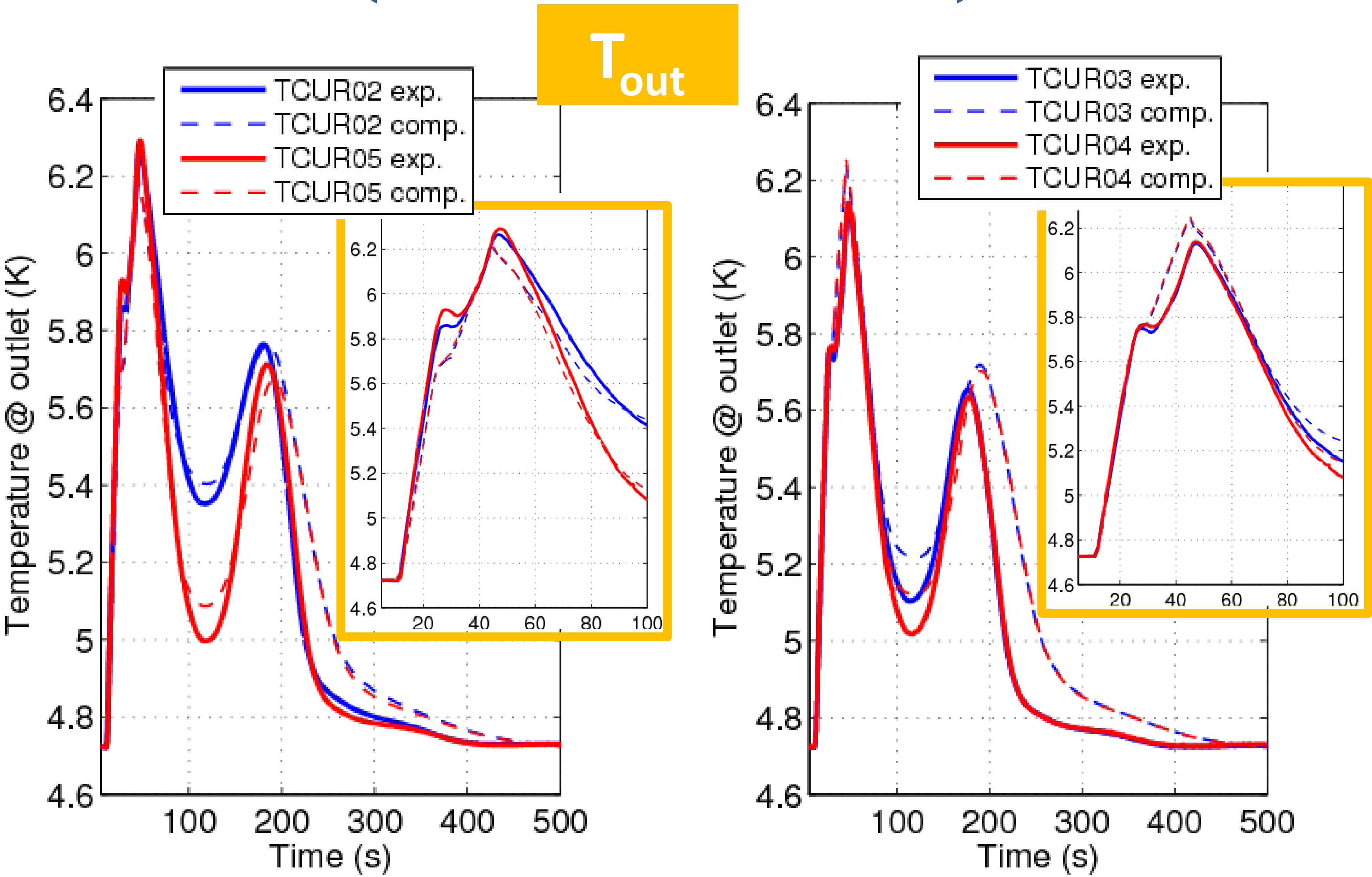
- Perform scan in nτ
- Find optimum nτ that, <u>during the current pulse</u>, minimizes

$$< \frac{\left|T_{comp}(t) - T_{\exp}(t)\right|}{T_{\exp}(t)} >$$

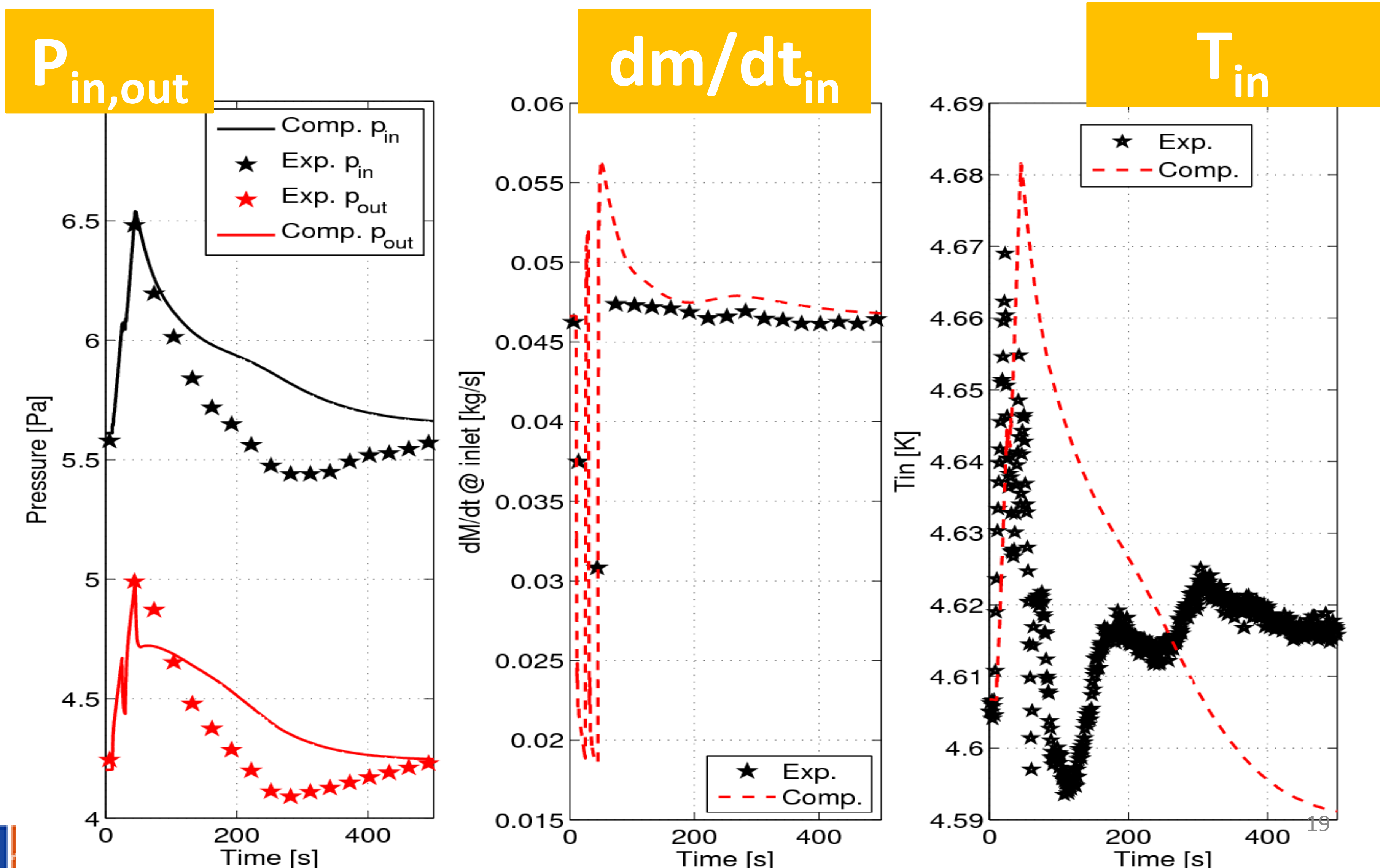
over different thermometers



Calibration of nτ (II) (PF1 –1kA/s-1kA/s)



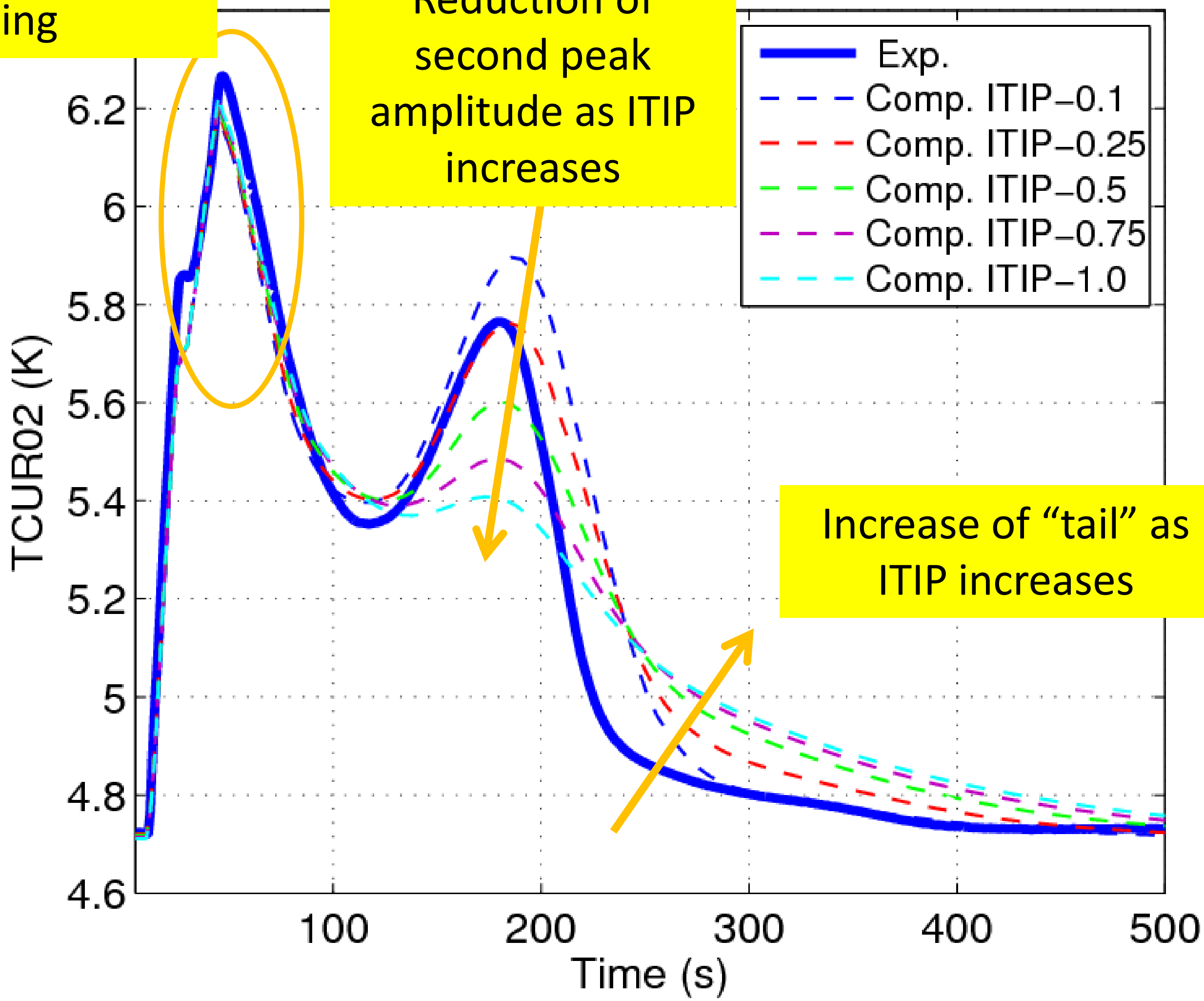
Calibration of nτ (III)
(PF1 –1kA/s-1kA/s)



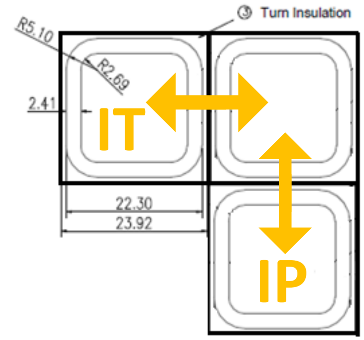
Effect of the ITIP coupling on the 2nd peak

1st peak almost unaffected by ITIP coupling

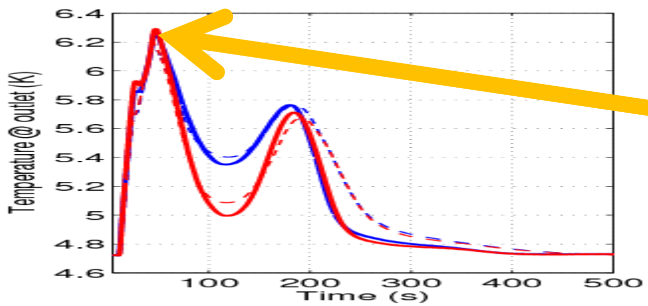
Reduction of second peak amplitude as ITIP increases

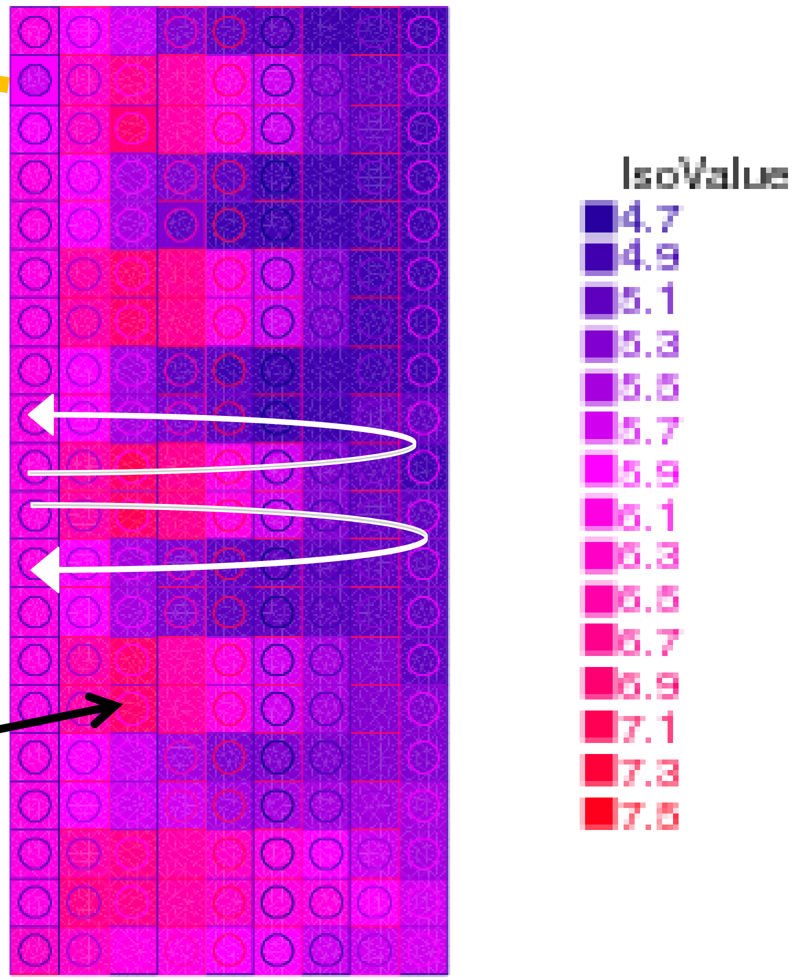


Increase of “tail” as ITIP increases



Temperature map @ t_peak

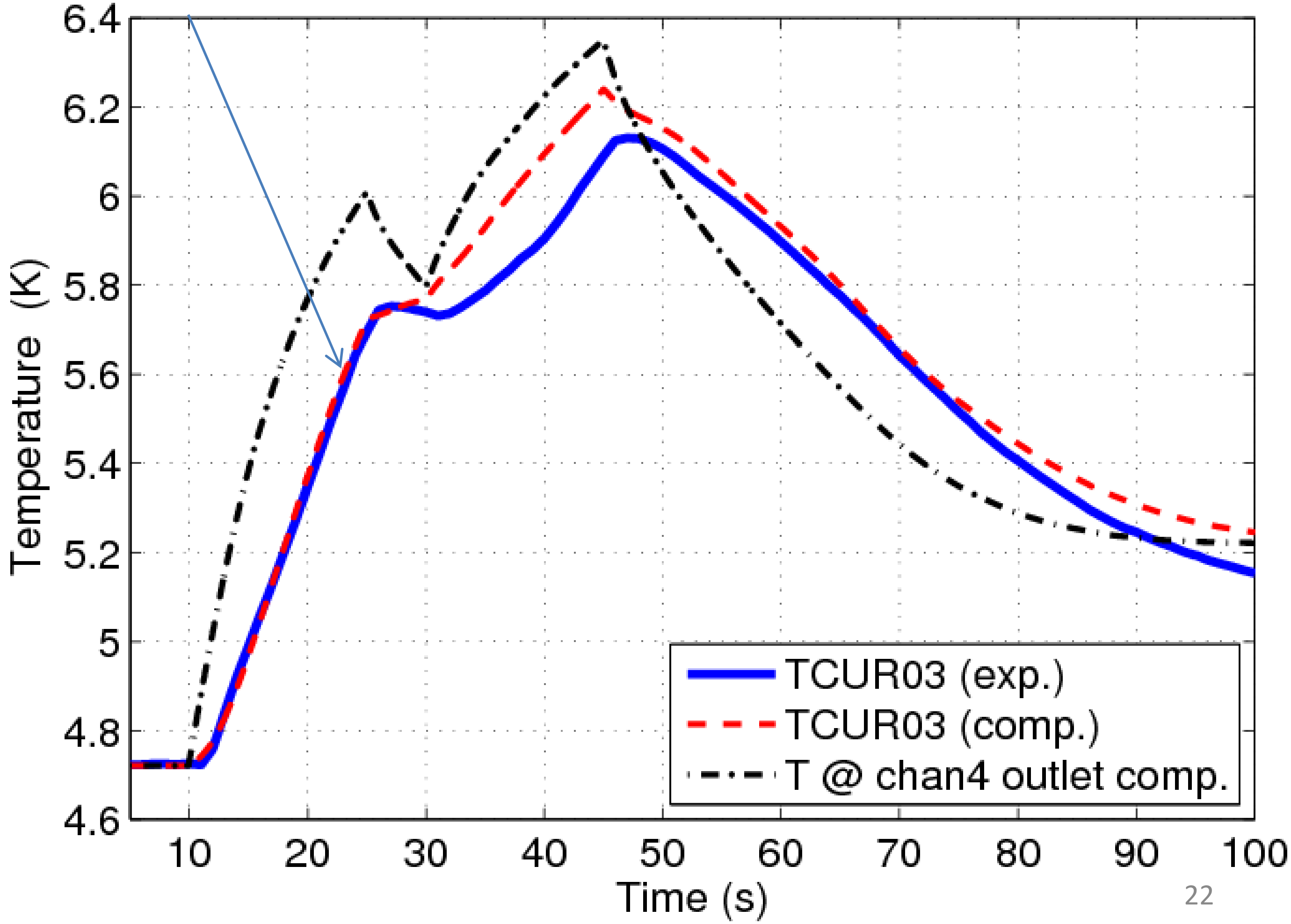




- Cooling geometry still visible
- Hot spot ~ in 3rd turn (transit time in turns comparable to pulse time)

Effect of circuit

- Smoothing effect of outlet manifold needed to reproduce temperature evolution



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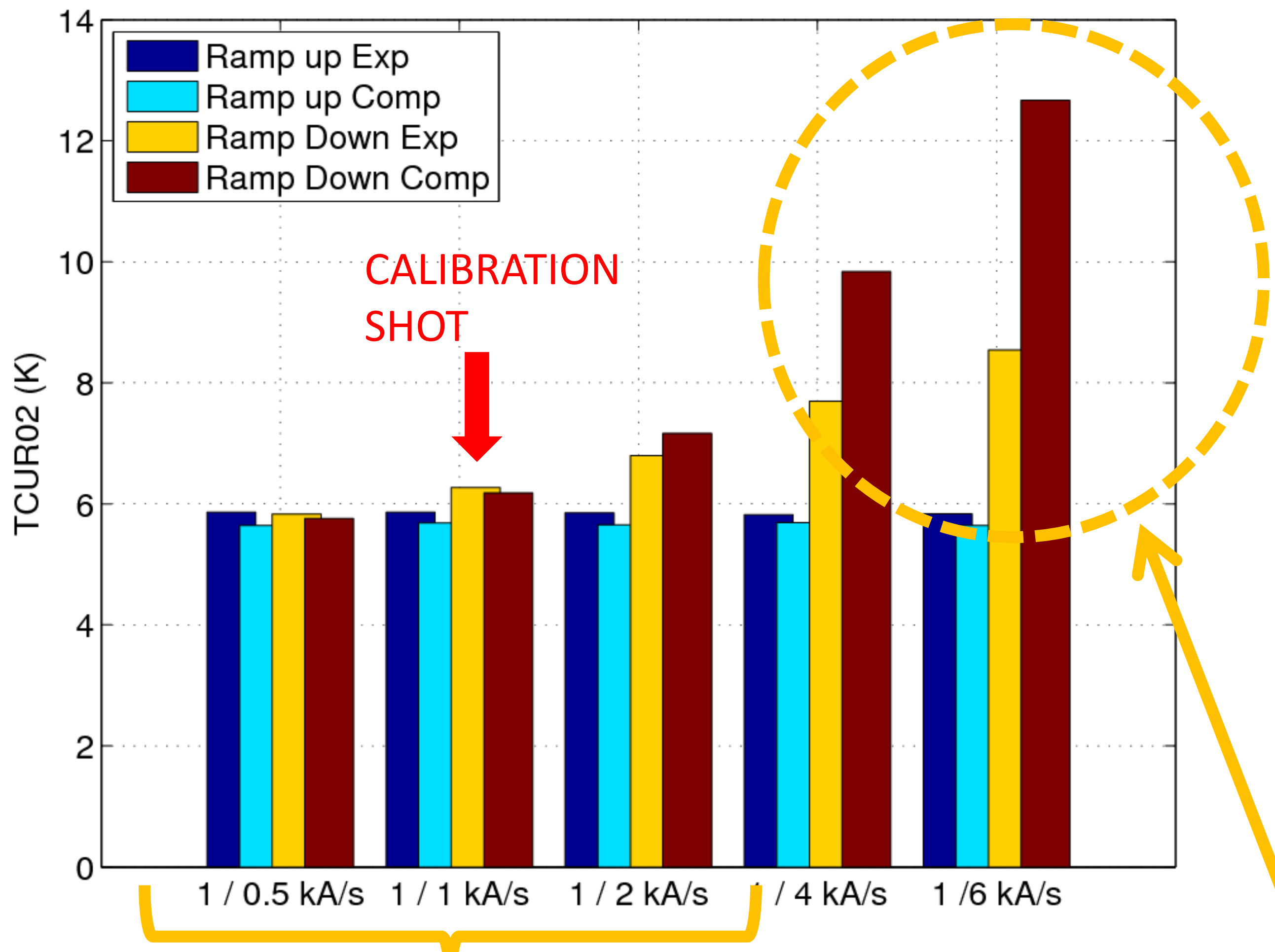
Summary of results (all shots)



Good agreement
@ low ramp rates

Increasing discrepancy @
higher ramp rates

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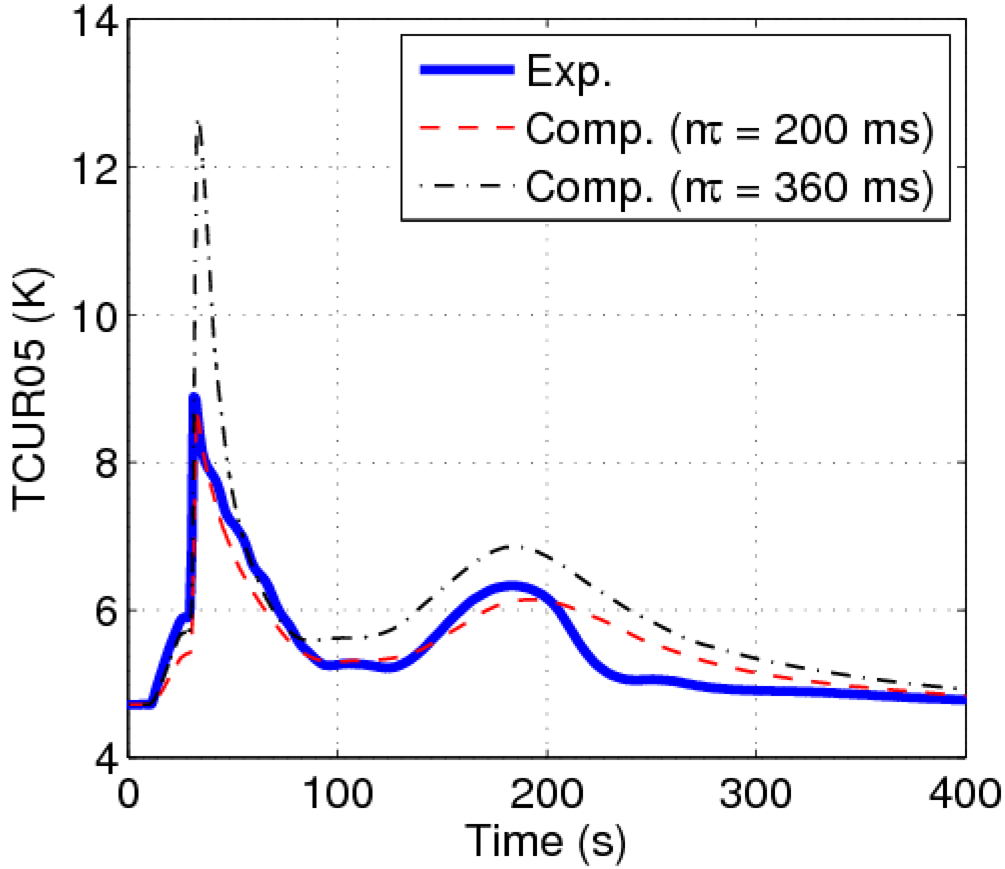
1 kA/s – 6 kA/s



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Conclusions and perspective

- A first analysis of a set of trapezoidal scenarios in the KSTAR PF1 coils has been performed with 4C
- At low ramp rates, 0.5-2 kA/s, $n\tau = n\tau_{opt}$ leads to very good agreement in the temperature signal at the coil outlet; other measured signals are also reproduced with acceptable qualitative agreement
- At higher ramp rates, 4-6 kA/s, $n\tau = n\tau_{opt}$ leads to overestimate the temperature at the coil outlet
- In all cases $n\tau_{opt} >> n\tau_{design}$ = 60 ms
- More detailed circuit modeling and AC loss analysis will be performed to confirm these results